Title
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Neutrino Factory and Muon Collider Collaboration R&D Program[†]

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Abstract

The Neutrino Factory and Muon Collider Collaboration (*MC*) comprises some 140 scientists and engineers located at U.S. National Laboratories and Universities, and at a number of non-U.S. research institutions. In the past year, the *MC* R&D program has shifted its focus mainly toward the design issues related to the development of a Neutrino Factory based on a muon storage ring. In this paper the status of the R&D activities is described, and future plans are outlined.

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KEYWORDS: muons, cooling, solenoid, radio-frequency, targets

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1. INTRODUCTION

Muon beam R&D activities in the U.S. are carried out under the auspices of the Neutrino Factory and Muon Collider Collaboration (*MC*), a broad collaboration of U.S. National Laboratories, U.S. Universities, and a number of non-U.S. research institutions. The three "sponsoring" National Laboratories are Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), and Lawrence Berkeley National Laboratory (LBNL). The *MC* is represented by a Spokesperson, currently Andrew Sessler from LBNL, Associate Spokespersons (currently Robert Palmer from BNL and Alvin Tollestrup from FNAL), an Executive Board and a Technical Board (see Table 1 for a list of members of these two groups). The *MC* presently numbers some 140 members from 30 institutions, and has grown considerably in the past year. Encouraging international cooperation and coordination for intense muon beam R&D is a priority of the Collaboration.

Though the initial emphasis of the *MC* was to carry out R&D aimed at a Muon Collider, the recent interest in neutrino physics has led to a shift in focus toward a (technically simpler) Neutrino Factory based on a muon storage ring with an energy in the range of 20–50 GeV. This change of emphasis did have some implications for the R&D program, as will be discussed later. In particular, the initial study of cooling components for a collider was aimed at the later stages of muon cooling, where the beam emittance would permit small-aperture components (resulting in a choice of 805 MHz for the RF cavities). A Neutrino Factory, on the other hand, emphasizes the initial stage of cooling where the beam emittance is high (resulting in a choice of 201-, or possibly 175-, MHz cavities, with correspondingly increased dimensions for other components such as solenoids and LH_2 absorbers).

2. R&D GOALS

The approach taken by the *MC* to define the overall R&D program was to decide what we wished to accomplish in a five-year time span in each area and then "work backwards" to see what would be needed to reach that goal. For this exercise, we assumed a technology-limited schedule, that is, we assumed that the required financial resources and personnel would be available and considered how much time would be needed to achieve our technical goals. With this approach, we expect that a five-year technology-limited plan will result in:

- all optics designs being completed and self-consistent
- validation experiments being completed or well along
- all required hardware being defined
- prototypes of the most challenging and costly components being completed or well along, i.e., we would know how to build the "hard parts"

- being ready to begin the design of, and provide cost estimates for, most of the remaining components

At the end of the five-year period, the above goals would put the *MC* in position to begin a formal Conceptual Design Report (CDR) for a Neutrino Factory. It is expected that this CDR stage would take 1–2 years to complete, subsequent to which construction could commence after obtaining government approval. It is worth noting that to accomplish this aggressive schedule would require making use of significant engineering resources early in the process. Furthermore, completing this program will require augmented funding levels compared with the present. At present funding levels the activities would be completed, but over a somewhat longer time period.

As an "intermediate milestone" we envision preparing a Zero-level Design Report (ZDR) after three years. Even earlier, by Summer 2001, we expect to prepare a report for the community summarizing the status of Neutrino Factory R&D. This information will permit the high-energy physics community to consider and evaluate the physics potential of a Neutrino Factory and assess the R&D activities and resources necessary to prepare for project construction.

3. R&D ACTIVITIES UNDER WAY

Collaboration R&D activities are organized into four main categories:

- Beam simulations and theory (organized by J. Wurtele, LBNL/UC-Berkeley)

- Targetry experiments (organized by K. McDonald, Princeton University)

- MUCOOL experiments (organized by S. Geer, FNAL)

- Component development, including 201 MHz superconducting RF (SCRF) cavities for the acceleration section of the facility, an induction linac with internal superconducting (SC) solenoid, a low-frequency, high-gradient RF cavity for the proton driver, a 20-T solenoid for the targetry experiment, and diagnostics for the muon beam

In addition to these "standing" programs, the *MC* has expended significant effort participating in feasibility study activities. The first such study, organized at FNAL by D. Finley and N. Holtkamp,[1] has been completed. A follow-up study, organized jointly by BNL (S. Ozaki and R. Palmer) and the *MC* (M. Zisman, LBNL) has recently begun.

3.1 Targetry

The goals of the targetry program are as follows:

- demonstrate performance of a MW-level target in a high-field solenoid

- demonstrate target lifetime (both liquid and solid targets will be examined)

- measure neutron and pion yields to benchmark particle production codes, e.g., MARS[2] or FLUKA[3]

There is an approved experiment, E951 at BNL, to carry out much of this work. Presently, the focus is on getting the A3 beam line ready for beam. This effort should be completed by the end of this year, in anticipation of initial beam tests (see Fig. 1) beginning next year. Calculations to model the thermal and mechanical behavior of the target under the influence of an intense proton beam are now under way. These will be used to guide the experimental program and also to interpret its results. Design of several key components needed for the experimental program has begun. A 20-T pulsed solenoid, to be used to capture the pion beam, is being designed in collaboration with the National High Magnetic Field Laboratory (NHMFL) in Florida. A 70-MHz high-gradient RF cavity is also being designed. This component will be used to test the performance of a high-gradient cavity in a high radiation field. Placing RF cavities in this harsh environment is required in some Neutrino Factory scenarios, so we will gain operational experience on this possibility. Because Hg is electrically conductive, its behavior when "shot" through a magnetic field will be studied initially without beam at NHMFL.

3.2 MUCOOL

The goals of the MUCOOL experiment are to:

- fabricate cooling channel components and bench test a complete cooling cell

- test cooling channel components in a muon beam

As noted earlier, it is now envisioned that the components to be tested with beam will be those representative of the initial portion of the cooling channel, directly following the phase rotation and bunching. This requires large aperture cavities, presently taken to be 201 MHz. Other components—solenoids for beam focusing and LH_2 absorbers—must have correspondingly large dimensions. Initial development focused on smaller 805-MHz components; this work is now well along and will be completed in about one more year.

3.2.1 805 MHz components

The focus here is on development of high-gradient normal conducting RF (NCRF) structures. Two different cavity types are being investigated. The first is a high-power open cell cavity being fabricated at FNAL. This cavity will be used to explore high-gradient performance. A second cavity based on a pillbox shape with beryllium end windows has been designed at LBNL and is being fabricated at the University of Mississippi. The 125 μm thick Be windows serve to increase the shunt impedance of the cavity while giving rise to relatively little scattering of the muon beam. This unit will be used to study the behavior of the Be windows at high gradient and with a solenoidal magnetic field.

In preparation for fabricating the Be window cavity, deformation tests have been carried out both at room temperature[4] and at liquid-nitrogen temperature. The experimental setup for one of the room temperature tests is shown in Fig. 2. In this case, the heat to deflect the window was provided by a halogen lamp, which produces a temperature profile across the window similar to what RF heating would give. In subsequent tests, RF heating was used and the window deformation was quantified by observing the shift in resonant frequency of the cavity, as shown in Fig. 3. In the experiment, two different foils were used, each 125 μm thick. A standard aluminum window that was not prestressed showed a change in frequency as soon as any heating took place, and showed a nonlinear frequency shift with temperature. In contrast, a Be foil that was prestressed during its manufacture was found to give no frequency shift until reaching a temperature where the prestress was exceeded, and thereafter showed a linear frequency shift with temperature. These tests are encouraging, but there is still much to do to validate the concept for the larger size required for a 201-MHz cavity.

To test the two cavities described above, a 5-T solenoid has been designed and fabricated at LBNL. The solenoid features two independently powered coils that can be run either with the same polarity (“solenoid mode”) or with opposite polarity (“gradient mode). Figure 4 shows measurement results demonstrating that the magnet meets its 5-T design specification in both modes. This magnet has now been installed in the Lab G test area at FNAL, where the high-power cavity tests will be carried out.

3.2.2 201 MHz Components

The process of designing a 201 MHz cavity has begun at FNAL. Both a beryllium window design and a gridded cavity design (see Fig. 5) will be investigated. The gridded design may have fabrication advantages over the Be window approach, but has the disadvantage of placing additional material in the beam path, which can degrade the cooling performance.[5]

Design of a prototype absorber[6] is under way, based on the cooling channel requirements developed in Ref. 1. There are several issues to be considered. The thickness of the containment windows must be minimized (consistent with safety considerations) to reduce straggling and multiple scattering. Evaluation of alternative window profiles (hemispherical, ellipsoidal, torispherical) and materials (AlBeMet, beryllium), determination of a suitable operating pressure, and dissipation of the roughly 100 W of beam power at cryogenic temperature are the main issues. An example design is shown in Fig. 6. Details of the work are given in Ref. 6.

3.3 Beam Simulations and Theory

The goals of the beam simulation and theory program include:

- development of complete end-to-end simulations for a Neutrino Factory (covering target, capture, front end, acceleration, storage ring), including the effects of all errors

- development of concepts for emittance exchange (longitudinal → transverse)

- development of analytic tools to aid in the design process

In the past year, the beam simulation effort has concentrated mainly on the front end portion of the facility, including capture, phase rotation, bunching and cooling. A complete description of the front end was developed, both with and without the use of an initial RF phase rotation close to the target. The latter case was the design basis used in Ref. 1. This process requires further optimization. It is now clear that the front end must be treated in an integrated fashion to achieve high performance. In particular, minimizing the energy spread of the beam after phase rotation is critical to attaining high throughput in the cooling channel that follows. The optimization of the channel will continue as part of the second feasibility study mentioned earlier.

Other studies in the area of beam simulations include looking at error sensitivities of the front end and working on the designs for the acceleration section and the storage ring. The topic of emittance exchange—a process required for cooling the longitudinal degrees of freedom—will be scrutinized at an upcoming (September 2000) workshop at BNL, organized by R. Fernow and G. Hanson. Though this topic has long been viewed as a Muon Collider (as opposed to Neutrino Factory) problem, it is clear that a practical solution would be of interest for the Neutrino Factory case as well.

It is worth noting that this R&D activity is already functioning as an international group. There are regular weekly phone conferences to discuss technical progress that include FNAL, BNL, LBNL, UC-Berkeley, ANL, University of Chicago, Indiana University, and CERN.

3.4 Component Development

Component development is a catch-all category used to cover the work on items not included in the other R&D programs. In a broad sense, the goal of this activity is to identify, and demonstrate, any critical technologies needed for a Neutrino Factory. At present, there are a few specific tasks under way:

- fabrication and testing of a 201-MHz superconducting RF (SCRF) cavity

- fabrication and testing of an induction linac module having an internal superconducting solenoid, along with its pulsed power system

- demonstration of a high-gradient, low frequency NCRF cavity for use in the proton driver

The first of these tasks is just being launched at Cornell, supported by NSF funds. This activity requires a significant upgrading of the cavity cleaning and processing facilities to accommodate the large sized cavity. The first cavity will be ordered this year. The second item builds on design concepts developed at LBNL for the feasibility study summarized in Ref. 1. It will begin with engineering design studies and then proceed to prototype development. The last area above is already under way at FNAL and BNL, and is supported mostly by programs other than the *MC*. However, the production of very short (1 ns) bunches is primarily motivated by *MC* needs and we expect to collaborate in the work to the extent possible.

4. R&D PLANS

In this section we indicate the main activities planned by the *MC* during the next several years, building on the progress made to date. The activities described are based on the technology-limited approach discussed in Section 2.

4.1 Targetry

In the next year, the E951 experiment at BNL will get under way. First the beam line will be commissioned and then tests of prototype Hg targets will commence. Engineering design of the pulsed target solenoid and its 5-MW power supply will be carried out, after which fabrication of a system to use in the beam tests will be done. Engineering of a high-gradient 70-MHz NCRF cavity will be completed. This frequency corresponds to that of the now-decommissioned SuperHILAC accelerator at LBNL, which will provide four 1-MW tetrodes to power the cavity.

In addition to the liquid-target activities, additional emphasis will be placed on development of a solid-target option for an “entry level” facility. Studies in Ref. 1 point to the viability of a carbon target for a proton beam power of about 1.5 MW. A prototype carbon target assembly will be developed and tested. This work will be a collaboration between FNAL and ORNL. The ORNL group will also look into the “facility” aspects of the target area, building upon the expertise developed in support of the Spallation Neutron Source project under construction at Oak Ridge. The high proton beam power needed for generating the muon beam will make the target housing a remote-handling area, with the attendant engineering issues that such an area brings. This is a feature new to high-energy physics facilities and must be assessed prior to launching a proposal.

4.2 MUCOOL

Starting next year, the focus of the RF development work will shift to 201 MHz. As noted, a preliminary design of a cavity has been done, but this needs iteration before fabrication begins. The design cycle for a new RF cavity, from concept to testing, takes about three years to complete, so delivery and testing of the cavity will be 2–3 years from now.

A solenoid for testing the cavity will also be needed. Specifications for this magnet will result from the second feasibility study. In the FNAL feasibility study, it was shown that such magnets, while feasible, are potentially costly. Thus, the R&D effort will focus heavily on issues of cost reduction. It is envisioned that some, though not all, of the development can proceed with scale model tests, saving both time and money.

An important goal of the *MC* is to carry out an experiment to demonstrate cooling. At present, we need further guidance from the beam simulation group on the proper approach to take, so the experiment is not yet well defined. Defining a demonstration experiment and identifying the required resources to carry it out will be an important activity over the next several years.

4.3 Beam Simulations and Theory

Without question, the key activity for the beam simulation and theory group is to optimize the performance of the front end portion of the Neutrino Factory facility. After that, it will be important to understand the error sensitivity of the front end, particularly the cooling channel. The cooling channel issues to be assessed include: solenoid strength and multipole errors; voltage, phase, and higher-order modes of the RF cavities; absorber thickness variations; energy straggling; and multiple scattering tails. It is only through such detailed studies that we can define component specifications, diagnostics to measure what must be controlled, and plans for testing the key issues.

Historically, the initial design of accelerators has been based on analytic work followed by simulations (“tracking”) to assess higher-order effects. A muon-based accelerator would likewise benefit from more solid analytical underpinnings. Thus, on the theory front, work toward a fully six-dimensional analytical theory is an important goal. This will permit us to make progress on the key topic of emittance exchange. To extend the cooling channel performance to the level required for a Muon Collider will require an ability to cool the beam longitudinally as well as transversely. As noted earlier, even for the Neutrino Factory parameter regime the large energy spread of the incoming beam is difficult to manage and would potentially benefit from some amount of longitudinal phase space reduction.

4.4 Component Development

Prototypes of the high-profile components will be fabricated and tested. A 201 MHz SCRF cavity will be tested at design gradient, both CW and pulsed. We will also explore alternative fabrication approaches to find the most cost-effective and reliable methods.

A prototype induction linac module, complete with internal superconducting solenoid, will be fabricated and tested with a realistic pulsed power system. The design will be based on the concept developed in Ref. 1 (see Fig. 7). The alternative CERN approach based on low-frequency NCRF cavities will be monitored closely as an alternative technology, though the *MC* does not presently envision embarking on a separate development effort in that area.

Consideration of "operational" diagnostics will get under way. By this is meant the development of devices needed to transport the beam, characterize its properties, and maintain these properties during the acceleration and storage cycle.

The second feasibility study will be completed and a report written. This study will estimate the performance of a "high-end" Neutrino Factory and identify any R&D needs beyond those found in the first feasibility study.[1] Any additional cost drivers that arise will also be identified. As noted earlier, this information will be provided to the high-energy physics community for discussion at the Snowmass meeting in 2001.

5. SUMMARY

In this paper we have outlined the R&D status and plans of the Neutrino Factory and Muon Collider Collaboration, the umbrella organization for intense muon beam R&D in the U.S. The *MC* R&D program is vigorous and healthy. There are clear directions to proceed on all hardware fronts and there are clear challenges identified for the beam simulation effort. The *MC* will continue to coordinate closely with our European and Japanese counterparts in this forefront R&D effort. It is worth noting that a shared muon beam test facility would be a valuable resource and a natural base to collaborate globally in this effort. Membership in the *MC*, as well as financial support, have grown at a healthy rate in the last few years, and we look forward to these positive trends continuing. In particular, the involvement of NSF-supported institutions and groups has served to strengthen the effort, and expanded involvement of international groups would strengthen the effort even more.

6. ACKNOWLEDGMENTS

The breadth of the program outlined here is the work of many dedicated people. I would like to thank Andy Sessler, Bob Palmer, and Alvin Tollestrup for their helpful comments on the R&D program. Editorial suggestions by Bill Turner were helpful in preparing the final version of this document. The detailed plans outlined briefly here are primarily the product of the leaders of the main R&D groups, Kirk McDonald, Steve Geer, and Jonathan Wurtele. I would like to thank Norbert Holtkamp for helping lead the way to a solid and well focused R&D program, and Maury Tigner for his efforts to integrate the NSF groups into the *MC* program smoothly and effectively. The open and collegial interactions with the European R&D effort are due in no small part to the collaborative attitude of Helmut Haseroth, Colin Johnson, and Alessandra Lombardi, whose help is appreciated. Lastly, I would like to thank all the members of the Collaboration for having the audacity to launch a grass-roots design effort toward a new type of machine in somewhat uncertain times.

7. REFERENCES

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Table1. Current members of *MC* Executive and Technical Boards.

Executive Board

Name	**Institution**	**Collaboration Role**
A. Sessler	LBNL	Spokesperson
R. Palmer	BNL	Associate Spokesperson
A. Tollestrup	FNAL	Associate Spokesperson
J. Gallardo	BNL	Secretary
D. Cline	UCLA	
S. Geer	FNAL	
D. Kaplan	IIT	
K. McDonald	Princeton University	
A. N. Skrinsky	BINP	
D. Summers	U. Mississippi	
M. Tigner, *pro tem*	Cornell University	
J. Wurtele	LBNL/UC-Berkeley	

Technical Board

Name	**Institution**	**Collaboration Role**
A. Sessler	LBNL	Spokesperson
Steve Geer	FNAL	MUCOOL Leader
Kirk McDonald	Princeton University	Targetry Leader
Jim Norem	ANL	E932 Leader
Harold Kirk	BNL	E910 Leader
John Corlett	LBNL	
Norbert Holtkamp	FNAL	
Colin Johnson	CERN	
John Miller	NHMFL	
Bob Palmer	BNL	
Maury Tigner	Cornell University	
Jonathan Wurtele	LBNL/UC-Berkeley	Simulations/Theory Leader
Mike Zisman	LBNL	Project Manager

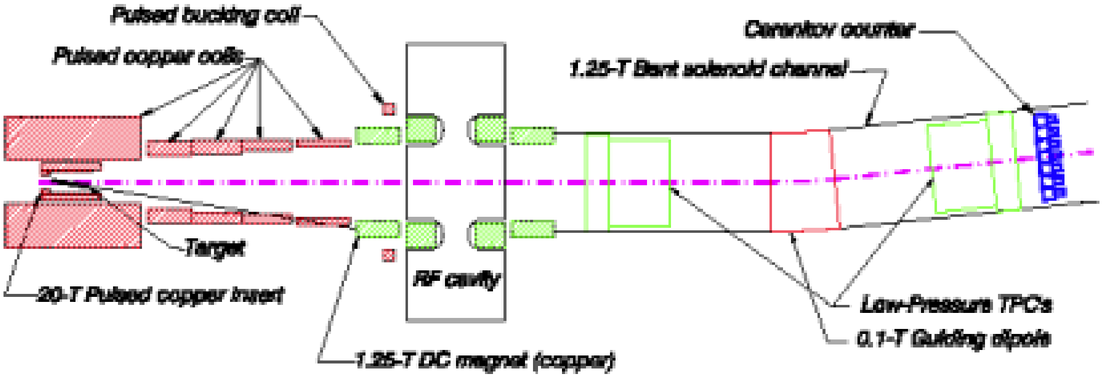

Fig. 1. Planned experimental arrangement of targetry experiment in the A3 beam line at BNL.

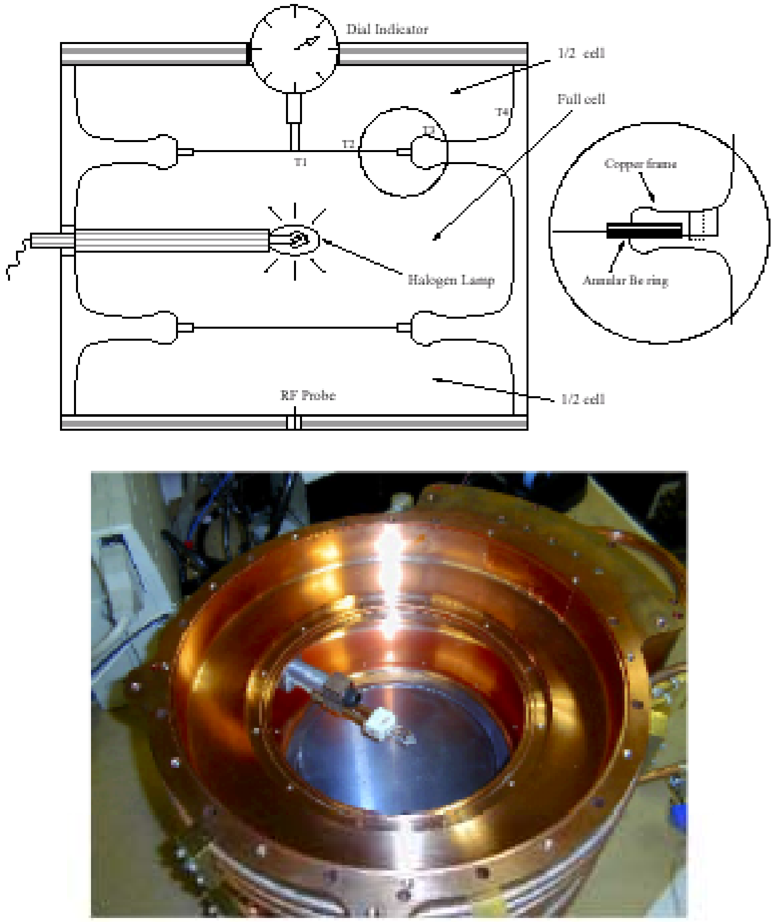

Fig. 2. (top) Schematic of Be window heating test setup with halogen lamp; (bottom) photograph of low-power pillbox cavity used for test.

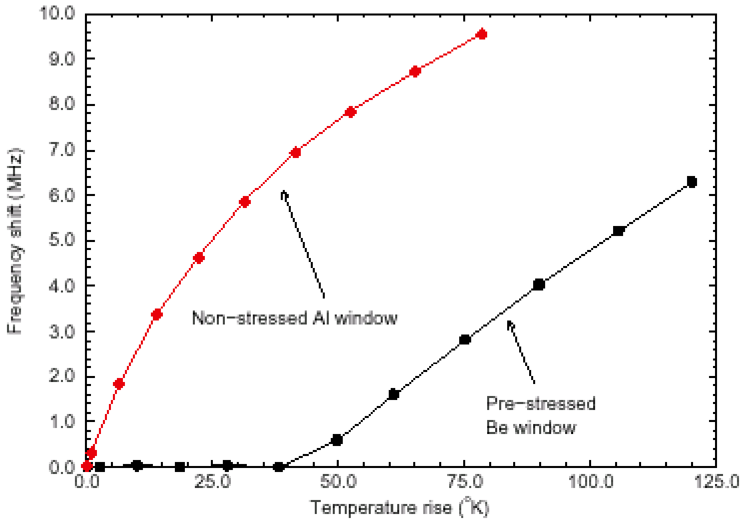

Fig. 3. Frequency shift as a function of temperature rise in the foil window. A prestressed Be window deflects considerably less than a non-prestressed Al window.

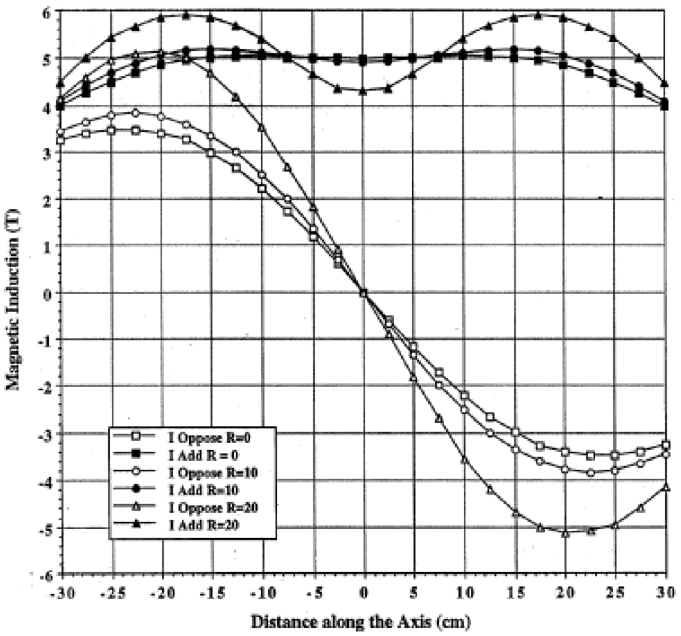

Fig. 4. Measurement results for 5-T solenoid to test 805-MHz cavities. The magnet has two independently powered coils and can be run with the coil polarities identical or opposite.

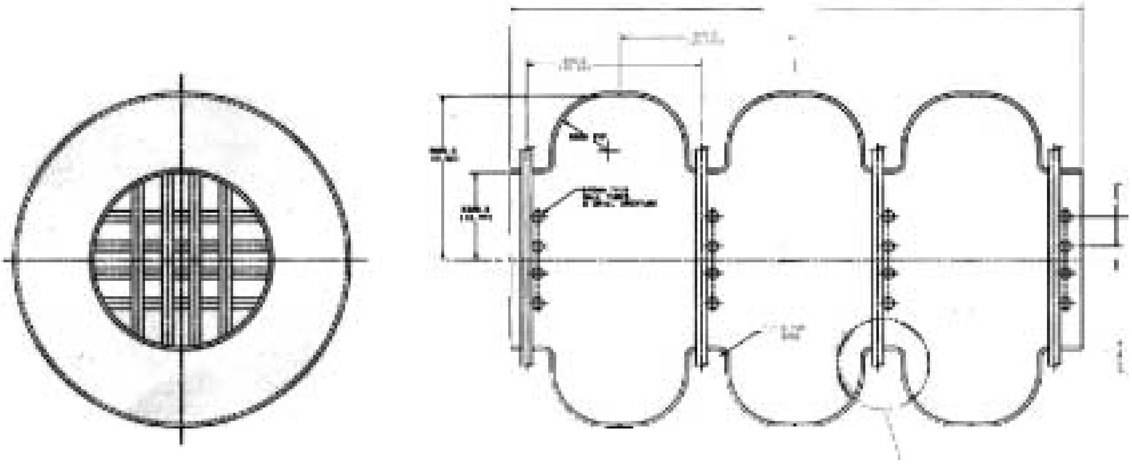

Fig. 5. Preliminary design of three-cell gridded NCRF cavity for 201 MHz operation.

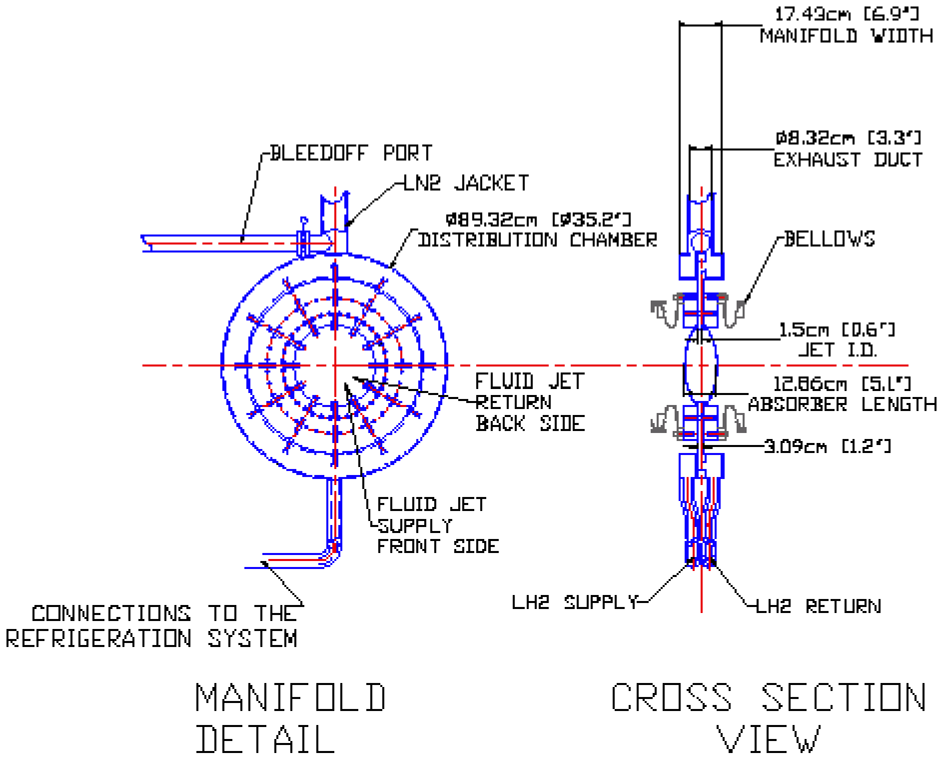

Fig. 6. Mechanical design of external cooling loop absorber suitable for FOFO channel (see Ref. 6).

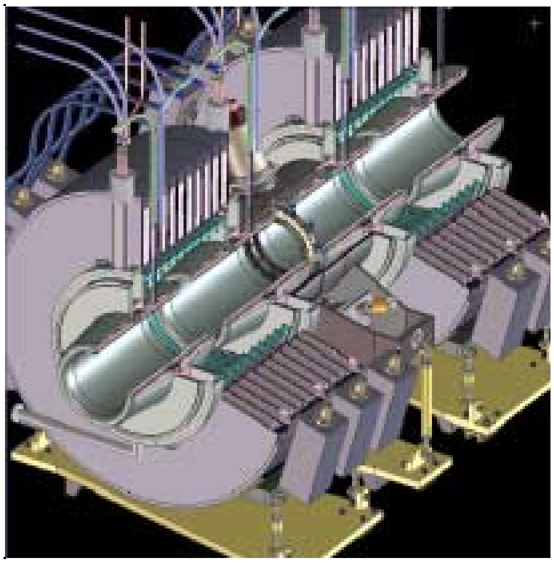

Fig. 7. Cutaway view of proposed induction linac module with superconducting solenoid coils on the inside.