Feasibility study of the distribution of 4x1 MW beam power onto the 4-horn system of the EUROnu SPL Super Beam

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Neutrino Beams & Instrumentation (NBI), CERN, Nov. 8, 2012
The Work Package 2 addresses the issues concerning the proton energy and the beam profile specific to neutrino beams.

Use of a proton driver (4MW mandatory), an accumulator, a target and the hadron collector:

- Design study based on the Superconducting Proton Linac (SPL) at CERN

Use of four targets (instead of one):

- To decrease the power dissipated and then minimize the radiation issues
- To reduce stress on target via lower frequency (12.5 Hz)

**Main task of this present work:** Define an optical system to ensure the beam distribution onto the 4 targets of the horn system.
SPL/accumulator: what we know

SPL

- Use of the High Power Super Conducting Proton Linac (HP-SPL) under study at CERN
- Essential element of the staged approach towards renewing the CERN proton injector complex
- The current design studies foresee a beam power of 4 MW at 50 Hz repetition frequency with protons of about 4.5 GeV kinetic energy and a pulse duration of about 400 μs for neutrino physics applications
- Pulse duration of the proton beam delivered on the SPL-Super Beam target-horn station ≤ 5 μs to limit the energy stored in the magnetic field generated by the pulsed current of the horn
- For this reason an additional accumulator ring is required interfacing the SPL and the target-horn station

Accumulator

- Dedicated design studies exist only for the Neutrino Factory
- Requires a combination of accumulator and compressor ring (to achieve a bunch length of 2 ns rms after compression)
- For the SB the accumulator ring is sufficient
- A 6-bunch per pulse option is most suited: allows the lowest values of the local power distribution inside the target
- Circumference of the ring 318.5 m*

### SPL Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>4.5 GeV</td>
</tr>
<tr>
<td>Beam power</td>
<td>4.0 MW</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Average pulse current</td>
<td>40 mA</td>
</tr>
<tr>
<td>Peak pulse current</td>
<td>64 mA</td>
</tr>
<tr>
<td>Chopping ratio</td>
<td>62 %</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>0.6 ms</td>
</tr>
<tr>
<td>Protons per pulse for PS2</td>
<td>1.5 x 10^{14}</td>
</tr>
<tr>
<td>Beam duty cycle</td>
<td>2.0 %</td>
</tr>
<tr>
<td>Number of klystrons (704 MHz)</td>
<td>57</td>
</tr>
<tr>
<td>Peak RF power</td>
<td>219 MW</td>
</tr>
<tr>
<td>Average power consumption</td>
<td>38.5 MW</td>
</tr>
<tr>
<td>Cryogenics av. Power consumption</td>
<td>4.5 MW</td>
</tr>
<tr>
<td>Cryogenic temperature</td>
<td>2.0 K</td>
</tr>
<tr>
<td>Length</td>
<td>534 m</td>
</tr>
</tbody>
</table>

*Feasibility Study of Accumulator and Compressor for the 6-bunches SPL based Proton Driver, M. Aiba, CERN-AB-2008-060-B1
Beam switchyard (SY)

- Energy: 4.5 GeV
- Beam power: 4 MW
- Protons per pulse: $1.1 \times 10^{14}$
- Rep. rate: 50 Hz
- Pulse duration: 3.2 μs
- Beam shape: Gaussian
- Emittances rms: $3 \pi \text{ mm mrad}^{**}$

- Target length: 4.5 GeV
- Target radius: 4 MW
- Beam shape: Gaussian
- Rep. rate / line: 12.5 Hz
- Pulse duration: 3.2 μs
- Sigma*: 4 mm

\[
B \cdot \rho = \frac{1}{q \cdot c} \sqrt{E_k (E_k + 2E_0)}
\]

- Beam rigidity:
  - 16.16 T.m (4 GeV)
  - 17.85 T.m (4.5 GeV)

- Proton beam from accumulator
- 1-4 beam separator
- 4 proton beam lines
- Decay volume
- Target station
- $\pi \rightarrow \mu \nu$
- Beam dump

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*The target and horn for the SPL-based Super-Beam: preliminary design report, C. Bobeth, M. Dracos, F. Osswald, EUROnu WP2 Note 11-01

**Feasibility Study of Accumulator and Compressor for the 6-bunches SPL based Proton Driver, M. Aiba, CERN-AB-2008-060-B1
• Use of 2 bipolar kickers (or bipolar pulsed magnets): ± 45° rotation wrt the z axis
• K1 (K2) deflects to D1 and D3 (D2 and D4)
• Need of 1 compensating dipole per beam line (1 angle for each target): Apply a symmetry in the system

\[ B = \frac{\sin(\alpha)}{0.2998 \cdot L_{eff}} \cdot E_k \]

Angle of deflection (rad)  
Magnetic field (T)  
Magnetic length (m)  
Kinetic energy (GeV)

E. Bouquerel – NBI, CERN, Nov.8, 2012
SY: Operation mode

Repetition rate: 
\[ \frac{50}{4} = 12.5 \text{ Hz} \]
**PSI Graphic Transport Framework by U. Rohrer based on a CERN-SLAC-FERMILAB version by K.L. Brown et al**

**SY: Beam optics investigations**

Configuration
Kicker – Dipole - Target

Simulations done with TRANSPORT code**

Elian Kickers

<table>
<thead>
<tr>
<th></th>
<th>s (m)</th>
<th>B (T)</th>
<th>Eff. length (m)</th>
<th>Half aperture (cm)</th>
<th>Beam radius at element (cm)</th>
<th>disp. r16 (cm(%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kicker</td>
<td>1.75</td>
<td>0.83*</td>
<td>1.5</td>
<td>37</td>
<td>1.73</td>
<td>1.73</td>
</tr>
<tr>
<td>Dipole</td>
<td>18.8</td>
<td>-0.83*</td>
<td>1.5</td>
<td>37</td>
<td>9.71</td>
<td>9.82</td>
</tr>
<tr>
<td>Target</td>
<td>22.5</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*83 mrad deflection angle

- Radius of the beam at target location 7 times greater than the original size (target radius: 1.5 cm)
- High dispersion term value (1.38 cm/%)
SY: Beam focusing

Aim and wanted conditions at target:

- Beam waist at the middle of each target ($\sigma = 4\text{mm}$)
- Beam circular cross section, Gaussian distribution

Several possible configurations studied with TRANSPORT:

1- K-Q-Q-D-T Two quadrupoles located between the kicker and the dipole,
2- K-Q-Q-Q-D-T Three quadrupoles located between the kicker and the dipole,
3- K-D-Q-Q-Q-D-T Three quadrupoles located between the dipole and the target,
4- K-Q-Q-Q-D-Q-Q-Q-T Three quadrupoles located between the kicker and the dipole and 3 between the dipole and the target

$K$ stands for kicker
$Q$ stands for quadrupole
$D$ stands for dipole
$T$ stands for target
SY: Beam focusing

Suitable solution up to now: 3 quadrupoles between the dipole and the target station

Beam envelopes (1 beam-line)

Total volume 960 m³

Summary of the physical parameters

<table>
<thead>
<tr>
<th>Kicker1</th>
<th>Dipole1,3</th>
<th>Kicker2</th>
<th>Dipole2,4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field strength (T)</td>
<td>0.83</td>
<td>0.83</td>
<td>0.96</td>
</tr>
<tr>
<td>Angle of deflection (mrad)</td>
<td>±83.0</td>
<td>-</td>
<td>±96.0</td>
</tr>
<tr>
<td>Magnetic length (m)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Aperture H/V (mm/mm)</td>
<td>250/350</td>
<td>250/250</td>
<td>250/600</td>
</tr>
<tr>
<td>Total intensity (kA)</td>
<td>115.6</td>
<td>82.6</td>
<td>152.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quadrupole1</th>
<th>Quadrupole2</th>
<th>Quadrupole3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field gradient (T/m)</td>
<td>0.71</td>
<td>1.34</td>
</tr>
<tr>
<td>Aperture radius (mm)</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Magnetic length (m)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Function</td>
<td>F</td>
<td>D</td>
</tr>
<tr>
<td>Total intensity (kA)</td>
<td>20.3</td>
<td>38.4</td>
</tr>
</tbody>
</table>
SY: modes

**Abnormal conditions**

- **Failure of 1 target**, rep. rate becomes 16.6 Hz for each target (same intensity):
  
  Power of the incoming beam becomes 1.33 MW instead of 1MW (still tolerable for targets)
  
  Tolerance on the field errors of the optical elements: 1%.

- **The failure of a second target** aborts the experiment:
  
  2 working targets not sufficient for the physics
  
  2MW not tolerable for each target (=radiation safety issues)

- **Any dysfunction or failing** magnet aborts the experiment
  
  Risk of having the beam hitting magnets or not centred/focussed onto the target (= safety issues)
  
  Addition of beam dumps and instrumentations after the pair of kickers and after each dipole to manage safety

**Failure modes**

Preliminary beam dump design (FLUKA*)

98% of the beam stopped by the dump:

- 45% in C and 53% in Fe (remaining 2% stopped by concrete material)
- Peak of the energy absorbed: \(1.2 \times 10^{-4}\) GeV/cm\(^3\)/p (Fe material)


FLUKA: a multi-particle transport code, A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773
Additional instrumentations

Additional beam instrumentations if required:

• Beam collimation up stream the kicker 1 to cut off any eventual halo of the beam when leaving the accumulator

• At this stage of the feasibility study no precision exists on the position, the dimensions and the aperture of such collimator yet (Any alignment tuning or remote control to be defined if required)

• A consequent variation of the energy of the proton beam coming from the SPL-accumulator may induce chromatic focusing errors within the system (addition of sextupoles may be required for correction)

• Addition of:
  - Beam monitors to measure the transverse position of the beam (avoid the beam from not hitting the centre of the targets)
  - Collimators to suppress any eventual halo from the beam
Thank you for your attention
Parameters of the accumulator

<table>
<thead>
<tr>
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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>4.5 GeV</td>
</tr>
<tr>
<td>Relativistic $\gamma$</td>
<td>6.32907</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>6</td>
</tr>
<tr>
<td>Beam size, $\sigma$</td>
<td>2 mm</td>
</tr>
<tr>
<td>Transverse emittances (rms)</td>
<td>$3\pi \text{mm.mrad}$</td>
</tr>
<tr>
<td>Total bunch length</td>
<td>120 ns</td>
</tr>
<tr>
<td>RMS momentum spread (dp/p)</td>
<td>$0.863 \times 10^{-3}$</td>
</tr>
<tr>
<td>Circumference</td>
<td>318.448 m</td>
</tr>
<tr>
<td>Average $\beta$ function ($\beta_x, \beta_y$)</td>
<td>20.20 m</td>
</tr>
<tr>
<td>Momentum compaction, $\alpha_0$</td>
<td>0.0249643</td>
</tr>
<tr>
<td>Nominal tune, $Q_x/Q_y$</td>
<td>7.77, 7.77</td>
</tr>
<tr>
<td>Natural chromaticity, $Q'_{nat}$</td>
<td>-8.4, -7.9</td>
</tr>
<tr>
<td>2nd order momentum compaction, $\alpha_1$</td>
<td>4.68</td>
</tr>
<tr>
<td>Beam pipe half-height</td>
<td>50 mm</td>
</tr>
</tbody>
</table>