# A TAPERED-FOIL EMITTANCE-EXCHANGE EXPERIMENT AT LANSCE*

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## *Abstract*

We are planning an experiment at the Los Alamos Neutron Science Center (LANSCE) to demonstrate a technique for reducing the transverse emittance of the proton beam by passing the beam through a wedge-shaped energy degrader to produce a non-symplectic correlation between transverse position and energy, then removing this correlation with a bending magnet. This technique was proposed by Peterson [1] in 1983. We present a specific beam-line layout that is expected to mitigate several complications associated with fielding an experiment to demonstrate the technique with a low emittance ($\varepsilon_n$ = 0.6 mm.mrad) proton beam. We present simulated results and expected outcomes of this demonstration.

## INTRODUCTION

This work is motivated by the need to produce an electron beam with very small transverse emittances for use in an X-ray free electron laser. Requirements on the longitudinal emittance are modest, so it's natural to look for ways to perform an emittance exchange to transfer some of the initial transverse emittance to the longitudinal dimension.

One technique for reduction of transverse emittance was proposed by Peterson in Ref. [1]. The beam is passed through an energy-degrader foil that is tapered in the transverse direction thereby producing a correlation between energy and horizontal position. This correlation can then be removed by passing the beam through a bending magnet. This is illustrated in Fig. 1.

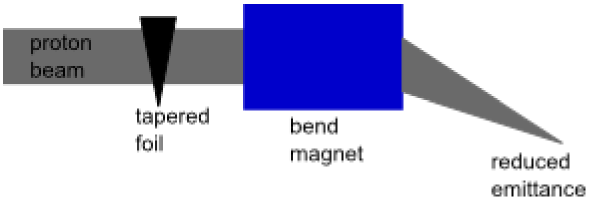

Figure 1: Illustration of the emittance-reduction technique described in the text.

In order to demonstrate this technique, we are planning to conduct an experiment using the proton beam at LANSCE, whose unnormalized emittance is about 0.4 mm· mrad. Simulations for designing this experiment are presented in the following sections.

## CHOICE OF SYSTEM PARAMETERS

The small initial emittance of the beam requires that system parameters be chosen carefully in order to realize a reduction in emittance. Below we describe the choices of 1) The thickness of the energy-degrader foil, 2) The beam spot size at the foil, 3) The bend angle, and 4) Focusing magnets.

We employed the computer program G4beamline[2] to simulate the passage of the proton beam through the degrader foil. This provided particle distributions and the ability to examine energy loss and angular scattering to guide our choices of system parameters.

The 800MeV proton beam produced by the LANSCE linac has an RMS momentum spread of about 0.4%. This drives the choice of the maximum energy-loss in the foil (foil thickness) as the induced slew must overwhelm this initial spread. We chose a maximum momentum loss of 0.8%, i.e. 20 times the initial RMS spread. (Simulations with smaller momentum slew failed to yield good final results.) In order to minimize scattering and particle-loss due to nuclear interactions, we chose beryllium as the material for the foil. A thickness of 29.7mm is required to get the 0.8% momentum loss. Fig. 2 shows the width of momentum-loss distribution from a simulation of the 1463.3MeV/c proton beam passing through a uniform 29.7mm-thick beryllium foil. This width blurs the correlation that's produced by the tapered foil. We have found that using a foil with a maximum thickness that's large enough to produce a momentum slew that overwhelms the uncorrelated momentum distribution is important in realizing a reduction in horizontal emittance.

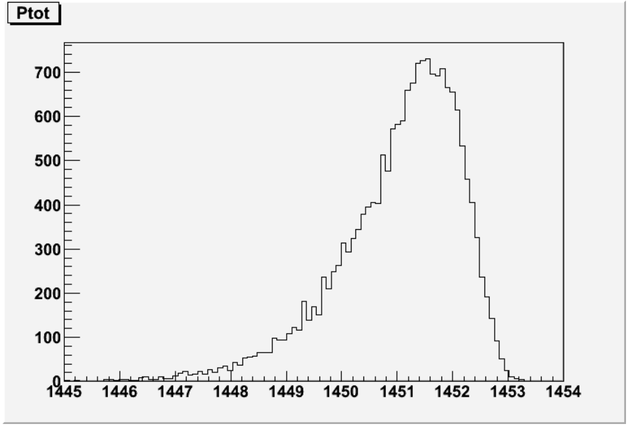

Figure 2: The distribution of total momenta of protons that have passed through a 29.7mm-thick beryllium foil. (Counts per bin vs. momentum in MeV/c.) The original momentum was 1463.3MeV/c.

The simulation of the proton beam passing through the uniform 29.7mm-thick Be foil showed that it produces RMS scattering of about 2.9mrad. This scattering will add in quadrature to the divergence of the initial beam and results in an increase in emittance. In order to keep this emittance growth small, one must place the foil where the initial beam divergence is relatively large, i.e. where the beam spot size is small; this is illustrated in Fig. 3.

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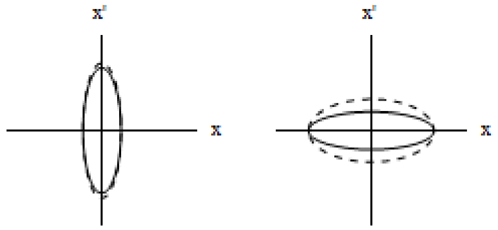

Figure 3: An illustration of emittance growth due to foil scattering. In each of the two examples an increase in divergence was added in quadrature to that existing in the solid ellipse. The results are the dashed ellipses. Clearly, the beam on the right, with the smaller spot size, experiences less emittance growth.

A spot size of 150μm was chosen; with the initial beam emittance of 0.4mm·mrad, this means the beam divergence will be 2.7mrad, about the same as that produced at the maximum thickness of the foil. This yields an acceptable increase in emittance that doesn't overwhelm the reduction produced by the dispersion.

The horizontal width of the foil is chosen to be 4 times the RMS beam spot size in order to ensure that almost all of the beam strikes the foil.

Point-to-point imaging from the foil to the final focus was employed in order to maintain a reasonable beam size, to fully remove the energy-position correlation, and to enable collimation to eliminate outliers in the particle distributions. A pair of quadrupole triplets provides the necessary focusing.

The bending magnet must provide dispersion that matches the energy-position correlation induced by the energy-degrader foil. With a 0.8% momentum slew, a 150um RMS beam spot, and a foil that covers 4 times the RMS spot size, the required dispersion is 4x150um/0.8% = 0.075m. A bend of about 1.6 degrees provides this dispersion.

## SIMULATIONS

With the system parameters chosen, the simulation is performed as follows: The initial proton beam distribution is generated by G4beamline[2], which then simulates the passage of the beam through the energy-degrader foil. The resulting particle distribution is saved in a file.

We use Trace3D [3] to compute 1st-order 6-by-6 transport matrices for the beam optics. These matrices and the particle distributions are read by the computer program MATLAB [4], which propagates the particles to the final focus and other locations of interest by multiplying the transport matrices by the 6-element vector describing each proton. MATLAB is also used to compute emittances and to provide graphs.

Figure 4 shows momentum vs. position distributions immediately downstream of the foil and at the final focus. The system appears to perform as desired, inducing then removing a correlation.

### *Results of Simulations*

Figure 5 shows horizontal phase space distributions and cuts that are applied to exclude outliers from the emittance computations. The initial beam distribution has a horizontal emittance of 0.4mm.mrad. This increases to 0.54mm.mrad after the foil, and at the final focus it has been reduced to 0.19mm.mrad. The goal of reducing the horizontal emittance is achieved in this simulation.

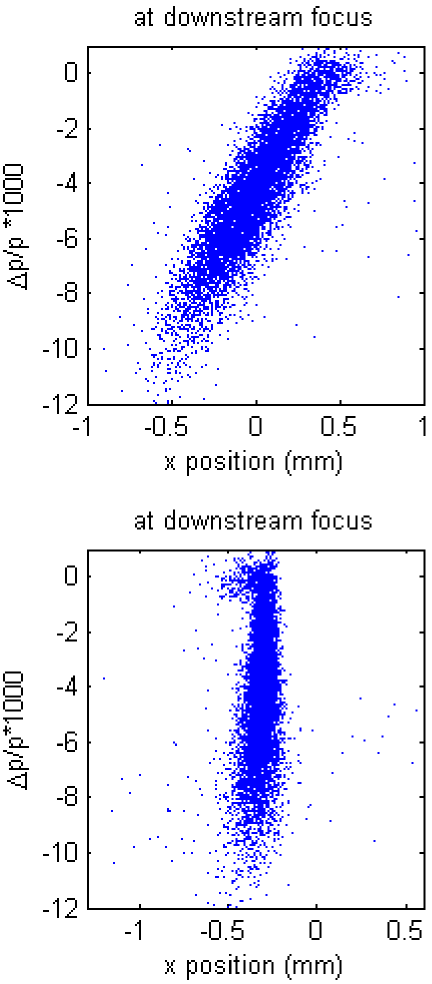

Figure 4: Plots of the momentum vs. position distributions immediately downstream of the tapered foil (top) and at the final focus (bottom).

More aggressive collimation, beyond the cuts illustrated in Fig. 5, provide further reduction of emittance, however collimating the initial beam would also provide reduced emittance. The result of collimation is shown is Fig. 6. A window is centered on the horizontal beam distribution, and the width of the window is varied to retain the core of the distribution and exclude the tails. In Fig. 6 the emittance is shown as a function of the fraction of protons retained in the core. For comparison, the same treatment is applied to the initial beam distribution. This technique appears likely to provide an improvement by a factor of about 2 over collimating alone. Further system optimization may increase the improvement.

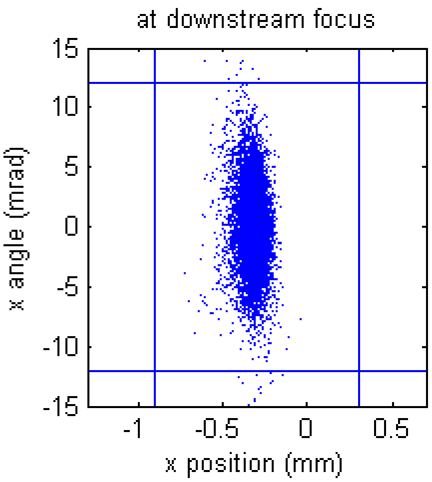

Figure 5: Horizontal phase space distribution of the protons at the final focus. The lines indicate cuts that are applied in computing the beam emittance; many protons lie far outside these cuts due to large-angle scattering in the tapered foil.

## FURTHER WORK

The next steps to take are to optimize the system, in particular the magnitude of the induced momentum slew, and to assess the impacts of the foil on the vertical and longitudinal emittances.

The simulations presented here used first-order beam optics; higher-order codes will be necessary for more detailed simulations.

Though the proton beam available at LANSCE will provide a good opportunity to demonstrate and gain experience with this technique, the ultimate goal is to employ this technique with low-emittance electron beams. Preliminary work is underway to determine the efficacy of the technique in that application.

## CONCLUSION

The simulation shown here indicate that the tapered-foil technique can significantly reduce the horizontal emittance of the proton beam at LANSCE. More detailed simulations need to be performed to verify that non-linearities won't spoil this result. These simulations are being performed in anticipation of fielding an experiment to demonstrate the principle.

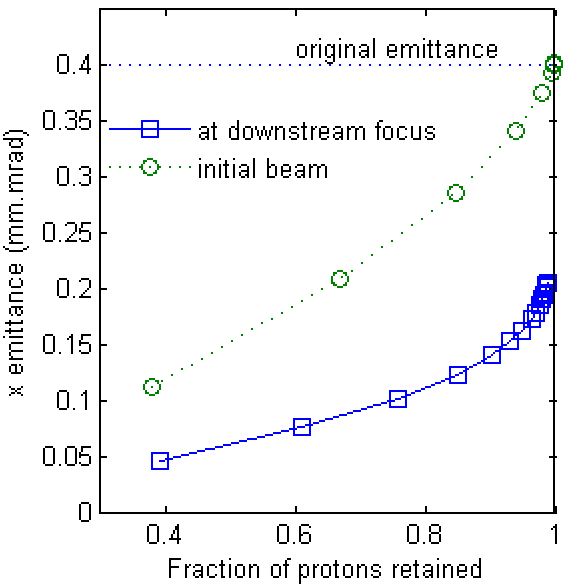

Figure 6: The horizontal emittance of the proton beam vs. the fraction of protons retained in the computation. A variable-width window excludes protons from the computation. The results of this process on the beam at the final focus is shown in blue, and for comparison the process has been carried out on the initial beam too. The original emittance of the initial beam is shown as a dashed line.

## REFERENCES

[1] J.M. Peterson, Proceedings of PAC 1983, p. 2403-2405.

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[3] K. R. Crandall and. D. P. Rusthoi, "Trace3D User Documentation," LANL Report LA-UR-97-886. (1997).

[4] MATLAB. http://www.mathworks.com/products/matlab/