MUON CAPTURE FOR THE IDS NEUTRINO FACTORY *

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Abstract

We have developed a new method for capture, bunching and phase-energy rotation of secondary beams from a proton source, using high-frequency rf systems. [1] The method is the baseline for muon capture in the International Scoping Study (ISS)[2] for a neutrino factory. In this method, a proton bunch on a target creates secondaries that drift into a capture transport channel. 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. For the International Design Study (IDS), the method must be optimized for performance and cost. In this paper we describe variation studies toward obtaining the maximum number of muons for a neutrino factory, as well as for a future muon collider.

INTRODUCTION

The goal of the IDS-Neutrino Factory 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[3]. The design is based on ref. [4]. It consists of:

- a proton source with a baseline intensity goal of 4MW beam power (50Hz, 10 GeV protons, ~2ns bunches. (~5×10^{13}p/ bunch),
- a target, capture and cooling section that produces π's that decay into μ's and captures them into a small number of bunches.
- an accelerator that takes the μ's to 25 (or 50) GeV and inserts them into storage rings. μ decays in the straight sections provide high-energy ν beams for:
- ~100 kton ν-detectors at 4000-7500km baselines with sufficient resolution to identify ν-interactions.

The goal is > 10^{21} ν's /beamline/ year in order to obtain precise measurements of ν-oscillation parameters.

The present paper discusses the capture and cooling system. Cooling and acceleration of μ's before decay requires relatively high gradient rf (>~10MV/m), and relatively high frequency rf systems are needed to obtain this affordably. We follow ref. [4], and set 201.25MHz rf as an acceptable baseline. The π's (and resulting μ's) are initially produced with broad energy spreads, much larger than the acceptance of any accelerator, and much larger in phase space than a 200MHz rf bucket. In this paper we present a method for capturing this large phase space of μ's into a string of ~200MHz bunches, rotate the bunches to equal energies, where they can be cooled and accelerated to full energy. The method captures both μ$^+$'s and μ$^-$'s simultaneously and can be adapted to feed a μ$^+$-μ$^-$ collider.

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IDS BASELINE SYSTEM

The front end system that is under study here is shown in Figure 1. 10 GeV protons are targeted onto a Hg jet target that is encapsulated in a 20 T solenoid. π's created from the target are captured as they traverse the ~10 m long solenoid, that has a field profile that starts at 20 T and 7.5cm radius at the target and tapers off to ~1.75 T and 25cm radius at the end. This section captures π's and μ's with transverse momenta p_t < eBr/2 = 0.225GeV/c, with an adiabatic damping of the transverse momentum.

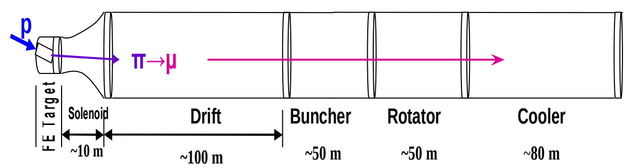

Figure 1: Overview of the front end, consisting of a target solenoid (20 T), a tapered capture solenoid (20 T to 1.75T, 12 m long), Drift section (99 m), rf Buncher (51 m), an energy-phase Rotator (54 m), and a Cooler (80 m).

The taper is followed by a Drift section, where π's decay to μ's, and the bunch lengthens, developing a high-energy "head" and a low-energy "tail". The separation of particles that develops is given by:

$$\delta(\mathrm{ct_i}) = \mathrm{L}\left(\frac{1}{\beta_i} - \frac{1}{\beta_0}\right) ,$$

where δct indicates the time delay from a reference particle of speed β_0, L is the distance from the production target and β_i is the particle longitudinal speed v_z/c.

In the Buncher, rf voltages are applied to the beam to form it into a string of bunches of different energies. This is obtained by requiring that the rf wavelength of the cavity is set to an inverse integer (1/N) of the ct between reference particles:

$$\lambda_{rf}(\mathrm{L}) = \frac{\delta \mathrm{ct}_{0N}}{\mathrm{N}} = \frac{\mathrm{L}}{\mathrm{N}}\left(\frac{1}{\beta_N} - \frac{1}{\beta_0}\right)$$

In ref. 1, the baseline was produced with muons with p_0 = 280MeV/c, p_N = 154 MeV/c and N=18 as reference particles. The reference particles (and all intermediate bunch centers) remain at 0-phase throughout the buncher. The rf frequency decreases from 330 to 240 MHz along the 51m Buncher while the rf gradient in the cavities increases from 0 to 12 MV/m. (see fig. 2)

In the Rotator, the reference particles are moved to accelerating/decelerating phases as the wavelength separation is also lengthened (18 → ~18.05). At the end of the buncher the reference particles are at the same momentum (~215MeV/c) and the rf frequency is matched to 201.25 MHz at the end. μ's with initial momenta from ~80 to 500 MeV/c have been formed into a train of 201.25 MHz bunches with average momenta of ~215MeV/c and $\delta p_{rms}/p \approx 10\%$. The bunch train is ~80m long with ~50 bunches. (see figs. 4 and 5)

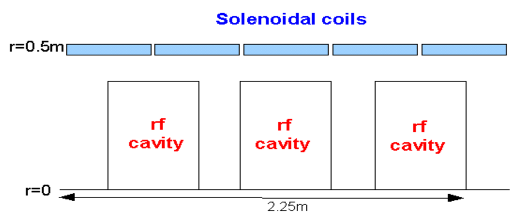

Figure 2: Baseline Layout of RF + magnets in Buncher and Rotator. The rf is in 0.5m cavities with 0.25 drifts, with a 1.75T focusing solenoid field throughout.

The μ's are matched into a cooling section which consists of rf cavities, LiH absorbers for cooling and alternating solenoids for focusing (B oscillates from 2.7 to -2.7T with a 1.5 m period; see fig. 3). After ~60m of cooling, we find that the system accepts ~0.1μ^+/ 10 GeV proton within reference acceptances of $\varepsilon_{L,N}$ <0.15m, $\varepsilon_{t,N}$ <0.03m, which are the acceptances of the downstream acceleration and storage rings. As a bonus, the method simultaneously produces bunch trains of both signs (μ^+ and μ^-) at equal intensities.

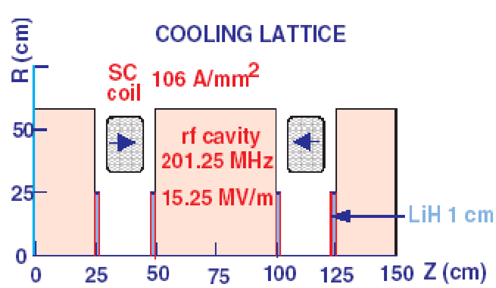

Figure 3: Baseline cooling channel cell layout, with LiH absorbers, rf cavities and focusing coils.

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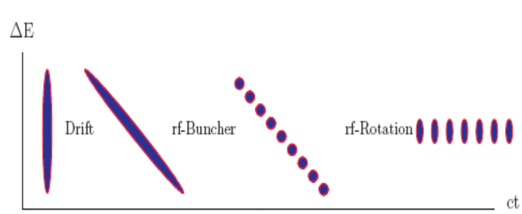

Figure 4: Longitudinal beam dynamics in the front end. A short large-energy spread bunch drifts, developing a time-energy correlation, is Bunched and then phase-energy Rotated to obtain a string of ~equal-energy bunches with small δE.

ADAPTATION TO THE IDS

For the IDS, the method must be reoptimized for practicality and cost. The initial concept had a continuous variation of frequency from cell to cell; an implementation with ~12 separate frequencies in the buncher and in the rotator obtains adequate performance. These rf cavities will be grouped into units with matched power supplies, and the configurations will be costed.

Variations that improve performance and/or reduce cost will be considered. The initial design separated the drift, bunch, rotation and cooling into distinct sections; a more integrated design that combines the functions could be more efficient.

The phase-energy rotation is done adiabatically, a short nonadiabatic high-gradient rotation comprising ¼ synchrotron oscillations is also possible.[1] This was less efficient in simulation, but may be cost-effective.

Performance estimates and optimizations have been and will be obtained using ICOOL[5], G4Beamline[6], and G4MICE[7] particle tracking simulations, and the results are consistent. As rf and magnet designs are developed, more accurate models will be used in these codes.

A variation that improves performance is replacement of the LiH absorbers by H_2 absorbers. Because of the lower scattering. The acceptance is increased by ~25%, although H_2 cooling may increase expense. If the rf cavities are filled with H_2 gas the gas can suppress rf breakdown while cooling μ's. Performance may also be improved by varying focusing along the absorber length. A variant cooling scheme that includes initial δE cooling may also help.

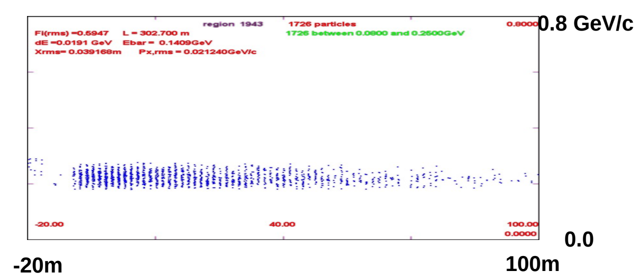

Fig. 5: Captured μ's at end of cooling. (cτ vs P_μ) μ's are captured in a ~80m long train of λ=1.5m bunches. (ICOOL result.)

EXTENSION TO MUON COLLIDERS

The ISS baseline is a relatively long system producing a relatively long bunch train. For the IDS shorter variants will be considered, and in ref. [8] a version with N=10 wavelengths between the reference momenta is developed. In that example, the section lengths are reduced: the Drift is 57m, the Buncher is 31m, and the Rotator is 36m, and slightly larger rf gradients are used. The N=10 variant obtains ~0.08μ^+/ 8 GeV proton in the reference acceptance, within a shorter bunch train than the ISS baseline (<50m). This is approximately as efficient as the ISS baseline.

The same method is also considered for the initial μ-capture section of a μ^+-μ^- Collider[9, 10]. The simultaneous capture of μ^+ and μ^- is an important advantage. The key difference is that the μ's must cooled by much larger factors, and the multiple bunches must be combined into single μ^+ + μ^- bunches for maximal luminosity. The plan is to cool the bunches by large factors, place the bunches at different energies (by rf) and recombine them after a transport. This recombination is easier if the bunch train is shorter, so N=10 or less is preferred. ~70% of the μ's are in the first ~12 bunches at the head of the bunch train and the collider would use only these first ~twelve (see fig. 6). A reoptimization to capture at higher energy (~300MeV/c rather than ~200 MeV/c) also produces a shorter train of bunches with more μ/bunch, but requires early energy cooling for efficient capture.

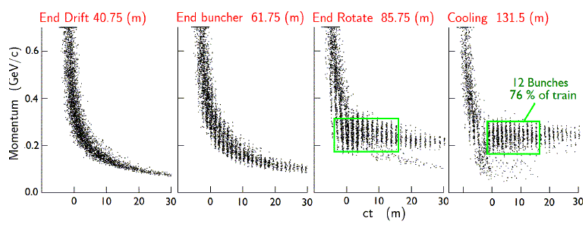

Figure 6: Bunch train generation in a N=7 μ front end; the μ's within the green box are candidates for collider acceptance.

RF GRADIENT LIMITATIONS

The μ capture concept requires using relatively high gradient rf field interleaved with strong solenoidal magnetic fields, and it is currently uncertain that this is possible at the baseline parameters.[11] However there are several mitigation strategies:

1) While 15 MV/m in 2T fields at 200 MHz may break down, lower gradients (4 to 8 MV/m in B =1.3T?) are likely to be practical. A modified (longer) version at lower fields can be implemented if needed.

2) The baseline rf cavities are Cu pillbox with Be windows on axis. Cavity modifications (Be or Al or breakdown-resistant coatings) can extend the gradient ability. Open-cell rather than pillbox cavities may support greater fields.

3) Gas-filled (H_2) rf cavities suppress breakdown in high magnetic fields, and can provide superior cooling to LiH slabs. There is a concern that the large number of ionization electrons produced in the gas may drain energy from the cavities if not neutralized.

4) The magnetic field can be changed from a constant value to alternating solenoid or "magnetically insulated" or to a lattice with low B-fields at rf cavities. The lattice may have more limited acceptance, however. (Recent simulations do show that an alternating-solenoid lattice has acceptable dynamics.)

An experimental program exploring rf gradients within magnetic fields has been initiated and will provide guidance in setting parameters for the IDS study.[11] Simulations are also studying the above design variations. If the results are inconclusive in the IDS timeframe, a conservative configuration will be implemented in the IDS, to be informed and modified as research establishes a secure rf/magnet configuration.

CONCLUSION

We have presented the front end of the IDS neutrino factory as an example of the high-frequency approach for capturing muons from a broad momentum spread into a train of bunches that can then be cooled and accelerated for a ν-factory or muon collider. Variations and constraints on the approach are discussed.

The method is much more general than the present example. Except for the ionization cooling, the method is not specific to μ's and could be adapted for e^+ and $\bar{p}$ capture scenarios. The 200 MHz is a convenient frequency for initial ν-factory design; higher or lower frequencies can be used and may be provide better optima, after cost and field constraints are considered.

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