Delivering High Intensity Proton Beam:

Lessons for the Next Beam Generations

S. Childress
Fermilab

Presentation Outline

- Key Proton Beam Considerations

- The First Generation “Super Beams”: - Hundreds of kW’s
  - CNGS
  - NuMI
  - T2K

- Lessons for the Mega-Watt Beams to Come

Key Proton Beam Considerations

A New Regime for Beam Control Requirements

- **The most compelling feature for these proton beams is that they can damage most materials very quickly – a few seconds or even one cycle of mis-steered beam**
- **Adjacent photo shows the result of a single wayward 450 GeV SPS beam pulse of 3.4 e13 protons (CERN TT40 line Oct.'04) Magnet vacuum chamber destroyed. Views are from inside beam tube**
- **Now need millions of pulses!**

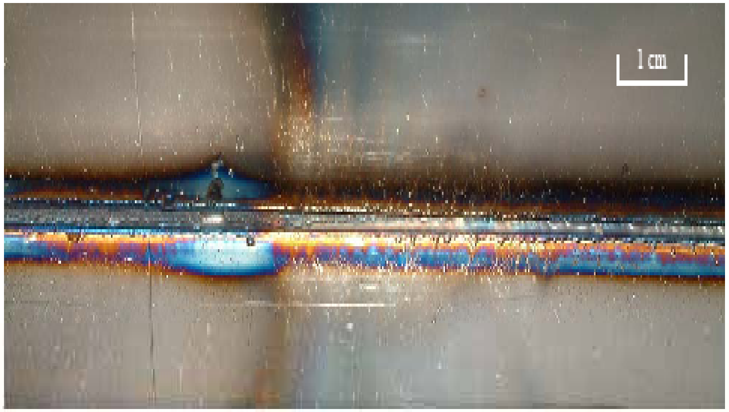


Figure 4. Damage observed on the inside of the vacuum chamber, on the beam impact side. A groove approximately 110 cm long due to removed material was clearly visible, starting at about 30 cm from the entrance.

Figure 5. Damage observed on the inside of the vacuum chamber, on the side opposite to the beam impact. Molten material has been projected across the chamber and has condensed in droplets on the other wall.

Significant Targeting Constraints

- **NuMI**
  - **Maintain beam cebtered on target to < 0.25 mm (Physics background constraint)**
  - **Preclude 2nd beam pulse at 1.5 mm off center (6.4 mm target width; 11mm baffle ID). Wayward beam at significant angle could hit target cooling or horns**

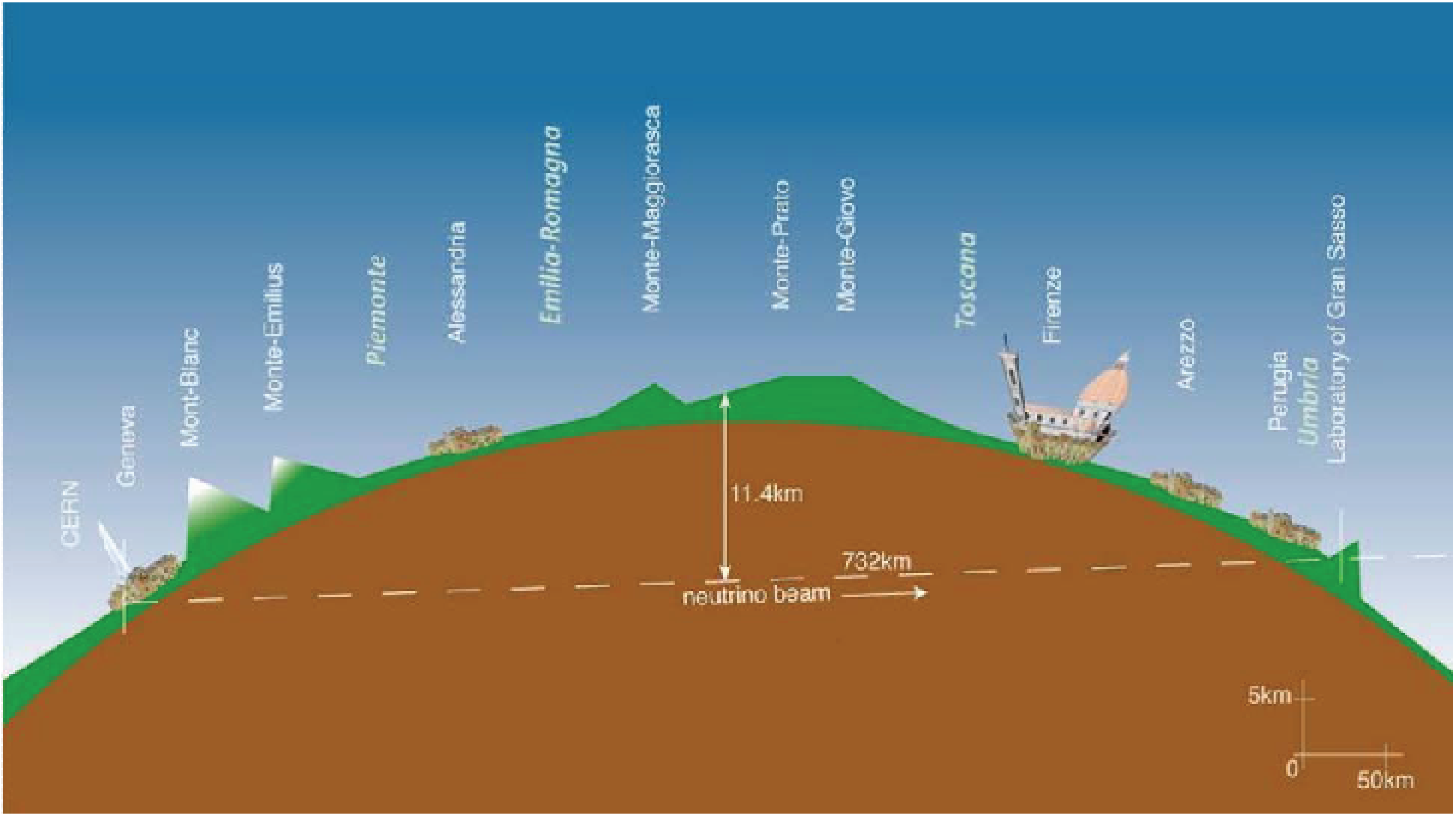
- **CNGS**
  - **Maintain beam on target to < 0.5 mm. Preclude 2nd beam pulse at > 0.5mm. (Elevated stress on target for high intensity offset beam)**

Significant Limits on Allowable Beam Loss for Accident and DC Operation

- **T2K**
  - **Maximum allowable beam loss at 10 Watts/point in superconducting magnets region**
- **NuMI**
  - **For 400 kW beam maximum fractional point beam loss allowed is ~ 10-5 for environmental (ground water) protection.**
- **All Beams**
  - **Maintain machine quality vacuum to eliminate interface vacuum window. Also prevents gas ionization bkgds for BPMs**
  - **“No mass” BPM’s for position measurement; low mass profile monitors for beam transport**
  - **Beam loss control to < 10-4 of beam to minimize residual activation**

CNGS Proton Beam

CERN Neutrinos to Gran Sasso



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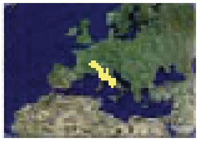


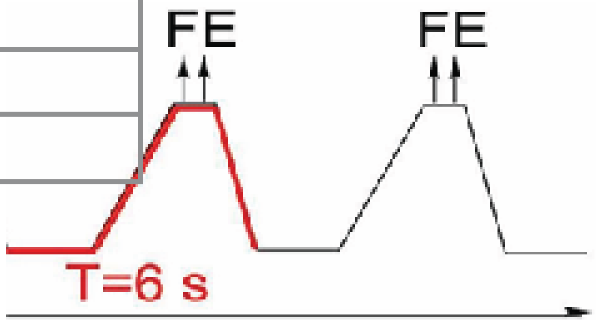
CNGS Proton Beam Parameters

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 Δp/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] (4σ)	2
Bunch spacing [ns]	5
Beta at focus [m]	hor.: 10 ; vert.: 20
Beam sizes at 400 GeV [mm]	0.5 mm
Beam divergence [mrad]	hor.: 0.05; vert.: 0.03

500kW beam power

Upgrade phase: $3.5\ 10^{13}$ p

Expected beam performance: 4.5 x 10^{19} protons/year on target



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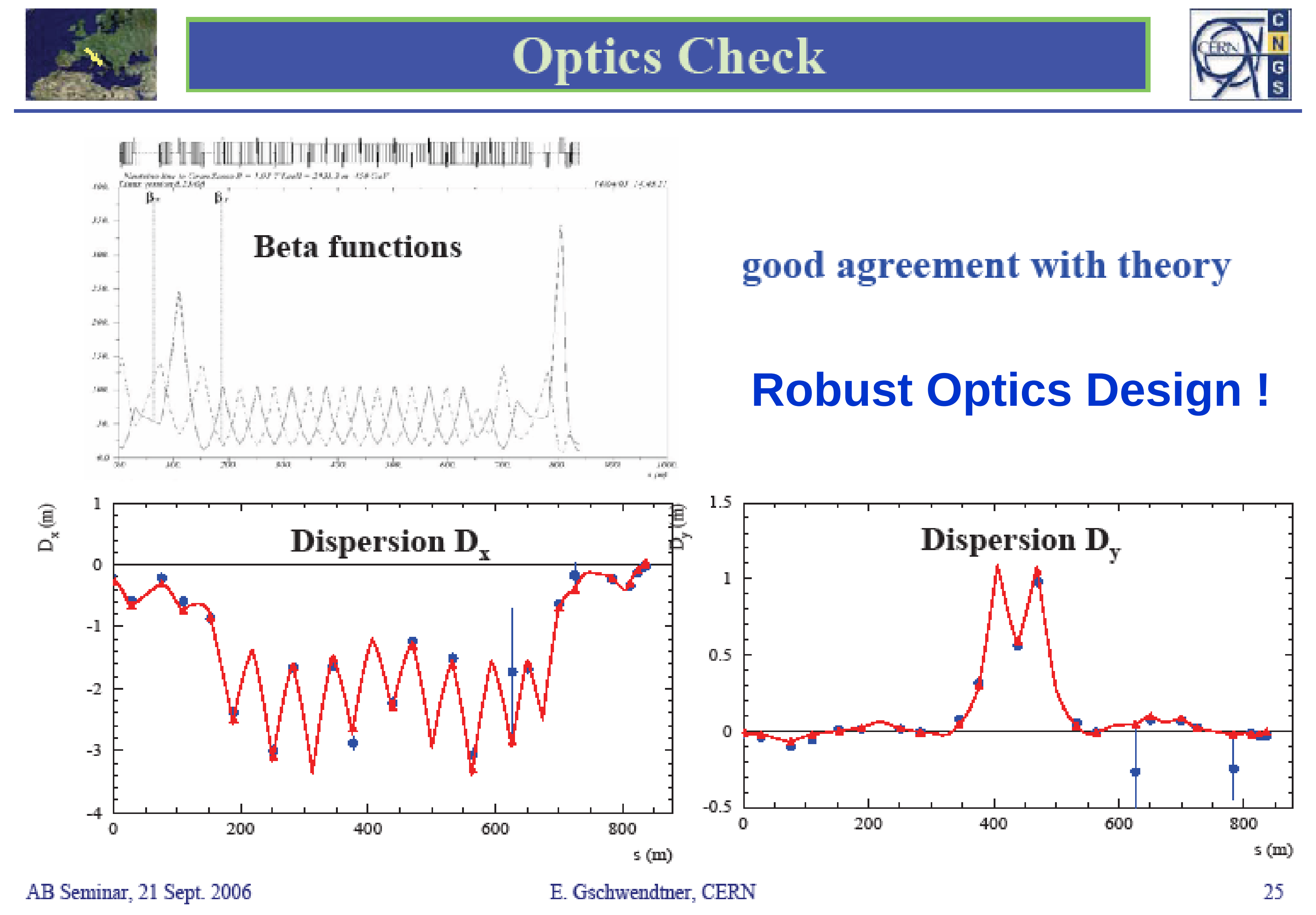

Optics Check

good agreement with theory

Robust Optics Design !

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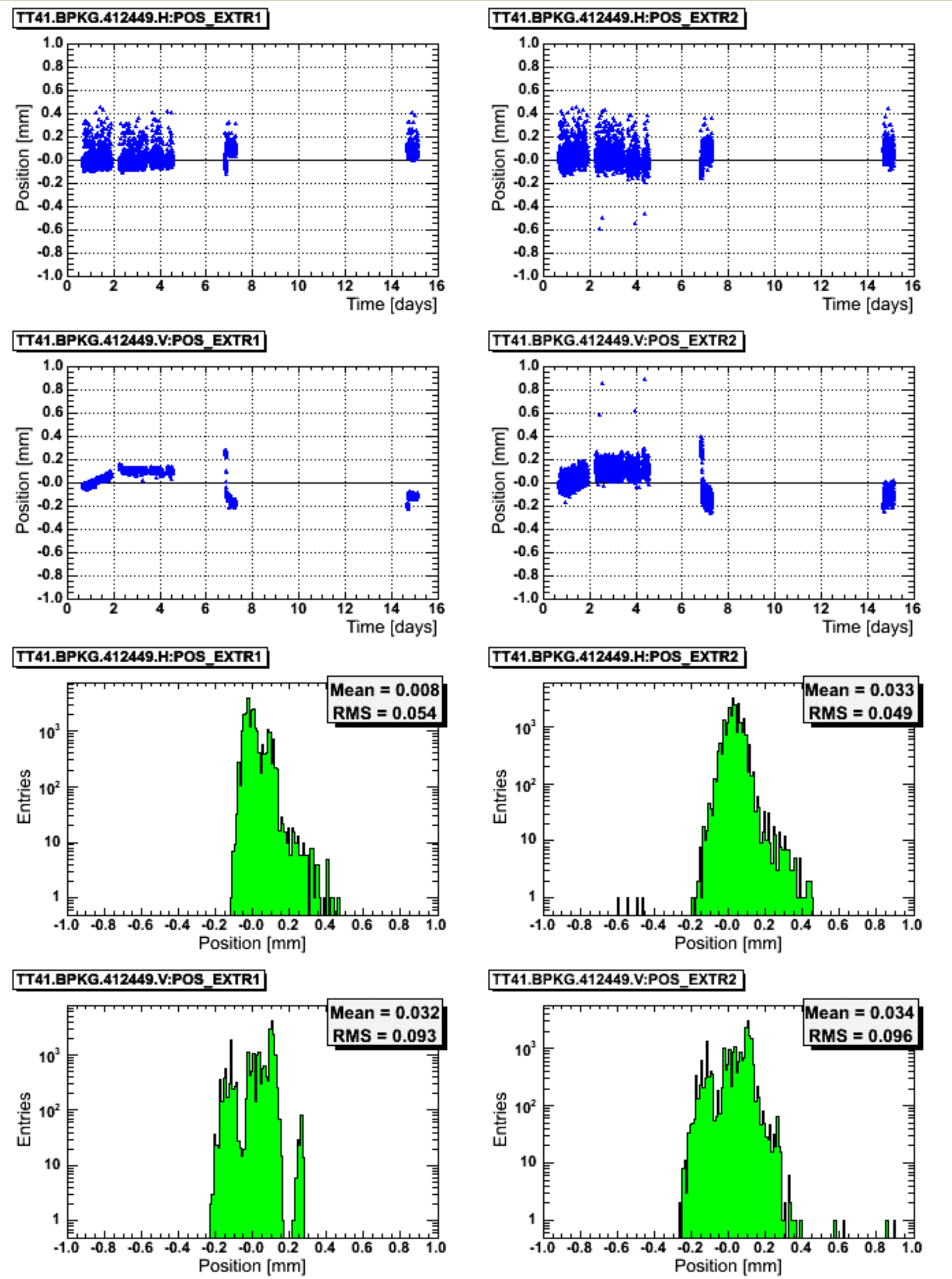
CNGS Beam Stability - 2007



The ~ 15 day period of high intensity was analyzed for stability and interlock performance

Stability of the beam measured with the last BPM in front of the target.

- **46’500 extractions in 23’700 cycles**
- **4 outliers : wrong readings (and interlocks !!) from the BPMs.**
- **Some steering at the target sufficient to keep the muon beam well centered.**
- **All extractions well within the 0.5 mm tolerance. Includes some steering.**

CNGS List of Interlocked ‘Elements’

Extraction channel & SPS ring :

- **Beam position in extraction bump** (M)
- **Settings of orbit bumpers** (M)
- **Beam loss in extraction channel** (M)

Transfer line & target :

- **Vacuum**
- **Extraction kicker**
- **CNGS decay tube shutter**
- **CNGS target assembly**
- **Power Converters** (M)
- **Magnets**
- **Horn**
- **Beam losses** (M)
- **Position at target, trajectory** (M)
- **Screen positions** (M)
- **Hadron stop cooling**

(M) = maskable

In 2007 run lost ~ 3% of extractions due to interlock trips. 2008 goal is < 1%.

CNGS Beam Operation to Date

- **2006: CNGS Commissioning**
  - $8.5 \cdot 10^{17}$ pot
- **2007: 6 weeks CNGS run**
  - $7.9 \cdot 10^{17}$ pot
  - **Maximum intensity: $4 \cdot 10^{13}$ pot/cycle**
    - **Radiation limits in PS**

→ OPERA detector completed by June 2008

→ CNGS modifications finished

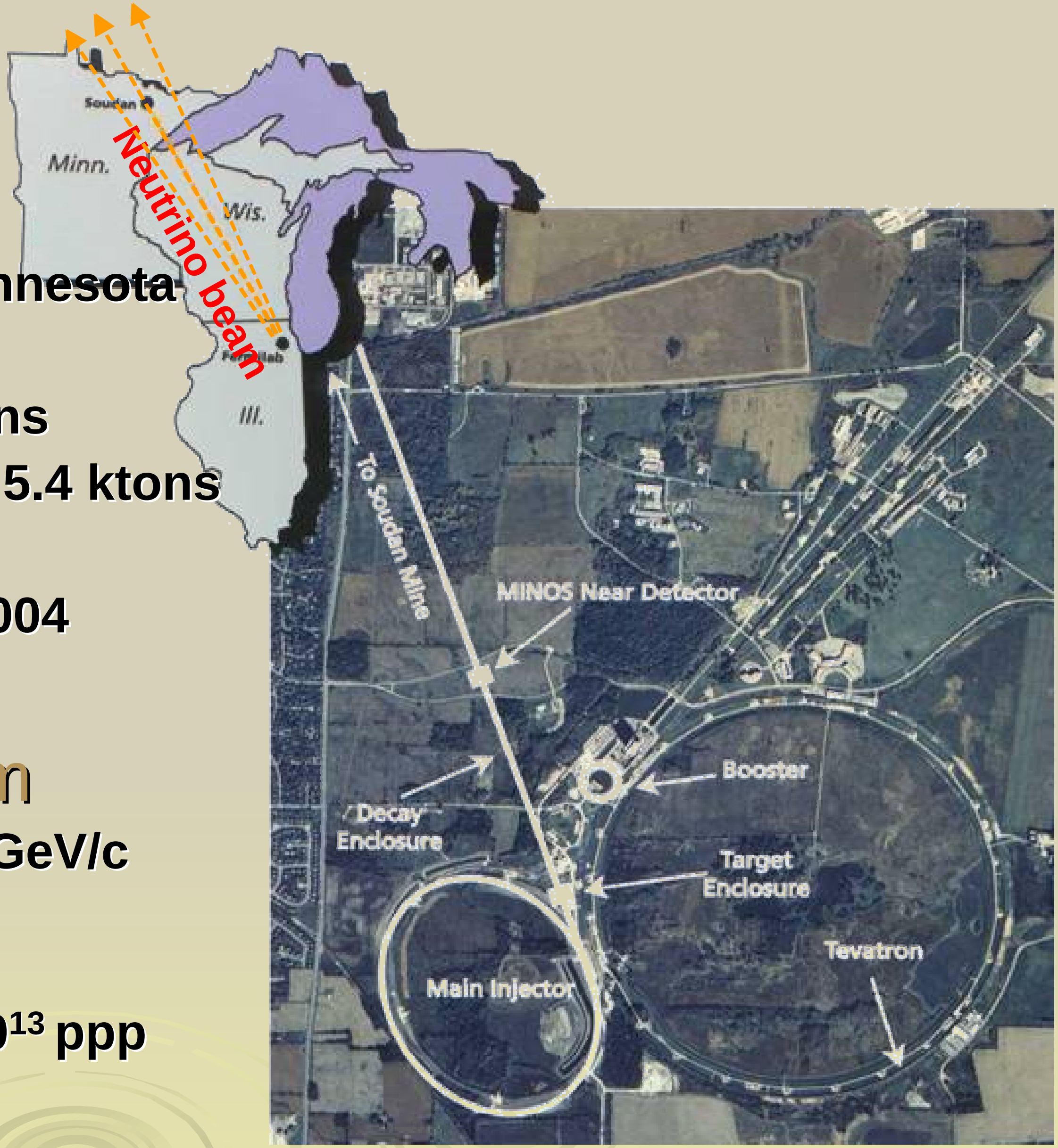
- **2008: CNGS run: June-November** → NOW! ←
  - $5.43 \cdot 10^{17}$ pot on Friday, 27Jun08, after 9 days running

    Expected protons in 2008: ~$2.6 \cdot 10^{19}$ pot

NuMI Proton Beam

NuMI: Neutrinos at the Main Injector

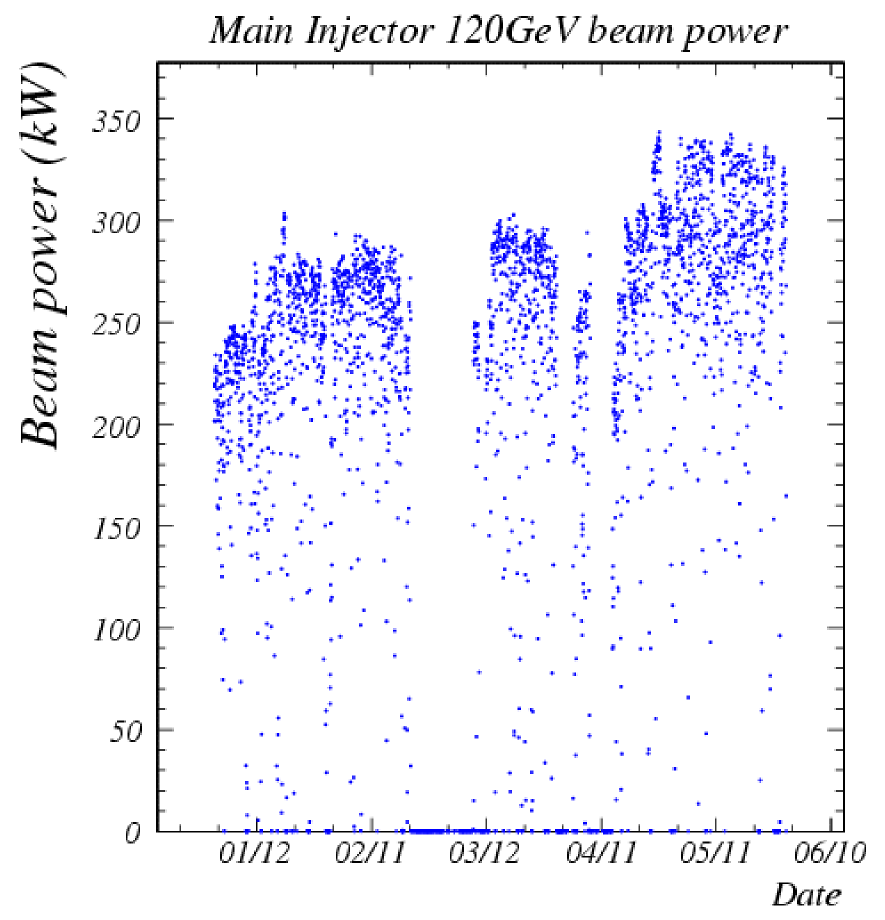
- Search for oscillation ν_μ disappearance
- 735 km baseline
  - From Fermilab to Minnesota
  - Elevation of 3.3°
  - Near detector: ~1ktons
  - Far detector: MINOS 5.4 ktons
- Commissioned in late 2004
- Operating since 2005



NuMI Proton Beam

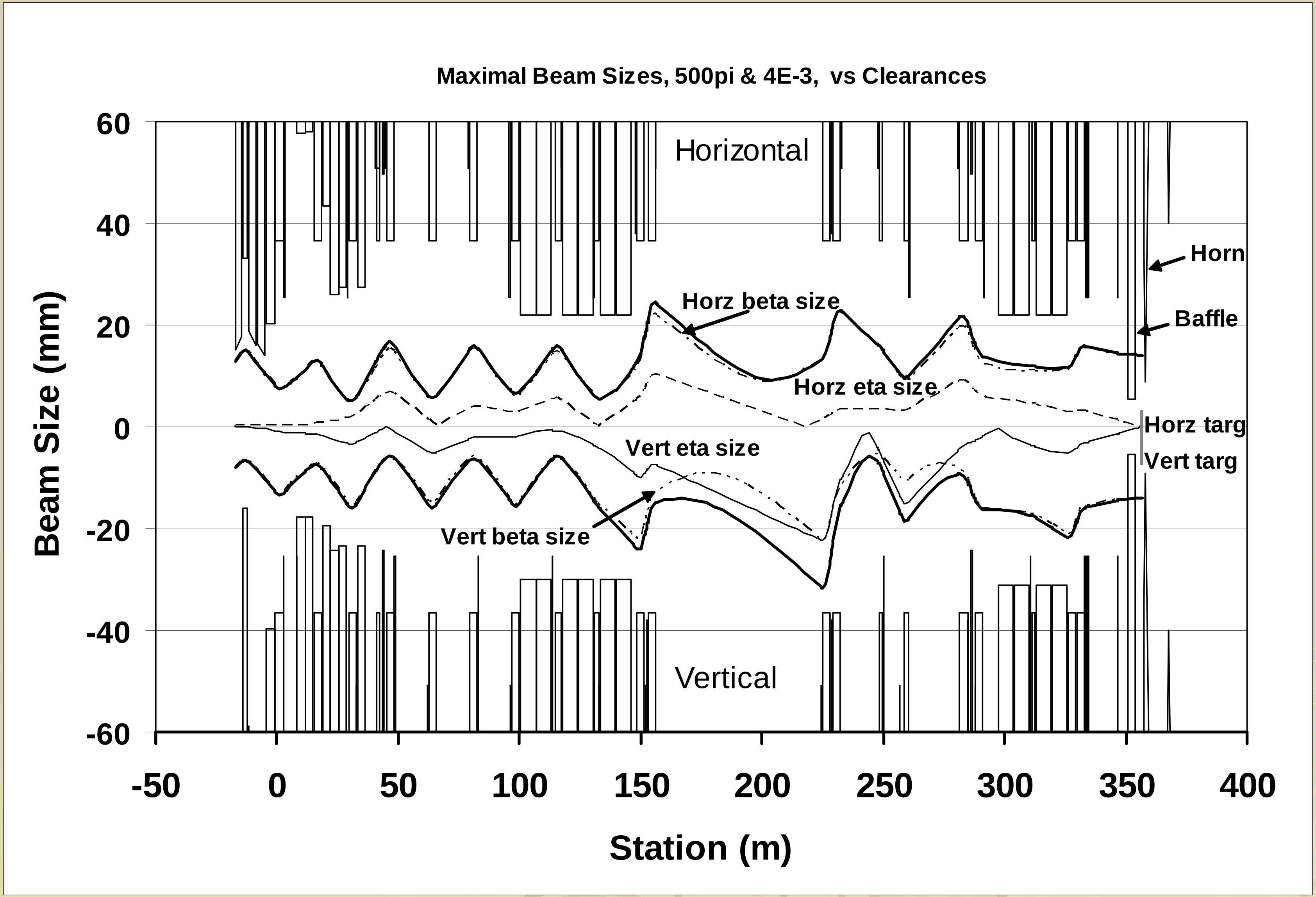
- From Main Injector: 120 GeV/c
- Cycle length: 2.2 s
- Pulse length: 10μs
- Beam intensity: 3-3.7 · 10^{13} ppp
- $\sigma \sim 1$mm

Main Injector Beam Power 2008



- Main Injector beam power at 120 GeV since multi-batch slip stacking was implemented in January.
- At the end of April all the multi-batch slip stacking optimization and the MI collimation system were commissioned allowing increasing the MI beam power to 340 KW.
- The next goal for the MI beam power at 120 GeV is 400 KW.

500 Pi Beam Envelope vs. Apertures



Keys to NuMI Proton Beam Operation

- **Comprehensive beam permit system**
  - ~ 250 parameters monitored
- **Open extraction/primary beam apertures – capability of accepting range of extracted beam conditions**
  - Superb beam loss control
- **Good beam transport stability**
- **Autotune beam position control**
  - No manual control of NuMI beam during operation
- **Normal operation is “mixed mode” sharing same cycle with Pbar stacking [2 + 9 batch operation]**

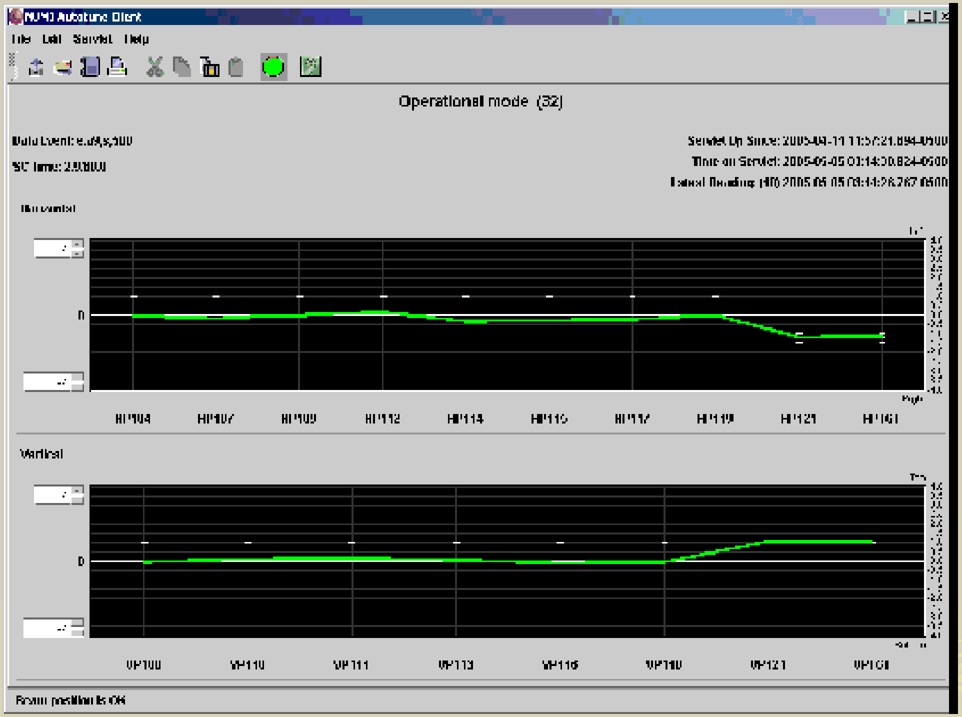
NuMI Beam Permit System

- **Dedicated hardware based on Tevatron fast abort system**
- **Permit to fire NuMI extraction kicker is given prior to each beam pulse, based on good status from a comprehensive set of monitoring inputs**
  - ~ 250 inputs to NuMI BPS
- **Inputs include Main Injector beam quality prior to extraction, NuMI power supply status, target station and absorber status, beam loss and position for previous pulse**
- NuMI BPS was prototyped with MiniBooNE, with excellent results
- Very similar in function to the new LHC,CNGS beam interlock system

With the very intense NuMI beam, perhaps our most important operational tool.

Autotune Primary Beam Position Control

- **Automatic adjustment of correctors using BPM positions to maintain primary transport & targeting positions**
- **Commissioned at initial turn on for correctors**
- **Vernier control for targeting. Initiate tuning when positions 0.125 mm from nominal at target**
- **Very robust . Separate corrector files for mixed mode and NuMI only**



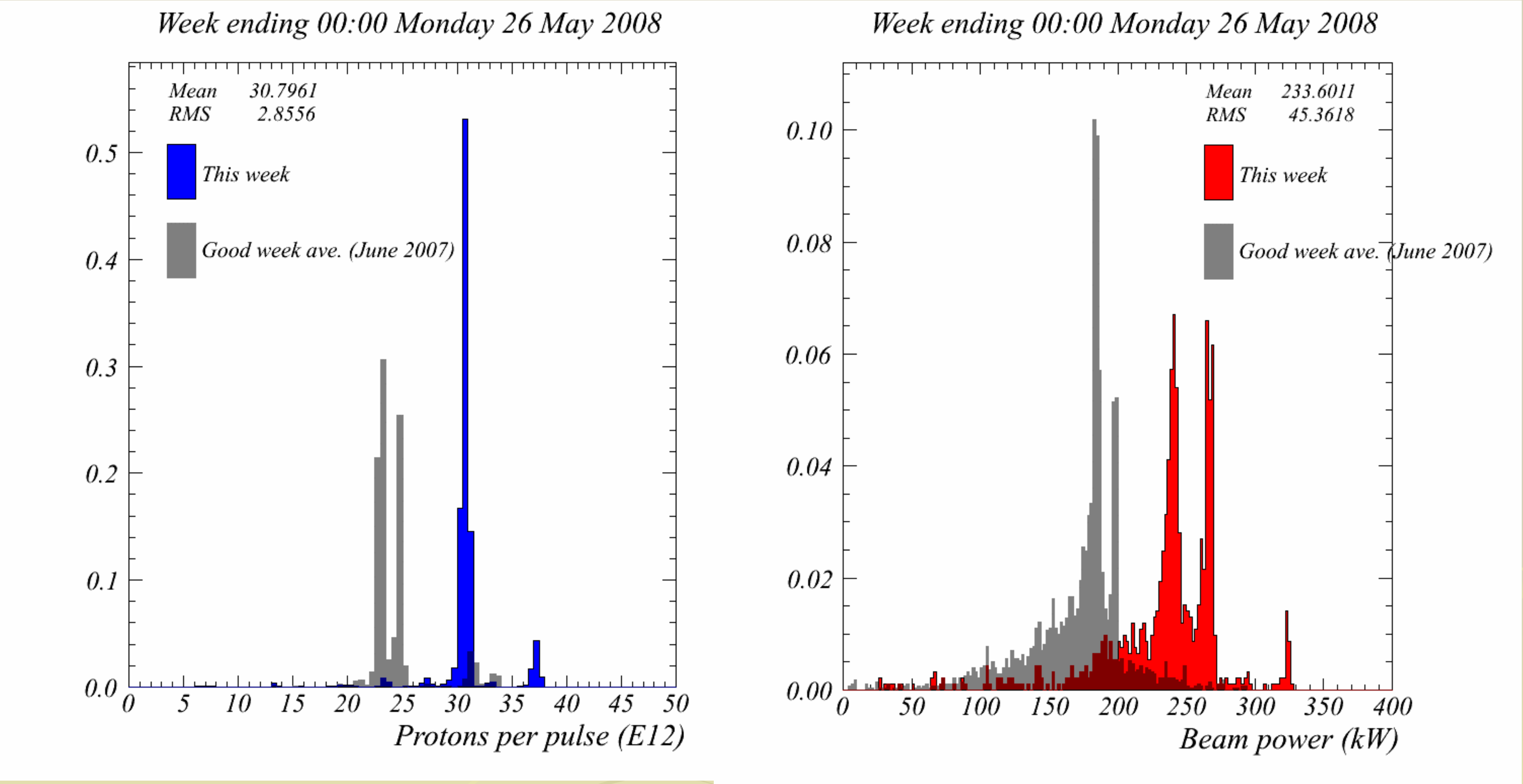
Operational mode (32)

Beam position is OK

Autotune Beam Control Monitor

Ave. Intensity/Pulse & Beam Power

Compared to 2007 Operation

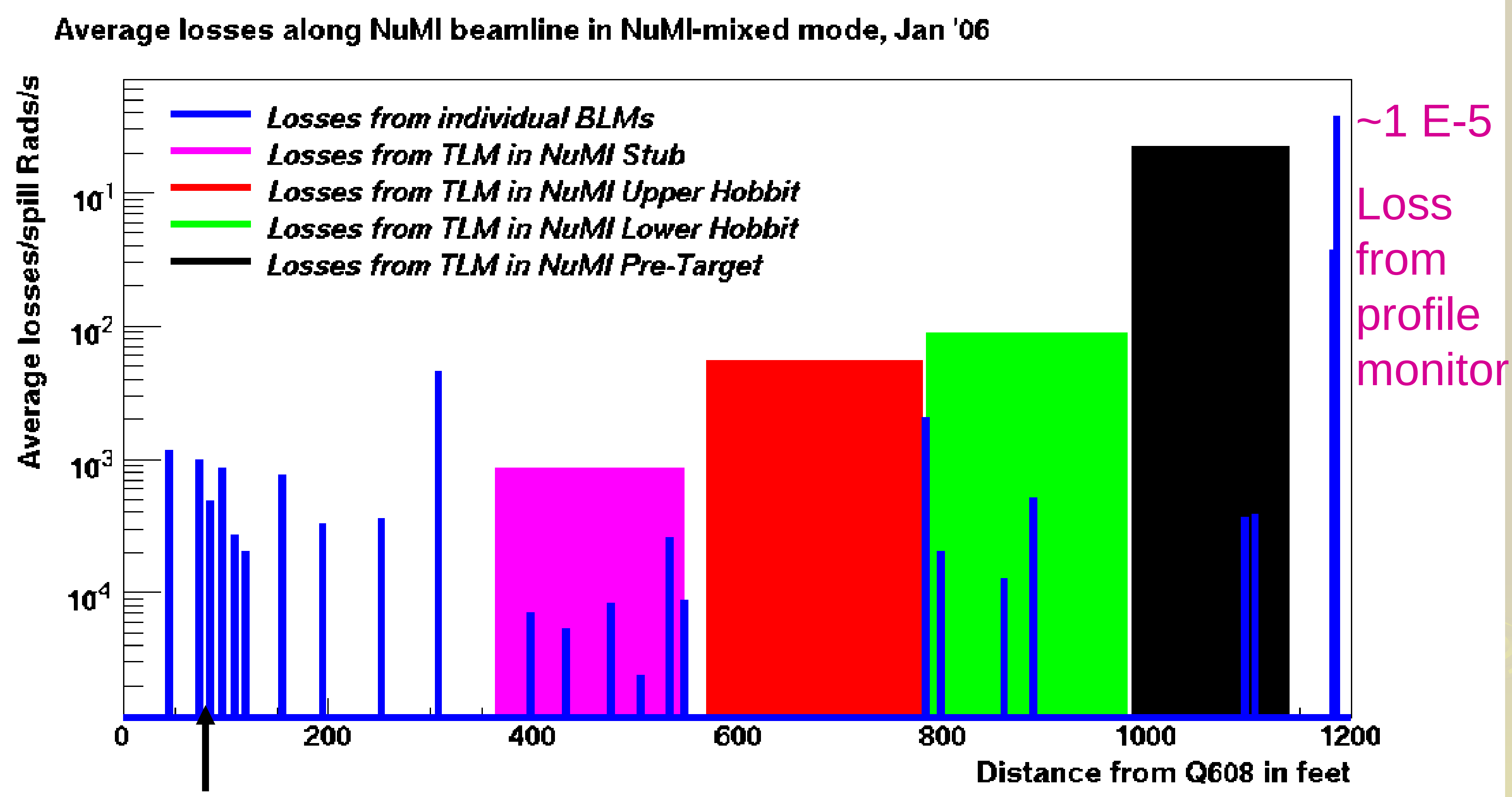


< 3.08 e13 ppp>

< 233.6 kW >

Primary Beam Loss – Mixed Mode

Average per Pulse for One Month

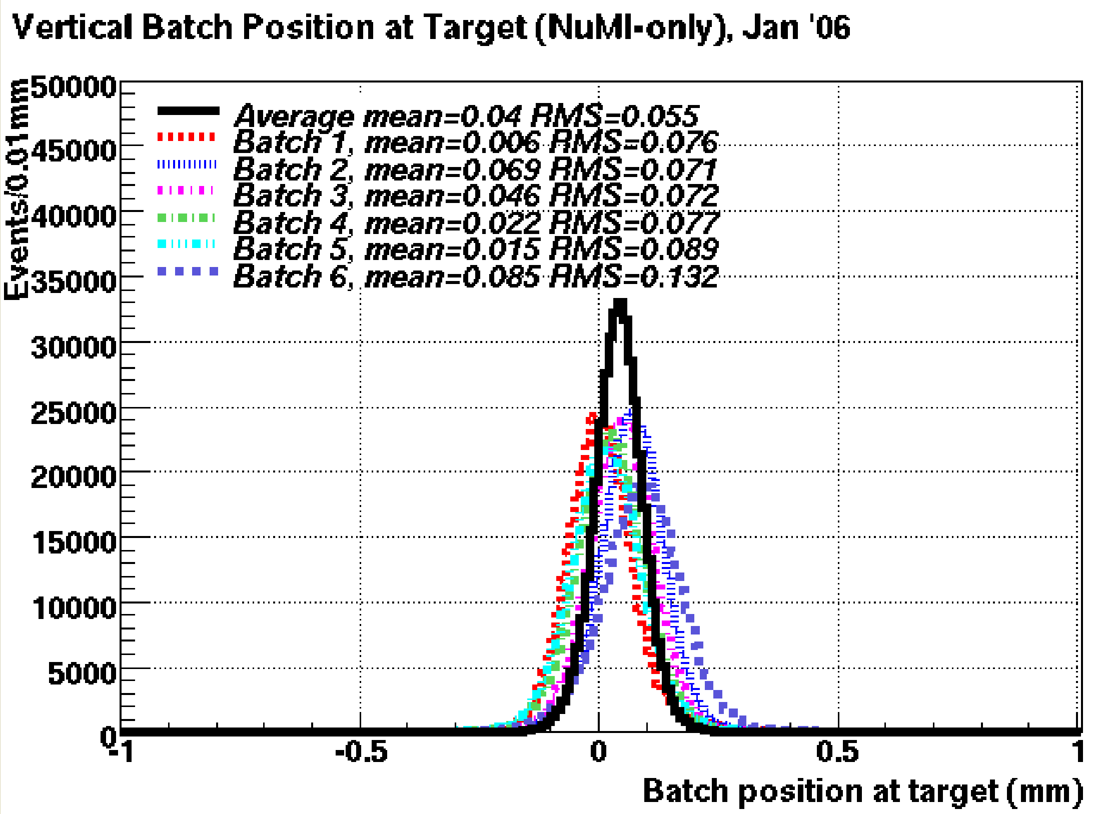


~1 E-5

Loss from profile monitor

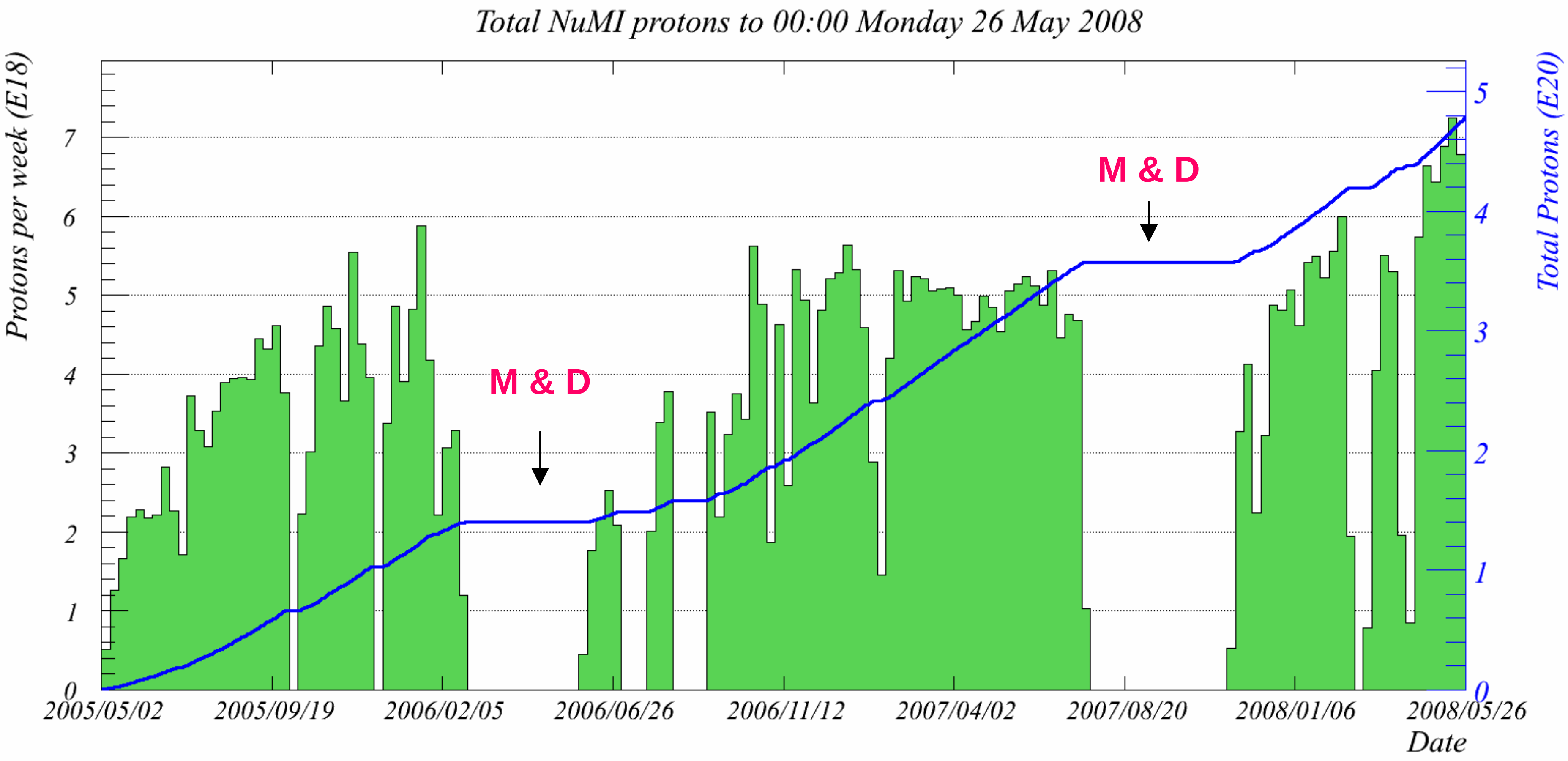
Extraction

Vertical Beam Stability on Target - NuMI Only Mode 1 Montth Data

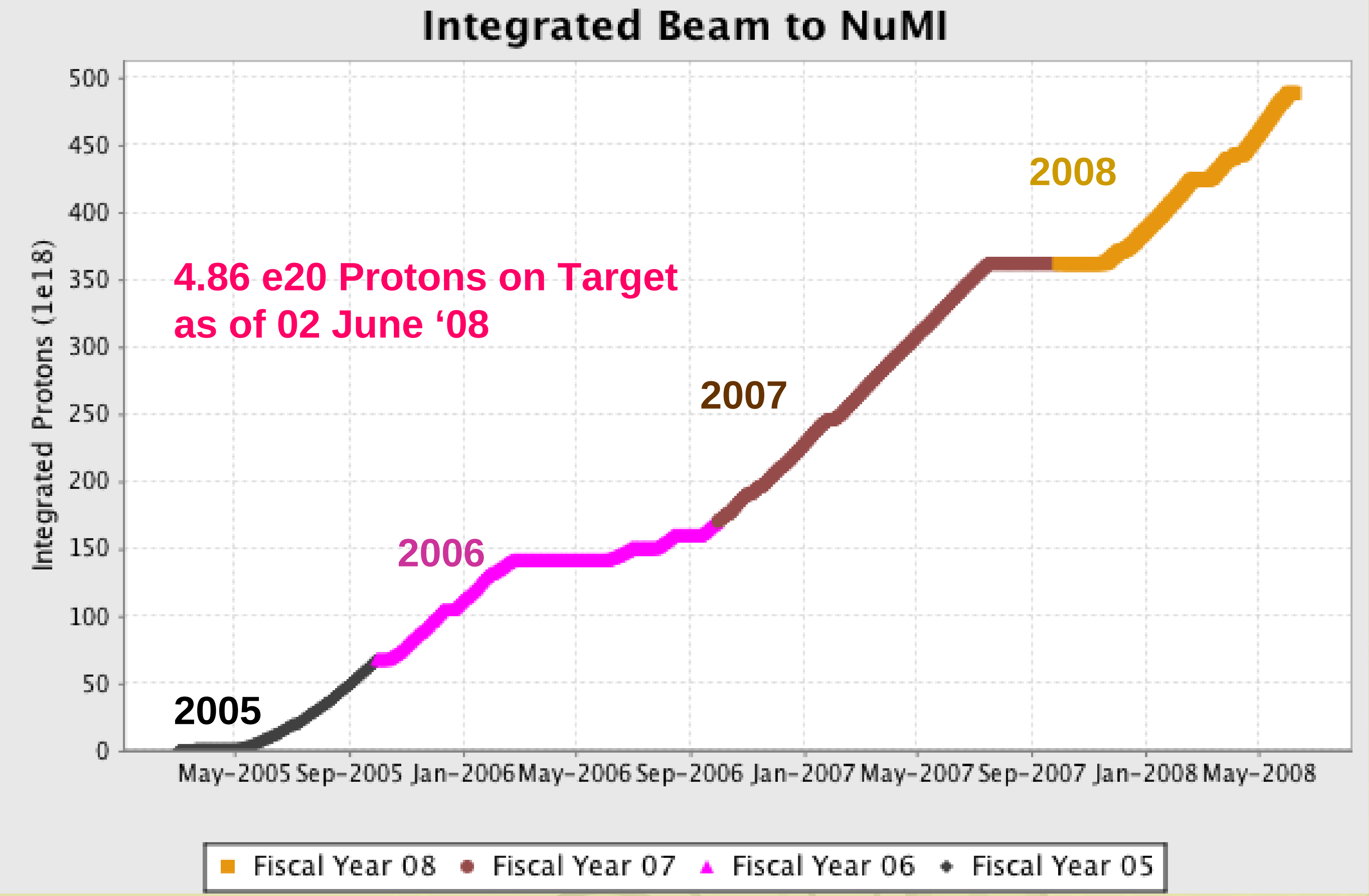


Note greatly expanded scale (+/- 1mm). RMS variation < 60 µ m for the mean of all batches. Autotune uses batches # 2-4.

NuMI Protons per Week



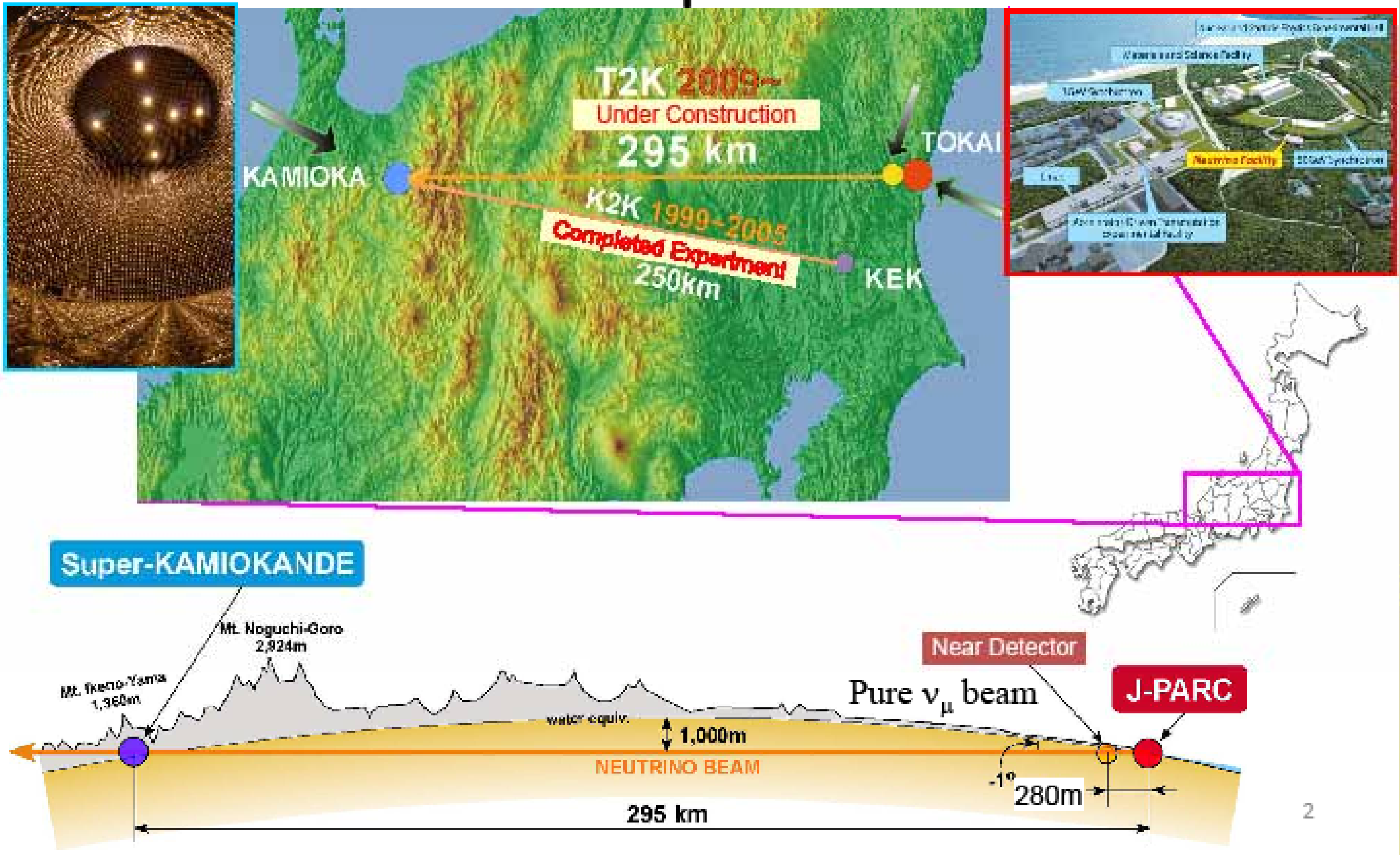
NuMI Integrated Protons:

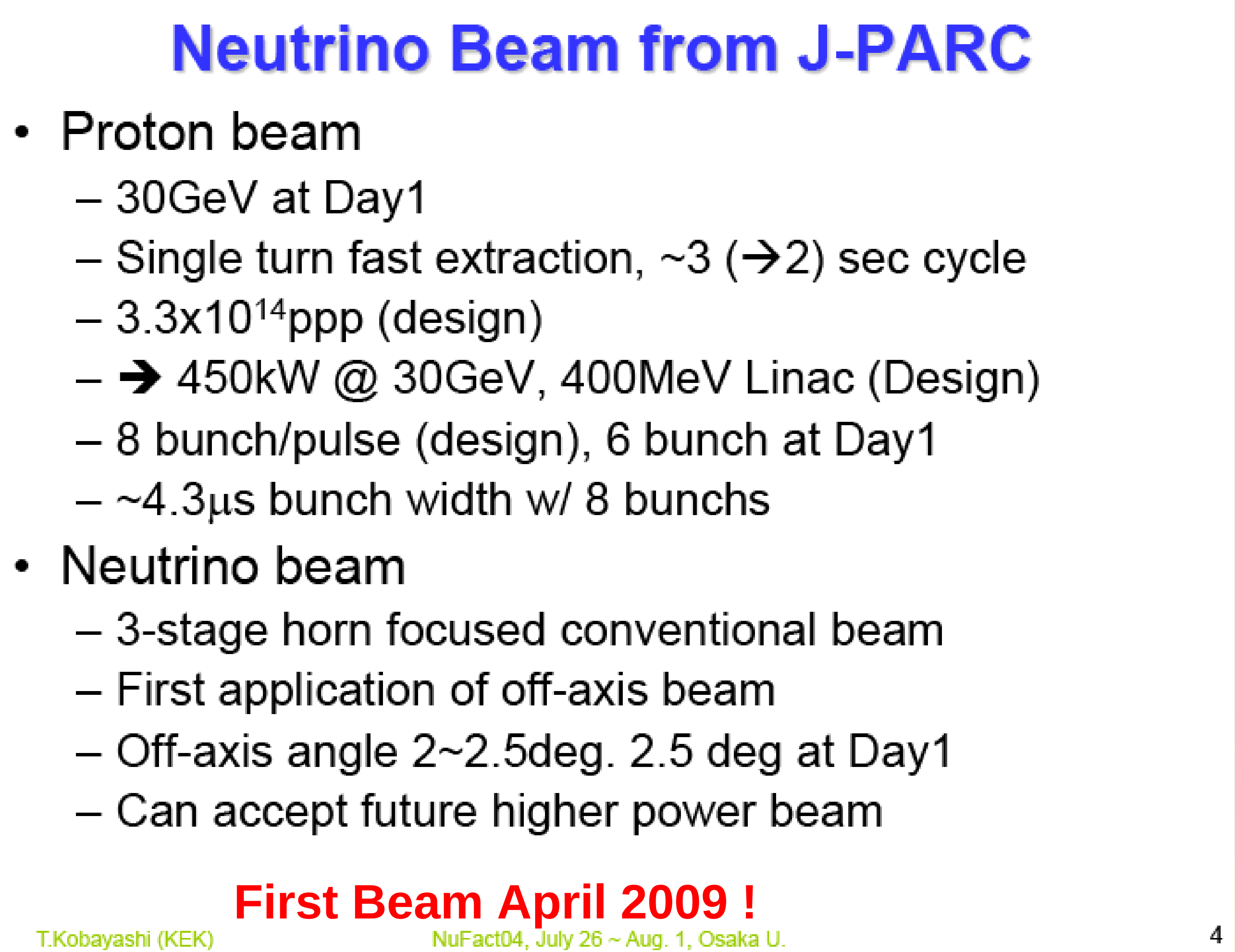


4.86 e20 Protons on Target
as of 02 June '08

T2K Proton Beam

T2K (Tokai to Kamioka)
LBL ν experiment





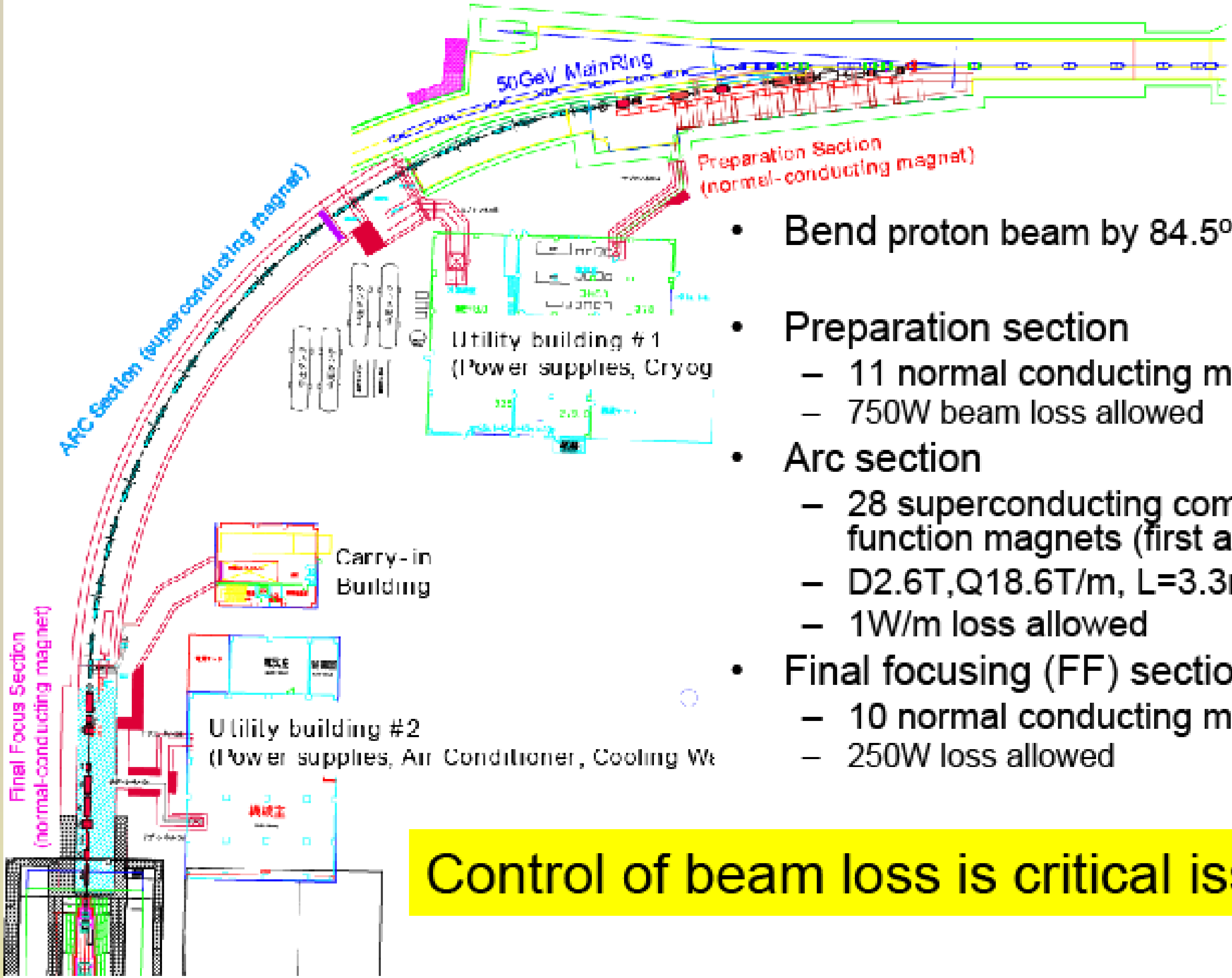
Neutrino Beam from J-PARC

- Proton beam
  - – 30GeV at Day1
  - – Single turn fast extraction, ~3 (→2) sec cycle
  - – 3.3x10^{14}ppp (design)
  - – → 450kW @ 30GeV, 400MeV Linac (Design)
  - – 8 bunch/pulse (design), 6 bunch at Day1
  - – ~4.3μs bunch width w/ 8 bunchs
- Neutrino beam
  - – 3-stage horn focused conventional beam
  - – First application of off-axis beam
  - – Off-axis angle 2~2.5deg. 2.5 deg at Day1
  - – Can accept future higher power beam

First Beam April 2009 !

T.Kobayashi (KEK) NuFact04, July 26 ~ Aug. 1, Osaka U. 4

Primary beam line

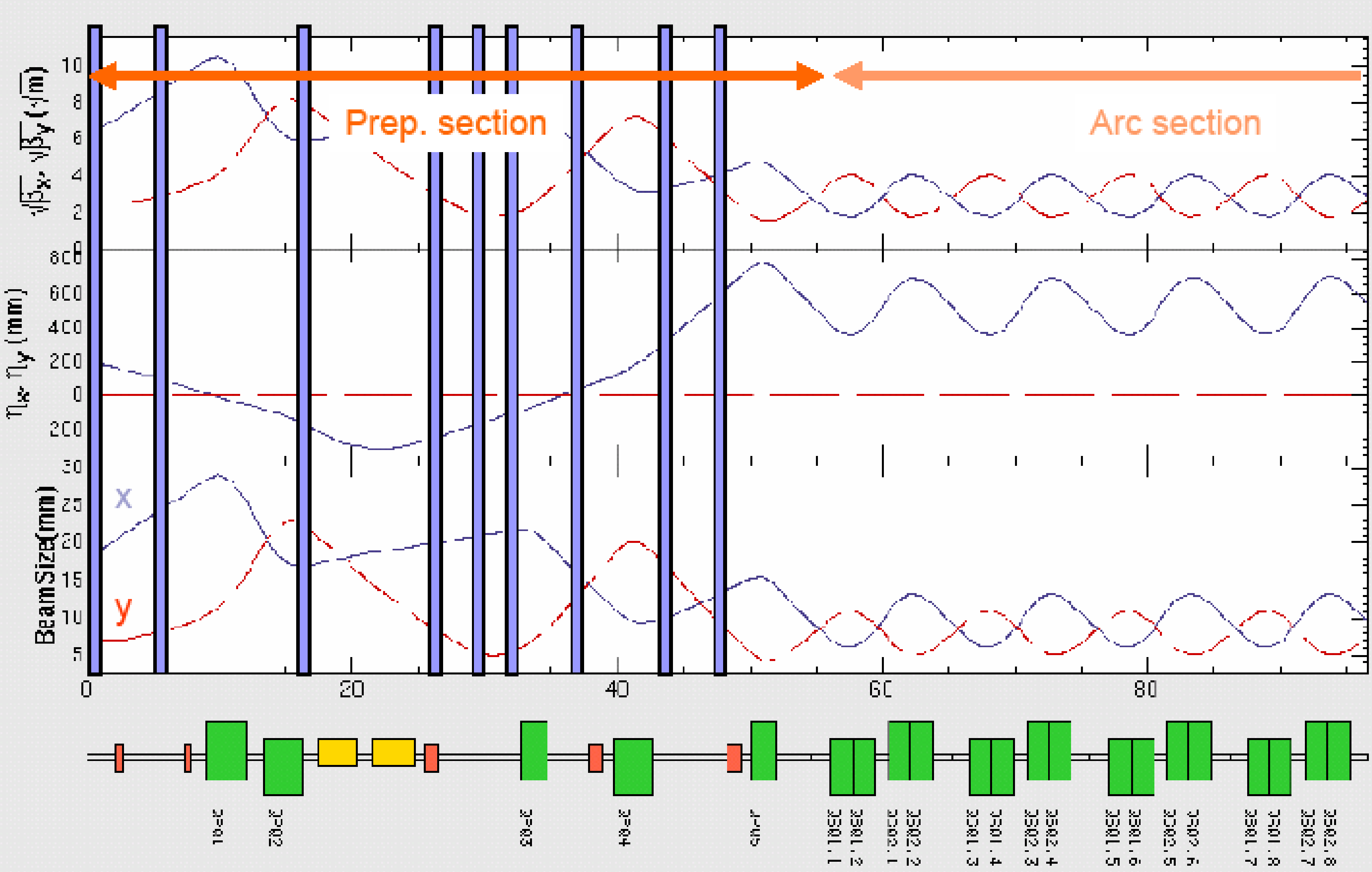


- Bend proton beam by 84.5°
- Preparation section
  - 11 normal conducting magnets
  - 750W beam loss allowed
- Arc section
  - 28 superconducting combined function magnets (first application)
  - D2.6T,Q18.6T/m, L=3.3m
  - 1W/m loss allowed
- Final focusing (FF) section
  - 10 normal conducting magnets
  - 250W loss allowed

Control of beam loss is critical issue

Tuning of the Prep. section

There are 9 position/profile monitors and 5 Q-magnets



T2K Beam Loss Control

- **Design emittance for extracted beam:**
  - **6 pi mm mr at 50 GeV**
  - **10 pi mm mr at 30 GeV**
- **Admittance of preparation section & collimation: 81 pi mm mr**
- **Admittance of superconducting arc section: > 200 pi mm mr**
- **Modeling shows beam energy deposition in arc section is 4 orders of magnitude smaller than in preparation section**

- **Beam stability requirement at target = 1.0 mm.**

- **Full instrumentation package of monitors- next slide**

- **Machine Safety System will inhibit beam when parameters are out of tolerance.**

Proton beam monitors

Position: 20 x ESMs
Profile: 19 x SSEM s
Intensity: 5x CTs

- **Being assembled**
- **Installation started in prep sect**

Loss: 50 x Ionization chambers

- **Twenty monitors are purchased in this FY**

OTR detector (provided by Canada)

- Provide all-time profile just in front of target
- **Mirrors, rad-hard camera delivered**
- Manufacturing, assembling in progress

Electronics

- FADC for CT/ESM being produced by US
- FADC for SSEM prepared by Korea

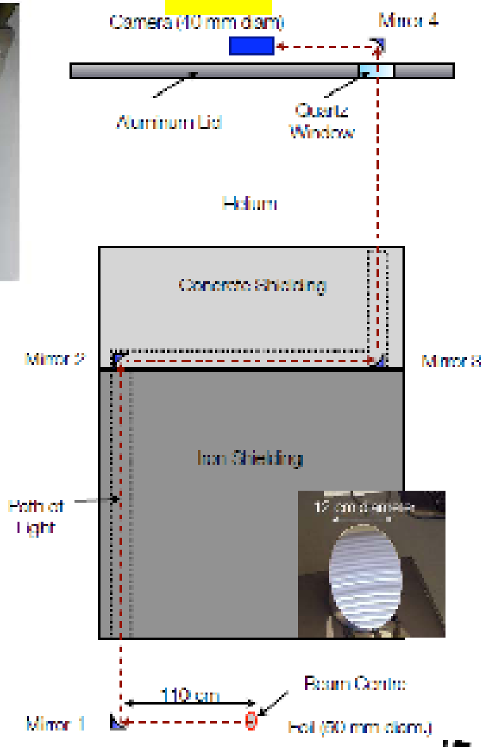
ESM

CT

SSEM

Installed monitor chamber

OTR



Lessons for Mega-Watt Proton Beams

Lessons For MW Proton Beams

- **In large part do the same things we currently do, but <u>ever more carefully!</u> The tolerance for error becomes much smaller.**
- **The most important protection is with a comprehensive and well tested beam interlock (or permit) system. No pulse should be extracted until all parameters are at specifications within tight tolerances.**
- **Robust designs for beam optics and aperture clearance. Beam loss should be very low at normal conditions. For abnormal conditions extraction should be inhibited.**
- **Develop capability for monitoring instrumentation stability during operation. Inaccurate BPM readings are very dangerous. But BPM's are the essential continuously active beam monitors.**
- **A robust automated beam control system can reliably maintain beam targeting to high precision. It's first mission should be to "do no harm".**
- **Something new – we must cool vacuum exit windows.**

Acknowledgments

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