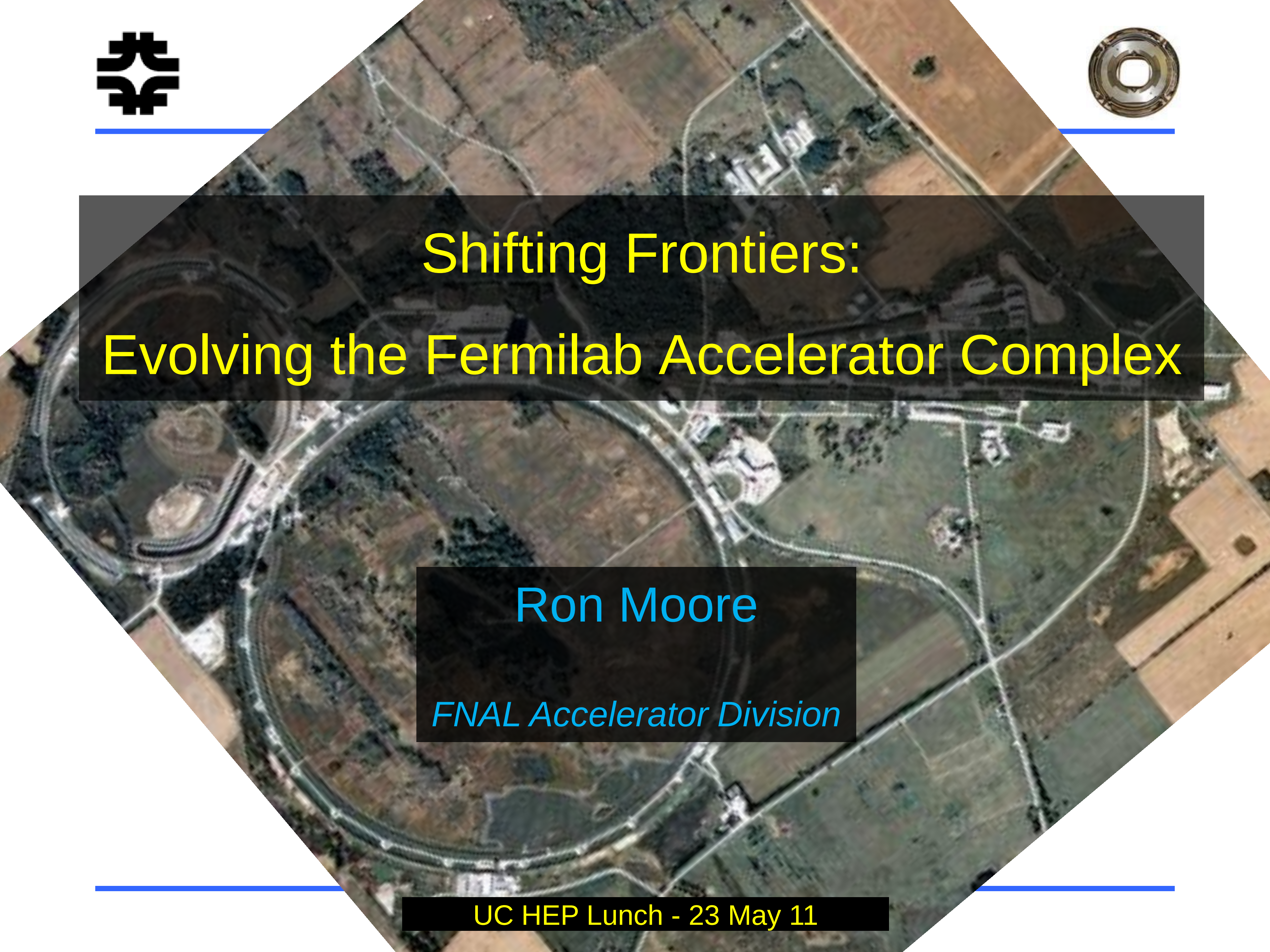


Shifting Frontiers:

Evolving the Fermilab Accelerator Complex

Ron Moore

FNAL Accelerator Division

Contents

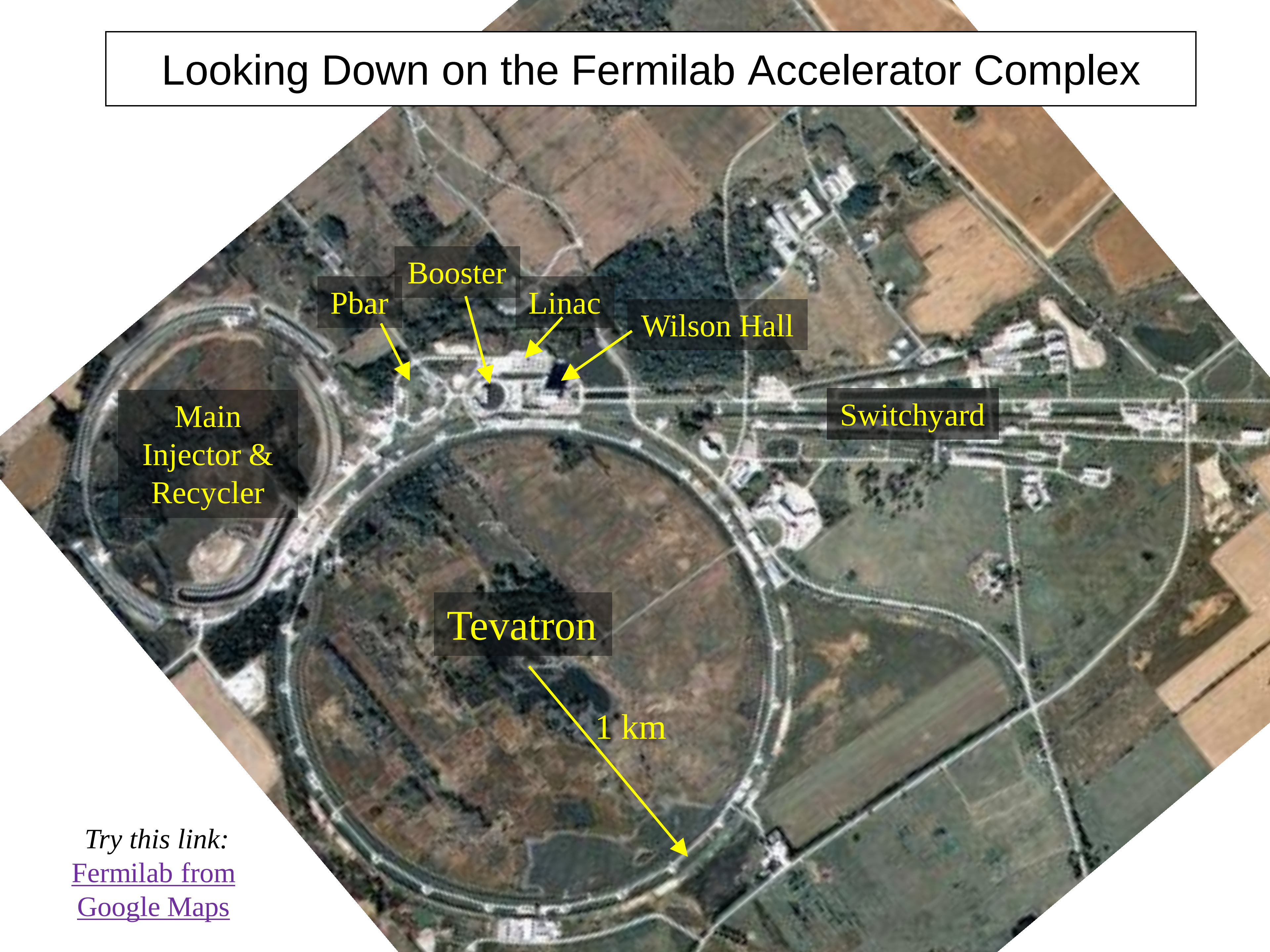
- Overview of the Accelerator Complex
- Termination of the Tevatron
- Proton Source Improvements
- NOvA / mu2e / g-2
- Summary

- Thanks to colleagues who supplied information & slides
  - Bill Pellico, Steve Werkema, Tony Leveling, Don Cossairt, Chris Polly

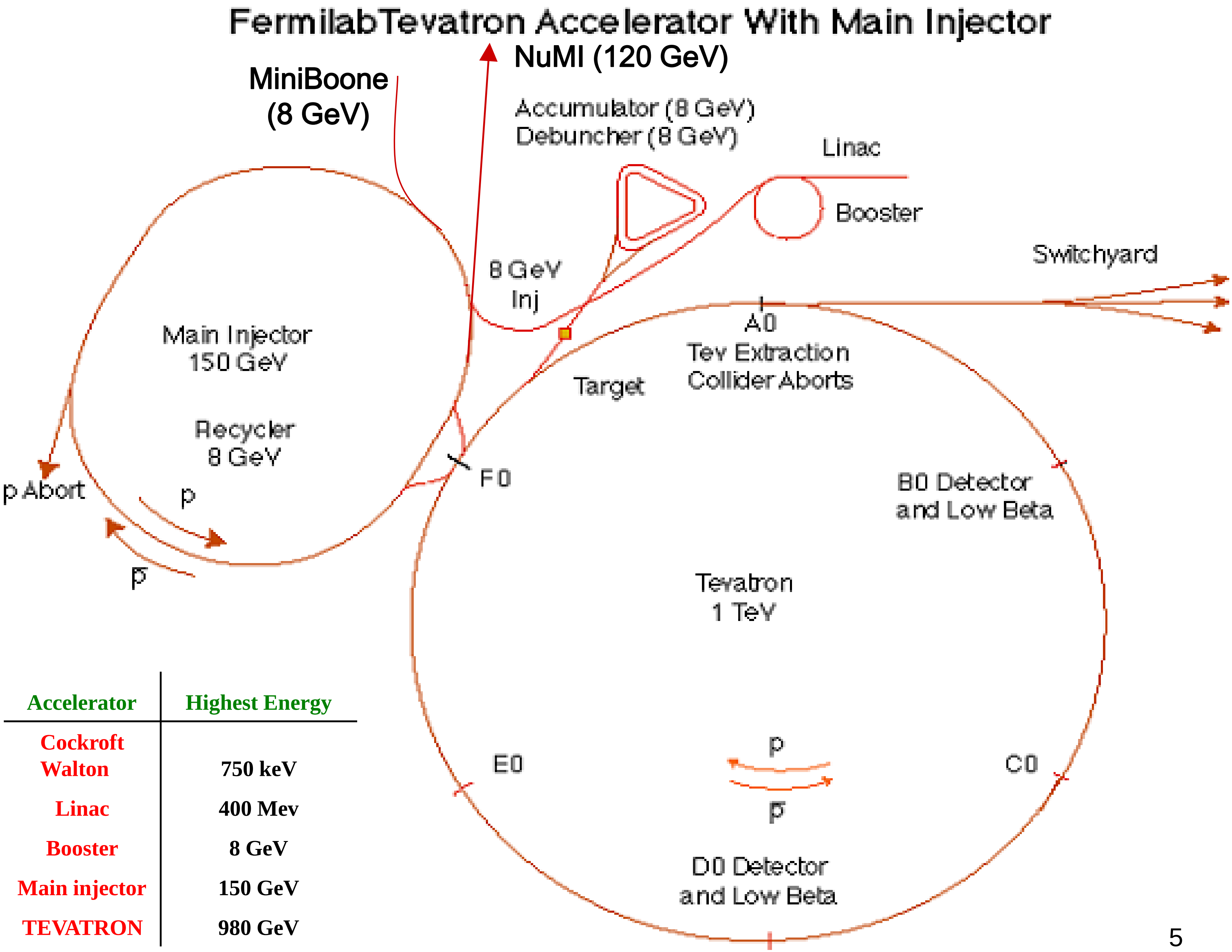
FNAL Accelerator-Based Experiments

- Booster Neutrino Beam – 8 GeV protons
  - MiniBoone, SciBoone → MicroBoone
- NuMI (Neutrinos at Main Injector) – 120 GeV protons (320 kW)
  - MINOS, Minerva → NOvA, LBNE?
- MTBF (Meson Test Beam Facility) – 120 GeV protons to Switchyard
  - primary, secondary, tertiary beams for short-term users
- Tevatron Collider – proton-pbar collisions @ $\sqrt{s}$ = 1.96 TeV
  - CDF and D0
- Rich, diverse programs all running simultaneously

Looking Down on the Fermilab Accelerator Complex

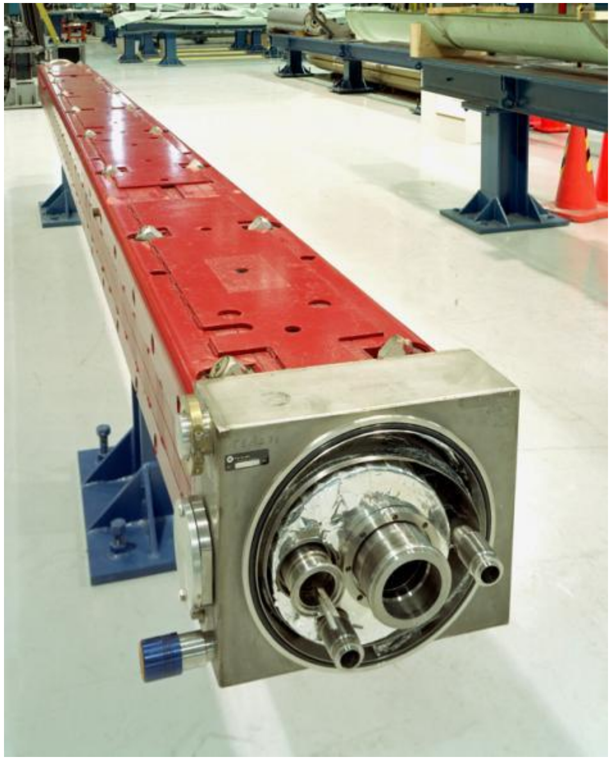


Try this link:
[Fermilab from Google Maps]



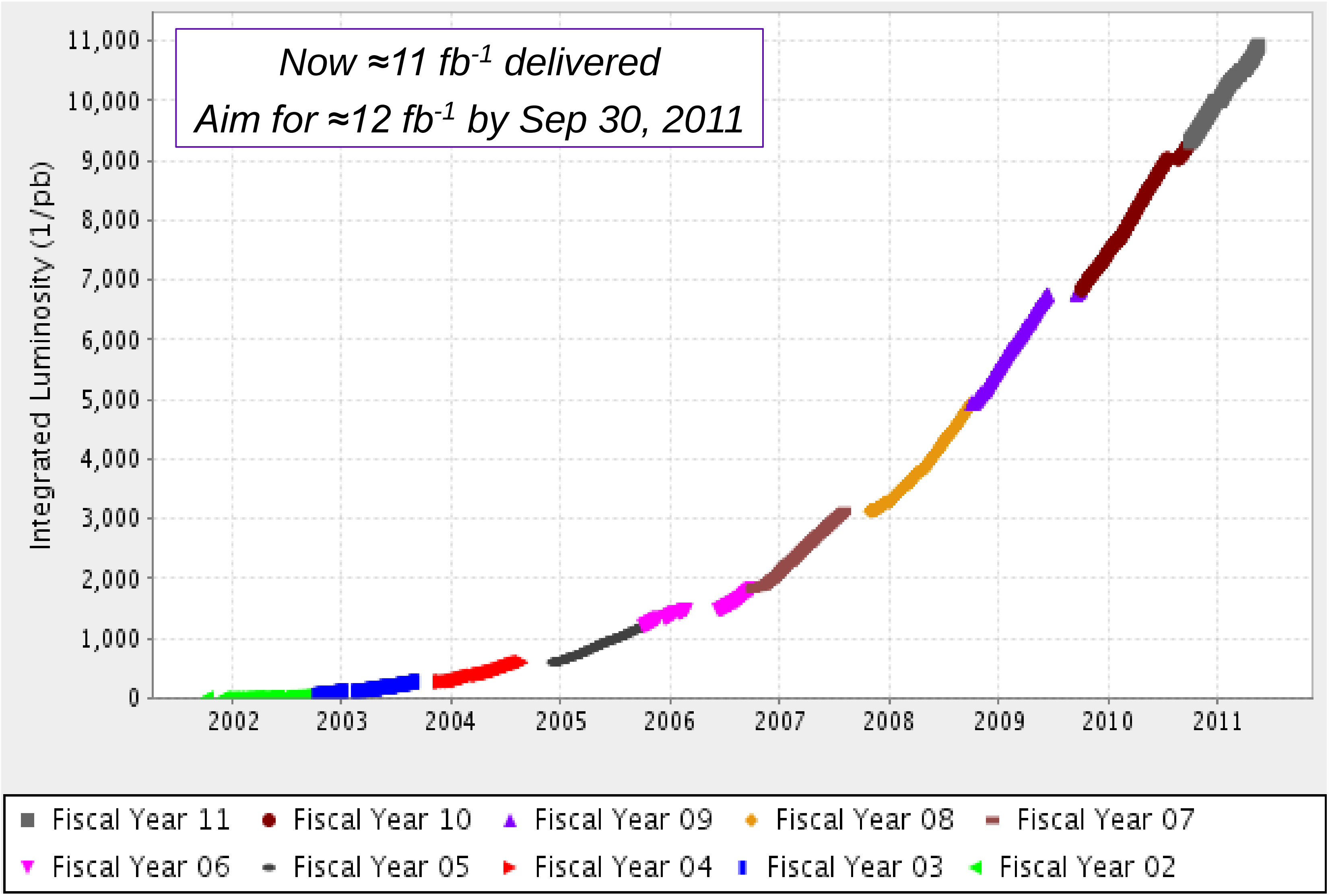
Accelerator	Highest Energy
Cockroft Walton	750 keV
Linac	400 Mev
Booster	8 GeV
Main injector	150 GeV
TEVATRON	980 GeV

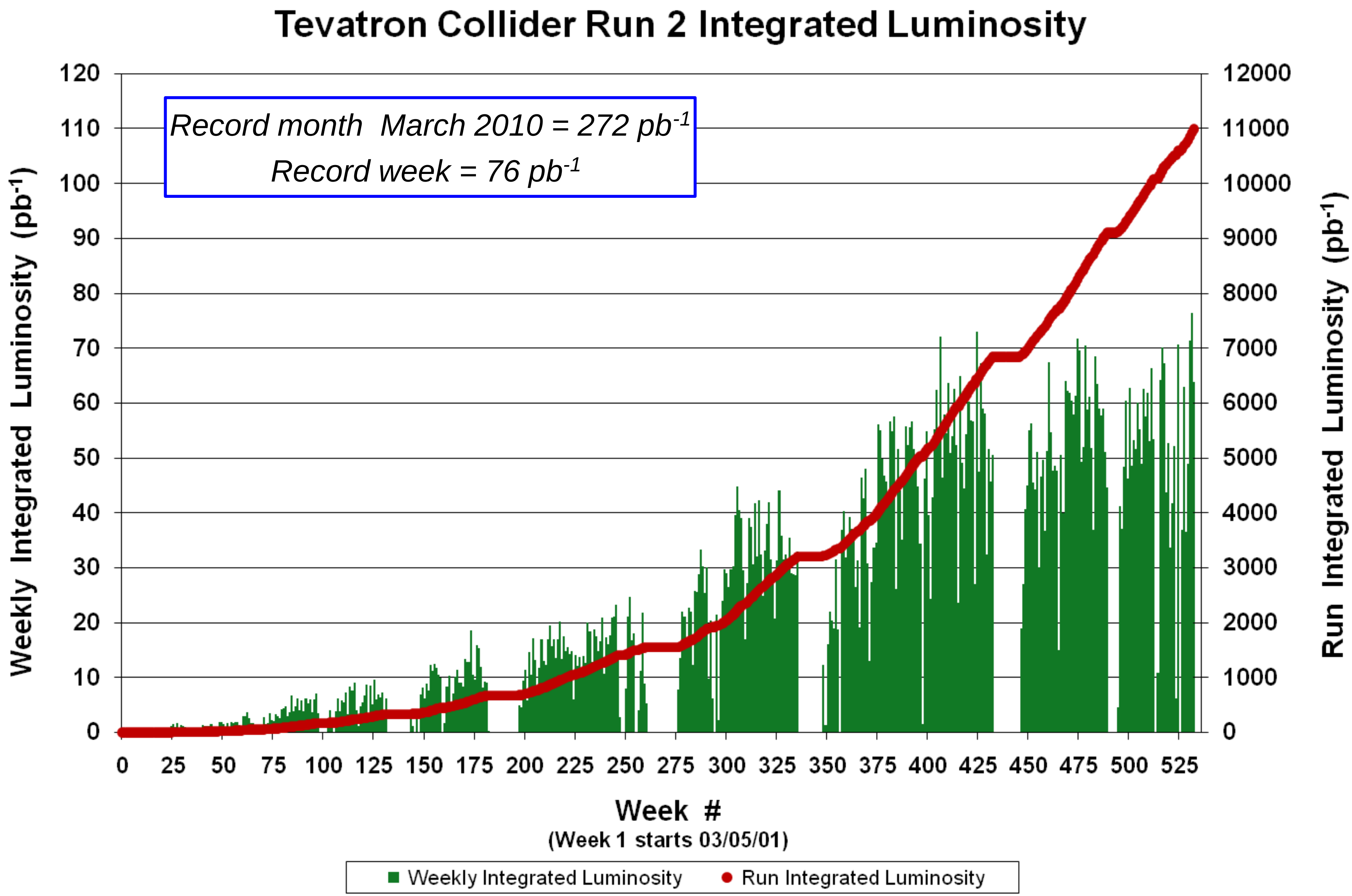
The Tevatron



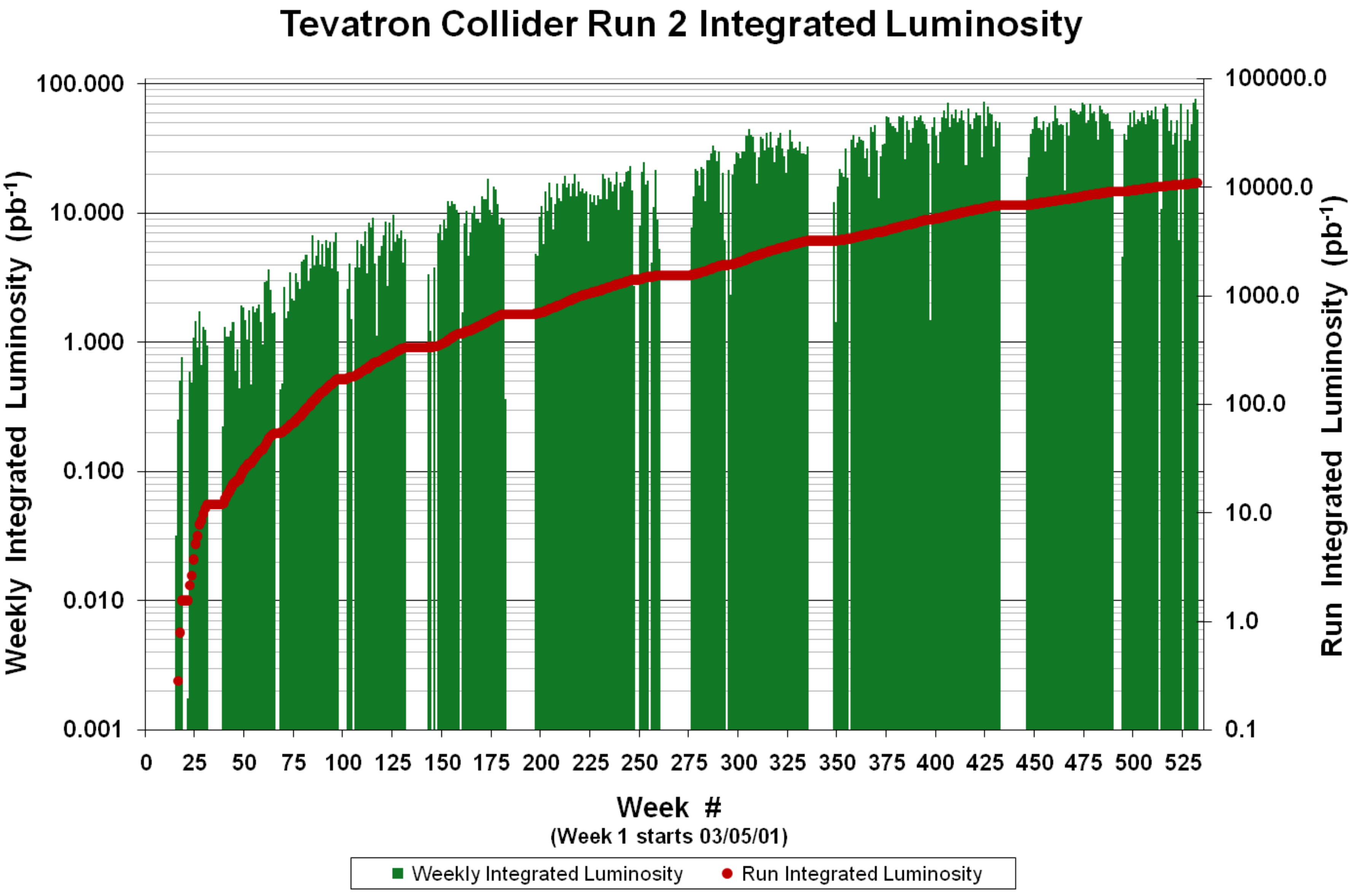
- First large scale application of superconducting magnet technology
- 800 GeV protons for fixed target experiments
- proton-pbar collisions @ $\sqrt{s}$ = 630 GeV, 1.8 TeV, 1.96 TeV
- Collider Run 2 – 36x36 bunches, will get close to 12 fb^{-1} per experiment

Tevatron Run 2 Delivered Luminosity

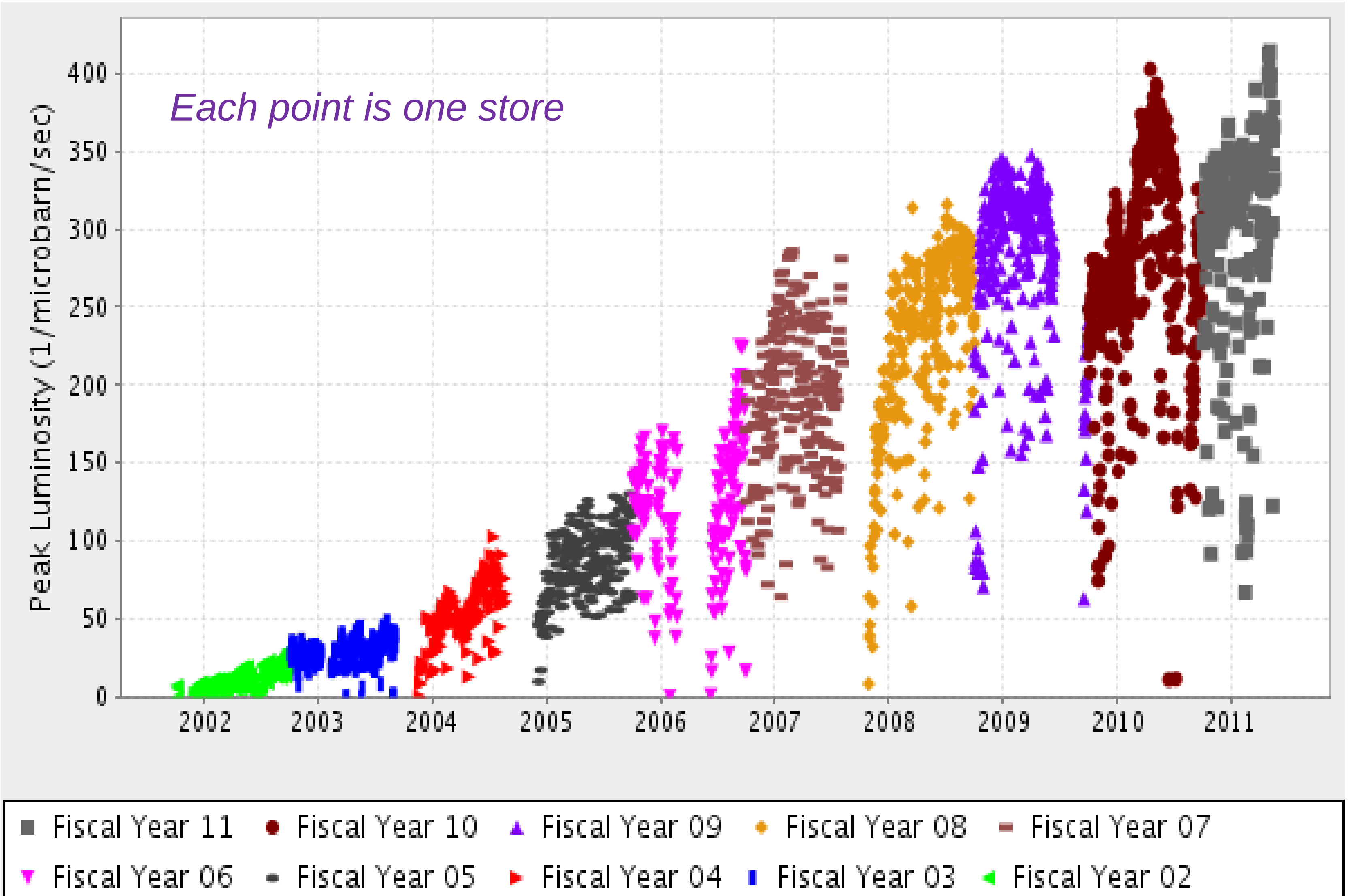




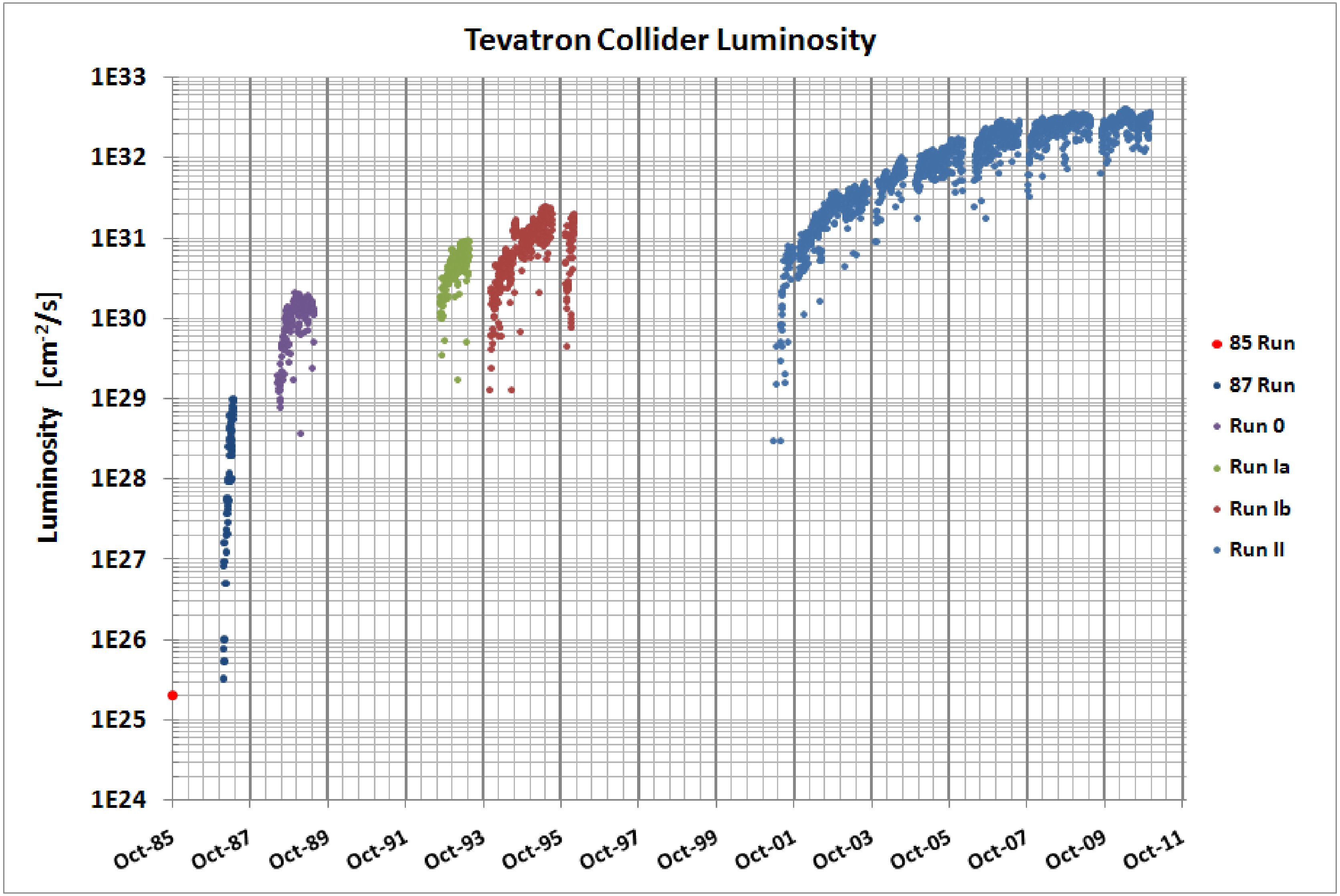
Tevatron Collider Run 2 Integrated Luminosity
Record month March 2010 = 272 pb-1
Record week = 76 pb-1
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
120
110
100
90
80
70
60
50
40
30
20
10
0
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 375 400 425 450 475 500 525
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity


Tevatron Collider Run 2 Integrated Luminosity
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
100.000
10.000
1.000
0.100
0.010
0.001
100000.0
10000.0
1000.0
100.0
10.0
1.0
0.1
0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 375 400 425 450 475 500 525
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity

Tevatron Run 2 Peak Luminosities



25+ Years of Tevatron Luminosity

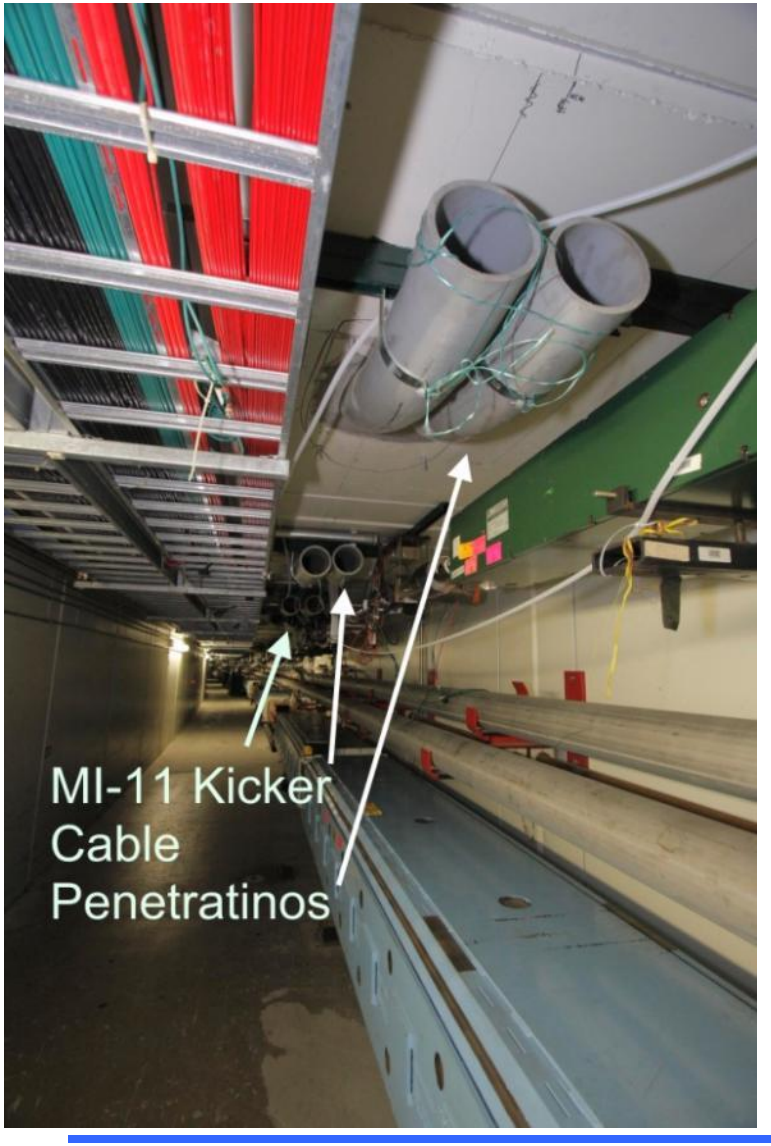


Tevatron Reliability

Year	Stores	Normal Terminations	% Normal Terminations	Avg Store Hrs/Week (outside of planned shutdowns)
2003	186	55	30%	-
FY04	162	106	65%	100
FY05	211	145	69%	110
FY06	163	101	62%	100
FY07	235	187	80%	110
FY08	304	242	80%	106
FY09	293	258	88%	108
FY10	403	356	88%	120
FY11*	265	226	86%	107

Improved Reliability

Main Injector & Recycler



- Occupy same tunnel
- Main Injector provides 400 kW protons @ 120 GeV
  - 320 kW MINOS + 80 kW pbar production
- Recycler is permanent magnet storage ring for antiprotons
  - will become proton stacking machine

Making Pbars isn't Easy

- Photo of recently replaced production target
- Target rotates after every beam pulse to spread damage
- Be cover shattered by incoming protons ~ 8 E12/pulse every 2.2 sec
- Grooves in Inconel also caused by incident protons

The End of the Tevatron

- In January, DOE Office of Science denied request for extension
- Planning for last colliding beam store on Sept 30
- Tevatron decommissioning begins soon afterward
  - CDF + D0 + small section of Tevatron tunnel → public exhibits
  - Removing Tevatron components requires considerable time, effort + $
  - Some items in tunnel and in service buildings will be scavenged
- Antiproton production will also come to an end
- Pbar rings and Recycler will be “repurposed” for g-2 and mu2e

The Scavengers

- No interest in Tevatron superconducting magnets, but other items can/will be reused at Fermilab and possibly elsewhere
- BPM (beam position monitor) and BLM (beam loss monitor) electronics, RF infrastructure, vacuum equipment, cryo dewars, controls, power supplies, transformers, instrumentation…
- NOvA (θ_{13} neutrino mixing angle + phase) is first customer
  - RF & controls for Main Injector + Recycler upgrades in 2012
- mu2e, Project X, LBNE also making lists & checking them twice
- electron lens(es) and Pelletron to BNL?
- electrostatic separators for p/d EDM storage ring experiment?

Focusing on Intensity

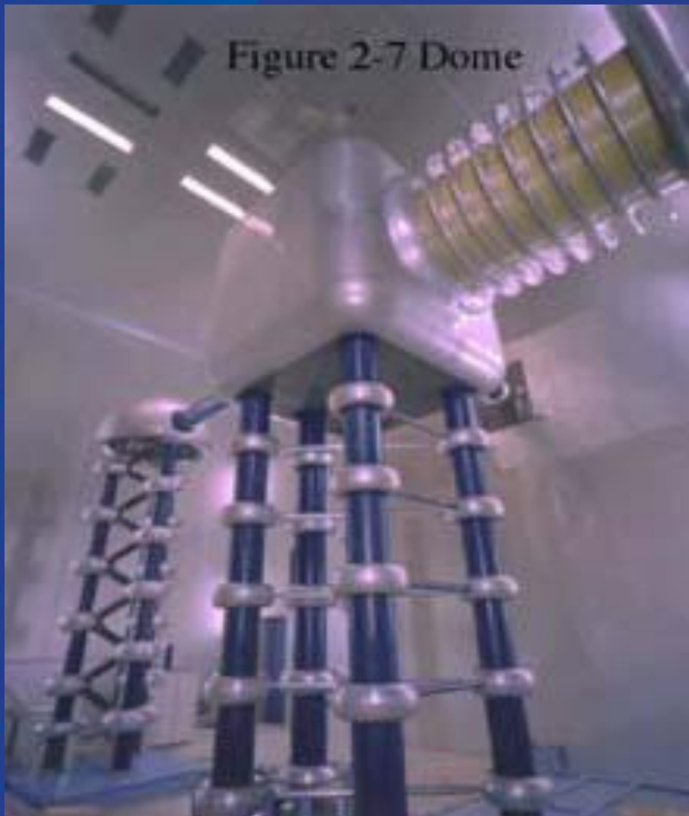
- NuMI / MINOS / Minerva & MiniBoone run until March 2012
- ~9 mo shutdown for Main Injector upgrades & NOvA construction
  - Linac and Booster work, too
- 120 GeV proton power: currently 400 kW → 700 kW for NOvA
  - Recycler becomes a proton stacking machine
  - More Booster throughput
- Need even more 8 GeV proton flux for MicroBoone, g-2 & mu2e
  - Booster will need to run @ 15 Hz reliably with decreased beam loss
  - Only runs @ ~7 Hz now

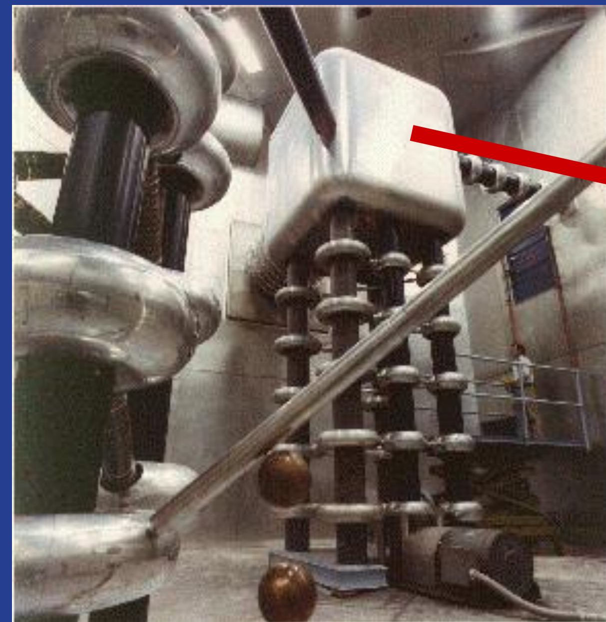
Proton Source

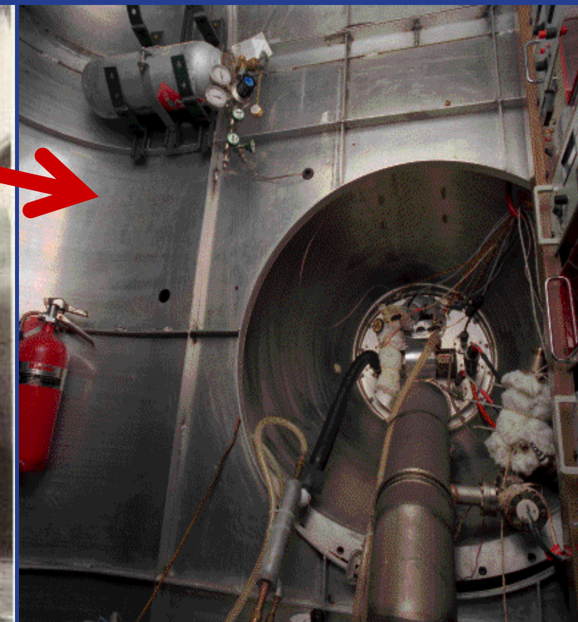
Pre-Accelerator Linac Booster

Pre - Accelerator

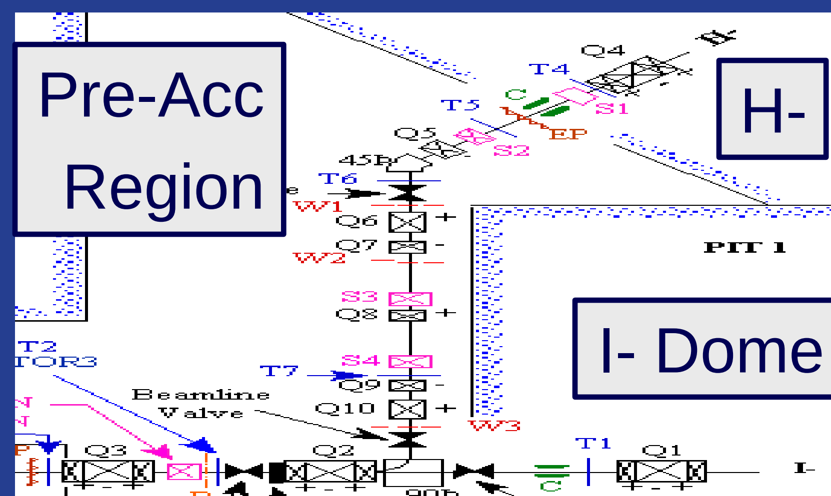
Inside H- Dome







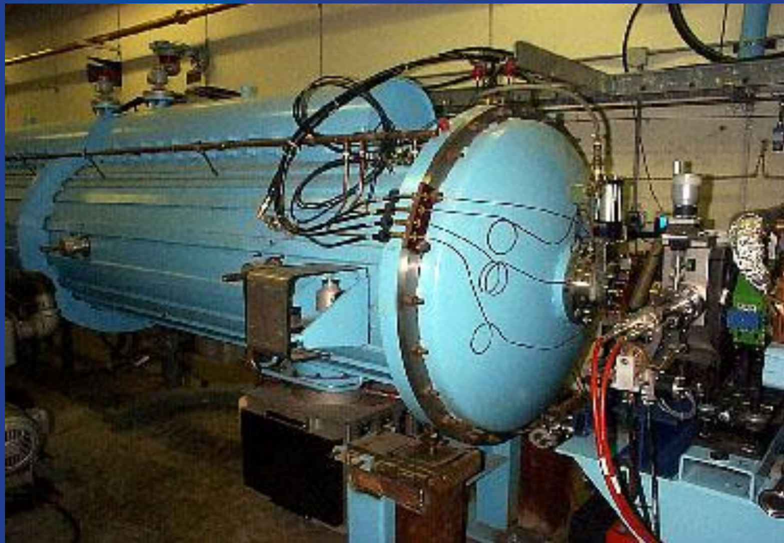
H-



I-

750 kV Cockroft-Walton generators

LINAC



200 MHz Alvarez LE DTL Accelerating Cavity

5 MW 7835 Power Amplifier

800 MHz Klystron High Energy Linac

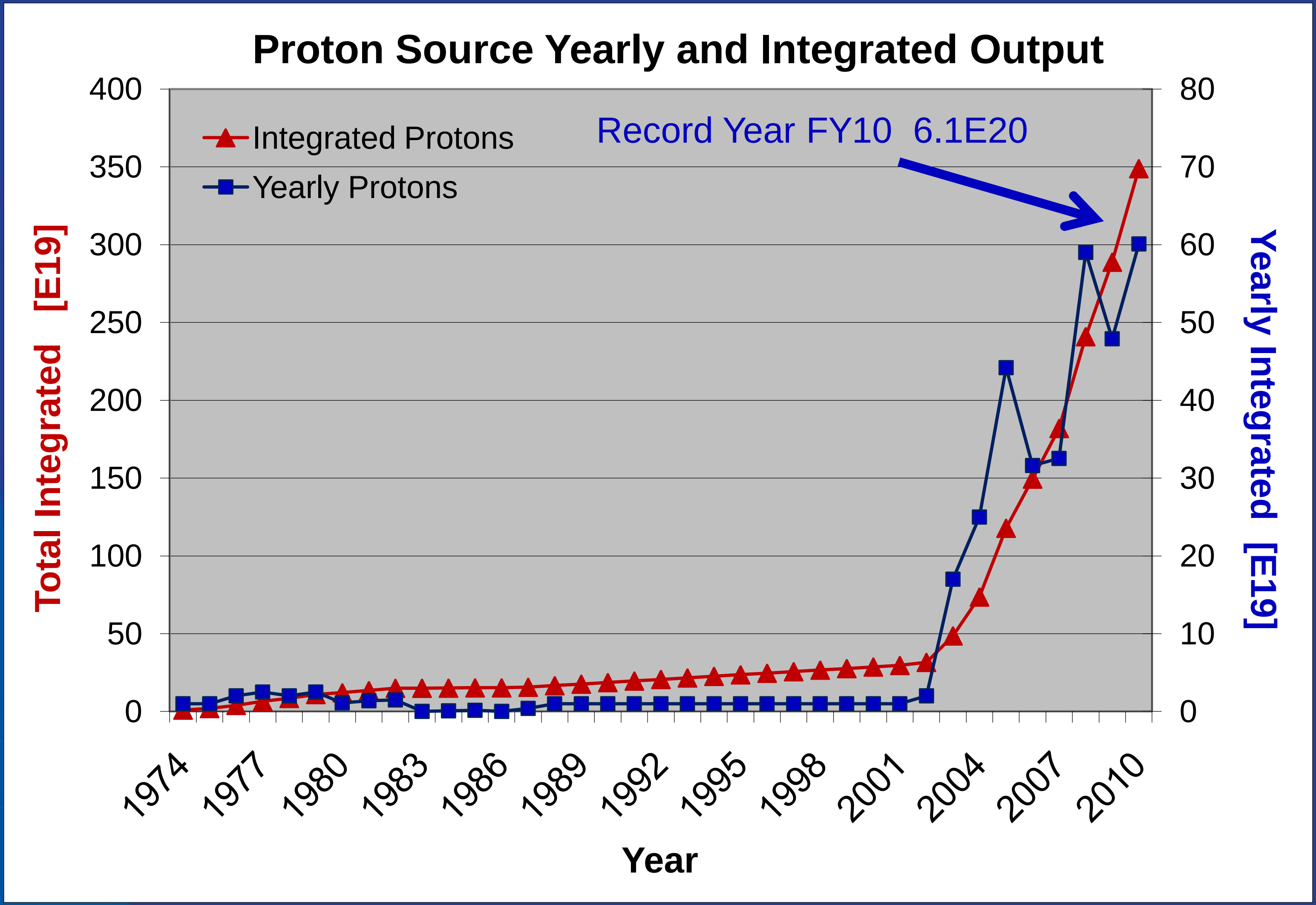
Booster

- 15 Hz synchrotron
  - beam not on all cycles (yet)
- 400 MeV to 8 GeV
- Combined function magnets
  - dipole + quadrupole
- 84 bunches

First 30 Years of Proton Source Operations

- Averaged about 1E19 protons/year
- Users
  - fixed target
  - Run -1, 0, 1 collider operation + pbar production
- Booster duty cycle was much less than 1 Hz
- Booster beam efficiency was under 70%
- Major Linac Upgrade 1995: 200 → 400 MeV
  - Installation of side-coupled tanks + klystrons

Proton Throughput History



Start Neutrino Program and Run 2 Requirements

- Requested rep rate increased by about factor of 10
- Requested proton flux increased by about factor of 10

- Beam quality required significant improvements
  - MI slip-stacking requirements
  - Booster activation issues (beam loss)
  - Protons for collider program
- Reduced scheduled repair/study periods

HEP requests greater than Proton Source could deliver!

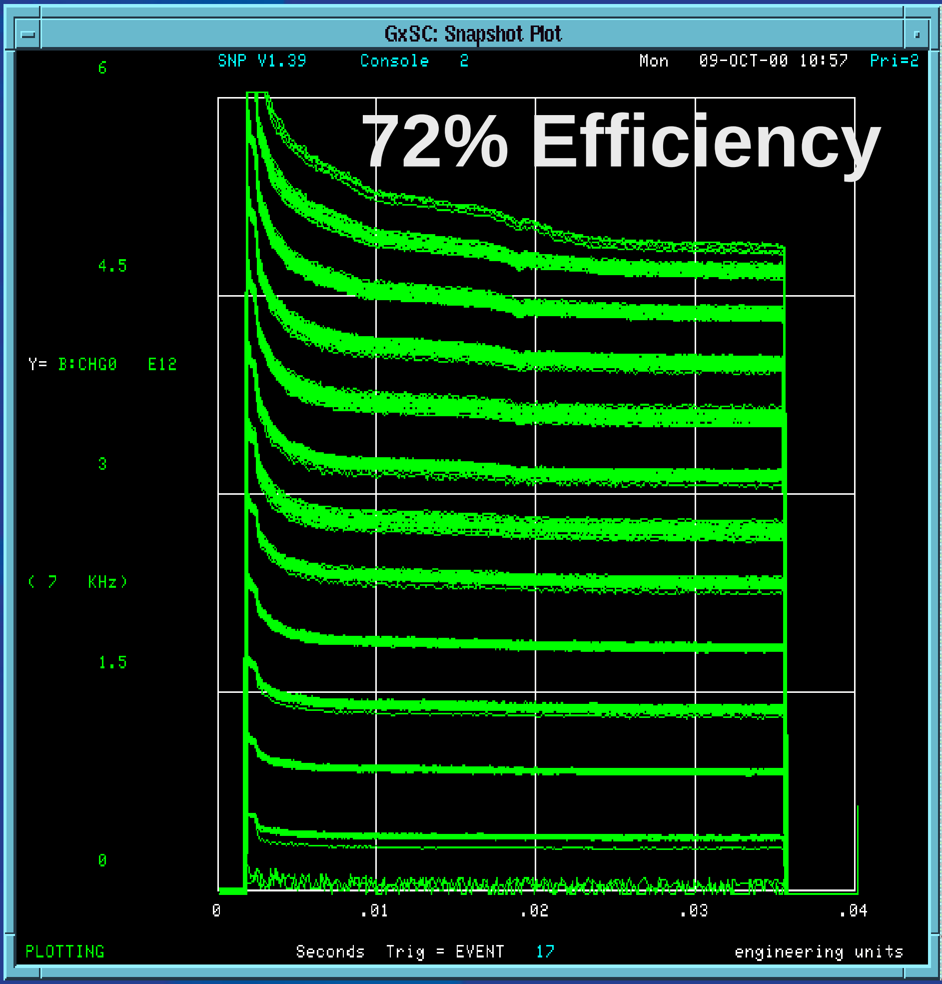
Improvements led to performance of ~1.1 E17 protons/hr @ ~7 Hz

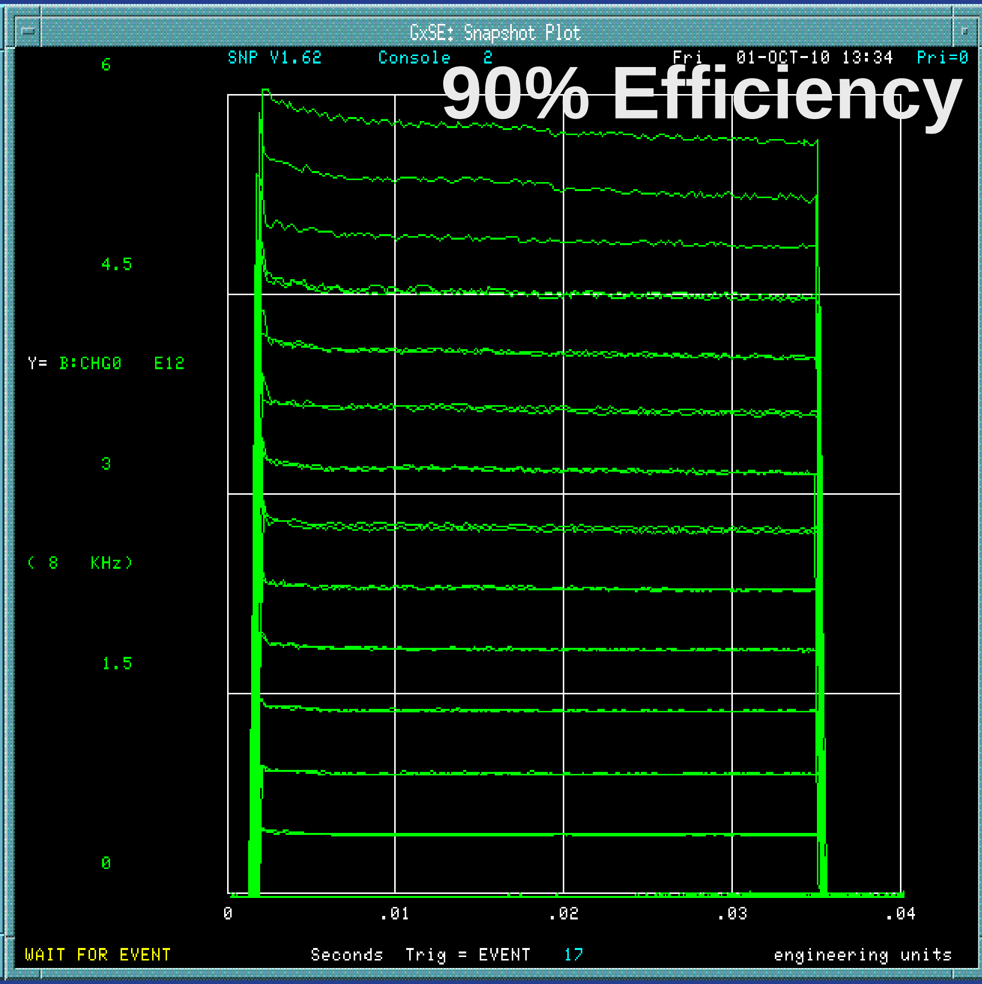
Completed Proton Source Upgrades since 2001

- Improved Beam Quality
  - **New Booster Corrector Magnets**
    - Orbit Control
    - Corrected Harmonics
  - Removal of an extraction region
    - Aperture restriction
  - Added damping
  - New injection region
- Increased Proton Throughput
  - Added shielding
  - Collimation System
    - Controlled loss point
    - Reduced component activation
  - Improved Low Level control – Cogging/Notching

Efficiency Improvements - 2000 to 2010

Beam Acceleration Cycles in Booster





Proton Improvement Plan (PIP)

- The demands of upcoming experimental program require unprecedented performance of Proton Source

- We are developing a plan which addresses:
  - maintaining viable and reliable operation of Linac and Booster through at least 2025
  - increasing Booster RF & beam delivery rep rate to 15 Hz
  - doubling flux to 2.25E17 protons/hr (@ 15 Hz) by Jan 1, 2016

- Task Force Report: *link to AD Document Database entry*

- >$40M to implement all items

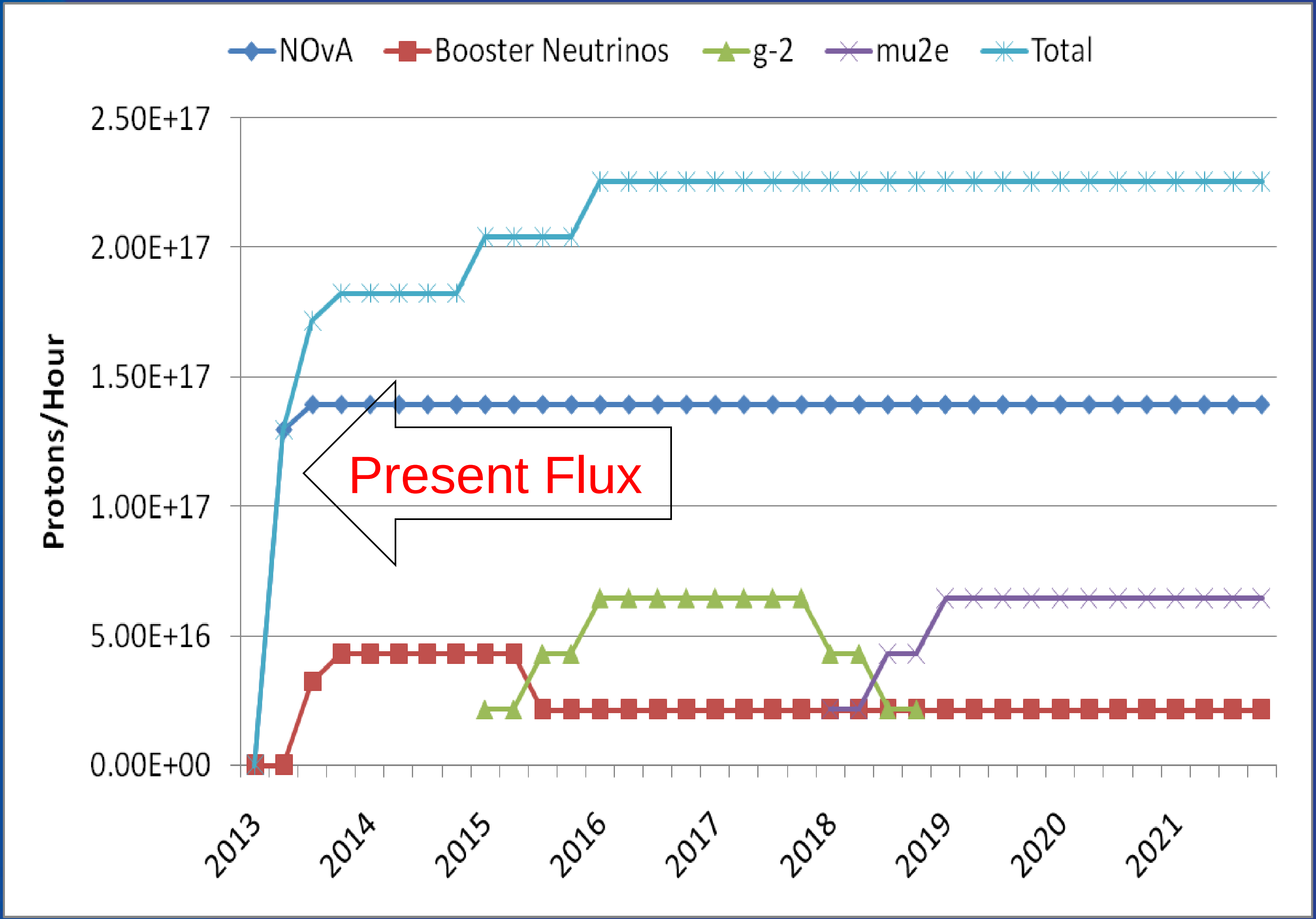
Proton Task Force Report

Task charge: Reliable operation for 15 years

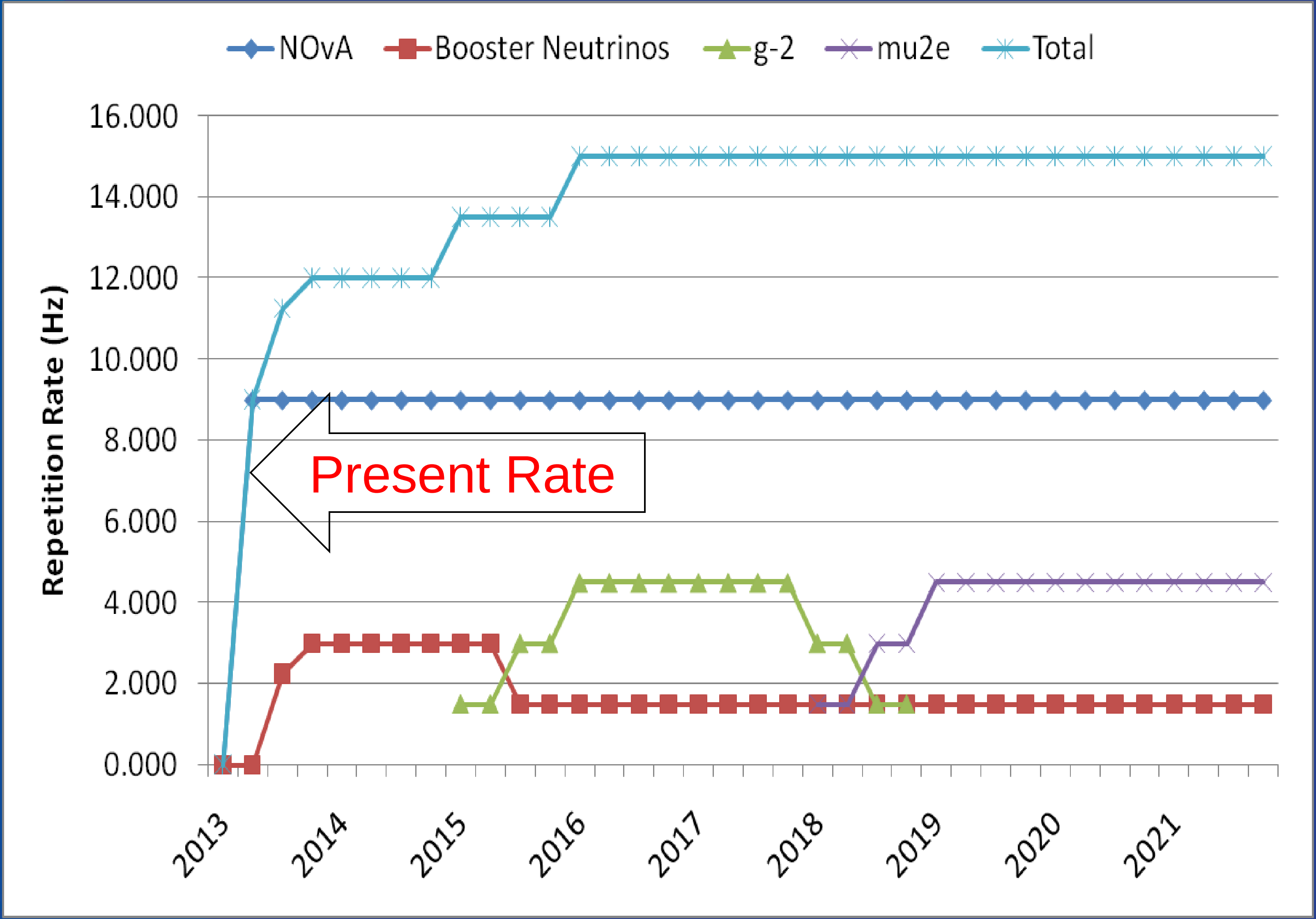
Areas of Concern

- Pre-Accelerator
  - complete RFQ installation
- Linac
  - low energy RF drive system (tube availability)
  - low energy DTL (drift tube linac)
- Booster
  - high level RF systems (solid state amplifiers and more)
  - combined function magnets
  - tunnel radiation/activation (keep safe for personnel)
- Utilities
  - LCW (low conductivity water) systems
  - electrical transformers and switch gear

PIP - Proton Flux Goals



PIP – Cycle Rate Goals

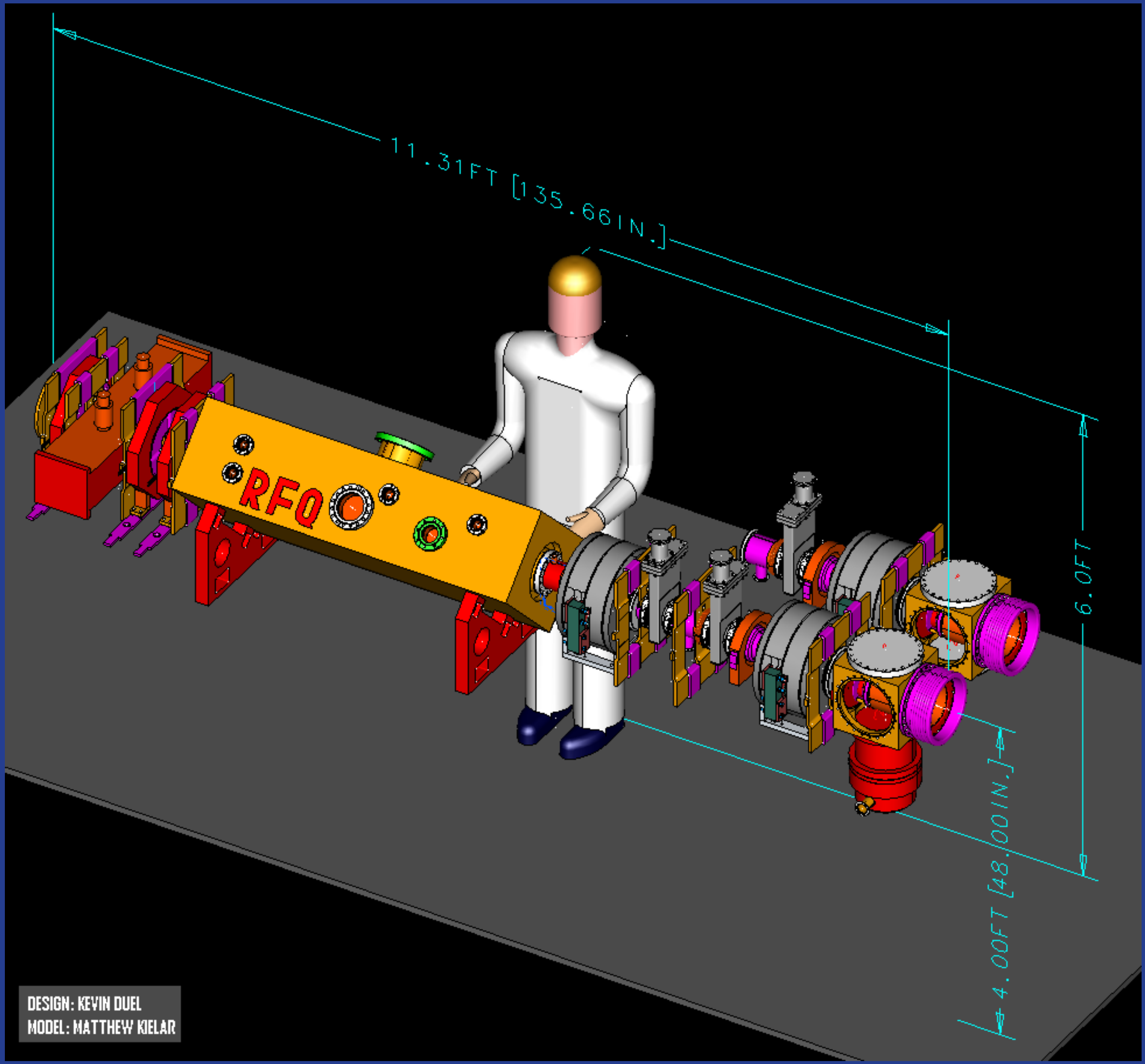


Proton Source Projects in Progress

- **Pre-Accelerator**
  - New RFQ injector*
- **Linac**
  - Linac Beam Dump Repair
  - Line Power Regulation (PLC Based Controls)
- **Booster**
  - Short Kicker (20 ns goal)
  - Low Level Upgrade
  - Lattice and Aperture studies (Magnet Moves)
  - Transverse Dampers
  - Beam Dynamics Correction – New Correctors
  - Booster Solid State RF upgrades*

*** Projects included in Proton Task Force report and PIP**

Pre-Accelerator Upgrade 2009 to 2012



Beam Testing

End of Summer

RFQ arrives late May

Pre Accelerator Project

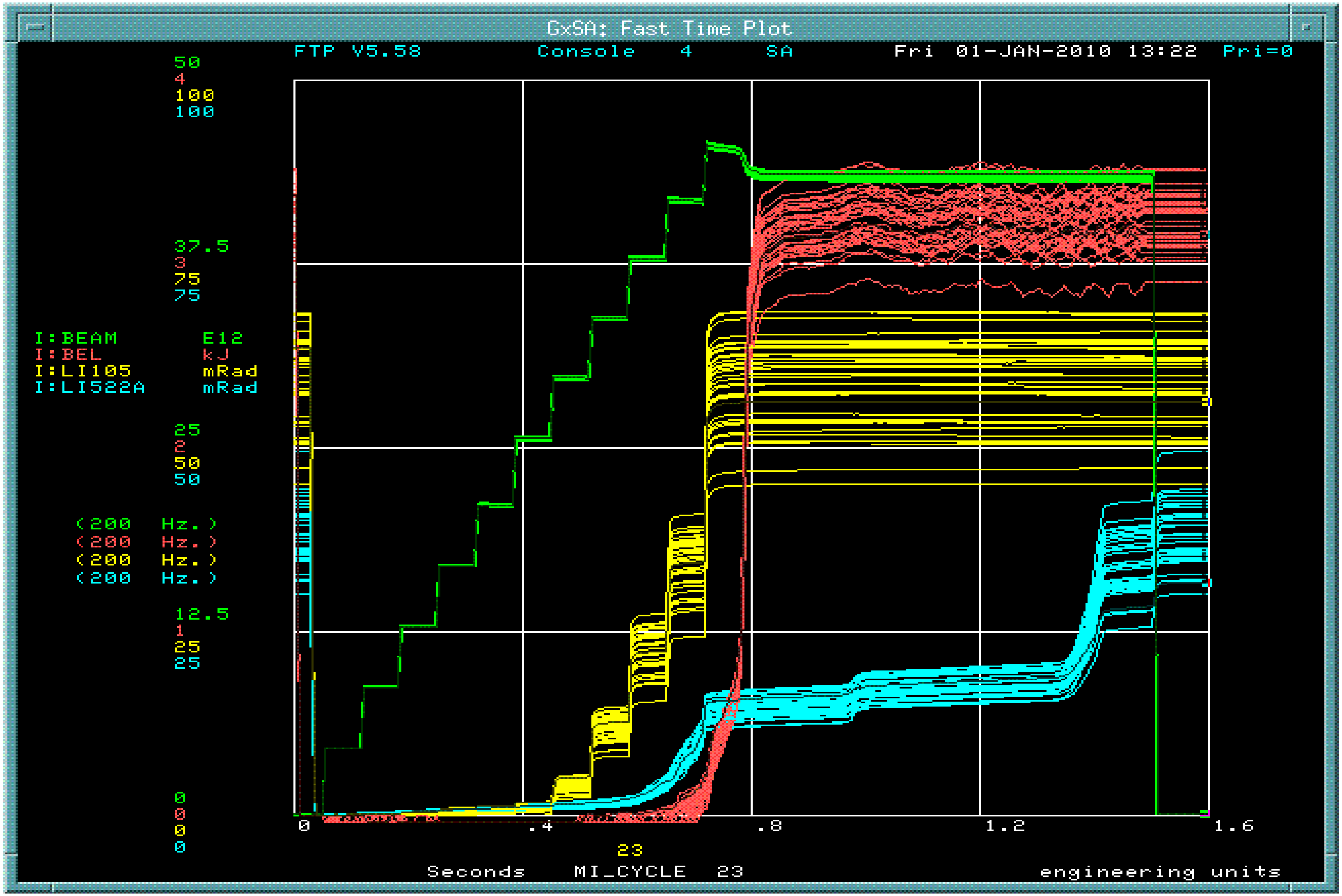
- Remove Cockcroft-Waltons and 750 KeV line
- Two Round Slit Magnetron H- 35 KeV Sources (Beam – This Week!)
- New Transport Line
  - 750 KeV Radio Frequency Quadrupole (RFQ) (May Delivery ?)
  - New Transport Lines
    - LEBT
      - Solenoids (Completed)
      - Trims (June Delivery)
    - MEBT
      - New Buncher Cavity (Delivered)
      - New High Gradient Quadrupoles (Oct. Delivery)

Scheduled Installation - 2012 Shutdown

After 2012 - Plan for 700 kW to NOvA

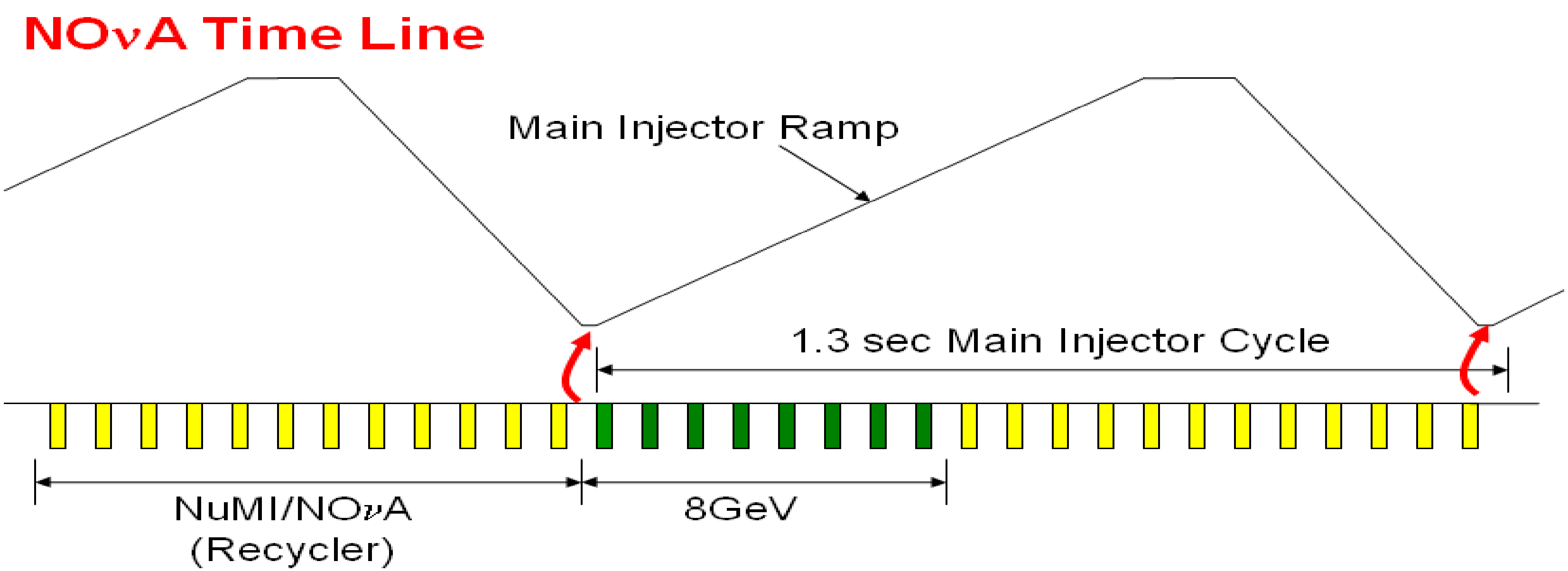
- No sharing protons with pbar production *(more protons/cycle)*
  - 2 more proton batches/cycle available (9 → 11 batches)
- Proton stacking in Recycler *(more protons/cycle + more cycles/hr)*
  - Negligible filling time from Recycler (not waiting @ 8 GeV for Booster)
  - Recycler can accommodate 1 more batch (12) than MI slip-stacking
- Decreasing Main Injector ramp time 1.5 → 1.33 sec *(more cycles/hr)*
  - Upgrade quadrupole bus power supply + 2 additional RF stations
- Increasing Booster flux to get 14×10^{16}/hr *(NOvA alone)*
  - Current total flux = 11×10^{16}/hr @ ≈7 Hz (NuMI + pbar + MiniBoone)
  - MINOS: 4.3×10^{12}/batch @ 5 Hz → NOvA: 4.3×10^{12}/batch @ 9 Hz
- *(In reality, Booster flux must be higher to include 8 GeV program)*

11 Batch Loading in MI (now)



Sharing Beam with NOvA

- 8 GeV program must coexist with NOvA running
- Each 1.33 sec MI ramp cycle spans 20 Booster 15 Hz “ticks”
- NOvA needs 12 Booster “ticks” to fill Recycler
- Up to 8 ticks available for MicroBoone, g-2, mu2e



New Life for Pbar Source

- g-2 & mu2e will (re)use Pbar Source, albeit in different ways

- g-2
  - 8 GeV protons to make π in AP0 target station
  - Single pass around Debuncher as decay line, transport 3.1 GeV μ^+
  - Transport μ^+ through new beam line to BNL storage ring

- mu2e
  - batches of 8 GeV protons "reformatted" in Debuncher to 3 or 4 bunches
  - single bunches kicked into Accumulator, then slow-spilled
  - new transport line to carry beam to production target & experiment
  - 25 kW of 8 GeV protons in (former) pbar rings! *(designed for 12 W pbars)*
    - Radiation issues are very challenging

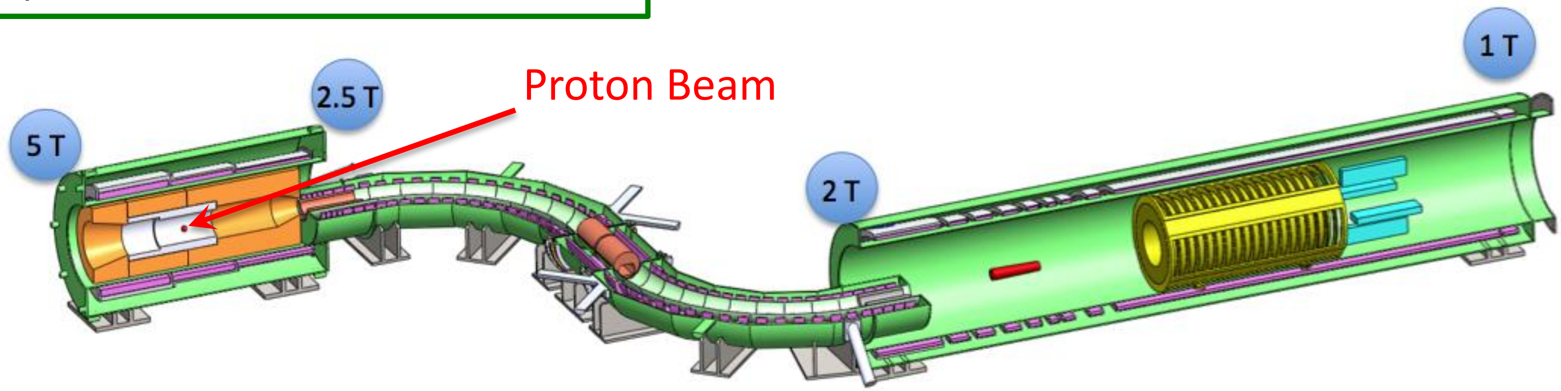
- Develop plan to merge accelerator designs in sensible way
  - cost, scheduling, ease of operations – they cannot run simultaneously

Mu2e Experiment

Goal is to search for μ^- to e^- conversion with a sensitivity of $< 6 \times 10^{-17}$ (90% C.L.)

Proton beam hits production target in Production Solenoid.
Pions captured and accelerated towards Transport Solenoid by graded field.
Pions decay to muons.

Muons captured in stopping target.
Conversion electron trajectory measured in tracker, validated in calorimeter.
Cosmic Ray Veto surrounds Detector Solenoid.



Transport solenoid performs sign and momentum selection.
Eliminates high energy negative particles, positive particles and line-of-site neutrals.

- need ~7.2×10^{20} protons on target
- start operations in 2018
- going for CD-1 in August 2011

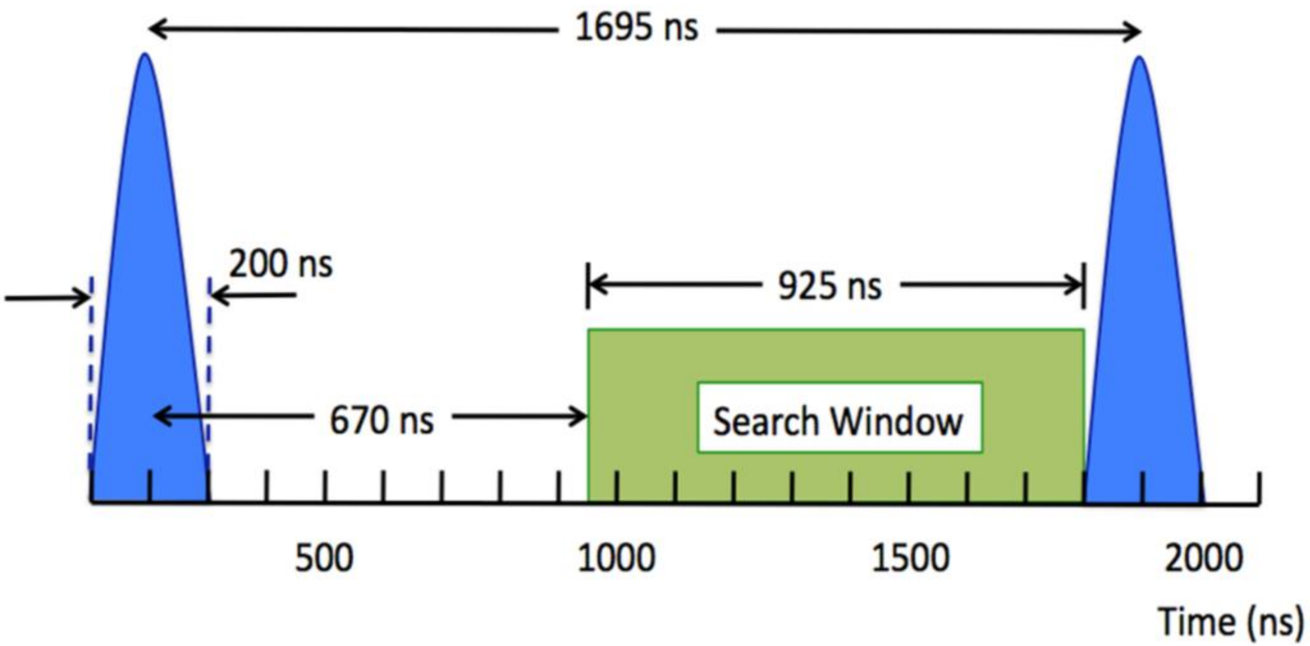
mu2e Beam Structure

What we need to do:

- Put narrow proton pulses on the pion production target every 1.7 μsec
- ~3×10^7 protons/pulse
- 10^{-10} Extinction between pulses
- Transport to the pion production target (new beamline)

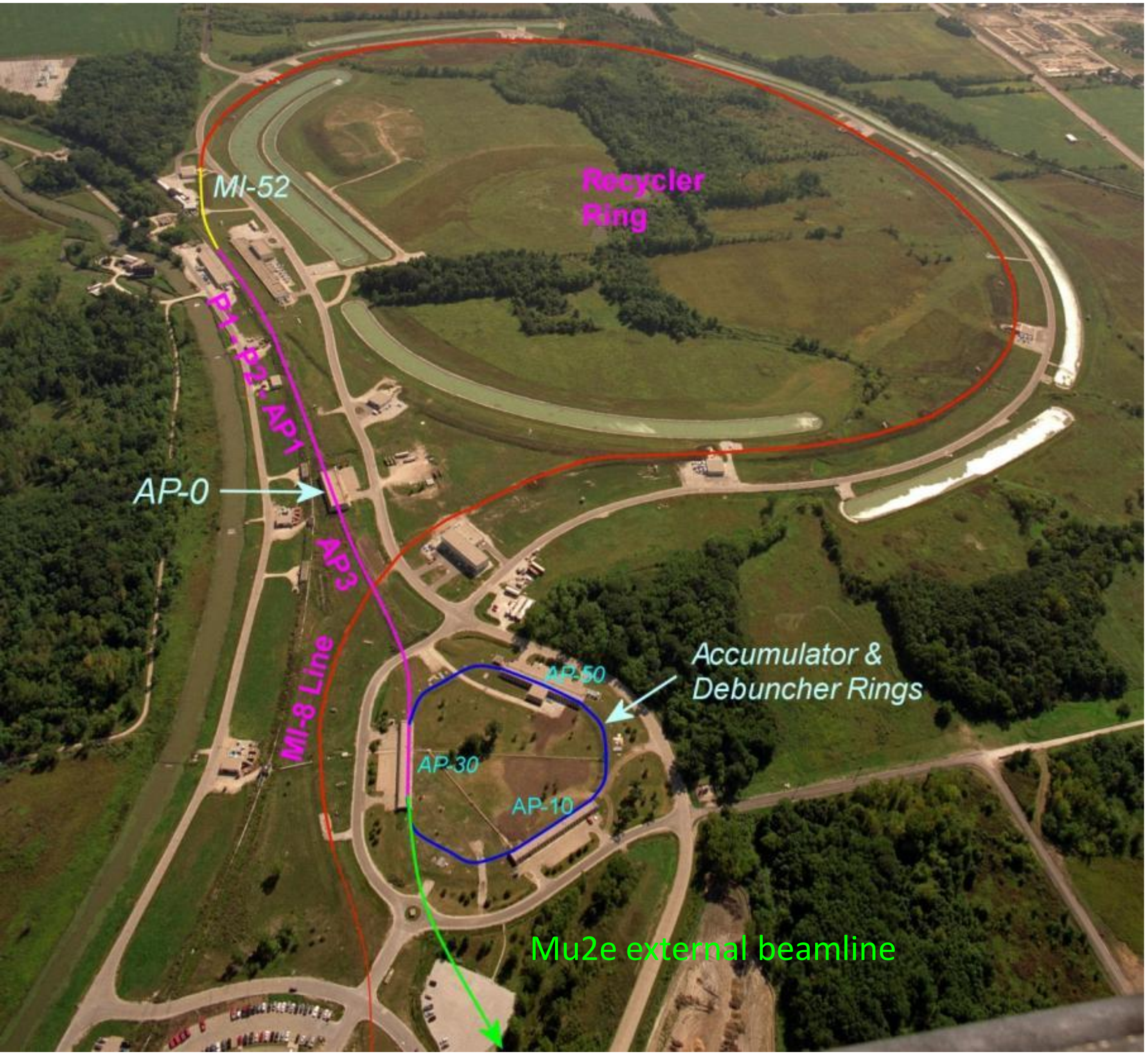
- 200 ns base width is accomplished using new RF systems in Accumulator.

•1695 ns pulse separation is the Debuncher revolution period. One pulse extracted per beam turn.



Also need new (faster) kicker systems

mu2e Proton "Slingshot"



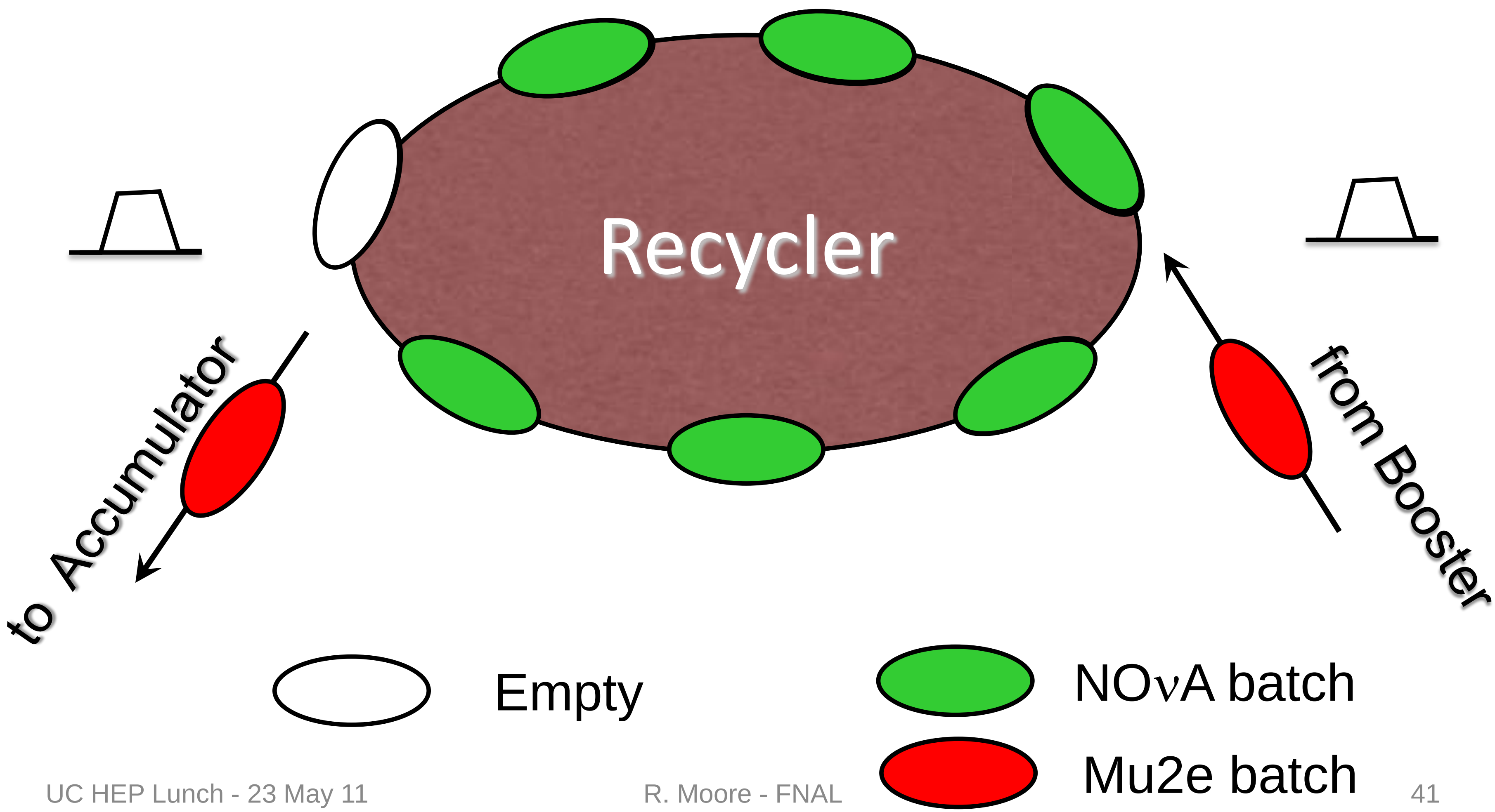
8 GeV proton beam from Booster takes a long path through mostly existing beam lines to the Mu2e production target.

- Booster → MI-8 line
- Partial turn in Recycler
- Extracted at MI-52 from Recycler to the P1 beam line*
- P1 → P2 → AP1 → AP3 → Accumulator Ring
- Multiple proton batches stacked in Accumulator
- *h*=4 RF bunch formation in Accumulator
- One bunch at a time extracted to the Debuncher
- Resonantly extracted to the Mu2e external beamline*

* New beamlines

Sharing Beam with NOνA

Tl Recycler Extraction Kicker Fires ng.



Another View Pbar + Mu2e

Enhanced shielding

Transport to Mu2e target

Mu2e Experimental Hall

Radiation Safety

Mu2e radiation safety system must be designed for 25 kW beam power (18 Tp/s)

The plans for the Mu2e radiation safety system:

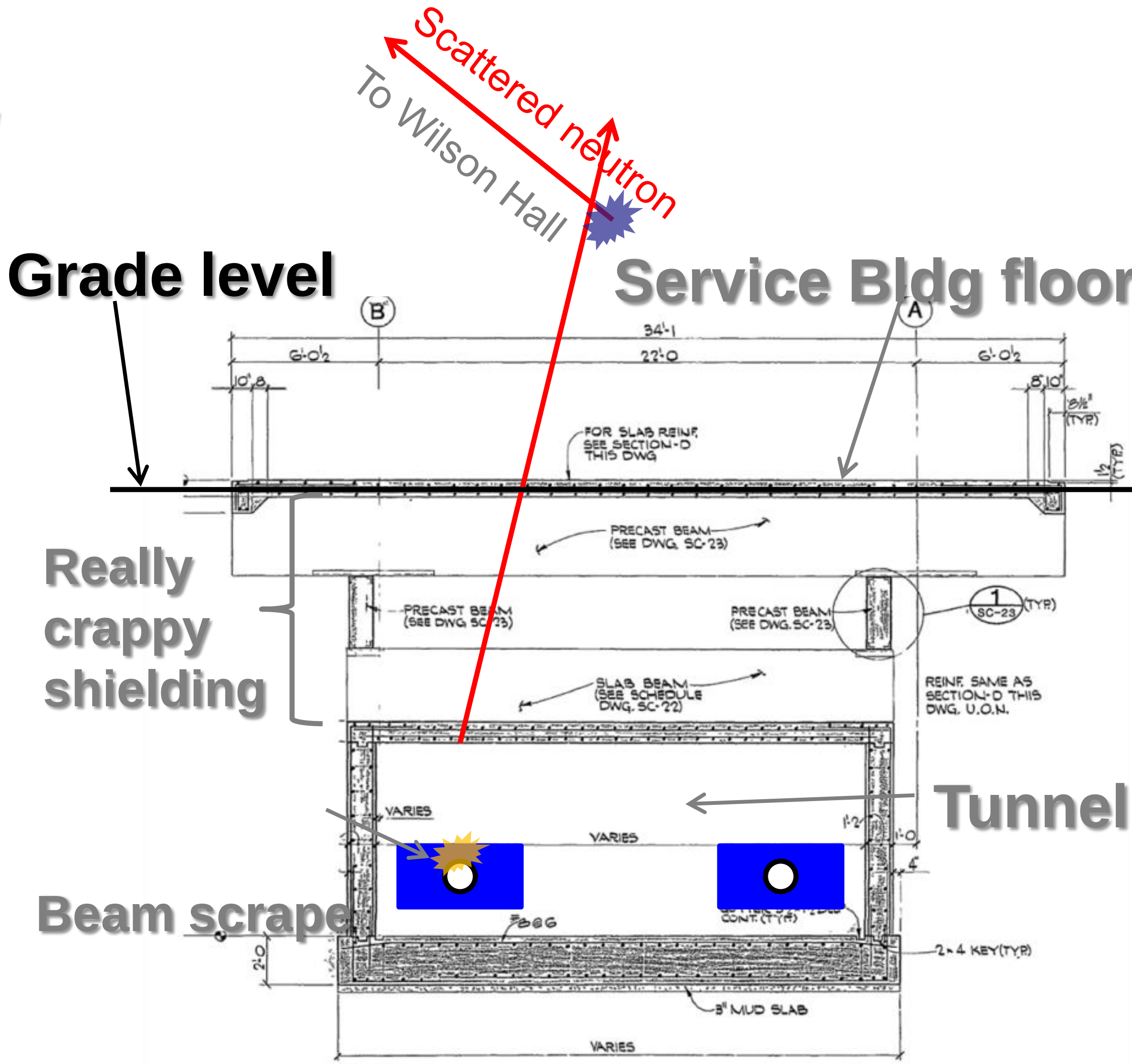
1. Electronic Berm (remove beam permit on detection of beam loss)
2. Exclude access to Antiproton Source service buildings during operations with beam
3. Radiation safety fences with interlocked gates
4. AP Service Building shielding enhancement

Radiation Safety

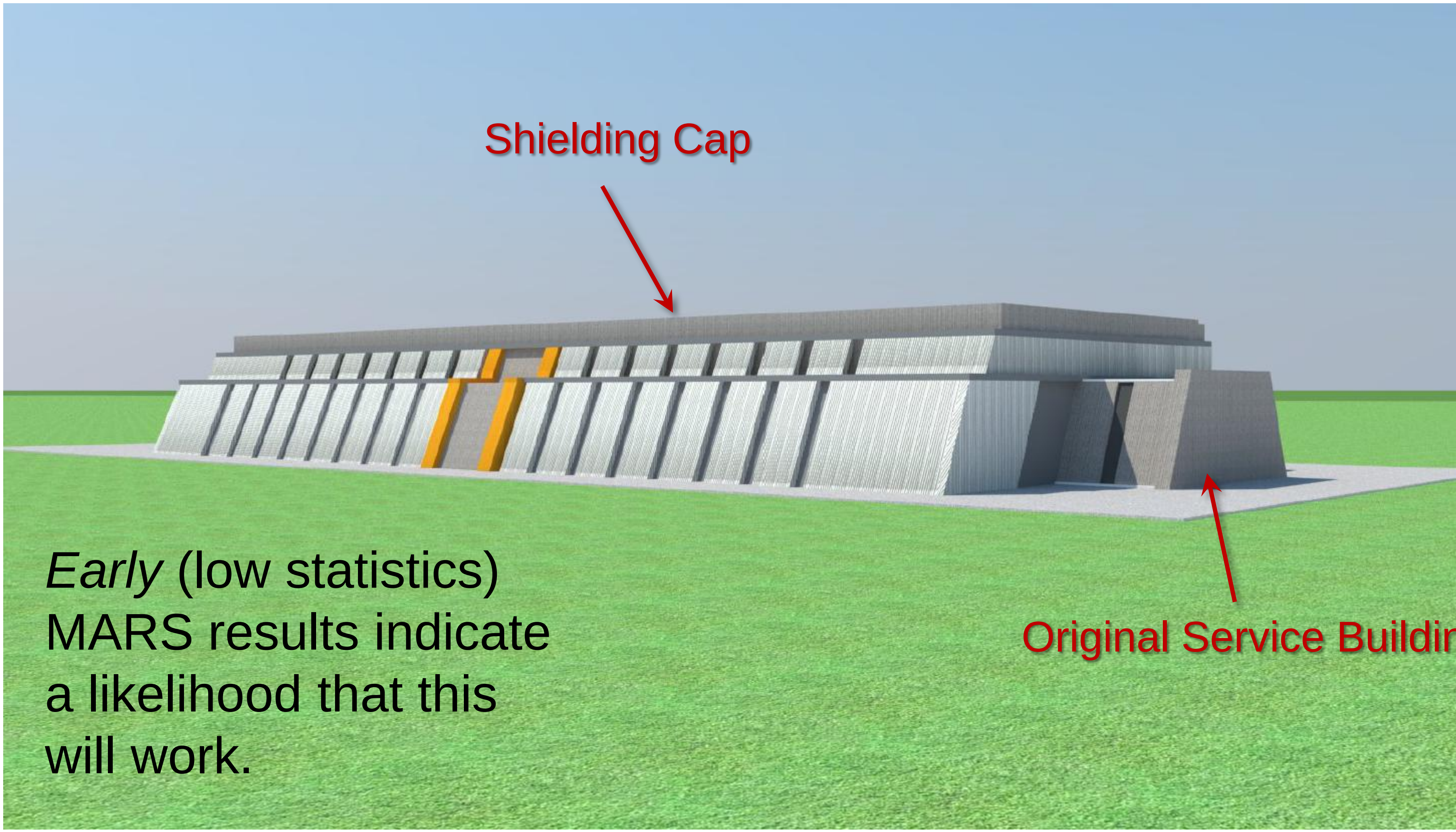
Skyshine due to poor service building shielding has been determined to be a significant radiation safety concern.

What is skyshine?

Skyshine is radiation scattered from air molecules. Accelerator-produced skyshine is primarily neutron radiation, scattered after emerging more or less vertically from the beam enclosure. *It can cause elevated radiation fields above ground level at considerable distances from the source.*

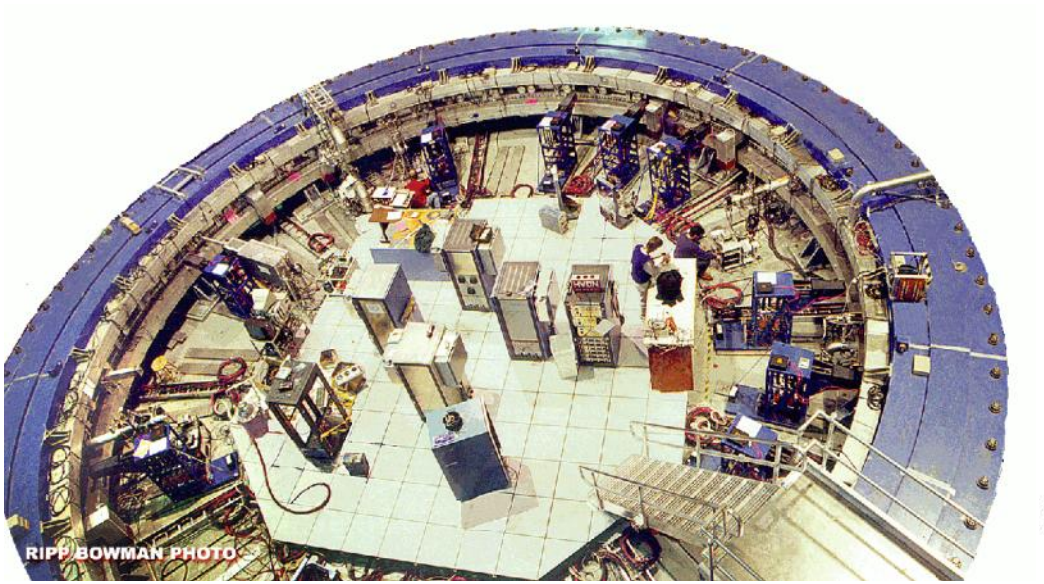


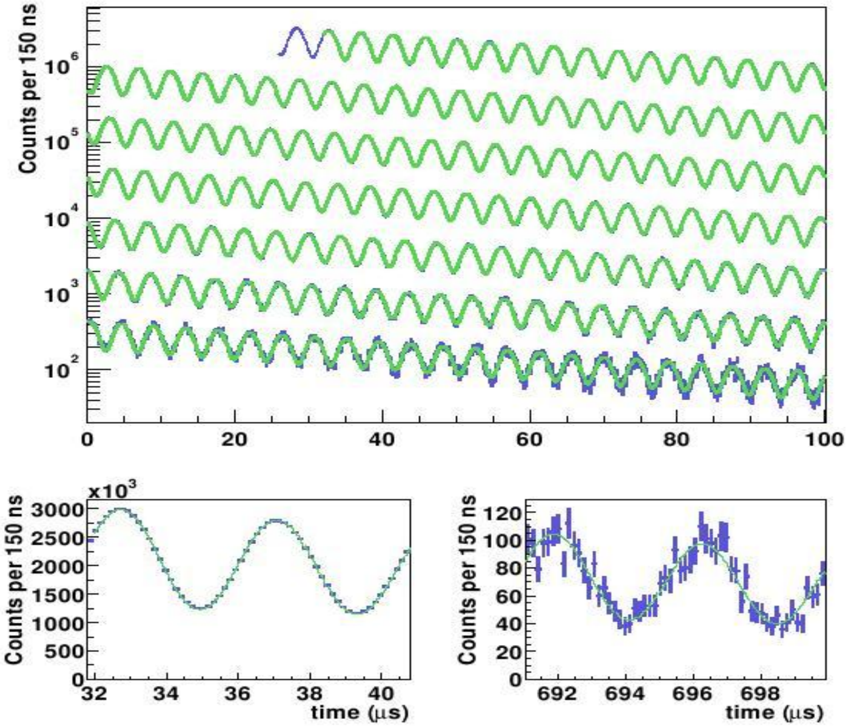
Enhanced Service Building Shielding



Early (low statistics) MARS results indicate a likelihood that this will work.

g-2 Experiment

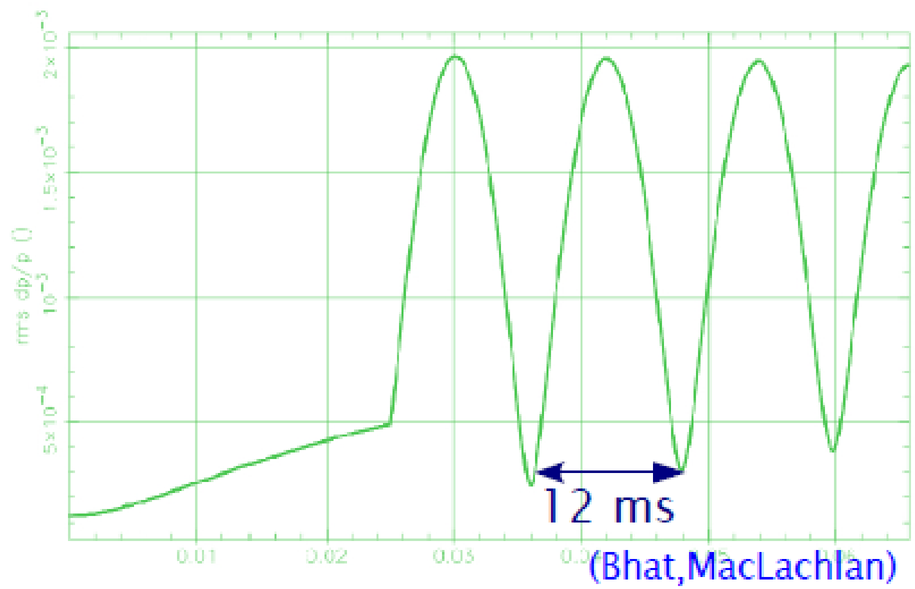




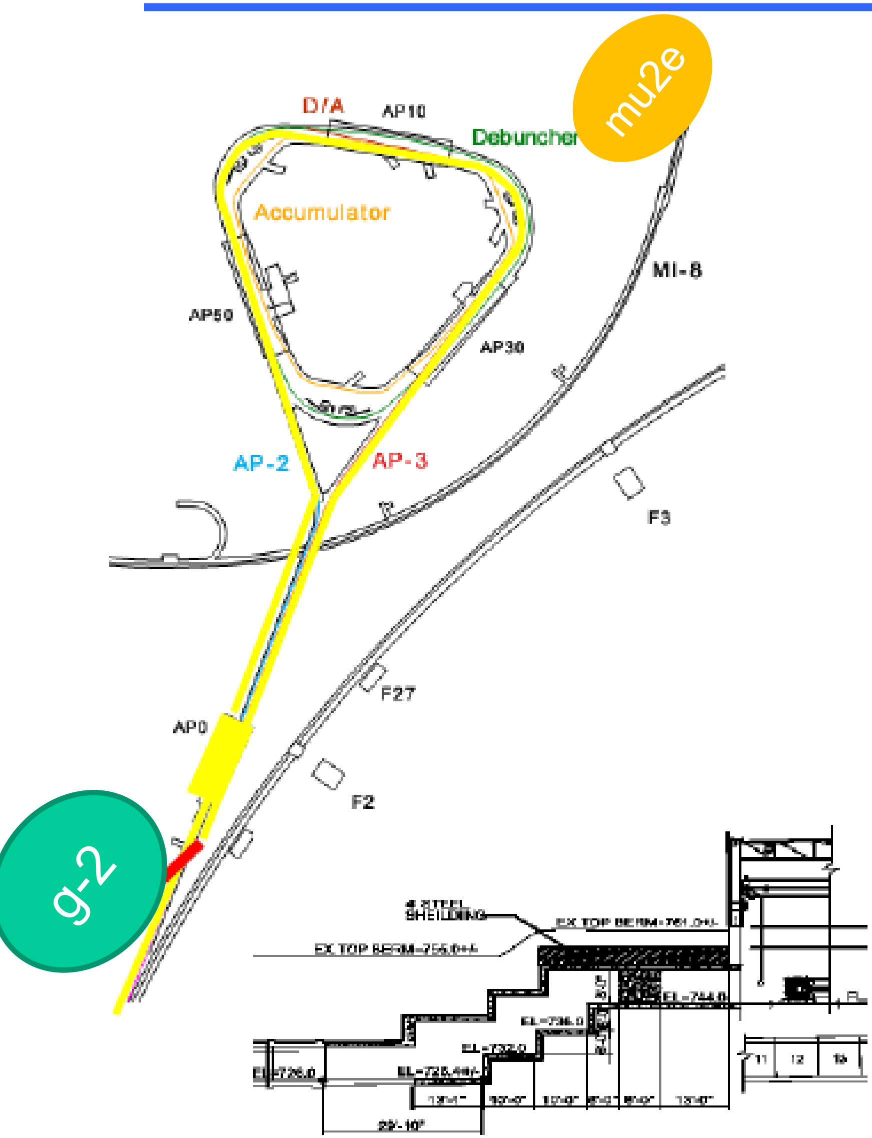
- Measure μ anomalous magnetic moment to < 0.14 ppm
  - 4×10^{20} protons on target
- Exploit existing infrastructure – help defray some costs & do it quickly
  - Move the BNL g-2 storage ring to FNAL
  - Reuse pbar production target and Debuncher
  - Start taking data in 2015 (before mu2e)

g-2 Beam Needs

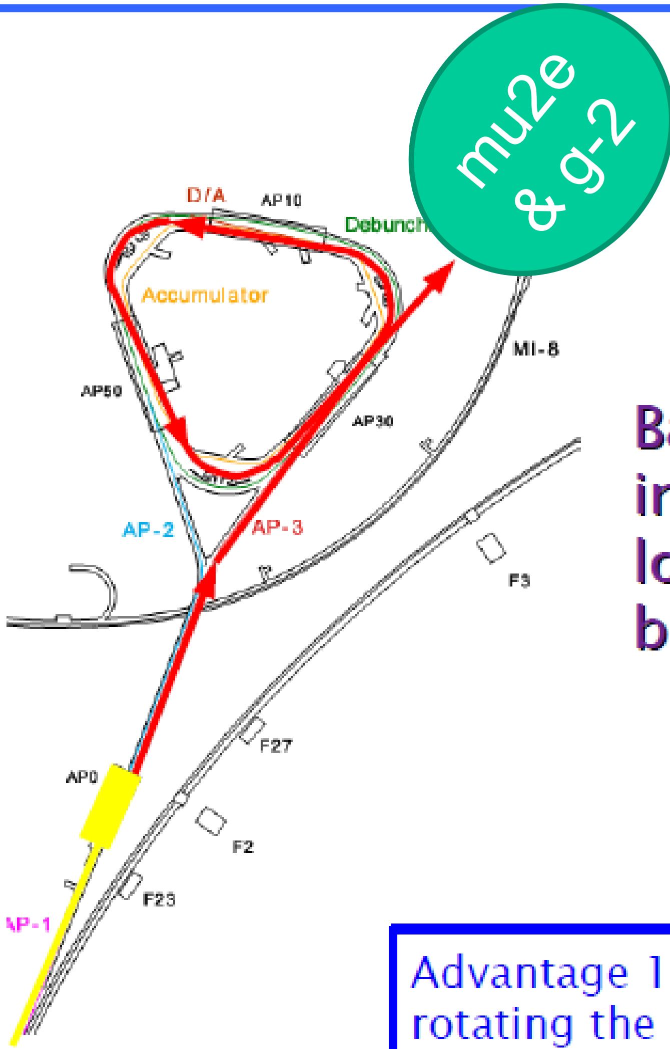
- 1 Booster batch (84 bunches) injected into Recycler and manipulated into 4 bunches
- Extract to P1 line to π production target at AP0
  - differing needs from mu2e Recycler kicker specs



g-2 Beam Needs



- Like to use pbar target station as-is
  - Incident power only ~27 kW
  - Upgrade supplies for higher rate
  - BNL design as backup
- Original idea to site storage ring near AP0 target station
  - Transport lines + Debuncher would run opposite polarity as do now
- Use transport lines & Debuncher as π decay line and capture 3.1 GeV μ
- Transport μ to BNL storage ring (new beamline)
- Want >800 m total line length



Basic idea...inject secondary beam into Debuncher via the AP3 line, loop once around Debuncher, and bring beam out the Mu2e tunnel

Advantage 1: Both g-2 and Mu2e use positive beams rotating the same way. No need to flip the Debuncher polarity when switching between experiments.

Merging g-2 & mu2e

- How to accommodate accelerator needs of both experiments
  - Won't run simultaneously, but could interleave with some overhead
  - Recycler kicker needs are different
  - g-2 requires additional quadrupole magnets in pbar transport lines
  - Aperture in pbar rings is issue
  - Real estate in service buildings

Recycler Kicker Specs

Comparison of kicker requirements

Kicker Requirement	g-2	Mu2e
Rise Time	< 180 ns	< 57 ns
Flattop	> 60 ns	1500 ns
Fall Time	< 5000 ns	< 57 ns
Avg Rate	20 Hz	5 Hz

- Both experiments have 2 possible layouts
  - Need to merge to move forward on both expeditiously

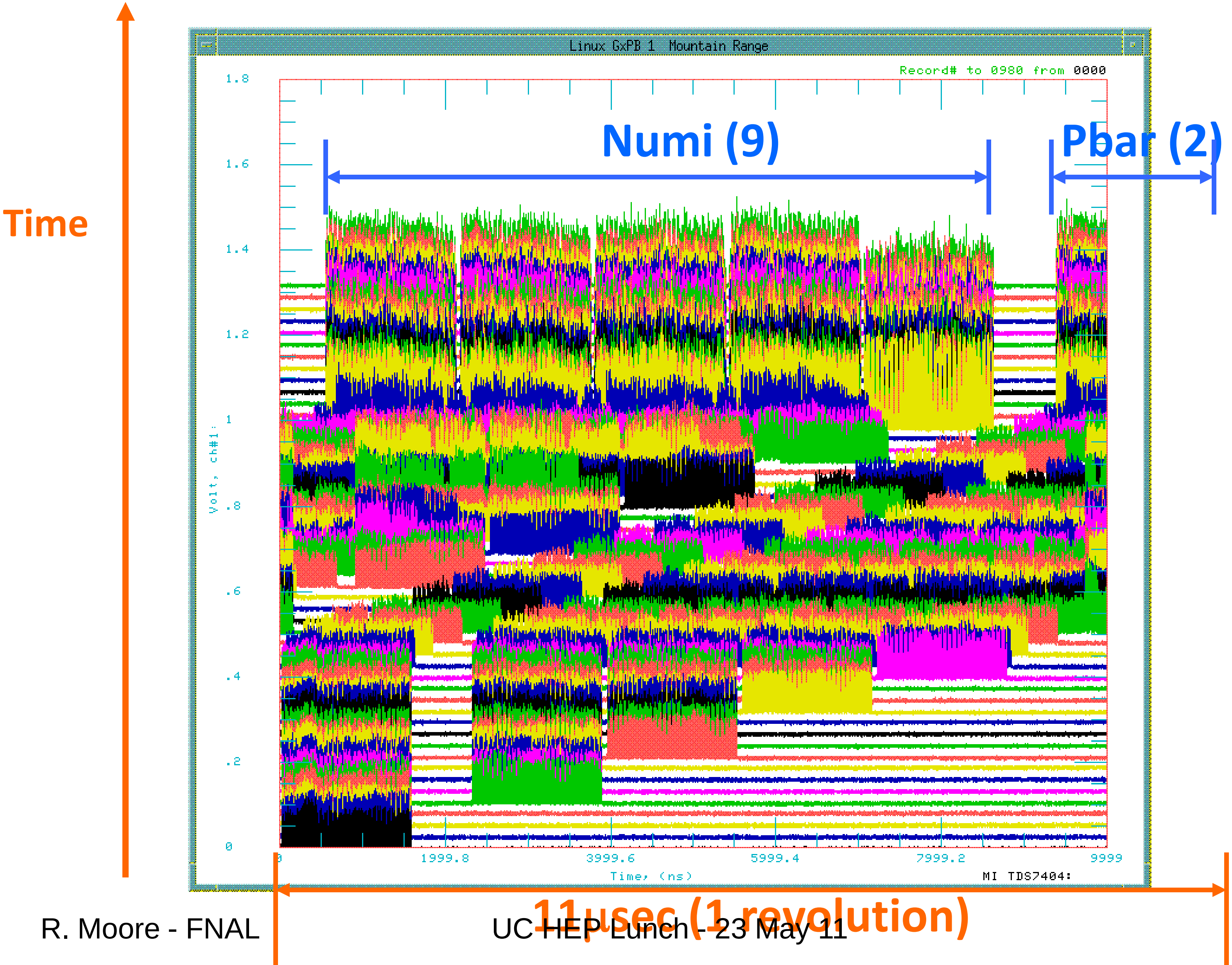
- mu2e CD-1 review in August
- g-2 CDR due in December

- Many issues to iron out

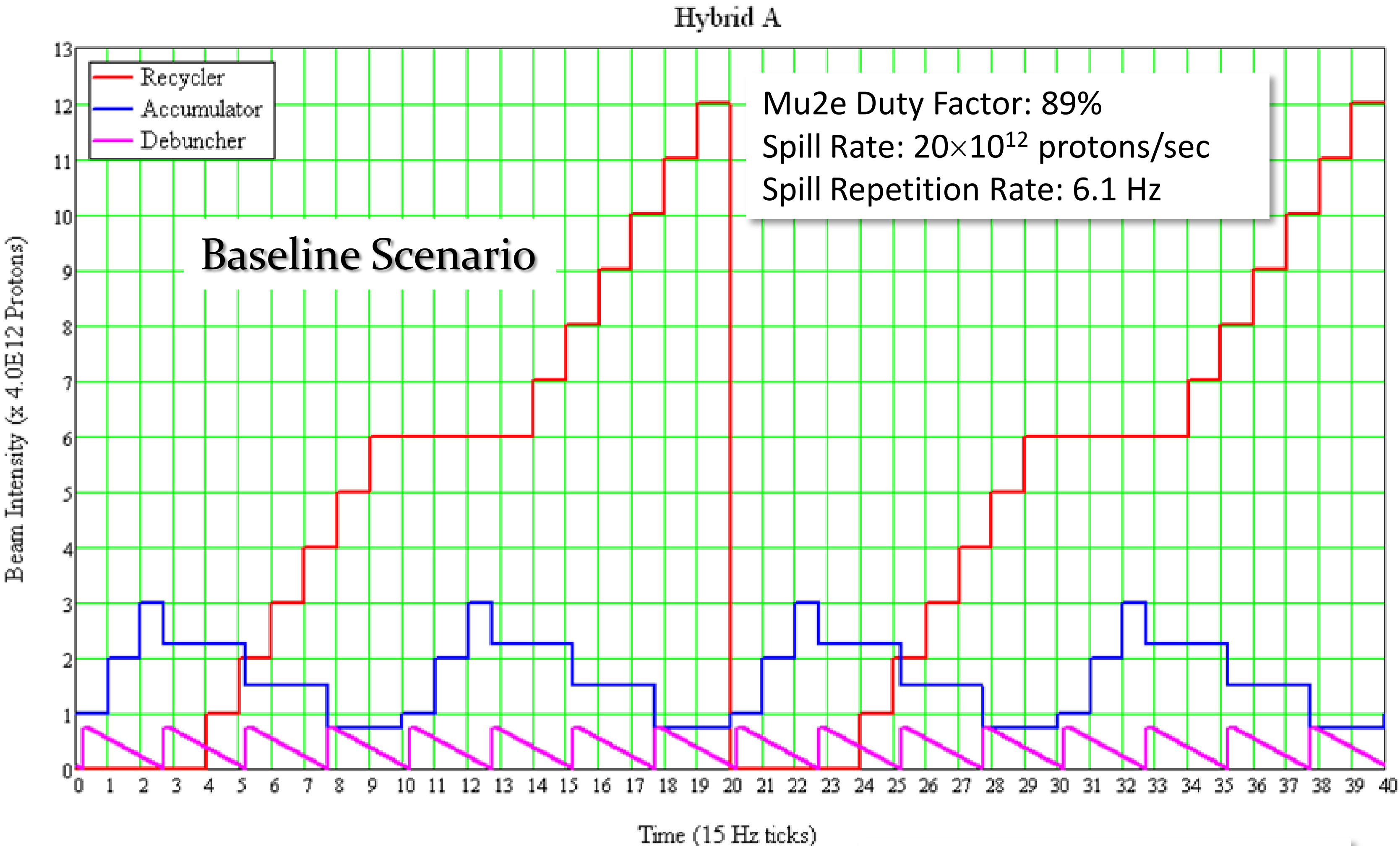
Summary

- 27 years after first beam, Tevatron will cease operation Sep 30
  - Should get close to 12 fb^{-1} total for Collider Run 2
  - Pbar production will end, too
- Intensity frontier will push Proton Source flux & rate to extremes
  - Planning upgrades to keep Linac and Booster viable until 2025
  - Must run reliably while keeping beam losses under control
- Accelerator designs for g-2 and mu2e need to merge
- FNAL Accelerator Division looks forward to meeting the challenging demands of NOvA, MicroBoone, g-2, mu2e

11 batch slip stacking in MI



Mu2e Accelerator Timeline

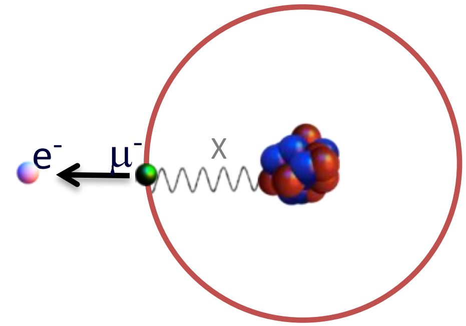


Mu2e Duty Factor: 89%
Spill Rate: 20×10^{12} protons/sec
Spill Repetition Rate: 6.1 Hz

Hybrid A: 3 Booster Batches
Hybrid B: 2 Booster Batches

Mu2e Physics Summary

- μ^- to e^- conversion – μ^- converts to an e^- in the field of a nucleus
  - No emission of neutrinos
  - Nucleus remains intact – coherent
  - Signal is a monoenergetic 105 MeV e^-
- Goal is to search for μ^- to e^- conversion with a sensitivity of < 6 x 10^{-17} (90% C.L.):

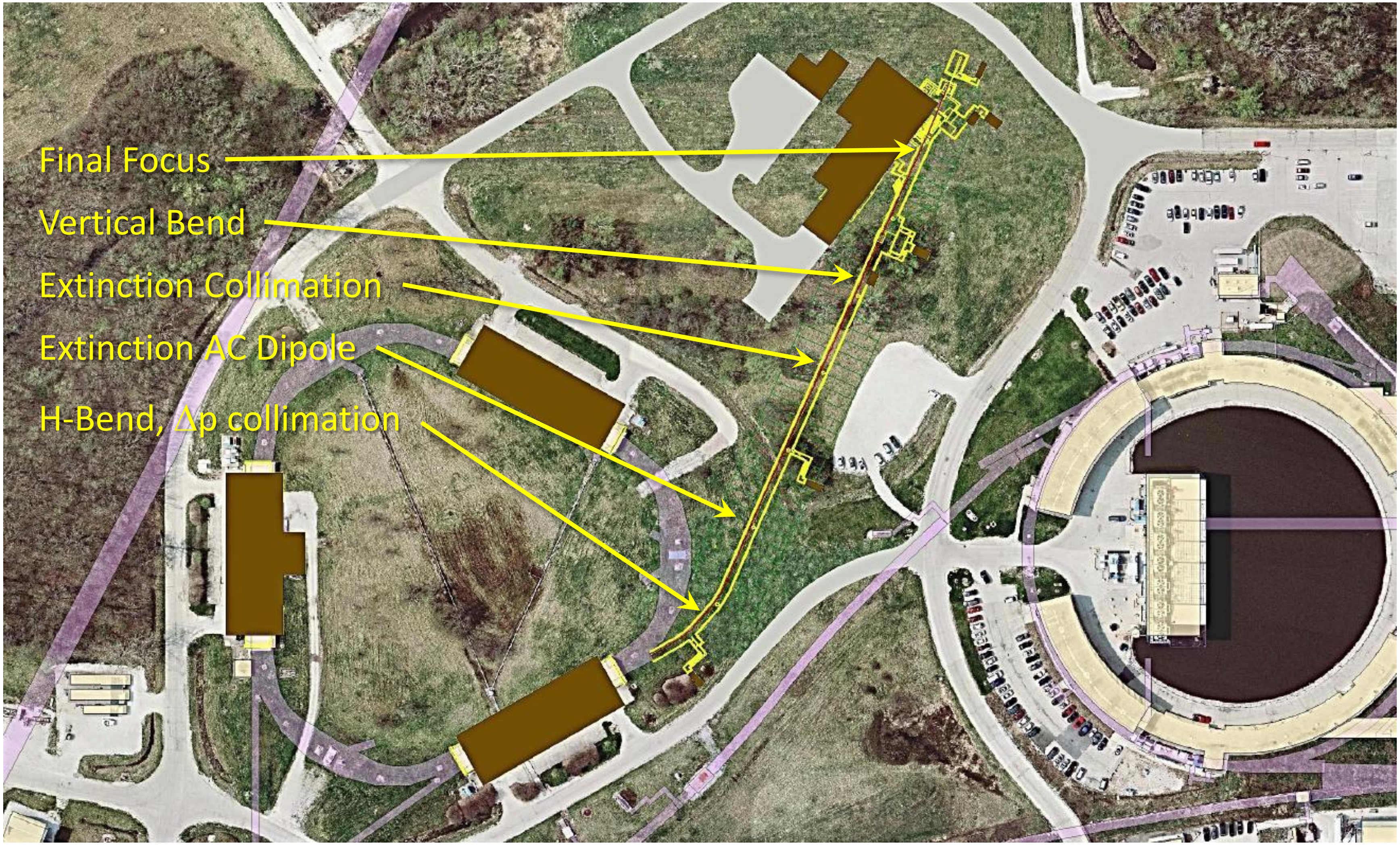


Coherent recoil of nucleus

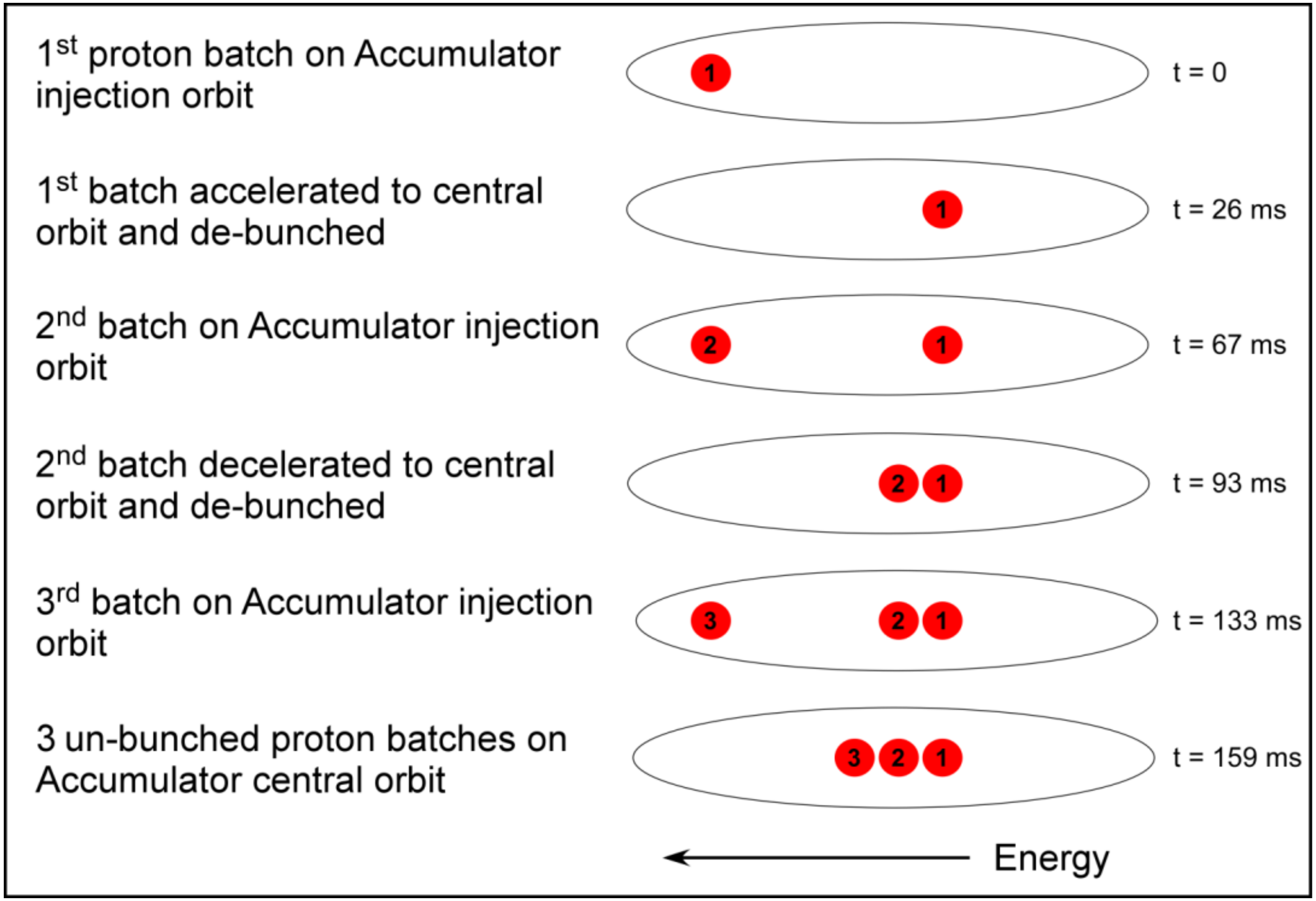
$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

- Observation is unambiguous evidence of physics beyond the SM
  - Provides information about flavor structure of new physics that is not easily accessible at the LHC.
- A null result at the proposed sensitivity will severely constrain new physics models.
  - CLFV is predicted at observable rates in most new physics models.
  - Mu2e can probe mass scales up to 10^4 TeV, far beyond the reach of the LHC.

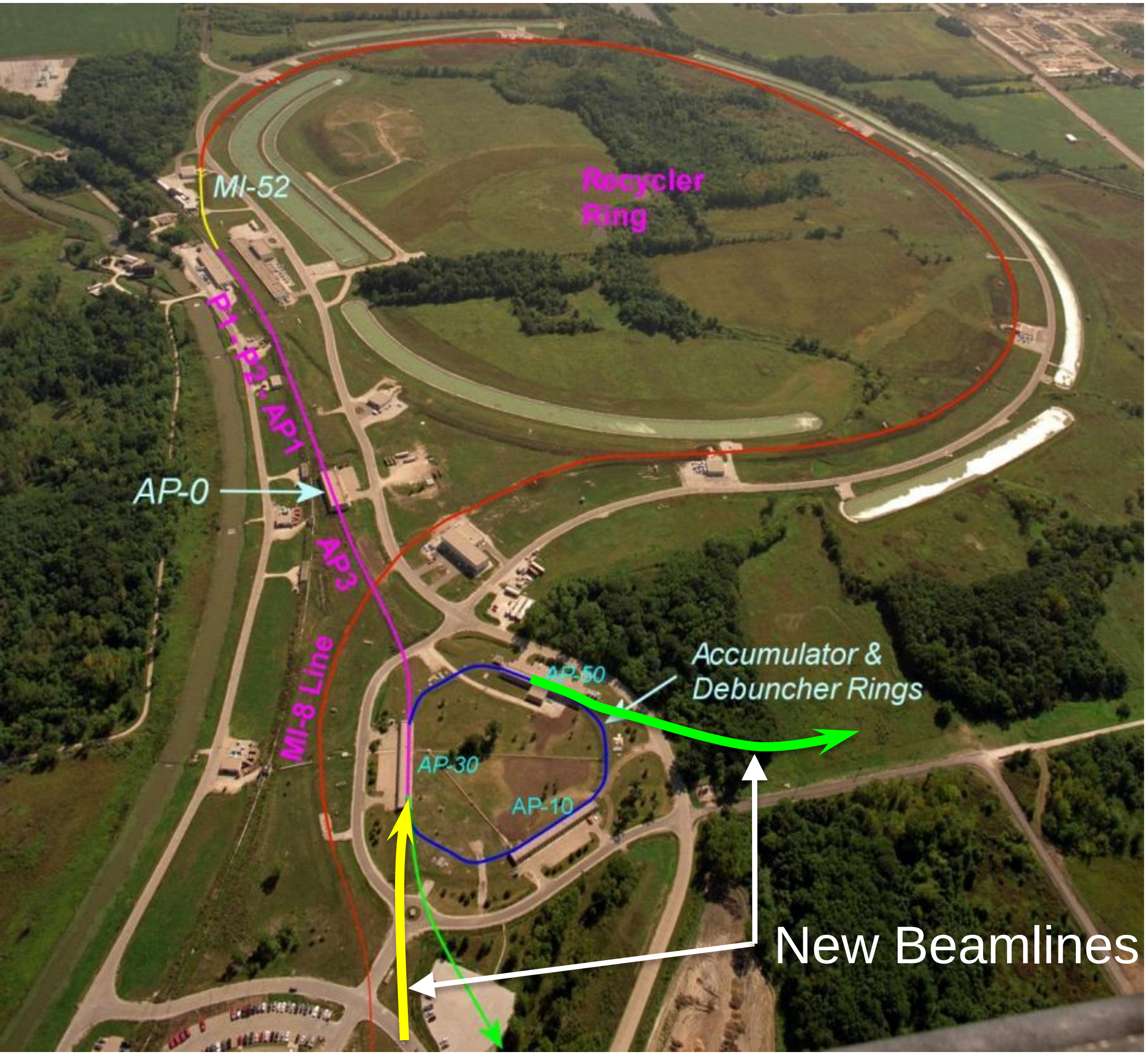
External Proton Beamline



Proton Stacking



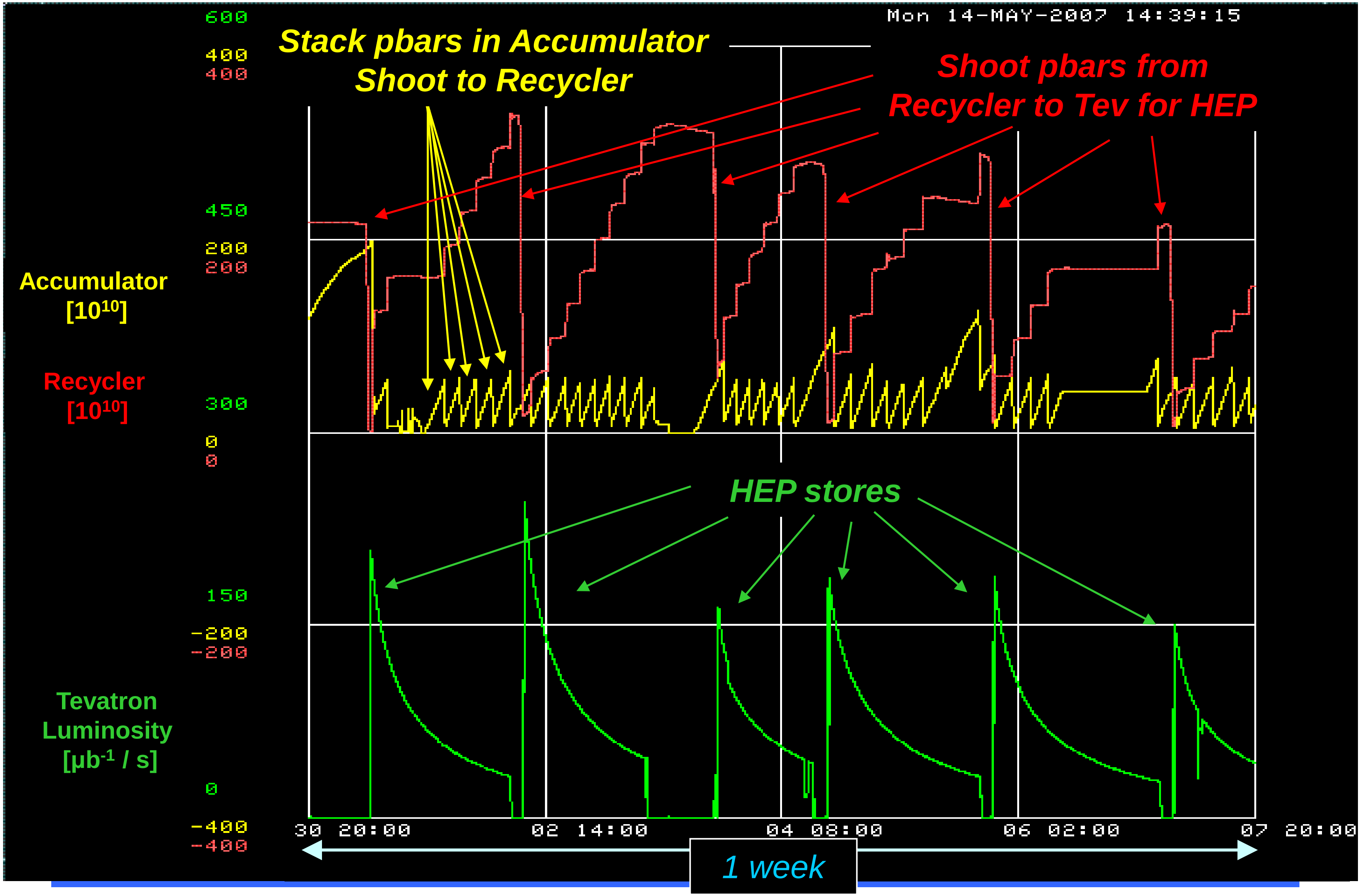
Alternate to Proton Slingshot



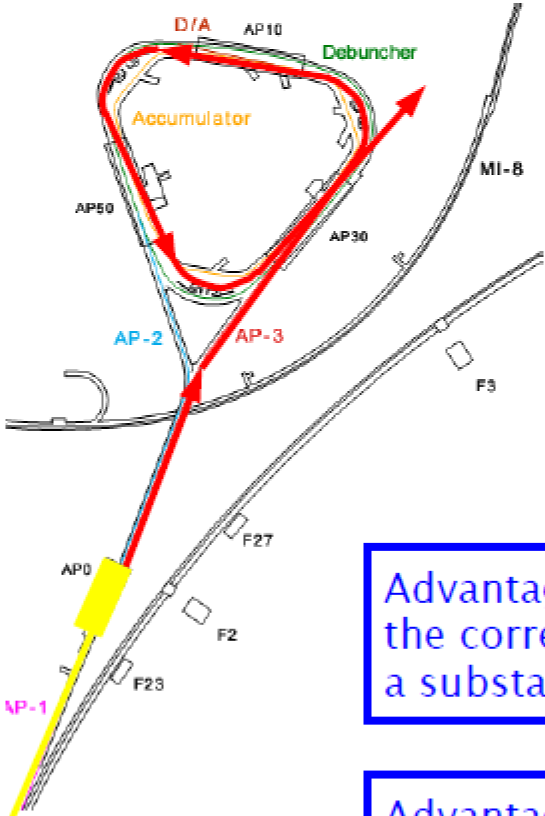
8 GeV protons from Booster is injected directly into Accumulator (revamp old AP4 beam line used when commissioning pbar rings)

- Booster → New Beamline
- New Beamline → Accumulator
- Beam extracted to Mu2e from Debuncher at AP50

Antiproton Production Flow



g-2 & mu2e on common campus



Comparison of path lengths

Proposal Plan	Length [m]
AP2	280
Debuncher	330
AP3	340
Stub	50
Total	~1000

Unified Plan	Length [m]
AP3	280
Debuncher	505
Mu2e	100*
Stub	50*
Total	~1000

Advantage 2: Uses more of Debuncher which already has the correct lattice. Cuts ~175m of beamline that needed a substantial addition of quads.

Advantage 3: Avoids complication of trying to increase density of quads in the vicinity of AP0, gives John more room to accommodate beamline stub.