4 K SRF Operation of the 10 MeV CEBAF Photo-Injector*

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Abstract

Superconducting radio-frequency (SRF) accelerating cavities are often operated in superfluid liquid helium with temperature near 2 K to enhance the cavity quality factor Q_0 and to help manage heat loads, which are particularly important at large SRF accelerator facilities. This 2 K temperature paradigm, however, need not put SRF technology out of the reach of small institutions or even limit SRF operation at large facilities that need 10-100 MeV beam energy. At the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab there are regularly scheduled maintenance periods during which cryogenic plant often increases the liquid helium temperature from 2 K to 4 K, reducing power consumption by $\sim$ 50 % and saving megawatts of wall-plug power. During recent maintenance periods, we accelerated a continuous-wave electron beam at the CEBAF photo-injector to a total energy of 6.3 MeV at currents up to 80 μA using two 5-cell niobium cavities in the quarter-cryomodule at 4 K. This contribution describes the SRF and cryogenic performance and uses measured beam quality and energy stability as key metrics. These measurements indicate that 4 K operation of niobium SRF cavities in CEBAF is a sensible and cost effective mode for high quality beam operation, provided the cryogenic load associated with lower Q_0 is manageable for the number of cavities needed to operate. For Jefferson Lab, this enhances our scientific reach allowing additional low-energy $\sim$ 10 MeV experiments each year.

INTRODUCTION

Two cryogenic plants provide liquid helium at 2 K to the CEBAF cryomodules to support 12 GeV beam operations. However, during extended maintenance periods when high energy beam experiments are not performed the cryoplants transition to 4.3 K to reduce their power consumption and save upon operational costs. Cryomodules routinely sit idle during these periods, since it is believed the degraded intrinsic quality factor of superconducting niobium cavities at this temperature precludes productive beam operation. We used several of these maintenance periods to investigate the potential for operating injector cryomodules at 4 K with a couple goals in mind. First, there are a number of experiments which could use low energy $\sim$10 MeV electron beams, e.g. the production of spin-polarized positron beams [1] or the Bubble Chamber experiment [2] aimed at quantifying nucleosynthesis in stars. Second, there is interest in evaluating the performance of Nb_3Sn coated cavities in the accelerator environment using one of the CEBAF cryomodules [3], where the stability of a 2 K cryomodule operated at 4 K needs to be studied.

While operating cryomodules with elliptical cavities at 4 K has been demonstrated, for example TRISTAN [4], LEP [5], and CESR [6] operated for years in such a configuration, a direct comparison of the quality of beams accelerated in the same cryomodule at 2 and 4 K at higher frequencies (where average dissipated power density is higher) had not been studied. In this contribution we describe the SRF gradient reach of the CEBAF injector quarter-cryomodule at 4 K, and compare beam quality and energy stability delivered at 2 K and 4 K.

4 K CRYOMODULE MEASUREMENT

The injector quarter-cryomodule is the first superconducting module at CEBAF, accelerating the beam up to $\sim$ 10 MeV using two 5-cell cavities each operated up to E_{acc} = 10 MV/m. The cavities, designated as #7 and #8 due to their position with respect to RF couplers in the tunnel, were tested at 4 K to determine stable operating gradients. Individually, cavity #7 reached E_{acc} = 9.5 MV/m and cavity #8 reached E_{acc} = 10 MV/m, before being limited by window arcing above E_{acc} = 10.5 MV/m. In both cases the helium liquid level remained stable with the JT valve opened to 70 %, which we considered a heat load limit not to exceed. Next, both cavities were simultaneously powered to E_{acc} = 8 MV/m, again with the JT valve open to 70 %. While the quality factor of the cavities was not measured during these tests, assuming a typical $Q_0 = 3\cdot10^8$ at 4.3 K, we estimate about 200 Watts was dissipated into the helium bath for this configuration.

4 K AND 2 K BEAM MEASUREMENTS

After stable operating conditions for the quarter-cryomodule were determined, the injector was setup for beam quality measurements with average intensity ranging from 60 μA at 2 K to 80 μA at 4 K test.

The lower maximum intensity at 2 K was caused by an unrelated operational hardware issue. For convenience the cavities were operated at typical gradients for injector op-

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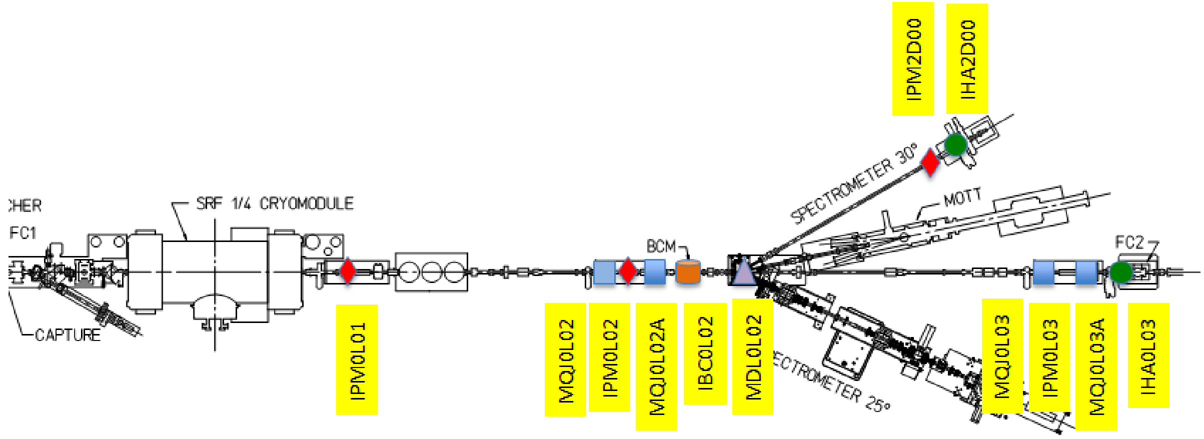

Figure 1: Injector layout showing beam diagnostic equipment, which was used to assess beam qualities at 4 and 2 K. Quarter-cryomodule, which was run at 4 and 2 K, is to the left in the picture.

eration, E_{acc}^{cav7} = 5.00 MV/m and E_{acc}^{cav8} = 5.32 MV/m. The electron beam was characterized with diagnostics downstream of the quarter-cryomodule (see Fig. 1). The beam momentum was measured using a spectrometer, by finding the magnetic field (MDL0L02) necessary to deflect the beam a known angle. The (normalized) beam emittance and Twiss parameters were determined using a profile monitor (IHA0L03) to measure the variation of beam size as a function of an upstream quadrupole magnet (MQJ0L02). The energy spread was determined by extracting the dispersive contribution of the beam size as measured at a dispersive location (IHA2D00). Additionally measurements of the beam intensity (IBC0L02) and position (IPM0L01, IPM0L2, and IPM2D00) at the helicity reversal rate (30 Hz) were made to assess the intrinsic noise in the beam structure. Results of these measurements (see Table. 1) indicate there was no discernible difference in the beam quality when the quarter-cryomodule is operated at 4 K versus 2 K.

Parameter	Unit	4 K	2 K
Cavities	#	0L02-7,8	0L02-7,8
Gradient	MV/m	5.00, 5.32	5.00, 5.32
Momentum	MeV/c	6.34	6.47
Normalized ϵ_x	mm-mrad	0.38±0.01	0.44±0.01
Normalized ϵ_y	mm-mrad	0.34±0.01	0.54±0.01
Momentum Spread	%	0.22	0.14
Energy Spread	keV	14	9
RMS widths @ 30 Hz Helicity Reversal			
IBC0L02 Charge asym.	ppm	130.4	139.4
IPM0L01 Δx	μm	3.4	3.2
IPM0L02 Δx	μm	10.0	13.1
IPM2D00 Δx	μm	12.8	15.1
IPM0L01 Δy	μm	3.2	3.2
IPM0L02 Δy	μm	4.9	6.8
IPM2D00 Δx	μm	7.6	8.8

Table 1: Beam measurement details. Beam measurements show small differences between 4 and 2 K operation, resulting from a slightly different optics setup between different days.

DISCUSSION

Gradient and beam measurements of the CEBAF injector quarter-cryomodule operated at 4 K show that, despite a higher heat load, it performs very similarly when at 2 K. The original CEBAF cryo-pair design features two cavities in the same helium vessel. On one hand such design, adopted due to cleanliness considerations, increases helium inventory required for operation, but at the same time it provides cavities with a large helium bath, where RF power is dissipated. We want to note that preliminary 4 K measurements of the third cryomodule in the injector 0L04 were limited to about E_{acc} = 3 MV/m, corresponding to about 20 Watts of dissipated power, for a single cavity operation. 0L04 is a new cryomodule with C100 cavities.

The new cryomodule features a new helium vessel design, which conforms to a single cavity and reduces helium inventory needed to maintain cavities at 2 K. The smaller helium volume and a different helium gas return configuration is probably the reason for the difference between two cryomodule during 4 K operation.

In terms of beam properties, measurements show no significant difference between 4 and 2 K operation, i.e., if the table columns in the Table 1 were unlabeled, one would not be able to tell which beam results from which operation. Both beams are similar to what is used during regular CEBAF operation, and any difference between the beams resulted from a slightly different optics setup between different days rather than a contribution from a different cryogenic arrangement.

CONCLUSION

During recent maintenance periods at CEBAF we accelerated a continuous-wave electron beam at the photo-injector to a total energy of 6.3 MeV at currents up to 80 μA using two 5-cell niobium cavities in the quarter-cryomodule at 4 K. Beam parameters under such cryomodule conditions were compared with a similar measurements, when cryomodule was at 2 K. Beam parameters were very similar between 4 and 2 K with any difference resulting from slightly different optics. These measurements indicate that 4 K operation of niobium SRF cavities in CEBAF is a sensible and cost effective mode for high quality beam operation, provided the cryogenic load associated with lower Q_0 is manageable for the number of cavities needed to operate. For Jefferson Lab, this enhances our scientific reach allowing additional low-energy $\sim$ 10 MeV experiments each year.

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