200 MHZ NB-CU CAVITIES FOR MUON ACCELERATION*

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Abstract

As a first step toward a muon collider, a neutrino factory is being actively studied. The neutrino factory calls for nearly 500 meters of 200 MHz SRF cavities to provide 7.5 GeV. The desired gradient is in the range of 15 -17 MV/m at a Q_0 of 6×10^9. Nb-Cu is the technology of choice driven mainly by the cost concern. A Cornell/CERN collaboration was established to address the unique challenges imposed by the large size of these cavities. A 200 MHz single cell elliptical Nb-Cu cavity has been fabricated and tested at 4.2 K and at 2.5 K in a vertical dewar fitted in a radiation shielded pit, 5 m deep and 2.5 m in diameter. The low field Q_0 reached 1.5×10^{10} at 4.2 K. Two multipacting barriers show up at E_{acc} = 3 MV/m and 1 MV/m. Both barriers can be processed through. Helium processing is effective in reducing field emission and improving accelerating gradients by a factor of as much as 2. E_{acc} reached 11 MV/m, or 75% of the desired gradient, at a Q_0 of 6×10^8. The major challenge is the Q-drop of the cavity, which shows a much stronger field dependence rate than expected. This is to be addressed by further film studies, including bias sputtering.

INTRODUCTION

Fig. 1 shows the schematic layout of the study-II version neutrino factory [1][2]. The proton driver provides 1 - 4 MW of protons on the target. The high-power target is immersed in a 20 T superconducting solenoidal field to capture pions produced in proton-nucleus interactions. Muons, produced from pion decays, go through three induction linacs to achieve phase rotation. The following bunching section bunches muons into 201.25 MHz RF buckets and the cooling section cools the transverse normalized RMS emittance to 2.7 mm rad. A superconducting linac with solenoidal focusing raises the muon beam energy to 2.48 GeV. A four-pass superconducting recirculating linac (RLA) accelerates muons to 20 GeV. In the racetrack-shaped superconducting storage ring, $\sim$ 35% of the stored muons decay toward a detector located about 3000 km from the ring.

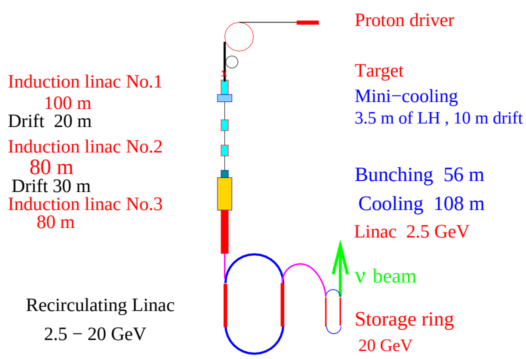

Figure 1: Schematic of the neutrino factory [2].

Because of the large phase space and short muon lifetime, the accelerating system should provide rapid acceleration and large acceptance. SRF is thus a preferred choice. The need for very large beam acceptance has driven the design to a low RF frequency of 200 MHz [3]. The layout of the acceleration system is shown in Fig. 2. It consists of a pre-accelerator linac followed by a four-pass RLA.

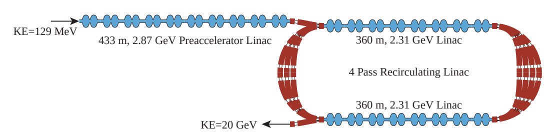

Figure 2: Accelerating system layout.

The linac calls for three type of cryomodules, populated by 2-cell cavities and focusing solenoids. The RLA cryomodules have the same layout as the long cryomodules in the linac, but uses quadrupole triplet focusing [2]. Two type of cavities are required, parameters of which are listed in Table 1.

Driven largely by cost reasons, Nb-Cu technology is adopted [3]. A Cornell/CERN collaboration has been established to fabricate and test single-cell 200 MHz Nb-Cu cavities to address challenges in this untested regime.

Table 1: Parameters for SRF cavities for neutrino factory

	Type I	**Type II**
Frequency(MHz)	201.25	201.25
Cells per cavity	2	2
Aperture diameter(mm)	460	300
E_{acc}	15	17
Input power(kW)	980	1016
Q_0	6×10^9	6×10^9

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CAVITY FABRICATION

The prototype cavity is fabricated at CERN with the standard film niobium sputtering technique that has been used for manufacture of LEP2 cavities. The shape of the prototype cell is the result of a trade-off between the optimization of RF parameters ($E_{pk}/E_{acc}, B_{pk}/E_{acc}, R/Q$) and the geometry imposed by the requirements for film deposition of niobium using the technique of DC Magnetron Sputtering. The diameter of the cell measures 1370 mm, while the diameter of the cut-off tubes is 400 mm. The ratio between these diameters is higher than usual to reduce the risk of leak problems at the end flanges. The consequences are a higher R/Q but also a higher value for the ratio of E_{pk}/E_{acc}. On the other hand having the possibility of enlarging the radius gives more flexibility to optimize the shape for sputtering. Fig. 3 shows the dimensions of the cavity. RF parameters of the cavity are listed in Table 2.

Table 2: 200MHz Nb-Cu cavity RF parameters

Parameter	**Value**	**Unit**
G	250	Ω
R/Q	121	Ω
E_{pk}/E_{acc}	1.69	-
B_{pk}/E_{acc}	4.34	mT/(MV/m)
$E_{acc}/\sqrt{U}$	0.518	(MV/m)/$\sqrt{J}$

Once the geometry has been fixed, the minimum thickness to avoid collapse under the atmospheric pressure has been calculated by simulating the structure with ANSYS. The two half cells were formed by spinning two 8 mm thick OFE copper sheets. We removed electrolytically 400 μm from the surface to reduce the imperfections induced by the mechanical process. The cavity was then welded by ACCEL with an electron beam from the inside, to avoid welding projections inside the cavity. Further mechanical smoothing has been done at CERN by grinding locally all the sharp points of the internal surface. Chemical polishing (SUBU) was performed twice on the whole cavity to remove 20 μm + 20 μm, the standard value to prepare the copper surface before the deposition of the niobium film. Fig. 4 shows the photo of a half cell under rinsing.

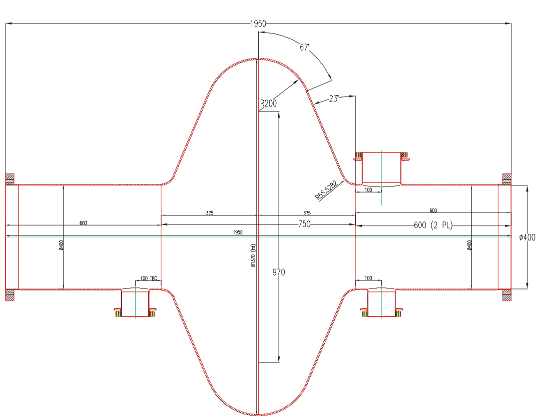

Figure 3: Dimensions of the 200 MHz Nb-Cu cavity.

Figure 4: A half cell that is being rinsed.

The deposition was made by using the existing infrastructure of the LEP2 cavities. The cavity was rinsed at 100 bars with ultra pure water on the automatic programmable machine. A special vacuum valve was installed on the cavity to insulate the cavity from the outside after drying the cavity. The cavity, filled with dry and dust-free N2, was then sent by airplane and truck to LEPP.

VERTICAL CAVITY TEST AND RESULTS

Test Facilities

After arriving at LEPP, the cavity was rolled into the clean room for installation of the input coupler and for pump down. Fig. 5 shows a photo of the cavity during clean room assembling of RF couplers.

Facilities at LEPP have been upgraded to allow vertical tests of this 2 m long cavity. A 72 inch diameter dewar, manufactured by Cryofab, is fitted into a pit of 5 m deep and 2.5 m in diameter. The pit is lined with low-carbon steel sheets and the earth magnetic field is attenuated to 200 mG.The radiation from the test pit is shielded by an 80-ton movable block. Up to 2 kW RF power (CW) at 200 MHz range is available from a solid state amplifier

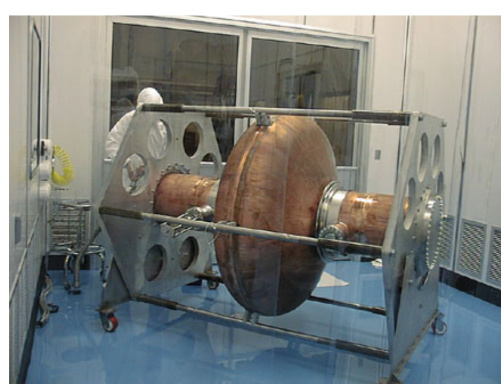

Figure 5: Assembling RF couplers on 200 MHz Nb-Cu cavity in the new LEPP clean room.

manufactured by QEI. High power RF cables are all fitted with LC connectors or $7/8''$ flanged coax connectors. The 2 kW input coupler, manufactured by Ceramaseal, is fitted with a bellow allowing an adjustable Q_{ext} (from 10^9 to 10^{10}). Fixed couplers (connector DN16 type 7/16) rated at 500 W, obtained from CERN, are also used. A new 200 MHz RF electronics system was built. Home molded foam (Versi-Foam from RHH Foam System) blocks are installed around the cavity to displace space and save usage of LHe. In addition, we pre-cooled the LHe vessel and the foam ballast with LN2 before starting LHe transfer.

Cavity Performance

The cavity performance at different temperatures are shown in Fig. 6. The low-field Q_0 at 4.2 K reached 1.5×10^{10}, which is consistent with the expected value from a reduced BCS resistance at 200 MHz. The high Q also indicates a uniform coating over the large ($\sim 3\ m^2$) RF surface. At 2.5 K, the low-field Q_0 reached 2×10^{10} and the accelerating gradient reached 11 MV/m. The gradient was limited by the power capability of the input coupler (1.3kW at 200 MHz for the CERN fixed coupler).

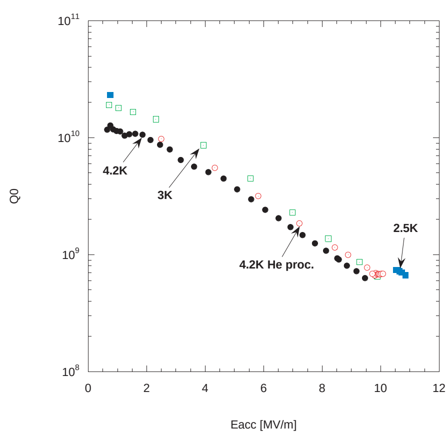

Figure 6: Performance of the 200 MHz Nb-Cu cavity.

Q Slope

The Q of the cavity declines as the gradient increases, a combined result of field emission loading and gradient dependent RF losses originated from film properties. As the bath temperature is reduced, the Q of the cavity improves progressively with the same level of γ rays generated by field emitted electrons. Clearly, the intrinsic film properties dominate the Q slope.

The Q slope has been previously observed for Nb-Cu cavities at higher frequencies. Existing data show that the Q-slope rate decreases as RF frequency goes down. Somehow, the measured Q-slope at 200 MHz is higher than the projected value by an order of magnitude. It should be mentioned that film sputtering was done with the existing infrastructures, which are not necessarily optimized for the new geometry of the 200 MHz cavity.

Multipacting

Two multipacting barriers were consistently observed, one at 3 MV/m and the other at 1 MV/m. The barrier at 3 MV/m is shown in Fig. 7, the result in which was obtained when the cavity was cold tested for the first time. The abrupt Q drop was accompanied with strong γ-ray bursts. The barrier at 1 MV/m has a similar but less pronounced symptom.

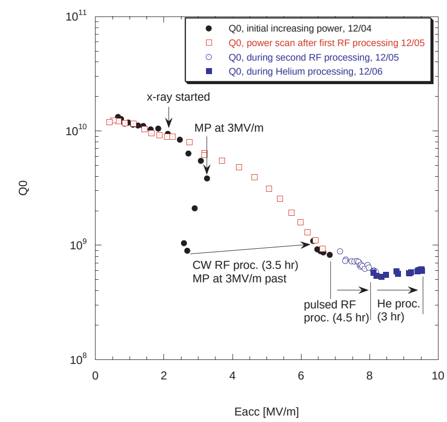

Figure 7: Multipacting barrier at 3 MV/m. This barrier is processed through by RF processing of a few hours.

Due to the narrow resonance nature, a multipacting barrier is shown as a switch in the oscilloscope trace of the reflected power after the RF is shut off. Two switches were observed in the reflected power signal for the 200 MHz Nb-Cu cavity, as indicated by arrows in Fig. 8

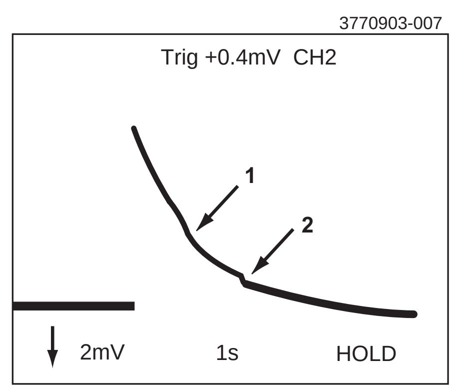

Figure 8: Two multipacting barriers are shown as two switches in the reflected power signal, indicated by arrows.

Simulations with the code MULTIPAC [4] confirmed the existence of a multipacting barrier at 3 MV/m (2-point, first-order). But no barrier is predicted at 1 MV/m, even with an artificially inflated secondary emission coefficient. Nevertheless, the second-order 2-point multipacting is expected at 1 MV/m, since the power level of 2-point multipacting has an order dependence of 1/(2N-1) [5].

These multipacting barriers can be processed through within a few hours. In principle, they are not expected to limit the cavity gradients. However, these barriers may become "hard" and require much longer processing if the cavity surface is contaminated, as was evident in a more recent test of another 200 MHz cavity.

Field Emission and Radiation Background

After the multipacting barrier at 3 MV/m was past during the first cold test, strong field emission took over. Extended RF processing only yielded small improvement. Helium processing was applied, which improved the accelerating gradient by a factor of 2. γ ray dose rate was progressively reduced by helium processing. Additional HPR turned out to be necessary and improved the gradient further to 9.5 MV/m. The radiation level was only 30 R/h at 9.5 MV/m, in contrast to 100 R/h at 6 MV/m before the second HPR.

Fig. 9 shows the gradient dependence of the radiation dose rate measured on the cavity axis 0.75 m above the cavity top flange. The two multipacting barriers are reflected by two peaks at the corresponding gradients. Above 4 MV/m, the radiation is mainly due to field emission and its field dependence fits very well into the modified Fowler-Nordheim formula. The field enhancement factor β is in the range of 600 - 900.

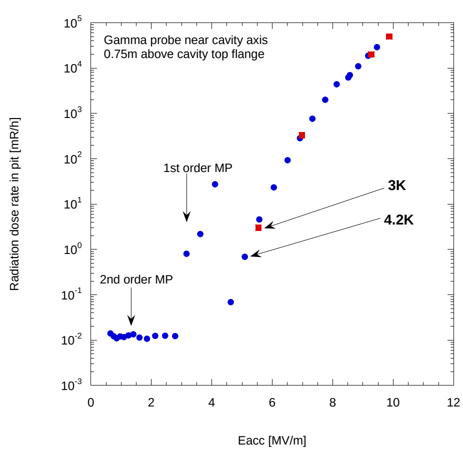

Figure 9: Radiation dose rate near the 200 MHz Nb-Cu cavity.

Fast and Slow Cool Down

A 200 MHz Nb-Cu cavity was tested twice consecutively with very different cool down speeds. For a slow cool down, the cavity was parked at the temperature range of 60 - 150 K for 100 hours. The cavity went through the same temperature range within only two hours for a fast cool down. The Q of the cavity was found to be essentially the same within the accuracy of measurement calibration. It is concluded that the 200 MHz Nb-Cu cavity is free of "Q-virus" (caused by precipitated hydrogen).

Performance in Presence of External Magnetic Field

To study the effect of an external magnetic field effect on a cold 200 MHz Nb-Cu cavity, a rather simple configuration was adopted, in which a superconducting coil (the end face diameter being 40 mm) was installed against the cavity equator. The cavity was cooled down prior to turning the magnet. As shown in Fig. 10, the cavity is not affected by an external field of $\leq$ 1200 Oe. Above 1200 Oe, an irreversible RF loss due to the external field is observed.

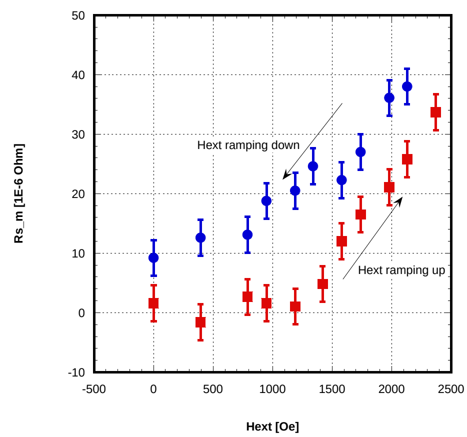

Figure 10: External magnetic field effect on the additional surface resistance of a 200 MHz Nb-Cu cavity.

These results are consistent with the fact that niobium is a type-II superconductor with its H_{c1} being close to 1200 Oe at 4.2 K. This measurement has been done only at low accelerating gradients at present.

CONCLUSION

A 200 MHz sputtered Nb-Cu cavity has been successfully fabricated and tested. The low field Q_0 reached 1.5×10^{10} at 4.2 K. E_{acc} reached 11 MV/m, limited by the input coupler. Multipacting barriers at 3 MV/m and 1MV/m can be processed through within a few hours. The film has a stronger Q-slope than projected. This effect is to be studied at 500 MHz with seamless cavities and improved sputtering, including biased sputtering.

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