Fermilab Proton Beam for *Mu2e*

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NuFact09
Muon Physics Working Group
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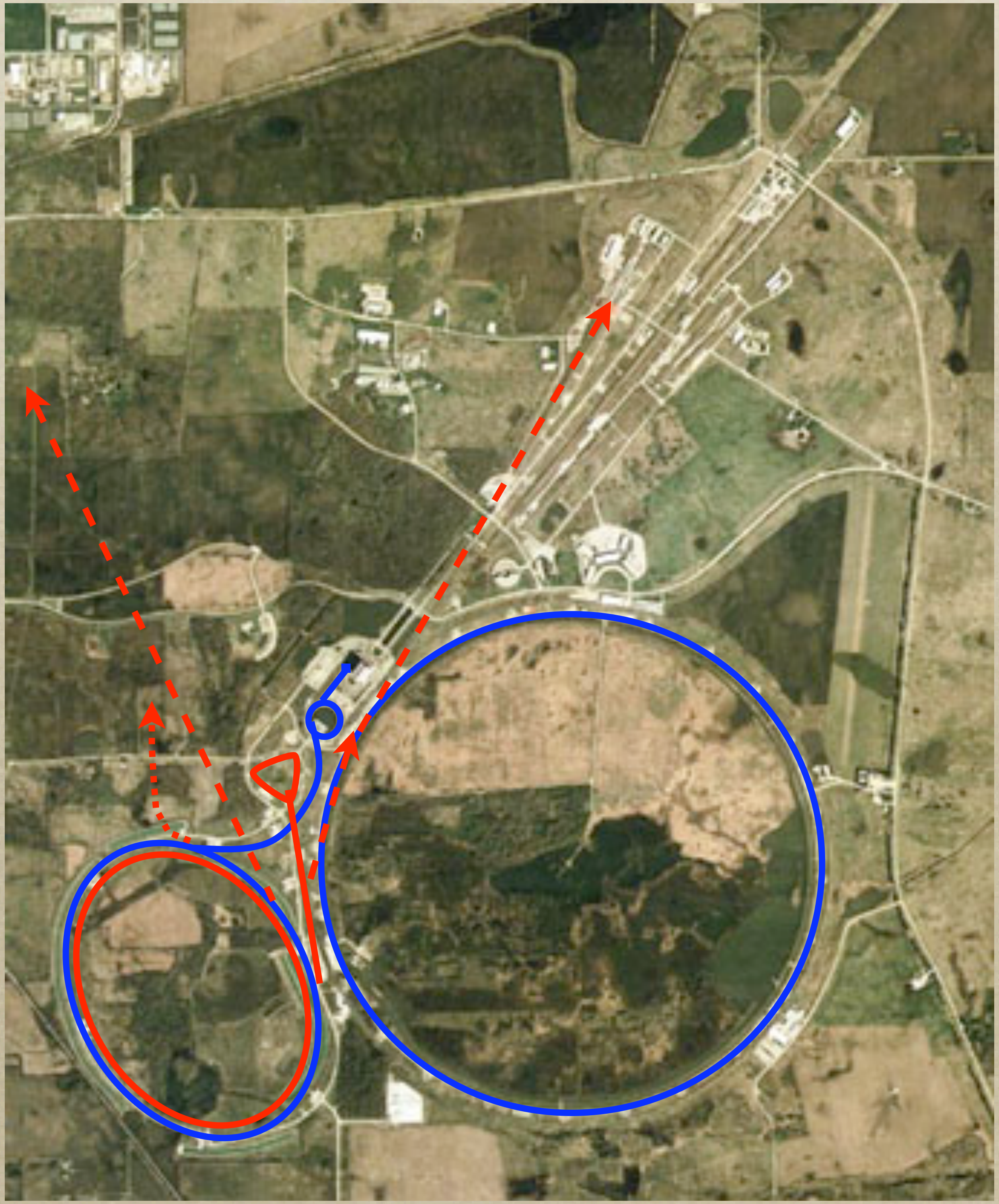
Fermilab Beam for Mu2e

- *Overview of Requirements*
- *Use of Existing Facility*
- *Possible Operating Scenarios*
- *Extraction*
- *Beam line design efforts*
- *Extinction*
- *R&D Plans & Directions*

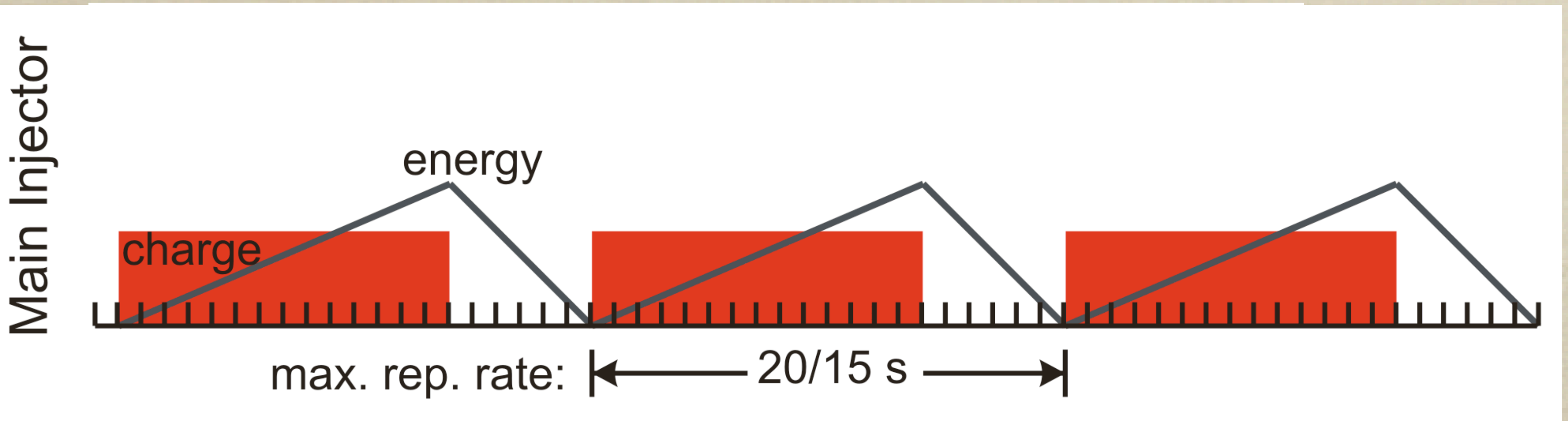
Proton Availability

- *Daily Operation*
  - *Set up p-pbar store in Tevatron, ...*
  - *Produce more antiprotons, and drive the **neutrino** program*
    - *time line governed by 15 Hz Booster operation*
  - *7 Booster pulses to MI every 2.2 s*
    - *5 for NuMI*
    - *2 for pbar production*
  - *Off-load pbars to Recycler ~every hour*
  - *Spare pulses to miniBooNE*
  - *1 pulse to SY120 occasionally...*



NuMI/NOvA, after Run II

- *Following Run II, the NOvA experiment will ultimately require 12 Booster cycles per MI cycle*



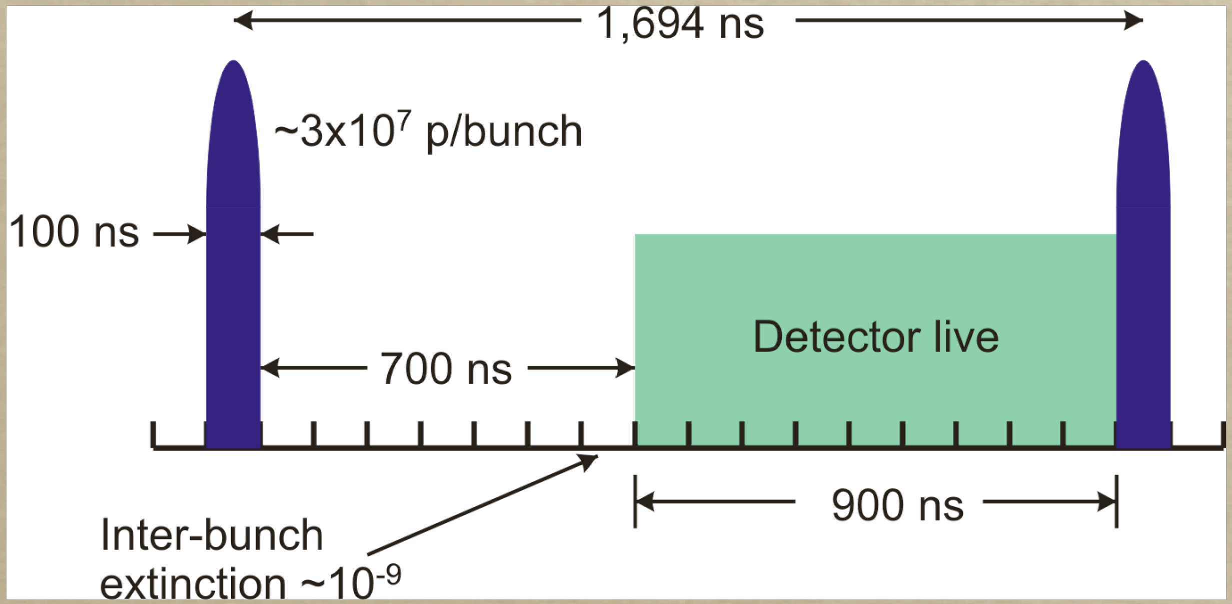
- *1.333 sec = 20 * 1/15 s (20 Booster cycles)*

- *Booster has been upgraded to perform at this level; if can run "flat out" at 15 Hz, leaves 8 Booster cycles for "other program(s)"*

Continued Booster upgrade program being performed to achieve full 15 Hz operation

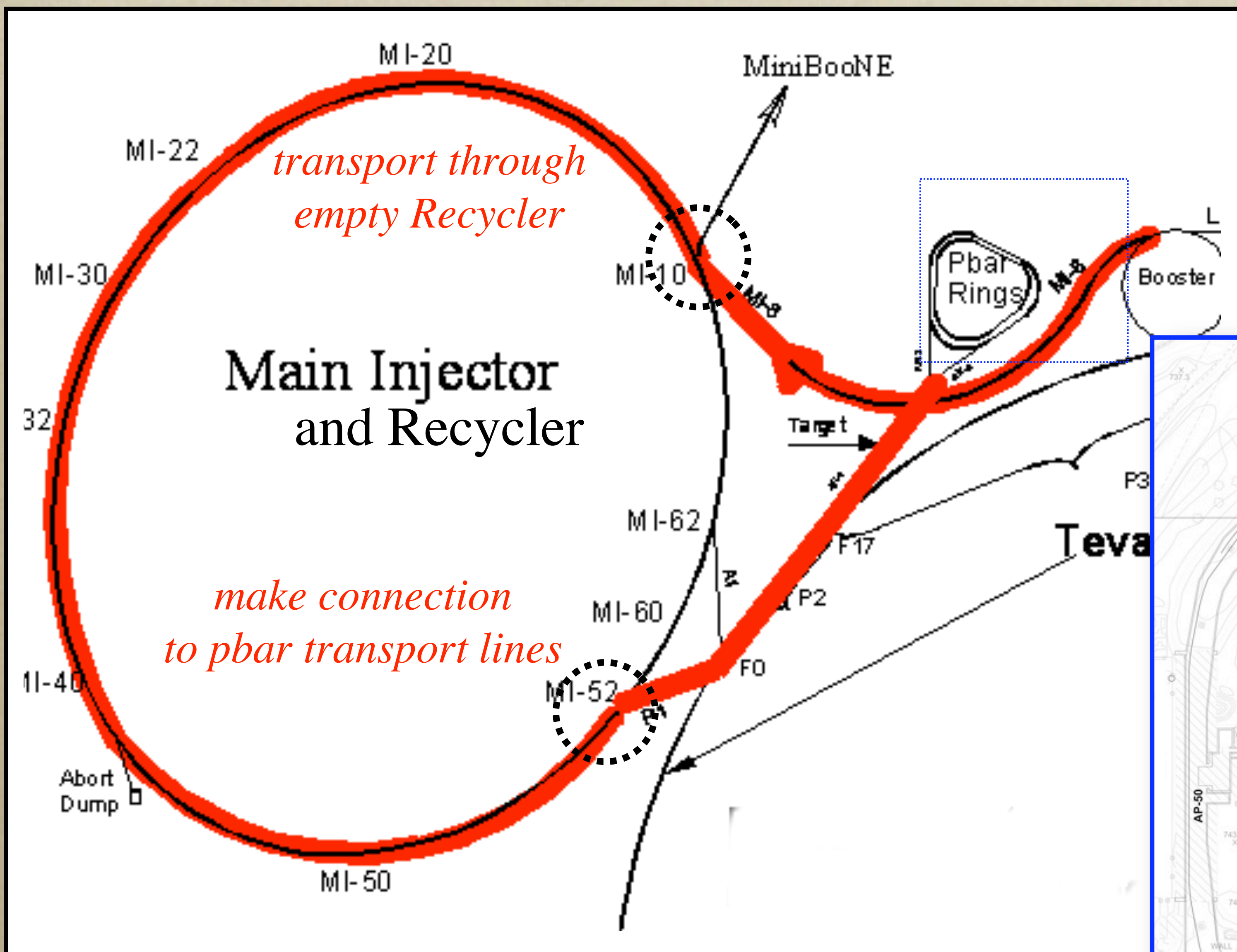
Pulsed Beam Structure for Mu2e

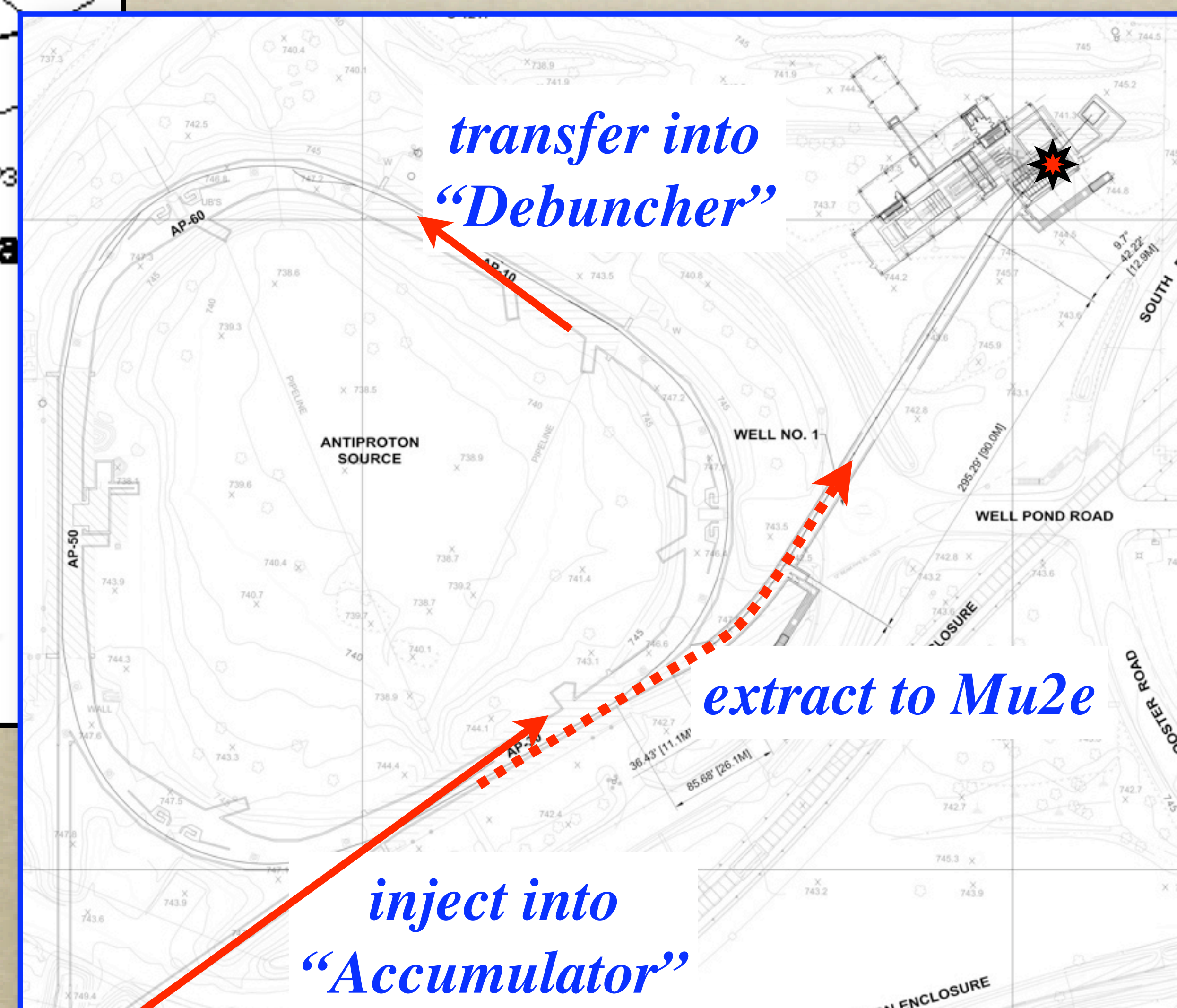
- Tied to prompt rate and machine: FNAL near-perfect
- Want pulse duration << τ_{μ}^{Al} , pulse separation ≥ τ_{μ}^{Al} ~ 864 ns
  - FNAL ***Debuncher*** ring has circumference **1.7μs** !
- Extinction between pulses < 10^{-9} needed
  - = # protons out of pulse/# protons in pulse



- 10^{-9} based on simulation of prompt backgrounds

Beam Transport from Booster





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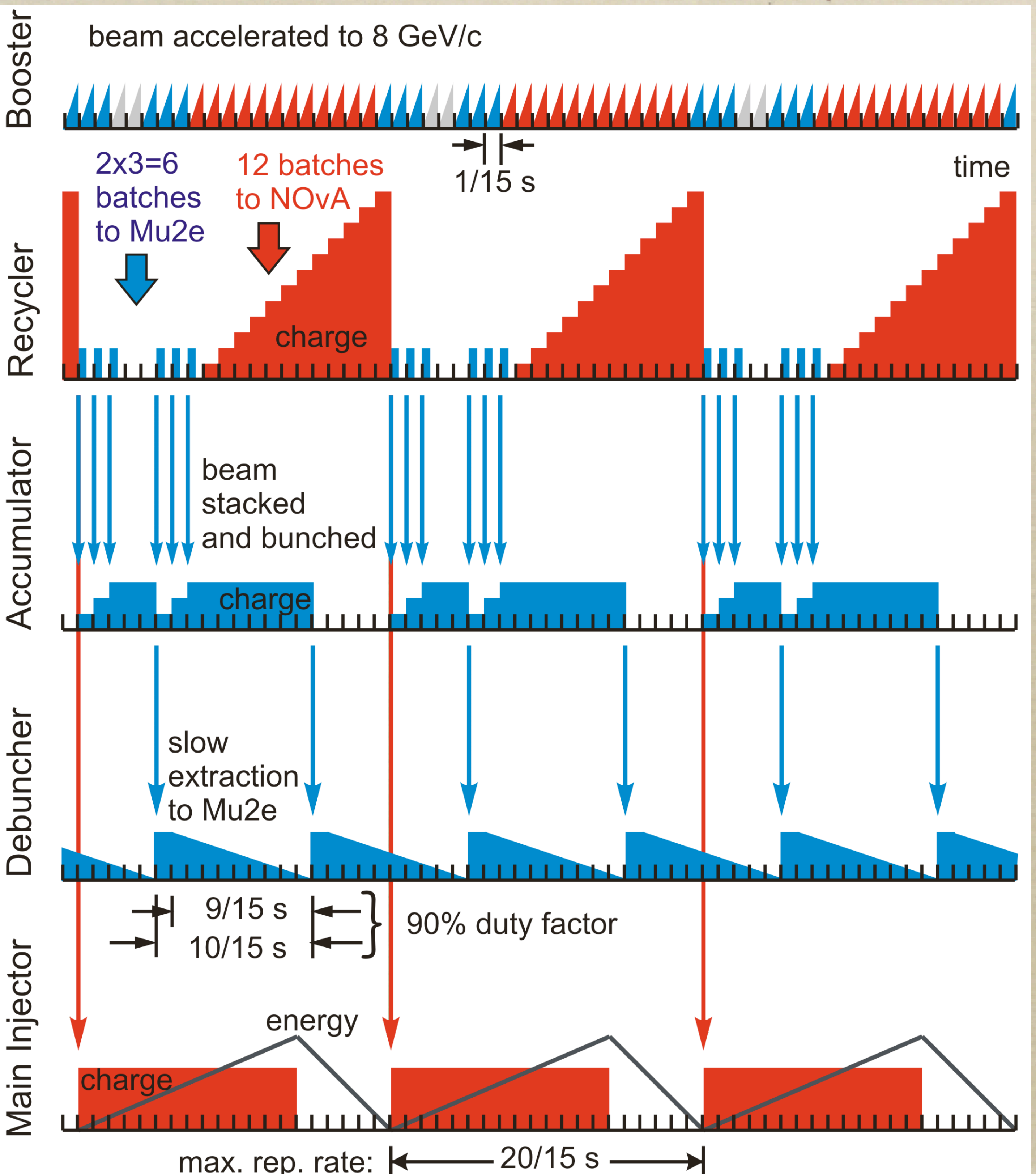
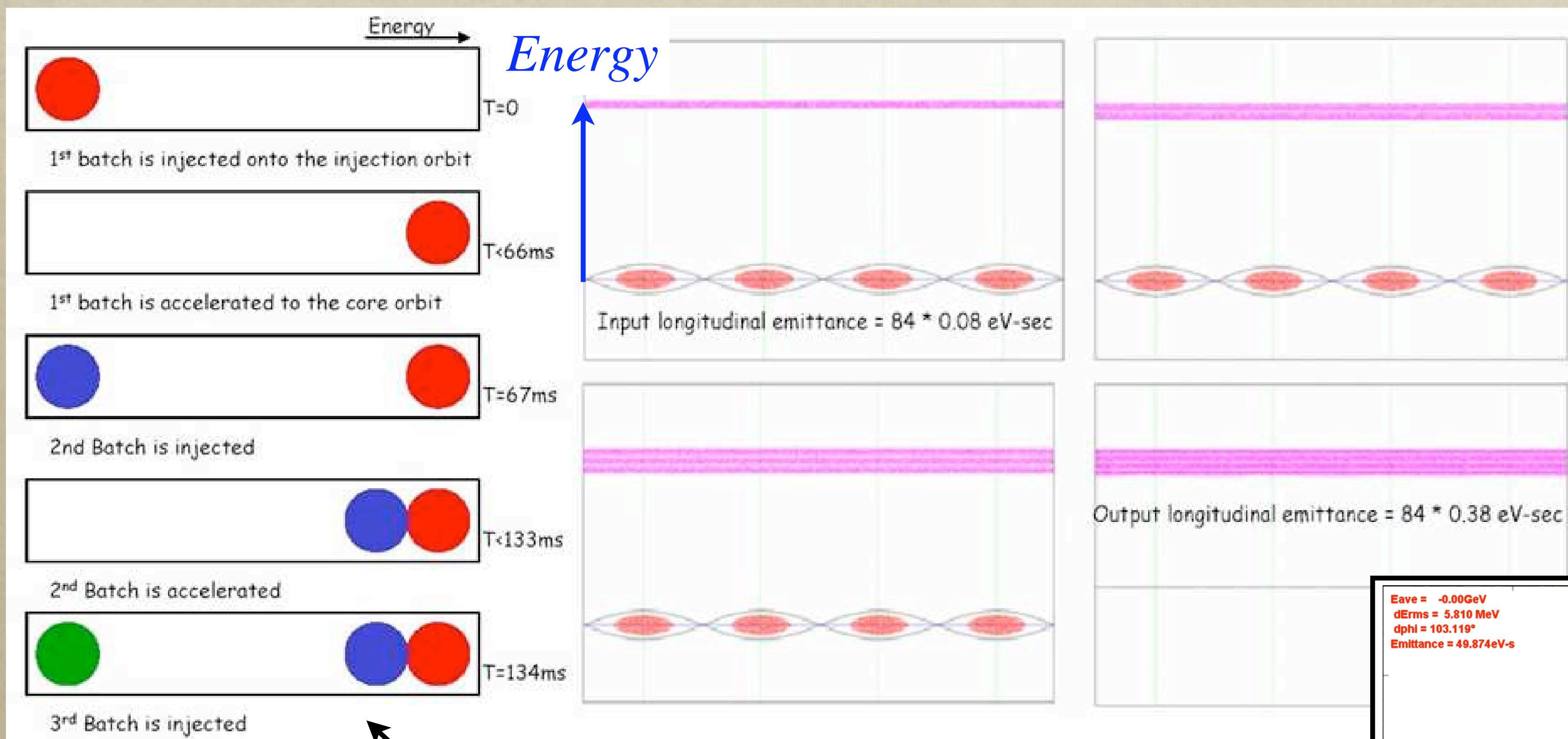
Operating Scenario: Proposal

- *Inject/stack beam into Accumulator, form single bunch, and transfer to Debuncher for slow spill*
- *In principle, w/ $4x10^{12}$ (4 Tp) per Booster batch, Mu2e receives 18 Tp/s on target, $1.8x10^{20}$ in 10^7 s.*
- *15 Hz Booster assumed*
- *Does not affect NOvA operation*
- *Will require improved safety mitigation for "pbar" rings*

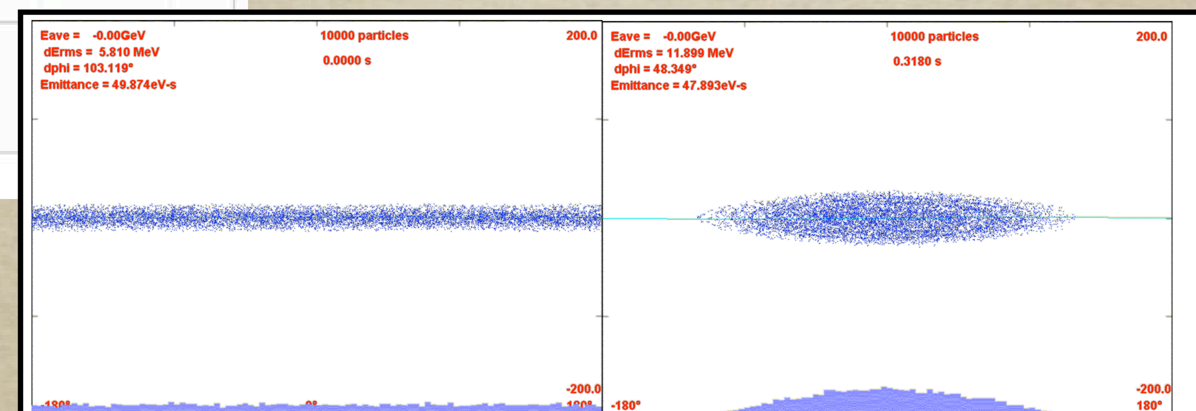


Bunch Formation



Aperture restrictions of Accumulator dictate can stack up to 3 cycles of Booster beam. Hence, would only use 6 cycles out of the available 8.

- *momentum stack in Accumulator*
- *form single bunch; x-fer to Debuncher*
- *phase rotate, re-capture*
- *<40 ns bunch, Δp/p ~ 0.8% (rms)*



A: initial debunched beam. B: After adiabatic bunching in Accumulator.

C: After ϕ-E rotation in Debuncher D: After h=4 bunching in Debuncher.

RF Requirements

- Accumulator:
  - 53 MHz (h=84), 80 kV (~30-50 kV presently avail.)
  - 625 kHz (h=1), 4 kV (~2 kV presently available)

- Debuncher:
  - 588 kHz (h=1), **40** kV (~0.5 kV at present)
  - 2.35 MHz (h=4), **250** kV (~0.8-2 kV at present)

High Bunch Charge

- *Space Charge will be an issue in this scenario...*
  - *For N particles* ***uniformly*** *distributed about the ring,*

$$\Delta\nu_{s.c.} = \frac{3r_0 N}{2\epsilon\gamma^2(v/c)} = \frac{3\ (1.5\times10^{-18})(1.2\times10^{13})}{2\ (20\pi\times10^{-6})(9.5^2)} \approx 0.005$$

  - *Include "bunching factor":* $\mathcal{B} \approx \dfrac{1700\ \text{nsec}}{40\ \text{nsec}\cdot\sqrt{2\pi}} \approx 17$

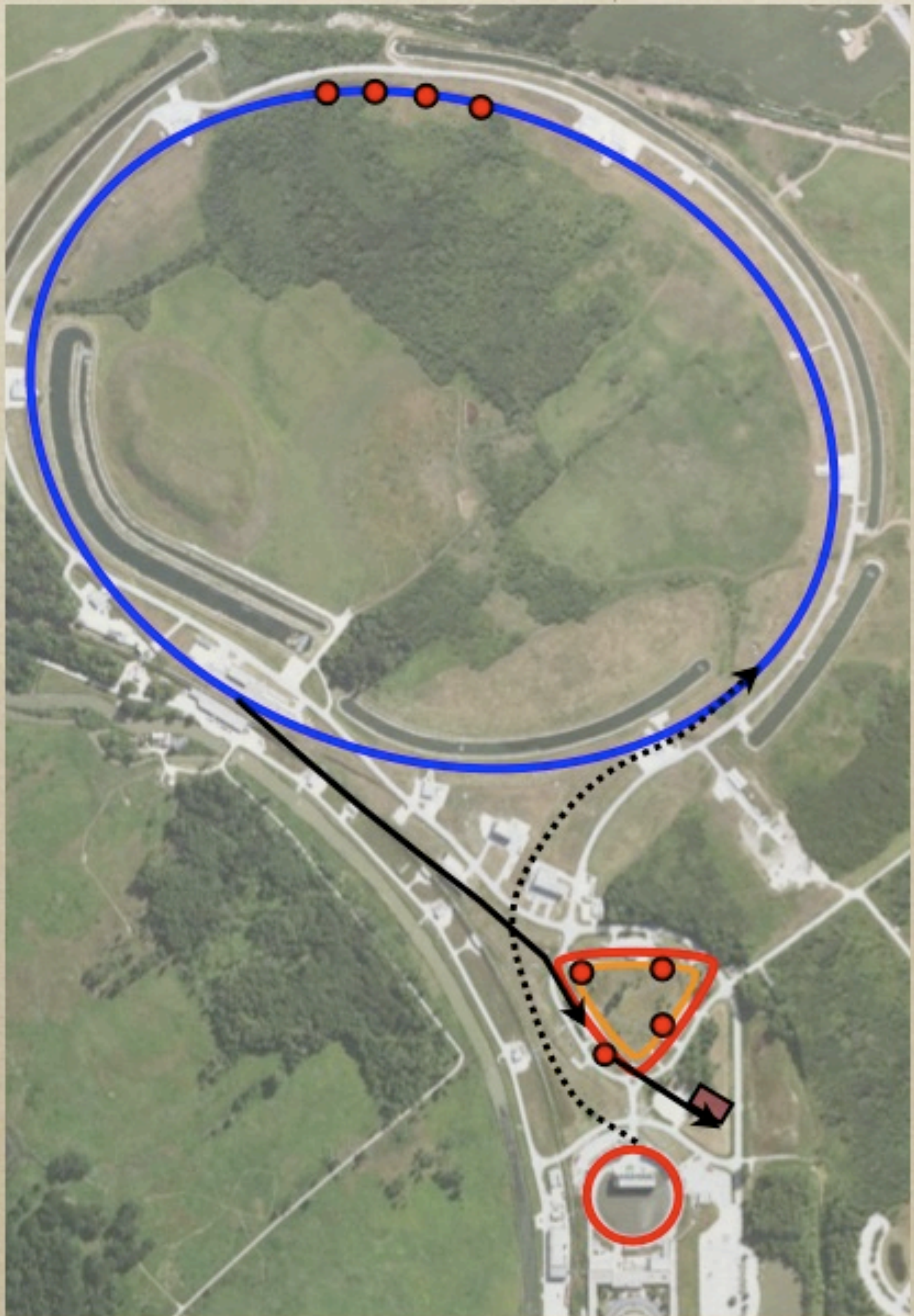
  - *Thus, expect at "design parameters":* $\Delta\nu_{s.c.} \approx 0.1$

Why is Space Charge an Issue?

- *Harder to maintain bunch length, as bunch tries to push itself apart (need more voltage)*
  - *has not been part of the calculations so far*
- *Particles within the bunch behave differently*
  - *small (transverse) oscillation particles see a different field gradient than large oscillation particles -- thus, have different tunes (prev. slide)*
  - *makes controlling "resonant" extraction harder*

Possible Alternate Scenario

- *Circulate beam from Booster in the Recycler, form 4 bunches, transfer to Accumulator ring, transfer 1-at-a-time to the Debuncher, and slow spill over ~16 ms*
- *Each bunch is only 1 Tp, not 12 Tp*
- *Repeat for each available Booster cycle (66.7 ms)*



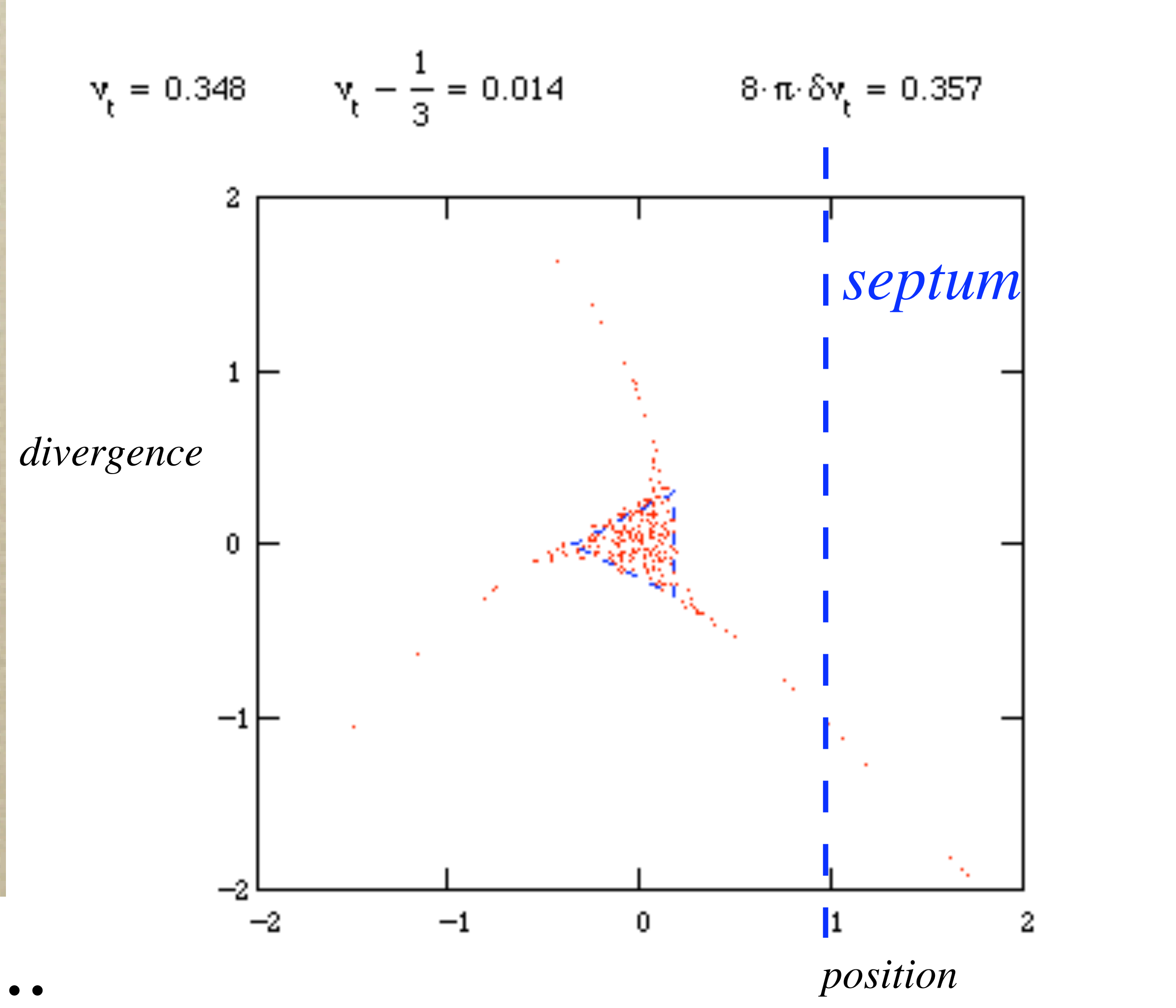
Other Alternatives

- *Similar to Proposal, stack 3 Booster batches, form 4 bunches send to Debuncher 1-by-1*
  - *4 spills over ~150 ms each; reduces space charge by 1/4, keeps instantaneous rate as in Proposal*
- *Similar to "Alternate", go thru Recycler, directly to Accumulator, form 4 bunches, then send to Debuncher 1-by-1*
- *Several variations possible; optimize cost, etc.*

Resonant Extraction

- *Once beam is in the Debuncher, "slow" spill over next 10-600 ms (depending upon scenario)*

- *Resonant Extraction*
  - *adjust betatron tune to be near rational value*
  - *use feedback to control rate of particle extraction*



generic example…

Extraction w/ space charge

The Space Charge Effect in Slow Extraction by Third Integer Resonance

Yu.Senichev, V.Balandin
Institute for Nuclear Research of RAS,
60-th October Anniversary prosp., 7a, Moscow, 117312, Russia

EPAC94

1 INTRODUCTION

With the development and construction of high intensive beam accelerators and storage rings more and more attention is being focussed on the problem of the self-field effect of accelerated particles on the stability of their motion. This problem endures second birth, which connected with, on the one hand, requirement to know more exactly the parameters of beam and on other hand, with more powerful computers for an investigation. At first the analytical methods were used in mainly, among which the equations of Kapchinsky and Sacherer take significant place. They gave necessary information about the envelope of high intensive beam with the elliptical distribution. As far as the improvement of computer technology, the new numer-

$$\frac{e}{p_0c}A_{sc}(x,y) - \frac{e}{p_0c}A_{ex}(x,y), \qquad (1)$$

where A_{sc}, Φ_{sc} - the vector and the scalar potential of the space charge field and A_{ex} -the vector potential of the external field. It is assumed here, that the transverse currents are absent:

$$A_{sc} = \frac{v}{c}\Phi_{sc}(1+hx), \qquad (2)$$

where v is the longitudinal velocity equal for all particles. The vector potential of the external field has components up to the octupole inclusive:

$$-\frac{e}{cp_0}A_{ex}(x,y) = hx + (K+h^2)\frac{x^2}{2} - K\frac{y^2}{2} +$$

- *Phase space distortions in the presence of space charge, near third-integer resonance, can be very significant*

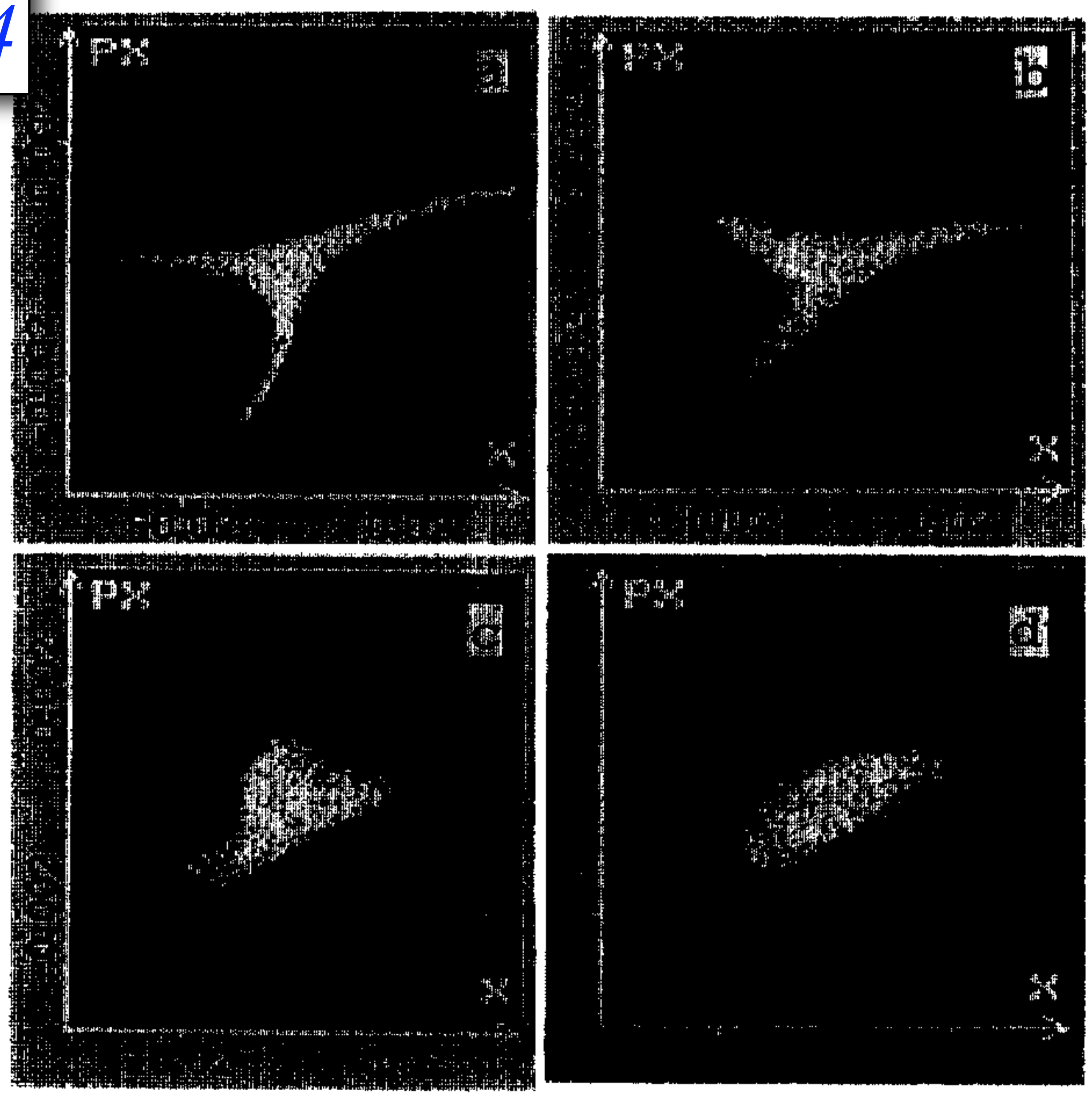


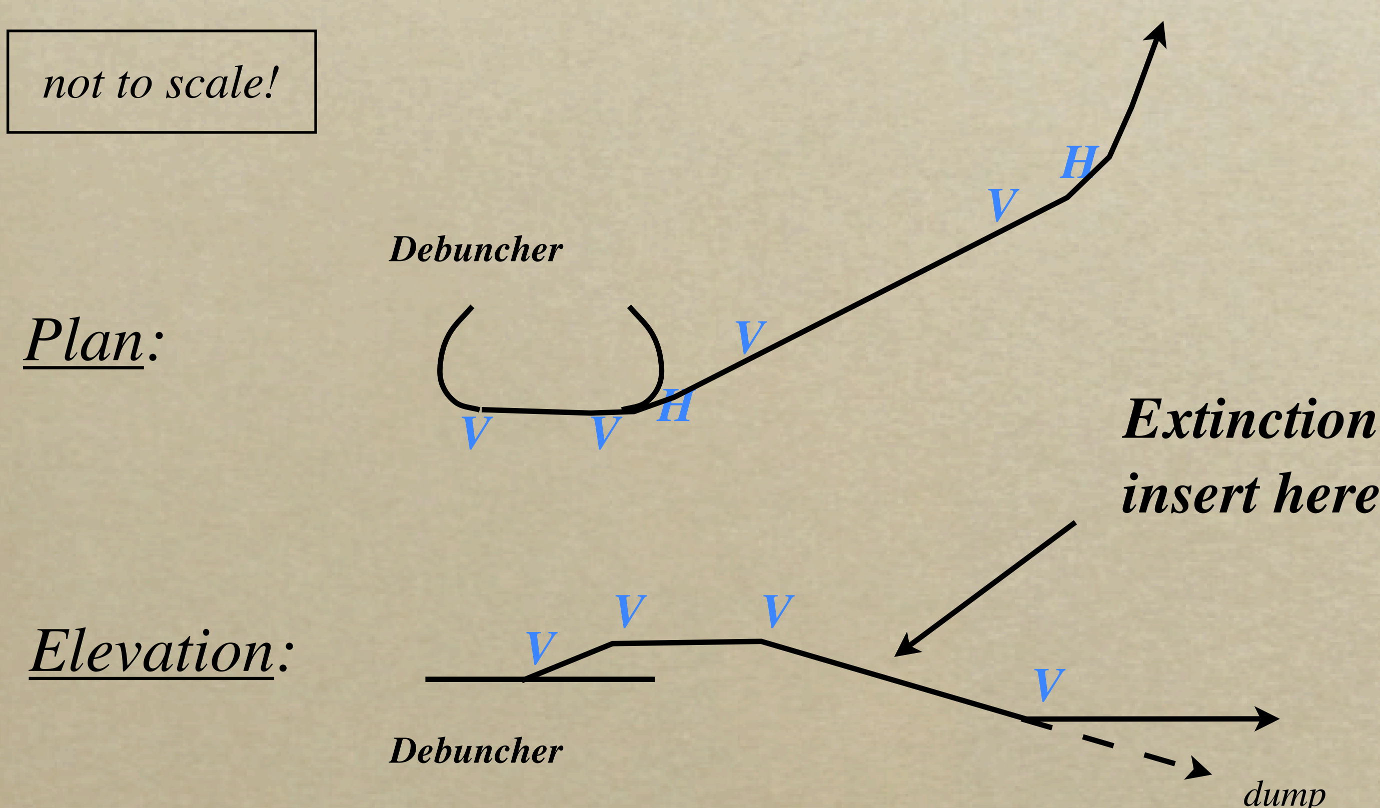
Figure 2: The phase portraits of the beam at a)$\Delta\nu_L$=0.01, b)$\Delta\nu_L$=0.03, c)$\Delta\nu_L$=0.06 and d)$\Delta\nu_L$=0.1

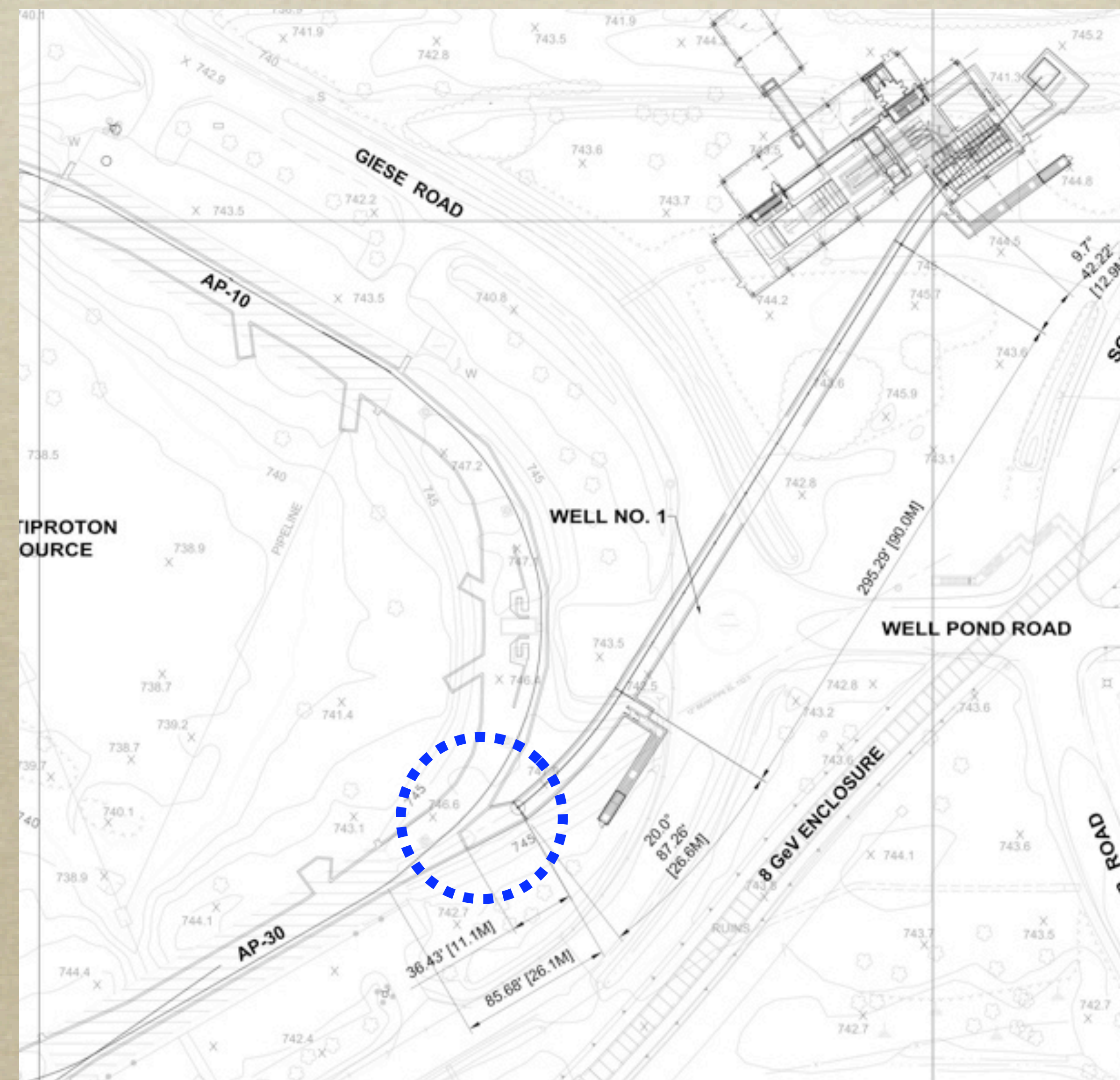
Extraction Issues

- *Work beginning on Debuncher extraction with large momentum spread* ***and*** *space charge*
  - *Fermilab Computing Division's Accelerator Modeling and R&D Department is engaged in this work*
- *Examining both third- and half-integer*
- *Simulations will provide input for fast-corrector feedback system*
  - *requirements for providing smooth spill to experiment*

Mu2e Beam Line

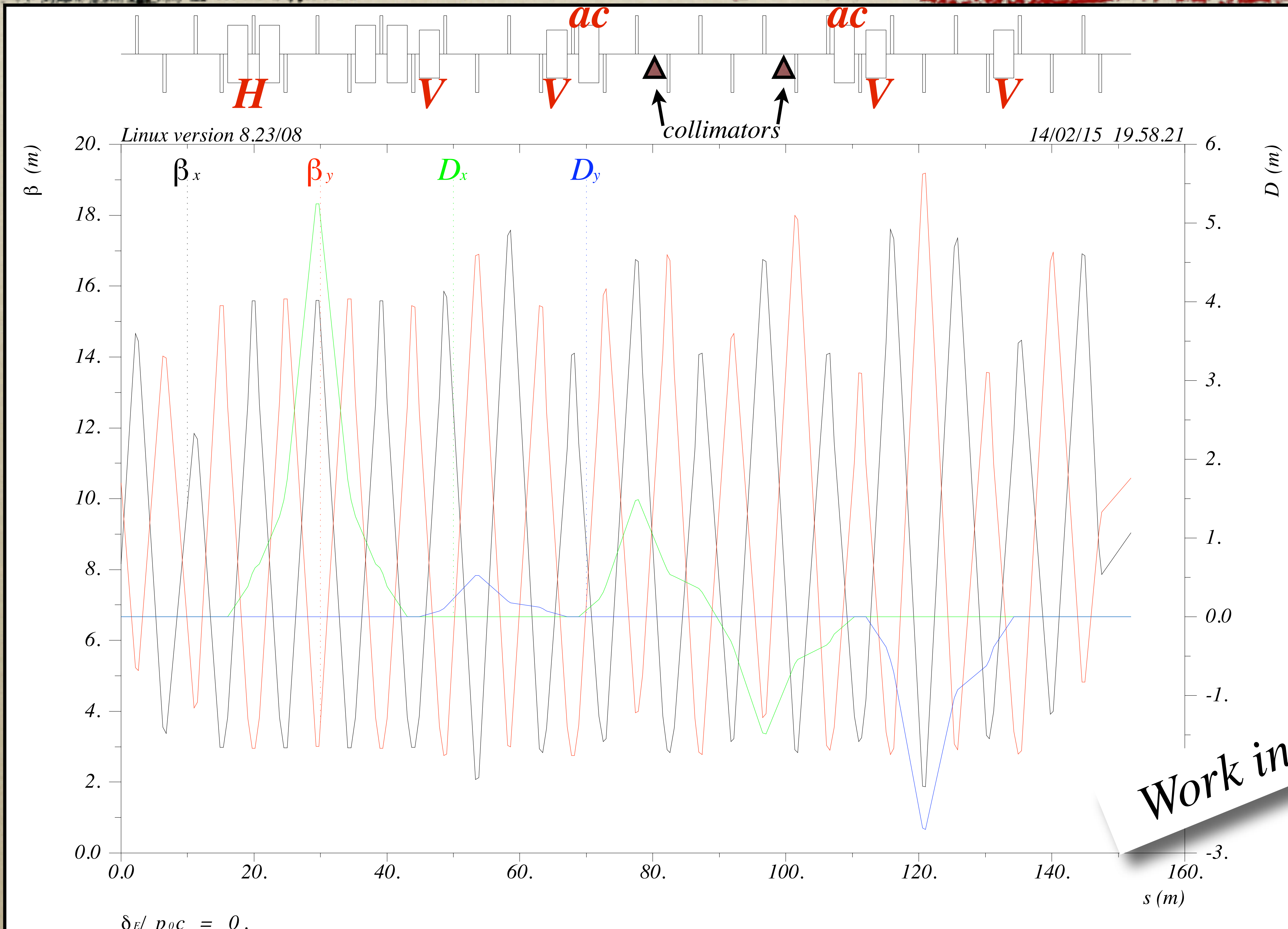
- *Design work proceeding, utilizing existing "stub" in ring tunnel for final exit point*





Work in progress

Preliminary Beam Line Optics



Work in progress

Extinction

- *Need extinction at level of 10^{-9}*
- *Internal -- what do we start with?*
    - *during bunch formation, how do particles get left behind?*
    - *after bunch formation, how do particles access the "gap"?*
- *External -- what is our last resort?*
    - *AC dipole system*

Internal Extinction

- *Bunch formation in the rings may generate particles in the gap*
- *One-by-one bunch transfers with kickers from Accumulator to Debuncher would help extinct particles in the gap*
- *Beam-gas scattering, RF noise, etc., will alter energy/phase of individual particles; could "slip" into gap*
- *Will investigate requirements of an "extinction system" (kicker system) internal to the ring*
- *Also, looking at a passive momentum scraping to help the situation...*

Internal Extinction

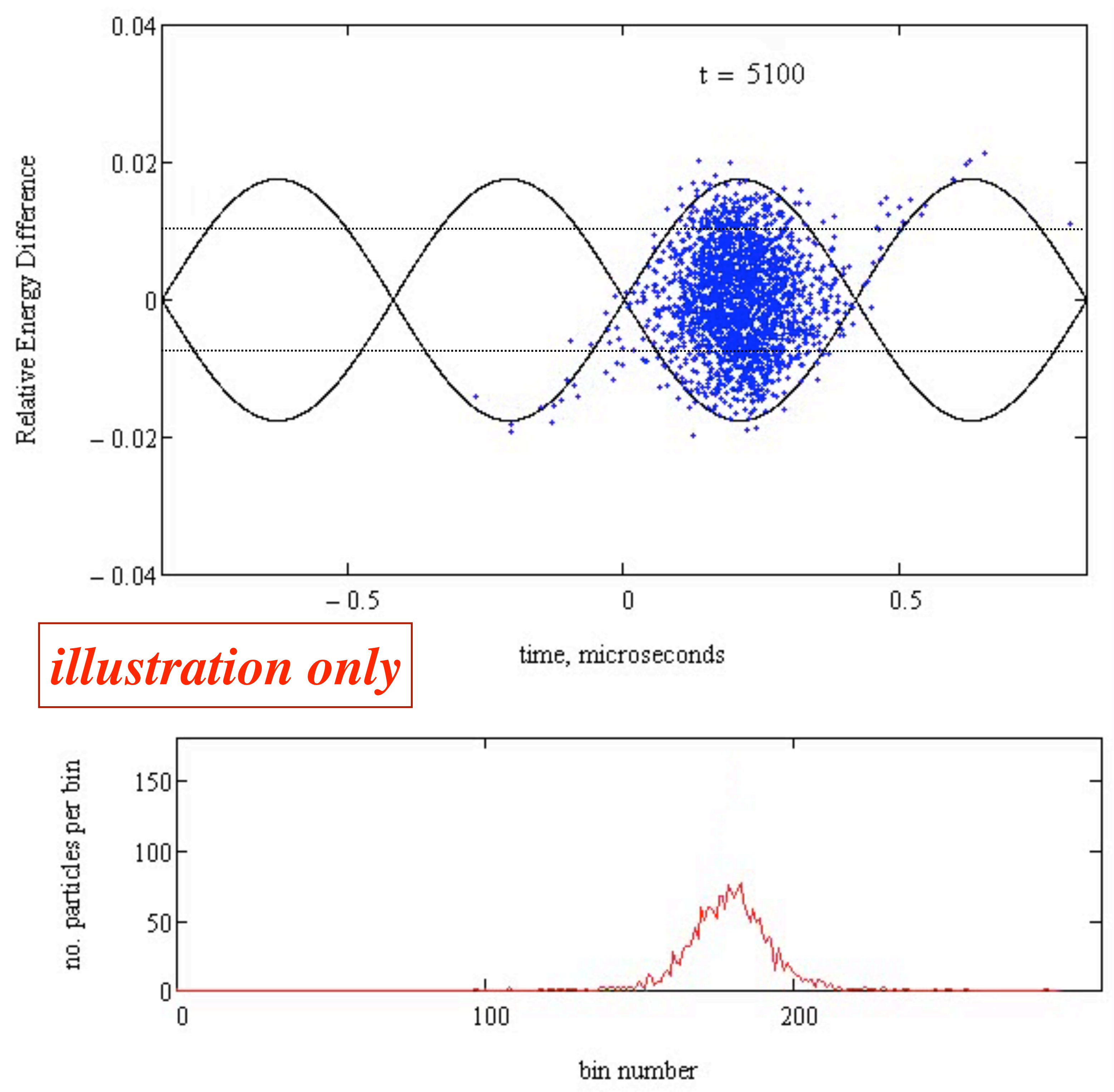
Let's assume some noise sources…

- *here,* $\Delta\phi_{rms} \sim 1^o$

  (for dramatization)

- 0.1^o *more typical*

- *utilize scrapers at high momentum dispersion locations to catch particles before they escape bucket…*



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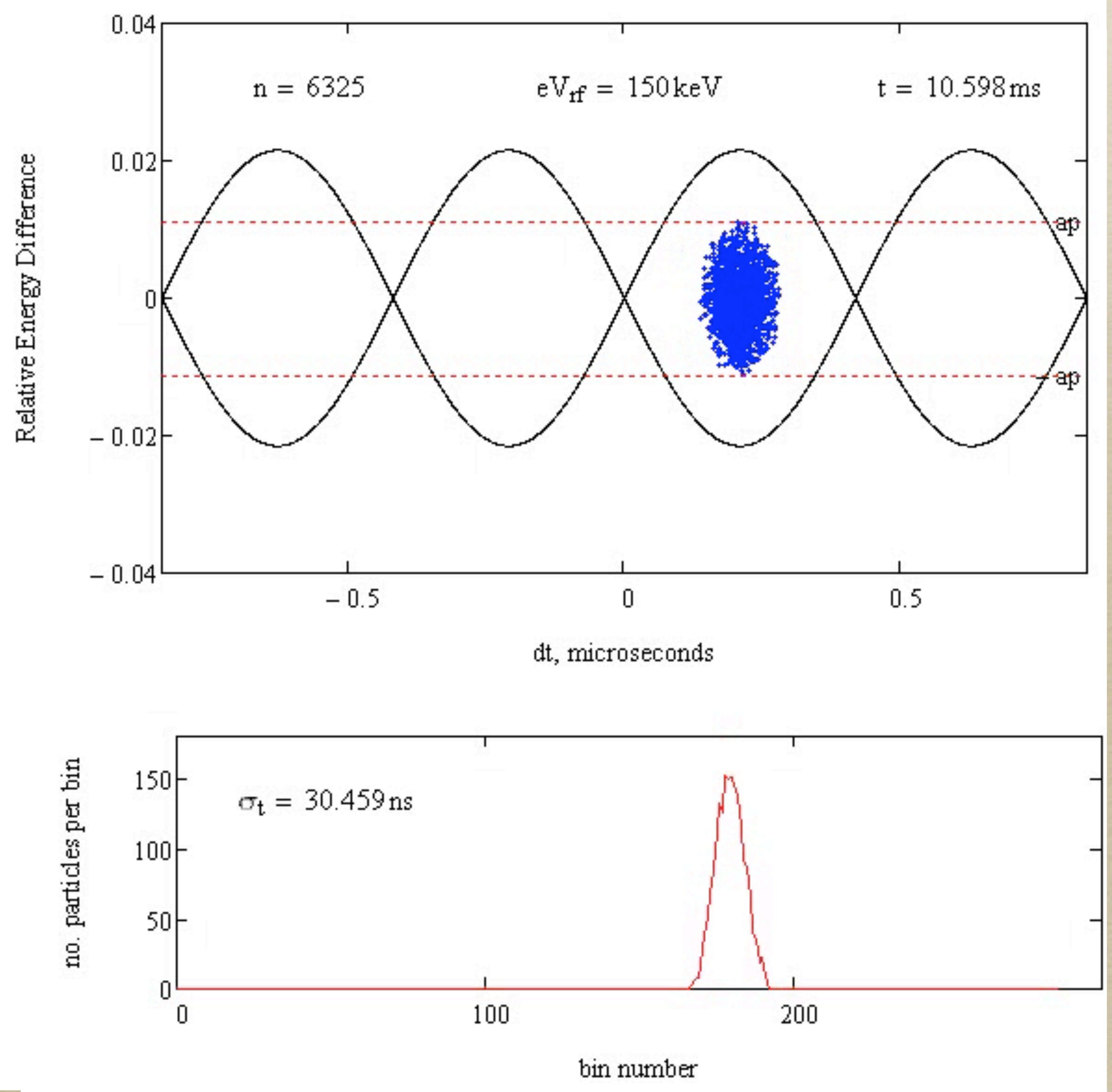
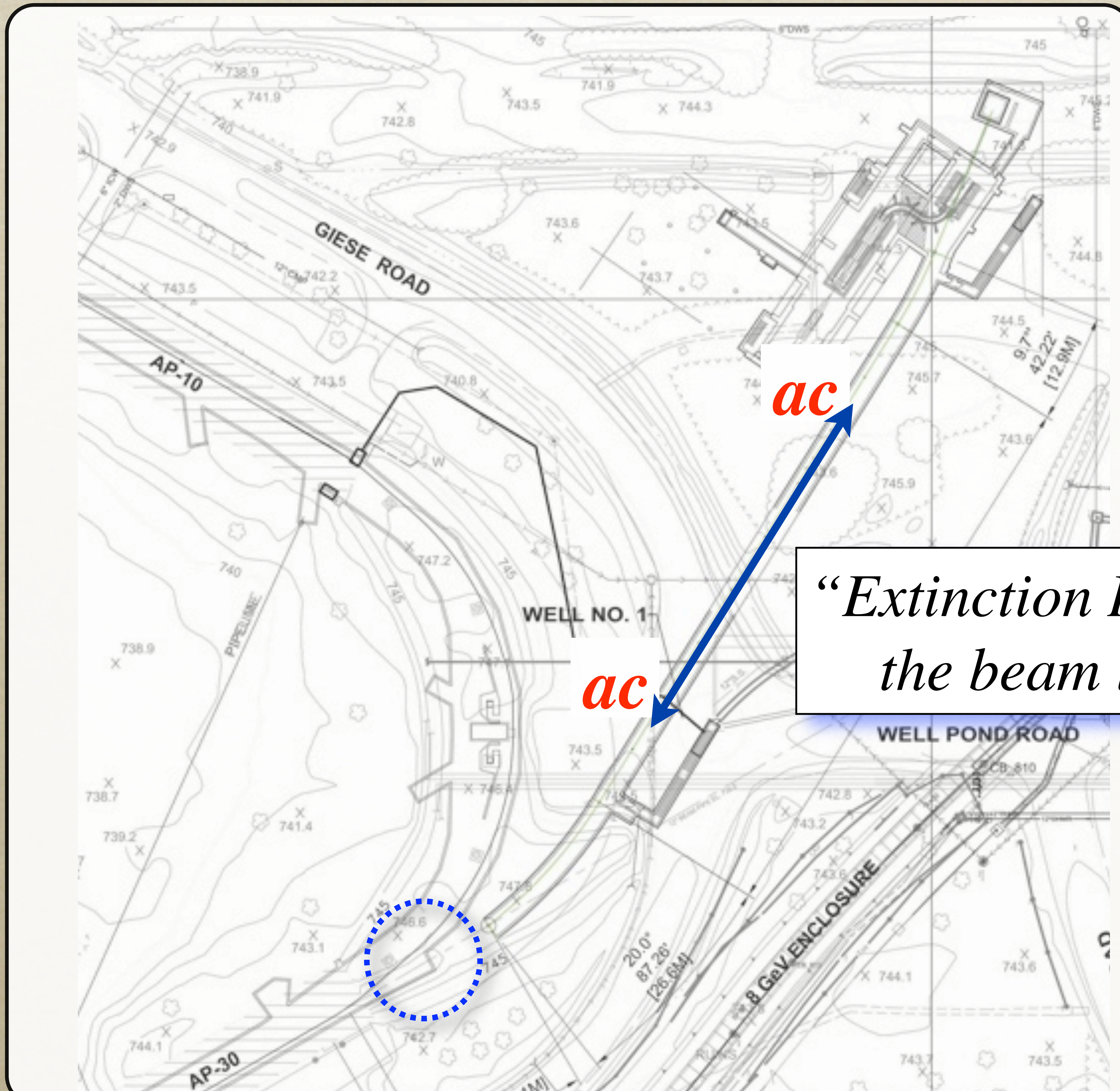


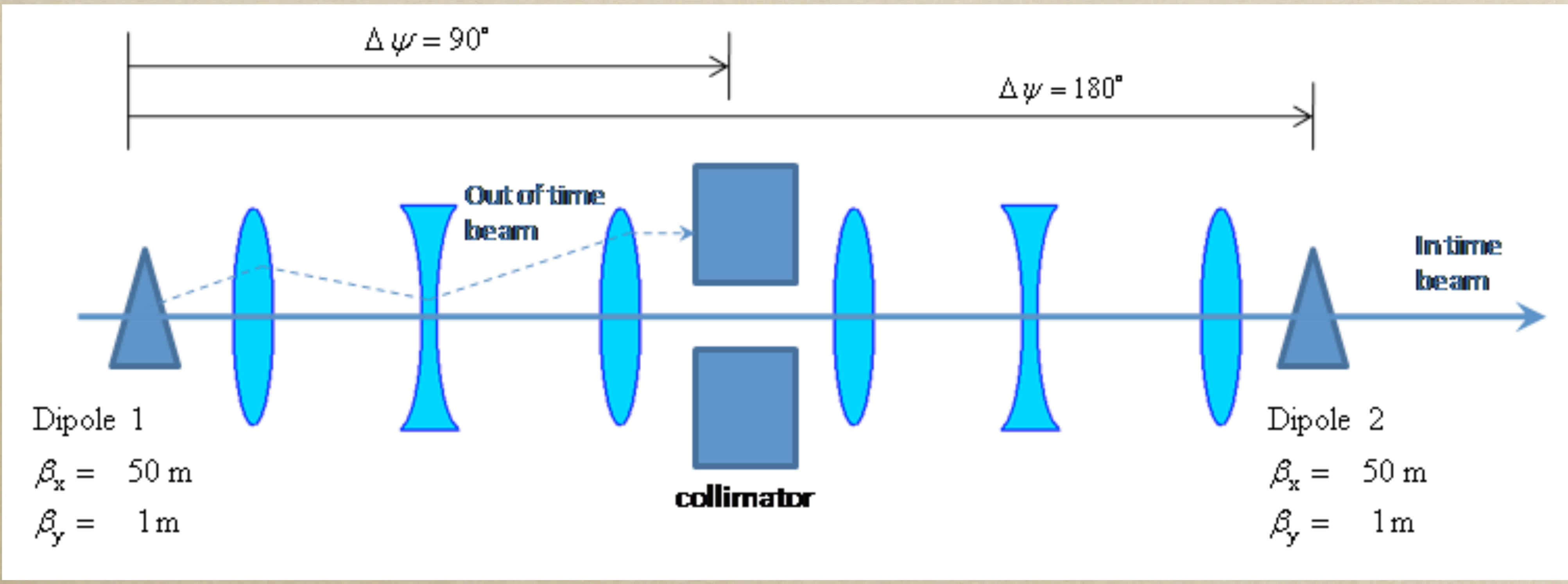
External Extinction



"Extinction Insert" within the beam line design

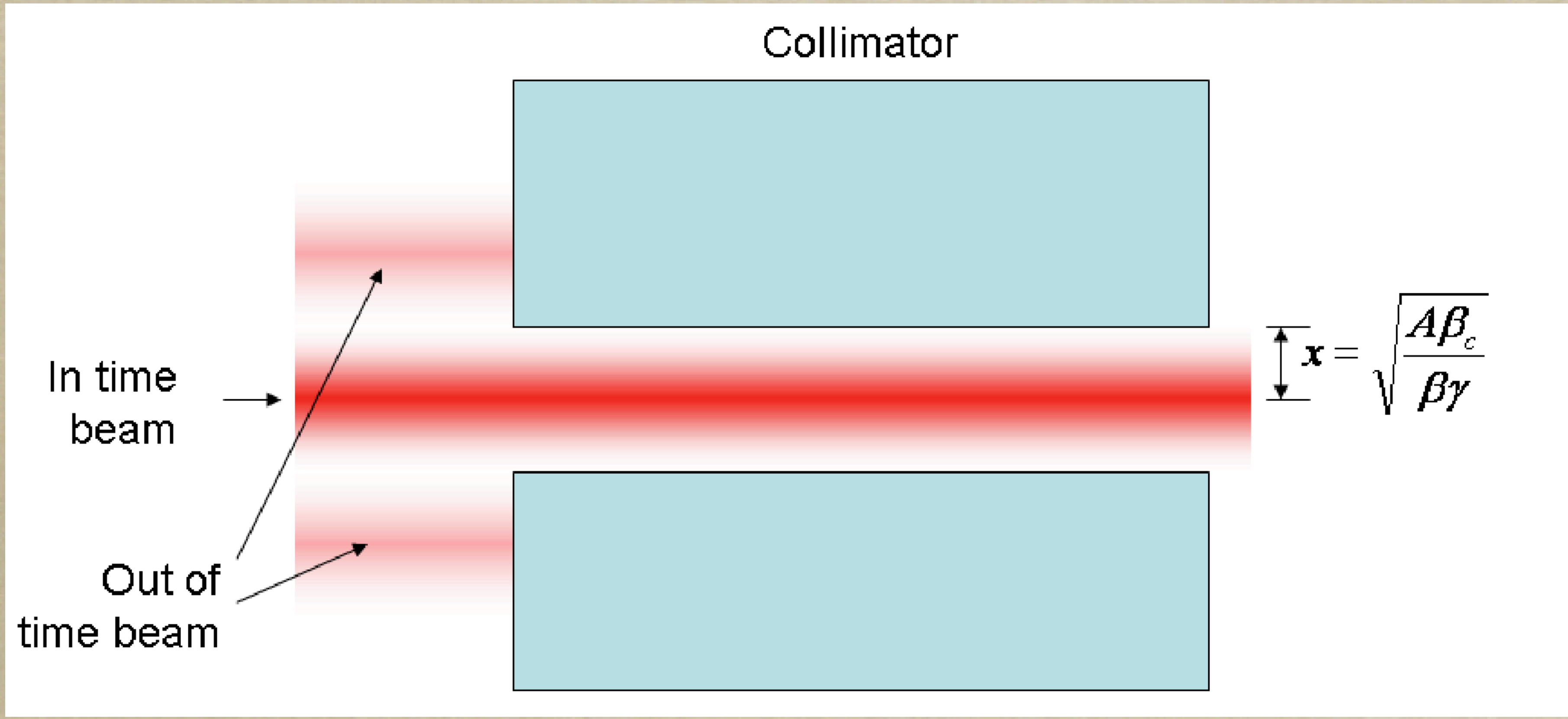
Extinction Insert Concept

(from the Proposal)

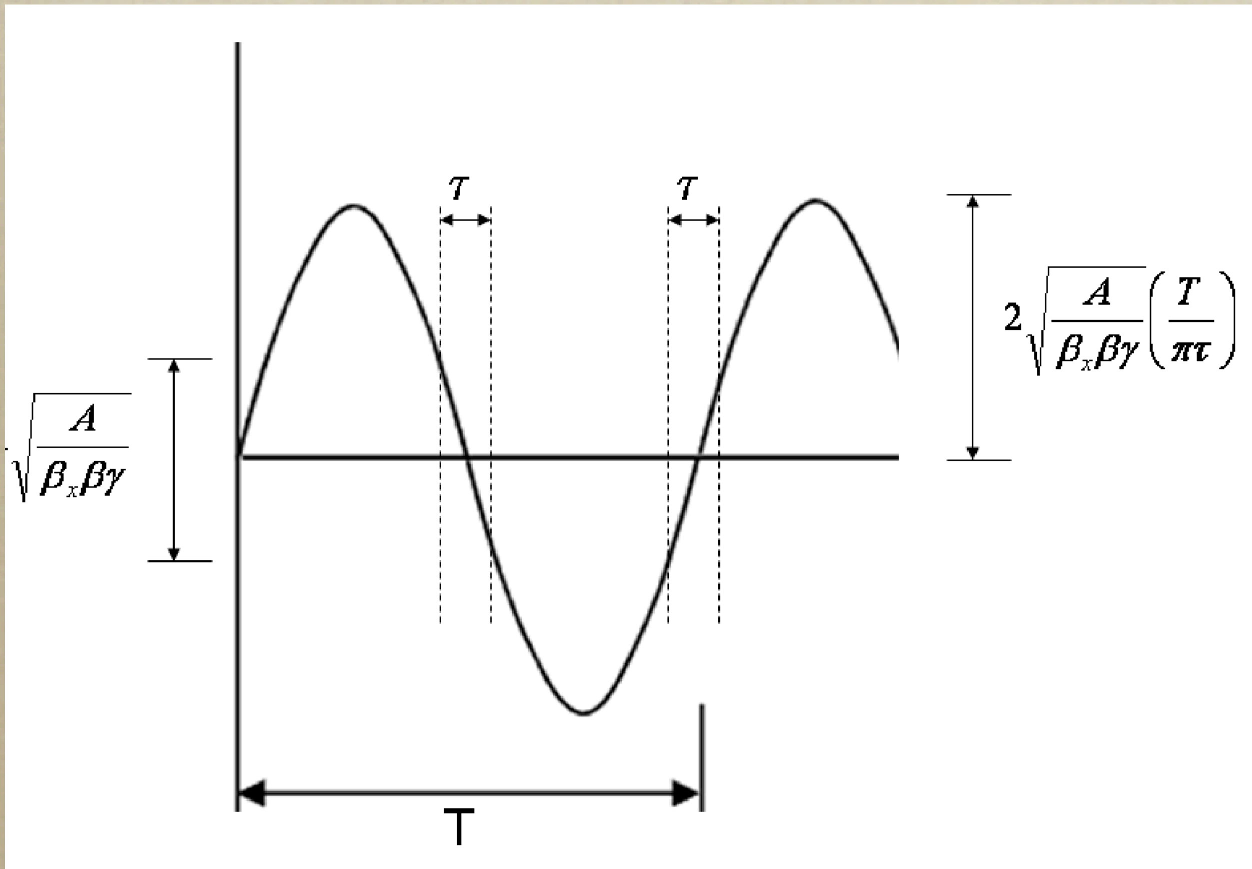


- *design insert as part of transport line between Debuncher and experiment*

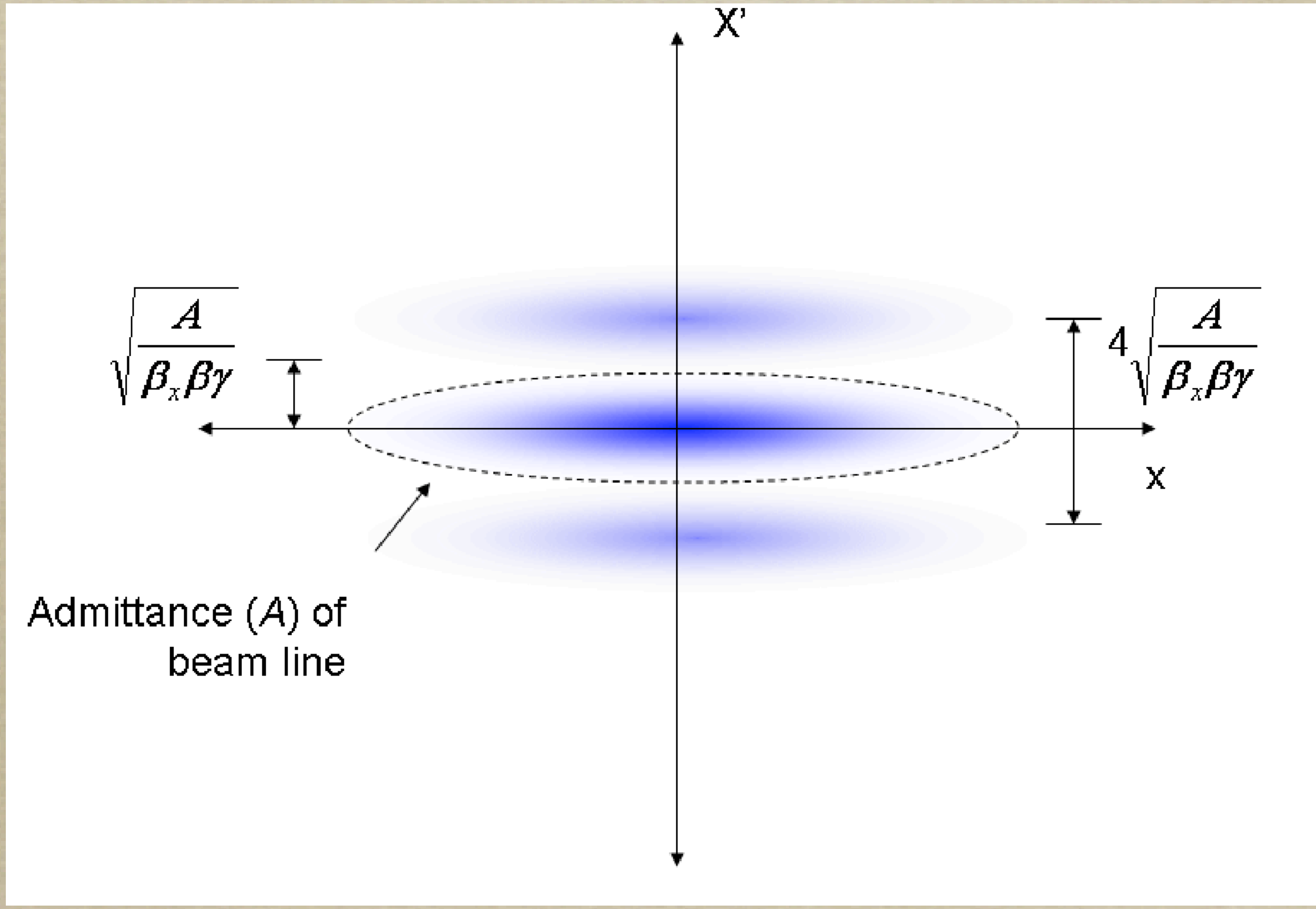
- *"AC dipoles" kick out-of-synch particles into collimators*
- *Likely wish 2-stage collimator system*



AC Dipole Requirements



- *Optical design and extinction requirement will determine amplitude of kick*



- *Dipole frequency:*

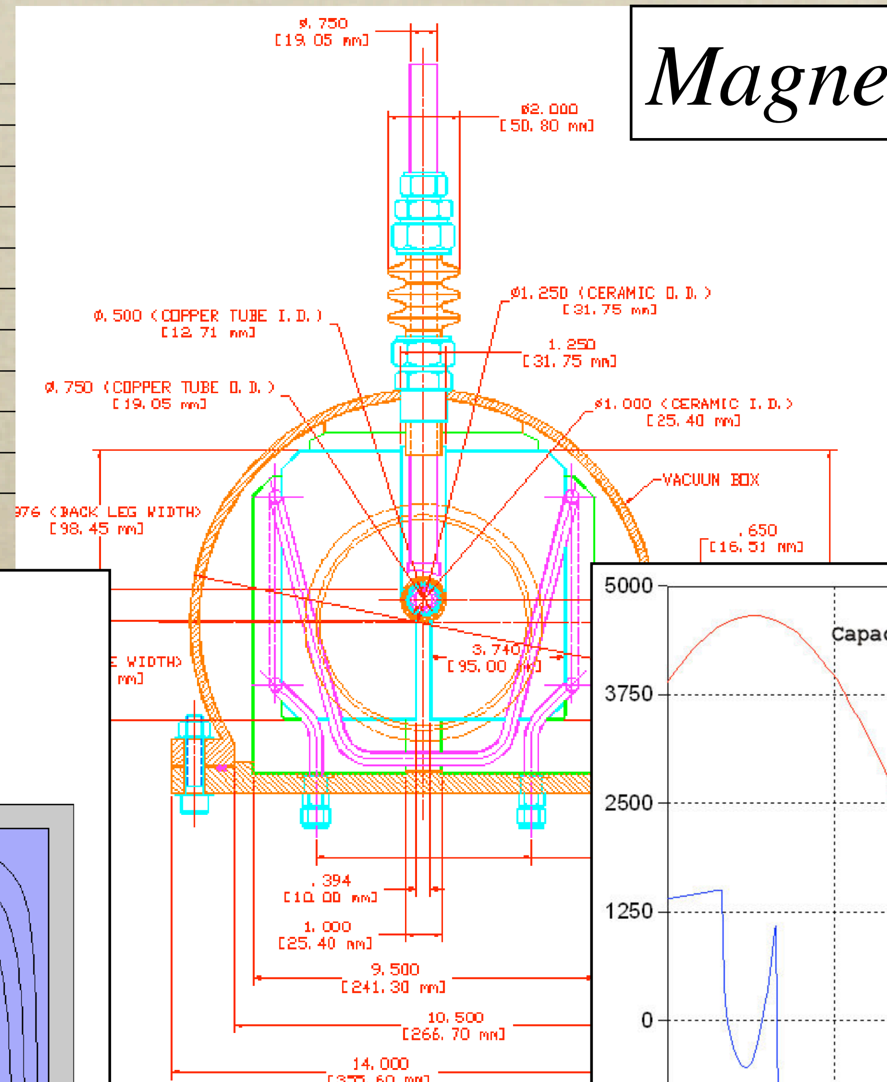
  $^1/_2$ Debuncher revolution frequency
  ~ 300 kHz

AC Dipole System R&D

Table I. AC Dipole specification.

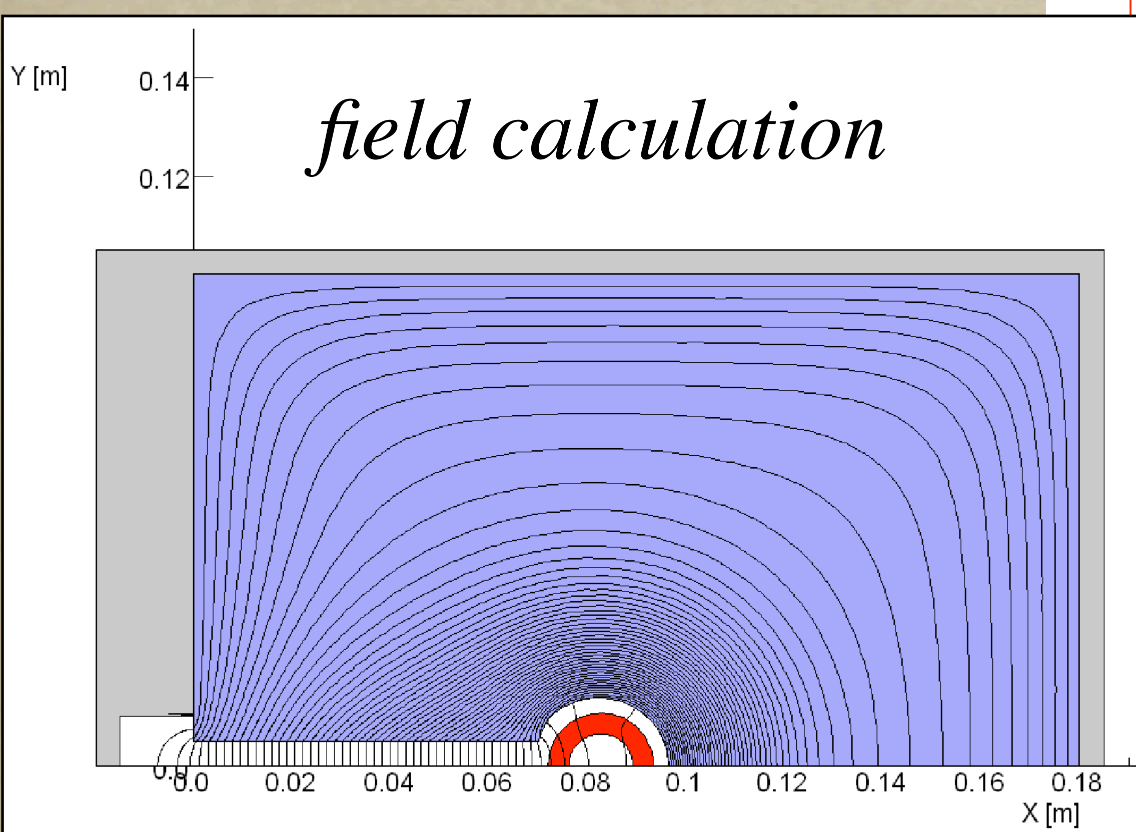
Parameter	Unit	Value
Integrated strength	T-m	0.12
Magnet gap	mm	10
Effective length	m	2.0
Good field area width	mm	50
Center field	T	0.06
Current form		Sine wave
Current frequency	kHz	300
Operational regime		Continuous
Radiation level		low

Magnet Design

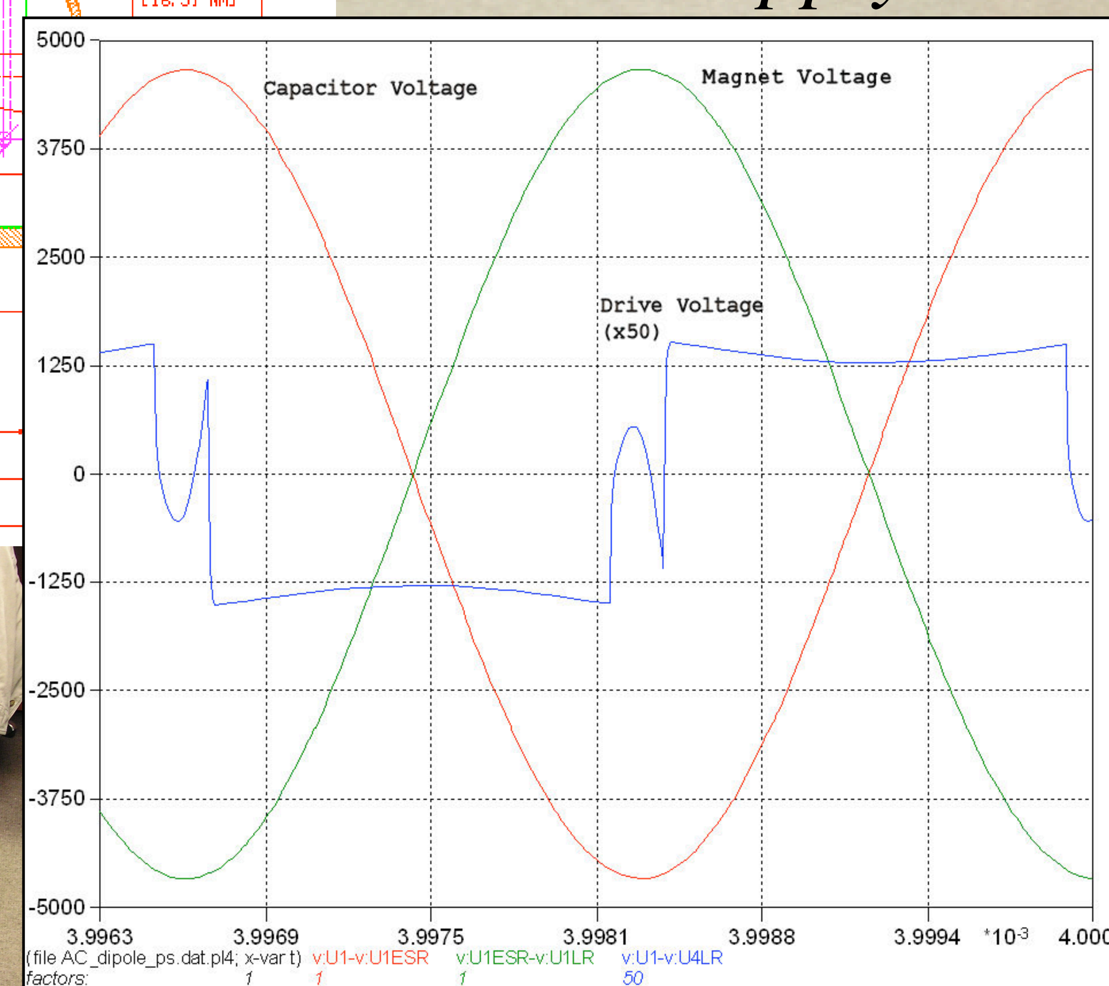


U.S.-Japan collaboration

Power Supply Calc



prototype transformer



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Other Option(s)...

- *In AC dipole scheme, large field is required due to the necessary fast rise time*
- *Starting to take fresh look at a pulse-shaping network to produce "square" wave (w/ lower field strength?)*
  - *will also look at associated optics options*

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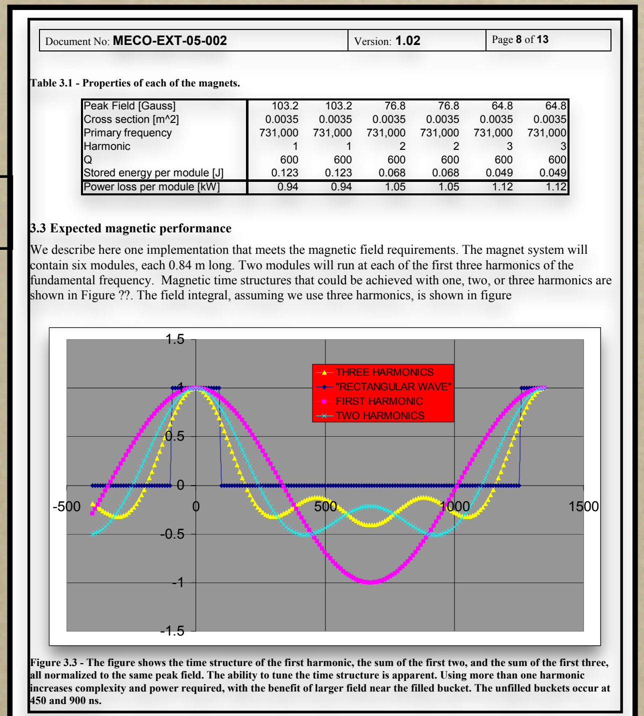

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Table 3.1 - Properties of each of the magnets.

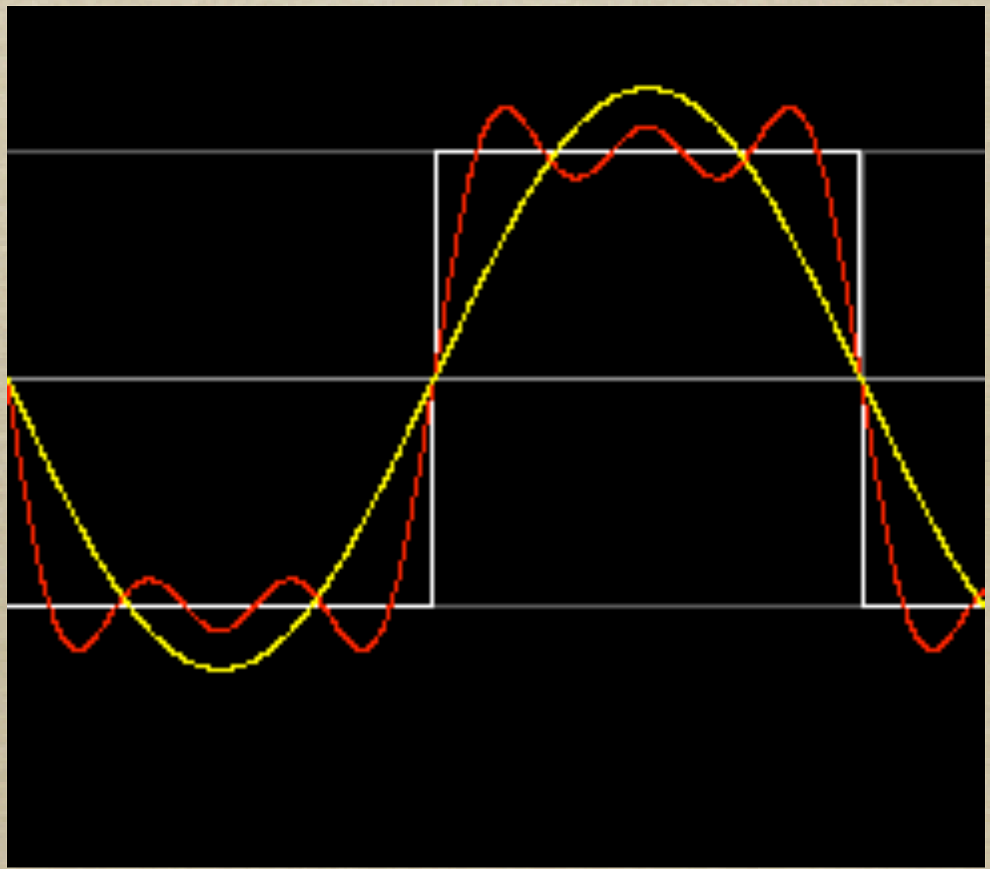
Peak Field [Gauss]	103.2	103.2	76.8	76.8	64.8	64.8
Cross section [m^2]	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035
Primary frequency	731,000	731,000	731,000	731,000	731,000	731,000
Harmonic	1	1	2	2	3	3
Q	600	600	600	600	600	600
Stored energy per module [J]	0.123	0.123	0.068	0.068	0.049	0.049
Power loss per module [kW]	0.94	0.94	1.05	1.05	1.12	1.12

3.3 Expected magnetic performance

We describe here one implementation that meets the magnetic field requirements. The magnet system will contain six modules, each 0.84 m long. Two modules will run at each of the first three harmonics of the fundamental frequency. Magnetic time structures that could be achieved with one, two, or three harmonics are shown in Figure ??. The field integral, assuming we use three harmonics, is shown in figure

Figure 3.3 - The figure shows the time structure of the first harmonic, the sum of the first two, and the sum of the first three, all normalized to the same peak field. The ability to tune the time structure is apparent. Using more than one harmonic increases complexity and power required, with the benefit of larger field near the filled bucket. The unfilled buckets occur at 450 and 900 ns.

Here, with 3 harmonics…



Extinction Monitoring

- *group of interested parties forming*
    - *accel and detector*
  - *collaborating with Osaka group*

Joint Effort: gating of a PMT system

FERMILAB-PUB-06-09

Proton Synchrotron Radiation at Fermilab

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Abstract. While protons are not generally associated with synchrotron radiation, they do emit visible light at high enough energies. This paper presents an overview of the use of synchrotron radiation in the Tevatron to measure transverse emittances and to monitor the amount of beam in the abort gap. The latter is necessary to ensure a clean abort and prevent quenches of the superconducting magnets and damage to the silicon detectors of the collider experiments.

Keywords: Synchrotron Radiation, Abort Gap, Transverse Profile
PACS: 07.85.Qe, 29.27.–a

The gated PMT on loan from LBNL is a Hamamatsu R5916U-50 which is a microchannel plate PMT and has a minimum gate width of 5 ns. It has no detectable sensitivity to light present before the gate and has an extinction ratio of 10^7. Its drawbacks are a gain of only 5×10^5 and a gating duty cycle of only 1%, both of which have been addressed in modified versions of the tube recently purchased and soon to be installed. Because of the narrow gating capability, measurements of the DC beam can be made between bunches as well as in the abort gaps.

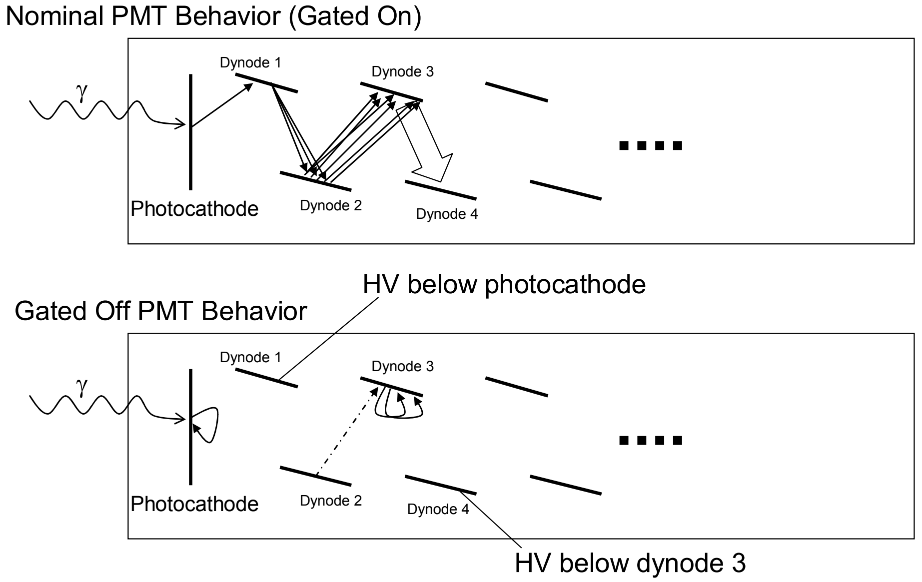

FIGURE 4. Design of a gated PMT whereby two dynodes are held at the wrong voltage, shutting off the amplification process. When gated on, the dynodes are pulsed to their nominal voltages, and the PMT functions normally.

- *Examining also:*
    - *quartz crystal detector; MCP*
- *Can use collaborators here!*

Future R&D Efforts

- *As well as further development of plans and design, anticipate beam studies being carried out over next year or so in support of Mu2e*

- *Further develop --*
  - *Operating Scenario*
  - *MI8/REC transfer design*
  - *Radiation Safety*
  - *Bunch formation systems*
  - *Beam Line design*
  - *Extinction design*
  - *Target design*

- *Engineering Studies--*
  - *AC dipole development*
  - *Kicker R&D*
  - *RF systems design*
  - *DEB fast corrector development*
  - *Extinction monitoring devices*

- *Beam studies at Fermilab--*
  - *Bunch formation techniques*
  - *Stopband measurements*
  - *Bunch capture in ring*
  - *Extinction measurement*
  - *Slow spill technique*

Some References

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