Proton Driver: Status and Plans

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Proton Drivers

• Types of structure
  – Linac + Accumulator + Compressor rings
  – Linac + RCS + RCS (+ storage ring)
  – Linac + RCS + FFAG
  – Linac + FFAG

• Major issues
  – low (uncontrolled) beam loss
  – halo control
  – injection/accumulation
    • beam chopper
  – bunch compression
Possible “show stoppers”

- Halo control/preparation for injection
- Bunch compression
- Injection
- Beam chopper

Diagram:
- Achromat for collimation
- Stacked 1.2 GeV, 50 Hz Booster Synchrotrons
- Stacked 5 GeV, 25 Hz Main Synchrotrons
- 180 MeV, 234 Mhz H⁻ Linac
- 2 bunches of $2.5 \times 10^{13}$ protons in each ring
- 4 bunches of $2.5 \times 10^{13}$ protons in each ring
H⁻ Injection/Accumulation
Normalised dispersion $D_x/\sqrt{\beta_x} \approx 1.6$ in injection dipole
Figures in red are equivalent emittances in $\pi$ mm.mrad; those in blue are equivalent $\Delta p/p$ values ($\times 10^{-3}$).
Foil Heating

CERN NF Foil Temperatures (25Hz)

Fermilab Injection: closed orbit bumps

closed orbit (mm)

time (μs)
Laser Stripping

- Ring lattice designed for laser stripping injection for ESS
- Problems in controlling emittance
Linac and Beam Chopper

• EU/FP6 CARE/HIPPI study
  – linacs up to 200MeV
  – parallel chopper designs under development at RAL and CERN
  – CERN study leading to LINAC4 (possibly also SPL)
  – RAL study for NF and possible ISIS upgrade.
Complete Cycle, Booster RCS
Bunch Compression ~1-2 ns rms

\[ \varphi_L = A^{1/2} \frac{\omega_0}{\pi \beta^2 E} \frac{1}{12} \frac{2 \pi \beta^2 E \eta}{\text{heV} \cos \varphi_s} \]

- **High RF Voltage**
  - Bunch shortens as RF voltage increases during adiabatic compression, but only as fourth root of \( V \).
  - Required voltage rapidly becomes very large.

- **High RF frequency**
  - Leads naturally to shorter bunches but with small longitudinal emittance and high charge per unit phase space area.
  - Experience of high intensity machines suggests an empirical limit of \( 1-2 \times 10^{12} / \text{eV.s} \) for machines which pass through transition. However, no theoretical basis exists.
Bunch Rotation

- Slow adiabatic decrease of RF voltage to reduce momentum spread without emittance increase.

- Rapid increase of RF voltage so that the mis-matched bunch rotates in ¼ synchrotron period into upright configuration.

- Factors of 2 - 4 in compression, but emittance growth unless bunch is “used” immediately.
Use of Unstable Fixed Point

Step 1. Bunch lengthening at unstable fixed point in RCS, $V = 2$ MV, $\delta = 4$, $\gamma < \gamma_1$

- Switch phase of RF voltage to unstable fixed point to stretch bunch.
- Then switch RF phase back to stable fixed point so that bunch rotates to upright position with minimum length.
- Compression factor may be distorted by non-linear voltage regions.

Bunch length: ±12.5 ns (5.6 ns rms)
Momentum spread: ±5.0 x 10^{-3}
Longitudinal emittance: $\varepsilon_L \sim 0.7$ eV.s
Number of particles per bunch: 2.5 x 10^{13}

Momentum spread:

<table>
<thead>
<tr>
<th>$p$</th>
<th>$\Delta p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.45 \times 10^{-2}$</td>
<td>±5.0 x 10^{-3}</td>
</tr>
<tr>
<td>$3.45 \times 10^{-2}$</td>
<td>±5.0 x 10^{-3}</td>
</tr>
</tbody>
</table>

$\gamma_1 = 10.375$

Voltage (MV): 2.0
Harmon. no.: 4
Unstable Fixed Point + Separate Compressor Ring

Step 1. Bunch lengthening in RCS at unstable fixed point, $V = 2\text{MV}$, $k = 4$, $\gamma < \gamma_t$

- Stretch bunch at unstable fixed point (as before, $\gamma < \gamma_t$, volts on)

- Transfer to separate compressor ring with $\gamma > \gamma_t$ for phase space rotation. No volts needed.

- Non-linearity problems exist but are reduced.

Step 2. Bunch rotation in a separate Compressor Ring, $V = 0$, $\gamma > \gamma_t$. Final bunch length = 1.3 ns (rms).

<table>
<thead>
<tr>
<th>Bunch length (nsec)</th>
<th>(±)</th>
<th>2.5 → 45.3 → 4.5</th>
<th>5.6 → 16.9 → 1.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p / p$</td>
<td>$\pm 6.0 \times 10^{-3}$</td>
<td>$\pm 2.48 \times 10^{-2}$</td>
<td>$\pm 2.6 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\gamma_t$</td>
<td>10.375/5.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volts (MV)</td>
<td>2.0/0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harm. no.</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Flexible Momentum Compaction

- Lattice gymnastics involving frequency slip parameter $\eta = 1/\gamma_t^2 - 1/\gamma^2$.
- Set $\eta = 0$ and impose RF voltage to create large $\Delta p/p$ without change in bunch length.
- Switch $\eta$ back on and bunch will rotate to short length.
- Experiment at Brookhaven AGS with transition jumping quadrupoles achieved 2.5 ns for $5 \times 10^{12}$ protons (factor $\sim 3$ in compression).
Compression with $\gamma \geq \gamma_t$

In a separate compressor ring with $\gamma \geq \gamma_t$, $V = 1.5\,\text{MeV}$, $h = 8$ bunch (centred on $180^\circ$) elongates and rotates in phase space to final upright (compressed) state. Requires a ring with $\gamma$ insensitive to transverse space charge during compression.

- **Work with $\gamma$ close to, and just above, $\gamma_t$.**
- **Space charge assists compression.**
- **High RF voltage (1.5 MeV at $h=8$) based on $\varphi_s = 180^\circ$**
- **Simulation gives the required ~1-2 ns bunches but sensitive to space charge depression of $\gamma_t$.**

<table>
<thead>
<tr>
<th>Bunch length (ns)</th>
<th>$\pm 12.5 \rightarrow \pm 4.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p$</td>
<td>$5.6 \rightarrow 1.12$</td>
</tr>
<tr>
<td>$\Delta m$</td>
<td>$\pm 5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Delta \gamma$</td>
<td>$\rightarrow \pm 2.7 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\gamma_t$</td>
<td>5.0</td>
</tr>
<tr>
<td>Volts (MV)</td>
<td>1.5</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>8</td>
</tr>
</tbody>
</table>
Bunch Compression in RAL 5 GeV RCS Proton Driver

- $\gamma_t = 6.5$, $\gamma = 6.33$ at top energy, $\eta = -0.0013$
- Voltages chosen to avoid instabilities (microwave: $V_{sc} < 0.4 V_{applied}$)
- Model assumes inductive $Z_i/n \approx 5 \Omega$
- During final 500 revs of accelerating cycle, an additional $h=24$ voltage system swings in, rising to a peak of 500 MV
- Final bunch length = 1ns rms, $\epsilon_L = 1.0 \text{eV.s}$, $\Delta p/p = 1.6\%$
- Higher order momentum effects need to be taken into account
- Lattice resistant to space charge depression of $\gamma_t$ for currents of ~1250 A
\( \gamma_t = 6.5, \gamma = 6.33 \) at top energy, \( \eta = -0.0013 \)

**Voltages chosen to avoid instabilities** (microwave: \( V_{sc} < 0.4 V_{applied} \))

**Model assumes inductive** \( Z_n/\gamma \sim 5\Omega \)

**During final 500 revs of accelerating cycle**, an additional \( h=24 \) voltage system swings in, rising to a peak of 500 MV

**Final bunch length** = 1 ns rms, \( \varepsilon_L = 1.0 \text{ eV}.s, \Delta p/p = 1.6\% \).

**Higher order momentum effects need to be taken into account**

**Lattice resistant to space charge depression of** \( \gamma_t \) **for currents of** \( \sim 1250 \text{ A} \)
CERN SPL

- 2.2 GeV SPL injected 5 microbunches (352 MHz) out of 8 into 140 buckets (44 MHz) (plot left)
- 5.0 GeV SPL would inject 44 (352 MHz) out of 70 into 5 buckets (5 MHz).
4 MW, 50 Hz, 10 GeV Proton Driver

- 10 GeV non-scaling FFAG
  - $n=5$, $h=40$, radius = twice booster radius = 127.576 m

- 3 GeV RCS booster
  - mean radius = 63.788 m

- 180 MeV $H^-$ linac

- Achromatic $H^-$ collimation line

Bunch compression for 5 bunches:

- Longitudinal bunch area = 0.66 eV.s
- 1.18 MV/turn compresses to 2.1 ns rms
- Add $h=200$, 3.77 MV/turn for 1.1 ns rms
Proton Drivers

Table 1
Upgrade Parameters of Existing and Proposed Proton Drivers.
The pulse structure is given in terms of the pulse duration $\tau_p$, the number of bunches $N_b$ making up each pulse, and the final compressed rms bunch length $\tau_b$.

<table>
<thead>
<tr>
<th>Driver</th>
<th>Power (MW)</th>
<th>Type</th>
<th>Energy (GeV)</th>
<th>Frequency (Hz)</th>
<th>Protons per pulse ($\times 10^{13}$)</th>
<th>Pulse structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL-AGS</td>
<td>1</td>
<td>Synch</td>
<td>28</td>
<td>2.5</td>
<td>9</td>
<td>$\tau_p$</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Synch</td>
<td>28</td>
<td>5</td>
<td>18</td>
<td>720</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Synch</td>
<td>40</td>
<td>5</td>
<td>12.5</td>
<td>720</td>
</tr>
<tr>
<td>FNAL</td>
<td>2</td>
<td>Synch$^1$</td>
<td>8</td>
<td>15</td>
<td>10</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Linac$^2$</td>
<td>8</td>
<td>10</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>FNAL MI</td>
<td>2</td>
<td>Synch</td>
<td>120</td>
<td>0.67</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>CERN-SPL</td>
<td>4</td>
<td>LAR</td>
<td>2.2</td>
<td>50</td>
<td>23</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>LAR</td>
<td>3.5</td>
<td>50</td>
<td>14</td>
<td>1.7</td>
</tr>
<tr>
<td>J-PARC</td>
<td>0.75</td>
<td>Synch</td>
<td>50</td>
<td>0.3</td>
<td>31</td>
<td>4.6</td>
</tr>
<tr>
<td>RAL</td>
<td>4</td>
<td>Synch</td>
<td>5</td>
<td>50</td>
<td>10</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Synch</td>
<td>6-8</td>
<td>50</td>
<td>8.3</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>FFAG</td>
<td>10</td>
<td>50</td>
<td>5</td>
<td>2.3</td>
</tr>
<tr>
<td>RAL/CERN</td>
<td>4</td>
<td>Synch</td>
<td>30</td>
<td>8.33</td>
<td>10</td>
<td>3.2</td>
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<tr>
<td>KEK/Kyoto</td>
<td>1</td>
<td>FFAG</td>
<td>1</td>
<td>$10^4$</td>
<td>0.06</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>FFAG</td>
<td>3</td>
<td>$3 \times 10^3$</td>
<td>0.06</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Status

• Parameters needed so that comparisons may be made with:
  – BNL’s scheme of single 25 GeV bunches (15/50 Hz)
  – FNAL’s 8 GeV linac, accumulator+compressor scheme
  – CERN’s 5 GeV SPL, accumulator+compressor scheme

• Comparable tracking studies required
  – injection schemes, foil heating etc
  – bunch compression

• How close can these scenarios come to generating the preferred pulse structure?
Plans

• Bid submitted for 3 yrs continuation funding to UK/PPARC
• Covers
  – theoretical study of RAL RCS-FFAG 10GeV, 4MW proton driver
    • Development of FFAG space charge tracking code.
    • Injection tracking with space charge in the booster.
    • Space charge tracking for booster and driver rings.
  – completion of PD front-end test stand
• More substantial bid provisionally submitted to CCLRC for high intensity proton “test facility”
  – exact details to be agree
  – could include an electron model for NFFAG proton driver.
• Accumulator and Compressor ring for SPL (what energy?)
  – injection modelling and bunch compression
• Other SPL scenarios
• Continued work on Ruggiero FFAG proton driver
• other:
180 MeV $H^-$ beam

RF cavity systems

Low field injection dipole

Beam loss collectors

Mean radius = 63.788 m

$n = h = 3$ or $5$

Main dipoles

RF cavity systems

Extraction system

Triplet quads
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of superperiods</td>
<td>4</td>
</tr>
<tr>
<td>Number of cells per superperiod</td>
<td>4 straights + 3 bends</td>
</tr>
<tr>
<td>Length of cells</td>
<td>4x14.1+3x14.6</td>
</tr>
<tr>
<td>Mean radius</td>
<td>63.788 m</td>
</tr>
<tr>
<td>Betatron tunes</td>
<td>Q_v=6.38, Q_h=6.30</td>
</tr>
<tr>
<td>Transition gamma</td>
<td>6.57</td>
</tr>
<tr>
<td>Energy range</td>
<td>0.18-3 GeV</td>
</tr>
<tr>
<td>gamma</td>
<td>1.19-4.197</td>
</tr>
<tr>
<td>Main dipole fields</td>
<td>0.185-1.0996 T</td>
</tr>
<tr>
<td>Secondary dipole fields</td>
<td>0.0551-0.327 T</td>
</tr>
<tr>
<td>Triplet length/quad gradient</td>
<td>3.5 m/1.0-5.9 Tm⁻¹</td>
</tr>
</tbody>
</table>