Accelerator Preparations for Muon Physics Experiments at Fermilab

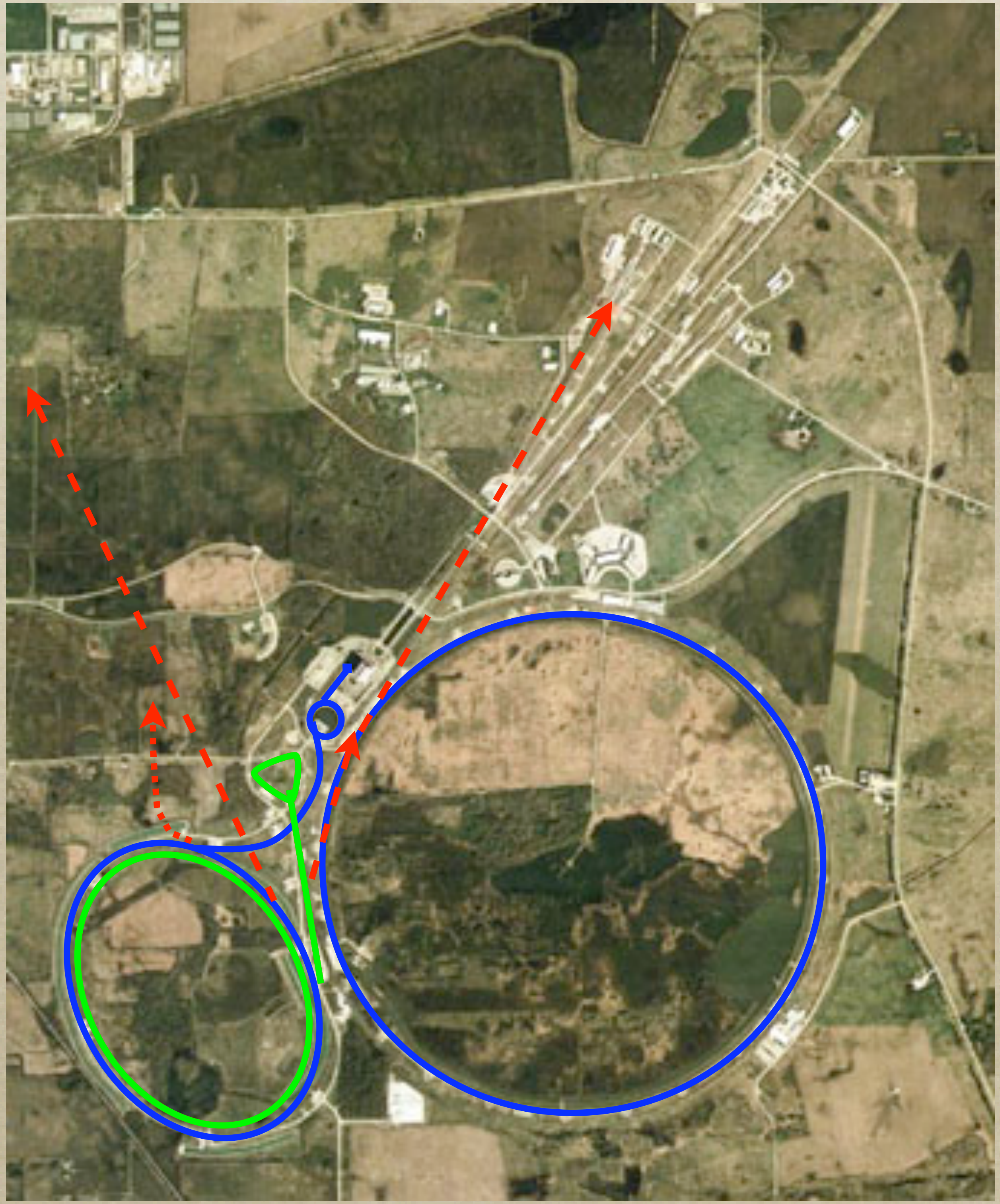
- *Outline:*
  - *Overview*
  - *Mu2e and New g-2 proposals*
  - *Possible Operating Scenarios*
  - *Issues and Plans*
  - *Integration*

Mike Syphers
Fermilab

DPF09
Accelerators Session
Wayne State University
28 July 2009

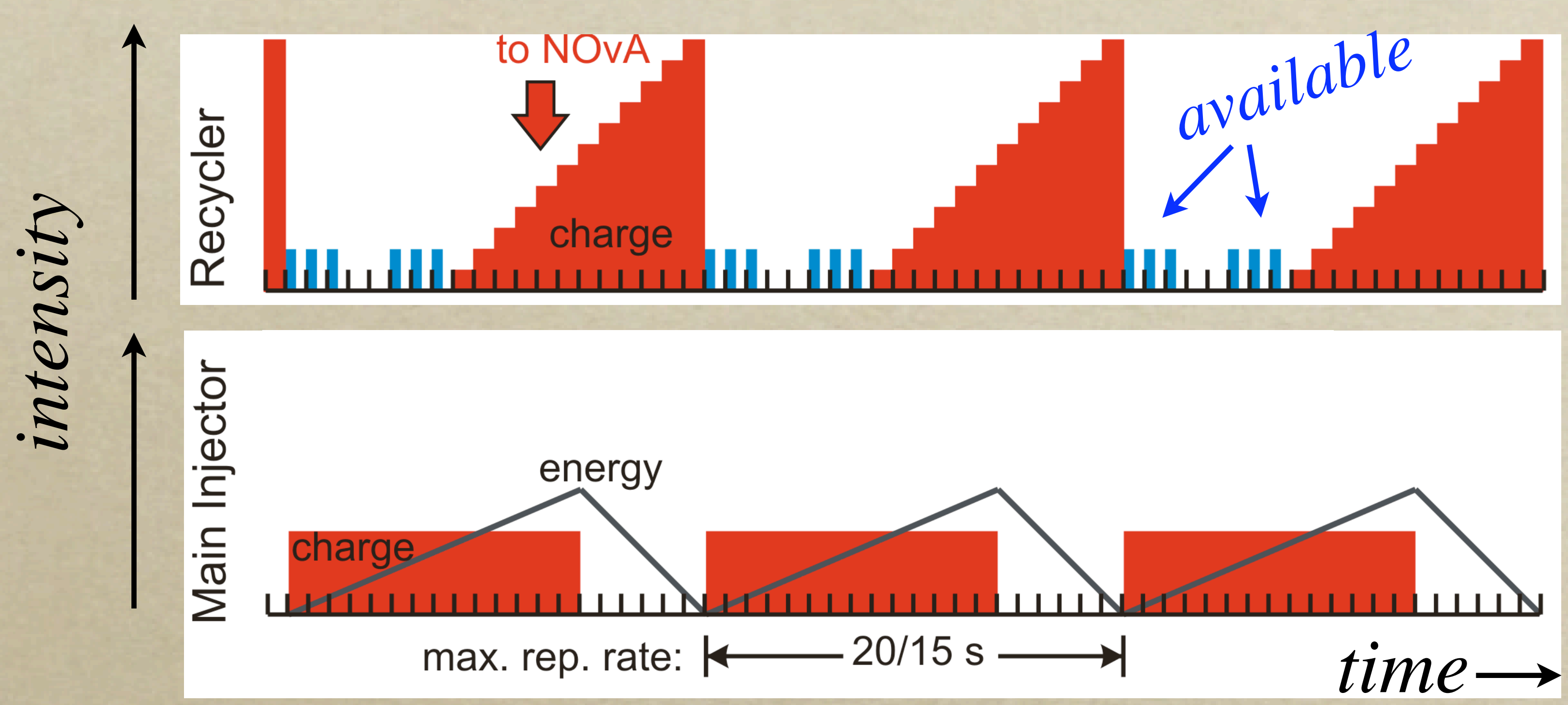
Proton Availability

- *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*



- *20 15-Hz Booster cycles (1.333 sec) per NOvA cycle*
- *Booster has been upgraded to perform at this level; if can run "flat out" at 15 Hz, leaves up to 8 Booster cycles for "other program(s)"*

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

Proposals

- *To date, two experimental collaborations have submitted proposals to Fermilab PAC:*
  - ***Mu2e*** *has been given "Stage I Approval"*
    - *Project being formed, seeking CD-0 from DOE*
  - ***New g-2*** *is still under consideration*
    - *Polishing the cost estimate; will present to the Fermilab PAC again in November*

Proposal to Search for $\mu^- N \rightarrow e^- N$ with a Single Event Sensitivity Below 10^{-16}

Mu2e Experiment

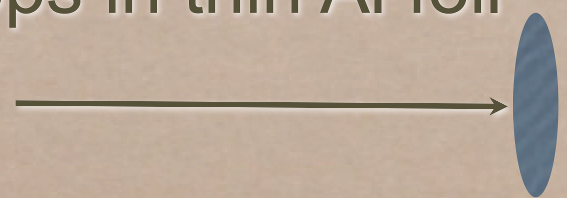
The New $(g-2)$ Experiment:

A Proposal to Measure the Muon Anomalous Magnetic Moment to ± 0.14 ppm Precision

New $(g-2)$ Collaboration: R.M. Carey[1], K.R. Lynch[1], J.P. Miller[1],

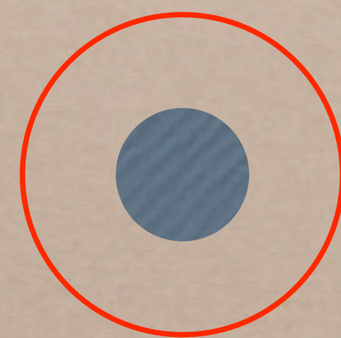
Mu2e

μ^- stops in thin Al foil



the Bohr radius is ~ 20 fm, so the μ^- sees the nucleus

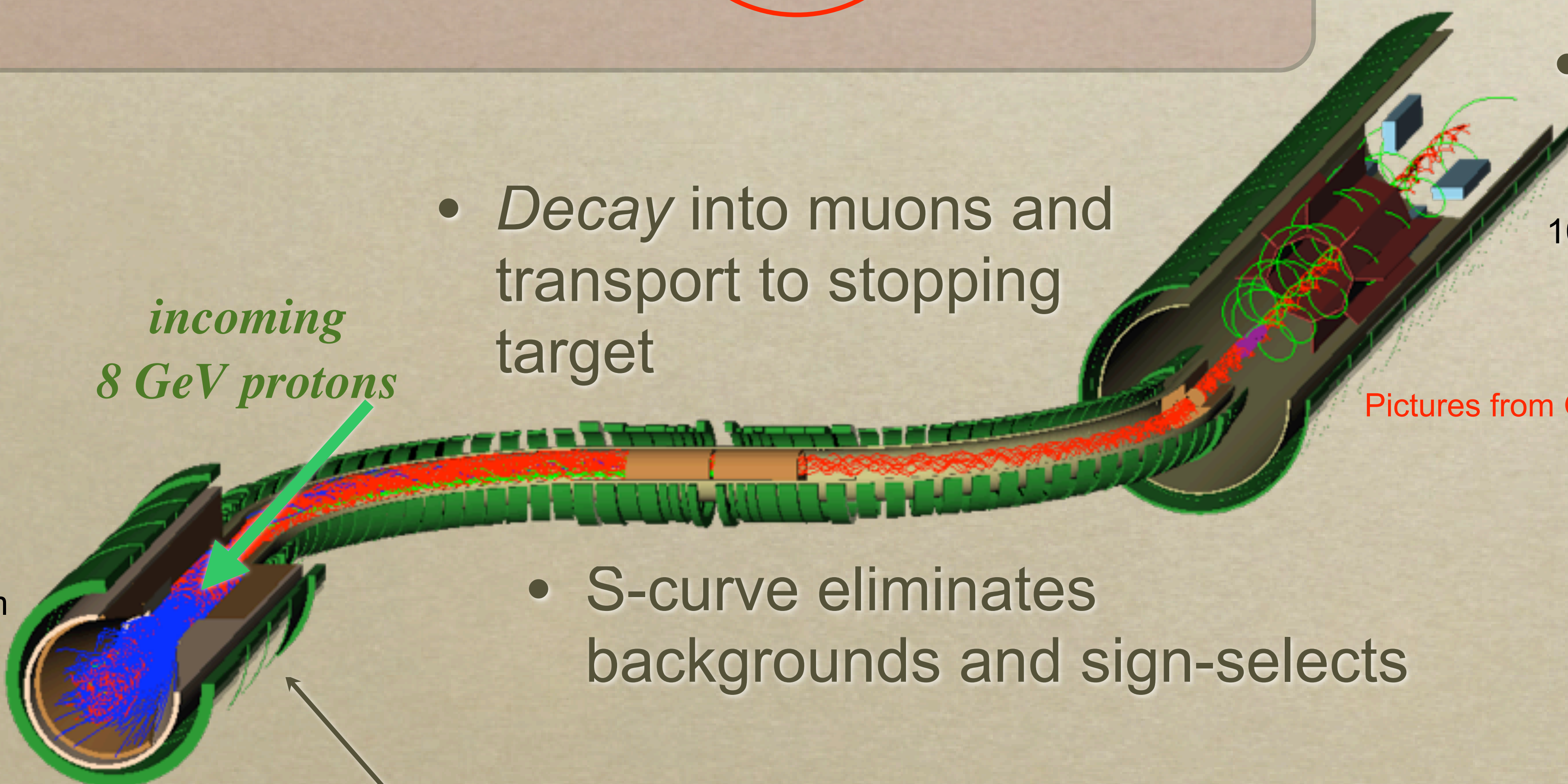
μ^- in 1s state



(bound lifetime is ~864 ns)

Al Nucleus ~4 fm

if μ converts into an e, then is "ejected" with a very specific energy (~105 MeV)



- *Tracking and Calorimeter*

10 m × 0.95 m

- *Decay* into muons and transport to stopping target

incoming 8 GeV protons

Pictures from G4Beamline/MuonsInc

4 m × 0.30 m

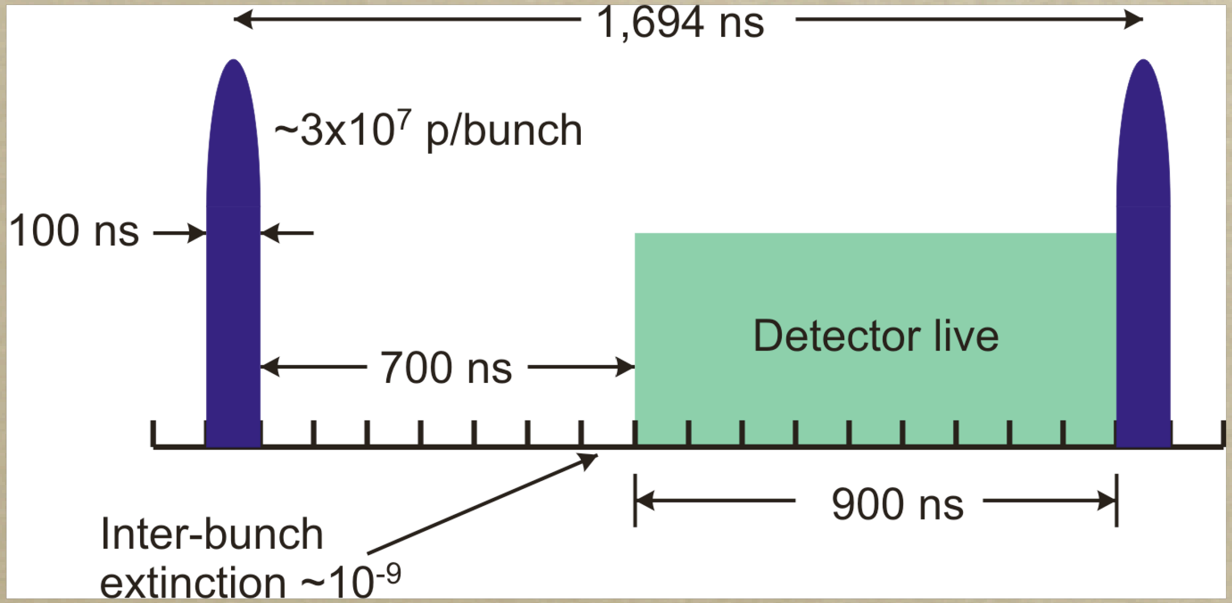
- S-curve eliminates backgrounds and sign-selects

- *Production*: Magnetic mirror reflects π's into acceptance

MJS / Fermilab

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}
  - FNAL Debuncher has circumference **1.7μsec** !
- Extinction between pulses < 10^{-9} needed
  - = # protons out of pulse/# protons in pulse



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

g-2 Experiment at BNL

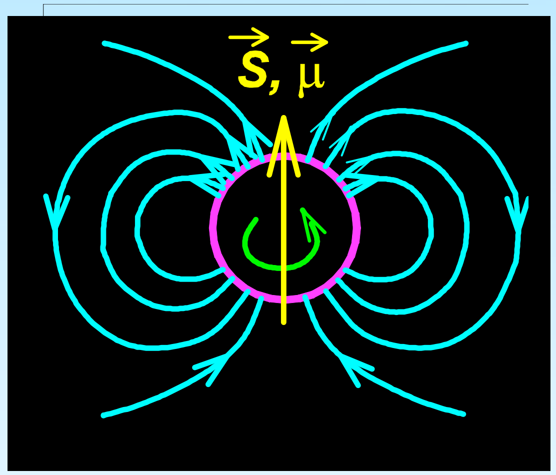
Summary of μ_s

$$\vec{\mu}_s = g_s \left(\frac{e\hbar}{2m}\right)\vec{s}$$

the moment consists of 2 parts

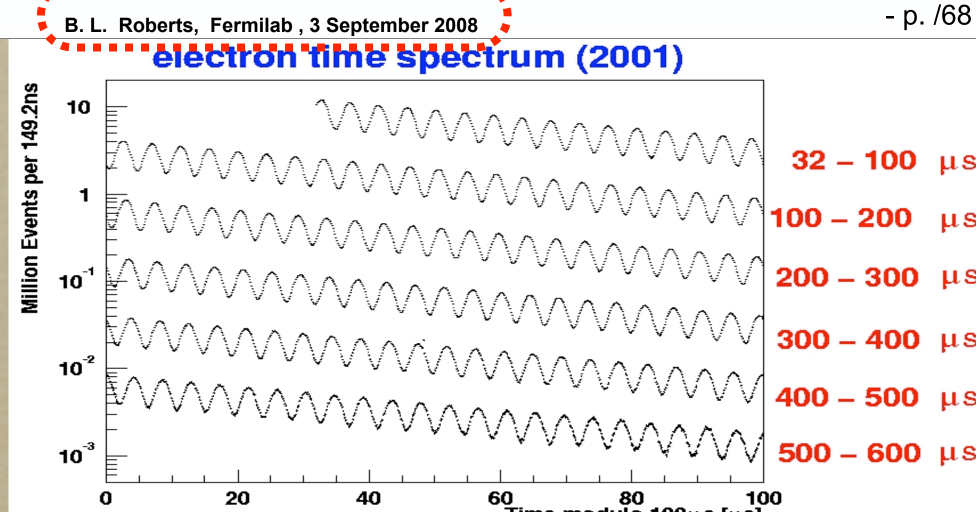
$$\mu = (1+a)\frac{e\hbar}{2m}$$

Dirac + Pauli moment



the anomaly $a = \left(\frac{g-2}{2}\right)$; or $g = 2(1+a)$

QED predicts a

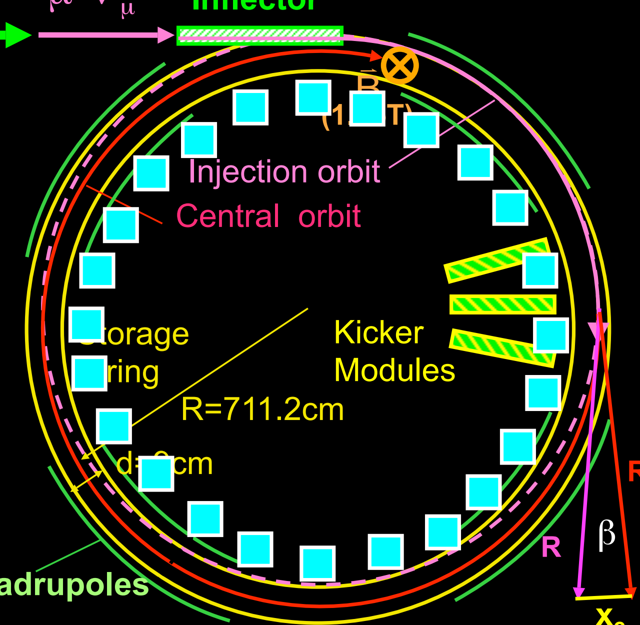


Experimental Technique

- $x_c \approx 77$ mm
- $\beta \approx 10$ mrad
- $B\cdot dl \approx 0.1$ Tm

- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$



(thanks to Q. Peng)

MJS / Fermilab

g-2 Experiment at BNL

$$a_\mu = 11\,659\,208.0(6.3) \times 10^{-10} \;\; (0.54\,\text{ppm})$$

$$\Delta a_\mu^{(\text{today})} = (30.0 \pm 8.3) \times 10^{-10}$$

Su

$\vec{\mu}_s$

the mo

$\mu = (1+a)\frac{}{2m}$

Dirac + Pauli moment

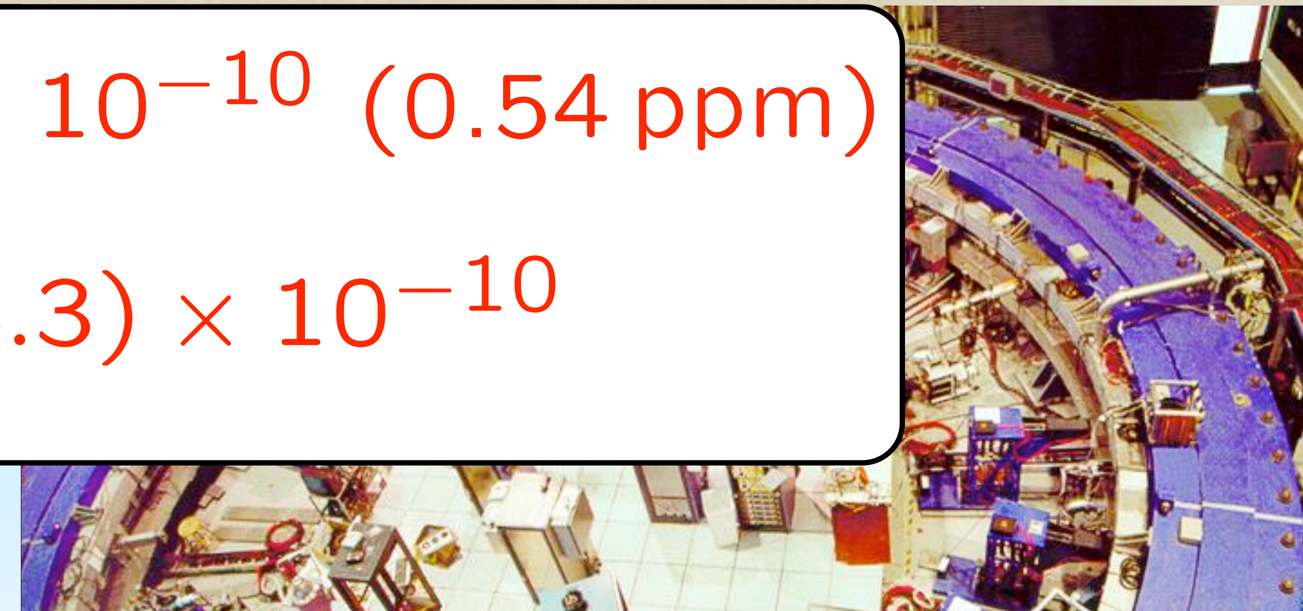
the anomaly $a = \left(\frac{g-2}{2}\right)$; or $g = 2(1+a)$

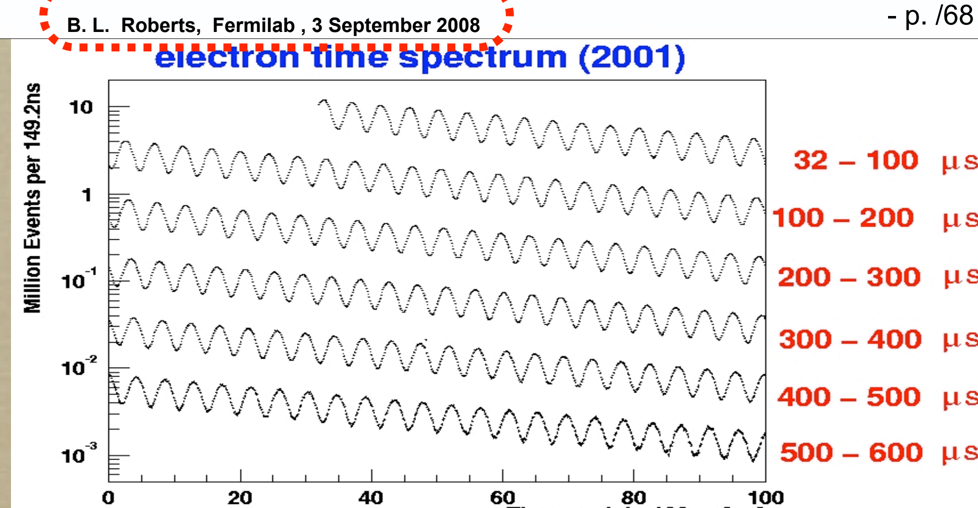
QED predicts a

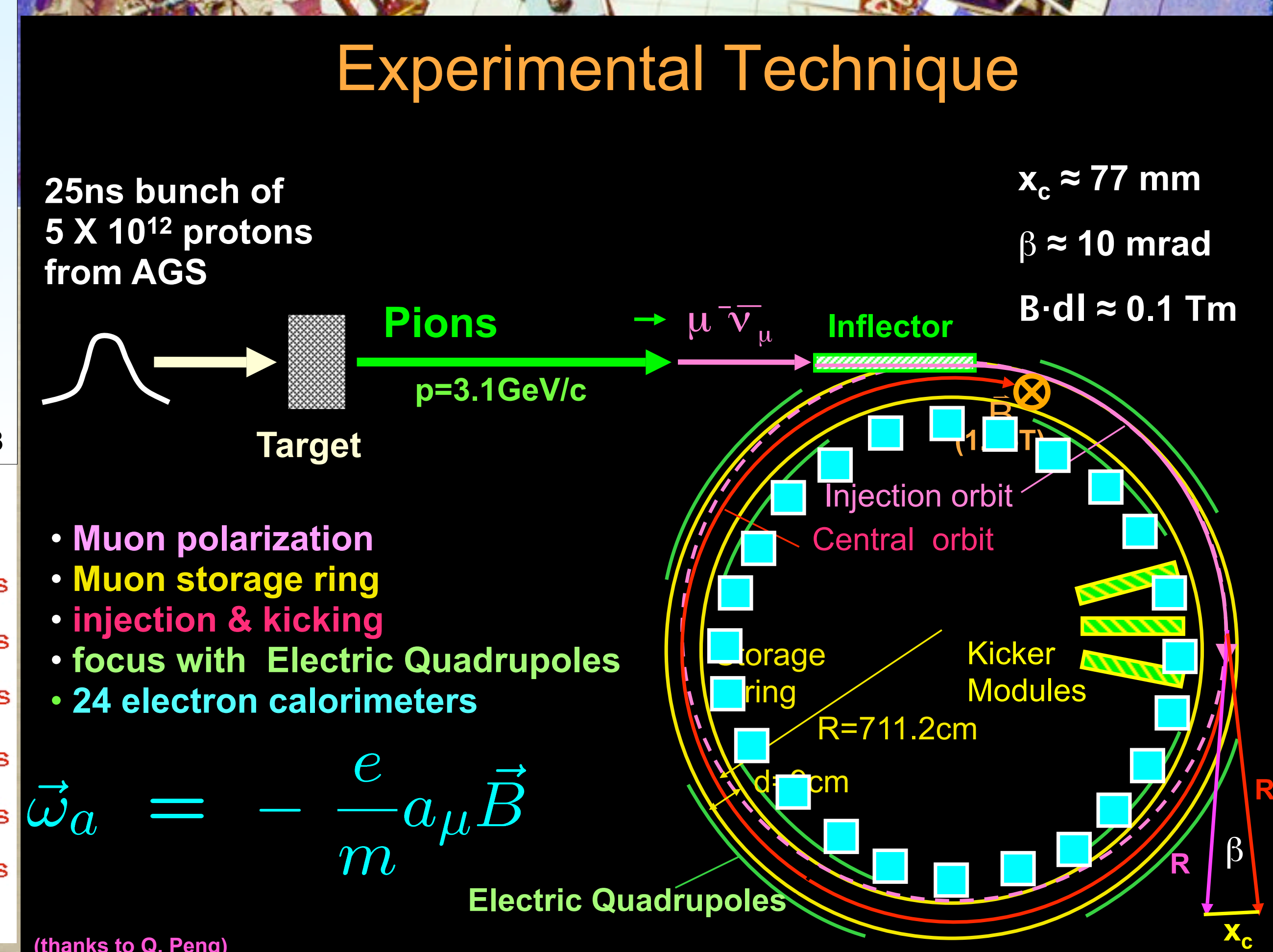
BOSTON UNIVERSITY

B. L. Roberts, Fermilab, 3 September 2008

- p. /68







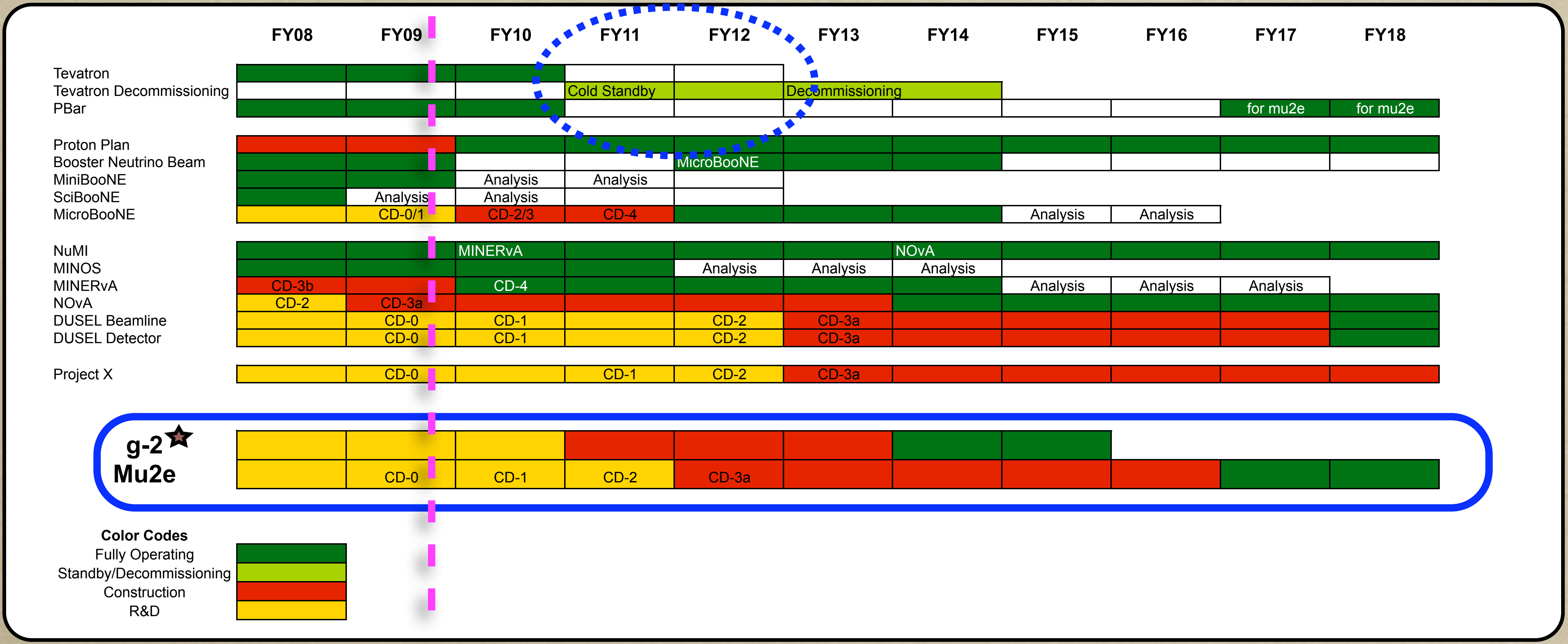
MJS / Fermilab

The New g-2 Experiment: FNAL

- *Performed at BNL, funding ran out but not the physics*
  - *3σ difference between theory / measurement seen at BNL*
- *3.09 GeV/c is "magic momentum" where the precession of the muon's spin will be purely due to magnetic fields, not electric fields; use 8.9 GeV/c proton beam infrastructure at Fermilab*
- *So, requires a special ring, with very pure dipole field -- 1 ppm*
  - *move the existing ring from BNL to Fermilab*
- *Fermilab has potential of many more protons/sec for g-2:*
  - *use "spare" Booster cycles at Fermilab injector complex*
  - *4 Tp/pulse * 6/20 pulses * 15 Hz * 10^7 s/yr = 1.8 x 10^{20}/yr*

Time Line of Events

- *While Mu2e is already* approved, *if New g-2 is also approved it would likely come on line first*
- *Mu2e beam scenarios were studied first, and will be presented here first*
- *Upon studying proposed operating scenarios, looking for similarities and potential overlap*

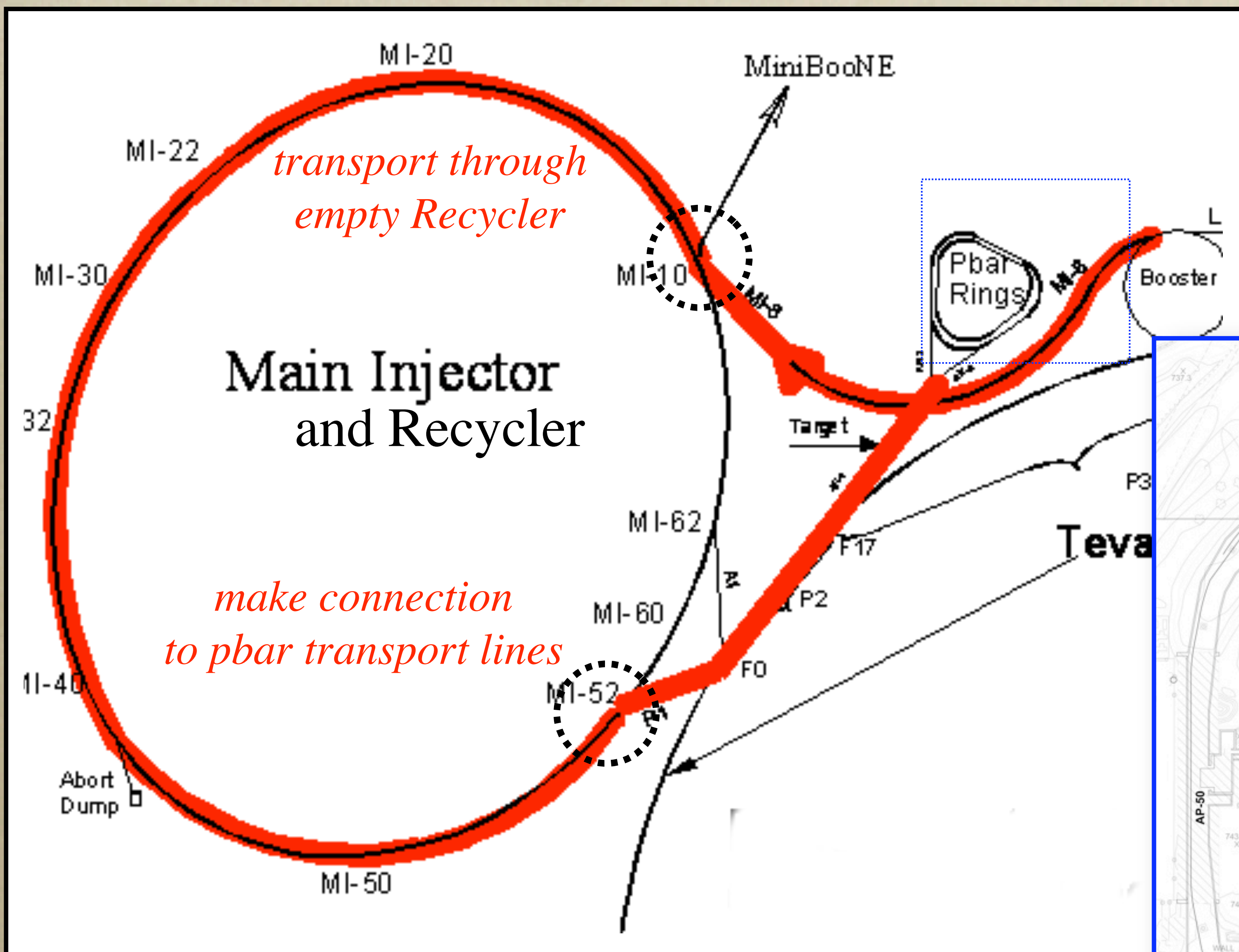


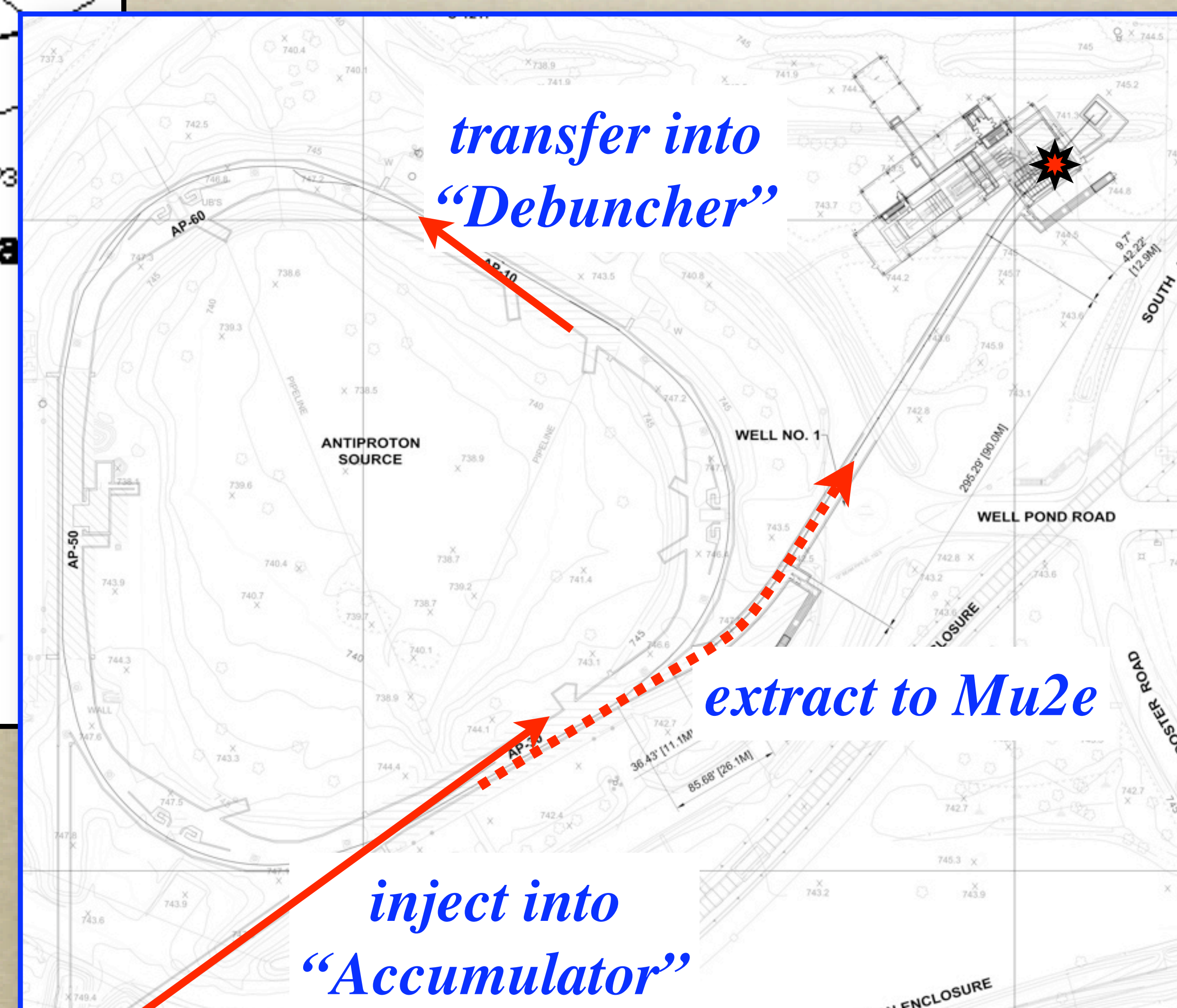
MJS / Fermilab

Mu2e Baseline Beam Proposal

- *Experiment "cycle" time of 667 ms*
    - *3 Booster batches fed into Accumulator ring*
        - *form single bunch -- 1.2 x 10^{13} (!!)*
    - *transfer bunch into Debuncher ring; phase rotate to form ~30-40 ns (rms) bunch; slow extract*
- *repeat twice during single 1.333 s NOvA cycle*
    - *NOvA uses 12/20*15 Hz cycles = 9 Hz*
    - *Mu2e would use 6/20*15 Hz cycles = 4.5 Hz*
        - *Note: 18×10^{12} p/sec (18 Tp/s) on average (25.7 kW @ 8.9 GeV)*

Beam Transport from Booster

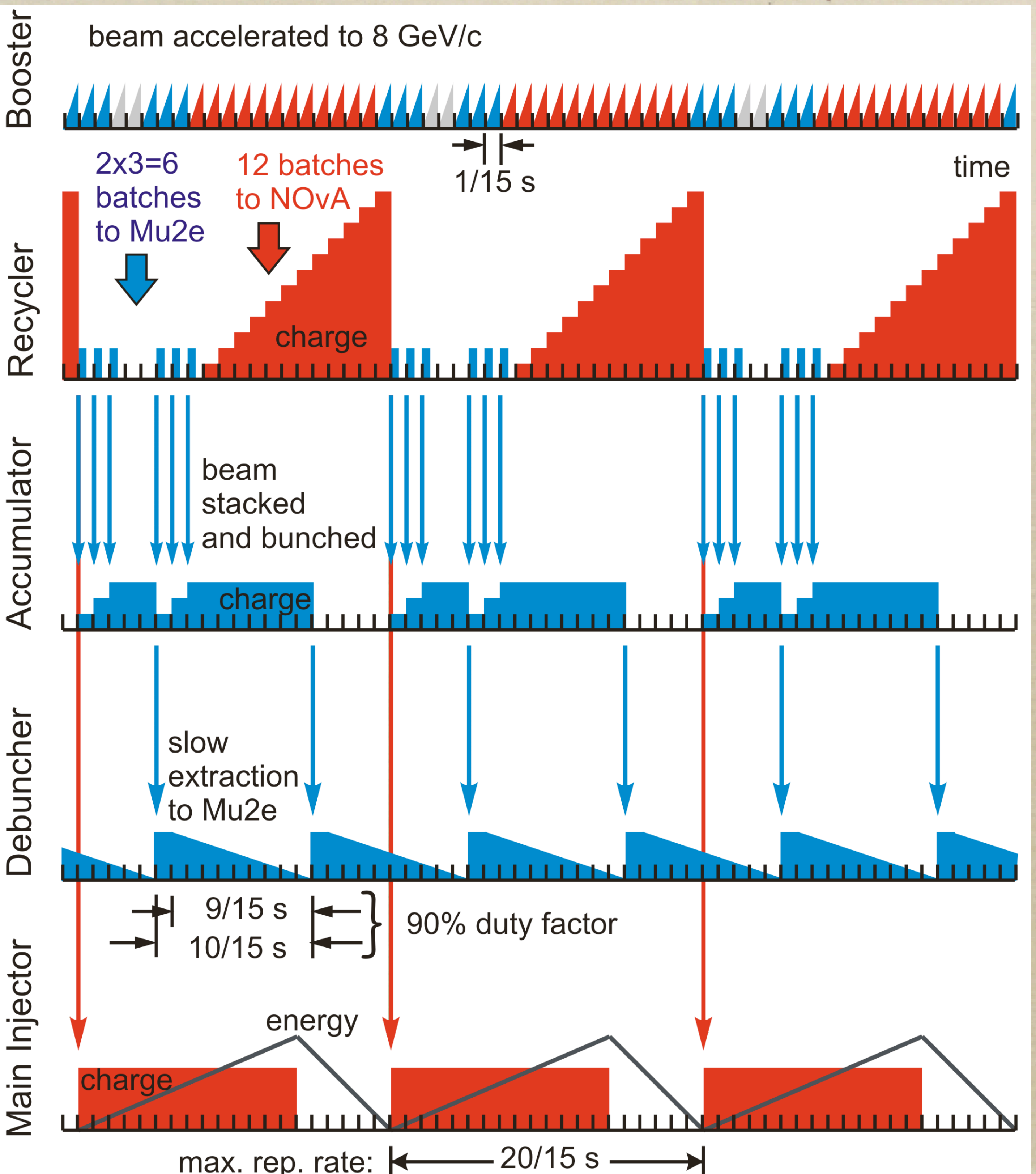




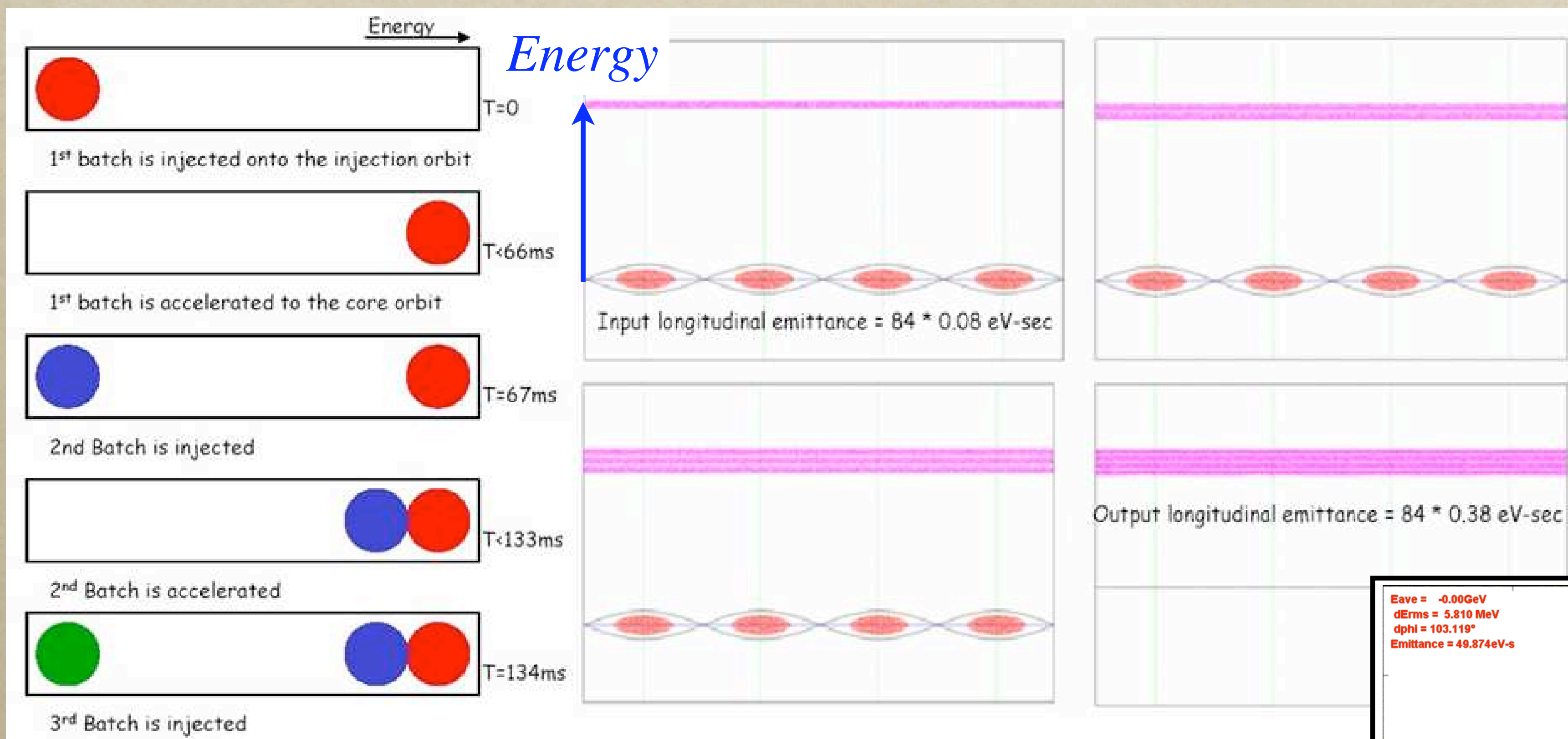
MJS / Fermilab

Mu2e Operating Scenario: Proposal

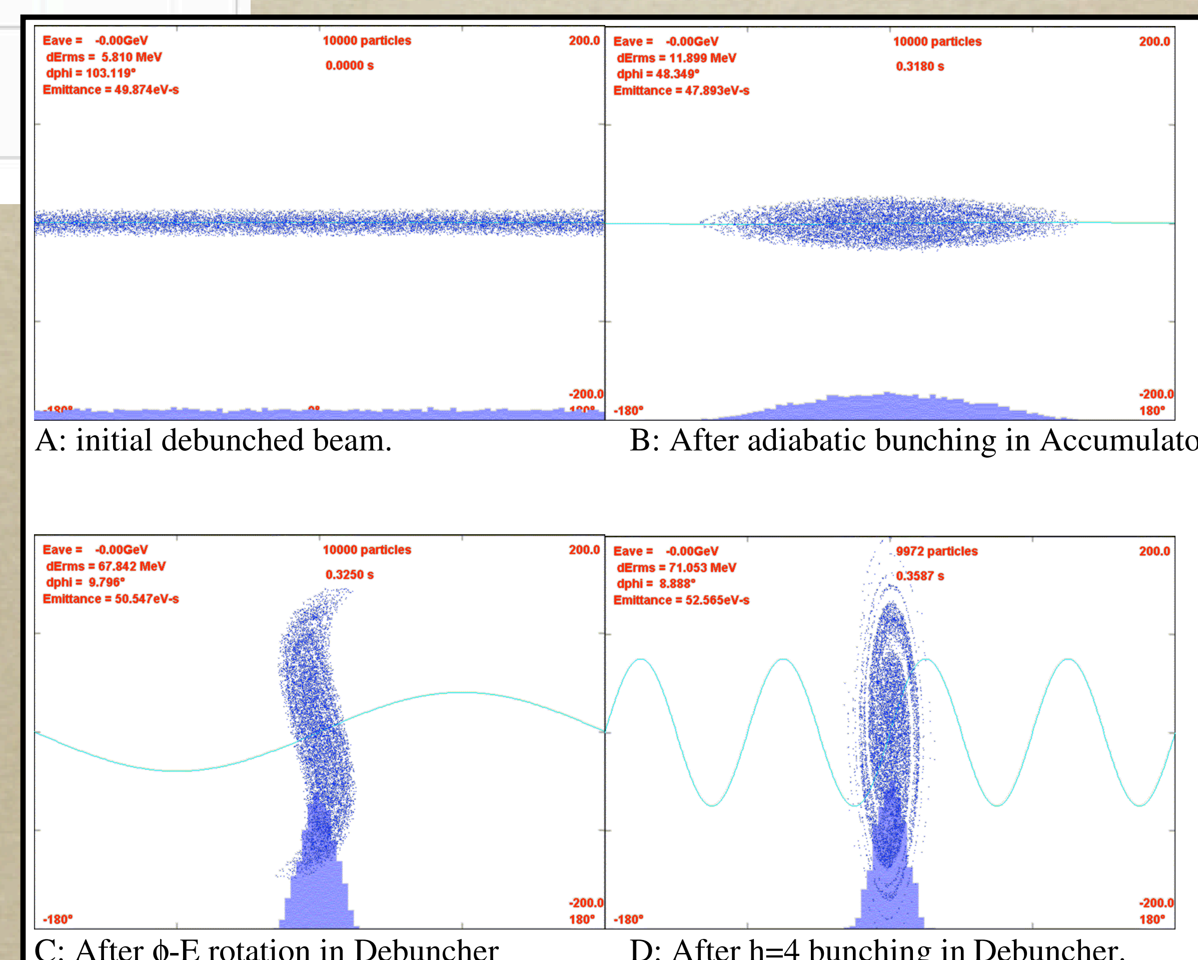
- *Inject/stack beam into Accumulator, form single bunch, and transfer to Debuncher for slow spill*
- *In principle, w/ $4x10^{12}$ (4 Tp) per Booster batch, Mu2e receives 18 Tp/s on target, $1.8x10^{20}$ in 10^7 s.*
- *15 Hz Booster assumed*
- *Does not affect NOvA operation*
- *Will require improved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



Bunch Formation -- Mu2e Proposal



- *momentum stack in Accumulator*
- *form single bunch; x-fer to Debuncher*
- *phase rotate, re-capture*
- *40 nsec bunch, $\Delta p/p \sim 0.8\%$ (rms)*

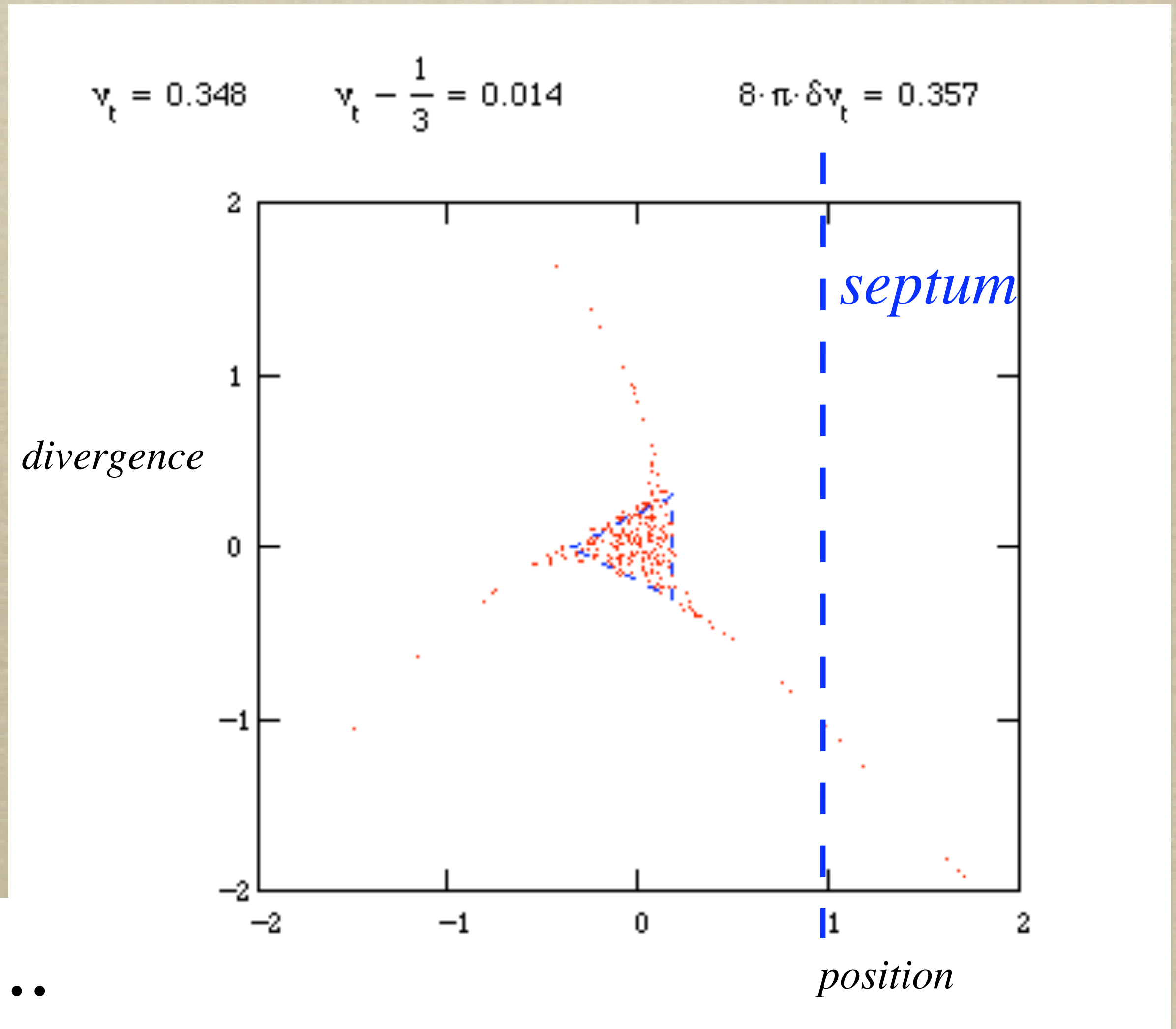


A: initial debunched beam.
B: After adiabatic bunching in Accumulator.
C: After ϕ-E rotation in Debuncher
D: After h=4 bunching in Debuncher.

MJS / Fermilab

Resonant Extraction

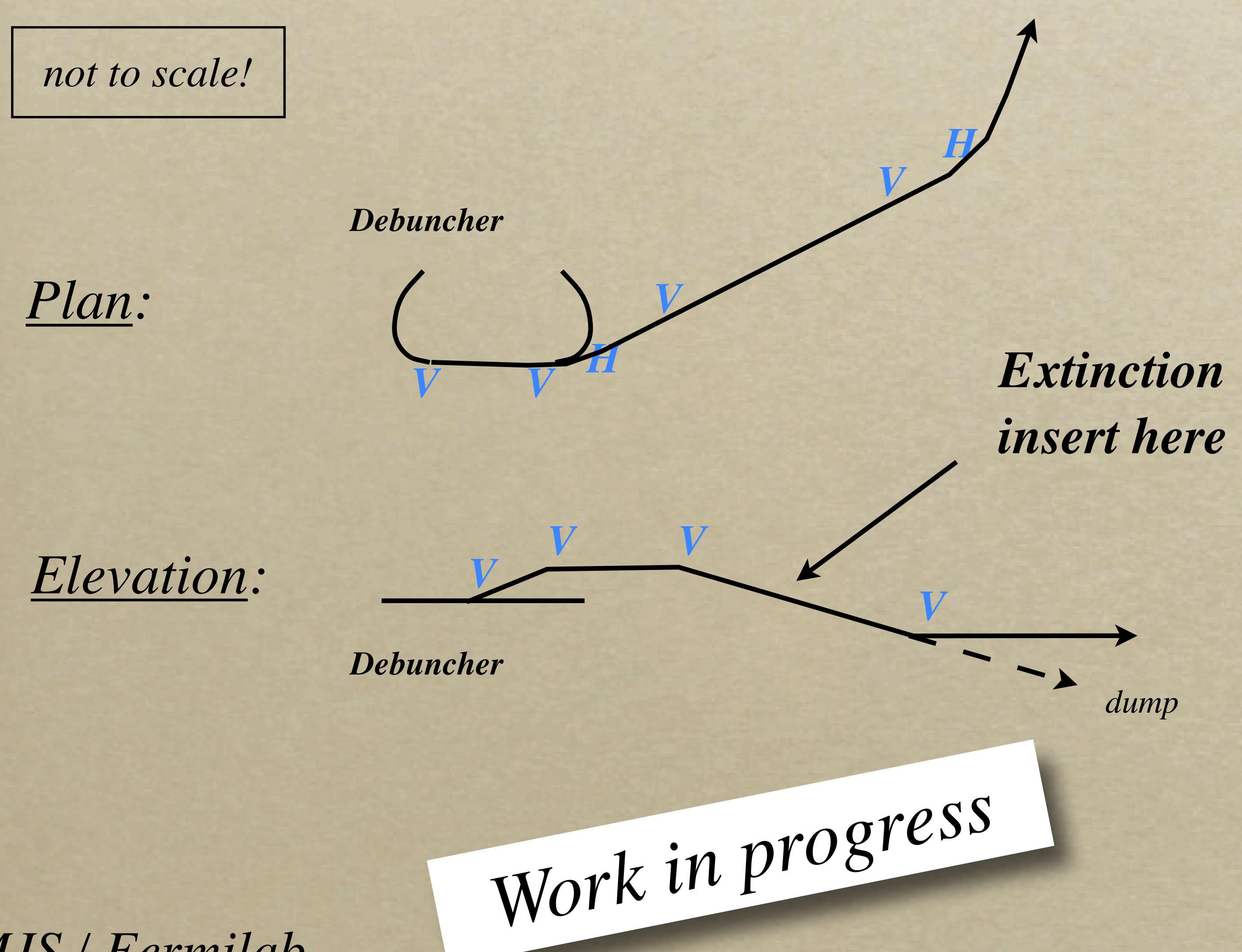
- *Once beam is in the Debuncher, "slow" spill over next 10-600 ms (depending upon scenario)*
    - *Mu2e receives ~3-8 x 10^7 protons every 1.7 μs*
- *Resonant Extraction*
    - *adjust betatron tune to be near rational value*
    - *use feedback to control rate of particle extraction*

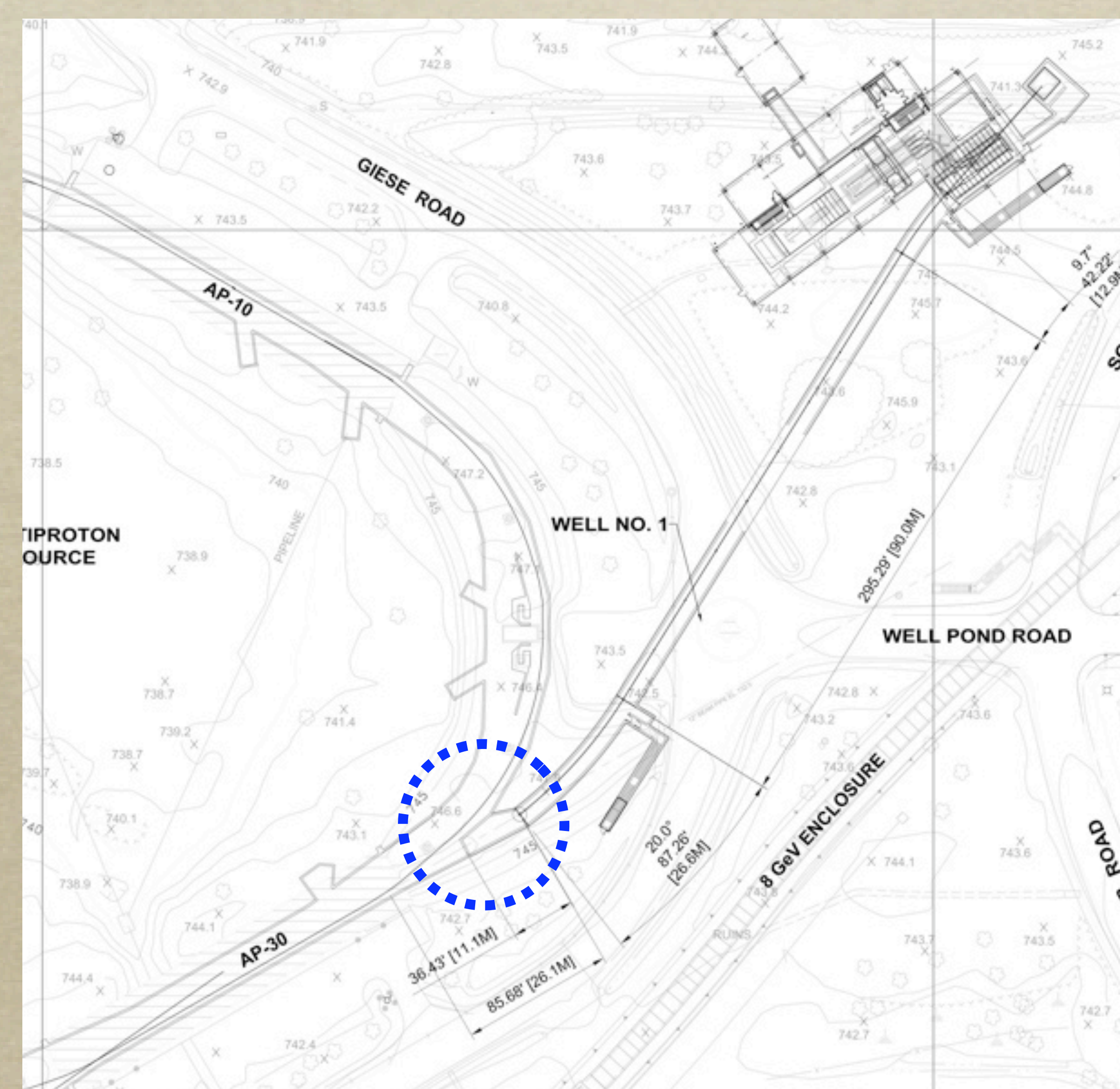


generic example...

Mu2e Beam Line

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





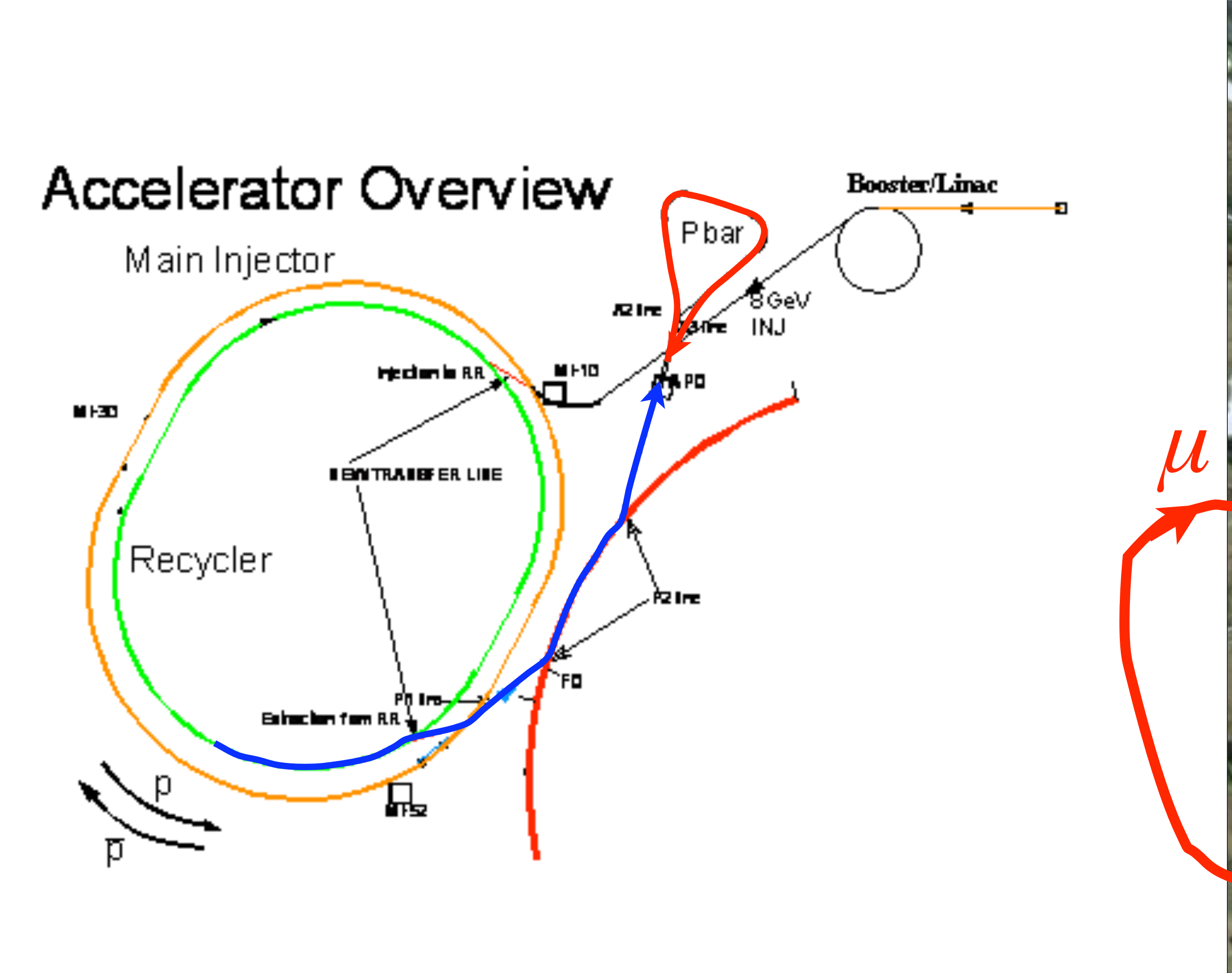
The g-2 Baseline Proposal

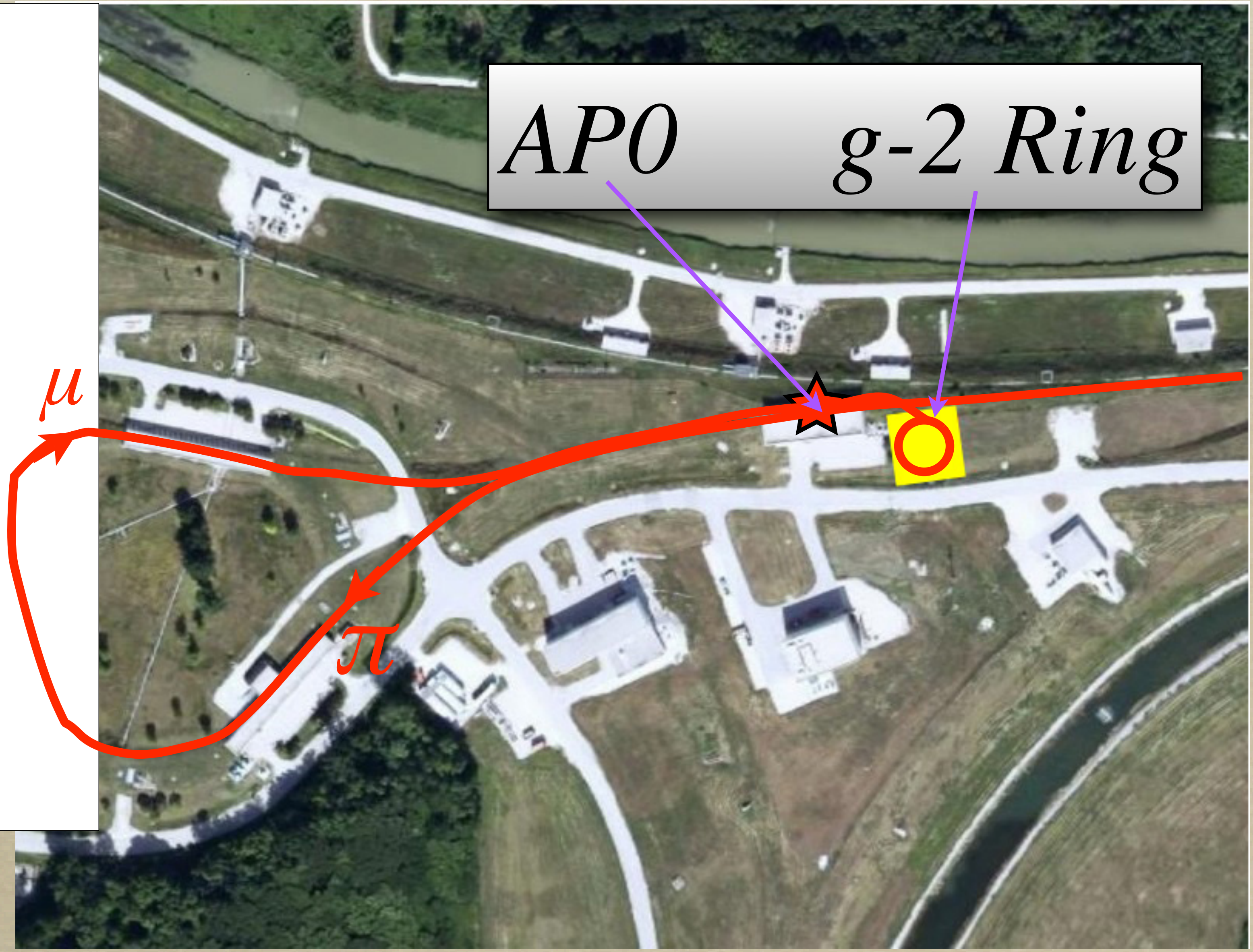
- *Deliver same average rate (18 x 10^{12}/s) to target as Mu2e, also over 6 Booster cycles, every NOvA cycle* *(conservative -- could be 8 cycles)*
  - *here, though, operates "per Booster cycle"*
    - *generate 4 bunches in the Recycler -- takes about 30 ms to perform*
    - *transfer one-at-a-time to g-2 Ring, every 10 ms -- all within one Booster cycle*
  - *Note: bunches ~30 ns (rms) in length, ~ 10^{12} each*

(similar bunch length req's as in Mu2e)

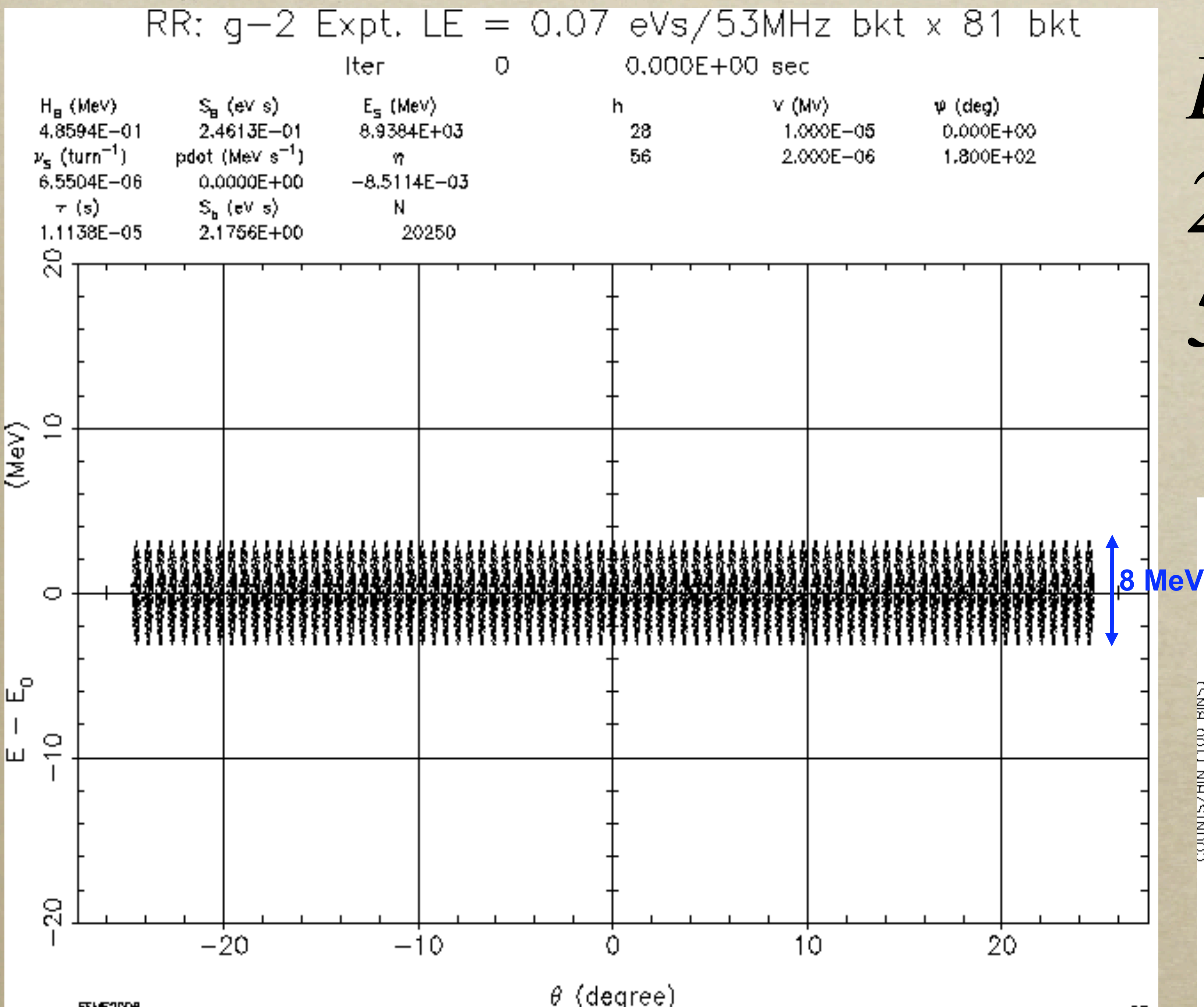
g-2 Proposal Operational Scenario

- *Generate 4 “mis-matched” bunches in Recycler that phase rotate in 20 ms; extract one every 10 ms toward pbar rings*
- *Target at AP0 target hall; use pbar rings as 1-pass “decay channel” for pions; accumulate muons in g-2 ring*





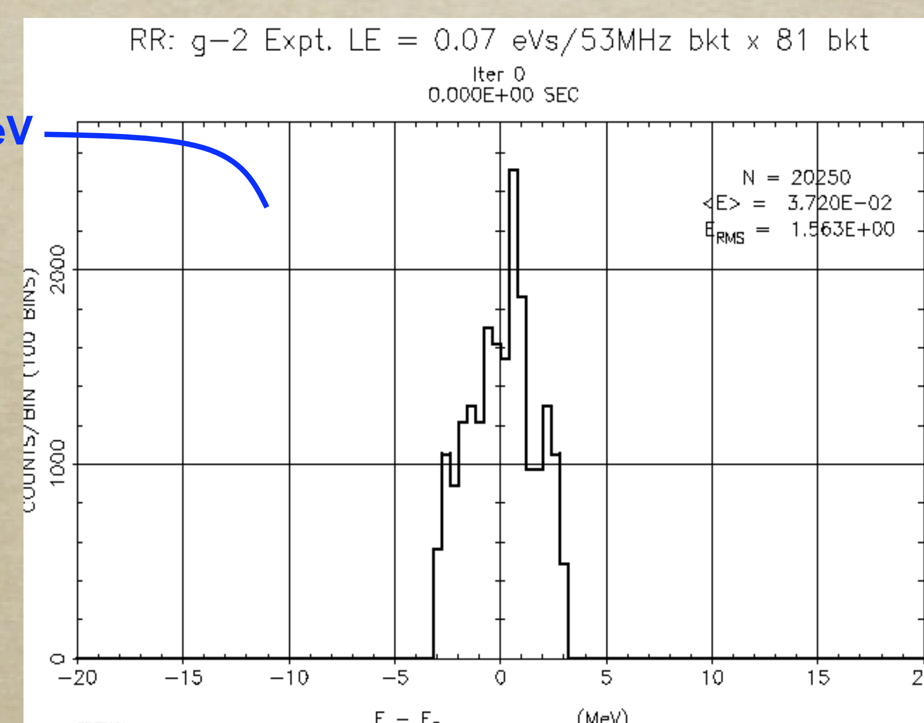
Simulations*



Broadband: 4 kV

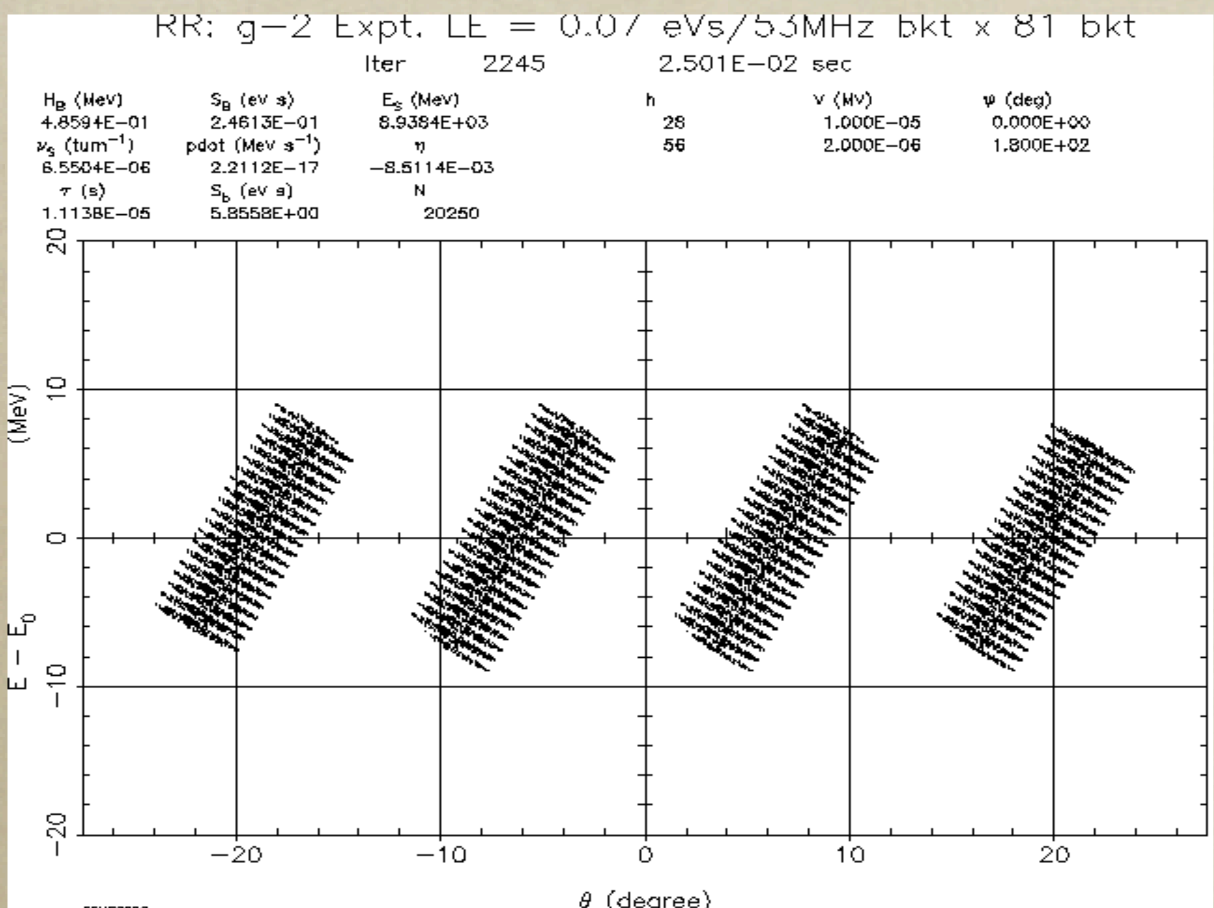
2.5 MHz: 80 kV

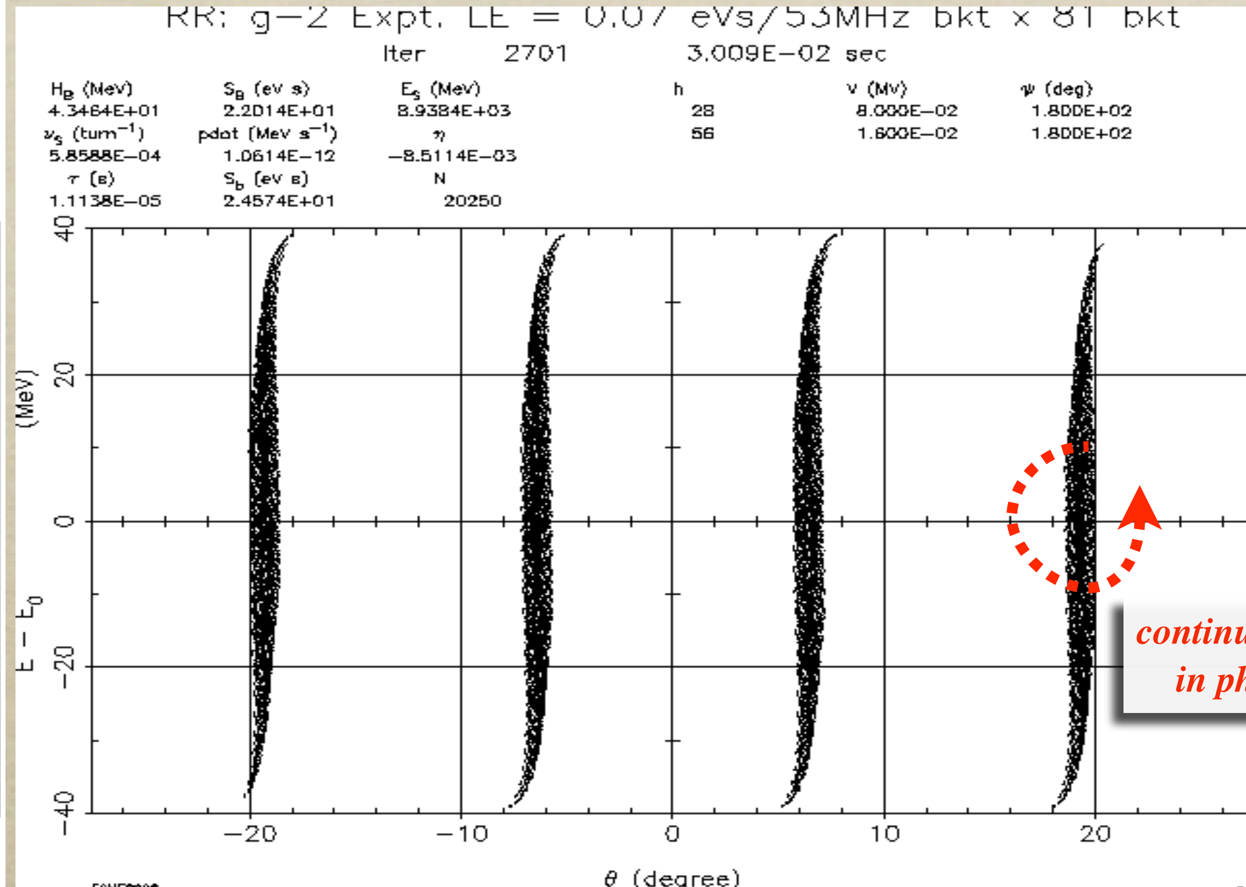
5.0 MHz: 16 kV



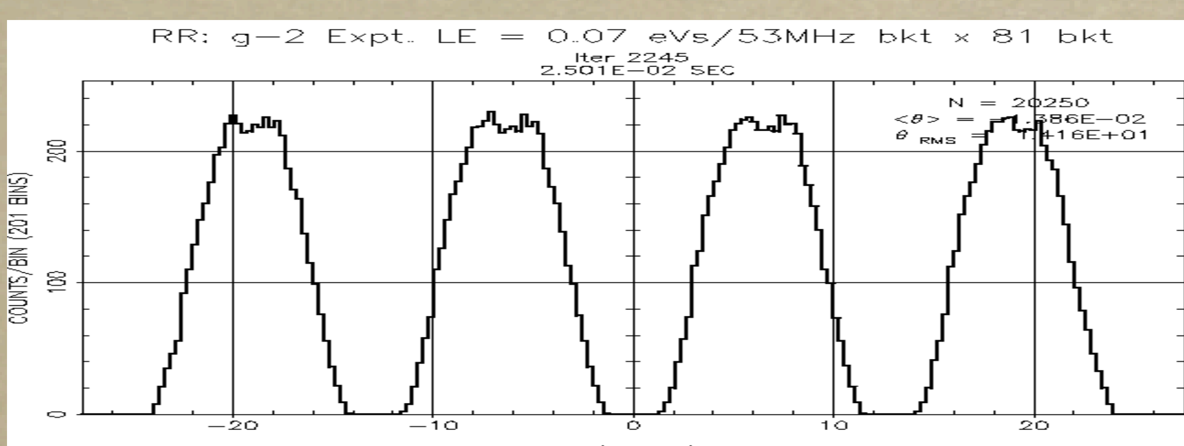
**C. Bhat and J. MacLachlan*

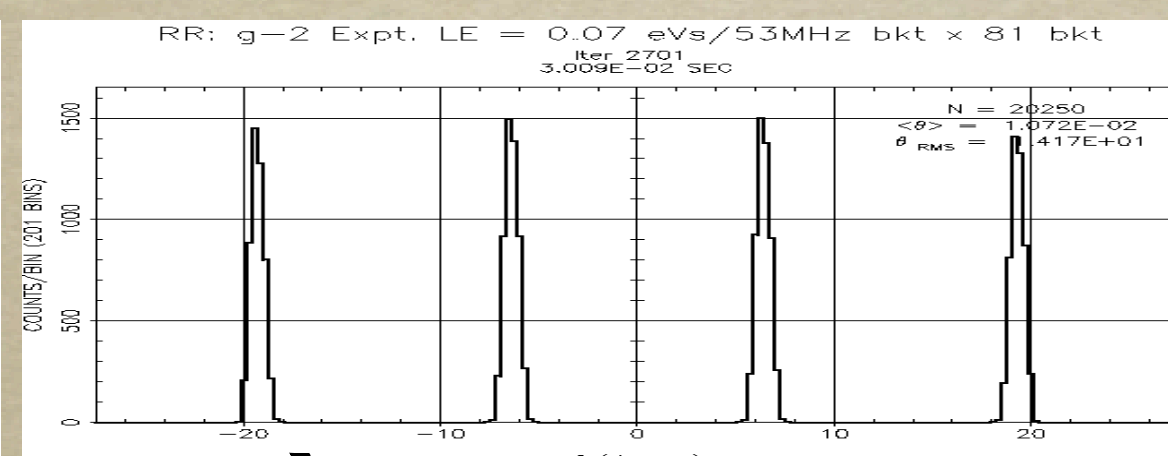
Rotate into 4 Bunches





continues to tumble in phase space

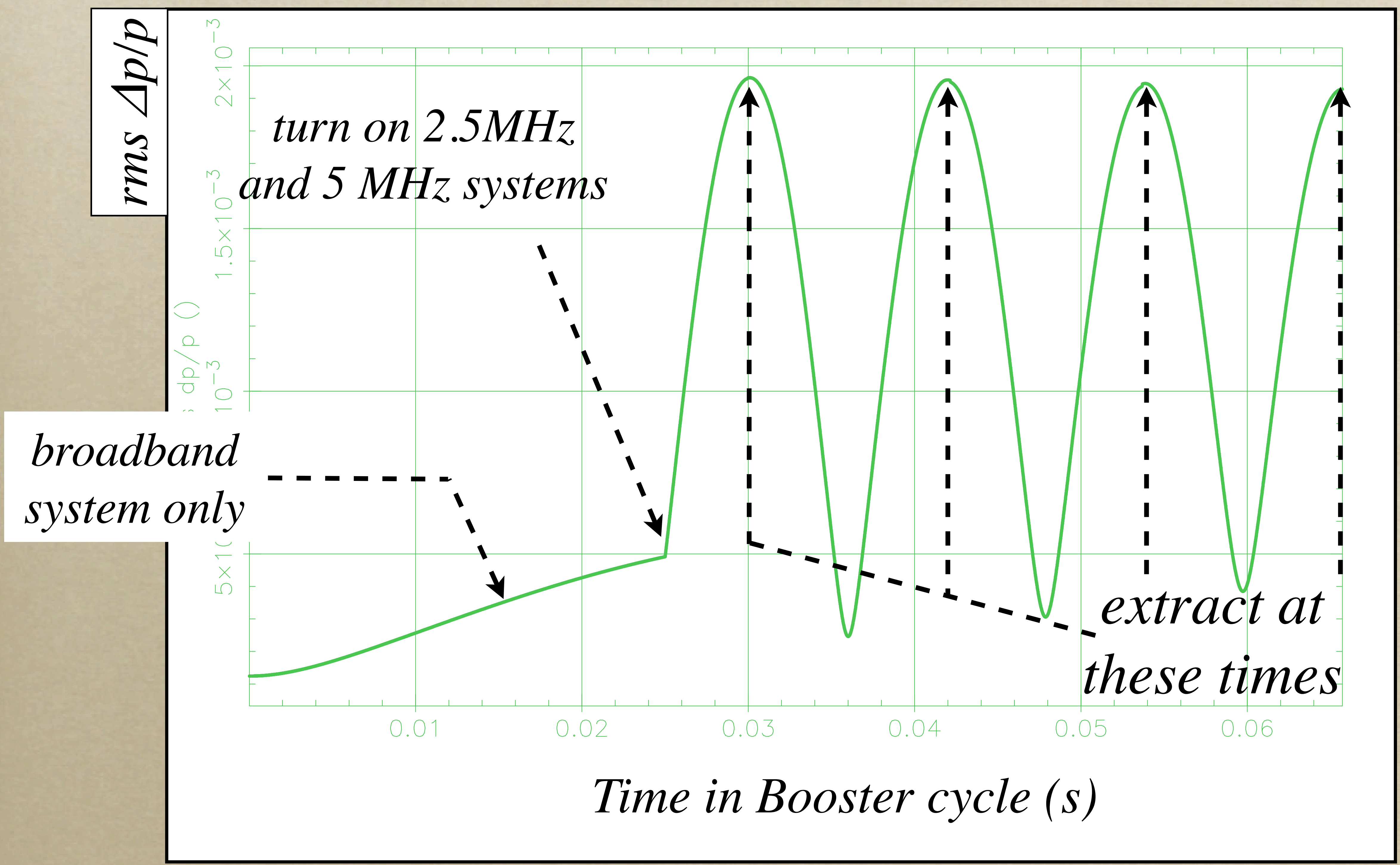




Extraction of the 1st Bunch

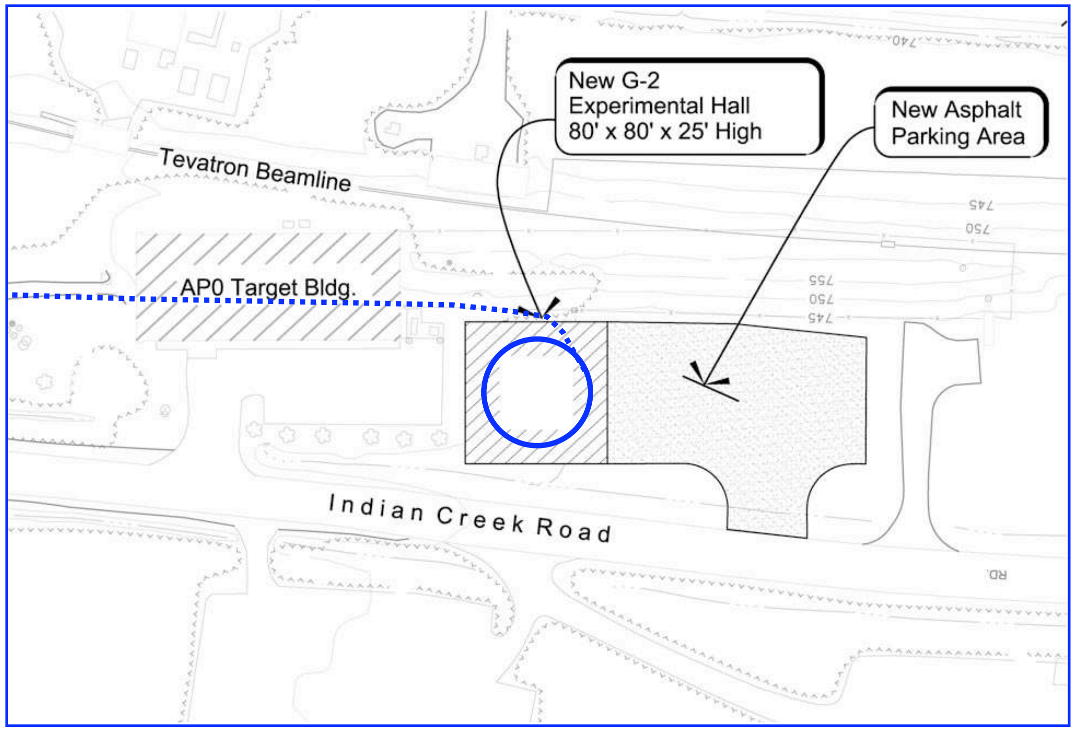
MJS / Fermilab

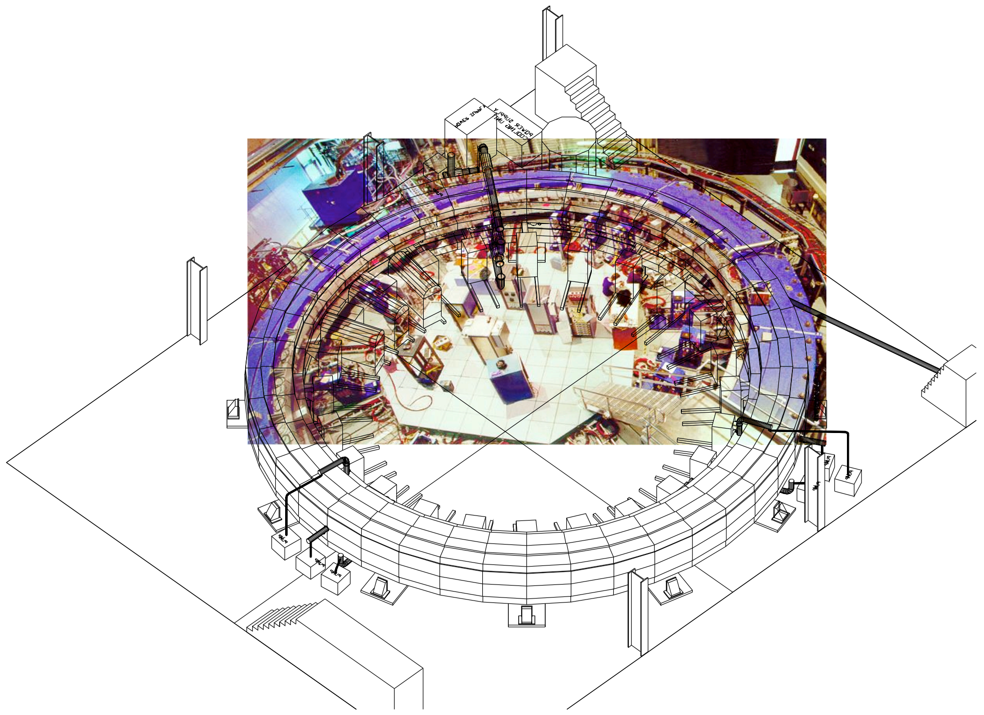
Momentum Spread vs. Time



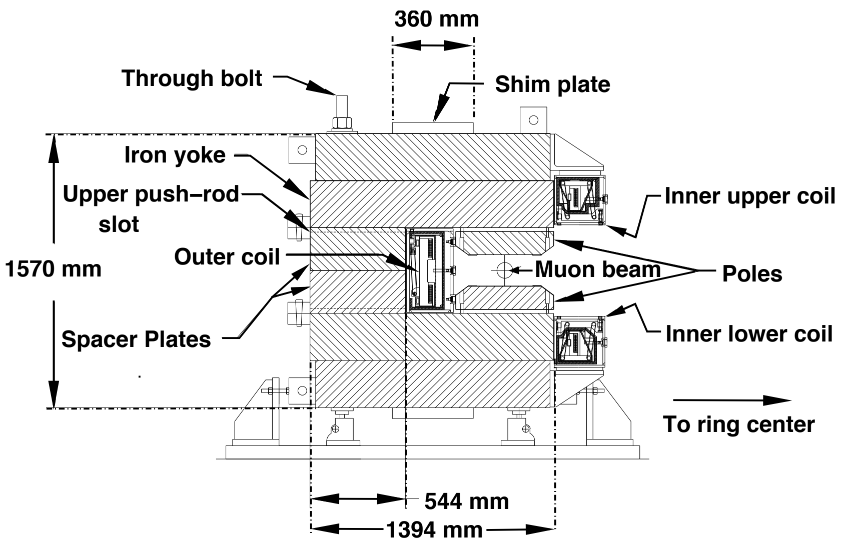
g-2 Experiment Building

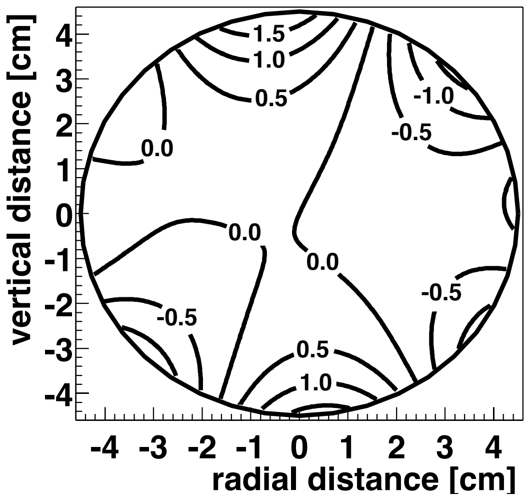
proposed siting:





- *New building*
- *New beam line from AP0 target hall*
- *E821 magnet, etc.*





Mu2e: 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":* $\mathcal{B} \approx \frac{1700\ \text{nsec}}{40\ \text{nsec}\cdot\sqrt{2\pi}} \approx 17$

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

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*

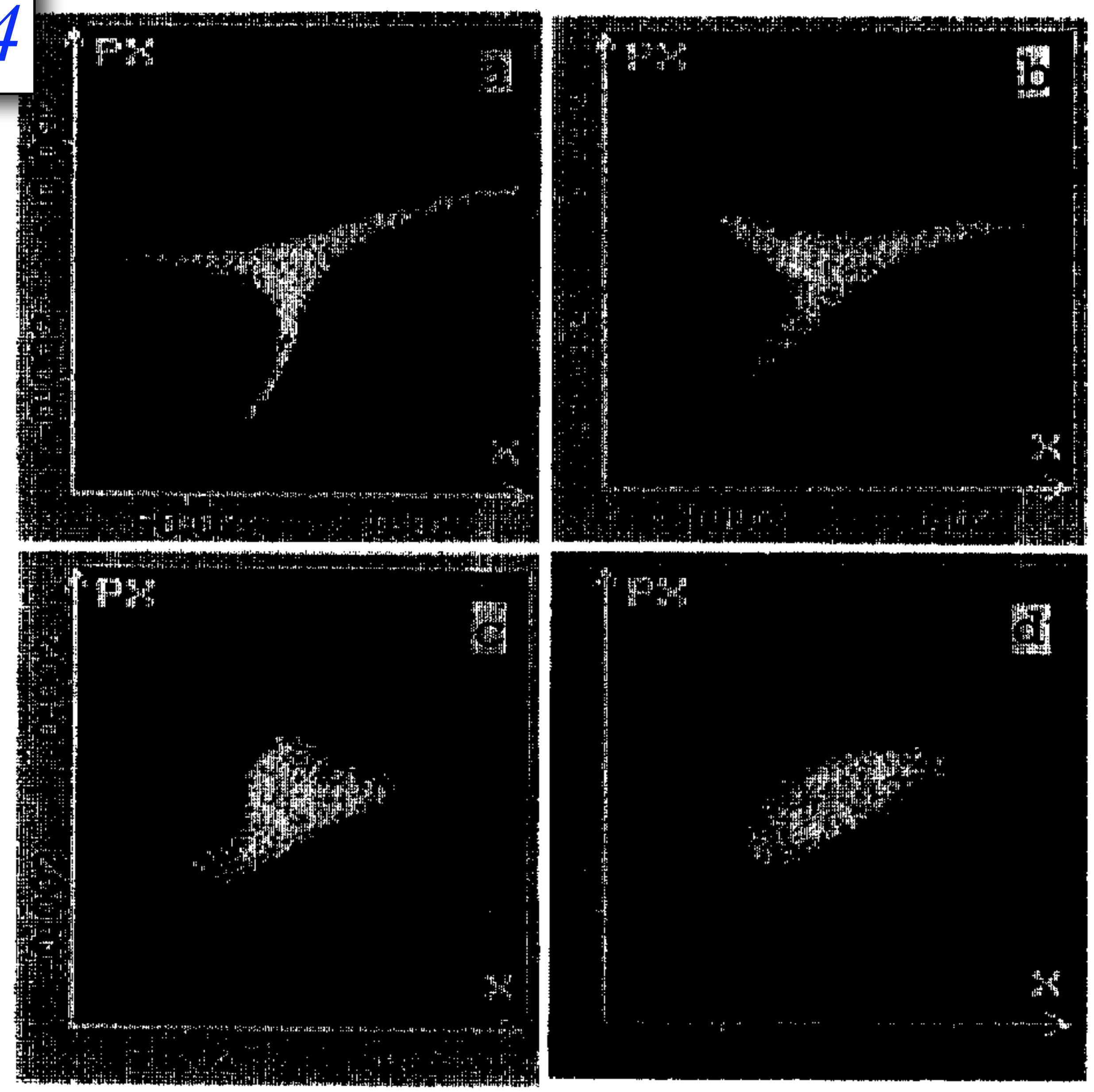
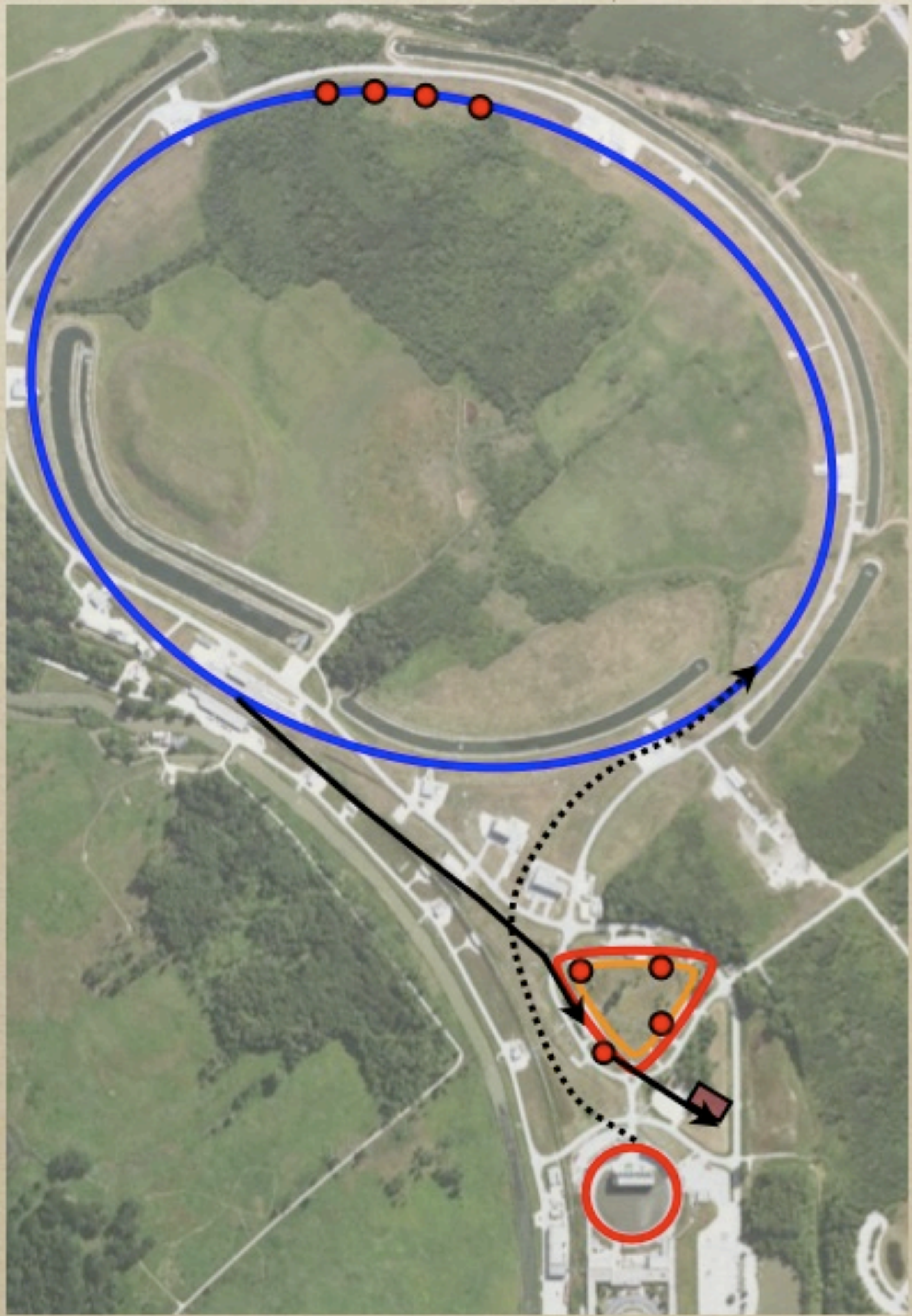


Figure 2: The phase portraits of the beam at a)$\Delta\nu_L$=0.01, b)$\Delta\nu_L$=0.03, c)$\Delta\nu_L$=0.06 and d)$\Delta\nu_L$=0.1

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)*



Mu2e 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

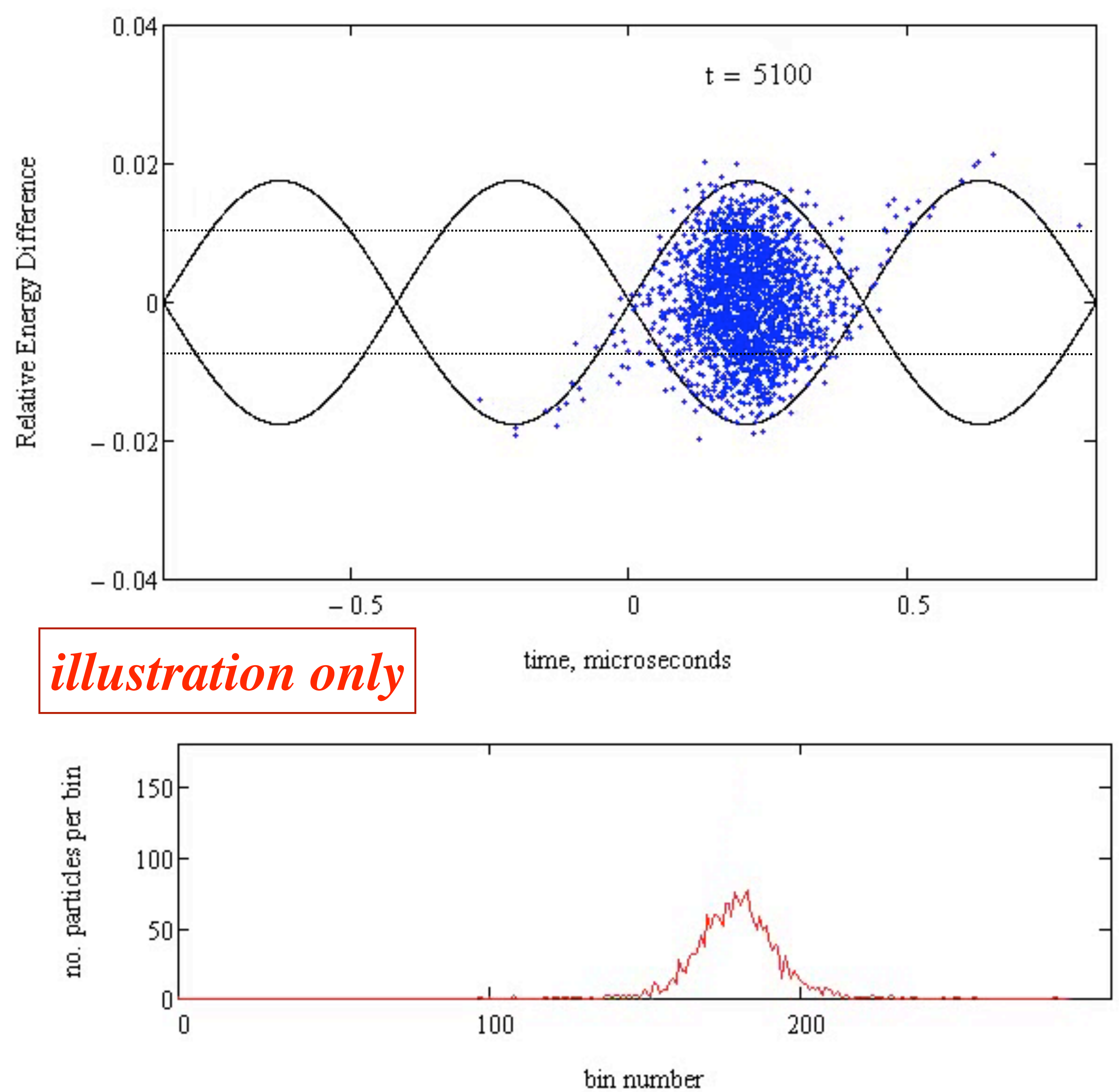
Let's assume some noise sources…

- *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…*



Internal Extinction

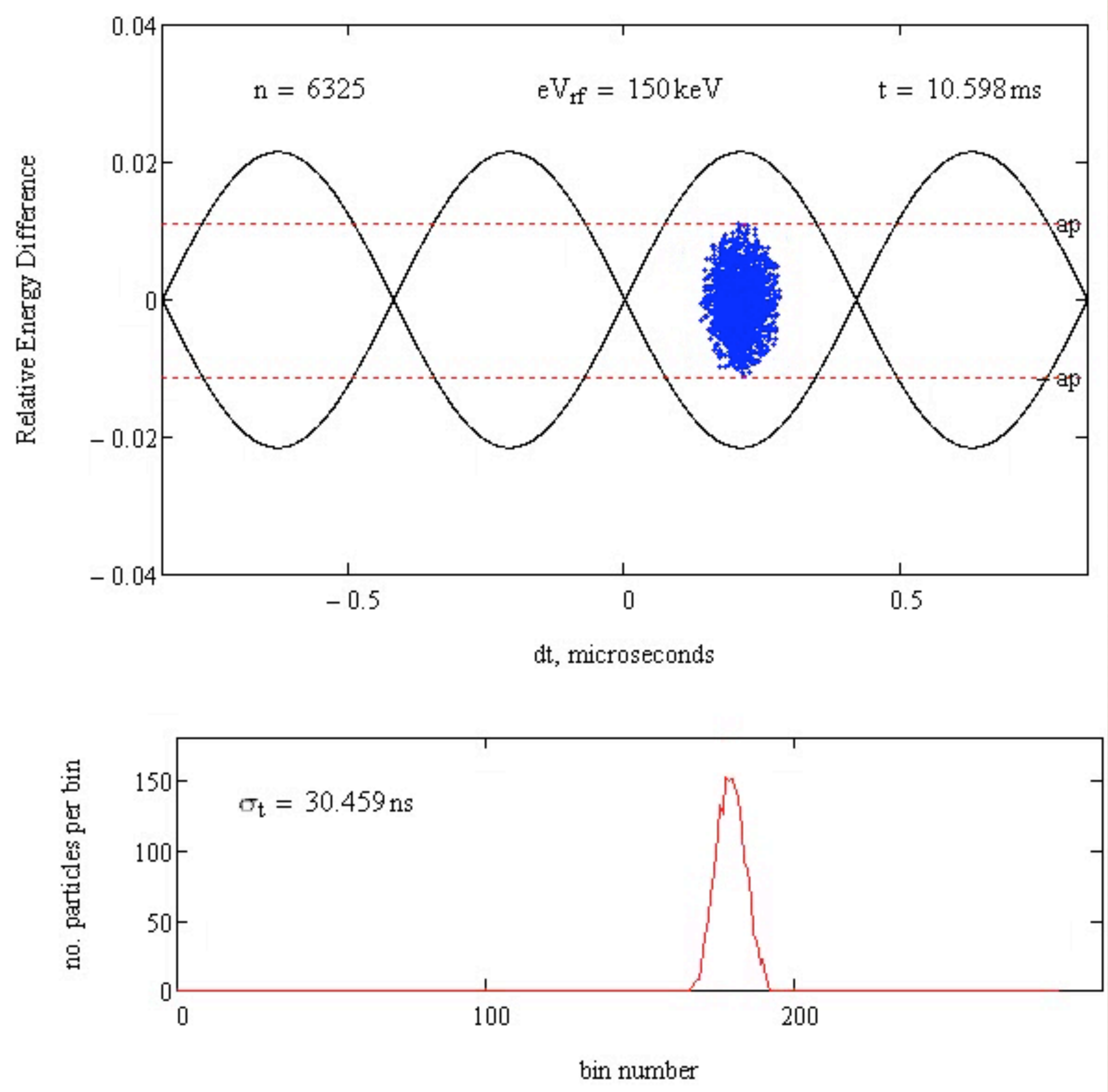
Let's assume some noise sources…

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

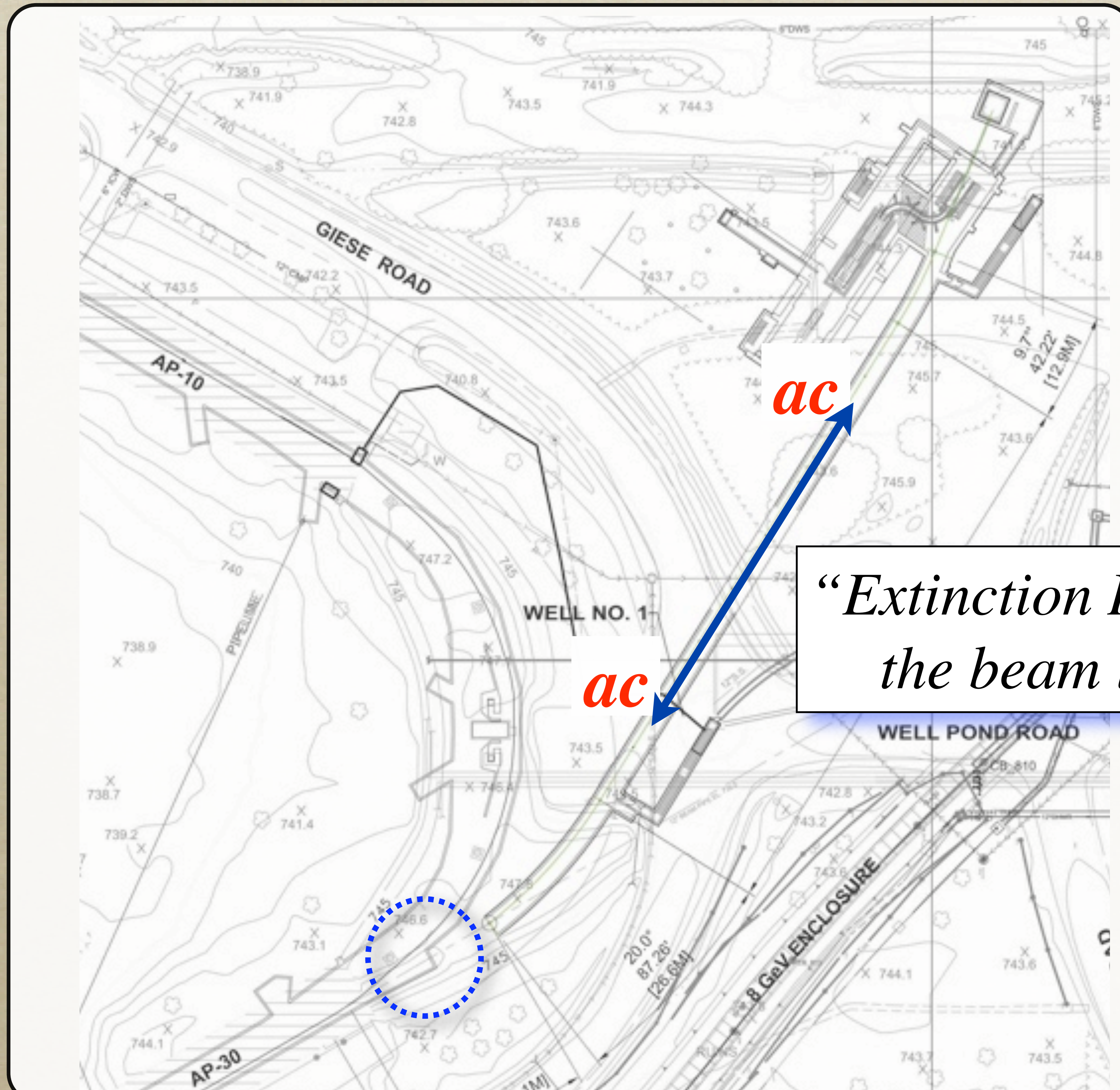
  (for dramatization)

- *0.1^o more typical*

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



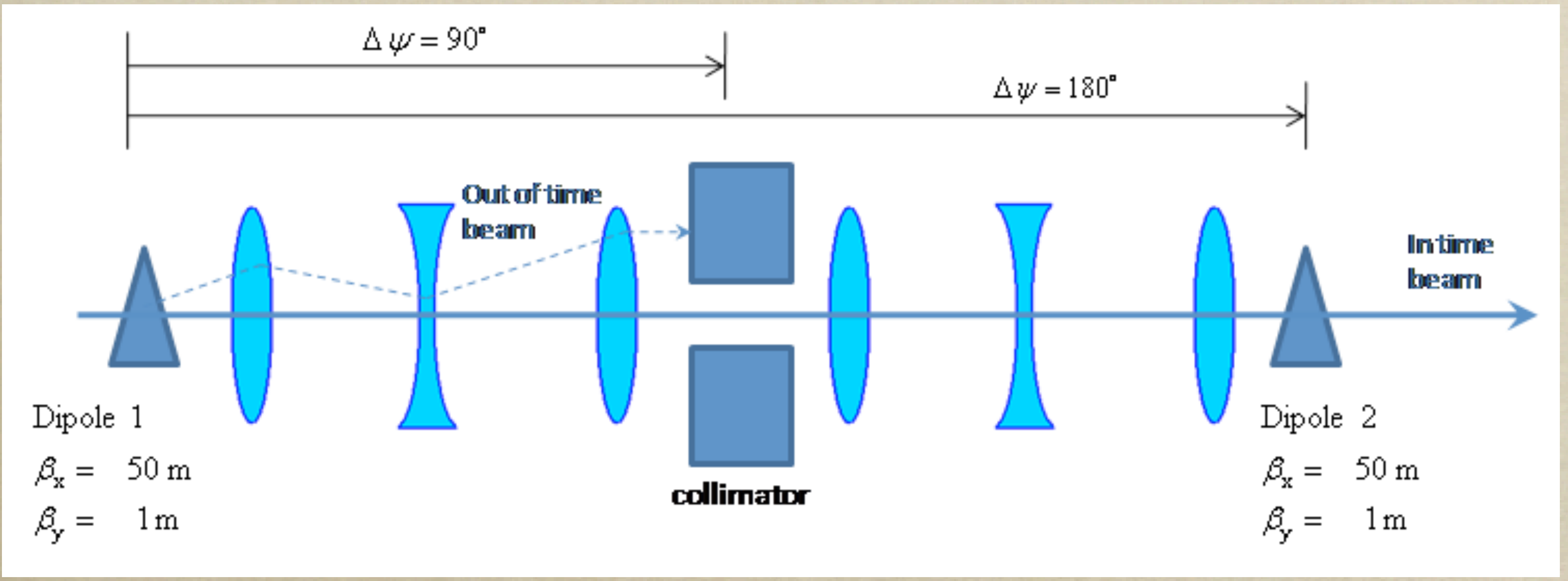
External Extinction



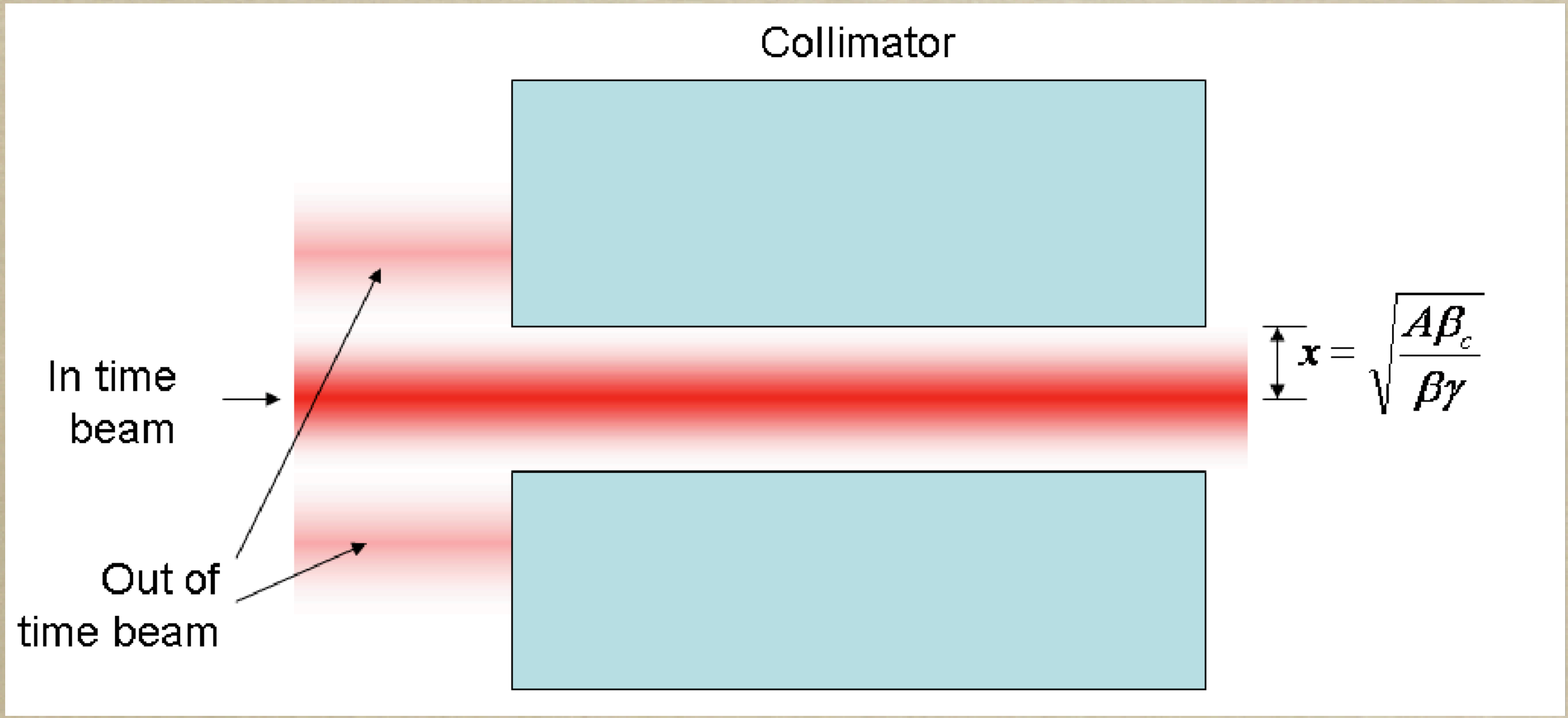
“Extinction Insert” within the beam line design

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*

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

Randy Thurman-Keup

Fermi National Accelerator Lab, P.O. Box 500, Batavia, IL 60510

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.

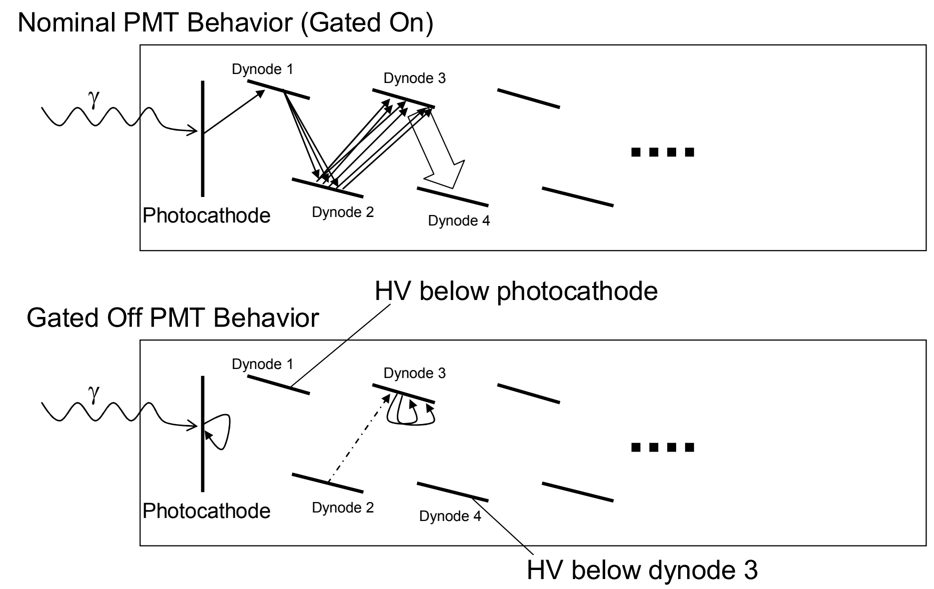


FIGURE 4. Design of a gated PMT whereby two dynodes are held at the wrong voltage, shutting off the amplification process. When gated on, the dynodes are pulsed to their nominal voltages, and the PMT functions normally.

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

Integration into a Common Program?

- *Both (all) 8 GeV programs assume a 15 Hz Booster*
- *Injection into Recycler ring from MI-8 line required for both programs; will use same system delivered by NOvA project*
- *Could use single Recycler RF "system" for both Mu2e / g-2*
  - *g-2 is somewhat less demanding on bunch length, "extinction"*
- *Could use a single Recycler extraction kicker system*
  - *very little (if any) additional cost to convert the g-2 system (4 pulses/BooCyc) to Mu2e operation (1 long pulse/BooCyc)*
  - *Note: Transfer kickers necessary in DEB/ACC for Mu2e have similar requirements as does Recycler extraction kicker for g-2*
- *Can gain experience with Recycler RF and extraction using g-2 before the more demanding Mu2e comes on line*

Possible Schedule Scenario

- *Begin to construct g-2 building (new civil); bring g-2 ring to FNAL*
- *Run II ends -- shutdown begins*
  - *tie-in g-2 building with beam line (new civil), cryo to bldg, etc.*
  - *reconfig Recycler, beam lines, AP0 target area; remove aperture restrictions from Debuncher/Accumulator, etc.*
- *Run g-2 while building Mu2e beam line and experimental hall (civil)*
- *Shutdown the complex following g-2 to tie-in Mu2e beam line to the DEB/ACC rings*
- *Commission / run Mu2e*

Summary

- *Mu2e is approved for Fermilab, becoming an actual project; g-2 seeking approval, presently "scrubbing" its cost estimate*
- *Both use "extra" pulses of Booster during NOvA era*
    - *similar beam requirements -- intensity, bunch length, etc.*
- *Much on-going work to do: beam optics, scenario development, beam tests of extraction techniques, bunch formation, extinction measurements, ...*
- *With coordinated effort, can minimize costs to both experiments*
- *Could give smooth, continuous program following completion of Run II*
    - *g-2 accel efforts could be "tune up" leading to Mu2e*
- *Could pave way for other experiments and/or R&D efforts using facility*
    - *kaon program, muon cooling experiments, targeting R&D, ...*

Some References

- *D. McGinnis, "Beam Emittances and RF structure at Injection into the Main Injector for the Multi-Stage Proton Accumulator," Beams-doc-2138.*
- *J. Reid, R. Ducar, "Booster RF Repetition Rate Limit," Beams-doc-2883.*
- *D. Neuffer, "More Rebunching Options for the mu2e Conversion Experiment," Beams-doc-2787.*
- *Mu2e Collaboration, "Proposal to Search for $\mu - N \rightarrow e - N$ with a Single Event Sensitivity Below 10^{-16}," FERMILAB-PROPOSAL-0973.*
- *E. Prebys, "AC Dipole System for Inter-Bunch Beam Extinction in Mu2e Beam Line," FERMILAB-CONF-09-190-APC.*
- *M. Syphers, "Possible Scheme to Ameliorate Space Charge and Momentum Spread Issues," MU2E-doc-398.*
- *New g-2 Collaboration, "The New (g-2) Experiment: A Proposal to Measure the Muon Anomalous Magnetic Moment to ±0.14 ppm Precision," FERMILAB-PROPOSAL-0989.*
- *C. Ankenbrandt, et al., "Preparation of Accelerator Complex for Muon Physics Experiments at Fermilab," Beams-doc-3220.*
- *M. Syphers, "Preparations for Muon Experiments at Fermilab," FERMILAB-CONF-09-153-AD.*