# Neutrino factory front-end: muon capture and cooling optimization

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**Abstract**
The neutrino factory is one of the designs proposed for a future intense neutrino beam facility. The layout discussed here focuses on the front-end of the current baseline. The challenges inherent to the cooling of muons are shown together with possible baseline optimization.

## 1 A neutrino factory: why and how ?

Past experiments have demonstrated that neutrinos change flavour [1] and have mass, a physics 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 are captured and cooled with a sophisticated set of devices. After primary bunching and longitudinal phase rotation of the muon beam in RF cavities, the muons are cooled through ionization cooling. At the end of the cooling channel and within the transverse $A_\perp$ = 30 mm and longitudinal $A_\parallel$ = 150 mm acceptances, the 200-300 MeV/c muons are accelerated by a series of RLA's followed by a FFAG ring up to 25 GeV. An intense neutrino beam is created by the decay of muons in few turns inside a storage ring, and sent to two detectors potentially located at 4000 and 7500 km, where precision measurements of the neutrino oscillation parameters are performed.

## 2 The challenges of muons cooling

In muon ionization cooling, the particles are passed through materials (LiH absorbers are under current consideration) provoking ionization and thus reducing their momentum. The longitudinal momentum is restored, using 201 MHz 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 an intense magnetic field. Results [3] from the Muon Test Area (MTA) at FNAL[1] with multi-cell or pillbox 201 and 805 MHz cavities designed and built at LBNL[2] and Jefferson Laboratory (VA, U.S.), have shown that the peak gradient achievable, for breakdown free operation, is well limited below the Kilpatrick limits of 14.8(26.1) MV/m for 201(805) MHz cavities (Fig. 1-2). In order to understand in details the origin of RF cavities breakdown, several efforts are carried out. Field emitter modelling and tracking simulations [4] are performed at BNL[3], to study the electron penetration range in metal, and the temperature rise effects. Different experiments are proposed at the MTA to explore in details the effect of magnetic field in cavities. It includes the design of a support that will permit to rotate the cavity by 0-15° in the magnet, in order to study effect of $\vec{E} \times \vec{B}$, the design of a 805 MHz cavity with its surface parallel to the magnetic field lines. Also different cavity designs are suggested by either replacing part of the cavity material with Be, or using Cu or Be pair buttons at the cavities windows.

## 3 Cooling in a reduced field gradient

The performance of muon cooling using a reduced field gradient has been explored [5] using G4MICE [6] and ICOOL [7] codes. The interaction of muons with material such as LiH are modelled differently in both codes, thus leading to different cooling performances (Fig. 3). Further examination of the model available in the codes will be done. Both simulations are showing that the performance of the cooling

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[1] Fermi National Accelerator Laboratory, IL, U.S.
[2] Lawrence Berkeley National Laboratory, CA, U.S.
[3] Brookhaven National Laboratory, NY, U.S.

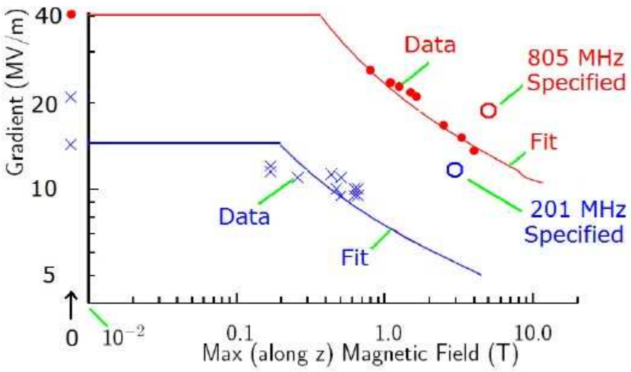

**Fig. 1:** Peak gradient as a function of the magnetic field.

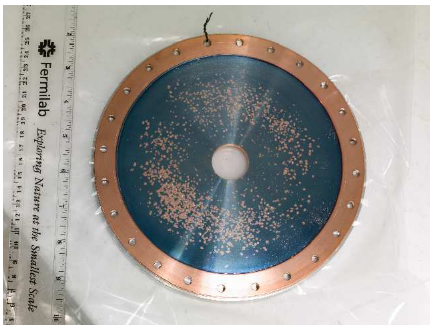

**Fig. 2:** Surface damage on a Cu window.

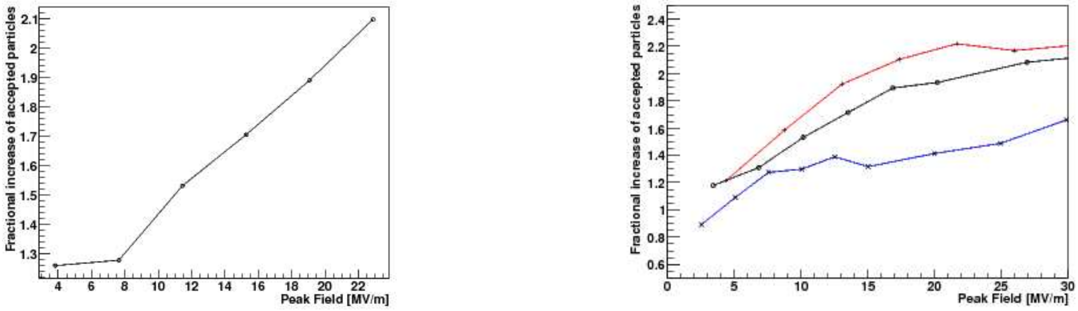

**Fig. 3:** Fractional increase of accepted particles as a function of the peak field gradient, simulated in ICOOL (left) for 45° off-crest phasing, and G4MICE (right) for 30° (blue), 40° (black) and 60° (red) off-crest phasing.

channel is roughly proportional to the peak field gradient achievable for gradients below 20 MV/m.

## 4 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 [9] for different beam energies. Beam and target geometry optimum parameters have been determined using MARS [8] simulation code. The pion/muon capture performance has been studied in MARS using two field maps with different field tapers (Fig. 4). 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 less than 6% increase (Fig. 5) in the muon yield at 50 m downstream of the target for muon kinetic energies of 40-180 MeV [10]. Further studies with different magnets and currents configuration are carried out 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 $\beta$ are on-going. 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.

## 5 Alternative Designs

As an alternative to the problem of breakdown in the RF cavities, a shielded RF lattice design is presently under study. 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 simulations in G4MICE show that a 3 m long lattice would be preferred [11]. Further simulation in ICOOL will be carried out. The idea of using high-pressure gas filled (HPRF) cavities is being investigated on the

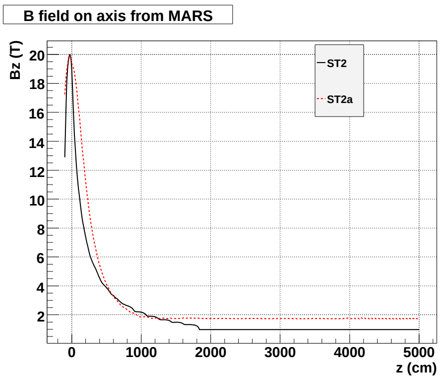

**Fig. 4:** ST2 and ST2a field configurations.

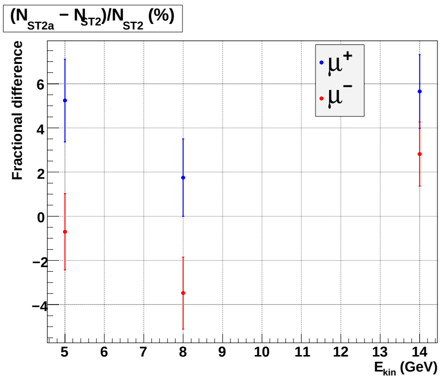

**Fig. 5:** Fractional difference in the muon yield.

technical side [12]. Whereas the cavity gradient is not expected to be degraded in strong magnetic field, safety issues such as gas flammability and isolations has to be studied in details. 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 with a reasonable channel performance, using 10 MV/m gradient in the RF [13]. Further study with lower gradient will be performed and the rotation channel investigated.

## Acknowledgements

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