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AN ENGINEERING PROTOTYPE OF A LATE STAGE IONIZATION COOLING CELL FOR A MUON COLLIDER*

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Abstract

Achieving the low emittances necessary for a muon collider requires ionization cooling. Much of that cooling occurs in compact cooling cells where superconducting coils and conventional RF cavities are closely interleaved. The real challenges for these cooling cells reside in their engineering challenges: high field solenoids, RF cavities, and absorbers, often designed near technological limits, placed in close proximity to each other. We thus propose to build a prototype ionization cooling cell to demonstrate the capability of constructing an ionization cooling channel reaching the lowest emittances and to provide engineering input for the design of such beamlines. The magnets and cavities will be powered at their design values, and an absorber will be included along with a mechanism for heating the absorber similarly to how a beam would.

THE RECTILINEAR COOLING CHANNEL

To achieve a high luminosity in a muon collider, the transverse emittance of the muon beam must be rapidly reduced, on a time scale comparable to the muon lifetime. This is accomplished by passing the muon beam through matter, reducing the beam momentum, then re-accelerating the beam restoring only the longitudinal momentum, resulting in a reduction of transverse momentum and thereby transverse emittance. To minimize the increase in the beam emittance due to scattering in the matter, the beam must have a high divergence when it passes through the material, requiring strong focusing to generate a small beta function in the absorber. As the beam emittance is reduced, the required beta function reduces in proportion, thus requiring increasingly stronger focusing and higher magnetic fields to accomplish that focusing as the beam cools.

Most cooling in currently proposed muon collider designs comes from a rectilinear cooling channel. The cooling channel consists of repeated compact cells laid out in a straight line. Each cell consists of one or two RF cavities, an identical number of absorbers, all of which are surrounded by a number of solenoids to focus the muon beam. The longitudinal field goes through a single oscillation through the cell, and is roughly zero at the absorber. The oscillatory magnetic field enables the beta functions at the absorber to be lower than one could achieve with a uniform solenoid field with the same maximum field magnitude. Dispersion and wedge-shaped absorbers are used to reduce longitudinal emittance by coupling the longitudinal and transverse dimensions.

A first, complete rectilinear cooling channel for a muon collider has been designed and simulated [1]. Two mechanisms are known to limit the achievable emittance: collective effects, primarily related to the short bunches [2], and the dynamic acceptance of the channel reducing more rapidly than the equilibrium emittance [3]. Engineering considerations where taken into account to a limited degree for that design. For the final stage of the design, a more detailed study of the magnets was performed [4], showing that the magnet design was reasonable.

A COOLING CELL PROTOTYPE

The primary challenge in a cooling channel is to create the magnetic and RF fields specified by the beam simulations when all the required components must be integrated into a beamline.

A cooling cell must be compact with high magnetic fields to achieve its low beta functions, and its performance is correlated to the amount of RF voltage achievable per cell. The superconducting magnets must be in close proximity to RF cavities operating at a significantly different temperature. Forces from the magnets must be supported. RF power must be delivered to the RF cavities. An absorber must be integrated into the system. Heat deposited by the beam in the absorber and from muon decays must be managed.

We propose to build a 1.5 cell prototype of an ionization cooling cell. The prototype would construct and power everything that would be required for a cooling cell in a functional ionization cooling channel. It would be a model of the most challenging cell that could be constructed with readily available technology. It would demonstrate that a cooling cell that causes the muon beam to reach the lowest emittances in the rectilinear cooling channel can be constructed and operated. The design process would provide essential information on engineering limitations to be used in the beam physics design of ionization cooling channels. The prototype would contain RF for one cell, magnets for that cell, and magnets for the half cells on either side of the central cell so that the magnets and RF cavities see fields and forces close to what they would have in the full channel.

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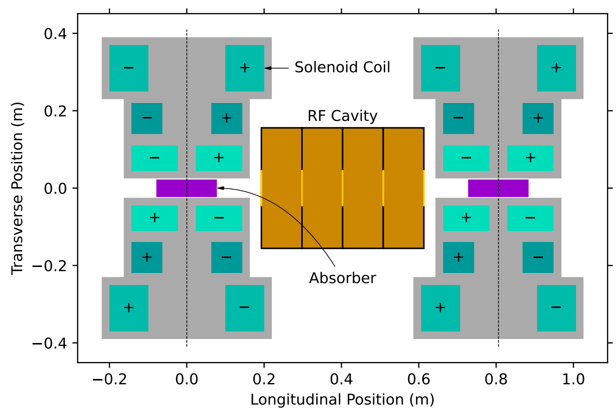

Figure 1: Prototype layout based on the final cooling stage of [1]. Vertical dashed lines are the boundaries of what would be the periodic cell.

The cooling cell prototype needs to be considered in the larger context of an ionization cooling prototyping and demonstration program. The solenoids being used are somewhat unique and will likely require an early prototype program. Large RF gradients in high magnetic fields can lead to breakdown if not carefully managed. Experiments have demonstrated that beryllium cavity walls can allow high gradients to be reached [5], but there are good reasons to want to consider other options, such as aluminum [5], hard copper alloys [6], or copper at cryogenic temperatures [7]. Thus an expanded program should be undertaken, at RF frequencies similar to what would be used in a muon cooling channel.

A muon cooling demonstrator that puts beam through a significant number of cooling cells should also be built. The demonstrator would use less challenging cooling cells to keep costs manageable and to avoid issues related to dynamic acceptance [3]. It would also address delivering and measuring the muon beam, and operating such a channel.

PARAMETERS FROM SIMULATION

Since we wish to prototype a cooling cell reaching the lowest emittances achievable in a rectilinear cooling channel, we start with the parameters from the final stage of the cooling channel in [1]. Figure 1 shows how the components in the prototype would be laid out if we built that cell.

Each cell has two sets of three types of coils, placed symmetrically with respect to the cell boundary as shown in Fig. 1; geometric parameters and current densities in [4]. The axis of each solenoid is tilted by 0.6 degrees, with the tilt signs alternating from one group of 3 to the next, to generate a dipole field which will induce dispersion in the beam. We do not expect a physical solenoid tilt to be the best way to produce that dipole field, a canting of the solenoid winding is likely to be a better solution.

The RF cavity is modeled as four 650 MHz ideal closed cylindrical pillbox cavities, each 105 mm long, and having a maximum accelerating gradient of 28 MV/m. There are 25 μm beryllium windows at the entrance and exit of each

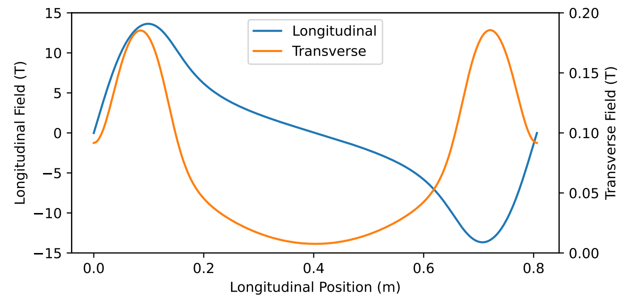

Figure 2: Magnetic fields on the axis one cell. On the axis, the transverse fields are all in the same direction.

cavity to reduce the ratio of peak surface to accelerating fields. The cavity apertures have a radius of 45 mm. This simplistic model will need to be replaced by an actual cavity design, which will have a different geometric footprint, due to the cavity cell shape, space required for input couplers, and other required hardware.

The absorber is a wedge (extruded triangle) of lithium hydride, with a 120° angle at the point of the triangle, which is 11 mm from the beam axis. The face of the triangle opposite that point is 45 mm away, and the wedge is 45 mm thick in the extruded direction. The solenoid tilt axis is perpendicular to the extrusion axis of the wedge.

Figure 2 shows the field for the cell we are using as the initial basis of the prototype. The goal of the prototype is not necessarily to recreate the exact coil geometry described above, but to reproduce the magnetic field profile, and create the required RF acceleration. We will adjust the coil layout and current densities to produce that field profile while limiting engineering complexity.

MAGNET DESIGN PLAN OVERVIEW

The proposed Muon Cooling experiment consists of three major systems: SC magnets (solenoids), RF cavities, and the beam pipe with absorbers. Conceptual design studies (CDS) and modeling of these systems is a key step toward practical demonstration of 6D muon cooling. The CDS will demonstrate feasibility and technological limits of the major systems of the muon cooling channel, assess the technological readiness of the system for engineering design and fabrication, and develop the R&D plan, resource requirements, and timeline.

The magnet analysis in [4] showed that the required solenoid field profile with maximum field in the aperture of 15.1 T can be generated by multilayer superconducting (SC) solenoid coils made of two superconductors, Nb_3Sn and Nb-Ti. The dipole field component was generated by special shell-type dipole coils. All the coils are placed inside a strong stainless steel mechanical structure to control the coil deformations and stresses under large Lorentz forces. Magnet operation at 4.5 K limits the quench margin of the SC magnet system, which is determined by Nb_3Sn coils, to 91%. Magnet operation in superfluid liquid He would increase its quench margin to 85%.

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Comprehensive CDS of SC magnets would focus on the following tasks:

Magnetic Design and Analysis: This task will optimize the solenoid coil configuration to provide the required field components (solenoid, dipole) along the beam orbit (Fig. 2) and coil operating margins based on selected superconductors, conductor geometries, and performance parameters. The dipole field component will likely be produced by introducing an axial coil block top-bottom asymmetry. Possible field errors related to conductor geometries and coil geometrical errors during fabrication and operation need to be carefully addressed. Optimal conductor grading will help to minimize the solenoid coil volume and its cost.

Conductor Design and Performance Parameters: The three radial layers of solenoid coils placed in radially reduced field suggests conductor grading in the coil. The innermost layer will be exposed to magnetic fields above 15 T and, thus, requires using Nb_3Sn. The other two layers may use Nb-Ti. The possibility of further Nb-Ti conductor grading needs to be studied and optimized. Using Rutherford cables for coil winding looks to be an attractive option from the viewpoint of solenoid fabrication, operation, and protection. Practical experience with large-aperture solenoids made of Nb-Ti Rutherford cable exists and looks very promising [8].

Mechanical Design and Analysis: To stabilize the magnetic field characteristics and to reduce the probability of spontaneous quenches caused by turn motion, it is necessary to ensure the mechanical stability of turns in the solenoid coils. Finite element analysis has to be performed to optimize prestress of various solenoid coils, to minimize stress in major elements of the coil support structure, and to determine the coil cross-section deformation at room and helium temperatures. This analysis will develop a robust mechanical design that is tolerant of manufacturing uncertainties in prestress and part sizes.

Magnet Powering and Quench Protection: The key topics of this task are the electrical connections of various solenoid coils inside an individual magnet and the magnet connection to the power supply, as well as the quench protection problem analysis and optimization. The magnet design and cable parameters as well as the parameters of the quench protection system should be chosen and optimized to provide reliable magnet protection during a quench.

Cryostat Design and Thermal Analysis: A superconducting solenoid cryostat includes a vacuum vessel, thermal shields, superinsulation, support system, current leads, cryogenic feedthroughs, and instrumentation. To keep the magnet at its nominal operating temperature, a cryostat design has to be optimized to minimize the three main heat leak components: convection, radiation, and conduction. Thermal and mechanical analysis for the cryostat has to be performed in cooling-down, warming-up, and operation modes, including magnet quench.

System Integration: The aforementioned tasks overlap with and impact each other. The design and analysis iteration process will choose the optimal design solution and performance parameters. Interaction and feedback to and from beam dynamics and radiation studies is critical. This task should also provide synergies with ongoing developments in other fields and SC magnet R&D programs.

RF DESIGN PLAN

An RF system needs to be designed that ideally would achieve equal or better performance to the design described above. Power must be delivered to the cavity, requiring not only an RF power source but also waveguides and input couplers. Cooling of the cavity must be included. The physical space required for this and support for the cavity must be incorporated in the mechanical design that includes the solenoids, beam pipe, and other components. The RF design program would include the following tasks:

Decide upon the type of the cavity with input from the studies on RF breakdown in magnetic field: Based on our understanding of RF breakdown and the corresponding mitigation methods, studied in the program described above, we will adopt the cavity type that represents the best chance to achieve high gradient for ionization cooling, including considerations of engineering feasibility, cost, and safety.

Design the RF cavity: The cavity design highly depends on the type of the cavity. Each type of cavity has its own challenges and design focus. For example, for the copper cavity with beam windows, the main challenge is the production of the extremely thin beam windows, and the corresponding mechanical stability and thermal heating management. For the cryogenic copper cavity, the integration of the cryogenic system of both the cavity and the surrounding SRF magnet will be the first of this kind, and requires detailed engineering studies. The auxiliary parts, such as RF power feeding coupler, the cooling circuit, the frequency tuner, the vacuum system, etc. should be studied as well. They affect not only the RF performance, but also the surrounding SRF solenoid. Another possible important consideration is the higher order modes (HOMs), especially for closed cavities with beam windows. HOM dampers should be implemented if deemed necessary by a beam dynamics study. Multipacting simulations are an essential component of the design process [9].

Optimize the integration between the RF and the SRF magnet system: These two systems are highly coupled with each other. The dimensions for the RF system are bounded the minimum bore size of the magnet. Also the magnet needs to leave longitudinal gaps for RF power feed lines to pass through. Both systems require vacuum, cooling, feedback controls, safety systems, etc., with potential novel synergies between them. The design of both systems should converge and be optimized as a whole.

A 805 MHz cavity cell design, including a method for distributed coupling to a cavity constructed from those cells, is described in [10]. The design could be scaled to 650 MHz. Since the results in [5] showed high gradients in magnetic fields could be achieved with beryllium walls, this design extends the required beryllium foils to sufficient radius that the field on the copper cavity walls is sufficiently low.

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