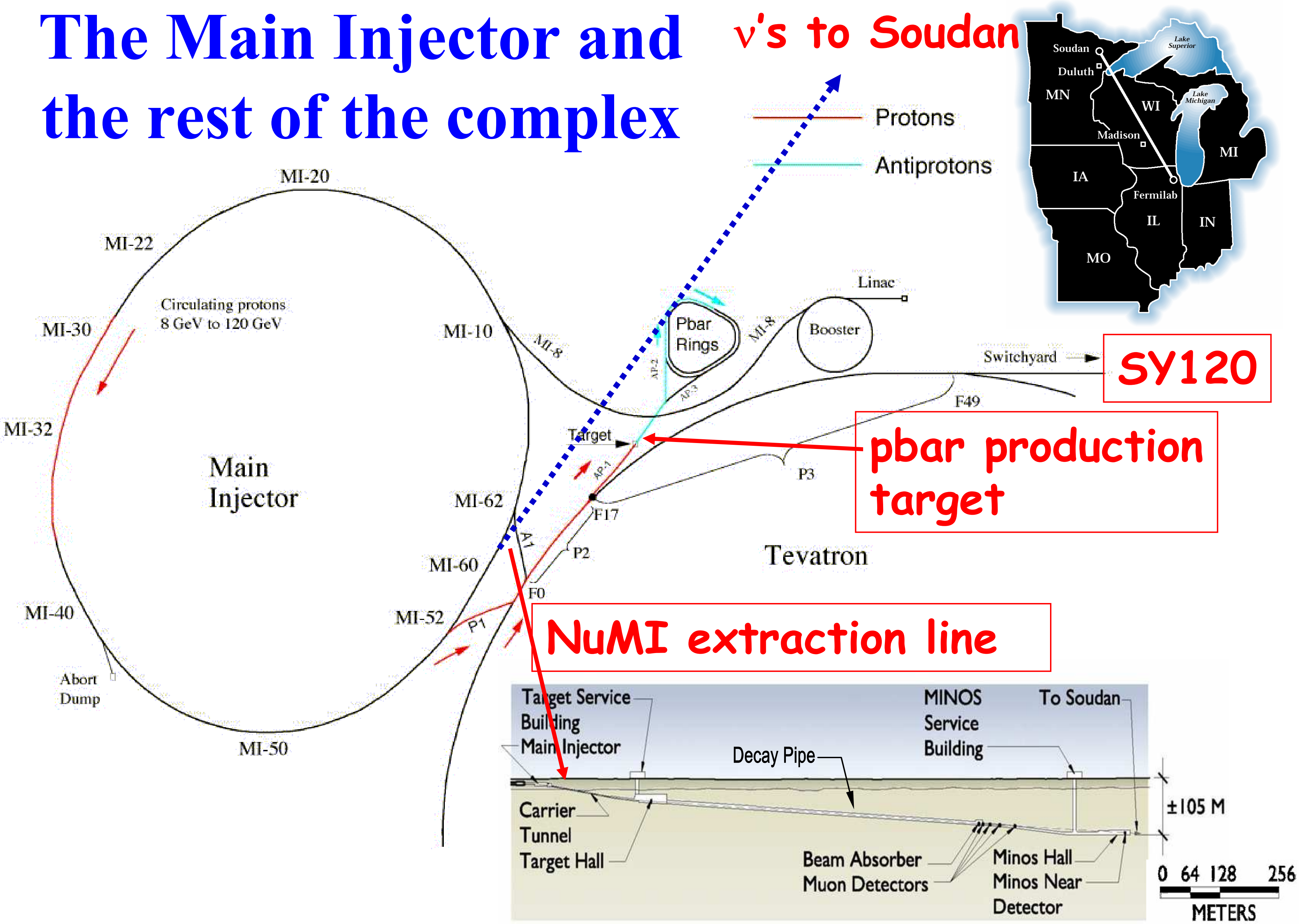
# Proton Intensity Upgrades

A. Marchionni, Fermilab AD/MID
URA Visiting Committee, May 8-9, 2006

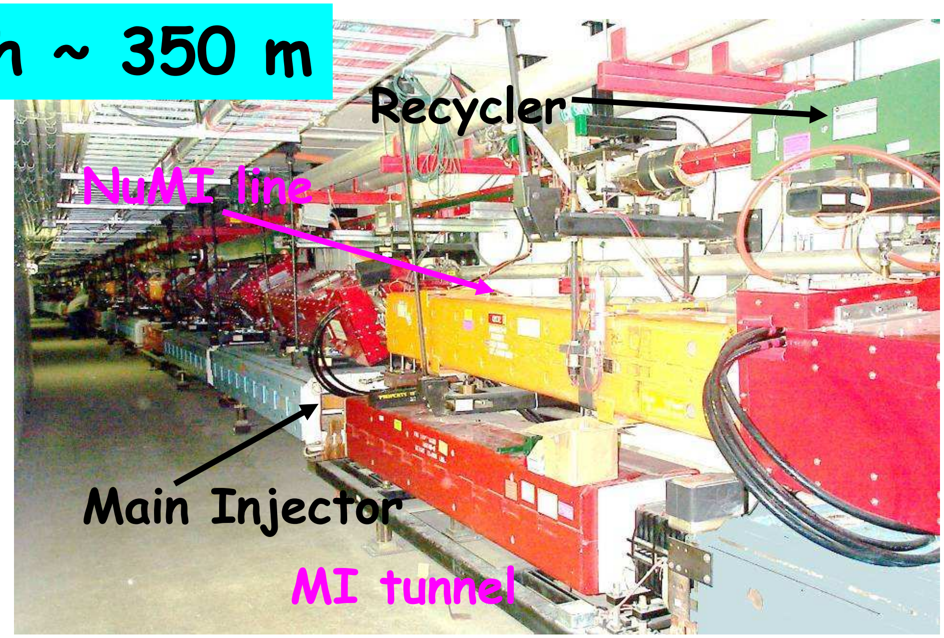
- Present operation of Main Injector and NuMI
  - NuMI designed for 400 kW, achieved a max beam power of 270 kW
- Present Proton Plan:
  - multi-batch stacking in Main Injector
- SNuMI (super-beam upgrades to NuMI)
  - Recycler as an 8 GeV proton pre-injector
  - momentum stacking in the Accumulator
- Preliminary cost estimates and time scale
- Conclusions

# The Main Injector and the rest of the complex



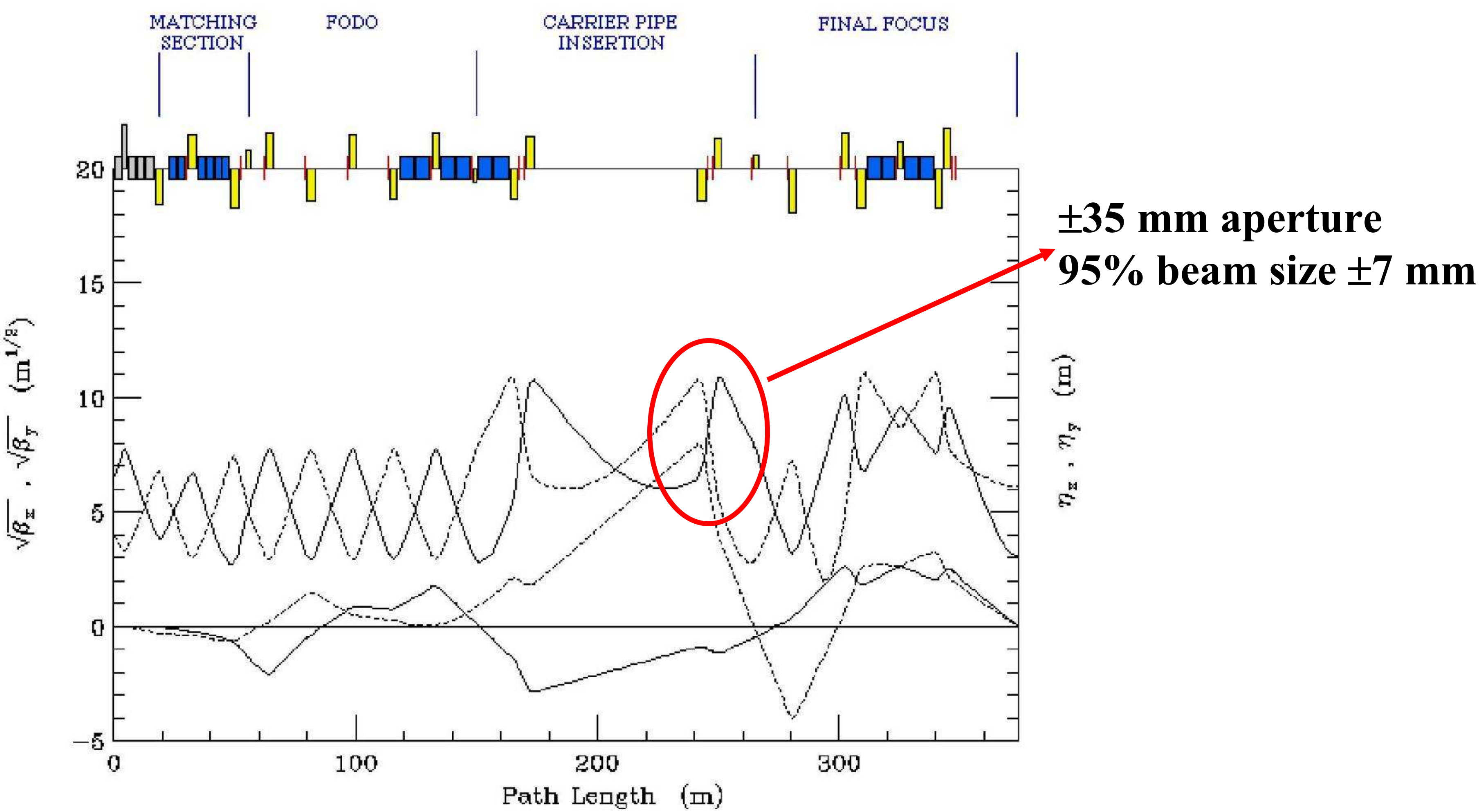
# The NuMI primary proton line

Total length ~ 350 m

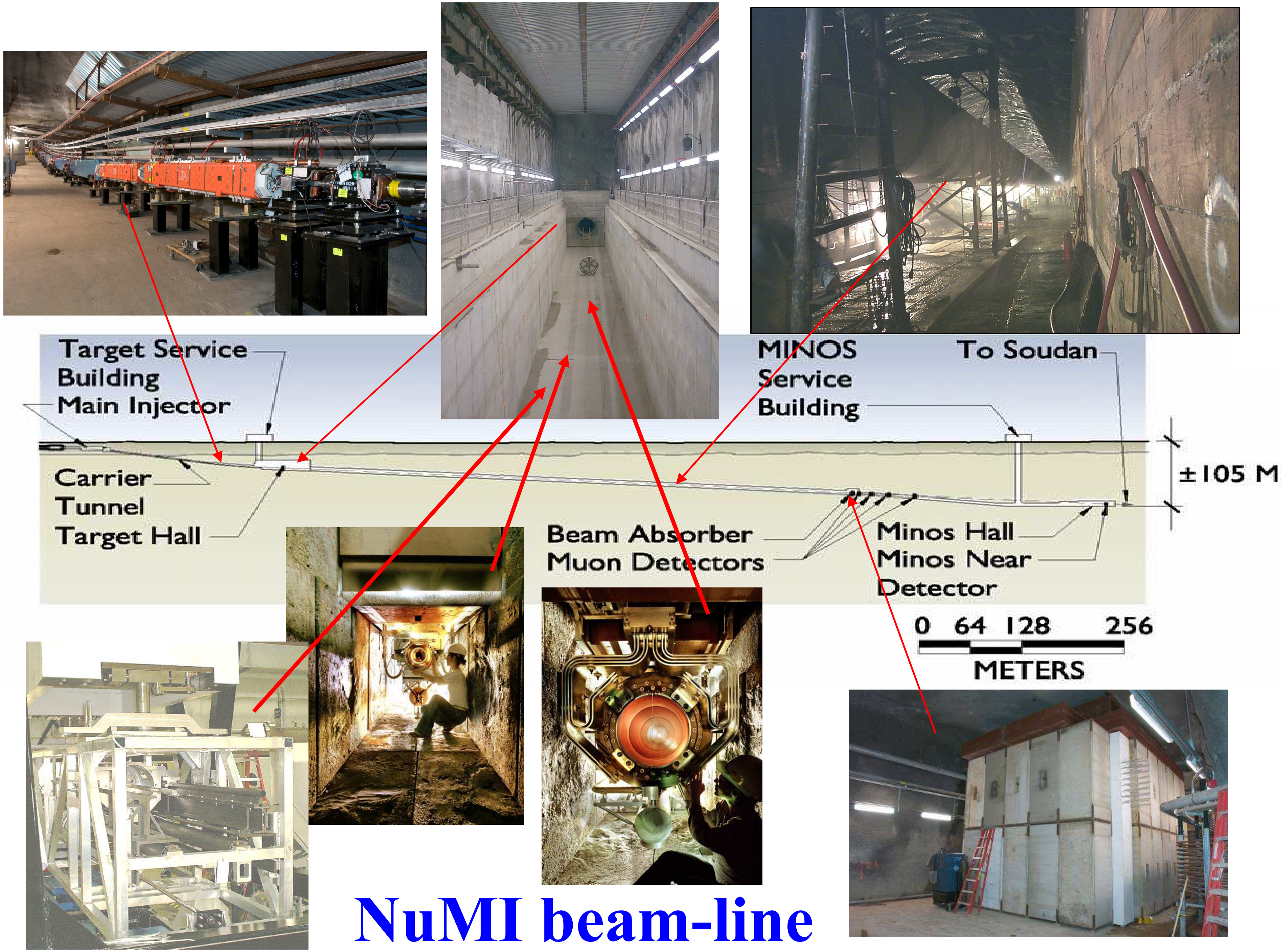


# NuMI Primary Proton Line

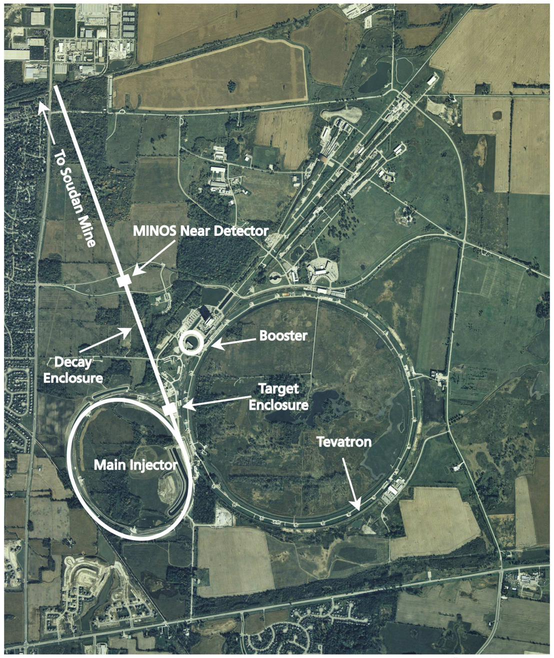



Specifications: fractional beam losses below $10^{-5}$

Large aperture line !




# NuMI beam-line



FERMILAB #98-765D

# Present operation of Main Injector & NuMI

❖ **Main Injector is a rapid cycling accelerator at 120 GeV (presently running at 205 GeV/s)**
  - ➢ 1.467 s cycle time (for 1 batch injection)

❖ **up to 6 proton batches (~ $5\times10^{12}$ p/batch) are successively injected from Booster into Main Injector at 15 Hz**

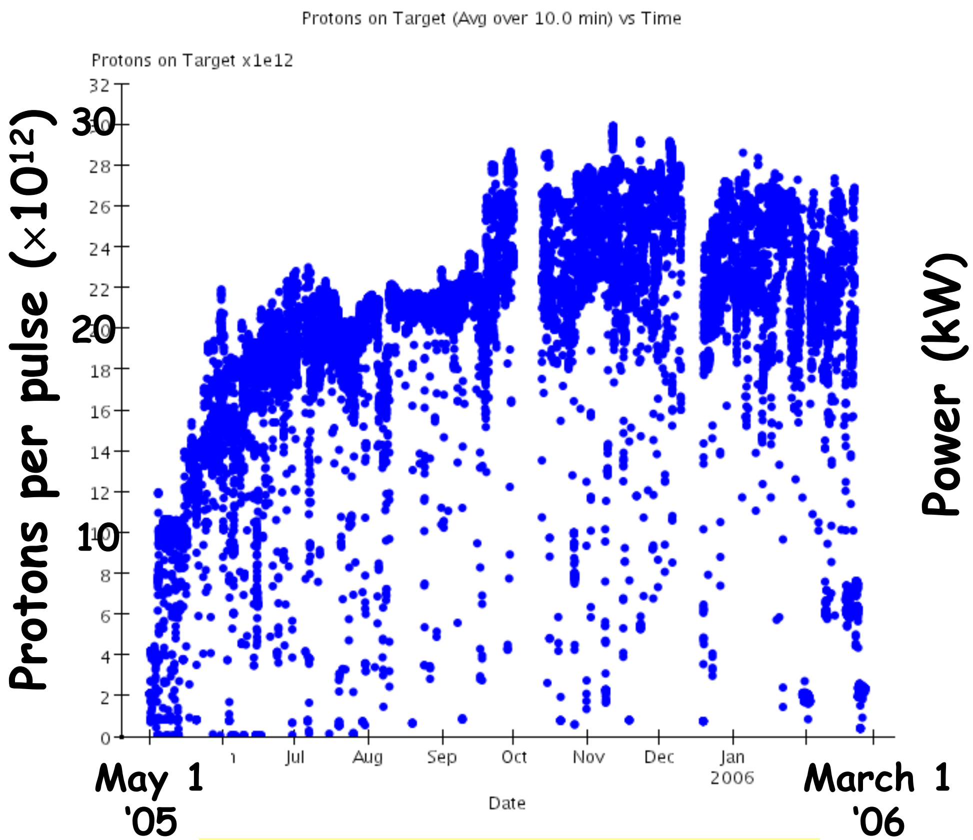
❖ **Main Injector has to satisfy simultaneously the needs of the Collider program (anti-proton stacking and transfers to the Tevatron) and NuMI**

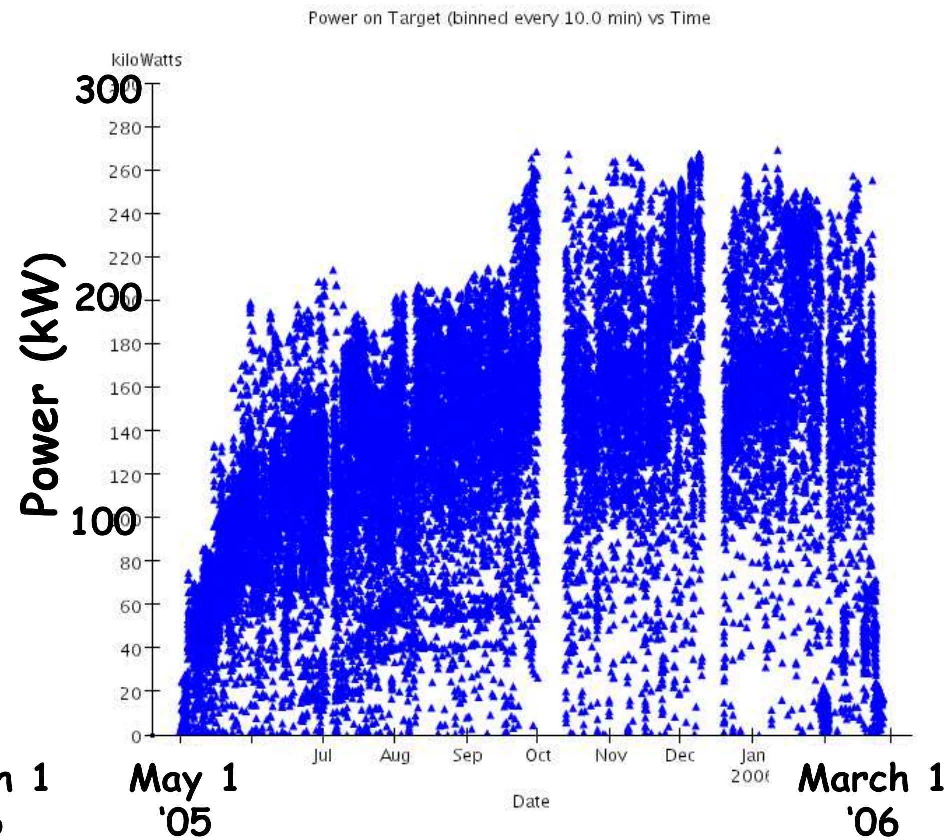
❖ **Mixed mode: NuMI & anti-proton stacking (2 s cycle time)**
  - ➢ two single turn extractions within ~ 1 ms:
    - 1 slip-stacked batch to the anti-proton target
    - 5 batches to NuMI (~$2.5\times10^{13}$ ppp) in ~ 8 μs

❖ **NuMI only (2 s cycle time)**
  - ➢ 6 Booster batches extracted to NuMI (~$3\times10^{13}$ ppp) in ~ 10 μs

❖ **NuMI design values: $4\times10^{13}$ ppp every 1.9 s ⇒ 400 kW**

# NuMI first year running




1.4E20 pot integrated

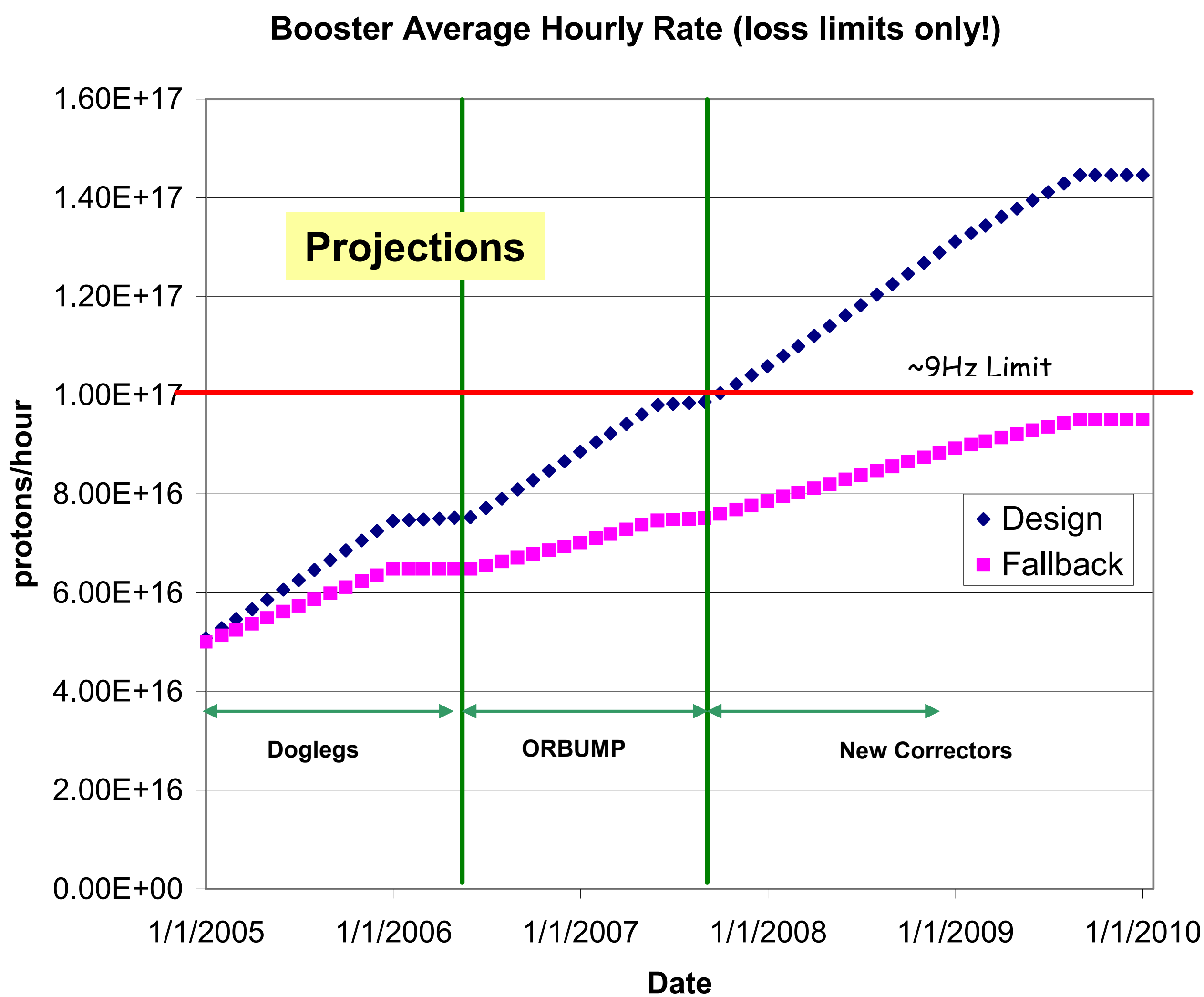
Peak values

- max beam power of 270 kW stably for ~ ½ hour
- peak intensity of $3\times10^{13}$ ppp

Averages over the last months

- beam power 170 kW
- proton intensity $2.3\times10^{13}$ ppp
- cycle spacing 2.2 s

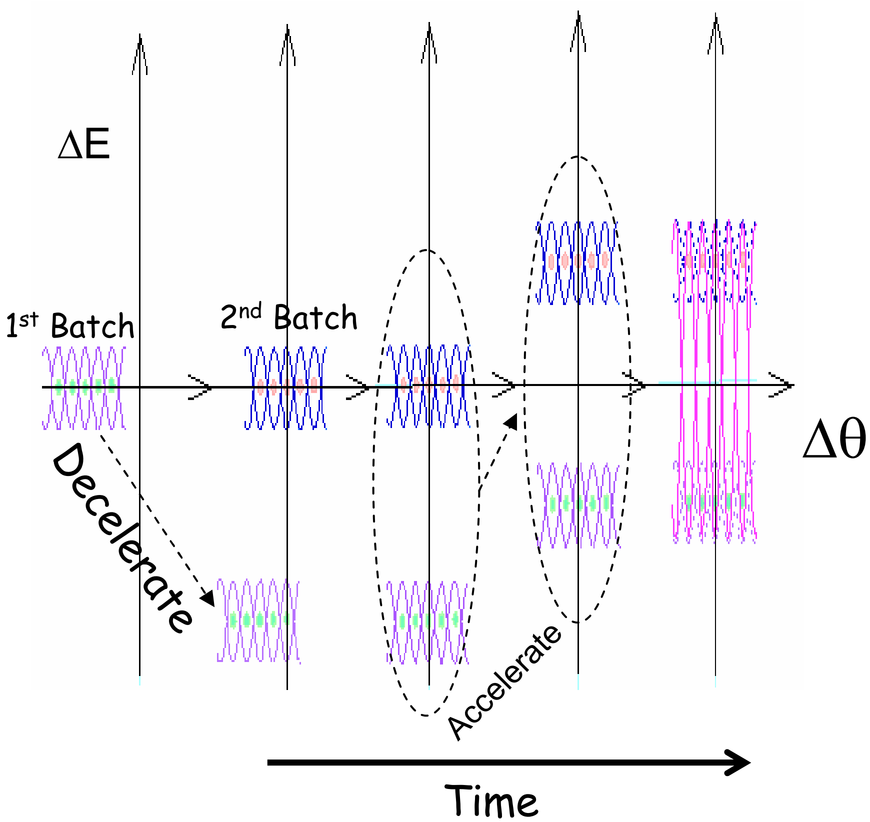
# Booster performance and projections

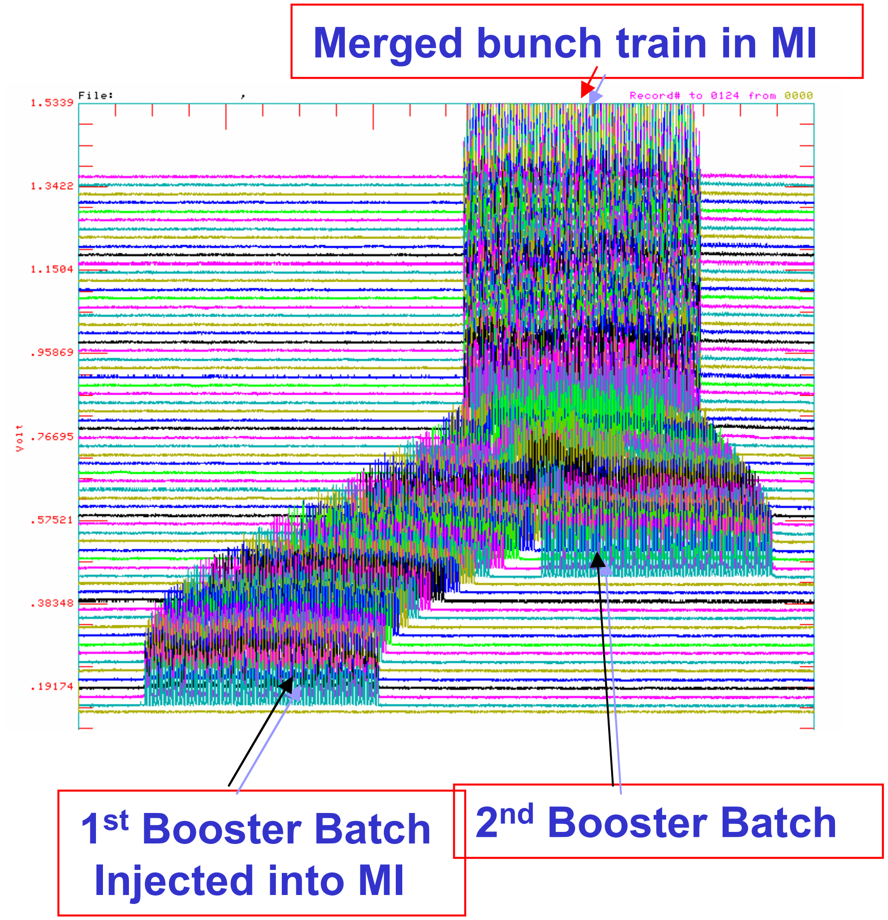



Booster performance '05/'06: ~ $6.5 \times 10^{16}$ protons/hr

# Slip-stacking

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




K. Koba Seiya et. al., PAC2003

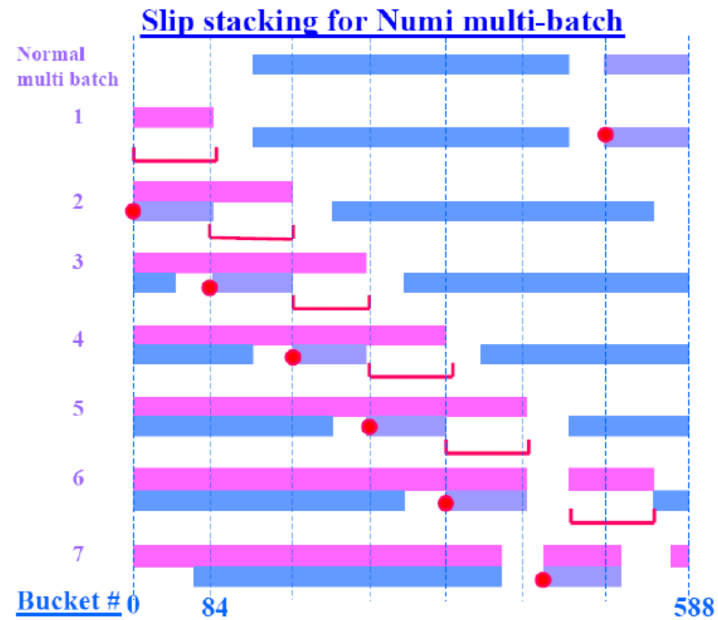
➢ during last year achieved $8 \times 10^{12}$ protons on the anti-proton target

# Multi-batch slip-stacking in MI

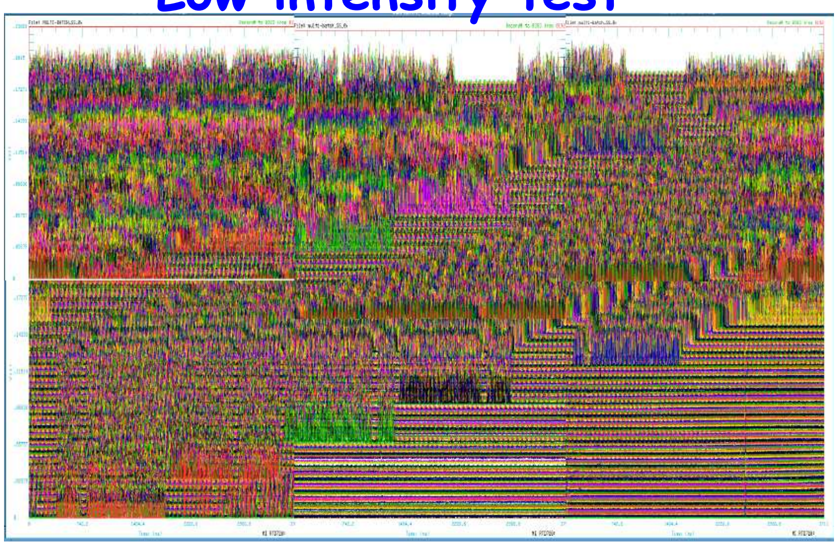
❖ While running in mixed mode, it is possible to slip-stack 4 out of the 5 NuMI batches, in addition to a slip-stacked batch for the anti-proton source

❖ final phase of the present Proton Plan:

↳ 360 kW, $3.2\times10^{20}$ protons/year to NuMI

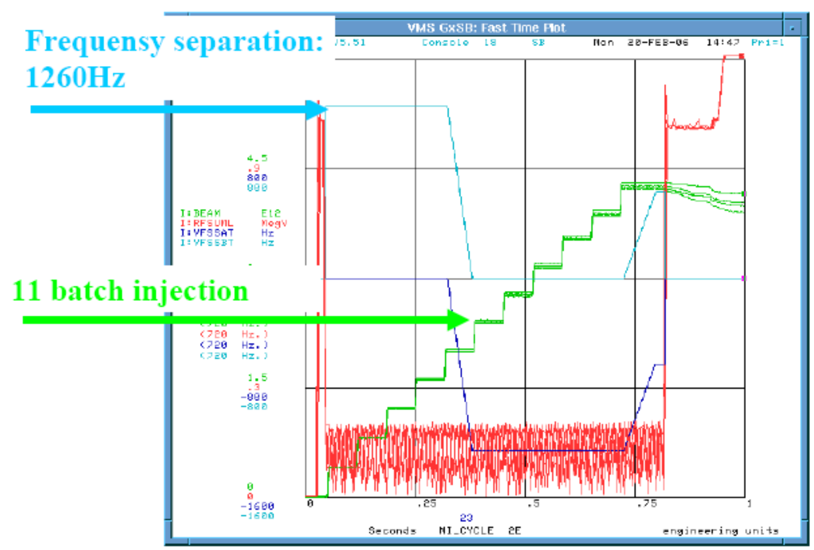



Low intensity test



I. Kourbanis, K. Seiya

Multi-batch Slip Stacking in MI (Beam and Frequency Curves)



# Main Injector 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 | 4.3 MV |

- design acceleration rate of 240 GeV/s
- presently there is enough RF power to safely accelerate $6\times10^{13}$ protons/cycle at a maximum rate of 205 GeV/s
- a **$\gamma_t$-jump system and an upgrade of the RF system** are the major modifications that would allow to raise the intensity up to $1\times10^{14}$ protons/cycle

# Main Injector RF system

I. Kourbanis, beams-doc-1927

- **The current MI RF system consists of 18 stations**
  - presently each cavity is driven by a single Eimac 4CW150000E power tetrode mounted directly on the cavity providing up to 175 KW (operationally)
  - cavity impedance, at energies above transition, is ~ 500 KΩ (R/Q=104)
  - with slip stacked beam we need a moving bucket area ≥1.8 eV-s after transition
  - presently enough power to stably accelerate up to $6\times10^{13}$ ppp at 205 GeV/sec (1.467 s cycle time)
- **We have a total of 3 spare RF cavities allowing the expansion to 20 stations**
  - adding 2 more RF stations will allow us to increase the max accel. rate to 240 GeV/sec reducing MI cycle time to 1.333 s
- **Each cavity has an extra port available for the installation of a second power tube (up to ~ $1\times10^{14}$ ppp)**

# SNuMI stage 1: 700 kW
# Recycler as an 8 GeV proton pre-injector

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 pre-injector

- 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
- 6 batches ($5\times10^{12}$ p/batch) at 120 GeV every 1.467 s ⇒ 390 kW

❖ Recycler momentum aperture is large enough to allow slip-stacking operation in Recycler, for up to 12 Booster batches injected

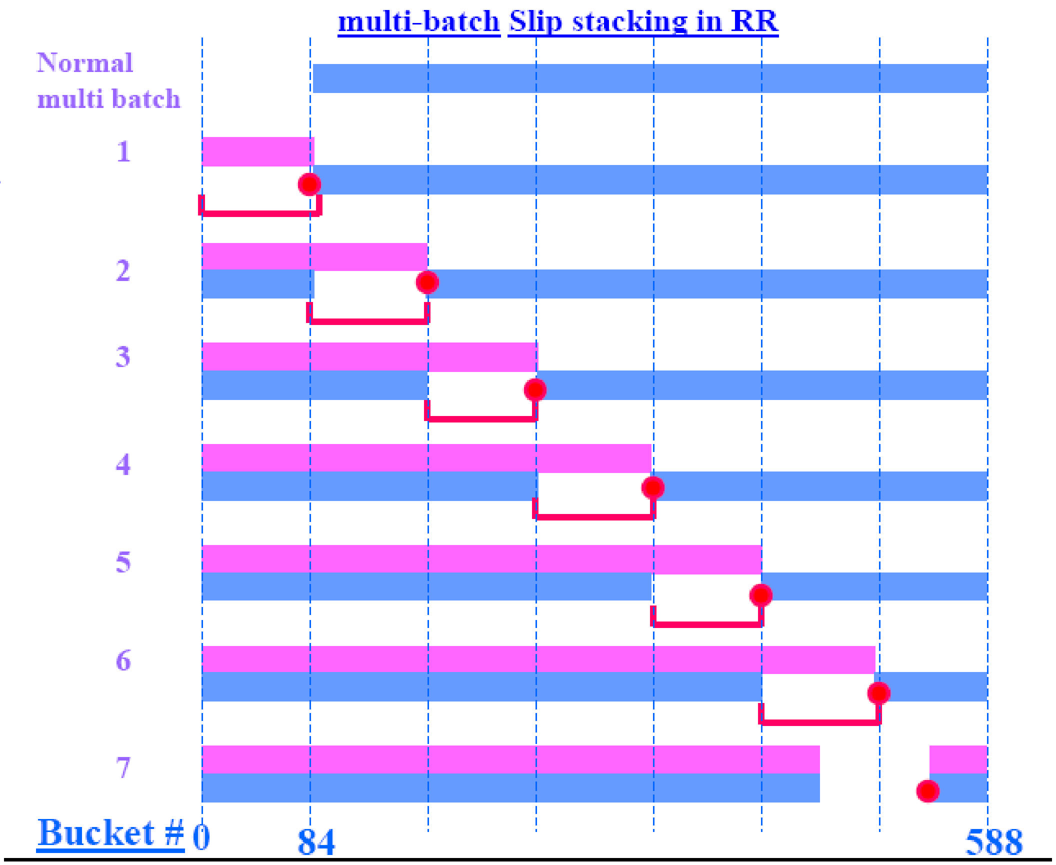
- 6 batches are slipped with respect to the other 6 and, at the time they line up, they are extracted to MI in a single turn and there re-captured and accelerated
- ~$4.7\times10^{12}$ p/batch, 95% slip-stacking efficiency

➥ $5.4\times10^{13}$ ppp at 120 GeV every 1.467 s ⇒ 700 kW

# Multi-batch slip-stacking in Recycler

I. Kourbanis, K. Seiya, beams-doc-2179

- Recycler momentum aperture measured to be 1.5% full span
- Two RF systems required each at a frequency of 52809000±1300 Hz, producing 150 kV each
- Transient beam loading compensation is crucial
  - R/Q smaller than 100



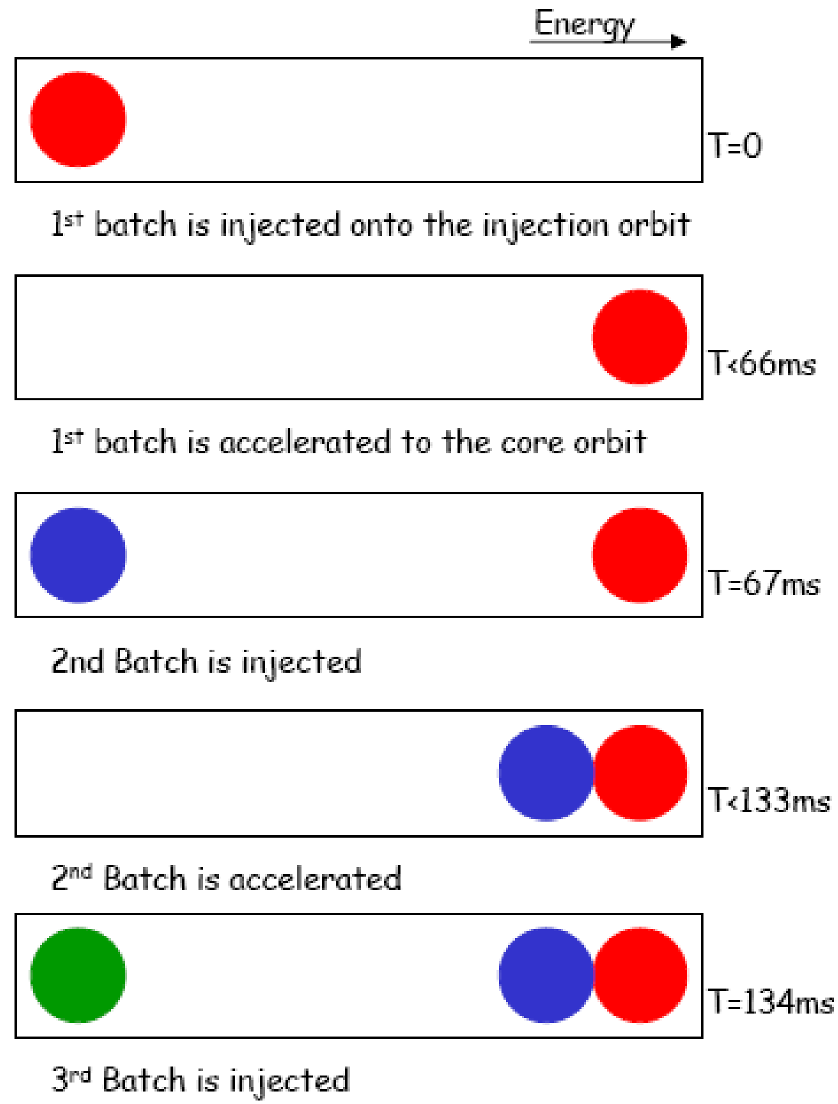
# SNuMI stage 2: 1 MW
# Momentum stacking in the Accumulator

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 ring
  - after acceleration in the Booster, beam will be transferred to the Accumulator
  - the Accumulator was designed for momentum stacking
    - momentum stack up to 4 Booster batches every 267 ms
    - limit Booster batch size to $4\times10^{12}$ protons
      - $84\times0.08$ eV-s $\Rightarrow$ $84\times0.38$ eV-s (19% emittance dilution)
  - 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**

# 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



# SNuMI scenarios

| | Slip-stacking in Recycler Ring 1 | Slip-stacking in Recycler Ring 2 | Momentum stacking in Accumulator 1 | Momentum stacking in Accumulator 2 |
|---|---|---|---|---|
| Booster batch intensity | 4.7E12 | 4.7E12 | 4.0E12 | 4.0E12 |
| No. Booster batches | 12 | 12 | 24 | 18 |
| Booster average rep rate (Hz) | 9.5 | 10.5 | 15 | 15 |
| MI cycle time (s) | 1.467 | 1.333 | 1.6 | 1.333 |
| MI intensity (ppp) | 5.4E13 | 5.4E13 | 9.6E13 | 7.2E13 |
| Beam power to NuMI (kW) | 705 | 780 | 1150 | 1040 |
| Protons/hr | 1.3E17 | 1.5E17 | 2.2E17 | 1.9E17 |

# Charge for SNuMI stage 1, 700 kW

*R. Dixon, February, 2006*

- I would now like you to develop **a conceptual design and cost estimate for a modification to the Recycler and Main Injector to provide a 0.7 MW 120 GeV beam to NuMI after the collider program ends**. The main feature of this upgrade is to convert the Recycler into a proton accumulator, shortening the Main Injector cycle time from 2.2 seconds to 1.5 seconds.
- The conceptual design should include modifications to the Recycler and the Main Injector such as the removal of pbar specific devices, modification of injection and extraction lines, slip stacking, collimation, dampers.
- The conceptual design should include all NuMI target hall modifications required operate the facility at 0.7 MW such as the target, horns, and the decay pipe cooling system.
- The conceptual design should consider all aspects of high power acceleration and transport; beam stability, RF power, instrumentation, collimation, transport and targeting, radiation shielding, groundwater and air activation for all facilities.
- **The conceptual design and cost estimate should be documented in a report suitable for presentation to the Directorate in the fall of 2006.**

# 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

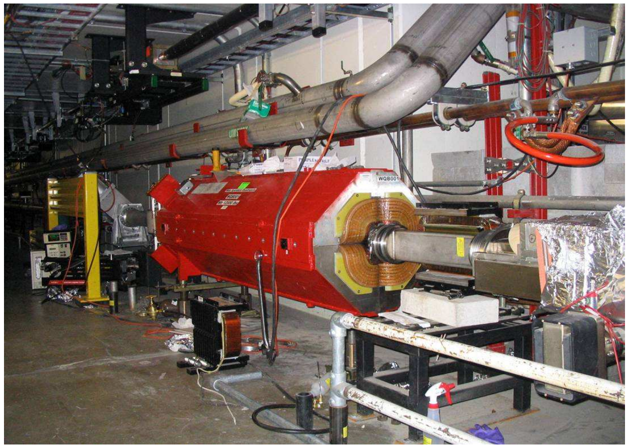
## Booster
E. Prebys

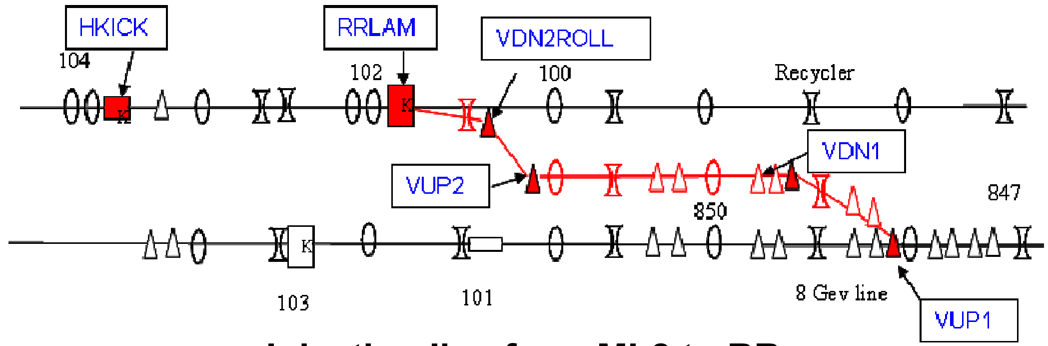
1. Booster rep rate up to 9.3 Hz
2. Beam quality

## Engineering Support
R. Reilly

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

# Recycling the Recycler

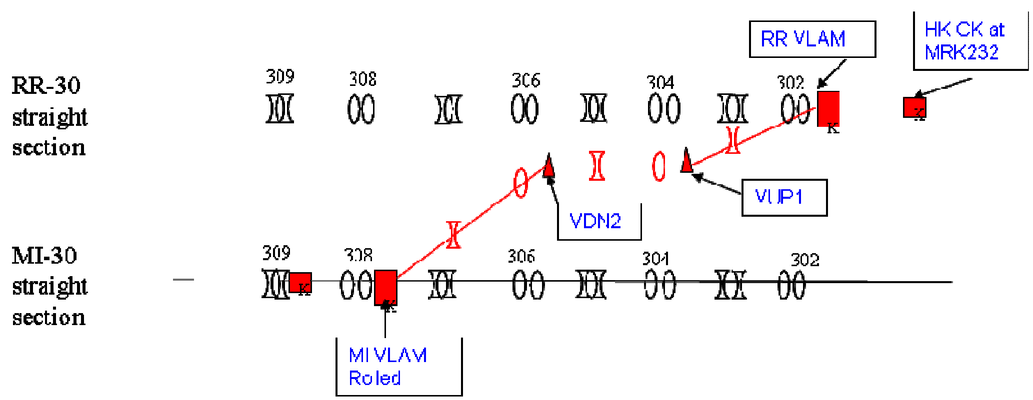





Injection line from MI-8 to RR

- **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
- **53 MHz RF system for Recycler**
- **Instrumentation**

Extraction line in the 30 section

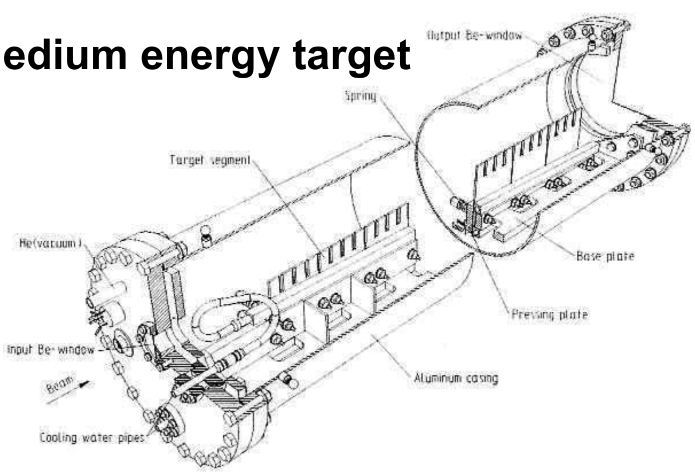



*Have preliminary designs and cost estimates*

# Upgrading NuMI

- **Issues:**
  - running the primary proton line at higher rep-rate
  - removing larger heat load in the target chase
  - thermal shock, heat damage and radiation damage to target and horns
  - thermal shock to decay pipe window and beam absorber
  - radiation safety
- **Off-axis neutrino beam better optimized in 'Medium Energy' configuration**
  - target less constrained, it is external to the horn !

**Medium energy target**




*Engineering support freed up after shutdown to look into these issues for the major NuMI components*

# SNuMI *preliminary* cost estimate

- **Booster:** repetition rate upgrade to 15 Hz
- **Main Injector:** RF and shielding upgrades
- **Recycler:** new injection and extraction transfer lines, RF systems
- **Accumulator:** new injection and extraction lines, new RF systems
- **NuMI:** upgrade primary proton line, new target and horn, target chase cooling, installation of Helium bags, work cell upgrade

## Includes only M&S, no inflation, no contingency

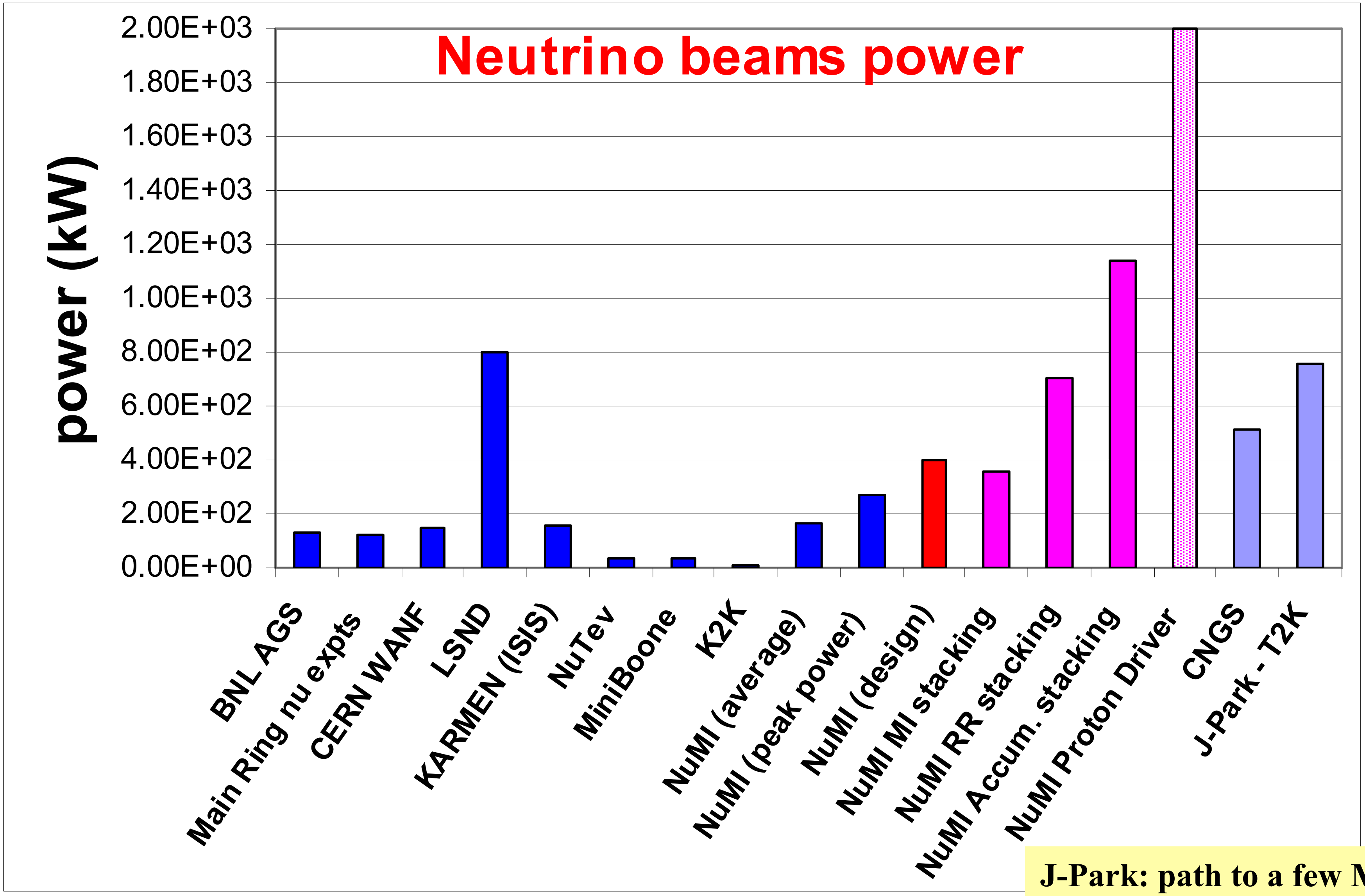
| | 700 kW cost estimates (k$) | 1 MW cost estimates (k$) |
|---|---|---|
| **Booster** | 600 | |
| **Main Injector** | 700 | 12500 |
| **Recycler** | 5700 | 1000 |
| **Accumulator** | | 15000 |
| **NuMI** | 2900 | 3500 |
| **TOT** | **9900** | **32000** |

# SNuMI *preliminary* time scale

- **Main assumptions:**
  - 2010: year-long shutdown to complete all upgrades required for 1 MW
  - 2011: start using the Recycler at 400 kW and gradually implement slip-stacking over multi-batches up to 700 kW beam power
  - 2012: short shutdown to fix eventual problems and start momentum stacking in Accumulator, increasing beam power to 1 MW
  - 2013: run steadily at 1 MW
- **Efficiency factors:**
  - Complex uptime: 0.85
  - Average to peak performance: 0.9
  - NuMI line uptime: 0.9

| Year | Running time (weeks) | Initial power (kW) | Final power (kW) | Integrated protons/year |
|---|---|---|---|---|
| **2011** | 44 | 400 | 700 | $5.3\times10^{20}$ |
| **2012** | 38 | 700 | 1000 | $7.3\times10^{20}$ |
| **2013** | 44 | 1000 | 1000 | $9.9\times10^{20}$ |

# The power of neutrino beams




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

# Conclusions

- The Main Injector has presently operated up to ~ $3.15 \times 10^{13}$ ppp and at a maximum beam power of 270 kW
- With the termination of the Collider program, a set of upgrades to the accelerator complex can increase the beam power up to 1 MW
  - the use of the Recycler as a proton pre-injector, together with multi-batch slip-stacking, allows to reach a power of 700 kW
    - adding 2 RF cavities in MI allows 10% reduction of MI cycle time
  - momentum stacking in the Accumulator allows to increase the beam power to 1 MW
- A project is being developed to achieve these goals, addressing all issues both in the accelerator complex and the NuMI beam-line
  - a conceptual design and cost estimate for the 700 kW first phase is due in the fall of 2006

# Cost estimates details

| | 700 kW cost estimate (k$) | 1 MW cost estimates (k$) |
|---|---|---|
| **Booster** | | |
| Transformers in bias supplies | 200 | |
| Feeder | 300 | |
| 480 V distribution system | 100 | |
| **Sub-totals** | **600** | |
| **Main Injector** | | |
| RF system upgrade | | 12000 |
| Gamma-t jump | | 500 |
| Shielding | 700 | |
| **Sub-totals** | **700** | **12500** |
| **Recycler** | | |
| Decommissioning anti-proton devices | 100 | |
| New injection line | 800 | |
| New extraction line | 1200 | |
| Rework MI30 straight section | 100 | |
| Abort Line | 1000 | |
| 53 MHz RF system | 1000 | |
| Dampers | 300 | |
| Instrumentation (DCCT, BPM,..) | 500 | |
| Infrastructure | 600 | |
| Manpower | 100 | |
| 7.5MHz RF system | | 1000 |
| **Sub-totals** | **5700** | **1000** |
| **Accumulator** | | **15000** |
| **NuMI** | | |
| Primary proton beam | 900 | |
| Target | 300 | |
| Horn, strip-line, power supply | 1200 | |
| Target chase cooling | | 2500 |
| Helium bags | 500 | |
| Work cell upgrade | | 1000 |
| **Sub-totals** | **2900** | **3500** |
| **Totals** | **9900** | **32000** |

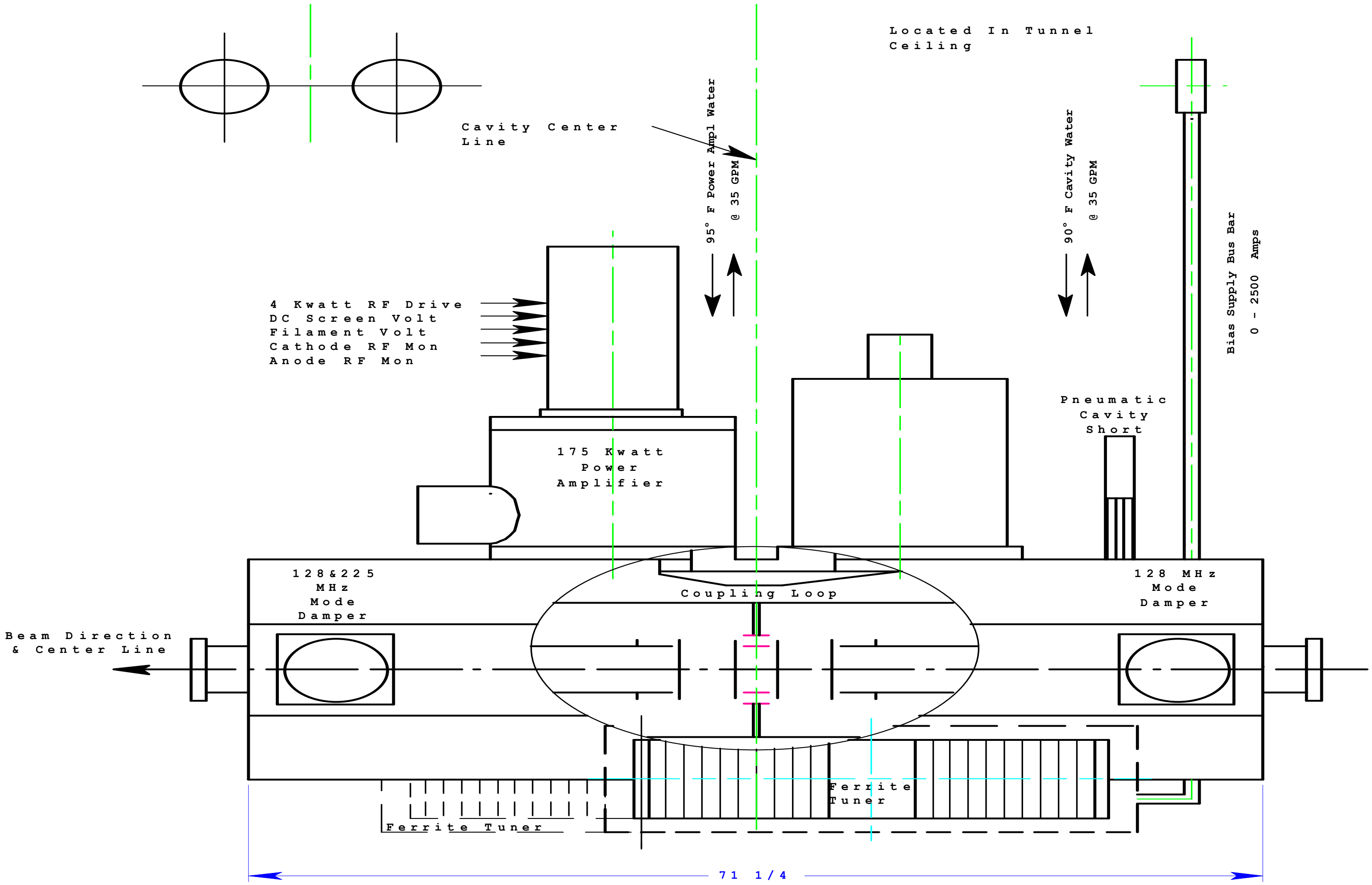
# Main Injector ramps

| Delta t | Time | Momentum | Pdot |
|---|---|---|---|
| 0.08000 | 0.08000 | 8.884 | 0.00 |
| 0.02533 | 0.10533 | 8.96 | 6.00 |
| 0.04154 | 0.14687 | 9.5 | 20.00 |
| 0.11111 | 0.25798 | 22 | 205.00 |
| 0.30732 | 0.56530 | 85 | 205.00 |
| 0.15385 | 0.71915 | 115 | 185.00 |
| 0.05081 | 0.76996 | 119.7 | 0.00 |
| 0.06650 | 0.83646 | 119.7 | 0.00 |
| 0.11308 | 0.94953 | 105 | -260.00 |
| 0.17308 | 1.12261 | 60 | -260.00 |
| 0.20417 | 1.32678 | 11 | -220.00 |
| 0.03909 | 1.36587 | 6.7 | 0.00 |
| 0.04864 | 1.41451 | 7.7945 | 45.00 |
| 0.04864 | 1.46316 | 8.889 | 0.00 |
| 0.00100 | 1.46416 | 8.889 | 0.00 |

| Delta t | Time | Momentum | Pdot |
|---|---|---|---|
| 0.08000 | 0.08000 | 8.884 | 0.00 |
| 0.02533 | 0.10533 | 8.96 | 6.00 |
| 0.04154 | 0.14687 | 9.5 | 20.00 |
| 0.09615 | 0.24303 | 22 | 240.00 |
| 0.26526 | 0.50829 | 85 | 235.00 |
| 0.13187 | 0.64016 | 115 | 220.00 |
| 0.04273 | 0.68288 | 119.7 | 0.00 |
| 0.06650 | 0.74938 | 119.7 | 0.00 |
| 0.09639 | 0.84578 | 105 | -305.00 |
| 0.15385 | 0.99962 | 60 | -280.00 |
| 0.19600 | 1.19562 | 11 | -220.00 |
| 0.03909 | 1.23471 | 6.7 | 0.00 |
| 0.04864 | 1.28336 | 7.7945 | 45.00 |
| 0.04864 | 1.33200 | 8.889 | 0.00 |
| 0.00100 | 1.33300 | 8.889 | 0.00 |

**Increasing the max. pdot to 240 GeV/sec from 205 GeV/sec reduced the MI cycle time by 13%.**

# Schematic of MI RF Cavity

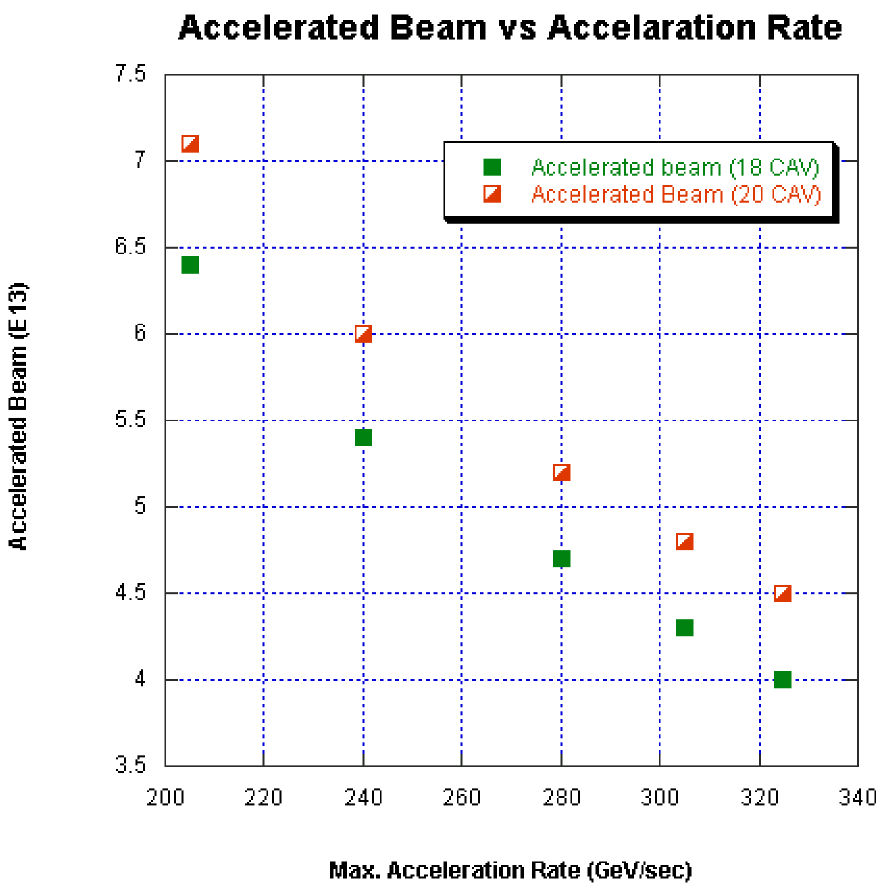


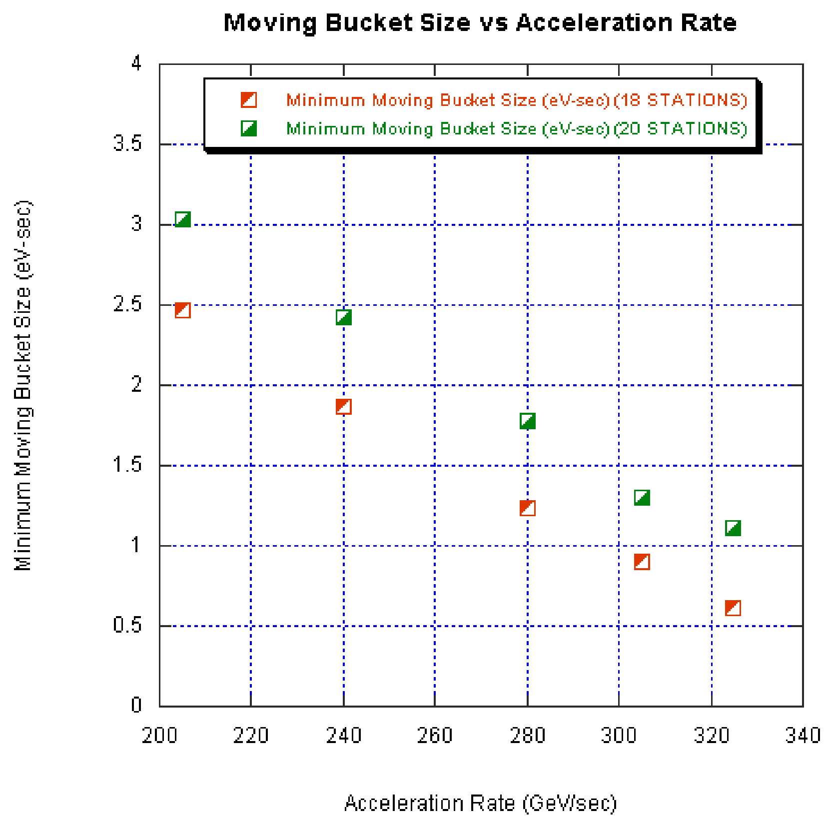

As Viewed From Aisle Side

**Present Main Injector Cavity**

# Main Injector RF system II

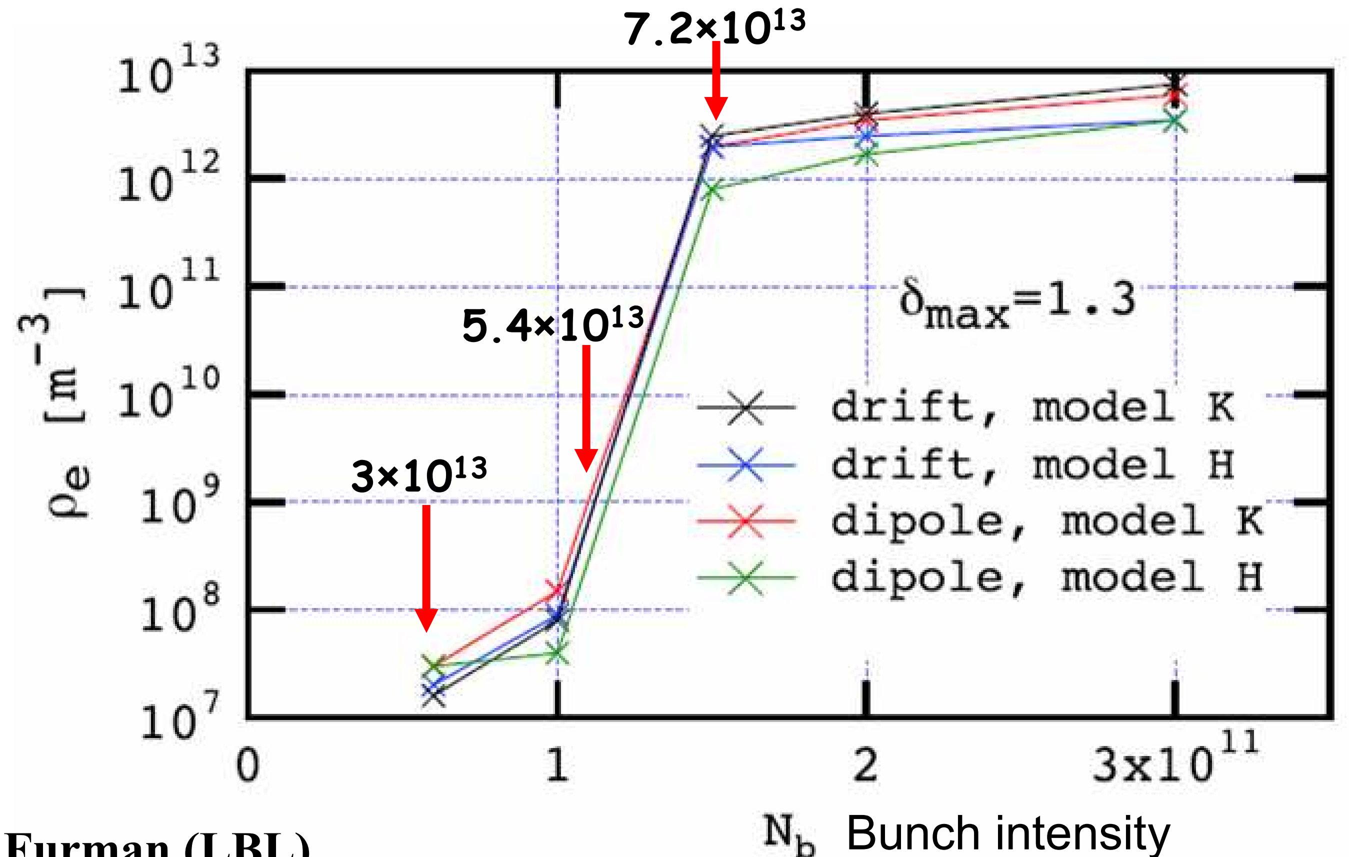
**I. Kourbanis, beams-doc-1927**



# Electron cloud effects ?

- Electron Cloud can limit the performance of high-power positron, proton, and ion machine
- Simulations suggest that MI might be near a threshold




**M. Furman (LBL)**

***FERMILAB-PUB-05-258-AD***

# Activities in Electron Cloud

- started investigation of dynamic pressure rises around the ring using ion pumps
- presently installing two ion gauges at different locations (better bandwidth ?)
- **borrowed an electron detector from Argonne (RFA type)**
  - **being installed**
  - **directly measures electron current incident on the beampipe**
- **Collaboration with LBL on simulations** – ***M. Furman, J. Corlett, B. Zwaska, X. Zhang***
- **Collaboration with SLAC on SEY** – ***B. Kirby, W. Chou***
  - **directly measures secondary emission yield of MI beam-pipe**
- **Parallel measurements effort in Tevatron** – ***X. Zhang***
  - **will allow testing with different beam parameters**