18. HIGH-POWER RF SYSTEMS: 201.25 AND 402.5 MHZ

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18.1 Introduction

The RF systems for the buncher and the cooler are required to match the muon beam into the longitudinal acceptance of the cooling channel and replenish the beam energy lost during ionization cooling. Since they must operate inside the strong solenoid fields they must be normal conducting. These systems require a large number of RF cavities operating at high-gradient, and a large amount of pulsed RF power. They are technically challenging and expensive and have therefore been the focus of continued development during Study-II. The cooling channel layout has continued to evolve since Study-I with emphasis on integration of realistic components into the available space along with optimization of the channel performance. The buncher and cooling channel systems must accommodate liquid-hydrogen absorbers, high-gradient RF cavities, windows, tuners, superconducting solenoids, diagnostics, pumping, harmonic cavities and other equipment. The system must be designed in such a way as to allow assembly and access for maintenance.

The buncher and cooling channel will be made of a large number of modules. The module layouts are described in Sections 18.4.2 and 18.4.3. Each module contains two or four 201.25 MHz closed-cell cavities and is powered by one or two high-power klystrons. The density of equipment in the building is therefore high and the systems must be carefully laid out to allow access for installation and maintenance. Following the cooling channel is a matching section containing RF and solenoids but no absorbers.

The proposed buncher, cooling channel and matching section is approximately 183 m long and requires 190 cavities and 84 klystrons. The total installed power is approximately 780 MW (approx. 1.56 MW average), and the installed voltage is 1080 MV.

The cooling channel is followed by an acceleration section employing 299 two-cell superconducting RF cavities at 201.25 MHz. These structures are also challenging because of the high-gradient and large physical size. The power requirements of these Sections are not as high as the normal conducting RF Sections but the pulse length is much longer. Many cavities can be powered from a single klystron station. Several multi-cell RF cavities may share a common cryostat. The final energy at the end of the accelerating Section is 20 GeV, compared with the 50 GeV of Study-I. This reduces the size and cost of the acceleration Section significantly.

18.2 NCRF Specifications for Cooling Channel and Buncher

Table 18.A shows the inventory of RF cavities contained in the Study-II parameter list. The cooling channel simulations have assumed ideal pillbox cavities with lengths that are determined by the space available in the chosen lattices (and zero space between cavities). The gradients and phases of these cavities have been adjusted to optimize the cooling channel performance while keeping the gradients and RF power requirements within feasible limits. Table 18.B shows the peak cavity power and klystron output power to meet these requirements and the total power for each cavity type. Both tables also show how the required voltages could be obtained using practical re-entrant or "omega" shaped cavities with closed off irises of finite thickness. The loss of active length in this case is compensated by the greater efficiency of the rounded design. To be conservative the iris diameter used for the omega cell was sufficient to accommodate any reasonable beryllium foil. In practice the foils may be smaller and in any case will decrease in size towards the end of the cooling channel. Ideally the cavity shape would be optimized for each foil size. This would maximize the efficiency and minimize the cost. Note that the RF power requirements are dominated by the cooling Sections 1.1-1.3 and 2.1-2.3, which have the largest number of cavities and the highest gradients.

Table 18.A. Parameters for the ideal (pillbox) and practical (omega) NCRF cavities

ideal pillbox dimensions from parameter list						
Section	**radius**	**length**	**freq**	**#cavs**	**Epk***	**Veff**
	(m)	(m)	(MHz)		(MV/m)	(MV)
b1	0.570	0.373	201.25	4	6.40	2.07
b2	0.570	0.373	201.25	8	6.00	1.94
b3	0.570	0.373	201.25	8	8.00	2.59
1.1-1.3	0.570	0.466	201.25	68	15.48	5.76
2.1-2.3	0.570	0.559	201.25	74	16.72	6.71
match	0.570	0.559	201.25	22	16.72	6.71
b1 402.5 MHz	0.285	0.186	402.5	2	6.40	1.03
b2 402.5 MHz	0.285	0.186	402.5	4	8.00	1.29
Omega cavities						
b1	0.607	0.405	201.25	4	7.41	2.07
b2	0.607	0.405	201.25	8	6.95	1.94
b3	0.607	0.405	201.25	8	9.27	2.59
1.1-1.3	0.607	0.405	201.25	68	20.62	5.76
2.1-2.3	0.615	0.483	201.25	74	23.06	6.71
match	0.615	0.483	201.25	22	23.06	6.71
b1 402.5 MHz	0.308	0.288	402.5	2	6.57	1.03
b2 402.5 MHz	0.308	0.288	402.5	4	8.21	1.29

* note: Kilpatric number is about 15 MV/m at 201.25 MHz

Table 18.B. Voltage and power requirements for the NCRF cavities

ideal pillbox dim.'s							
Section	Veff	Rs†	Pc*	Pkly**	#cavs	Ptot	sum
	(MV)	(MΩ)	(MW)	(MW)		(MW)	(MW)
b1	2.07	8.899	0.567	0.628	4	2.51	
b2	1.94	8.899	0.499	0.552	8	4.42	
b3	2.59	8.899	0.886	0.982	8	7.85	
1.1-1.3	5.76	10.701	3.646	4.038	68	274.60	
2.1-2.3	6.71	11.428	4.635	5.134	74	379.91	
match	6.71	11.428	4.635	5.134	22	112.95	782.23
b1 402.5 MHz	1.03	6.275	0.200	0.222	2	0.444	
b2 402.5 MHz	1.29	6.275	0.313	0.347	4	1.387	1.831
Omega cavities							
b1	2.07	10.220	0.494	0.547	4	2.19	
b2	1.94	10.220	0.434	0.481	8	3.85	
b3	2.59	10.220	0.772	0.855	8	6.84	
1.1-1.3	5.76	10.220	3.818	4.228	68	287.54	
2.1-2.3	6.71	11.794	4.491	4.974	74	368.09	
match	6.71	11.794	4.491	4.974	22	109.43	777.93
b1 402.5 MHz	1.03	8.368	0.150	0.166	2	0.333	
b2 402.5 MHz	1.29	8.368	0.235	0.260	4	1.040	1.373

† Rs, calculated, = V^2/P, * Real cavity, Qo assumed 85% of theoretical,
** Klystron forward power for 3τ filling

18.3 RF Station Description

Each RF station consists of a modulator for two klystrons, distribution system, low-level RF and controls driving two or more cavities. The modulator must provide a flat top DC pulse of up to 125 µs with a recharge time of less than 20 ms. This is equivalent to a repetition rate of 50 Hz, however not every 50 Hz pulse is required. The output from the AGS appears as 6 pulses spaced at ~20 ms followed by ~300 ms gap. (The AGS cycles at 2.5 Hz). The "average" duty factor is ~1.9×10^{-3}.

The RF power source must provide approximately 10 MW of peak power to drive two cavities. The source will most likely be a multi-beam klystron, which should give good reliability and a long operational lifetime.

The distribution will be via high-power coaxial lines, with the power split between two or more cavities with appropriate delays to maintain the proper phase . The cavities will use coaxial feedthroughs and loop-type couplers. The peak power requirements will require careful design of the components, although the average power of around 10 kW per coupler is quite modest. Provision should be made for adjusting the phase of individual cavities and for handling the reflected power during the initial part of the cavity fill time.

Each station will require a water distribution system and a rack of low-level RF hardware and controls.

18.3.1 RF Power Source and equipment

The ionization cooling channel requires high peak RF power sources at 201.25 MHz and 402.5 MHz to efficiently bunch and cool the muon beam. Table 18.B lists the peak RF power requirements for each Section of the cooling channel. There are 190 201.25-MHz cavities in the channel that require 782 MW of RF power for a pulse length of 125 μs at 15 Hz (average) and six 402.5-MHz cavities that require up to 1.8 MW at 15 Hz. An examination of the requirements shows that an RF source of about 6 or 12 MW would be ideal for the 201.25 MHz cavities and a source of 500 to 750 kW for the 402.5 MHz cavities. The RF for the 201.25 MHz cavities could be supplied by existing gridded tubes at about the 5 MW level. However, the low gain and lifetime of gridded tubes make the R&D effort to develop an alternative most attractive. Preliminary calculations at SLAC [18.4] have shown that a 201.25 MHz klystron could be built with a reasonable amount of R&D. The gain, efficiency, and lifetime are higher than a gridded tube at 50 dB, 50-70% and 50,000 hours, respectively. SLAC has examined two designs a single-gun diode design, and a multibeam klystron. The multibeam klystron is the most attractive in that it reduces the overall length of the tube from 7.5 m to between 3.5 and 4.0 m. The length reduction factor of the multibeam klystron and its potential for higher efficiency make it the optimum candidate for the Neutrino Factory. The length of the multibeam klystron is, also, consistent with the manufacturing capabilities of current tube manufacturers. However the manufacture of a 7.5 m diode tube would be a big step and would require new and costly facility upgrades. Figure 18.AA shows a 9-beam MBK developed by Thompson for TESLA. Two such tubes have been built and tested, and have demonstrated efficiencies of 63 - 66% [ref.18.1A]. To provide RF power overhead for dynamic regulation of the RF phase and amplitude, a 12 MW multibeam klystron has been selected as the high-power RF source for the Neutrino Factory. This provides an RF power overhead margin of about 20 % for regulation. The design should be a fully integrated horizontal package incorporating the tube, solenoid, and high-voltage terminal as pioneered at CERN for LEP. This would facilitate the replacement and installation of tubes in the facility. With a mean time between failures (MTBF) of 50,000 hours and 73 tubes, a tube would be expected to need replacement about every 30 days, after the initial break-in period. Many of these “failures” towards the end of life are gradual and replacement can be scheduled for routine maintenance periods. Another advantage of the horizontal design, besides the ease of handling, is the reduced cost of the RF building because of the lower building height requirement. Because of the large size and costs of waveguide, the transmission lines from the tubes to the cavities will be large coaxial lines of 0.31 to 0.36 m diameter pressurized to 1.75 atmospheres of dry air. Power splitters would divide the RF power from each tube to supply the appropriate RF power to the cavities. Sections b1 and b2 of the buncher will require a 12-way splitting of the power; Section b3 an 8-way split , and Sections 1.1 to 2.3 a 2-way split. Splitters with proper built-in phase delays would further divide the power to each cell or cavity Section of the cooling channel.

The 402.5 MHz system can use currently existing 900 kW diode RF klystron amplifiers. Because of their long length, it would be advisable to fund a small R&D development of an integrated horizontal package for the tube. Again, as for the multibeam klystron, this would improve the efficiency of tube handling and provide cost saving because of reduced building height requirement. Again, coaxial transmission lines with splitters would be used to provide the RF power to the cavities. Only 3 klystron tube amplifiers are required to supply the requirements of the 402.5 MHz buncher RF.

Figures 18.A and 18.B show a cross Section and plan of a portion of the RF building gallery along a 201.25 MHz Section. The RF building is approximately 190 m long and 30 m wide. With the horizontal packaging of the 201.25 and 402.5 MHz klystrons the height of the building roof line need only be 5.5 m. Because of the large footprint of the equipment, the klystrons are arranged side by side and on both sides of the gallery. Not shown in the figures are the transmission line splitters required to supply the RF power to the cavities as well as the utilities. The 402.5 MHz klystron system footprint will be much the same, but about half the size, and these klystrons will be located in Sections b1 and b2 interspersed between the 201.25 MHz equipment.

Figure 18.AA. Thomson TH 1801 multi-beam klystron

18.3.2 RF Station Controls and LLRF

The low level RF (LLRF) and control system provides the drive power for the final klystron amplifier, contains feedback loops for phase, amplitude and cavity frequency control, personnel safety and equipment protection. A frequency reference line running the length of the complex provides an RF phasing reference to which each cavity is locked. A microprocessor in each RF station processes error information to control the amplitude and phase to keep the cavity tuned to the reference frequency. The microprocessor communicates with, and accepts directions from, the central control room. The system is similar to systems currently in use at Fermilab or planned for the SNS project. The LLRF system will include fast circuits to detect sparks and malfunctions and immediately inhibit the RF to protect the equipment and cavities. Other hard-wired fast circuits will monitor for high RF leakage from equipment and contact with high-voltage and current and activate interlocks for personnel protection. The equipment would be housed in five standard racks next to the klystron and associated equipment, figure 18.B.

18.3.3 High-voltage Modulator and Power Supply

The high-voltage modulator and power supply for the 201.25 MHz will use the latest solid-state design. Currently available Insulated Gate Bipolar Transistors (IGBT) modulator technology will be built by industry to provide the pulse power requirements of the klystron, see fig. 18.AAA. The Neutrino Factory will use IGBT modulators similar to designs currently being built for the SNS project. They are very reliable, efficient and cost effective. A 19 beam klystron, the basis of this design, has a calculated efficiency of 70% and klystron tube perveance of $0.5x10^{-6}$. The specifications for the modulator and power supply are given in table 18.C. The overall efficiency of the modulator and power supply from the AC mains is about 95%.

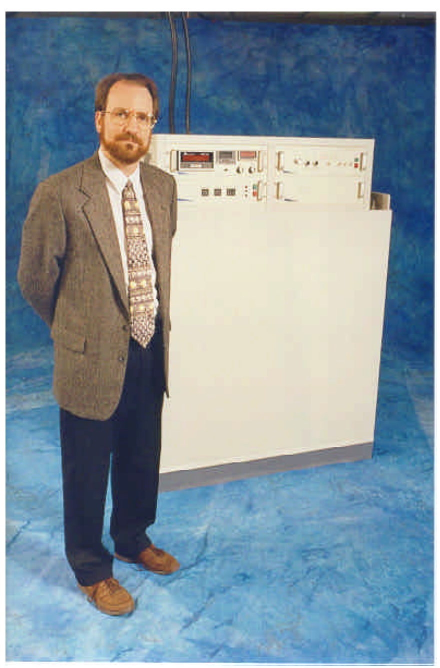

Figure 18.AAA. Compact modulator from Diversified Technologies, Inc., Medford, Ma.
(Capacitor bank and regulator not shown in this picture)

Table 18.C. High-voltage modulator parameters

Klystron frequency	201.25	402.5
High-voltage	80	60
Pulse Length (μs)	125	35
Current (A)	215	31
Duty Factor	0.19%	0.0525%
Average power (kW)	33	1.0
Voltage Droop	0.1%	0.1%

18.3.4 NCRF Mains Electrical Power and Water System

The mains AC power for the normal conducting RF must support 84 tubes with 33 kW average power and three tubes with 1.0 kW average power, solid-state amplifiers and solenoid power supplies, cooling water systems and miscellaneous other loads. These all require a 480 V three phase supply. In addition to this AC power is required at 120 V and 208 V for racks and other miscellaneous equipment. This gives a total of 6.8 MW at the AC mains. Table 18.D shows a summary of the AC power requirements.

Table 18.D. NCRF Systems AC Mains Power Requirements

Item	power (MW)
Klystron modulators (95% efficiency)	2.9
Amplifiers & supplies	1.0
Cooling + miscellaneous loads	2.3
Racks etc.	0.6
Total	6.8

The cooling water system will be sized to accommodate the average power of 6.8 MW with a proper temperature rise for safe and efficient operation of the equipment. Each klystron station requires 75 gpm of low-conductivity water (LCW), for cooling the klystron and associated equipment and 20 gpm LCW to cool and maintain temperature control of the cavity. This gives a total water requirement of 7,980 gpm. This could be divided up between room temperature and higher and chilled systems for cavity control at 20 gpm per station. For all these systems we assume a supply header pressure of 100 psi and return pressure of 40 psi.

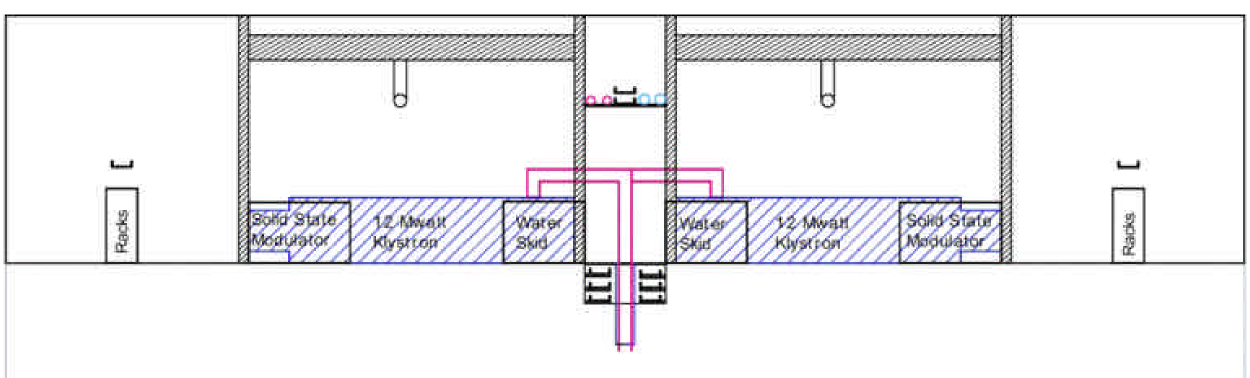

FIGURE 18.A. Cross Section of cooling channel equipment gallery

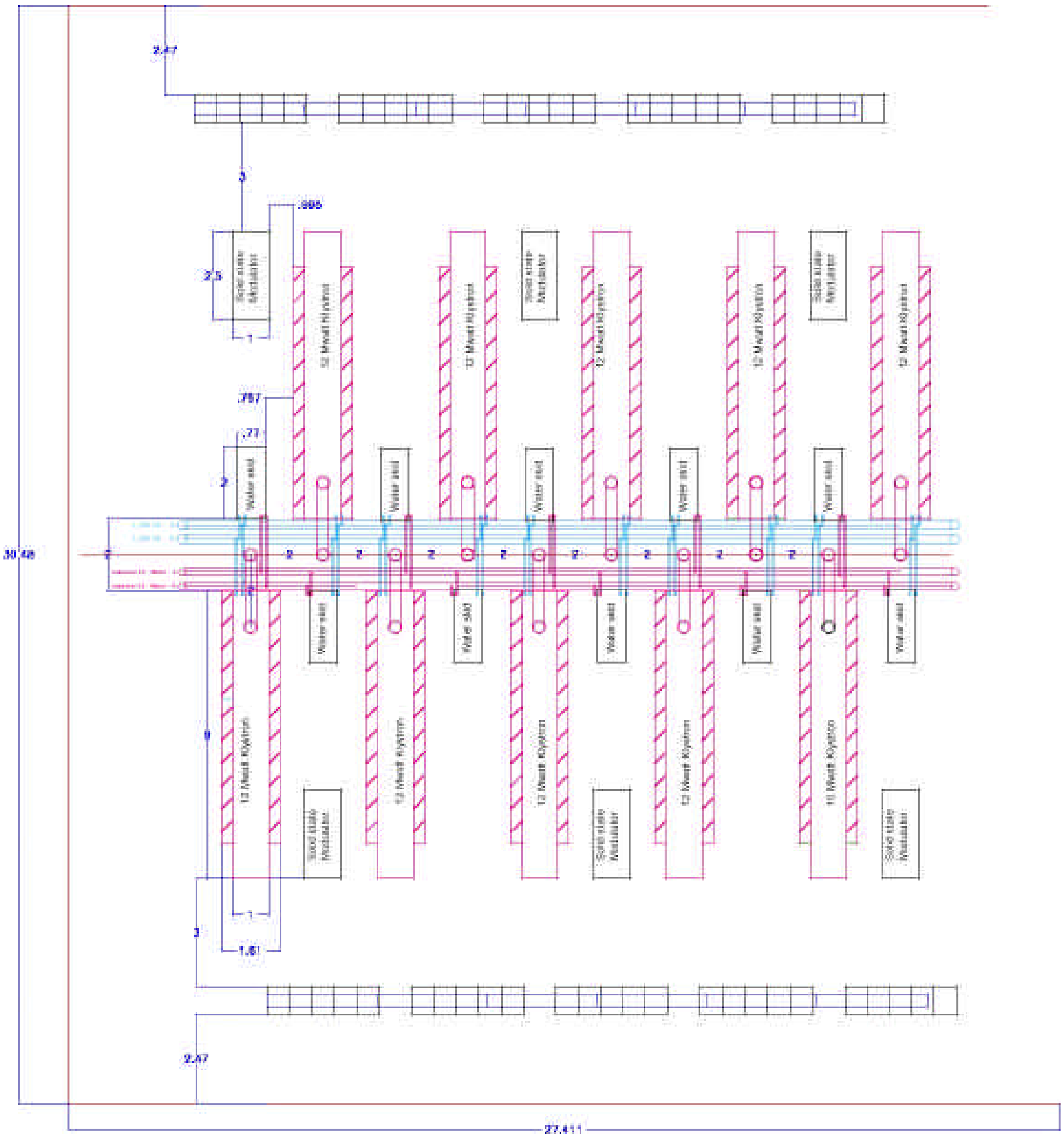

FIGURE 18.B. Cooling channel linac equipment gallery, plan view

18.4 NCRF Cavities at 201.25 MHz and 402.5 MHz

The 201.25 MHz normal-conducting cavities in the cooling Sections must operate at very high accelerating gradients. This would be impractical with conventional open-iris structures, given the large size of the beam iris required. A great improvement can be made in the shunt impedance of the cavity by closing the iris with a thin conducting barrier. This barrier must use the smallest amount of material to minimize scattering of the muon beam. It is proposed to close the irises with thin beryllium foils. Other methods of closure, such as grids of thin-walled tubes will be evaluated in the future. The foils must be thick enough to conduct away the heat from the RF currents and keep the temperature to a predetermined level. The foils will be pre-stressed in tension during manufacture in order to keep them flat. This method had been tested experimentally and works well up to the point where the thermal expansion exceeds the pre-stress and the foils begin to move. Foil thicknesses have been chosen for Study-II that will keep the temperatures below this critical level. The use of tapered foils, or foils with stepped thickness, can reduce the amount of material intercepted by the core of the beam, reducing the amount of scattering significantly. Table 18.D2 shows the thickness of the foils used in the simulations of the various types of cavities in the buncher and cooling channel.

Table 18.D2. Beryllium foil thicknesses for various cells in the buncher and cooling channel.

type	Section	frequency	length	gradient	Thickness*	Radius*
		MHz	m	MV/m	μm	cm
end	b1	402.5	0.186	-6.4	75	18
end	b2	402.5	0.186	-6	75	18
end	b1	201.25	0.3728	6.4	100	21
middle	b1	201.25	0.3728	6.4	120/240	14/21
end	b2	201.25	0.3748	6	100	21
middle	b2	201.25	0.3748	6	105/210	14/21
end	b3	201.25	0.3748	8	180	21
middle	b3	201.25	0.3748	8	187/374	14/21
end	1.1	201.25	0.466	15.48	200/400	12/18
middle	1.1	201.25	0.466	15.48	700/1400	14/21
end	1.3-2.1	201.25	0.5592	16.72	248/495	12/18
middle	1.3-2.1	201.25	0.5592	16.72	917/1834	14/21
end	2.1	201.25	0.5592	16.72	128/256	10/15
middle	2.1	201.25	0.5592	16.72	495/990	12/18

* dual values imply a stepped-thickness foil

The normal-conducting cavities in the buncher can be of the same design as those in the first cooling Section, though they would be operated at lower gradient. This will allow the use of thinner foils to minimize the scattering. The buncher Section also contains a small number of harmonic cavities operating at 402.5 MHz. These fit into the spaces that are occupied by the hydrogen absorbers in the cooling cells farther downstream. For these cavities the foils occupy most of the diameter of the end walls, but the gradients are much lower so the losses in the foils are manageable.

The normal conducting cells must have some cooling to remove the average power losses in the walls and to stabilize the frequency. The Study-II design has been evaluated for room temperature operation, although the option of operating at reduced temperature (e.g. liquid nitrogen) has been kept open. This option would lower the wall resistance and reduce the peak power requirements at the expense of adding an additional refrigeration system.

18.4.1 201.25 MHz Closed-Cell Description

The cooling channel simulations have used simple pillbox cavities that have continuous, flat, conducting end walls from the center all the way to the outer radius. The cavity lengths assumed for the simulations are just the available space divided by the appropriate number of cells. In practice the cavities must be closed by assemblies of foils or grids that should be demountable from the cavities for assembly or repair. This requires a finite thickness for each iris, reducing the length available for RF and lowering the effective shunt impedance. This can be mitigated by rounding the outer walls of the cavity to improve the quality factor and restore the shunt impedance. Any practicable assembly of foils (or grids), requires some space for flanges and access. We have assumed a minimum spacing of 50 mm between cavities, as shown in figure 18.C. The dimensions of the cavities have been adjusted to fit the remaining available space. Note that the resulting cavity lengths are significantly shorter than the optimum for a particle of this velocity (beta = 0.87). In future studies a cavity length that is more optimal may be achieved by adjusting the total cell length appropriately. The cavity shape is slightly reentrant in order to maximize the inductance, minimize the capacitance, and hence get the highest shunt impedance [ref. 18.1]. Figures 18.C and 18.D show the cavities separated by a pair of foils. This would allow variable thickness foils to be used where the stepped side is not exposed to RF. Figure 18.E shows a MAFIA simulation of the electric field in two half-cells separated by a pair of foils. Some field enhancement can be seen on the noses. Alternatively a single foil of twice the thickness could be used in the center of the iris, heated from both sides (except for the end cells). Another advantage of the closed-cells is that there is no RF coupling through the iris so the cavities can be individually phased for optimum performance of the cooling channel. One penalty of the omega shape is some field enhancement on the "nose", see figure 18.F. Although the nose is made with as large a radius as practical, it still may have an enhancement factor of as much as 1.7 over the field on axis. However, the highest surface field in table 18.B is only about 1.5 times the Klipatric number for this frequency. One positive aspect of this field concentration is that it is not on the foil but on the solid copper so a breakdown to this point may be less of an issue. Figure 18.Fb shows the azimuthal magnetic field. The distribution on the foil, and therefore the RF heating, is similar to the pillbox model, although there is some shielding due to the noses.

Figure 18.G shows the profile of the cavity from the downstream part of the cooling channel where only two cavities are used per cooling cell. The cavities are longer and closer to the optimum for this particle velocity (although there is still room for some improvement). Figures 18.H a and b show the 2D electric and magnetic field profiles for this case.

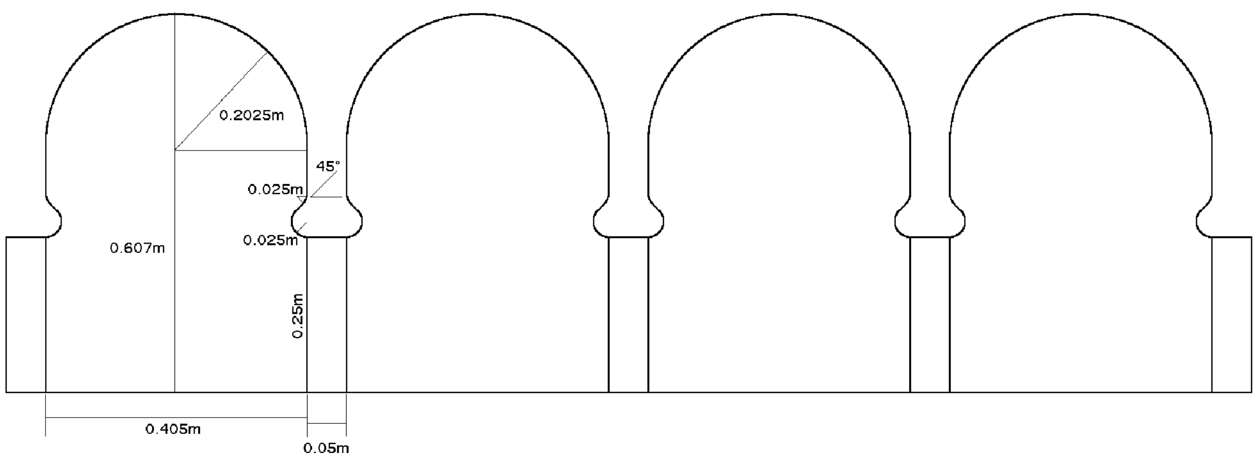

FIGURE 18.C. Profile of cavities for buncher and first cooling Section

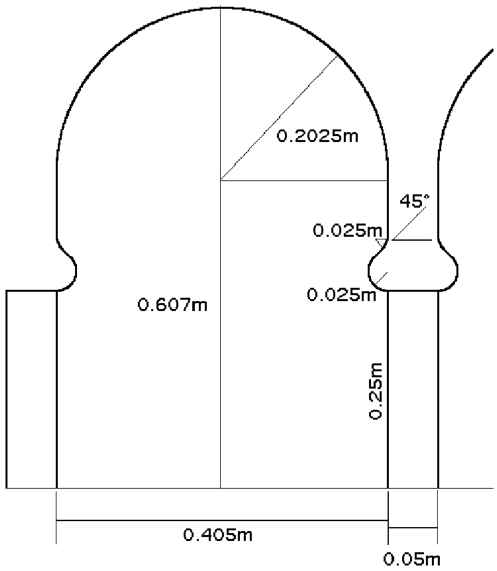

FIGURE 18.D. Section 1 cavity

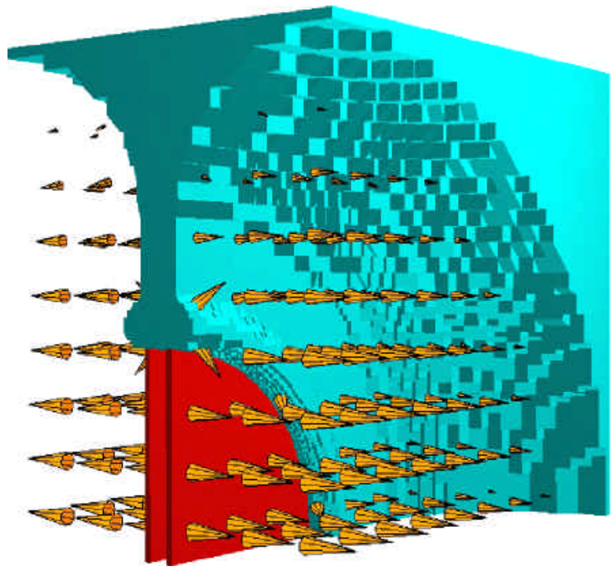

FIGURE 18.E. MAFIA model with 2 foils

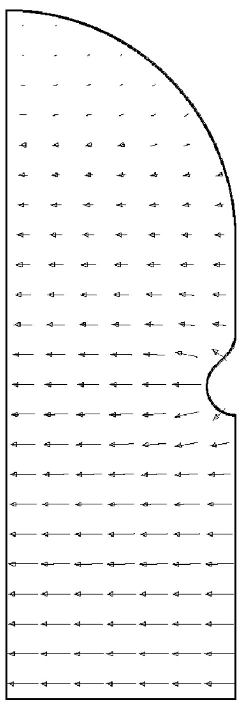

FIGURE 18.Fa. URMEL 2D E-field

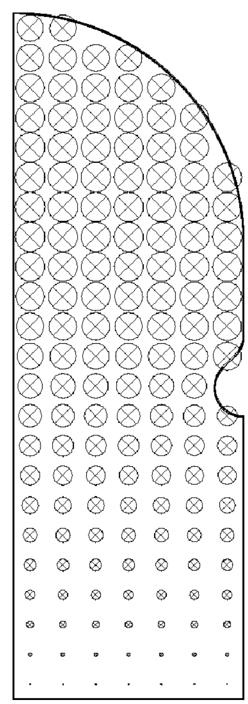

FIGURE 18.Fb. Azimuthal H-field

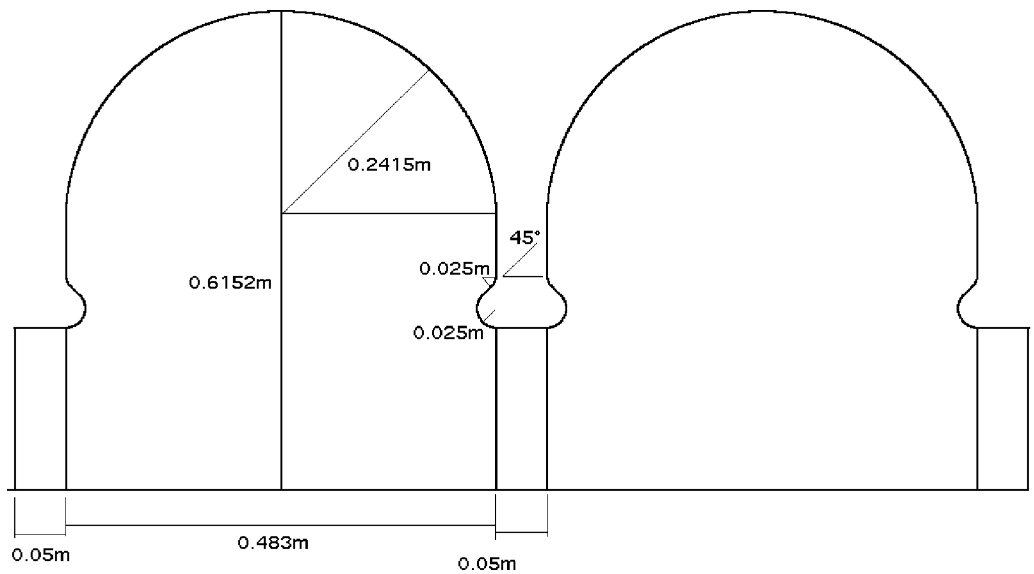

FIGURE 18.G. Profile of cavities for second cooling Section

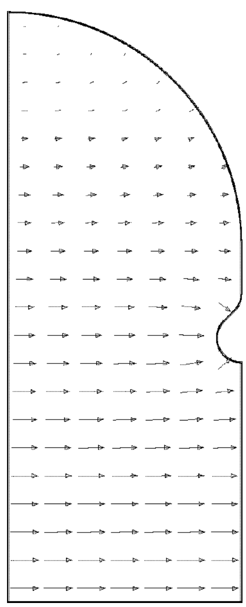

FIGURE 18.Ha. URMEL E-field

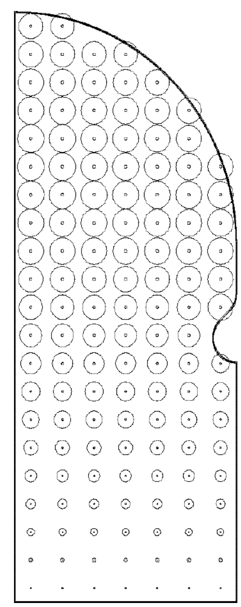

FIGURE 18.Hb. Azimuthal H-field

18.4.2 Foil Requirements

The closed-cell cavity design described above assumes that beryllium foils will be used to seal off the beam irises. Other methods, including grids of thin walled tubes, have been discussed, and show promise, but are not as far advanced in understanding or testing as the foils. Hence pre-stressed foils have been chosen as the baseline design for Study-II. The foils are made of thin high-purity beryllium sheet bonded to a thicker ring of slightly lower grade material, see figure 18.I. The exact details of this process are proprietary but the combination of materials used results in a small but significant difference in the thermal expansion of the foil relative to the ring assembly. This produces a tensile pre-stress on cool down from the joining operation, which helps to keep the foil flat.

When the foils are heated by RF, and only cooled by conduction to the edges, they assume an approximately parabolic temperature profile, see figure 18.J. The calculated RF-induced profile is slightly flatter than parabolic and can be used in ANSYS as a load set for the stress calculations. Figure 18.K shows an example of the temperature distribution in a thin foil from such an analysis.

The foils remain flat until the thermal expansion exceeds the tensile pre-stress. At this point compressive stress is generated in the foil, and it starts to deflect by buckling into a gently bowed shape, see figure 18.L. The maximum allowed temperature difference is about 35°C and is approximately independent of the radius and thickness. Of course a thicker foil can take more power before reaching the buckling temperature, as shown in figure 18.M. A set of foils (table 18.D), has been specified for the set of cavities used in table 18.A, that keeps the temperatures below the critical point. For the larger irises the foils become quite thick and the scattering of the muon beam becomes significant. One way to reduce this is to make the windows thinner in the middle, where the core of the beam passes, and thicker towards the outside, where there are fewer particles, see figure 18.N. It is thus possible to reduce the scattering while maintaining the same temperature rise in the foil. Figure 18.O shows the temperature profile for a thin window of uniform thickness and for windows with thicker profiles starting at different radii. As can be seen from the figure, adding material at large radius has a significant effect on the temperature profile up to about one third of the way in. Beyond this point, there is diminishing return and much past halfway there is little to be gained by adding more material. Simulations have shown that such a stepped window reduces the multiple scattering significantly compared with a uniform foil for the same temperature. Going to multiple steps in thickness, or to a continuous taper, should yield further small improvements in scattering but the simulations do not show a significant improvement in transmission through the cooling channel.

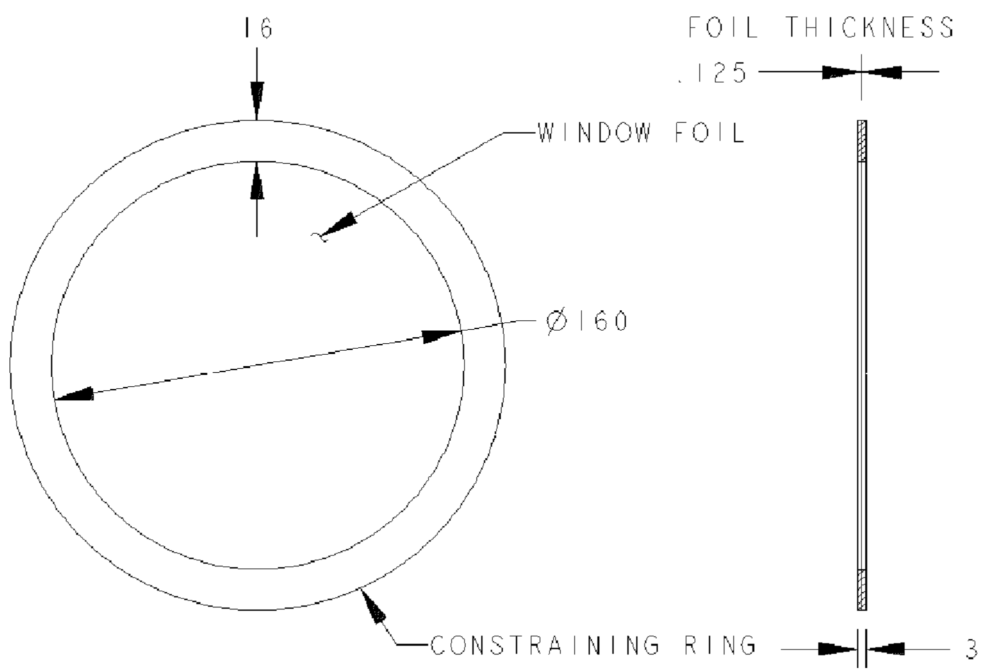

FIGURE 18.I. Layout of beryllium test window (all dimensions in mm)

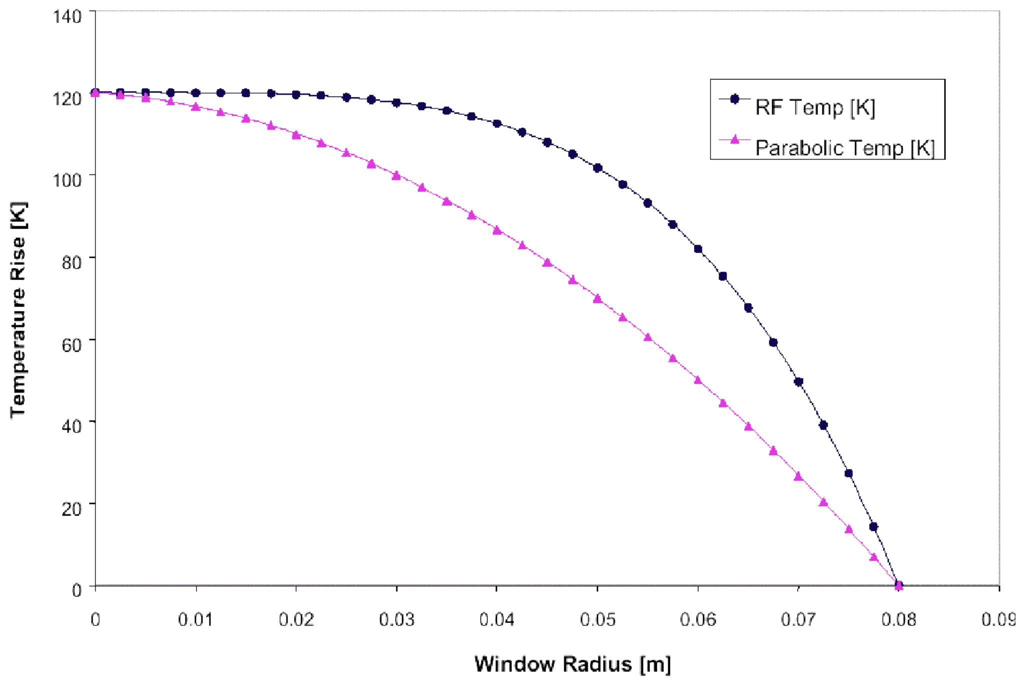

FIGURE 18.J. Actual temperature profile for RF heating and parabolic approximation from halogen lamp tests.

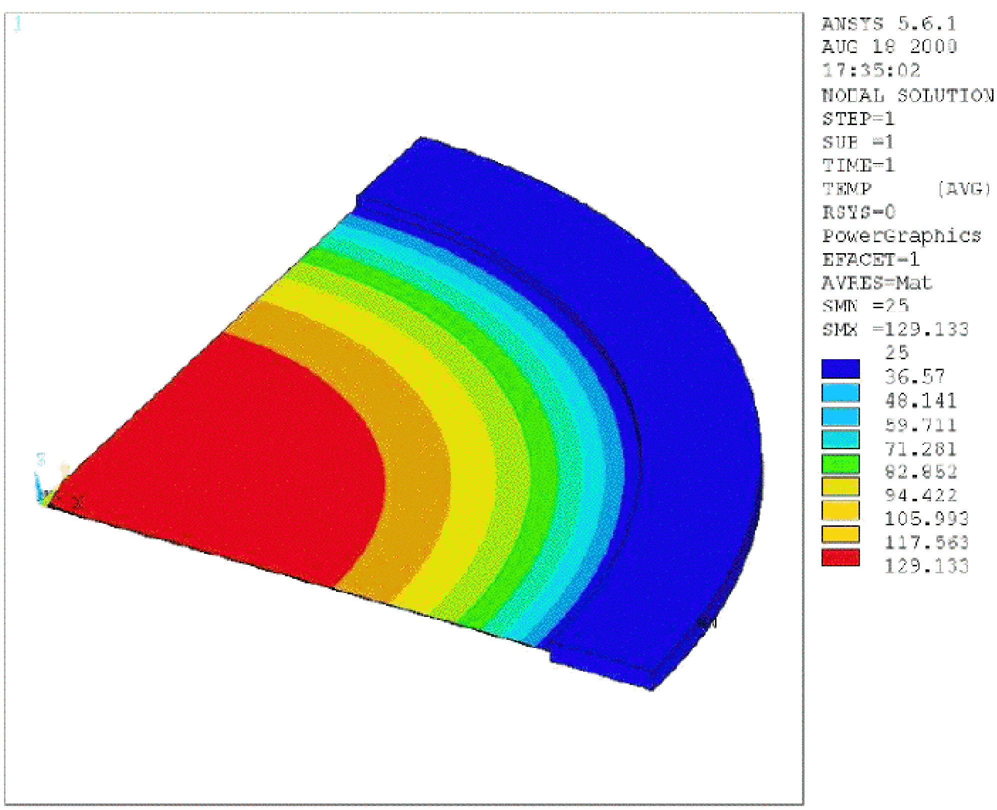

FIGURE 18.K. ANSYS calculated temperature profile for thin window with 60W loading

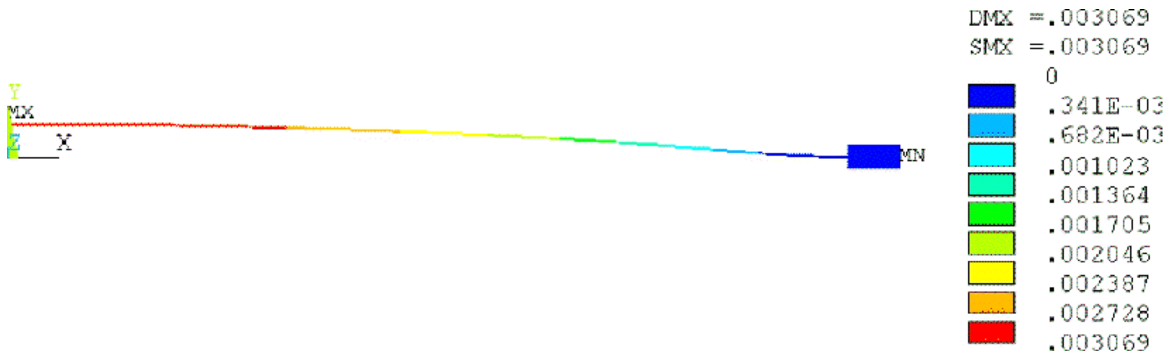

FIGURE 18.L. ANSYS model showing example of buckling displacement (dimensions in m).

The pre-stressed foil properties have been investigated experimentally in a low-power test cavity at 805 MHz using a halogen lamp as a heat source, [ref. 18.2]. These experiments used small (160 mm diameter) foils and the results have been extrapolated to larger foils. We have assumed that the same pre-stress can be achieved in the larger foils, but this must be validated experimentally as part of the future R&D program. It should be straightforward to obtain the desired pre-stress by adjusting the combination of materials in the outer ring but some experimentation may be required to find the optimum combination.

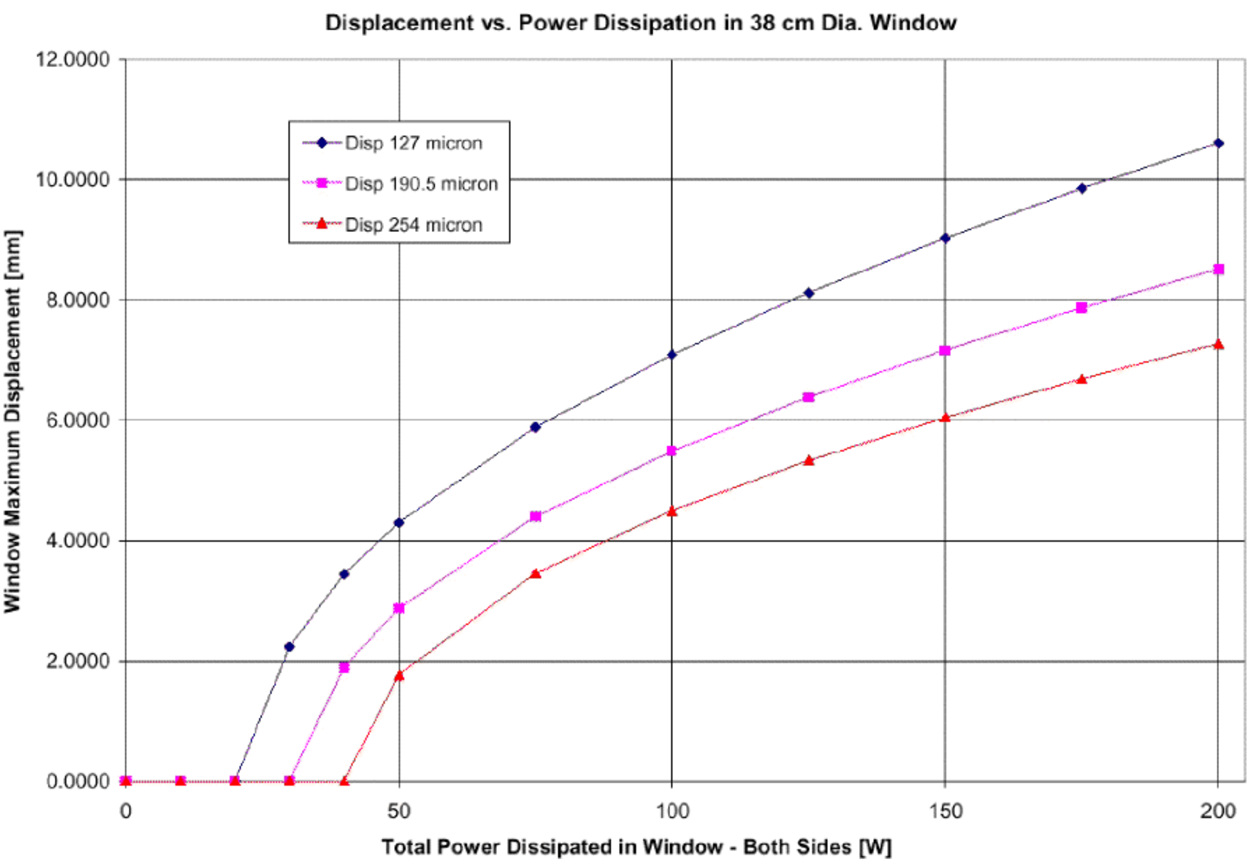

FIGURE 18.M. ANSYS calculated displacement vs. power for larger windows

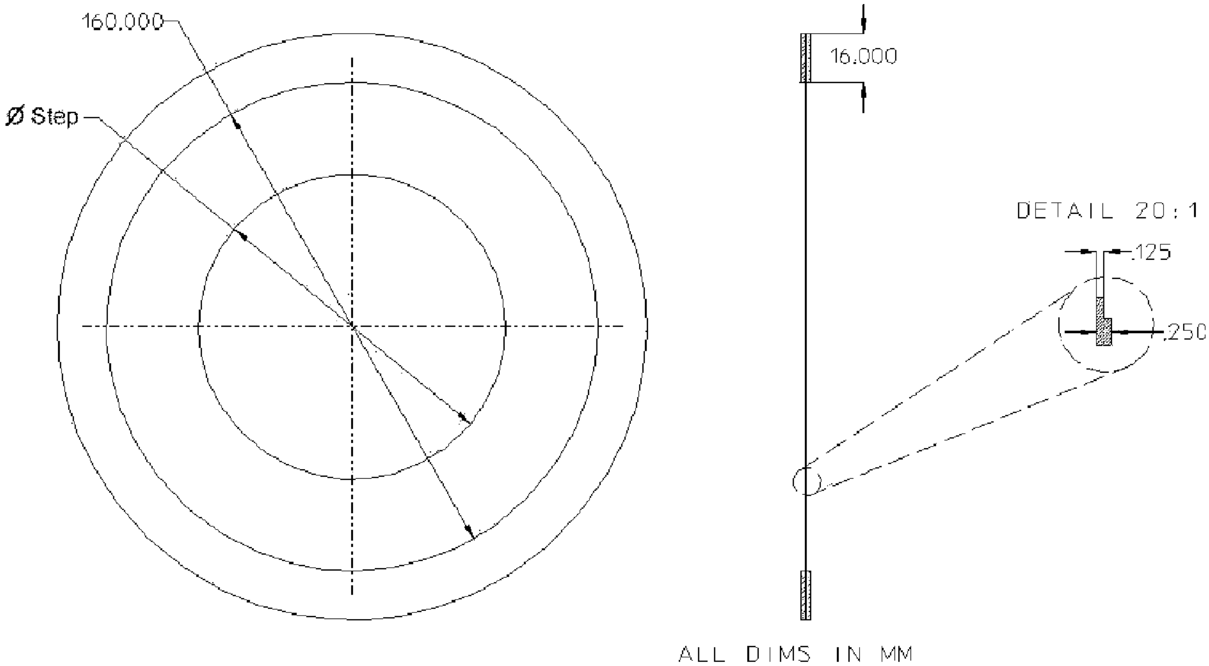

FIGURE 18.N. Stepped-thickness window design

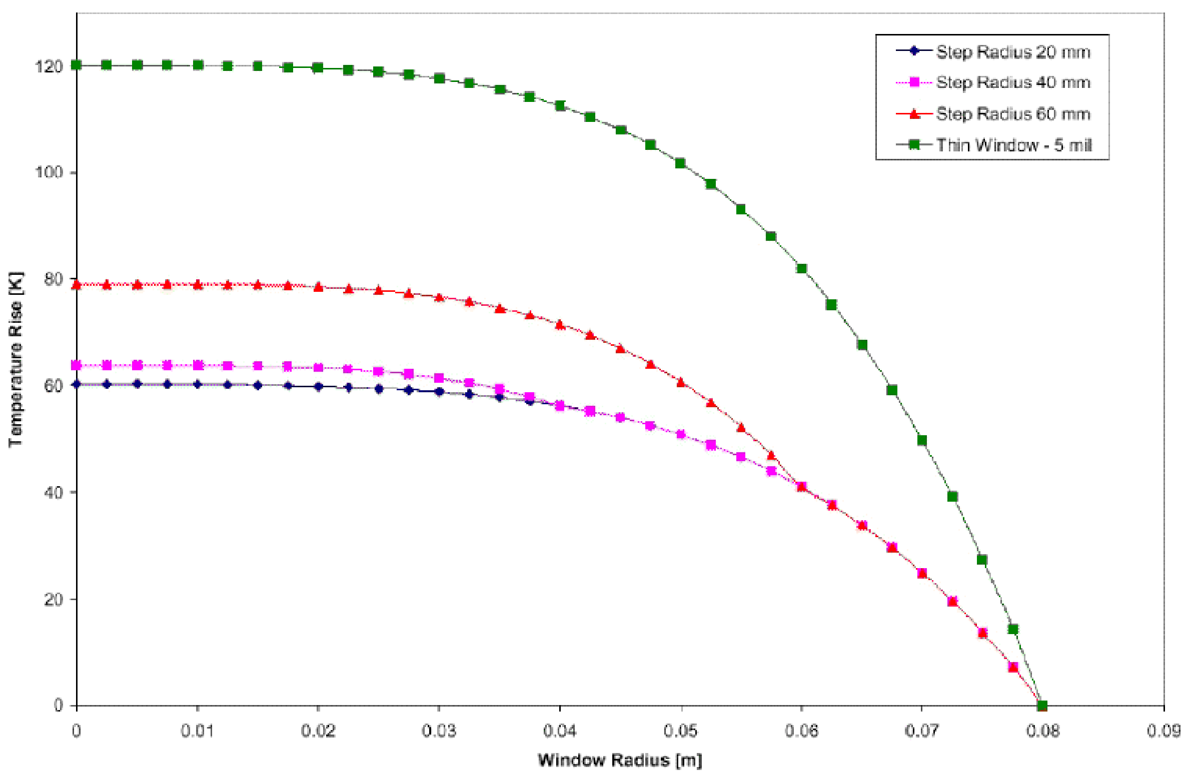

FIGURE 18.O. Temperature profile of uniform thin window and windows with steps to thicker outer region at various radii.

One issue with the closed-iris structures is the possibility of multipactoring due to the high secondary yield of beryllium or aluminum (foils or tubes) This could cause outgassing and possibly breakdown in the cavity, which might damage the delicate structures. Persistent multipactor discharge may also heat the surfaces involved. Unlike copper, the secondary yield of aluminum does not reduce with RF conditioning because of a stable surface oxide layer. It is expected that beryllium may behave similarly, although the handbook values for beryllium oxide are lower than those for aluminum oxide. It is proposed to suppress this problem by the application of low secondary emission coatings such as titanium nitride (TiN). This issue will be investigated experimentally in a high-power cavity as part of the ongoing muon collaboration 805 MHz R&D program. The cavity is designed to use demountable foils or copper blank-off plates and can be conditioned to very high-gradient using the high-power klystron test stand in the Lab G facility at FNAL. The foils will be coated on one side with TiN and conditioning tests can thus be run with all copper surfaces, uncoated beryllium windows, coated beryllium windows or combinations of these. Windows of various thickness and with stepped profiles will be tested and the conditioning can be attempted with a wide range of magnetic fields in an available 5 T superconducting solenoid.

18.4.2 2.75 m lattice implementation

The cooling channel lattice is a tightly packed assembly of equipment including liquid-hydrogen absorbers, superconducting solenoids, high-gradient RF cavities, instrumentation, vacuum equipment etc. Our studies show that it is possible to integrate all these components into the available cell length. Several iterations have been performed on this layout to try to make the most efficient use of the space. Constraints include the size of the RF cavities, which is dictated by the frequency, the size of the absorbers, which is determined by the beam size, and the cell length, which has been fixed for this study at 2.75 m for the buncher and first cooling section and 1.65 m for the second cooling section. This dimension can and should be re-evaluated for subsequent studies as part of the overall system optimization. The sizes of the coil packs and cryostats have been chosen to allow practical current densities and the coil diameters have been kept small to minimize the amount of superconductor required, and therefore the cost. The largest coil is the central one that surrounds the RF cavities. The inner diameter of this coil has been left large enough to allow the cavity structures to pass through during assembly. The RF feeds must come out through the wall of the cryostat, and may be angled to give clearance to other hardware. Pumping ports will be short and wide to give good conductance and may also penetrate the cryostat. Clearance is required at the end of each cooling cell to allow for installation or removal of one absorber/RF module from the channel. This is achieved by using a collapsible flange in the outer cryostat wall, which is reinforced after it is made up in order to handle the possible magnetic forces. RF shields will be used to keep beam-induced signals from escaping into the outer cryostat and vacuum system. Figure 18.P shows the proposed cooling channel layout for the first cooling section lattice, including all major components except the beam instrumentation package, which will occupy the clearance opening at the end of each cell or, possibly, the space between the RF cavities and the hydrogen absorber. The space in the cryostat outside of the cavities will be evacuated to minimize the load on the RF structures. This approach also provides insulation for the cavities if they are operated below room temperature. This approach also obviates the need for UHV connections between each cavity and between the cavities and the hydrogen absorbers. The flanges are required only to provide RF continuity (for screening) and to separate the UHV of the RF system from the guard vacuum of the cryostat.

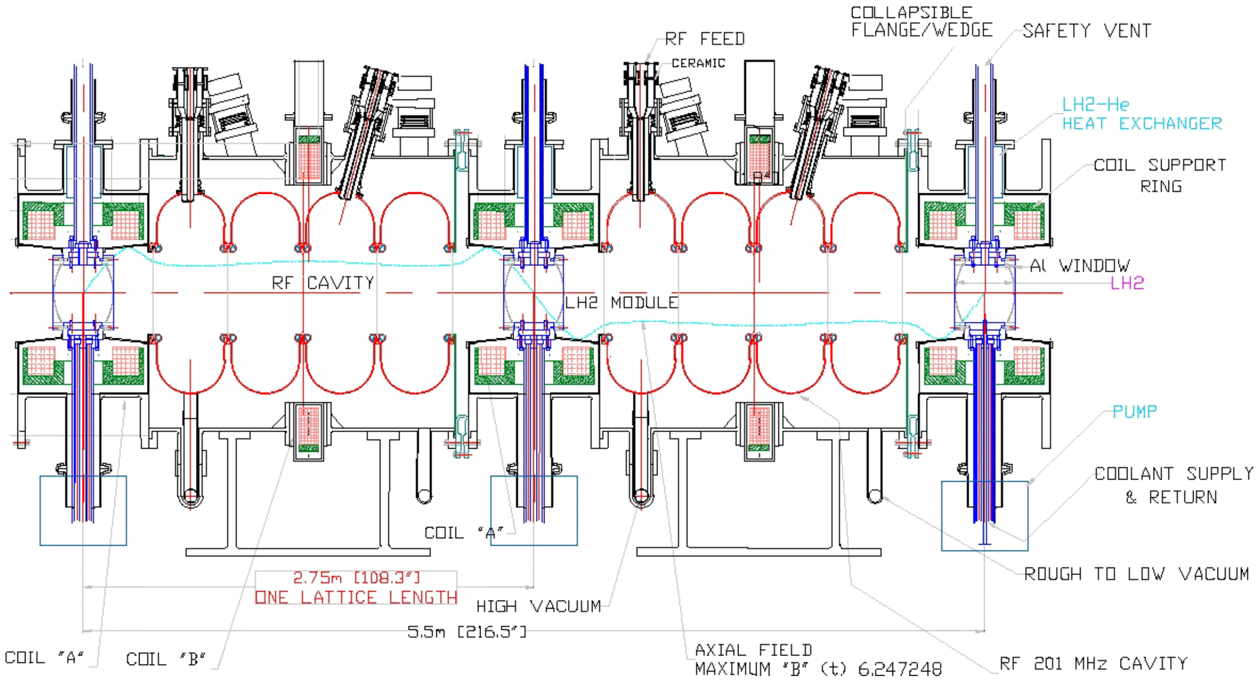

FIGURE 18.P. Cooling channel Section 1, four cavities per cell

18.4.3 1.65 m Lattice Implementation

The 1.65 m lattice for the downstream part of the cooling channel will use a similar layout to the upstream part, but with smaller hydrogen absorbers and only two RF cavities per cell. The density of equipment is similarly high. In this case the cavity lengths are closer to the optimum for this particle velocity, but could be improved in future studies if the cell length were increased slightly. Figure 18.Q shows the proposed cooling channel layout for the second lattice type, including all major components except the instrumentation package.

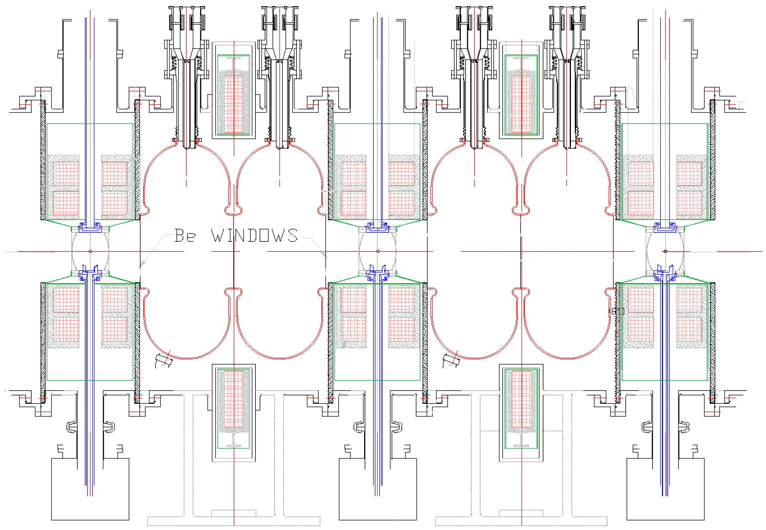

FIGURE 18.Q. Cooling channel Section 2, two cavities per cell

18.4.4 402.5 MHz Buncher Cavity

The buncher harmonic cavities, figure 18.U, are smaller, simpler versions of the 201.25 MHz cavities. They are rounded pillboxes and are closed by similar foils (or grids) that are smaller and thinner than the large cavities. There is adequate space for the cavities to be the optimal length for this particle speed. Though the power requirements are modest, cooling water will be used to stabilize the frequency and remove the small amount of average power dissipated in the walls. The harmonic cavities are installed in some of the buncher cells in the location where the hydrogen absorbers are placed in the normal cooling Sections, i.e., inside the bore of the smaller solenoid coils. If required due to radial space constraints, the diameter of the cavity could be reduced slightly at the cost of a little more power and somewhat thicker foils.

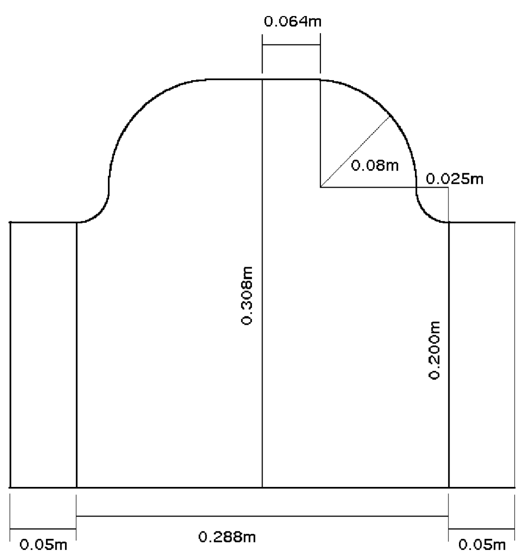

FIGURE 18.U. 402.5 MHz buncher harmonic cavity

18.4.5 Tuning Requirements

Since there is negligible beam loading, the tuning requirements for the cavities are simply to compensate for temperature variations due to water supply and RF heating. If we assume bulk water temperature fluctuations are of the order of 1°C or less, and a thermal expansion coefficient of copper of approximately 17 ppm/°C, then the frequency variation would be about 3.4 kHz. Since the average power is modest, it should be easy to limit the temperature rise due to RF heating to 10°C or less. A worst-case cold start with the cavities around 0°C and a normal operating temperature of 40°C would produce a frequency detuning of about 136 kHz. Simple 2D calculations show that if the length of the cavity is varied from the nominal value the frequency sensitivity is about 236 kHz/mm, so a small range of motion would be adequate to achieve the required tuning range. A tuning scheme similar to that used for the superconducting cavities, where the cavity is mechanically stretched or compressed within elastic limits, could easily achieve this range of motion. Alternatively a moving plunger tuner could be used to tune the cavity inductively but this would require an additional aperture in the cavity and would be harder to package within the confines of the cryostat.

It would also be possible to tune the cavities over a limited range by controlling the water temperature, but the water stability would have to be a fraction of a degree to keep the frequency stable to within the bandwidth of the cavity (3.3 kHz unloaded, 6.6 kHz critically coupled). Moreover, each cavity would then require an independent water circuit and controller, which would be inconvenient.

Depending on the elastic range of motion of the cavities, it may be desirable to have some kind of "fixed" tuning after assembly to account for manufacturing tolerances (analogous to the "dimpling" of linac cavities). This could be a specific part of the cavity which is designated to be deformed or the cavity as a whole could be designed such that it can be stretched or compressed beyond the elastic limit to achieve a permanent tuning. If detailed analysis shows that the cavity has a sufficiently large elastic tuning range, it may even be possible to relax the requirement of keeping the foils flat and allow some movement to take place. (Pre-bowing of the foils would ensure that this happens in a predictable manner.) This would allow thinner foils to be used with a concomitant reduction in scattering.

In the event that vibrations of the foils or other parts of the system should produce troublesome fluctuations in the RF fields, the deforming type tuner could be augmented with a fast piezo-electric actuator allowing feedback at audio frequencies. This has been demonstrated to reduce the effect of microphonics in superconducting cavities.

18.4.6 Vacuum Requirements

The operating vacuum in the high-gradient cavities should be in the 10nTorr range or better. Operating much above this range is likely to produce more frequent arcing and would require significantly longer time to condition the cavities initially and after any vent. The reliability of the RF window is also strongly influenced by the vacuum level. The frequency of window arcs and the lifetime of anti-multipactor coatings on the ceramic are both degraded by operating at pressures above about 100nTorr. These conditions will require strong pumping and good conductance to the RF cavities. Because of the presence of strong solenoid magnetic fields, ion pumps may not be used in close proximity to the cavity during operation, though they may be useful during initial conditioning with solenoids off. Cryopumps or titanium sublimation pumps may be useful close to the cavities with magnetic fields on. It would be advantageous to pump the cavities through the RF coupler if there proves to be sufficient conductance, since this will ensure the best possible vacuum at the RF input window. A large diameter coaxial feed with a short distance to the pump may have sufficient conductance by itself. If not it can be supplemented by an additional pumping port on the cavity body. A thorough bakeout to above 150 °C after assembly would be advantageous but may be incompatible with the superconducting components. In that case, the individual components will be baked separately before final assembly into the cryostat.

18.5 SCRF Specifications for Acceleration

Based on the high real estate gradient desired to minimize muon loss, superconducting cavities are selected to provide an active gradient of 15 – 17 MV/m, and a real estate gradient of 7.4 MV/m. At such high-gradients, the peak RF power demand for copper cavities that provide 7.5 GV 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 for 3 ms rise time.

As a result of experience at LEP, CEBAF, TTF, Cornell, KEK and CEA-Saclay, the science and technology of superconducting cavities and associated technologies are highly developed[18.H1]. In all, SRF systems totaling one km in active length have been installed in a variety of accelerators and routinely operated to provide a total of 5 GV. The largest installation is for LEP-II where 500 m of niobium coated copper cavities provide more than 3 GV of acceleration [18.H2]. The NuFactory calls for nearly 500 m to provide 7.4 GV.

Although sheet metal Nb cavites used for TESLA are capable of providing gradients of the order of 20 MV/m and higher[18.H3], we have chosen Nb/Cu technology developed at CERN[18.H4] for LEP-II for several reasons:

1) Because of the lower RF frequency (201.25 MHz), 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 for Nufact.

2) High thermal conductivity copper provides better stability against quenching of superconducting cavities over sheet Nb. This is especially beneficial at 201.25 MHz because of the high stored energy per cell (roughly one kJ per cell at design gradient).

3) The wall thickness of large size 201.25 MHz cavities may need to be greater than 6 mm for mechanical stability against atmospheric load and for reducing, Lorentz force detuning and microphonic from external vibrations.

4) A coated copper cavity allows the use of pipe cooling instead of the more usual bath cooling. Pipe cooling saves liquid helium inventory (estimated at 100,000 Liters for standard bath cooling of 600 cells). It also opens additional avenues for improving the mechanical stability for large scale cavities.

Recent results from CERN [18.H5] on 400 MHz Nb/Cu cavities (figure 18.H1) reached accelerating gradients of 15 MV/m at 2.5 K at a Q of 2 x 10^9. Because of the lower frequency for Nufact, we can expect the Q to be four times higher. We have chosen an operating temperature of 2.5 K and a Q value of $6x10^9$. LEP results at 4.5 K will imply a much lower Q < $2x10^9$ at the design gradient for Nufact, even when scaled for the lower frequency. And LEP cavities have never reached Nufactory design gradients at 4.5 K.

Modeling the Q vs. E (figure 18.H1) obtained for LHC 400 MHz cavities and incorporating the Q increase for 201.25 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. Figure 18.H2 shows the peak magnetic field expected for 17 MV/m in a 2-cell cavity with 300 mm beam aperature. It corresponds to Eacc = 13 MV/m for the LHC cavity geometry because of the relatively smaller beam pipe and optimized cavity Nufact cavity geometry discussed below.

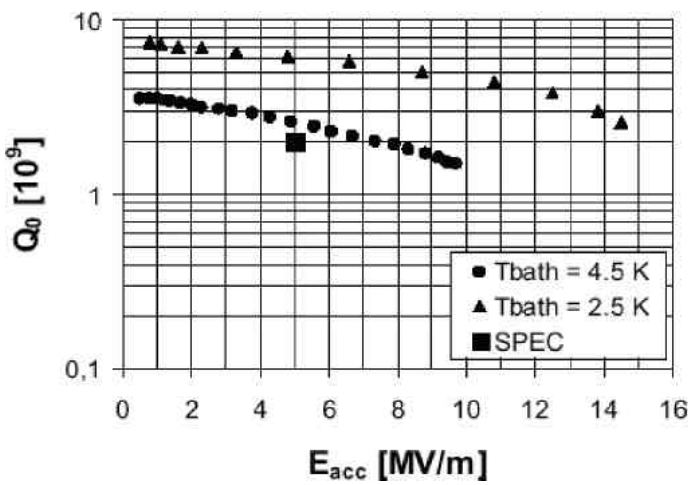

FIGURE 18.H1. Qo vs. gradient for Nb/Cu CERN 400 MHz, LHC cavity.

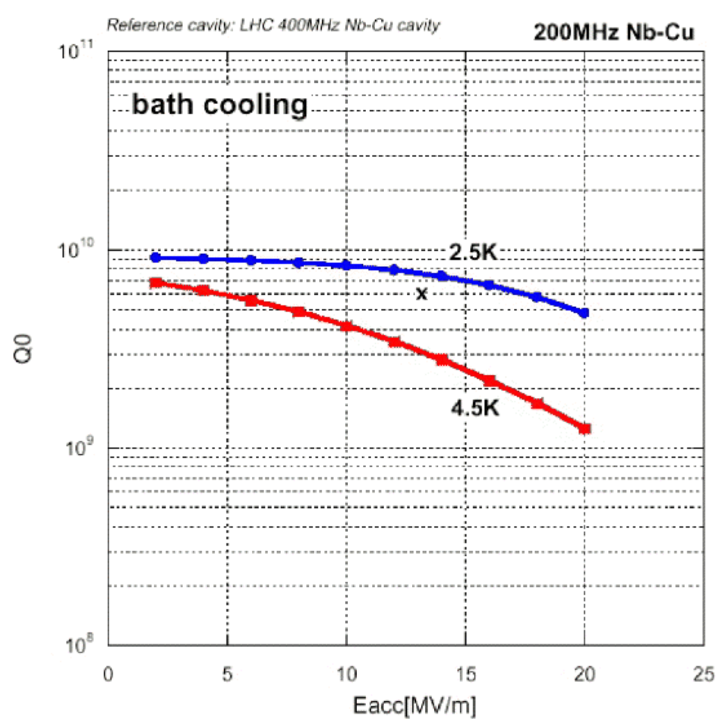

FIGURE 18.H2. Qo vs. gradient expected for 201.25 MHz cavity. X marks the operating peak surface magnetic field for a Nufact 2-cell, 300 mm aperture cavity.

Accelerator physics studies show that an aperture of 300 mm (diameter) is acceptable for the Neutrino Factory except for the first 1000 MeV of the preaccelerator linac, where an aperture of 460 mm has been chosen. Because of the higher peak fields arising from the larger aperture the gradient for the first Section of the pre-accelerator has been reduced to 15 MV/m. The corresponding surface magnetic field is still 12% less than the peak magnetic field for the LHC cavity at 15 MV/m.

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 the 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[18.H1]:

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

Once the fill time and detuning tolerance are selected, the loaded Q of the cavity can be found to minimize the peak power required. A conservative estimate for detuning tolerance in these large 201.25 MHz structures is 40 Hz. Cavities at TTF and CEBAF show microphonic excitation of < 10 Hz[18.H6]. For a fill time of 3 ms, the optimum Q_L is 1×10^6 (bandwidth = 200 Hz) and the required peak power is about 500 kW per cell. Coaxial couplers developed for the KEK-B factory[18.H7] have delivered 380 kW CW to one amp beams. In pulsed mode, higher power performance can be expected from input couplers. For a wall thickness of 8 mm, the calculated Lorentz force detuning at 17 MV/m is 128 Hz. Most of this can be taken care of with feedforward techniques developed at TTF for TESLA [18.H8].

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 1.5×10^6. Adopting a 4 ms fill time would decrease input power to 350 kW per cell at best $Q_L = 1.5 \times 10^6$

18.5.1 SCRF Structures at 201.25 MHz

To improve the real-estate gradient it is important to have a large filling factor of cavities in the cryomodule. This pushes structures 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 stiffening schemes. Trading-off between these factors, 2-cell units at are chosen. In the first 1000 MeV of the preaccelerator linac, where apertures of 460 mm are needed, gradients are lowered to 15 MV/m to keep the peak surface fields comparable. The input coupler power is kept at the 500 kW level by providing one coupler at each end.

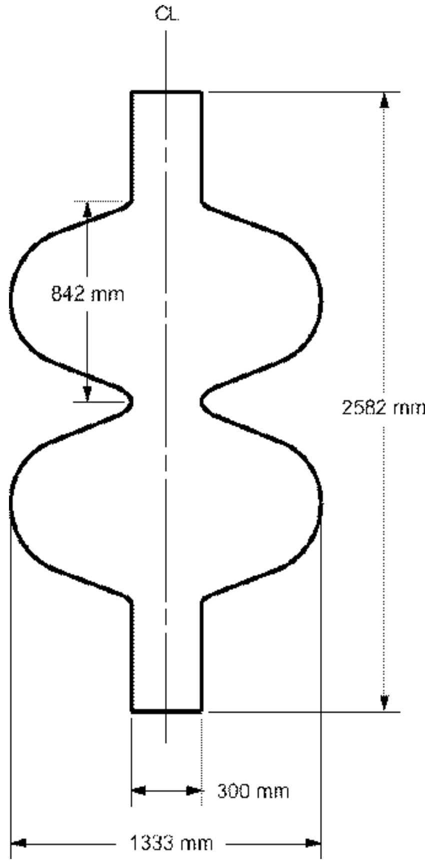

Figure 18.H3. Two-cell geometry, large aperture

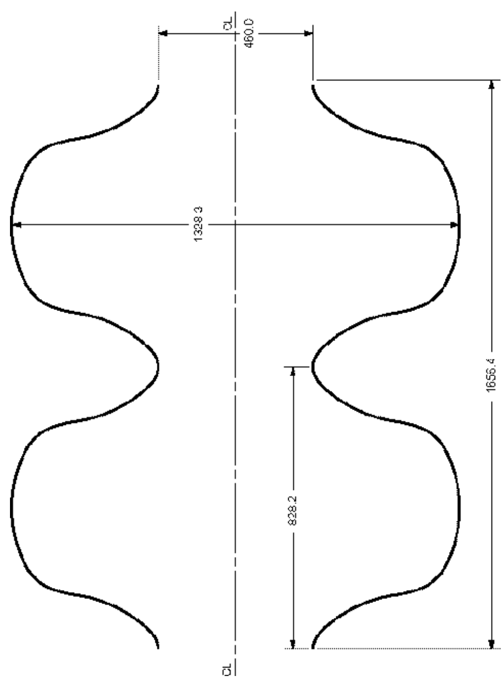

Figure 18.H4. 2-cell geometry, small aperture

The performance of a superconducting cavity depends on the peak surface fields. Minimizing E_{pk} is important to avoid field emission that lowers the cavity Q and increases heat load. 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 (figure 18.H1). In the 400 MHz LHC cavity which reached Eacc = 15 MV/m, 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 201.25 MHz, 2-cell cavities, it is possible to improve the Neutrino Factory cavity geometry (see figure 18.H3) to reduce the peak fields to 14% below LHC-cavity values. Relative to CERN cavity performance there is adequate safety margin for both improved structure choices. Table18H1 lists the properties of the 2-cell-300 mm aperture and Table18H2 for the 2-cell- large aperture units. Figure 18.H3 shows the 2-cell geometry with 300 mm aperture and figure 18.H4 shows the 2-cell geometry with 460 mm aperture. Figure 18.H5 shows the deformation (exaggerated) due to Lorentz Force detuning for the 2-cell, 300 mm diameter cavity.

Table18H1 2-cell, 300 mm diameter cavity parameters

RF freq	MHz	201.25
No. of cells per cavity		2
active cavity length	m	1.5
number of cavities		256
linac		76
RLA		180
aperture diameter	mm	300
Eacc	MV/m	17
Energy gain per cavity	MV	25.5
stored energy per cavity	Joule	2008
R/Q	Ohm/cavity	258
Ep/Eacc		1.43
Hp/Eacc	Oersted/MV/m	38
Epk at 17 MV/m	MV/m	24.3
Hpk at 17 MV/m	Oe	646
Q0		$6x10^9$
Bandwidth	Hz	200
Input power per cavity	kW	1016
RF on-time	ms	3
RF duty factor	%	4.5
Dynamic heat load per cavity	watt	18.9
Operating temperature	K	2.5
QL		10^6
Microphonics Detuning tolerable	Hz	40
Wall thickness	mm	8
Lorentz force detuning at 15 MV/m	Hz	128

Table18H2. 2-cell. 460 mm aperture cavity Parameters

RF freq	MHz	201.25
No. of cells per cavity		2
active cavity length	m	1.5
number of cavities		43
aperture dimater	mm	460
Eacc	MV/m	15
Energy gain per cavity	MV	22.5
stored energy per cavity	Joule	1932
R/Q	Ohm/cavity	208
Ep/Eacc		1.54
Hp/Eacc	Oersted/MV/m	44
Epk at 15 MV/m	MV/m	23.1
Hpk at 15 MV/m	Oe	660
Q0		$6x10^9$
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

Input Power Coupler

The antenna type coaxial design will be chosen based on the successful experiences of CERN (LEP-II), DESY (HERA and TTF) and especially the success of the KEK input coupler for KEK-B[18.H7]. Figure 18.H6 - shows the dimensions of the KEK, 508 MHz coupler, which will be scaled proportionately to 201.25 MHz. The lengths of the various Sections will be adjusted to fit the final cavity and cryostat designs adopted. The waveguide-to-coaxial transition is of the door-knob variety. As in all high-power applications, the main window will be at room temperature and remote from the cavity. At KEK-B, it is a disk shaped, water cooled, 95% pure alumina ceramic with a central hole for the inner conductor. A teflon coaxial centering disk between the window and doorknob serves to limit the flow of air to the cavity in the unlikely event of a ceramic window break. The inner conductor is made of OFHC copper pipe and is water-cooled. The outer conductor is made of copper plated (30μm) stainless steel and has fins cooled by a 4.5 K stream from the refrigerator. This reduces both the dynamic and static coupler associated heat leaks.

Benefiting from simulation codes recently available for calculating and avoiding multipacting [18.H9], the dimensions of the inner and outer conductors will be chosen so that multipacting will not be a serious problem. The coaxial design also permits application of a DC bias voltage between the two conductors to curtail any possible multipacting that may develop near the window or other sensitive regions.

The coupler will be equipped with standard diagnostics for vacuum, gas species, temperature and light monitoring. Vacuum and light levels can be used to trip the RF in case of arcs.

The Q_{ext} value of the input coupler can be fixed after initial adjustment of the position of the inner conductor by the use of appropriate spacing washers during final assembly. From experience at KEK we expect that the Q_{ext} for the non-accelerating modes of the fundamental pass band will be of the same order as the Q_{ext} for the accelerating mode, i.e. a few x10^5.

The design of the input coupler will be finalized during the prototyping stage and will be based on the KEK-B coupler.

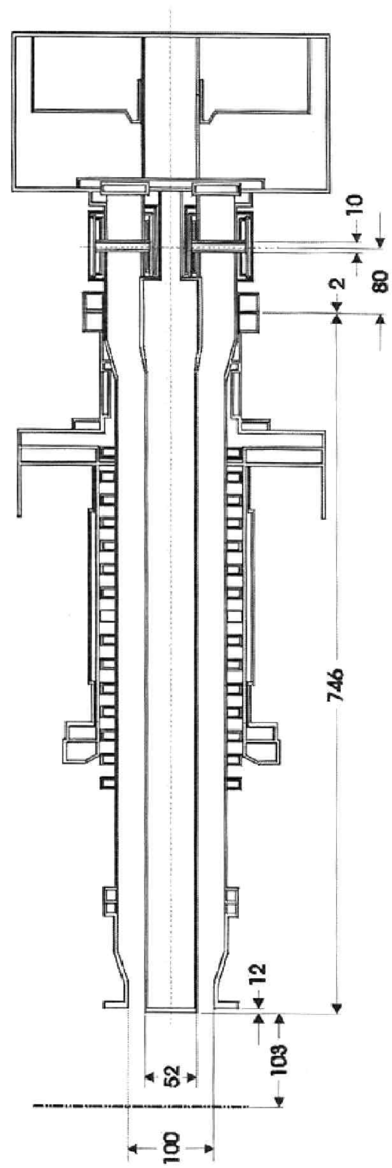

Figure 18.H6. KEK 508 MHz coupler

Higher Order Mode (HOM) Couplers

The function of the HOM couplers is to damp the higher order modes to Q_{ext} values of 10^4 - 10^5 to prevent resonant build up of beam induced fields that may make the beam unstable or increase the HOM power. The HOM couplers extract beam induced HOM power from the cavity and deposit it at room temperature loads. Because of large muon bunch length we do not expect HOM's to be a serious issue.

Two couplers are needed with a relative azimuthal angle of about 90 degrees to ensure damping of both polarizations of dipole modes. One coupler is attached to each end of the cavity. The HOM couplers must reject the accelerating mode by means of a narrow band filter built into the coupler.

Detailed calculations will be carried out during the prototyping stage for the HOM spectra, possible trapped modes, and expected HOM power. Codes exist and procedures have been well established for electron applications.

A possible candidate is loop type coupler (figure 18.H7) because it is demountable, compact, has relaxed mechanical tolerances, and demonstrated performance in mode damping[18.H10]. The plane of the loop is orthogonal to the beam axis. The loop couples mainly to the magnetic field of dipole modes and mainly to the electric field of longitudinal modes. The rejection filter is formed by the inductance of the loop and the capacity between the loop end and the outer conductor. A capacitive coupling links the loop to the external load via a type N connector. The loop is cooled by conduction through an upper stub. Final tuning of the filter can be carried out outside the clean room once the coupler is attached and the cavity sealed. Q_{ext} values are typically 10^3 to 10^5 for high impedance modes in a 9-cell TELSA cavity. These Q's will be even lower for 2-cell, Neutrino Factory cavities.

Power tests carried out under CW operating conditions showed good thermal behavior up to an accelerating field of 21 MV/m in TESLA cavities.

The design of the HOM couplers will be finalized during the prototyping stage and will be based on successful HOM coupler designs for the TESLA test facility (TTF).

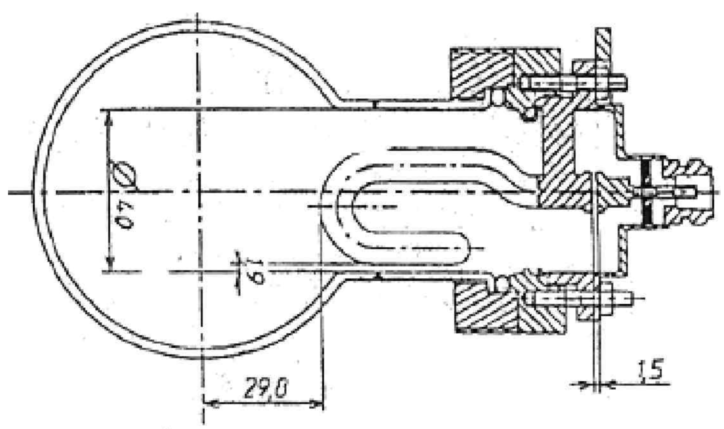

Figure 18.H7. TESLA-type HOM coupler

Tuner

The function of the tuner is to match the cavity resonance frequency with the desired accelerator operating frequency. If the cavity is not being used for acceleration, the tuner must detune the cavity frequency a few bandwidths away from resonance, so that the beam will not excite the fundamental mode. During accelerator operation the tuner must correct for slow changes in the cavity frequency due to changes in the liquid helium bath pressure, or in the lengths of the cavity and He vessel support system. Tuning is achieved by varying the total length of the cavity within the elastic limit so that the field flatness is preserved. The tuning coefficient of 2-cell cavity is of the order of 50 Hz/μm. Plunger tuners are not advisable in superconducting cavities because of moving parts and the danger of dust introduction.

If a mechanical tuner is adopted, the length of the cavity will be controlled by an electromechanical system acting differentially with respect to the cavity body. If each cavity is enclosed in its own helium vessel the latter must have some flexibility built in.

A mechanical tuning system is generally composed of a stepping motor, gear box, a screw and nut assembly, and a lever arm with a flex mechanism attached. A fast piezo electric element can be added for fine tuning, compensating Lorentz force detuning, figure 18.H8, as well as microphonics. Figure 18.H9 shows the lowest frequency vibrational mode of the two-cell cavity that could be excited by vibrations. The stiffness will be increased to raise the frequencies of these modes.

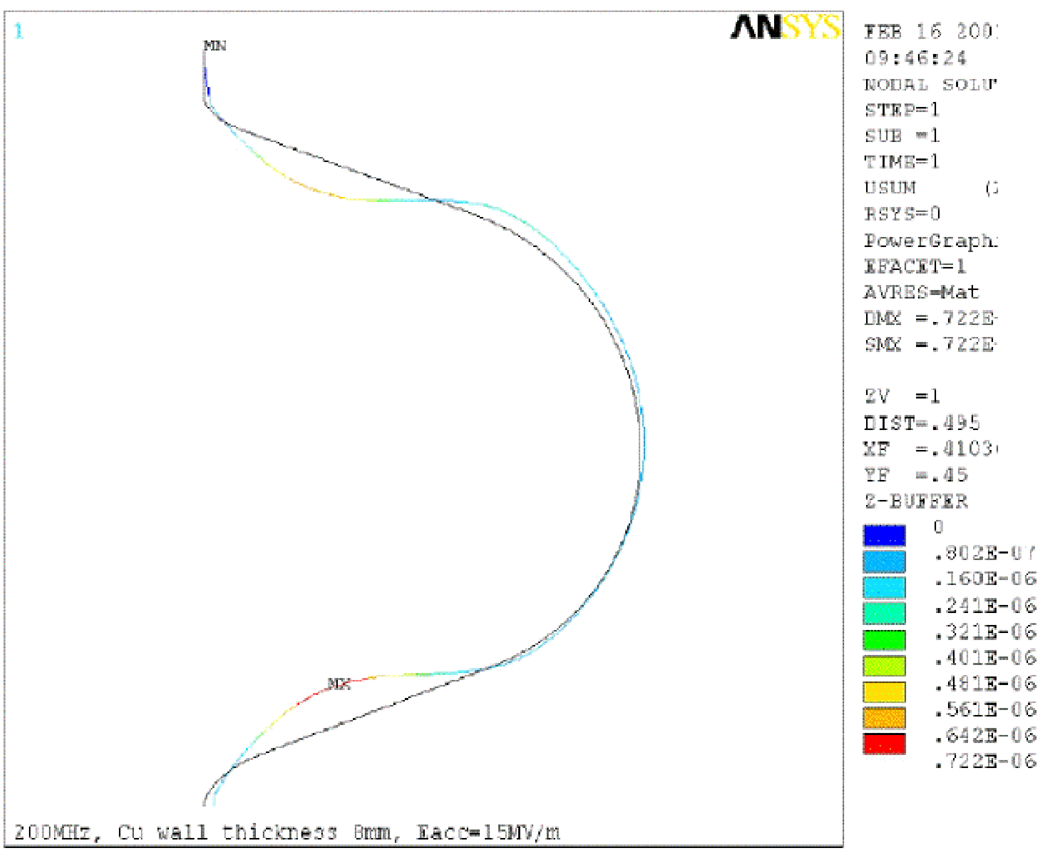

Figure 18.H8. Lorentz force detuning for 8 mm wall thickness cavity.

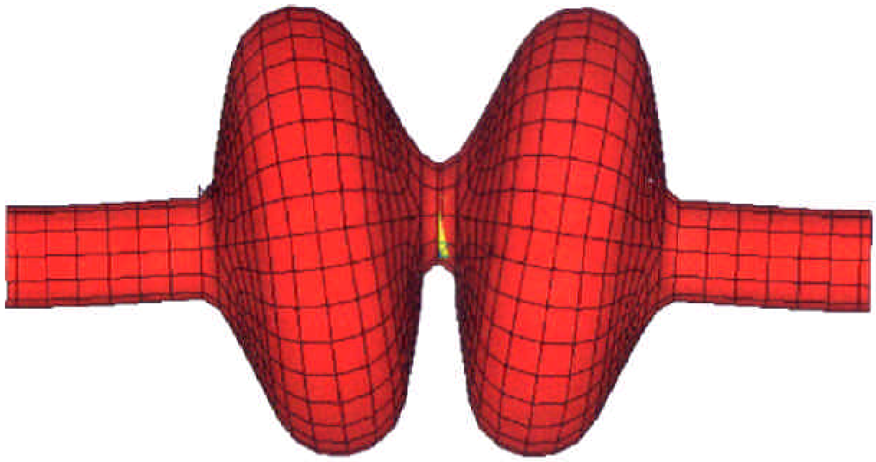

Figure 18.H9. Vibrational mode of 2-cell cavity

Alternatively a thermal tuner will be considered, modeled after the LEP system [18.H11]. This uses three Ni tubes as tuner bars located in the cryomodule insulation vacuum. The tuner rib cage can also help raise mechanical resonant frequency of cavity longitudinal modes. For slow tuning in one direction (constriction) the temperature of the tubes is lowered by flowing cold helium gas. For tuning in the opposite direction the temperature is raised by centrally located electric heaters. The typical tuning speed is 10 Hz/sec. Heat losses are minimized by counter flow cold He gas through the tuner tubes. For fast tuning, coils can be wound around the Ni tubes to produce a magnetic field that changes the length of the tubes by the magnetostrictive effect. Rapid (ms) tuning ranges of kHz are possible.

Tuners are an active part of the complete RF control system, which stabilizes the frequency, amplitude and phase variations induced by sources such as the RF drive, beam current variations, Lorentz force detuning, and microphonics . The design of the tuner will be finalized during the prototyping stage and will be based on several successful tuner designs in operation for CEBAF and TTF.

18.5.2 Cryogenics for SCRF

Figure 18.H10 shows a 3D cad model of the long 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. Mature cryomodule designs (see figure 18.H11), available at CERN for LEP-II and LHC will be adapted to the Neutrino Factory needs during the prototyping stage. From LEP 12.5-m long LEP cryododules, 4.5 K static heat leaks of 100 watt per cryomodule are expected. Thin beryllium windows will be placed on the beam line at each end of the cryomodule to protect the cavity vacuum and to keep the cavity surfaces clean during installation into the beam line. Tables 18H3, 18H4 and 18H5 give cryomodule parameters. Table 18H6 gives a summary for the total SCRF requirements.. *The hardware implementation of the refrigerator is described in section ?*

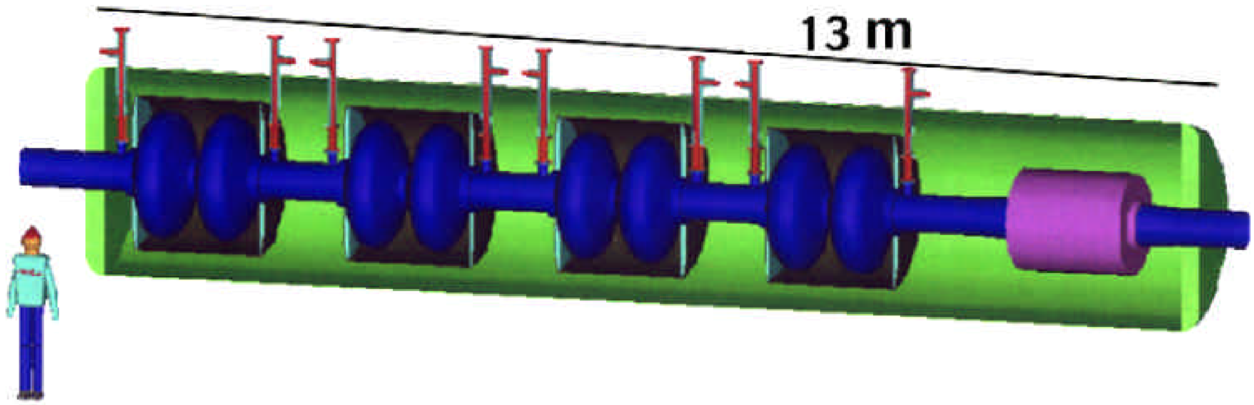

Figure 18.H10. Long cryomodule

Figure 18.H11. LEP cryomodule

Table18H3. Short Cryomodule Parameters

No. of cryomodules	11
No. of cavities in one cryomodule	One 2-cell
No. of input couplers	2
Overall length	5 m
Active length	1.5 m
Cavity dynamic heat load @2.5 K	18 W
Couper dynamic heat load @2.5 K	1 W
Coupler static heat load @ 2.5 K, 5- 8 K, 40- 80K	2 W, 4 W, 40 W
Cryomodule static heat load @ 2.5 K, 5 - 8 K, 40 - 80 K	6 W, 60 W, 600 W
Total 11 cryomodule heat load @ 2,5, 5-8 K, 40 - 80 K	300, 700, 7000 W

Table18H4. Intermediate Cryomodule Parameters

No. of cryomodules	16
No. of cavities in one cryomodule	Two 2-cell
No. of input couplers	4
Overall length	8 m
Active length	3 m
Cavity dynamic heat load @2.5 K	36 W
Couper dynamic heat load @2.5 K	2 W
Coupler static heat load @ 2.5 K, 5- 8 K, 40- 80K	4 W, 8 W, 80 W
Cryomodule static heat load @ 2.5 K, 5 - 8 K, 40 - 80 K	7 W, 70 W, 700 W
Total 16 cryomodule heat load @ 2,5, 5-8 K, 40 - 80 K	790, 1250, 12,500 W

Table18H5. Long Cryomodule Parameters

No. of cryomodules	64
No. of cavities in one cryomodule	Four 2-cells
No. of input couplers	8
Overall length	13 m
Active length	6 m
Cavity dynamic heat load@2.5 K	4x 19 = 76 W
Couper dynamic heat load @2.5	8 x 0.5 = 4 W
Coupler static heat load @2.5, 5-8, 40 - 80 K	8, 16, 160 W
Cryomodule static heat load @ 2. 5K, 5- 8, 40 - 80 K	10, 100, 1000 W
Total 64- cryomodule heat load @ 2.5, 5- 8 , 40 - 80 K	6300, 7400, 74,000 W

Table18H6. Overall Parameters for NuFactory SCRF

No. of cryomodules	91
No. of 2-cell cavities	299
No. of input couplers	598
Overall length	1015 m
Active length	449 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, 141 kW
Assuming efficiency mulitipliers of 600, 225 , 20	
AC power for refrigeration	12.6 MW
Total peak RF power with 20% margin for control/losses	362 MW
Average RF power	16.3 MW
AC Power for RF (efficiency multiplier = 2)	35.6 MW
Total AC Power	48 MW

18.5.3 RF Power Source for SCRF

The superconducting linac and recirculating linear accelerator (RLA) designs employ a total of 299 cavities. The linac contains 120 cavities running at a gradient of 17 MV/m. The early part of the linac operates at a gradient of 15 MV/m. The remaining cavities all run at a gradient of 17 MV/m. The RF pulse length is 3 ms and the average repetition rate is 15 Hz, although the recovery time between pulses is only 20ms. Each cavity is driven by two 500 kW couplers. With a 20% RF power overhead, this works out to 1.2 MW per cavity and a total RF requirement of 360 MW.

An examination of the average power requirement demonstrates that a very high efficiency source is required. The best candidate for the required source again is a multi-beam klystron (MBK). This could be the same basic design as that used for the NCRF but with increased thermal capacity to handle the increased average power. However Thompson has developed a 7 beam MBK with an efficiency near 70%, see Section 18.3.1 and reference 18.1A. Scaling this design to 201.25 MHz would produce a 5 MW, 19 beam MBK with each beam having a perveance of 5×10^{-5}. The tube with gun and collector would be about 5.7 m in length and could be manufactured by industry after some initial R&D. A 37 beam MBK has also been developed by the Russians [18.3].

Each tube will drive four cavities through 8-way power splitters. The specifications for the modulator, an IGBT-type like the NCRF, are 50 kV at 142 A and average power of 320 kW. To save costs the modulator will be designed to operate two 5 MW tubes requiring twice the current and average power rating. A total 74 tubes and 37 modulators are required to supply the RF power requirements.

The multi-beam klystron may be designed with a vapor-cooled collector to save on the cooling water requirement. Such a system is at least 10 times more efficient than conventional water cooling. With vapor cooling each tube will require 120 gpm of near room temperature cooling water with total installed capacity of 8,880 gpm. Assuming an efficiency of 95% each modulator station will require 694 kW of installed AC power for a total of 25 MW.

18.6 Conclusions

The normal conducting and superconducting systems have continued to evolve since Study-I. Both cavity designs have been studied in some detail and feasible solutions have been developed for the required cooling channel and acceleration parameters. Ongoing R&D programs are addressing the practical aspects of cavity fabrication and conditioning. No fundamental "show-stopping" problems have arisen. The cooling channel layout, though densely packed has shown the feasibility of assembling all of the vital components. There is room for further optimization of the cooling channel, notably by adjusting the total cell length, to reduce the RF power requirements and minimize the superconducting magnet costs. The superconducting RF accelerating section has been developed using design choices that are consistent with the state of the art at various laboratories around the world.

An ongoing R&D program is in place to demonstrate the practical implementation of these NCRF and SCRF technologies at 201.25 MHz.

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Appendix: 18.A1. RF options

NCRF R&D

The normal conducting RF structures for the neutrino factory bunching and cooling sections are challenging because of the high gradients required and the large transverse dimensions of the incoming muon beam. Conventional open-cell structures become inefficient with such large beam irises. This can be compensated up to a point by increased RF power but ultimately the cost becomes prohibitive. The solution we are pursuing is to close the beam iris with a conducting barrier of low-Z material to restore the shunt impedance. Simulations indicate that thin beryllium foils or arrays of thin walled tubes restore the shunt impedance with acceptable beam scattering. For a continuous foil the minimum thickness is determined by the power dissipation on the surface. In vacuum, at close to room temperature, the heat can only be removed heat by radial conduction through the foil to the water-cooled flange. This produces a temperature gradient in the foil, with the maximum in the center. The result is a tendency for the center material to expand and the foil to bow, detuning the cavity. This tendency can be eliminated, up to a point, by arranging for the foil to be pre-stressed in tension. This keeps the foil flat up to some temperature at which the thermal expansion exceeds the pre-stress.

Alternatively the foils could be pre-bowed (to predetermine the direction of motion), and the movement accommodated by tuning the cavity. The pre-stressed foil has been simulated in ANSYS and investigated experimentally in a series of tests on small foils at 800 MHz. These will continue as part of the R&D effort, including high power testing of a cavity with foils in the Lab G facility at Fermilab. Other structures under consideration include grids of thin-walled tubes and other fabricated structures, see figs A1 and A2. The advantage of closed tubes would be the ability to flow cooling gas through the structure, potentially allowing larger apertures or less material to be used. Simulations suggest that the grids provide adequate isolation between cavities with tolerable scattering of the muon beam. The tubes themselves cause local concentrations of the electric and magnetic fields near the surfaces but the kicks to particles from these components are estimated to be small compared to other transverse deflections. R&D is needed to develop these structures and test prototypes under realistic conditions. Manufacturing of pre-stressed foils large enough for the 201.25 MHz cavities needs to be investigated further. Fabrication technology for the arrays of thin-walled tubes also needs to be explored. Cost-effective manufacturing methods need to be developed for the 201.25 MHz cavities themselves. We are contemplating processes such as spinning or cold forming for the large cavity shells and electron beam or laser welding for the joining processes. Suitable windows, tuners and ancillary equipment must be developed for these high powers and gradients.

Given the high RF power requirements and the inapplicability of superconducting RF due to the high magnetic field, it is tempting to consider running even the copper cavities at lower temperature to improve the conductivity and reduce the wall losses. Anecdotal evidence suggests that the losses may improve by a factor of two or more at liquid nitrogen temperature, although hard data for actual operating structures has not been forthcoming so far. This would reduce the peak RF power requirements at the expense of increased refrigeration capacity. The cost trade-off between these two expensive systems will be investigated further. We have been at pains to maintain the possibility of low-temperature operation in the design up to this point and none of the proposed hardware configurations preclude this option.

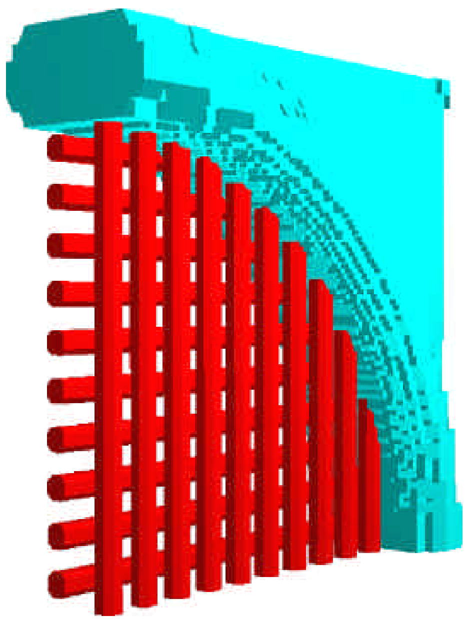

Figure18A1. Grid of thin-walled tubes

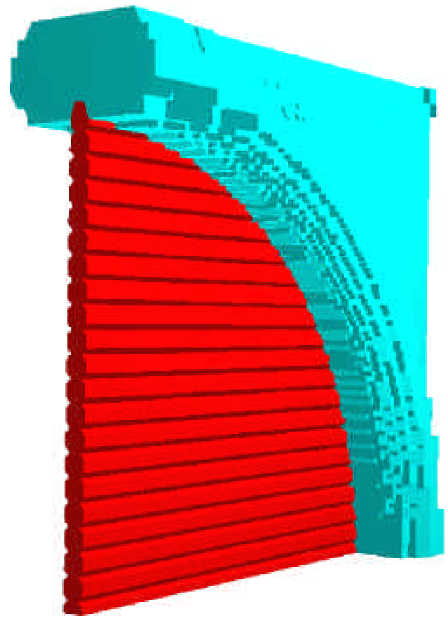

Figure18A2. Continuous array of tubes

Large scale integration of the RF structures into the lattice will also be the subject of ongoing R&D. The close proximity of the RF to superconducting solenoids, the liquid hydrogen absorbers, instrumentation etc. makes for some technical challenges and results in many tradeoffs. For example the diameter and therefore cost of the largest solenoid coil could be reduced by reshaping the center RF cavities but at the penalty of reduced shunt impedance. The shunt impedance is also strongly dependent on the amount of longitudinal space available. Figure18A3 shows how the shunt impedance per cavity and per m varies with length. We will continue to explore the cost minima of these tradeoffs.

The cost of RF power at this high level has prompted us to adopt a multi-beam klystron (MBK), as our baseline power source for these studies. MBK's have been developed at other frequencies for applications such as the TESLA test program and have been successful at meeting expected power outputs and efficiencies see ref [18.1A], figures 18A5, 18A6, 18A7, 18A8. Preliminary contacts with tube manufacturers suggest that development of a 201.25 MHz tube would be technically feasible and economically viable given the scale of the neutrino factory. This type of source will be investigated further as part of the ongoing R&D plans. Other potential sources might include improved tetrodes or "diacrodes" and other beam-based devices such as inductive output tubes (IOT's), hollow beam tubes ("hobetrons"), etc. Figure18A9 shows a prototype high average power IOT [A1]. Table A1 compares this to an equivalent conventional klystron. We will continue to study these alternatives and watch developments in the field.

The cost and performance of power supplies and modulators has improved in recent years due to developments in solid-state switching devices (such as IGBT's and SCR's), and thanks to the intensive R&D activities for linear accelerators. We will continue to refine our proposed design and take advantage of any further advances in this field.

The objectives of the R&D plan are as follows:

- Perform high power tests of the open- and closed-cell cavities in Lab G. at Fermilab.
- Demonstrate the required gradient can be achieved in the high magnetic field.
- Investigate the conditioning and performance of the cavity containing beryllium foils, with varying levels of magnetic fields
- Investigate the effectiveness and necessity of anit-multipactor coatings such as TiN.
- Study the effectiveness of foils, grids and other assemblies suitable for the 201.25 MHz cavity.
- Investigate the manufacturing methods for the 201.25 MHz cavity itself, and for foils or other structures suitable for the large diameter iris. Prepare a conceptual design for a high-power 201.25 MHz test cavity and, eventually, build and evaluate such a cavity.
- Continue to work on the integration and optimization of the RF within the cooling channel layout.
- Develop high-power RF windows, couplers and ancillary equipment for the cavities.
- Continue to evaluate high-power RF sources and modulators, working with potential vendors to identify critical R&D items.

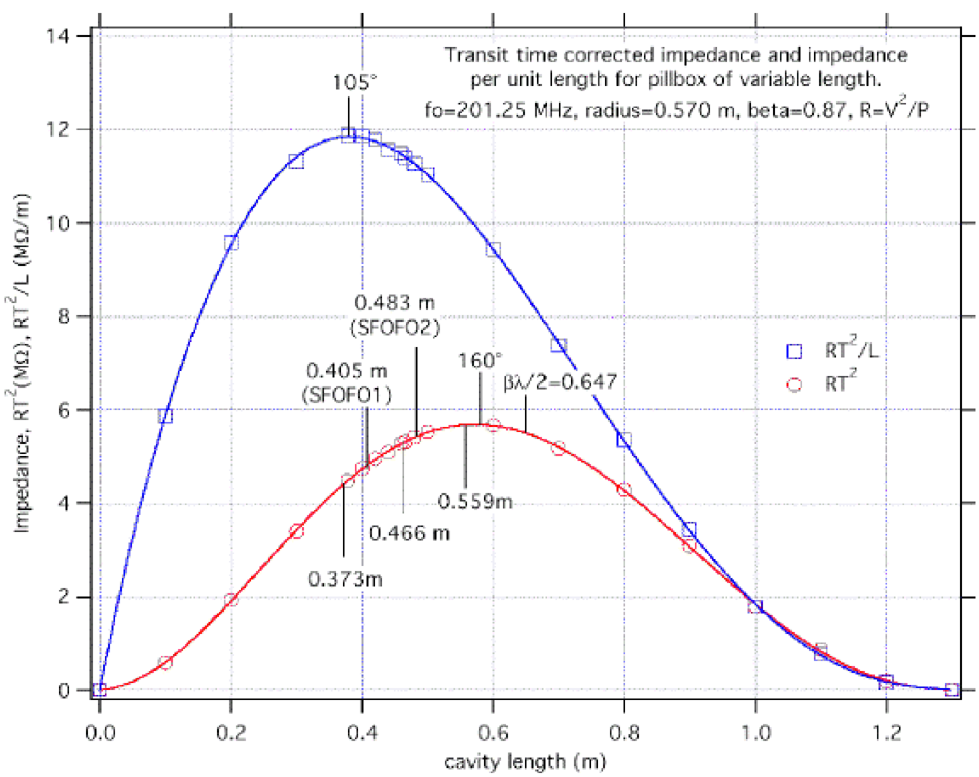

Figure18A3. Cavity impedance verses length for ideal pillbox, beta=0.87

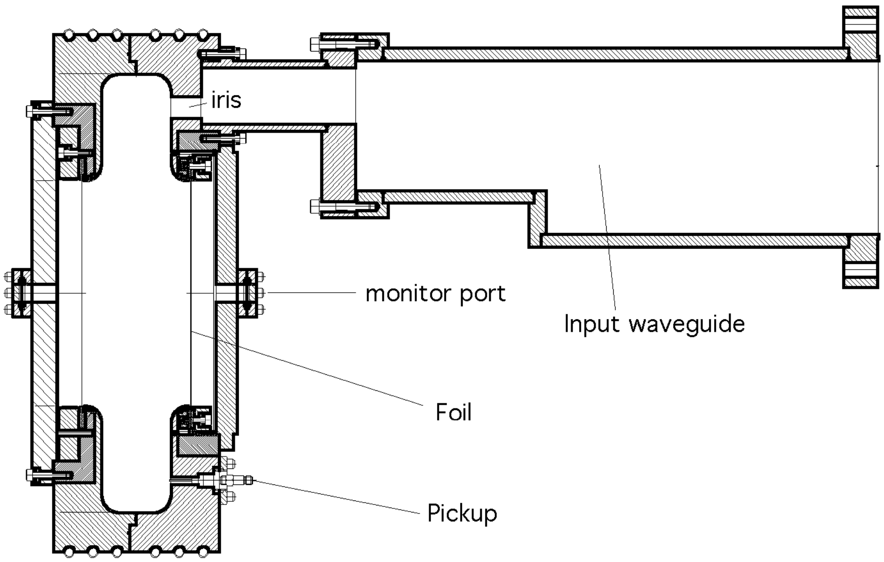

Figure18A4. 805 MHz high power test cavity

Figure18A4A. Lab G at Fermilab with test solenoid installed

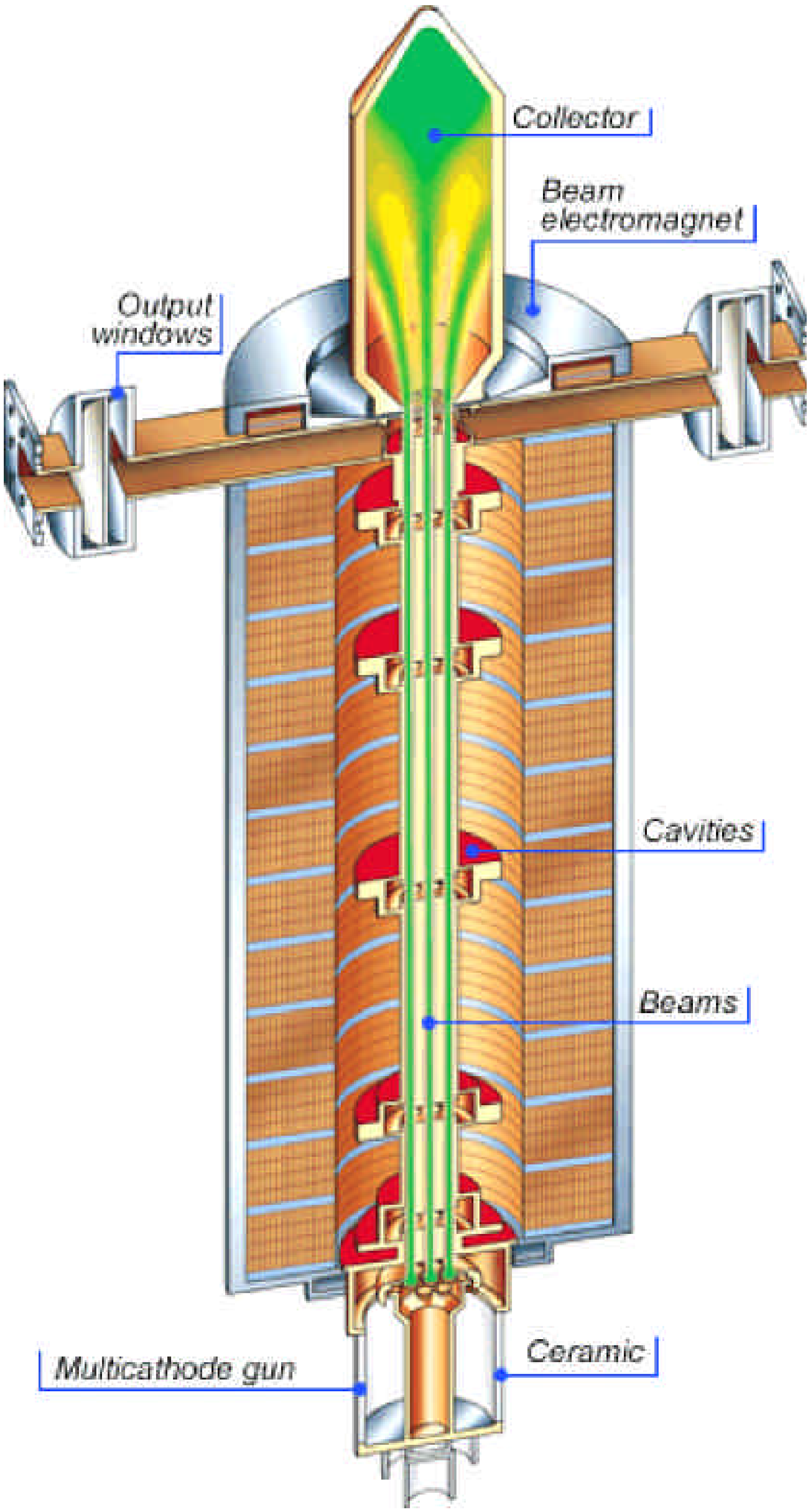

Figure18A5. Schematic of multi-beam klystron
(http://www.tte.thomson-csf.com)

Figure18A6. Cathode of Thompson multi-beam klystron
(http://www.tte.thomson-csf.com)

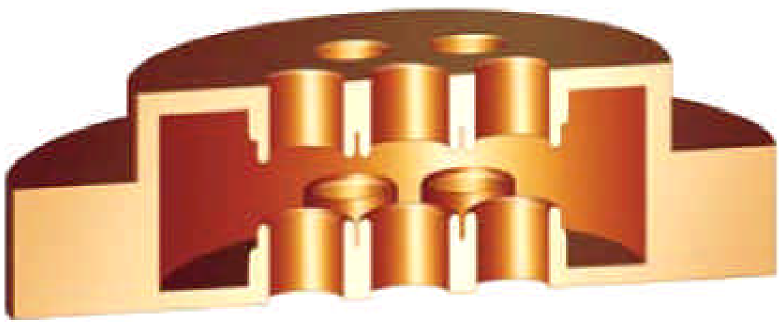

Figure18A7. Cavity of muti-beam klystron
(http://www.tte.thomson-csf.com)

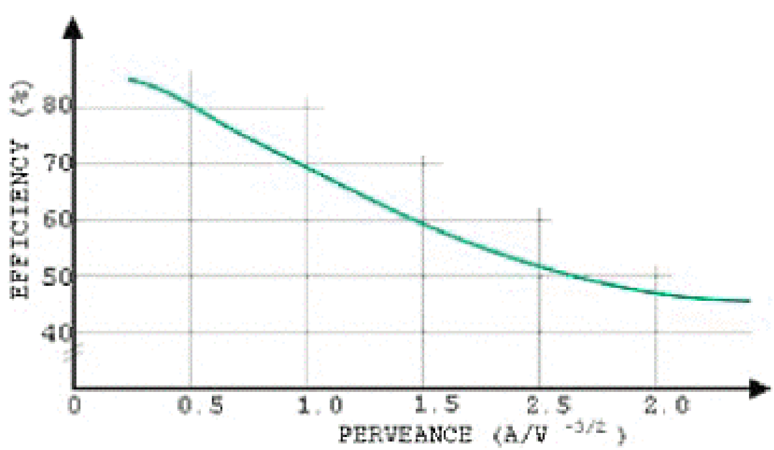

Figure18A8. Klystron efficiency vs. beam perveance.
(http://www.tte.thomson-csf.com)

Figure18A9. 1 MW CW HOM IOT

Table A1:Comparison between HOM-IOT (expected results) and klystron, both operated at 1MW CW / 700 MHz

Device	HOM-IOT	Klystron
Effective efficiency	73 %	60 %
Relative consumption	82 %	100 %
Assembly volume (approx.)	30 cbf	200 cbf
Assembly weight (approx.)	1,000 lbs	5,000 lbs
DC beam voltage	45 kV	90 kV
Gain	25 dB	46 dB

[A1] H.P. Bohlen "Advanced high-power microwave vacuum electron device development", Proc. 1999 Particle Accelerator Conference, pp.445-449

SCRF R&D

The history of SRF development for LEP, CEBAF, CESR, KEK-B and TTF (TESLA) shows that it takes many years to design, prototype and test structures in order to be ready for production. The lowest frequency at which SRF cavities have been made for accelerating velocity of light particles is 350 MHz for LEP-II. Therefore R&D and prototyping for a Neutrino Factory at 201.25 MHz should be started at least five years in advance.

At present SRF R&D is in progress to address the following issues
- Achieve 17 MV/m at Q of 6 x10^9 in a single cell 201.25 MHz cavity
- Stiffen the 2-cell cavity designs to reduce Lorentz force detuning and microphonics sensitivity
- Explore pipe cooling to reduce liquid He inventory and stiffen multi-cell structures
- Reduce structure cost

A collaboration has been set up with CERN to produce a one-cell Nb/Cu cavity at 201.25 MHz. CERN will provide the copper cavity, coat it with 1 - 2 micron thick niobium film by their standard DC magnetron sputtering technique, and send it to Cornell for testing after high pressure rinsing and evacuation. To test the cavity, Cornell is upgrading its test facilities. Figure 18.H12 shows a 3D cad model of the CERN cavity inside the test dewar. A test pit 2.5 m diameter by 5 meter deep is under excavation (Figure 18.H13) to accommodate the test dewar, which has been ordered. A 201.25 MHz low power (2 kW) RF test system is under construction. The clean room and high pressure rinsing system are being upgraded to accommodate the large cavity.

ANSYS calculations have started on the 2-cell cavities to determine the mechanical resonant modes and frequencies. The resonant frequencies are low (See figure 18.H9). Exploration has started on stiffening schemes with and without pipe cooling. Figure 18.H14 compares calculated Q vs E curves for pipe cooling and bath cooling operations.

At 201.25 MHz, structure costs will be substantial. Multicell cavities are usually fabricated in parts that have to be machined, cleaned and electron beam welded. This is an expensive, labor intensive process. We are collaborating with INFN in Italy to spin monolithic copper cells out of a single tube. INFN has experience at 1300 MHz. As a first step they will spin a single cell 500 MHz cavity. In a future stage, the procedure will be extended to 201.25 MHz and multicell cavities.

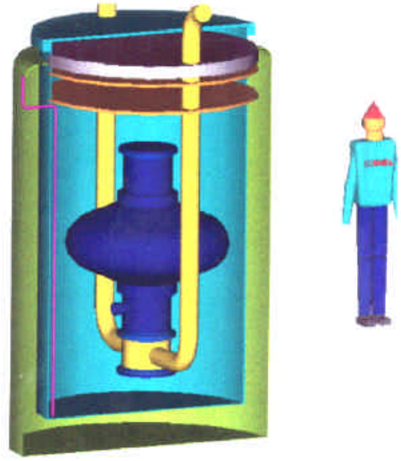

Figure 18.H12. Vertical dewar test

Figure 18.H13 200 MHz Test pit (2.5 m diameter and 5 m deep) under construction at Cornell. The other pits are for testing existing cavities.

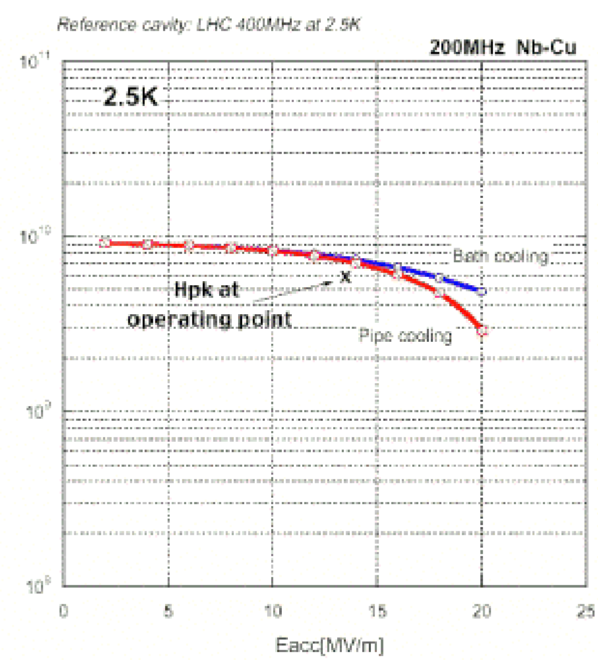

Figure 18.H14. Comparison of pipe with bath cooling at 2.5 K for a 200 MHz single cell cavity. The He carrying pipe diameter is 10 mm. Spacing between pipes is 70 mm.

R&D and Protoyping

The goal would be to design, construct and high-power test a cryomodule with the first single cell 201.25 MHz cavity, equipped with couplers and tuners. To prepare this test continuing R&D, design and prototyping are necessary in the following areas:

- high-power input coupler
- higher order mode coupler
- mechanical/thermal tuner
- piezo /magnetostrictive tuner
- cryomodule
- system integration
- high-power test

Appendix: 18.A2. Cost estimates

Table 18.A2 shows the cost estimate for a multibeam klystron system of 84, 12 MW klystrons for supplying the required RF to the cooling channel. The first item is the R&D costs to develop the 12 MW multibeam klystron

Table 18.A2.12 MW , 201.25 MHz Klystron Cost

R&D klystron amortized over 84 Tubes	$ 112k
Tube	525 k
Solenoid	200 k
Modulator shared with another klystron	200 k
Transmission Line components	100 k
Water Skid	60 k
Station Relay Racks, LLRF and Control	120 k
Utilities, Safety Interlocks	100 k
Installation	120 k
Total = $1537 k	
System Costs for RF requirements: 84 Klystrons = $129.1 M	

The cost of system of the three 402.5 MHz klystron amplifiers system is $3.525 M or $1.175 M each.

The cost of a long-pulse 19-beam MBK with shared modulator for the SCRF system would be about 25 % higher than that for the NCRF system, or about $1.92 M for each klystron and $142.0 M total, see table 18.A3.

Table 18.A3. 5 MW Long Pulse Klystron Costs

R&D klystron amortized over 74 Tubes	$ 123 k
Tube	595 k
Solenoid	200 k
Modulator shared with another klystron	400 k
Transmission Line components	100 k
Water Skid	160 k
Station Relay Racks, LLRF and Control	120 k
Utilities, Safety Interlocks	100 k
Installation	120 k
Total = $1918 k	
System Costs for Spreadsheet RF requirements: 74 Klystrons = $142.0 M	

350 MHz LEP cryomodules cost 1.5 M Swiss Francs = 1 M$ (?)each. They contain 4 x 4 cell units and the overall cryomodule length is 12.5 m. Scaling with √diameter the long cryomodule cost will be 1.32 M$. Scale the other cryomodule costs with length. Therefore the linac will cost 64x 1.32 + (8/12) x16 x1.32 + (5/12) x 11x 1.32 = 106 M$.

Refrigeration estimate *costs merged with Mike Green's system?*
2.5 K system will cost 1.6 M$ per kW
4.2 K system about 1.2 M$ per kW
70 K system 0.1 M$ per kW(?)

Refrigeration 1.6 x 11 + 1.2 x 14 + 141 x 0.1 = 48.5 M$

NCRF structure cost ~$250 k/m ± 100% (based on PEP-II costs)
Effective RF length ≈ 94m
NCRF structure cost ≈ $23.5 M
"bottoms up" NCRF structure cost estimate needed here (started).