Chapter 14

R&D Plans

14.1 Introduction

In this section we summarize the key R&D activities required to validate the design concepts described in this Neutrino Factory Feasibility Study. Topics will be covered in the order in which they appeared in the facility descriptions given earlier in this document. Items covered here fall into two categories: i) those required to validate or improve the components that drive the fabrication costs of the facility, and ii) those required to address the performance and/or feasibility of fabrication of particular components. In the first case, R&D will mainly involve hardware fabrication and testing without beam. In the second case, performance tests with beam may be required in addition to prototyping. For each hardware area, the main R&D topics will be listed in the context of the two categories above.

The R&D items listed here fall into the broader R&D effort of the Neutrino Factory and Muon Collider Collaboration (MC). A five-year R&D plan, currently under way, has been completed by the MC and is available [1]. We will not repeat that information here. What we cover below are topics that have arisen in the context of this—and, in some cases, the previous—Feasibility Study.

It is important to note that much of the hardware development effort envisioned here requires different people at different institutions. Thus, there is no fundamental reason that the program cannot proceed in parallel on several fronts. Indeed, it *must* proceed this way if we are to complete the R&D tasks in a reasonable time frame. Clearly, however, our progress requires funding commensurate with the program needs; this is the resource over which we have the least control.

14.2 Proton Driver

The upgrade of the AGS to reach higher intensity is relatively minor, as it has already operated at 70% of the design intensity specified here. The aspect where additional work is required is related to the need for short, 3 ns, bunches. The peak current required in this case, about 400 A, is seven times higher than what the AGS has achieved to date. Efforts to reduce the ring broadband impedance below 10 Ω will be worthwhile. For example, development of bellows shields capable of operating reliably in this beam current regime should be examined. The new B Factories (PEP- II and KEKB) are operating in similar regimes of peak and average beam current without experiencing reliability problems with bellows. In parallel with this effort, it will be important to explore other means to mitigate transverse instabilities in the AGS, *e.g.*, by introducing tune spread by means of octupoles.

For the new rf cavities, the 4L2 ferrite material must be characterized in the appropriate frequency regime. (The use of 4M2 ferrite, which has been used elsewhere, is an acceptable fallback solution if the ”standard” AGS cavity ferrite does not have the required properties.)

The trade-offs between using a thinner vacuum chamber wall and stronger sextupoles should be studied. In addition, it will be necessary to examine all of the power supply tracking algorithms to make sure they will work properly at a three-times-higher ramp rate. All of these kinds of issues have been solved previously in other accelerators, so there are no real unknowns here.

Experimentally, the AGS should continue with efforts to produce short bunches, to understand the present limitations and make sure that the ring impedance is well understood.

14.3 Target System

The main technical issue to deal with here concerns the survivability of a mercury jet in a 1 MW proton beam. Experiments are already under way at the AGS to study this, and an effort to predict the behavior of the mercury jet via simulations is proceeding in parallel. Ultimately, yield measurements to validate the MARS predictions should be carried out. These will include a (pulsed) 20-T solenoidal field.

Testing of a mercury jet in a high magnetic field is already in progress in Europe using a 13-T magnet at Grenoble. If necessary, tests could be repeated at the full 20-T field at the NHMFL.

The potential of failure fatigue for the jet nozzle must be studied. There is a pressure shock traveling back toward the nozzle after each proton beam pulse. A verification experiment for the shock effects, along with corresponding simulation work, should be carried out to permit a realistic means to mitigate it. Means to "pulse" the mercury jet should also be examined as a possible workaround.

Alternative designs, such as a "band" target (see Section B.2.1), should be examined. In addition to the mechanical issues of the band itself, compatibility with the solenoid configuration envisioned for the target must be assessed via a solid engineering concept.

Studies of the cost-benefit tradeoffs between capture efficiency and magnetic field should be made to optimize the target solenoid field. Present indications are that the penalty of a decrease from 20 T to 18 T is minor in terms of intensity, but the corresponding studies of magnet cost must be carried out. Studies of more optimal conductor for the hollow-conductor magnet are also needed. A conductor having wrapped ceramic insulation should have a more favorable power consumption than the MgO insulated conductor, while providing the same magnetic field. Studies of the alternative Bitter-magnet technology are also needed, focusing on issues of lifetime. The Bitter magnet is more efficient than a hollow-conductor magnet, but its resistance to corrosion in the high radiation environment must be studied.

There are a number of technical issues to consider in completing the design of the target containment area. These include:

- *Beam stop design.* A study of various materials should be undertaken to compare the advantages of low-Z and high-Z materials. Issues include secondary particle showers, residual activation, and decay heating.

- *Beam containment window design.* Adequate cooling designs must be developed, possibly including a combination of bulk coolant flow and edge cooling. If water cooling is required, adequate machine-protection interlocks must be developed. At present, beryllium looks like the most promising material. There is some commonality between the windows for the rf cavities and the beam containment that should be exploited. Since these are replaceable components, techniques for remote replacement must be developed.

- *Component cooling.* Activation of coolants, primarily light water, must be studied. In particular, ^{7}Be and tritium must be considered in the design of the cooling system.

- *Radiation damage.* The effect of radiation damage on the iron magnet "plug," the hollow-conductor copper coils, and the superconducting coil must be studied. Effects of intense radiation on mechanical properties (strength, elasticity) and buildup of corrosion products must be assessed. Materials tests in this context are already in the planning stages.

There are several R&D issues related to the facility configuration and design of the nuclear shielding for the solenoids. The first facility issue deals with the location of, and access to, the target and magnet support systems, namely, vacuum pumps, ducts, valves, cryogenic lines, electrical cables, and diagnostic equipment, to ensure that they are readily maintainable. A target hot cell is already configured with access and maintenance in mind; a more detailed iteration of the facility design would accomplish the same for the other support systems. The second facility issue is the extent to which remote handling capability and equipment are needed downstream from the target/capture region. An extrapolation of the shield analysis that was done for the floor shield over the tunnel, $-0.8 < z < 36$ m, indicates that similar requirements apply downstream. If verified, this requirement would have an impact on the overall facility design and cost.

There are several issues that deal with the nuclear shield design. These can be addressed with R&D activities that simultaneously address mechanical and thermal questions. It has been determined that the optimum shield for the high-field solenoids is 80% tungsten-carbide, 20% water, so the shield design is based on using tungsten-carbide balls. Scale model tests are needed to investigate how to distribute the balls in a homogeneous matrix, and to assess properties such as pressure drop and heat transfer coefficient. This shield is a costly component, and it is important for it to be efficiently designed.

14.4 Phase Rotation and Capture

In this Study, the induction linac (IL) design is closer to present day experience than was the case for Study-I, so the technical uncertainty is lower. Nonetheless, the gradients required are high, so a prototype induction cell, along with its magnetic pulse compression system, should be fabricated. Furthermore, there are several possibilities that might lead to a more cost-effective implementation. Development of less lossy (thinner) amorphous alloys should be undertaken, in conjunction with industry. Being able to use a mass-produced material with acceptable loss properties will result in lower capital costs initially, and lower power costs for the operating facility as well. Candidate materials need to be tested to validate the properties on which the design is based. In addition, the branched magnetics concept should be developed. If it is acceptable to drive a single core with two independent unipolar pulsers, it would eliminate one induction linac in our design. Radiation tests on the Mylar core insulation should be made, to be sure there is no degradation over the expected life of the facility.

The design of the IL core is strongly influenced by the internal superconducting solenoids, in the sense that the inner diameter of the core is set by the need to avoid the fringe field from the solenoid. Quantifying the effects on the core of the solenoid fringe field must be done. In addition, means to reduce the solenoid fringe field, thereby permitting the IL core inner diameter to be reduced, should be examined as part of a cost-benefit tradeoff study.

For the capture area, studies of the radiation heat load need to be refined, and extended through the IL region. The shielding requirements, especially for the upstream solenoids, have a strong impact on the inner diameter, and hence the cost, of these magnets, and an optimization is required. It would clearly be prudent to consider the future upgrade to 4 MW in this regard, as it would be undesirable to have to upgrade the magnets and shielding later.

The present mini-cooling absorber design is not optimized. The main requirements for mini-cooling are: *i*) energy loss equivalent to that of $2 \times 1.75\,\mathrm{m}$ of liquid hydrogen; and *ii*) low multiple scattering. Liquid-hydrogen mini-cooling, while straightforward, is technically, complicated—undesirably so. Simpler solutions involve non-cryogenic liquids or low-Z solids. It is clear that some R&D is called for to flesh out these options. Table 14.1 summarizes the lengths and corresponding radiation-length fractions for liquid hydrogen and various alternative materials.

While hydrogen minimizes scattering effects, it is likely that solid lithium or beryllium would also be acceptable. (Lithium hydride presents practical difficulties since it is neither commercially available nor readily manufactured in large, shaped pieces.) Simulations show that, compared with liquid hydrogen, solid lithium mini-cooling absorbers reduce the number of muons per proton by only about 5%, and beryllium causes only about a 10% reduction. These performance degradations are small, and they can probably be avoided by raising the solenoidal field somewhat to compensate for the increased scattering. (This would entail reoptimizing the front end.) Stronger focusing will increase the cost of the solenoids, but will reduce the size of the beam, allowing smaller absorber diameter. An overall optimization of the system, involving both simulations and engineering, should be done.

The roughly 5 kW of power dissipated in each mini-cooling absorber appears manageable. Cooling tubes affixed to the large ($\sim$1 m^2) perimeter surface can easily transfer such heat. Conductive heat transfer through the material, from the core to the periphery, requires only $\sim 10°\mathrm{C}$ temperature rise, small compared with the melting points of lithium and beryllium (186°C and 1350°C, respectively). Water, freon, or some other convenient refrigerant might be suitable, with a choice other than water preferred in the lithium case to reduce the risk of reaction should cracks develop in the cladding.

Table 14.1: Comparison of possible minicooling absorber materials.

Material	Length (cm)	Radiation length (%)
LH_2	175	20
LiH	38	35
Li	57	37
CH_4	49	45
Be	17	48
H_2O	25	70

On the practical side, the feasibility and cost of fabricating large cylinders of these materials must be evaluated. Preliminary contacts with manufacturers [2], [3] suggest that these are not fundamental problems. After design work, fabrication of a prototype disk, followed by bench (and perhaps beam) tests of its thermal performance, would be desirable.

14.5 Buncher and Cooling

The solenoid designs need to be cost optimized and the results put back into the simulations. In particular, the forces on the focusing coils in Lattice 2, with its 1.65-m cell length, are quite high. Lowering these forces will reduce costs. A somewhat longer cell length should help here.

Absorber development R&D is well under way. Techniques to produce very thin windows have already been developed. Pressure tests are planned to validate the safety aspects of the design. Because the power density is high, cooling of the absorber to avoid density fluctuations is challenging. A program of fluid dynamics modeling and bench tests is under way, to be followed by beam tests with 400 MeV protons at Fermilab.

Development of diagnostics is an ongoing process. Prototype devices of the types mentioned in Chapter 5 must be built and tested. Some of these tests will be carried out in conjunction with the rf cavity tests in Lab G at Fermilab. Possible backgrounds from the cavity can be assessed this way. Where possible, diagnostics devices will be tested in a beam, either the 400 MeV proton beam at Fermilab or possibly a muon beam at BNL or elsewhere.

Emittance exchange offers the potential of doubling the intensity of the facility. This is a difficult problem, presently the subject of simulation effort. This effort will be continued to see if an acceptable scheme can be developed. If a good solution is found, hardware development will follow, including new components, such as wedge absorbers, that are called for in the design concept.

In practice, the most critical technical component of the cooling channel is the rf system. The rf peak power requirement is very high for the cooling channel; means to reduce this will yield large benefits. The main issue is to optimize the cavity design for minimum power requirements at the required gradient, and then optimize the cooling lattice design with a suitable cell length. (To date, we have always done this process in inverted order, leading to a non-optimal rf cavity design.) The normal conducting rf structures for the Neutrino Factory buncher and cooling sections are challenging due to the high gradients required and the large transverse dimensions of the incoming muon beam. 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 aluminum tubes, restore the shunt impedance while maintaining 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 by radial conduction through the foil to a water-cooled flange. This produces a temperature gradient in the foil, with the maximum temperature 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 that 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. Such a pre-stressed foil has been simulated in ANSYS and investigated experimentally in a series of tests on small foils at 805 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. 14.1 and 14.2. An 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 their surfaces, but the kicks to the beam from this source are estimated to be small compared with other transverse deflections. R&D is needed to develop all of these candidate 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 must 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 the high-power and high-gradient regime we require.

Given the high rf power requirements, and the inapplicability of superconducting rf due to the high magnetic field, it is interesting to consider running the conventional copper cavities at lower temperature to improve their conductivity and thus reduce the wall losses. Anecdotal evidence suggests that wall losses may decrease by a factor of two at liquid-nitrogen temperature, although hard data for actual operating structures has not been forthcoming thus far. This would reduce the peak rf power requirements, at the expense of increased refrigeration capacity. The cost tradeoff between these two expensive systems will be evaluated. Up to this point, we have taken care to maintain the possibility of low-temperature operation in the design; none of the proposed hardware configurations preclude this option.

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 cavities to superconducting solenoids, the liquid-hydrogen absorbers, and the instrumentation makes for some technical challenges and results in many tradeoffs. For example, the diameter—and therefore the 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. Figure 14.3 shows how the shunt impedance per cavity, and per meter, 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. MBKs 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 [4], Figs. 14.4, 14.5, 14.6, 14.7. Preliminary contacts with tube manufacturers suggest that development of a 201.25 MHz MBK 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 (IOTs) or hollow beam tubes (*hobetrons*). Figure 14.8 shows a prototype high average power IOT [5] . Table 14.2 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

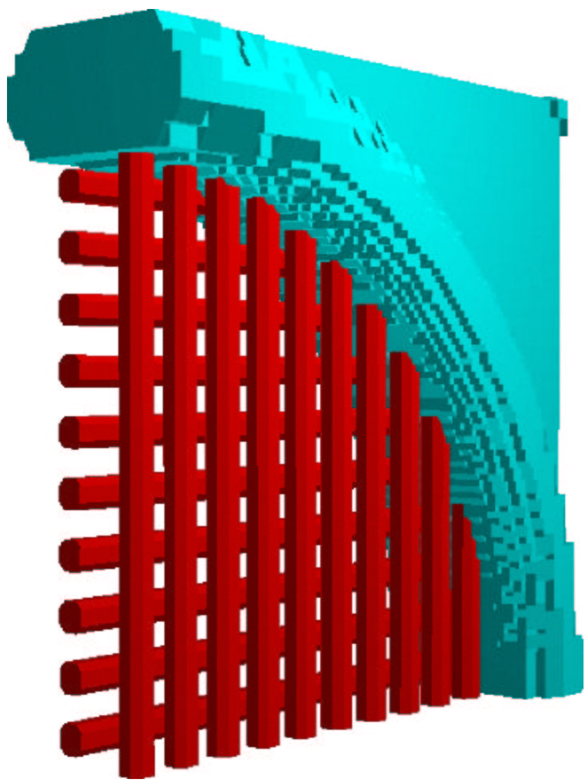

Figure 14.1: Grid of thin-walled tubes.

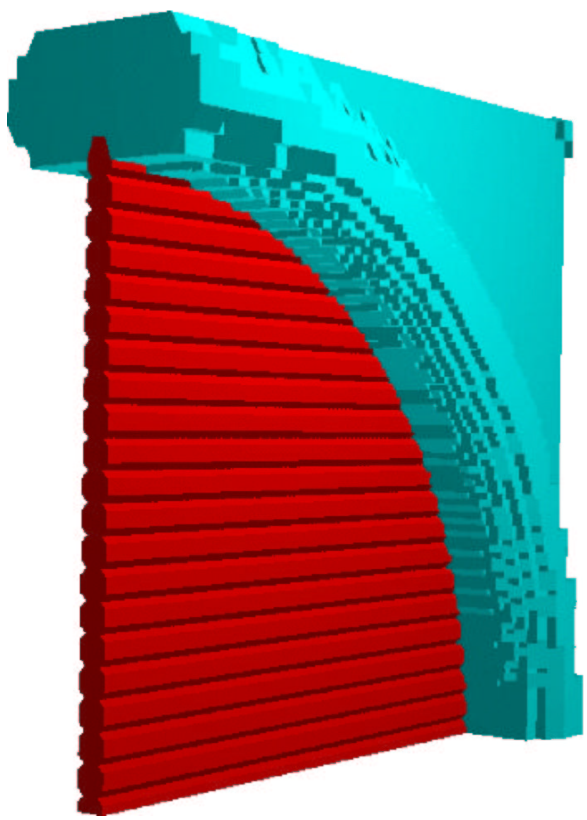

Figure 14.2: Continuous array of tubes.

modulators have improved in recent years due to developments in solid-state switching devices (such as IGBTs and SCRs), and thanks to the intensive R&D activities for linear accelerators. We will continue to refine our proposed design to take advantage of any further advances in this field.

The objectives of the R&D plan for the Buncher and Cooling Channel rf system are as follows:

- Perform high power tests of the open- and closed-cell cavities in Lab G at Fermilab
- Demonstrate that the required gradient can be achieved in the high magnetic field
- Investigate the conditioning and performance of a cavity containing beryllium foils, with varying levels of magnetic fields
- Investigate the necessity and effectiveness of anti-multipactor coatings, such as TiN
- Study the effectiveness of foils, grids, and other assemblies suitable for the 201.25 MHz cavity
- Investigate 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 then 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

14.6 Acceleration System

The most challenging aspect of the acceleration system is the 201-MHz superconducting rf (SCRF) cavities. The history of SCRF development for LEP, CEBAF, CESR, KEKB 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 SCRF cavities have

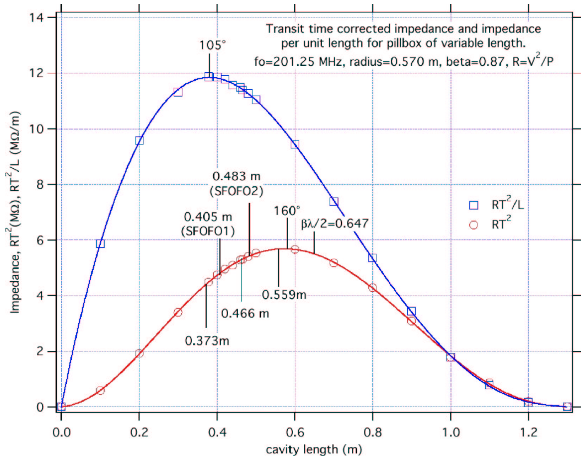

Figure 14.3: Cavity impedance versus length for an ideal pillbox, β= 0.87.

Table 14.2: Comparison between HOM-IOT (expected results) and klystron, both operated at 1 MW CW and 700 MHz.

Device	HOM-IOT	Klystron
Effective efficiency (%)	73	60
Assembly volume (ft^3)	30	200
Assembly weight (lbs)	1,000	5,000
DC beam voltage (kV)	45	90
Gain (dB)	25	46

been made for accelerating relativistic particles is 352 MHz for LEP-II. Therefore, R&D and prototyping for a Neutrino Factory at 201.25 MHz has been started now.

At present, SCRF R&D is in progress to address the following issues:

- Achieving 17 MV/m at a Q of 6×10^9 in a single-cell 201.25-MHz cavity
- Stiffening the 2-cell cavity designs to reduce Lorentz force detuning and microphonics sensitivity
- Exploring pipe cooling, both to reduce liquid-He inventory and to help stiffen multi-cell structures
- Reducing structure cost

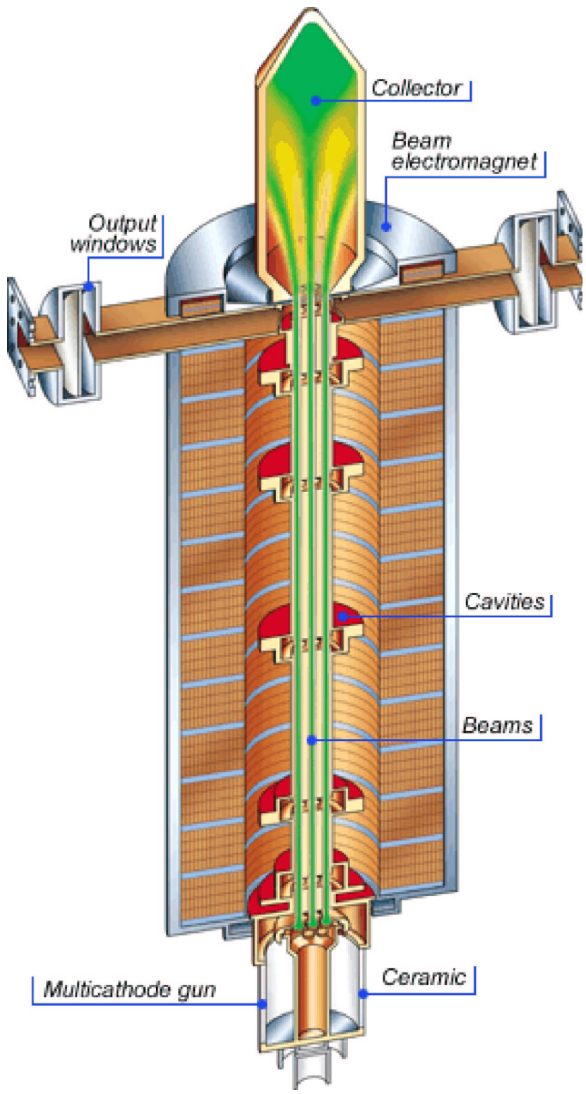

Figure 14.4: Schematic of multi-beam klystron.
http://www.tte.thomson-csf.com

Figure 14.5: Cathode of Thompson multi-beam klystron.

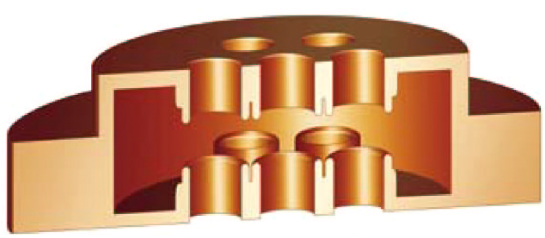

Figure 14.6: Cavity of multi-beam klystron.

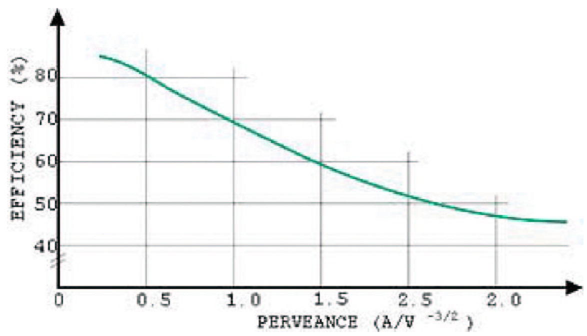

Figure 14.7: Klystron efficiency *vs.* beam perveance.

Figure 14.8: 1 MW cw HOM-IOT.

A collaboration has been set up with CERN to produce a single-cell Nb/Cu cavity at 201.25 MHz. CERN will provide the copper cavity, coat it with 1–2 μm thick niobium film using 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 14.9 shows a 3D CAD model of the CERN cavity inside the test dewar. A test pit 2.5 m diameter by 5 m deep is under excavation (Fig. 14.10) to accommodate the test dewar, which has been ordered. A 201.25-MHz, 2-kW rf test system is under construction. The clean room and high-pressure rinsing system at Cornell 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. Not surprisingly, the resonant frequencies are low. Exploration has started on stiffening schemes, with and without pipe cooling. Figure 14.11 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-Legnaro in Italy to spin monolithic copper cells out of a single tube. Legnaro 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 multi-cell cavities.

One long-term goal of the R&D is 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
- piezoelectric/magnetostrictive tuner
- cryomodule
- system integration
- high-power testing

Future R&D on structure stiffening, feed-forward, and active tuning to compensate Lorentz force detuning and microphonics could lower the required peak power by reducing

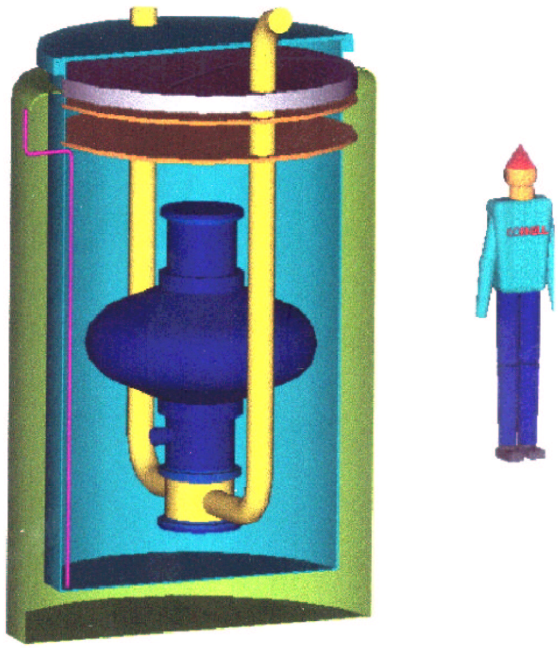

Figure 14.9: Vertical dewar test.

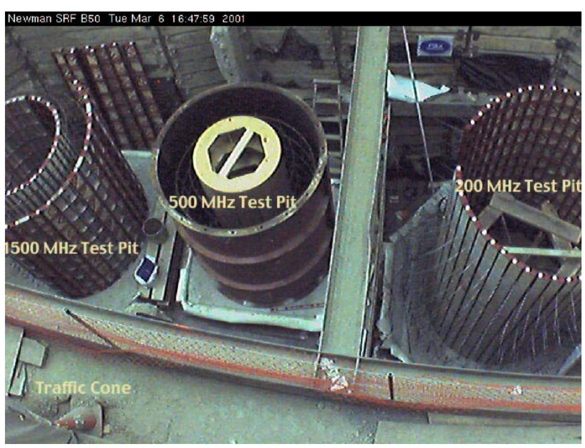

Figure 14.10: 200 MHz test pit (2.5 m diameter and 5 m deep) under construction at Cornell. The other pits are for testing existing cavities.

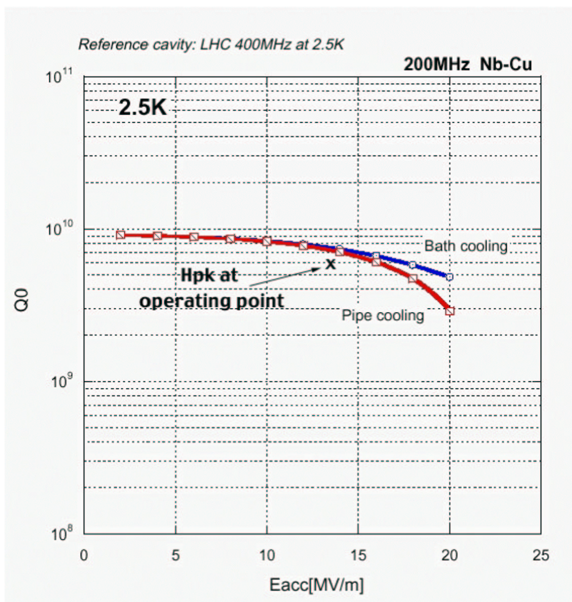

Figure 14.11: Comparison of pipe with bath-cooling at 2.5 K for a 200 MHz single-cell cavity. The He-carrying pipe diameter is 10 mm; spacing between pipes is 70 mm.

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 the optimum Q_L increases to 1.5×10^6. Adopting a 4 ms fill time would then decrease the input power requirement to 350 kW per cell at the best Q_L of 1.5×10^6—a level already reached at KEKB.

The acceleration system arc design, while reasonably straightforward, requires a number of nonstandard components. Design concepts for the injection chicane and the arc magnets are needed. Depending on their complexity, prototypes might be needed for some of these.

14.7 Storage Ring

The arc magnet concept proposed here is novel, and a prototype device is certainly called for. In addition to evaluating the coil fabrication aspects, measurements of field quality suitable for the tracking studies must be performed. Thereafter, the tracking must be carried out to ensure a design with acceptable dynamic aperture for injection and storage.

Optics designs to reduce or eliminate the contributions to the detector from the ends of the straight section, where the Twiss parameters are not suitable in terms of the beam angular divergence, must be done. It should be possible to "hide" the matching regions from the detector with suitable horizontal or vertical bends, but this must be verified with an actual lattice design.

Finally, the cost-benefit tradeoffs between the present compact design and a conventional ring with a liner to protect the magnets from beam decay products must be quantified.

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