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Muon Accelerator R&D Programme

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An accelerator complex that can produce ultra-intense beams of muons presents many opportunities to explore new physics. A facility of this type is unique in that, in a relatively straightforward way, it can present a physics program that can be staged and thus move forward incrementally, addressing exciting new physics at each step. A directed R&D program is presently underway to evaluate the designs and technologies required to provide muon-based high energy physics (HEP) accelerator capabilities. An overview of the status of the designs for the Neutrino Factory and Muon Collider applications is provided. Recent progress in the technology R&D program is summarized.

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1. Introduction

Muon-based facilities [1] offer the unique potential to provide the next generation capabilities and world leading experimental support spanning physics at both the Intensity and Energy Frontiers. Muon beams of high brilliance have been proposed as the essential ingredients of a Muon Collider (MC) [2] or a Neutrino Factory (NF) [3] since the 1960's. The MC addresses the high-energy frontier: looking at precise Higgs physics and beyond, while the NF addresses the precision frontier: looking at CP-violation in the neutrino sector. The present designs of a NF or a MC front-end (up to the beginning of the cooling section) are similar, as can be seen from the schematic layouts reported in Figure 1.

In this way, a common R&D program and staging path may be envisaged and a NF may be considered as a first step in a MC accelerator complex. MC's may be developed with a center of mass energy up to many TeV and, due to the large muon mass as compared to the electron one, may easily fit in the footprint of existing HEP laboratories. In addition, the large muon mass implies a reduction in the rate of beamstrahlung by a factor of 10^4 over an e^+e^- collider of the same center of mass energy. As a consequence, the annihilation-energy distribution is much narrower at a MC than an e^+e^- collider at the same energy.

An informal Neutrino Factory and Muon Collider Collaboration was formed in 2002, and later became directly funded by the DoE Office of Science with a Project Manager. In 2011 the U.S. Muon Accelerator Program (MAP) [4] was formed, with the task of assessing the feasibility of muon accelerators for Neutrino Factory and Muon Collider applications. Now on the recommendation of the P5 [5], the MAP program is entering a ramp-down phase. Over the course of the past 2 years, MAP has developed a detailed technical plan for moving forward with its program to evaluate the feasibility of muon accelerators for high energy physics applications. There are 3 principal elements of this plan: 1) A Muon Accelerator Staging Study (MASS) [6] working group was created in 2012 and charged with identifying a clear path towards future muon accelerator capabilities which would allow cost and technical risks to be controlled. The working group was also charged with reviewing each accelerator sub-system and to prepare a set of recommendations on specific design thrusts that should be pursued in order to optimize technical performance, risk and/or cost. 2) An Initial Baseline Selection (IBS) process has been implemented to carry out the detailed development and evaluation of the design concepts required for each stage of a muon accelerator facility, from the proton driver through the neutrino factory and collider systems. The MASS recommendations are actively being incorporated into this process. The IBS process outlines a roughly 2.5 year effort to evaluate each of the major design concepts for a muon-based facility and to document those concepts at a level where they could serve as inputs to a future conceptual design for a muon accelerator facility. 3) An R&D program to demonstrate critical concepts for muon accelerators and to validate the technologies critical to muon accelerator capabilities. A particular focus of this program is the development of the technologies required for a muon ionization cooling channel – an accelerator system unique to this type of facility. It also supports the initial demonstration of the ionization cooling process with the Muon Ionization Cooling Experiment (MICE) at the Rutherford Appleton Laboratory.

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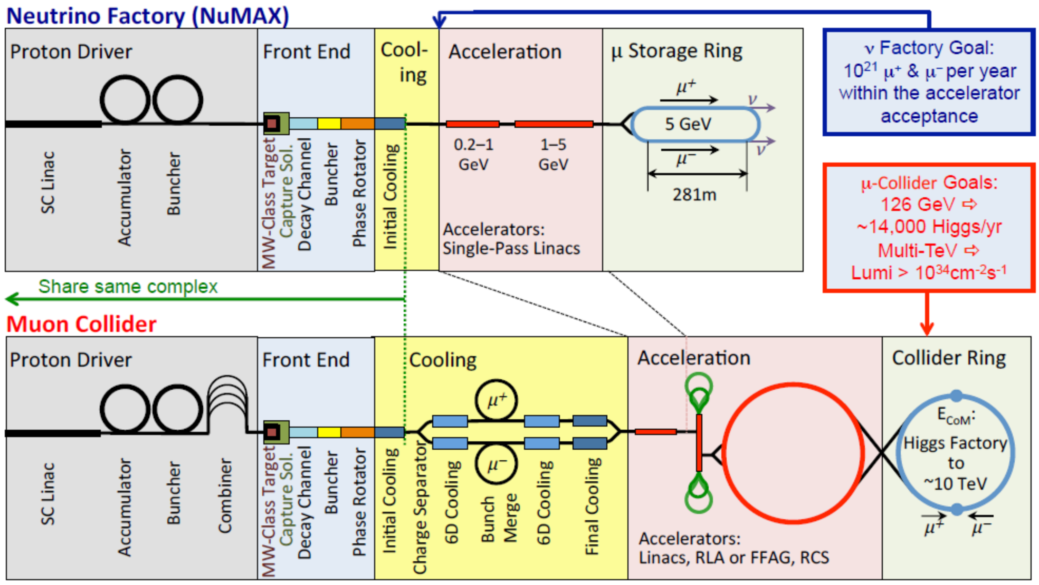

Figure 1: A block diagram showing the key systems needed for a NF and MC capabililty. Much of the major components are shared, thus enabling a cost effective facility.

1.1 Motivation for a staged approach

The feasibility of the technologies required for Neutrino Factories and/or Muon Colliders must be validated before a facility based upon these could be proposed. The staging plan consists of a series of facilities (see Fig. 2) with increasing complexity, each with performance characteristics providing unique physics reach. The facilities along this staged path are:

- nuSTORM [7]: a short-baseline Neutrino Factory like facility enabling a definitive search for sterile neutrinos, as well as neutrino cross-section measurements that will ultimately be required for precision measurements at any long-baseline experiment
- NUMAX: (Neutrinos from Muon Accelerator CompleX): a long-baseline 5 GeV Neutrino Factory, optimized for a detector at SURF 1300 km from Fermilab, providing a precise and well-characterized neutrino source that exceeds the capabilities of conventional superbeams
- NUMAX+: a full-intensity Neutrino Factory, upgraded from NuMAX, with performances similar to IDS-NF as the ultimate source to enable precision CP-violation measurements and potential exploration of new physics in the neutrino sector.
- Higgs Factory: a collider capable of providing between 3500 (startup) and 13,500 Higgs events per year (10^7 sec) with exquisite energy resolution enabling direct Higgs mass and width measurements.
- Multi-TeV Collider: if warranted by LHC results, a multi-TeV Muon Collider, with an ultimate energy reach of 6 to 10 TeV, likely offers the best performance and least cost and power consumption for any lepton collider operating in the multi-TeV regime.

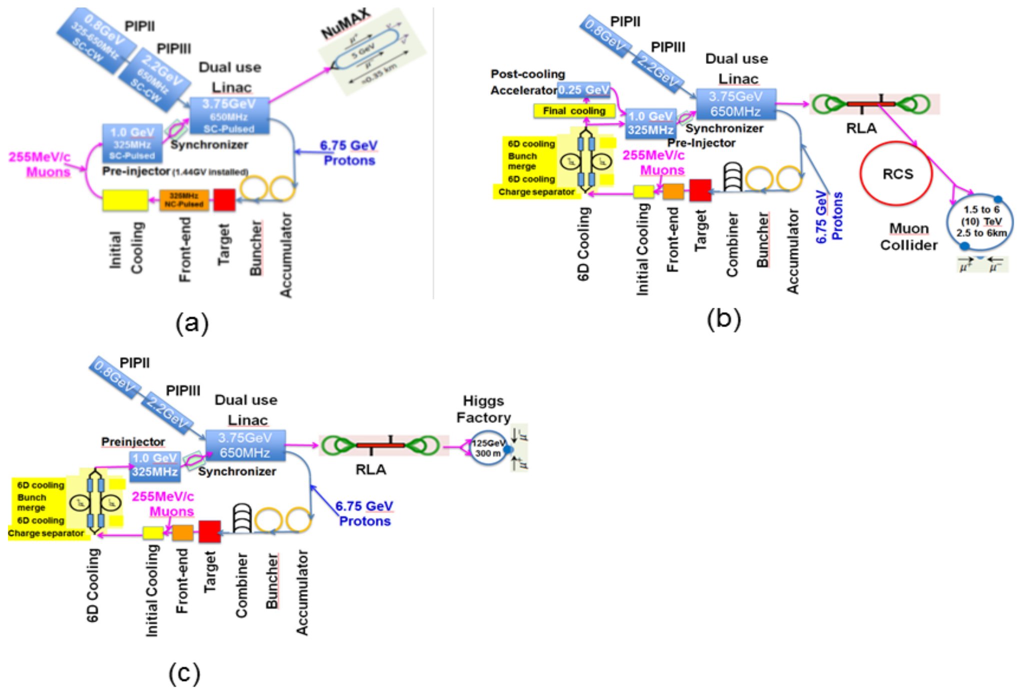

Figure 2: A possible staged scenario. (a) Layout of a muon based Neutrino Factory, (b) Layout of a muon based Higgs Factory, (c) Layout of a multi-TeV Muon Collider

1.2 The MAP R&D Effort

The MAP R&D effort falls into three pricipal categories. The first is the design and simulation effort that spans the following areas: proton driver, high power target, muon capture front-end, cooling, acceleration and storage, collider and machine detector interface. The second major category is technology R&D that spans the development of: normal conducting RF cavities capable of operating in multi-Tesla magnetic fields; superconducting RF cavities suitable for use in an ulta-fast muon acceleration chain; very high field magnets including those utilizing high temperature superconductors; rapid-cycling magnets for the ultra-fast muon acceleration chain; and high power target and absorber concepts. The research into RF cavities operating in magnetic fields is supported by the MuCool Test Area (MTA) experimental facility at Fermilab. The third major category of R&D is largescale system and physics demonstrations to validate key concepts. The two principal efforts of this type have been the MERcury Intense Target (MERIT) demonstration of liquid metal jet technology for targets capable of handling multi-MW incident beam power [8] and the MICE experiment [9] aimed at the explicit demonstration of ionization cooling of muons. At the conclusion of the IBS process, the MAP R&D plan envisions a major system demonstration of the technology required for a high performance 6D ionization cooling channel.

1.2.1 Design and Simulation

Target and Solenoid Capture: Results from the MERIT experiment have provided a proof-of-principle demonstration for a free Hg-jet target technology that could survive beam powers up to the 4 MW and the required bunch structure. The present concept is for a graphite (or carbon carbon composite) target and proton beam dump inside a 20 T solenoid field, which field tapers down to 2 T, used throughout the rest of the Muon Collider/Neutrino Factory front-end over 5 m. The use of carbon hopefully removes technical risks and will benefit from developments at other facilities (e.g. spallation sources). The solenoid field is to be provided by superconducting coils (with cable-in-conduit conductor as used in the ITER project), except for a 5-T resistive coil insert near the target. Target optimizations (length, angle, position of dump) was performed via MARS15 (2014) for a 1 MW, 6.75 GeV proton driver with 50 Hz pulses 3 ns long and the results are reported elsewhere [10].

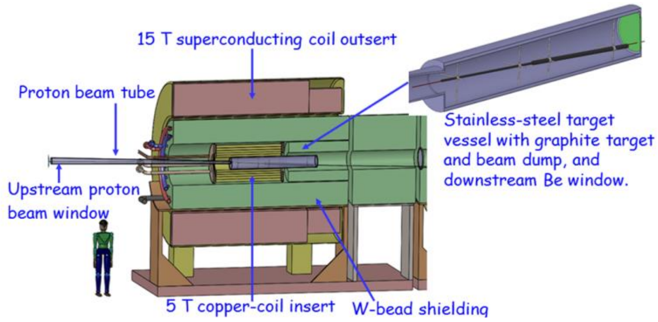

Figure 3: Sketch of the target system concept.

Front-end and Chicane: A front-end channel [11] for manipulating the longitudinal and transverse phase-space in order to efficiently capture and transport a muon beam from the production target towards the accelerator chain has been designed. In that method, a set of properly tuned rf cavities captures the muon beams into strings of bunches and aligns them to nearly equal central energies, and a following set of rf cavities with absorbers cools them by a factor of three in transverse emittance. We showed that this scheme can simultaneously capture species of both signs with a notable rate of 0.12 muons of each sign per incident 8 GeV proton and we analyzed the sensitivity in performance of the channel against the number of cavities, accelerating gradient and magnetic field. In order to “remove” the significant background of electrons and protons which may result in heat deposition on superconducting materials and activation of the machine, preventing manual handling we have designed of a secondary particle handling system [9]. The system comprises a solenoidal chicane that filters high momentum particles, followed by a proton absorber that reduces the energy of all particles, resulting in the rejection of low energy species that pass through the chicane.

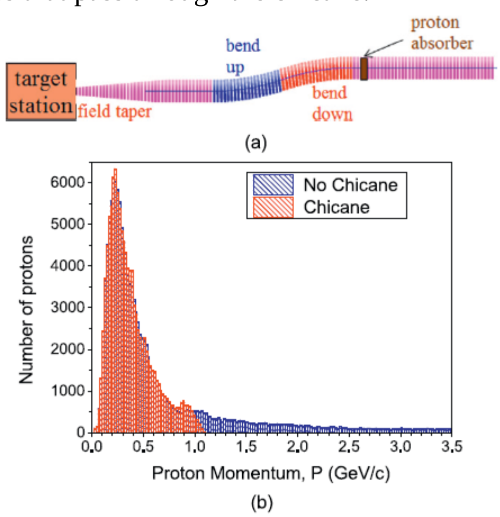

Figure 4: (a) Conceptual design of the chicane system and (b) chicane “removes” protons with momentum > 1 GeV/c.

Cooling: The initial muon beam 6D emittance is approximatelly six orders larger than the final goal for a Muon Collider. Because muon decay, synchrotron, electron and stochastic coooling are too slow and thus ionization cooling appears to be the most promising solution. Ionization cooling is achieved by reducing the beam momentum through ionization energy loss in absorbers and replenishing the momentum loss only in the longitudinal direction through rf cavities. This mechanism can effectively reduce the transverse phase space of a beam in the same way as radiation damping does to an electron beam. However it does not effectively cool the longitudinal momentum spread because the energy-loss rate is not sensitive to beam momentum except for very low-energy muons. In order to reduce the longitudinal emittance, the so-called “emittance exchange” technique is commonly used, where a dispersive beam is passed through a discrete or continuous absorber in such a way that the high-energy particles traverse more material than the low-energy particles. The net result is a reduction of the longitudinal emittance at the cost of simultaneously increasing the transverse emittance. By controlling the amount of emittance exchange the six-dimensional emittance can be reduced.

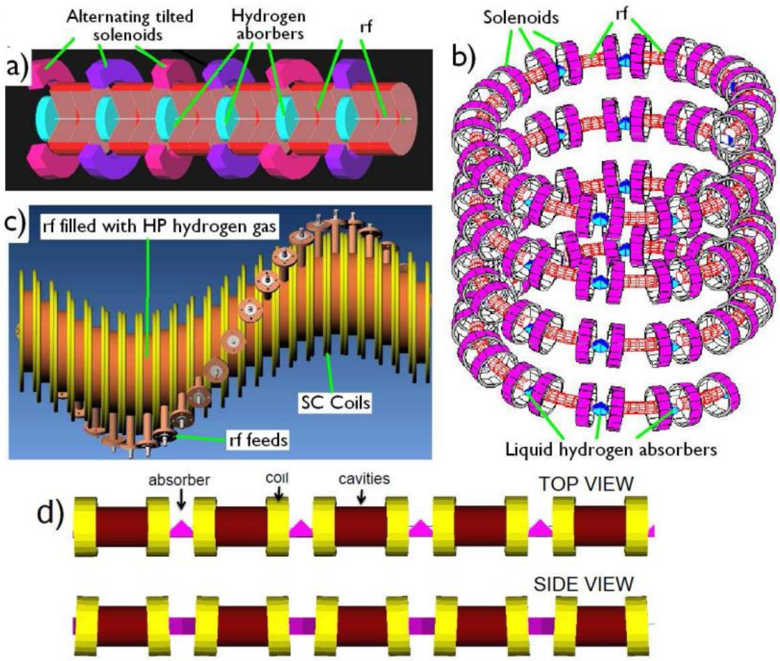

Figure 5: Alternative cooling channels: (a) helical snake; (b) Guggenheim, (c) helical cooling channel with discrete absorbers; and (d) rectilinear cooling chahnel.

Figure 5 shows some of the schemes have been studied. The Helical snake [Fig. 5(a)] can cool both muon signs simultaneously and thus save money. Therefore, it has been proposed as a potential solution for a Neutrino factory. However it’ s performanse is worse for late stage cooling so two other options are considered for Muon Collider applications: One is a Helical Cooling Channel [12] [Fig. 5(c)] and the other is a Rectlinear Cooling Channel [Fig. 5(d)]. The later is a linear version of the reverse focus focus used in a Guggenheim channel [Fig. 5(b)] [13]. A complete end-to-end simulation [14] using a rectilinear channel, showed a notable reduction of the 6D emittance by at least five orders of magnitude and the results are in good agreement with the theoretical predictions. Some of the key results are illustrated in Fig. 6. Most

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importanty, all cooling 6D stages were within Nb3Sn magnet technology and a detailed magnet feasibility study has demostarted feasibility of the design.

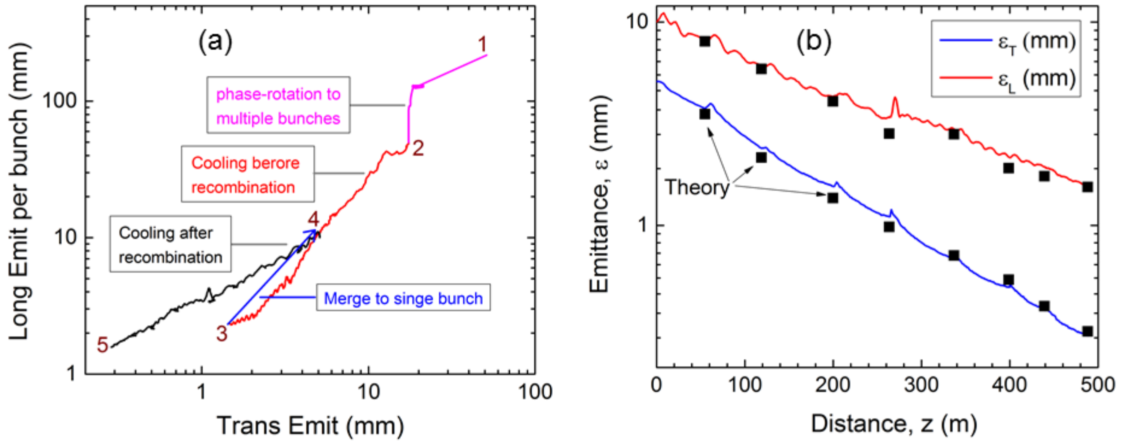

Figure 6: End-to-end cooling simulation for a Muon Coolider with a rectilinear channel. Note the notable reduction of 6D emittance by 5 orders of magntitude. Results agree well with theoretical predictions.

Acceleration: As noted earlier there are free classes of machines. One is NUMAX with acceleration up to 5 GeV. The other is a Higgs factory with acceleration up to 63 GeV. And finally, a high energy collider to 15, 3, 6 TeV Center of Mass energies. For NUMAX, a dual use with 325 MHz and 650 MHz cavities is considered. When the energy is high enough, Recirculating Linear Accelerators (RLAs) [15] are used up to 63 GeV. An example is shown in Fig. 7. For further acceleration pulsed rapid cycling synchrotrons are considered. But still, the acceleration and corresponding magnetic field ramps must be fast, with time constants corresponding to frequencies approaching 1000 Hz.

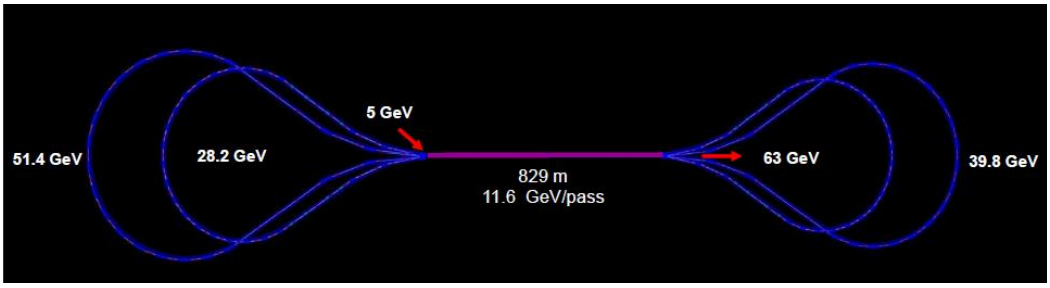

Figure 7: 5 pass RLA from 5 GeV to 63 GeV.

Collider Ring and Backgrounds: Lattice designs for 63 GeV Higgs Factory, 1.5 TeV and 3.0 TeV Collider have been designed [16] and the required parameters have been identified. The design goals are to obtain high-luminosity, acceptable detector backgrounds and manageable heat loads. Based on the detailed MARS15 model and intense simulations, a sophisticated radiation protection system has designed for the entire Collider ring to bring peak power density in the superconducting coils below the quench limit and reduce the heat deposition in the cold mass by a factor of 100. At this moment background simulation for 63 GeV Collider design is complete (see Fig. 8) and similar studies for the 1.5 and 3 TeV will soon become available.

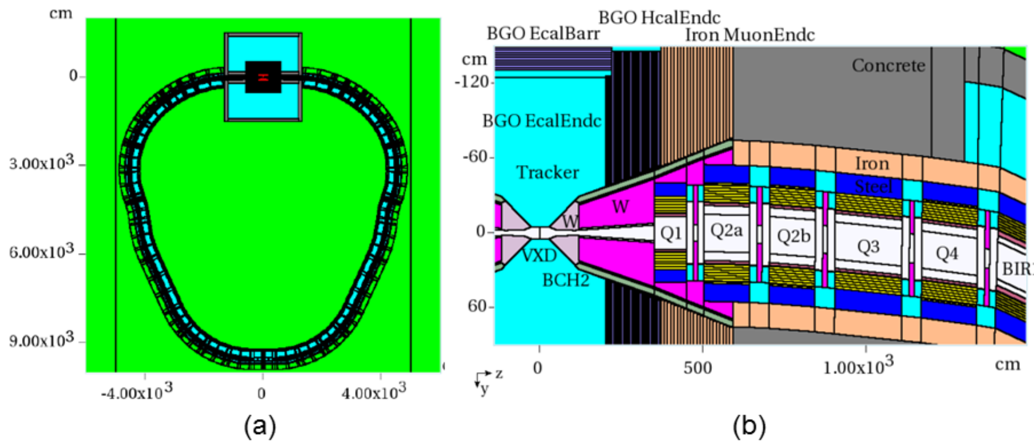

Figure 8: (a) MARS15 model of HF collider including experimental hall and the SiD-like detector at IP. (b) MARS model HF MDI MARS15 model with tungsten nozzles on each side of IP, tungstenmasks in interconnect regions and tungsten liners inside each magnet.

1.2.2 Technology R&D

RF in magnetic fields: The MTA R&D effort generally falls into one of three categories: (i) providing support for the Muon Ionization Cooling Experiment (MICE) [17]; (ii) developing RF cavities filled with high-pressure gas as a way of circumventing the problem of RF breakdown; and (iii) developing more traditional, evacuated RF cavities capable of precisely studying and/or ameliorating the problem of RF breakdown in strong magnetic fields.

A demonstration of ionization cooling via MICE requires the assembly, commissioning, and operation of an RF cavity and coupling coil (RFCC) module: a large-diameter solenoid that surrounds four 201 MHz RF cavities. The assembly of such a module (including RF couplers, tuners, cryogenic supply, instrumentation, etc.) is a significant effort. A single-cavity module (SCM) is currently being commissioned in the MTA. The experience gained during SCM assembly and systems integration efforts can be directly applied to the RFCC effort, expected to commence in the near future.

Another R&D thrust in the MTA is the characterization of 805 MHz RF cavities loaded with high-pressure gas. As discussed above, RF breakdown in strong magnetic fields is an obstacle on the path to the full design of an ionization cooling channel [18]. High-pressure hydrogen gas-filled RF (HPRF) cavities circumvent this problem [19]. The dense gas suppresses RF breakdown via Paschen's Law, and additionally serves as an ionization cooling medium for muon beams. Tests with an 805 MHz gas-filled cavity have demonstrated surface gradients as high as 65 MV/m in a 3 T solenoidal magnetic field. Furthermore, this technology has been shown to work in the presence of intense, ionizing particle beams with no discernible B-field effects.

In parallel with these other efforts, work continues on the characterization of RF breakdown in 805 MHz RF cavities under vacuum and in multi-Tesla magnetic fields. To study this issue, we have developed an experimental program based on a modular pillbox cavity operating at 805 MHz [20]. The cavity is modular in that its end walls may be unmounted relatively easily, as shown in Figure 9. This drastically simplifies the inspection and characterization of breakdown damage. It also allows for the evaluation of materials other than copper (e.g. beryllium) as candidates to ameliorate the breakdown problem. The modular cavity has a design frequency of 805.0 MHz and an unloaded Q 25600. The cavity is magnetically coupled in the radial direction to a narrow feeder waveguide through a coupling iris, the design of which is illustrated in Fig. 9. This set up more closely resembles the configuration of our 6D cooling lattices.

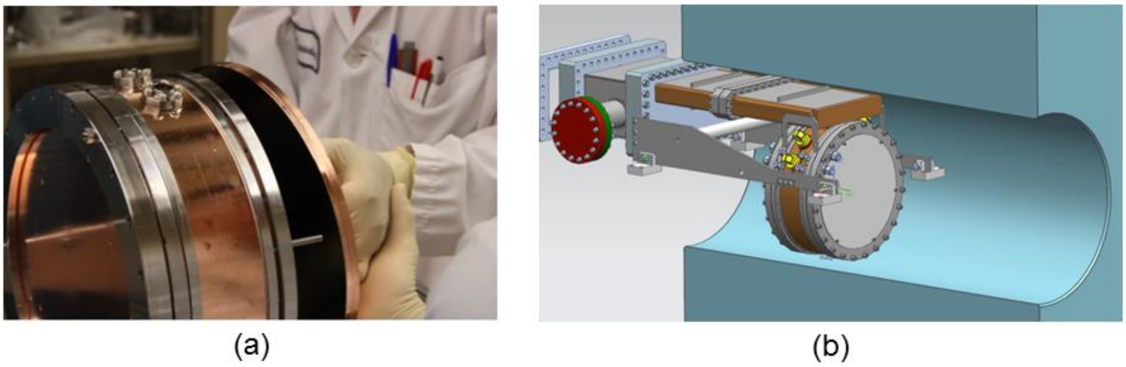

Figure 9: Modular cavity design. The picture on the left shows the unmounting of the cavity end plates. Note that once the clamp ring is removed, the end plates can be pulled off cleanly.

MICE: The International Muon Ionization Cooling Experiment will provide the demonstration of ionization cooling. The experiment is being built in a series of Steps. Step IV, which consists of a tracking spectrometer upstream and downstream of an absorber/focus-coil module will be completed in early in 2015. In this configuration, the emittance of the muon beam upstream and downstream of the absorbed will be measured precisely allowing the emittance reduction and the factors that determine the ionization-cooling effect to be studied in detail. Each tracking spectrometer consists of a scintillating-fibre tracker placed within a 4 T field provided by the superconducting spectrometer solenoid. The muon beam is transported to the absorber/focus-coil module: a 22 liter volume of liquid hydrogen placed inside a superconducting focusing coil. The properties of lithium hydride, and possibly other absorber materials, will also be studied. All the components of Step IV have been manufactured and integration of the experiment in the MICE Hall at the Rutherford Appleton Laboratory is underway. The following step V, or simpler modification of it, will observe cooling, with re-acceleration in 201 MHz room temperature cavities.

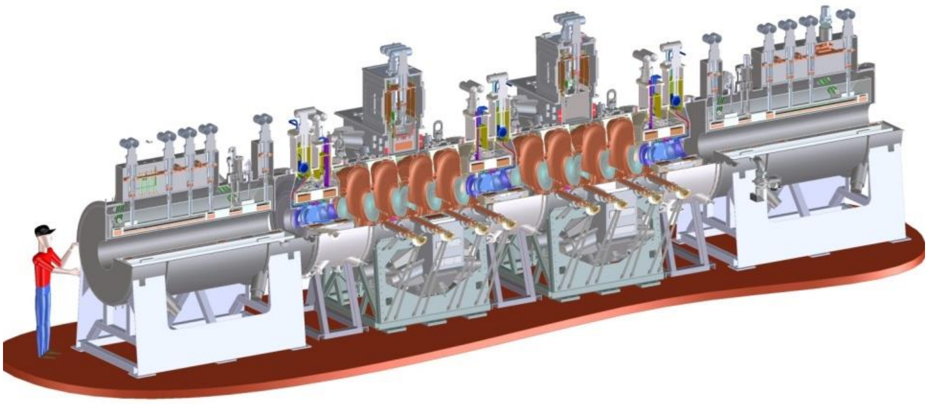

Figure 10: Conceptual design of the MICE configuration

1.3 Summary

The unique feature of muon accelerators is the ability to provide cutting edge performance on both the Intensity and Energy Frontiers. For the last 3 years US Muon Accelerator Program has pursued options to deploy muon accelerator capabilities: 1) Near term (NuSTORM), 2) Long term (NuMAX), and 3) Along with the possibility of a follow-on Muon Collider option. In light of the recent P5 recommendations that this directed facility effort no longer fits within the budget-constrained US research portfolio, the US effort is entering a ramp-down phase.

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