Super Beam: conventional MW power neutrino beam

SPL (4-5 GeV, 4 MW) -> Accumulator ring

proton driver

Magnetic horn capture (collector)

Target

p (50 Hz)

hadrons

~300 MeV $\nu, \mu$ beam to far detector

SPL Super Beam

proton beam $p$

hadrons

target

hadron collector (focusing)

Decay tunnel

Decay tunnel

Detector

physics

15/05/2012

M. Dracos
SPL proton kinetic energy: ~4 GeV

Neutrino energy: ~300 MeV

\[ \Delta m_{\text{sun}}^2 = 7.7 \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m_{\text{atm}}^2 = 2.4 \times 10^{-3} \text{ eV}^2 \]
\[ \theta_{23} = 45^\circ \]
\[ \theta_{13} = 10^\circ \]
\[ \delta_{\text{CP}} = 0 \]
Combination of Super Beam with Beta Beam

**Beta Beam (γ~100)**
- $\nu_e \rightarrow \nu_\mu$ (β+)
- $(T)$
- $(CP)$

**Super Beam**
- $\nu_\mu \rightarrow \nu_e$ ($\pi^+$)
- $(CPT)$
- $(CP)$

- $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ (β−)
- $(T)$
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ($\pi^-$)

**Similar $\nu$ spectrum**

**Combination of CP and T violation tests**

**Bonus:** the unoscillated neutrinos of one facility can be used to well study the efficiencies of the other one

**2 beams**

**1 detector**
WP2 activities

- Beam simulation and optimization, physics sensitivities
- Beam/target interface
- Target and target station design
- Horn design
- Target/horn integration
- Cost
- Safety
The WP2 team

- Cracow University of Technology
- STFC RAL
- IPHC Strasbourg
- Irfu-SPP, CEA Saclay
- external partners

Technological Challenge

Can we conceive a neutrino beam based on a multi-MW proton beam?

Can we design a target for a multi-MW proton beam?

Can we do it with a reliable design without compromising the physics reach?

Target

- huge energy deposition (300-1000 J/cm³/pulse)
- Severe problems from: sudden heating, stress, activation
- Solid versus liquid targets
- cooling

Horn

- cooling
- vibrations
- pulser (up to 350 kA, 50 Hz)

Safety

Lifetime (supposed to run for 10 years)
Evolution of the system

**initial design**
- horn+reflector
- Hg target

- solid target
- 300 kA
- 600 kA
- 230 cm
- ~300-350 kA
- 112 cm

**final design**
- simpler optimized shape with reduced current!

15/05/2012  M. Dracos
How to mitigate the power effect

4 target/horn system (4x4 m²) with single decay tunnel (~25 m)

- send 4 MW/system every 50/4 Hz
- in case of failure of one horn/target, continue with the 3 remaining ones sharing the 4 MW power

solid targets able to afford up to ~1.5 MW proton beam

we get rid of Hg, but what about particle production?

more expensive but more reliable system
Comparison Mercury/Carbon

- Neutrino intensity is higher with graphite
- Neutrino contamination is lower
- High energy tail for graphite is more important

Neutrino production

Graphite target must be longer (76 cm, 2 interaction lengths)
The Bonus…

Released power:
- Hg: ~ 1 - 0.6 MW
- C: ~ 0.8 - 0.1 MW
- lower for graphite!

neutron flux dramatically reduced wrt Hg! (~ x15)
From Liquid to Solid Targets

Free mercury jet

Packed bed canister in symmetrical transverse flow configuration, titanium alloy spheres

Beryllium or Graphite cylinder
pencil like Beryllium target

15/05/2012 M. Dracos
Solid Target

Packed bed canister in symmetrical transverse flow configuration (titanium alloy spheres)

Helium Flow

Helium Velocity
Maximum flow velocity = 202 m/s
Maximum Mach Number < 0.2

Helium Gas Temperature
Total helium mass flow = 93 gr/s
Maximum Helium temperature = 584°C
Helium average outlet temperature = 109°C

First tests with beam in the new HiRadMat®SPS facility at CERN in 2014
Studies on horn

Horn displacement (max. 1.2 mm)

Cooling tubes

Strip lines

Eigen frequency studies

$ f = 144.2 \text{ Hz}$
4-Horn system

supporting structure

Displacement studies
T2K like installation
Radiation Studies

Vertical view
$P_{\text{tot}} = 3.4 \text{ MW}$

Beam dump
$780 \text{ kW}$

Graphite blocks, helium conduction across 2 mm gaps, $T_{\text{max}} = 575 ^\circ \text{C}$, tensile stress $< 1.56 \text{ MPa}$
Safety and Activation studies

around the target station after 200 running days (1 year)

- after 1 day
- after 1 week
- after 1 month
- after 6 months

15/05/2012
M. Dracos
Power Supply for horn pulsing
(Another challenge)

- 8 MODULES

- For each HORN:
  - Current of 350kA max at 12.5Hz
  - Energy recuperation (>90%) and reinjection
  - Lifetime > 13 Bcycles (10 years, 200 days/year)

- Each MODULE delivers a current of 44kA max at F=50Hz

M. Dracos
**4-proton lines**

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

**Configuration 3: K-D-Q-Q-Q-T**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>4-5 GeV</td>
</tr>
<tr>
<td>Beam Power</td>
<td>4 MW</td>
</tr>
<tr>
<td>Proton per pulse</td>
<td>1.1 x 10^{14}</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>3.2 μs</td>
</tr>
<tr>
<td>Beam shape</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Emittances rms</td>
<td>3π mm mrad**</td>
</tr>
<tr>
<td>Target length</td>
<td>78 cm</td>
</tr>
<tr>
<td>Target radius</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>Beam shape</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>12.5 Hz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>3.2 μs</td>
</tr>
<tr>
<td>Sigma</td>
<td>4 mm</td>
</tr>
</tbody>
</table>
Neutrino Spectra

- $\nu_\mu$ OFF
- $\bar{\nu}_\mu$ OFF
- $\nu_\mu$ ON
- $\bar{\nu}_\mu$ ON

horn on/off

$\nu_\mu$: $3.9\times10^{14}$ (98.0%)
$\bar{\nu}_\mu$: $6.3\times10^{12}$ (1.6%)
$\nu_e$: $1.7\times10^{12}$ (0.42%)
$\bar{\nu}_e$: $6\times10^{10}$ (0.015%)

$\nu_\mu$: $2.2\times10^{14}$ (95.3%)
$\bar{\nu}_\mu$: $1\times10^{13}$ (4.4%)
$\nu_e$: $6.4\times10^{11}$ (0.28%)
$\bar{\nu}_e$: $1.2\times10^{11}$ (0.05%)

15/05/2012
M. Dracos
Physics Performance

better results with the new horn geometry and target

very promising (baseline)

final design
Physics Performance

\[ \sin^2 2\theta_{13} = 0.1 \]

arXiv:1203.5651v1
Physics Performance

- SPL-1: CERN to Fréjus (130 km)
- SPL-2: CERN to Canfranc (650 km)

1 Mton WC detector (440 kton fiducial), 5% syst.

\[ \text{sgn } \Delta m^2 \]

arXiv:1110.4583
For $\sin^2 2\theta_{13} = 0.1$, it is quite likely that with ~Mt yr atm neutrino data from a WC detector we will determine the hierarchy (T. Schwetz)

\begin{tabular}{|l|c|c|c|}
\hline
 & \beta B & SPL & T2HK \\
\hline
Detector mass & 440 kt & 440 kt & 440 kt \\
Baseline & 130 km & 130 km & 295 km \\
Running time ($\nu + \bar{\nu}$) & 5 + 5 yr & 2 + 8 yr & 2 + 8 yr \\
Beam intensity & $5.8 \times 10^{18}$ He (Ne) dcys/yr & 4 MW & 4 MW \\
Systematics on signal & 2\% & 2\% & 2\% \\
Systematics on backgr. & 2\% & 2\% & 2\% \\
\hline
\end{tabular}

- solid line: LBL+atm.
- dashed line: LBL
HP-SPL Super Beam at CERN

near detector
After EUROν

• R&D is needed for:
  - target
  - horn
  - horn pulsing system

• When?
  - next relevant EU call (Horizon2020)?
Conclusions

• The SPL to Fréjus Super Beam project is under study in FP7 EUROnu WP2:
  – Conventional technology
  – Many synergies with other projects
  – Very competitive CP sensitivity

• Work in EUROv:
  – physics performance has been improved.
  – the proposed system is now feasible and reliable

• We have started freezing all elements of this facility.

• Cost estimation very soon.

• The physics potential of this project is very high (also for astrophysics) especially in case of SB/BB combination.

• R&D is needed.
End
### HP-SPL for Neutrino Beams

- CDR for 2.2 and 3.5 GeV HP-SPL already published (CERN 2000-012, CERN 2006-006)

#### Linac4 (160 MeV) vs SC-linac (4 MW, 5 GeV)

<table>
<thead>
<tr>
<th>Linac4 (160 MeV)</th>
<th>SC-linac (4 MW, 5 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁻ source</td>
<td>β=0.65</td>
</tr>
<tr>
<td>RFQ</td>
<td>β=1.0</td>
</tr>
<tr>
<td>chopper</td>
<td></td>
</tr>
<tr>
<td>DTL</td>
<td></td>
</tr>
<tr>
<td>CCDTL</td>
<td></td>
</tr>
<tr>
<td>PIMS</td>
<td></td>
</tr>
<tr>
<td>3 MeV</td>
<td>643 MeV</td>
</tr>
<tr>
<td>50 MeV</td>
<td>160 MeV</td>
</tr>
<tr>
<td>102 MeV</td>
<td>5 GeV</td>
</tr>
</tbody>
</table>

#### Operating Parameters

- **Linac4 (160 MeV)**
  - **3 MeV**
  - **50 MeV**
  - **102 MeV**
  - **160 MeV**
  - **643 MeV**
  - **5 GeV**

- **SC-linac (4 MW, 5 GeV)**
  - **β=0.65**
  - **β=1.0**

#### Frequency Bands

- **352.2 MHz**
- **704.4 MHz**

#### Linac4 & SC-linac

- **Linac4 (160 MeV)**
  - **H⁻ source**
  - **RFQ**
  - **chopper**
  - **DTL**
  - **CCDTL**
  - **PIMS**
  - **Linac**
  - **PIMS**

- **SC-linac (4 MW, 5 GeV)**
  - **β=0.65**
  - **β=1.0**

#### Acceleration Stages

- **Linac4 (160 MeV)**
  - **Linac 4**
  - **PS**
  - **ISOLD E**

- **SC-linac (4 MW, 5 GeV)**
  - **SPS**
  - **PS2**

#### Under Construction

- **Under construction**
  - (high power already foreseen)

#### 15/05/2012

M. Dracos

---

**Notes**

- **H⁻**
  - **linac 2 GeV, 4 MW**
  - **Accumulator ring**
  - **Magnetic horn capture**
  - **Decay tunnel**
  - **Target**

- **Fast ejection**
  - **RF (h=146)**
  - 3 empty buckets
  - **140 bunches**
  - **17.2 ms**

- **Fast injection**
  - **RF (h=146)**
  - **3.3 ns**
  - **3 empty buckets**

- **DRIFT SPACE**
  - **DEBUNCHER**
  - **457 m**
  - **53.2 ns**

- **PUFFER**
  - **1 ns rms**
  - **(on target)**

- **Target**
  - **H⁺**
  - **140 bunches**
  - **1.62 x 10¹² protons/bunch**
  - **l_r (rms) = 1 ns (on target)**

---

**Graph:**

- **PROTON ACCUMULATOR**
  - **T_{acc} = 3.316 μs**
  - (1168 periods @ 352.2 MHz)

- **BUNCH COMPRESSOR**
  - **T_{acc} = 3.316 μs**
  - (1168 periods @ 352.2 MHz)

- **Fast ejection**
  - **RF (h=146)**
  - **3 empty buckets**
  - **140 bunches**

- **Fast injection**
  - **RF (h=146)**
  - **3 empty buckets**
  - **140 bunches**

---

**Equations:**

- **E_{l,b} = 0.6 μm r.m.s**

**References:**

- **CDR for 2.2 and 3.5 GeV HP-SPL already published (CERN 2000-012, CERN 2006-006)**
The MEMPHYS Project
(within FP7 LAGUNA DS)

Mainly to study:

• **Proton Decay (GUT)**
  - up to \( \sim 10^{35} \) years lifetime

• **Neutrino properties and Astrophysics**
  - Supernovae (burst + "relics")
  - Solar neutrinos
  - Atmospheric neutrinos
  - Geoneutrinos
  - neutrinos from accelerators (Super Beam, Beta Beam)

**Water Cerenkov Detector with total fiducial mass: 440 kt:**
- 3 Cylindrical modules 65x65 m
- Readout: 3x81k 12” PMTs, 30% geom. cover.
  (#PEs =40% cov. with 20” PMTs).

(arXiv: hep-ex/0607026)
Physics Performance

\[ \sin^2 2\theta_{13} = 0.1 \]

Enrique Fernandez-Martinez

M. Dracos

P. Huber