Collector and the SPL Super-Beam Project

Marcos Dracos

IPHC-IN2P3/CNRS Strasbourg
Why this SB?

- Staging neutrino facilities towards the NF
- Cover "high" $\theta_{13}$ range
- Cost effective facility
  - Low intensity SPL already approved,
  - Detector could already be approved to cover other physics subjects (proton life-time, cosmological neutrinos…)

17 Dec. 2008 M. Dracos, EUROnu-WP2
Present and future injectors

Proton flux / Beam power

Stage 1 (2013)

Stage 2 (2017)

(LP)SPL: (Low Power)
Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS
(~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS
(50 to 1000 GeV)
SLHC: “Superluminosity” LHC
(up to $10^{35}$ cm$^{-2}$s$^{-1}$)
DLHC: “Double energy” LHC
(1 to ~14 TeV)

Stage 3 (>2017): HP-SPL
Stage 3: HP-SPL

**Linac4 (160 MeV)**

- $3 \text{ MeV}$
- $50 \text{ MeV}$
- $102 \text{ MeV}$

**SC-linac (5 GeV)**

- $180 \text{ MeV}$
- $643 \text{ MeV}$
- $5 \text{ GeV}$

**H- source**

- RFQ
- Chopper
- DTL
- CCDTL
- PIMS

**β**

- $0.65$
- $1.0$

**Length:** $540 \text{ m}$

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### HP-SPL beam characteristics

<table>
<thead>
<tr>
<th></th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy (GeV)</strong></td>
<td>$2.5$ or $5$</td>
<td>$2.5$ and $5$</td>
</tr>
<tr>
<td><strong>Beam power (MW)</strong></td>
<td>$3$ MW ($2.5$ GeV) or $6$ MW ($5$ GeV)</td>
<td>$4$ MW ($2.5$ GeV) and $4$ MW ($5$ GeV)</td>
</tr>
<tr>
<td><strong>Rep. frequency (Hz)</strong></td>
<td>$50$</td>
<td>$50$</td>
</tr>
<tr>
<td><strong>Protons/pulse ($\times 10^{14}$)</strong></td>
<td>$1.5$</td>
<td>$2$ ($2.5$ GeV) + $1$ ($5$ GeV)</td>
</tr>
<tr>
<td><strong>Av. Pulse current (mA)</strong></td>
<td>$20$</td>
<td>$40$</td>
</tr>
<tr>
<td><strong>Pulse duration (ms)</strong></td>
<td>$1.2$</td>
<td>$0.8$ ($2.5$ GeV) + $0.4$ ($5$ GeV)</td>
</tr>
</tbody>
</table>
SPL Super-Beam Project

H- linac 2.2, 3.5 or 5 GeV, 4 MW

Proton driver

Accumulator ring + bunch compressor

Magnetic horn capture (collector)

Target

ν, μ

Decay tunnel

300 MeV νμ beam to far detector

to be studied in EUROν WP2

to be studied by LAGUNA

CERN

130km

Fréjus

17 Dec. 2008

M. Dracos, EUROnu-WP2
### SPL (CDR2) main characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>H^-</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>3.5 GeV</td>
</tr>
<tr>
<td>Mean current during the pulse</td>
<td>40 mA</td>
</tr>
<tr>
<td>Mean beam power</td>
<td>4 MW</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>0.57 ms</td>
</tr>
<tr>
<td>Bunch frequency</td>
<td>352.2 MHz</td>
</tr>
<tr>
<td>Duty cycle during the pulse</td>
<td>62 (5/8) %</td>
</tr>
<tr>
<td>rms transverse emittances</td>
<td>0.4 π mm mrad</td>
</tr>
<tr>
<td>Longitudinal rms emittance</td>
<td>0.3 π deg MeV</td>
</tr>
<tr>
<td>Length</td>
<td>430 m</td>
</tr>
</tbody>
</table>

**Note:**
- bunch compressor to go down to 3.2 μs (important parameter for hadron collector pulsing system)
- possible energy upgrade to 5 GeV could be the subject of a 3rd CDR
Proton Target

- 300-1000 J cm\(^{-3}\)/pulse
- Severe problems from: sudden heating, stress, activation
- Safety issues!
- Baseline for Super-Beam is solid target, mercury is optional (baseline for NF)
  - Extremely difficult problem: need to pursue two approaches:
    - Liquid metal target (Merit experiment)
    - Solid target (extensive R/D program at STFC and BNL)
- Envisage alternative solutions
Proton Target

CC target

Horn

Helium cooling of target

Proposed rotating tantalum target ring (realistic?)

He IN

He OUT

cooling is a main issue...

fluidised jet of particles

Work at BNL and RAL
Experience on T2K target (750 kW)
very useful

Liquid Mercury (MERIT)
Proposed collection system

taking into account the proton energy and collection efficiency, the target must be inside the horn

proton beam

horn

300 kA

40 cm

80 cm

3.7 cm

16.6 cm

8.5°
Hadron production

2.2 GeV protons

Particles coming out of the target

$p_T$ distribution not the same for all targets

⇒

the choice of the target could influence the hadron collection system (horn shape)

From now on Hg will be considered
Hadron production uncertainties

2.2 GeV protons

disagreement between models (Monte Carlo production, interaction and transport codes)

more development is needed (simulation, measurements)
Proton Energy and Pion Spectra

- pions per proton on target.
- Kinetic energy spectrum
  - 2.2 GeV:
    - $<E_k> = 300\text{MeV}$
  - 3.5 GeV:
    - $<E_k> = 378\text{MeV}$

hadrons boosted forward
Proposed design for SPL

for pions coming out of the target

for a Hg target, 30 cm length, \( \varnothing 15 \) mm
\( (N_{\text{particles}} \times 10^{16}/\text{sec, FLUKA}) \)

\[
\begin{array}{cccccccccc}
E_k (\text{GeV}) & p & n & \gamma & e^+ & e^- & \pi^+ & \pi^- & \mu^+ & \mu^- & K^+ & K^0 \\
2.2 & 1.4 & 17 & 5.0 & 0.08 & 0.17 & 0.24 & 0.18 & 4 & 1 & 7 & 6 \\
3.5 & 1.8 & 23 & 7.0 & 0.15 & 0.28 & 0.41 & 0.37 & 10 & 3 & 35 & 30 \\
4.5 & 2.3 & 25 & 7.7 & 0.21 & 0.35 & 0.57 & 0.39 & 11 & 3.3 & 93 & 68 \\
8 & 3.1 & 33 & 11.0 & 0.41 & 0.63 & 1.00 & 0.85 & 30 & 9.5 & 413 & 340 \\
\end{array}
\]

\( \pi^+ \) angle
horn region (0.26-1.22 rad)

relatively better collection when \( p_{\text{proton}} \)

the target must be inside the horn
Horn geometry

- 2.2 GeV proton beam:
  - $<p_{\pi}> = 405$ MeV/c
  - $<\theta_{\pi}> = 60^\circ$

- 3.5 GeV proton beam:
  - $<p_{\pi}> = 492$ MeV/c
  - $<\theta_{\pi}> = 55^\circ$
Proposed design for SPL

- Proton beam
- Hg target
- Horn
- Reflector

Dimensions:
- 40 cm
- 80 cm
- 70 cm
- 3.7 cm
- 16.6 cm
- 20.3 cm
- 4 cm

Currents:
- 600 kA
- 300 kA

Notes:
- Very high current and frequency inducing severe problems
Energy deposition in the conductors

MARS

4MW, 2.2 GeV proton beam

(1MeV = 1.82 kW)
Main Technical Challenges

• Horn: as thin as possible (3 mm) to minimize energy deposition,
• Longevity in a high power beam (currently estimated to be 6 weeks!),
• 50 Hz (vs a few Hz up to now),
• Large electromagnetic wave, thermo-mechanical stress, vibrations, fatigue, radiation damage,
• Currents: 300 kA (horn) and 600 kA (reflector)
  – design of a high current pulsed power supply (300 kA/100 μs/50 Hz),
• cooling system in order to maintain the integrity of the horn despite of the heat amount generated by the energy deposition of the secondary particles provided by the impact of the primary proton beam onto the target,
• definition of the radiation tolerance,
• integration of the target.
Power Supply for horn pulsing (major issue)

values considered by CERN

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_o$</td>
<td>7 kV</td>
</tr>
<tr>
<td>$I_M$</td>
<td>300 kA (14.5 rms)</td>
</tr>
<tr>
<td>$\tau_0$</td>
<td>100 $\mu$s</td>
</tr>
<tr>
<td>$L$</td>
<td>0.6 (0.4 Horn) $\mu$H</td>
</tr>
<tr>
<td>$R$</td>
<td>500 (180 Horn) $\mu$Ω</td>
</tr>
<tr>
<td>$C$</td>
<td>1500 $\mu$F</td>
</tr>
</tbody>
</table>
3 Solutions proposed by ABB

schematic versions

option 1

option 2

option 3

at the capacitors ends

μs

in the charge
$\theta_{13}$ Sensitivity

- **Detector:**
  - Water Cerenkov
  - 440 kt
  - at Fréjus (130 km from CERN)

- **Run:**
  - 2 years with positive focusing.
  - 8 years with negative focusing.

- Computed with $\delta_{CP}=0$ (standard benchmark) and $\theta_{13} = 0$

- **Parameter…**
  - $\Delta m_{23} = 2.5 \times 10^{-3} \text{eV}^2$
  - $\Delta m_{12} = 7.1 \times 10^{-5} \text{eV}^2$
    - $\sin^2(2\theta_{23}) = 1$
    - $\sin^2(2\theta_{12}) = 0.8$
Sensitivity 3.5GeV

Minimum: $\theta_{13} = 1.2^\circ$ (90% CL)

no strong dependence on proton energy for 2.2<p<5 GeV
Present Collectors

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Current</th>
<th>Rep. Rate</th>
<th>Pulses per time period</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Numi</em> (120 GeV)</td>
<td>200 kA</td>
<td>0.5 Hz</td>
<td>6 Mpulses 1 year</td>
</tr>
<tr>
<td><em>MiniBooNE</em> (8 GeV)</td>
<td>170 kA</td>
<td>5 Hz</td>
<td>11 Mpulses 1 year</td>
</tr>
<tr>
<td><em>K2K</em> (12 GeV)</td>
<td>250 kA</td>
<td>0.5 Hz</td>
<td>11 Mpulses 1 year</td>
</tr>
<tr>
<td><em>Super-Beam</em> (3.5 GeV)</td>
<td>300 kA</td>
<td>50 Hz</td>
<td>200 Mpulses 6 weeks</td>
</tr>
<tr>
<td><em>CNGS</em> (400 GeV)</td>
<td>150 kA</td>
<td>2 pulses/6 sec</td>
<td>42 Mpulses 4 year</td>
</tr>
</tbody>
</table>

*In operation*
- NuMi horn 1
- NuMi horn 2
- MiniBooNE
- KEK horn 1
- KEK horn 2

*CERN horn prototype for SPL*

*In operation*
- CNGS horn 1
- CNGS horn 2

*Completed*
- MiniBooNE
Horn prototype

- For the horn skin AA 6082-T6 / (AlMgSi1) is an acceptable compromise between the 4 main characteristics:
  - Mechanical properties
  - Welding abilities
  - Electrical properties
  - Resistance to corrosion
  - Same for CNGS

...but Al not compatible with Mercury!

- tests done with: 30 kA and 1 Hz, pulse 100 μs long
- new tests to be done with 50 Hz

Electrical and water connections
New ideas

use the advantage of the small horn size

protons

2.5 m

protons

protons

2.5 m

protons

2 options (only one pulser):
• send at the same time 1 MW per target/horn system
• send 4 MW/system every 50/4 Hz

possibility to use solid target?

minimize power dissipation and radiation problems (pulser problems remain as before)

same decay tunnel Ø 3 m

tunnel to be studied in EURONuν
New (crazy) ideas

**use a cryogenic horn (toroidal coil)**

- superconducting wire (1 mm Ø) in superfluid He,
- DC power supply
- blow gas He to avoid quenching problems

- No problem with power supply (pulser no more needed)
- Proton compressor no more needed

to be studied in EURONu
Conclusions

• LP-SPL already approved, HP-SPL possible before 2020.
• Many studies needed on targets.
• Collector studies are necessary to increase the system lifetime.
• Target/horn integration to be considered since the beginning.
• New studies have started in the framework of EUROν FP7 project.
• New ideas are welcome…
End
Comparisons

- CNGS combined
- Double CHOOZ
- Beta Beam Disappearance
- T2K
- BNL
- SPL 5y
- SPL 1y+4y
- SPL 2y+8y
- Beta Beam (5y+5y)

\[ \sin^2 \theta_{13} \]

\[ \delta_{CP} \text{ (deg.)} \]
CERN horn prototype

Protons

Hg Target

Cooling system

Current of 300 kA

To decay channel

$B = 0$

$B \propto \frac{1}{R}$

Initial design satisfying both, neutrino factory and super-beam
Decay Tunnel

Flux vs decay tunnel length

(2.2 GeV option)

- Decay tunnel length 60 m
- Decay tunnel length 20 m
- Decay tunnel length 100 m

short decay tunnel