SRF990716-09

Presented at the 1999 Cryogenic Engineering and Intl. Cryogenic Materials Conf., Montreal, Quebec, CA

SUPERCONDUCTING RF CAVITIES AND CRYOGENICS FOR THE CESR III UPGRADE

E. Chojnacki and J. Sears

Cornell University, Laboratory of Nuclear Studies
Ithaca, NY, 14853, USA

ABSTRACT

The Cornell high energy electron/positron storage ring (CESR) is undergoing a phased upgrade to replace its normal-conducting copper RF cavities with superconducting niobium cavities. The accelerator continues to operate at ever increasing record luminosity part way through the upgrade (2 SRF cavities and 2 NRF cavities), with completion scheduled for Fall 1999. Details of the SRF cryomodule, its fabrication, refrigeration, and accelerator performance will be presented along with lessons learned regarding design and operation.

INTRODUCTION

The Cornell high energy electron/positron storage ring is nearing completion of a luminosity upgrade, CESR III, one facet of which replaces the four normal-conducting multi-cell copper RF cavities with four single-cell superconducting (SRF) niobium cavities.[1] The principal reason for the SRF upgrade is to achieve ever higher stored beam current, shorter bunch length, and thus higher collision luminosity in CESR for the CLEO high energy physics detector as well as beam for the CHESS synchrotron light source.

SRF cavities are well suited for high beam intensity by their inherently high fundamental mode shunt impedance R and consequent high accelerating gradient, high unloaded Q_o, low beam impedance loss factor $\propto R/Q_o$, and ease of thorough higher order mode (HOM) damping.[2] There is a compound benefit by which the high gradient allows fewer cavities to achieve the same accelerating voltage and each cavity has a lower loss factor.

In a storage ring, the loss factors and Q's presented by the RF cavities in the HOM's as well as fundamental mode determine the threshold in beam current at which various beam instabilities arise. Multi-bunch beam instabilities had indeed been encroached in CESR as the current was pushed to record levels of several hundred mA, arising from high-loss normal conducting RF (NRF) cavities which had been in place until recently.[1,3] The CESR run in Spring of 1999, however, was the first with only SRF cavities in place (three of four) and all NRF cavities removed. Thresholds for multi-bunch instabilities during the SRF-only run were greatly advanced,[4] thus they are expected to present no limitation to the upgrade goal of 1 Amp total beam current and luminosity 1.7×10^{33} cm^{-2}s^{-1}.

Technologies other than SRF cavities are available to combat storage ring beam instabilities, such as RF feedback in conjunction with exacting NRF cavity design. Indeed, modest RF feedback is utilized even in SRF cavity systems. But the NRF approach tends to be power hungry with both feedback and fundamental mode RF. SRF cavities and

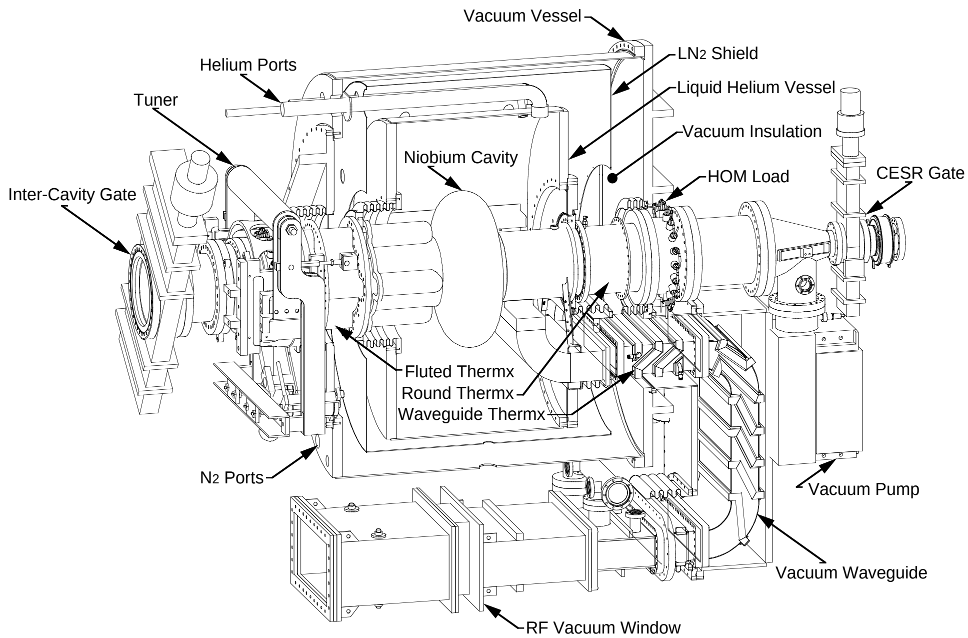

Figure 1. Illustration of the Cornell Mark II SRF cryomodule.

cryostats are admittedly technically complex, but great insight and streamlining of SRF installations is occurring world-wide at numerous accelerator facilities. This CESR III SRF upgrade represents a forward-looking approach to maintaining extremely high luminosity in a storage ring, taking a step closer to the ideals of textbook treatments of particle acceleration. Presented below are descriptions of salient features of the Cornell Mark II SRF cryomodule, design and fabrication details, a brief description of the refrigeration system, a performance update, and suggested improvements throughout.

CRYOMODULE LAYOUT

Shown in Figure 1 is an illustration of the Cornell Mark II SRF cryomodule, the fourth and final of which will be installed Fall 1999. The 500 MHz single-cell superconducting niobium cavity has a 24 cm aperture and resides inside a liquid helium (LHe) vessel, external to which is vacuum insulation, a thermal radiation shield maintained at liquid nitrogen (LN_2) temperature, layers of magnetic field shielding μ-metal, layers of mylar/fiberglass superinsulation, followed by the room temperature vacuum vessel enclosure. The He vessel is gravitationally suspended from the vacuum vessel by four $^1/_2$" diameter Invar rods, Invar chosen for its low thermal expansion and high tensile strength. Conduits for LHe, He gas, electronic wiring, and safety venting connect the He vessel to ports mounted near the top of one of the vacuum vessel end plates. Ports for LN_2, N_2 gas, electronic wiring, vacuum pumping, and safety venting are similarly mounted near the bottom of the same vacuum vessel end plate.

There are three main structural/thermal transitions between the cavity and external environment: a “fluted” beampipe, a round beampipe, and the rectangular waveguide RF feed. The fluted beampipe is required to allow two low frequency dipole HOM’s to escape the cavity. Outboard of each beampipe thermal transition is a room temperature beamline HOM load. Following the round beampipe HOM load is a taper and small gate valve leading to oval CESR beampipe. The fluted beampipe HOM load has an integral fixture ring around which the cavity tuner clamps. The tuner mechanically adjusts cavity frequency around 500 MHz via longitudinal elastic deformation allowed by bellows joints

Table 1. Parameters of the Cornell B-cell SRF cavity.

Frequency	500 MHz
Aperture	24 cm
Effective gap	30 cm
Gradient	> 6 MV/m
Unloaded Q_o at 6 MV/m gradient	$> 10^9$
Q_{ext}	2×10^5
Shunt Impedance R	89 GΩ
Delivered power at 1 Amp beam current	325 kW
HOM power at 1 Amp beam current	10 kW
Number of cavities in CESR	4

between the beampipe and He/vacuum vessels, with a large beamline sliding joint outboard of the HOM load. The cavity round beampipe is anchored to both the He and vacuum vessels.

Following the large sliding joint is a large inter-cavity gate valve (24 cm aperture) which maintains large-aperture beampipe to an adjacent mirror-image cryomodule. The beampipe between cryomodules is maintained large aperture since a significant portion of the SRF cavity's beam impedance is contributed by the tapers up and down to oval CESR beampipe, which is nominally 9 cm × 5 cm.

The rectangular waveguide RF feed immediately exterior to the He vessel is cooled for 30 cm by cold He gas boil-off from the He vessel flowing through tracing welded to the waveguide walls. Next is a waveguide double-E bend similarly cooled by LN_2 flowing through tracing. Following this is a short thermal transition from LN_2 to room temperature, a waveguide vacuum pumping section, and finally the waveguide vacuum window. This slightly convoluted waveguide path was arrived at by tight space considerations in the CESR tunnel and the need to mate to existing waveguide feeds.

DESIGN AND FABRICATION

The design of the Cornell Mark II cryomodule evolved disparately over several years, handed off a number of times at Cornell and volleyed between Cornell and the vendor Meyer Tool & Mfg. A coherent vision of the entire cryomodule assembly process would have made fabrication and assembly faster and efficient. Happily, a workable process developed and has proceeded quite well to meet all scheduled installations.

All components that share the CESR ultra-high vacuum, except the cavity and RF window, as well as numerous ancillary components were fabricated and assembled at Cornell. The bulk of the vacuum and He vessels were fabricated and partially assembled at Meyer Tool & Mfg., Chicago. The niobium cavity was fabricated by ACCEL Instruments, Germany. The waveguide vacuum window was fabricated by Thomson Components and Tubes Corp., France.

The SRF cavity known as the Cornell B-cell is a single cell elliptical type with 4" × 17" rectangular waveguide coupling.[2] It has design parameters as listed in Table 1. CESR operation at 1 Amp beam conditions will have the cavity matched at about 9 MV/m gradient, where the cavity tuning angle ψ will be about equal to the synchronous phase φ= 80˚, requiring 325 kW forward power delivered by each of the four cavity couplers. Operation at lower cavity voltage will require slightly mismatched tuning, slightly higher forward power, and some reflected power. Computations of cavity modes have indicated total HOM power of up to 10 kW for 1 Amp beam current.[5] Design and fabrication details for the HOM loads[6] and RF window[7] have been presented elsewhere.

Prior to assembly, all major cryomodule components are subjected to acceptance tests. The cavity must achieve >6 MV/m gradient with unloaded $Q_o > 10^9$ in a vertical test. Each HOM load must dissipate >10 kW RF power at the test frequency of 2.45 GHz.[6] The RF window must transmit >400 kW CW at 500 MHz traveling wave and experience >125 kW CW standing wave with the electric field maximum at the window ceramic.[7] The assembled He and vacuum vessels (with a dummy copper cavity insert) must remain vacuum tight, demonstrate mechanical integrity, and have <40 W static heat leak upon cooling to LN_2 temperature.

Since thermal impedance is a central theme throughout the cryomodule, nearly all of the beamline vacuum components are made from thin-walled sheet metal welded into heavier duty flanges. The majority of the SRF cavity is made from 3 mm thick niobium sheet so the interior surface has low thermal impedance to the LHe bath. The beamline thermal transitions are made from 1.25 mm thick stainless steel sheet to have high thermal impedance along their length. The interior of the beamline transitions are electroless plated with 3.8 μm of copper to reduce wall-current heating from beam image currents and HOM's propagating to the HOM loads. The vacuum waveguide within the cryostat is made from 1.60 mm thick stainless steel sheet with the interior electroplated with 25 μm of copper. The thicker waveguide plating is required to ensure good electrical conductance, since as much as 400 kW CW of 500 MHz RF propagates through it.

Dimensional tolerances on beamline mating surfaces and bolt patterns were specified as ±0.002", required due to long lever arms and numerous joints on the beamline assembly that must eventually mate to opposite ends of the vacuum vessel, CESR beampipe, and the waveguide feed. This tolerance was easily achieved on individual pieces, but upon welding of, e.g., flanges to thin-walled beam tube, distortions frequently degraded tolerance to ±0.010" in linear dimensions and flatness. The specified tolerance on finished assemblies could be easily achieved by the common practice of first rough machining parts, then welding, then finish machining with inclusion of precision dowel-pin holes for alignment during assembly. This is the technique by which ACCEL Instruments fabricated the electron-beam welded niobium cavity to meet tight tolerances on all mating flanges. Though tolerances on the vacuum and helium vessels are somewhat relaxed from that of the beamline, there again, post-machining weld distortions along with the omission of fixturing during welding allowed tolerances to stray to nuisance levels. Achieving the specified dimensional tolerances on all cryomodule components and inclusion of alignment pins would have significantly expedited cryomodule assembly.

The volume of the entire He vessel is 520 L, typically maintained at 470 L to have the LHe level a few cm above the cavity equator top. This large volume is due in part to the coupler E-plane elbow oriented below the cavity, necessitating a significant LHe volume just to reach the equator bottom. Further, the He vessel is not contoured to the cavity nor weld sealed. Removable He vessel end plates with indium tongue and groove seals were implemented to facilitate potentially repetitive assembly/disassembly.

REFRIGERATION

Liquid He is provided by two 600 W refrigerators for a total of 1200 W supplying a 2000 L storage dewer. LN_2 is periodically delivered by a vendor to a 56000 L storage tank. Due to the refrigerator's suction pressure being about 3 psi above atmosphere and an additional 2 psi differential between the cryomodule and refrigerator, the cryomodule LHe temperature is nominally 4.5 K. Rigid transfer lines transport LHe, cold gaseous He, and LN_2 between the refrigerator and LHe dewer to a centrally located main valve box. From the main valve box, rigid transfer lines lead to satellite valve boxes supplying:

1) a pair of SRF cryomodules in CESR's East RF station,
2) a pair of SRF cryomodules in CESR's West RF station,
3) an SRF cryomodule in CESR's RF processing area,
4) the CLEO detector superconducting solenoid,
5) a pair of interaction region superconducting quadrupoles to be installed as part of the Phase III upgrade.

The main valve box also has one spare transfer line port.

The rigid transfer lines have a heat leak to LHe of < 0.5 W/m, contributing about 12 W per cavity feed. The largest heat leak is in the valving and flexible lines, contributing about 50 W per cavity feed. Thus, delivering LHe to four SRF cryomodules consumes about 250 W of refrigeration power, which does not include the cryomodule heat load discussed in the next section.

A key control for stable refrigerator operation was found to be maintaining a steady cold He gas return flow rate from the various LHe heat loads. Since the SRF cavity heat deposition varies with RF amplitude, an analog electronic circuit was implemented to heat a resistive load in the LHe vessel at the difference between a chosen "level load" and the dynamic RF load. The leveled load is nominally set at 60 W.

CRYOMODULE HEAT LEAK

There are seven main sources of heat loading LHe within the cryomodule itself:

1) Round beampipe thermal transition,
2) Fluted beampipe thermal transition,
3) Waveguide thermal transition,
4) Radiation from LN_2 shield to LHe vessel,
5) LHe boil-off gas cooling the waveguide thermal transition,
6) RF wall dissipation in the SRF cavity,
7) Infra-red radiation impinging from beamline apertures and waveguide duct.

Calculations of heat leak for the beampipe and waveguide thermal transitions were performed with a computer code that takes into account thermal and electrical conductivity variation with temperature. These results are presented below. Heat leak due to impinging IR radiation has not been thoroughly addressed, but briefly discussed below.

Round and Fluted Beampipe Thermal Transitions

The 24 cm diameter round beampipe wall is comprised of 1.25 mm thick stainless steel with 3.81 μm of copper plated on the interior. The end attached to the LHe vessel is at 4.5 K and the end attached to the vacuum vessel is at 300 K. A copper ring indirectly cooled by LN_2 is welded to the beampipe two thirds of the way from the LHe to vacuum vessel. Thermometers on the beampipe have shown the copper ring to be close to 100 K. The *static* heat leak for the round beampipe is then calculated to be 4.31 W. The additional heat due to image current of a 1 Amp beam is 0.10 W. The additional heat due to 5 kW of HOM RF power assumed to be at 1 GHz in the TM_{01} mode is 0.16 W. The total calculated *operational* heat leak of the round beampipe thermal transition with beam is then 4.57 W.

The fluted beampipe thermal transition is very similar to the round, with the flutes approximately doubling the cross-sectional area. Thus, simply multiplying the round beampipe calculations by two, the *static* heat leak for the fluted beampipe is calculated to be 8.62 W. Including image current from a 1.0 Amp beam and 5 kW of HOM power, the total calculated *operational* heat leak for the fluted beampipe thermal transition with beam is then 9.14 W.

Waveguide Thermal Transition

The waveguide wall is comprised of 1.60 mm thick stainless steel with 25.4 μm of copper plated on the interior. The end attached to the LHe vessel is at 4.5 K and the end attached to the LN_2 cooled waveguide double-E bend is taken to be 100 K. The waveguide thermal transition is cooled for 30 cm by cold He gas boil-off from the He vessel flowing through tracing welded to the waveguide walls. Commissioning of three cryomodules between 1997-1999 showed a mass flow of 134 mg/s yielded the most stable cavity operation.

With no cold He gas flowing through the waveguide tracing and no RF power, the *static* heat leak for the waveguide thermal transition is calculated to be 8.81 W. With 134 mg/s cold He gas flow and no RF power the heat leak drops to 1.99 W. With 134 mg/s cold He gas flow and 350 kW of 500 MHz RF propagating through the waveguide the *operational* heat leak for the waveguide thermal transition is calculated to be 5.30 W.

Radiation from LN_2 Shield to LHe Vessel

The surface area of the LHe vessel exterior is approximately 4.1 m^2, including beampipe apertures. The radiative heat transfer from the LN_2 shield to the LHe vessel is

Table 2. Liquid He heat loads within the Cornell Mark II SRF cryomodule.

Heat source	Operation [W]	Static [W]	Avg measured [W]
Round beampipe	4.57	4.31	—
Fluted beampipe	9.14	8.62	—
Waveguide	5.30	8.81	—
LN_2 shield radiation	8.2	8.2	—
Waveguide gas flow	14.0	—	—
RF cavity wall dissipation	72.8	—	—
Total	**114.01**	**29.94**	**34.2**

then approximately $\sigma\,(T_{LN}^4 - T_{LHe}^4) \times Area$, where $\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4 is Boltzman's constant. This yields a heat leak of 8.2 W.

LHe Boil-off Gas Cooling the Waveguide Thermal Transition

The LHe boil-off gas cooling the waveguide thermal transition is warmed to room temperature and returned to the refrigerator. This He gas heat load on the Cornell refrigerator/liquifier with 134 mg/s mass flow consumes 2.8 W for refrigeration and 11.2 W for liquefaction, or a total of 14 W.

RF Wall Dissipation in the SRF Cavity

The CESR B-cell has a design $R/Q_o = V^2 / Q_o P_{wall} = 89$. Operating at $Q_o = 10^9$ and a gradient of 6 MV/m with an effective gap of 0.3 m gives 1.8 MV acceleration and $P_{wall} = 36.4$ W. However, two of three CESR B-cells to date have achieved only $Q_o = 5 \times 10^8$ which raises $P_{wall} = 72.8$ W.

Infra-red Radiation Impinging from Beamline Apertures and Waveguide Duct

It is expected that nearly all IR radiation along the beampipe simply passes through the cavity apertures unreflected. The few divergent IR rays that impinge on the cell are most likely completely reflected unattenuated by the highly IR reflective niobium cavity.

IR radiation impinging from the waveguide duct is also most likely completely reflected unattenuated by the highly IR reflective niobium waveguide coupler. The worse-case IR radiation impinging the coupler is launched by the exposed cross section of the ceramic window (251 cm^2) and the remaining cross section of 4" $\times$ 17" room-temperature waveguide (188 cm^2). The hottest possible ceramic window has a quadratic radial temperature profile with 353 K at the center and 293 K at the edge, yielding an average ceramic temperature of 333 K. This gives a radiation power launched from the ceramic of 17.5 W. The remaining cross section of 4" $\times$ 17" room temperature (293 K) waveguide launches 7.8 W. The maximum IR radiation power impinging the coupler via the waveguide duct is then 25.3 W. Most of this IR power is attenuated in the waveguide double-E bend if it has even a slightly IR dull surface.[8] And as mentioned previously, the small IR power making its way to the waveguide coupler will most likely be completely reflected unattenuated by the niobium surface.

Heat Leak Measurements

Measurements of heat load in the Cornell Mark II cryomodule have been performed in several instances, the most reliable of which was during a recent warm-up of three cryomodules installed in CESR in which the decreasing LHe levels were monitored with time. In this static condition there was no waveguide thermal transition gas flow and of course no beam or RF. The measurements yielded an average heat load of 34.2 W.

Table 2 summarizes the above calculated heat loads for operational and static conditions, with measurements to be compared to static conditions. There is good agreement between calculated and measured static conditions. Operational conditions were taken as: 134 mg/s waveguide thermal transition mass flow, 350 kW waveguide RF at 500 MHz, 1 Amp beam, total of 10 kW HOM RF, cavity $Q_o = 5 \times 0^8$, and cavity

$V = 1.8$ MV. Obviously, operational conditions are strongly dependent on cavity Q_o. Despite the low Q_o achieved by two of three CESR B-cells to date, the Cornell refrigerator has sufficient capacity to supply the full complement of CESR III upgrade LHe needs.

PERFORMANCE

The three Cornell SRF cryomodules installed is CESR to date have performed quite satisfactorily. All cavities have exceeded the 6 MV/m minimal gradient, Q's of all HOM's are <100, and cryogenic heat loads have been within tolerance.

This SRF upgrade has been phasing in over the last few years, wherein during bi-yearly standard-maintenance downs a single-cell SRF cavity/cryostat replaces a five-cell NRF cavity. Thus, until Spring 1999, CESR operated with a mix of SRF and NRF cavities. As mentioned in the Introduction, multi-bunch beam instabilities arising from the NRF cavities occurred during this time as the beam current was pushed to record levels. Even with the instability, a maximum beam current of 550 mA and luminosity of 8×10^{32} $cm^{-2}s^{-1}$ were achieved. A short run in Spring 1999 with three SRF and no NRF cavities in CESR showed great advance in the instability threshold current.[4] A new feedback system and these high thresholds for beam instabilities should allow achievement of the upgrade goal of 1 Amp beam current and luminosity 1.7×10^{33} $cm^{-2}s^{-1}$.

As is becoming apparent with SRF installations world-wide, the most difficult aspect of commissioning the Cornell SRF cryomodules has been RF-based discharges tripping vacuum thresholds in the input power coupler.[7,9] Signals from photo-multiplier arc detectors directly viewing the Cornell RF window ceramic rarely accompany such vacuum trips, though they do so prodigiously during unattached window processing.[7] It is then very likely that condensed gases in the cold regions of the waveguide coupler enhance the metal's secondary electron emission coefficient, making familiar multipactor barriers more virulent. Further, the high coupling coefficient characteristic of SRF cavities, e.g., $\beta = 5000$ for the Cornell B-cell, dictates that negligible traveling wave power is present without beam loading. As such, processing without beam can at best condition narrow regions of the waveguide at the standing wave's electric field crests. Indeed, during conditioning, vacuum trips in the Cornell B-cell coupler occur at strictly repeatable traveling wave power thresholds as beam loading increases.[9] Fortunately, considerable progress in traveling wave power has been made, employing a number of commissioning strategies since the first barrier at 90 kW made itself apparent in the first cryomodule installed in Fall 1997.[9] To date, over 220 kW has been coupled to the beam in a single cryomodule and the pattern is expected to continue by which the barriers become milder with increasing power threshold.

To make matters more challenging in the power coupler, about a meter of the interior of the vacuum waveguide double-E bend is corrugated with a sharp $^1/_{16}$" sawtooth pattern to ostensibly deter multipacting and attenuate IR radiation. This array of electric field singularities very likely generously seeds many of the multipactor resonances encountered. The following modifications were thus implemented for the input coupler waveguide in all Mark II cryomodules succeeding the first:

1) The corrugated waveguide was aggressively acid etched prior to copper electroplating to dull the sharp ridges,
2) Sharp corners were removed elsewhere in the waveguide and vacuum pumping holes were moved from the waveguide centerline to near the sidewalls where the electric field is much lower,
3) All components of the vacuum waveguide, except as part of the niobium cavity, were vacuum baked prior to final assembly,
4) Vacuum pumping speed was modestly increased by larger waveguide pumping ports,
5) Cold He gas mass flow through the waveguide thermal transition was increased to stabilize and lower its operating temperature,
6) The thickness of copper plating on the waveguide was increased to ensure minimal RF heating, especially on the hydrogen-condensing LHe-LN_2 thermal transition.

These improvements and clever in situ processing strategies[9] have enabled every cryomodule to RF power process faster and further than its predecessor. More advanced

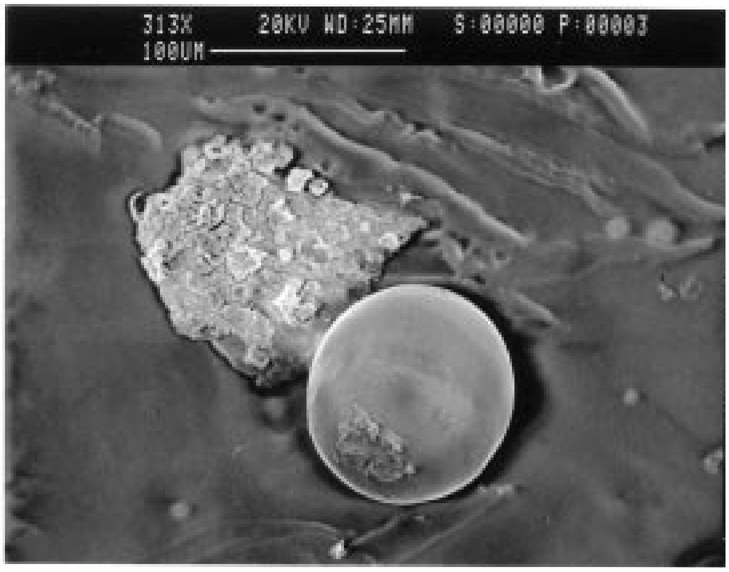

Figure 2. SEM photo of a partially melted stainless steel sliver wiped from the equator bottom of a B-cell.

modifications which could implement a potentially multipactor-free coupler, such as using elliptical or wedge-shaped waveguide, will have to await next-generation cryomodule R&D.

In an interesting and amusing note, when the second cryomodule was tested at high power in a processing area, the cavity quenched at a gradient around 5 MV/m, below the 6 MV/m acceptance threshold. A thermometer on the equator bottom, used to verify LHe level, showed a >50 K rise during quench, indicating a contaminant found its way into the cavity and settled in the gravitational well. Since tear-down and re-assembly of the cryomodule to re-etch the cavity would require many months turn-around, there was nothing to lose in performing the risky operation of using a long stick to wipe the cavity equator bottom in situ. Thus, a 2 m × 15 cm L-shaped, Teflon sheathed, ultra-clean stick with a methanol-soaked clean-room cloth tied to the end was inserted through the HOM load and fluted beampipe, then lowered and rotated inside the cavity to wipe the equator bottom. Shown in Figure 2 is an SEM photo of the largest contaminant picked up by the cloth. X-ray analysis showed the spherical object to be nearly pure Fe and the attached flake to contain Fe, Cr, and Ni, indicating partially melted stainless steel. Apparently, a stainless sliver from a sheared tongue and groove seal migrated to the cavity bottom and partially melted when subjected to high RF wall current during testing. Fortunately, the melted stainless did not wet well to the niobium, and after removal, cavity performance improved considerably, exceeding the 6 MV/m gradient acceptance threshold. The same thermometer indicates that quenches at the higher gradient still originate at the cavity equator bottom. This cryomodule now serves as CESR's E1 RF station.

CONCLUSION

Having already achieved a beam current of 550 mA and luminosity of 8×10^{32} $cm^{-2}s^{-1}$ with the phased SRF installations, there is great anticipation of continued forging of frontiers in accelerator science, high energy physics, and synchrotron light sources as we near completion of the CESR III upgrade. This gives encouragement for continued competitiveness on the world stage of electron/positron storage rings by achieving our upgrade goal of 1 Amp beam current and 1.7×10^{33} $cm^{-2}s^{-1}$ luminosity.

ACKNOWLEDGMENT

The success of this SRF upgrade to CESR was made possible by the National Science Foundation and many talented members of the Cornell University Laboratory of Nuclear Studies, especially H. Padamsee, S. Belomestnykh, and R. Ehrlich.

REFERENCES

1. D.L. Rubin, Results of the CESR upgrade, *Proc. 6th European Part. Accel. Conf.*, Stockholm, (1998).
2. H. Padamsee, *et. al.*, Design challenges for high current storage rings, *Part. Accel.* 40:17 (1992).
3. M. Billing, Observation of a longitudinal coupled bunch instability with trains of bunches in CESR, *Proc. 1997 Part. Accel. Conf.*, Vancouver, BC, 2317 (1997).
4. M. Billing, private communication.
5. S. Belomestnykh and W. Hartung, Calculations of the loss factor of the BB1 superconducting cavity assemblies, *Cornell LNS Report SRF960202-01* (1996).
6. E. Chojnacki and W.J. Alton, Beamline RF load development at Cornell, *Proc. 1999 Part. Accel. Conf.*, New York, NY, (1999).
7. E. Chojnacki, *et. al.*, Tests and designs of high-power waveguide vacuum windows at Cornell, *Part. Accel.* 61:[309]45 (1998).
8. N. Jacobsen and E. Chojnacki, Infra-red propagation through various waveguide inner surface geometries, *Cornell LNS Report SRF990301-01* (1999).
9. S. Belomestnykh, *et. al.*, Commissioning of the superconducting RF cavities for the CESR luminosity upgrade, *Proc. 1999 Part. Accel. Conf.*, New York, NY, (1999).