Beam Preparation for Injection to CSNS RCS

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Main topics

- RCS injection design and requirements
- LRBT transport line
- Transverse halo collimation by triplets and foil scrapers
- SCOMT code and simulation results
- Momentum spread reduction and momentum tail collimation
RCS Injection Design
## CSNS Main Parameters

<table>
<thead>
<tr>
<th>Phase</th>
<th>I</th>
<th>II</th>
<th>ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power on target [kW]</td>
<td>120</td>
<td>240</td>
<td>500</td>
</tr>
<tr>
<td>Beam energy on target [GeV]</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Ave. beam current [μA]</td>
<td>76</td>
<td>151</td>
<td>315</td>
</tr>
<tr>
<td>Pulse repetition rate [Hz]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Protons per pulse [$10^{13}$]</td>
<td>1.9</td>
<td>3.8</td>
<td>7.8</td>
</tr>
<tr>
<td>Linac energy [MeV]</td>
<td>80</td>
<td>130</td>
<td>230</td>
</tr>
<tr>
<td>Linac type</td>
<td>DTL</td>
<td>DTL</td>
<td>DTL+SCL</td>
</tr>
<tr>
<td>Target number</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Target material</td>
<td>Tungsten</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderators</td>
<td>$H_2O$ (300K), $CH_4$ (100K), $H_2$ (20K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of spectrometers</td>
<td>5</td>
<td>18</td>
<td>&gt;18</td>
</tr>
</tbody>
</table>
RCS Lattice & Injection

Injection (chicane & bumps)
RF (h=2)
RF (h=4) (for upgrade)
Collimation (transverse & longitudinal)
Extraction (kickers & septum)
Instrumentation

Betatron amplitude functions [m] versus distance [m]

Dispersion functions [m] versus distance [m]

Horizontal  Vertical
Design Criteria for Injection System

• **Layout**
  – Orbit bumping for facilitating installation of injection devices
  – Minimize proton traversal on stripping foil
  – Weak perturbation to ring lattice
  – Minimize local radiation level

• **Phase space painting**
  – Better uniform beam distribution to alleviate space charge effect

• **Requirement to injection devices**
  – Control difficulties of fabrication of the devices (magnets, PS, stripper)
  – Control power consumption
Injection Scheme

- **From lattice**
  - In one of dispersion-free long straights (9 m)
    - No residual dispersion
    - Possible due to low injection energy
    - Minor perturbation to betatron matching
  - Doublets: double-waist
  - Closed-orbit chicane
    - Facilitate installation
    - DC+offset bumpers

- **Phase space painting**
  - Keeping both correlated and anti-correlated schemes
  - Ring bumpers in both horizontal and vertical

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy (GeV)</td>
<td>0.08/0.13</td>
</tr>
<tr>
<td>Injection rigidity (Tm)</td>
<td>1.231/1.704</td>
</tr>
<tr>
<td>Accumulated particles</td>
<td>1.9/3.8 × 10^13</td>
</tr>
<tr>
<td>Injection time (ms)</td>
<td>0.15~0.30</td>
</tr>
<tr>
<td>Painting planes</td>
<td>H &amp; V</td>
</tr>
<tr>
<td>Painting transverse emittance (pi.mm.mrad)</td>
<td>200~250</td>
</tr>
<tr>
<td>Injection emittance (pi.mm.mrad, r.m.s.)</td>
<td>1.0</td>
</tr>
<tr>
<td>Injection current (mA)</td>
<td>15~35</td>
</tr>
</tbody>
</table>
BC1~4: DC Chicane magnets; BH1~4: Horizontal painting magnets; BV1~4: Vertical painting magnets
Main Characteristics of the Injection System

• **All bump magnets are in one long drift**
  – Possible due to low beam rigidity and long drift (9m)
  – Minimize injection errors due to beam jitter and injection matching (vertical steering)
  – Both correlated and anti-correlated painting
  – BCs, BHs and BVs are powered in series to reduce the field quality requirement and the cost (multipole field self-cancellation as two bumpers are close within each pair)

• **Non-stripped H-minus stopped directly by an absorber**
  – Maximum 10W at CSNS-II, even lower for thicker foil
  – Almost no H- particles missing the foil with a well defined beam (4~8 pi.mm.mrad)
Injection Strippers

- **Two Stripper**
  - Main stripper for converting at least 98% H- beam into H+
    - Alumina or Carbon $\sim 80 \mu g/cm^2$
    - Two free sides
    - Surveillance and replacement
  - Auxiliary stripper for converting partially-stripped H0 beam to injection dump
    - Thicker alumina foil 200 $\mu g/cm^2$
    - One free side

- **Electron collector**
  - EP instability
  - Taking use of BC3 fringe field
  - Natural cooling (<18W)
Detailed painting studies

- Using 3D ORBIT simulations including space charge
  - Focusing on: distribution uniformity, emittance blowup and foil traversal
- Different working points
- Correlated and anti-correlated painting schemes
- Linac peak current dependence
- Chopping rate dependence
  - Balance between transverse and longitudinal beam losses
- RF voltage curve dependence
- Longitudinal painting (only with momentum offset)
Some Simulation Results

Anti-correlated painting

Tune spread at painting end (WP: 5.78/5.86)

Emittance blowup vs chopping rate

Emittance blowup vs linac current
Upgrading potential with injection energy of 230 MeV

- Preliminary Injection design for CSNS-II’ (500 kW) has been carried out
  - Vertical painting by steering magnets in injection line
- Problems with increased energy of 230 MeV (or 250 MeV)
  - H- Lorentz stripping in LRBT
  - H0 Stark states decay in bumpers
Linac to Ring Beam Transport Line
Main functions of LRBT

- Transfer H- beam from linac to RCS
- Transfer H- beam to linac beam dumps
- Match to transverse requirements at injection foil
- Debuncher to reduce momentum spread
- Transverse halo collimation
- Momentum tail collimation
- Reserved potential for upgrading
- Beam transport for medium energy proton applications
Main Beam Characteristics in the LRBT

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CSNS-I</th>
<th>CSNS-II</th>
<th>CSNS-II’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>H-minus</td>
<td>H-minus</td>
<td>H-minus</td>
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<tr>
<td>Beam energy (MeV)</td>
<td>80</td>
<td>130</td>
<td>230</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Bunch frequency (MHz)</td>
<td>324</td>
<td>324</td>
<td>324</td>
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<tr>
<td>Gamma</td>
<td>1.085</td>
<td>1.139</td>
<td>1.245</td>
</tr>
<tr>
<td>Beta</td>
<td>0.389</td>
<td>0.478</td>
<td>0.596</td>
</tr>
<tr>
<td>Beam rigidity (T.m)</td>
<td>1.320</td>
<td>1.704</td>
<td>2.322</td>
</tr>
<tr>
<td>Average current (uA)</td>
<td>81</td>
<td>158</td>
<td>328</td>
</tr>
<tr>
<td>Peak current (mA)</td>
<td>20</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Beam power (kW)</td>
<td>6.5</td>
<td>20.5</td>
<td>75.5</td>
</tr>
<tr>
<td>Emittance ($\pi$ mm.mrad, r.m.s)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Acceptance ($\pi$ mm.mrad)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>momentum spread (%)</td>
<td>0.05~0.5</td>
<td>0.05~0.5</td>
<td>0.05~0.5</td>
</tr>
</tbody>
</table>
LRBT layout and beam envelope
Layout design of LRBT

- **Long straight section**
  - Basically triplet cells of 60 degrees
  - Reserved space of 85 m for linac upgrading
  - Debunchers in different CSNS phases
  - Transverse halo collimation
  - Transverse matching to both linac and bending sections

- **Achromatic bending sections**
  - Two achromatic bending sections: symmetric 90° + anti-symmetric 20°
  - Modest dispersion for momentum collimation and resistant to space charge effect

- **Two beam dumps**
  - Dump-A: low as 200 or 400 W, straight end, for initial linac commissioning and dumping scraped H0
  - Dump-B: large as 6.5 kW, possible for full beam power commissioning, and for dumping scraped protons
Transverse Halo Collimation by Triplets and Foil Scrapers
Transverse Halo Collimation in LRBT

• **Purposes**
  
  – To avoid the missing hit of H- on the injection foil
  
  – To reduce the halo production during phase space painting
  
  – To reduce the beam losses in the injection magnets
  
  – To increase the collimation efficiency of the momentum tail
  
  – Stripped particles can be used for other application experiments while in normal operation
Comparison among different collimation methods

- **FODO cells and immediate beam dumps**
  - Used by SNS and AUSTRON
  - No need to enlarge Q apertures
  - More collimators and radiation

- **Achromat and remote beam bumps**
  - Proposed by ESS
  - Expensive with more beam line and dumps
  - Effective for very high beam power

- **FODO cells and remote beam dumps**
  - Used by J-PARC
  - Cheap with one beam dump
  - Relatively large beam loss
LRBT Collimation Scheme

- **Scheme**
  - Two triplet cells of 60° in the straight section, three double-waists
  - Three pairs of scrapers (stripping foil) at each waist to make hexagonal emittance cut
  - H+, H0 and H- mixed transport, H+ guided to beam dump after the switch magnet

- **Merits**
  - No local beam dump or absorber, clean beam line
  - Only one beam dump → low cost
  - H+ transported together with H- without beam loss, no aperture increase to the quadrupoles and the debuncher → low cost
    - As a comparison, FODO or doublet cells have mismatched focusing for protons
  - Allowing deep collimation (about 2%), limiting emittance within 9 πmm.mrad
  - Scraped beam halo can be used for other applications
Triplet cells and foil scrapers

Beam envelopes of H- and proton beams within one triplet cells
Plots in phase space
Left: after first scraper
Middle: at D quad exit
Right: at the third waist
Lower: protons after switch
SCOMT Code and Simulation Results
A new simulation code – SCOMT has been developed to deal with beam transfer problems in LRBT
- No existing codes to tackle the problems concerning the transfer of mixed beams

Main functions of SCOMT:
- Macro-particles tracking thru beam line elements
  - With different input distribution options
- Stripping process with probability when a particle hits a scraper foil (H- to H0, H- to p, H0 to p)
- Nuclear interaction effect between a foil hitting particle and the foil (multiple scattering, Nuclear reaction)
  - Multiple scattering is based the Moliere theory with correction
  - Nuclear reaction is based on an empirical formulae
- Statistical analysis
- Linear space charge effect included
Simulation results in LRBT

- **Main beam losses in LRBT**
  - Multiple scattering: some become large halo
  - Nuclear reaction or large angle elastic scattering: immediate loss
  - Partial stripping (H- to H0), some will lose when hitting a downstream foil

- **Optimization of foil thickness**
  - Thicker foil: better stripping efficiency, larger scattering
  - Existing optimum foil thickness

- **Stability studies**
  - With linac beam wobbling, no large variation on current intensity (even for scraped proton beam, <5%)
Momentum Spread Reduction and Momentum Tail Collimation
Debunchers to reduce momentum spread

- To reduce momentum spread
  - At linac exit: about ±0.1%
  - Enhanced by longitudinal space charge

- To correct jitter of average momentum
  - Variation of linac RF phase and voltage

- Foreseen for three phases
  - Higher linac energy ➔ higher voltage, longer drift distance
  - Different cavities due to different β values
  - Different locations

- Detailed study including longitudinal space charge (PARMILA)
Debunchers at different phases

<table>
<thead>
<tr>
<th></th>
<th>CSNS-I</th>
<th>CSNS-II</th>
<th>CSNS-II'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>80</td>
<td>130</td>
<td>230</td>
</tr>
<tr>
<td>Drift distance (m)</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Eff. voltage (kV)</td>
<td>360</td>
<td>550</td>
<td>1050</td>
</tr>
</tbody>
</table>
Momentum Collimation in the LRBT

Necessity of momentum collimation in LRBT

- Momentum tail has been observed in many linacs. It might damage the injection devices and increase radioactivity in the region.
- It is too large ($\delta > 0.005$) for the debuncher to correct it.
- A momentum collimator is used to scrape the tail

Momentum collimator

- One stage of momentum collimator is planned at a dispersive location
- With the bending angle of $45^\circ$ and long drift, modest dispersion of 5m cutting all particles with $\delta > 0.005$
- Collimator to absorb particles of energy up to 250MeV
Thanks for your attention!