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# Study of the CERN neutrino factory front-end designs

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As part of the International Scoping Study we look at the performance of the CERN neutrino factory front-end designs for a set of standard beam-target configurations. The number of positive accepted muons per pion for 10 GeV protons on tantalum is ~0.016.

## 1. Introduction

One task of the International Scoping Study (ISS) [1] is to make a comparison of the performance of existing neutrino factory front-end designs. This comparison is being made using (1) similar levels of detail in the simulations, (2) the same simulation code, and (3) the same initial beam distributions. The simulations carry the beam through all the stages of the front end in a self-consistent manner, i.e. later front end stages see the correlated beam distribution from the previous section. The CERN group investigated a number of possible front end configurations. The baseline pion collection system is a magnetic horn, but most of their simulations were done using solenoid collection. The original front end design used phase rotation and initial cooling using 44 MHz cavities, followed by a second cooling stage using 88 MHz rf. One of the last neutrino factory activities of the CERN group was to produce a second front end design that only used 88 MHz. The CERN designs were based on a 2.2 GeV proton driver beam. Recently it was decided that the SPL proton beam energy should be raised to 3.5 GeV.

All of the simulations in this report were done using ICOOL version 2.92 [2]. The rf cavities were modeled with finite length pillbox fields, which include all radial variations and transit time effects. We assumed open cavities, so no rf windows were needed. We assumed that all the liquid hydrogen absorbers in the cooling channels had 300 μm thick aluminum windows. The magnetic channel was modeled initially with continuous solenoids. The final modeling used a periodic channel of solenoids, where the field is derived from current sheets.

The initial MARS beam distributions were provided by Stephen Brooks on the surface of the cylindrical target region. A new program MARS2IC was written to track the particles from the surface of the target to a plane at fixed z at the end of the target. For the short

mercury and tantalum targets the tracking took place in the tapered solenoid field design from US Study 2 [3]. The longitudinal field varies by ~5% over the length of the target. For the long carbon targets we assumed a constant 20 T field was present over the whole target. For the horn studies the particles were tracked to the end of the target using the fields from the CERN baseline horn design. The particle distributions at the end of the target were used in subsequent ICOOL simulations of the front end performance.

## 2. The 44 / 88 MHz front end

The original front end design had a 30 m decay region, 30 m phase rotation, 46 m of initial cooling, 32 m of acceleration, and 112 m of final cooling [4-6]. The solenoidal focusing field increased from 1.8 to 5 T along the channel. No field reversals have been used in these simulations. The reference particle kinetic energy increased from 200 to 300 MeV. The CERN group did not specify the design of a tapered solenoid collection system around the target, so we used the US Study 2 design out to the point where the field fell to 1.8 T.

The 44 MHz cavities were assumed to have an average electric field on-axis of 2 MV/m including transit time effects. The transit time factor for 1 m long cavities is 0.96, so the peak electric field on-axis is 2.08 MV/m. The corresponding average field for the 88 MHz cavities was assumed to be 4 MV/m including transit time effects. The transit time factor for 1 m long cavities is 0.86, so the peak electric field on-axis is 4.68 MV/m. With an average accelerating gradient of 2 MV/m the specified 32 m acceleration channel was not long enough to increase the particle's energy from the specified 200 to 280 MeV/c. Thus we had to increase the accelerator length to 42 m.

For the horn capture we used the original CERN design [7]. This is a very compact design 1 m long with two radially nested horns extending out to a radius of 1 m. It was originally designed for use with a 2.2 GeV beam. Following CERN's design we left a 0.5 m long drift space at the end of the horn, so the field of the first solenoid in the decay channel did not overlap the horn field. This was followed by the 44 / 88 MHz front end, except for the omission of the tapered capture solenoid.

We use the program ECALC9 [8] to calculate the number of muons inside the accelerator acceptance. We use the momentum band from 100 to 500 MeV/c, a normalized transverse acceptance of 30 mm and a normalized longitudinal acceptance of 300 mm.

The front end performance is summarized in Table 1 for positive particles. Column five gives the total number of muons at the end of the channel per incident pion. The next column is $\mu/\pi$ in the accelerator acceptance. The following column is the number of accepted muons per incident proton on target. The last column is the accepted $\mu/p$ normalized per unit beam energy. This last quantity represents the best figure of merit for choosing a target material and beam energy, and for comparing different front end designs.

**Table 1**. CERN 44 / 88 MHz design.

| $E_b$ [GeV] | target | L [cm] | collection | $\mu / \pi$ | $\mu_A / \pi$ | $\mu_A$ / p | $\mu_A$ / p GeV |
|---|---|---|---|---|---|---|---|
| 10 | Ta | 20 | solenoid | 0.129 | 0.011 | 0.010 | 0.0010 |
| 4 | Hg | 25 | horn | 0.007 | 0.001 | 0.0002 | 0.00004 |

For the solenoid collection the number of accepted positive muons ($\mu_A / \pi$) is ~0.01 for 10 GeV protons on tantalum. The simulations used 10,000 initial particles. The horn system modeled here does not work for the energy range considered in this study. The original compact horn design does not give sufficient focusing for a 4 GeV beam. In addition more design work is clearly needed to funnel the beam from a 1 m radius horn to the 30 cm radius aperture of the solenoid channel. Most of the losses occur at this location.

We defer further discussion of horn focusing since this requires a new design effort. We also defer any more discussion of the 44 / 88 MHz channel because we feel that CERN's all-88 MHz design is superior.

## 3. The all-88 MHz front end

A revised CERN design [9] only used 88 MHz rf cavities. This design had a 15 m decay region, 8 m phase rotation, and 90 m of cooling. The solenoidal focusing field was 4 T along the whole channel. No field reversals have been used in these simulations. The reference particle kinetic energy was 200 MeV. CERN did not specify the design of a tapered solenoid collection system around the target, so we used the US Study 2 design out to the point where the field fell to 4 T. The average rf gradient used was 4 MV/m including transit time factors. The transit time factor for 0.9 m long cavities is 0.88, so the peak electric field on-axis is 4.57 MV/m. Simulations at CERN showed that this design at 2.2 GeV performed as well as the original 44 / 88 MHz design [9]. Each cooling cell had a 0.5 m matching solenoid [9]. The strength of this solenoid could be varied in order to keep the beta function in the cooling cell approximately constant.

Our initial studies used a continuous solenoid field in the channel (after the initial tapered field in the collection region). However, there is a preliminary engineering design NF-087 [10] for the rf cavities. This design incorporates the solenoids around a neck in the cavities. The solenoids are 45 cm long with an inner radius of ~15 cm. The overall length of the cavity is 90 cm. We found that this solenoid configuration produced large (~68%) modulation of the solenoid field on-axis. Large field modulation typically leads to stop bands, so we prepared a third, low-modulation design. In this model the solenoids were 60 cm long on a 90 cm period with an inner radius of 50 cm. This solenoid configuration produced 7% modulation on-axis, but it is incompatible with the NF-087 rf cavity design.

A comparison of front-end performance is shown in Table 2 for positive particles from 10 GeV proton interactions on tantalum.

**Table 2.** CERN all-88 MHz front end.

| solenoid design | $\mu / \pi$ | $\mu_A / \pi$ | $\mu_A / p$ | $\mu_A / p$ GeV |
|---|---|---|---|---|
| continuous | 0.236 | 0.015 | 0.013 | 0.0013 |
| NF-087 | 0.098 | 0.008 | 0.008 | 0.0008 |
| low modulation | 0.226 | 0.016 | 0.014 | 0.0014 |

We use the low-modulation design for the following studies since it satisfies our "realism criterion" of using a periodic solenoid lattice, and it gives the same performance as the continuous channel.

The longitudinal phase space of all positive muons that reach the end of the cooling channel for 10 GeV protons on tantalum is shown in Fig. 1.

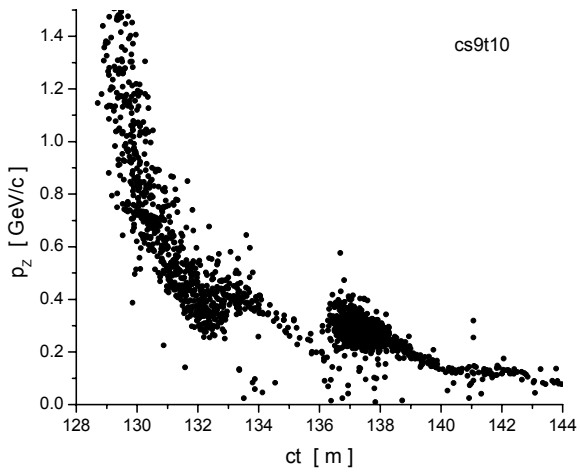


**Figure 1.** Longitudinal phase space at the end of the cooling section.

There is one clear bunch at around 137 m. The timing of the SPL "bunch-to-bucket" can accept two 88 MHz buckets. There is evidence of a second partially formed bucket around 132 m. However the wavelength of the rf system is 3.4 m. If the acceptance is centered on the clear bucket at 137.5 m, the acceptance of the second bucket would have to be centered at 134.1 m. Thus many of the particles near the second "bucket" will lie outside the acceptance. Both buckets are used in calculating the acceptance since they both occur within the assumed 22.7 ns spacing between SPL proton bunch interactions on the target.

The momentum distribution at the end of the cooling section is shown in Fig. 2.

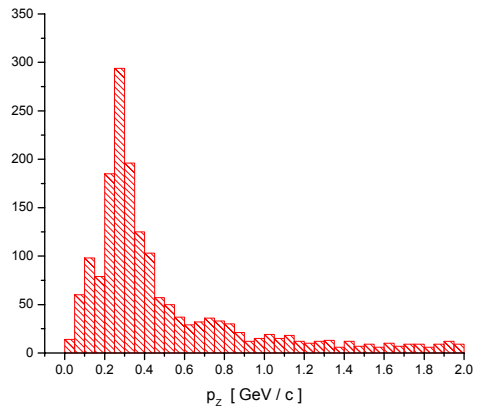


**Figure 2.** Momentum distribution for all positive muons at the end of the cooling section.

The momentum distribution extends all the way out to 5 GeV. Recall that our acceptance criterion requires the momentum to be in the range 0.1-0.5 GeV/c. For 10 GeV interactions there is a considerable loss of high momentum muons that do not satisfy this requirement. The projected time distribution at the end of the channel is shown in Fig. 3.

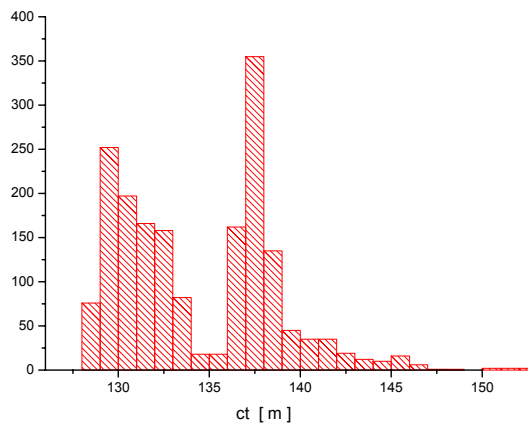


**Figure 3.** Time distribution for all positive muons at the end of the cooling section.

We have seen in Fig. 1 that most of the accepted particles lie in the second peak.

The change in muon normalized transverse emittance is shown in Fig. 4.

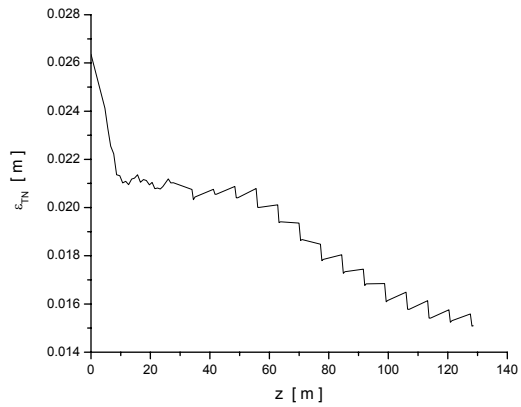


**Figure 4.** Normalized transverse emittance versus distance along channel.

The cooling channel is working here, but at a slower rate than in the original design simulations. The growth in the number of muons in the accelerator acceptance is shown in Fig. 5.

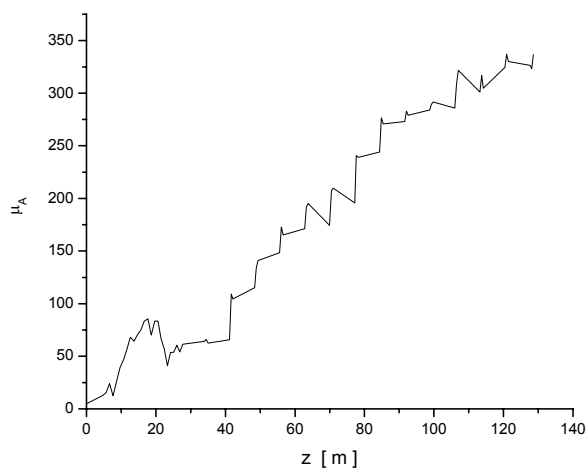


**Figure 5.** Number of muons in the accelerator acceptance versus distance along the channel.

There is a steady growth in the number of accepted muons up to the end of the cooling channel. This shows that one could increase the performance of this channel by making the cooling channel longer.

A survey of the performance for positive particles for the ISS reference beam cases is shown in Table 3.

**Table 3.** CERN all-88 MHz beam-target survey.

| $E_b$ [GeV] | target | L [cm] | $\mu / \pi$ | $\mu_A / \pi$ | $\mu_A$ / p | $\mu_A$ / p GeV |
|---|---|---|---|---|---|---|
| 4 | C | 66 | 0.286 | 0.018 | 0.006 | 0.0015 |
| 4 | Hg | 25 | 0.210 | 0.017 | 0.003 | 0.0009 |
| 10 | Ta | 20 | 0.226 | 0.016 | 0.014 | 0.0014 |
| 40 | C | 66 | 0.271 | 0.010 | 0.026 | 0.0007 |
| 40 | Hg | 25 | 0.206 | 0.011 | 0.043 | 0.0011 |

All these runs were based on 10,000 initial particles. Although the total number of muons per incident pion at the end of the channel is large (e.g. ~0.23 for tantalum at 10 GeV), the number of accepted muons per incident pion is much smaller (e.g. ~0.02).

## 4. Discussion

We have found that the all-88 MHz front end channel has significantly better performance than the 44 / 88 MHz channel. In addition, its total length is 113 m and its peak solenoid field is 4 T, compared to 259 m and 5 T for the 44 / 88 MHz channel. Thus it is probably much cheaper as well. However, the number of accepted $\mu_A / \pi$ for 10 GeV protons on tantalum (0.016) is much smaller than the number (0.097) found for the US Study 2a front-end [11]. The overall figure of merit here is 0.0014 $\mu_A$ /p GeV, compared to 0.0087 $\mu_A$ /p GeV for the US design. This factor of 6 loss in efficiency may be primarily a problem with the mismatch between the initial longitudinal emittance of the beam at the target and the acceptance of the 88 MHz rf buckets [12]. Some of the loss could probably be recovered with additional optimization of the channel parameters for the higher incident beam energy.

## Acknowledgements

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**References**

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