3 GeV, 1.2 MW, RCS Booster and 10 GeV, 4.0 MW, NFFAG Proton Driver

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Introduction

Studies for the ISS:
1. Proton booster and driver rings for 50 Hz, 4 MW and 10 GeV.
2. Pairs of triangle and bow-tie, 20 (50 GeV) $\mu^\pm$ decay rings.

Studies after the ISS:
1. A 3 - 5.45 MeV electron model for the 10 GeV, proton NFFAG.
2. An alternative proton driver using a 50 Hz, 10 GeV, RCS ring.
3. A three pass, $\mu^\pm$ cooling, dog-bone re-circulator
Proton Driver Parameter Changes for ISS

- Pulse repetition frequency \( F = 15 \) to \( 50 \) Hz
- 4 MW, proton driver energy \( T = (8 \) or \( 26) \) to \( 10 \) GeV
- No. of \( p \) bunches & \( \mu^\pm \) trains \( n = 1 \) to \( (3 \) or \( 5) \)

Reasons for the changes:

- For adiabatic proton bunch compression to \( \sim 2 \) ns rms
- For lower peak & average beam currents in \( \mu^\pm \) rings
- To allow partial beam loading compensation for the \( \mu^\pm \)
Bunch Train Patterns

NFFAG ejection delays:
\[(p + m/n) T_d\] for \(m = 1\) to \(n (=3, 5)\)

Pulse < 40 µs for liquid target
Pulse > 60 µs for solid target

\[T_p = \frac{T_d}{2}\]

Acceler. of trains of 80 \(\mu^\pm\) bunches

\(\mu^\pm\) bunch rotation

Decay rings, \(T_d\)

\(h = 2^3 3^3 5\)

80 \(\mu^-\) or \(\mu^+\) bunches
Schematic Layout of 3 GeV, RCS Booster

200 MeV $H^-$ → $H^-, H^\circ$ beam

cavities

R = 63.788 m

$n = h = 3$ or $5$

dipoles

extracted

triplet

triplet

collectors

dipoles

8° dipole
Booster Betatron and Dispersion Functions
Parameters for 50 Hz, 0.2 to 3 GeV Booster

- Number of superperiods: 4
- Number of cells/superperiod: 4(straights) + 3(bends)
- Lengths of the cells: 4(14.0995) + 3(14.6) m
- Free length of long straights: 16 x 10.6 m
- Mean ring radius: 63.788 m
- Betatron tunes (Q_v, Q_h): 6.38, 6.30
- Transition gamma: 6.57
- Main dipole fields: 0.185 to 1.0996 T
- Secondary dipole fields: 0.0551 to 0.327 T
- Triplet length/quad gradient: 3.5 m/1.0 to 5.9 T m⁻¹
Beam Loss Collection System

- Primary H,V Collimators
- Secondary Collectors
  - $\mu = 90^\circ$
  - $\mu = 160^\circ$
- Local shielding
- Momentum collimators
- Radiation hard magnet
- Secondary $\Delta p$ collector

Diagram: Main dipoles
Choice of Lattice

- ESS-type, 3-bend achromat, triplet lattice chosen
- Lattice is designed around the $H^-$ injection system
- Dispersion at foil to simplify the injection painting
- Avoids need of injection septum unit and chicane
- Separated injection; all units between two triplets
- Four superperiods, with $>100$ m for RF systems
- Locations for momentum and betatron collimation
- Common gradient for all the triplet quadrupoles
- Five quad lengths but same lamination stamping
- Bending with $20.5^\circ$ main & $8^\circ$ secondary dipoles
Schematic Plan of $H^-$ Injection

Optimum field for $n = 4$ & $5$, $H^\circ$ Stark state lifetimes.

0.0551 T, Injection Dipole

- Horizontal painting via field changes, momentum ramping & rf steering
- Separated system with all injection components between two triplets.
- $H^-$ injection spot at foil is centred on an off-momentum closed orbit.
Electron Collection after $H^-$ Stripping

Foil support

Stripping Foil

Cooled copper graphite block

$\rho = 21.2 \text{ mm}, B = 0.055 \text{ T}$

$200 \text{ MeV}, 80 \text{ kW}, H^- \text{ beam}$

$170 \text{ injected turns, } 28.5 \ (20 \text{ av.}) \text{ mA}$

Foil lattice parameters: $\beta_v = 7.0 \text{ m}, \beta_h = 7.8 \text{ m}, D_h = 5.3 \text{ m}, D_h / \sqrt{\beta_h} = 1.93 \text{ m}^{1/2}$

$H^- \text{ parameters at stripping foil; } \beta_v = 2.0 \text{ m}, \beta_h = 2.0 \text{ m}, D_h = 0.0 \text{ m}, D_h' = 0.0$
Anti-correlated, $H^-$ Injection Painting

<table>
<thead>
<tr>
<th>Vertical acceptance</th>
<th>$H^-$ injected beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial closed orbits</td>
<td></td>
</tr>
<tr>
<td>Final closed orbits</td>
<td></td>
</tr>
<tr>
<td>Collapsed closed orbits</td>
<td></td>
</tr>
</tbody>
</table>

$\Delta p/p$ spread in $X$ closed orbits

Small $v$, big $h$ amplitudes at start
Small $h$, big $v$ amplitudes at end.

For correlated transverse painting: interchange $X$ closed orbits
Why Anti-correlated Painting?

Assume an elliptical beam distribution of cross-section \((a, b)\).

The transverse space charge tune depressions/spreads are:

\[
\delta Q_v = 1.5 \left[ 1 - \frac{S}{\int (\beta_v \frac{ds}{b(a+b)})} \right] \delta Q_v \text{ (uniform)}
\]

\[
4S = \int \left[ \frac{\beta_v}{b(a+b)^2} \right] \left[ \frac{y^2 (a + 2b)/ 2b^2}{a} \right] ds
\]

Protons with \((x = 0, y = 0)\) have \(\delta Q_v = 1.5 \delta Q_v \text{ (uniform distrib.)}\)

Protons with \((x = 0, y = b)\) have \(\delta Q_v \sim 1.3 \delta Q_v \text{ (uniform distrib.)}\)

Protons with \((x = a, y = 0)\) or \((x = a/2, y = b/2)\) have \(\sim 1.3\) factor.

\(\delta Q\) shift is thus less for anti-correlated than correlated painting.

The distribution may change under the effect of space charge.
Emittances and Space Charge Tune Shifts

Design for a Laslett tune shift (uniform distribution) of $\delta Q_v = 0.2$. An anti-correlated, elliptical, beam distribution has a $\delta Q_v = 0.26$.

For $5 \times 10^{13}$ protons at 200 MeV, with a bunching factor of 0.47, the estimated, normalised, rms beam emittances required are:

- $\epsilon_{\sigma n} = 24 (\pi) \text{ mm mrad}$
- $\epsilon_{\text{max}} = 175 (\pi) \text{ mm mrad}$

The maximum, vertical beam amplitudes (D quads) are 66 mm. Maximum, horizontal beam amplitudes (in F quads) are 52 mm.

Maximum, X motions at high dispersion regions are $< 80$ mm. Max. ring/collimator acceptances are $400/200 (\pi) \text{ mm mrad}$. 
Fast Extraction at 3 GeV

- Horizontal deflections for the kicker and septum magnets
- Rise / fall times for 5 (3) pulse, kicker magnets = 260 ns
- Required are 4 push-pull kickers with 8 pulser systems
- Low transverse impedance for (10 Ω) delay line kickers
- Extraction delays, $\Delta T$, from the booster and NFFAG rings
- R & D necessary for the RCS and the Driver pulsers
RF Parameters for 3 GeV Booster

- **Number of protons per cycle**: $5 \times 10^{13}$ (1.2 MW)
- **RF cavity straight sections**: 106 m
- **Frequency range for $h = n = 5$**: 2.117 to 3.632 MHz
- **Bunch area for $h = n = 5$**: 0.66 eV sec
- **Voltage at 3 GeV for $\eta_{sc} < 0.4$**: 417 kV
- **Voltage at 5 ms for $\phi_s = 48^\circ$**: 900 kV
- **Frequency range for $h = n = 3$**: 1.270 to 2.179 MHz
- **Bunch area for $h = n = 3$**: 1.1 eV sec
- **Voltage at 3 GeV for $\eta_{sc} < 0.4$**: 247 kV
- **Voltage at 5 ms for $\phi_s = 52^\circ$**: 848 kV
Schematic Layout of Booster and Driver

- 3 GeV RCS booster
- 200 MeV H^- linac
- 10 GeV NFFAG
- 66 cells
- H^°, H^-
- H^- collimators
- 200 MeV H^- linac
Homing Routines in Non-linear, NFFAG Program

- A linear lattice code is modified for estimates to be made of the non-linear fields in a group of FFAG magnets.
- Bending radii are found from average field gradients between adjacent orbits & derived dispersion values, D.
- D is a weighted, averaged, normalized dispersion of a new orbit relative to an old, and the latter to the former.
- A first, homing routine obtains specified betatron tunes. A second routine is for exact closure of reference orbits.
- A final, limited-range, orbit-closure routine homes for γ-t. Accurate estimates are made for reference orbit lengths.
- Full analysis needs processing the lattice output data & ray tracing in 6-D simulation programs such as Zgoubi.
Non-linear Fields and Reference Orbits

- Low ampl. Twiss parameters are set for a max. energy cell.
- Successive, adjacent, lower energy reference orbits are then found, assuming linear, local changes of the field gradients.
- Estimates are repeated, varying the field gradients for the required tunes, until self-consistent values are obtained for:
  - the bending angle for each magnet of the cell
  - the magnet bending radii throughout the cell
  - the beam entry & exit angle for each magnet
  - the orbit lengths for all the cell elements, and
  - the local values of the magnet field gradients
The Non-linear, Non-scaling NFFAG

- **Cells have the arrangement:** O-bd-BF-BD-BF-bd-O
- **The bending directions are:** - + + + -
- **Number of magnet types is:** 3
- **Number of cells in lattice is:** 66
- **The length of each cell is:** 12.14 m
- **The tunes, Q_h and Q_v, are:** 20.308 and 15.231
- **Non-isochronous FFAG:** \( \xi_v \approx 0 \) and \( \xi_h \approx 0 \)
- **Gamma-t is imaginary at 3 GeV, and \( \approx 21 \) at 10 GeV**
- **Full analysis needs processing non-linear lattice data & ray tracing in 6-D simulation programs such as Zgoubi**
Lattice Cell for the NFFAG Ring

Lengths and angles for the 10.0 GeV closed orbit
10 GeV Betatron & Dispersion Functions
## Gamma-t vs. $\gamma$ for the Driver and E-model

<table>
<thead>
<tr>
<th>Proton Driver</th>
<th>Electron Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma = E/E_0$</td>
<td>$\gamma = E/E_0$</td>
</tr>
<tr>
<td>10.805</td>
<td>10.980</td>
</tr>
<tr>
<td>10.379</td>
<td>10.393</td>
</tr>
<tr>
<td>9.100</td>
<td>9.219</td>
</tr>
<tr>
<td>8.673</td>
<td>8.632</td>
</tr>
<tr>
<td>8.247</td>
<td>8.045</td>
</tr>
<tr>
<td>7.608</td>
<td>7.458</td>
</tr>
<tr>
<td>6.968</td>
<td>6.871</td>
</tr>
<tr>
<td>4.197</td>
<td></td>
</tr>
</tbody>
</table>


Loss Levels for NFFAG Proton Driver

- Beam power for the 50 Hz Proton Driver = 4 MW
- Total loss through the extraction region < 1 part in $10^4$
- Average loss outside coll./ extr. region < 1 part in $10^4$
- Total loss in primary & sec. collimators = 1 part in $10^3$

- Remotely operated positions for primary collimators.
- Quick release water fittings and component flanges.
- Local shielding for collimators to reduce air activation.
Vertical Collimation in the NFFAG

Loss collectors

Y

3 GeV proton beam  10 GeV proton beam

Coupling may limit horizontal beam growth
Loss Collection for the NFFAG

- Vertical loss collection is easier than in an RCS
- $\Delta P$ loss collection requires beam in gap kickers

- Horizontal beam collimation prior to the injection
- Horizontal loss collection only before the ejection

- Minimize the halo growth during the acceleration
- Minimise non-linear excitations as shown later.
NFFAG Loss Collection Region

- Direct beam loss localised in the collection region
- Beam 2.5 $\sigma$, Collimator 2.7 $\sigma$ and Acceptance 4 $\sigma$
## NFFAG Non-linear Excitations

<table>
<thead>
<tr>
<th>Cells</th>
<th>$Q_h$</th>
<th>$Q_v$</th>
<th>3rd Order</th>
<th>Higher Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.25</td>
<td>0.25</td>
<td>zero</td>
<td>$nQ_h=nQ_v$ &amp; 4th order</td>
</tr>
<tr>
<td>5</td>
<td>0.20</td>
<td>0.20</td>
<td>zero</td>
<td>$nQ_h=nQ_v$ &amp; 5th order</td>
</tr>
<tr>
<td>6</td>
<td>0.166</td>
<td>0.166</td>
<td>zero</td>
<td>$nQ_h=nQ_v$ &amp; 6th order</td>
</tr>
<tr>
<td>9</td>
<td>0.222</td>
<td>0.222</td>
<td>zero</td>
<td>$nQ_h=nQ_v$ &amp; 9th order</td>
</tr>
<tr>
<td>13</td>
<td>4/13</td>
<td>3/13</td>
<td>zero to 13th except $3Q_h=4Q_v$</td>
<td></td>
</tr>
</tbody>
</table>

Use $(13 \times 5) + 1 = 66$ such cells for the NFFAG Variation of the betatron tunes with amplitude?

$\gamma-t$ imaginary at low energy and $\sim 20$ at 10 GeV
Bunch Compression at 10 GeV

For 5 proton bunches:
Longitudinal areas of bunches = 0.66 eV sec
Frequency range for a h of 40 = 14.53-14.91 MHz
Bunch extent for 1.18 MV/turn = 2.1 ns rms
Adding of h = 200, 3.77 MV/turn = 1.1 ns rms

For 3 proton bunches:
Longitudinal areas of bunches = 1.10 eV sec
Frequency range for a h of 24 = 8.718-8.944 MHz
Bunch extent for 0.89 MV/turn = 3.3 ns rms
Adding of h = 120, 2.26 MV/turn = 1.9 ns rms

Booster and Driver tracking studies are needed
50 Hz, 10 GeV, RCS Alternative

- Same circumference as for the outer orbit of the NFFAG
- Same box-car stacking scheme for the $\mu^\pm$ decay rings
- Same number of proton bunches per cycle (3 or 5)
- Same rf voltage for bunch compression (same gamma-t)
- Increased rf voltage for the proton acceleration (50% ?)
- 3 superperiods of (15 arc cells and 6 straight sections)
- 5 groups of 3 cells in the arcs for good sextupole placings
- 2 quadrupole types of different lengths but same gradient
- 2 dipole magnet types, both with a peak field of 1.0574 T
10 GeV NFFAG versus RCS

Pros:
- Allows acceleration over more of the 50 Hz cycle
- No need for a biased ac magnet power supply
- No need for an ac design for the ring magnets
- No need for a ceramic chamber with rf shields
- Gives more flexibility for the holding of bunches

Cons:
- Requires a larger (~ 0.33 m) radial aperture
- Needs an electron model to confirm viability
R & D Requirements

Development of an FFAG space charge tracking code. Tracking with space charge of booster and driver rings.

Building an electron model for NFFAG proton driver. Magnet design & costing for RCS, NFFAG & e-model.

Development of multiple pulse, fast kicker systems. Site lay-out drawings & conventional facilities design

NFFAG study (with beam loading) for $\mu^\pm$ acceleration