Neutrino Factory Front-End: muon capture and cooling optimization

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A neutrino factory: why and how ?

Past experiments have demonstrated that neutrinos can change flavour while traveling [1], and as a consequence have a non-zero mass. This physics is not predicted by the Standard Model.

In order to fully explore this phenomena, an intense neutrino beam needs to be produced in a dedicated facility. One of the proposed scheme, the Neutrino Factory [2], uses a 5-15 GeV proton beam on a Hg jet target. The pions produced, decay into muons which need to be captured and cooled with a sophisticated set of devices, due to their short lifetime (see figure 1).

After primary bunching and longitudinal phase rotation of the muon beam in RF cavities, the muon momentum is reduced, using LiH absorbers interleaved with 201 MHz cavities, in which the longitudinal momentum loss is recovered (see figure 2).

At the end of the cooling channel (transverse $A_\perp$=30 mm and longitudinal $A_{//}$=150 mm acceptances) the 200-300 MeV/c muons are accelerated by a series of Recirculating Linear Accelerators (RLAs), followed by a Fixed Field Alternating Gradient (FFAG) ring up to 25 GeV.

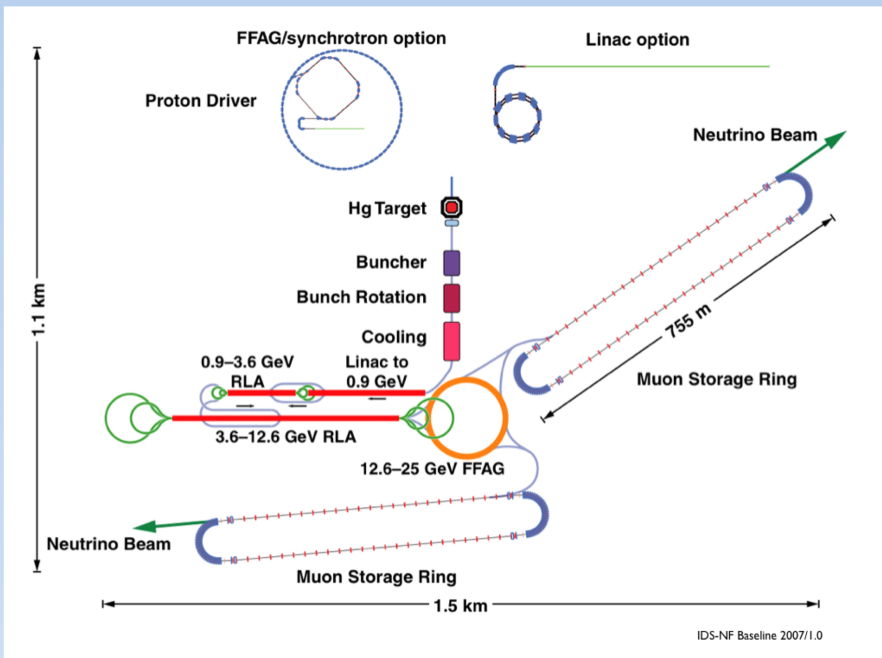

Fig. 1: The Neutrino Factory layout

An intense neutrino beam is created by the decay of muons in few turns inside a storage ring and sent to 2 detectors potentially located at 4000 and 7500 km, where precision measurement of the neutrino oscillation parameters will be done.

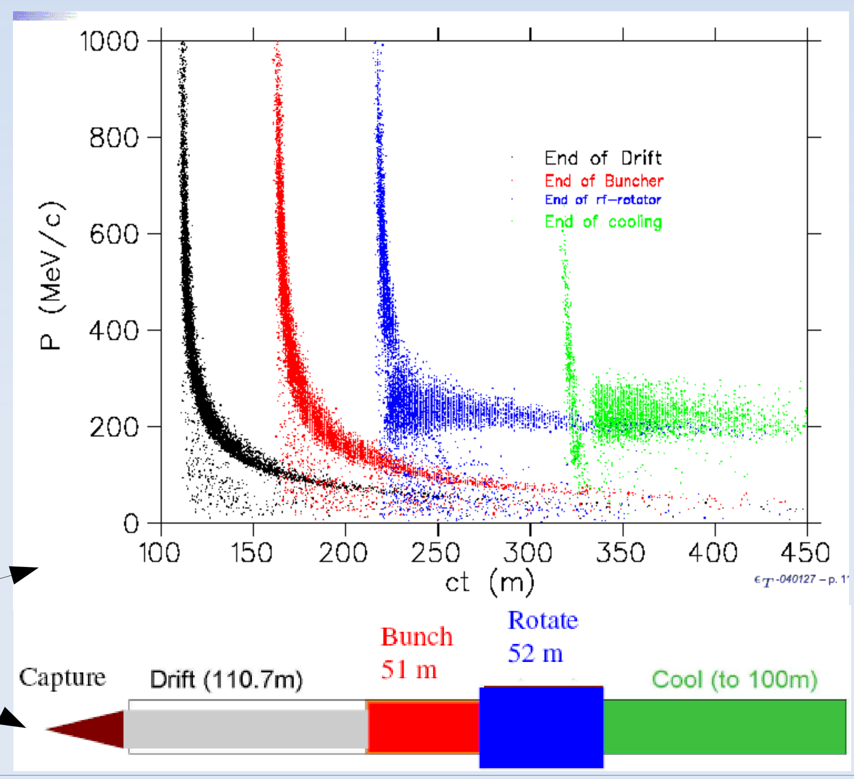

Fig. 2: Muon momentum change for different sections of the lattice and overall layout of the front end

The challenges of muons cooling

In muon ionization cooling, the particles are passed through materials provoking ionization and thus reducing their momentum. The longitudinal momentum is restored then using RF cavities alternated with the absorbers. In order to keep transverse focusing of the muon beam, superconducting solenoid magnets are used and as a result, the RF cavities are sitting in intense magnetic fields.

Results from the Muon Test Area (MTA) [3] at the Fermi National Accelerator Laboratory (FNAL) with multi-cell or pillbox 201 and 805 MHz cavities designed at Lawrence Berkeley National Laboratory (LBNL) and built at LBNL and Jlab, have shown that the peak gradient that can be achieved in RF cavities (fig. 3 & 4) for breakdown free operation is limited well below the Kilpatrick limits of 14.8 MV/m (201 MHz) and 26.1 MV/m (805 MHz).

In order to understand in details the origin of RF cavities breakdown in high magnetic field, efforts are carried out on different fronts.

Field emitter modelling and tracking simulations are performed at Brookhaven National Laboratory (BNL) [4] to study:
- the electron penetration range in metal
- the temperature rise effects.

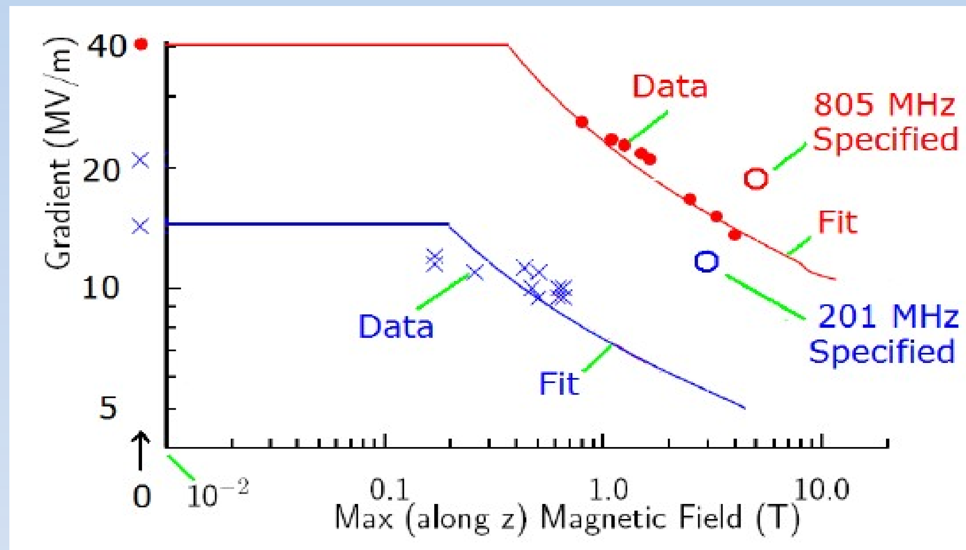

Fig. 3: Peak gradient as a function of the B field

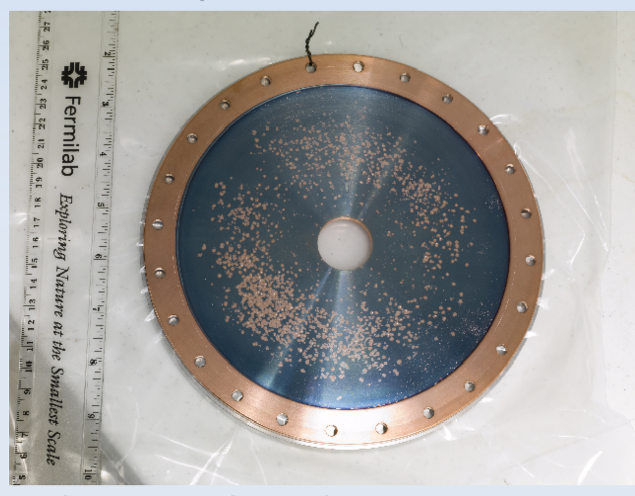

Fig. 4: Surface damage on a Cu window due to stressing

Different experiments are proposed at the MTA to explore in details the effect of magnetic fields in cavities. It includes the design of a support that will permit to rotate the cavity by a given angle (0 to 15°) in the magnet in order to study effect of ExB fields, the design of a 805 Mhz cavity with its surface parallel to the magnetic field lines, and different cavity designs by either replacing part of the cavity material with Be [5] or using Cu or Be pair buttons at the cavities windows for further study of material dependence on cavities breakdown.

Cooling in a reduced field gradient

The performance of muon cooling using a reduced field gradient has been explored [6] using G4MICE, a code designed at Rutherford Appleton Laboratory (RAL) for the Muon International Cooling Experiment (MICE) and ICOOL, a code designed at BNL and used for the neutrino factory current baseline simulation.

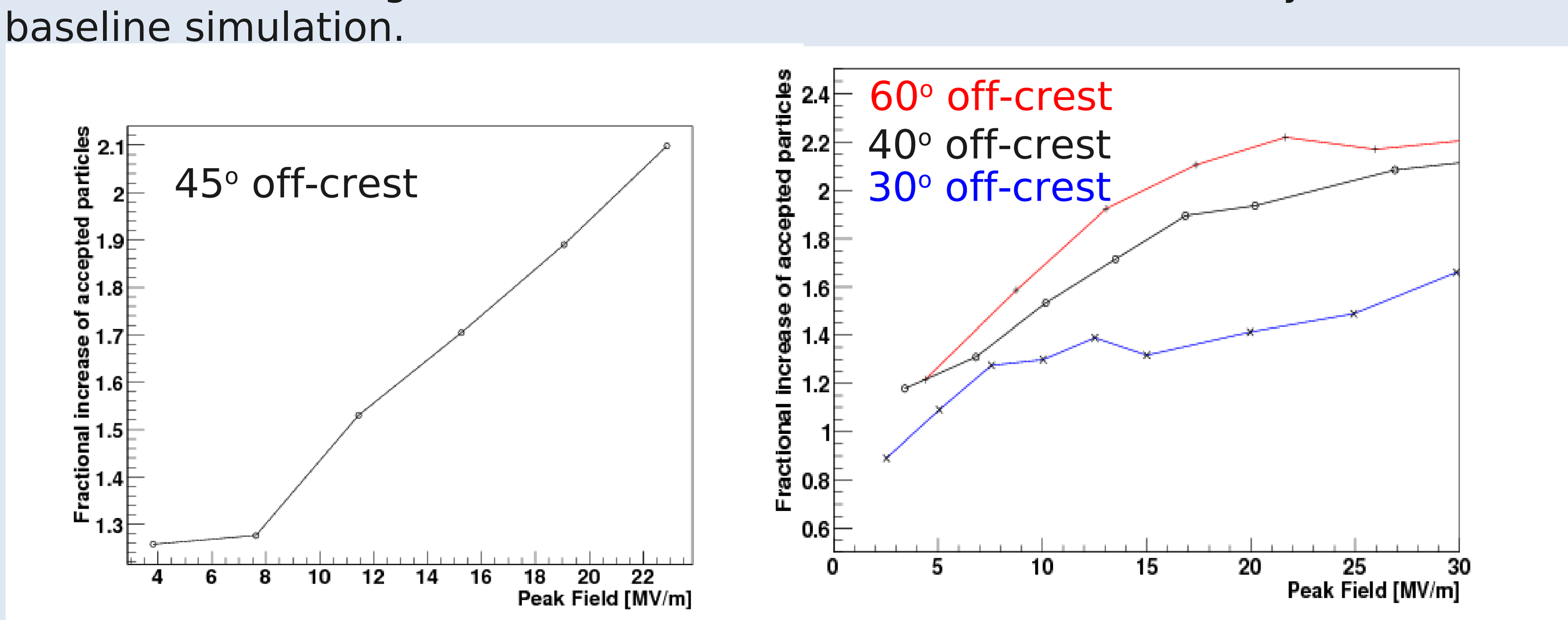

Fig. 5: Fractional increase of accepted particles as a function of the peak field gradient, simulated in ICOOL on the left plot and G4MICE on the right plot.

The interaction of muons with material such as LiH are modelled differently in G4MICE and ICOOL thus leading to different cooling performance (fig. 5) and further examination of the model available in both code will be done.

Both simulation are showing that the performance of the cooling channel is roughly proportional to the peak field gradient achievable for gradients below 20 MV/m.

Optimization of the Front End

The pion production as a function of the beam angle to the Hg jet and the beam entry position has been studied (BNL), for different beam energies and beam and target geometry optimum parameters have been defined using MARS simulation code [7].

The pion/muon capture performance has been studied in MARS, using two field map with different field tapers (fig. 7). Results from past studies were giving a 10% increase in the muon collection for the ST2a field map. The results from the current MARS simulation are giving for three different proton beam energies < 6% increase (fig. 6) in the muon yield at 50 m down the target for 40 < Eμ < 180 MeV [8]. Further studies with different magnets and currents configuration are being carried out (RAL & BNL) in order to better define the dependence of the field map at target on the muon collection.

Improvement studies of the longitudinal and transverse beam matching as well as tapering of the betatron function β are on-going.

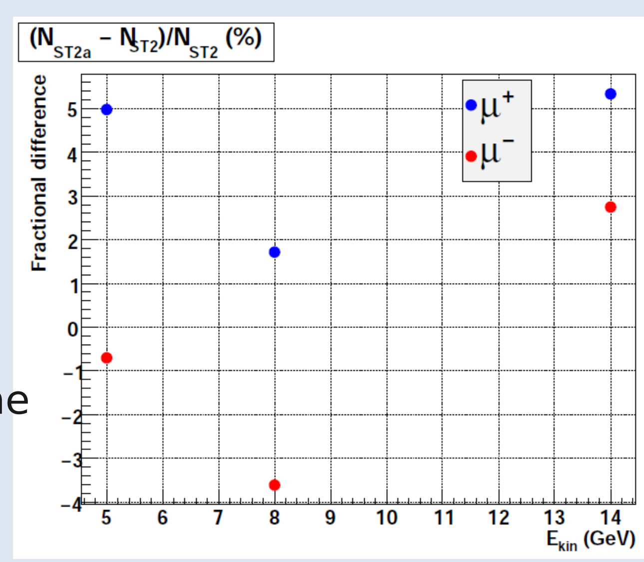

Fig. 6: Fractional difference in muons yield compared to ST2.

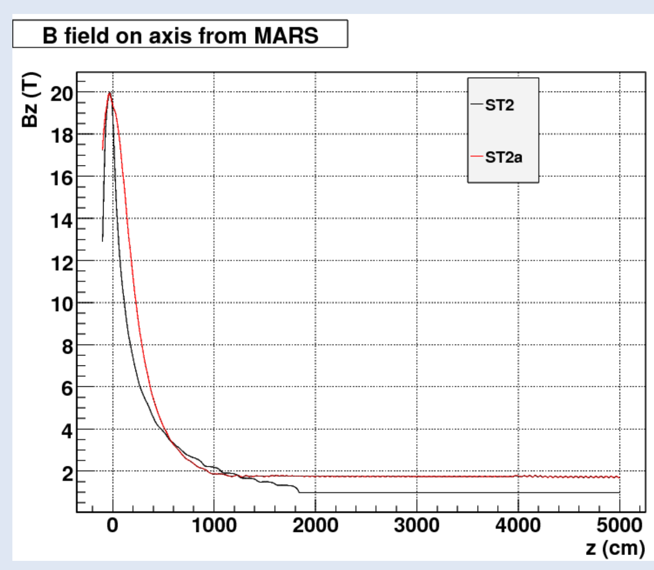

Fig. 7: Magnetic field on axis in MARS from ST2 and ST2a field configuration.

Variations of the current bunching and rotator scheme at FNAL are also under study and the muon acceptance performance will be compared to the current design.

Alternative designs

As an alternative to the problem of breakdown in the RF cavities in presence of magnetic field, a shielded RF lattice design is presently under study (C. Rogers, RAL). RF cavities can be kept away from strong magnetic field by increasing the cell length to move the RF from the fringe field and adding Fe for further shielding. Preliminary results from simulation in G4MICE show that a 3 m long lattice would be preferred [9], further simulation in ICOOL will be carried out.

The idea of using high-pressure gas filled (HPRF) cavities is being investigated on the technical side at LBNL. Whereas the cavity gradient is not expected to be degraded in strong magnetic field, safety issues such as gas flammability and isolation has to be studied in details.
Preliminary evaluation of the performance using H_2 gas and LiH has started [10].

A previous rotation and muon cooling lattice design from CERN was using 44 and 88 Mhz cavities in a single bunch to bucket configuration preserving the longitudinal bunch structure. This lattice is being re-examined with the revised proton driver parameters and target configuration and its performance will be compared to the current baseline. In parallel a 88 Mhz rotation scheme has been studied where the channel performance looks good using 10 MV/m gradient in the RF [11]. Further study with lower gradient will be performed and the rotation channel performance investigated.

References:

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