BEAM BREAKUP IN SUPERCONDUCTING RECIRCULATING LINACS

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INTRODUCTION

The performance and operational flexibility of superconducting recirculating linacs can be limited by a variety of collective phenomena which are grouped under the name beam breakup. These coherent effects include both multipass beam breakup, which is driven predominantly by the high- Q superconducting cavities and limits the average current, and single-bunch beam breakup, which is driven by the short-time (Q -independent) wakefields and limits the total bunch charge. The superconducting radio frequency (SRF) environment has a number of features which distinguish it from room temperature configurations with regard to these beam-environment interactions. Typically the unloaded Q s of the lower higher order modes (HOM) are at the 10^9 level and require significant damping through couplers. High gradient CW operation, which is a principal advantage of SRF, allows for better control of beam quality, which for its preservation requires added care with respect to collective phenomena. Gradients are significantly higher than those attainable with copper in CW operation but remain significantly lower than those obtainable with pulsed copper cavities. A CW superconducting linac is recirculated for several passes to optimize for cost. The focusing in later passes is limited by the requirement of stable transport on the first pass, and this constraint exacerbates the effects of short-time wakefields both through the weakened focusing strength and the inflexibility inherent in having multiple beams in a single focusing channel. In this note the various beam breakup phenomena found in recirculating SRF linacs are described and appraised relative to beam performance.

Q Dependence of Collective Effects

The Q dependence of the various beam-cavity interactions provides a fundamental differentiation which is in many ways more basic in the underlying accelerator physics than whether the phenomena occur in a linear or circular accelerator. At one extreme are coupled-bunch effects (cumulative and multipass BBU and storage ring coupled-bunch instabilities) which are made more severe by high- Q modes. For bunch-to-bunch coupling, wakefields must linger for at least the duration of the bunch spacing, and, moreover, a long or CW train of bunches can coherently excite a mode for a time of order Q/ω . The mode Z/Q is essentially a geometric property of a cavity and is insensitive to wall material or de- Q -ing efforts through couplers. It describes the single-pass excitation of a cavity mode by a beam bunch. On the other hand, $Z = (Z/Q)Q$ describes the coherent summation of multiple excitations over the filling time of the mode. Therefore, it is the impedance $Z = (Z/Q)Q$, not Z/Q , which determines the average current limits for tolerable emittance degradation or the onset of exponential growth, and the coupled-bunch phenomena are extremely sensitive to Q .

At the other extreme are single-bunch, single-pass effects which are driven by the short-time behavior of wakefields. For short bunches (nanoseconds to picoseconds) the inherently short sampling time results in lost frequency resolution (smearing of hundreds of megahertz to hundreds of gigahertz) which effectively averages frequency dependent, possibly high- Q impedances over the mode spectrum. In addition, for picosecond linac bunches, the wakefield at short times is dominated by the impedances at frequencies well above cutoff where modes can be expected to overlap. Thus, it is the impedance Z/Q , not Z , which determines the peak current limits for tolerable emittance degradation, and these limits are insensitive to Q .

Regenerative Beam Breakup

A train of bunches passing offset through an accelerating structure can excite transverse deflecting modes through a longitudinal electric field which increases linearly off axis for such modes. For a low energy beam, the excitation can be strong enough to deflect the beam significantly during transit through a single structure into regions of higher longitudinal field and increased coupling. Therefore, there can be closure of a feedback loop within a single structure: an excited cavity mode deflects a beam which in turn further excites the mode. Stability comes from the damping of the fields through wall losses and couplers. This effect is known as regenerative beam breakup, and for a standing wave structure has a threshold current given by¹

$$I_{th} = \frac{\pi^3 E k}{2 Z'' L^2} \quad (1)$$

where Z'' is the transverse impedance per unit length, L is the length of the RF structure, E is the beam energy and k is the wavenumber of the HOM. Above threshold, there is exponential growth of the cavity excitation; any offset will ultimately grow to the point of destruction of the beam. Since SRF structures usually are only a few cells long to prevent the appearance of trapped modes, the dependence of the threshold current on the square of the length lessens the importance of this current limit in practice. At a few MeV, however, an undamped ($Q \sim 10^9$), gigahertz SRF cavity would be limited to currents typically of the order of a milliamperere. Note that the threshold current depends on Z'' , not Z''/Q , and is therefore inversely proportional to the damped Q .

Multipass Multibunch Phenomena

When a linac beam is recirculated through an accelerator structure, the feedback system formed by the cavities and beam is closed and instability can result at sufficiently high currents. Suppose that the first cavity has an excited HOM which deflects the beam. Recirculation brings the beam back through that first cavity for one or more passes. Since the lattice can translate the deflection into a transverse offset, the excited mode can now be enhanced as was the case in regenerative BBU. In addition, many cavities can participate in this instability if HOM frequencies overlap. Figure 1 shows the bunch displacement of succeeding bunches at the exit of a recirculating linear accelerator with bunch number, at a current above the threshold for this *multipass beam breakup*.²

Figure 1 Exponential growth of beam excitation above threshold of multipass beam breakup

Multipass beam breakup in linacs and coupled-bunch instabilities in storage rings are both caused by the interaction of the beam bunches with high- Q higher order modes. The basic difference is that multipass beam breakup involves an infinity of bunches each of which undergoes a finite number of passes, whereas the coupled-bunch instability involves a finite number of bunches each of which undergoes essentially an infinity of passes. Also, given the isochronicity of typical recirculating linac lattices, transverse deflecting modes are of primary importance in linacs, whereas both longitudinal and transverse modes can drive instabilities in storage rings.

The growth rates and threshold current for multipass beam breakup are given by solution of an eigenvalue equation³

$$\begin{aligned}
 D_i = I \sum_{p=2}^{n_p} \sum_{r < p} \sum_{\ell=1}^{n_0} \left(T_{i,\ell}^{pr} \right)_{12} e^{M_0 \Omega r(p-r)} Z_{\ell} h_{\ell}(\Omega) D_{\ell} \\
 + I \sum_{p=1}^{n_p} \sum_{\ell=1}^{i-1} \left(T_{i,\ell}^{pp} \right)_{12} Z_{\ell} h_{\ell}(\Omega) D_{\ell}
 \end{aligned} \tag{2a}$$

$$\text{where } h_n(\Omega) = \frac{H_n(\Omega) \sin(\omega_n \tau)}{1 + H_n(\Omega)^2 - 2 H_n(\Omega) \cos(\omega_n \tau)} \quad (2b)$$

$$H_n(\Omega) = e^{-\frac{\omega_n \tau}{2Q}} e^{-i\Omega \tau}$$

and

$T_{i,\ell}^{pq}$	is the transfer matrix for (x, p_x) from pass ℓ to pass i		
Z_n	$= \frac{Z_n'' \ell e}{2Q f_b}$	ℓ	= cavity length
n_0	= number of cavity sites	n_p	= passes
f_b	$= \frac{1}{\tau}$ = bunching frequency	I	= average beam current
$s_k(\omega_n \tau)$	$= e^{\frac{k\omega_n \tau}{2Q}} \sin(k\omega_n \tau)$		
Z_n''	= transverse impedance of cavity/unit length		
M_0	= number of bunches in one recirculation		

The inverse of the threshold current appears as the eigenvalue. To find thresholds for instability, a plot of complex current eigenvalues has been found useful. First the coherent frequency Ω is swept in real frequency with an arbitrarily small imaginary part corresponding to growth. For n_0 cavities there are n_0 families of eigenvalues, with the actual threshold current corresponding to the smallest possible real value obtained. Figure 2 illustrates the eigenvalue structure for a multicavity, multipass linac. The lowest positive current crossing gives the threshold current. Note that there is a finite value of current below which there is stability.

Figure 2 Complex current plot (amperes) for the determination of threshold current of multipass beam breakup driven by 400 cavities in a four-pass configuration

For an HOM of a single cavity, the threshold current is inversely proportional to the transverse impedance Z , and since (Z/Q) is constant, inversely proportional to the damped Q . For a many cavity machine, however, HOM mode frequencies can be expected to overlap. Then, as Q increases, fewer modes overlap and the threshold current does not drop as rapidly with $1/Q$. Also, for a few passes, the threshold current is found to be insensitive to pass numbers for fixed final energy. Below the threshold of multipass beam breakup there exists a steady-state cavity excitation which displace bunches and in some cases can lead to an effective emittance degradation. Since this steady state is a forced oscillation of the cavity, the cavity excitation is at a harmonic of the bunching frequency for equally spaced, equally charged bunches. Thus, all bunches receive the same kick, the phase of which depends on the relationship between the bunch harmonic frequency and the HOM frequency. This kick in principle can be compensated with DC magnetic elements. Clearly, HOMs which are near harmonics of the bunch frequency are of most concern. For user flexibility, bunches can be differentially loaded to provide, for example, different end stations of a linac with different bunch current.² For example, a 1500 MHz bunching could be differentially loaded at 500 MHz to form three classes of bunches (1,4,7,10,...), (2,5,8,11,...), and (3,6,9,12,...). Since the basic periodicity of the system is at 500 MHz, HOMs neighboring on harmonics of 500 MHz are now of particular importance. For 500 MHz harmonics which are not also harmonics of 1500 MHz, each of the three classes of bunches receives a different kick. The resulting offset cannot be corrected by DC elements, and thus there is an effective emittance increase during transport through the linac which requires an RF device (e.g., RF separators) to sort out. For average currents at the hundred microampere level, this effect is negligible.

The extreme case of differential bunch loading occurs when short trains (possibly one) of very highly charged bunches are used. The strong wakefields generated can influence both the transverse and longitudinal phase space of succeeding members of the high-charged train or of low-charged fellow-traveling bunches. Control of the Q of both transverse and longitudinal HOMs is required to relieve this possible source of phase space degradation.

Single-Bunch, Single-Pass Effects

In addition to the coupled-bunch phenomena which have been described so far, there is a large class of single-bunch, single-pass effects which limit the peak current (more precisely, bunch charge and length) handling capabilities. In a single pass through an RF structure, there is insufficient time for the bunch to experience the long-term ringing associated with the high Q s characteristic of superconducting cavities. Thus, these current limits are not particularly sensitive to the success or failure of damping the HOM Q s. However, there do remain some features of the collective phenomena which distinguish superconducting cavities from room temperature ones.

Because of the efficiency of the cavities (maximization of shunt impedance is not as crucial as with room temperature cavities) and the requirement of coupling through the beam pipe to avoid sites for multipactoring and breakdown, a typical SRF cavity has a large aperture. This increase in opening reduces the coupling impedance of higher order modes; for transverse modes this coupling can be an order of magnitude below that which would be expected for an optimized room temperature cavity. Secondly, although the gradient achieved in SRF cavities is larger than that which can be achieved in CW room temper-

ature cavities, it remains significantly less than that achieved in pulsed room temperature cavities. Thus, for CW operation, SRF machines have a clear advantage from an impedance point of view over room temperature machines, since the SRF impedance per megavolt is lower. However, in comparison to pulsed, room temperature linacs, the situation is not as clearcut where the SRF cavities offer less impedance per unit length, but depending on gradient, may in fact offer more impedance per megavolt.

Energy spread is induced by the variation of the longitudinal wakefield across the bunch. At 5 MV/m gradient, the induced energy spread is found to be less than 1% for a 1 mm long bunch at peak currents of 500 A in a typical 1500 MHz cavity. With adjustment of the RF phase to remove the linear part of the variation, residual spread at the 0.1% level can be expected. Improvement of achieved gradient directly improves the residual energy spread.

Recirculating SRF linacs also are susceptible to single-bunch transverse beam breakup which is analogous to that which has been extensively simulated and analyzed for single pass linear colliders. There are, however, several issues which are special to the SRF devices. First, given the smooth, large aperture design of SRF cavities, the contribution of bellows, valves, and other discontinuities gain relatively more importance than for small aperture room temperature cavities, and care must be taken to minimize the strength of such impedance sources if the full potential of the superconducting environment is to be realized. Secondly, although SRF cavities, because of their open structure and typically low frequencies, offer reduced transverse impedance, the weak focusing on higher passes inherent in a multipass device can exacerbate this head-tail beam breakup. Here it is found that constant phase advance lattices (in the first pass) with their added focusing strength offer considerably better performance at low injection energies than constant magnetic gradient configurations. Finally, it appears difficult, if not impossible to arrange for the pseudo-Landau-damping which is thought to be effective in limiting emittance degradation in single-pass linacs because of the differences in focusing experienced by the overlapping beams of different energy. For the most part, however, the considerably lower transverse impedance offered by low frequency SRF cavities outweighs these limitations.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy under contract DE-AC05-84ER40150.

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