Beam possibilities for the cooling experiment

Beam requirements for the cooling experiment

The muon beam that needs to be cooled is characterised by its average energy, energy spread, beam size and angular divergence. In a neutrino factory design, the beam has properties that vary along the cooling channel. One should vary the beam characteristics in a test experiment to reproduce this variety of conditions all the way down to the equilibrium emittance which is a characteristic of the cooling channel. Here is an example of typical beam properties for the CERN 88 MHz scenario:

- o **Beam energy E_μ:** central kinetic energy tunable from E_μ=100 MeV (momentum p_μ=176 MeV/c) up to E_μ=300 MeV (p_μ=392 MeV/c).
- o **Energy spread:** $\Delta E_\mu = \pm 10\%$. If this wide energy spread cannot be obtained, a scan of energies could be performed to cover the energy spread of the beam at various stages of the cooling channel.
- o **Beam size:** Δx, Δy = 50 mm rms in both projections.
- o **Angular divergence:** Δx', Δy' = up to 200 mrad rms in both projections - this giving transverse beam emittances of up to 10'000 mm·mrad.
- o **Beam purity:** N_π/N_μ, $N_e/N_\mu \leq 1\%$ after rejection of background.

One of the characteristics of a cooling channel is the equilibrium emittance. A beam at equilibrium emittance would traverse the cooling channel without reduction or increase of its emittance. A precise measurement of this quantity, and comparison of it with the expected value obtained by theoretical calculations, is one of the quantitative aims of the experiment. The beam should be able to provide the largest acceptance that fits into the channel, down to emittances substantially below the equilibrium emittance.

Possible Beamlines

The choice having been made to perform this experiment in a single particle mode, one is naturally led to existing muon beam lines at RAL, PSI and TRIUMF. As it turns out, the available space at TRIUMF is somewhat too limited, and we will concentrate here on the existing PSI beam line and on an alternative at RAL.

The PSI beam line μE1

The PSI experimental hall is nicely described at **http://gfa.web.psi.ch/ehalle/ehalle.html** a map of which is reproduced in figure 1. The beam line μE1 is the channel where clean muons of appropriate energies for the muon cooling experiment can be produced and where enough floor space for the setup can be made available.

Figure 2 shows the layout of the existing μE1 beam line, and in addition a possible (tentative) extension line for the proposed cooling experiment. Pions are produced on a 4-6 cm long Carbon target hit by the 1.8 mA 590 MeV (1 MW) proton beam from the PSI ring cyclotron. The cyclotron is a CW mashine (100% duty cycle) with an RF structure at 50.63 MHz, i.e. a bunch separation 20 ns, and a bunch length of 0.6 ns full width. This particular time structure is quite similar to that of LHC, providing interesting possibilities for the detector readout in the diagnostics sections.

The pions from the target are captured with a set of quadrupoles, momentum selected by a bending magnet and then focused by a quadrupole doublet onto the entrance of the decay channel. This channel is an 8 m long superconducting solenoid with 12 cm inner free diameter and up to 5 Tesla field strength. The muons are collected from pions decaying in flight. About half of the pions decay inside the solenoid. The decay length is expressed by $\lambda_\pi = 5.5\ \mathrm{m} \cdot \mathrm{p}_\pi/(\mathrm{MeV/c})$.

Figure 3 shows the $\pi \rightarrow \mu$ decay kinematics. For any chosen pion momentum on the y-axis, the shadowed area defines the physically allowed muon momenta in the lab system. The left side of this area corresponds to backward $\pi \rightarrow \mu$ decays in the center of mass system, while the right edge are foreward decays. Clean, i.e. pion free muon beams can be obtained if one stays away from the diagonal $\mathrm{p}_\pi = \mathrm{p}_\mu$.

Figure 4 illustrates a Monte Carlo calculation of π/μ spectra for the case of 200 MeV/c nominal pion momentum. These spectra are representative for the particle fluxes available at the exit of the solenoid. In the μE1 channel the total particle flux is about $10^{10}\mathrm{s}^{-1}$. By setting the extraction magnets to an acceptance band different from the pion momenta, a pure muon beam with $\leq 10^{-3}$ pion contamination is generated.

At present, the tunable pion energy is limited to 200 MeV (300 MeV/c), which allows to produce clean muons up to 150 MeV (230 MeV/c), cf. figure 3. If the full range of desired muon energies (100-300 MeV) should be made available, the pion injection magnet has to be replaced by a new one allowing to inject pions up to 450 MeV/c. Such an upgrade costs ~250 CHF and could be installed at PSI during one of the annual shutdowns.

Since the existing μE1 area (regularly used by the μSR community) is not compatible with the energy and space requirements of the cooling experiment, a beam line extension behind the μSR bending magnet is proposed as tentatively sketched in figure 2. The new part of the beam line consists of quadrupoles and bending magnets available at PSI. The ~10 m long flight path after the last bend allows installation of the TOF measurement requested by the Nufact community.

Another important feature is using the 50 MHz RF signal as time reference with the arriving particles. This time structure measurement usually allows separation of different particle species, e.g. elimination of target positrons or pions. In this case the full flight path from the primary to the secondary target (~40 m) is used. E.g. at 450 MeV/c, ΔTOF($\mu - \pi$) is 2.5 ns, and ΔTOF(e-μ) = 3.5 ns, both values being larger than the proton bunch length of 0.6 ns. At lower beam momentum the TOF differences get larger and are easier to utilise for particle separation.

Beam calculations were made using programs TRANSPORT and TURTLE. Some fluxes resulting from these studies are given in Table 1. The fluxes are based on the well known beam characteristics and intensities of the μE1 and πE1 channels at PSI. The fluxes for negative particles are typically 5-10 times lower.

Given $5{\cdot}10^7$ proton bursts per second, one can count how many good muons are expected during the active life time of the cooling channel, which will be assumed to 50 times 100 μs (0.05% duty cycle). The cooling experiment will then see a total of 250'000 proton bursts per second. If one considers that only about 1/6 of these will be in phase with the cooling RF, that one operates with 0.1 muons per proton burst, and that the emittance generation section of the experiment will keep about 1/4 of the incoming beam, we arrive at a rate of ~1000 good muons per second. This should be sufficient to measure the ratio of incoming to outgoing emittance with a statistical precision of $\pm 10^{-3}$ in a few minutes. As shown in table 1, for operation in the highest momentum range the useful rate will probably drop due to the declining pion production cross sections.

p_π (E_π) MeV/c (MeV)	π^+ flux accepted at solenoid entrance $10^9 s^{-1}$	μ^+ flux at solenoid exit $10^9 s^{-1}$	p_μ (E_μ) MeV/c (MeV)	max. μ^+ flux at the experiment $10^7 s^{-1}$
200 (105)	3.5	1.9	115 (50)	3.0
300 (192)	10.6	4.2	176 (100)	8.1
350 (237)	8.8	3.0	233 (150)	7.0
400 (285)	3.7	1.1	287 (200)	2.0
450 (332)	1.2	0.3	392 (300)	0.5

Table 1: Calculated pion and muon fluxes for the μE1 channel extension proposed for the muon cooling experiment.

Figure 1: The PSI experimental hall. Beam line μE1 on the lower right with the 8 m long superconducting solenoid is the conceivable channel for the cooling experiment.

Figure 2: Top view of the existing μE1 channel with the proposed extension line for the cooling experiment. The experimental area is intentional, based on preliminary information from the Nufact community.

Figure 3: Plot of the $\pi \to \mu$ decay kinematics for p_π, p_μ $\leq$500 MeV/c. The shadowed area defines the kinematically allowed region. Clean muon beams can be produced by chosing p_μ different from p_π. This is usually on the left edge of the allowed region corresponding to the backward muon decays in the center of mass system.

Figure 4: Pion and muon spectra at the exit of the superconducting solenoid, for a nominal pion momentum of 200 MeV/c.