Investigation of an Ultrafast Harmonic Resonant RF Kicker

By

Yulu Huang

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ABSTRACT

Investigation of an Ultrafast Harmonic Resonant RF Kicker

Yulu Huang (Nuclear Technology and Applications)

Directed by Dr. Hongwei Zhao, Dr. Haipeng Wang, Dr. Robert.A.Rimmer and Dr.

Shaoheng Wang

An Energy Recovery Linac (ERL) based multi-turn electron Circulator Cooler Ring (CCR) is envisaged in the proposed Jefferson Lab Electron Ion Collider (JLEIC) to cool the ion bunches with high energy (55 MeV), high current (1.5 A), high repetition frequency (476.3 MHz), high quality magnetized electron bunches. A critical component in this scheme is a pair of ultrafast kickers for the exchange of electron bunches between the ERL and the CCR. The ultrafast kicker should operate with the rise and fall time in less than 2.1 ns, at the repetition rate of ~ 10 s' MHz, and should be able to run continuously during the whole period of cooling. These specifications, high repetition rate and fast rise-and-fall time being combined together, are well beyond the state-of-art of traditional pulsed power supplies and magnet kickers.

To solve this technical challenge, an alternative method is to generate this high repetition rate, fast rise-and-fall time short pulse continuous waveform by summing several finite number of (co)sine waves at harmonic frequencies of the kicking repetition frequency, and these harmonic modes can be generated by the Quarter Wave Resonator (QWR) based multifrequency cavities. Assuming the recirculator factor is 10, 10 harmonic modes (from 47.63 MHz to 476.3 MHz) with proper amplitudes and phases, plus a DC offset are combined together, a continuous short pulse waveform

with the rise-and-fall time in less than 2.1 ns, repetition rate of 47.63 MHz waveform can be generated. With the compact and matured technology of QWR cavities, the total cost of both hardware development and operation can be reduced to a modest level.

Focus on the technical scheme, three main topics will be discussed in this thesis: the synthetization of the kicking pulse, the design and optimization of the deflecting QWR multi-integer harmonic frequency resonator and the fabrication and bench measurements of a half scale copper prototype.

In the kicking pulse synthetization part, we begin with the Fourier Series expansion of an ideal square pulse, and get a Flat-Top waveform which will give a uniform kick over the bunch length of the kicked electron bunches, thus the transverse emittance of these kicked electron bunches can be maintained. By using two identical kickers with the betatron phase advance of 180 degree or its odd multiples, the residual kick voltage wave slopes at the unkicked bunch position will be totally cancelled out. Flat-Top waveform combined with two kicker scheme, the transverse emittance of the cooling electron bunches will be conserved during the whole injection, recirculation, and ejection processes.

In the cavity design part, firstly, the cavity geometry is optimized to get high transverse shunt impedance thus less than 100 W of RF losses on the cavity wall can be achieved for all these 10 harmonic modes. To support all these 10 harmonic modes, group of four QWRs are adopted with the mode distribution of 5:3:1:1. In the multi-frequency cavities such as the five-mode-cavity and the three-mode-cavity, tunings are required to achieve the design frequencies for each mode. Slight segments of taper design on the inner conductor help to get the frequencies to be exactly on the odd harmonic modes. Stub tuners equal to the number of resonant modes are inserted to the outer conductor wall to compensate the frequency shifts due manufacturing

ABSTRACT

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errors and other perturbations during the operation such as the change of the cavity temperature. Single loop couple is designed for all harmonic modes in each cavity. By adjusting its loop size, position and rotation, it is possible to get the fundamental mode critical coupled and other higher harmonic modes slightly over coupled. A broadband circulator will be considered for absorbing the reflected power. Finally in this part, multipole field components due to the asymmetric cylindrical structure around the beam axis of the cavity as well as the beam-induced higher order mode (HOM) issues will be analyzed and discussed in this thesis.

A half-scale copper prototype cavity (resonant frequencies from 95.26 MHz to 857.34 MHz) was fabricated to validate the electromagnetic characteristics. With this half scale prototype, the tuning processes of multiple harmonic frequencies, unloaded quality factor measurements of each mode, and bead-pull measurements are performed. The bench measurement results matched well with the simulation results, which have validated our cavity design and construction methods. Finally, a simple mode combining experiment with five separate signal generators was performed on this prototype cavity and the desired fast rise/fall time (1.2 ns), high repetition rate (95.26 MHz) waveform was captured, which finally proved our design of this ultrafast harmonic kicker.

Key Words: fast kicker, QWR, deflecting, harmonic modes

CONTENTS

ABSTRACT	I
CONTENTS	1
CHAPTER 1 INTRODUCTION	1
1.1 OVERVIEW	1
1.2 JLEIC MULTI-TURN CIRCULATOR COOLER RING.....	4
1.3 ULTRA-FAST KICKER REQUIREMENTS IN THE MULTI-TURN ERL-CCR SCHEME	7
1.4 ORGANIZATION OF THE DISSERTATION	16
CHAPTER 2 CAVITY FUNDAMENTALS AND THE CRITICAL ISSUES IN CAVITY DESIGN	19
2.1 ACCELERATING OR DEFLECTING/CRABBING CAVITIES	19
2.2 SINGLE-FREQUENCY OR MULTI-FREQUENCY CAVITIES	23
2.3 SUPERCONDUCTING AND NORMAL CONDUCTING CAVITIES	24
2.4 RF PARAMETERS	25
2.5 TUNING OF THE RF CAVITIES	28
2.6 RF POWER COUPLING	28
2.7 PANOFSKY-WENZEL THEOREM	30
2.8 MULTIPOLE COMPONENTS	31
2.9 HIGHER ORDER MODES	36

CONTENTS

CHAPTER 3	HARMONIC KICKER WAVEFORM SYNTHESIZATION AND BEAM DYNAMICS TRACKING.....	39
3.1	HARMONIC KICKER WAVEFORM SYNTHESIZATION	39
3.2	BEAM DYNAMICS TRACKING SIMULATION IN ELEGANT.....	46
3.3	ERROR ANALYSIS.....	56
CHAPTER 4	DEFLECTING QWR HARMONIC CAVITY DESIGN	58
4.1	FIELD DISTRIBUTION IN THE DEFLECTING QWR HARMONIC CAVITY	58
4.2	MULTI-CAVITY SCHEME WITH KICK-DRIFT TRACKING.....	59
4.3	OPTIMIZATION OF THE TRANSVERSE SHUNT IMPEDANCE.....	63
4.4	TAPER SLOPE AND TUNER DESIGN	70
4.5	COUPLER DESIGN.....	77
4.6	RF PARAMETERS IN THE CAVITY	80
CHAPTER 5	MULTIPOLE ANALYSIS	82
5.1	FIELD NON-UNIFORMITY IN THE CAVITY AXIS.....	82
5.2	MULTIPOLE COMPONENTS IN THE CAVITY.....	83
5.3	EMITTANCE GROWTH CAUSED BY SEXTUPOLE.....	91
CHAPTER 6	HIGH ORDER MODES ANALYSIS.....	93
6.1	BEAM-INDUCED MODES.....	93
6.2	DEFLECTING WORKING MODES.....	98
6.3	HIGH ORDER MODES	100
CHAPTER 7	MECHANICAL DESIGN AND FABRICATION OF THE HALF SCALE COPPER PROTOTYPE	101

CONTENTS

7.1 FIBRACATION AND EBW OF THE OUTER CONDUCTOR.....	102
7.2 FIBRACATION AND EBW OF THE INNER CONDUCTOR.....	103
7.3 EBW OF THE OUTER CONDUCTOR WITH INNER CONDUCTOR.	106
7.4 DESIGN AND THE FIBRACATION OF THE STUB TUNERS.....	106
7.5 DESIGN AND THE FIBRACATION OF COUPLERS.....	107
7.6 DISCUSSION.....	108
CHAPTER 8 RF MEASUREMENTS OF THE HALF SCALE COPPER PROTOTYPE.....	109
8.1 RESONANT FREQUENCY AND TUNING SENSITIVITY MEASUREMENTS.....	109
8.2 TRANSMISSION AND REFLECTION COEFFICIENTS, UNLOADED QUALITY FACTOR Q MEASUREMENTS	112
8.3 BEAD-PULL MEASUREMENT.....	115
8.4 MODE COMBINATION EXPERIMENT.....	120
CHAPTER 9 CONCLUSION.....	123
REFERENCES.....	125
APPENDIX I LEAST-MODES + HIGHEST HARMONIC SCHEME.....	133
APPENDIX II GEOMETRY SHUNT IMPEDANCE FOR THE FIRST 100 MODES IN THE FIVE-MODE CAVITY	136
PUBLICATIONS	141

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Human exploration to the material world which we survive on in the world is an endless effort. Since last century, our cognition to the material structure gradually went thorough the atom and molecule levels, the nucleus level, the proton and neutron level, and finally the interior of the hardons, to the quarks and gluons level. As a very important instrument in the high energy physics researches, particle accelerators play a critical role during this period. At the same time, the relavent technologies of the particle accelerator developed rapidly with the motivation of the high energy physics requirements.

Exploring the substructure of matter with partial accelerator, the microscale it could achieve, which also the resolution capability λ (the De Broglie wavelength) is determined by the energy E of the beam be accelerated, as expressed in Equ.(1.1) .

$$\lambda = \frac{h}{p} = \frac{hc}{E\beta} \quad (1.1)$$

Here $h=4.136 \times 10^{-24}$ GeV•s is the Planck constant, $c=299792458$ m/s is the velocity of light in the vacuum, β is the relative velocity v/c , and when the particle velocity is close to the speed of light, $\beta \approx 1$. To explore the matter substructure in a deeper level, higher energy accelerator is needed. Fig.1.1 shows the scale of the material world and the corresponding observational methods^[1].

Comparing with the accelerated beams bomarding to fixed targets, the colliders could significantly increase the effictive interactive energies thus are favored by many laboratories around the world. The facilities currently under operation such as the

Large Hadron Collider (LHC) in European Organization for Nuclear Research (CERN)^[2], the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory (BNL)^[3], the B-factory (KEKB) in The High Energy Accelerator Research Organization (KEK)^[4], the Cornell Electron Storage Ring (CESR) in Cornell^[5], the Beijing Electron Positron Collider (BEPC) and its upgrade BEPC-II^[6]. Facilities that had already been shut down included the Electron-proton storage ring for particle physics (HERA) in German Electron Synchrotron (DESY)^[7], the Tevatron in Fermi National Accelerator Laboratory (FNAL)^[8], the Stanford Linear Collider (SLC)^[9], the Stanford Positron Electron Accelerating Ring (SPEAR)^[10], PEP and PEP-II^[11] in the Stanford Linear Accelerator Center (SLAC). And finally the facilities still under design and construction such as the International Linear Collider (ILC)^[12], the Circular Electron Positron Collider (CEPC)^[13] and Super proton-proton Collider (SppC)^[14] have resulted in extended discussions around Chinese scientific communities.

FIG.1.1 Scales of the material world and the corresponding observational methods

Advancing to the 21st century, a new frontier has emerged—understanding how quarks and gluons are assembled to form nucleons. The Nuclear Science Advisory Committee of the US Department of Energy and National Science Foundation considered and proposed an electron-ion collider as an ideal gluon microscope to fulfill the requirements of the experimental physics^[15-16]. Currently, within the United

States, two groups are independently studying the possibilities of electron-ion colliders (EICs).

At the Thomas Jefferson National Accelerator Facility (TJNAF or JLab), scientists utilizing its 12 GeV Continuous Electron Beam Accelerator Facility (CEBAF) as the full energy electron injector, have proposed to build such an electron-ion collider at JLab, which is called the JLab Electron Ion Collider (JLEIC, formerly MEIC)^[17-19], as shown in Fig.1.2. This collider is proposed to collide highly polarized electrons (3-10 GeV) with polarized protons (20-100 GeV), polarized light ions and heavy ions up to lead (8-40 GeV/u), center-of-mass energy is between 15 GeV-65 GeV, the design luminosity is $10^{34}\text{cm}^{-2}\text{sec}^{-1}$.

FIG.1.2 Schematic drawing of the proposed JLEIC at JLab

At the Brookhaven National Laboratory (BNL), with its Relativistic Heavy Ion Collider (RHIC), scientists have proposed to build such an electron-ion collider at BNL, which is called eRHIC (high energy electron-ion collider)^[20-21], as shown in Fig.1.3. This collider is proposed to collide polarized electrons (5-21 GeV) with protons (50-250 GeV) and heavy ions up to Au (100 GeV/u). The design luminosity of the electron-proton collision is $10^{34}\text{cm}^{-2}\text{sec}^{-1}$ and for the electron-Au collision is $10^{32}\text{cm}^{-2}\text{sec}^{-1}$.

FIG.1.3 Schematic drawing of the proposed eRHIC at BNL

1. 2 JLEIC MULTI-TURN CIRCULATOR COOLER RING

To achieve the high luminosity, a significant reduction of the six dimensional beam emittance is needed, and thus for delivering a small beam spot at the interaction point. For the electron bunches, their emittance can be maintained by the synchrotron radiation damping in the ring collider. For the ion bunches, the space charge effect at low energy will not only affect the accumulation of the ions, but also result to a large emittance growth. Without a synchrotron radiation damping, the emittance of ion bunches will be larger and larger under the effects of space charge and others. Then the ion bunches must be cooled to maintain a small emittance.

The present JLEIC design utilizes conventional electron cooling^[22], which was first demonstrated by Gersh Itskovich Budker in 1966. It utilizes the coulomb interactions between the electrons and heavy ions to compress the horizontal envelope, divergence angle and momentum spread of the heavy ions. The interaction process can be described as followings: Injecting a bunch of electrons with a great energy monochromaticity and collimation to a straight section inserted in the heavy ion storage ring. Adjusting the energy and direction of the electron bunches to make sure

the average velocity of the electrons is equal to the velocity of ions in the cooling section. The motion direction of the electron bunches is same to the ion bunches'. The electron bunches and ion bunches will exchange their energies and momentums via coulomb interactions. Since the electron mass is much smaller than heavy ions, the light electrons will take away the transverse and longitudinal momentum of heavy ions, thus to compress the horizontal envelope, divergence angle and momentum spread of the heavy ions without obvious beam loss of the heavy ion bunches. From the point of thermodynamics, the temperature of the electron bunches is much lower than the heavy ion bunches, with the heat exchange, the high-temperature ion bunches are cooled by the low-temperature electron bunches, that so called "electron cooling"^[23].

To achieve the design luminosity, JLEIC adopts a scheme of multi-phase cooling^[18-19], as listed in Table 1-1.

Table 1-1 JLEIC multi-phased electron cooling

	Phase	Function	Proton (Gev/u)	Electron (MeV)	Cooler type
Booster	1	Assisting accumulation of injected positive ions	0.11 ~ 0.19	0.062 ~ 0.1	DC Cooling
	2	Emittance reduction	2	1.09	
Collider Ring	3	Suppressing IBS and maintaining the emittance during stacking of beams	7.9	4.3	Bunched Beam Cooling (ERL)
	4	Suppressing IBS and maintaining the emittance during collision	100	55	

In the low energy booster, continuous electrons are called for cooling of coasting ion beam for assisting the accumulation of positive ions and reducing the initial

emittance of the ion bunches. The matured DC electron cooling is adopted. In the medium to high energy collider ring, the high-energy bunched magnetized electron beam will be responsible for the cooling of the medium energy ions (up to 100 GeV/u) and suppressing the Intra-beam scattering (IBS) to maintain the emittance during stacking of beams and collision. To get the high energy, high current, high repetition rate, and high quality magnetized electron bunches, the Energy Recovery Linac (ERL) based Circulator Cooler Ring (CCR) is proposed, as shown in Fig.1.4.

FIG.1.4 A schematic drawing of a bunched beam cooler based on an ERL, with upgrade circulator ring connection in green.

In the previous baseline design, JLEIC adopts a single turn ERL cooling scheme, as the black solid line shown in the Fig.1.4. In this design, the magnetized electron bunches (about 200 mA) from the source are accelerated in the SRF linac to the required energy (20-55 MeV), then the electrons will be merged with the ions, continuously cooling the ion bunches in a long cooling channel immersed in a strong solenoid field, then spent electrons are returned to the linac with a 180 degree rf phase shift for the energy recovery. Finally energy recovered electrons are sent to a dump; while the recovered energy is used to accelerate new incoming electron bunches.

A relative high electron beam current (about 1.5 A in 476.3 MHz repetition rate in continuous wave operation) is proposed for the upgrade scheme. To reduce the

technical challenges on the high current magnetized electron source, the high order modes (HOM) damping in the SRF ERL and the high beam power at dump, a multi-turn electron circulator cooler ring (CCR) is proposed to recirculate and reuse the low emittance electron bunches, as the green dot line shown in Fig.1.4. The electron bunches will be recirculated 10-30 (determined by the emittance maintainance of the cooling electron bunches and single injection bunch charge limit) turns in the CCR, hence the bunch repetition rate and the beam current in the source and the ERL can be reduced by an equal factor (from 150 mA, 10 turns, in 47.63 MHz repetition rate to 50mA, 30 turns, in 15.88 MHz repetition rate).

Current JLEIC design assumes the bunch repetition frequency is 476.3 MHz and the recirculating factor of the cooling electron bunches is 10 in the CCR, then the kicker is required to operate at a pulse repetition rate of 47.63 MHz with pulse width of around 2 ns. Only every the 10th bunch in the CCR will experience a transverse kick and be kicked to the ERL at the extraction kicker after performing cooling while the rest of bunches in the CCR will not be disturbed. A new bunch from the ERL will then be kicked to this blank space in the CCR with an identical injection kicker in order to continue the cooling at the same repetition rate.

1.3 ULTRA-FAST KICKER REQUIREMENTS IN THE MULTI-TURN ERL-CCR SCHEME

A critical component in this scheme is the ultrafast kicker needed to periodically deflect individual electron bunches in and out of the circulator ring from and to the driver ERL, while leaving the adjacent bunches in the orbit of the circulator ring undisturbed. For the current design, the repetition frequency of the cooling electron bunches is 476.3 MHz, which is equal to the repetition frequency of the ion bunches, this fast kicker should fulfill the following requirements.

(1) The repetition rate of the kicking pulse is $476.3 \text{ MHz}/N$, here N is the recirculating factor of the cooling electron bunches in the CCR, and is determined by the emittance maintainance requirement of the cooling electron bunches and the beam dynamics requirements of high single charge from the injector. In this paper, we use a recirculating factor of 10 for investigation, situations with more recirculating turns are also discussed based this design.

(2) The rise-and-fall time of the kicking pulse is less than 2.1 ns , which is corresponding to the 476.3 MHz bunch repetition frequency, thus only individual electron bunches will be deflected and leaving the adjacent bunches in the orbit of the circulator ring undisturbed.

(3) Assuming the kick angle is 1 mrad , then the required kick voltage is about 55 kV for the 55 MeV cooling electron bunches.

(4) The kicker should run continuously to provide a cooling beam to counteract the emittance growth during the cooling.

FIG.1.5 Schematic drawing of the kicking pulses

Fig.1.5 shows the schematic drawing of the kicking pulse. These specifications, with the high repetition rate and the fast rise-and-fall time combined together, are well beyond the state-of-art of traditional pulsed power supplies and the pulsed magnet kickers. Several solutions have been explored to pursue these technologies. Such as the Beam-beam kicker which adopts a high pulse current, low energy beam to produce the deflecting force, they normally provide a kick duration of less than a

nanosecond^[24]. And the RF harmonic kickers proposed to produce the pulses using harmonic rf cavities^[25-26].

1. 3. 1 BEAM-BEAM KICKER

The deflecting force of the beam-beam kicker is produced by a high peak current, low energy beam bunches (kicker-beam). This kicker beam can be injected into the vacuum chamber of the storage ring along or across the beam orbit. The beam-beam kicker with relative reasonable parameters can provide the kick duration of about fractions of a nanosecond. Depending on the injection position of the kicker beam, the beam-beam kicker can be classified as a head-on beam-beam kicker and a cross beam-beam kicker.

FIG.1.6 General scheme of a head-on beam-beam kicker

Fig.1.6 illustrates the principle of a head-on beam-beam kicker operation. The low energy, high peak current (electron) bunch is injected into the vacuum chamber of the storage ring. It moves at some the distance of d along the orbit of the high energy beam (HEB) circulating in the ring. Both the electric and magnetic forces of the low energy beam (LEB) kick the HEB when two bunches pass each other. The low energy beam (LEB) leaves the vacuum chamber goes to the beam dump before the arrival of the next high energy bunch. Therefore, the beam-beam kicker interacts with one bunch

only in the ring, and the kick duration is related to the LEB bunch length and the required spacings for the LEB injection and ejection. Assuming the total length is 60 cm and the LEB travels in the speed of light, and then the pulse duration time is about 2 ns. The pulse strength is determined by the distance d between the LEB and HEB, and the charge of the LEB.

FIG.1.7 General scheme of a cross beam-beam kicker

Fig.1.7 shows the scheme of this cross beam-beam kicker. The kicker beam travels across the orbit of the storage ring, thus this scheme requires no additional magnets for the injection and ejection of the kicker beam. Comparing with the head-on beam-beam kicker, a large advantage of this cross scheme is the kicking angle does not depend on the beam-beam distance d , if the distance d is much larger than the length of the LEB. But the kicking is produced only by the electric field while the magnetic force has a zero contribution as its integrating over the whole pass, then a higher beam charge of the LEB is required to achieve the same kicking strength.

The ultimate possibilities of the beam-beam kicker are determined by the source of the low energy beam. During operation, when the LEB travels through the vacuum chamber, it will generate a wakefield if the chamber is not perfectly conductive. A finite conductivity allows the induced magnetic field to penetrate into a metal wall

resulting the magnetic force decays more slowly than the electric force. This gives a net wakefield force in addition to the later bunches. Another matter must be taken into account is the LEB which is also deflected when passing by the high energy bunch. It will result in the emittance growth of the LEB and finally will affect the deflection stability. Finally, the charge stability of the kicker beam will also affect this deflection stability.

1.3.2 RF HARMONIC KICKER

An efficient rf-based kicker concept is proposed to produce the pulses using harmonic rf cavities. These cavities will simultaneously resonate at multiple harmonic frequencies and will be excited with appropriate amplitudes and phases which corresponding to the Fourier components of a periodic narrow pulse. This narrow pulse will then effectively synthesize a continuous waveform of periodic short pulses, as shown in Fig.1.8. The frequencies, phases, and relative amplitudes of each harmonic must be controlled precisely in order to maintain the pulse-to-pulse stability during the injection, recirculation and extraction of all bunches in the CCR.

FIG.1.8 Normalized continuous kicker waveform in 47.63 MHz repetition rate (bottom) resulting from the summation of a DC offset plus 10 harmonics of the base frequency of 47.63 MHz (top).

An early usage of the harmonic summation concept is a single-cavity, double-frequency buncher developed by S.O.Schriber and D.A.Swenson in Los Alamos in 1979 for the PIGMI project (pion generator for medical irradiation)^[27], as shown in Fig.1.9. The cavity utilizes the TM₀₂₀-like mode as the first harmonic of the fundamental TM₀₁₀-like mode. Field distributions on or near the axis, which seen by the beam, are essentially identical for these two modes. Many beam bunching applications require two bunchers being physically as close as possible. The harmonic buncher described next accomplishes this property with a single cavity with an excitation of two modes.

FIG.1.9 Geometry structure of the single-cavity double-frequency buncher is given at left. The electric field distributions in the quarter model are shown in the middle. The electromagnetic parameters of an aluminum prototype are list at right.

Followed this application, the harmonic summation concept was then used in the design of a multi-frequency RF structures. The multi-harmonic impulse cavities designed by F.Casper in CERN and Y.Iwashita in Kyoto University to achieve a high accelerating gradient^[28-29]. Since the duration time of the pulse is very short, a very high pulsed accelerating gradient can be achieved. With the superposition of a series of harmonic modes, the total power loss can be reduced significantly. Assuming the shunt impedances of all modes are same, for the single mode cavity, the total power loss is proportional to the square of the accelerating gradient. For the multi-frequency

cavities, the total power loss is the summation of the power losses of all harmonic modes. The power loss of each single harmonic is proportional to its own shunt impedance. Then the total power loss of whole system can be reduced by increasing the number of harmonic modes. Assuming the harmonic number is N , the accelerating gradient and the shunt impedance of each harmonic are the same, then the total power loss can be reduced by a factor of N with a multi-frequency structure. Fig.1.10 shows the copper prototype of a multi-frequency half-wavelength coaxial resonator developed Y.Iwashita. In this model, many tuners and couplers are designed to fine-tune the resonant frequency and coupling strength of each harmonic mode separately. The beam pipe is in the middle of the cavity structure. By the superposition of a series of cosine harmonics, the impulse wave can be used for the accelerating or for the deaccelerating. By the superposition of a series of sine harmonics, the impulse wave can be used for the bunching or for the debunching.

FIG.1.10 Copper prototype of a multi-frequency, half-wavelength coaxial resonator and the superposition of harmonics to generate the impulse train wave

Another application of the superposition of harmonic modes in the longitudinal direction is a compact noninvasive electron bunch-length monitor developed and tested by B.Roberts in 2012 ^[30-31]. A periodically bunched electron beam can be described mathematically as a Fourier series of expansion, expressed in compact trigonometric form in Equ.(1.2).

$$I(t) = a_0 + a_1 \cos(\omega_0 t + \theta_1) + a_2 \cos(2\omega_0 t + \theta_2) + a_3 \cos(3\omega_0 t + \theta_3) + \dots \quad (1.2)$$

Here $I(t)$ is the time-varying electron beam current. The constant term a_0 represents a DC offset. The ω_0 is the bunch repetition frequency. The amplitude and phase terms (a_n, θ_n) influence the bunch length and shape. The cavity bunch-length monitor described herein was designed to exclusively resonate at many harmonics of TM modes. The first mode, (TM010) is as same as the bunch frequency. The higher order modes (TM020, TM030, etc.) correspond to harmonic frequencies of the Fourier series expansion. When the electron bunches passing through the cavity, harmonic frequencies are excited, with the Fast Fourier Transform from the frequency domain to the time domain, the bunch distribution in the time domain can be get. Fig.1.11 shows the the cavity bunch-length monitor model and the TM modes from TM010 through TM080.

FIG.1.11 The cavity bunch-length monitor model and the TM modes from TM010 through TM080.

All the applications discussed above are to use the harmonic superposition concept in the longitudinal direction which is same to the beam motion. Applying the harmonic superposition concept in the transverse direction to deflect the beam for separation purpose has already been discussed by George D.Gollin from the

University of Illinois at Urbana Champaign in 2002. In his report, a Fourier Series Kicker which use a series of Fourier harmonic waves to approximate the required short kicking pulse is proposed for the TESLA Damping Ring^[25]. Fig.1.12 shows the Fourier series kicker scheme. In this design, 16 cavities are adopted to generate 16 harmonic modes. With the synthesized waveform, every 33th bunch will experience a transverse kick while the rest bunches will not be disturbed. The duration time of the kicking pulse is several nanoseconds and the repetition frequency of the pulse is several MHz. But the kicker is not in the ring, it was designed to be on the bypass and only be excited in the injection and ejection process.

FIG.1.12 Fourier series kicker scheme in the TESLA Damping Ring

Consider for the long-term stable cw operation, a simple solution is to introduce a skew beam pipe to a longitudinal kicker device like the compact noninvasive electron bunch-length monitor^[30-31], and establish a series of harmonic electromagnetic fields in the cavity with external power supplies, thus the bunch can be kicked by the transverse component of the longitudinal kick. However, the longitudinal component still has a non-negligible effect on the bunch, which will reduce the kicker efficiency and may result in longitudinal instability in the circulation ring^[26].

Another transverse kick application is a traditional stripline kicker with a compact structure developed for the SLAC PEP-II project^[32-35]. Fig.1.13 shows the 3D model of the stripline kicker, the electromagnetic field distribution in the center cross section, and the external circuit. In this design, the electron bunches are deflected by the TEM wave traveling through two electrodes in opposite pole. To avoid the cancellation of the electric deflection and magnetic deflection, the electron bunches must travel in the opposite direction of the TEM traveling wave. However as a traveling wave device, a significant power is required, most of which ends up to the matching loads.

FIG.1.13 3D model of the stripline kicker, the electromagnetic field distribution in the center cross section, and the external circuit.

1. 4 ORGANIZATION OF THE DISSERTATION

Chapter 2 gives a brief introduction of the RF cavity fundamentals, with a discussion about the critical problems in the cavity design. Comparisons between the accelerating cavities and deflecting cavities, single-frequency cavities and multi-frequency cavities, normal conducting cavities and superconducting cavities are briefly discussed. The RF properties related to the resonant cavities, such as the

unloaded quality factor, the shunt impedance and so on, are derived. Other critical issues such as the multipole components and high order modes are also investigated.

Chapter 3 gives a detailed discussion on the synthesization of the harmonic waveform and the beam dynamics tracking simulation in ELEGANT. Four different kicking waveforms are compared in this chapter: the Flat-Top waveform gives a uniform kick for the kicking bunch, the Zero-Gradient waveform gives zero gradient for the recirculating bunch; the Least-Mode waveform has the least number of required harmonics, and the Equal-Amplitude waveform has every harmonic with equal amplitude with no DC offset. ELEGANT tracking simulation was taken for the one-kicker, two-kicker, and multi-kicker situations. The best kicking pulse for each situation is discussed based on the transverse emittance growth of the electron bunches during the recirculation. Finally, the error analysis is done for all kicking waveforms.

Chapter 4 introduces the design and optimization of the harmonic kicker cavity. Multi-cavity scheme is introduced with the related beam dynamics tracking simulation in ELEGANT. The cavity geometry is optimized to achieve high transverse shunt impedance thus reducing the total power loss. The stub tuner design and coupler design for the multi-frequency harmonic cavity design are discussed based on the 5-mode cavity in detail.

Chapter 5 describes the geometry related field non-uniformity and the calculation methods for the multipole components. ELEGANT tracking simulation with the sextupole components was done and shows ignorable effect on the beam emittance.

Chapter 6 gives the detailed calculation of the high order modes (HOM) in the cavity. In this chapter, HOMs excited by the continuous electron bunches with single time structure was analyzed and the methods to calculate the HOM power loss are derived. Eigenmode simulation of the first 100 modes on the five-mode cavity shows that the HOM power loss of the high order modes that aboving the deflecting working

modes are ignorable. Significant power loss on the highest deflecting working mode (476.3 MHz mode, which is equal to the bunch repetition frequency) can be avoided by the structure design optimization.

Chapter 7 covers the details of the design and fabrication process of a half scale 5-mode cooper cavity prototype, including the selection of the cavity material, the electron beam welding (EBW) of the cavity components as well.

Chapter 8 describes the bench measurements on this half scale prototype cavity, and the comparison between the simulation and the measurement results. The tuning sensitivity, unloaded quality factors, the field distribution measurements with the bead-pull technique, and finally the modes superposition experiment are carried out and reported here.

The conclusions are made in Chapter 9, including the work that already done and the plan for the next step. Such as the beam dynamics tracking simulation with 3D field map, the construction of the vacuum prototype cavity, the preparation of the multi-turn recirculating test facility, and kicking field uniformity improvement etc.

CHAPTER 2

CAVITY FUNDAMENTALS AND THE CRITICAL ISSUES IN CAVITY DESIGN

The most important and common used acceleration components in the particle accelerator are the RF cavities to impart energy or momentum to the transversing charged particles. Depending on the application, RF cavity can be in an optimized design to be for particle accelerating or deflecting, at single-frequency or multi-frequency, and built as superconducting or normal conducting.

2.1 ACCELERATING OR DEFLECTING/CRABBING CAVITIES

The most common rf cavity used in the particle accelerator is the elliptical cavity that operated in the TM₀₁₀ mode^[36], where the longitudinal momentum is generated by the on-axis longitudinal electric field. Elliptical cavities are mainly used in the acceleration for high velocity beta particles. For the low-beta and medium-beta particles, the TEM class cavities are widely used to get a compact cavity structure, such as the spoke cavity^[37], Half Wavelength Resonator^[38] and Quarter Wavelength Resonator^[39].

Unlike the accelerating cavities discussed above, the deflecting and crabbing cavities are the rf structures that used to give a transverse momentum to the charged particles. The rf structure of the deflecting and crabbing cavities are the same, the only difference is the rf phase relative to the beam bunch when the transverse momentum is applied. For the deflecting cavities, a net transverse momentum is applied at the center of the bunch. The whole bunch will then be deflected away from the original orbit for bunch separation applications. For the crabbing cavities, opposite transverse

momentum is applied at the head and tail of the bunch, thus the bunch will be rotated to enable the head-on collision at the interaction point in the collider design. Fig.2.1 shows the bunch separation scheme in a deflecting cavity system and its dependence of the angle of displacement on the beam energy and transverse voltage, and Fig 2.2 shows the bunch rotation scheme in a crabbing scheme and the head-on collision at the interaction point in a particle collider^[40]. Except the applications discussed above, the deflecting and crabbing cavities can also be used in the beam diagnostics^[41], beam emittance exchange^[42] and short pulse x-ray generation using compressed beam bunches^[43].

FIG.2.1 Bunch separation scheme in a deflecting cavity system and its dependence of the angle of displacement on the beam energy and transverse beam voltage.

FIG.2.2 Bunch rotation scheme in a crabbing scheme and the head-on collision at interaction point in a particle collider.

The first normal conducting deflecting cavity is at 2.856 GHz, a rectangular deflecting cavity designed at Stanford in 1960^[44], as shown in Fig.2.3. The cavity was operated in TM_{012} mode, and the electron bunches were mainly deflected by the magnetic field.

FIG.2.3 First normal conducting cavity developed by Stanford.

The first superconducting deflecting cavity was designed by the CERN-KfK Karlsruhe collaboration in 1977. It was a disk-loaded niobium cavity operated at TM_{110} mode. The operation temperature is 1.8K, resonant frequency is 2.856 GHz. The total length of the cavity is 2.74 m with 104 elements, as shown in Fig.2.4^[45].

FIG.2.4 First superconducting deflecting cavity developed by CERN-KfK Karlsruhe collaboration.

The first superconducting crabbing cavity is a 508.9 MHz squashed elliptical cavity operated at TM_{110} mode developed and installed in 2007 at KEK for the KEKB electron-positron collider, as shown in Fig.2.5^[46]. A similar cavity structure was then developed at Argonne National Laboratory (ANL) for the Advanced Photon Source (APS) to generate short pulsed x-ray, as shown in Fig.2.6^[47-48]. For the elliptical cavities operated in the TM_{110} mode, the on-axis longitudinal electric field is zero and the deflection is mainly contributed by the transverse magnetic field. For a symmetrical geometry, this mode has two polarizations with the same frequency (degeneracy) that generates a transverse momentum in two directions perpendicular each other. Therefore the geometry is adapted into a squashed elliptical shape to remove the degeneracy of the two polarizations. This kind of deflecting cavity is mainly used in the high frequency situation, in the low frequency situation, the cavity size is large with a possible poor mechanical stability.

FIG.2.5 First superconducting crabbing cavity developed in KEK.

FIG.2.6 Squashed elliptical cavity used at ANL to generate short pulsed x-ray.

Just like the accelerating structure, it is also feasible to use the TEM-like structure for deflecting and crabbing applications in the low frequency, such as the parallel-bar structure^[49], the RF-dipole structure^[50], the double quarter wave resonator (DQWR) structure^[51] and the single quarter wave resonator which will be discussed in the paper. Fig.2.7 shows the geometry structure of the Parallel-bar cavity, the RF-dipole cavity, and the Double Quarter Wave Cavity.

FIG.2.7: The geometry structures of Parallel-bar, RF-dipole, and Double Quarter Wave cavities.

2. 2 SINGLE-FREQUENCY OR MULTI-FREQUENCY CAVITIES

The resonant frequencies in the rf cavities are always not in single mode. Once the cavity geometry is determined, infinite resonant frequencies are excited within the cavity boundary. Generally, the working mode is the lowest frequency mode in the cavity, which is called the fundamental mode. The cavity geometry is optimized at this frequency and the unwanted high order modes above this working mode are damped. In some special applications, a series of working modes are required. Then multiple cavities or multiple modes resonant within one cavity are needed.

When designing a RF cavity with multiple resonant modes simultaneously, two critical techniques are the tuning of each mode and the input power supply for each mode. In the tuning process, it is critical to consider the cross-talk between all these

modes when trying to tune them separately. For the input power coupling, it is critical to mention the reflected power when coupling all modes with a single input coupler. The cross-talk between these modes when coupling each mode with a separated coupler is another issue.

Commonly used multi-frequency rf cavities include the disk cavities operated at TM_{0N0} mode ^[30-31], half wavelength resonator ^[29], and the quarter wavelength resonator which will be discussed in this paper.

2. 3 SUPERCONDUCTING AND NORMAL CONDUCTING CAVITIES

Choosing superconducting or normal conducting technology in a particle accelerator is mainly determined by the beam energy, beam current, beam power and the duty factor with the considerations of the construction and operation costs, technology in use risk and the operation stability^[52]. Generally, the room-temperature operation is favourable in the low energy, high beam power and low duty factor situation. The superconducting technologies are more favourable in the high energy, low beam power and high duty factor situation.

From the point of the cavity itself, the advantages of the normal conducting cavities are less infrastructural required, simpler technology (if it is in the pulsed mode operation) and simpler tuning process. The disadvantages are higher RF power, more expensive amplifiers, thermal problems and lower gradients (if it is in a high duty factor operation mode). The main advantages of the superconducting cavities are superior cooling by the liquid helium thus possible less thermal problems, stable operation, less RF power, smaller amplifiers, well suited for the cw operation and for a larger beam aperture. The disadvantages are less tolerant against beam loss, cryogenic system requirement, and complicated cavity fabrication and more sensitive to the

external disturbance, such as the microphonics, Lorentz force detuning, and helium pressure fluctuation and so on.

2. 4 RF PARAMETERS

In general, the rf parameters of the resonant cavity can be divided into two groups [52], as summarized followings.

(1) RF parameters depend on the surface resistance R_s , such as the power loss on the cavity wall P_c , the unloaded quality factor Q_0 , the shunt impedance R_{sh} and so on. These parameters are significantly different for superconducting and normal conducting cavities.

(2) RF parameters independent on the surface resistance R_s , such as the geometry shunt impedance R_{sh}/Q_0 and the geometry factor G . These parameters are only dependent on the geometry of the cavity. It is mostly used to compare different cavity geometries independent to the preference of the technology.

2. 4. 1 SURFACE RESISTANCE R_s

In the case of normal conducting cavities, the surface resistance is mainly determined by the cavity frequency. The surface resistance is proportional to the square root of the frequency, as shown in Equ.(2.1).

$$R_s = \sqrt{\frac{\pi \mu f}{\sigma}} \quad (2.1)$$

Here μ is the permeability of the cavity wall, σ is the conductivity of the cavity wall, f is the cavity resonant frequency. The resistance of the normal conducting cavity in copper is normally several $m\Omega$.

In the case of superconducting cavities in niobium, the surface resistance includes two parts. One is the residual resistance, which is determined by the surface process

technology. The other one is the BCS resistance, which is related to the temperature and frequency, as shown in Equ.(2.2).

$$R_s(BCS) = 2 \bullet 10^4 \frac{1}{T} \left(\frac{f}{1.5}\right)^2 e^{\frac{17.67}{T}} \quad (2.2)$$

Here T is the operation temperature of the cavity. The BCS resistance is highly dependent on the temperature. It decreases exponentially with lower temperature. And on the other hand, the BSC resistance increases quadratically with the frequency. As a consequence, 4 K is chosen as the operation temperature when the cavity frequency is low and 2 K is normally chosen at higher frequencies.

The surface resistance of superconducting niobium cavities is typically several nΩ, about five orders of magnitude lower than for normal conducting copper cavities.

2. 4. 2 DISSIPATED POWER P_c

The surface resistance results in a dissipation of energy on the cavity wall, which could be calculated by Equ.(2.3).

$$P_c = \frac{1}{2} R_s \int |H|^2 dS \quad (2.3)$$

Here S is the whole cavity inner surface area.

The power losses are normally several orders of magnitude lower for superconducting niobium cavities than normal conducting copper cavities because of the surface material resistance dependency.

2. 4. 3 UNLOADED QUALITY FACTOR Q_0

The unloaded quality factor of a cavity is defined by Equ.(2.4).

$$Q_0 = \frac{\omega U}{P_c} \quad (2.4)$$

Here U is the stored energy, and can be calculated by the integration of the electric or magnetic field in the cavity, as Equ.(2.5).

$$U = \frac{1}{2} \mu_0 \int |H|^2 dV = \frac{1}{2} \epsilon_0 \int |E|^2 dV \quad (2.5)$$

Here V is the cavity volume. The stored energy is independent to the surface resistance. It depends only on the cavity geometry and the field level.

The unloaded Q factor depends inversely proportionally on the surface resistance. Typical Q_0 for normal conducting cavities are between 10^3 and 10^5 , and between 10^7 and 10^{11} for superconducting cavities.

2. 4. 4 SHUNT IMPEDANCE R_{sh}

The shunt impedance describes the ability of the cavity to convert RF power into voltage, and can be defined as Equ.(2.6).

$$R_{sh} = \frac{V^2}{P_c} \quad (2.6)$$

The ratio of the shunt impedance and the unloaded quality factor can be defined as the geometry shunt impedance, as shown in Equ.(2.7).

$$\frac{R_{sh}}{Q_0} = \frac{V^2}{\omega U} \quad (2.7)$$

The geometry shunt impedance is independent to the surface resistance, and can be used to compare different RF structures.

2. 4. 5 GEOMETRY FACTOR G

Another rf parameter that independent to the surface resistance is the geometry factor G, which is defined as the product of surface resistance R_s and quality factor Q_0 , as shown in Equ.(2.8).

$$G = R_s Q_0 = \frac{\omega \mu_0 \int |H|^2 dV}{\int |H|^2 dA} \quad (2.8)$$

For a given frequency and field distribution, the geometry factor is also related to the ratio between the cavity volume and cavity surface.

2. 5 TUNING OF THE RF CAVITIES

RF cavities should be tuned to its designed target frequency during the operation to achieve excellent performance. The tuning of the cavity is based on the Slater perturbation theory, which describes the tuning of cavity frequencies with the perturbation on the electromagnetic fields.

There are two methods to tune the cavity, one is the volumetric perturbation, which is to change the cavity frequency by deforming the cavity with squeezing or stretching on one cavity dimension; the other one is the material perturbation, which is to change the cavity frequency by inserting perturbation object to the cavity.

2. 6 RF POWER COUPLING

The electromagnetic fields in the rf cavity are produced by the rf power generated and transmitted by an external power source such as power amplifiers or high power klystrons. The two main choices of rf couplers are coaxial antennas and waveguides. The preference of a coupler type in any cavity system is determined by the cavity frequency, cavity type, use of standing wave or travelling wave, maximum rf power required to be transmitted, and the pulsed or continuous wave (cw) operation. The coaxial type couplers are more compact compared to waveguides where the size of the waveguide coupler is determined by the cut off frequency.

There are always at least two coupler ports in the cavity design, one is for the input power, and the other one is for the RF signal pick up. More couplers are needed when HOM damping is necessary.

At each coupler port, the coupling strength of the resonant mode can be determined by the external quality factor, which is defined in Equ.(2.9).

$$Q_{ext} = \frac{\omega U}{P} \quad (2.9)$$

Where ω is the cavity resonant angular frequency, U is the stored energy of the cavity and P is the power exiting the cavity through the power coupler with a matched load. Higher external Q means less power exiting the cavity through this port, and the coupling strength is weaker.

For the cavities only with one input coupler port and one pick up port, the total RF power loaded to the cavity system includes three parts, the power dissipated in the cavity wall P_c , the power exiting the cavity through the input coupler port P_1 and the power exiting the cavity through the pickup coupler port P_2 , as described in Equ.(2.10).

$$P_{total} = P_c + P_1 + P_2 \quad (2.10)$$

Divided by ωU at each hand,

$$\frac{P_{total}}{\omega U} = \frac{P_c}{\omega U} + \frac{P_1}{\omega U} + \frac{P_2}{\omega U} \quad (2.11)$$

Then the relations of the quality factors of each part can be summarized in Equ.(2.12).

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext1}} + \frac{1}{Q_{ext2}} \quad (2.12)$$

Here Q_L is defined as the loaded quality factor.

The coupling strength at the input coupler port β_1 can be defined as:

$$\beta_1 = \frac{P_1}{P_c} = \frac{Q_0}{Q_{ext1}} \quad (2.13)$$

The coupling strength at the input coupler port β_2 can be defined as:

$$\beta_2 = \frac{P_2}{P_c} = \frac{Q_0}{Q_{ext2}} \quad (2.14)$$

Then the Equ.(2.12) can be rewritten as Equ.(2.15).

$$\frac{Q_0}{Q_L} = 1 + \beta_1 + \beta_2 \quad (2.15)$$

In the cavity rf measurements, the unloaded quality factors of the resonant modes can be calculated from Equ.(2.15) by measuring the loaded factors Q_L , coupling strengths β_1 and β_2 at each port.

2. 7 PANOFSKY–WENZEL THEOREM

For the deflecting and crabbing cavities, the transverse momentum acquired by the particle can be related to the transverse gradient of the longitudinal electric field along the beam axis by Panofsky-Wenzel Theorem.

In 1956, W.K.H.Panofsky and W.A.Wenzel found that when the charged particles passing through the TE mode cavity (no electric field component along the beam motion direction), the deflection from the electric field and the magnetic field were cancelled, they gave the conclusion that pure TE mode can not be used for deflection [53]. This conclusion is sometimes misinterpreted as concluding that if the electric field acting on a particle is purely transverse, the deflection impulses from the electric and magnetic fields must cancel one another.

In 1993, M.Jean Browman rederived Panofsky and Wenzel's result and showing that, for a non-TE mode cavity, the longitudinal electric field can be zero everywhere along the path of the particle and still not be identically zero everywhere in the cavity. In such a non-TE mode, the transverse gradient of the longitudinal electric field does not have to be zero along the path of the particle, so the particle can be deflected [54].

In deflecting and crabbing cavities the transverse momentum experienced by a particle passing along the beam axis is a direct result of the interaction of the particle and the transverse electric and magnetic field components present in the cavity, as shown in Equ.(2.16).

$$\vec{p}_t = \int_{-\infty}^{\infty} \vec{F}_t dt = \frac{q}{\beta c} \int_{-\infty}^{\infty} [\vec{E}_t + \vec{v} \times \vec{B}_t] dz \quad (2.16)$$

Where $\vec{F}_t$ the transverse Lorentz Force, q is the charge of the particle, $\vec{v}$ is the velocity of the particle of magnitude v , and $\vec{E}_t$ and $\vec{B}_t$ are the corresponding transverse electric and magnetic field components. Equ.(2.16) is strictly valid only when the longitudinal velocity $v_z = \beta c$ is much larger than the transverse velocity, and when the velocity does not change too much in the cavity.

According to the Panofsky-Wenzel Theorem, the transverse momentum experienced by the charged particles can also be calculated from the transverse gradient of the longitudinal electric field along the beam axis, as shown in Equ.(2.17).

$$\vec{p}_t = -i \frac{q}{\omega} \int_{-\infty}^{\infty} \vec{\nabla}_t E_z dt = -i \frac{q}{\omega} \lim_{r_0 \rightarrow 0} \frac{1}{r_0} \int_{-\infty}^{\infty} [E_z(r_0, z) - E_z(0, z)] dz \quad (2.17)$$

Where ω is the frequency of the deflecting mode, r_0 is the transverse off set in the direction of the deflection from the beam axis, and $E_z(r_0, z)$ is the longitudinal electric field component at the off set r_0 . This theorem is valid for any type of deflecting mode of any geometry. The entire length along the beam line must be considered in determining the transverse voltage since a small amount of the transverse field extends into the beam apertures at the ends of the cavity.

2.8 MULTIPOLE COMPONENTS

In the design and construction of the rf cavities, the extrusion of the all ports including power coupler, vacuum pumping, signal pick up, high order modes coupler and other considerations on the cavity geometry design, will result to a complex asymmetry cavity structure. The asymmetric cylindrical structure will produce higher order multipole field components, such as quadrupole, sextupole and octopole, which could lead to the beam emittance growth and affect the beam quality.

2. 8. 1 INFLUENCE OF THE MULTIPOLE COMPONENTS ON BEAM DYNAMICS

The motion of particles in an accelerator can be described by a six dimensional vector (x, y, p_x, p_y, s, p_z) , where s is the longitudinal position of the particle along the beam orbit, p_z is the longitudinal momentum of the particles, x and y are the horizontal and vertical position, and p_x and p_y are the corresponding transverse momentum.

The analysis of the multipole components in the rf cavity can refer to the analysis methods in the magnetic multipole field. Unlike in the DC magnets, rf cavities have a monopole components b_0 where the integrated component corresponds to the accelerating voltage^[40].

$$\Delta p_z = \int b_0 ds \quad (2.18)$$

For deflecting and crabbing rf cavities with symmetry structures, the monopole component is zero, however it may exist in the presence of any deformation in the rf structure, such as the extrusion of enlarged beampipes, power coupler ports, higher order modes coupler ports, vacuum ports and so on.

The dipolar kick seen by the particles is given by the integrated dipole component b_1 , where the integrated component corresponds to the transverse momentum change of the particles.

$$\Delta p_x = \int b_1 ds \quad (2.19)$$

The tune is the number of oscillations for a complete revolution where the corresponding tune shift (ΔQ) depends on the quadrupole multipole component. The horizontal and vertical tune shift are given by Equ.(2.20).

$$\Delta Q_{x,y} = \mp \frac{1}{4\pi} \frac{q}{p} b_2 \beta_{x,y} \quad (2.20)$$

where $\beta_{x,y}$ is the beta function at the rf cavity location.

The variation of the tune with momentum defined as the chromaticity ξ is given by

$$\xi_{x,y} = \frac{\Delta Q_{x,y}}{\Delta p/p} = \mp \frac{1}{4\pi} \int b_2 \beta_{x,y}(s) ds \quad (2.21)$$

The chromaticity shift depends on the sextupole component b_3 and can be determined by

$$\Delta \xi_{x,y} = \pm \frac{1}{2\pi} \frac{q}{p} b_3 D \beta_{x,y} \quad (2.22)$$

where D is the dispersion.

The amplitude detuning is the dependency of the tune on the amplitude of the oscillations which depends on the octupolar component b_4 and is defined as

$$\Delta Q_{x,y} = \frac{3}{8\pi} \frac{q}{p} b_4 \beta_{x,y}^2 9J_{x,y} \quad (2.23)$$

The analysis of the multipole components is up to octupolar component, higher multipole components are much weaker and their contributions to transverse beam dynamics are negligible. The numerical values obtained by rf cavities can be compared to that from magnets in the accelerator in understanding the severity of the effects and can be minimized by modifying the rf geometry.

2.8.2 CALCULATION OF THE MULTIPOLE COMPONENTS IN RF CAVITIES

The representation of the multipole components in the rf cavityies can be derived similarly to the multipole fields presented in a magnet. The fields in the magnets are often expressed in terms of multipole components^[55], as shown in Equ.(2.24).

$$B(r, \phi) = B_{ref} \sum_{n=1}^{\infty} (a_n + ib_n) \left(\frac{r}{r_{ref}} \right)^{n-1} e^{i(n-1)\phi} \quad (2.24)$$

Here B_{ref} is the magnetic strength on the reference orbit, a_n is the normal multipole components of the nth multipole component, b_n is the skew multipole components of

the n th multipole component. Here $n=1$ is corresponding to the dipole field, $n=2$ is corresponding to the quadrupole field, $n=3$ is corresponding to the sextupole field and $n=4$ is corresponding to the octupole field, and so on. Unlike magnetic field in a magnet, the rf B field has the monopole component $n=0$, which is independent to the r dimension. It only exists in the pure TE_{0xx} (in cylindrical coordinate) type of rf cavity.

Similarly, close to the beam axis, the electromagnetic fields in an rf cavity within the beam aperture can be represented as a similar form ^[56].

$$E_{acc}(r, \phi, z) = E_z(r, \phi, z) = \sum_{n=0}^{\infty} E_z^{(n)}(z) r^n e^{jn\phi} \quad (2.25)$$

$$E_{def}(r, \phi, z) = E_x(r, \phi, z) = \sum_{n=1}^{\infty} E_x^{(n)}(z) r^{n-1} e^{j(n-1)\phi} \quad (2.26)$$

$$H_{def}(r, \phi, z) = H_y(r, \phi, z) = \sum_{n=1}^{\infty} H_y^{(n)}(z) r^{n-1} e^{j(n-1)\phi} \quad (2.27)$$

Where z -direction is the particle moving direction and x -direction is the deflecting direction. The monopole component $n=0$ of E field exists in the z direction however, which contributes to the beam energy gain/loss, is independent to the r dimension. Only $n=1$ term of E_z component is related to the deflecting E or B field which has been described by the Panofsky-Wenzel Theorem mentioned above.

The multipole field components $E_z^{(n)}(z)$, $E_x^{(n)}(z)$, $H_y^{(n)}(z)$ along the beam line can be obtained by using the Fourier series expansion of $E_z(r, \phi, z)$, $E_x(r, \phi, z)$, $H_y(r, \phi, z)$ as shown in Equ.(2.28-2.30).

$$E_z^{(n)}(z) = \frac{1}{2\pi} \int_0^{2\pi} E_z(r, \phi, z) e^{-jn\phi} d\phi \quad (2.28)$$

$$E_x^{(n)}(z) = \frac{n}{2\pi} \int_0^{2\pi} E_x(r, \phi, z) e^{-j(n-1)\phi} d\phi \quad (2.29)$$

$$H_y^{(n)}(z) = \frac{n}{2\pi r^{n-1}} \int_0^{2\pi} H_y(r, \phi, z) e^{j(n-1)\phi} d\phi \quad (2.30)$$

Expanding them in the azimuthal direction,

$$E_z^{(n)}(z) = \frac{1}{\pi r^n} \int_0^{2\pi} E_z(r, \phi, z) [\cos(n\phi) + i \sin(n\phi)] d\phi \quad (2.31)$$

$$E_x^{(n)}(z) = \frac{n}{2\pi r^{n-1}} \int_0^{2\pi} E_x(r, \phi, z) [\cos((n-1)\phi) + i \sin((n-1)\phi)] d\phi \quad (2.32)$$

$$H_y^{(n)}(z) = \frac{n}{2\pi r^{n-1}} \int_0^{2\pi} H_y(r, \phi, z) [\cos((n-1)\phi) + i \sin((n-1)\phi)] d\phi \quad (2.33)$$

Here the real part is the normal multipole component, and the image part is the skew multipole component.

The time dependent multipole field components can be expressed as,

$$E_z^{(n)}(z, t) = \frac{1}{\pi r^n} \int_0^{2\pi} E_z(r, \phi, z) e^{jn\phi} e^{j\omega t} d\phi \quad (2.34)$$

$$E_x^{(n)}(z, t) = \frac{n}{2\pi r^{n-1}} \int_0^{2\pi} E_x(r, \phi, z) e^{j(n-1)\phi} e^{j\omega t} d\phi \quad (2.35)$$

$$H_y^{(n)}(z, t) = \frac{n}{2\pi r^{n-1}} \int_0^{2\pi} H_y(r, \phi, z) e^{j(n-1)\phi} e^{j\omega t} d\phi \quad (2.36)$$

The transverse momentum acts on the particles from the nth multipole component can be calculated by

$$\Delta p_t^{(n)}(z) = \frac{1}{c} r^{n-1} \int_{-\infty}^{\infty} F_t^{(n)}(z) dz \quad (2.37)$$

This transverse momentum can be calculated with two methods.

(1) Panofsky-Wenzel Theorem:

$$\Delta p_t^{(n)}(z) = -j \frac{q}{\omega} \int_{-\infty}^{\infty} \nabla_t E_z^{(n)}(z) e^{j\omega t} dz \quad (2.38)$$

(2) Lorentz Force:

$$\Delta p_t^{(n)}(z) = \frac{q}{c} r^{n-1} \int_{-\infty}^{\infty} [E_x^{(n)}(z)e^{j\omega t} + jcB_y^{(n)}(z)e^{j\omega t}] dz \quad (2.39)$$

For relativistic particles traversing through an rf cavity, the multipole components are defined following the standard definition for magnets,

$$A_z^{(n)} + jB_z^{(n)} = \frac{1}{qc} F_t^{(n)}(z) \quad [\text{T/m}^{n-1}] \quad (2.40)$$

The above equation can be also expressed by following the Panofsky-Wenzel Theorem,

$$A_z^{(n)} + jB_z^{(n)} = -j \frac{n}{\omega} E_{acc}^{(n)}(z, t) = -j \frac{n}{\omega} E_z^{(n)}(z) e^{j\omega t} \quad (2.41)$$

Or by

$$A_z^{(n)} + jB_z^{(n)} = \frac{1}{c} [E_x^{(n)}(z) + jcB_y^{(n)}(z)] e^{j\omega t} \quad \text{following Lorentz force method as,} \quad (2.42)$$

The multipole component factors can be calculated from the integration by the following,

$$a_z^{(n)} + jb_z^{(n)} = \int_{-\infty}^{\infty} [A_z^{(n)} + jB_z^{(n)}] dz \quad [\text{T/m}^{n-1}] \quad (2.43)$$

where b_n corresponding to the normal part and a_n corresponding to the skew part.

2. 9 HIGHER ORDER MODES

The parasitic modes in any resonant rf structure are the modes present in the cavity, in addition to the fundamental operating mode that are excited by the beam. Depending on the frequencies, these parasitic modes can be divided into three classes.

(1) Low Order Modes (LOM), modes with frequencies below the operating frequency;

(2) Same Order Modes (SOM), modes with closed frequencies to the fundamental pi mode within the same passband but with different field configuration from the pi mode;

(3) High Order Modes (HOM), modes with frequencies above the operating frequency.

Beam passing through the cavity, the parasitic modes are excited. These beam-induced modes will cause significant rf power loss, and affect the following bunches' beam quality in the high current situation.

The beam-induced power depends on the intensity and the decay time of each mode. The intensity of each mode is determined by the longitudinal and transverse geometry shunt impedance [R/Q], where the longitudinal [R/Q] can be calculated from Equ.(2.44),

$$\left[\frac{R}{Q} \right]_{z,n} = \frac{V_{z,n}^2}{\omega_n U} = \frac{\left| \int_{-\infty}^{\infty} E_{z,n} e^{-j\omega_n t} dz \right|^2}{\omega_n U} \quad (2.44)$$

And the transverse [R/Q] can be calculated from Equ.(2.45),

$$\left[\frac{R}{Q} \right]_{t,n} = \frac{V_{t,n}^2}{\omega_n U} = \frac{\left| \int_{-\infty}^{\infty} [E_{x,n} \pm jcB_{y,n}] e^{-j\omega_n t} dz \right|^2}{\omega_n U} \quad (2.45)$$

Without any other external coupler, the decay time is the nature decay time, which could be calculated from the unloaded quality factor,

$$\tau_n = \frac{Q_{0,n}}{\omega_n} \quad (2.46)$$

Here ω_n is the frequency of each mode and $Q_{0,n}$ is the unloaded quality factors.

The modes excited by the charged particles may affect other particles in the same bunch or the particles in the bunches trailing behind, depending on the decay time of the wakefields.

The longitudinal effects may lead to energy spread in the beam. In addition, a beam at an offset to the beam axis may generate transverse effects that can lead to an emittance growth and instabilities due to transverse instabilities.

Damping of unwanted modes is achieved by additional couplers added to the design, with the external couplers, the decay time of these modes can be calculated from the loaded quality factor as:

$$\tau_n = \frac{Q_{L,n}}{\omega_n} \quad (2.47)$$

The resultant longitudinal and transverse impedances are reduced and given by,

$$Z_{z,n} = \left[\frac{R}{Q} \right]_n Q_{L,n} \quad (2.48)$$

$$Z_{t,n} = \frac{\omega_n}{c} \left[\frac{R}{Q} \right]_n Q_{L,n} \quad (2.49)$$

With a strong damping achieved from the higher order mode dampers, the longitudinal and transverse impedances can then be suppressed to the accepted levels.

CHAPTER 3

HARMONIC KICKER WAVEFORM SYNTHESIZATION AND BEAM DYNAMICS TRACKING

There are several mathematical solutions to approximate the ideal kick waveform with a finite number of rf harmonics. In this chapter, four schemes are explored to determine the amplitudes and phases of these harmonics, which result in four different kicker waveforms.

3.1 HARMONIC KICKER WAVEFORM SYNTHESIZATION

When approximating the ideal kick waveform with a finite number of rf harmonics, the relationship between the total kick voltage and the amplitude, frequency, and phase of each harmonics can be summarized as following,

$$V_t = V_0 + \sum_{n=1}^N V_m \cos(n\omega_0 t + \varphi_n) \quad (3.1)$$

where V_t is the total kick voltage, the constant term V_0 represents a DC offset, ω_0 is the bunch repetition frequency in the ERL for 10 turns recirculation (47.63 MHz, 476.3 MHz/10), N is the harmonic number, and φ_n is the rf phase of the n th harmonic.

Different kicking waveform synthesization scheme shows difference in following three aspects:

- (1) total harmonic number;
- (2) amplitude and phase of each harmonic;
- (3) DC offset.

3.1.1 THE FLAT-TOP SCHEME

The flat-top scheme comes directly from the fast Fourier transform of periodic rectangular pulses. Fig.3.1 shows the ideal periodic rectangular pulses of the ultra fast kicker. Every 10th bunch in the 476.3 MHz bunch train will experience a 55 kV transverse kick. For the kicked bunches, the kick voltage is uniform along the bunch length. At other positions, the kick voltage is always zero.

FIG.3.1 The ideal periodic rectangular pulses produced by the ultra fast kicker.

With the fast Fourier transform of this periodic rectangular pulse, it could be expanded to a Fourier series with an infinite number of elements, the amplitudes and phases of the series are related to the width and amplitude of the original square pulse. The frequencies of these elements start from 47.63 MHz and increase in positive integer multiples. Reconstructing these pulses with a DC component and a few finite number harmonics, the original square pulse can be approximated to semi-square wave in some extent depending on the harmonic number. Fig.3.2 shows the reconstructed waveforms with first 500 harmonics and first 10 harmonics. With the comparison of these two reconstructed waveforms, it is easy to find that when the harmonic number is large enough, the synthesized waveform is almost the same like the original square pulse. And if the harmonic number is very small, obvious waveform fluctuations are found in the synthesized waveform.

FIG.3.2 Reconstructed waveforms with first 500 harmonics (upper plots) and first 10 harmonics (bottom plots).

For the synthetic waveform with a small number of harmonics, the kick voltage along the bunch length for the kicked bunch can be optimized to be uniform by adjusting the width of the original square pulse.

Considering a normalized periodic square pulse in voltage of width b , amplitude 1, within one period of $(-b/2, 2\pi-b/2)$, can be expanded as the following form,

$$F(N, b, x) = \frac{b}{2\pi} + \frac{2}{\pi} \cdot \sum_{n=1}^N \frac{1}{n} \sin(n \cdot \frac{b}{2}) \cos(n \cdot x) \quad (3.2)$$

Here N is the harmonic number, x is variable, can be considered as distance. If we consider $\pm 3\sigma$ of ($\sigma=2\text{cm}$) electron bunch length, for 10 harmonics, we can solve the following equation to optimize the width b .

$$F(10, b, 0) = F(10, b, 0.06) \quad (3.3)$$

A series of b is can be obtained from this equation, as can be shown in Fig.3.3.

We define the flatness as:

$$flatF(N,b,x) = \frac{\max F(N,b,x) - \min F(N,b,x)}{F(N,b,0)} \quad (3.4)$$

Here $\max F(N,b,x)$ and $\min F(s,b,x)$ is the maximum value and minimum value of the $F(N,b,x)$ in Interval $[0,x]$. $F(N,b,0)$ is the kick voltage at the bunch center $x=0$.

Calculate the flatness for several widths, we can get:

$$flatF(10,0.859324,0.06) = 9.504 \times 10^{-5} \quad (3.5)$$

$$flatF(10,1.474168,0.06) = 3.4308 \times 10^{-5} \quad (3.6)$$

$$flatF(10,2.079633,0.06) = 1.6348 \times 10^{-5} \quad (3.7)$$

Larger b gives better flatness, but also requires larger amplitude and power for each mode, and a wider pulse also has effect on the un-kicked bunch. Thus in this case, minimum b is enough.

FIG.3.3 Pulse top flatness with different pulse width

A flat-top kicking pulse gives the most uniform kick for the kicked bunch and zero kick at the centroid of the recirculating bunches. However, this waveform fluctuates in between the kicking pulses such that there will be a residual slope and a head-tail distortion for the recirculating bunches.

3. 1. 2 THE ZERO-GRADIENT SCHEME

The zero-gradient scheme is synthesized by setting constraints of zero amplitude and zero gradient at these intermediate bunch positions, which leaves these bunches undisturbed during circulation^[35,57].

The amplitude and phase of each harmonic can be derived by analytical method, the phases of all harmonics are the same, and the amplitude of each mode can be calculated from the following equations.

$$V_0 = \frac{V_{total}}{N} \quad (3.8)$$

$$V_n = \frac{V_{total} \bullet 2(N-n)}{N}, n = 1, 2, \dots, N \quad (3.9)$$

However, the kicking pulse is less-uniform for the kicked bunch, leading to some emittance growth on its injection to the CCR.

3.1.3 THE LEAST-MODE SCHEME

The least-modes scheme is synthesized by removing the gradient constraints from the zero-gradient scheme, which will reduce the harmonic modes number by half^[35]. In this scheme, the phases of all harmonics are still the same. If the harmonic number is even, the amplitude of each harmonic can be calculated from Equ.(3.10).

$$V_1 = V_2 = \dots = V_{n-1} = 2V_n = 2V_0 \quad (3.10)$$

If the harmonic number is odd, the amplitude of each harmonic can be calculated from Equ.(3.11).

$$V_1 = V_2 = \dots = V_n = 2V_0 \quad (3.11)$$

This actually provides a more uniform kicking pulse but introduces a larger slope at the intermediate positions between kicking pulses.

3.1.4 THE EQUAL-AMPLITUDE SCHEME

The equal-amplitude scheme has every harmonic with equal amplitude, same phase and no DC offset but has the largest kicking pulse curvature and large slopes at the intermediate positions. The amplitude of each harmonic can be calculated from:

$$V_n = \frac{V_{total}}{N}, \quad n=1,2,\dots,N \quad (3.12)$$

3.1.5 COMPARISON OF THE FOUR WAVEFORM SCHEMES

Four different synthesized kick waveform schemes for a recirculating factor of 10 and bunch repetition frequency of 476.3 MHz are shown in Fig.3.4.

FIG.3.4 Four different synthesized kick waveform schemes for a recirculating factor of 10 and the bunch repetition frequency of 476.3 MHz.

Fig.3.5 shows a comparison of the kicking pulse curvature over $\pm 3\sigma$ of a 3 cm (rms) electron bunch. The nonuniformity of the kicking pulse can be defined by the percentage difference between the peak amplitude of the pulse at the center of the bunch and the pulse amplitude head and tail of the full bunch length. In this 10 turn circulation scheme, the nonuniformity is less than 0.01% for the flat-top scheme, 3.5% for the least-modes scheme, 6.4% for the zero-gradient scheme and 15% for the equal amplitude scheme. The nonuniform kicking pulse will have an adverse effect on the

transverse beam quality of the kicked bunch and increase the transverse emittance, which will be discussed in the following sections.

FIG.3.5 Comparison of the kicking pulse curvature over $\pm 3\sigma$ of 3 cm kicked electron bunch for the four waveform schemes with a recirculating factor of 10.

Table 3-1 Normalized kick amplitude for each harmonic.

Mode (MHz)	Flat-Top	Zero-Gradient	Least-Modes	Equal-Amplitude
47.63	0.249	0.180	0.200	0.100
95.26	0.227	0.160	0.200	0.100
142.89	0.192	0.140	0.200	0.100
190.52	0.148	0.120	0.200	0.100
238.15	0.100	0.100	0.100	0.100
285.78	0.053	0.080	...	0.100
333.41	0.012	0.060	...	0.100
381.04	-0.022	0.040	...	0.100
428.67	-0.044	0.020	...	0.100
476.3	-0.055	...	...	0.100
DC	0.140	0.100	0.100	...
Total	1.000	1.000	1.000	1.000

Table 3-1 summarizes the normalized kick voltages for each harmonic in the different waveform schemes, in which the positive values means that harmonic modes are stimulated at 0 phase and negative ones at π phase.

3. 2 BEAM DYNAMICS TRACKING SIMULATION IN ELEGANT

To make a comparison of different waveform schemes, the effects on transverse beam quality for both kicked and unkicked bunches were simulated using ELEGANT [58].

Table 3-2 Input parameters in ELEGANT simulation.

Parameter	Value	Unit
Electron energy	55	MeV
RMS bunch length	3	cm
Bunch distribution	Gaussian	
Bunch frequency	476.3	MHz
Normalized transverse emittance	1.074	mm mrad
Normalized vertical emittance	1.074	mm mrad
Energy spread	3E-4	
Recirculation turns	10	No.
Kick angle	1	mrad
Total kick voltage	55	kV

In the simulation, a single round electron bunch with Gaussian distribution is generated for the 10-turn recirculation. The circulator ring was approximated by a one turn linear transfer matrix; the kicker waveform was generated using a series of zero length rf deflectors with appropriate frequencies, phases, and amplitudes that are combined at a single point; the DC component is simplified as a zero frequency rf deflector with the appropriate phase and amplitude. In reality, this DC voltage can be

replaced by a steering magnet ^[57,59-60]. Parameters used in the simulation are summarized in Table 3-2.

3.2.1 ONE KICKER SCHEME TRACKING

In the one kicker scheme tracking, only one kick is used for both injection and ejection. A single bunch with an initial positive transverse momentum angle will receive a negative kick from the kicker and injected to the design orbit. After 10 turns, the bunch receives another negative kick and is extracted to the ERL, as shown in Fig.3.6.

FIG.3.6 One kicker tracking scheme with only one kicker for injection and extraction.

To make sure the electron bunches will not be extracted in the first 9 turns, the total length of the circulator ring should fulfill the following condition,

$$L = (10N + \delta)\lambda_{10} \quad (3.13)$$

Here 10 is the recirculating turn number, λ_{10} is the bunch separation distance of the 476.3 MHz bunch train, which is about 0.63 m. N is integer number, which will finally determine the total length of the ring. δ is the bunch spacing number in the waveform that the bunch walks per turn relative to the kicker position, which should not be the co-prime with the recirculation turn number, in this 10-turn case,

$$\delta = \pm 1, \pm 3, \pm 7, \pm 9 \quad (3.14)$$

Fig.3.7 shows the tracking scheme with different δ .

Fig.3.8 shows the transverse emittance growth in the x-xp plane for these four different kicking waveforms from the injection, recirculation to the extraction. And Fig.3.9 gives the turn-by-turn normalized horizontal emittance growth for a single electron in one kicker scheme.

FIG.3.7 Kicker scheme for 10-turn recirculation with one kicker, the alternating bunch kick is in one bunch spacing (upper) and three bunch spacing (lower).

FIG.3.8 transverse emittance growth in the x-xp plane for these four different kicking waveforms from the injection, recirculation to the extraction for the single kicker scheme.

For the Flat-Top waveform, less than 1% emittance growth has been seen due to the uniform kick when the bunch is kicked into the ring, but the large gradient of the residual kick voltage caused by the wave fluctuation in the following turns results in a large emittance growth turn by turn, and after 10 turns of recirculation, the emittance is nearly 4.8 times larger than the initial value. For the Zero-Gradient waveform, 5% emittance growth is seen due to the non-uniformity kick pulse, but negligible emittance growth during the subsequent turns because of the near zero residual kick voltage as the bunch recirculates. For the Least-Modes waveform, there is 2% emittance growth when kicked in, and about 2.5 times growth during the recirculation. It is a compromise between a flat-top kick and a non-residual gradient kick. For the Equal Amplitude scheme, 25% emittance growth occurs when kicked in, and about 5.5 times growth during the recirculation. Although there is no DC offset required, this is clearly the least favourable option.

FIG.3.9 Turn-by-turn normalized horizontal emittance growth for a single electron bunch in one kicker scheme.

3. 2. 2 TWO KICKER SCHEME TRACKING

One challenge to use only one kicker for both injection and extracting is the possible beam-beam effect during the kicking process. Then a more suitable scheme could use two kickers that one for injection and one for extraction, which is shown in Fig.3.10. In this scheme, electron bunches will be kicked into the circulator ring by Kicker1, and after 10 turns recirculation, then be kicked out from Kicker 2.

FIG.3.10 Two kickers tracking scheme with Kicker 1 for injection and Kicker 2 for extraction.

The rf phase difference between two kickers and the path length of the cooler ring L1 is adjusted so that the recirculating bunch will not be kicked out by Kicker 2 in the first 9 turns, and is finally ejected in the last turn. The path length of the recirculation path L2 is adjusted to make sure the recirculating bunches experience the same waveform slope at both kicker locations. The bunch distortion due to the wave slopes between kicking pulse can be totally canceled out by setting the betatron phase advance between the two kickers to be exactly 180 degrees (or its odd multiples). The total ring length must therefore satisfy the following equation,

$$L1+L2=(10N+\delta)\lambda_{10} \quad (3.15)$$

$$\delta = \pm 1, \pm 3, \pm 7, \pm 9 \quad (3.16)$$

Fig.3.11 shows the kicker scheme for 10-turn recirculation with two identical kickers, the alternating bunch kick is in one bunch spacing (left) and three bunch spacing (right).

FIG.3.11 Kicker scheme for 10-turn recirculation with two identical kickers, the alternating bunch kick is in one bunch spacing (left) and three bunch spacing (right).

The cancellation of the residual kick with two identical kickers is demonstrated in Fig.3.12. For a single particle in a bunch, a transverse kick will change its transverse momentum. As the particle proceeds along the orbit, the transverse momentum and position follow a betatron oscillation. If the two kickers are separated in a distance with 180 degree (or its odd multiples) betatron phase advance, and the rf phases of the two kickers are set in such a way that the recirculation bunches experience the same wave slope at the two kicker positions, then these particles in the bunch that experience a small residual kick from the extraction kicker (Kicker 2) will experience the same kick from injection kicker (Kicker 1), and return to the original phase space orbit. In this way, the emittance is preserved locally even with nonuniform residual kick voltage variations along the bunch.

With the cancellation of the residual kick voltage between two identical kickers, negligible emittance growth has been seen during 10 turn recirculation for all kicker waveform schemes, as shown in Fig. 3.13. The emittance growth mainly comes from the injection kicker when the bunch is first kicked into the CCR, and from the extraction kicker when the bunch is finally kicked out of the ERL.

FIG.3.12 The cancellation scheme of the residual kick with two identical kickers. A single particle in the phase space, receives two identical residual kicks with 180 degrees phase advance in $x-x'$ plane, and returns to its original phase space orbit.

FIG.3.13 Transverse emittance growth in the $x-xp$ plane for these four different kicking waveforms from the injection, recirculation to the extraction for the two kicker scheme with the cancellation effect.

Fig.3.14 The beam emittance in the x-xp phase space before and after the 180 degree betatron phase advance.

The beam emittance in the x-xp phase space before and after the 180 degree betatron phase advance are shown in Fig.3.14. The turn-by-turn normalized horizontal emittance change is shown in Fig.3.15. The growth proportions of these four schemes are listed in Table 3-3.

FIG.3.15 Turn-by-turn normalized horizontal emittance for a single electron bunch in the two kicker scheme with 180 degrees betatron phase advance in between. The monitor is placed immediately after the injection kicker for the first 10 turns and after the extraction kicker for the last turn.

Table 3-3 Emittance growth proportion for different kicking waveform schemes.

	injection	extraction
Flat-Top	0.03%	0.03%
Least-Modes	1.5%	4.4%
Zero-Gradient	5.2%	15.8%
Equal-Amplitude	25.3%	68.6%

3. 2. 3 PRE-KICKER AND POST-KICKER SCHEME

If necessary the emittance growth due to the kicking pulse curvature could be compensated by introducing another two identical kickers, one before the injection kicker with a betatron phase advance of $\Delta\psi_x = \pi$ and the other one followed after the extraction kicker with the same betatron phase advance, as shown in Fig. 3.16.

FIG.3.16 Compensation scheme for the nonuniform kicking pulse by using identical predistortion kicker (Kicker 3) and postdistortion kicker (Kicker 4).

With the predistortion and postdistortion correction in the phase space, the distortion of the electron bunch due to the kicking pulse curvature is totally removed and the emittance performance of the least-mode scheme, zero-gradient scheme and the equal-amplitude scheme is almost the same as the flat-top scheme. The schematic drawing of the beam distortion correction scheme in the phase space is shown in

Fig.3.19 Turn-by-turn normalized horizontal emittance growth for a single electron bunch with a predistortion kicker to compensate the nonuniform kicking pulse but no postdistortion kicker.

If the beam quality after the recirculation can be ignored, the Kicker 4 can be removed from Fig.3.16, the tracking result with three kickers (Kicker1, Kicker 2, and Kicker 3) is shown in Fig. 3.19.

3. 3 ERROR ANALYSIS

All above discussion is in the ideal situation, the beam optics are perfect thus the 180 degree betatron phase advance is exact, the rf frequencies, phases and amplitudes of all modes are precisely controlled thus the kicking pulse at two kickers are identical and the recirculating bunches will drop on two identical wave slopes to get a complete cancellation.

But in the actual operation, there are many systematic and random errors, such as the manufacturing errors on the beam optics device, the different phase advance experienced by different particles in the bunch due to the energy spread, the rf signal

delay due to the cable length error, the frequency, amplitude, and phase control error on different harmonic modes and in different kicker cavities and groups and so on. These errors may lead to residual distortion which will further enlarge the emittance growth.

Table 3-4 summarizes the additional emittance growth due to +/- 5% deviations in the betatron phase advance, the voltage amplitude in one of the kickers and the rf phase delay between two kickers. In practice, it is easy enough to control the errors within 5% deviation but here it is used to show the tolerance estimate. Here the errors are calculated from the largest emittance deviation during the 10-turn circulation, and the emittance growth is relative to the ideal situation for each kicking scheme and for each error source. The least-modes scheme is more sensitive to the betatron phase error and the voltage amplitude error. The flat-top scheme is more sensitive to the time delay error but is still within acceptable limits. In the actual operation, these errors need to be carefully controlled to meet the beam dynamics requirement.

Table 3-4 Calculated relative emittance growth due to errors in the beam optics and rf control system.

	Betatron phase errors		Voltage amplitude errors		Time delay errors	
	+5%	-5%	+5%	-5%	+5%	-5%
Flat-Top	3.73%	5.33%	0.75%	0.81%	5.25%	4.70%
Least-Modes	20.08%	16.23%	2.71%	2.64%	2.63%	2.25%
Zero-Gradient	0.19%	0.36%	0.01%	0.13%	1.60%	0.80%
Equal-Amplitude	2.89%	2.62%	0.43%	0.39%	4.73%	-0.07%

CHAPTER 4

DEFLECTING QWR HARMONIC CAVITY DESIGN

The QWR has been widely used as an accelerating cavity^[39], and proposed as a deflecting and crabbing cavity^[51,61] due to its compact structure at low frequency.

In the crabbing applications, the design finally evolved into a symmetric double quarter wave structure to cancel the longitudinal on-axis electric field and meet the beam dynamics requirements for multipole components^[62]. In deflecting applications, especially at very low frequency cases like this kicker cavity (47.63 MHz), an asymmetric single QWR would be more compact. However, the cavity structure near the beam pipe must be optimized to reduce the on-axis longitudinal electric field component in order to reduce beam loading in the high current application.

4.1 FIELD DISTRIBUTION IN THE DEFLECTING QWR HARMONIC CAVITY

The section views of this deflecting QWR cavity model with the electromagnetic field distributions of the fundamental mode (47.63 MHz) are shown in Fig.4.1. The electron bunches traveling through the cavity will be deflected by both the transverse electric and magnetic fields.

For relativistic electron bunches traveling in the z direction and being deflected in the x -direction as shown in Fig.4.1, the effective transverse kick voltage of the n th harmonic mode can be calculated from:

$$V_m = \int_{-\infty}^{\infty} [E_{xm}(z) \cos(\frac{2\pi z}{\lambda_n}) + cB_{ym}(z) \sin(\frac{2\pi z}{\lambda_n})] dz \quad (4.1)$$

Here λ_n is the wavelength of the n th harmonic.

The total kick voltage from all harmonic modes is

$$V_t = V_0 + \sum_{n=1}^{10} V_m \cos(n\omega_0 t + \varphi_n) \quad (4.2)$$

Here the constant term V_0 represents a DC offset which could be achieved with a small steering magnet in operation. ω_0 is the bunch repetition frequency in the ERL (47.63 MHz), N is the harmonic number (10 for the flat-top scheme), and φ_n is the rf phase of the n th harmonic. $t=z/c$, c is the speed of light.

FIG.4.1 Deflecting QWR cavity model of the fundamental mode (47.63 MHz) with the left view section showing the magnetic field distribution (left) and the front view section for the electric field distribution (right).

4.2 MULTI-CAVITY SCHEME WITH KICK-DRIFT TRACKING

Since the QWR cannot support even harmonics of the fundamental, additional cavities are needed to obtain the full set of modes. Four quarter wavelength resonators are designed and optimized in order to generate 10 harmonic modes for a flat-top kick profile as a proof-of-principle device for a 10 turn recirculation cooler ring, which is illustrated in Fig.4.2.

4.2.1 MULTI-CAVITY SCHEME

The relationship between cavity number M and maximum harmonic number N can be supported as:

$$2^M - 1 \leq N \quad (4.3)$$

With four cavities, the maximum number of useful harmonic modes that can be obtained is 15, and with five cavities, up to 31 harmonic modes can be generated.

FIG.4.2 10 harmonic modes in a four-cavity system with the highest harmonic electric field (left) and magnetic field (right) distribution shown in each cavity.

4. 2. 2 DISCUSSION ON THE RECIRCULATION TURN, HARMONIC NUMBER AND CAVITY NUMBER

Depending on the number of harmonic modes needed, the total cavity number and the harmonic mode distribution within one cavity can be adjusted.

Table 4-1 lists the relationships among the recirculation number, harmonic number and cavity number, with the mode distribution in each cavity based on the Flat-Top scheme. For the 10 turn case, 4 cavities are needed and there are five modes in the first cavity.

From this point of view, the least-modes waveform has a great advantage by using only half the number of harmonic modes. In this 10 turn recirculation example, only three cavities would be needed to generate five modes with the distribution proportion of 3 : 1 : 1. It would also be possible to use five single frequency cavities to generate

the kick waveform. A single frequency cavity is much easier to build and tune and could be more compact, for example by using a folded structure. It would also be possible to use superconducting cavities to get a much higher kick voltage. However for larger numbers of modes needed for more recirculation passes this would be less practical.

Table 4-1 The relationships among the recirculation number, harmonic number and cavity number, with the mode distribution in each cavity based on the Flat-Top scheme.

Recirculation Turn	10	15	25	30
Harmonic Number	10	15	25	30
Cavity number	4	4	5	5
Mode distribution	5:3:1:1	8:4:2:1	13:6:3:2:1	15:8:4:2:1
Modes in Cavity#1	1,3,5,7,9	1,3,5,7,9,11 ,13,15	1,3,5,7,9,11,13, 15,17,19,21,23, 25	1,3,5,7,9,11,13,15, 17,19,21,23,25,27, 29
Modes in Cavity#2	2,6,10	2,6,10,14	2,6,10,14,18,22	2,6,10,14,18,22,26 ,30
Modes in Cavity#3	4	4,12	4,12,20	4,12,20,28
Modes in Cavity#4	8	8	8,24	8,24
Modes in Cavity#5			16	16

4. 2. 3 MULTI-CAVITY KICK-DRIFT TRACKING

Unlike a stripline rf kicker, in which all harmonic modes can be combined at a single device, the resonant cavity kickers in our design provide the kick at four different locations, with drift in between, as shown in Fig. 4.3.

FIG.4.3 Multi-cavity kick-drift tracking scheme with off-axis injection and extraction for flat-top waveform (the kick voltage is reversed at the last cavity as it is mainly used for curvature correction).

The drifts between the cavities will introduce additional transverse displacement, and the beam optics design needs to carefully cancel the displacement. In the simulation, we continue to approximate the kick in each cavity with a series of zero length deflectors, but with a drift space between each pair of two cavities. For the best cancellation effect, the 180 degree phase advance should be enforced between each pair of two identical cavities; the phase advance between two kicker systems (from K24 to K11) should be 180 degrees minus the phase advance over a kicker length of drift (from K21 to K24), i.e. $(\pi - \varphi)$ in Fig.4.3. For this simplified kick-drift model for nonmagnetized electron bunches, the betatron phase advance is given by^[63]:

$$\varphi = \int_0^L \frac{ds}{\beta(s)} \quad (4.4)$$

Here L is the total drift space,

$$L = L_1 + L_2 + L_3 \quad (4.5)$$

$\beta(s)$ is the betatron amplitude function.

With this adjustment, the residual kick was totally cancelled, and the tracking result shows that the emittance growth is almost the same as the result of the single kick model as shown in Fig. 4.4.

FIG.4.4 Tracking result in the multi-cavity kick-drift scheme.

4.3 OPTIMIZATION OF THE TRANSVERSE SHUNT IMPEDANCE

To minimize the power requirements at a given kick voltage, it is necessary to maximize the transverse shunt impedance R_{tn} , for each mode, which is defined as:

$$R_{tn} = \frac{V_m^2}{P_{cn}} \quad (4.6)$$

Here P_{cn} is the total rf loss on the cavity wall for the nth mode.

Neglecting the effects of the beam pipe and the small reverse deflection from the magnetic field, the transverse kick voltage acquired by an on-crest particle is the integral of the time-dependent transverse electric field along the beam line^[49]:

$$V_m = \int_{-b}^b (E_{xn} \cos(\frac{2\pi z}{\lambda_n})) dz \quad (4.7)$$

For the n th mode, we may approximate the electric field in the end capacitor gap (width g) as a constant up to radius a , the inner conductor radius, and falling to zero at the outer conductor, radius b , with a fringing factor defined as:

$$F_n = \frac{\int_{-b}^b E_{zn} dz}{2a \frac{V_{0n}}{g}} \quad (4.8)$$

where V_{0n} is the electric potential difference between inner and outer conductor at the end capacitor for the n th mode. Then the transverse kicker voltage acquired by an on-crest particle from the n th harmonic mode can be written as:

$$V_n = \frac{2aV_{0n}T_nF_n}{g} \quad (4.9)$$

where T_n is the transit time factor for the n th harmonic mode:

$$T_n = \frac{\int_{-b}^b E_{zn} \cos\left(\frac{2\pi z}{\lambda_n}\right) dz}{\int_{-b}^b E_{zn} dz} \quad (4.10)$$

Without beampipes, and neglecting the power loss in the capacitive end gap, the total power dissipation of the n th mode P_{cn} in the cavity consists of three parts; the inner cylindrical conductor (radius= a , length $\approx \lambda/4$) P_{an} , the outer cylindrical conductor (radius= b , length $\approx \lambda/4$) P_{bn} , and the inductive end disk (radius from a to b) between inner and outer conductors P_{endn} .

$$P_{cn} = P_{an} + P_{bn} + P_{endn} \quad (4.11)$$

The power dissipation on the inner conductor of the n th mode P_{an} can be calculated from:

$$\begin{aligned}
P_{an} &= \frac{1}{2} R_{sn} \int [H_{\varphi n} \sin(\frac{2\pi x}{\lambda_n})]^2 dS \\
&= \frac{1}{2} R_{sn} \int_0^{\frac{\lambda_1}{4}} [H_{\varphi n} \sin(\frac{2\pi x}{\lambda_n})]^2 2\pi a dx \\
&= \frac{R_{sn} \lambda_1 I_{0n}^2}{32\pi a}
\end{aligned} \tag{4.12}$$

Similarly, the power dissipation on the outer conductor of the nth mode P_{bn} can be calculated from:

$$P_{bn} = \frac{R_{sn} \lambda_1 I_{0n}^2}{32\pi b} \tag{4.13}$$

and the power dissipation on the inductive end disk of the nth mode P_{endn} can be calculated from:

$$\begin{aligned}
P_{endn} &= \frac{1}{2} R_{sn} \int [H_{\varphi n}]^2 dS \\
&= \frac{1}{2} R_{sn} \int [H_{\varphi n}]^2 2\pi r dr \\
&= \frac{R_{sn} I_{0n}^2}{4\pi} \ln\left(\frac{1}{\xi}\right)
\end{aligned} \tag{4.14}$$

where I_{0n} is the rf current of the nth mode on the inductive end of cavity wall, which depends on the cavity input power; λ_1 is the wavelength of the fundamental mode in the cavity, which also determines the cavity length; x is taking the inner conductor electrode center as the origin, so the integration from $x=0$ neglects the gap distance g . ξ is the radius ratio between inner and outer conductors,

$$\xi = a/b \tag{4.15}$$

R_{sn} is the surface resistance of the nth mode,

$$R_{sn} = \sqrt{\frac{\pi f_n \mu}{\sigma}} \tag{4.16}$$

f_n is the frequency of the n th mode, σ is the conductivity of the cavity material, in this case is copper, and μ is its permeability.

Then the transverse shunt impedance can be found as:

$$R_{tn} = \frac{128\pi(b\xi)^2 Z_0^2(\xi) T_n^2 F_n^2}{g^2 R_{sn} \lambda_1 \left(\frac{1}{b\xi} + \frac{1}{b} + \frac{8}{\lambda_1} \ln\left(\frac{1}{\xi}\right) \right)} \quad (4.17)$$

where $Z_0(\xi)$ is the characteristic impedance of the transmission line, which can be calculated from:

$$Z_0(\xi) = \frac{\eta_0}{2\pi} \ln\left(\frac{1}{\xi}\right) \quad (4.18)$$

$\eta_0 = 120\pi \Omega$ is the vacuum wave impedance.

From this formula it can be seen that R_{tn} is larger when the gap distance g is small, but this gap should be big enough to stay clear of the passing beam. Higher harmonic modes will have lower shunt impedance since the surface resistance will increase with frequency and the transit time factor will decrease at the same time. The outer conductor radius b is limited by the transit time factor of the highest mode (the time it takes the electron to transverse the cavity should not exceed one-half of an rf period so that the electron does not see a reversal of the electric field), as shown in Equ.(4.19).

$$2b = \frac{\lambda_{10}}{2} \quad (4.19)$$

$$\lambda_{10} = \frac{1}{10} \lambda_1 \quad (4.20)$$

In this kicker design the total transverse voltage is only 55 kV so it is convenient to use the same b to a ratio for all four cavities, with b set by the highest harmonic frequency (476.3 MHz), which will simplify fabrication.

When the size of outer conductor is determined, then the next important thing is to optimize the ratio between inner and outer conductors.

Over write the Equ.(4.17) to the following form,

$$\frac{R_{tn}R_{sn}}{T_n^2} = \frac{128\pi(b\xi)^2 Z_0^2(\xi) F_n^2}{g^2 \lambda_1 \left(\frac{1}{b\xi} + \frac{1}{b} + \frac{8}{\lambda_1} \ln\left(\frac{1}{\xi}\right) \right)} \quad (4.21)$$

Ignoring the fringe field effect, then

$$F_n = 1 \quad (4.22)$$

In Equ.(4.21), the difference of the fringe field between the fundamental mode and highest mode is negligible thus the fringe field factor can be treated to be frequency-independent. The left hand is mode dependent and the right hand is only geometry dependent. From this formula, the transverse impedance at different ratio ξ is shown in Fig.4.5 (black). The optimized ξ is about 0.48. In this situation, however the total kick voltage could be under-estimated due to the lacking of the fringe fields, thus this ratio ξ should be smaller when the fringe field effect is added.

FIG.4.5 Optimized ξ from the analytical solution to get high transverse shunt impedance for fundamental mode ($b=157$ mm, $g=70$ mm, T_n is approximated to 1).

The fringe field factor can be estimated from the conformal mapping method^[64]. Fig.4.6 shows the comparison of the fringe field between conformal mapping result

with open boundary (blue solid) and SuperFish^[65] result (red dot) for the fundamental mode.

FIG.4.6 Comparison of the fringe field between conformal mapping result with open boundary (blue solid), with-enforcement closed boundary result (green dash) and the Superfish result (red dot) for the fundamental mode.

Assuming the transverse electric field in the conformal mapping is E_{cn} , then the fringe field factor can be defined as:

$$F_n = \frac{\int_{-b}^b E_{cn} dz}{2a \frac{V_0}{g}} \quad (4.23)$$

The fringe field is over estimated with this formula due to lacking boundary condition to push the field to zero on the cavity outer cylindrical wall. With this called over-estimated fringe field, the shunt impedance varies with the ratio is shown in Fig.4.5 (red). The optimized ratio here was about 0.25.

To compensate the error caused by the lacked boundary condition, an enforcement factor is introduced to the conformal mapping result to push the field to be zero at cavity outer cylindrical wall. Then the fringe field factor can be defined as:

$$F_n = \frac{\int_{-a}^a E_{cn} dz + 2 \int_a^b E_{cn} \left(\frac{b-z}{b-a} \right) dz}{2a \frac{V_0}{g}} \quad (4.24)$$

With this enforcement, the shunt impedance varies with the ratio is shown in Fig.4.5 (green). The optimized ratio here is about 0.35.

Thus the optimum ratio in a real cavity should be between 0.2-0.5 and near 0.4. With this estimated range, further optimization can be done in CST ^[66] with a significantly reduced effort.

Selecting b as 157 mm (set by the highest mode), R_t varies at different gap value g and different inner conductor ratios, as shown in Fig.4.7. The optimum ratio is 0.35, so the optimum $a=55$ mm in this situation. The shunt impedance increases rapidly with the decrease of the capacitor gap, but the optimum ratio is fairly constant over this range. In the present design the gap is fixed at 70mm. This optimization is based on the fundamental mode, but the trend is the same for the higher harmonic modes.

FIG.4.7 Optimization of the shunt impedance of the fundamental mode for different gaps g when b is 157 mm.

4. 4 TAPER SLOPE AND TUNER DESIGN

After the cavity dimensions are determined for the lowest mode, it is crucial to make sure that every other mode is on its target frequency. Tuning of single mode QWRs is typically done by mechanically deforming a thin plate mounted at the capacitive end disk of the cavity, adjusting the distance between the bottom plate and the electrode of the inner conductor, or to tune the QWR by deforming the walls of the cavity and introducing movable plungers in the magnetic field area^[67-68], as shown in Fig.4.8.

FIG.4.8 Tuning of the QWR by deforming a thin plate mounted at the capacitive end disk of the cavity, deforming the walls of the cavity, and introducing movable plungers in the magnetic field area.

For a multifrequency structure, the tuning is more challenging since each mode cannot be tuned independently from the others. Thus a successful tuning scheme requires a number of independent tuners, equal to the number of modes, whose positions are set by a convergent iterative process.

Consider the equivalent circuit of this capacitor loaded cavity as shown in Fig. 4.9. The resonant frequency can be calculated by the susceptance method. In the plane T_0 , the total susceptance is zero at resonance, as shown:

$$\sum B = \omega C_0 - \frac{1}{Z_0} \cot\left(\frac{2\pi}{\lambda} l\right) \quad (4.25)$$

Or,

$$2\pi f Z_0 C_0 = \cot\left(\frac{2\pi}{\lambda} l\right) \quad (4.26)$$

Here Z_0 is the characteristic impedance of the transmission line and is determined by the ratio between inner and outer conductor. C_0 is the capacitor in the gap, l is the total length of the cavity.

FIG.4.9 The cavity schematic model (top) and the equivalent circuit of this capacitor loaded QWR cavity (bottom).

The transcendental equation (4.26) can be solved with the graphical method as shown in Fig.4.10. The left hand of equation can be represented as a straight line through the origin, and the right hand can be represented as a series of cotangent curves. The horizontal ordinates of the points of intersection are the solutions of the equation, which are the resonant frequencies of the cavity with close to odd multiple harmonic distributions. Once the cavity length and the load capacitor are determined, the resonant frequencies are only related with the transmission line impedance along the cavity length, the resonant frequencies can be tuned to harmonic by adjusting the geometry ratio ξ along the cavity wall, for example, tapering the cavity wall or insert the perturbation objects.

FIG.4.10 Graphical method to get the resonant frequencies from the transcendental equation (4.26)

For this cavity, multistage tuning is adopted. Specially designed tapers on the inner conductor are used to tune the higher order modes to the odd multiples of the fundamental mode. Then stub tuners on the outer conductor are used to compensate any frequency shifts due to manufacturing tolerances, temperature drifts and other perturbations during operation. The following discussions are based on the five-odd-mode cavity design and tuning as an example.

For a simple cavity model constructed as shown in Fig. 4.9, the cavity length can be adjusted to reduce the maximum frequency deviation of any mode from the target frequency. This minimizes the amount of tuning needed from the tapers and stub tuners. As shown in Fig.4.11, a cavity length of 1579 mm requires a tuning amount from the tapers and the stubs of less than 0.3% for all modes.

In order to see the frequency response of each mode to a tuner at different locations along the cavity wall, a trial stub was inserted on the outer cylindrical wall and moved along the axial distance, as shown in Fig.4.12. The frequency tuning range of the stub tuner is much less than the required tuning amount in Fig. 4.11, so the

initial frequency offset cannot be corrected with these stubs alone. Tapers on the inner conductor are much more effective and are used in order to obtain the initial harmonic frequencies, while stub tuners are used for fine tuning.

FIG.4.11 Normalized required tuning amount (for tapers and stub tuners) verses cavity length, the curve inflection is due to the tuning range going to other direction from the target frequency.

FIG.4.12 Tuner position simulation for the 5 harmonics modes cavity with a cylinder trail stub radius $R=20$ mm, insertion height $H=10$ mm, perturbation moving along the outer conductor wall in the axial direction.

4. 4. 1 STRAIGHT SLOPE TAPER DESIGN

The basic cavity structure is cylindrically symmetric along the length, and the relative frequency response of each mode to variations of taper segments on the inner conductor is similar to the tuner response on the outer conductor in Fig.4.12.

For the five-odd-mode cavity, five tapering points are needed. There are many possible methods to choose these taper segments and just one is presented here. As shown in Fig.4.13, two end points at a1 and a5 are chosen to get the lowest tapering slopes along the cylinder while the three straight tapering transition points at a2 to a4 correspond to three nonzero frequency response points in Fig. 4.12 for all modes (at 530 mm, 690 mm, 1190 mm).

FFIG.4.13. Taper points chosen on the inner conductor.

After the taper positions are chosen, the tapering sensitivity on each location is simulated by changing the tapering values from a1 to a5, which results in a 5X5 taper matrix M_{taper} ,

$$M_{taper} = \begin{pmatrix} 97.498 & 145.92 & 2.9292 & -109.15 & -146.26 \\ 192.46 & -305.64 & -2.59 & 296.68 & -204.4 \\ 117.35 & -119.21 & -70.182 & 68.726 & -56.246 \\ 14.09 & -30.406 & 185.68 & -182.93 & -69.952 \\ 2.278 & 42.572 & -239.39 & 207.79 & -119.58 \end{pmatrix} \quad (4.27)$$

where each element m_{ij} is the first order (linear) frequency response of mode i to the variation at the taper point j in units of Hz/mm. Fig.4.14 shows the response of each mode at each taper point.

The optimum taper design can be achieved by solving the taper tuning equation:

$$M_{taper} \Delta a_n = \Delta f_n \quad (4.28)$$

Where Δa_n is the tapering value in mm at the nth taper point,

$$\Delta a_n = (\Delta a_1 \quad \Delta a_2 \quad \Delta a_3 \quad \Delta a_4 \quad \Delta a_5) \quad (4.29)$$

FIG.4.14 Frequency response of each mode at each taper point.

To avoid the unreasonable solution when solving the taper tuning equation, the taper matrix should not be ill-behaved [$\det(M)$ is not close to zero]. When choosing the taper points, one obvious criterion is to avoid the zero response points for all modes, like position 800 mm in Fig.4.12.

To provide a bi-directional tuning range by the stub tuners, the cavity tapering optimization is done with five stub tuners (80 mm in diameter) partially inserted (at 25 mm depth), as the baseline. The position of these stubs should also avoid this zero response points for all modes. Here the final designed stub diameter is double the size of the initial trail stub, thus four times of tuning range larger than the small one at a given inert length. Too much insertion for a small stub will also result in a high electric field on the stub edge. For convenience the three middle tuner positions are chosen corresponding to the middle tapering points enabling any manufacturing tolerance on the tapering point to be quickly corrected by the corresponding stub tuner. The other two are set to have good tuning sensitivity to all modes. The other two are set to have good tuning sensitivity to all modes.

The frequency response to varying the tapering values is not always exactly linear, however linear approximations are used to generate the matrix and the residual error due to any nonlinearity can be eliminated by resolving the matrix equation iteratively in order to get to the target frequency within only a few cycles. The frequency convergence with taper design iterations is shown in Fig4.15.

FIG.4.15 Frequency convergence with taper simulation iteration number.

4.4.2 STUB TUNER DESIGN

Similarly the five stub tuners, avoiding the zero response points for all modes, at 400 mm, 530 mm, 690 mm, 1190mm, and 1400mm locations have been chosen (0mm is at the cavity open gap wall end), they can be used for the compensation tuning of any manufacturing errors and other perturbations during the operation such as change of the cavity temperature.

Just as for the tapering design, after the tuner positions are chosen, the tuning sensitivity of each stub is calculated by changing the insertion distance, which will resulting another 5X5 tuning matrix M_{tuner} , the element n_{ij} in this matrix means the first order frequency response of the i^{th} mode to the j^{th} tuner in units of Hz/mm. The harmonic tuning can likewise be achieved by solving the stub tuning equation:

$$M_{\text{tuner}} \Delta h_n = \Delta f_n \quad (4.30)$$

Δh_n is the stub insertion depth value in mm of the n th tuner,

$$\Delta h_n = (\Delta h_1 \quad \Delta h_2 \quad \Delta h_3 \quad \Delta h_4 \quad \Delta h_5)^T \quad (4.31)$$

The fields in the cavity are stronger on the inner conductor than on the outer conductor, so the frequency response to varying the tuner position is also not linear. However the error due to the nonlinearity can also be eliminated by solving the matrix equation iteratively just as was done on the taper design.

Using larger diameter tuner stubs can produce more linear matrix elements for the same tuning range, but a few iterations are still needed to get to the target frequencies.

4.5 COUPLER DESIGN

Two methods have been explored to drive this harmonic cavity. First, the harmonic frequencies can be generated by a frequency divider after a signal source at the bunch repetition frequency, and these harmonic signals can then be filtered,

amplified, and combined at low level with a precise phase delay at each harmonic channel and then fed into a wide band amplifier. Second, several narrow band amplifiers can be used at high power level, and their outputs can then be phase shift adjusted before combining together and sending into the cavity. Any combined technique has to consider building a circulator to prevent reflected power from any mismatch for any mode. Then the beam phase relative to the bunch repetition frequency can be precisely controlled and tuned.

The rf power can be fed into the cavity through a single loop coupler in the high magnetic field area for the coupling of all modes, as shown in Fig.4.16.

FIG.4.16 Single loop coupler in the high magnetic field area for the coupling of all modes

FIG.4.17 Coupling strength of each mode along the cavity wall with a size fixed coupler loop.

The coupling strength of each mode is depending on the size, rotation, and position of the coupler loop. Fig.4.17 shows the coupling strength of each mode along the cavity wall with a size fixed coupler loop.

The rotation angle is defined as Fig.4.18. And the coupling strength of each mode at different rotation angle for a size fixed coupler loop at fixed position is shown in Fig.4.19.

FIG.4.18 The definition of the rotation angle.

FIG.4.19 Coupling strength of each mode at different rotation angle for a size fixed coupler loop at fixed position

4. 6 RF PARAMETERS IN THE CAVITY

For the 55 MeV electron bunches at 1 mrad kick angle, with the flat-top kick waveform of this optimized cavity design, the shunt impedance and dissipated power on the copper cavity wall in each mode is listed in Table 4-2.

Table 4-2 Calculated electromagnetic parameters of each mode for room temperature copper.

Cavity	Operation Frequency (MHz)	Quality Factor (Q_0)	Kick Voltage (kV)	Transverse Shunt Impedance (Ω)	Dissipated Power (W)
Five-Mode Cavity	47.63	8586	13.711	7.527E6	24.98
	142.89	14689	10.532	3.954E6	28.05
	238.15	18973	5.503	2.916E6	10.39
	333.41	22472	0.630	1.859E6	0.21
	428.67	25536	-2.432	1.131E6	5.23
Three-Mode Cavity	95.26	12002	12.462	1.080E7	14.38
	285.78	20784	2.917	4.082E6	2.08
	476.3	27056	-3.011	1.560E6	5.81
One-Mode Cavity	190.52	15298	8.129	1.153E7	5.73
One-Mode Cavity	381.04	19435	-1.209	8.861E6	0.17
DC			7.768		
Total			55	3.117E7	97.03

The total power dissipated for all modes is less than 100 W, two to three orders lower than the stripline kicker for a same kick angle.

With the total kick voltage and the total power dissipation, an equivalent transverse shunt impedance can be defined as:

$$R_t = \frac{(V_t)^2}{P_{total}} = \frac{(V_0 + \sum_{n=1}^N V_n \cos(n\omega_0 t + \varphi_n))^2}{\sum_{n=1}^N P_n} \quad (4.32)$$

CHAPTER 5

MULTIPOLE FIELD ANALYSIS

The asymmetric cylindrical cavity structure will produce higher order multipole field components, such as the quadrupole, sextupole and octopole, which could lead to emittance growth of the electron bunches^[69]. Unlike the double quarter wavelength cavity^[51] and TEM-like (transverse electric and magnetic field) deflecting cavities^[49-50], the beam axis in this kicker cavity is not in the structure symmetric plane, which will result in a more nonuniform deflection.

In this paper, only the multipole components up to sextupole of the kicker cavity are analysed, higher multipole components like octopole and above are much weaker and their contributions to transverse beam dynamics are negligible. In the analysis, the multipole component factors can be calculated with numerical methods. Compare these factors with the definitions used in the accelerator magnet, the cavity performance can be understood better and the cavity geometry optimization can be taken correspondingly.

5.1 FIELD NON-UNIFORMITY ALONG THE CAVITY AXIS

If the beam axis is in the z-direction, and bunches will be kicked in the x-direction, the field within the beam pipe varies across the beam aperture in both x and y directions. The normalized transverse voltage variations are shown in Fig.5.1.

FIG.5.1 Normalized transverse voltage variations in x any y direction, offset= 0 is the beam line center

5.2 MULTIPOLE COMPONENTS IN THE CAVITY

Field non-uniformity in the cavity will result to the multipole field in the cavity. According to the discussions in chapter 2 and Equ.(2.43), the multipole components in the cavity can be calculated by two methods^[70],

(1) by using the Lorentz Force

$$\begin{aligned}
 b_n &= \int_0^L B^{(n)} dz = \int_0^L \frac{1}{ec} F_{\perp}^{(n)} dz \\
 &= \int_0^L \frac{1}{ec} [e(E_t^{(n)}(z)e^{j\omega t} + ecB_t^{(n)}(z)e^{j\omega t})] dz \\
 &= \int_0^L \left[\left(\frac{1}{c} E_x^{(n)}(z) + B_y^{(n)}(z) \right) e^{j\omega t} \right] dz
 \end{aligned} \tag{5.1}$$

(2) by using the Panofsky Wenzel Theorem

$$b_n = \int_0^L B^{(n)} dz = \int_0^L \frac{nj}{\omega} E_{acc}^{(n)} dz = \int_0^L \frac{nj}{\omega} E_z^{(n)} e^{j\omega t} dz \tag{5.2}$$

In this chapter, our calculation is based on the Panofsky Wenzel Theorem, and the calculation with Lorentz Force should give the same result.

For a single mode in the cavity, close to the beam axis, the electromagnetic fields in an rf cavity within the beam aperture can be represented as,

$$E_z(r, \phi, z, t) = \sum_{n=1}^{\infty} E_z^{(n)}(z) r^n (\cos(n\phi) + i \sin(n\phi)) e^{j\omega t} \quad (5.3)$$

Here the cosine part is the normal component; sine part is the skew component.

The normal component of longitudinal electric multipole field $E_{z-nor}^{(n)}(z)$ and the skew component $E_{z-skew}^{(n)}(z)$ along the axis can be obtained by using the Fourier series expansion,

$$E_{z-nor}^{(n)}(z) = \frac{1}{r^n \pi} \int_0^{2\pi} E_z(r, \phi, z) \cos(n\phi) d\phi \quad (5.4)$$

$$E_{z-skew}^{(n)}(z) = \frac{1}{r^n \pi} \int_0^{2\pi} E_z(r, \phi, z) \sin(n\phi) d\phi \quad (5.5)$$

The accurate extraction of electromagnetic fields is important in determining the higher order multipole component with precision. In reducing the errors introduced with field extrapolation, a finer tetrahedral meshing is used with multiple concentric cylinders within the beam aperture as shown in Fig. 5.2 with fixed number of points at each concentric cylinder.

FIG.5.2 Tetrahedral mesh used in concentric cylinders in extracting multipole field components.

The cavity is meshed with 60 points in each concentric cylinder 10mm, 15mm and 20mm. The longitudinal mesh size is 0.1 mm. Then the numerical field data were obtained for $E_z(r, \phi, z)$, $E_x(r, \phi, z)$, $H_y(r, \phi, z)$ at different values of ϕ for several fixed radial distances of r_0 and different longitudinal positions z .

The normal part of the time independent multipole field components of $E_z^{(n)}(z)$ along the axis can be derived by the discrete integral of Equ.(5.4) on the azimuthal direction,

$$E_{z-nor}^{(n)}(z) = \frac{1}{r^n \pi} \sum_{j=0}^J E_z(r, \phi, z) \cos(nj\phi_t)\phi_t \quad (5.6)$$

Here J is the total point number in the concentric cylinder, which is 60 in this case. ϕ_t is the step size,

$$\phi_t = \frac{360}{J} \frac{\pi}{180} \quad (5.7)$$

Fig.5.3 shows the normal part of the time independent multipole field components of $E_z^{(n)}(z)$ along the axis for the fundamental mode at radii 5 mm, 10 mm, and 15 mm for orders $n = 0-5$.

The normal part of multipole component factor for the fundamental mode can then be calculated from Equ.(5.2), the real part is

$$b_{n-re} = -\frac{n}{\omega} \sum_{z=1}^Z E_z^{(n)}(z) \sin(\omega \frac{zz_t}{c})z_t \quad (5.8)$$

The image part is,

$$b_{n-im} = j \frac{n}{\omega} \sum_{z=1}^Z E_z^{(n)}(z) \cos(\omega \frac{zz_t}{c})z_t \quad (5.9)$$

Here Z is the total sample point number in the longitudinal direction, z_t is the step size, the calculated results of real part and the image part of the normal multipole components for the fundamental mode at each r_0 of 10 mm, 15 mm and 20 mm are listed in Table 5-1 and 5-2.

FIG.5.3 Normal part of the time independent multipole field components of $E_z^{(n)}(z)$ for the fundamental mode at radii 5 mm, 10 mm, and 15 mm for orders $n = 0-5$.

Table 5-1 Real part of the normal multipole components for the fundamental mode at each r_0 of 10 mm, 15 mm and 20 mm.

	10 mm	15 mm	20 mm	Unit
Vz	0	0	0	V
Vt	1	1	1	MV
b1	3.335	3.335	3.335	mT
b2	23.698	23.71	23.708	mT/m
b3	333.143	333.435	333.486	mT/m ²
b4	-153.429	-153.204	-131.63	mT/m ³
b5	-2.613E4	-2E4	-1.752E4	mT/m ⁴

Table 5-2 Image part of the normal multipole components for the fundamental mode at each r_0 of 10 mm, 15 mm and 20 mm.

	10 mm	15 mm	20 mm	Unit
b1	-6.675E-7 j	2.819E-7 j	6.806E-7 j	mT
b2	-2.838E-4 j	1.092E-4 j	6.643E-5 j	mT/m
b3	0.01 j	3.911E-3 j	1.85E-3 j	mT/m ²
b4	-0.551 j	0.237 j	5.419E-3 j	mT/m ³
b5	-220.494 j	-25.053 j	12.533 j	mT/m ⁴

All the multipole component factors are normalized to 1 MV deflecting voltage, the real parts are corresponding to the deflecting phase and the image parts are corresponding to the crabbing phase.

The normal part of the time independent multipole field components of $E_z^{(n)}(z)$ along the axis can be derived as

$$E_{z-skew}^{(n)}(z) = \frac{1}{r^n \pi} \sum_{j=0}^J E_z(r, \phi, z) \sin(nj\phi_t) \phi_t \quad (5.10)$$

As shown in Fig.5.4.

FIG.5.4 Skew part of the time independent multipole field components of $E_z^{(n)}(z)$ for the fundamental mode at radii 5 mm, 10 mm, and 15 mm for orders $n = 0-5$.

The calculated results of real part and the image part of the skew multipole components for the fundamental mode at each r_0 of 10 mm, 15 mm and 20 mm are listed in Table 5-3 and 5-4.

Table 5-3 Real part of the skew multipole components for the fundamental mode at each r_0 of 10 mm, 15 mm and 20 mm.

	10 mm	15 mm	20 mm	Unit
V_z	0	0	0	V
V_t	1	1	1	MV
b_1	1.05E-4	1.101E-4	1.047E-4	mT
b_2	5.2E-3	5.095E-3	1.077E-3	mT/m
b_3	0.363	0.492	0.173	mT/m ²
b_4	-18.45	6.302	-12.472	mT/m ³
b_5	-865.413	-1.281E3	-773.258	mT/m ⁴

Table 5-4 Image part of the skew multipole components for the fundamental mode at each r_0 of 10 mm, 15 mm and 20 mm.

	10 mm	15 mm	20 mm	Unit
b_1	-7.629E-7 j	2.692E-8 j	-7.086E-8 j	mT
b_2	1.652E-4 j	9.475E-6 j	4.337E-5 j	mT/m
b_3	-7.129E-4 j	1.715E-3 j	-5.113E-3 j	mT/m ²
b_4	0.366 j	-0.012 j	0.21 j	mT/m ³
b_5	265.415 j	24.717 j	-1.025 j	mT/m ⁴

From the calculation results, compare to the normal components, the skew components are too small and could be ignored.

With the same methods, the multipole component factors for all modes in the four cavities can be calculated and be listed in Table 5-5,5-6,5-7,5-8.

From the calculation results, the multipole component factors are almost the same for all modes from the dipole to sextupole multipole field. From octupole multipole component, there is a large difference in the calculation results for all modes, and this difference is seems to be caused by the noise.

Table 5-5 Normal part of the multipole component factors in the five-mode cavity.

	47.63 MHz	142.89 MHz	238.15 MHz	333.41 MHz	428.67 MHz	Unit
V _z	0	0	0	0	0	V
V _t	1	1	1	1	1	MV
b ₁	3.335	3.338	3.340	3.338	3.336	mT
b ₂	23.708	23.53	23.143	22.647	22.283	mT/m
b ₃	333.486	335.003	333.781	333.916	340.267	mT/m ²
b ₄	131.63	127.535	235.989	404.166	642.379	mT/m ³
b ₅	17520	15420	16360	17820	19970	mT/m ⁴

Table 5-6 Normal part of the multipole component factors in the three-mode cavity.

	95.26 MHz	285.78 MHz	476.3 MHz	Unit
V _z	0	0	0	V
V _t	1	1	1	MV
b ₁	3.338	3.338	3.336	mT
b ₂	23.64	23.76	23.34	mT/m
b ₃	333.1	333. 89	333.787	mT/m ²
b ₄	122.521	323.8	734.297	mT/m ³
b ₅	17880	18782	18297	mT/m ⁴

Table 5-7 Normal part of the multipole component factors in the 190.52 MHz
one-mode cavity.

	190.52 MHz	Unit
V _z	0	V
V _t	1	MV
b ₁	3.34	mT
b ₂	23.443	mT/m
b ₃	333.267	mT/m ²
b ₄	176.404	mT/m ³
b ₅	18030	mT/m ⁴

Table 5-8 Normal part of the multipole component factors in the 381.04 MHz
one-mode cavity.

	381.04 MHz	Unit
V _z	0	V
V _t	1	MV
b ₁	3.338	mT
b ₂	22.541	mT/m
b ₃	333.471	mT/m ²
b ₄	513.785	mT/m ³
b ₅	21620	mT/m ⁴

5.3 EMITTANCE GROWTH CAUSED BY SEXTUPOLE

The emittance growth due to the sextupole was simulated in ELEGANT with zero length deflectors, and was shown to have no significant effect on the transverse

emittance during the recirculation. All multipole components are normalized to the dipole components, as summarized in Table 5-9.

Obvious chromaticity shift and transverse emittance growth are seen if the sextupole coefficient is artificially increased by three orders of magnitude in the simulation, as shown in Fig.5.5.

Table 5-9 Normalized multipole components.

Bn		Mode n	unit
B0	Deflect	1	
B1	Quad	7	1/m
B2	Sext	100	1 /m ²
B3	Octu	40	1 /m ³
B4		5253	1 /m ⁴

FIG.5.5 Emittance growth due to the sextupole multipole with artificially increased coefficient.

CHAPTER 6

HIGH ORDER MODES ANALYSIS

Beam passing through the cavity, high order modes are excited. These beam-induced modes will cause significant rf power loss, and affect the following bunches' beam quality in the high current situation.

6.1 BEAM-INDUCED MODES

These beam-induced modes are determined by the time-structure of the passing bunches. In some intense pulsed machines, such as Spallation Neutron Source (SNS) and European Spallation Source (ESS) that have multiple beam time-structures, each time structure will generate resonance excitations^[71].

In our case, the electron beam has a single time-structure (continuous electron bunches at 476.3 MHz repetition rate), then only integer multiples of the bunch repetition frequency will be excited, such as 476.3 MHz, 952.6 MHz, 1428.9 MHz and so on.

In our analysis, an electron bunch can be treated as a single point charge q , when it passes a cavity on axis, monopoles are excited and the induced voltages of the n th harmonic in a loss-free cavity can be calculated from Equ.(6.1).

$$\tilde{V}_{qn} = \frac{\omega_n}{2} \frac{R_n}{Q_n} |q| \exp(i\omega_n t) = V_{qn} \exp(i\omega_n t) \quad (6.1)$$

Here ω_n is the angular frequency of the n th harmonic, q is the point charge, time t is set to zero when the point charge passes the cavity. R_n is the longitudinal shunt impedance of the n th harmonic, and Q_n is the unloaded quality factor of this mode.

R_n/Q_n is defined as the longitudinal geometry shunt impedance, which can be calculated from Equ.(6.2).

$$\frac{R_n}{Q_n} = \frac{\left| \int_{-\infty}^{\infty} E_{zn}(z) \exp(i\omega_n z / v) dz \right|^2}{\omega_n U} \quad (6.2)$$

Here v is the particle velocity in m/s, U is the mode's stored energy in J. $E_{zn}(z)$ is the on-axis electric field of the n th mode in V/m.

If the decay term of each harmonic are included, the Equ.(6.1) can be rewritten as Equ.(6.3).

$$\tilde{V}_q = V_q \exp(i\omega_n t) \exp(-\frac{t}{\tau_n}) \quad (6.3)$$

Here τ_n is the decay time constant of the voltage of the n th harmonic. According to the definition of the decay time of stored energy in Equ.(2.47), the decay time constant of the voltage can be calculated from Equ.(6.4).

$$\tau_n = \frac{2Q_{Ln}}{\omega_n} \quad (6.4)$$

The bunch repetition frequency in the circulator ring is $f_{10}=476.3$ MHz, then the bunch separation distance in the time donmine can be expressed as T_b :

$$T_b = \frac{1}{f_{10}} \quad (6.5)$$

In the circulator ring, the everage beam current of the electron bunches is 1.5 A, then the single electron bunch charge is:

$$q = I \bullet T_b \quad (6.6)$$

Normalize the beam induced voltage of the n th harmonic V_{qn} in Equ.(6.1) to the R_n/Q_n of each mode, we could get the normalized beam induced voltage which is only related to the mode frequency, as shown in Equ.(6.7).

$$V_{qn-nor}(\omega) = \frac{\omega_n}{2} q \quad (6.7)$$

For the continues beam with a single time-structure, immediately following the Nth electron bunch, the beam induced voltage of the nth harmonic can be calculated from Equ.(6.8).

$$A(N, Q_{Ln}, \omega) = V_{qn-nor} \frac{1 - \exp(\frac{-NT_b}{\tau_n} + i\omega NT_b)}{1 - \exp(\frac{-T_b}{\tau_n} + i\omega T_b)} \quad (6.8)$$

During the gap between the Nth and (N+1)th bunch, and at the position that t_1 away from the center of the Nth bunch, the beam induced voltage of the nth harmonic can be calculated from Equ.(6.9).

$$B(N, Q_{Ln}, \omega, t_1) = A(N, Q_{Ln}, \omega) \exp(-\frac{t_1}{\tau_n} + i\omega t_1) \quad (6.9)$$

In the steady state, for example, after 10000 bunches, at any time t , the beam induced voltage for the nth harmonic can be expressed in Equ.(6.10).

$$V_{qn-st}(Q_{Ln}, \omega, t) = \begin{cases} A(N, Q_{Ln}, \omega), & \text{if } t_{11}(t) \leq \frac{T_p}{2} \\ B(N + 10000, Q_{Ln}, \omega, t_1) & \text{if } t_{11}(t) \geq \frac{T_p}{2} \end{cases} \quad (6.10)$$

Where:

$$t_{11}(t) = \text{mod}(\frac{t}{T_b}) \quad (6.11)$$

Here the operator mod ( ) is used to get the residue part in the bracket ( ).

T_p is the bunch length in time domain, here the bunch length in the ERL is $\sigma_t=8.96$ mm, and T_p can be calculated from Equ.(6.12).

$$T_p = \frac{\sigma_t}{c} \quad (6.12)$$

N is the passed bunch number at time t ,

$$N = \text{ceil}\left(\frac{t}{T_b}\right) \quad (6.13)$$

Here the operator ceil () is used to get the integer part in the bracket and plus one.

Then the normalized HOM power dissipated by the beam can be calculated from Equ.(6.14).

$$P_n(Q_{Ln}, \omega, t) = \frac{V_{qn-st}(Q_{Ln}, \omega, t)^2}{Q_{Ln}} \quad (6.14)$$

The time averaged normalized HOM power can be obtained by integrating the $P_n(Q_{Ln}, \omega, t)$ in 1000 periods of T_b :

$$P_{aven}(Q_{Ln}, \omega) = \frac{1}{1000T_b} \int_0^{1000T_b} P(Q_{Ln}, \omega, t) dt \quad (6.15)$$

Consider the beam spectrum roll-off at high frequency due to the beam bunch shape and length for the Top-hat (which is approximate to the Flat-Top shape here) shape in full width T_p and Gaussian shape (GS) in RMS 2σ (T_p), as shown in Fig.6.1.

FIG.6.1 High frequency roll-off of the Top-hat bunch and the Gaussian bunch

For the Top-hat bunch,

$$FT(\omega) = \frac{\left| \sin\left(\text{trunc}\left(\frac{\omega}{\omega_0}\right)\omega_0 \frac{T_p}{2}\right) \right|}{\text{trunc}\left(\frac{\omega}{\omega_0}\right)\omega_0 \frac{T_p}{2}} \quad (6.16)$$

Here the operator trunc () is used to get the integer part of the number in the bracket (). And,

$$\omega_0 = 2\pi f_0 \quad (6.17)$$

$$f_0 = 47.63 \quad MHz \quad (6.18)$$

For the Gaussian bunch,

$$GS(\omega) = \exp(-(\omega^2 (\frac{T_p}{4})^2)) \quad (6.19)$$

From Fig.6.1, for the Top-hat bunch, with the frequency goes higher, the roll-off curve shows fluctuations, and for the Gaussian bunches, the roll-off curve decay to zero at 50 GHz. In the JLEIC design, Top-hat bunches are chosen to meet the requirements of beam dynamics.

With the bunch structure, the time averaged normalized HOM power of the nth mode can be calculated from Equ.(6.20).

$$P_{aven-TH}(Q_{Ln}, \omega) = P_{ave}(Q_{Ln}, \omega) FT(\omega) \quad (6.20)$$

It can be plotted in the frequency domain, as shown in the Fig.6.2. When just consider the single time structure, the HOM power is large only when the HOM frequencies are on or close to the integral multiples of the bunch repetition frequency, and the HOM power decrease rapidly when the HOM frequencies deviated from the resonance value.

The total HOM power in the cavity can be calculated by the summation of the HOM power of all HOM modes, as shown in Equ.(6.21).

$$P_{total} = \sum_{n=1}^{N_m} P_{aven-TH}(Q_{Ln}, \omega_n) [\frac{R}{Q}]_n \quad (6.21)$$

Here N_m is the total number of the high order modes. When the total HOM power calculated from the Equ.(6.21) is very large, it is necessary to find out these modes and damp them.

FIG.6.2 Time averaged normalized HOM power in the frequency domain.

6. 2 DEFLECTING WORKING MODES

First consider ten deflecting working modes in all four cavities. The longitudinal and transverse geometry shunt impedances of each mode are list in Table 6-1. Disconsider the damping in the coupler port, the total power dissipation in the nature decay case is 190 kW from Equ.(6.21). The largest power dissipation happens on the mode of 476.3 MHz, which is equal to the bunch repetition frequency. If take this part away, the total power dissipation for the cavity in the nature decay case is only 0.027 W. Then the cavity structure that supporting this mode should be optimized to push the longitudinal geometry shunt impedance of this mode to zero.

The simplest method to solve this problem is removing this mode from the second cavity which supporting this mode and constructing another symmetrical Double Quarter Wave Resonantor for this single mode. On the other hand, the HOM mode close to 476.3 MHz in the second should be tuned away from the resonant value when

tuning the second cavity. The main problem in this solution is that the total number of the cavity is increased.

Table 6-1 Transverse and longitudinal geometry shunt impedance of all deflecting working modes in all cavities.

Cavity	Operation Frequency (MHz)	Transverse Geometry Shunt Impedance (Ω)	Longitudinal geometry shunt impedance (Ω)	Unloaded Quality Factor Q_0
5-mode cavity	47.63	735.32	0.90	8586
	142.89	225.07	2.47	14689
	238.15	126.02	3.84	18973
	333.41	68.31	4.09	22472
	428.67	38.14	3.77	25536
3-mode cavity	95.26	732.74	3.58	12002
	285.78	173.37	7.62	20784
	476.3	51.52	6.29	27056
1-mode cavity	190.52	642.32	12.47	15298
1-mode cavity	381.04	389.46	30.42	19435

Another solution is to optimize the electrode structure of the second cavity that support the 476.3 MHz mode to push the longitudinal shunt impedance of this mode to zero or a sufficiently small value, as shown in Fig.6.3. With this design, the introducing of the additional cavity is avoided. But on the other hand, the transverse shunt impedance will decrease with the longitudinal shunt impedance, which will affect the deflecting efficiency. In the present JLEIC design, the total power dissipation is very low, thus this affect can be ignored.

FIG.6.3 Optimization of the electrode to reduce the longitudinal geometry shunt impedance of the highest working mode 476.3 MHz.

6. 3 HIGH ORDER MODES

Consider the high order modes above the deflecting working modes in the cavity. Using the five-mode cavity as an example, with the CST MICROWAVE STUDIO, the transverse and longitudinal geometry shunt impedance of the first 100 modes were calculated and summarized in Appendix II. From the table, there are several high order modes with a big longitudinal shunt impedance, but the frequencies of these modes are far enough away from the resonance value. From Equ.(6.21) we can calculate the total HOM power dissipation in the cavity in the natural decay case is about 8.21 W. Thus the HOM issues in this cavity can be ignored. Similarly, the HOM in the three-mode cavity and two one-mode cavities can be analysed with the same methods.

CHAPTER 7

MECHANICAL DESIGN AND FABRICATION OF THE HALF SCALE COPPER PROTOTYPE

To validate the electromagnetic performance of this design, a half scale prototype with 5 odd harmonics of has been constructed, as shown in Fig.7.1. The fundamental mode is 95.26 MHz, and 5 odd harmonics (95.26 MHz, 285.78 MHz, 476.3 MHz, 666.82 MHz, 857.34 MHz) resonant simultaneously in this cavity. After these cavity components are machined and checked separately, all of them are sent to the chemical room for cleaning to meet the requirements for EBW (electron beam welding).

FIG.7.1 Half scale copper prototype and the section view.

7. 1 FIBRACATION AND EBW OF THE OUTER CONDUCTOR

The outer conductor is 809 mm (31.85 inch) long, 155.6 mm (6.125 inch) OD and 148.5 mm (5.845 inch) ID, and was fabricated from a commercial copper water pipe stock. The nominal composition of this pipe is 99.9% copper and 0.02% phosphorus and the electrical properties are more than adequate for this purpose. Tests showed that it could also be electron beam welded without any problems.

Five tuner ports, two beam pipes, and one coupler pipe are all made from 50.8 mm (2 inch OD) and 38.1 mm (1.5 inch) ID C101 (oxygen free) copper tube. A T-Slot aluminum fixture was fabricated for assembly and alignment during the electron beam welding of the five tuner ports to the cavity outer conductor, as shown in Fig.7.2.

FIG.7.2 EBW of the tuner pipes to the cavity wall. The T-Slot aluminum fixture was fabricated for assembly and alignment.

The capacitive-end flange with the pickup port is bolted to the cavity end flange, which allows the possibility of optimizing of the end gap structure near the beam pipe. Fig.7.3 shows the welding process of the cavity end flange to the cavity outer conductor wall. Fig.7.4 shows the welding process of the capacitive-end flange with the pickup port.

FIG.7.3 Welding process of the cavity end flange to the cavity outer conductor wall.

FIG.7.4 Welding process of the capacitive-end flange with the pickup port.

7.2 FABRICATION AND EBW OF THE INNER CONDUCTOR

The inner conductor is made from a 54.0 mm (2.125 inch) OD and 41.3 mm (1.625 inch) ID C101 copper tube. The four straight taper slopes on the inner conductor surface were NC machined to get the harmonic frequencies. A copper plate of 41.3 mm (1.625 inch) diameter with a 6.35 mm (1/4 inch) diameter threaded hole in the center was welded to the electric-field end of the inner conductor so a

demountable electric-end cap can be connected to the inner conductor, as shown in Fig.7.5. This welded plate can also be used to align the inner conductor during the electron beam welding of the magnetic end flange.

FIG.7.5 Demountable electric-end cap be connected to the inner conductor with threaded hole

The inductive end joints were electron beam welded for good electrical conduction. Two welding processes from both the inner surface and outer surface of the cavity are used here to connect the inner conductor to the inductive-end flange. Fig.7.6 shows the welding process of inductive-end flange to the inner conductor on the inner surface of the cavity. Fig.7.7 shows the welding process of inductive-end flange to the inner conductor on the outer surface of the cavity.

FIG.7.6 Welding process of inductive-end flange to the inner conductor on the inner surface of the cavity

FIG.7.7 Welding process of inductive-end flange to the inner conductor on the outer surface of the cavity.

7. 3 EBW OF THE OUTER CONDUCTOR WITH INNER CONDUCTOR

After the outer and inner conductors were welded with the attachend components separately, all of them were sent back to the chemical room for the second cleaning to meet the requirements for the final EBW between the inner and outer conductor. Fig.7.8 shows the cavity components before the final EBW and the final welding process between the inner and outer conductor.

FIG.7.8 Cavity components before the final EBW and the final welding process between the inner and outer conductor.

7. 4 DESIGN AND THE FIBRACATION OF THE STUB TUNERS

The manual stub tuner design is similar to a CEBAF waveguide stub tuner, as shown in Fig.7.9. The tuning sensitivity is 1.27 mm (0.05 inch)/turn, set by the chosen threaded rod. Bearings are used to minimize friction between the stubs and tuner ports.

FIG.7.9 Detail of the stub tuners.

RF fingers are fitted into grooves in the tuner port to get good rf contact, as shown in Fig.7.10.

FIG.7.10 RF finger fit into the grooves in the tuner port.

7.5 DESIGN AND THE FIBRACATION OF COUPLERS

A simple loop coupler inset to the high magnetic field area of all modes are used for the input power, and a probe at the high electric field area is used for the power pickup, as shown in Fig.7.11.

FIG.7.11 Loop coupler in the high magnetic field area and pickup probe in the high electric field area.

7. 6 DISCUSSION

The design, fabrication and welding process of the half scale prototype were discussed in this chapter. As this prototype cavity is just used for the bench measurements, to save the cost, the cavity size is adjusted to fit the standard pipes which could be used for cleaning and welding after simple machining.

CHAPTER 8

RF MEASUREMENTS OF THE HALF SCALE COPPER PROTOTYPE

A series of RF measurements had been taken on this half scale prototype after the final welding. With these measurements, the electromagnetic performance of the cavity can be obtained, and with the comparisons between the design parameters and the measurement results, the design concept can be validated and the fault in the design can be recognized, then the further optimization can be proceeded. With this prototype cavity, the resonant frequency, tuning sensitivity, and unloaded quality factor have been measured for all modes. Bead-pull measurements with dielectric and metallic perturbing objects have been made and all these results compared with the numerical simulations. A demonstration of mode superposition in the cavity has also been performed.

8.1 RESONANT FREQUENCY AND TUNING SENSITIVITY MEASUREMENTS

The resonant frequencies in the cavity can be got by measuring the transmission coefficients between the input coupler port and the pickup port (S_{21} or S_{12}), or the reflection coefficients at either of the port (S_{11} or S_{22}). On the resonant frequencies, the transmission coefficient is the maximum and the reflection coefficient is the minimum. Fig.8.1 shows the setup to measure the resonant frequencies with the transmission coefficient S_{21} .

FIG.8.1 setup to measure the resonant frequencies with the transmission coefficient S21.

The resonant frequencies of the first five harmonic modes were measured and summarized in Table 8-1. All mode frequencies are slightly higher than the design values but the manufacturing errors are less than 0.2% for all modes.

TABLE 8-1. Resonant frequency measurements

Target Frequency (MHz)	Measured Frequency (MHz)	Frequency Shift (%)
95.26	95.420	+0.17
285.78	285.950	+0.06
476.3	476.785	+0.10
666.82	666.906	+0.01
857.34	857.827	+0.06

Even though the frequency shift due to the manufacturing and welding is very small, the resonant frequencies of all modes are almost on their target values, it is still possible to fine tune the resonant frequencies to get the more accurate measurement results. With five carefully designed stub tuners, the frequencies of the first five modes

can be tuned to +/- 0.001% within the target value (about +/-1 kHz for the fundamental mode and about 10 kHz for the highest mode).

Before the tuning process, it is important to get the tuning sensitivity of each mode to each tuner, which means the tuning matrix M_{tuner} in Equation (4.30). The tuning sensitivity of each stub tuner is measured by changing the insertion distance, which will result in a 5X5 tuning matrix M_{tuner} , as shown in Equation (8.1), the element n_{ij} in this matrix means the first order frequency response of the i^{th} mode to the j^{th} tuner in units of Hz/mm. Comparing to the simulation results, the maximum relative error is 0.129%.

$$M_{\text{tuner}} = \begin{pmatrix} -31.26 & -26.93 & -17.80 & +3.465 & +9.370 \\ -4.803 & +33.07 & +8.583 & -100.3 & -9.134 \\ +47.09 & -126.9 & -180.2 & -150.2 & -104.3 \\ -153.5 & -216.8 & +74.25 & +20.08 & -265.5 \\ -404.6 & +97.17 & -401.0 & +14.33 & -422.1 \end{pmatrix} \quad (8.1)$$

With this tuning matrix and the tuning equation in (4.30), the frequencies can be tuned to their targets with several iterations, as shown in Fig 8.2.

FIG.8.2 Tuning of the resonant frequencies with several iterations.

Fig.8.3 shows the first five modes be tuned to the targets with only 3 iterations in the measurement.

FIG.8.3 First five modes were tuned to the targets with only 3 iterations in the measurement.

8. 2 TRANSMISSION AND REFLECTION COEFFICIENTS, UNLOADED QUALITY FACTOR Q MEASUREMENTS

The unloaded quality factors Q_{0n} for the resonant modes in the cavity can be got by measuring their loaded quality factors Q_{Ln} , the coupling strength β_{1n} at the input coupler port, and the coupling strength β_{2n} at the pickup port, as shown in Equation (8.2).

$$Q_{0n} = Q_{Ln} (1 + \beta_{1n} + \beta_{2n}) \quad (8.2)$$

Here the loaded quality factors Q_{Ln} for each mode can be got from the “bandwidth method” when measuring the transmission coefficient S_{21} ^[72], as shown in Equation (8.3).

$$Q_{Ln} = \frac{f_{0n}}{f_{2n} - f_{1n}} \quad (8.3)$$

Here f_{0n} is the resonant frequency of the nth mode, which also corresponded to the peak value of the S_{21} curve. f_{1n} and f_{2n} are the -3dB frequencies at each side of the resonance. In the measurement, Q_{Ln} can be displayed directly on the VTA.

The coupling strength of each mode at the input coupler port β_{1n} can be calculated from the reflect coefficient $S_{11}(f_{0n})$ at this port^[73], as shown in Equ.(8.4).

$$\beta_{1n}(f_0) = \frac{1 \pm |S_{11}(f_{0n})|}{1 \mp |S_{11}(f_{0n})|} \quad (8.4)$$

Here the upper sign is used for the over coupling ($\beta_{1n} > 1$) situation, the lower sign is used for the under coupling ($\beta_{1n} < 1$) situation. When β_{1n} is very small, such as $\beta_{1n} \ll 1$, and when $|S_{11}(f_{0n})| \sim 1$, Equ.(8.4) shows great errors, and Equ.(8.5) is adopted at this situation.

$$\beta_{1n} \approx \frac{1 - |S_{11}(f_{0n})|/|S_{11}(|f| \gg f_{0n})|}{1 + |S_{11}(f_{0n})|/|S_{11}(|f| \gg f_{0n})|} \quad (8.5)$$

Here $|S_{11}(f_{0n})|$ is the reflect coefficient at the resonance of the nth mode, and $|S_{11}(|f| \gg f_{0n})|$ is the reflect coefficient far away from the resonance of the nth mode.

At the pickup port, the coupling strength of each mode β_{2n} is very weak, $\beta_{2n} \ll 1$, $S_{22}(f_{0n}) \sim 1$. To get the accurate value of β_{2n} , we can measure the transmission efficient $S_{21}(f_{0n})$ instead of the reflect coefficient $S_{22}(f_{0n})$, and calculate to get the external quality factor Q_{e2n} at the pickup port, as shown in Equ.(8.6).

$$Q_{e2n} = \frac{4\beta_{1n}}{1 + \beta_{1n}} Q_{Ln} \cdot 10^{\frac{|S_{21}(f_{0n})|(dB)}{10}} \quad (8.6)$$

Then the coupling strength of each mode at the pickup port β_{2n} can be calculated from Equ.(8.7) approximately.

$$\beta_{2n} = \frac{Q_{Ln}(1 + \beta_{1n})}{Q_{e2n}} \quad (8.7)$$

It is important to note that the cable must be calibrated to exclude the loss in the transmission line when using the transimission coefficient instead of the the reflect coefficient to determine the coupling strength at the pickup port.

The transmission coefficient between the input coupler port and the pickup port S_{21} was measured and plotted in Fig. 8.4 (left), and the reflection coefficient S_{11} at the input coupler port is shown in Fig. 8.4 (right).

FIG.8.4 The transmission coefficient between the input coupler port and the pickup port (left), and the reflection coefficient at the input coupler port (right) as a function of frequency.

The unloaded quality factors of the five harmonic modes were measured and compared with the CST simulation in Table 8-2.

Table 8-2 Unloaded quality factors from the simulation and measurement.

Mode (MHz)	CST	Measurement	Error
95.26	5665	5301	-6.43%
285.78	9770	9277	-5.04%
476.3	12531	11282	-9.96%
666.82	14834	13152	-11.34%
857.34	17109	14095	-17.62%

The unloaded Q factors are lower than the simulation values for all modes, and this difference may be caused by imperfection of the copper material, joint losses and rf contact losses at the stubtuners, but the values are quite acceptable for this experiment.

8.3 BEAD-PULL MEASUREMENT

8.3.1 Field Distributions in the Simulation

From the CST numerical simulations, the distribution of different field components along the beam axis can be plotted, as shown in Fig.8.5. All field components are normalized to the stored energy and frequency. The magnetic field is multiplied by the free space impedance ($\eta_0 = 120\pi$) to give a fair comparison of the respective contribution of the electric and magnetic field to the transverse kick.

FIG.8.5 On-axis field magnitude square of the different components of the electric field E_x (top left), E_z (top right) and the magnetic field H_y (bottom).

The dominant field component is the deflecting electric field E_x (top left in Fig.8.5), the longitudinal electricfield E_z (top right in Fig. 8.5) is much smaller than the deflecting field (maximum 10% in magnitude squared). The transverse magnetic field H_y (bottom in Fig. 8.5 is much weaker, and much smaller for the lowest harmonic mode (0.1% in magnitude squared) and relatively larger for the highest harmonic mode (6% in magnitude squared).

8.3.2 Bead-pull technique

The electromagnetic field distribution and mode orientation in the cavity can be obtained by a bead-pull technique, which is based on the Slater theorem. In the measurement, a small metallic or dielectric object attached to a string is pulled through the rf structure, while a small amount of rf power is fed into the structure at the frequency of the resonant mode. The frequency shift due to the insertion of the perturbing object is measured during the passage of the bead. The relative change in resonant frequency is proportional to the relative change in stored energy and can be expressed as Equ(8.8) as a function of the local electric and magnetic field strength^[74].

$$\frac{\Delta\omega}{\omega_0} = -F_E \frac{\varepsilon_0 |E|^2}{U} + F_H \frac{\mu_0 |H|^2}{U} \quad (8.8)$$

Where $\Delta\omega=\omega-\omega_0$, and ε_0 and μ_0 are the dielectric and magnetic constants of the free space, U is the stored energy in the cavity, and F_E , F_H are the geometry factors associated with the bead shape, dimension and couplings to the E field and H field.

Table 8-3 Perturbation factors for sphere (radius=a).

Bead	F_E	F_H
Dielectric Bead	$\pi a^3 \frac{\varepsilon_r - 1}{\varepsilon_r + 2}$	
Metallic Bead	πa^3	$\frac{1}{2} \pi a^3$

The geometry factors for the sphere are listed in Table 8-3, ϵ_r is the relative dielectric constant of the bead. For a perfect sphere, the form factors are the same in the longitudinal and transverse directions.

The frequency shift in the cavity resonance can be obtained with a network analyzer from the peak of the absolute S21 measurement. But for small perturbations it is more convenient to measure the phase shift instead of the frequency shift^[75-76] when the network analyser is locked to the drive frequency, as shown in Eq. (8.9).

$$\frac{\Delta\omega}{\omega} = \frac{1}{2Q_L} \tan(\varphi) \quad (8.9)$$

Where Q_L is the loaded quality factor of resonance and φ is the phase of the transmission coefficient between two ports coupled to the field in the cavity. When φ is much smaller than 45 degrees, $\tan(\varphi)$ can be approximated to φ .

8.3.3 Field distribution measurement with bead-pull technique

FIG.8.6 Complete bead pull measurement setup.

The complete measurement setup is shown in Fig. 8.6. Stepping motors controlled by a LabVIEW program on a PC are used to position the bead. A transverse alignment system consisting of X-Y stage stepping motors is installed which allows the bead position be controlled separately in the X and Y directions at each end of the cavity

beam pipe. With this system, it is relatively easy to do the measurement accurately on the axis and at various offsets.

An Agilent E5071C network analyzer that is interfaced by a GPIB device to the PC is used to measure the frequency shift or phase shift, the LabVIEW interface to get the phase shift is shown in Fig.8.7. A broadband amplifier is employed to increase the rf signal to noise ratio.

FIG.8.7 LabVIEW interface to get the phase shift.

Two types of perturbing objects were used in the measurement, a small dielectric (Teflon) sphere and a small metallic (brass) sphere, as shown in Fig.8.8. With the dielectric bead, the electric field in all directions can be picked up, and with the metallic bead, both the electric and magnetic fields will be measured.

FIG.8.8 Pertubing objects employed in the measurement with their dimensions measured by caliper. (Left: Teflon. Right: Brass).

The beads used are not perfectly spherical, so an aluminum pillbox cavity is employed to calibrate the form factor, as shown in Fig. 8.9. The resonant mode used here is TM₀₁₀. By pulling the bead in the longitudinal direction (left), through the known field the longitudinal form factor can be calibrated, and by pulling the bead in the radial direction (right), the transverse form factor can then be calibrated.

FIG.8.9 Pillbox cavity used for calibration of the perturbing beads.

The form factors obtained by calibration are listed in Table 8-4. Since the beads are not perfect spheres and there is a finite through hole at the bead center, the form factors are different in these two directions.

Table 8-4 Form factors obtained by calibration.

Bead	Transverse	Longitudinal	Transverse
	F_{Ex}	F_{Ez}	F_{Hy}
Dielectric Sphere	2.21E-8	2.23E-8	
Metallic Sphere	3.60E-8	3.18E-8	1.91E-8

With the calibrated beads, the final measurement results are summarized in Fig. 8.10. The longitudinal electric field and the magnetic field are too weak to be separated out.

FIG.8.10 Result of the measurement with the dielectric (top) and the metallic (bottom) bead, and the comparison with simulation results.

8. 4 MODE COMBINATION EXPERIMENT

The half scale multiharmonic cavity was also used to demonstrate a simple multiharmonic frequency combination experiment. Fig.8.11 shows the schematic and bench setup of this experiment.

Five rf signal generators were used to generate the five odd harmonic frequencies (from 95.26 MHz to 857.34 MHz). The signal generators are synchronized to a 10 MHz reference signal and input to a multi channel rf combiner that feeds the cavity input coupler. An oscilloscope was used to monitor the cavity pickup signal. A

synchronized source (Agilent 5071B) was used to generate a 95.26 MHz rf signal as the oscilloscope trigger. The amplitude and phase of each harmonic mode could be adjusted independently and sequentially, in order to fulfill the requirements of the flat-top kicking pulse scheme.

FIG.8.11 Schematic drawing (top) and bench setup (bottom) for the mode combination experiment.

The voltage waveform of each harmonic and then the combined signal were directly viewed on the oscilloscope. The mode combination results are shown in Fig. 8.12 with each mode added in turn starting with the lowest mode. Comparison of the combined kick pulse captured from the oscilloscope display with the simulation is shown in Fig. 8.13, and the agreement is very good.

FIG.8.12 The result of the odd harmonic modes combined one by one viewed on the oscilloscope display. Here the fifth mode is in the reverse phase to make the final kicking pulse more flat. The final working pulse is a flat-top kicking pulse which is the combination of a DC component and 10 continues harmonic modes separated in four cavities, here we just use five odd harmonic modes in the first cavity for a demonstration purpose.

FIG.8.13 Comparison of the combined kick pulse from the oscilloscope display image capture with the simulation curve.

CHAPTER 9

CONCLUSION

An ultrafast rf kicker concept suitable for the JLEIC bunched beam electron cooler ring has been demonstrated in this thesis. By using four QWR based deflecting cavities, and 10 harmonic modes with the distribution 5 : 3 : 1 : 1 and an additional DC offset, a flat-top kicking pulse can be synthesized with excellent performance in conserving the transverse emittance of the cooling electron bunches during the recirculation.

The cavity was designed and optimized to get high transverse impedances so the sum of the rf wall losses in all four cavities is less than 100 W for a total kicking voltage of 55 kV. Straight taper segments on the inner conductor of the 5-mode and 3-mode cavities were used to get the higher deflecting modes to be harmonic. Stub tuners were used to compensate the frequency shifts due to the manufacturing tolerances. A single loop input coupler on each cavity can be used on the multimode cavities. By adjusting the loop position and loop size, it is possible to get the fundamental mode of each cavity to be critically coupled and higher harmonics slightly over coupled. Broadband circulators may be considered for the reflected power.

A half scale 5-mode prototype cavity was fabricated in order to validate the electromagnetic characteristics and optimization from the numerical simulations. The frequency shift due to manufacturing tolerances was less than 0.2% for all modes and could be easily corrected by a combination of the 5 stub tuners. The unloaded quality factors of the five modes were measured and were within 20% of the calculated values. Bead-pulling measurements using both dielectric and metallic beads moving along the

beam axis showed a good agreement with the simulated profile of the electric field. Finally an experiment to combine the five modes together, to get the desired kicking pulse was performed.

Further optimizations of the cavity structure to reduce the longitudinal E-field component, and investigations into HOM analysis using the wakefield method for high current operation are under way. Real vacuum compatible cavities are planned to be designed and fabricated in the near future to measure the actual kicking effect on an electron beam.

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APPENDIX I

LEAST-MODES + HIGHEST HARMONIC SCHEME

Consider the last three harmonic modes are in the inverse phase to give compensation to the voltage curvature to get a flat top kick. It is also possible to introduce a higher harmonic with the inverse phase to correct the voltage curvature in the Least-Mode scheme, as shown in Fig.1.1. The comparison of the normalized kick voltage of each mode between the Flat-Top scheme and the Least-Mode scheme is listed in Table 1-1. This scheme with the reduced harmonic number will significantly benefit the design and construction of the future full scale cavity

FIG.1.1 Introduce a higher harmonic with the inverse phase to correct the voltage curvature in the Least-Mode scheme.

Table 1-1 The comparison of the normalized kick voltage of each mode between the Flat-Top scheme and the Least-Mode scheme.

Harmonic Frequency (MHz)	Flat-Top	Least-Modes	Least-Modes+476.3MHz
47.63	0.249	0.200	0.200
95.26	0.227	0.200	0.200
142.89	0.192	0.200	0.200
190.52	0.148	0.200	0.200
238.15	0.100	0.100	0.100
285.78	0.053	...	...
333.41	0.012	...	...
381.04	-0.022	...	...
428.67	-0.044	...	...
476.3	-0.055	...	-0.090
DC	0.140	0.100	0.190
Total	1.000	1.000	1.000

The relationships between the recirculation turn, harmonic number and the cavity number for the Least-Modes+476.3 MHz harmonic scheme are listed in Table 1-2.

Table 1-2: The relationships between the recirculation turn, harmonic number and the cavity number for the Least-Modes+476.3 MHz harmonic scheme.

Recirculate Turn	10	15	25	30
Harmonic Number	6	8	13	16
Cavity number	3	3	4	4
Mode distribution	3:2:1	5:2:1	7:3:2:1	8:5:2:1
Modes in Cavity#1	1,3,5	1,3,5,7,15	1,3,5,7,9,11, 25	1,3,5,7,9,11,13,15
Modes in Cavity#2	2,10	2,6	2,6,10	2,6,10,14,30
Modes in Cavity#3	4	4	4,12	4,12
Modes in Cavity#4			8	8

APPENDIX II

GEOMETRY SHUNT IMPEDANCE FOR THE FIRST 100 MODES

IN THE FIVE-MODE CAVITY

	Operation Frequency (MHz)	Transverse geometry shunt Impedance (Ω)	Longitudinal geometry shunt Impedance (Ω)	Unloaded Quality Factor Q_0
1	47.629	735.32	0.90	8586
2	142.879	225.07	2.47	14689
3	238.124	126.02	3.84	18973
4	298.069	0.99	0.05	3831
5	333.345	68.31	4.09	22472
6	428.612	38.14	3.77	25536
7	468.371	1.75E-4	2.06E-3	32168
8	475.517	3.74	0.46	31536
9	493.709	2.02E-3	2.66E-4	32617
10	500.253	12.97	1.75	32000
11	521.657	18.95	2.77	28512
12	537.127	4.7E-3	7.31E-4	33603
13	543.246	13.152	2.09	33067
14	590.025	8.86E-3	1.66E-3	34653
15	596.561	11.27	2.16	34322
16	613.922	6.57	1.33	30941

17	652.743	2.69E-4	2.69E-4	35947
18	660.099	6.09	1.43	35803
19	706.506	0.75	0.2	32903
20	723.566	1.13E-4	3.2E-5	37451
21	730.171	2.54	0.73	37564
22	793.899	0.29	9.67E-2	34523
23	800.624	2.67E-2	9.21E-3	38827
24	803.965	0.48	0.17	39342
25	877.761	0.52	0.22	38894
26	880.082	0.10	0.04	35940
27	883.627	2.18	0.91	37569
28	884.183	0.30	0.13	40514
29	893.512	0.03	0.01	37024
30	897.320	6.48E-5	2.80E-5	39790
31	911.973	1.18E-4	5.29E-5	40062
32	920.087	3.39	1.55	38077
33	936.057	2.14E-4	1.01E-4	41107
34	949.952	2.36	1.15	37207
35	964.425	0.60	0.30	42274
36	964.678	0.55	0.28	42290
37	969.311	1.38E-2	7.00E-3	42178
38	970.559	4.65	2.35	37177
39	992.304	3.80	2.01	39897
40	1010.707	3.90E-3	2.15E-3	43694
41	1038.466	4.39	2.55	38542

42	1040.031	0.02	1.21E-2	42820
43	1047.604	1.34	0.79	43775
44	1059.318	3.30	1.99	38658
45	1059.575	0.19	0.12	44864
46	1101.059	3.54	2.31	44369
47	1111.919	2.71E-3	1.80E-3	46689
48	1117.460	0.19	0.13	33544
49	1129.923	0.12	8.24E-2	45214
50	1150.018	2.00	1.42	35687
51	1159.971	0.81	0.59	44356
52	1171.719	0.01	7.429E-3	48775
53	1178.964	1.45	1.09	27383
54	1201.337	0.21	0.16	42558
55	1208.286	0.42	0.33	5177
56	1211.805	1.81	1.43	32607
57	1234.272	2.03E-2	1.67E-2	50901
58	1237.193	1.32	1.09	43875
59	1246.252	1.87	1.56	39842
60	1250.515	0.16	0.14	38006
61	1263.225	5.23	4.49	39249
62	1265.459	0.11	9.89E-2	40636
63	1268.470	0.06	0.05	40497
64	1276.893	0.44	0.38	41089
65	1287.746	0.34	0.31	41580
66	1288.091	0.41	0.36	41607

67	1293.807	0.41	0.37	44385
68	1304.652	1.98E-2	1.81E-2	51936
69	1311.091	4.68E-3	4.33E-3	41861
70	1315.343	1.70	1.59	40307
71	1329.725	5.64E-2	5.36E-2	42858
72	1333.920	2.88	2.76	44651
73	1340.150	0.47	0.45	42954
74	1342.621	0.22	0.21	42901
75	1344.836	2.37	2.31	40204
76	1362.298	0.47	0.47	47327
77	1374.401	1.71E-2	0.02	48120
78	1374.573	3.05E-3	3.10E-3	47716
79	1389.046	0.96	1.00	40137
80	1408.888	1.96	2.09	34134
81	1413.472	0.27	0.29	45545
82	1420.477	0.85	0.93	45691
83	1420.965	1.48	1.61	44984
84	1430.973	4.48E-2	4.93E-2	28146
85	1435.047	0.94	1.04	44118
86	1435.482	0.30	0.34	40165
87	1448.698	9.24E-3	1.04E-2	47360
88	1449.171	6.06E-3	6.85E-3	31640
89	1452.401	3.47E-2	3.94E-2	40075
90	1465.548	5.33E-3	6.16E-3	45071
91	1472.131	0.04	0.05	28545

92	1482.475	1.36	1.61	47345
93	1487.665	9.40E-2	0.11	28547
94	1501.256	6.06E-3	7.35E-3	44045
95	1505.952	0.56	0.69	33481
96	1509.068	8.26E-2	0.1	32383
97	1509.537	1.88	2.31	41043
98	1512.151	3.53E-2	4.34E-2	35545
99	1515.058	0.11	0.14	34325
100	1522.104	2.53E-3	3.16E-3	32779

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