Beams for REDTOP

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REDTOP Requirements

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- As presented in 2016, the REDTOP beam requirements for an untagged eta experiment can be summarized here:
  - ~2 GeV kinetic energy primary proton beam
  - 10^{11} protons per second, high duty factor
- **Scenario I:** Use existing infrastructure with appropriate upgrades
  - Use Delivery Ring, presently used for Muon g-2 and soon for Mu2e
    - » magic muon momentum of 3.1 GeV/c corresponds to a proton energy of 2.3 GeV
  - The Delivery Ring will be outfitted with
    - » RF for the Mu2e experiment, to be run at 8 GeV kinetic energy
    - » a slow extraction system for uniform beam spills to Mu2e
  - However, DR is run "d.c." and the system will presently accept either 8 GeV proton beam or lower energy secondary beams (muons, for instance)
  - Suggestion: inject 8 GeV protons, decelerate 8 to 2 GeV, then slow spill
- **Scenario II:** Use PIP-II system with future possible upgrades
  - When completed, PIP-II linac will deliver up to ~1.5 MW CW beam at 0.8 GeV
  - Space reserved to upgrade the beam energy to ~0.9-1.0 GeV if desired
  - Discussions of future replacement of Booster synchrotron have begun
    - » may lead to further upgrade of linac energy to ~2 GeV for injection into a new ring
    - » would enable high-power low-energy program, perhaps with new experimental area, etc.

Use of Existing Infrastructure

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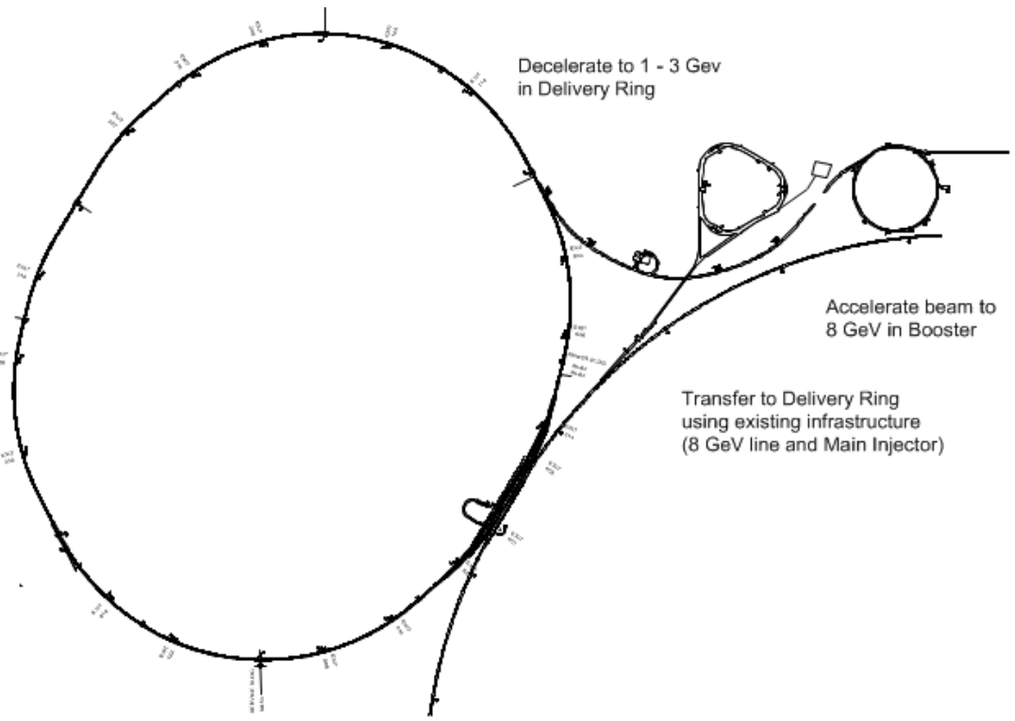
http://redtop.fnal.gov/the-accelerator-complex/



10^{11} p/s = $\bar{R}/df$ = $N \cdot \frac{1}{T}/df$ = $4 \cdot 10^{12} \cdot \frac{1}{50\ s} \cdot \frac{5}{4}$

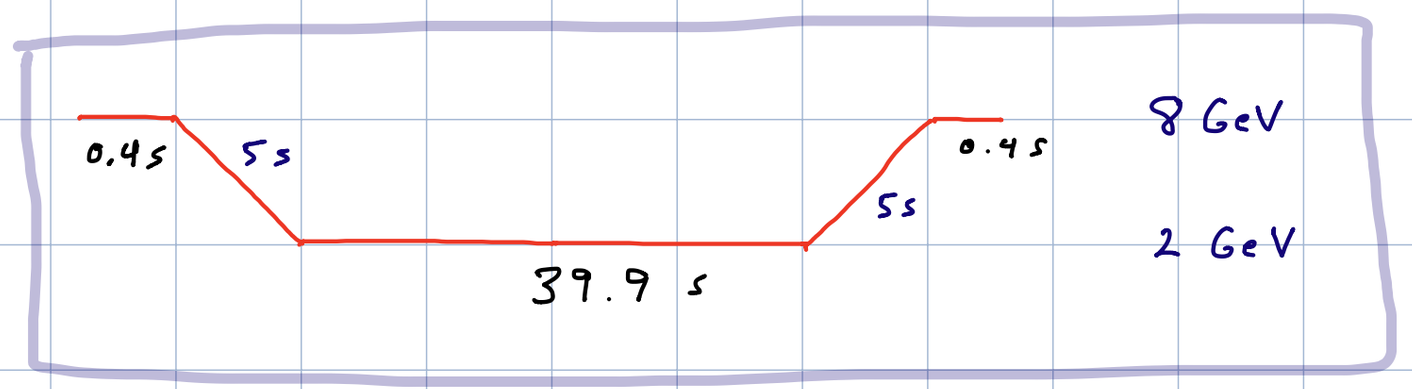
$N = 4 \cdot 10^{12}$

or, = $\frac{N}{n \cdot T_0} \cdot \frac{1}{df}$ $T_0 = \frac{4}{3}$ s

so, need $n \cdot df \approx 30$

$38 \cdot \frac{4}{5} = 30.4$

$\frac{4}{3}$ s $\cdot 38 = 50.7$ s = total time



Straw man time-line:

1 BOO every 38 MI cycles:

extra BOO cycles exist; so,
hit on High Intensity Program: 0

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- REDTOP wants 10^{11} p/s delivered to their target, at a beam kinetic energy of ~2 GeV (+/- 10%)

- ***Concept***:
  - Delivery Ring is ~ same circumference as Booster
  - take one Booster batch — $4x10^{12}$ — re-bunch in Recycler and send directly to Muon Delivery Ring *a' la* the Mu2e scenario
    - » i.e., send all 4 bunches, re-bunched at ~2.4 MHz, to the DR
  - decelerate from 8 GeV to 2 GeV in ~5 sec using 2.4 MHz system
  - allow beam to de-bunch, then slow spill (*a' la* Mu2e) over the next ~40 sec
  - reset the magnets to 8 GeV (~5 sec) and repeat…

- Systems Questions
  - At what rate can magnets be ramped? What would be PS needs?
  - What RF voltage is required? What other RF requirements (LLRF, etc.)?
  - What vacuum is required? How would any modifications be implemented?
  - Are apertures adequate at 2 GeV? Can slow spill work at 2 GeV?

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- One suggestion was to use MC1 for Exp. Hall once Muon g-2 was complete with data taking
- present suggestion is to utilize DR50 area of the Delivery Ring

Mu2e

Muon g-2

- slow extract using identical system as for DR30 extraction to Mu2e
  - » the two systems could be used as “spares” for each other
- With this scenario, could imagine running Mu2e and REDTOP in a “leap frog” arrangement over time

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- Use of DR50 area
  - previously housed the antiproton deceleration experiments, E-670, E-835; thus, much infrastructure in place, including experiment control room upstairs
  - initial look at experimental “hall” appears likely to be able to support REDTOP
  - would need to be able to extract, steer, and “aim” beam to the detector from the DR50 straight section

- Transition Avoidance
  - Early concern was transition crossing; in DR, transition occurs at 6.2 GeV (kinetic) — γ_t = 7.64
  - A new lattice configuration was found that can raise the transition gamma to γ_t =10; during deceleration it can be “relaxed” back to its design value before final energy/extraction is reached.

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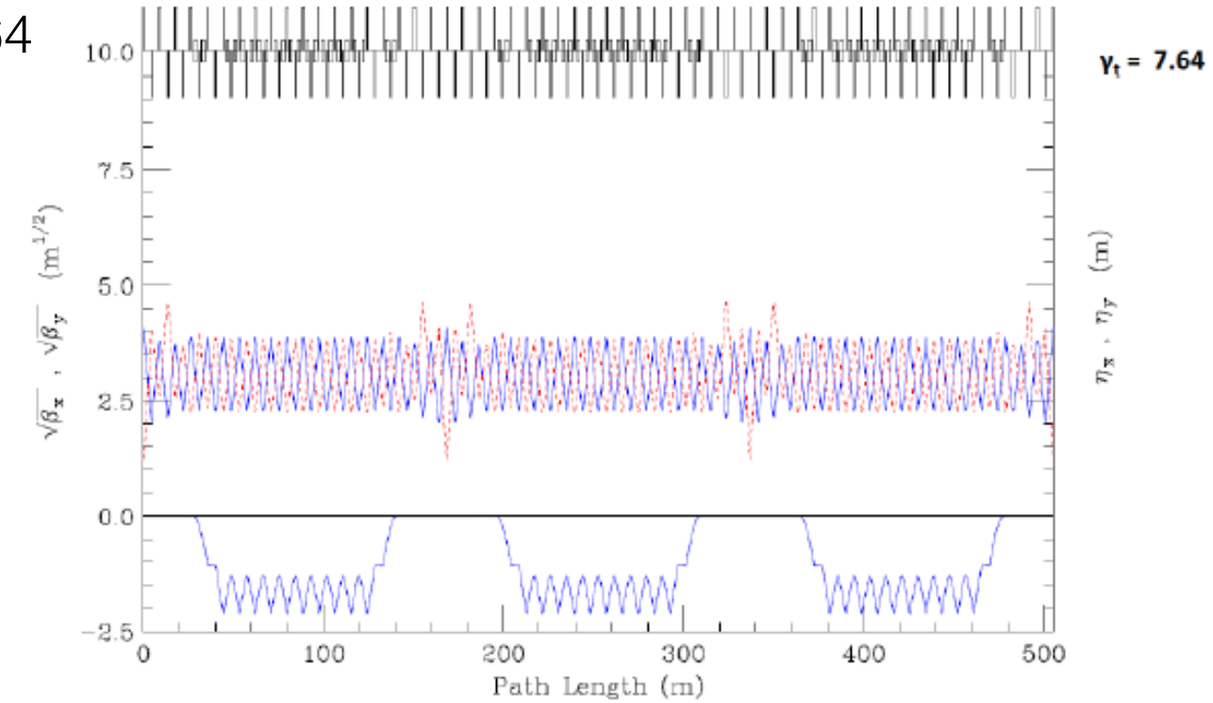
γ_t = 7.64



γ_t = 10.0

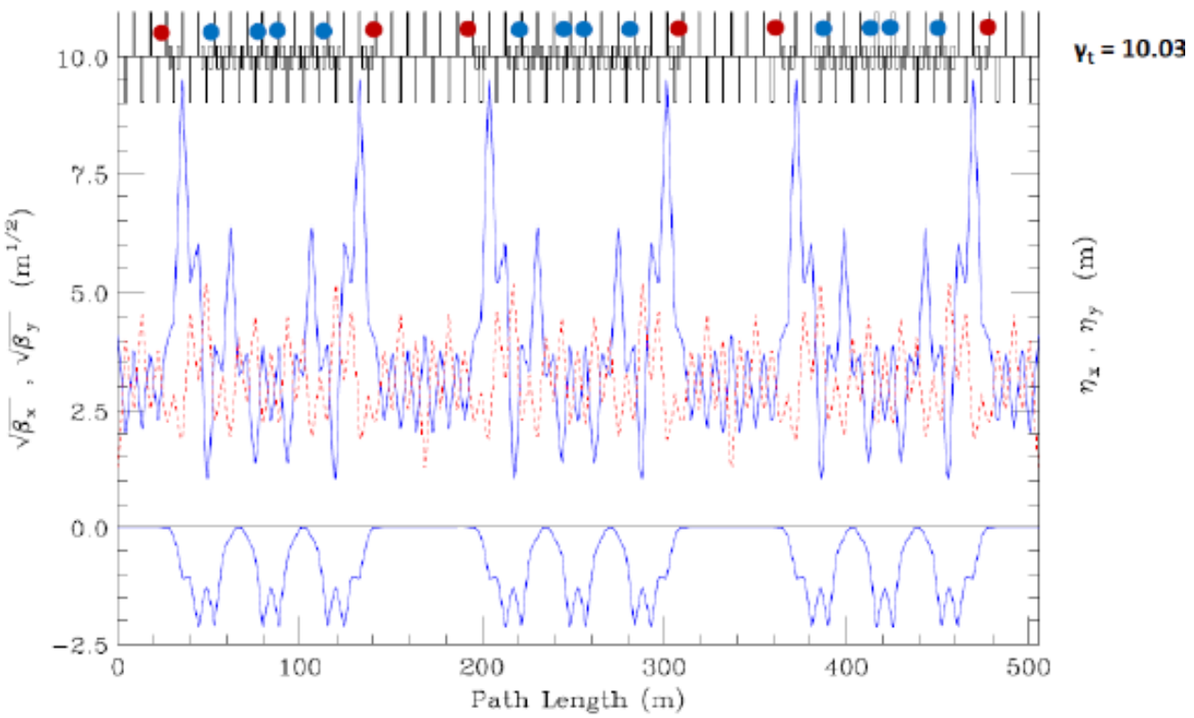


Table 1: Variation of γ_t, β_{max}, and the 15π 99% Beam Envelope with Strength q of the Arc Quadrupoles

p (GeV/c)	8.89	8.33	7.76	7.20	6.63	6.07
KE (GeV)	8.00	7.45	6.88	6.32	5.76	5.21
γ_{BEAM}	9.53	8.93	8.33	7.74	7.14	6.55
$\gamma_{transition}$	10.03	9.43	8.83	7.74	7.64	7.64
β_{max} (m)	94.9	72.5	49.5	30.1	15.1	15.1
q (m^{-1})	.0697	.0573	.0416	.0236	0.0	0.0
3σ (mm)	15.0	13.6	11.6	9.4	6.9	6.9

The nominal injection gradient of the SQC quads is 10.46 T/m. Implementing this scheme requires the nQ07, nQ13, and nQ19 gradients change to 4.26, 13.56, 13.56 T/m, respectively. In terms of current this means shunting ~140-150 A around the nQ07, while adding ~70-75 A to the nQ13, nQ19 quadrupoles.

J. Johnstone, M. Syphers
NA-PAC 2016, WEPOA41

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- Upgrading the Delivery Ring to have variable energy, in range of ~1-8 GeV could open other possibilities for future low-energy experiments. REDTOP already thinking ahead to experiments with η' meson (~4 GeV ± 20% or so).

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.

from 2016

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

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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 (∼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

J. Johnstone, next talk

might be OK; but have room for upgraded vac system

Table 1: Relativistic γ and β, momentum pc, field strength B relative to 8 GeV value of 1.7 T, transverse beam size σ relative to size at 8 GeV, slip factor $\eta = 1/\gamma_t^2 - 1/\gamma^2$, 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 constant 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	
β	0.875	0.923	0.939	0.948	0.954	0.971	0.982	0.987	0.991	0.993	0.994	
pc	1.696	2.250	2.572	2.784	2.995	3.825	4.848	5.863	6.874	7.882	8.889	GeV/c
$B/(1.7\ \mathrm{T})$	0.191	0.253	0.289	0.313	0.337	0.430	0.545	0.660	0.773	0.887	1.000	
σ/σ_0	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	
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

Use of PIP-II Infrastructure

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- PIP-II Linac project will be able to provide protons / H^- beams of kinetic energy 0.8 GeV at high power levels (up to ~1.5 MW CW)
- The project has reserved space and equipment for possible immediate upgrade of the final energy to 0.9-1.0 GeV
  - tagged eta experiment would require 890 MeV
- The PIP-II project will generate 1.2 MW from the Main Injector for the LBNF/DUNE program. Further upgrades are being discussed for reaching 2.4 MW or possibly beyond following the PIP-II completion.
  - the next “bottleneck” for reaching these higher power levels is the present Booster synchrotron at Fermilab
  - a possible Booster replacement is being discussed
    - » create new Rapid-Cycling Synchrotron to replace the existing Booster
    - » this RCS could accelerate between about 2 GeV and 8 GeV, with an upgrade to 2 GeV for the PIP-II linac system
    - » this, in addition, would create a high-power low-energy beam source/facility for physics

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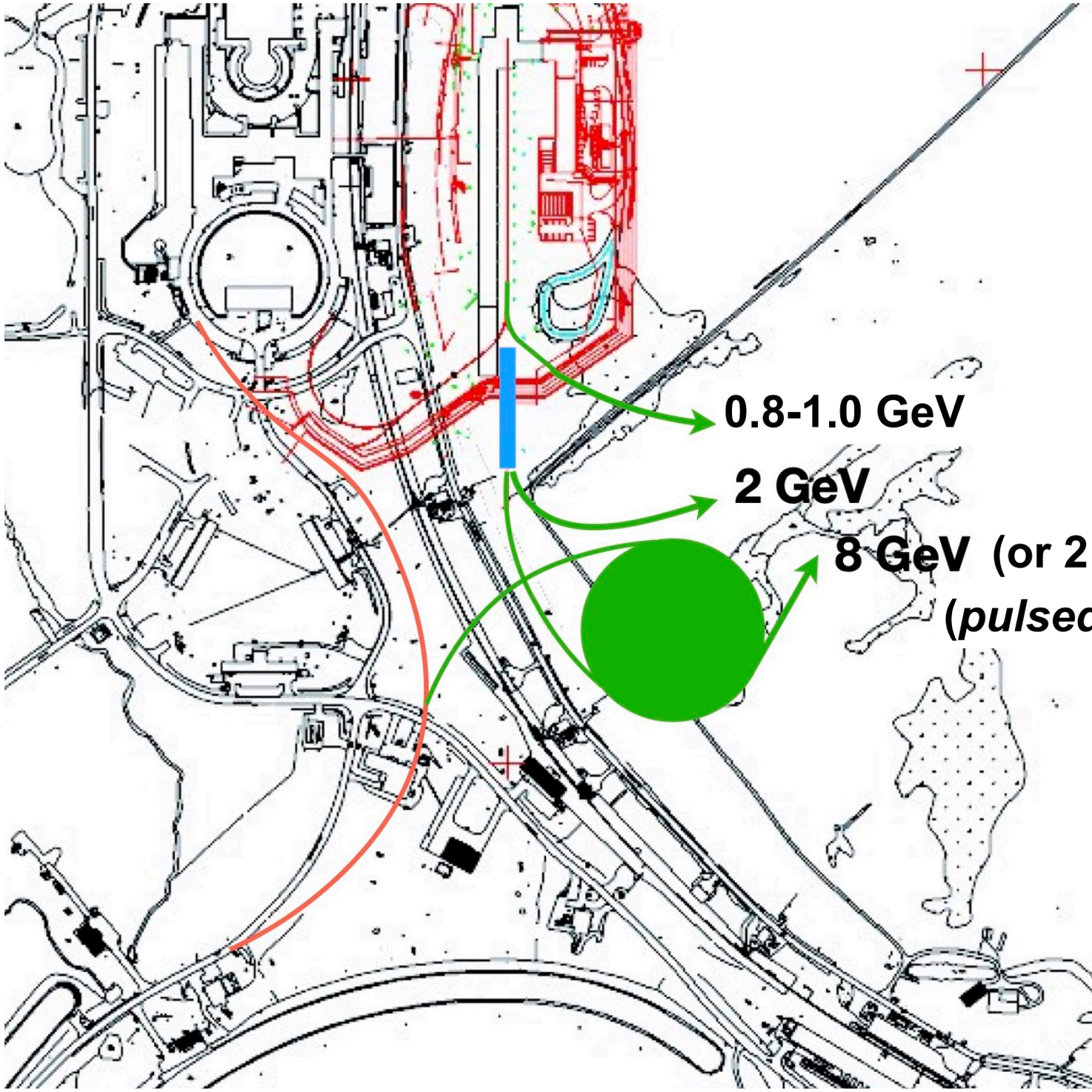
Preliminary, schematic only



Summary

- **Phase I — untagged η's using the Delivery Ring**
- With upgrades to power supply system, etc., can arrange for Delivery Ring to operate at variable energies from ~1 - 8 GeV
  - accelerating cavities exist; slow spill system will exist for Mu2e; magnetic fields required for REDTOP similar to those for g-2
  - more accelerator studies/design needed to finalize concept, but conceptually doable
- No hit on neutrino or other programs; one BOO cycle every 800 or so, and presently we have spare cycles to give
- Enables untagged eta, eta' experiments at ~2 and ~4 GeV, respectively
- **Phase II — tagged η's using PIP-II beams**
- PIP-II project has space and equipment to upgrade to ~1 GeV output energy, enough to deliver beam to 920 MeV *tagged* eta experiment
- Further linac upgrades and Booster replacement options being explored; could lead to high-power 1-8 GeV beams direct from PIP-II campus