PRESENT AND FUTURE HIGH-ENERGY ACCELERATORS FOR NEUTRINO EXPERIMENTS

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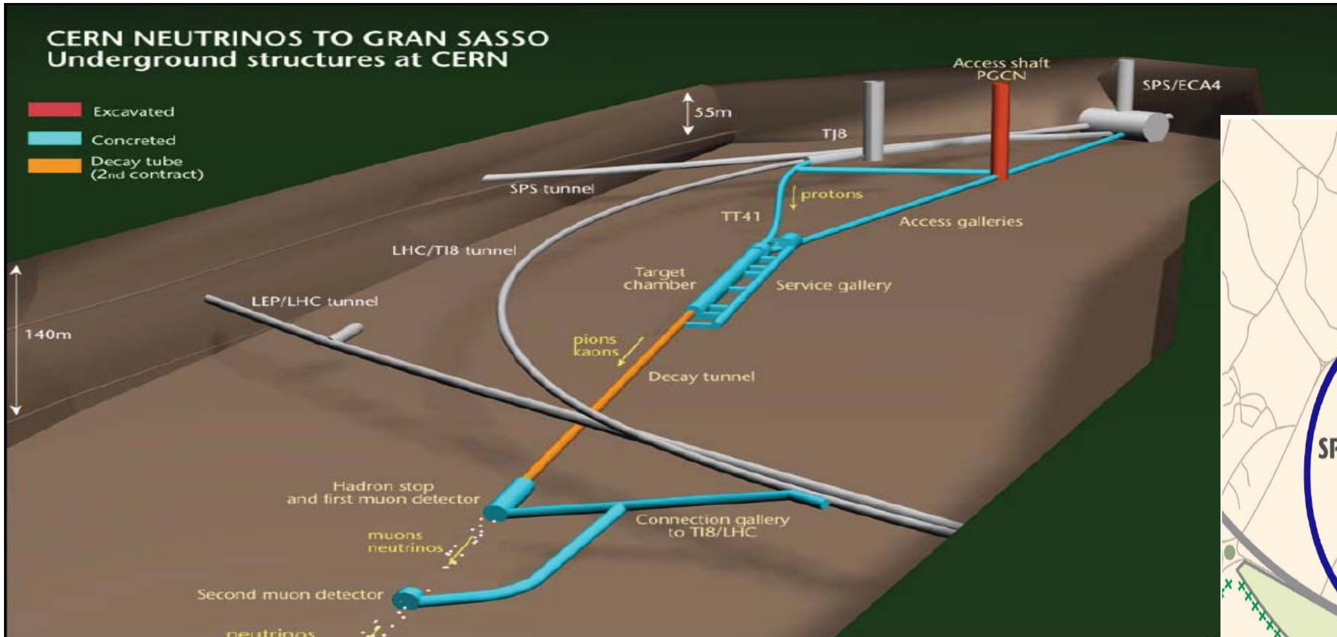
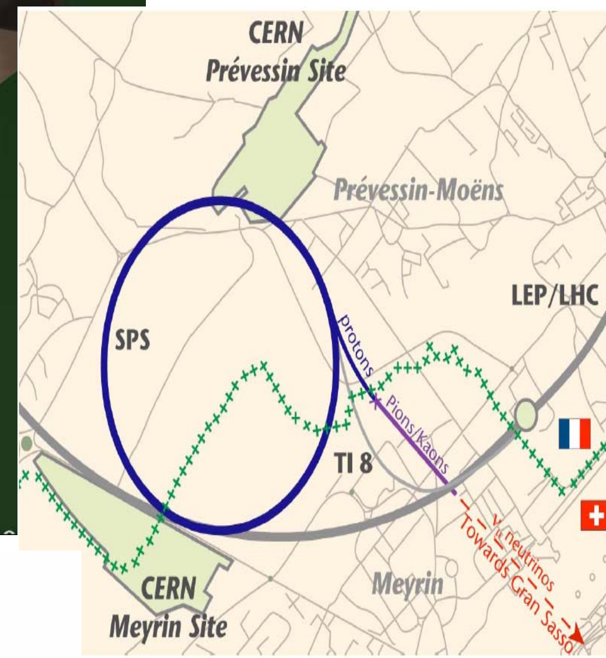
Introduction

- There is an active neutrino program making use of the high-energy accelerators both at CERN with CNGS and at Fermilab in the USA with NuMI.
- The prospects for high intensity beams in those two locations during the next decade will be reviewed.

The CERN Neutrino Program (CNGS)



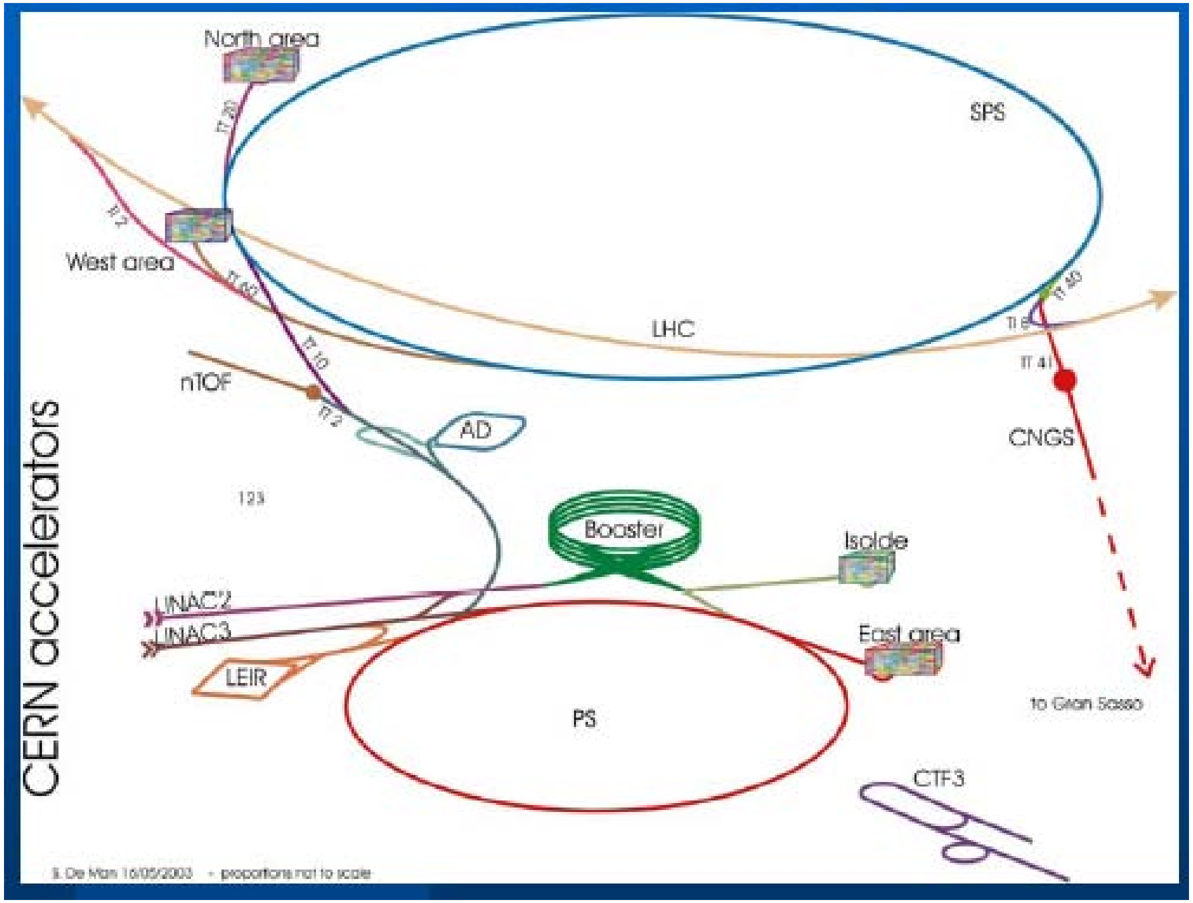


Beam parameters	Nominal CNGS beam
Nominal energy [GeV]	400
Normalized emittance [μm]	H=12 V=7
Emittance [μm]	H=0.028 V= 0.016
Momentum spread $\Delta p/p$	0.07 % +/- 20%
# extractions per cycle	2 separated by 50 ms
Batch length [μs]	10.5
# of bunches per pulse	2100
Intensity per extraction [10^{13} p]	2.4
Bunch length [ns] (4 σ)	2
Bunch spacing [ns]	5

← **Nominal Intensity**

CNGS facility was designed for 1.38E20 pot per year

CERN Accelerator Complex



CERN Accelerators for Neutrino Beams

Courtesy G. Arduini

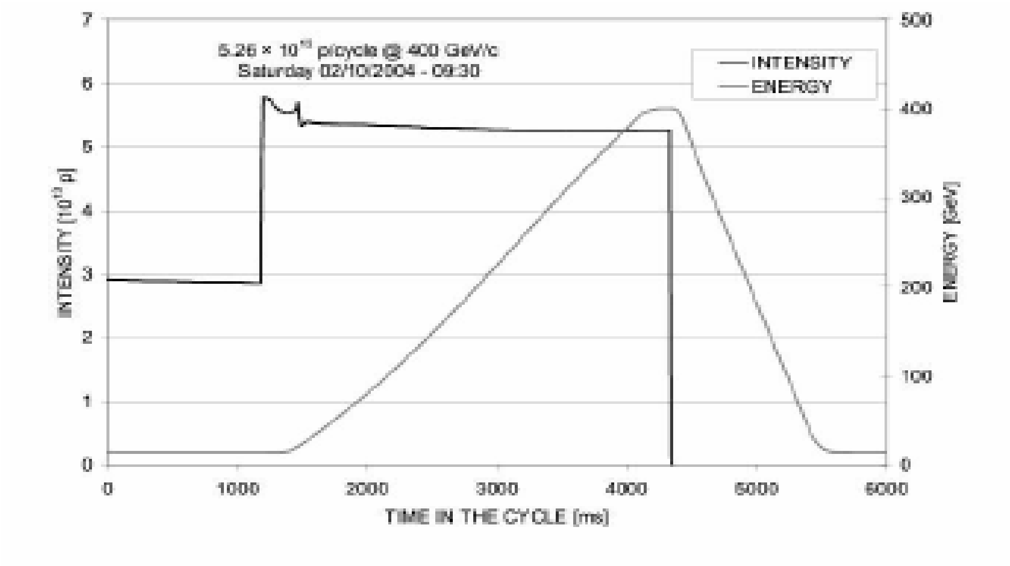
Accelerator	Inj. Kinetic Energy [GeV]	Ext. Kinetic Energy [GeV]	Commissioning year
Linac 2	0.00075	0.05	1979
PSB	0.05	1.4	1972
PS	1.4	13.1	1959
SPS	13.1	399.1	1976

All the CERN Accelerators for Neutrino Beams are more than 28 years old with PS approaching 50 years. These are the same accelerators that are going to be used as LHC injectors.

Recent Accelerator upgrades

- The CERN Accelerator chain has been upgraded mainly in preparation for the nominal LHC beam, which has much higher bunch intensity but lower total beam intensity than the CNGS neutrino beam.
  - In the Booster acceleration at harmonic h=1 replaced the h=5 used in the past in order to help the coupled bunch instabilities.
  - The PS injection energy was increased to 1.4GeV from 1.0 GeV and the harmonic number was changed from h=20 to h=8.
  - The impedance at SPS was significantly reduced eliminating the microwave instability and reducing the longitudinal emittance blow-up during acceleration.

High Intensity SPS Operation



Record SPS Intensity 5.3E13 at 400 GeV.

Accelerator	Injected Intensity (E13)	Accelerated Intensity (E13)	Extracted Intensity (E13)	Acc. Eff. (%)
Booster	4.3	3.84	3.65	84.9
PS	3.57	3.42	3.15	88.2
SPS	3.0x2	5.7 after tr.	--------	
SPS	2.9x2	5.5 after tr.	5.3	91.3

Typical beam intensities in different machines. The overall efficiency is ~62!

Beam loss limitations and cures

- Losses at extraction in the PS
  - Change the present multi-turn extraction to a resonant island extraction will reduce this loss by a factor of 3. Requires new hardware.
- Low energy losses in the SPS (Injection, Transition)
  - Reduce the Vertical aperture limitations at Injection
  - Reduce transient beam loading at transition
- SPS Extraction losses (Beam in the kicker gap)
  - Use transverse feedback at low energy

Beam Intensity for Neutrinos with the present CERN Injectors

- With the present injectors the beam intensity available from the SPS for neutrinos is 4.8-5.7E13 p per 6 sec cycle (depending on the magnitude of the loss reduction).
- The total of protons to the CNGS target depends not only on the peak beam intensity but also on the beam availability and the beam sharing with other users.
- Under the scenario that 85% of the SPS is dedicated to neutrino running up to 1.1E20 pot per year can be delivered to the target for the neutrino experiment.
  - 200 days (1.7E7 sec) of operation with 80% machine efficiency is assumed.

New CERN Injectors

- In order to maximize the LHC performance, most of the CERN injectors are to be replaced with new higher performance accelerators.
- In the first stage, a new linac, Linac4 is built, injecting protons at 160 MeV, thus halving the space charge effects in PSB.
- In the second stage, the PS is replaced by PS2, a new 50 GeV synchrotron. The PS2 will be double the size of PS and able to accelerate up to 1.1E14protons per pulse (3.6 sec).
  - The injection energy of the PS2 has to be higher than 3.5 GeV.
  - The old PS will be used as injector till a 3.5-4 GeV superconducting linac the SPL is built.

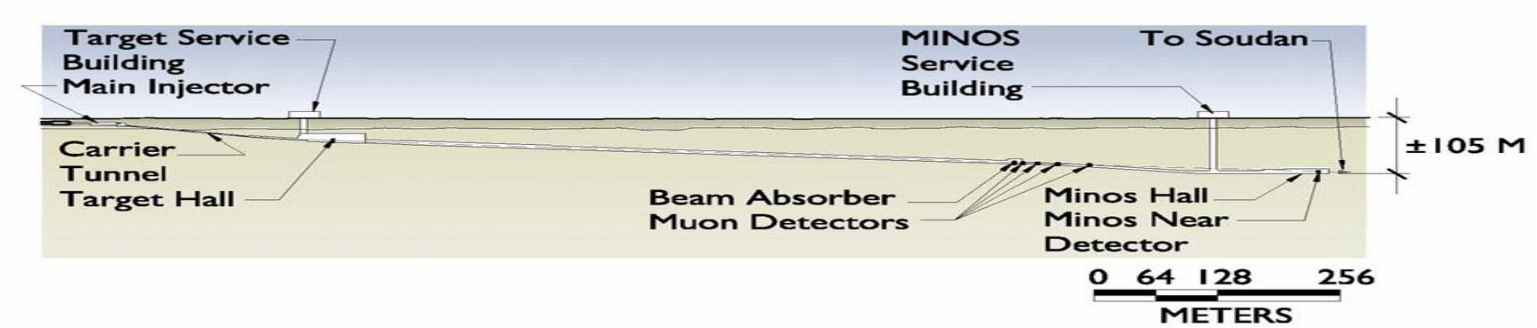
Proton Intensity and Flux for Neutrinos with the new Injectors

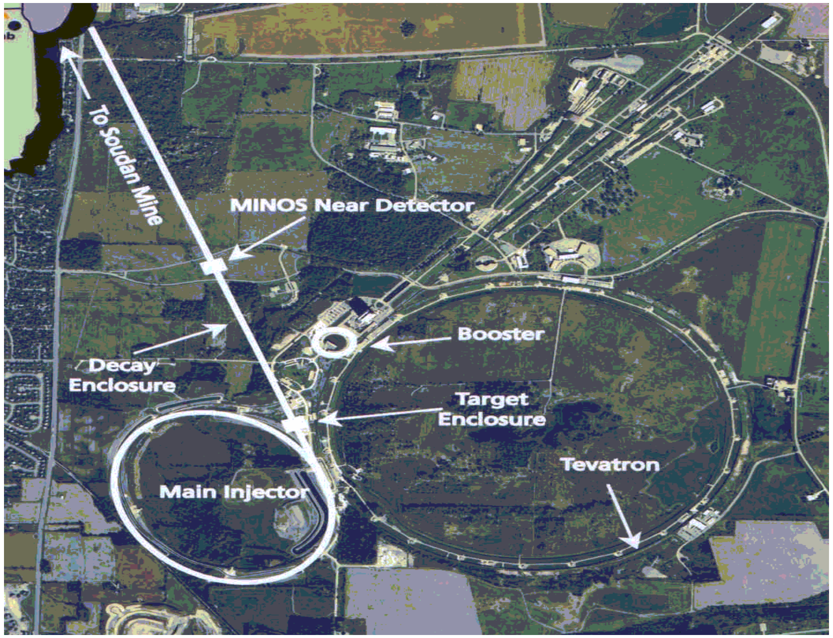
- With the new injector PS2, the length of the SPS cycle can be reduced to 4.8 sec. A total of 1.0E14 protons can be accelerated to 400 GeV for a total beam power of 1.3MW.
  - A new rf system will be needed in the SPS to accelerate this intensity.
- The total protons per year to CNGS can reach 2.4E20 pot assuming 85% SPS availability.
  - The CNGS facility will need a re-design and a major rebuild.

Protons on CNGS target per year (E19) different scenarios (Meddahi, Shaposhnikova)

200 days of operation with 80% machine availability is assumed.	SPS cycle length	6 sec		4.8 sec	
	Injection momentum	14 GeV		26 GeV	
	Beam sharing / Max SPS Intensity @ 400 GeV (E13)	0.45	0.85	0.45	0.85
Present injectors + machines' improvements	4.8-"Nominal CNGS"	5	9.4		
	5.7-"Max. SPS"	5.9	11.1		
Future injectors +SPS RF Upgrade	7-"Ultimate CNGS"			9	17.1
Future injectors +new SPS RF system + CNGS new equipment design	10-"Max. PS2"			12.9	24.5

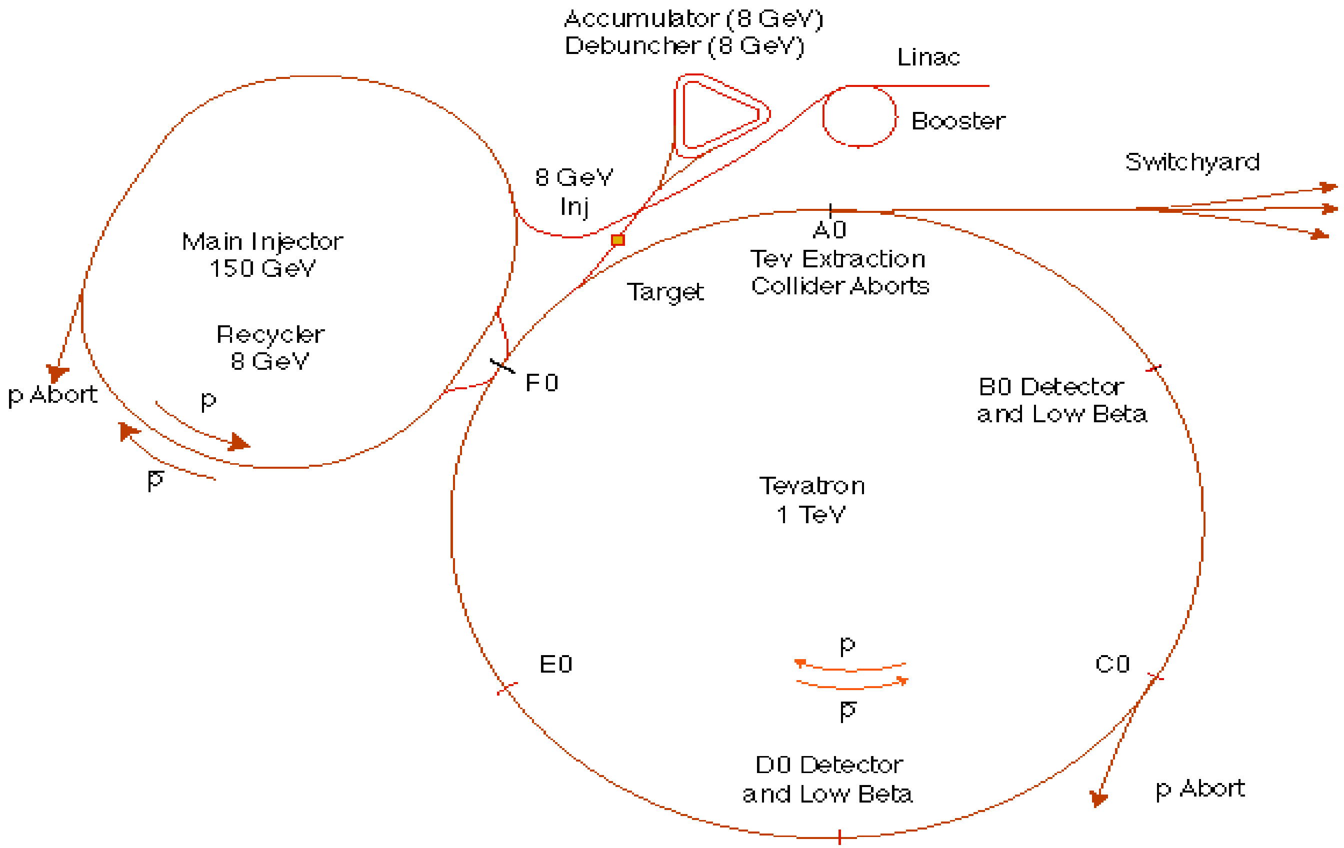
The Fermilab Neutrino Program (NuMI)





- NuMI was designed for 400kW primary proton beam
  - 120 GeV
  - 7.8 μsec spill
  - 1.9 sec rep rate
  - 5 Booster batches
    - (2.5×10^{13} prot/spill) Initial
    - (4.0E13 prot/spill) Design

Fermilab Proton Accelerators



Fermilab Accelerators for Neutrino Beams

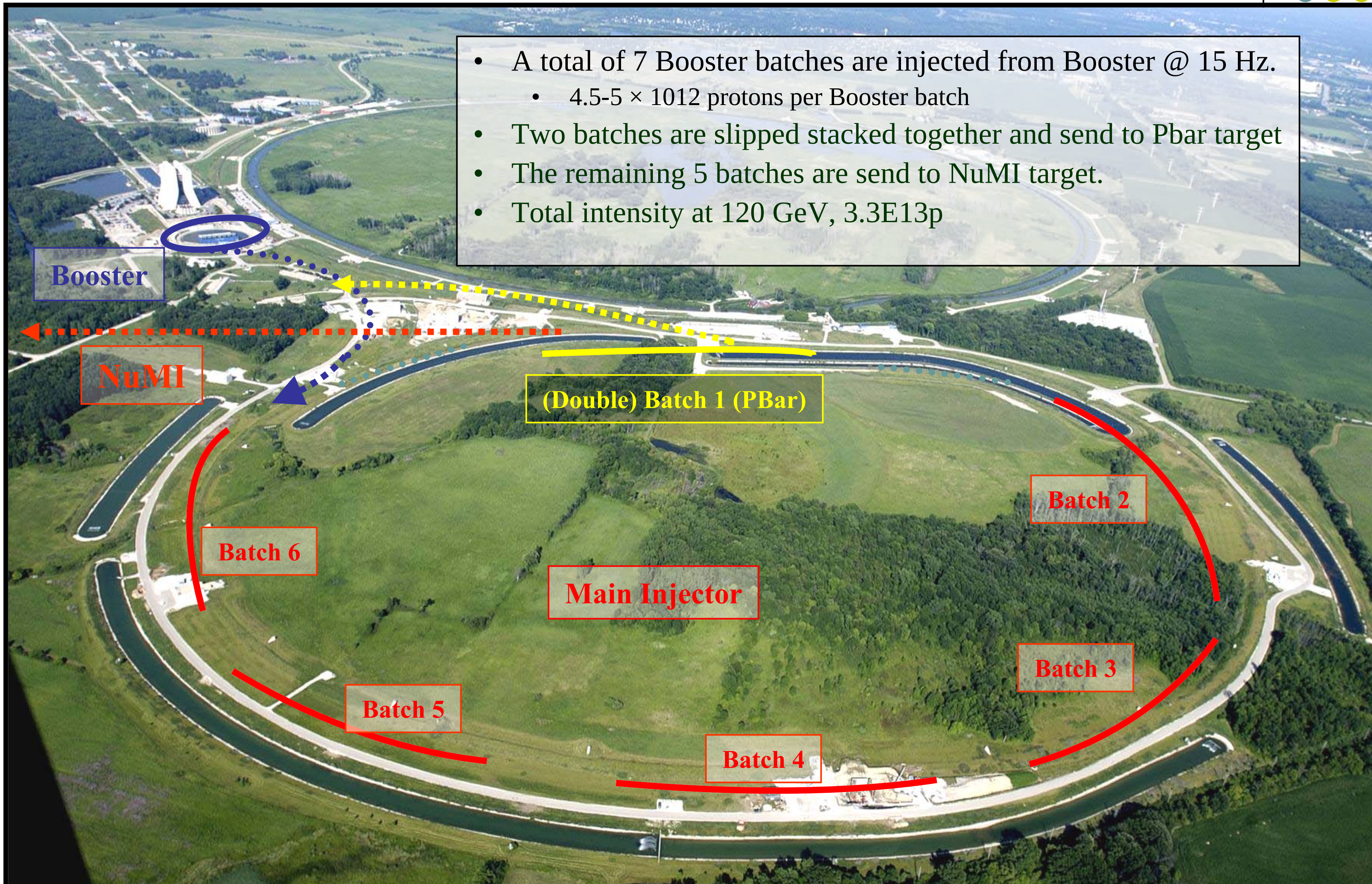
Accelerator	Injection Kinetic Energy [GeV]	Extraction Kinetic Energy [Gev]	Commissioning year
Linac	0.025	0.4	1970
Booster	0.4	8	1971
Main Injector	8	119	1999
Recycler	8	8	2004
Debuncher/ Acumulator	8	8	1986

- The High energy part of the linac was upgraded in 1993 raising the extraction energy to 400 MeV from 200 MeV.
- The Booster has also been upgraded with a new injection system and a collimation system.

Current NuMI operation

- Currently a total of 7 Booster are injected in Main Injector in a mixed mode cycle. Two batches are slip staked together and are send to the pbar target while the remaining 5 are send to NuMI .
- The total Main Injector intensity at 120 GeV is 3.3E13 out of which 2.45E13 are send to NuMI target.
- The Main Injector rep. rate in the mixed mode operation (2.4 sec) is set by the pbar stacking requirements and not the cycle length (2.0 sec)
- The beam power to NuMI target is 196 KW with 1.7E20 pot per year.
  - For the proton projections a total of 308 days (2.7E7 sec) of running is assumed with 61% overall efficiency.

Main Injector mixed mode cycle



- A total of 7 Booster batches are injected from Booster @ 15 Hz.
  - 4.5-5 × 1012 protons per Booster batch
- Two batches are slipped stacked together and send to Pbar target
- The remaining 5 batches are send to NuMI target.
- Total intensity at 120 GeV, 3.3E13p

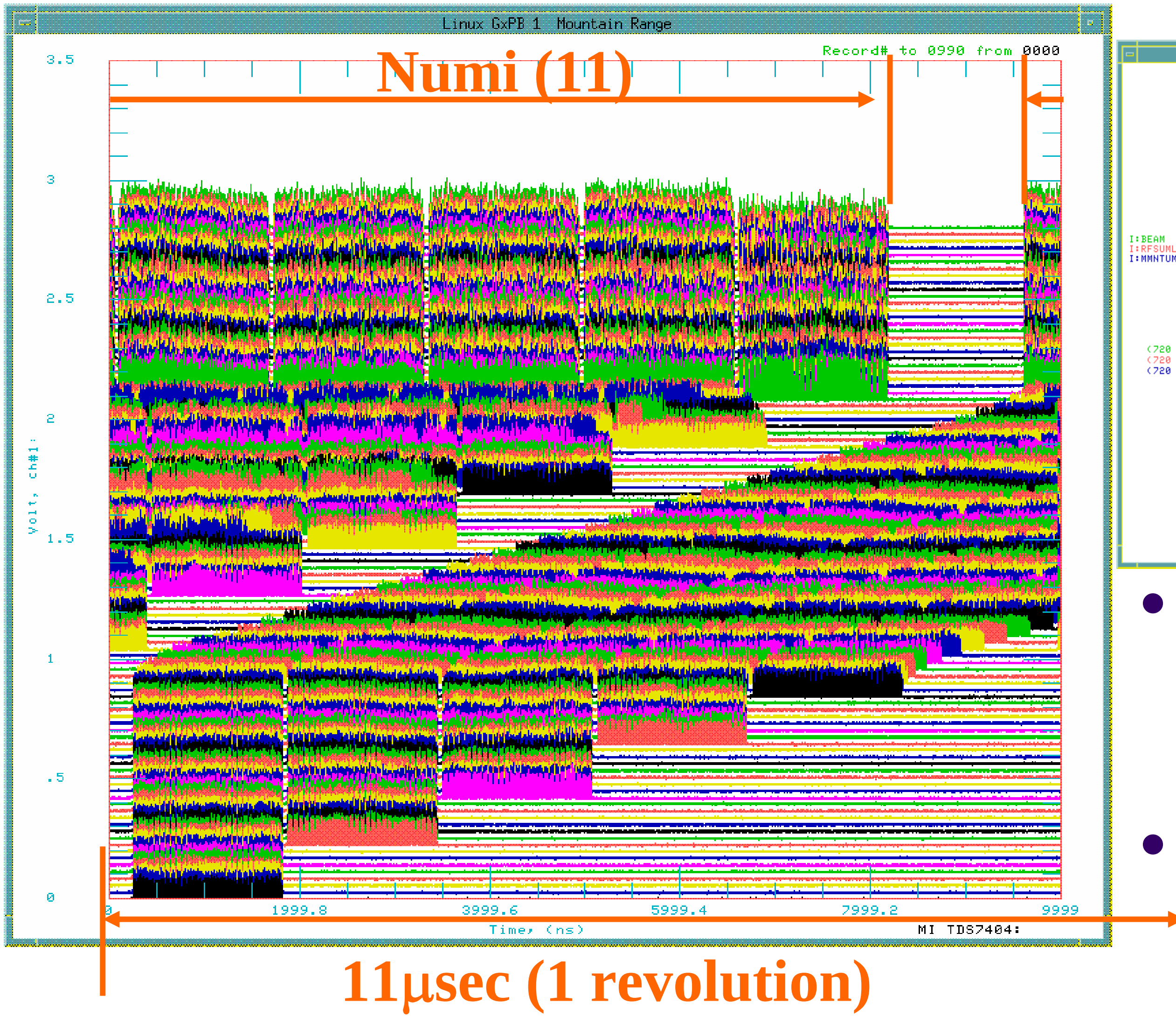
Fermilab Power Upgrade scenarios

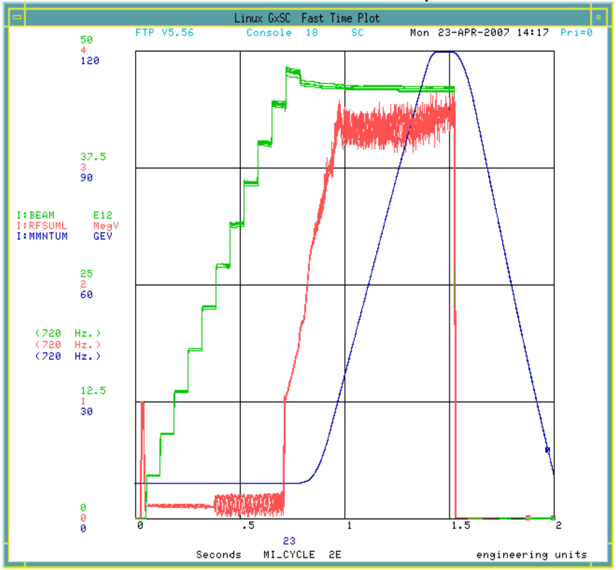
- All Fermilab's power upgrade scenarios depend on Main Injector.
  - Large beam acceptance and momentum aperture.
  - Can accelerate to 120 GeV in 1.5sec
  - Has an rf system that can be easily upgraded for more beam power.
- The intensity increases come from stacking (slip stacking and then momentum stacking) of the Booster batches at 8 GeV.
- Three stages of upgrades; "The Proton Plan", "The NOvA Project", "SNuMI"

"Proton Plan"

- In this first stage the Main Injector intensity to NuMI is increased by implementing multi-batch slip stacking.
  - A total of 10 batches are slipped stacked and recaptured. An additional batch is injected and the whole beam is accelerated to 120 GeV
- Assuming an intensity of 4.3E13 p per Booster batch and an efficiency of 95%, the total Main Injector intensity at 120 GeV is 4.5E13 with 3.7E13 delivered to the NuMI target.
- The beam power to NuMI will be increased to 320 KW and the total number of protons per year to NuMI to 2.8E20.

“Proton Plan” multi-batch slip stacking status

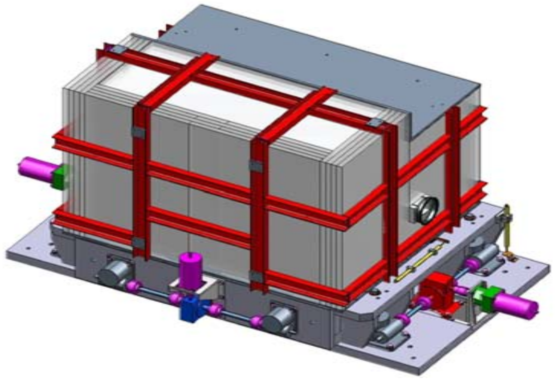


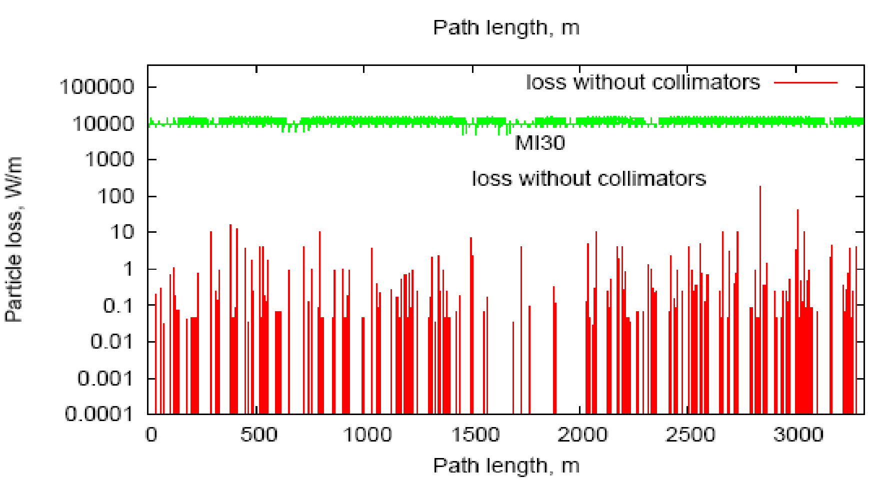


- Record:
  - 4.63E13 protons to MI abort at 120 GeV.
  - 92% efficiency
- Goal:
  - 4.5E13 protons to 120 GeV (NuMI + pBar)
  - 95% efficiency (Collimators)

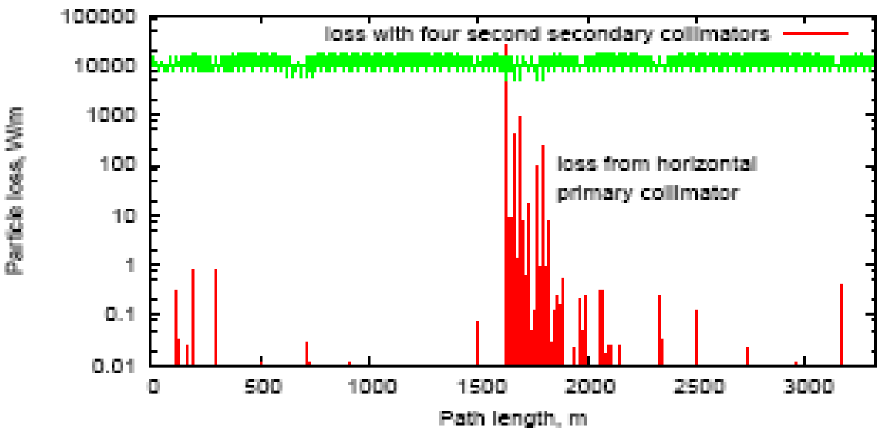
Main Injector Collimation

- Collimation system designed to handle loss from multi-batch slip stacked cycles
- Similar to Booster collimation system
  - .5 mm thin tungsten primary (scattering) collimator
  - Four secondary collimators
- On track for installation in 2007 shutdown





w/o collimation



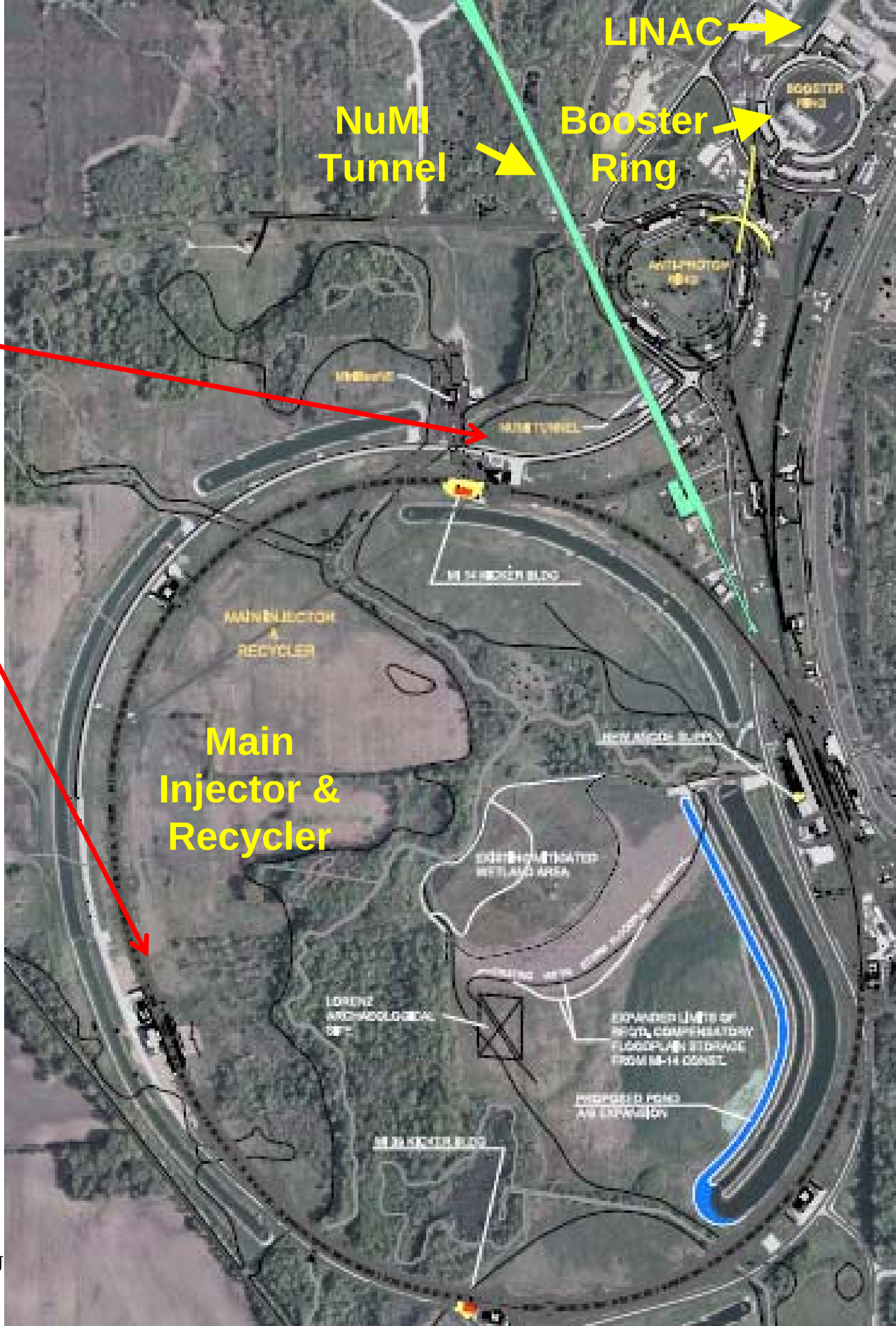
with collimation

The “NOvA Project”

- In this stage planned to happen after the end of the collider run, the Recycler is re-configured from an antiproton storage ring to a proton ring where the slip stacking is taking place.
  - A total of 12 Booster batches can be slipped stacked this time.
- The Main Injector cycle time will be reduced to 1.33 sec from 2.2 sec.
- The beam intensity in the Main Injector is increased by only 9% while the beam power and the protons per year to the NuMI target are increased by a factor of two to 700 KW and 6.1E20 respectively.

Machine modifications/upgrades for the “NOvA Plan”

- Recycler Ring, RR
  - New injection line into RR
  - New extraction line from RR
  - New 53 MHz RF system for slip stacking
  - 5 new kicker systems (include injection gap clearing kickers)
- Main Injector
  - Two 53 MHz cavities
  - Quad Power Supply Upgrade
  - RR Low Level RF System

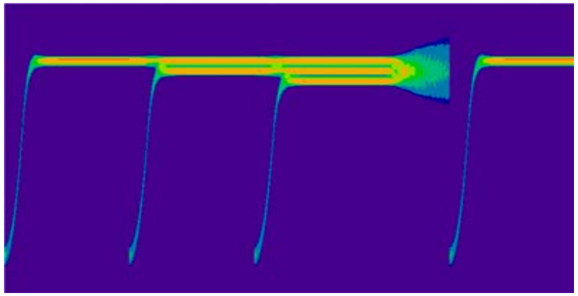


The “SNuMI plan”

- The number of Booster batches stacked in the Recycler cannot be increased any more by using slip stacking because of the large momentum aperture required and the beam losses.
- It has been proposed to use momentum stacking in the Accumulator in order to further increase the intensity in the Main Injector and to NuMI.
  - No transient beam loading
  - Speed of the process
  - Small longitudinal emittance dilution
  - No need of transfer cogging in the Booster.

Multi-stage Proton Accumulator Scheme

- Momentum stack in the Accumulator
  - Inject in a newly accelerated Booster batch every 67 mS onto the high momentum orbit of the Accumulator
  - Decelerate new batch towards core orbit and merge with existing beam
  - Momentum stack 3 Booster batches
  - Extract a single Accumulator batch



- Box Car Stack in the Recycler
  - Load in a new Accumulator batch every 200mS
  - Place six Accumulator batches sequentially around the Recycler
- Load the Main Injector in a single turn

Proton intensity and flux for “SNuMI”

- Assuming 4.7E12 protons per Booster batch, the Main Injector intensity reaches 8.3E13 ppp and the beam power to NuMI the 1.2 MW.
  - In order to accelerate this high beam power a second power tube needs to be installed in every Main Injector cavity.
  - A γt system for transition crossing in Main Injector is also planned.
  - Any e-cloud instabilities need to be addressed.

Present & Future Operating Scenarios for NuMI

	Present Conditions Multi-batch slip-stacking in MI	Proton Plan Multi-batch slip-stacking in MI	NOνA Multi-batch slip-stacking in Recycler	SNuMI Momentum Stacking in the Accumulator, boxcar stacking in Recycler
Booster intensity (protons/batch)	$4.3\text{-}4.5\times10^{12}$	4.3×10^{12}	4.3×10^{12}	4.7×10^{12}
No. Booster batches	7 →	11 →	12 →	18
MI cycle time (s)	2.4 →	2.2 →	1.333 →	1.333
MI intensity (ppp)	3.3×10^{13}	4.5×10^{13}	4.9×10^{13}	8.3×10^{13}
To anti-proton source (ppp)	8.8×10^{12}	8.2×10^{12}	0	0
To NuMI (ppp)	2.45×10^{13}	3.7×10^{13}	4.9×10^{13}	8.3×10^{13}
NuMI beam power (kW)	192 →	320 →	700 →	1200
PoT/yr to NuMI	2×10^{20} →	3×10^{20} →	6×10^{20} →	10×10^{20}

Conclusions

- There is an active program of upgrades to the accelerators both at CERN and Fermilab that will raise the power available to neutrino experiments to 1.2MW.
- The CERN upgrades depend on new injectors while the Fermilab upgrades depend on the Main Injectors and the re-configuration of existing antiproton storage rings.