Delivering High Intensity Proton Beam:
Lessons for the Next Beam Generations

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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 $3.4 \times 10^{13}$ protons (CERN TT40 line Oct.’04) Magnet vacuum chamber destroyed. Views are from inside beam tube.

- Now need millions of pulses!
Significant Targeting Constraints

- **NuMI**
  - Maintain beam centered on target to < 0.25 mm (Physics background constraint)
  - Preclude 2\(^{nd}\) 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 2\(^{nd}\) 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
## CNGS Proton Beam Parameters

<table>
<thead>
<tr>
<th>Beam parameters</th>
<th>Nominal CNGS beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal energy [GeV]</td>
<td>400</td>
</tr>
<tr>
<td>Normalized emittance [μm]</td>
<td>H=12  V=7</td>
</tr>
<tr>
<td>Emittance [μm]</td>
<td>H=0.028  V=0.016</td>
</tr>
<tr>
<td>Momentum spread Δp/p</td>
<td>0.07 % +/- 20%</td>
</tr>
<tr>
<td># extractions per cycle</td>
<td>2 separated by 50 ms</td>
</tr>
<tr>
<td>Batch length [μs]</td>
<td>10.5</td>
</tr>
<tr>
<td># of bunches per pulse</td>
<td>2100</td>
</tr>
<tr>
<td>Intensity per extraction [10(^{13}) p]</td>
<td>2.4</td>
</tr>
<tr>
<td>Bunch length [ns] (4σ)</td>
<td>2</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>5</td>
</tr>
<tr>
<td>Beta at focus [m]</td>
<td>hor.: 10 ; vert.: 20</td>
</tr>
<tr>
<td>Beam sizes at 400 GeV [mm]</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Beam divergence [mrad]</td>
<td>hor.: 0.05; vert.: 0.03</td>
</tr>
</tbody>
</table>

Expected beam performance: 4.5 \(\times\) 10\(^{19}\) protons/year on target

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500kW beam power

Upgrade phase: 3.5 \(\times\) 10\(^{13}\) p
Robust Optics Design!

Beta functions

good agreement with theory

Dispersion $D_x$

Dispersion $D_y$

AB Seminar, 21 Sept. 2006
E. Gschwendner, CERN
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
- Hadron stop cooling

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\cdot10^{17} \text{ pot}
- 2007: 6 weeks CNGS run
  - 7.9\cdot10^{17} \text{ pot}
  - Maximum intensity: 4\cdot10^{13} \text{ pot/cycle}
    - Radiation limits in PS
- OPERA detector completed by June 2008
- CNGS modifications finished
- 2008: CNGS run: June-November \rightarrow NOW! \leftarrow
  - 5.43\cdot10^{17} \text{ pot on Friday, 27Jun08, after 9 days running}

Expected protons in 2008: \sim2.6\cdot10^{19} \text{ pot}
NuMI Proton Beam
NuMI: Neutrinos at the Main Injector

- Search for oscillation $\nu_\mu$ 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: 10$\mu$s
- Beam intensity: 3-3.7 $\cdot$ 10$^{13}$ ppp
- $\sigma \sim$1mm
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

### Graph: Maximal Beam Sizes, 500pi & 4E-3, vs Clearances

- **Horizontal**
  - Horz beta size
  - Horz eta size
- **Vertical**
  - Vert beta size
  - Vert eta size
  - Vert targ

### Axes:
- **Beam Size (mm)**
- **Station (m)**

### Values:
- Beam sizes range from -60 to 60 mm.
- Stations from -50 to 400 m.

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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
Ave. Intensity/Pulse & Beam Power
Compared to 2007 Operation

Week ending 00:00 Monday 26 May 2008

Week ending 00:00 Monday 26 May 2008

< 3.08 e13 ppp>
< 233.6 kW >

NuFACT08 – 4 July
S. Childress – Proton Beams
Primary Beam Loss – Mixed Mode
Average per Pulse for One Month

Average losses along NuMI beamline in NuMI-mixed mode, Jan ’06

- Losses from individual BLMs
- Losses from TLM in NuMI Stub
- Losses from TLM in NuMI Upper Hobbit
- Losses from TLM in NuMI Lower Hobbit
- Losses from TLM in NuMI Pre-Target

Extraction

~1 E-5 Loss from profile monitor

NuFACT08 – 4 July
S. Childress – Proton Beams
Vertical Beam Stability on Target - NuMI
Only Mode 1 Month Data

Vertical Batch Position at Target (NuMI-only), Jan '06

Note greatly expanded scale (+/- 1mm). RMS variation < 60 μm for the mean of all batches. Autotune uses batches # 2-4.
NuMI Protons per Week

Total NuMI protons to 00:00 Monday 26 May 2008
**NuMI Integrated Protons:**

Integrated Beam to NuMI

4.86 e20 Protons on Target as of 02 June ‘08

- 2005
- 2006
- 2007
- 2008
T2K Proton Beam
T2K (Tokai to Kamioka)
LBL ν experiment
Neutrino Beam from J-PARC

• Proton beam
  – 30GeV at Day1
  – Single turn fast extraction, \( \sim 3 \rightarrow 2 \) sec cycle
  – \( 3.3 \times 10^{14} \) ppp (design)
  – \( \Rightarrow \) 450kW @ 30GeV, 400MeV Linac (Design)
  – 8 bunch/pulse (design), 6 bunch at Day1
  – \( \sim 4.3 \mu \text{s} \) bunch width w/ 8 bunchs

• Neutrino beam
  – 3-stage horn focused conventional beam
  – First application of off-axis beam
  – Off-axis angle 2\( \sim 2.5 \)deg. 2.5 deg at Day1
  – Can accept future higher power beam

First Beam April 2009!
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:
  - $6 \pi \text{ mm mr at } 50 \text{ GeV}$
  - $10 \pi \text{ mm mr at } 30 \text{ GeV}$

- Admittance of preparation section & collimation: $81 \pi \text{ mm mr}$

- Admittance of superconducting arc section: $> 200 \pi \text{ mm mr}$

- 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
Lessons for Mega-Watt Proton Beams
Lessons For MW Proton Beams

- In large part do the same things we currently do, but ever more carefully! 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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