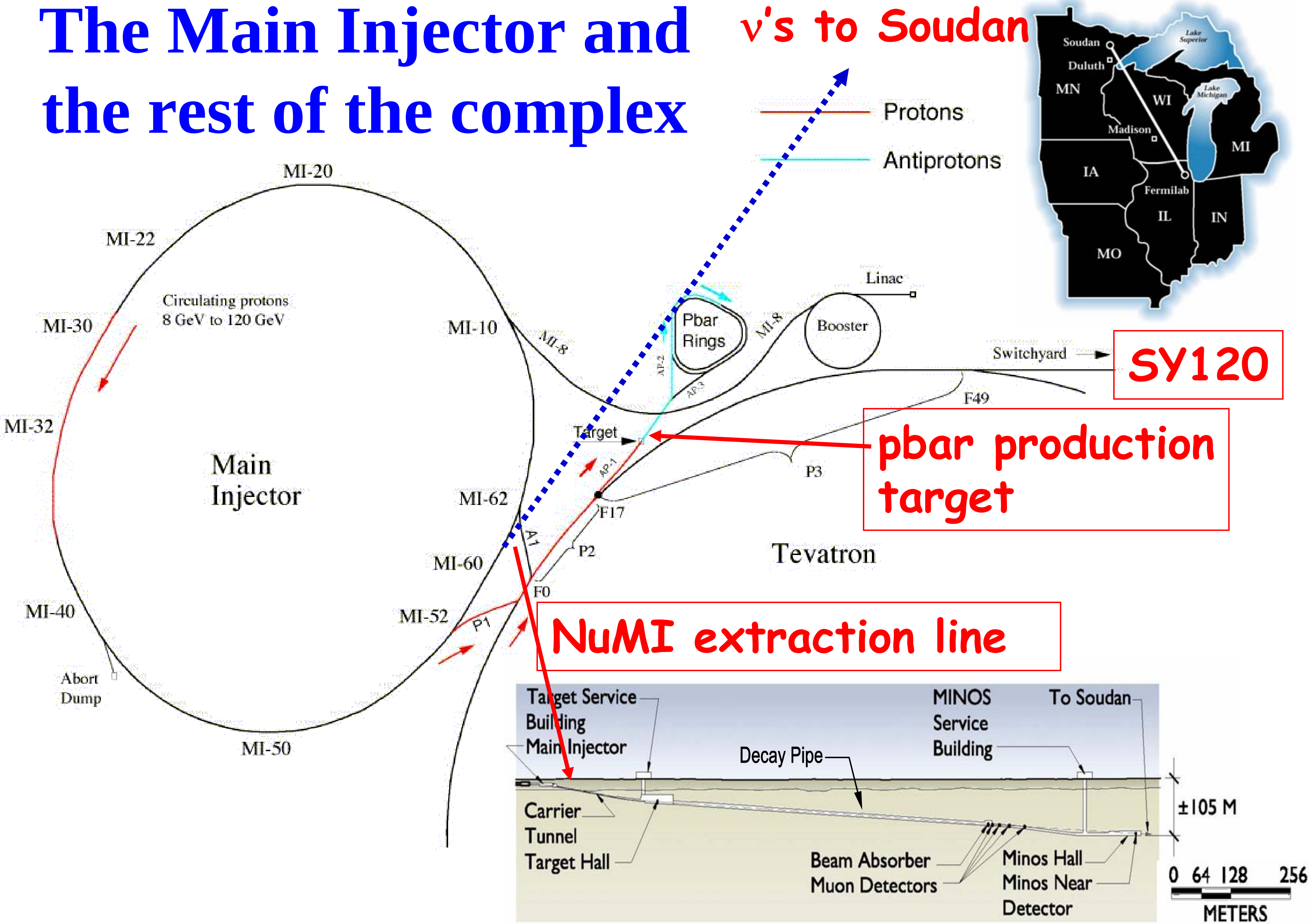
# Main Injector and NuMI upgrades and beyond

*A. Marchionni*

*Workshop on Long Baseline Neutrino experiments*
*March 6-7, 2006 - Fermilab*

- **Main Injector and NuMI primary proton line**
  - **NuMI designed for 400 kW, achieved a max beam power of 270 kW**
- **Main Injector and NuMI intensity steps**
  - **multi-batch stacking in MI**
  - **Recycler as an 8 GeV proton accumulator**
  - **momentum stacking in the Accumulator**
  - **Main Injector with a Proton Driver**
- **Exploring neutrino beams towards a DUSEL site**
- **Conclusions**

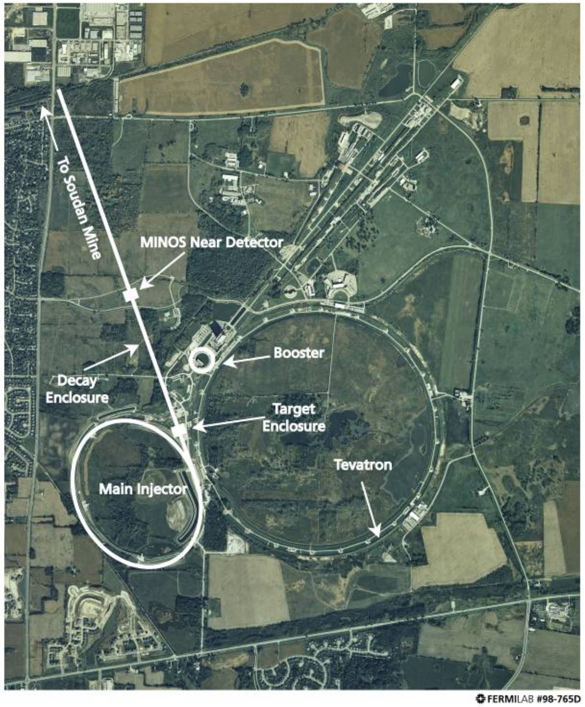
# The Main Injector and the rest of the complex



# Main Injector construction parameters

| | | | |
|---|---|---|---|
| Circumference | 3319.49 m | Harmonic Number | 588 (**7×84**) |
| Injection momentum | 8.88 GeV/c | RF Frequency (Inj.) | 52.8 MHz |
| Peak momentum | 150 GeV/c | RF Frequency (Extr.) | 53.1 MHz |
| Transition gamma | 21.8 | RF Voltage | 4 MV |

- there is enough RF power to safely accelerate $6\times10^{13}$ protons/cycle at a maximum rate of 205 GeV/s
- several studies concur with not finding major problems due to instabilities up to $6\times10^{13}$ protons/cycle (see Proton Driver Study I&II, TM-2136,TM-2169)
- a **$\gamma_t$-jump system and a substantial upgrade of the RF system** are the major modifications that would allow to raise the intensity up to $1.5\times10^{14}$ protons/cycle (TM-2169)

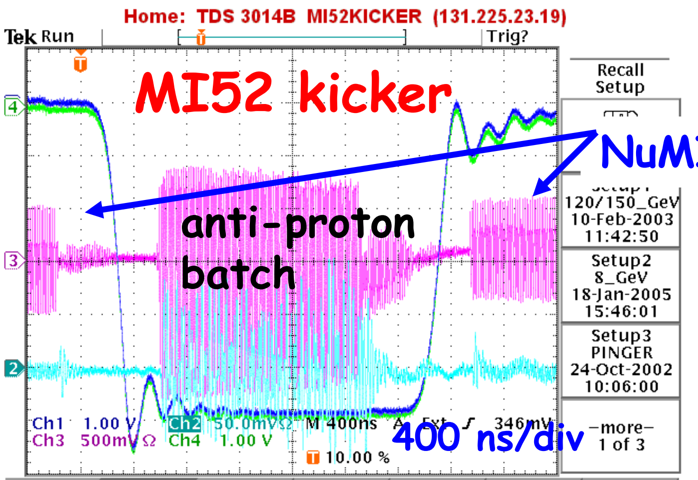



# Main Injector & NuMI

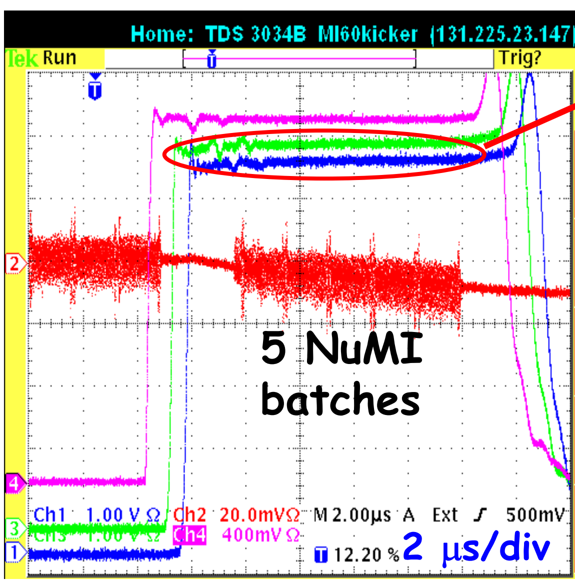
- **Main Injector is a rapid cycling (up to 240 GeV/s) accelerator at 120 GeV**
  - **from 8.9 to 120 GeV/c in ~ 1.5 s**
- **up to 6 proton batches (~ 5×10$^{12}$ p/batch) are successively injected from Booster into Main Injector**
- **now Main Injector has to satisfy simultaneously the needs of the Collider program (anti-proton stacking and transfers to the Tevatron) and NuMI**
- **achieved max beam intensity ~ 3.15×10$^{13}$ ppp**
- **present cycle length 2 s**

- **Mixed mode: NuMI & anti-proton stacking**
  - two single turn extractions within ~ 1 ms:
    - 1 batch to the anti-proton target, following the firing of the MI52 kicker
    - 5 batches to NuMI, following the firing of the NuMI kickers, in ~ 8 μs
  - the batch extracted to the anti-proton target comes from
    - either a single Booster batch
    - **or the merging of two Booster batches ("slip-stacking") (~ 0.8×10$^{13}$ ppp)**
  - ***the default mode of operation is mixed-mode with slip-stacking***
- **NuMI only**
  - up to 6 Booster batches extracted to NuMI in ~ 10 μs

# Extraction from the Main Injector




## NuMI kickers

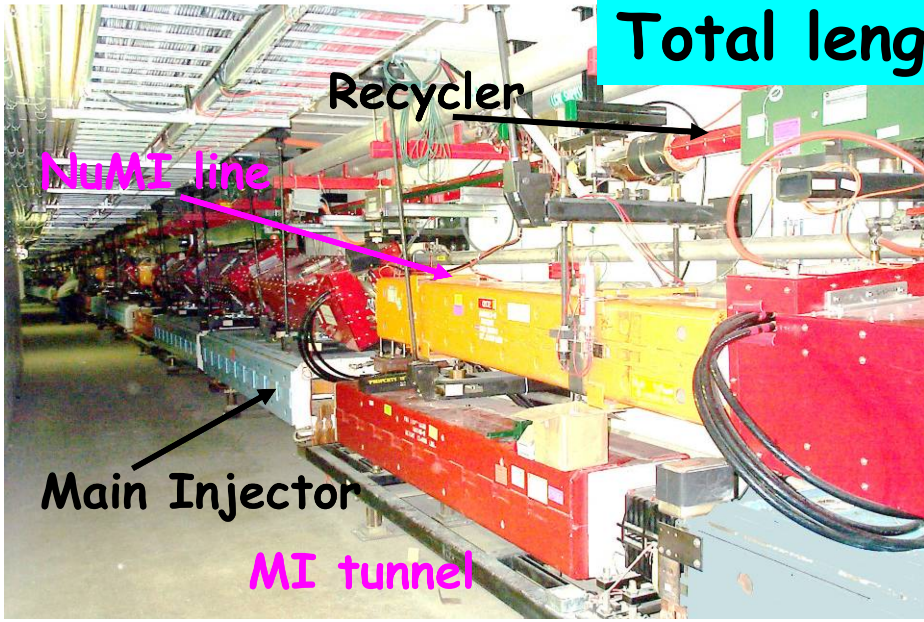


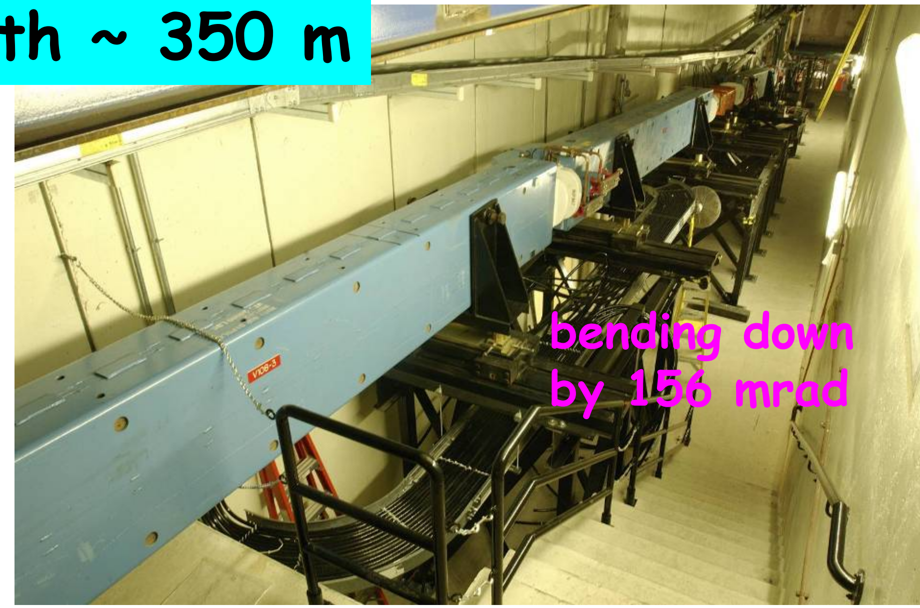

NuMI kickers flat region

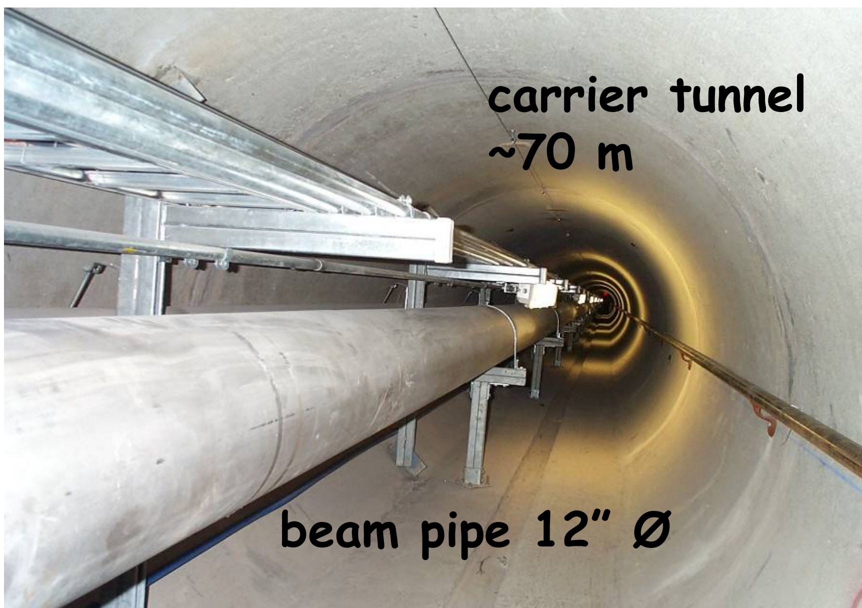
flat within ±0.8 % over 10 μs


# The primary proton line

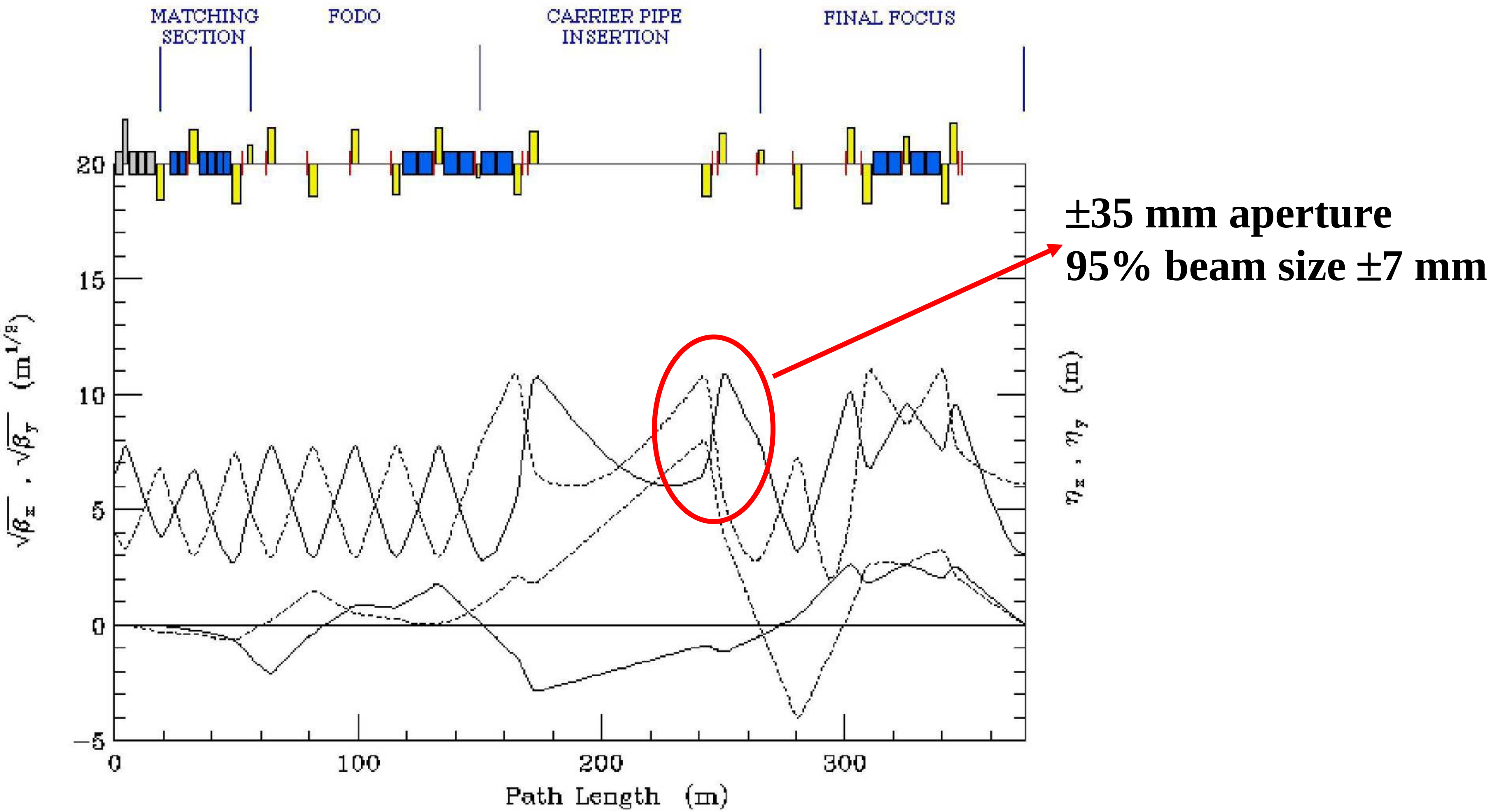
Total length ~ 350 m



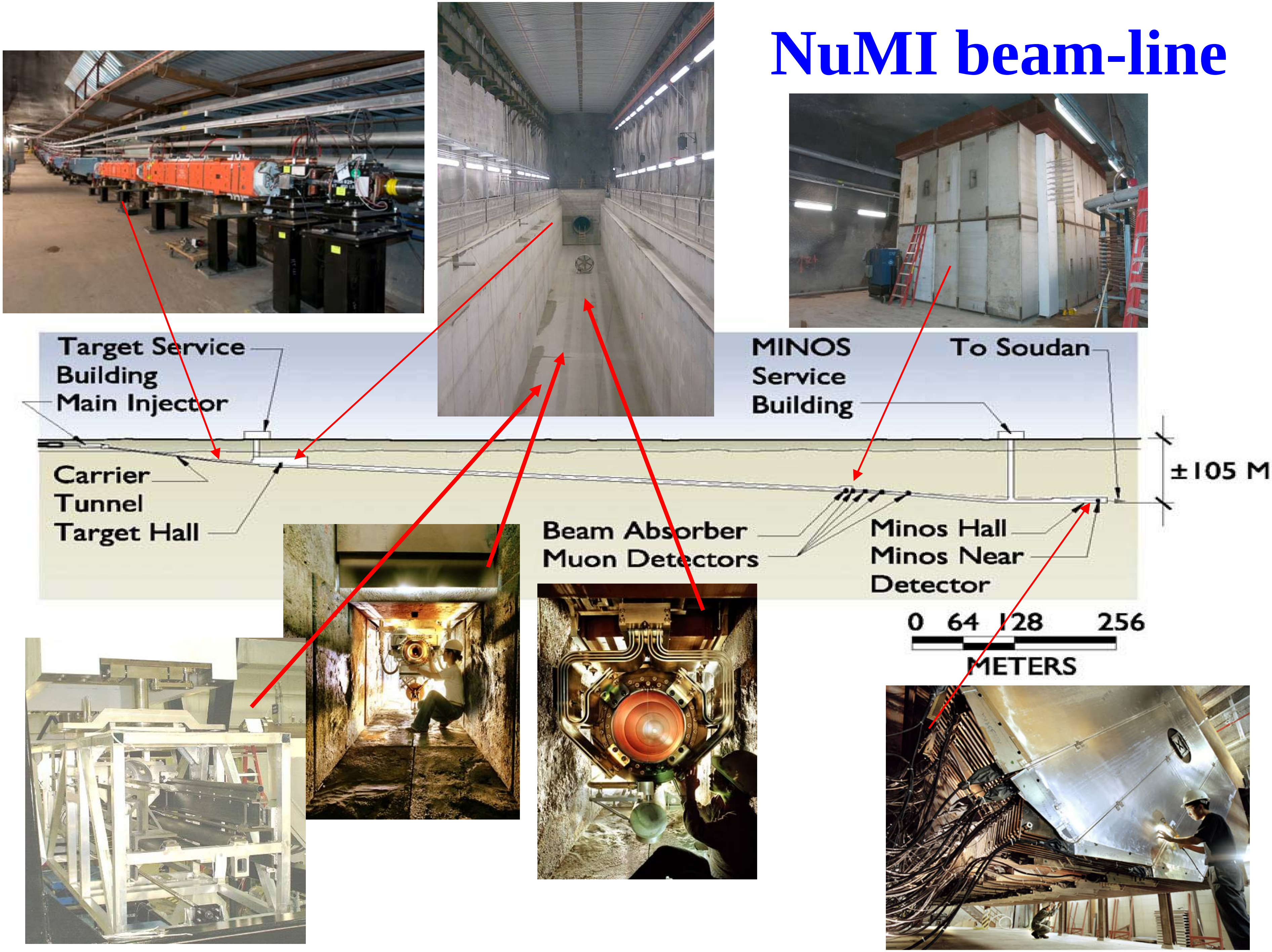

# NuMI Primary Proton Line



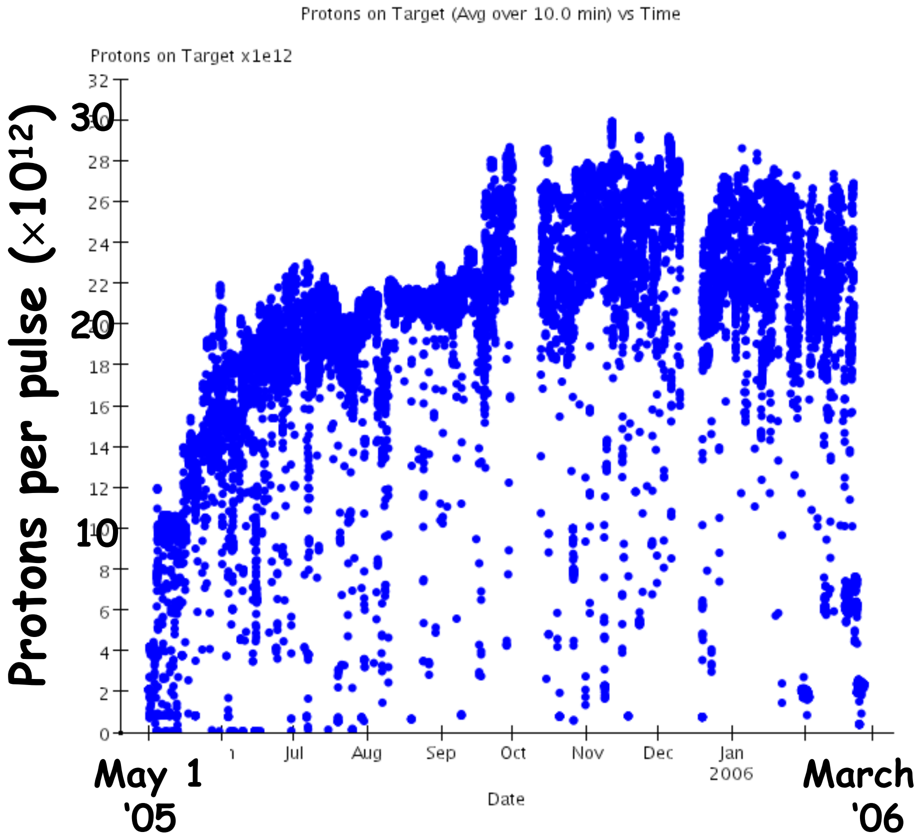

Specifications: fractional beam losses below $10^{-5}$

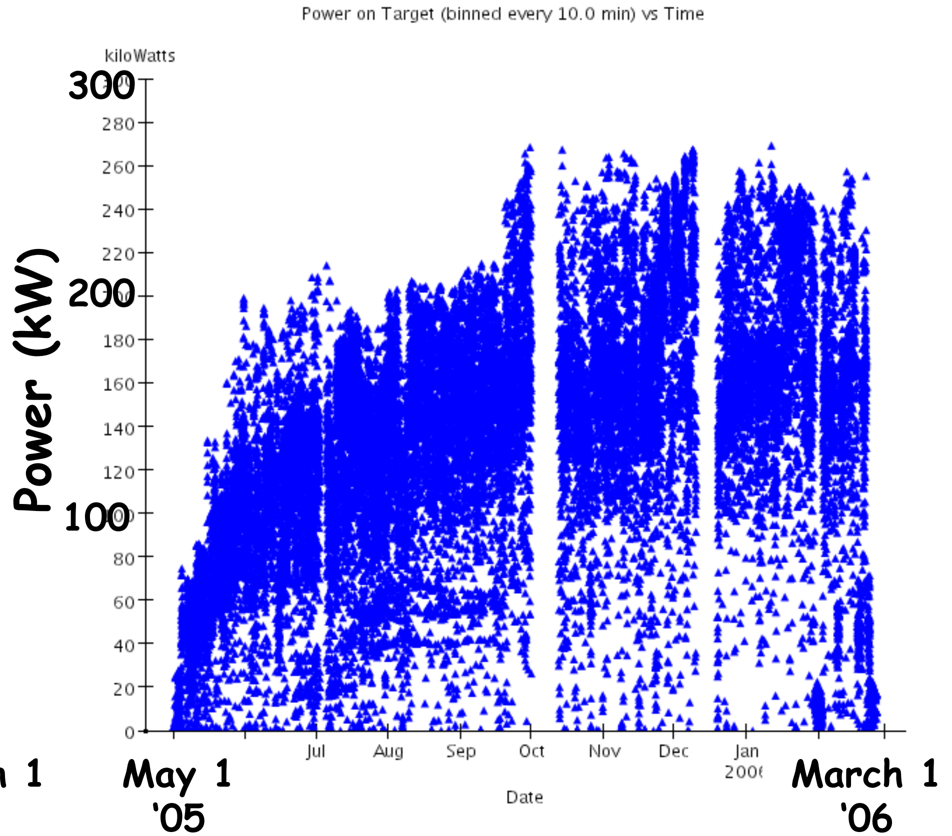
**Large aperture line !**

# NuMI beam-line



# NuMI last year running

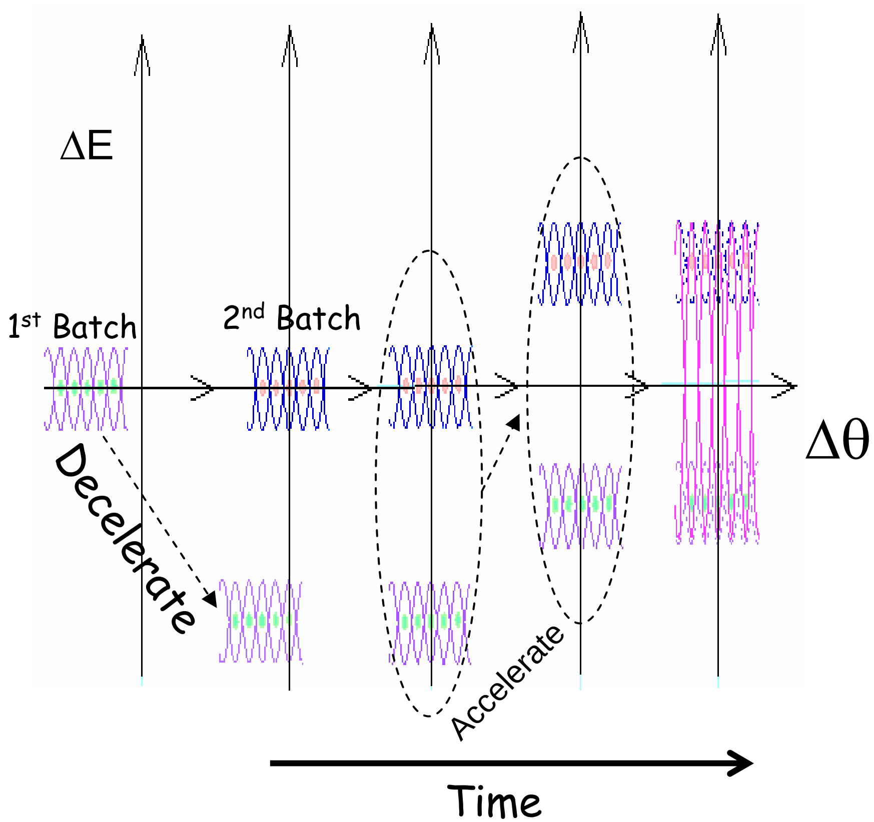


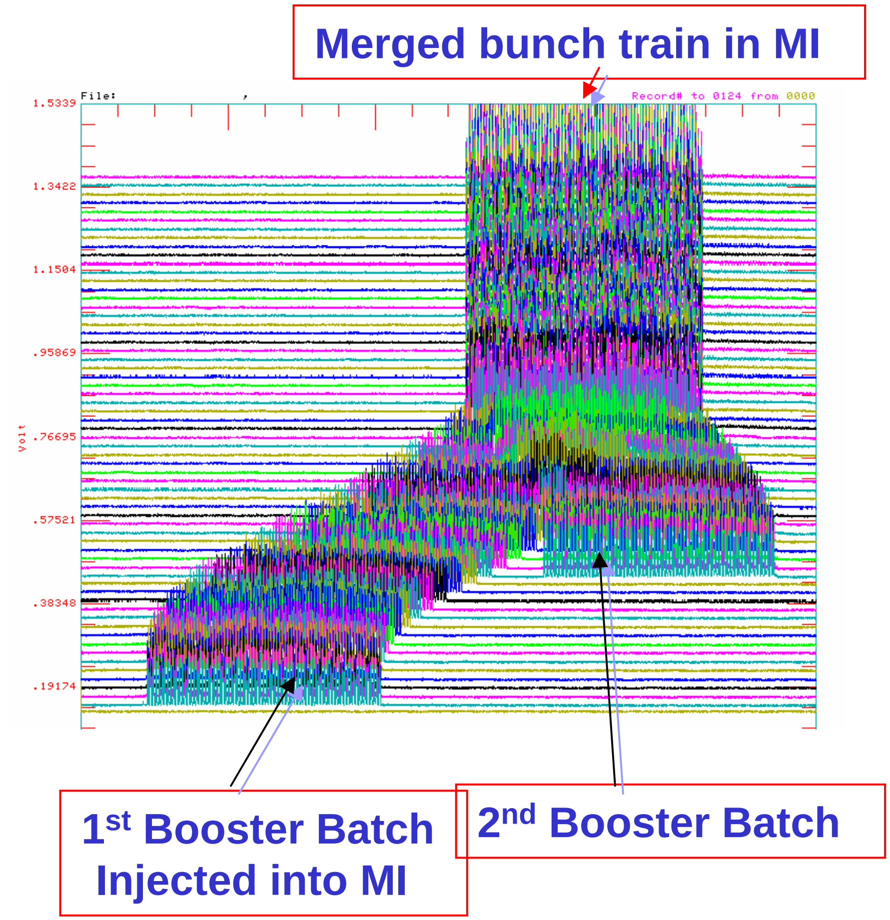




- average power of 165 kW in the last few months
- reached a max beam power of 270 kW down the NuMI line (stably for ~ ½ hour)
- reached a peak intensity of $3\times10^{13}$ ppp on the NuMI target

# Slip-stacking

- A scheme to merge two booster batches to double proton intensity on pbar production target



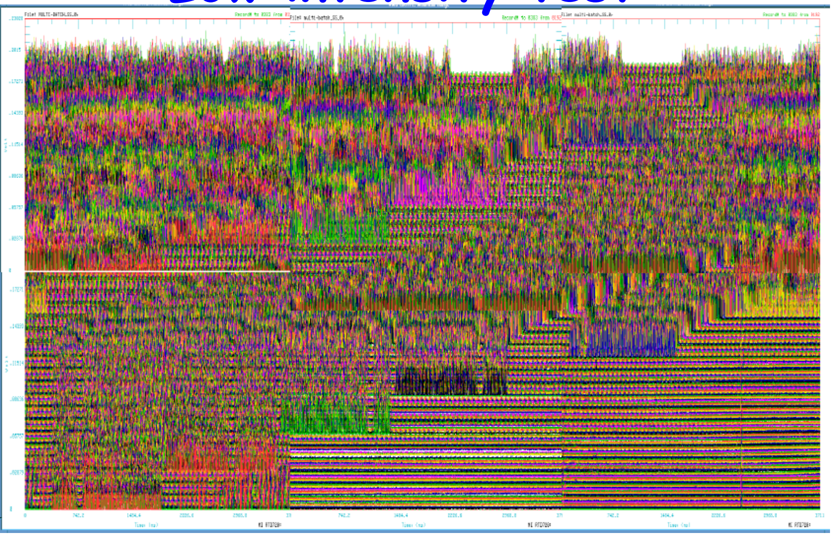

K. Koba Seiya et. al., PAC2003

➢ designed to achieve a slip-stacked batch of $1\times10^{13}$ protons in 3 Booster ticks

# Multi-batch slip-stacking in MI

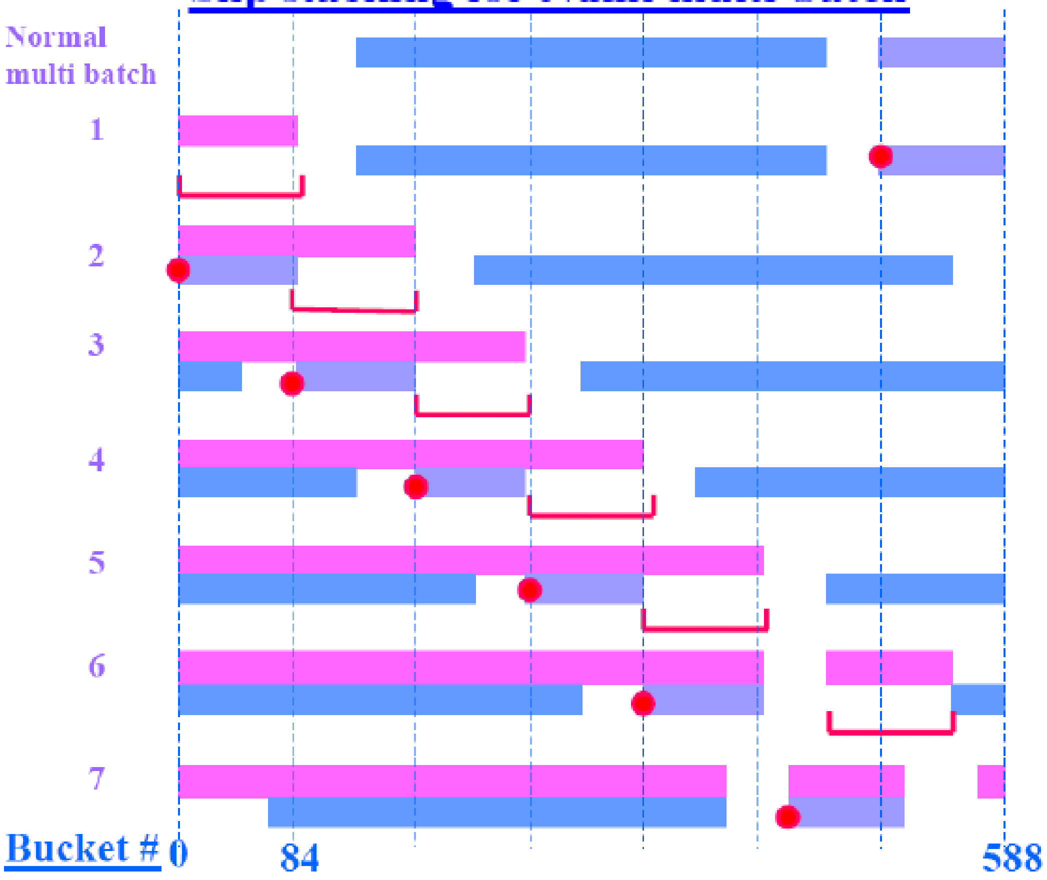
❖ **While running in mixed mode, it is possible to slip-stack 4 out of the 5 NuMI batches, in addition to a slip-stacked batch for the anti-proton source**

Low intensity test



I. Kourbanis, K. Seiya

Slip stacking for Numi multi-batch



# Multi-batch slip-stacking in MI

Proton Plan
http://www-accel-proj.fnal.gov/internal/Proton_Plan/index.html

- **a viable option while Tevatron still running**
- **Efficiency factors**
  - complex up 0.84 (44 weeks/year, $2.66\times10^7$ s/year)
  - uptime 0.85
  - collider operation 0.85
  - average to peak 0.9
  - slip-stacking efficiency 0.9
- **Proton intensities and average power**
  - Booster **$5\times10^{12}$ p/batch**
  - MI cycle time (11 batches injection) **2.2 s**
  - NuMI only cycles **$5\times10^{13}$ ppp** **430 kW**
  - NuMI mixed mode cycles **$4.1\times10^{13}$ ppp** **355kW**
- **NuMI protons/year $3.2\times10^{20}$**

# Recycler as an 8 GeV proton accumulator

S. Nagaitsev, E. Prebys, M. Syphers 'First Report of the Proton Study Group', Beams-doc-2178

- After the Collider program is terminated, we can use the Recycler as a proton accumulator
  - Booster batches are injected at 15 Hz rep rate
  - if we use the Recycler to accumulate protons from the Booster while MI is running, we can save 0.4 s for each 6 Booster batches injected
  - Recycler momentum aperture is large enough to allow slip-stacking operation in Recycler, for up to 12 Booster batches injected
  - 6 batches are slipped with respect to the other 6 and, at the time they line up, they are extracted to MI in a single turn
- With $5.4\times10^{13}$ ppp every 1.467 s $\Rightarrow$ 700 kW
- with $2\times10^{7}$ effective seconds/year $\Rightarrow$ $7.5\times10^{20}$ pot/year
- Decrease of MI cycle duration down to 1 – 1.1 s ?
  - need upgrade of MI magnet power supplies and RF system
  - careful consideration of losses

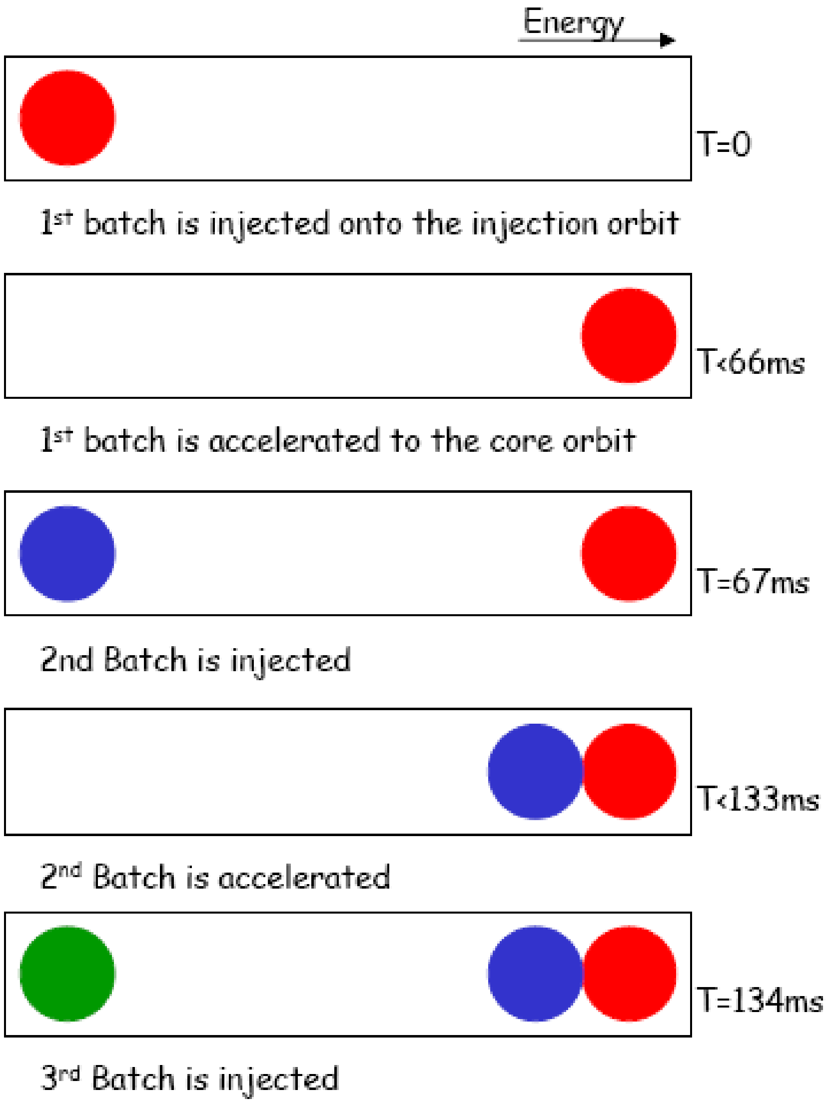
# Momentum stacking in the Accumulator

D. McGinnis, Beams-doc-1782, 2138

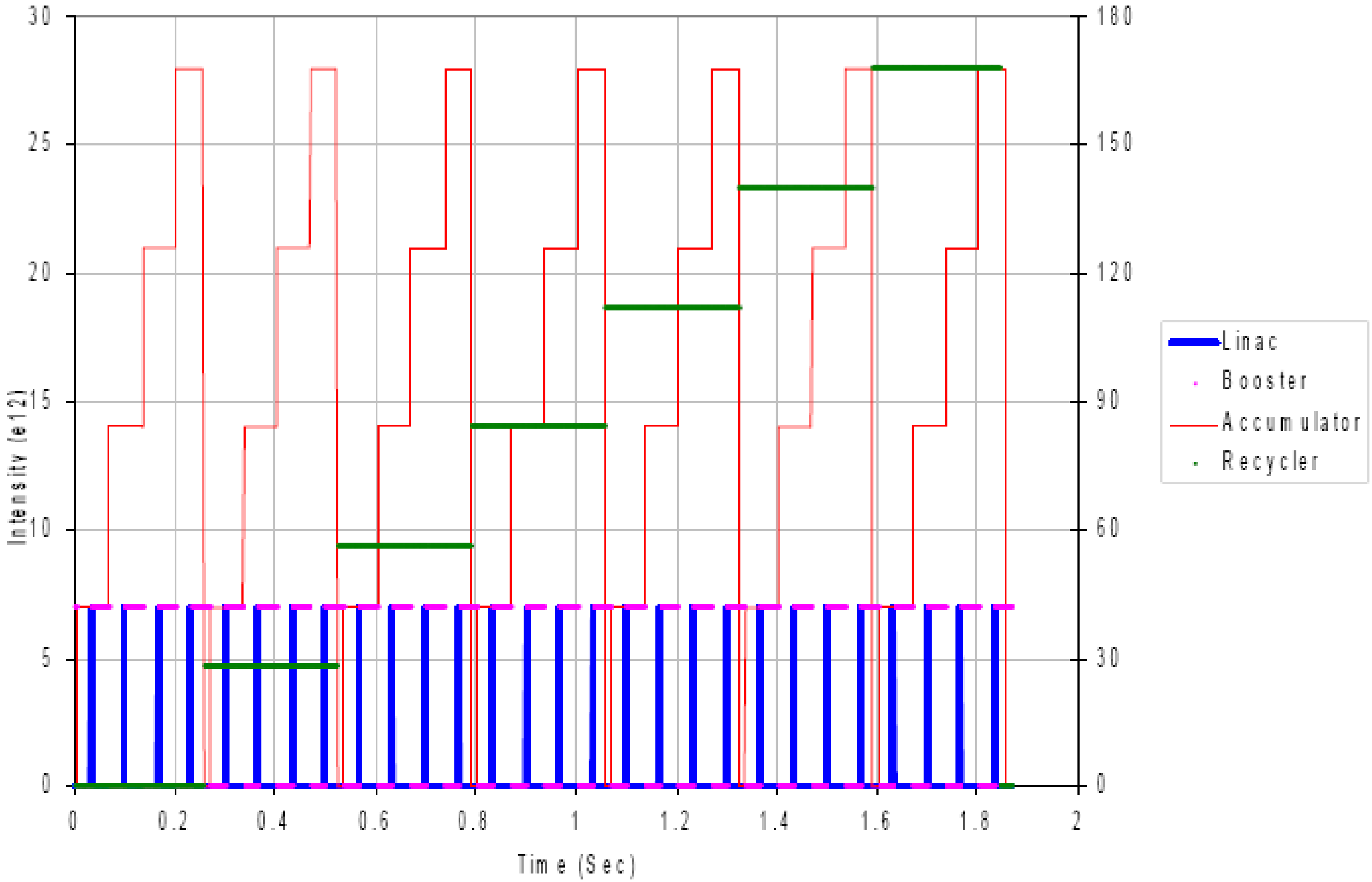
- **After the Collider program is terminated, we can *also* use the Accumulator in the Anti-proton Source as a proton accumulator**
  - **after acceleration in the Booster, beam will be transferred to the Accumulator ring**
  - **the Accumulator was designed for momentum stacking**
    - **momentum stack 4 Booster batches every 267 ms**
    - **limit Booster batch size to $4\times10^{12}$ protons**
  - **Box Car stack in the Recycler**
    - **load in a new Accumulator batch every 267 ms**
    - **place 6 Accumulator batches sequentially around the Recycler**
  - **Load the Main Injector in a single turn**
  - **$9.5\times10^{13}$ ppp in MI every 1.6 s $\Rightarrow$ 1.1 MW**
- **with $2\times10^{7}$ effective seconds/year $\Rightarrow$ $12\times10^{20}$ pot/year**

# Mechanics of Momentum Stacking

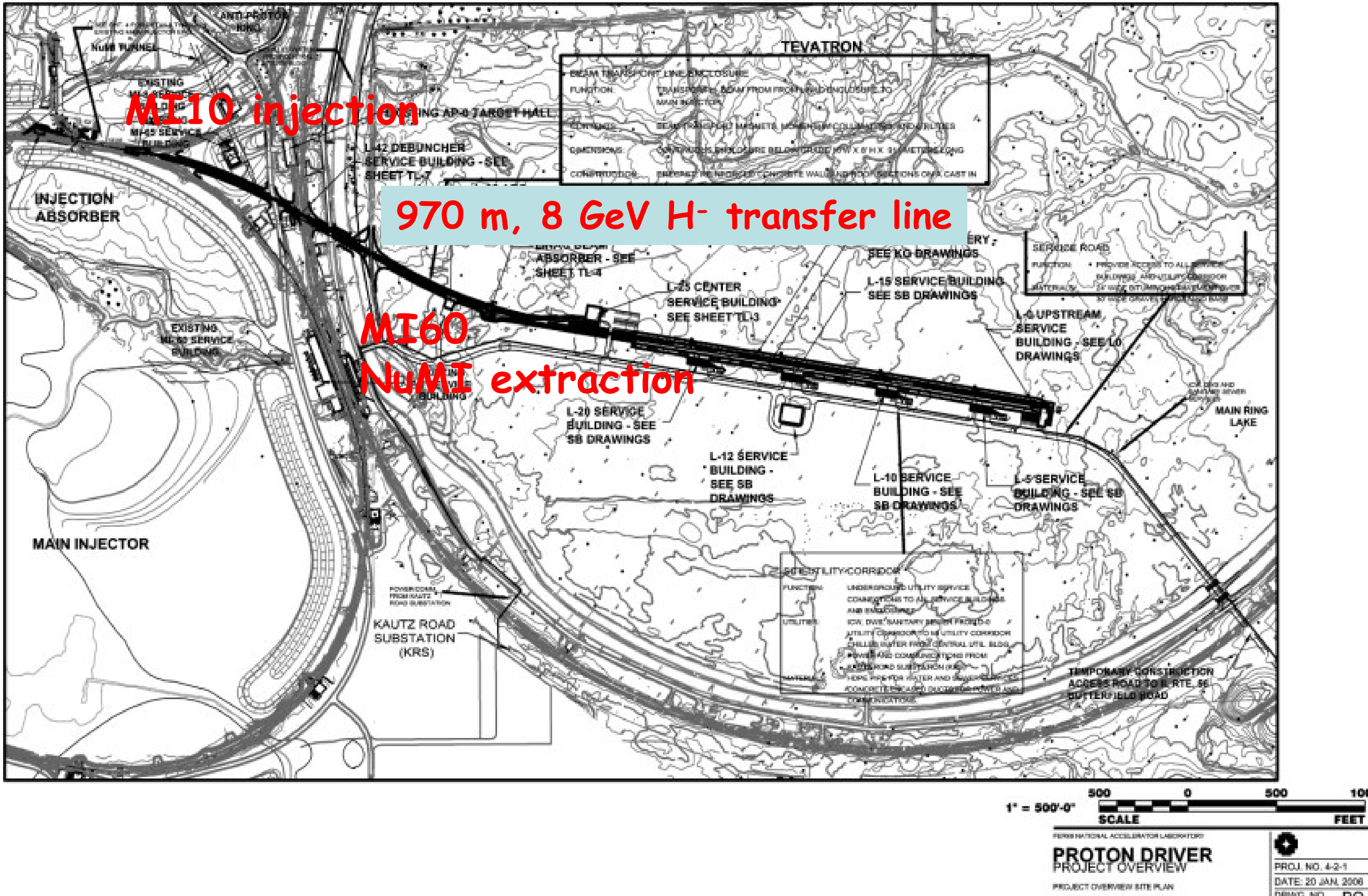
- Inject in a newly accelerated Booster batch every 67 mS onto the low momentum orbit of the Accumulator
- The freshly injected batch is accelerated towards the core orbit where it is merged and debunched into the core orbit
- Momentum stack 3-4 Booster batches



# Multi-stage Proton Accumulator Production Cycle



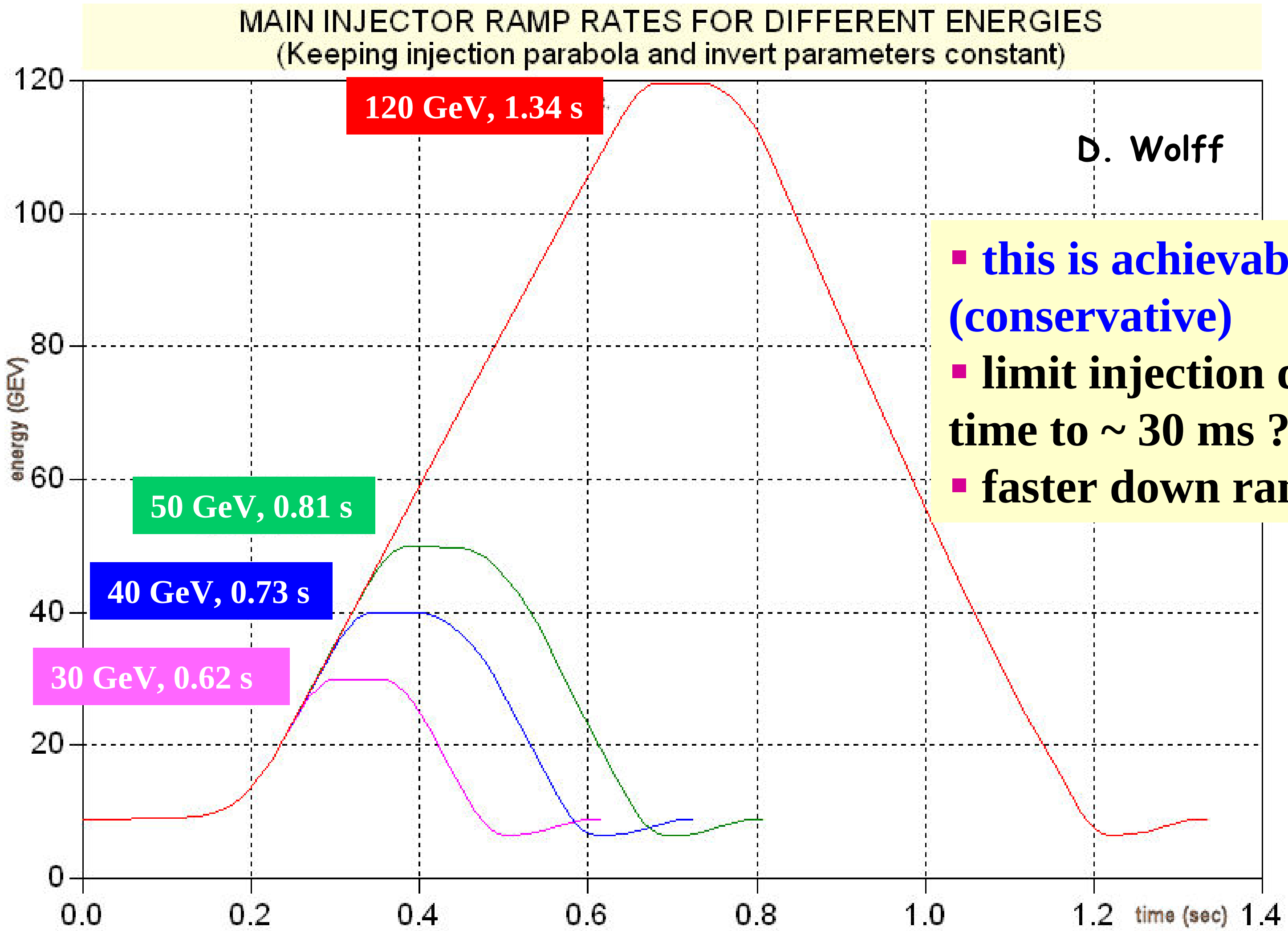
# Proton Driver Layout



# Proton Driver for Main Injector

- **Nominal injection charge ~$1.5\times10^{14}$ ppp**
  - **8 mA for ~270 turns in 3 msec**
  - **25 mA for ~90 turns in 1 msec**
- Nominal Transverse Emittance
  - **~1/2 π mm-mrad rms**
  - **will want to paint the MI acceptance phase space**
- Longitudinal Emittance
  - **Single bunch energy spread is not an issue, ~1 MeV**
  - **Energy control over the long pulse is important**
  - **Debuncher and momentum collimation in transport line will limit energy spread seen by Main Injector**
  - **< ±10 MeV is the design objective**
- **$1.5\times10^{14}$ ppp every 1.467 s corresponds to a beam power of 2 MW at 120 GeV**
  - **can we maintain 2 MW for lower proton energies ?**
- **with $2\times10^{7}$ effective seconds/year $\Rightarrow$ $20\times10^{20}$ pot/year at 120 GeV**

# Lowering the primary proton energy ?




- this is achievable now (conservative)
- limit injection dwell time to ~ 30 ms ?
- faster down ramp ?

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

# Main Injector, Recycler and NuMI upgrades

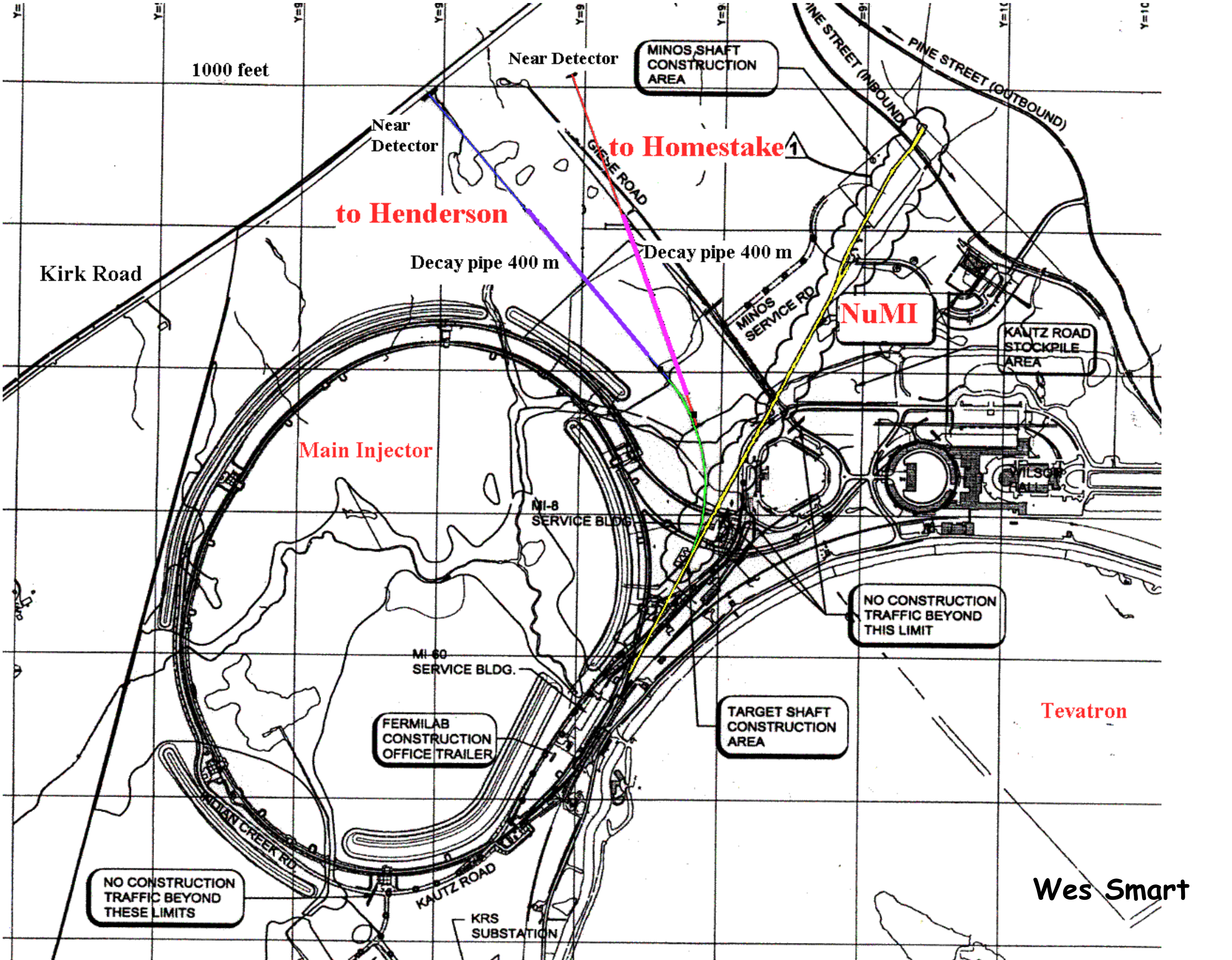
- A set of upgrades to the accelerator complex is necessary at each step in beam power
- The ‘Proton Plan’ project is carrying out the plan to implement multi-batch slip-stacking in MI and the necessary Booster upgrades
- A new Project is being setup in Accelerator Division, with a first charge to develop a conceptual design and cost estimate (by Fall 2006) for the use of the Recycler as an 8 GeV proton accumulator
  - this includes all NuMI Target Hall modifications necessary to operate the facility at 700 kW
- A study group  is addressing beam instability issues in Main Injector and Recycler Ring at high intensity (> $6\times10^{13}$ ppp)
  - we are starting to investigate ‘Electron Cloud’ effects in our machines
- Above $6\times10^{13}$ ppp we need substantial upgrades in Main Injector
  - a $\gamma_t$-jump system, conceptual design in FNAL-TM-2169
  - a new RF system in MI, preliminary study for a 2 MW system as part of the Proton Driver study

# Exploring the possibility of neutrino beams towards a DUSEL site

W. Smart

| | Latitude | Longitude | Vertical angle from FNAL (deg) | Distance from FNAL (km) |
|---|---|---|---|---|
| **Homestake** | 44.35 | -103.77 | -5.84 | 1289 |
| **Henderson** | 39.76 | -105.84 | -6.66 | 1495 |

- Use of the present extraction out of the Main Injector into the NuMI line
- Construction of an additional tunnel, in the proximity of the Lower Hobbit door in the NuMI line, in order to transport the proton beam to the west direction
- Radius of curvature of this line same as the Main Injector, adequate for up to 120 GeV/c proton beam with conventional magnets
- Assumptions:
  - **a target hall length of ~45 m (same as NuMI for this first layout, probably shorter )**
  - **decay pipe of 400 m (adequate for a low energy beam), we would gain in neutrino flux by increasing the decay pipe radius (> 1 m)**
  - **distance of ~300 m from the end of the decay pipe to a Near Detector (same as NuMI).**



1000 feet
Near Detector
Near Detector
MINOS SHAFT CONSTRUCTION AREA
PINE STREET (INBOUND)
PINE STREET (OUTBOUND)
to Homestake
GIESE ROAD
to Henderson
Kirk Road
Decay pipe 400 m
Decay pipe 400 m
MINOS SERVICE RD
NuMI
KAUTZ ROAD STOCKPILE AREA
Main Injector
MI-8 SERVICE BLDG
WILSON HALL
NO CONSTRUCTION TRAFFIC BEYOND THIS LIMIT
MI 60 SERVICE BLDG.
TARGET SHAFT CONSTRUCTION AREA
Tevatron
FERMILAB CONSTRUCTION OFFICE TRAILER
INDIAN CREEK RD
KAUTZ ROAD
NO CONSTRUCTION TRAFFIC BEYOND THESE LIMITS
KRS SUBSTATION
Wes Smart

# Conclusions I

❖ **A set of staged upgrades to the accelerator complex and the NuMI line has the ability to increase the beam power up to ~ 1MW, but a Proton Driver (or a new Booster) is needed to reach 2 MW**

❖ **Formal projects and study groups have been and are being set up to identify and address the issues in the accelerator complex and the NuMI line**

- **looking for more help**

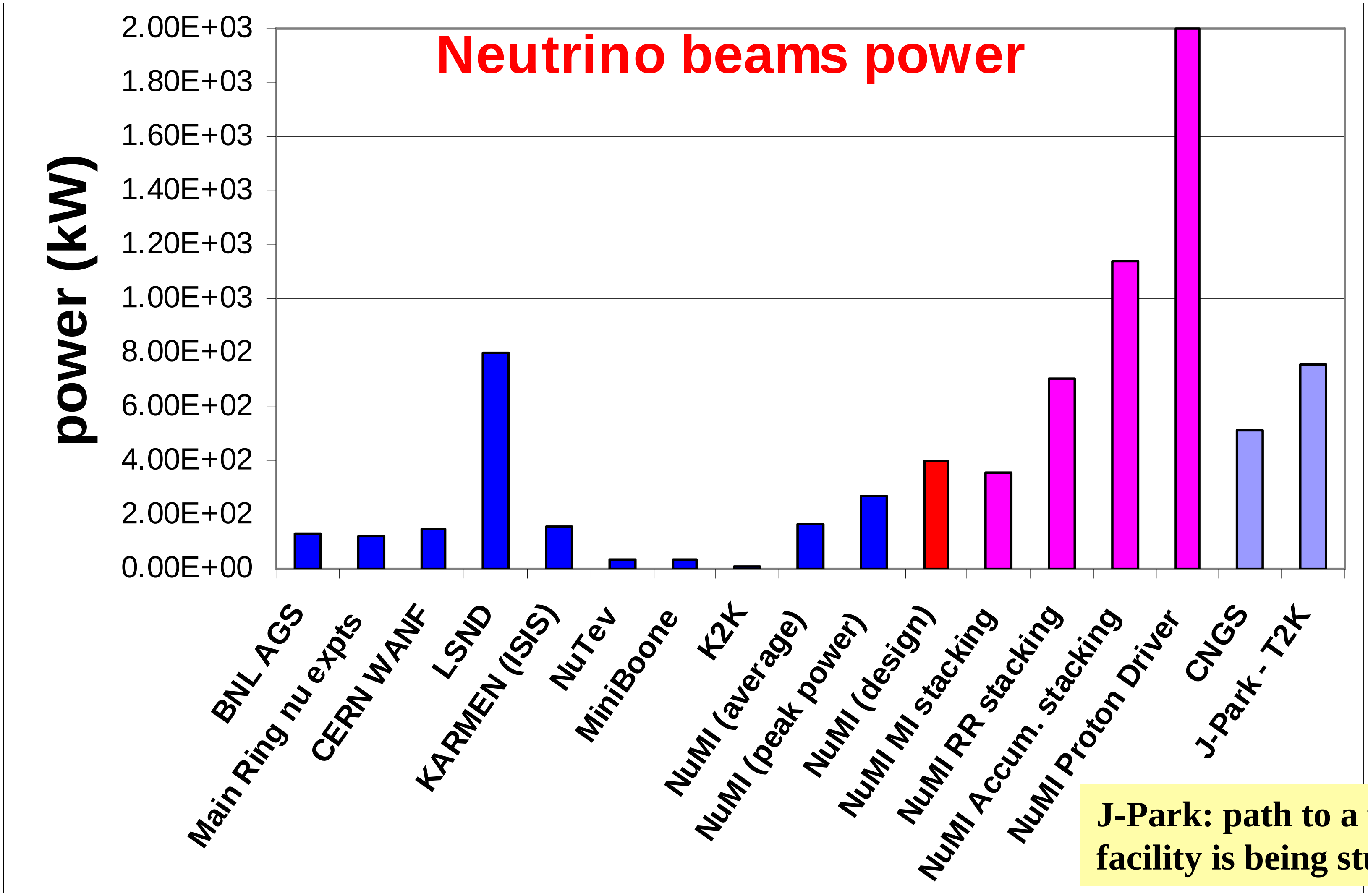
❖ **We need to clearly understand if we need to use protons of lower energy (< 120 GeV/c) for the generation of 'low energy' neutrino beams**

- **some of the 'upgrades' do not have the flexibility of reducing the MI extraction energy while keeping beam power ~ constant**
- **more studies needed to minimize cycle lengths in MI**

❖ **Preliminary layout of neutrino beams towards a DUSEL site**

- need optimization of decay pipe length and radius

# Conclusions II




**J-Park: path to a few MW facility is being studied**

"Faber est suae quisque fortunae" "Every Lab is the maker of its own fortune"

*Appius Claudius Caecus*

*(Roman politician, built the 1st paved roman road)*