Overview of the SuperNuMI Plan

A. Marchionni, Fermilab AD/MID

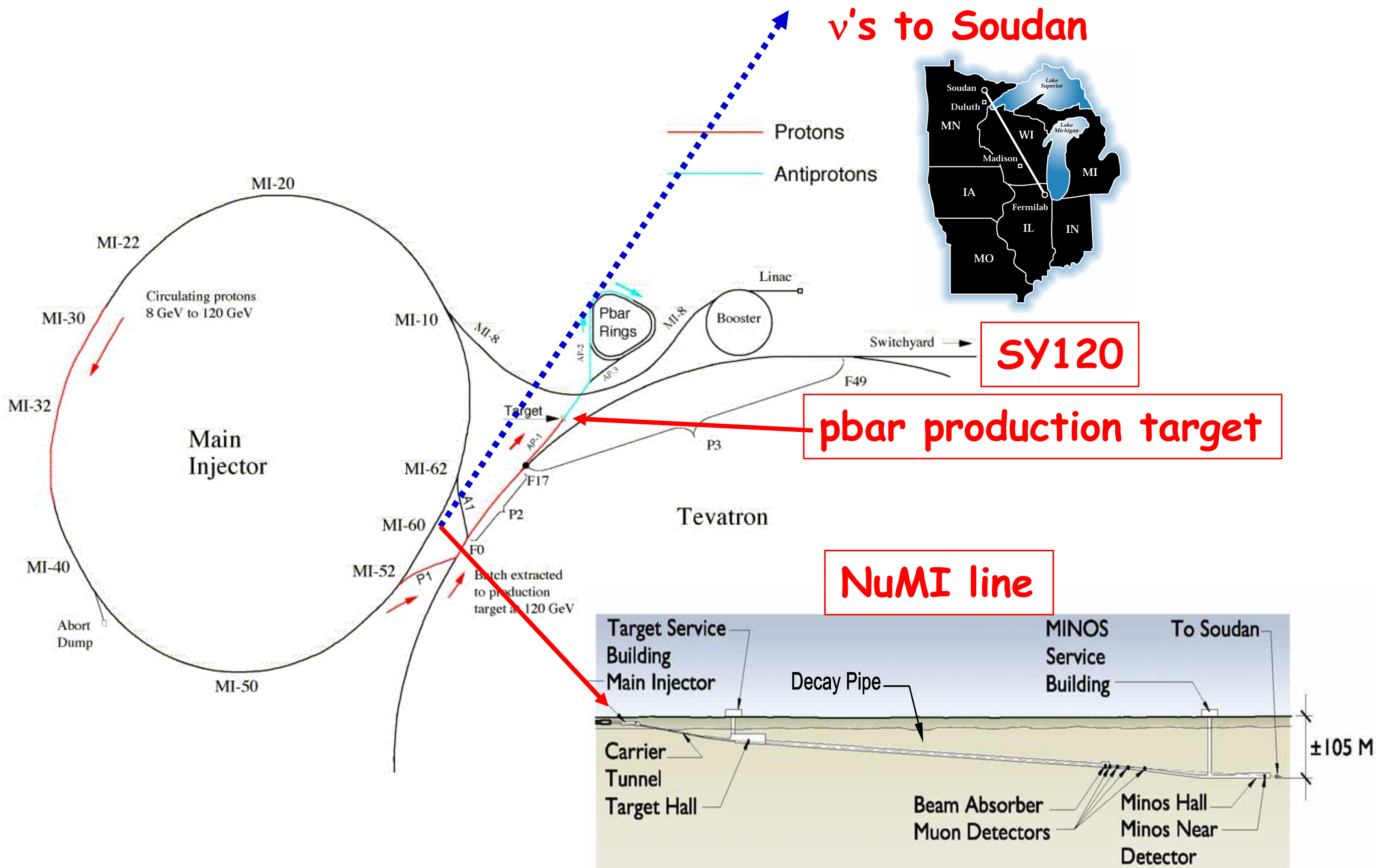
Accelerator Advisory Committee,

May 10-12, 2006

Overview

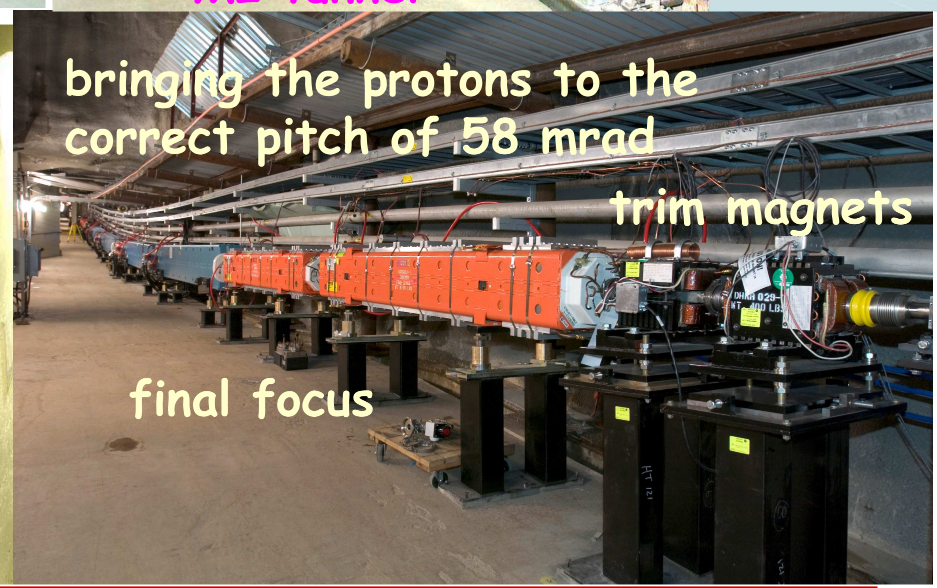
- Present operation of Main Injector and NuMI
- Main Injector capabilities
- SNuMI: super-beam upgrades to NuMI
- SNuMI stage 1: 700 kW
  - use of Recycler as 8 GeV proton pre-injector
- SNuMI stage 2: 1 MW
  - use of Accumulator for momentum stacking over multiple batches
- SNuMI charge and organization for stage 1
- Preliminary cost estimates and time scale
- Conclusions

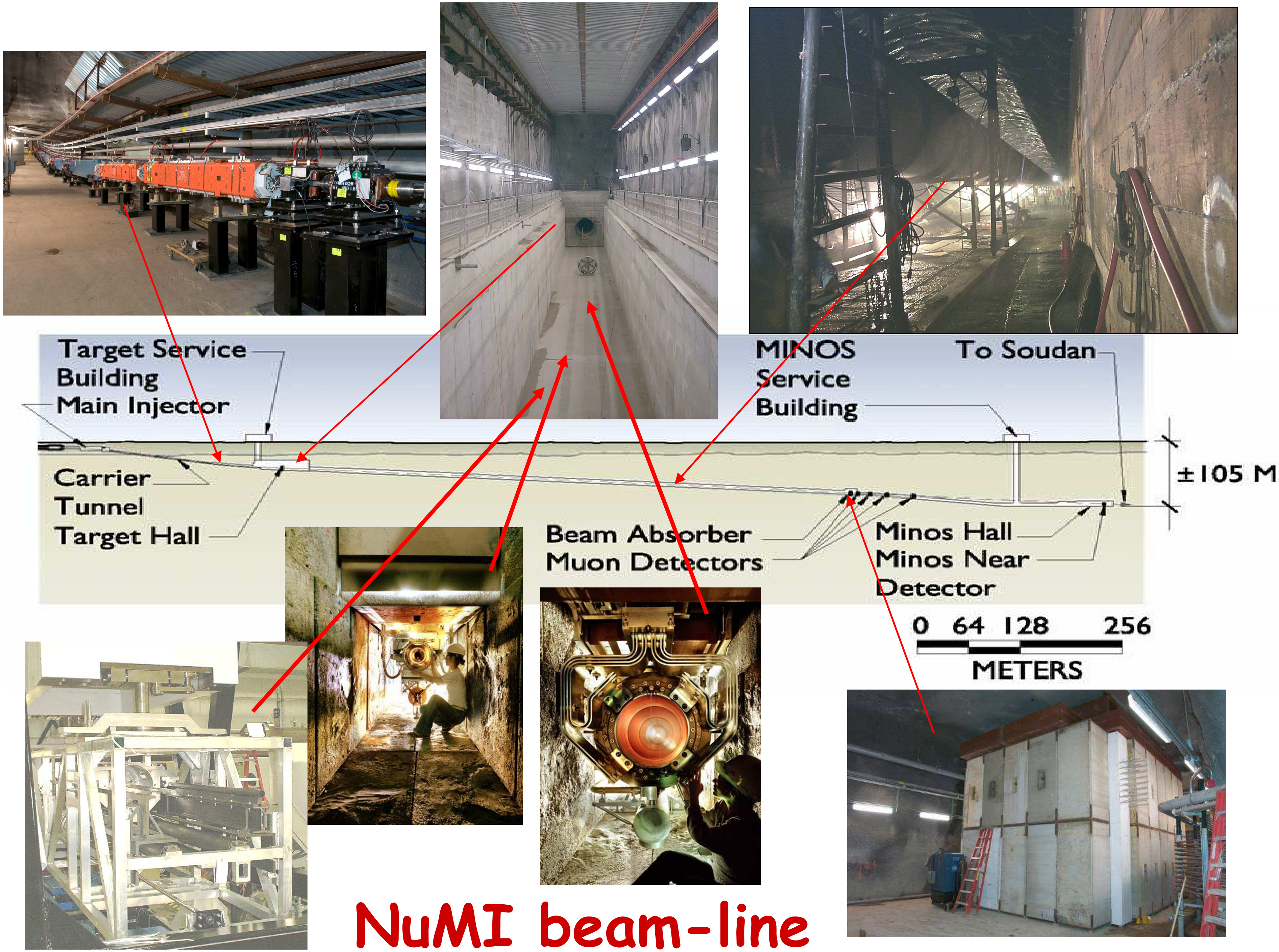
The Main Injector and the rest of the complex



The NuMI primary proton line

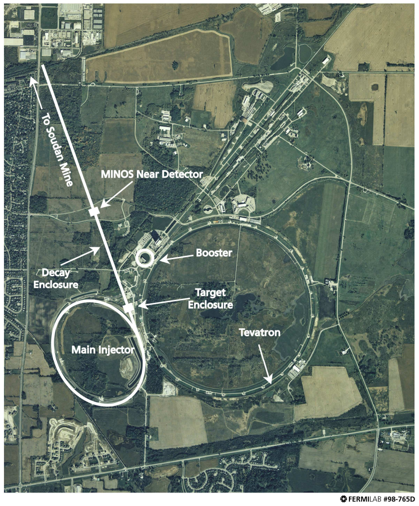
Total length ~ 350 m





NuMI beam-line

Present operation of Main Injector & NuMI

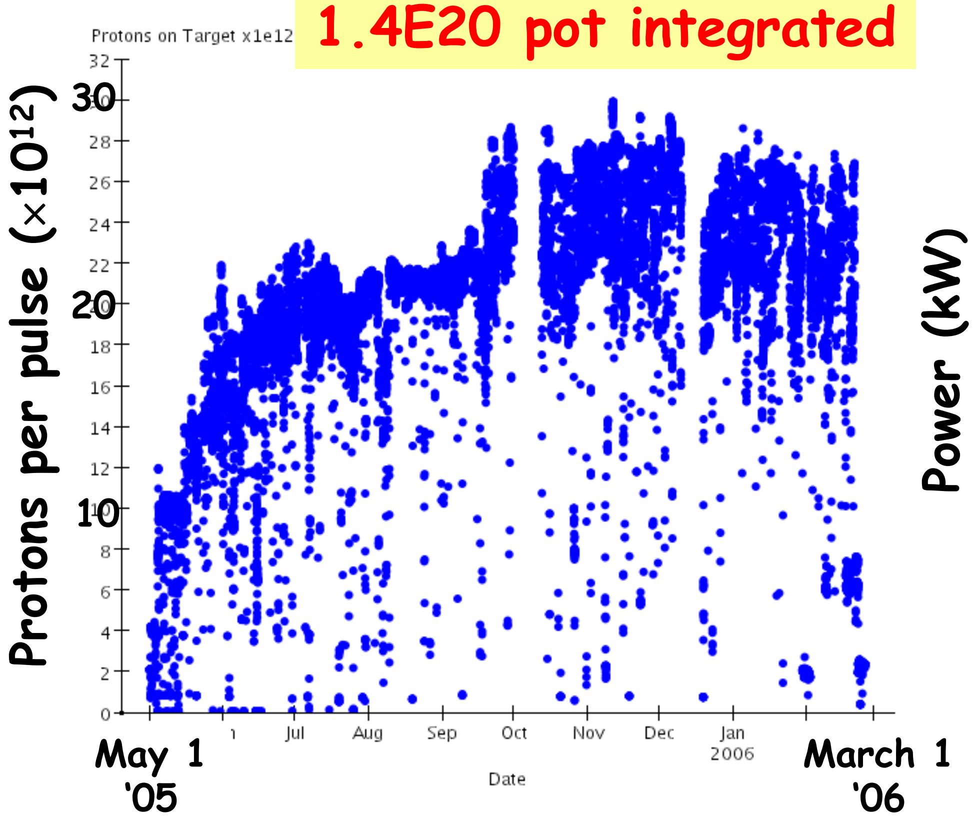


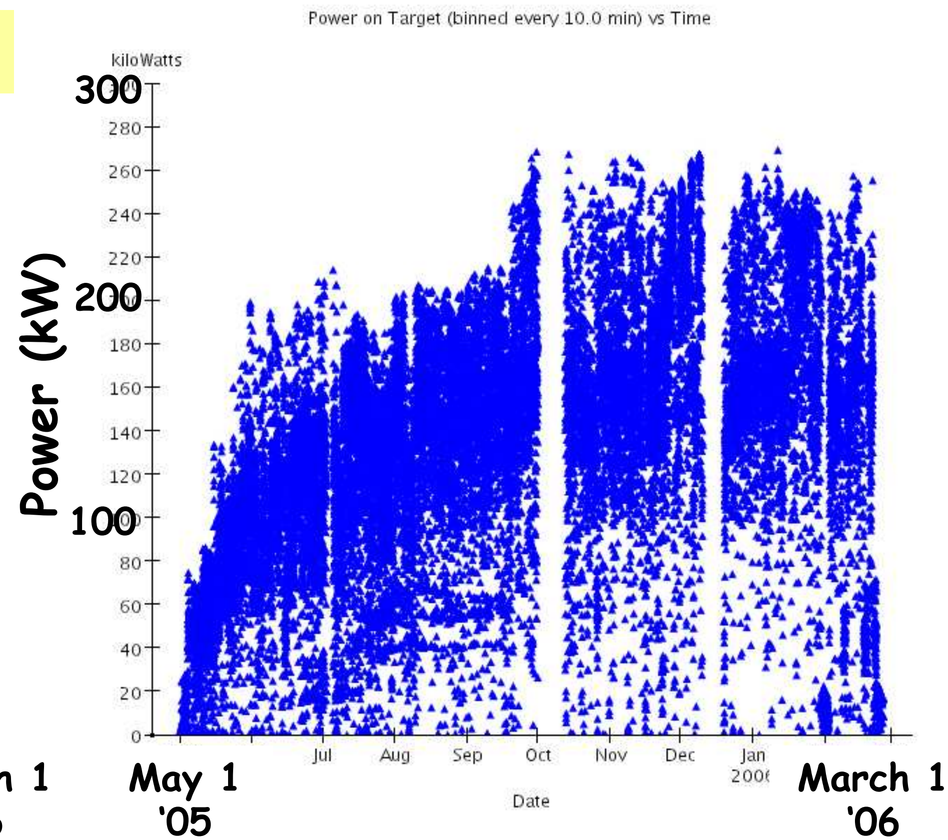
- Main Injector is a rapid cycling accelerator at 120 GeV (presently running at 205 GeV/s)
  - 1.467 s cycle time (for 1 batch injection)
- up to 6 proton batches (~ 5×10^{12} p/batch) are successively injected from Booster into Main Injector at 15 Hz

- 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 (~2.5×10^{13} ppp) in ~ 8 μs
- NuMI only (2 s cycle time)
  - 6 Booster batches extracted to NuMI (~3×10^{13} ppp) in ~ 10 μs
- NuMI design values: 4×10^{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 3×10^{13} ppp

Averages over the last months

- beam power 170 kW
- proton intensity 2.3×10^{13} ppp
- cycle spacing 2.2 s

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 6×10^{13} protons/cycle at a maximum rate of 205 GeV/s
- a **γ_t-jump system and an upgrade of the RF system** are the major modifications that would allow to raise the intensity up to 1×10^{14} protons/cycle

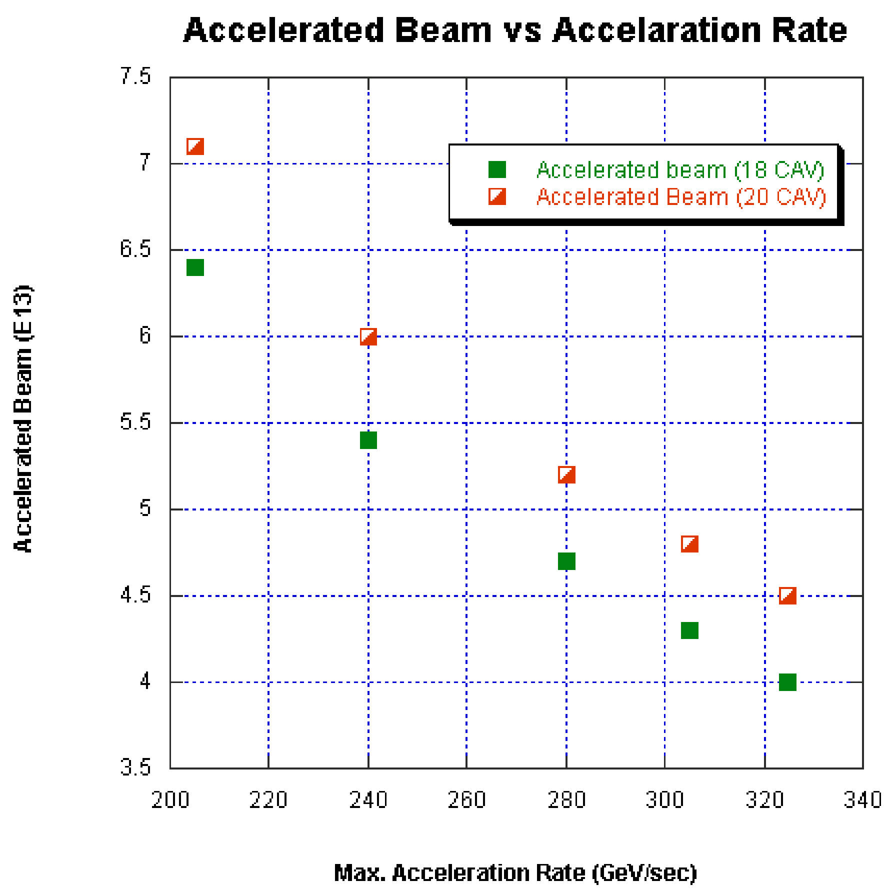
Main Injector RF system I

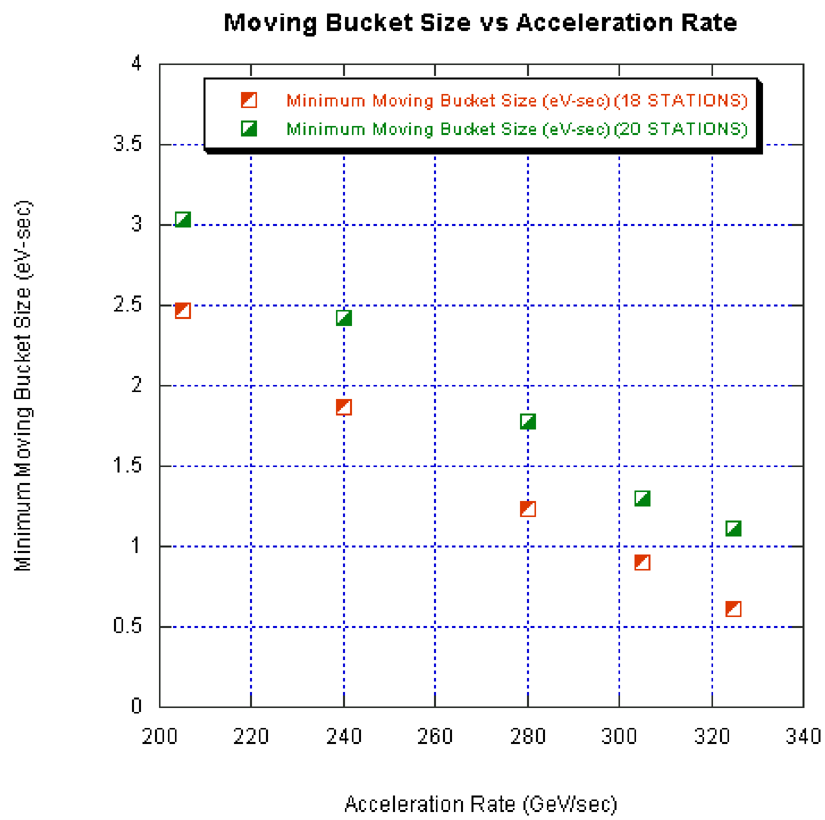
I. Kourbanis, beams-doc-1927

- 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 6×10^{13} ppp at 205 GeV/sec (1.467 s cycle time)
- We have a total of 3 spare 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 ~ 1×10^{14} ppp)

Main Injector RF system II

I. Kourbanis, beams-doc-1927





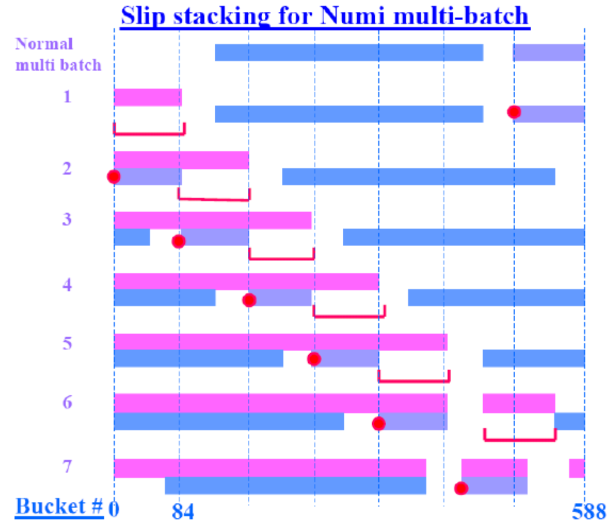
SNuMI stage 1: 700 kW
Recycler as an 8 GeV proton pre-injector

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 (5×10^{12} p/batch) at 120 GeV every 1.467 s $\Rightarrow$ 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
  - ~4.7×10^{12} p/batch, 95% slip-stacking efficiency
  - ➥ 5.4×10^{13} ppp at 120 GeV every 1.467 s $\Rightarrow$ 700 kW

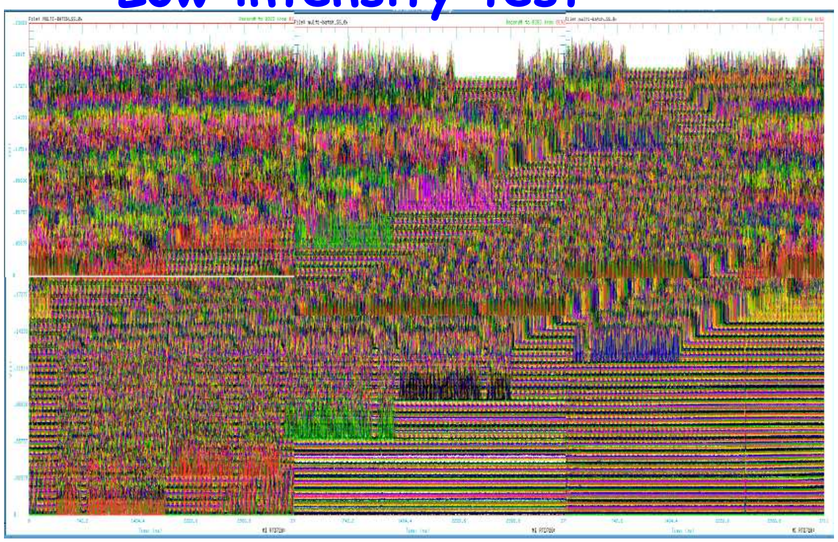
Multi-batch slip-stacking in MI

❖ 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

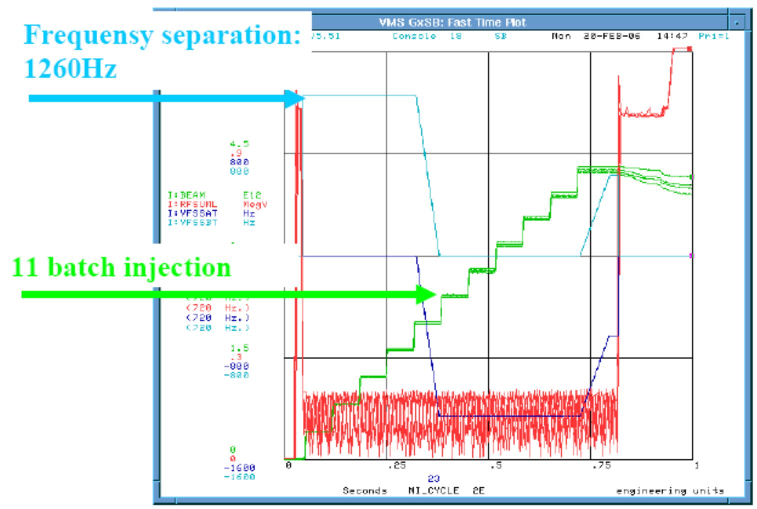


Multi-batch Slip Stacking in MI (Beam and Frequency Curves)

Low intensity test

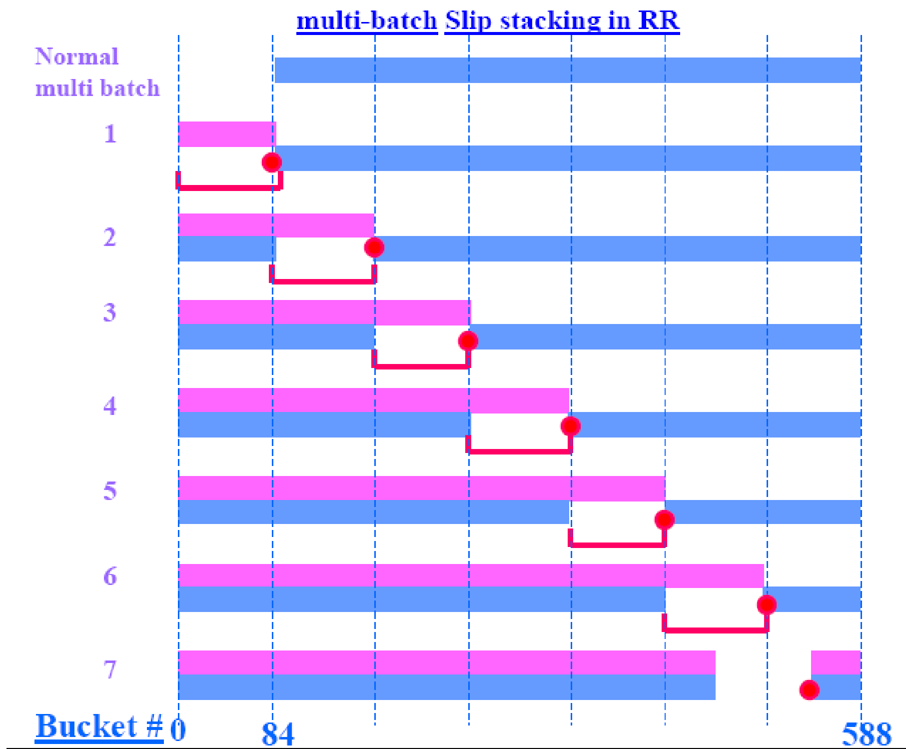


I. Kourbanis, K. Seiya



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 4×10^{12} protons
      - 84×0.08 eV-s $\Rightarrow$ 84×0.38 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
  - 9.5×10^{13} ppp in MI every 1.6 s $\Rightarrow$ **1.1 MW**

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

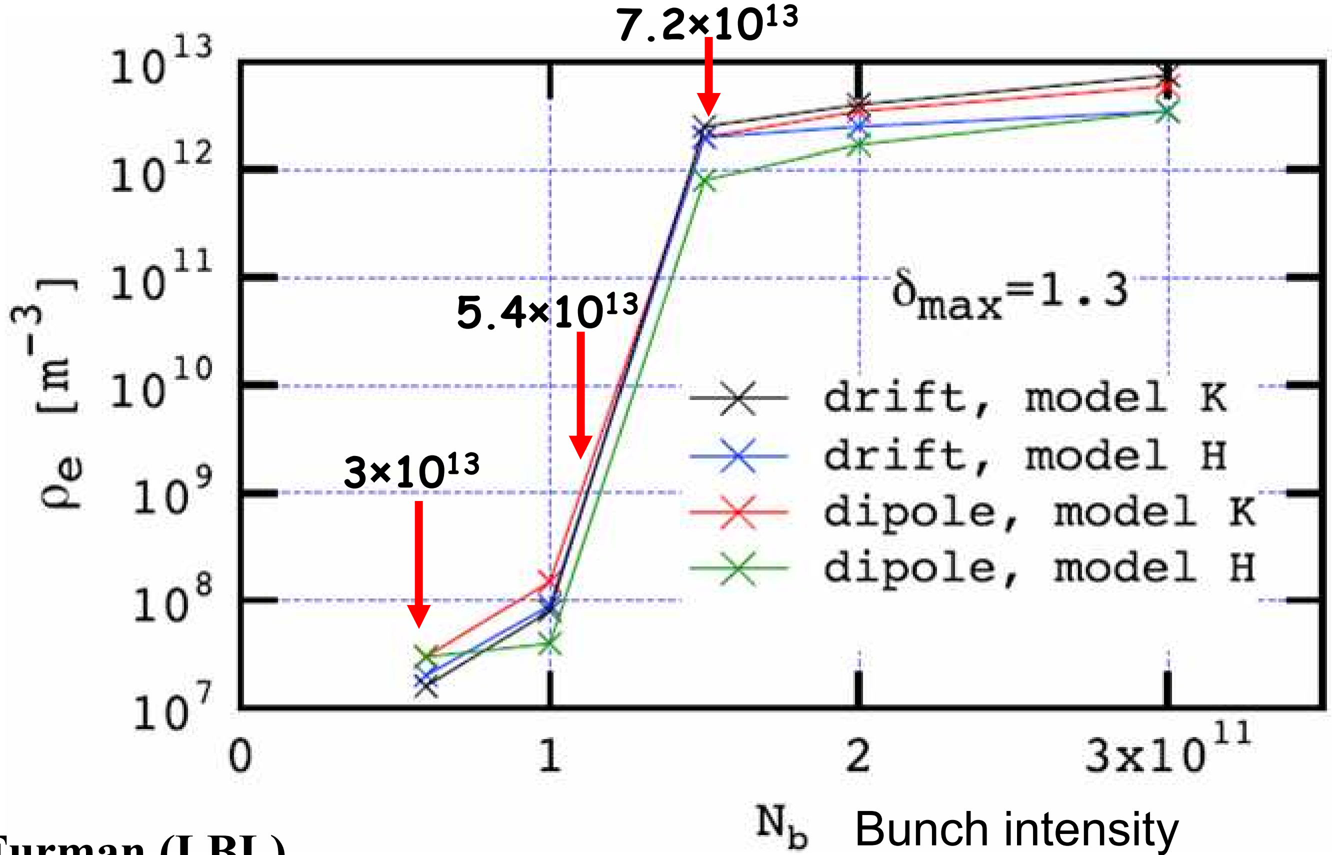
1. Booster rep rate up to 9.3 Hz
2. Beam quality

Engineering Support
R. Reilly

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

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.-L. Vay, J. Corlett, B. Zwaska, X. Zhang*
- Simulation of e-cloud and beam dynamics in MI – *P. Spentzouris, E. Stern*
- 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

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	5.3×10^{20}
2012	38	700	1000	7.3×10^{20}
2013	44	1000	1000	9.9×10^{20}

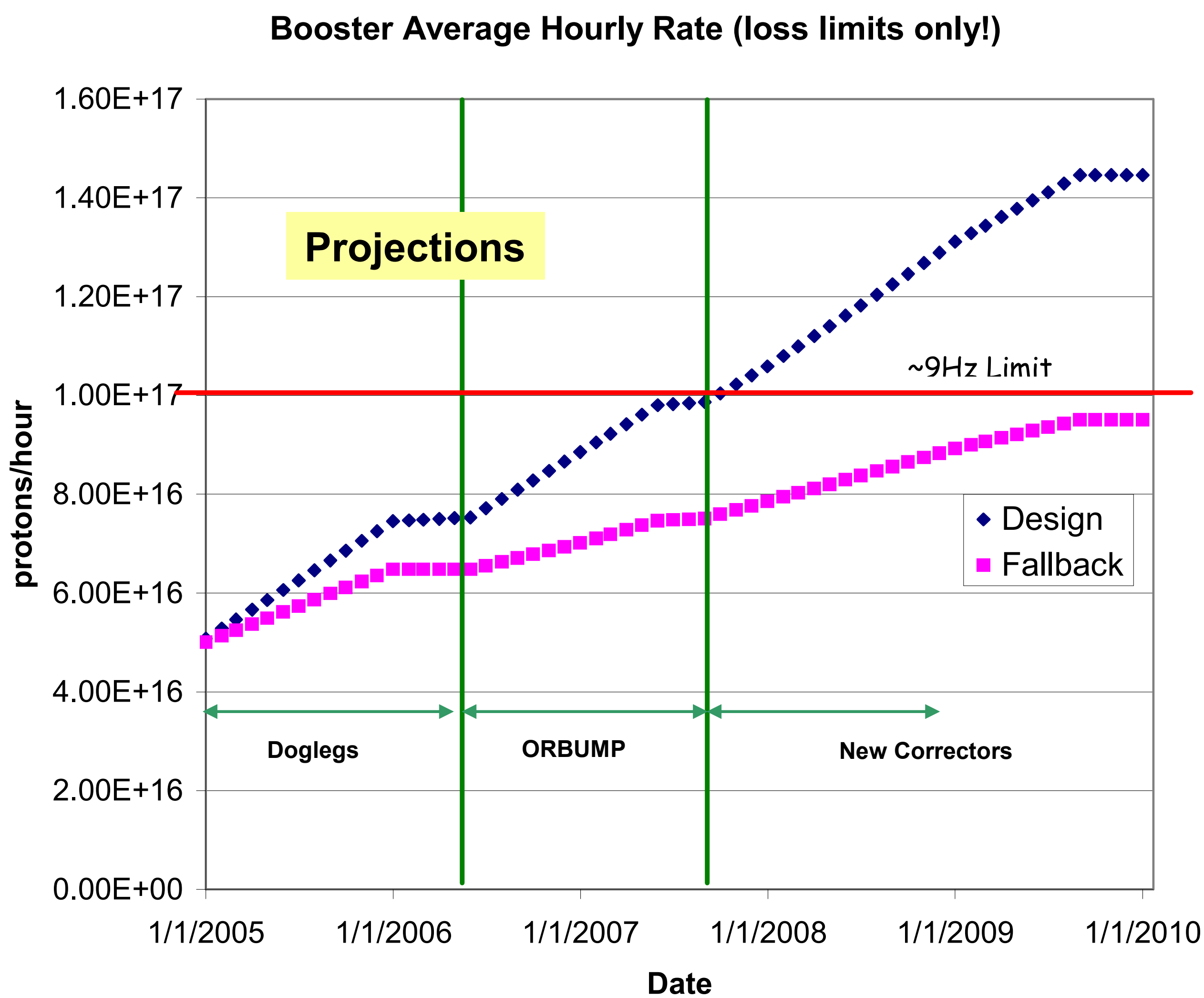
Conclusions

- The Main Injector has presently operated up to ~ 3.15×10^{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

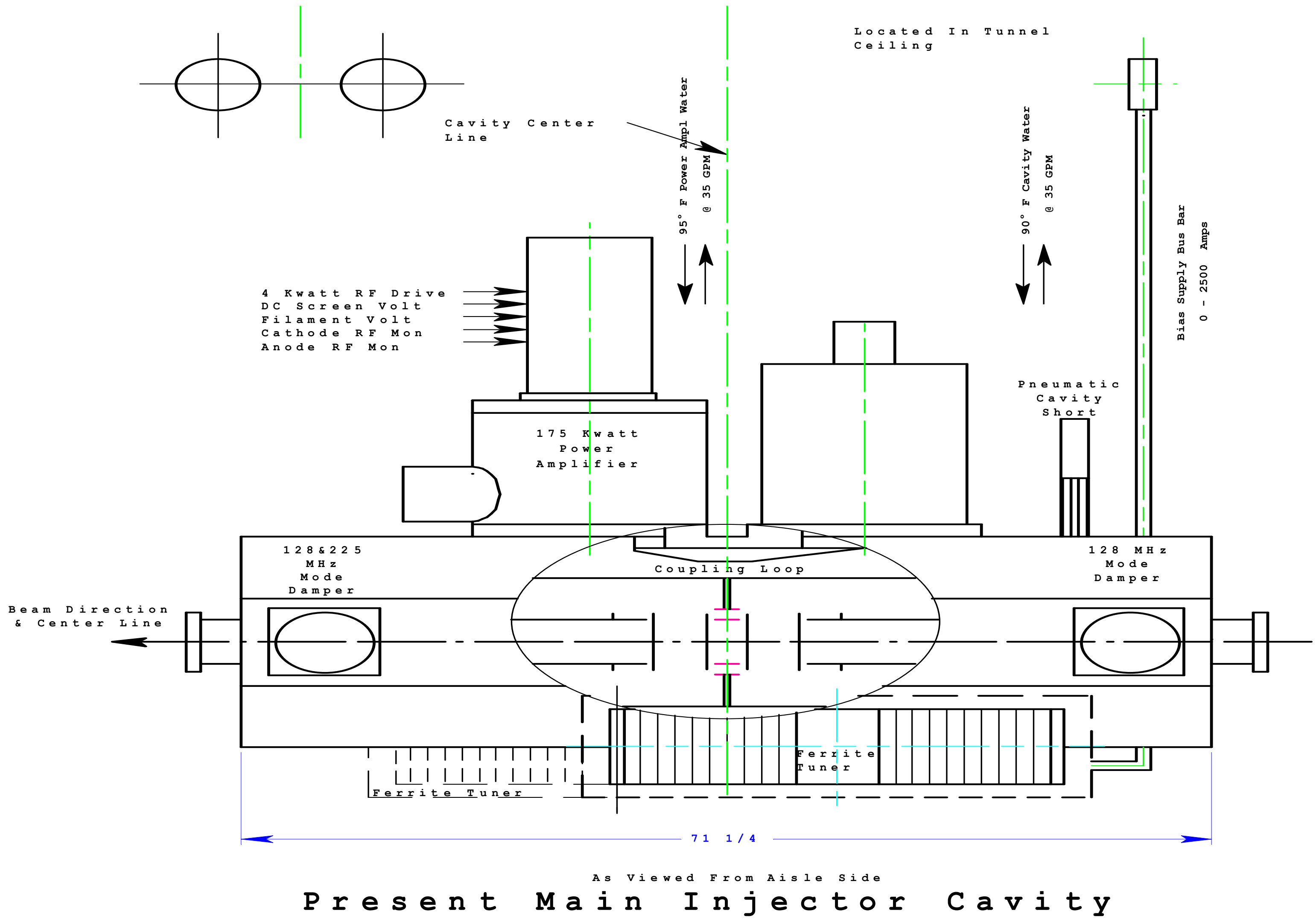
	700 kW cost estimate (k$)	1 MW cost estimates (k$)
Booster		
Transformers in bias supplies	200	
Feeder	300	
480 V distribution system	100	
Sub-totals	**600**	
Main Injector		
RF system upgrade		12000
Gamma-t jump		500
Shielding	700	
Sub-totals	**700**	**12500**
Recycler		
Decommissioning anti-proton 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**

Booster performance and projections



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

Schematic of MI RF Cavity



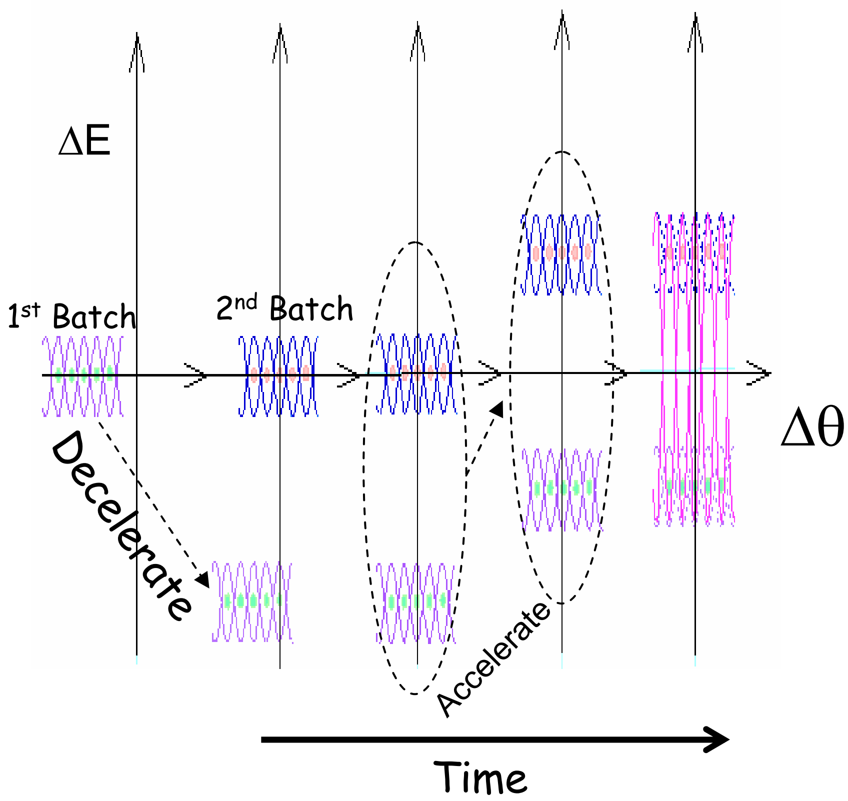
Main Injector ramps

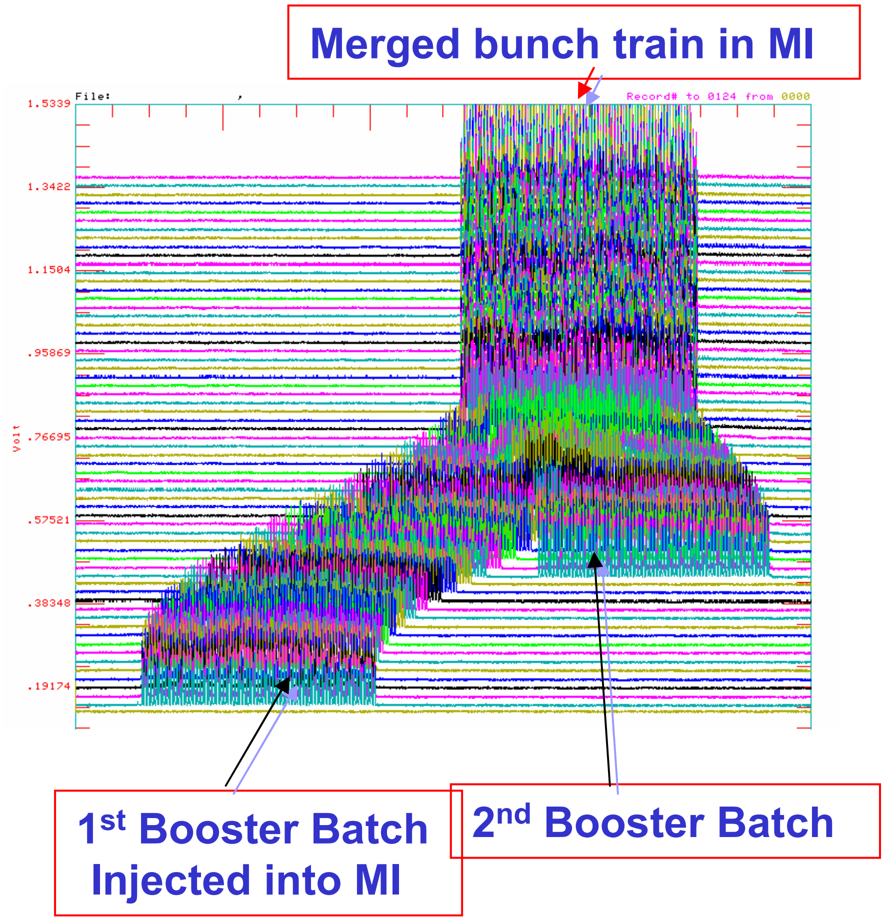
Delta t	Time	Momentum	Pdot
0.08000	0.08000	8.884	0.00
0.02533	0.10533	8.96	6.00
0.04154	0.14687	9.5	20.00
0.11111	0.25798	22	205.00
0.30732	0.56530	85	205.00
0.15385	0.71915	115	185.00
0.05081	0.76996	119.7	0.00
0.06650	0.83646	119.7	0.00
0.11308	0.94953	105	-260.00
0.17308	1.12261	60	-260.00
0.20417	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

Slip-stacking

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



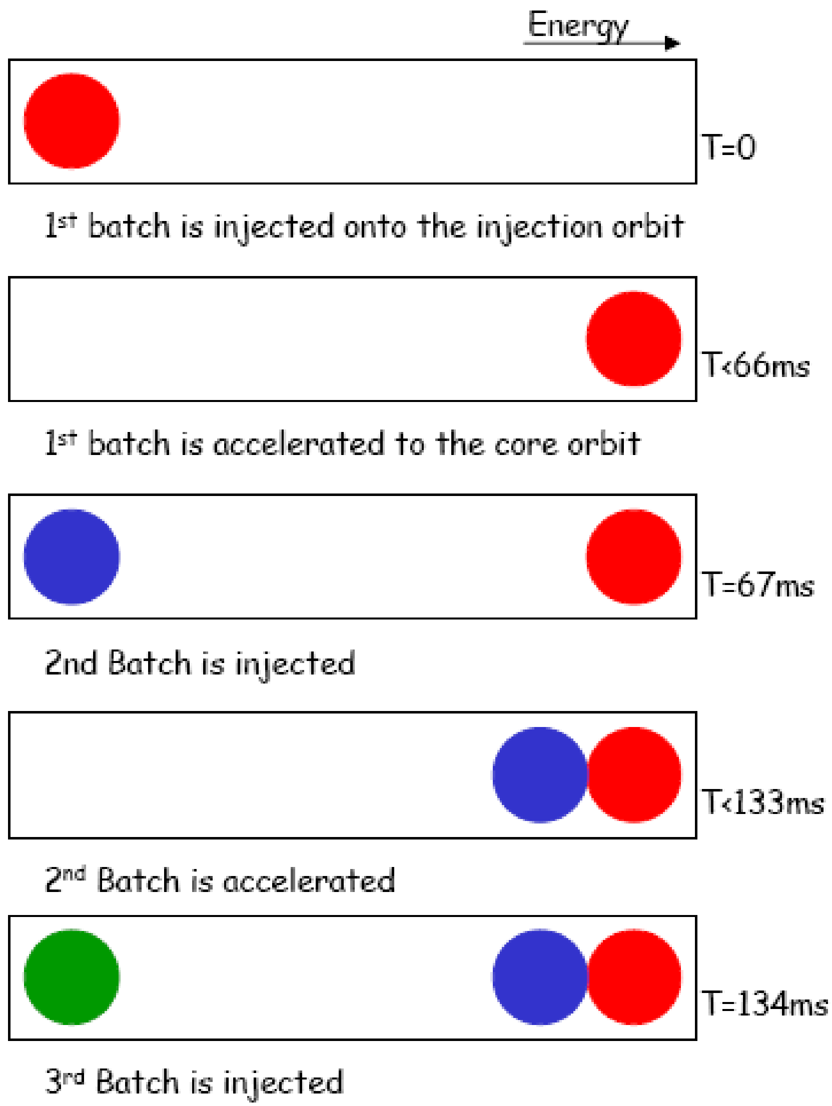


K. Koba Seiya et. al., PAC2003

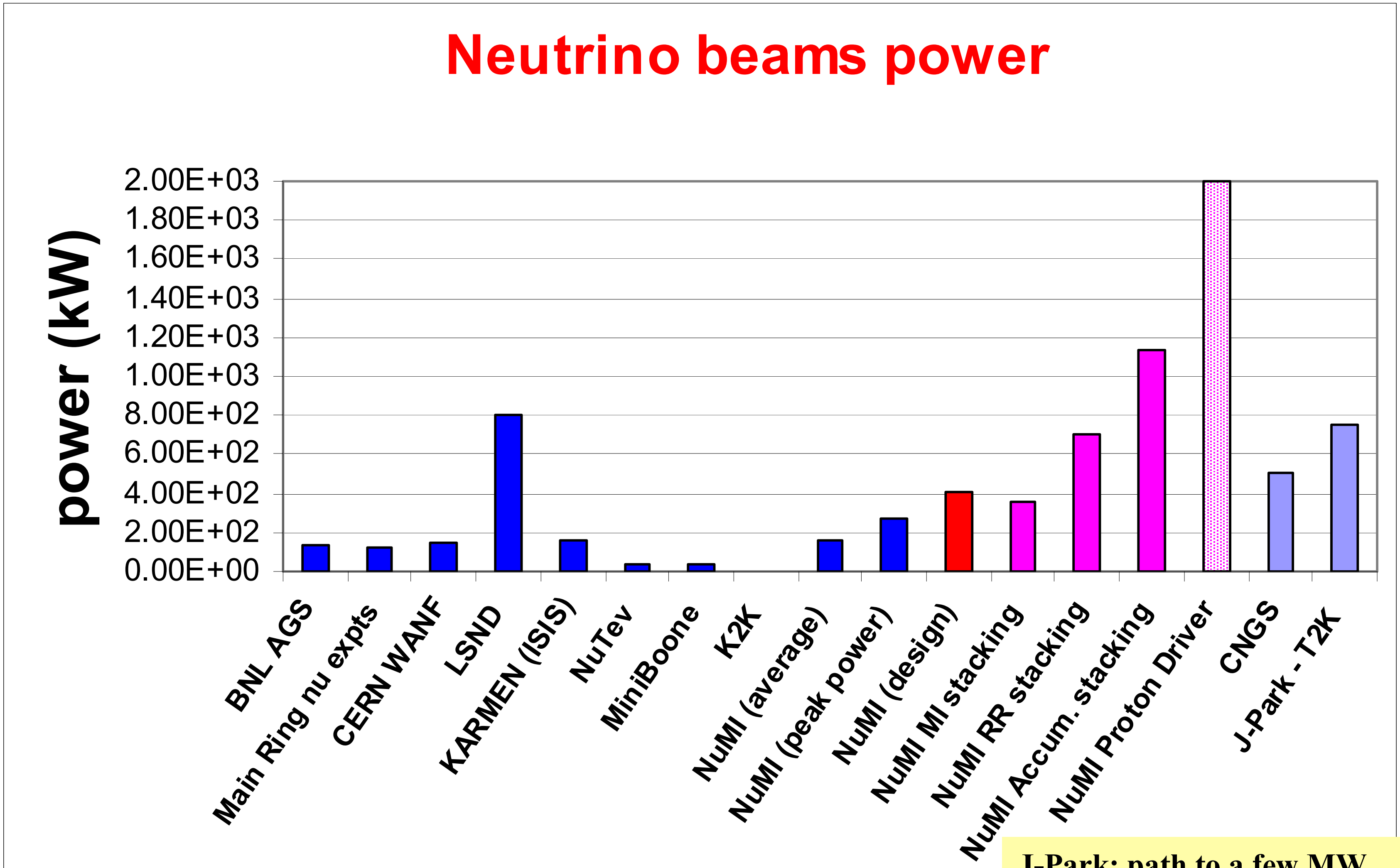
➢ **during last year achieved 8×10^{12} protons on the antiproton target**

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



The power of neutrino beams



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