Protons Drivers for ν Beams and other High Intensity Applications

R. Garoby

[using material from:
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- K. Gollwitzer, S. Nagaitsev (FNAL)
- J. Thomason (ISIS)
- M. Aiba, E. Benedetto, M. Benedikt, I. Efthymiopoulos, R. Steerenberg (CERN) ]
Introduction

• This talk will focus on the favoured proton drivers options for the generation of neutrino beams at FNAL, RAL, CERN and J-PARC.

• HPPAs for other applications at other places are not treated (e.g.: neutron spallation sources, ADS for waste treatment and/or nuclear power generation, medical isotope production etc...).

• «Green field» solutions are not covered.
• A proton driver:
  • is necessary for (almost) all types of neutrino facilities,
  • can be used (and present ones have been built) for other purposes.

• A Neutrino Factory is the most demanding application*, although the proton driver remains a modest part of the whole facility.

• Two types of set-ups are favoured:
  • Ring-based
  • SRF linac-based.

* IDS NF specifications:
  - 4 MW proton beam power
  - Proton kinetic energy 5 – 15 GeV
  - RMS bunch length 1 – 3 ns
  - 50 Hz repetition rate
  - 3 bunches, extracted > 80 µs apart
Status and plans at:

- FermiLab
- RAL
- CERN
- J-PARC
Project X: Mission Goals

- A neutrino beam for long baseline neutrino oscillation experiments
  - 2 MW proton source at 60-120 GeV

- High intensity, low energy protons for kaon and muon based precision experiments
  - Operations simultaneous with the neutrino program

- A path toward a muon source for possible future Neutrino Factory and/or a Muon Collider
  - Requires ~4 MW at ~5-15 GeV.

- Possible missions beyond HEP
  - Standard Model Tests with nuclei and energy applications
Project X: Reference Design Capabilities

- 3 GeV CW superconducting H-linac with 1 mA average beam current.
  - Flexible provision for variable beam structures to multiple users
    - CW at time scales >1 μsec, 15% DF at <1 μsec
  - Supports rare processes programs at 3 GeV
  - Provision for 1 GeV extraction for nuclear energy program

- 3-8 GeV pulsed linac capable of delivering 300 kW at 8 GeV
  - Supports the neutrino program
  - Establishes a path toward a muon based facility

- Upgrades to the Recycler and Main Injector to provide ≥ 2 MW to the neutrino production target at 60-120 GeV.

- Day one experiment to be incorporated utilizing the CW linac

⇒ Utilization of a CW linac creates a facility that is unique in the world, with performance that cannot be matched in a synchrotron-based facility.
Project X: Provisional Siting

**PHASE 1**
- BELOW GRADE STRUCTURES
  1. 3 GeV Continuous Wave (CW) Linac
  2. Experimental Area Switchyard
  3. Linac Beam Dump Endurance

**ABOVE GRADE STRUCTURES**
- 4. Uptown Service Building
- 5. Linac Gallery
- 6. Typical Linac Service Building
- 7. Cryogenic Service Building
- 8. Center Service Building

**PHASE 2 (Future)**
- BELOW GRADE STRUCTURES
  9. 3-8 GeV Pulsed Linac
  10. Proton Transport Line Enclosure

**ABOVE GRADE STRUCTURES**
- 11. Klystron Gallery
- 12. Linac Service Building
- 13. Linac Beam Absorber
- 14. Momentum Beam Absorber
- 15. Debuncher Service Building
- 16. Experimental Halls

Pulsed Linac

CW Linac

Pulsed 3-8 GeV Linac based on ILC / XFEL technology
Project X: Reference Design Accelerators

- Warm cw front end 162.5 MHz, 5 mA (H- ion source, RFQ, MEBT, chopper)
- 3-GeV cw SCRF linac (325, 650 MHz), 1-mA ave. beam current
- Transverse beam splitter for 3-GeV experiments
- 3-8 GeV: pulsed linac (5% duty cycle), 1.3 GHz
- Recycler and MI upgrades
- Various beam transport lines
**Project X: Superconducting RF H- Linacs**

<table>
<thead>
<tr>
<th>Section</th>
<th>Freq</th>
<th>Energy (MeV)</th>
<th>Cav/mag/CM</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSR0 ($\beta_G=0.11$)</td>
<td>325</td>
<td>2.5-10</td>
<td>18/18/1</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR1 ($\beta_G=0.22$)</td>
<td>325</td>
<td>10-42</td>
<td>20/20/2</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR2 ($\beta_G=0.4$)</td>
<td>325</td>
<td>42-160</td>
<td>40/20/4</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>LB 650 ($\beta_G=0.61$)</td>
<td>650</td>
<td>160-460</td>
<td>36/24/6</td>
<td>5-cell elliptical, doublet</td>
</tr>
<tr>
<td>HB 650 ($\beta_G=0.9$)</td>
<td>650</td>
<td>460-3000</td>
<td>160/40/20</td>
<td>5-cell elliptical, doublet</td>
</tr>
<tr>
<td>ILC 1.3 ($\beta_G=1.0$)</td>
<td>1300</td>
<td>3000-8000</td>
<td>224/28/28</td>
<td>9-cell elliptical, quad</td>
</tr>
</tbody>
</table>

- CW: Continuous Wave
- Pulsed
FNAL plans (6/10)

Project X: SRF cavities development

Spoke cavities

SSR0 – design, prototyping
SSR1 – prototyping, testing
SSR2 – design

Parameters of the single-spoke cavities

<table>
<thead>
<tr>
<th>cavity type</th>
<th>$\beta_G$</th>
<th>Freq MHz</th>
<th>$U_{\text{acc, max}}$ MeV</th>
<th>$E_{\text{max}}$ MV/m</th>
<th>$B_{\text{max}}$ mT</th>
<th>R/Q, $\Omega$</th>
<th>$G$, $\Omega$</th>
<th>$*Q_{0.2K} \times 10^9$</th>
<th>$P_{\text{max,2K}}$ W</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSR0</td>
<td>$\beta=0.114$</td>
<td>325</td>
<td>0.6</td>
<td>32</td>
<td>39</td>
<td>108</td>
<td>50</td>
<td>6.5</td>
<td>0.5</td>
</tr>
<tr>
<td>SSR1</td>
<td>$\beta=0.215$</td>
<td>325</td>
<td>1.47</td>
<td>28</td>
<td>43</td>
<td>242</td>
<td>84</td>
<td>11.0</td>
<td>0.8</td>
</tr>
<tr>
<td>SSR2</td>
<td>$\beta=0.42$</td>
<td>325</td>
<td>3.34</td>
<td>32</td>
<td>60</td>
<td>292</td>
<td>109</td>
<td>13.0</td>
<td>2.9</td>
</tr>
</tbody>
</table>

650 MHz cavities

650 MHz: $\beta=0.61$

650 MHz: $\beta=0.9$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LE650</th>
<th>HE650</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{\text{geom}}$</td>
<td>0.61</td>
<td>0.9</td>
</tr>
<tr>
<td>R/Q</td>
<td>Ohm</td>
<td>378</td>
</tr>
<tr>
<td>G-factor, Ohm</td>
<td>191</td>
<td>255</td>
</tr>
<tr>
<td>Max. Gain/cavity (on crest)</td>
<td>MeV</td>
<td>11.7</td>
</tr>
<tr>
<td>Acc. Gradient</td>
<td>MV/m</td>
<td>16.6</td>
</tr>
<tr>
<td>Max surf. electric field</td>
<td>MV/m</td>
<td>37.5</td>
</tr>
<tr>
<td>Max surf. magnetic field</td>
<td>mT</td>
<td>70</td>
</tr>
<tr>
<td>$Q_0$ @ 2° K</td>
<td>$\times 10^{10}$</td>
<td>1.5</td>
</tr>
<tr>
<td>$P_{2K,\text{max}}$</td>
<td>[W]</td>
<td>24</td>
</tr>
</tbody>
</table>
FNAL plans (7/10)

Project X upgrade (MC / NF): draft layout

4MW Target → Accumulator Ring

Compressor Ring

3-8 GeV Pulsed Linac

H- Source → 3 GeV, 100 mA CW Linac

Recycler / Main Injector 120 GeV

Neutrinos 2 MW

0.75 MW
Nuclear

1.5 MW
Kaons

0.75 MW
Muons
FNAL plans (8/10)

Project X upgrade (MC / NF): actions’ list

- Upgrade Project X
  - 4 MW at 8 GeV
    - Increase particles per linac bunch
    - Increase pulse linac duty factor
  - Increase beam current during the 8 GeV pulse to 5 mA (10 mA_{peak});
  - Increase rep. rate to 15 Hz;
  - Increase beam pulse length to 6.7 ms (10% duty cycle).

- Repackage linac beam for 12-15 Hz delivery
  - Accumulator Ring
    - Collect linac beam into bunches
  - Compressor Ring
    - Narrow bunches to <= 3 ns
  - Delivery as a single bunch (trombone system)
    - Multiple bunches arrive at target at same time
Project X upgrade: Combining bunches on target

Muon Collider Proton Driver Trombone Schematic
(not to scale; bunches arrive simultaneously on target)

Each beam line provides different trajectory to target
Project X upgrade: Main subjects of concern (!)

– Accumulator Ring
  • Striping
  • Instabilities

– Compressor Ring
  • Bunch Rotation
  • Dipole aperture and large momentum spread

– Delivery
  • Trombone
  • Beam sizes and angles at target
Status and plans at:

• FermiLab
• **RAL**
• CERN
• J-PARC
• Assumes an optimised 2RF system giving 300 µA in the synchrotron
• 4/5 pulse pairs to TS-1 (192 kW) and 1/5 pulse pairs to TS-2 (48 kW)
• Must keep beam to TS-2 for the foreseeable future
Further developments of the ISIS accelerator and target stations are possible with each stage giving of order a factor 2 enhancement of the neutron source characteristics.

0) Linac and TS1 refurbishment

1) Linac upgrade leading to ~0.5 MW operations on TS1

2) ~3.3 GeV booster synchrotron: MW Target

3) 800 MeV direct injections to booster synchrotron: 2 – 5 MW Target

4) 800 MeV direct injections to booster synchrotron
   + long pulse mode option

overlap with NF proton driver
1) Replace ISIS linac with a new ~180 MeV linac (~0.5MW)

2) Based on a ~3.3 GeV RCS fed by bucket-to-bucket transfer from ISIS 800 MeV synchrotron (1MW, perhaps more)

3) RCS design also accommodates multi-turn charge exchange injection to facilitate a further upgrade path where the RCS is fed directly from an 800 MeV linac (2 – 5 MW)
ISIS plans (4/9)

ISIS MW upgrade: «typical» 3.2 GeV RCS

Main RCS characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>0.8 – 3.2 GeV</td>
</tr>
<tr>
<td>Rep Rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>$C, R/R_0$</td>
<td>367.6 m, 9/4</td>
</tr>
<tr>
<td>Gamma-T</td>
<td>7.2</td>
</tr>
<tr>
<td>$h$</td>
<td>9</td>
</tr>
<tr>
<td>$f_{rf}$ sweep</td>
<td>6.1-7.1 MHz</td>
</tr>
<tr>
<td>Peak $V_{rf}$</td>
<td>~ 750 kV</td>
</tr>
<tr>
<td>Peak $K_{sc}$</td>
<td>~ 0.1</td>
</tr>
<tr>
<td>$\varepsilon_l$ per bunch</td>
<td>~ 1.5 eV s</td>
</tr>
<tr>
<td>$B[t]$</td>
<td>sinusoidal</td>
</tr>
</tbody>
</table>
### ISIS MW upgrade: 800 MeV linac

#### Main characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power for 2 MW, 30 Hz, 3.2 GeV RCS</td>
<td>0.5 MW</td>
</tr>
<tr>
<td>Beam pulse current before MEBT chopping</td>
<td>43.0 mA</td>
</tr>
<tr>
<td>Beam pulse current after MEBT chopping</td>
<td>30.0 mA</td>
</tr>
<tr>
<td>Number of injected turns for 370 m RCS</td>
<td>~500 turns</td>
</tr>
<tr>
<td>Beam pulse duration at the 30 Hz rep rate</td>
<td>~730.0 μs</td>
</tr>
<tr>
<td>Duty cycle for the extent of the beam pulse</td>
<td>~2.2 %</td>
</tr>
<tr>
<td>MEBT(out) normalised rms emittances</td>
<td>0.30, 0.42 (π) mm mr</td>
</tr>
</tbody>
</table>

#### Draft architecture

*74.8 MeV stage 1 (common to all options)*

![Draft architecture diagram](https://example.com/diagram.png)

<table>
<thead>
<tr>
<th>Options*</th>
<th>F (MHz)</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>648</td>
<td>ScL 1</td>
<td>ScL 2</td>
<td>ScL 3</td>
</tr>
<tr>
<td>2</td>
<td>648</td>
<td>CCL</td>
<td>ScL 2</td>
<td>ScL 3</td>
</tr>
<tr>
<td>3</td>
<td>(324) 972</td>
<td>(ScL a)</td>
<td>ScL b</td>
<td>ScL c</td>
</tr>
</tbody>
</table>

~200 MeV 800 MeV
ISIS plans (6/9)

ISIS Common Proton Driver for neutrons and NF

- Based on MW ISIS upgrade with 800 MeV Linac and 3.2 (~3.3) GeV RCS
- Assumes a sharing of the beam power at 3.2 GeV between the two facilities
- Both facilities can have the same ion source, RFQ, chopper, linac, H⁻ injection, accumulation and acceleration to 3.2 GeV
- Requires additional RCS machine in order to meet the power and energy needs of the Neutrino Factory
**ISIS plans (7/9)**

**ISIS Common Proton Driver: RCS beam sharing**

- Bunches will be transferred from the booster RCS at $\sim 3.2$ GeV, 50 Hz

Assume 4 – 5 MW from booster RCS, and 4 MW required from NF proton driver:

- **5 MW**
  - 3 bunches, $3.9 \times 10^{13}$ protons/bunch, 4.3 GeV
    - 2 MW to ISIS
  - 2 bunches, $3.9 \times 10^{13}$ protons/bunch, 6.4 GeV
    - 3 MW to ISIS
  - 3 bunches, $2.2 \times 10^{13}$ protons/bunch, 7.7 GeV
    - $3\frac{1}{3}$ MW to ISIS

- **4 MW**
  - 3 bunches, $1.76 \times 10^{13}$ protons/bunch, 9.6 GeV
    - $2\frac{2}{3}$ MW to ISIS
Parameters of 3.2 – 9.6 GeV RCS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of superperiods</td>
<td>6</td>
</tr>
<tr>
<td>Circumference</td>
<td>694.352 m</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>17</td>
</tr>
<tr>
<td>RF frequency</td>
<td>7.149 – 7.311 MHz</td>
</tr>
<tr>
<td>Betatron tunes ((Q_H, Q_V))</td>
<td>(8.72, 7.82)</td>
</tr>
<tr>
<td>Gamma transition</td>
<td>13.37 (flexible)</td>
</tr>
<tr>
<td>Beam power at 9.6 GeV</td>
<td>4 MW for 3 bunches</td>
</tr>
<tr>
<td>Injection energy</td>
<td>3.2 GeV</td>
</tr>
<tr>
<td>Extraction energy</td>
<td>9.6 GeV</td>
</tr>
<tr>
<td>RF voltage per turn</td>
<td>(\approx 3.7) MW</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Max B field in dipoles</td>
<td>1.2 T</td>
</tr>
<tr>
<td>Length of long drift</td>
<td>14 m</td>
</tr>
</tbody>
</table>

- Present-day, cost-effective RCS technology
- Only three quadrupole families
- Allows a flexible choice of gamma transition
ISIS MW Proton Driver: Necessary R & D

To realise ISIS MW upgrades, NF and generic high power proton driver development, common hardware R&D will be necessary in key areas:

- High power front end (FETS)
- RF Systems
- Stripping Foils
- Diagnostics
- Targets
- Kickers
- etc.

- In the neutron factory context SNS and J-PARC are currently dealing with many of these issues during facility commissioning and we have a watching brief for all of these
- Active programmes in some specific areas
Status and plans at:

- FermiLab
- RAL
- CERN
- J-PARC
CERN plans (1/11)

Current PS-based Proton Driver

[from EDMS Document No. 1108369 rev 1.1]

Draft layout

Short baseline experiment

Proton beam characteristics

<table>
<thead>
<tr>
<th></th>
<th>Old neutrino facility</th>
<th>New neutrino facility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PS dedicated</td>
<td>PS parallel</td>
</tr>
<tr>
<td>Proton Momentum</td>
<td>19.2 GeV/c</td>
<td>19.2 GeV/c</td>
</tr>
<tr>
<td>Protons/pulse</td>
<td>1.25x10^{13}</td>
<td>1.2x10^{13}</td>
</tr>
<tr>
<td>Max. rep. rate</td>
<td>1.2 s</td>
<td>14.4 s</td>
</tr>
<tr>
<td>Beam energy</td>
<td>38 kJ</td>
<td>38 kJ</td>
</tr>
<tr>
<td>Average beam power</td>
<td>32 kW</td>
<td>2.5 kW</td>
</tr>
</tbody>
</table>

Figure 1.3: The foreseen neutrino beam path (red) on the Meyrin site. The green lines represent the primary protons beam in the PS, TT2, TT1 and TT7.
CERN plans (2/11)

**SPS-based Proton Driver**

e.g. LAGUNA-LBNO DS (EU-FP7)

Long baseline experiment (2300 km)  
CERN-Pyhasalmi (Finland)

<table>
<thead>
<tr>
<th></th>
<th>SPS cycle length</th>
<th>6 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Energy</td>
<td>14 GeV</td>
<td></td>
</tr>
<tr>
<td>Beam sharing</td>
<td>0.45</td>
<td>0.85</td>
</tr>
<tr>
<td>Max SPS intensity @ 400GeV [x10^{13}]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Present injectors + machines’ improvement</td>
<td>4.8</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>5.9</td>
</tr>
</tbody>
</table>

1.3 x nominal CNGS performance
CERN plans (3/11)

New High Power PS-based Proton Driver

- New High Power PS (30-50 GeV, 2MW beam power) using the Low Power SPL (LP-SPL) as injector.
- Future Feasibility Study based on the work for LP-SPL and PS2 to be supported within the LAGUNA-LBNO DS (EU-FP7)

Long baseline experiment (2300 km)
CERN-Pyhasalmi (Finland)
CERN plans (4/11)

Reminder: PS2 main parameters...

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>PS2</th>
<th>PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy kinetic</td>
<td>GeV</td>
<td>4.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Extraction energy kinetic</td>
<td>GeV</td>
<td>20 - 50</td>
<td>13 - 25</td>
</tr>
<tr>
<td>Circumference</td>
<td>m</td>
<td>1346</td>
<td>628</td>
</tr>
<tr>
<td>Max. bunch intensity LHC (25ns)</td>
<td>ppb</td>
<td>$4.0 \times 10^{11}$</td>
<td>$1.7 \times 10^{11}$</td>
</tr>
<tr>
<td>Max. pulse intensity LHC (25ns)</td>
<td>ppp</td>
<td>$6.7 \times 10^{13}$</td>
<td>$1.2 \times 10^{13}$</td>
</tr>
<tr>
<td>Max. pulse intensity FT</td>
<td>ppp</td>
<td>$1.0 \times 10^{14}$</td>
<td>$3.3 \times 10^{13}$</td>
</tr>
<tr>
<td>Linear ramp rate</td>
<td>T/s</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Repetition time (50 GeV)</td>
<td>s</td>
<td>~ 2.5</td>
<td>1.2/2.4</td>
</tr>
<tr>
<td>Max. stored energy</td>
<td>kJ</td>
<td>800</td>
<td>70</td>
</tr>
<tr>
<td>Max. effective beam power</td>
<td>kW</td>
<td>320</td>
<td>60</td>
</tr>
</tbody>
</table>
CERN plans (5/11)

Reminder: PS2 integration...

- “Straight” H⁻ inj. line SPL → PS2 avoiding large bending radii to minimise Lorentz stripping of H⁻.
- Minimum length of inj. line TT10 → PS2 for ions and protons from PS complex.
- Minimum length HE line PS2 → SPS.
CERN plans (6/11)

SPL-based NF proton driver: Principle

- Accumulation of beam from the High Power SPL in a fixed energy Accumulator (5 GeV, 4MW beam power).
- Bunch compression («rotation») in a separate Compressor ring

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### Accumulator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>circumference</td>
<td>185.8 m</td>
</tr>
<tr>
<td>no. of accumulation turn</td>
<td>640 / 1920</td>
</tr>
<tr>
<td>transition gamma</td>
<td>6.33 (isochronous)</td>
</tr>
<tr>
<td>no. of simultaneous bunches</td>
<td>3 / 1</td>
</tr>
</tbody>
</table>

### Compressor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>circumference</td>
<td>200 m</td>
</tr>
<tr>
<td>rf voltage</td>
<td>1.7 MV</td>
</tr>
<tr>
<td>no. of compression turn</td>
<td>86</td>
</tr>
<tr>
<td>transition gamma</td>
<td>2.84</td>
</tr>
<tr>
<td>no. of simultaneous bunches</td>
<td>2 / 1</td>
</tr>
</tbody>
</table>

### Beam on target

- bunch spacing: 30 μs / -
- burst duration: 60 μs / -
- bunch length: 2 ns
- beam energy: 5 GeV
- beam power: 4 MW
- repetition: 50 Hz

---

Accumulation

- Duration: 400 μs
- SPL beam: [35 ± 7 bunches, 38 ± 7 gaps]
- Accumulator: [-100 ns pulses ~110 ns gaps]

Compressor

- Target: [2 ns bunches ~ 3 times]

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# CERN plans (7/11)

## HP-SPL: main characteristics

<table>
<thead>
<tr>
<th>Ion species</th>
<th>H⁻</th>
<th>Required for low loss in accumulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Energy</td>
<td>5 GeV</td>
<td>Required for muon production</td>
</tr>
<tr>
<td>Bunch Frequency</td>
<td>352.2 MHz</td>
<td>Required for flexibility and low loss in accumulator</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>50 Hz</td>
<td></td>
</tr>
<tr>
<td>High speed chopper (rise &amp; fall times)</td>
<td>&lt; 2 ns</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>2.5 or 5</td>
<td>2.5 and 5</td>
</tr>
<tr>
<td>Beam power (MW)</td>
<td>2.25 MW (2.5 GeV) &lt;br&gt;or &lt;br&gt;4.5 MW (5 GeV)</td>
<td>5 MW (2.5 GeV) &lt;br&gt;and &lt;br&gt;4 MW (5 GeV)</td>
</tr>
<tr>
<td>Protons/pulse (x 10^{14})</td>
<td>1.1</td>
<td>2 (2.5 GeV) + 1 (5 GeV)</td>
</tr>
<tr>
<td>Av. Pulse current (mA)</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Pulse duration (ms)</td>
<td>0.9</td>
<td>1 (2.5 GeV) + 0.4 (5 GeV)</td>
</tr>
</tbody>
</table>

2 × beam current \(\Rightarrow\) 2 × nb. of klystrons etc.
CERN plans (8/11)

**HP-SPL: block diagram**

Segmented cryogenics / separate cryo-line / room temperature quadrupoles:
- Medium $\beta$ (0.65) – 3 cavities / cryomodule
- High $\beta$ (1) – 8 cavities / cryomodule

Low energy
Intermediate energy
High energy
CERN plans (9/11)

HP-SPL: R & D objective

Design, construction and test of a string of 4 $\beta=1$ cavities equipped with main couplers $\&$ tuners inside a “short” prototype cryo-module before the end of 2014 tested in 2014.
CERN plans (10/11)

HP-SPL: Cavity § cryomodule design

SPL $\beta = 1$ cavity + helium tank + tuner + main coupler
CERN plans (11/11)

Summary of supporting activities

- **Current PS-based Proton Driver:**
  - Needs extensive investigation of impact on infrastructure (~on-going)
  - Requires more resources if current PS beam performance is insufficient (closely linked to the LHC Injectors Upgrade Project)

- **SPS-based Proton Driver:**
  - Study of beam ejection/Xfer line/target/decay tunnel foreseen within LAGUNA-LBNO DS
  - LAGUNA-LBNO DS expected to support investigation of SPS potential for higher intensity/flux (closely linked to the LHC Injectors Upgrade Project)

- **New High Power PS (with LP-SPL as injector):**
  - Conceptual Design Study foreseen within LAGUNA-LBNO DS

- **SPL-based Proton Drivers (LP-SPL as well as HP-SPL):**
  - Approved R § D on main SRF components, in collaboration with ESS and a number of EU laboratories/institutions, with some support from Brussels
  - Study of ring(s) foreseen within LAGUNA-LBNO DS
Status and plans at:

- FermiLab
- RAL
- CERN
- J-PARC
- Start of beam commissioning: December 2011.
- User program: 50 days of beam time until the end of March 2012.

---

**J-PARC plans (1/4)**

**Earthquake recovery schedule**

<table>
<thead>
<tr>
<th>Year</th>
<th>2011</th>
<th>2012</th>
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<tbody>
<tr>
<td>4</td>
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<tr>
<td>11</td>
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<tr>
<td>12</td>
<td>Beam Test</td>
<td>User Operation Start</td>
</tr>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
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<tr>
<td>3</td>
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</tr>
</tbody>
</table>

### Infrastructure
- Emergency Recovery → Full Recovery Work

### Linac
- Investigation → Recovery
- Alignment

### RCS
- 3GeV synchrotron
- Investigation → Recovery
- Cooling Water

### MR
- 50GeV synchrotron
- Investigation → Recovery
- Alignment

### MLF
- Materials & Life Experimental Facility
- Investigation → Shielding recovery → BL Components → New Hg Target
- Extended Building

### HD
- Hadron Experimental Facility
- Investigation → Recovery
- Beam Injection

### NU
- Neutrino Experimental Facility
- Investigation → Recovery
- Beam Injection
Achieved before the earthquake:
145 kW beam delivery to the T2K experiment
-> Recovery of the 145 kW beam is the first target of the FX operation

For higher beam power:

1. Increase beam loss capacity in ring collimator and reduction of activation
   - Additional shielding in ring collimators

2. Increase injected number of particles per pulse
   - Second harmonic cavity for manipulation of longitudinal bunch form
eqs to reduce the effect of space charge force
   - Lower emittance beam of the RCS by adopting 400 MeV injection

3. Increase repetition rate
   - Improvement/replacement of main magnet power supplies and rf system
   \[\rightarrow\text{R&Ds of high rep. time magnet power supply and high field gradient}
   \text{cavity are well in progress.}\]
The full energy (400 MeV) linac is necessary for the J-PARC facility to reach nominal performance (Beam power: 1MW@RCS, 0.75MW@MR)

Funding for construction of 181 to 400MeV part of the linac started with supplementary budget of JFY2008.

Installation is scheduled during the Summer 2013.
J-PARC plans (4/4)

Beam Power Planning

New estimates

J-PARC Power Expectation [MW]

- RCS power
- MR power

Original power upgrade plan of RCS

7 month summer/autumn shutdown for installation of ACS, new RFQ and IS.

3 month summer shutdown

Shutdown due to the earthquake

200 kW (achieved)

145 kW (achieved)

MR Improvements

Ring collimator shields, RF (6th fundamental, 2nd higher harmonics)

Ring collimator upgrade, RF (3rd HH)
Summary

• Many challenges remain for multi-GeV MW-class proton drivers, and even more when adding the requirements of NF and MC.
• For the time-being, neutrino facilities only «piggy-back» on existing or planned projects.
• Projects are at very different degrees of advancement:
  – J-PARC is recovering and getting back with an ambitious power upgrade plan,
  – Project X is at an advanced stage of proposal with extensive R & D,
  – Other projects are at the R&D stage/remote from approval (e.g. LAGUNA, ISIS MW upgrade),
  – 1 MW for conventional neutrino beam should be operational before 2020.
• Collaboration is worth enhancing, including apparented HPPA projects:
  – Many technologies are common (H⁻ ion source, RFQ, High Power RF, SRF, targets,…),
  – Resources are scarce!
THANK YOU FOR YOUR ATTENTION!
Spares
Fast phase rotation in the dedicated compressor ring (most economic from the RF point of view, but another ring is needed)

- Bunches will be extracted one by one from the RCS
- Compressor ring works above transition, but the rotation is very fast
- The bunches in the RCS will wait uncompressed for 200 µs
- We do not have a design for the compressor ring at the moment, but CERN design can be adopted
CERN plans

Reminder: PS2 for high beam intensities in SPS...

- PS2 provides up to twice line density of PS high-intensity beam
- Twice circumference gives up to ~4 times more intensity in total
  - ~1.0E14 per PS2 cycle (~1E14 with a longer kicker gap)
- Five-turn extraction will fill SPS with single shot instead of two from PS
  - Twice more intensity in SPS via twice higher line density.
  - No injection flat bottom in the SPS (two shot filling from PS presently)
- Clean bunch to bucket transfer PS2 40 MHz to SPS 200 MHz (cf. LHC)
  - ~6E11 protons per PS2 40 MHz bucket \( \rightarrow \) 1.2E11 in every fifths SPS 200 MHz bucket (extraction kicker gap by leaving buckets unfilled at PS2 injection)

\[
PS2 = \frac{15}{7} \text{PS} = \frac{15}{77} \text{SPS}
\]

![Diagram showing PS2 = 15/7PS = 15/77 SPS with bucket transfer and gaps for LSS4 extraction kicker rise/fall.](image)