Accelerator upgrades for NuMI

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Introduction

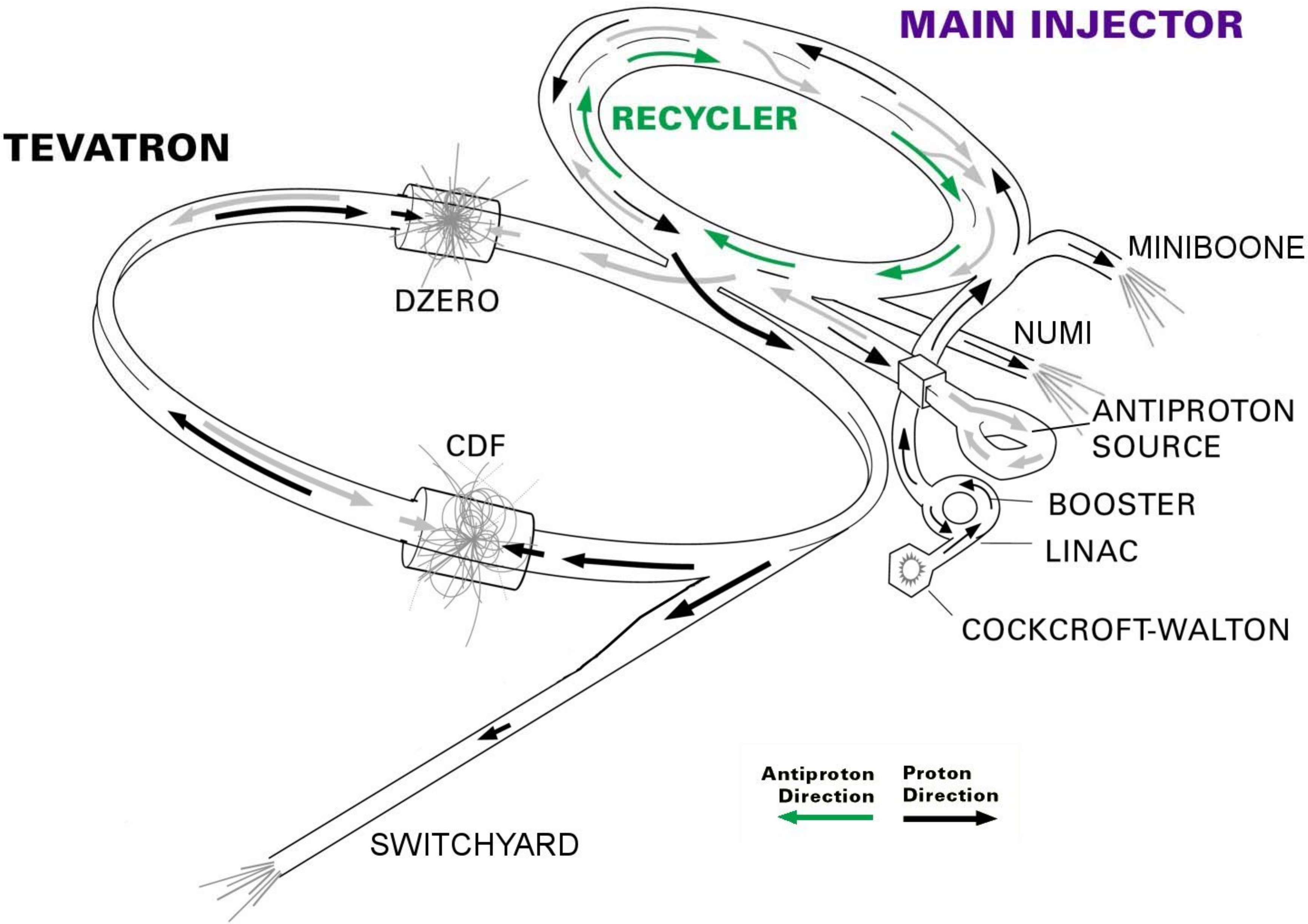
- Two potential neutrino experiments at Fermilab: Minerva and NOvA
  - NOvA requires proton exposure 5-10x that of MINOS
  - Additionally, studies are always underway on how to use many, many protons
    - New Superbeams, muon sources/colliders & neutrino factory

Outline

- Current Fermilab Accelerator Complex
  - Provides protons for antiproton and neutrino production
  - About 250 kW (total) @ 120 GeV
- Programs to improve proton beam power
  1. Proton Plan ⇒ underway
  2. Super NuMI ⇒ in planning
  3. HINS (proton driver) ⇒ in R&D
- Projections: power and timelines

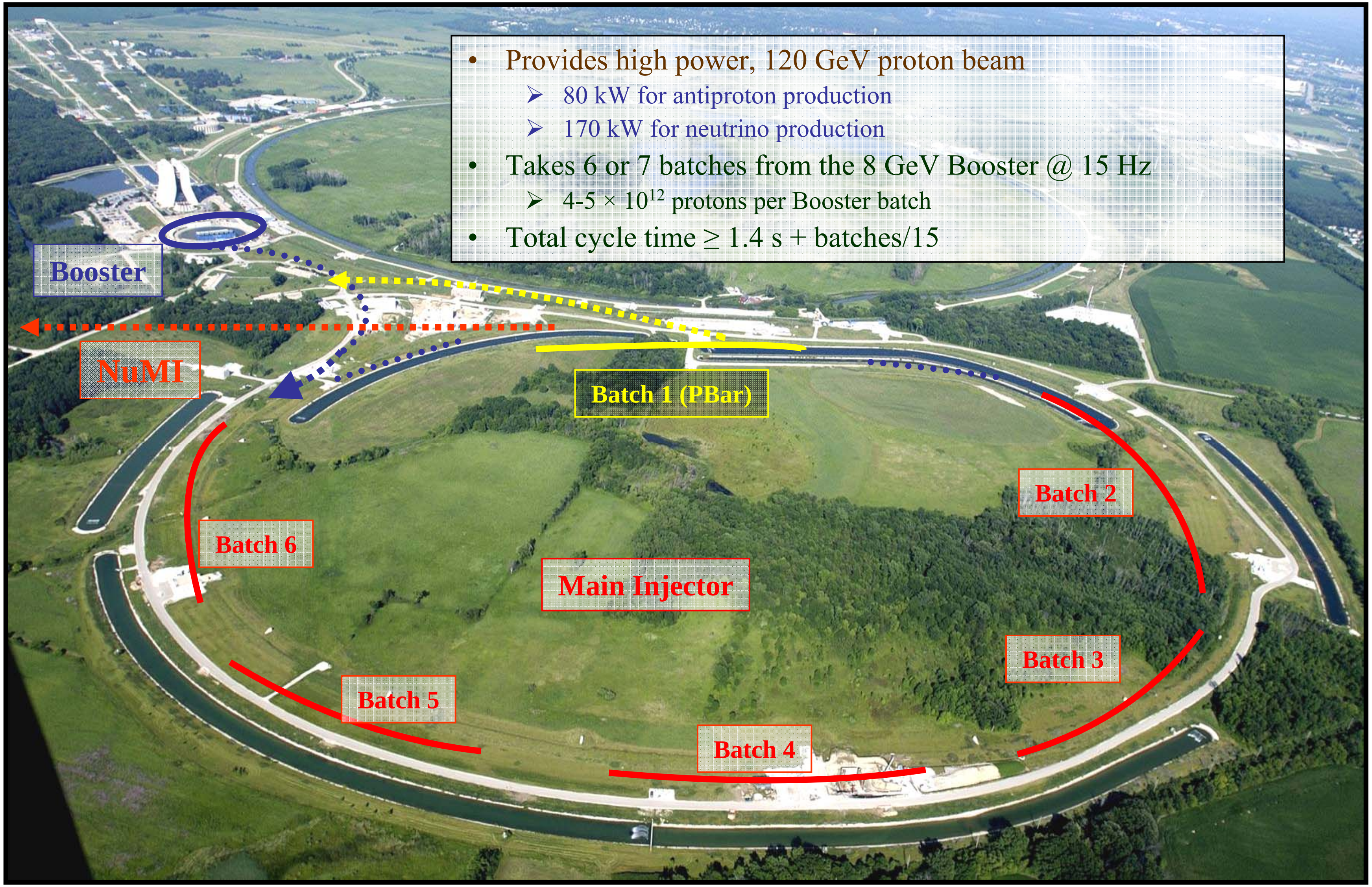
- Can NuMI withstand these proton intensities? -> Next talk

FERMILAB'S ACCELERATOR CHAIN



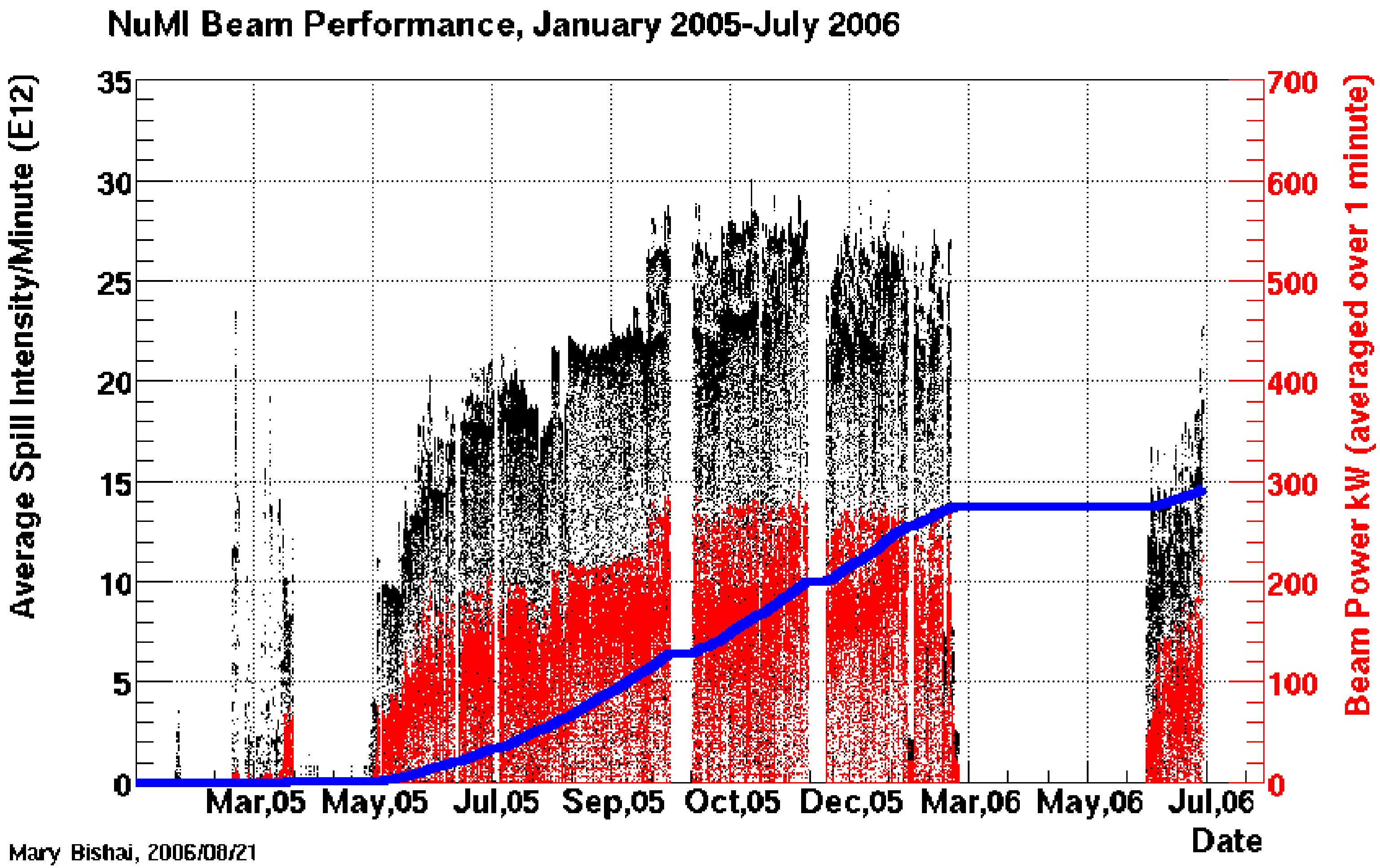
The Main Injector Today

- Provides high power, 120 GeV proton beam
  - 80 kW for antiproton production
  - 170 kW for neutrino production
- Takes 6 or 7 batches from the 8 GeV Booster @ 15 Hz
  - 4-5 × 10^{12} protons per Booster batch
- Total cycle time ≥ 1.4 s + batches/15



Past-Year NuMI Running

- Average power of 165 kW previous to the shutdown
- Maximum beam power of 270 kW down the NuMI line (stably for ~ ½ hour)
- Peak intensity of 3×10^{13} ppp on the NuMI target



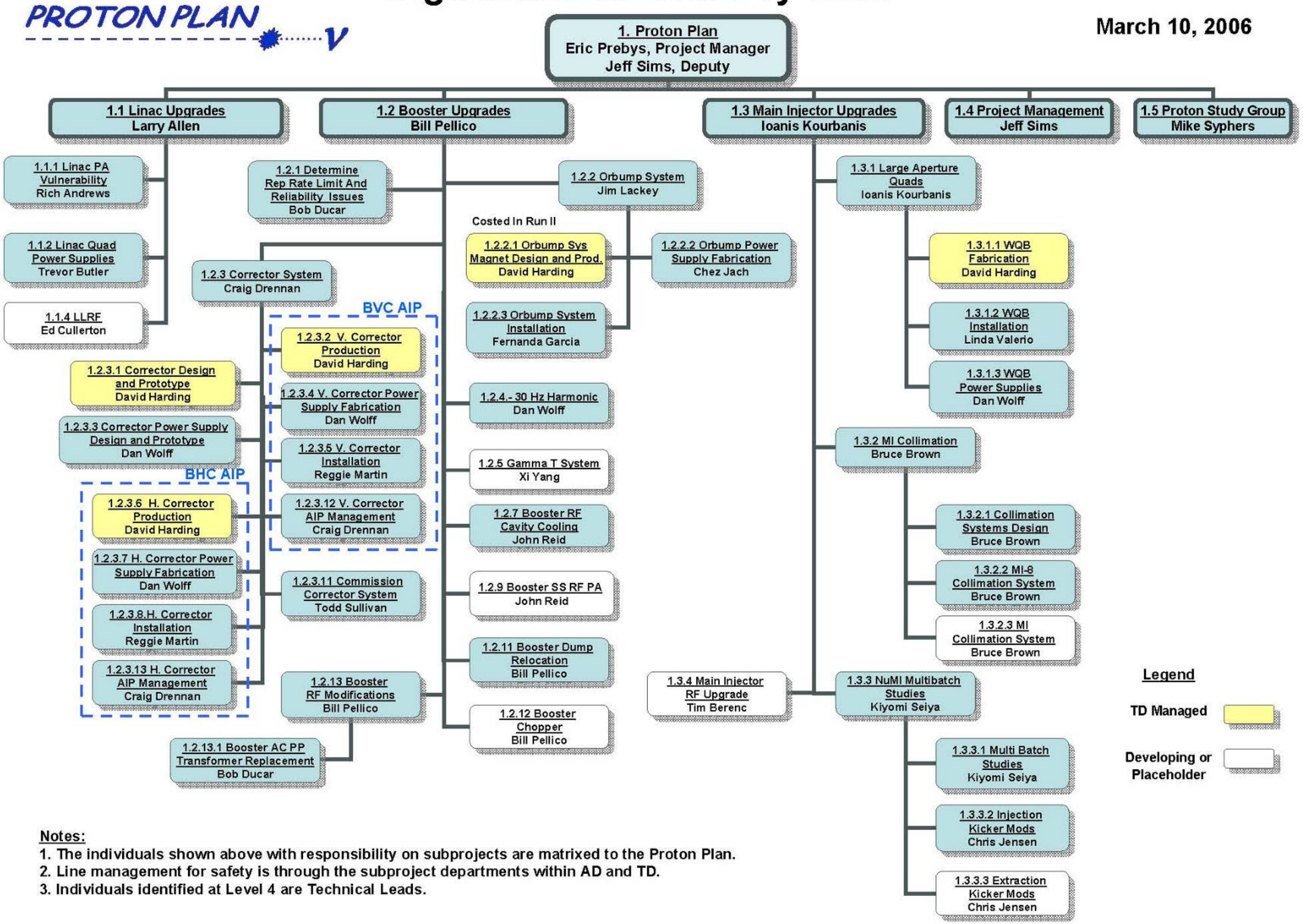
PROTON PLAN ν

- The implementation of slip stacking to NuMI in the Main Injector will gradually increase NuMI intensity to $3.7x10^{13}$ protons to NuMI per 2.2 second cycle or about $3x10^{20}$ p/yr. (~320 kW)

- This will increase by ~30% as protons currently used for pbar production become available. (430 kW)

- The Booster rep. rate and efficiently must increase to accommodate this, and it is hoped that there will be enough excess capacity to continue to operate the BNB at the $2x10^{20}$ p/yr level throughout this period.

Organizational Chart by WBS



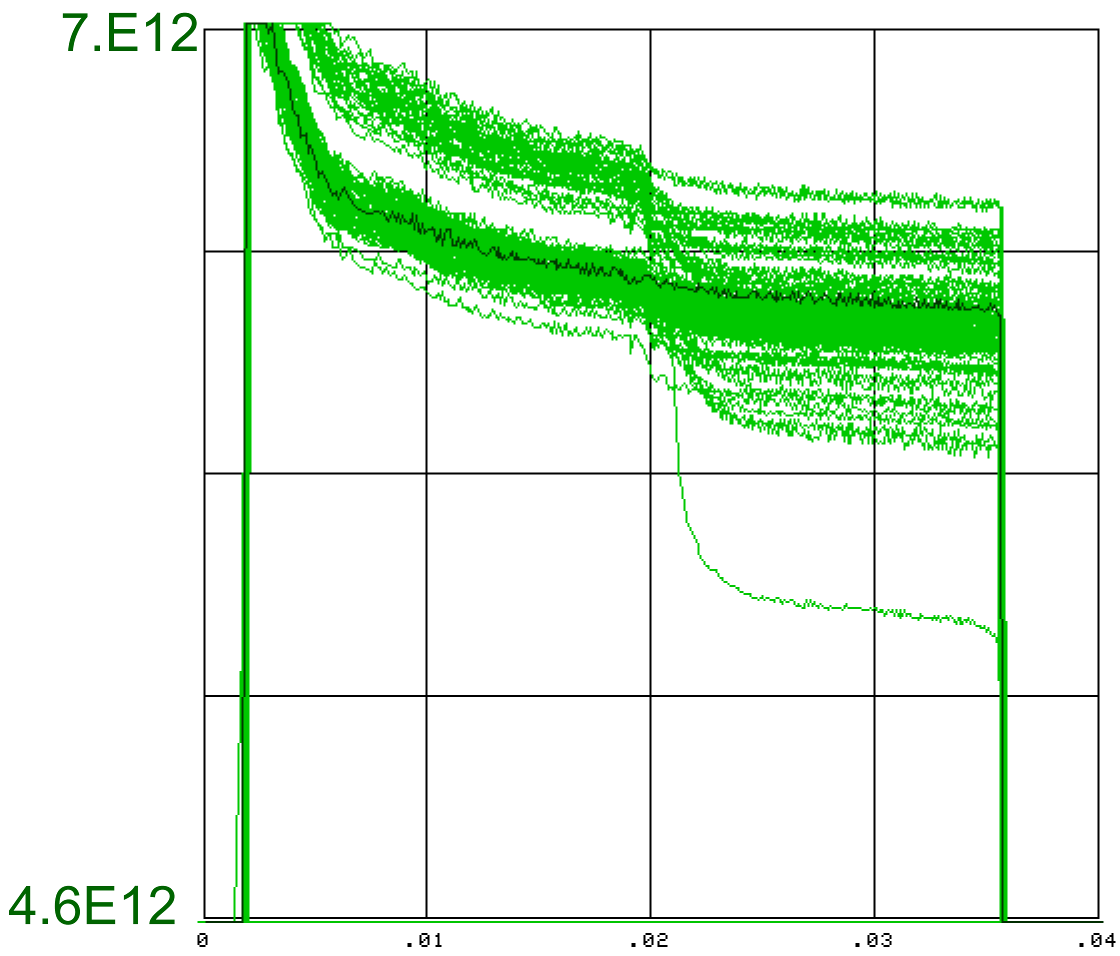
Notes:

1. The individuals shown above with responsibility on subprojects are matrixed to the Proton Plan.
2. Line management for safety is through the subproject departments within AD and TD.
3. Individuals identified at Level 4 are Technical Leads.

What the Booster Can Do

- Booster can inject > $9\text{x}10^{12}$ protons
- Extract as much as $6.6\text{x}10^{12}$
  - At 15 Hz: 36 x 10^{16} /hr.
  - Ultimate Booster Throughput?
- Losses are enormous
  - About 1200 J / cycle
  - At 1 W/m: 1 x 10^{16} /hr
- Running this way would maximize the number of protons per-batch, but severely limit the integrated number of protons delivered

Booster does not run this way

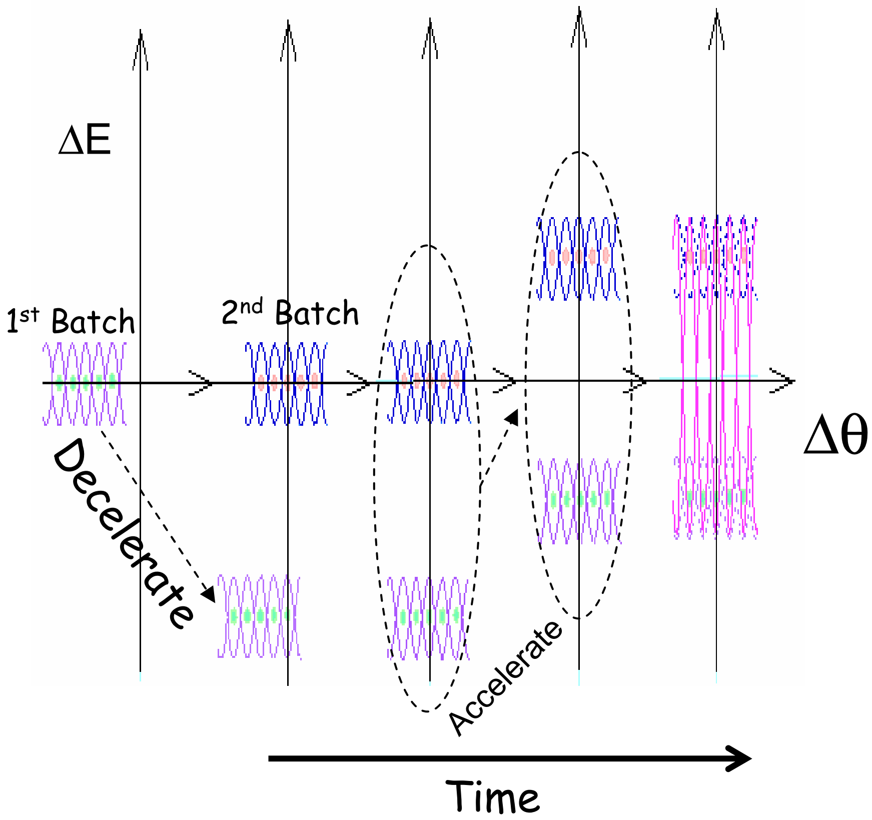


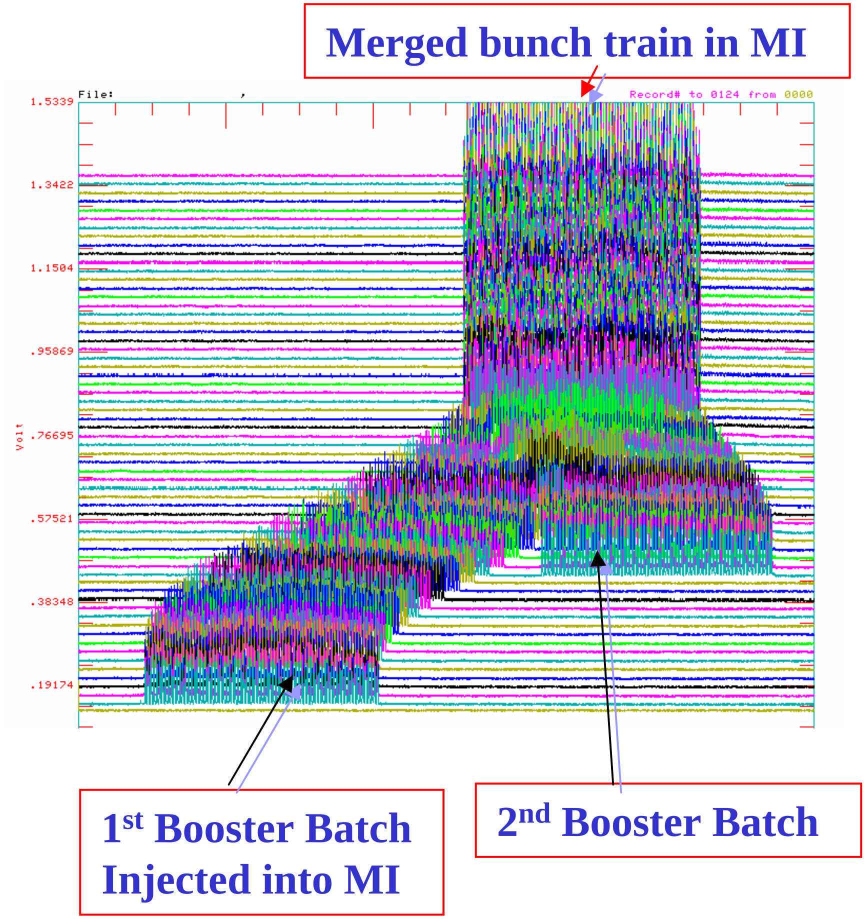
Limits to Proton Intensity

- Total proton rate from Proton Source (Linac+Booster):
  - ➢ Booster batch size
    - ~4-5E12 protons/batch
  - ➢ Booster repetition rate
    - 15 Hz instantaneous
    - Prior to shutdown: 7.5Hz average (pulsed components)
  - ➢ Beam loss
    - Damage and/or activation of Booster components
    - Above ground radiation
- Total protons accelerated in Main Injector:
  - ➢ Maximum Main Injector load
    - Six "slots" for booster batches (3E13)
    - Up to ~11 with slip stacking (4-5E13)
    - Possible RF stability limitations (under study)
  - ➢ Cycle time:
    - 1.4s + loading time (1/15s per booster batch)

Slip-stacking

- **Merge two booster batches through RF manipulations**





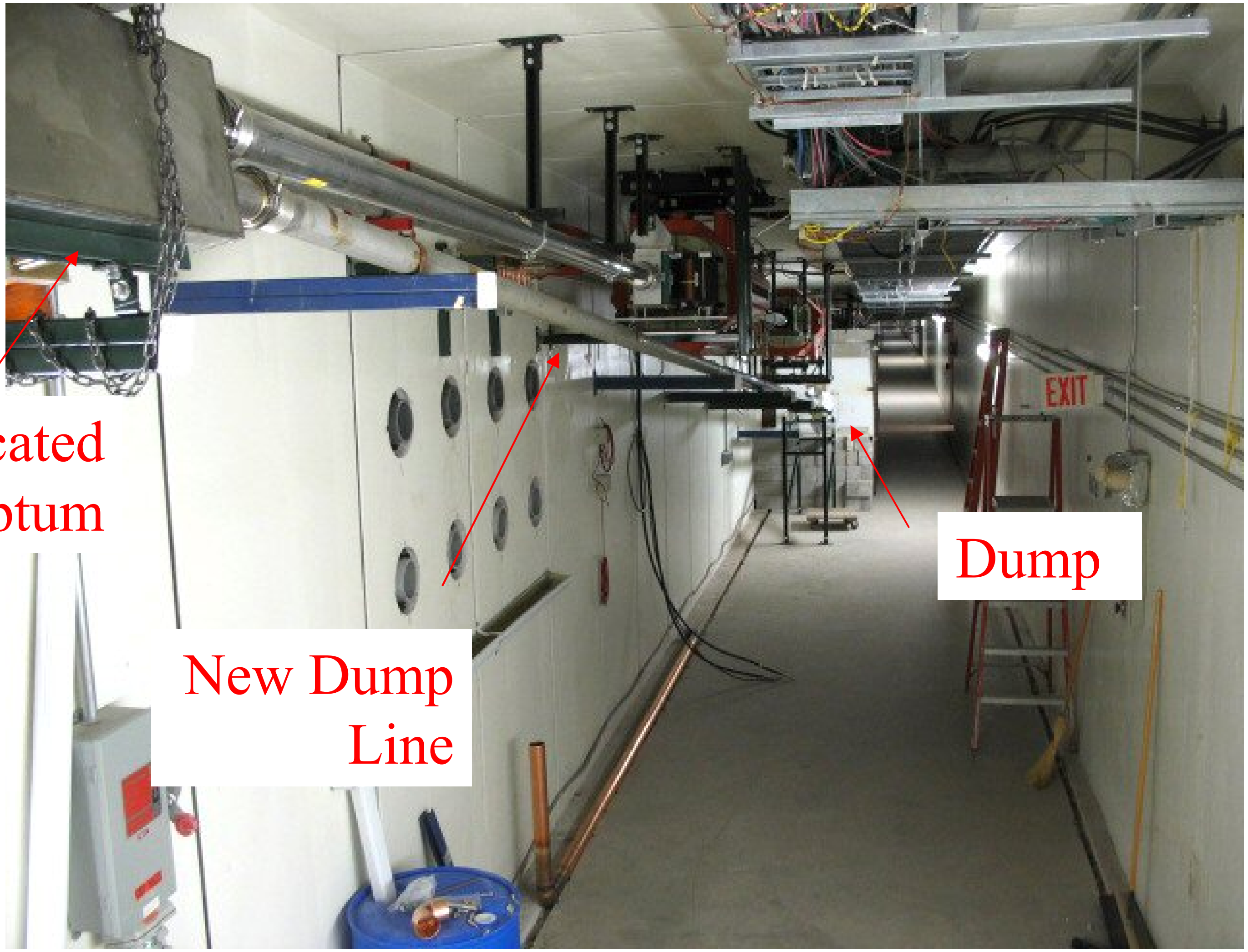
K. Seiya et. al., PAC2003/5

- **Doubles the azimuthal charge in the Main Injector**
  - **Booster loading time is doubled**

Main Injector Loading

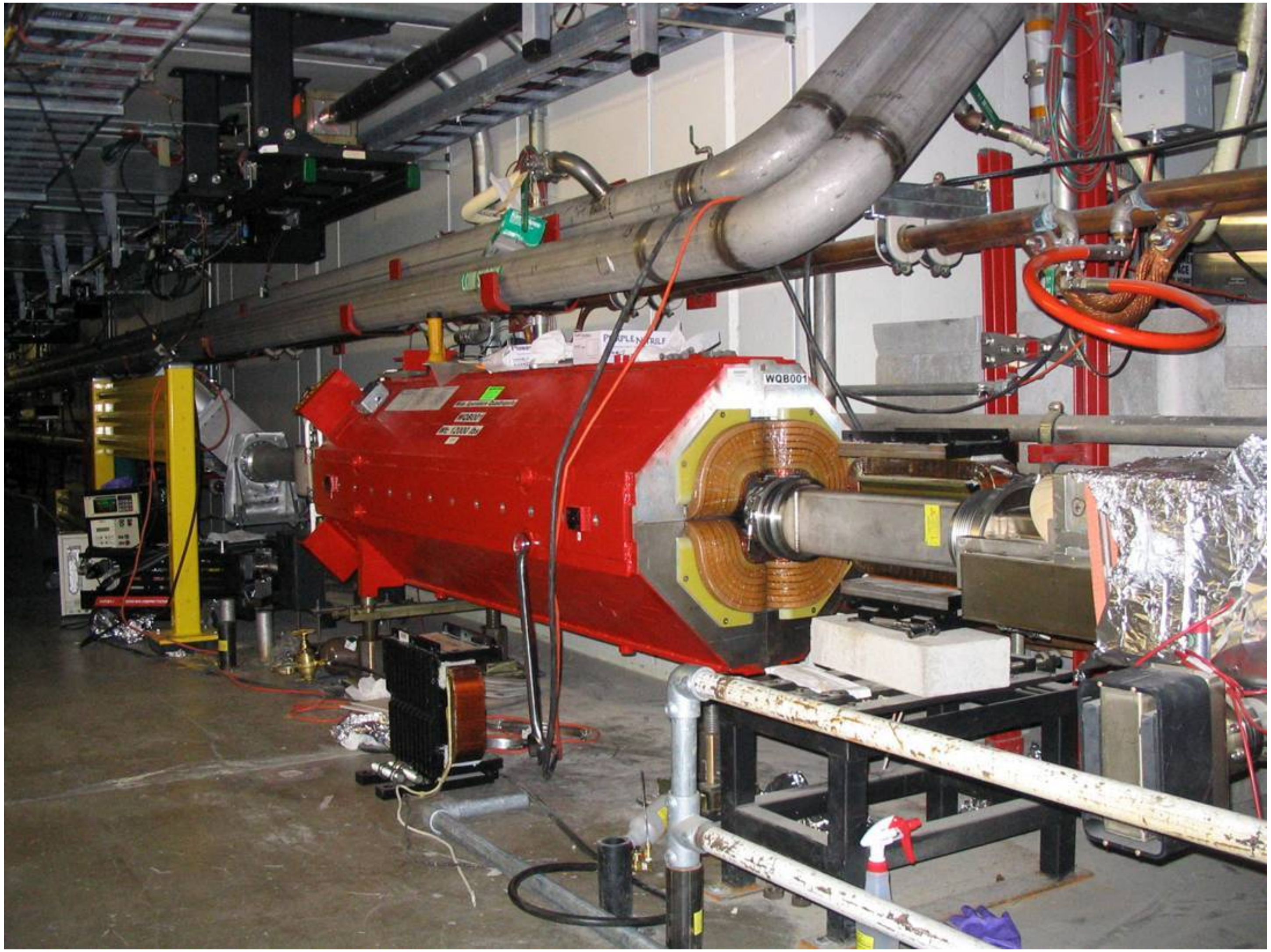
- Initial NuMI operation (“2+5”):
  - Two batches slip stacked for antiproton production.
  - Five more batches loaded for NuMI
  - All will be accelerated together.
  - This is the current standard operation.
- Ultimate NuMI operation (“2+9”):
  - Five batches will be loaded into the Main Injector, leaving one empty slot.
  - Six more batches will be loaded and slipped with the first to make two for antiproton production and 9 for NuMI.

MI-8 Dump Line

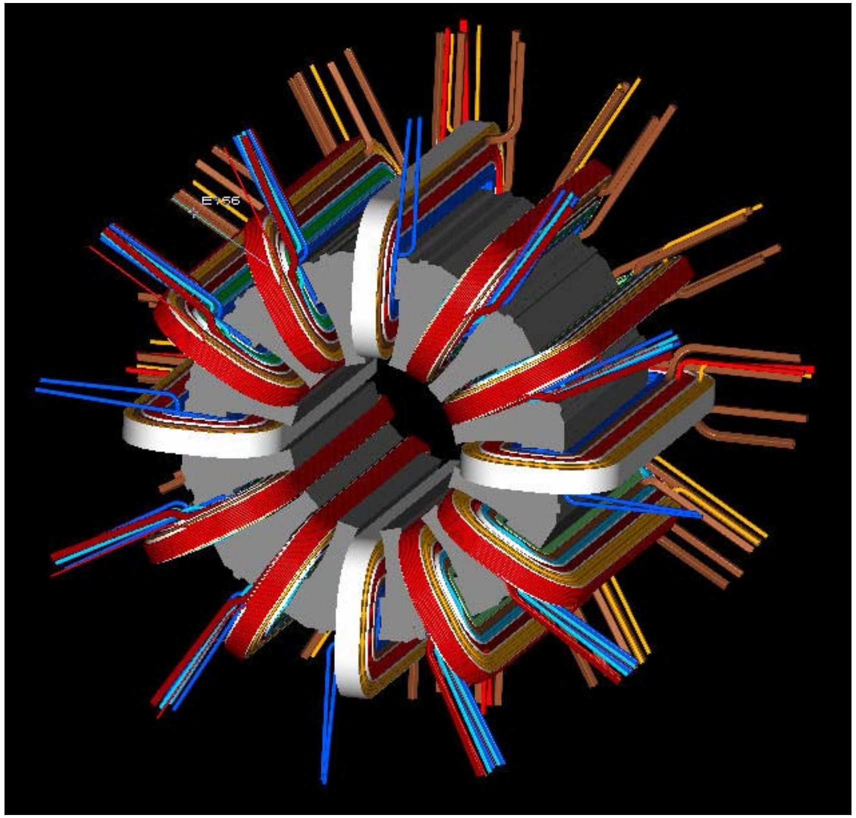


MI-8 Collimator

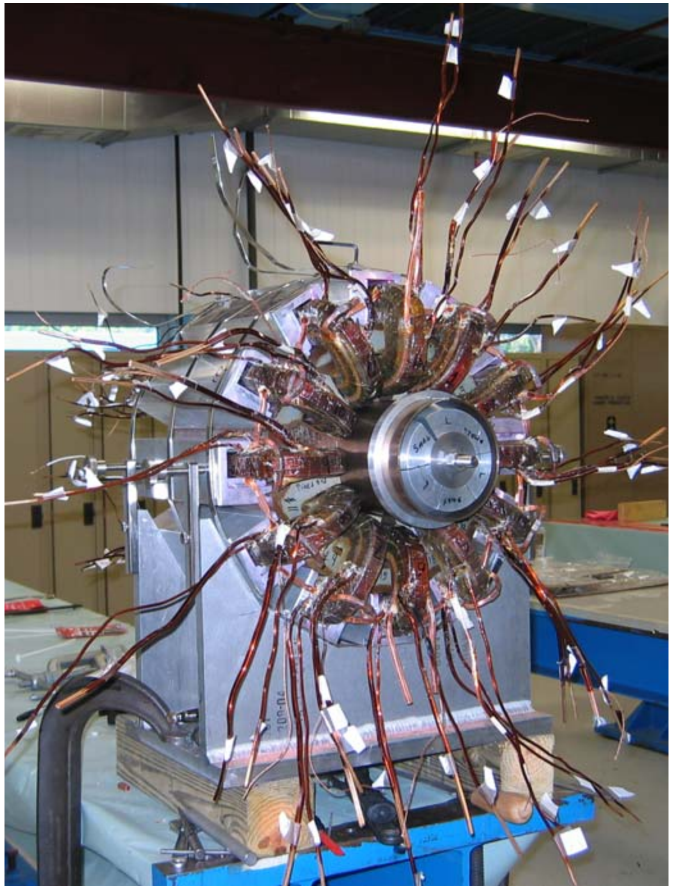
Main injector large aperture quads



Booster Corrector Upgrades



- Prototype in progress
  - Fabricated and assembled
  - Testing in Progess
- System to be installed 08-09



- Stronger fields
- More poles
- Faster slew rates

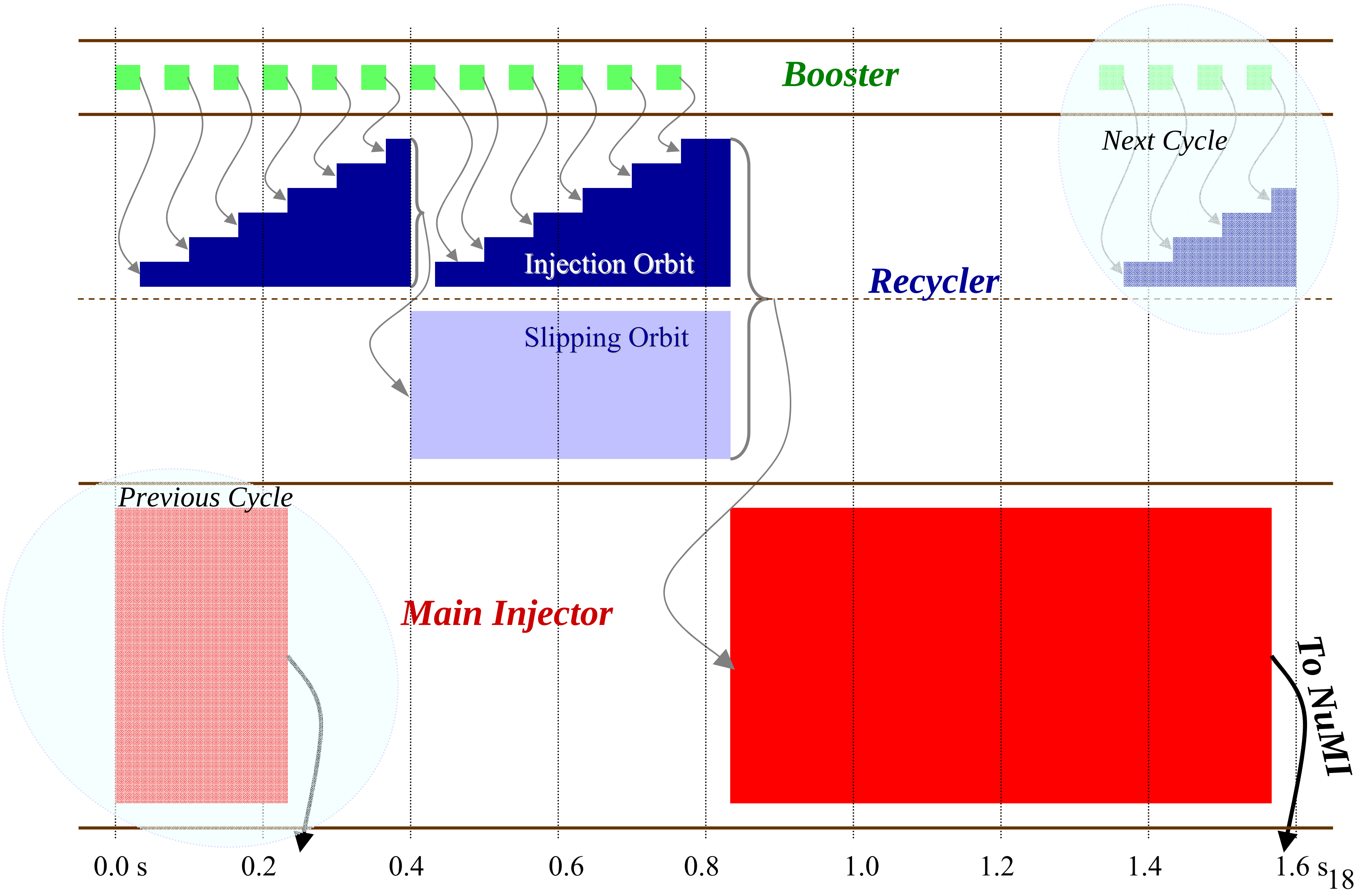
SNuMI (Super-NuMI)

- Evolving set of upgrades that take advantage of the present accelerator complex
  - Tevatron will be shutdown end of 2009
    - (LHC willing)
  - No new rings
  - Many new devices/tunnels
- Phase I: Recycler Ring
  - Allows shorter repetition time
  - In active planning
- Phase II: Accumulator Ring
  - Allows higher intensity
  - Under consideration

SNuMI Stage 1: 700 kW
Recycler as an 8 GeV Proton Pre-injector

- After the Collider program is terminated, we can use the Recycler as a proton pre-injector
  - ➢ Use the Recycler to accumulate protons from the Booster while MI is running
    - Save 0.4 s for each 6 Booster batches injected
- 6 batches (5×10^{12} p/batch) at 120 GeV every 1.333 s $\Rightarrow$ 430 kW
- Recycler momentum aperture is large enough to allow slip-stacking operation in Recycler, for up to 12 Booster batches injected
  - ➢ 4.3×10^{12} p/batch, 95% slip-stacking efficiency
  - ➢ 4.9×10^{13} ppp at 120 GeV every 1.333 s $\Rightarrow$ 700 kW

Sample Timeline



SNuMI 700 kW organization

Recycler Ring Upgrades
P. Derwent

1. Recycler Ring modifications (**Cons Gattuso**)
   1. Removal of pbar specific devices
   2. Injection/extraction lines
   3. Kickers
2. Slip-stacking schemes (**K. Seiya**)
3. Recycler Ring 53 MHz RF system (**D. Wildman**)
4. Dampers (**P. Adamson**)
5. Instrumentation (**P. Prieto**)
   1. BPM upgrade

NuMI Upgrades
M. Martens

1. Primary proton beam (**S. Childress**)
   1. Power supplies, magnet cooling and NuMI kickers for 1.5 s operation
2. Target & horns (**J. Hylen**)
   1. Target and Horns
   2. Water cooling of stripline
   3. Fabrication of stripline section for ME beam
   4. Cooling of target chase
3. Decay pipe & hadron absorber (**B. Lundberg**)
   1. Decay pipe upstream window
   2. Decay pipe cooling
   3. Eventual upgrade Hadron Absorber

Radiation safety for RR, MI and NuMI
T. Leveling

1. Shielding assessment
2. Ground water protection
3. Surface water protection
4. Activated air emission
5. Residual activation

Main Injector
I. Kourbanis

1. Additional RF cavities

Beam physics & Instability issues
B. Zwaska

1. MI & RR Impedance measurements
2. Longitudinal & transverse instabilities and damping
3. Electron cloud

Booster
E. Prebys

1. Booster rep rate up to 9.3 Hz
2. Beam quality

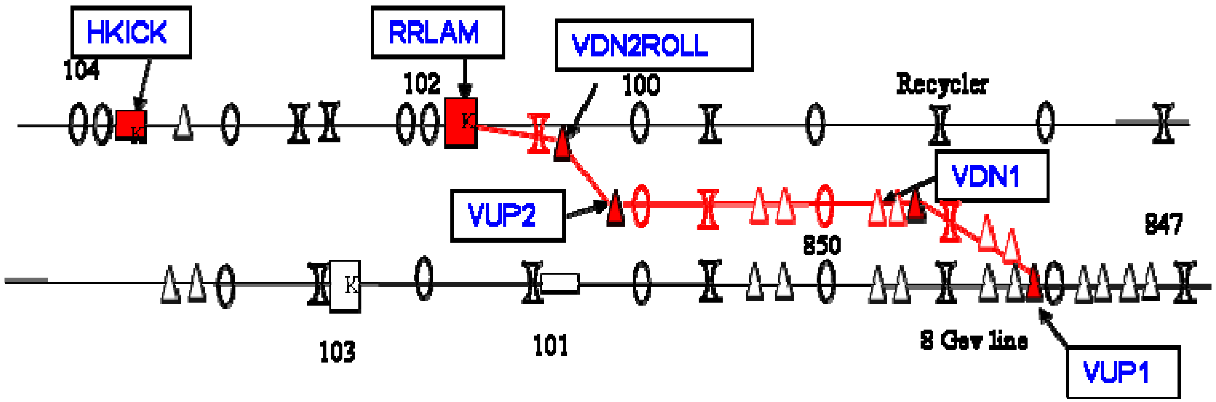
Engineering Support
R. Reilly

1. NuMI Target Hall and components (2 FTE)
2. Proton delivery (1 FTE)
3. Support from PPD on FEA

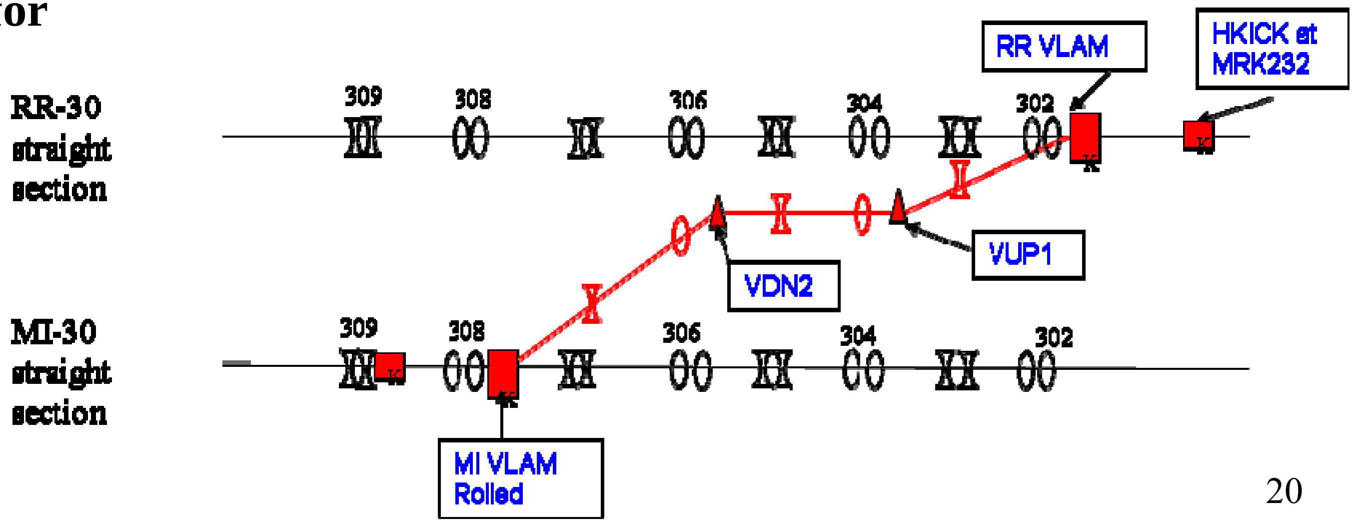
Recycler Modifications

- **Take anti-proton specific devices out**
- **Build new transfer lines**
  - direct injection into RR
  - new extraction line at RR-30
  - rework RR-30 straight section
- **Build 5 new kickers**
- **53 MHz RF system for Recycler**

Injection line from MI-8 to RR



Extraction line in the RR-30 section



Elements of the 700 kW Upgrade

- Transfer lines (2)
- Kickers (many)
  - Injection(twice), extraction, abort, cleaning
- Recycler 53 MHz RF System
  - 300 kV, low R/Q design
- Recycler instrumentation
  - BPMs, dampers
- Main Injector ramp time (power supplies)
- Beam Loss Control

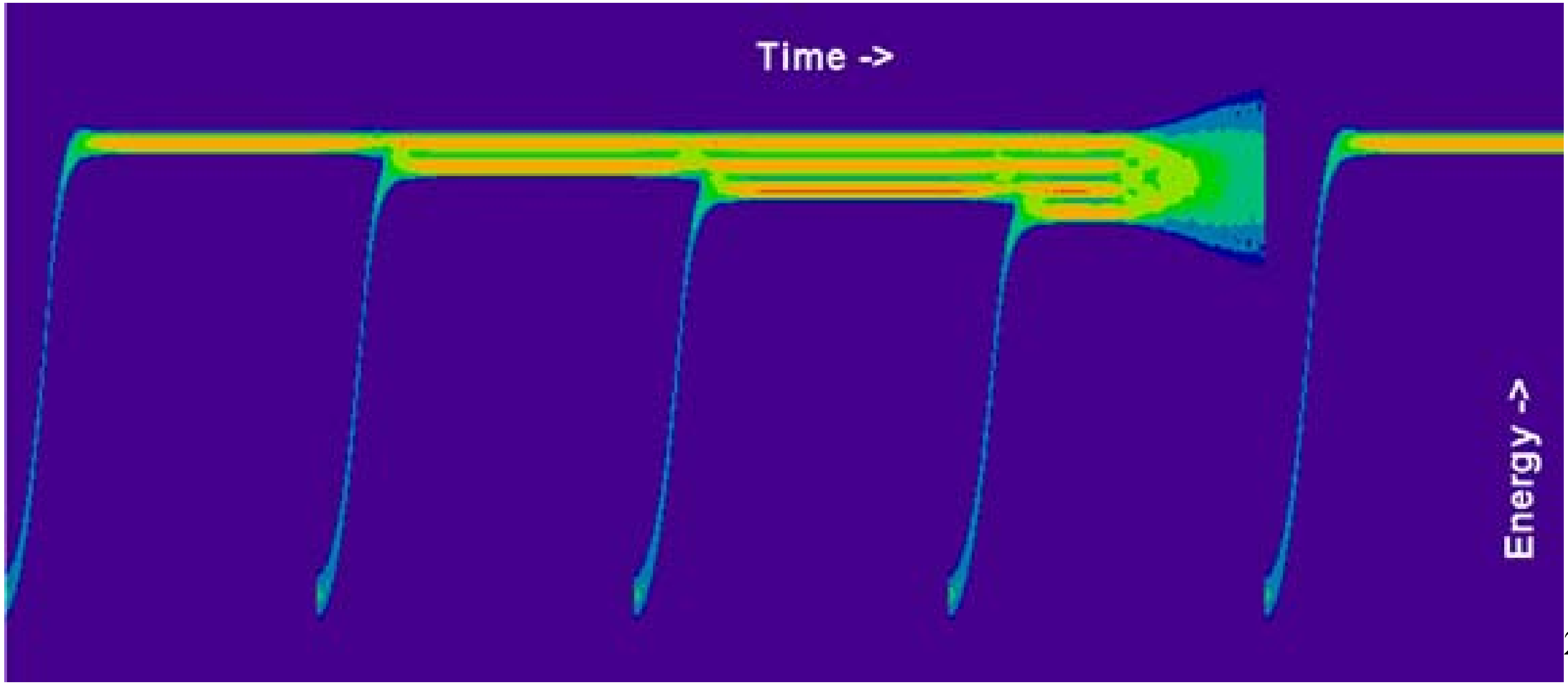
- Beam: same intensity as Proton Plan, but comes every 1.333 s, instead of 2.2 s
- Fallback: slip-stacking is expected to be made operational by the Proton Plan
  - If slip-stacking is untenable, this upgrade still provides 30% increased beam power through repetition rate and may be able to support other stacking methods

SNuMI stage 2: 1.2 MW
Momentum stacking in the Accumulator

- After the Collider program is terminated, we can *also* use the Accumulator as a proton ring
  - Transfer beam from Booster to Accumulator
    - Booster must be able to run at 15 Hz
  - Accumulator used for momentum stacking
    - momentum stack 3 Booster batches (4.6×10^{12} p/batch) every 200 ms
      - no need to cog in the Booster when injecting into the Accumulator
    - longitudinal emittance dilution of ~ 20% instead of a factor 3 like in slip-stacking
  - Box Car stack in the Recycler
    - load in a new Accumulator batch every 200 ms
    - place 6 Accumulator batches sequentially around the Recycler
  - Load the Main Injector in a single turn
  - 8.2×10^{13} ppp in MI every 1.333 s $\Rightarrow$ 1.2 MW
    - Requires RF upgrade

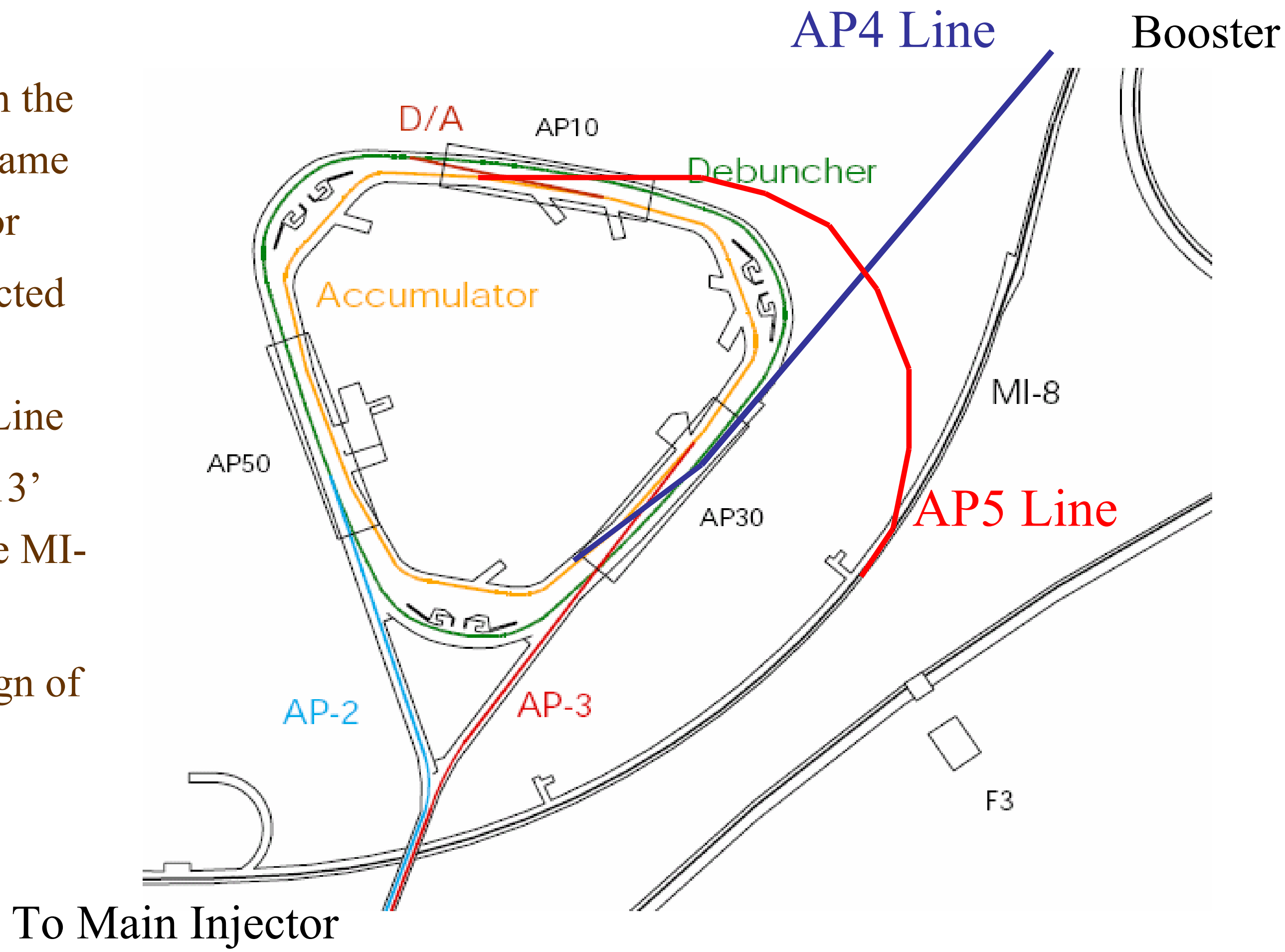
Momentum Stacking

- Beam is injected, accelerated, and debunched
- Multiple injections can be brought together
    - ➢ Different momentum beams separated horizontally
- Beam is accumulated until the momentum aperture of the Main Injector is reached
    - ➢ 4 injections shown – 3 planned for SNuMI



Accumulator transfer lines

- The Booster is connected to the Accumulator via a re-built AP4 Line
- AP4 must cross underneath the Debuncher and rise to the same elevation as the accumulator
- The Accumulator is connected to MI-8 line for SNUMI injection via the new AP5 Line
- The AP5 line must drop ~13' during the bend to reach the MI-8 elevation
- Started on conceptual design of AP4 and AP5



SNuMI scenarios

	Recycler without slip stacking	Recycler with slip stacking	Accumulator momentum stacking
Booster batch intensity	4.7E12	4.3E12	4.6E12
No. Booster batches	6	12	18
Booster average rep rate (Hz)	6	10.5	15
MI cycle time (s)	1.333	1.333	1.333
MI intensity (ppp)	2.8E13	4.9E13	8.3E13
Beam power to NuMI (kW)	400	700	1200
Protons/hr	7.6E16	1.3E17	2.2E17

8 GeV SC Linac

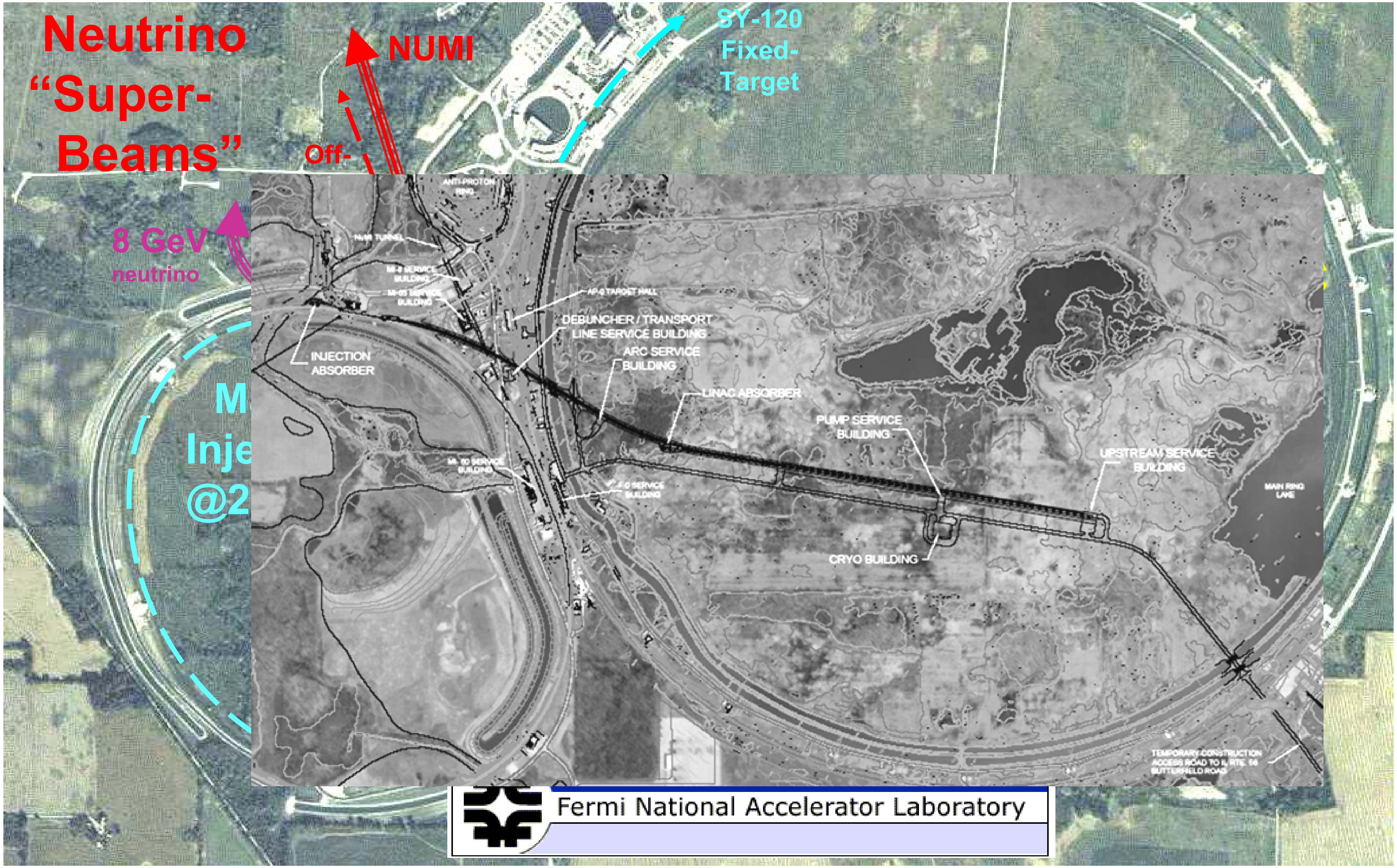
a.k.a. Proton Driver

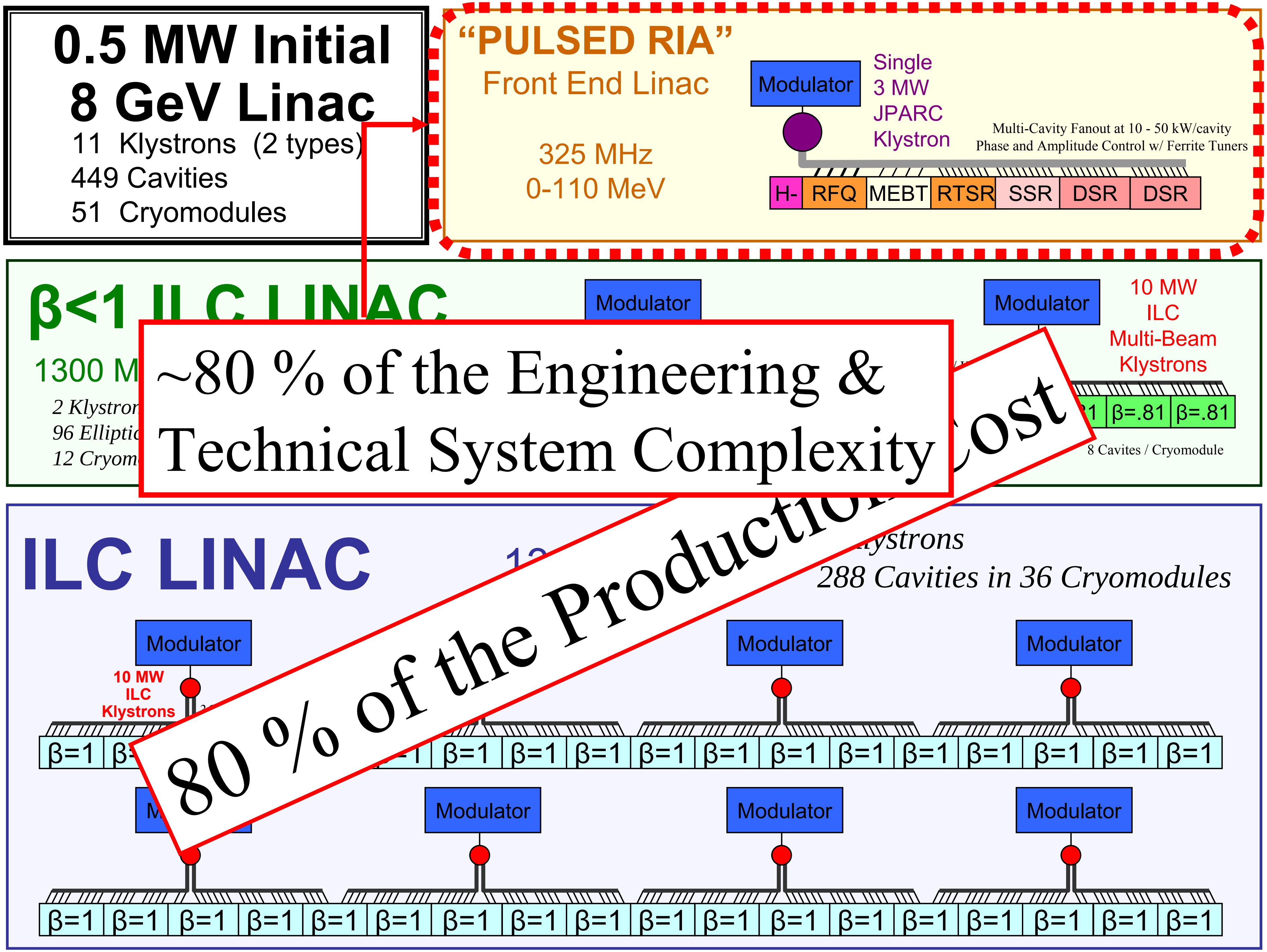
a.k.a. High Intensity Neutrino Source (HINS)

- New* idea incorporating concepts from the ILC, the Spallation Neutron Source, RIA and APT.
  - Copy SNS, RIA, and J-PARC Linac design up to 1.3 GeV
  - Use ILC Cryomodules from 1.3 - 8 GeV
  - H^- Injection at 8 GeV in Main Injector
- "Super Beams" in Fermilab Main Injector:
  - 2 MW Beam power at both 8 GeV and 120 GeV
    - 150×10^{12} protons per cycle
  - Small emittances => Small losses in Main Injector
  - Minimum (1.5 sec) cycle time (or less)

* ***The 8 GeV Linac concept actually originated with Vinod Bharadwaj and Bob Noble in 1994,when it made no sense because the SCRF gradients weren't there. Revived and expanded by G.W.Foster in 2004***

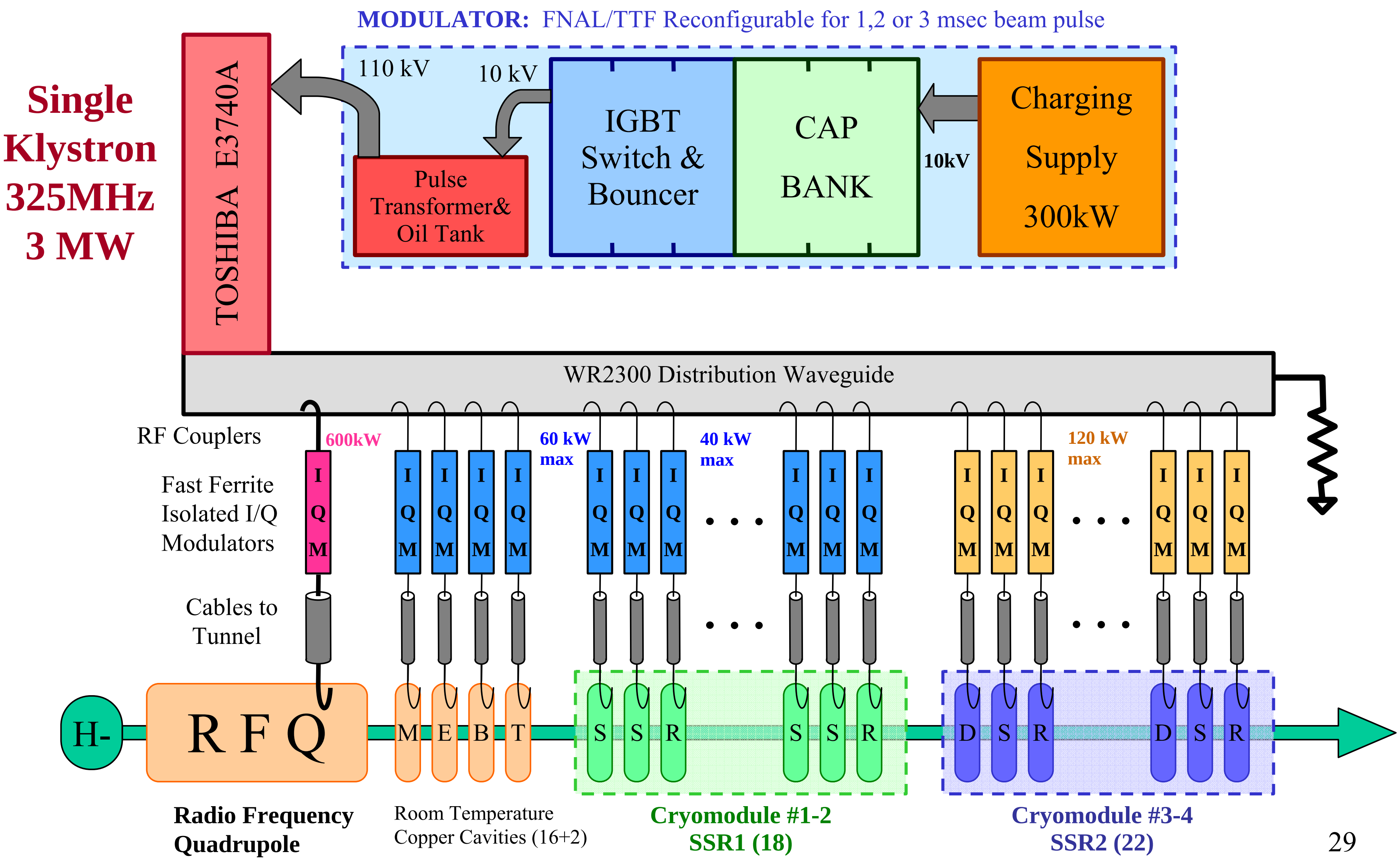
8 GeV Superconducting Linac




0.5 MW Initial
8 GeV Linac
11 Klystrons (2 types)
449 Cavities
51 Cryomodules
"PULSED RIA"
Front End Linac
325 MHz
0-110 MeV
Modulator
Single
3 MW
JPARC
Klystron
Multi-Cavity Fanout at 10 - 50 kW/cavity
Phase and Amplitude Control w/ Ferrite Tuners
H- RFQ MEBT RTSR SSR DSR DSR
β<1 ILC LINAC
1300 M
2 Klystror
96 Elliptic
12 Cryom
Modulator
Modulator
10 MW
ILC
Multi-Beam
Klystrons
β=.81 β=.81
8 Cavites / Cryomodule
~80 % of the Engineering &
Technical System Complexity
80 % of the Production Cost
ILC LINAC
288 Cavities in 36 Cryomodules
Modulator
10 MW
ILC
Klystrons
β=1

325 MHz Front End

a.k.a. One Klystron Linac



Proton Math

	Protons ÷	Cycle Time =	Power
• Current complex			
• No Improvements			
➢ Shared Beam	25×10^{12}	2.4 s	200 kW
➢ NuMI Alone	30×10^{12}	2 s	280 kW
• Proton Plan			
• Increase Beam Intensity			
➢ Shared Beam	37×10^{12}	2.2 s	320 kW
➢ NuMI Alone	49×10^{12}	2.2 s	430 kW
• SNuMI – Recycler	49×10^{12}	1.33 s	700 kW
• Reduce Cycle Time			
• SNuMI – Accumulator	83×10^{12}	1.33 s	1200 kW
• Increase Beam Intensity			
• HINS	150×10^{12}	1.33 s	2200 kW
• Increase Beam Intensity			

Schedule & Proton Power Projections

Note: ~ 1.7×10^7 s/yr (effective, at peak power)

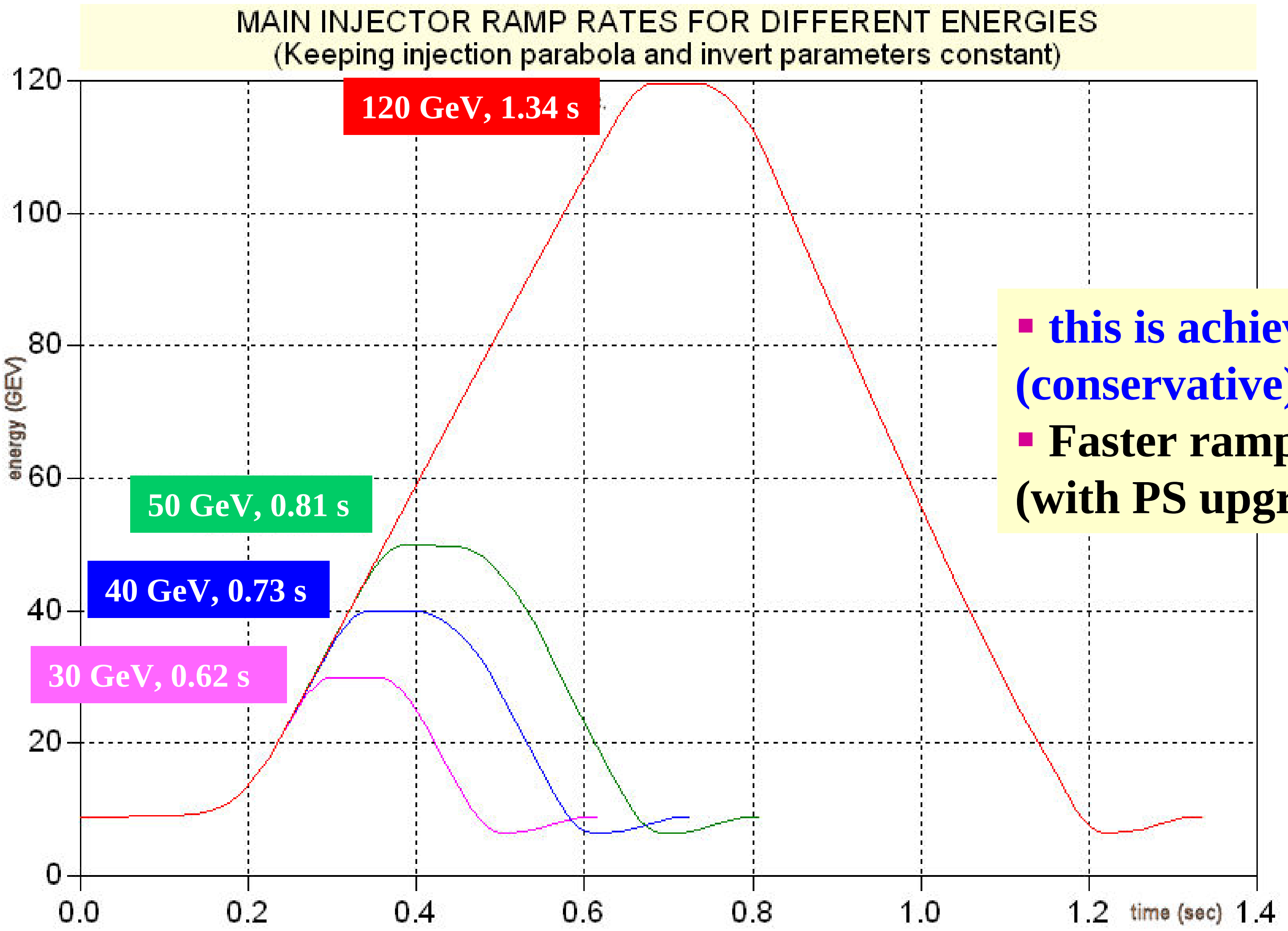
- Proton plan (in progress)
  - Ramp to a capacity of 430 kW in 2009
- SNuMI Recycler/Accumulator upgrades (in design – not approved yet)
  - Long shutdowns in 2010 & 2011
  - Ramp to 1.2 MW (700 kW) in 2013 (2012)
- High Intensity Neutrino Source (under consideration / R&D)
  - 2+ MW sometime in the future

FERMILAB-BEAMS-DOC-2393

	Current Complex	Proton Plan	SNuMI – Recycler	SNuMI – Accumulator	HINS
2006	2.3×10^{20}	2.3×10^{20}			
2007	2.3	2.8			
2008	2.3	3.1			
2009	2.3	3.4			
2010	3	4	2	2	
2011	3	4	4	4	
2012	3	4	6	7	
2013	3	4	6	10	
2014	3	4	6	10	
2015	3	4	6	10	0
2016	3	4	6	10	12
2017	3	4	6	10	20

Lowering the primary proton energy ?

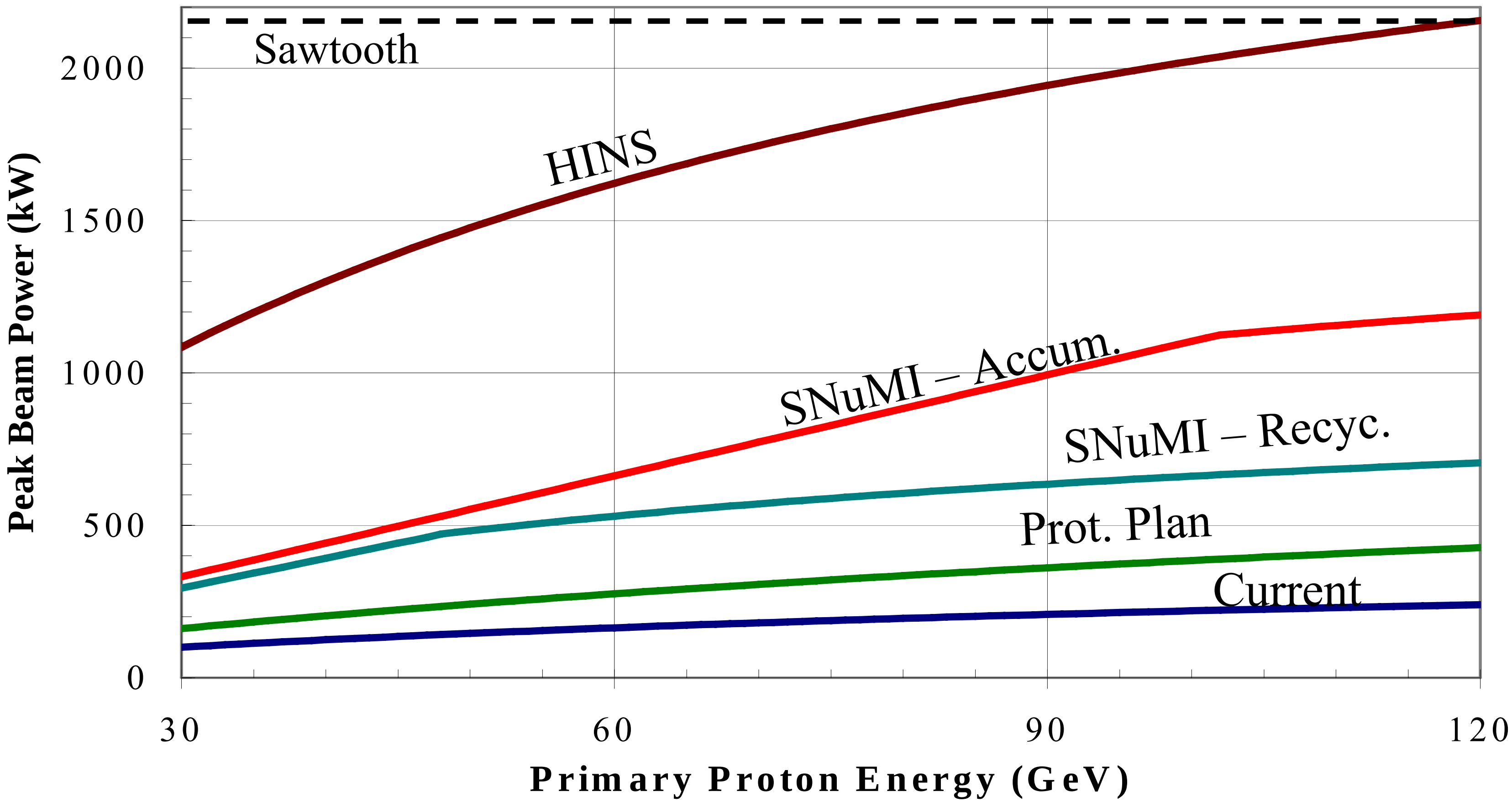
- **Injection dwell time 80 ms**
- **Flattop time 50 ms**
- **Maximum dp/dt 240 GeV/s**



- **this is achievable now (conservative)**
- **Faster ramps possible (with PS upgrades)**

Proton Energy Scaling

- Some ideas for neutrino beams have lower primary energy
- Reducing proton beam energy does not results in an equal reduction in cycle time
  - Worst for upgrades where Booster is heavily utilized
- Neutrino beams based on lower-energy protons will have lower beam power



Conclusions

- Fermilab proton complex can be upgraded to produce a Neutrino Superbeam
  - 270 kW peak (170 kW ave.) available today
  - 430 kW upgrades are in progress
    - Proton Plan → E. Prebys *et al.*
  - 700 kW & 1.2 MW upgrades are under study (likely if NOνA)
    - SNuMI → A. Marchionni *et al.*
  - ≥ 2 MW beams are under consideration – active R&D
    - HINS → G. Appolinari *et al.*
- These later upgrades all are technically feasible for the accelerators
  - Limitations are resources and the capacity of the NuMI line