SPL-based Proton Driver for ν Facilities at CERN: Updated Description

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SPL (beam in 2015 ?)

- relocation of Linac4, adding 366 m of SC RF,
- PS booster becomes obsolete,
- cavity power < 1 MW,
- TESLA/ILC type cryostats (INFN Milano) with 5-cell SC Nb cavities (CEA/INFN) and cold quadrupoles,
- layout and beam dynamics (CEA Saclay).
SPL layout (CDR-2)

1. AIR TUNNEL PULSION 10 X 3.4
2. SLAB FLOOR TANK HELIUM - 22.5 X 35 CONCRETE
3. POWER CONVERTERS - 54 40 X 35 X 4 CONCRETE - STEEL
4. CONTROL ROOM - 8X 10 X 10 CONCRETE - STEEL - GLASS
5. COOLING HEATING VENTILATION - SU 16 X 12 X 6
6. HELIUM COMPRESSOR - SH 30 X 65 X 56
7. COLD BOXES - BDH 25 X 40 X 12.5
8. AIR TUNNEL EXTRACTION 10 X 3 X 4
SPL beam dynamics (CDR-2)

Beam dynamics (CEA Saclay)

- Beam envelopes
- Output phase space
- Phase advance per metre
- Emittance evolution
# SPL beam characteristics

<table>
<thead>
<tr>
<th></th>
<th>CDR1 [2000]</th>
<th>CDR2 [2006]</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>2.2 GeV</td>
<td>3.5 GeV</td>
</tr>
<tr>
<td>average beam power</td>
<td>4 MW</td>
<td>4 MW</td>
</tr>
<tr>
<td>length</td>
<td>690 m</td>
<td>450 m</td>
</tr>
<tr>
<td>average RF power</td>
<td>24 MW</td>
<td>17.4 MW</td>
</tr>
<tr>
<td>average cryogenics power</td>
<td>9.6 MW</td>
<td>6.7 MW</td>
</tr>
<tr>
<td>repetition rate</td>
<td>50 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>beam pulse length</td>
<td>2.8 ms</td>
<td>0.57 ms</td>
</tr>
<tr>
<td>average pulse current*</td>
<td>13 mA</td>
<td>40 mA</td>
</tr>
<tr>
<td>peak current*</td>
<td>20.8 mA</td>
<td>64 mA</td>
</tr>
<tr>
<td>beam duty cycle</td>
<td>14 %</td>
<td>2.9 %</td>
</tr>
<tr>
<td>peak RF power</td>
<td>32 MW</td>
<td>163 MW</td>
</tr>
<tr>
<td>no. of 352.2 MHz klystrons (1 MW)</td>
<td>44</td>
<td>14</td>
</tr>
<tr>
<td>no. of 704.4 MHz klystrons (5 MW)</td>
<td>-</td>
<td>44</td>
</tr>
<tr>
<td>no. of tetrodes</td>
<td>79</td>
<td>3</td>
</tr>
<tr>
<td>cryo temperature</td>
<td>4.5 K</td>
<td>2 K</td>
</tr>
</tbody>
</table>

* after chopping
For $\nu$ physics, the time structure of the linac beam has to be changed:

- for a **beta-beam based facility**
  - $200$ kW beam @ 1-5 GeV
  - + super-beam [4 MW @ 3.5 GeV]
  - Long beam burst (~ms)
    $\Rightarrow$ direct use of linac beam

- for a **$\nu$ factory** [4 MW beam @ 4-10 GeV]
  - Short beam burst (~$\mu$s)
    $\Rightarrow$ accumulator
  - + Short bunches (~ns)
    $\Rightarrow$ compressor

The requirements of a $\nu$ factory are the most demanding.
### Parameters required by a $\nu$ factory*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power ($P$)</td>
<td>$\sim 4$ MW</td>
</tr>
<tr>
<td>Kinetic energy ($T$)</td>
<td>$4 – 10$ GeV</td>
</tr>
<tr>
<td>Bunch length</td>
<td>1-3 ns rms</td>
</tr>
<tr>
<td>Distance between bunches ???</td>
<td>$\geq 100$ ns</td>
</tr>
<tr>
<td>Burst length</td>
<td>1-3 $\mu$s</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$\leq 50$ Hz</td>
</tr>
</tbody>
</table>

* Partial understanding…
### Scenarios for accumulation & compression (3/7)

**Consequences for a linac-based driver**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy ((T))</td>
<td>Cost increases with (T) (\Rightarrow) Minimize (T) ((&lt; 4 – 8 , \text{GeV}))</td>
</tr>
<tr>
<td>Repetition rate ((f_{\text{rep}}))</td>
<td>Constant beam power imposes the number of protons/pulse (N_p)</td>
</tr>
<tr>
<td>Bunch length ((l_b))</td>
<td>Energy acceptance + longitudinal space charge restrict to low longitudinal emittance (\Rightarrow) minimum number of bunches ((N_b))</td>
</tr>
<tr>
<td>Distance between bunches ((d_b))</td>
<td>Accumulator circumference (C) is proportional to (N_b \times d_b) &amp; Laslett tune shift (\Delta Q) is proportional to (C) (\Rightarrow) minimize (d_b) to minimize (\Delta Q) &amp; cost</td>
</tr>
<tr>
<td>Burst length</td>
<td>Constraints the highest value of (C)</td>
</tr>
</tbody>
</table>
Scenarios for accumulation & compression (4/7)

With SPL CDR1 (2000): severe constraint due to the low beam energy

- **T** = 2.2 GeV
- **f_{rep}** = 50 Hz
- **N_{p}** = $2.27 \times 10^{14}$
- **I_{b}** = 1 ns
- **N_{b}** = 140
- **d_{b}** = 22.7 ns
- **C** = 3.316 µs

PROTON ACCUMULATOR
- $T_{RR}$ = 3.316 µs (1168 periods @ 352.2 MHz)
- Charge exchange injection
- 22.7 ns

BUNCH COMPRESSOR
- $T_{RR}$ = 3.316 µs (1168 periods @ 352.2 MHz)
- Fast injection (1 turn)
- 20 ms

**T**
- 2.2 GeV

**f_{rep}**
- 50 Hz

**N_{p}**
- $2.27 \times 10^{14}$

**I_{b}**
- 1 ns

**N_{b}**
- 140

**d_{b}**
- 22.7 ns

**C**
- 3.316 µs
**Scenarios for accumulation & compression (5/7)**

With SPL CDR2 (2006): higher beam energy => less constraints

First approach…

<table>
<thead>
<tr>
<th><strong>Kinetic energy (T)</strong></th>
<th>3.5 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Repetition rate (f_{rep})</strong></td>
<td>50 Hz (\Rightarrow N_p = 1.43 \times 10^{14} \text{ p/p} )</td>
</tr>
<tr>
<td><strong>Bunch length (l_b)</strong></td>
<td>For the same (\Delta p/p) acceptance + because of lower (N_p) + relaxing on (l_b) (2 ns instead of 1 ns) (\Rightarrow N_b \text{ (goal)} = 17) [8.41 \times 10^{12} \text{ p/b}]</td>
</tr>
<tr>
<td><strong>Distance between bunches (d_b)</strong></td>
<td>(d_b \text{ (goal)} = 90.86 \text{ ns}) (C \text{ (goal)} = 1.635 \mu\text{s})</td>
</tr>
</tbody>
</table>

Feasibility in the accumulator/compressor has been pre-checked
With a linac-based driver there is the possibility to do multiple accumulations with a single linac beam pulse, and therefore generate multiple bursts of beam onto the target.

This is of interest if:
- all parameters are constant in the $\mu$ channel during the whole duration of the proton beam on the target (transverse focusing, gradient in the RF cavities…). It is not unreasonable to hope for $\sim 1$ ms.
- the $\mu$ storage ring is long enough to contain all the successive bursts.

The main disadvantage is that the kickers must provide multiple kicks within $\sim 1$ ms.

This makes it possible to tailor the intensity per burst / the distance between bunches / the main cycling rate of whole facility…
Scenarios for accumulation & compression (7/7)

With SPL CDR2 (2006): other approach using multi-pulsing

<table>
<thead>
<tr>
<th></th>
<th>&gt; 3.5 GeV</th>
<th>3.5 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy (T)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repetition rate ($f_{rep}$)</td>
<td>6 bunches at 50 Hz</td>
<td>12 bunches at 25 Hz</td>
</tr>
<tr>
<td>Number of protons/bunch</td>
<td>$2.4 \times 10^{13}$ p/p</td>
<td>$2.4 \times 10^{13}$ p/p</td>
</tr>
<tr>
<td>Time interval between bunches</td>
<td>$95 , \mu s$</td>
<td>$95 , \mu s$</td>
</tr>
<tr>
<td>Total burst duration</td>
<td>$475 , \mu s$</td>
<td>$1.045 , ms$</td>
</tr>
<tr>
<td>Bunch length ($l_b$)</td>
<td>~ 3 ns ?</td>
<td>~ 3 ns ?</td>
</tr>
</tbody>
</table>

Fill & eject 6 times single bunches from an accumulator/compressor of 272 ns revolution period

Fill & eject 12 times single bunches from an accumulator/compressor of 272 ns revolution period

Many open questions to be studied …
Conclusions & outlook

The new SPL design (CDR2 – 2006) is largely improved:

• energy (3.5 GeV) is a compromise that can potentially satisfy EURISOL, neutrino applications, and LHC upgrade scenarios,
• design is more optimum (length reduced by 35% while the energy is increased by 60%, higher instantaneous current reducing the number of turns for accumulation in the ring…)
• upgrades are possible in terms of energy and/or power.

This typically illustrates the potential of a linac-based proton driver for a ν factory, which can be the basis of a high energy accelerator complex [→] and has a remarkable flexibility to adapt to the requirements of the following part of the facility.
ANNEX
Evolution of the CERN accelerator complex

- **Linac2**: 50 MeV, 160 MeV
- **PSB**: 1.4 GeV, ~5 GeV
- **PS**: 26 GeV, 40 – 60 GeV
- **SPL’**: 450 GeV
- **SPL**: ~1 TeV, ~14 TeV
- **Linac4**: 1.4 GeV
- **SPS**: 26 GeV, 40 – 60 GeV
- **PS2 (PS2+)**: 450 GeV
- **SPS+**: 1 TeV, ~14 TeV
- **LHC**: 7 TeV
- **DLHC**: “Double energy” LHC

**Output energy**
- 50 MeV
- 160 MeV
- 1.4 GeV
- ~5 GeV
- 26 GeV
- 40 – 60 GeV
- 450 GeV
- 1 TeV
- ~14 TeV

**Proton flux / Beam power**

**Devices**
- SPL: Superconducting Proton Linac (~ 5 GeV)
- SPL’: RCPSB injector (0.16 to 0.4-1 GeV)
- RCPSB: Rapid Cycling PSB (0.4-1 to ~5 GeV)
- PS2: High Energy PS (~5 to 50 GeV – 0.3 Hz)
- PS2+: Superconducting PS (~5 to 50 GeV – 0.3 Hz)
- SPS+: Superconducting SPS (50 to 1000 GeV)
- DLHC: “Double energy” LHC (1 to ~14 TeV)

R. Garoby (for the SPL study group) SPL-based Proton Driver for q Facilities ISS meeting, 25-28.04.06
## Scenarios for the proton accelerator complex

- **Stages of implementation**

<table>
<thead>
<tr>
<th>STAGE</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
</table>
| **DESCRIPTION**  
(_new accelerator_) | Linac4  
PSB  
PS  
SPS | Linac4  
PSB  
PS2 or PS2+  
(& PS)  
SPS | Linac4  
SPL  
PS2 or PS2+  
SPS | Linac4  
SPL  
PS2 or PS2+  
SPS+ |
| Performance of LHC injectors (SLHC) | ++ Ultimate beam from PS | ++ Ultimate beam from SPS | ++ Maximum SPS performance | +++ Highest performance LHC injector |
| Higher energy LHC | - | - | - | +++ |
| β beam | - | - | ++ (γ ~100) | ++ (γ ~200) |
| ν Factory | - | - | +++ (~5 GeV prod. beam) | +++ (~5 GeV prod. beam) |
| k, μ | - | ~150 kW beam at 50 GeV | ~200 kW beam at 50 GeV | ~200 kW beam at 50 GeV |
| EURISOL | - | - | +++ | +++ |
### Exotic scenarios for accumulation & compression

With SPL CDR2 (2006): other approach using multi-pulsing

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<td>(~ 2) ns</td>
<td>~ 2 ns</td>
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**Main issue:** The distance between bunches imposes a quantum \(\Delta f\) in the μ capture & bunch rotation channel. How much is acceptable? 10 MHz?