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Examination of the US Study 2a neutrino factory front-end design

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As part of the International Scoping Study we look at the performance of the US front end Study 2a design for a set of standard beam-target configurations. We also consider the sensitivity of the performance for several non-standard conditions: (1) the maximum gradient in the cooling channel rf cavities is reduced and (2) the proton bunch length at the target is varied.

1. Introduction

One task of the International Scoping Study (ISS) is to compare 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. All 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. This report examines the performance of the US Study 2a (ST2a) design [1]. All of the simulations in this report were done using ICOOL version 2.92.

2. Beam-target survey

All the initial beam distributions were created by Stephen Brooks using MARS 15. The lengths of the targets were 20 cm for tantalum, 25 cm for mercury, and 66 cm for carbon. The radius of all the targets was 1 cm. There was no tilt angle between the target and the beam, or between the target and the axis of the magnetic collection system. Reinteractions of produced particles in the target were included, but no magnetic field was used inside the target volume.

The initial MARS beam distributions were provided on the surface of the cylindrical target region. The mean values and standard deviations of the transverse momentum distributions on the target surface are given in Table 1.

Table 1. Transverse momentum on target surface

		positive		negative	
	E [GeV]	< p_T> [MeV/c]	$\sigma(p_T)$ [MeV/c]	< p_T> [MeV/c]	$\sigma(p_T)$ [MeV/c]
C	4	305	212	298	206
Hg	4	333	216	279	205
Ta	10	409	301	386	292
C	40	385	298	392	306
Hg	40	372	280	352	275

The error on the mean value of p_T in Table 1 is about 1 MeV/c.

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[1]. 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. The particle distributions at the end of the target were used in subsequent ICOOL simulations of the front end performance. The number of accepted muons was determined using the program ECALC9. We use a momentum band of 100-300 MeV/c, a normalized transverse acceptance of 30 mm, and a normalized longitudinal acceptance of 150 mm.

The momentum distribution at the end of the cooling channel for the 10 GeV tantalum case is shown in Fig. 1.

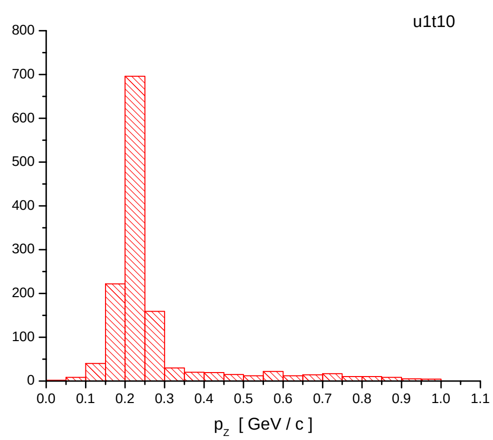

Figure 1. Momentum distribution for positive particles at the end of the cooling channel for 10 GeV protons on tantalum.

The 100-300 MeV/c momentum cut in the acceptance calculations includes most of the particles transmitted to the end of the channel.

[1] The field profile in the vicinity of the target is similar to that in Study 2a.

The front end performance for the ISS reference beam-target combinations is summarized in Table 2 for positive particles and Table 3 for negative particles. Column four gives the total number of muons at the end of the channel per incident pion. The next column is μ/π in the accelerator acceptance. The following column is the number of accepted muons per incident proton on target, which we designate as μ_A / p. The last column is the accepted μ_A /p normalized per unit beam energy. This last quantity represents the best figure of merit (FOM) for choosing a target material and beam energy, and for comparing different front end designs.

Table 2. ST2a positive beam-target survey.

E_b [GeV]	target	L [cm]	μ / π	μ_A / π	μ_A / p	μ_A / p GeV
4	C	66	0.256	0.133	0.045	0.0114
4	Hg	25	0.221	0.131	0.027	0.0066
10	Ta	20	0.187	0.097	0.087	0.0087
40	C	66	0.190	0.065	0.171	0.0043
40	Hg	25	0.156	0.071	0.271	0.0068

Table 3. ST2a negative beam-target survey.

E_b [GeV]	target	L [cm]	μ / π	μ_A / π	μ_A / p	μ_A / p GeV
4	C	66	0.267	0.151	0.045	0.0113
4	Hg	25	0.244	0.157	0.039	0.0098
10	Ta	20	0.199	0.113	0.107	0.0108
40	C	66	0.197	0.081	0.184	0.0046
40	Hg	25	0.171	0.085	0.330	0.0083

Each of the cases in Tables 2 and 3 used 10,000 initial particles, so one would expect about 1% accuracy in the results. In Study 2a with 24 GeV interactions in mercury we found essentially the same number of accepted muons per proton for both signs of particles [2]. The reference performance for Study 2a was 0.17 μ_A / p. This gives a reference figure of merit of 0.007 μ_A / p GeV.

The 10 GeV tantalum results in Tables 2 and 3 are 24% better than Study 2a for positive particles and 54% better for negative particles. One difference between these results was that the proton bunch length used here was 1 ns, while 3 ns was used is Study 2a (see section 4). A second difference is that MARS15 is used here, while MARS14 was used in Study 2a. Another difference is that the beam, target and solenoid are collinear here, while the beam-solenoid angle was 67 mrad and the target-solenoid angle was 100 mrad in Study 2a.

The 4 GeV results are also quite good. However, it may be very difficult to get 3 ns proton bunches at 4 GeV. In addition, it may also be very difficult use a carbon target with a 4 MW beam.

3. Reduced gradient

The 201 MHz rf cavities in the cooling channel must operate in the presence of strong magnetic fields. Previous experience with 805 MHz cavities showed that the maximum achievable gradient decreased when the magnetic field was increased [3]. The behavior of the 201 MHz cavities inside a field is not known at this time. However, for this study we assume that the maximum gradient is only 2/3 of the design value of 15.25 MV/m. If we have less acceleration available in each cell, we must reduce the amount of LiH absorber. For a given combination of gradient and absorber length we can then vary the rf cavity phase to recover as much of the lost performance as possible. We used the file of positive particles from 10 GeV interactions in tantalum for this study.

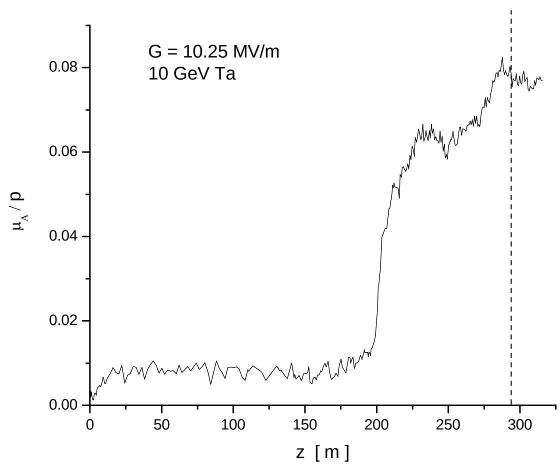

Figure 2. Muons in the accelerator acceptance for reduced gradient.

After optimizing the absorber thickness and cavity phase, we found that the number of muons per incident proton in the accelerator acceptance fell from 0.093 to 0.074. This is a reduction of 20%. The growth in accepted muons is shown in Fig. 2. The dashed line at 290 m represents the end of the Study 2a front end.

It is likely that the rf cavities will be produced with a range of maximum gradients. We did a study to see if the cavities could be located in the channel in such a way as to minimize the loss in performance from the reduced gradient. In this study 15.25 MV/m cavities were only used in the first part of the cooling channel. The remainder of the cooling channel was then filled with cavities with a gradient of 12.25 MV/m. The results are shown in Table 4.

Table 4. Effect of cavity distribution on performance

High grad cavities	Low grad cavities	μ_A / π	μ_A / p
64	65	0.0945	0.0894
32	97	0.0925	0.0875
16	113	0.0931	0.0881
12	117	0.0962	0.0910
8	121	0.0805	0.0762

There are a total of 129 cavities in the cooling channel. The 10 GeV Ta beam was used for this study. We see that the channel performance is not significantly degraded until the number of high gradient cavities at the beginning of the channel is reduced to less than 12.

4. Proton bunch length

As the proton bunch length increases, the longitudinal emittance increases, and more and more particles in the channel fall outside the front end acceptance. This can be seen over a wide range of bunch lengths in Fig. 3, where the FOM is plotted as a function of proton bunch length for positive particles from 24 GeV proton interactions in mercury.

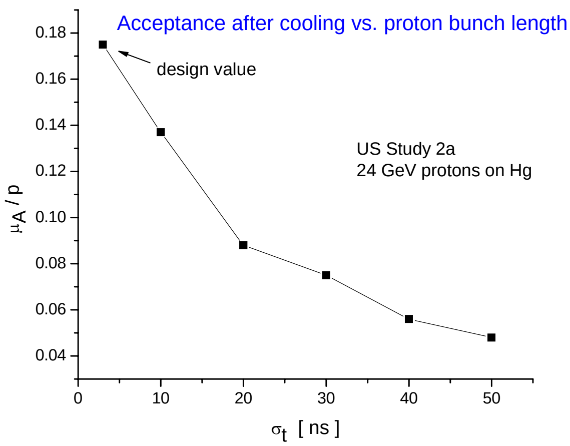

Figure 3. Study 2a performance as a function of proton bunch length. (wide range)

The FOM falls off almost linearly for bunches up to 20 ns. It then decreases at a reduced rate. This study was done by taking an existing beam file that was created with a 3 ns proton pulse length and resetting the times at the end of the target so that the time distribution had the desired standard deviation. This procedure ignores an intrinsic time spread of ~1 ns that comes from the momentum spread and the target length, but it should be acceptable for times down to ~3 ns.

A second study showed the dependence in more detail for 1-5 ns bunches. This can be seen in Fig. 4 where the FOM is plotted as a function of proton bunch length for positive particles for 24 GeV proton interactions in mercury.

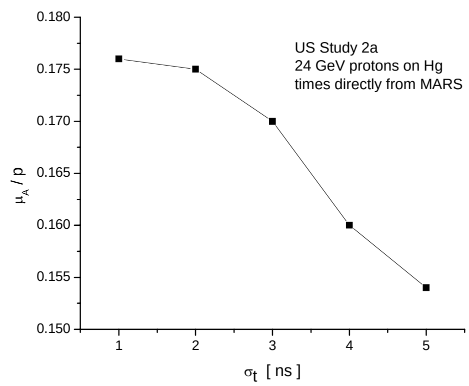

Figure 4. Study 2a performance as a function of proton bunch length. (short bunch scan)

We see that the FOM here also falls off steadily with increasing proton bunch length for bunches longer than ~3 ns. The performance seems to level out below 3 ns, but a clear answer to this question needs another study at higher statistics. This study was done by using MARS files created with different proton pulse lengths.[2] Each value is the average of three runs of 10,000 particles. The error on the acceptance is typically ±0.006.

5. Conclusions

We found that the Study 2a front end had a 10-40% higher figure of merit with the beam from 10 GeV proton interactions in tantalum than the reference value for 24 GeV interactions in mercury. The performance falls off approximately linearly with increasing proton bunch length, for bunches between 3-20 ns in length. If the rf gradient has to be reduced to 2/3 of its design value, the performance of the channel falls by 20%.

Acknowledgements

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[2] Thanks to Harold Kirk for providing these special beam files.

References

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