SRF FOR NEUTRINO FACTORIES

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Abstract

The Neutrino Factory calls for nearly 500 meters of 200 MHz SRF cavities to provide 7.5 GV. Such a facility is more demanding than the largest SRF installation to date, i.e., LEP-II, where 500 m of niobium-coated copper cavities provided more than 3 GV of acceleration. Based on the high real estate gradient desired to minimize muon loss, superconducting cavities are selected to provide active gradients of 15 – 17 MV/m, and a real estate gradient of 7.5 MV/m. At such high gradients, the peak RF power demand for copper cavities would become prohibitively expensive. By virtue of low losses, SC cavities can be filled slowly (rise time 3 ms) reducing the peak power demand to roughly half MW per cell.

1 NEUTRINO FACTORY AND ACCELERATING SYSTEM

Fig. 1 shows a generic neutrino factory from proton source to muon production, followed by cooling and acceleration[1]. Finally muons in the storage ring decay to produce the desired intense neutrino beam. Acceleration of a muon beam is challenging because of the large phase space and short muon lifetime. To minimize muon loss from decay, the highest possible gradient is necessary. SRF offers gradients of 15 MV/m and reduces the peak RF power needed by virtue of long fill times made affordable by superconductivity. SRF cavities also provide a large aperture that helps preserve helps beam quality and beam stability.

The acceleration system (Fig. 2) starts with a linac from about 200 MeV to 2.5 GeV followed by a 4-pass recirculating linac to the final energy of 20 GeV. Some designs call for a final energy of 50 GeV with a second recirculating linac. A pre-accelerator linac is necessary in the first stage because the beam is not relativistic and phase slippage in a recirculating linac would reduce acceleration efficiency. Experience at the 5-pass CEBAF recirculating linac shows that the final to initial energy ratio should be kept below 10 to 1. As a result, muon acceleration is based on a 4-pass choice. The need for very large beam acceptances drives the design to a low RF frequency of 200 MHz.

For a high real-estate gradient it is important to have a large filling factor of cavities in the cryomodule, pushing structure design towards multicell cavities. On the other hand, because of the low frequency and high gradient, the coupler power and stored energy per structure increases with number of cells. Also the mechanical resonance frequency of multi-cell cavities drops, demanding elaborate stiffening schemes. Trading-off between such factors, 2-cell units are chosen.

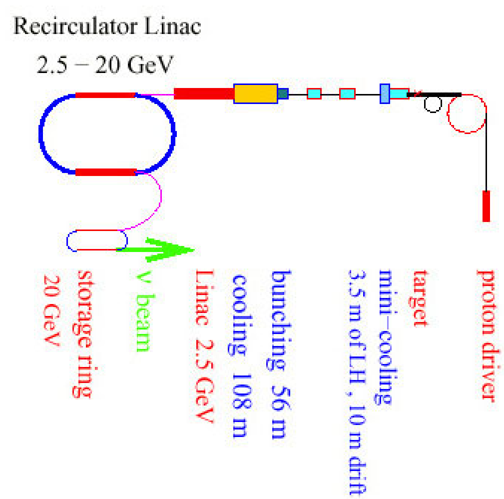

Figure 1: Layout for Neutrino Factory

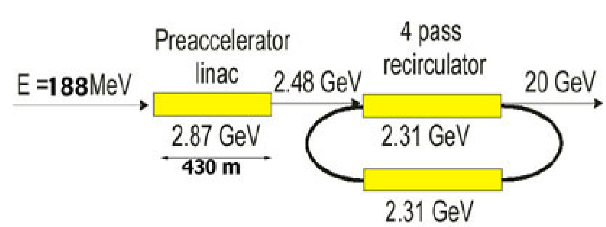

Figure 2: Layout for the muon acceleration system.

The linac calls for three types of cryomodules, populated by 2-cell cavities and focussing magnets (Fig. 3). Short cryomodules in the initial portion handle the large beam size. As the beam adiabatically damps during acceleration, intermediate length cryomodules take over. Cavities in these first modules have an aperture of 460 mm and a design gradient of 15 MV/m. At 0.75 GeV, longer modules have cavities of aperture 300 mm and a design gradient of 17 MV/m. Fig. 4 shows a 3D CAD model of a standard cryomodule with four, 2-cell units and focusing magnet. Each cavity has two input couplers, one on each end, and two HOM couplers, also one on each end. The input coupler power is kept at the 500 kW level by providing one coupler at each end. The antenna type coaxial design is chosen based on the successful experiences of CERN, DESY and especially the success of the KEK input coupler for KEK-B[2].

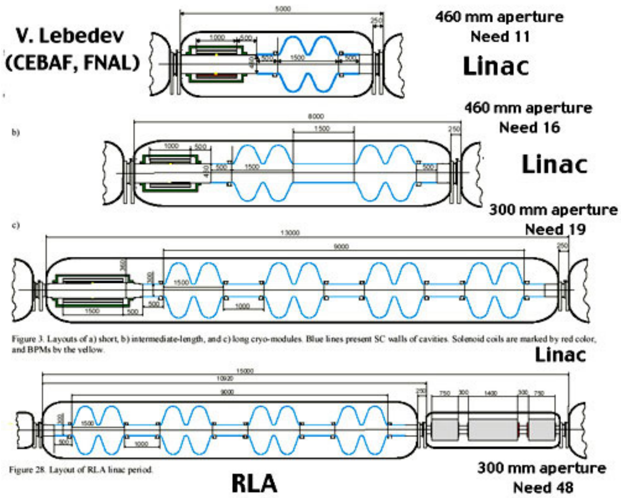

Figure 3: Cryomodules for the pre-accelerator linac and the recirculating linac.

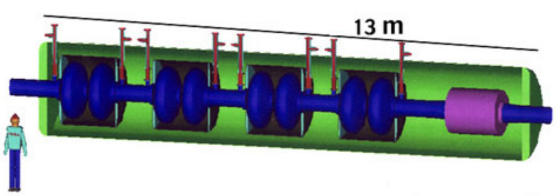

Figure 4: CAD model for the cryomodule.

2 NB/CU TECHNOLOGY CHOICE

Although sheet metal Nb cavities used for TESLA are capable of providing gradients of the order of 25 MV/m and higher, Nb/Cu technology is more suitable for the Nufactory for the following reasons:

- Because of the lower RF frequency and the accompanying thicker wall (e.g. 6 mm), the cost of raw sheet niobium becomes prohibitive (> 100 M$ at $500/kg) for the roughly 600 cells needed.
- High thermal conductivity copper provides better stability against quenching of superconducting cavities over sheet Nb cavities. This is especially beneficial at 200 MHz because of the high stored energy per cell (roughly one kJ per cell).
- The wall thickness of 200 MHz cavities may need to be greater than 6 mm for mechanical stability against atmospheric load and for reducing Lorentz force detuning and microphonics from external vibrations.
- A Nb coated copper cavity allows the use of pipe cooling instead of the more usual bath cooling. Pipe cooling saves liquid helium inventory and opens new avenues for stiffening.

3 STRUCTURES AT 200 MHZ

The performance of a superconducting cavity depends on the peak surface fields. Minimizing E_{pk} is important to avoid field emission. Minimizing H_{pk} is also important, since the Q of Nb/Cu cavities falls with surface magnetic field, one of the characteristic features of Nb/Cu cavities. In the 400 MHz LHC cavity which reached Eacc = 15 MV/m[3], the corresponding peak surface fields were Epk = 33 MV/m and Hpk = 750 Oersted. The LHC cavity has a beam pipe diameter of 300 mm. Keeping the same beam pipe diameter for 200 MHz, 2-cell cavities, it is possible to improve the neutrino factory cavity geometry (see Fig. 5) to reduce the peak fields to 14% below LHC-cavity values. Table 1 lists the properties of the 2-cell-300 mm aperture and Table 2 for the 2-cell- 460 mm aperture units. Fig. 5 shows the 2-cell geometries.

Results from CERN[3] on 400 MHz Nb/Cu cavities show accelerating gradients of 15 MV/m at 2.5 K and a Q of 2 x 10^9. At 4.5 K, gradients are below 10 MV/m. Modelling (Fig. 6) the Q vs. E curve obtained for LHC 400 MHz cavities and incorporating the Q increase for 200 MHz, ANSYS studies conclude that it will not be possible to reach Eacc = 15 MV/m at a Q of 6 x10^9, unless the operating temperature is reduced to 2.5 K. We have therefore chosen the operating temperature of 2.5 K. At 200 MHz, we can expect a Q of 8x10^9 but we have chosen a design Q of 6x10^9 to allow for some field emission loading.

Fig. 6 shows that the peak magnetic field expected for 17 MV/m in a 2-cell cavity with 300 mm beam aperture corresponds to Eacc = 13 MV/m for the LHC cavity geometry because of the relatively smaller beam pipe and optimized cavity Nufact cavity geometry.

A single-cell niobium coated copper cavity is under fabrication at CERN and will be tested at Cornell (Fig. 7 &8).

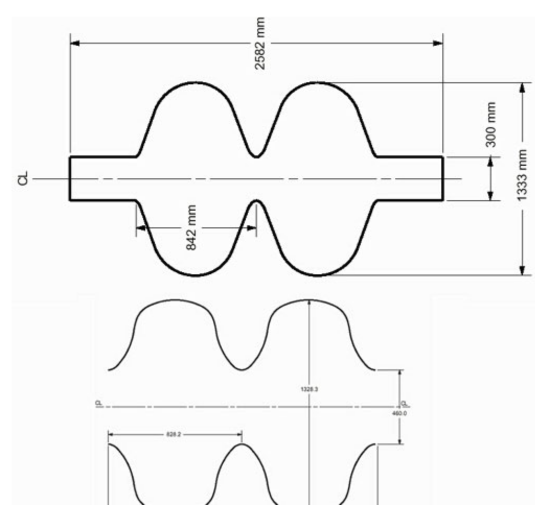

Figure 5: Geometry for the large and small beam pipe cavities.

Table 1:
2-cell, 300 mm-diameter cavity parameters.

RF freq (MHz)	201.25
No. of cells per cavity	2
Active cavity length (m)	1.5
No. of cavities	256
Linac	76
RLA	180
Aperture diameter (mm)	300
E_{acc} (MV/m)	17
Energy gain per cavity (MV)	25.5
Stored energy per cavity (J)	2008
R/Q (Ω/cavity)	258
E_p/E_{acc}	1.43
H_p/E_{acc} (Oe/MV/m)	38
E_{pk} at 15 MV/m (MV/m)	24.3
H_{pk} at 15 MV/m (Oe)	646
Q_0	6×10^9
Bandwidth (Hz)	200
Input power per cavity (kW)	1016
RF on-time (ms)	3
RF duty factor (%)	4.5
Dynamic heat load per cavity (W)	18.9
Operating temperature (K)	2.5
Q_L	10^6
Microphonics detuning tolerable (Hz)	40
Wall thickness (mm)	8
Lorentz force detuning at 15 MV/m (Hz)	128

Table 2:
2-cell, 460 mm-aperture cavity parameters.

RF freq (MHz)	201.25
No. of cells per cavity	2
Active cavity length (m)	1.5
No. of cavities	43
aperture diameter (mm)	460
E_{acc} (MV/m)	15
Energy gain per cavity (MV)	22.5
Stored energy per cavity (J)	1932
R/Q (Ω/cavity)	208
E_p/E_{acc}	1.54
H_p/E_{acc} (Oe/MV/m)	44
E_{pk} at 10 MV/m (MV/m)	23.1
H_{pk} at 10 MV/m (Oe)	660
Q_0	6×10^9
Bandwidth (Hz)	200
Input power per cavity (kW)	980
RF on-time (ms)	3
RF duty factor (%)	4.5
Dynamic heat load per cavity (watt)	18.3
Operating temperature (K)	2.5
Q_L	10^6
Microphonics detuning tolerable (Hz)	40

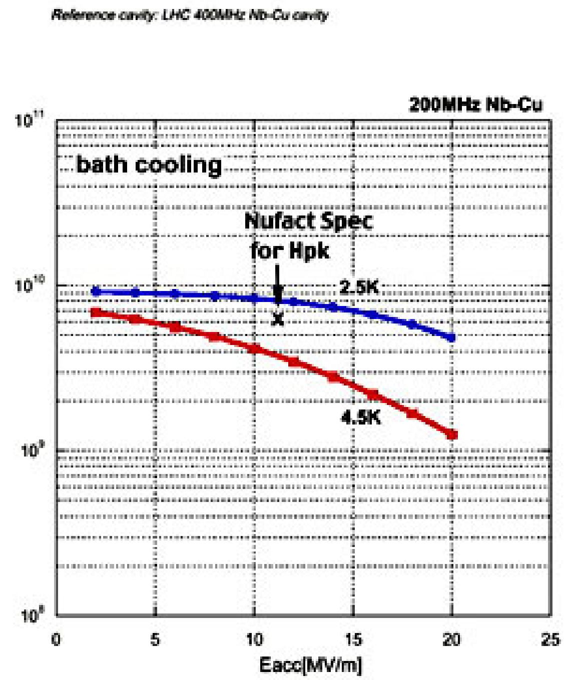

Figure 6: Q vs E curve expected for 200 MHz Nb/Cu cavity based on CERN LHC 400 MHz cavity results.

Figure 7: A comparison of the 200 MHz and 1500 MHz cavity sizes.

Figure 8: 200 MHz half-cell under preparation for electropolishing at CERN.

4 RF POWER

In selecting the RF pulse length (Trf), a trade-off must be made between peak RF power on the one hand with refrigerator load, tolerance to microphonics and to Lorentz force (LF) detuning on the other hand. Increasing Trf will lower the peak power, but increase the average RF power and refrigeration load. Increasing Trf will also drive Q_L toward higher values, decreasing the cavity bandwidth and thereby increasing its sensitivity to LF detuning and microphonics. The peak RF power (P_{pk}) needed to establish the fields depends on the stored energy (U), cavity time constant ($\tau = \frac{Q_L}{\omega}$) and the amount of detuning $\delta\omega$ expected from Lorentz force and microphonics as follows[4]:

$$P_{pk} = \frac{U\left(\frac{\omega}{Q_L}\right)\left[\left(Q_L\frac{\delta\omega}{\omega}\right)^2 + \frac{1}{4}\right]}{\left[\left(1 - \exp\left(-\frac{T_{rf}}{2\tau}\right)\right)\right]^2}$$

Once the fill time and detuning tolerance are selected, the loaded Q is found to minimize the peak power required. A conservative estimate for detuning tolerance in these large 200 MHz structures is 40 Hz. Cavities at TTF and CEBAF show microphonic excitation of < 10 Hz[5]. For a fill time of 3 ms, the optimum Q_L is $1\text{x}10^6$ (bandwidth = 200 Hz) and the required peak power is about 500 kW per cell. Coaxial couplers developed for the KEK-B factory[2] have delivered 380 kW CW to one amp beams. In pulsed mode, higher power performance can be expected from input couplers. Nevertheless it is prudent to use two couplers for each 2-cell unit.

Future R&D on structure stiffening, feed forward, and active tuning to compensate LF detuning and microphonics could lower the required peak power by reducing the detuning tolerance. For example if the detuning tolerance can be lowered to 20 Hz, the input power drops to 450 kW per cell and optimum Q_L rises to $1.5\text{ x}10^6$. Adopting a 4 ms fill time would decrease input power to 350 kW per cell at best $Q_L = 1.5\text{ x}10^6$

5 OVERALL SCALE OF NEUTRINO FACTORIES AND ACCELERATING SYSTEMS

Table 1 shows the overall parameters for the acceleration system including the size of the RF and refrigeration installations. The total AC power for the neutrino factory is in the range of 50 MW. Figures 9 to 11 show possible layouts of neutrino factories at sites around the world.

Table 3:

Overall Parameters for NuFactory SRF

No. of cryomodules	94
No. of 2-cell cavities	311
No. of input couplers	622
Overall length	1061 m
Active length	467 m
Filling factor	0.44
Total voltage	7.5 GV
Average Real Estate Gradient	7.4 MV/m
Total heat load @2.5, 5-8, 40 - 80 K	7.4, 9.4, 94 kW
Cryo load with x 1.5 safety factor 2.5, 5-8, 40 - 80 K	**11.1, 14.1, 14 kW**
Assuming efficiency mulitipliers of 225 , 20	
AC power for refrigeration	12.6 MW
Total peak RF power with 20% ma for control/losses	**362 MW**
Average RF power	16.3 MW
AC Power for RF (efficiency multiplier =	35.6 MW
Total AC Power	**48 MW**

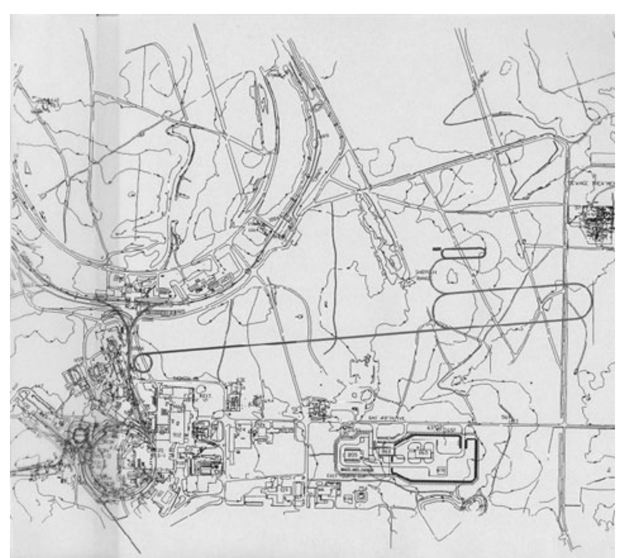

Figure 9: A possible Neutrino Factory Layout at BNL[1].

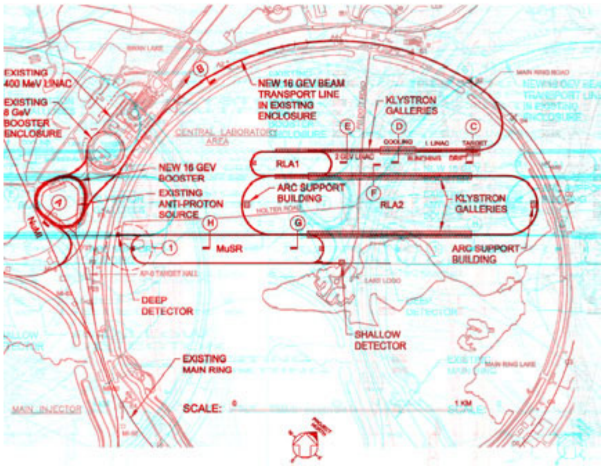

Figure 10: Possible Neutrino Factory Layout at FNAL[1].

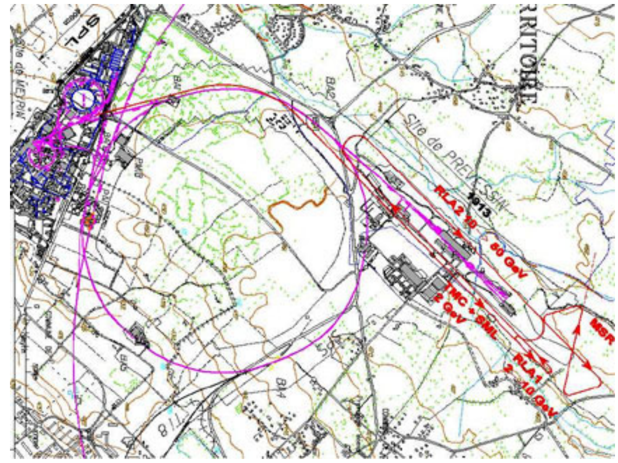

Figure 11: Possible Neutrino Factory Layout at CERN[6].

6 REFERENCES

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