Alternative muon front-end for the International Design Study (IDS)

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Abstract

We discuss alternative designs of the muon capture front end of the Neutrino Factory International Design Study (IDS). In the front end, a proton bunch on a target creates secondary pions that drift into a capture channel, decaying into muons. A sequence of RF cavities forms the resulting muon beams into strings of bunches of differing energies, aligns the bunches to (nearly) equal central energies, and initiates ionization cooling. This design is affected by limitations on accelerating gradients within magnetic fields. The effects of gradient limitations are explored, and mitigation strategies are presented.

INTRODUCTION

The goal of the IDS is to deliver a reference design report by 2012 in which the physics requirements are specified and the accelerator and detector systems are defined, with an estimate of the required costs [1]. The baseline consists of a proton source with 4MW beam power (50 Hz, 5-15 GeV protons, 1-3 ns bunches, $\sim$ 5 x10^{13} protons/bunch), a target, capture and cooling section that produces pions that decay into muons and captures them into a small number of bunches and an accelerator that takes the muons to 25 GeV and inserts them into storage rings. Muon decay in the straight sections provides high-energy neutrino beams for 100 kton neutrino detectors at 4000-7500 km baselines with sufficient resolution to identify neutrino interactions. The goal is $> 10^{21}$ neutrinos/beamline/year in order to obtain precise measurements of neutrino oscillation parameters. The present paper discusses alternative muon capture and cooling systems to the baseline discussed in [2].

RF GRADIENT LIMITATIONS

The π capture concept requires the use of RF fields near the Kilpatrick limit in 1-3 T solenoidal magnetic fields. In the buncher and rotator, RF cavities in a constant 1.5 T field are needed with gradients up to 13 MV/m at frequencies in the range 200-320 MHz. The cooler uses 200 MHz RF operating at 15 MV/m within a 2.7 T alternating solenoid field. Recent experiments appear to show that RF breakdown occurs at reduced gradient in magnetic fields. An 800 MHz Cu cavity that ran with peak field of 40 MV/m in the absence of fields achieved only 20 MV/m at 2 T and 15 MV/m in a 4 T solenoid. A 200 MHz test cavity obtained $>$ 20 MV/m in the absence of field but showed reduced performance in a weaker solenoid fringe field. Two models have been proposed for the breakdown; in one model emitted electrons are focussed by the solenoidal field resulting in cavity heating and subsequent damage [3]; in the second the field induces a torsional force on electrons moving within the cavity surface resulting in the destruction of the cavity [4]. Operation of 200 MHz RF within a stronger solenoid field will be tested soon [5], but it is not yet certain whether operation at baseline design parameters is possible. If limitations are found, we have several mitigation strategies that can be considered in maintaining a practical design.

BERYLLIUM CAVITIES

If surface heating is found to be the cause of RF cavity breakdown, one solution may be to use a different material for the cavity surface [6]. Beryllium has dual advantages of low density, leading to less energy deposition per unit volume, and low thermal expansion, perhaps resulting in less damage. This may result in higher RF gradients. Unfortunately Beryllium dust is toxic leading to a number of handling and safety issues that would need to be overcome.

MAGNETICALLY INSULATED CAVITIES

A novel idea for improving the cavity's gradient by suppressing breakdown events caused by field emissions on its surfaces has been proposed [7]. The concept involves designing an RF cavity with walls parallel to the contour lines of the external magnetic fields, thereby redirecting field-emitted electrons back to the cavity surface before they gain energy from the RF electric field. Such a cavity together with the proposed design of a lattice cell with magnetically insulated cavities for use in the final 6D cooling for a muon collider is shown in Figure 1. Simulations [8] examined the performance of those lattices and showed that they perform equally well to conventional lattices with pillbox cavities.

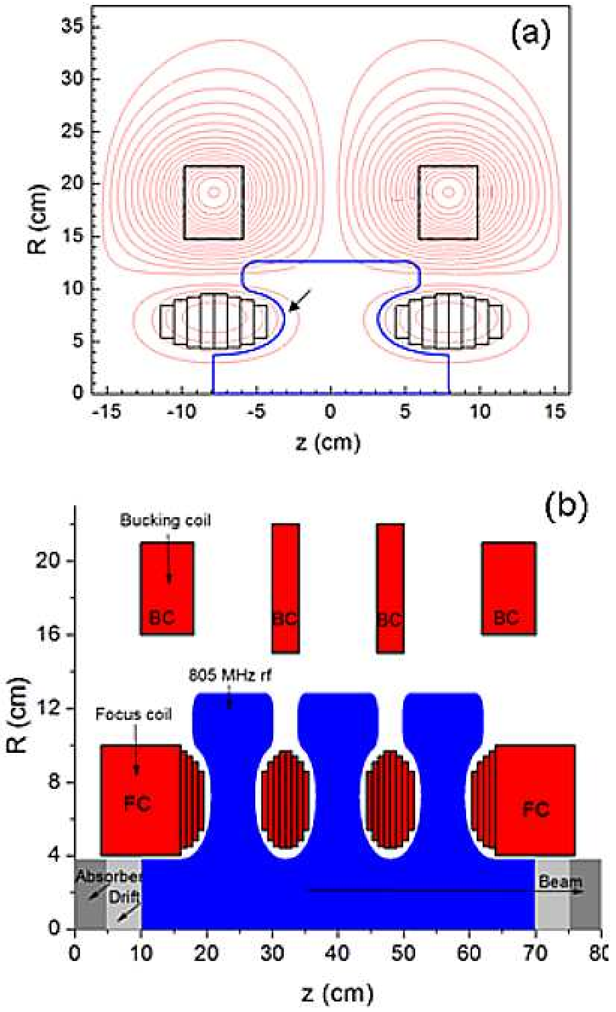

Figure 1: (a) Magnetically insulated cavity modelled in Poisson Superfish; (b) a cell of a muon collider lattice with magnetically insulated cavities.

GAS-FILLED RF CAVITIES

Experiments have shown that H_2 gas-filled RF cavities suppress RF breakdown in high magnetic fields, and can provide superior cooling to LiH slabs, since H_2 has less multiple scattering. Replacement of the LiH slabs requires a pressure of 120 atm of H_2 at room temperature, which may be challenging to implement. Gallardo and Zisman [9] have proposed to use only sufficient pressure to suppress breakdown (10-34 atm at room temperature) while introducing thinner LiH slabs to provide the added energy loss. This will provide adequate cooling with a minimal number and thickness of vacuum windows.

There is a concern that acceleration of ionization electrons produced in the gas may drain energy from the cavities and this is under investigation

MAGNETICALLY SHIELDED RF CAVITIES

We have developed [10] a lattice for the cooling section that has a much longer cell length and shielding of cavities, such that the magnetic field in the cavities is < 0.1 T. The increased cell length results in either weaker focussing and a worse cooling performance, or decreased acceptance and a worse transmission. However, with liquid H_2 absorbers, adequate cooling can be obtained. The advantage of this method is that the cooling channel requires little additional hardware development and can reproduce the nominal performance of the IDS baseline cooling channel, albeit with an increased hardware requirement and hence additional cost. In Figure 2 a schematic of the shielded cooling channel is presented. A 3 m half cell length has been used, enabling an RF packing fraction of 1/3. Due to the slight residual field and requirement for high gradient on-axis, normal conducting RF would be used. The coils have a 400 mm inner radius, 100 mm radial thickness and are 1 metre in length. Coil current densities are in the range 15-25 A/mm^2, indicating superconducting magnets might be preferable. The low current density relative to the FS2A baseline is seen as an advantage, as it may enable more radiation-hard superconductor and a more conservative temperature margin to be used in a linac that may have significant losses.

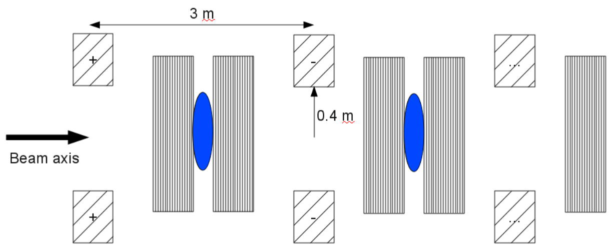

Figure 2: Schematic of the shielded RF lattice. Coils are shown with diagonal hatching, RF cavities vertical hatching and Hydrogen absorbers as filled ellipses.

In Figure 3 the rate of particles in a nominal accelerator acceptance is shown. Two variants of the shielded lattice are compared with the FS2A baseline [11]. The first variant has optical β of 1.2 m at the absorber and reference momentum of 230 MeV/c, with a comparable amount of hardware to the FS2A baseline. The other variant has a short section of acceleration, enabling better acceptance, followed by a cooling section. The optical β is also 1.2 m at the absorber but the reference momentum is 330 MeV/c. This leads to a better cooling performance but, as dp/p in each absorber is smaller, the cooling channel is longer, more hardware is required and cost is expected to be greater.

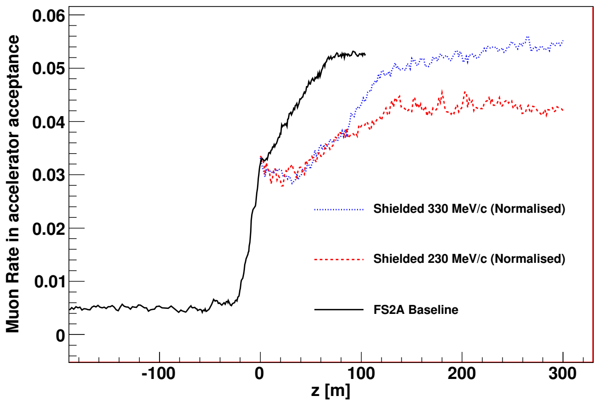

Figure 3: Rate of particles in an acceptance of 30 mm transverse, 150 mm longitudinal and +/- 100 MeV/c for variants on the shielded lattice as compared with the baseline.

LOWER FREQUENCY LATTICE

A lower frequency design was studied at CERN [12]. The target is followed by a 30 m long decay channel in a 1.8 T solenoidal field. A the end of the channel, a set of 44 MHz cavities with 2 MV/m field gradient rotates the muon bunch into one muon sign in a single bucket. The muons are then cooled using 44 MHz, 2 MV/m RF cavities interspaced with liquid Hydrogen absorbers. After this first cooling section, there is an intermediate acceleration stage using 44 MHz, 2 MV/m RF cavities followed by a second cooling stage using 88 MHz, 4 MV/m RF interspaced with liquid hydrogen absorbers. At the end of the second cooling stage, the muons are accelerated using 88 MHz, 4 MV/m and 176 MHz, 10 MV/m cavities to 2 GeV. Simulations were performed in the past using PATH [13] with reasonable transmission and cooling. A different proton beam structure was assumed to the current IDS baseline, with 2 GeV kinetic energy and a 75 Hz repetition rate. FLUKA [14] was used to provide the particle output at target.

A new simulation is being performed in ICOOL [15] using the IDS baseline proton beam parameters and particle output from MARS [16]. The size and configuration of the cavities may allow a breakdown-free solution by fitting the coil inside the cavity nose [17]. The cavity design will be re-examined if the simulation shows no degradation of the muon acceptance. The IDS acceleration stage after the front-end is designed based on 201 MHz cavities and a matching from the front-end to the acceleration system would require further study.

EXPERIMENTAL PROGRAM

An experimental program exploring RF gradients within magnetic fields is underway at Fermilab and will provide guidance in setting parameters for the IDS study. Simulations are also studying the above design variations. The IDS design will be modified as research establishes a reliable RF and magnetic configuration.

CONCLUSIONS

The muon front end group of the IDS has examined a number of options for alternative lattices that may be used to improve the front end performance and overcome obstacles such as the possibility of enhanced RF breakdowns in the presence of magnetic fields. Options have been demonstrated to match the baseline, but either require further hardware development to prove feasibility or are expected to be more costly.

ACKNOWLEDGEMENTS

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