Comments on Proton Beams for REDTOP

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The **R**are **E**ta **D**ecays with a **T**PC for **O**ptical **P**hotons (REDTOP) collaboration is looking to acquire $\sim$2 GeV protons at an instantaneous rate of 10^{11} p/s with high duty factor ($> 75\%$) in order to generate approximately 10^{12} η mesons in one year of running.[1] This note serves to present a possible scenario for generating such beams at Fermilab by enhancing the existing infrastructure of the Muon Campus to include the possibility of decelerating beam within the Delivery Ring (DR). Relevant issues for the accelerator complex to be capable of implementing this scenario are presented.

To meet the REDTOP requirements extraction from the Fermilab Booster synchrotron at approximately 2 GeV kinetic energy was being discussed, with this beam to be transferred to a new storage ring (installed in the Booster tunnel?) and extracted into the old Booster-to-Main Ring transfer line tunnel where the REDTOP experiment would presumably reside. However, in lieu of the soon to be completed Muon Campus infrastructure, we present a new "straw man" solution that transfers Booster beam to the DR, as one would do for the Mu2e experiment. Since a system will already be in place to resonantly extract beam from the DR to Mu2e, this system could – in principle – be used also to slow spill for REDTOP. The beam, however, would need to acquire the correct energy for the REDTOP experiment prior to extraction.

For the Muon g-2 experiment, the Delivery Ring will be operated DC and tuned to accept muons with a momentum of approximately 3.1 GeV/c, not far from the REDTOP desired momentum (2.8 GeV/c for 2.0 GeV kinetic energy). The Muon g-2 beam will only circulate the DR a few revolutions before being transferred to the Muon Storage Ring in the MC-1 experiment hall. However, when used for Mu2e the DR will also employ slow resonant extraction of its 8 GeV proton beam (8.9 GeV/c momentum) to the Mu2e experiment. Thus, it is not hard to reason that a path for REDTOP would be to deliver 8-GeV protons to the DR in the same way as for Mu2e, then decelerate to the desired energy before employing the resonant extraction system. Alterations to the DR power supply systems and to the RF system obviously would be required in order to perform the deceleration.

The desired rate for REDTOP is set by the present parameters of their detector, so to achieve 10^{11} p/s on target one would deliver a single pulse from the Booster of 4×10^{12} at 8 GeV to the DR and slow spill for 40 s. With such a long spill it is not unreasonable to assume a few seconds deceleration time. If we allow 10 s for both deceleration to $\sim$2 GeV and for re-setting to the injection energy (8 GeV) this would give a total cycle time of about 50 s; this time line would give REDTOP their desired instantaneous rate with a duty factor of 80%. With only one Booster cycle needed every 50 s, there would be essentially no impact on the neutrino program.

With this scenario in mind REDTOP can be thought of as a next step in the utilization of the Muon Campus as a Low/Medium-Energy Fixed Target Facility as a follow-on to Muon g-2 and Mu2e. Whether a new target hall would be developed on the Muon Campus, or whether the REDTOP experiment can be outfitted within an existing experimental hall (*e.g.*, MC-1 following the completion of Muon g-2) or some

[1] See http://redtop.fnal.gov

other variation, the development of a variable energy DR could create several years of running for η and η' meson physics for searches of small deviations from the Standard Model as well as providing a lower-energy facility for other new physics experiments at Fermilab.

Of course, in addition to adding power supply and RF capabilities to the DR there are other items that need to be understood for this scenario to work. For example, while a resonant extraction system is being developed for 8 GeV operation of Mu2e, at energies as low as 1.5 GeV the beam will be 2× larger transversely and so the effectiveness of the DR extraction system at these energies or any required alterations to the extraction system would need to be considered. Also, for Mu2e the slow spill time is less than one second, not 40 seconds, and so the beam lifetime will be an issue, especially at lower energies where the beam scattering off of residual gas will be greater; possible enhancements to the DR vacuum system will need to be evaluated accordingly. And, in addition, when decelerating from 8 GeV the beam will cross transition at about 6.2 GeV in the DR which will require further study.

Delivery Ring Enhancements

The Delivery Ring (formerly the Debuncher) was originally run DC at a bend field of 1.7 T corresponding to an antiproton kinetic energy of 8 GeV. A first look at the magnet and RF requirements for the DR to perform the above manipulations for REDTOP suggests that a reconfiguration of the power supply system is needed to ramp the magnets down and up in a suitable amount of time (as the ring is to be run DC for both Muon g-2 and Mu2e). The inductance of the magnet system generates a natural time constant of approximately 7 s.[2] If inverting power supply components were to be installed, a ramp time of ∼5 s is likely achievable. For deceleration, the existing 2.4 MHz cavity being installed in the DR for Mu2e would be insufficient for REDTOP, mainly due to the inherent frequency shift that would occur in going from 8 GeV to 2 GeV kinetic energy. However, if a second RF cavity of the same kind were installed, but tuned to a slightly lower frequency, the combination of the two could be used for the required deceleration.[3] A third cavity would provide even more latitude in the operation, but may not be necessary. Further studies on the cavities would be required, but the DR has space for either of these scenarios. It should be noted that a spare cavity is already being produced for Mu2e, which is also the same style cavity being installed in the Recycler for its upgrade.

Though the Delivery Ring cannot support "fast" acceleration at the moment, there appears to be nothing technically inherent preventing an upgrade to provide such functionality. The main power supply systems would require enhancements and the ring would need to be upgraded to a ramped correction magnet system. A near-duplicate 2.4 MHz cavity would need to be implemented for acceleration. Other items needing investigation include:

- Possible LLRF development
- Possible enhancements to resonant extraction system
- Possible enhancements to ring vacuum system
- Possible aperture enhancements for lower-energy transport from DR to REDTOP
- Possible instrumentation and controls upgrades

[2] Dan Wolff, REDTOP meeting of 3/14/16 and private communication.
[3] Joe Dey, REDTOP meeting of 2/18/16 and private communication.

Beam Physics to Address

To further evaluate the feasibility of outfitting the Muon Campus for variable energy beams from the Delivery Ring, other accelerator physics issues will require examination. For example:

- Deceleration through the transition energy of the DR ($\sim$6.2 GeV) at the ramp rates envisioned above
- The possible need to employ a transition energy adjustment (pulsed quad, "γ_t jump" system)
- An evaluation of the performance of the slow resonant extraction system at 2 GeV where the beam will be roughly 1.8 times larger than at 8 GeV and where the magnet field quality will be different as well
- A determination of the adequacy of the DR vacuum system for maintaining the beam for tens of seconds at 2 GeV energy
- A proper modeling of the 2- or 3-cavity deceleration system
- Re-tuning of the DR-to-REDTOP beam lines from 8 GeV to 2 GeV and possible impacts due to the apertures of these system elements
- Any further lattice and/or aperture optimizations for lower-energy operations

In summary, the requirements for REDTOP can be met in principle by adding deceleration capability to the Delivery Ring at Fermilab's Muon Campus. A first look at system requirements indicates that this might be feasible, but further study is warranted and other variations of this theme might become apparent.

Such a system would not only meet the needs of REDTOP but would enable variable energy beams from $\sim$1.5 GeV to 8 GeV kinetic energy and re-use the Muon Campus infrastructure for a next round of lower-energy, high-intensity experiments using the Booster as the proton source and the Delivery Ring to implement higher duty factor slow spills. Future investigations should clarify the upgrades required and the scale of the necessary investment.

A Parameter List

Table 1: Relativistic γ, momentum pc, field strength B, transverse beam size σ(relative to size at 8 GeV), slip factor $\eta = 1/\gamma_t^2 - 1/\gamma^2$, particle speed $\beta = v/c$, revolution frequency f_0 and RF frequency f_{RF} for various values of proton beam kinetic energy, W, in the Fermilab Delivery Ring, assuming a transition energy of 6.236 GeV.

W	1.000	1.500	1.800	2.000	2.200	3.000	4.000	5.000	6.000	7.000	8.000	GeV
γ	2.066	2.599	2.919	3.132	3.345	4.198	5.264	6.330	7.397	8.463	9.529	
pc	1.696	2.250	2.572	2.784	2.995	3.825	4.848	5.863	6.874	7.882	8.889	GeV
B	0.324	0.430	0.492	0.533	0.573	0.731	0.927	1.121	1.315	1.508	1.700	T
σ	2.289	1.987	1.859	1.787	1.723	1.524	1.354	1.231	1.137	1.062	1.000	
η	-0.217	-0.131	-0.100	-0.085	-0.072	-0.040	-0.019	-0.008	-0.001	0.003	0.006	
β	0.875	0.923	0.939	0.948	0.954	0.971	0.982	0.987	0.991	0.993	0.994	
f_0	0.516	0.545	0.554	0.559	0.563	0.573	0.579	0.583	0.585	0.586	0.587	MHz
f_{RF}	2.065	2.179	2.217	2.237	2.252	2.292	2.317	2.331	2.339	2.344	2.347	MHz

$(\gamma_t - 1)mc^2 = 6.236$ GeV