REDTOP Beam Modeling For Raised Transition Energy and Third Integer Resonance Extraction

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To explore physics Beyond the Standard Model (BSM), the experiment called Rare Eta Decays with a TPC for Optical Photons (REDTOP) is in its proposal phase at Fermi National Accelerator Laboratory to study η decays. The existing delivery ring will destabilize the beam as it is decelerated for REDTOPs use, so modifications to the magnet arrangement have been proposed and must be simulated. This work focused on using MAD-X to model the introduction of new quadrupoles and sextupoles to raise the transition energy and shape the beam for extraction.

I. INTRODUCTION

The REDTOP experiment, in its proposal phase at Fermilab, attempts to explore new physics by studying η and η' decays (and others after beam modifications)[1]. The first stage will focus on producing mesons and studying their rare or suppressed decays, the main 3 being the 3-π, $\gamma\ell^{\pm}\ell^{\mp}$, and $\pi^0\ell^{\pm}\ell^{\mp}$. By studying these decays in more detail, REDTOP will search for evidence of BSM[1]. BSM particles, such as the dark photon, are theorized to take part in these interactions, and REDTOP aims to discover these particles.

The mesons will be created by striking a CW (continuous wave) 1.9 GeV proton beam[2] onto foils of beryllium, producing around 10^{13} η mesons in one year. This requires decelerating an 8 GeV pulse beam, then extracting the beam in a continuous manner. The current design is to use a resonant slow extraction method, similar to the one proposed for Mu2e[3].

While REDTOP is designed to make use of Fermilab's current Muon Campus, the current arrangement will destabilize the beam. For example, the deceleration of the beam in the current delivery ring configuration will force the beam to cross its transition energy, causing major beam loss. To shape the beam for resonant extraction, new sextupoles must be introduced, producing fields designed to reduce the phase space of the beam. However, limiting the phase space causes particles outside the stable area to be lost. By altering 6 triplets of quadrupoles[4], it should be possible to raise the transition energy above the beam's energy, avoiding the first major cause of beam loss. By fine tuning the strength of the sextupoles, the desired shape can be achieved without large beam loss. Therefore, simulations must be run to understand how the modifications to the current delivery ring facilities will affect beam coherence and shape.

The program used for these simulations is MAD-X, a software developed at CERN for the design of the accelerators[5]. It is rooted in Fortran90, Fortran77, C, and C++. MAD-X was specifically used to obtain the Twiss (or Courant-Snyder) parameters of the beam's orbit and shape, as well as the dispersion of the beam from multiple passes around the ring. The program allows users to model accelerators in a straight-forward manner, and much of the code is intuitive. It was useful in this study because we could vary the strengths of each component quickly to test different designs and compare the results.

After modifying the created code for the delivery ring from previous work, we explored the effects of the changes on the beams and attempted to improve the system to ensure minimal beam loss.

II. PREPARING THE SIMULATIONS

A. Beam Lines

One advantage of MAD-X, as opposed to other software, is its use of beam lines. Beam lines take a list of elements, some of which can be beam lines also, and makes them a single element. For example, one straight section of the delivery ring can be represented as:

```
straight10 :  line = (mqf1,hqf1,mqq,hbpm,
ddd_10_1, bumpl2, qd1, vbpm, dr14, qf2,
hbpm, ddd_10_2, dr14, qd2, vbpm, dr45,
qf3, hbpm, ddd_10_3, bumpl1, qd3,
vbpm, dr67, mqq, hqf2jump, mqf4 );
```

where each element in the list represents a magnet, marker, drift tube, or other component in the accelerator. Each element must be defined prior and has two main descriptive values, length and a parameter determining its strength (for magnets). MAD-X takes these values and forms a matrix to describe their effect on the beam, and then multiplies all the matrices for the entire list. This element-by-element description, often called a "lattice", is then passed a beam, which must have certain defined properties, such as energy, mass of each particle, and the particle's charge. For example, an 8 GeV proton beam is described as:

```
Beam, particle = proton, sequence=debunch,
energy = 8.87710994;
```

where `energy` denotes the total energy in GeV, not just the kinetic energy. Once the accelerator and the beam

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have been created in MAD-X, specific modules are used to explore the beam's characteristics.

B. Twiss Module

The Twiss Module is capable of calculating the beam characteristics at each object along the beam line, and it tables these into a text file. Its full properties can be found in the user's guide[5], however this work used:

```
select,flag=twiss,column=name,s,
mux,betx,muy,bety,dx,dy, alfx, alfy;
twiss,centre,file=dbglow80Gevtwiss.out;
```

which specifically selected the element name (`name`), the position along the ring (`s`), the phase angle along the x-axis (`mux`), a parameter describing the width of the beam, or β_x (`betx`), the phase angle along the y-axis (`muy`), a parameter describing the height of the beam, or β_y (`bety`), the dispersion in each plane (`dx, dy`), and the orientation in each plane (`alfx, alfy`). The program then would measure these values at the center of each element and make a table in a file with the given name, listing general beam values, like α, $\gamma_{\rm tr}$, and rms values.

It was also useful to plot many of these parameters. The main variables plotted were β_x, β_y, and the dispersion of the beam along the x-axis (D_x), against the position along the beam line (s). MAD-X naturally plots in a postscript (.ps) file, which is called by:

```
  plot, haxis=s, hmin=0, hmax=510,
vaxis1=betx, bety, vaxis2=ndx,vmin=0,-0.5,
vmax=25,2.5, noline=false, colour=100, style=100,
file="twissplotdbglow80.ps",
title="twissplotdbglow80",noversion=true;
```

Up to 10 variables can be plotted on up to 4 vertical axes, and each axis can have an independent scale. MAD-X can also use 5 colors and 4 styles to differentiate the plots; the above code tells it to cycle through the colors and styles in the order the dependent variables are listed.

The data was collected and plotted for various beam energies, ranging from 1.9 GeV to 8 GeV, and for various $\gamma_{\rm tr}$ (a parameter describing the transition energy), from the current design's 7.64 to the highest required 10.0286. The plots and tables were then compared to understand how the different quadrupole strengths changed the description of the beam coherence.

C. Tracking Module

Once the changes to the quadrupoles were examined, the PTC tracking module was used to gather data on a normally-distributed collection of particles over multiple turns in the ring. Using R[6], plots were created of X versus Z, where $Z = \alpha \times X + \beta \times X'$ (a transformation to ease viewing), for each turn. The plots illustrated the changes to the phase space over time. The sextupole magnets were adjusted to shape the beam into a triangle for the third-integer resonance extraction process.

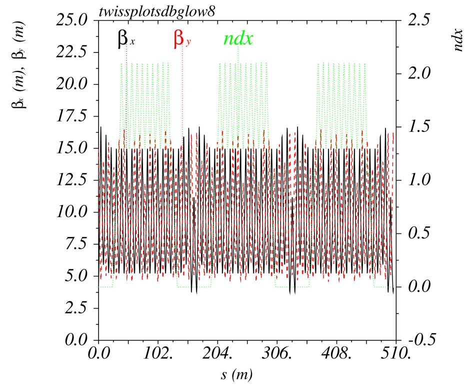

Figure 1: Twiss parameters for an 8 GeV beam at a $\gamma_{\rm tr} = 7.64$.

III. RESULTS

Before the modifications to the quadrupoles, to raise the transition energy, the Twiss plot had regularly oscillating beta functions, but a large change in dispersion over the length of the ring (see 1).

After raising the transition energy to 10.0286 GeV, the Twiss plot had sharp spikes in the beta functions, representing an increase in beam size; however, it also shows a decrease in overall dispersion (see 2). The increase in beam size is not an issue, as the σ_x, representing the rms size of the beam, is given by 1.

$$\sigma_x = \sqrt{\frac{\beta_x \epsilon_{95}}{6\beta\gamma}} \tag{1}$$

where $\beta\gamma = \frac{p}{m_p}$ (p is momentum, m_p is proton mass). The factor ϵ_{95} forces the beam to include 95 percent of the particles and is 1.5×10^{-5} for this beam, so the beam will be contained in the aperture.

The original modeling distribution of 5000 particles is Gaussian, with a rms of σ_x for X and a rms of $\frac{\sigma_x}{\beta_x}$ for X' . The original distribution, at 8 GeV, and final distribution (after 100 turns) can be seen in 3, where $Z = \alpha \times X + \beta \times X'$, a transformation made to ease viewing.

After adjusting the sextupoles and deceleration to 1.9 GeV, the beam will have the triangular shape, as in 4, which is the goal for extraction. The extraction utilizes the triangular phase space by adding a septum on one side of the beam pipe. As particles move outside the stable area, they will also cross the septum, where a magnet will redirect them to the target hall. The rate of the extraction can be controlled by adjusting the rate the particles exit the phase space, which can be done using tuning quadrupoles or continuously adjusting the sextupoles.

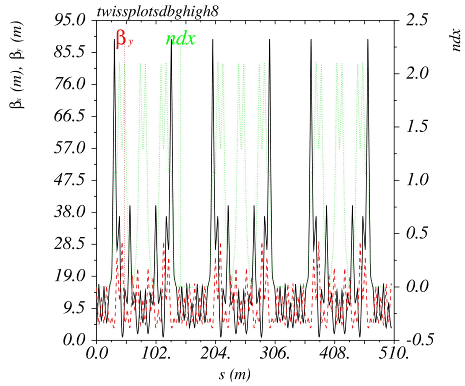

Figure 2: Twiss parameters for an 8 GeV beam at a $\gamma_{\mathrm{tr}} = 10.0286$.

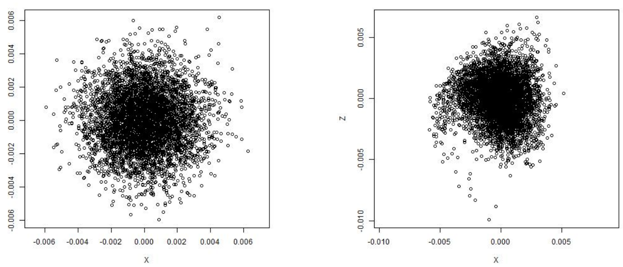

Figure 3: X vs Z from a Gaussian distribution of particles (8 GeV beam). Original on left, after 100 turns on right.

IV. CONCLUSION

From these simulations, it is apparent the modifications to the delivery ring have the desired effect of raising the transition energy and decreasing dispersion in multiple areas, while not raising the beta functions beyond the limits defined by the aperture of the ring. From the tracking module, it is clear there will not be beam loss due to the arrangement, and it is possible to power the sextupoles so the beam is in a triangular packet. From these simulations, the beam is stable, maintaining its shape

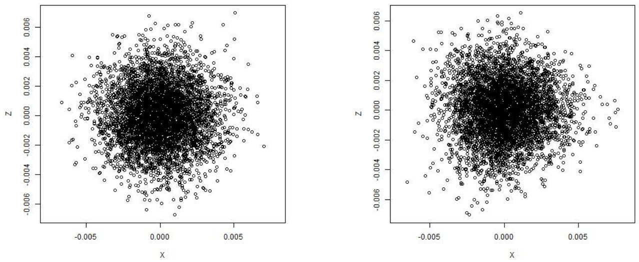

Figure 4: X vs Z from a Gaussian distribution of particles (1.9 GeV beam). Original on left, after 100 turns on right.

over many turns without any beam loss. Further simulations must be run to model the slow extraction with tuning quadrupoles or by varying the sextupoles and the deceleration of the beam using radio frequency cavities.

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