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Abstract. The primary subject of working group 7 at the 2012 Advanced Accelerator Concepts Workshop was muon accelerators for a muon collider or neutrino factory. Additionally, this working group included topics that did not fit well into other working groups. Two subjects were discussed by more than one speaker: lattices to create a perfectly integrable nonlinear lattice, and a Penning trap to create antihydrogen.

Keywords: muon collider, neutrino factory, integrable optics, Penning trap, antihydrogen, positron source

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MUON ACCELERATORS

Overview [M. Palmer]

The physics motivation for a high energy muon accelerator is twofold: to have collisions of elementary particles at the highest possible energies, and to have a high-intensity neutrino beam with a well-defined energy spectrum. For high-energy collisions, muons, like electrons, provide a precision probe of fundamental interactions, in contrast to hadron colliders. Muons, being 200 times heavier than electrons, have significantly less synchrotron radiation than electrons, allowing them to be bent. This permits multiple collisions in a circular collider ring, as well as acceleration making multiple passes through the RF cavities. Beamstrahlung is also significantly reduced for the same reasons. Muons also give a larger coupling to the Higgs mechanism, in the ratio of the squares of the particle masses. For neutrino production, muon decays provide equal fractions of electron and muon neutrinos with a well-defined spectrum, which can be easily distinguished in a magnetized detector.

The muon accelerator program (MAP) has the goal of establishing conceptual feasibility of a muon collider. They want to

- Demonstrate the feasibility of key concepts needed to build a multi-TeV muon collider
- Develop the critical elements of neutrino factory and muon collider designs
- Support an ongoing accelerator R&D and concept demonstration program
- Coordinate with the detector and HEP experimental community
- Support fundamental accelerator technical development that has the potential to contribute significantly to the machine design

Both a muon collider and neutrino factory consist of a number of subsystems. They begin with a proton driver producing a multi-MW beam. This beam hits a target, producing pions which decay into muons. Those muons are manipulated into a bunch train, which then has its phase space area reduced via ionization cooling. In a neutrino factory, there is a minimal amount of ionization cooling, and it is only in the transverse direction. For a muon collider, much more cooling is needed, and it must occur in all phase space dimensions. The resulting beam is then accelerated. For a neutrino factory, the final energy is about 10 GeV, at which point the beam enters a decay ring with long straight sections pointed toward a far-away detector. For a muon collider, the beam enters a collider ring at an energy in the TeV range.

There has been recent progress in a number of areas. For the Muon Ionization Cooling Experiment (MICE), significant progress has been made in the production and testing of the spectrometer and coupling solenoids. A cavity has been tested at high gradient with buttons made of different materials to understand how RF breakdown depends on cavity material. Cavities filled with hydrogen gas have been tested [1]. They have demonstrated a higher breakdown voltage in the presence of magnetic fields when compared to vacuum cavities. They have also tested adding a dopant

gas to the hydrogen to mitigate the effects of the beam-induced plasma on the cavity voltage. Very high field solenoids, useful for ionization cooling to very low emittances, have been constructed and tested.

The R&D priorities for the collaboration are primarily related to ionization cooling: understanding RF breakdown in magnetic fields, constructing high field solenoids, and a bench test of a 6-D cooling channel. They need to choose baseline concepts for the subsystems, particularly for cooling. Finally the solenoids around the target area that capture the pion beam present significant engineering challenges which must be addressed.

125 GeV Higgs Factory [D. Neuffer]

As an early stage of a muon collider, one could accelerate to a lower energy, to study the Higgs [2]. One can create a muon beam with a very small energy spread that allows one to resolve the Higgs resonance. The cooling process for a muon collider involves reduction of both transverse and longitudinal emittance, then a final stage where the transverse emittance is reduced and the longitudinal emittance is increased; the Higgs factory would skip this final stage to utilize the small longitudinal emittance. A 2 MW proton driver, instead of the 4 MW specified for the high energy collider and neutrino factory, should be sufficient for this machine. The energy could be precisely measured using beam polarization [3]. One could start with a 90 GeV machine producing Zs to have a machine for which the resonance scan would be simpler (due to the wider resonance). This would allow useful physics to be done while getting an operational understanding of how to perform the required measurements for the Higgs.

Ionization Cooling

Optimization of the Front End Channel [D. Stratakis]

Results from RF cavity tests have indicated that there may be problems operating cavities at high gradients in high magnetic fields. There is therefore a desire to study ionization cooling channel designs with lower fields at RF cavities. A design incorporating bucked solenoid coils has been proposed [4] for both the cooling and phase rotation sections of the neutrino factory front end. Longitudinal and radial arrangements of the bucked pairs have been studied. There appears to be an approximately 20% reduction in performance when using the bucked coils.

Engineering studies showed that additional space needs to be added to the lattice cells in the neutrino factory cooling channel. The effects of this additional space requirement are also being studied.

Charge Recombination [R. Fernow]

In a muon collider, different charge signs must be cooled in separate beamlines. The bunches must be merged into a single channel for subsequent acceleration. Such a recombination channel was successfully designed. Simulation showed good transmission and small emittance growth.

Improvements to a 805 MHz Cavity [Z. Li]

To try to increase the threshold for RF breakdown in prototype cooling channel RF cavities, a re-design of an existing 805 MHz cavity was undertaken [5]. The cavity design was improved to reduce surface fields. Corners on the input coupler were rounded, the iris edge was given a more elliptic shape, and the input waveguide was improved with a smaller coupling slot. The improved cavity had reduced surface fields.

Multipactoring simulations showed results that were consistent with damage seen in the cavity. The redesigned cavity gave a large improvement in multipactoring at the coupling slot. Field emission simulations showed a lower field emission current in the new design.

These results were used to optimize the cavity length. The optimum length was around 80 cm.

Hydrogen Gas Filled RF Cavity [K. Yonehara]

One can fill RF cavities with hydrogen gas in an ionization cooling channel. The gas becomes the absorber needed for ionization cooling. In addition, the gas stops dark currents, preventing breakdown in magnetic fields. The gas also acts as a coolant, and may make the cavity less sensitive to surface quality.

When a beam passes through the gas, the beam induces a plasma. The cavity voltage drops quickly after the beam enters because of this. An electronegative gas can be added to the cavity to reduce this energy loss [1]. There was less energy loss measured with a higher gas density, but this loss was lower than a computed estimate.

Solenoids for Final Cooling [H. Kirk]

The final cooling stages in a muon collider would like to have 30–40 T solenoids. Solenoids which could be parts of such a high field magnet have been constructed using the high temperature superconductor (HTS) YBCO. Two YBCO solenoids were constructed, an “insert” and a “midsert”, the former fitting inside the latter. Half the midsert was constructed and tested. It reach a peak field on the coil of 9.2 T and an axial field of 5 T. The full midsert is expected to reach an axial field of 10 T. The full insert reached a peak field on the coil of 16 T which corresponds to an axial field of 15 T [6]; this is a world record for an HTS solenoid.

The next steps in this project will be to combine the two solenoids to achieve 22 T. The combination will then be inserted into a 20 T resistive solenoid at the National High Magnetic Field Laboratory in Tallahassee. There are plans to construct a Nb₃Sn outsert, to create a 35 T magnet entirely of superconducting coils.

Parametric Ionization Cooling [V. Morozov]

Parametric ionization cooling in theory can achieve very low muon beam emittances by choosing a working point on a half-integer resonance [7]. One proposed implementation of this uses helical fields to avoid problems arising from magnet ends. It has a superimposed quadrupole field. To achieve good performance in this lattice, work needs to continue in correcting aberrations.

Acceleration [J. S. Berg]

The cost and efficiency of accelerating muon beams can be reduced by making a large number of passes through the RF cavities. The arcs need to have a high average bend field and the average RF accelerating gradient must be large to minimize muon decays. Controlling the beam’s time of flight to maintain RF synchronization and minimizing magnet apertures are also important design considerations. Two novel types of accelerators can help meet these requirements: fixed field alternating gradient accelerators (FFAGs) and hybrid synchrotrons.

FFAGs keep the fields in the magnet fixed, and accelerate the beam by around a factor of 2 [8]. They have a parabolic-like variation of time of flight with energy, which leads to a so-called “serpentine” mode of acceleration. The number of turns that can be achieved is limited by dephasing from the RF and longitudinal emittance distortion. The EMMA experiment [9] successfully demonstrated acceleration in a non-scaling FFAG.

An ordinary synchrotron increases its bending field with beam momentum. A hybrid synchrotron [10, 11] accomplishes the same thing on average by alternating fixed field superconducting dipoles with bipolar ramped dipoles. One has more control of the beam parameters than in an FFAG because the ramped dipoles and quadrupoles can be used to keep the tunes and time of flight constant, as well as minimizing the orbit excursion in the magnets. This allows one to achieve even more turns in a hybrid synchrotron than one would have in an FFAG.

INTEGRABLE OPTICS [D. BRUHWILER, S. NAGAITSEV, A. VALISHEV]

Introduction of additional tune shift with amplitude into an accelerator can be beneficial. It will improve the Landau damping of beam instabilities, and may improve stability of the machine against perturbation. Increasing the tune shift with amplitude requires increasing nonlinearities, which generally will negatively impact dynamic aperture. However, if the lattice is integrable, one can have a large tune shift with amplitude while maintaining a good dynamic aperture.

There are at least two methods for creating an integrable lattice in practice [12]. One can use an electron lens, or one can make a nonlinear lens profiled to match the lattice beta function.

An integrable lattice has been simulated using PyOrbit [13], including space charge at the level of the SNS. The integrable lattice gives good beam halo suppression both using a truly integrable optics lattice, as well as an octupole approximation to the nonlinearities.

An accelerator to test integrable optics has been proposed. Four experiments can be accommodated within the test machine: a thin electron lens, a thick electron lens, approximation of an integrable elliptic lattice magnet with octupole magnets, and magnets with the required profile for the integrable elliptic lattice. One can compare the dynamic aperture for an octupole approximation to the true integrable optics magnet.

PENNING TRAP FOR ANTIHYDROGEN [C. SO, J. WURTELE]

The Alpha experiment uses a Penning trap to create antihydrogen [14]. The Penning trap potentials are modified over time to first trap low energy antiprotons and positrons, then colliding the beams to produce electron cooling of the antiprotons and creating antihydrogen. The Zeeman shift in antihydrogen has been measured [15]. Frictional cooling should be able to increase the trapping rate.

The antihydrogen trap was simulated using a Vlasov-Poisson simulation for the positrons and a quasi-static Poisson-Boltzmann simulation of positrons. The results were compared with experiments, both for autoresonant excitation and injection.

OTHER TOPICS

Acceleration in a Crystal [V. Shiltsev]

In future energy frontier colliders, it is desirable to keep costs, size, and power limited to reasonable values. Simultaneously we would like to gain a large factor in performance over previous generation machines. One way of achieving this is by acceleration in a crystal, where the acceleration is driven by X-rays [16]. Theoretically one can achieve gradients approaching 1 TeV/m with this method. Muons are the best particles to accelerate in this fashion, though protons could be used as well. One gets transverse focusing simultaneously with the acceleration in the crystal.

Accelerators in a 233 km Tunnel [D. Summers]

A 233 km tunnel has been proposed which could house three different colliders: an e^+e^- collider at 240 and 500 GeV center of mass energy, a 40 TeV $p\bar{p}$ collider, and a 35 TeV muon collider [17, 18]. A 15 km tunnel would also be required on the Fermilab site.

The e^+e^- collider would use a crab waist crossing, but this makes beamstrahlung worse. A precision damping ring similar to the one required for the ILC would be needed on the Fermilab site. The ring could be used for Z - h production. It would have a luminosity of $6.3 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ at 240 GeV and $3.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at 500 GeV (including beamstrahlung).

The $p\bar{p}$ collider would use 2 T YBCO magnets with iron poles. It would have a luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$.

The muon collider would use the same magnets as the $p\bar{p}$ collider. Beam steering and a helical lattice would be used to reduce neutrino radiation. It would have a luminosity of around $10^{35} \text{ cm}^{-2}\text{s}^{-1}$.

Symplectic Dynamics [B. Erdelyi]

There are a number of theorems and concepts from symplectic dynamics that are of potential interest in beam physics [19]. There is a nonlinear generalization of emittance known as a capacity. One can map one ellipsoid inside another if the ordered eigenemittances are less in the former. A finite set of points can be mapped into another finite set of points. One volume only maps into another if the first volume is less than the second. One volume can be mapped

into another equal volume except for an infinitesimal portion. A “skinny” ellipsoid can get through a hole if it has the correct small dimensions; this is not necessarily possible for a “fat” ellipsoid.

Extreme Fields from Lasers [S. Bulanov]

Using high intensity lasers, two interesting types of experiments are possible: laser-laser collisions and laser-electron collisions [20]. There are three physics regimes, in order of increasing intensity required: radiation effects, QED effects, and Schwinger pair production (only accessible with laser-laser collisions). Thresholds for Schwinger pair production are lower for multiple colliding pulses [21]. The study of laser/e-beam interactions will result in a new powerful source of ultra short high brightness gamma-ray pulses. Electron-positron pair creation in vacuum in a multi-photon processes could also be demonstrated.

Polarized Positron Production [W. Gai]

For the ILC, positrons can be produced using a helical undulator and a rotating target [22]. A parametric optimization has been performed. One can achieve better capture with a flux concentrator instead of a quarter wave solenoid. A lithium lens is under consideration for capture.

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