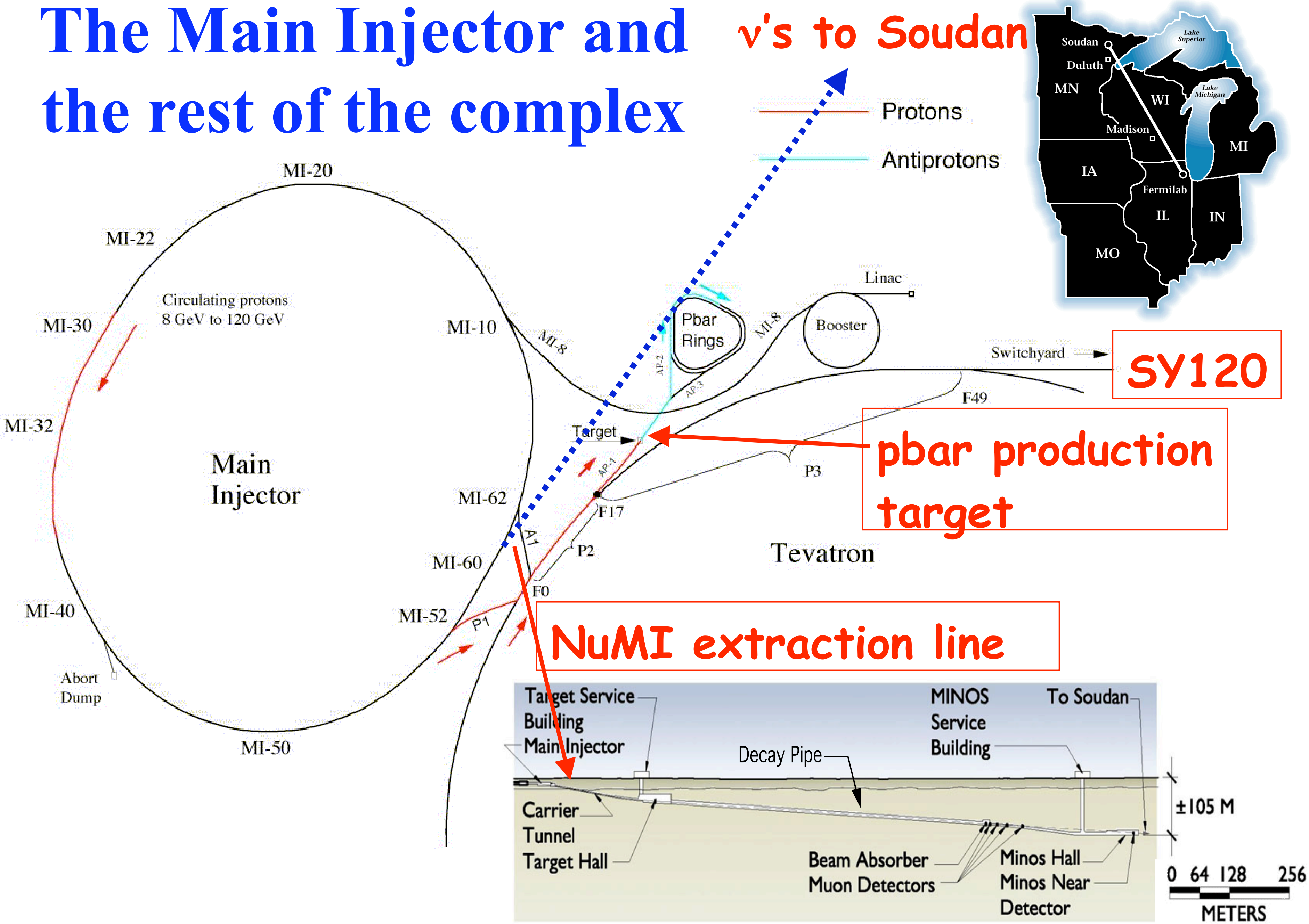
Accelerator and beam requirements

A. Marchionni, Fermilab AD/MID
NuSAG, May 20, 2006

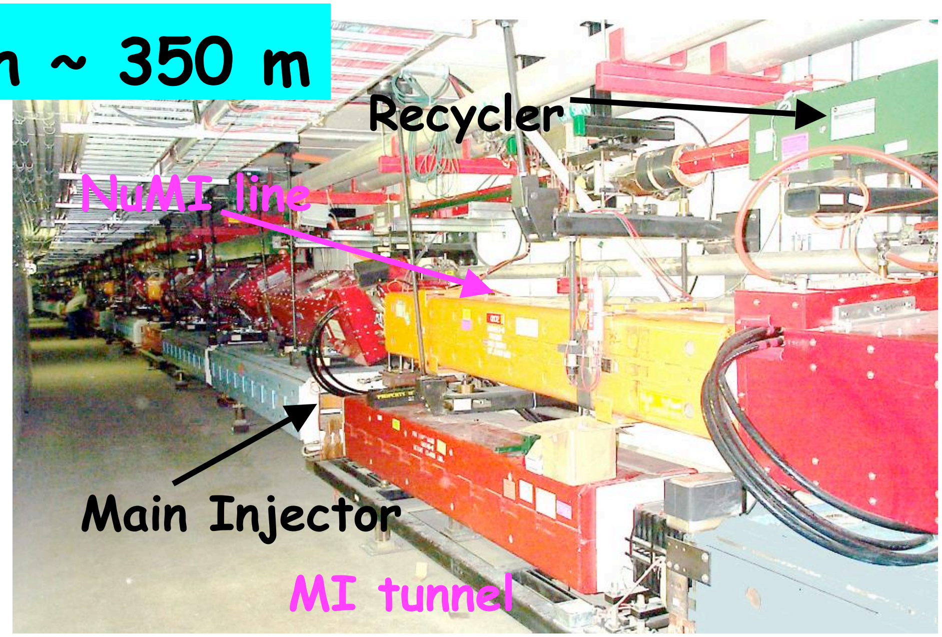
- Present operation of Main Injector and NuMI
  - NuMI designed for 400 kW, achieved a max beam power of 270 kW
- Present Proton Plan (ends with the Collider run):
  - multi-batch slip-stacking in Main Injector
- SNuMI (super-beam upgrades to NuMI)
  - upgrades to both accelerator complex and NuMI line
  - Recycler as an 8 GeV proton pre-injector
  - momentum stacking in the Accumulator
- Preliminary cost estimates and time scale for SNuMI
- R&D towards a High Intensity Neutrino Source
- A neutrino beam towards DUSEL

The Main Injector and the rest of the complex

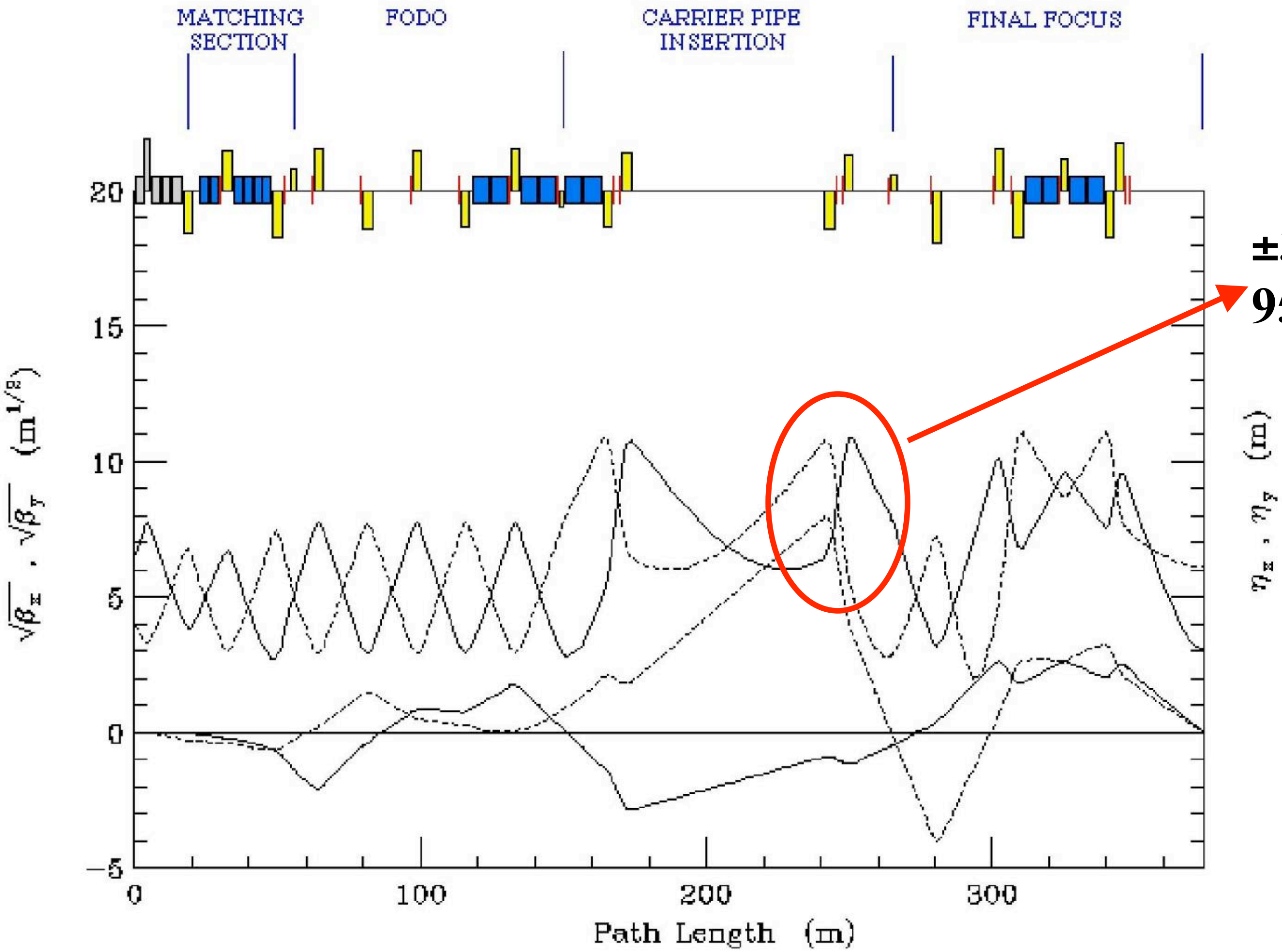


The NuMI primary proton line

Total length ~ 350 m



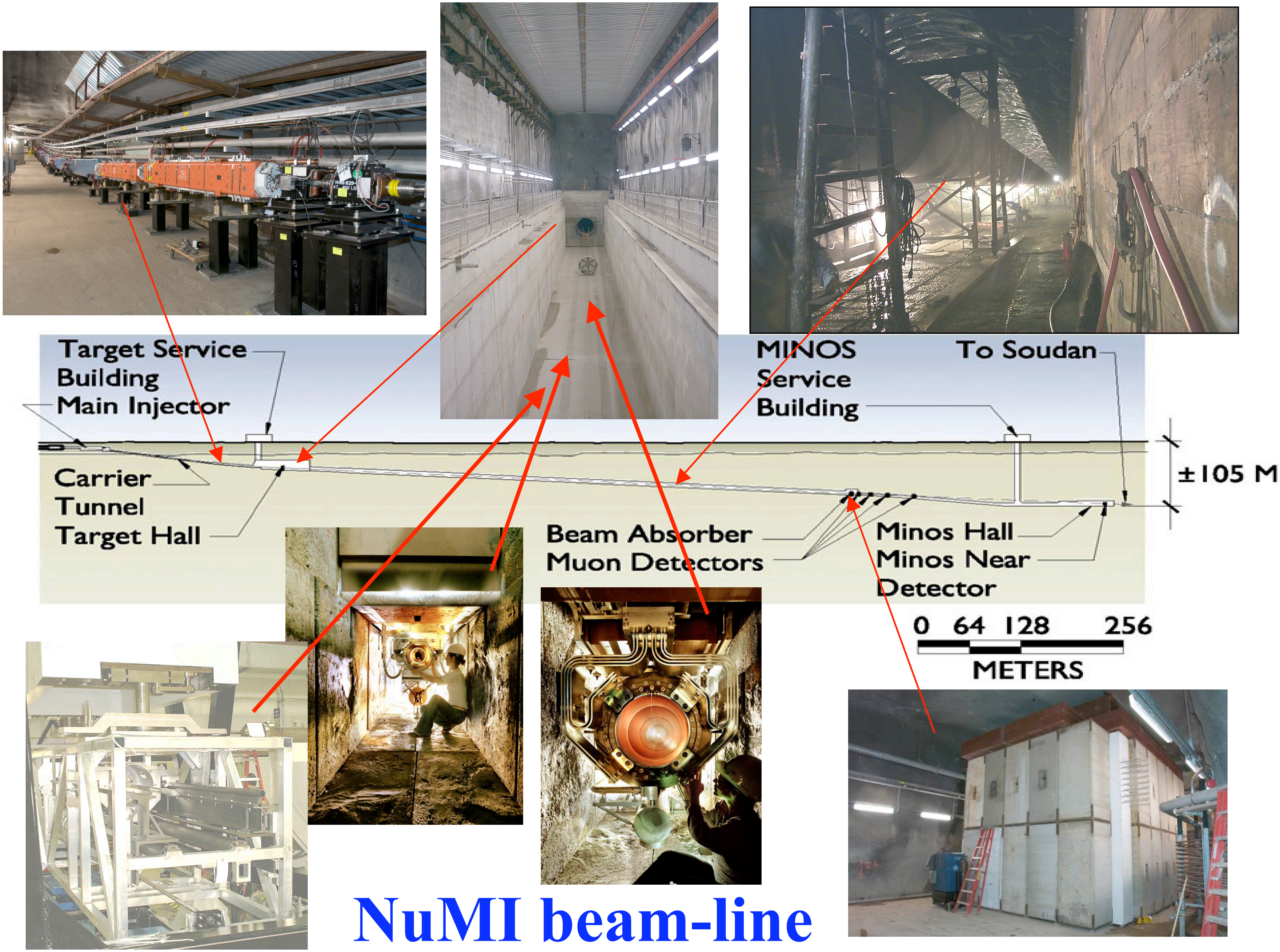
NuMI Primary Proton Line



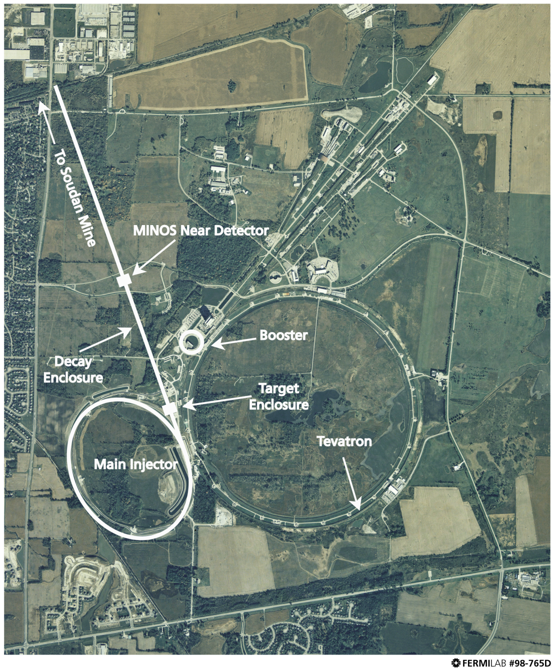
±35 mm aperture
95% beam size ±7 mm

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

Large aperture line !



NuMI beam-line



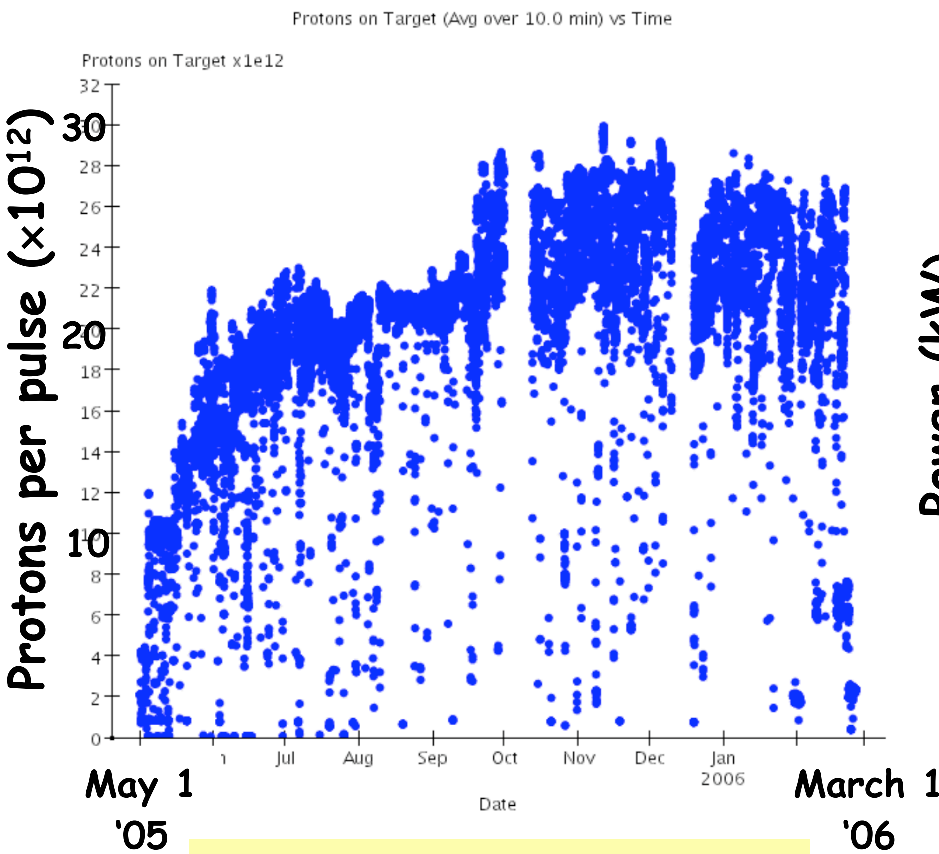
Present operation of Main Injector & NuMI

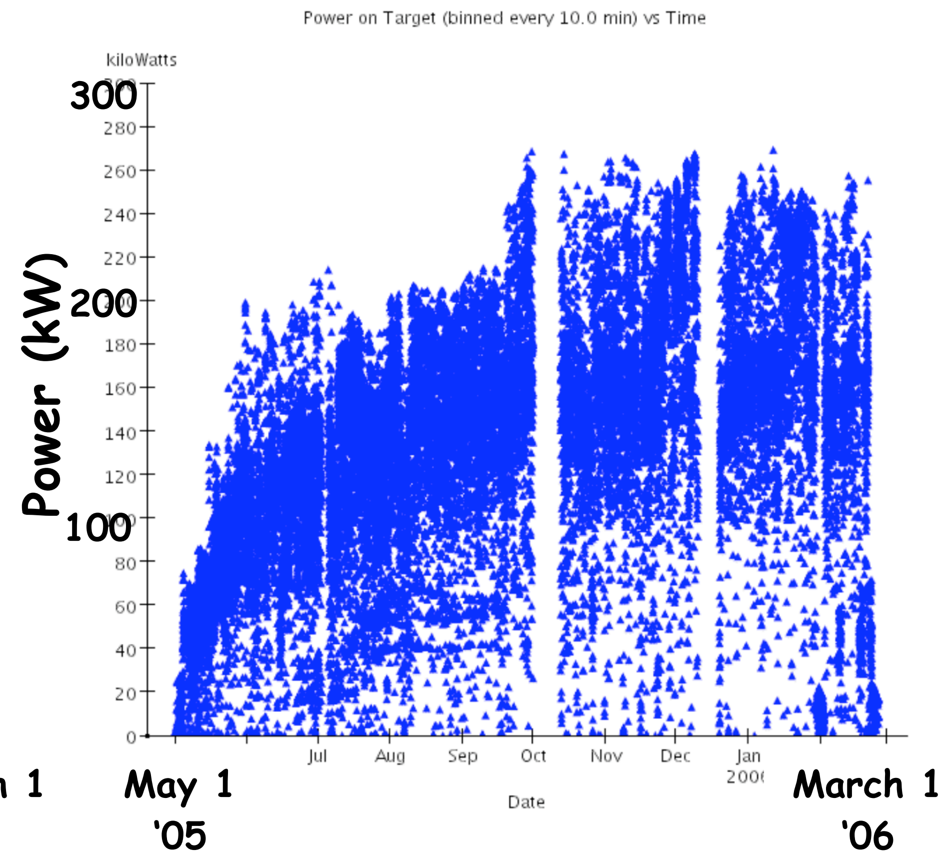
- ❖ **Main Injector is a rapid cycling accelerator at 120 GeV (presently running at 205 GeV/s)**
  - ➢ 1.467 s cycle time (for 1 batch injection)
- ❖ **up to 6 proton batches (~ 5×10^{12} p/batch) are successively injected from Booster into Main Injector at 15 Hz**

- ❖ **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

ϖ **NuMI design values: 4×10^{13} ppp every 1.9 s ⇒ 400 kW**

NuMI first year running





1.4E20 pot integrated

Peak values

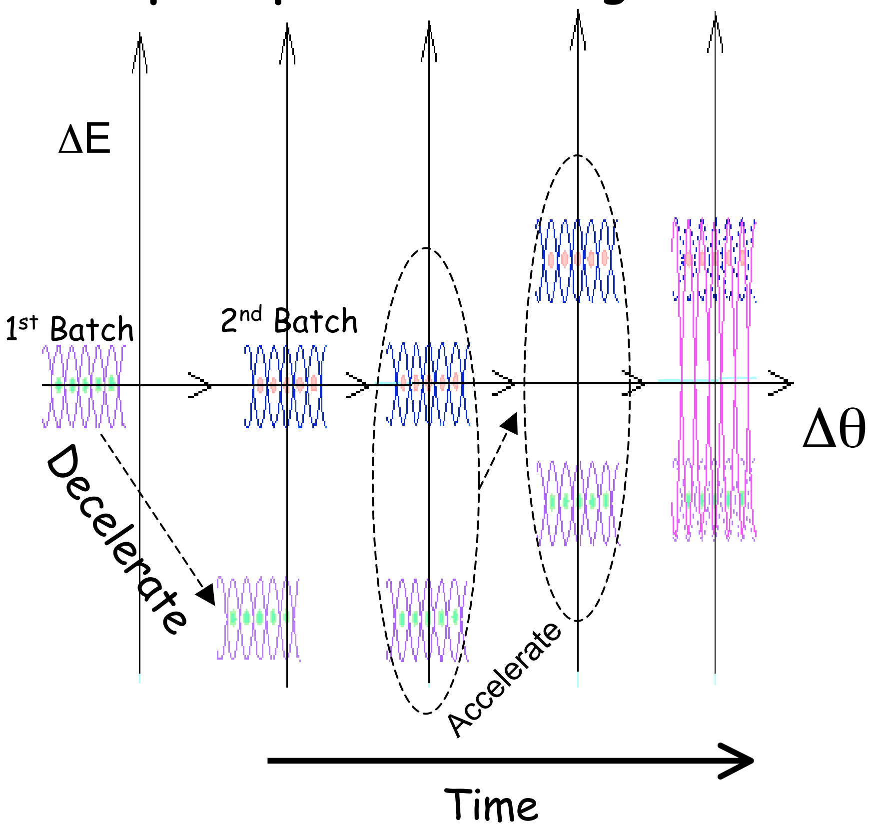
- max beam power of 270 kW stably for ~ _ hour
- peak intensity of 3_10^{13} ppp

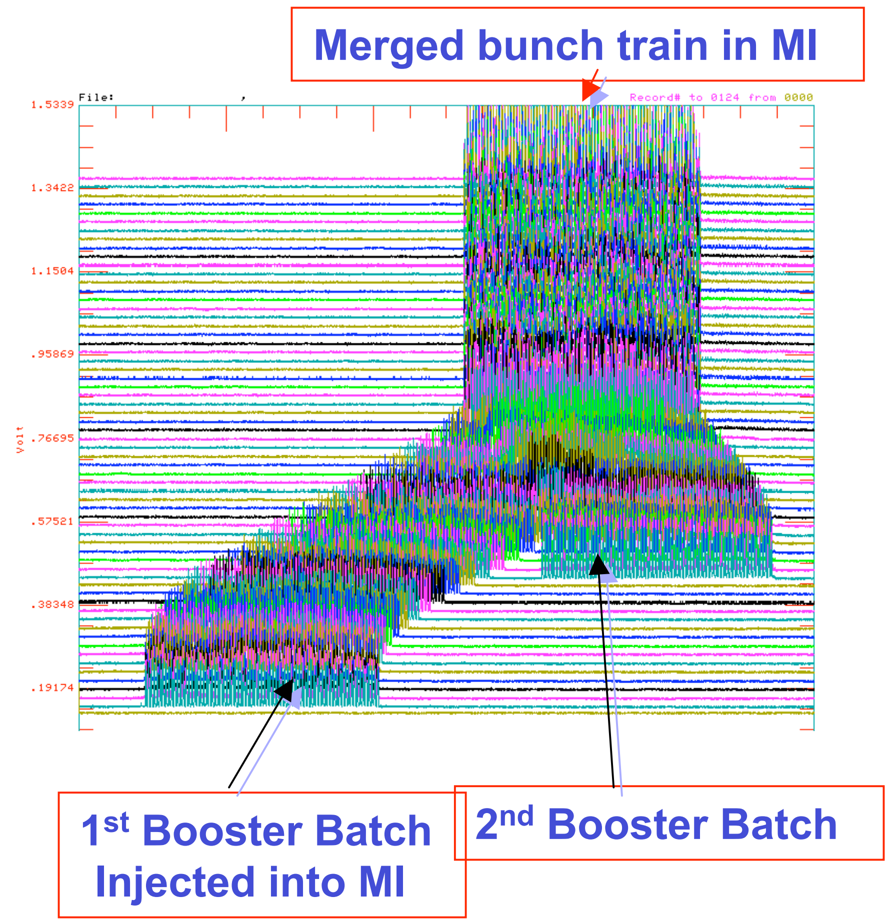
Averages over the last months

- beam power 170 kW
- proton intensity 2.3_10^{13} ppp
- cycle spacing 2.2 s

Slip-stacking

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



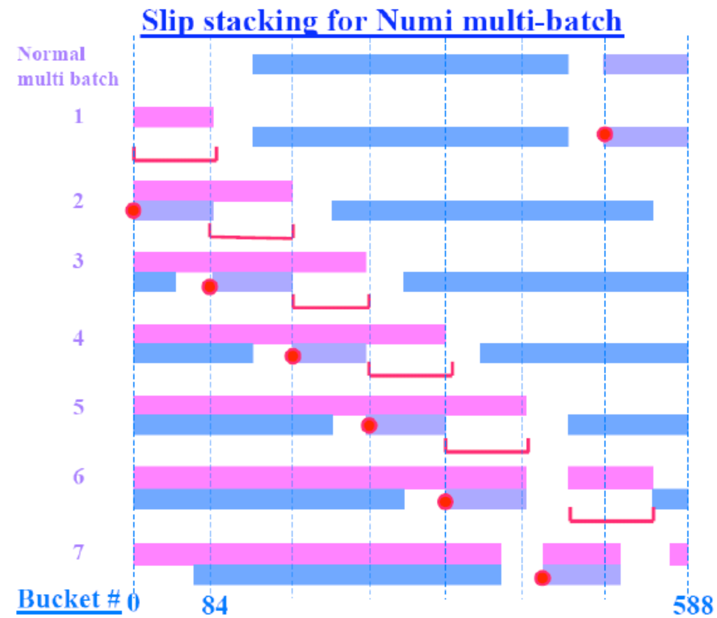


K. Koba Seiya et. al., PAC2003

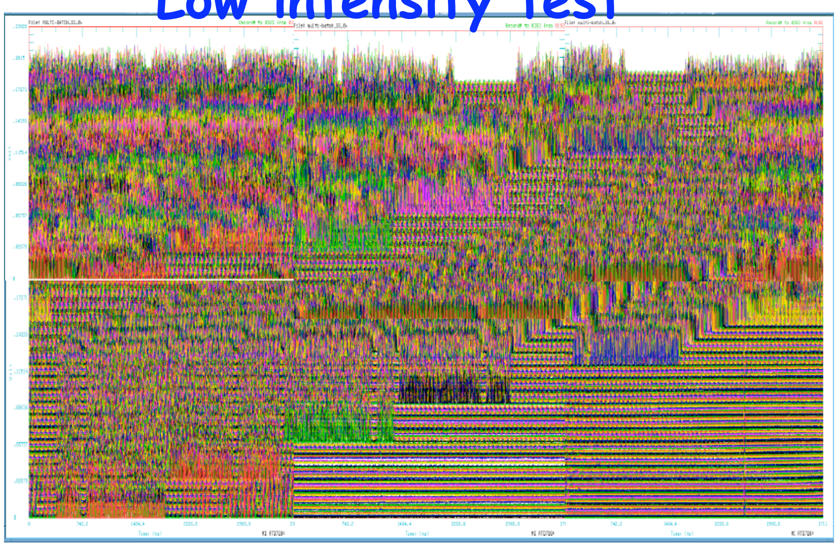
➢ during last year achieved 8_10^{12} protons on the anti-proton target

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_10^{20} protons/year to NuMI

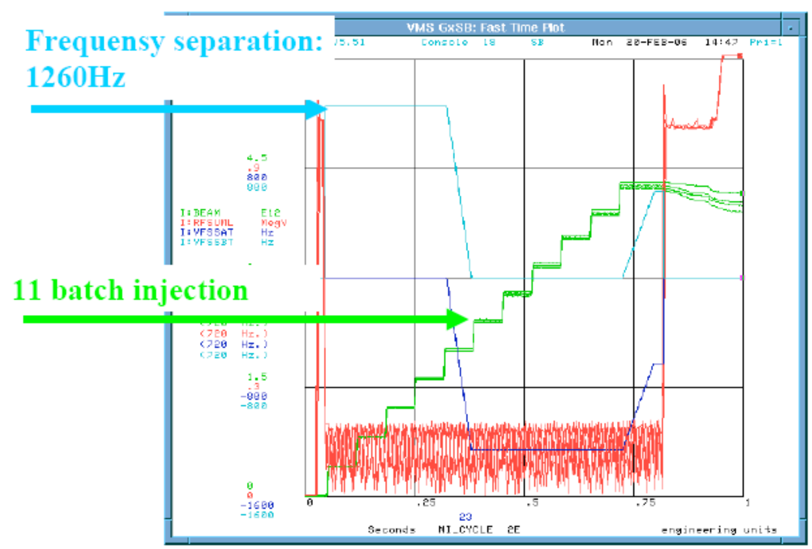


Low intensity test



I. Kourbanis, K. Seiya

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



Main Injector capabilities

- design acceleration rate of 240 GeV/s
- The current MI RF system consists of 18 stations
  - ¬ 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 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
- a γt-jump system and an upgrade of the RF system are the major modifications that would allow to raise the intensity above 6×10^{13} protons/cycle
  - Each RF cavity has an extra port available for the installation of a second power tube (up to ~ 1.5 MW beam power)

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

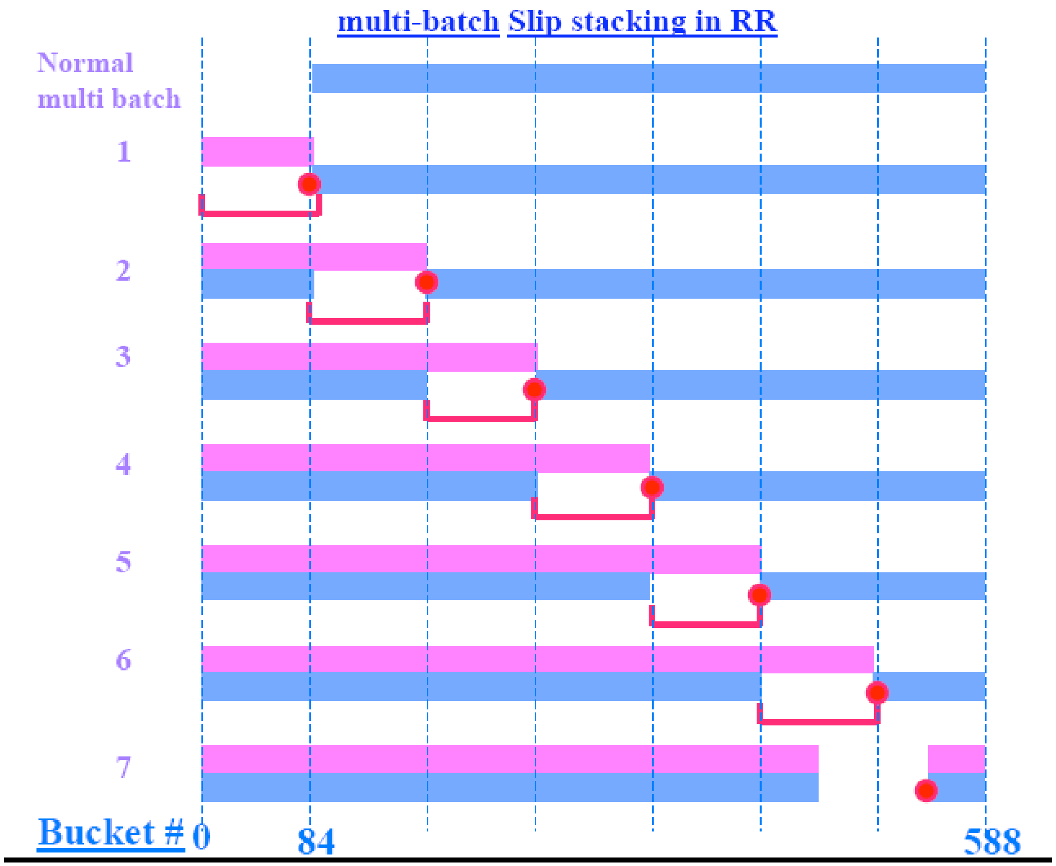
S. Nagaitsev, E. Prebys, M. Syphers 'First Report of the Proton Study Group', Beams-doc-2178

- 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 1.333 s ⇒ 430 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

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



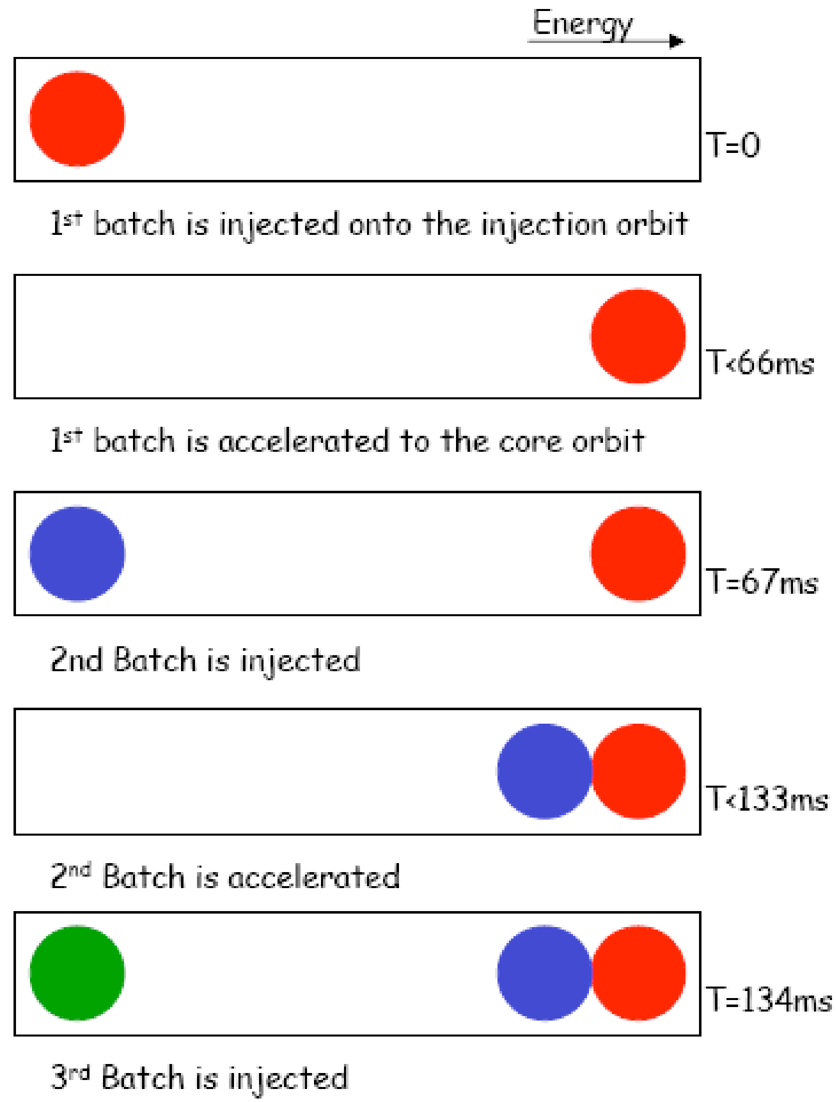
SNuMI stage 2: 1.2 MW
Momentum stacking in the Accumulator

D. McGinnis, Beams-doc-1782, 2138, 1783, 2253

- 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 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

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



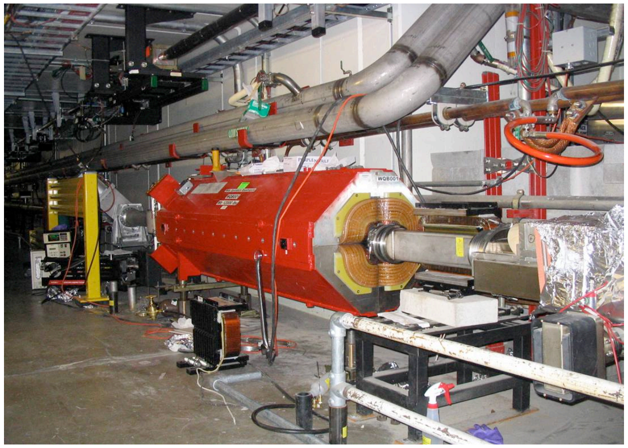
SNuMI scenarios

	Slip-stacking in Recycler Ring	Momentum stacking in Accumulator 1	Momentum stacking in Accumulator 2
Booster batch intensity	4.3E12	4.6E12	4.6E12
No. Booster batches	12	18	18
Booster average rep rate (Hz)	10.5	15	15
MI cycle time (s)	1.333	1.333	1.2
MI intensity (ppp)	4.9E13	8.2E13	8.2E13
Beam power to NuMI (kW)	700	1200	1300
Protons/hr	1.3E17	2.2E17	2.5E17

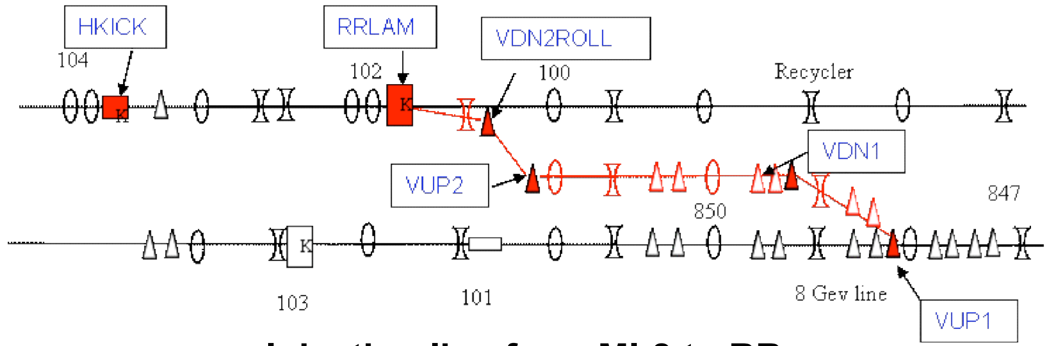
Charge for SNuMI stage 1, 700 kW

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.**



Recycling the Recycler

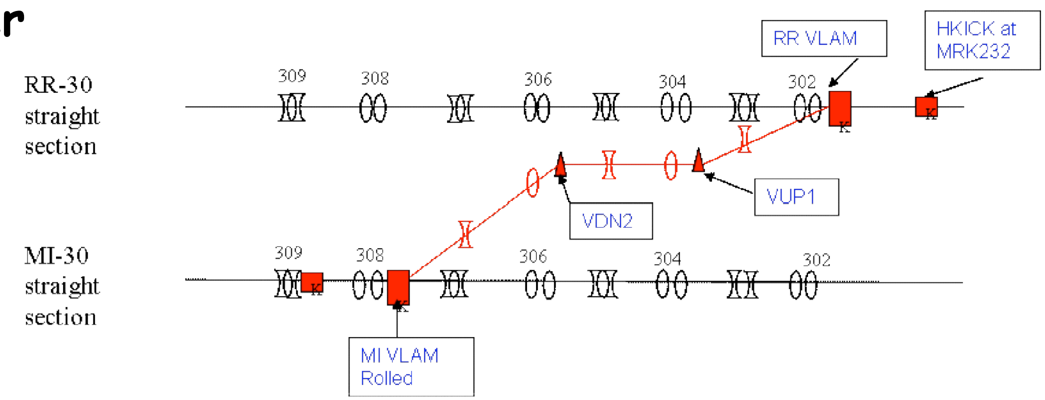


Injection line from MI-8 to RR

- 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

Have preliminary designs and cost estimates

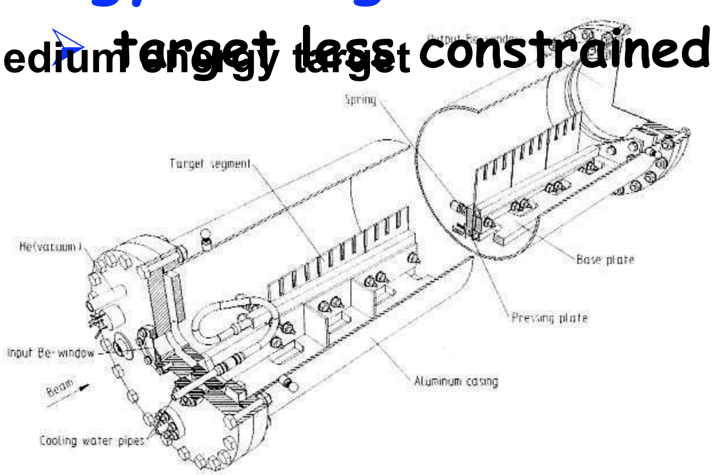
Extraction line in the 30 section



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 identified 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 continge

	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
    - capability actually up to 1.2-1.3 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}

R&D towards a High Intensity Neutrino Source

- New* idea incorporating concepts from the ILC, the Spallation Neutron Source and RIA
  - Copy SNS, RIA, and JPARC Linac design up to 1.3 GeV
  - Use ILC Cryomodules from 1.3 - 8 GeV
  - H^- Injection at 8 GeV in Main Injector
- 2 MW beam power at both 8 GeV and 120 GeV
- HINS R&D goals (2006-2009): prove, develop & build front-end (0-90 MeV)
  - much of technical complexity in front-end mechanical/RF systems

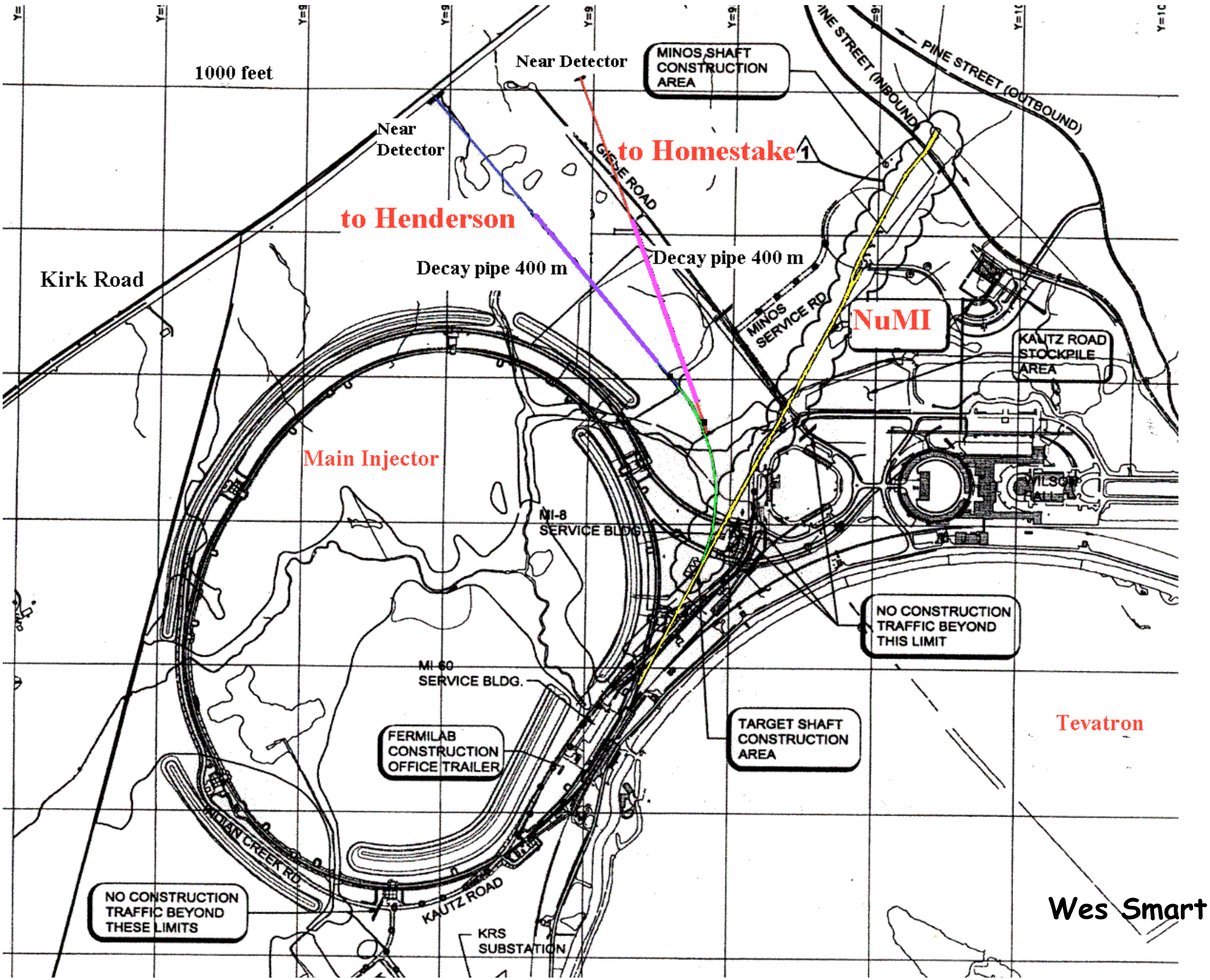
* *The 8 GeV Linac concept actually originated with V. Bharadwaj and B. Noble in 1994, when it made no sense because the SCRF gradients weren't there. Revived and expanded by G.W.Foster in*

Exploring the possibility of neutrino beams towards a DUSEL site

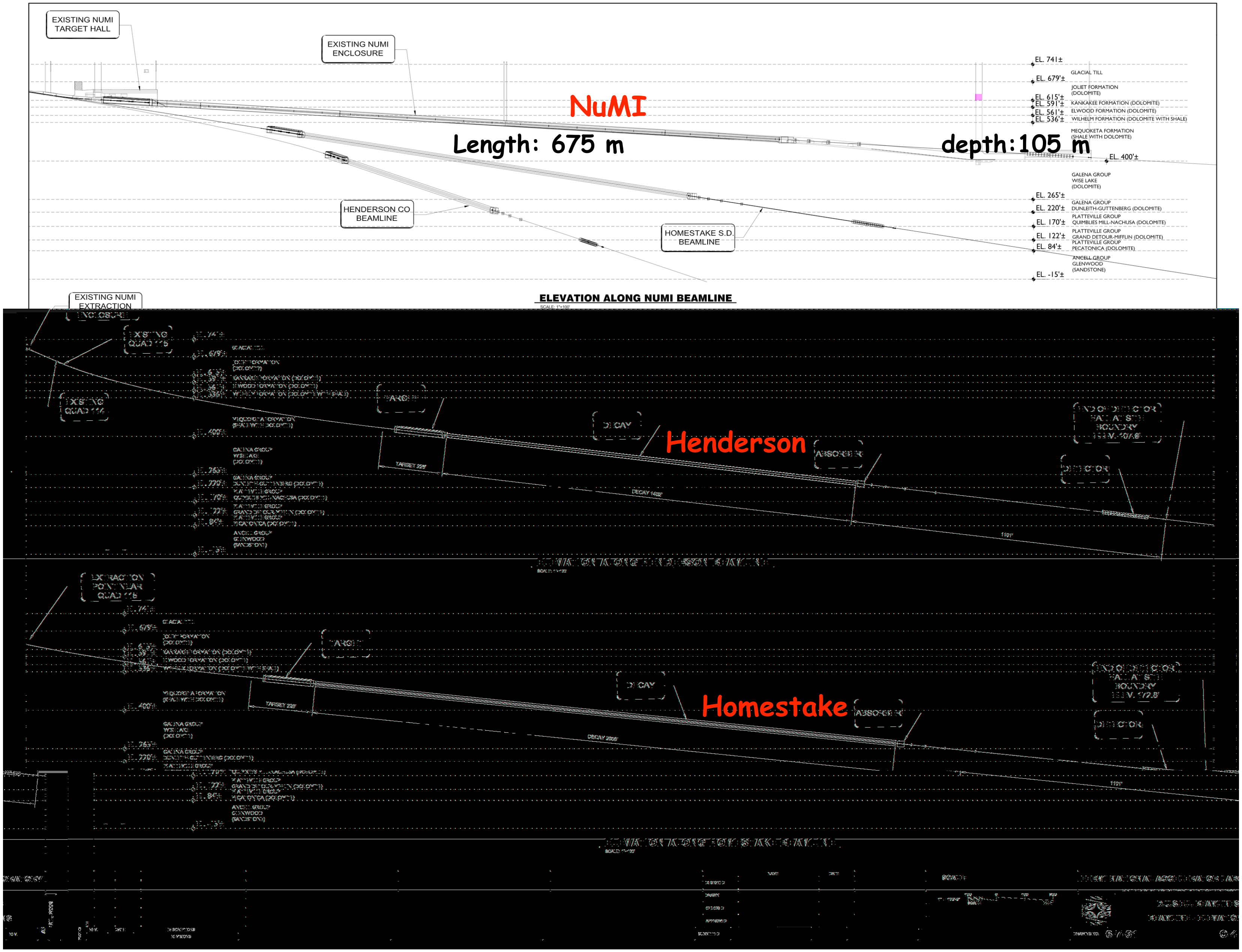
D. Bogert, W. Smart

	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

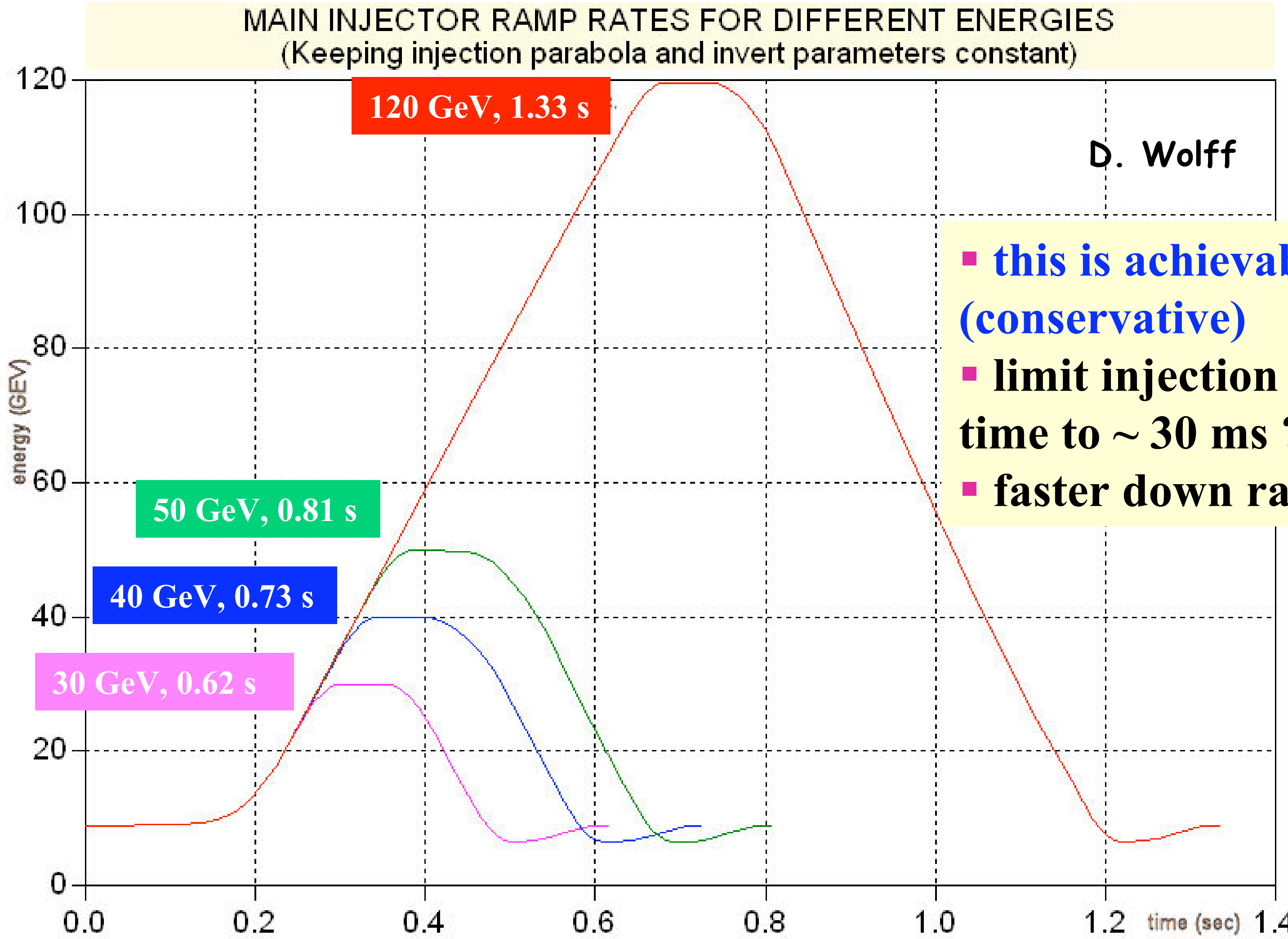
- **Use the present extraction out of the Main Injector into the NuMI line**
  - construction of an additional tunnel, in the proximity of the Lower Hobbit door in the NuMI line, in order to transport the proton beam to the west direction
  - radius of curvature of this line same as the Main Injector, 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)


1000 feet
Near Detector
Near Detector
MINOS SHAFT CONSTRUCTION AREA
PINE STREET (INBOUND)
PINE STREET (OUTBOUND)
to Homestake
to Henderson
GIESE ROAD
Decay pipe 400 m
Decay pipe 400 m
Kirk Road
MINOS SERVICE RD
NuMI
KAUTZ ROAD STOCKPILE AREA
Main Injector
WILSON HALL
MI-8 SERVICE BLDG
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

Max decay pipe lengths



Lowering the primary proton energy ?

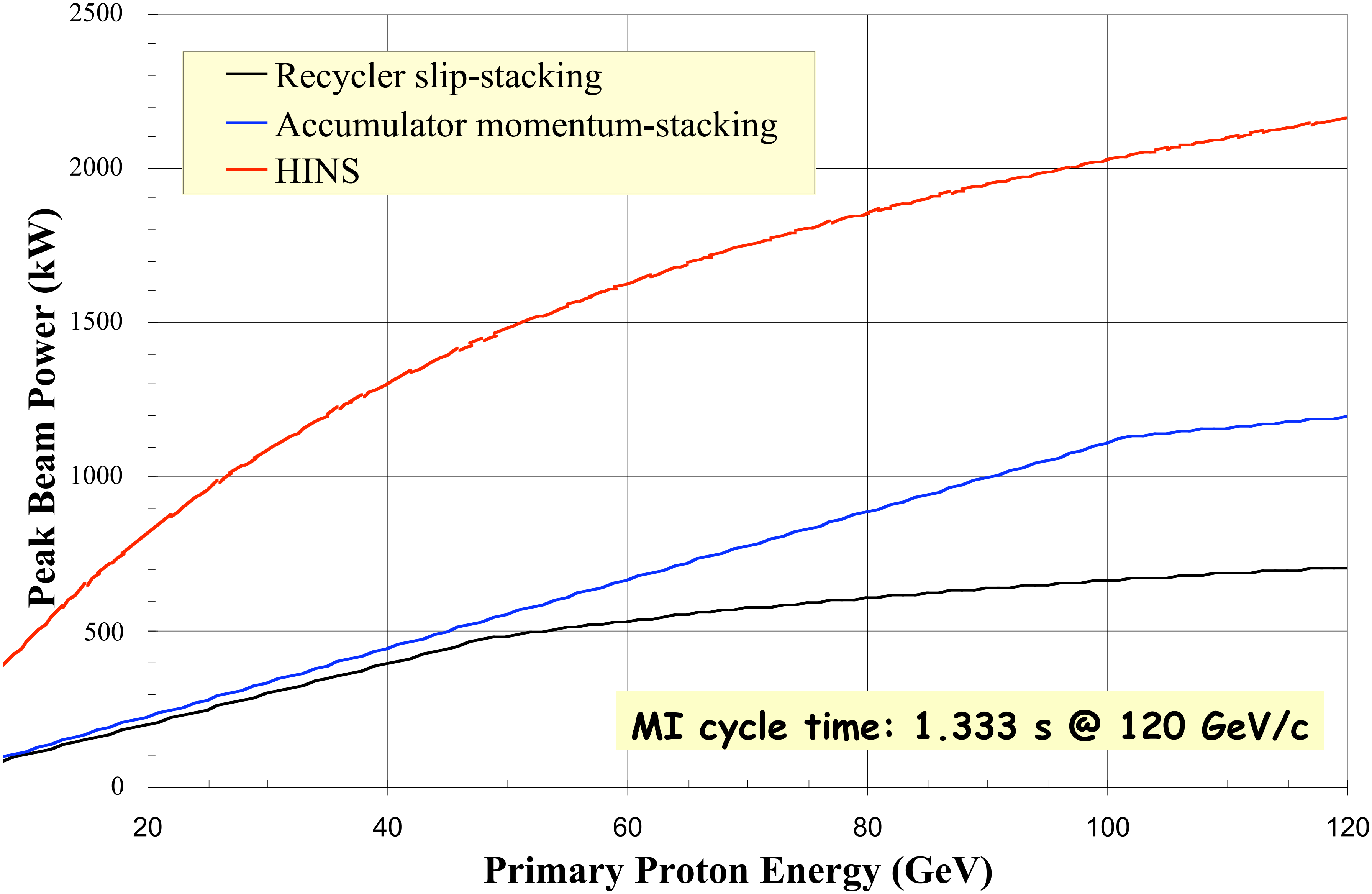


- **this is achievable now (conservative)**
- **limit injection dwell time to ~ 30 ms ?**
- **faster down ramp ?**

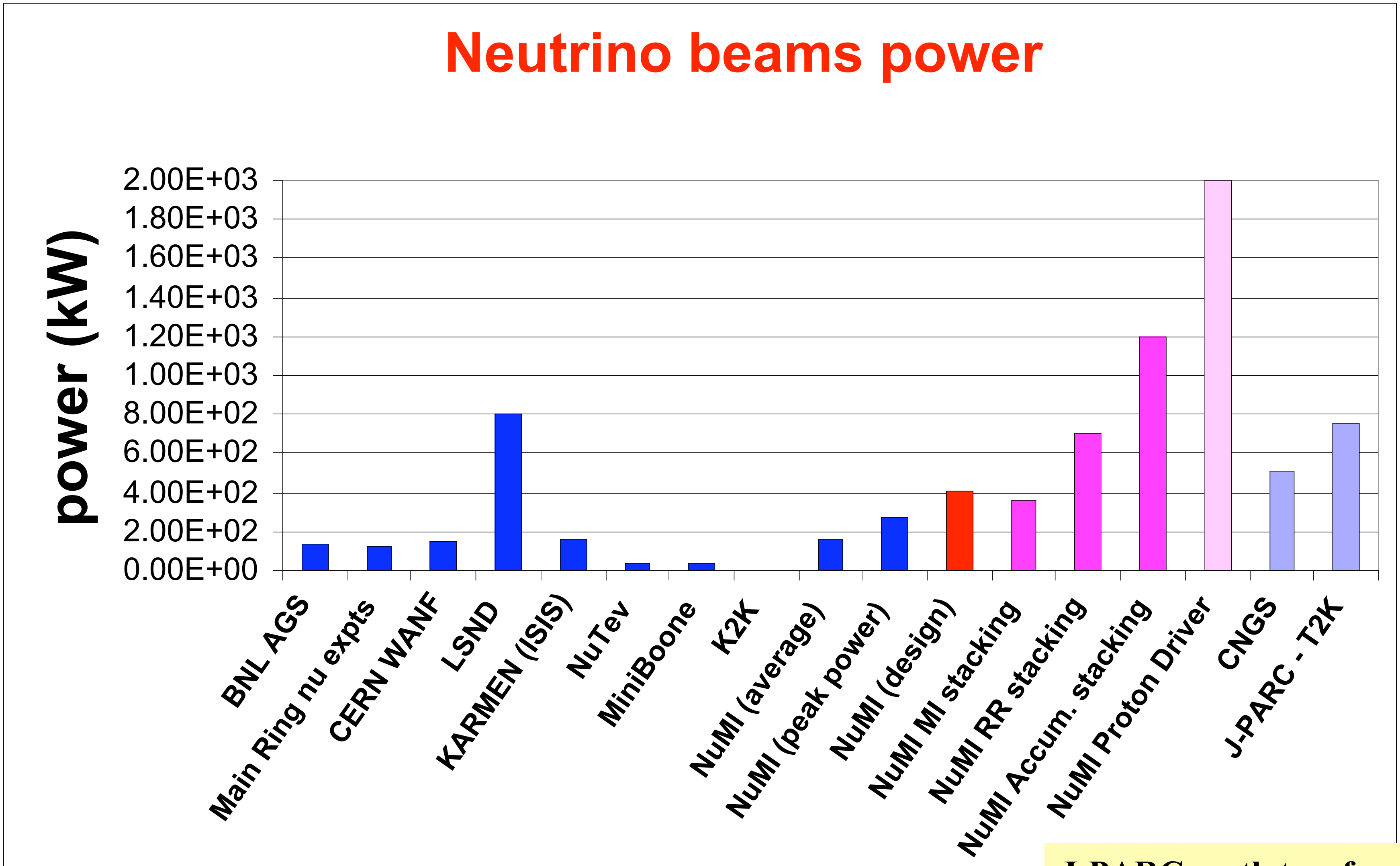
- **Injection dwell time 80 ms**
- **Flattop time 50 ms**
- **Maximum dp/dt 240 GeV/s**

Beam power vs proton energy

R. Zwaska



The power of neutrino beams

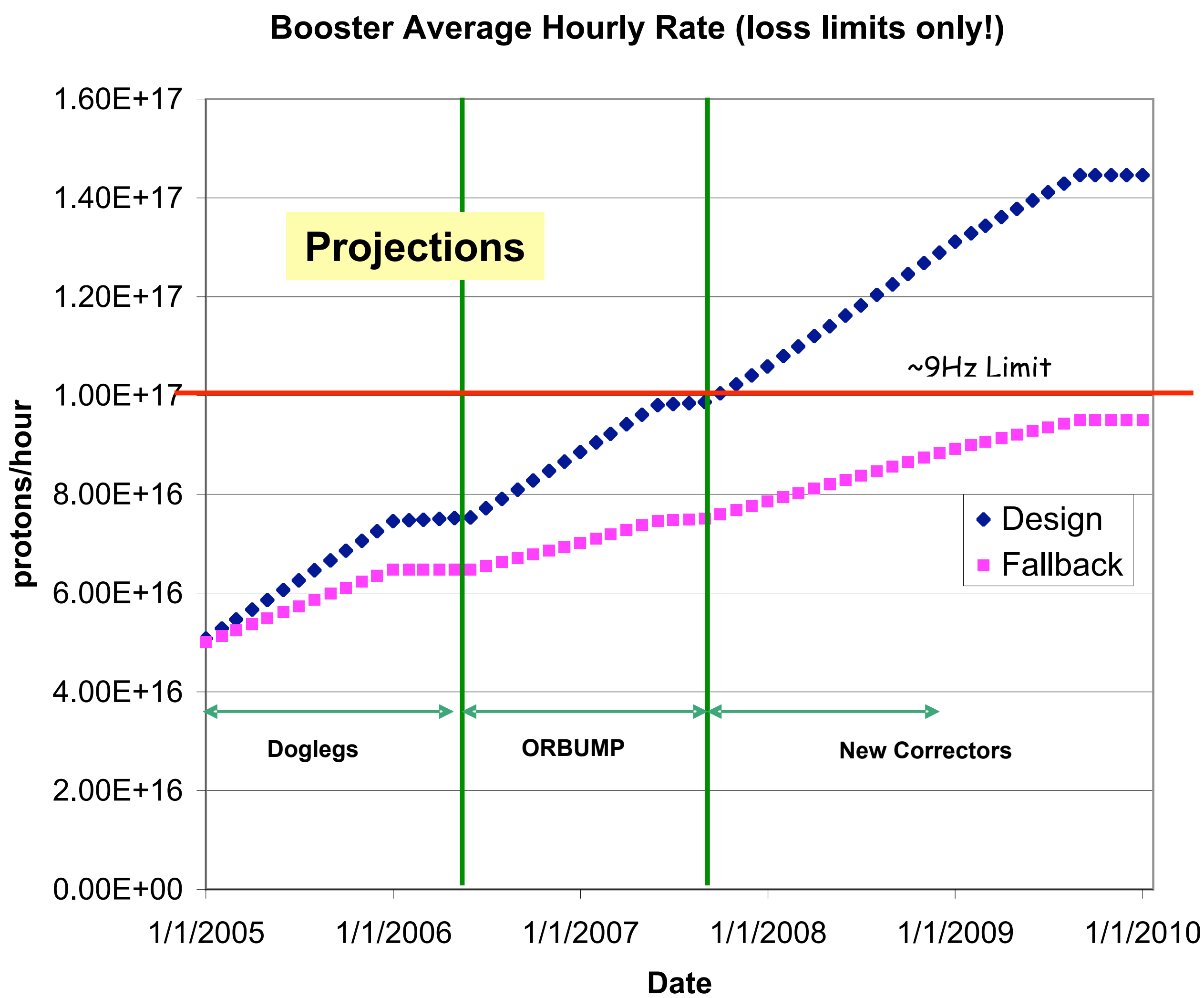


J-PARC: path to a few MW facility is being studied

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 1.2-1.3 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
  - momentum stacking in the Accumulator allows to increase the beam power to 1.2-1.3 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
- Fermilab could send neutrinos to DUSEL
  - preliminary layouts of a neutrino beam towards DUSEL, need

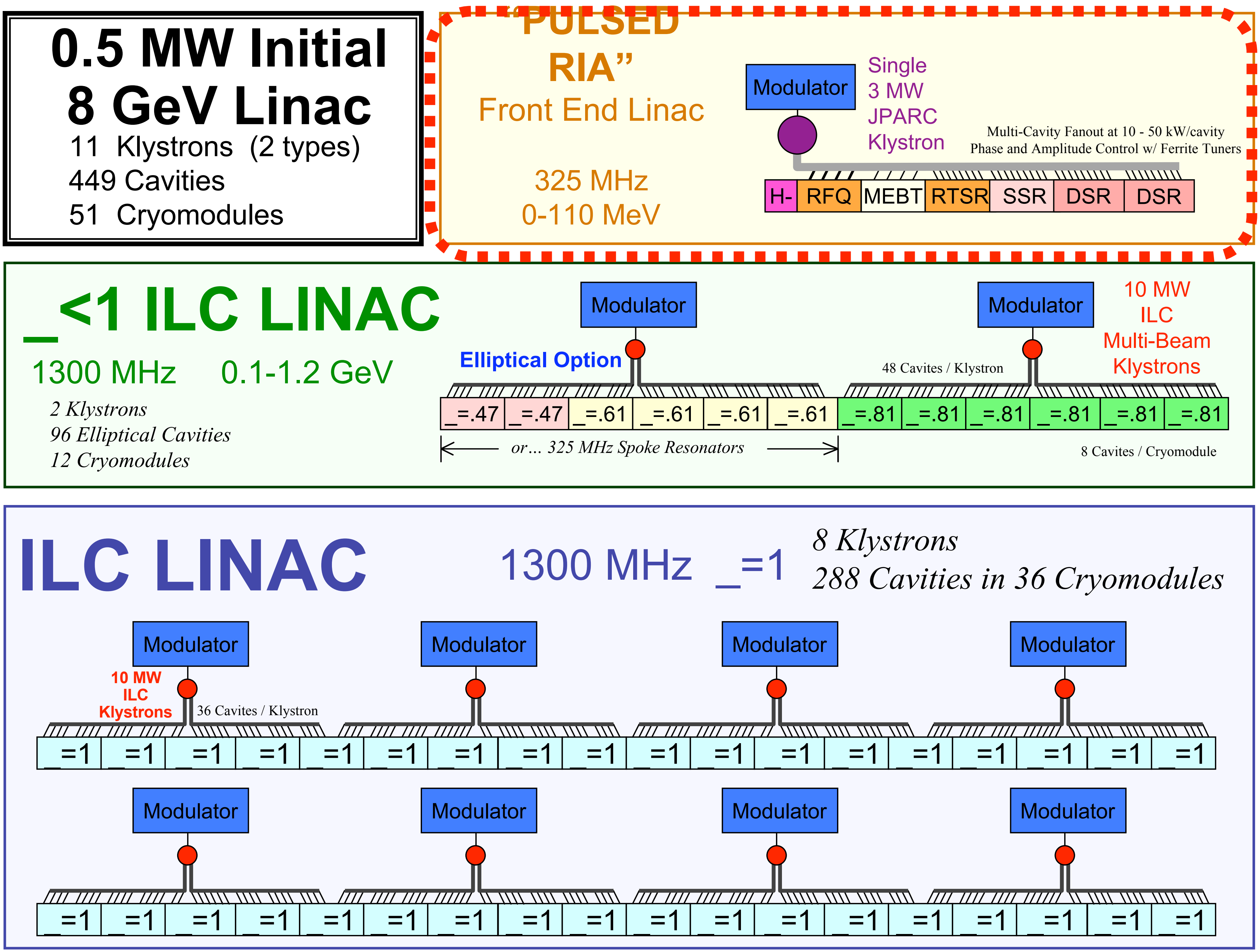
Booster performance and projections



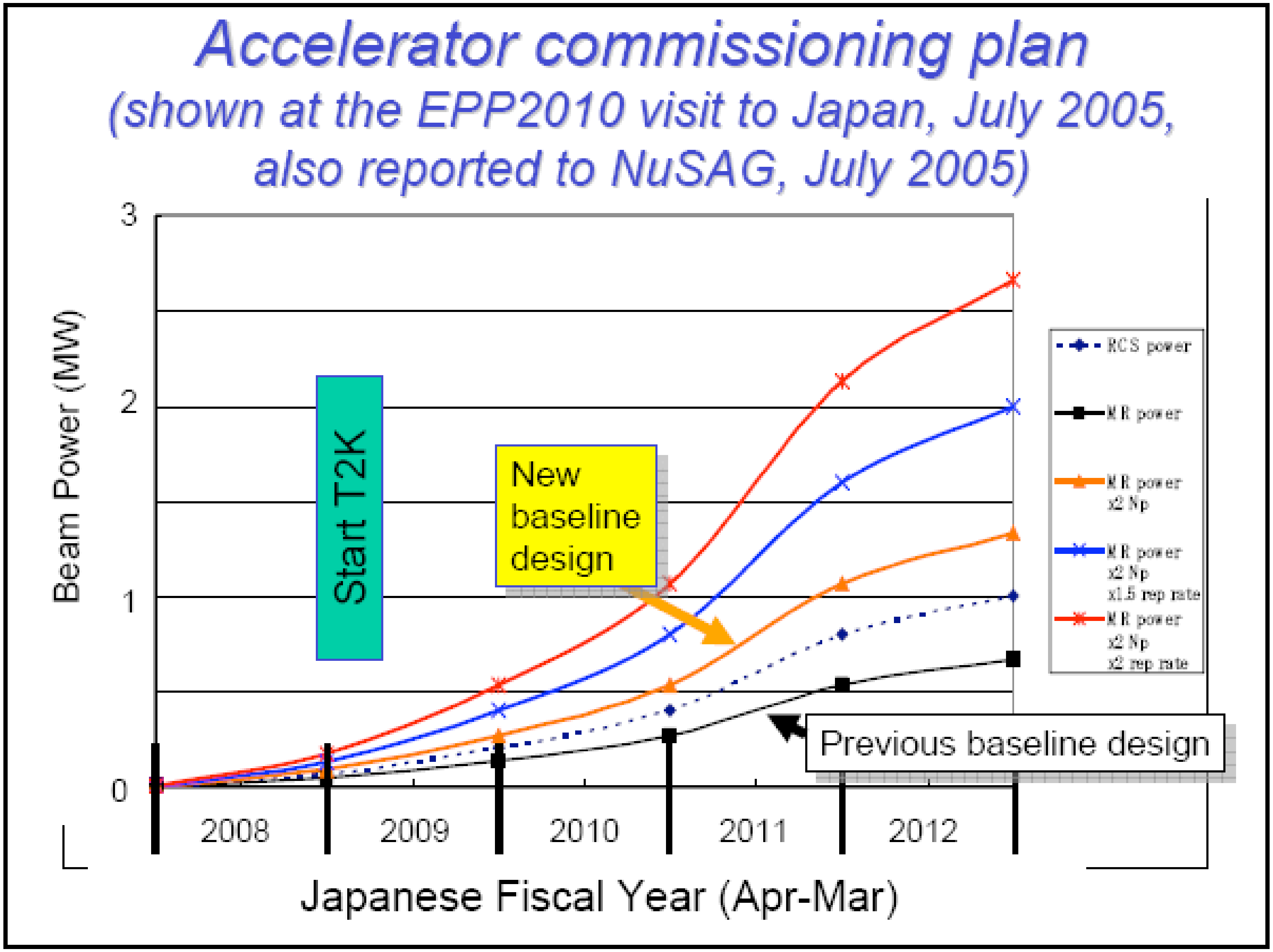
Booster performance '05/'06: ~ 6.5_10^{16} protons/hr

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**


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
_<1 ILC LINAC
1300 MHz 0.1-1.2 GeV
2 Klystrons
96 Elliptical Cavities
12 Cryomodules
Modulator
Elliptical Option
Modulator
10 MW
ILC
Multi-Beam
Klystrons
48 Cavites / Klystron
_=.47
_=.47
_=.61
_=.61
_=.61
_=.61
_=.81
_=.81
_=.81
_=.81
_=.81
_=.81
or… 325 MHz Spoke Resonators
8 Cavites / Cryomodule
ILC LINAC
1300 MHz _=1
8 Klystrons
288 Cavities in 36 Cryomodules
Modulator
10 MW
ILC
Klystrons
36 Cavites / Klystron
_=1

T2K - JPARC



Accelerator commissioning plan
(shown at the EPP2010 visit to Japan, July 2005,
also reported to NuSAG, July 2005)
Beam Power (MW)
0
1
2
3
Start T2K
New
baseline
design
Previous baseline design
2008
2009
2010
2011
2012
Japanese Fiscal Year (Apr-Mar)
RCS power
MR power
MR power
x2 Np
MR power
x2 Np
x1.5 rep rate
MR power
x2 Np
x2 rep rate