Commissioning and initial operation experience with the CSNS Linac

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On behalf of CSNS accelerator physics group
OUTLINE

• Introduction
• Front End Commissioning
• MEBT+DTL+LRBT Commissioning
  1、RF tuning
  2、Transverse matching
  3、Orbit Correction
• Issues and solutions
• Summary
Introduction: the CSNS Project

Parameters:
- Linac energy: 80MeV
- Energy: 1.6GeV
- Current: 15mA
- Average Power: 100kW
- Pulse length: 500μs
- Repitition rate: 25Hz

Upgrade plan:
- Linac energy: 80MeV -> 300MeV
- Current: 15mA -> 50mA
- Average Power: 100kW -> 500kW
**H⁻ Linac of CSNS**

**Electrostatic chopper**

- **H⁻ IS**
  - LEBT
  - RFQ
  - 3 MeV
  - MEBT
  - Buncher 1
  - Buncher 2
  - EMQ FFDD lattice
  - DTL
  - 80 MeV
  - LRBT
  - Debuncher
  - RING

**Solid State Amplifier**

- **4616 Tetrode RF Amplifier**
- **Low Level RF**

### Time Structure of Linac Beam Pulse

- 468 nsec
- 421.2 usec
- 40 msec

### Parameters of CSNS Linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ion Source</th>
<th>RFQ</th>
<th>DTL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Energy (MeV)</td>
<td>0.05</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Output Energy (MeV)</td>
<td>0.05</td>
<td>3.0</td>
<td>80</td>
</tr>
<tr>
<td>Pulse Current (mA)</td>
<td>20</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>RF frequency (MHz)</td>
<td>324</td>
<td>324</td>
<td></td>
</tr>
<tr>
<td>Chop rate (%)</td>
<td>50</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Duty factor (%)</td>
<td>1.3</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>
**Commissioning of CSNS Linac**

- **#1**
  Front end, full power (500μs, 25Hz, chopped)

- **#2**
  DTL tank1, reduced beam power (200μs, 5Hz, chopped)

- **#3**
  DTL tank1, full power (500μs, 25Hz, chopped)

- **#4**
  DTL tank1-3, reduced beam power (100μs, 1Hz, unchopped)

- **#5**
  DTL tank1-4, reduced beam power (100μs, 1Hz, unchopped)

- **#6**
  DTL tank1-4, reduced beam power (200~400μs, 1Hz, unchopped)
1. Front End Commissioning
Commissioning of Ion Source

- **Aim:** less spark and higher stability: major effort focus on long term operation with high stability, related to source body, HV supply, Cesium Temp., EMC, ……

- **Result:**

  Times: 9 in 48Hours
  Duration: ~30s

  Times: 4 in 72Hours
  Duration: ~0.05s
Chopper in LEBT

A electric chopper located in the third chamber of LEBT just before the entrance of RFQ to chop beam to the required structure for RCS

Courtesy of H.F. Ouyang, FE group, CSNS
Chopping experiments

Beam structure: 100us, 1Hz (37mA)
Chopping structure: 500ns, 1MHz
Applied chopping voltage: 3.8kV
Theoretical chopping voltage: 3.7kV

Both the rise/fall time for the chopped beam is about 4-5 periods of the working RF (1 period T=3.086ns)

Measured effect of chopper on the beam
Beam Commissioning of RFQ

<table>
<thead>
<tr>
<th></th>
<th>Design</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current [mA]</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Beam energy [MeV]</td>
<td>3.025</td>
<td>3.02 ± 0.015</td>
</tr>
<tr>
<td>Chopping rate [%]</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Pulse width [μs]</td>
<td>420</td>
<td>500</td>
</tr>
<tr>
<td>Pulse repetition rate [Hz]</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

CT measurement: beam transmission ～93%

Emittance (π mm-mrad): simulated=0.22, Measured=0.27
MEBT+DTL+LRBT commissioning
1、RF tuning
RF Tuning: Setting RF amplitude and phase

- Phase Scan Signature Matching Method
  XAL, Pasta (an RF phase scan and tuning application)

Model:
- Input energy
- RF amplitude
- Cavity phase offset
Phase Scan of Bunchers

Measured phase differences with two FCTs

\[ \Phi_{cavity} = -60.097^\circ \]

Buncher 1

Measured phase differences with two FCTs

\[ \Phi_{cavity} = 27.857^\circ \]

Buncher 2
Phase scan results of 4 DTL tanks:

DTL1

DTL2

DTL3

DTL4
Energy Measurements
(Phase Scan & TOF)

Beam energy from two methods

<table>
<thead>
<tr>
<th></th>
<th>Design [MeV]</th>
<th>Phase scan [MeV]</th>
<th>TOF [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ</td>
<td>3.026</td>
<td>3.029</td>
<td>3.027</td>
</tr>
<tr>
<td>DTL1</td>
<td>21.669</td>
<td>21.802</td>
<td>21.685</td>
</tr>
<tr>
<td>DTL2</td>
<td>41.415</td>
<td>41.52</td>
<td>41.566</td>
</tr>
<tr>
<td>DTL3</td>
<td>61.072</td>
<td>60.917</td>
<td>61.09</td>
</tr>
<tr>
<td>DTL4</td>
<td>80.01</td>
<td>79.87</td>
<td>80.28</td>
</tr>
</tbody>
</table>

The energy deviation is all < 1%
MEBT + DTL + LRBT commissioning
2、Transverse matching
Twiss Parameter Measurement

4 wire scanners

XAL: Beam Envelopes Fitting
(Red: x-rms  Blue: y-rms)
## Twiss Measurement Results by WSs

Twiss Parameters and emittance at RFQ Exit

<table>
<thead>
<tr>
<th></th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>Emittance (norm.rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[mm/mrad]</td>
<td>[( \pi )mm mrad]</td>
<td></td>
</tr>
<tr>
<td><strong>HORIZONTAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured (10mA)</td>
<td>-2.28</td>
<td>0.335</td>
<td>0.215</td>
</tr>
<tr>
<td>Measured (14mA)</td>
<td>-2.35</td>
<td>0.328</td>
<td>0.243</td>
</tr>
<tr>
<td>Designed</td>
<td>-1.773</td>
<td>0.233</td>
<td>0.215</td>
</tr>
<tr>
<td><strong>VERTICAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured (10mA)</td>
<td>1.1</td>
<td>0.076</td>
<td>0.213</td>
</tr>
<tr>
<td>Measured (14mA)</td>
<td>1.2</td>
<td>0.077</td>
<td>0.243</td>
</tr>
<tr>
<td>Designed</td>
<td>0.639</td>
<td>0.074</td>
<td>0.212</td>
</tr>
</tbody>
</table>
Transverse Emittance Measurement

**Simulated beam distribution at EM**

**Measured beam distribution at EM**

- Measured beam distribution at EM
- Simulated beam distribution at EM

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**Emittance Contour Plot**

- X vs. X
- Y vs. Y

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**BPM**—beam position monitor
**PR**—profile monitor
**CT**—current monitor
**Q**—quadrupole magnet
**EM**—emittance monitor
**GV**—gate valve
**ST**—steering magnet
**DR**—drift space
How to improve the DTL Transmission

- Optimize the magnet model, including the fringe field effect
- We do transverse matching based on the beam profile measurements at the exit of the DTL.
**Fringe Field Effect of MEBT Magnets**

- Huge difference in Twiss parameters between hard edge model and slice model
- Fringe field of magnets are considered in matching

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**Graphs:**

- **Betax** graph with Betax values plotted against z (m) for different magnets.
- **Betay** graph with Betay values plotted against z (m) for different magnets.

**Legend:**

- BETAx, BETAx7, BETAx9, BETAx11, BETAx13
- BETAy, BETAy7, BETAy9, BETAy11, BETAy13

**Note:**

- Len_Quad~79mm
• By adjust the last four magnets in the MEBT, the beam profile is approaching to Gaussian distribution.
Matching of LRBT
(Linac to Ring Beam Transport Line)

Before matching

After matching

Red line : X direction
Blue line : Y direction
MEBT + DTL + LRBT commissioning
3、Orbit correction
MEBT Orbit Correction

Before correction maximum: \( \pm 1.5\text{mm} \)

After correction maximum: \( \pm 0.15\text{mm} \)
LRBT Orbit Correction

before correction maximum: ± 14mm

(x,x',y,y') = (0.35mm, 1mrad, 1.4mm, 1.7mrad)

after correction maximum: ± 2mm
Issues and solutions
1: An EMQ in DTL was turned off

161 EMQs, FFDD

**MEBT**

<table>
<thead>
<tr>
<th></th>
<th>DTL1-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>x (cm) vs. cell no.</td>
<td><img src="image1.png" alt="Plot" /></td>
</tr>
<tr>
<td>y (cm) vs. cell no.</td>
<td><img src="image2.png" alt="Plot" /></td>
</tr>
</tbody>
</table>

Beam envelope along the MEBT and the DTL

Quad gradient

Phase advance/period
Drift Tube Fault

Envelope with T1Q13 ON

Envelope with T1Q13 OFF
100% Transmission

Envelope with T1Q13 ON

75% Transmission

Envelope with Only T1Q13 OFF
Rematch of DTL Lattice

Envelope with Only T1Q13 OFF

Envelope after rematch
Beam Profiles Comparison

LRWS01
Nominal
1*Quad Off
Rematching

LRWS02

LRWS01

LRWS02
2: The beam transmission of the DTL is decreasing during the operation

Commission surface

<table>
<thead>
<tr>
<th>Date</th>
<th>Beam Power</th>
<th>Beam Width</th>
<th>Beam Voltage</th>
<th>Beam Current</th>
<th>Beam Trans.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017/05/09</td>
<td>21.30 mA</td>
<td>Beam Power</td>
<td>Beam Voltage</td>
<td>Beam Current</td>
<td>Beam Trans.</td>
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</table>

Operation surface

<table>
<thead>
<tr>
<th>Date</th>
<th>Beam Power</th>
<th>Beam Width</th>
<th>Beam Voltage</th>
<th>Beam Current</th>
<th>Beam Trans.</th>
</tr>
</thead>
</table>

CT Display
From PARMILA results

**Normal state**, beam distribution at the output of the RFQ

**Abnormal state**, beam distribution at the output of the RFQ

Beam distribution at the input of the DTL
<table>
<thead>
<tr>
<th>Experiment</th>
<th>2020-12-22</th>
<th>2021-01-22</th>
<th>2021-02-22</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ transmission(%)</td>
<td>83.4</td>
<td>94.04</td>
<td>96.85</td>
</tr>
<tr>
<td>DTL1,2 transmission(%)</td>
<td>96.92</td>
<td>97.5</td>
<td>98.67</td>
</tr>
<tr>
<td>DTL 3,4 transmission(%)</td>
<td>98.93</td>
<td>98.83</td>
<td>99.32</td>
</tr>
<tr>
<td>DTL transmission(%)</td>
<td>95.88</td>
<td>96.36</td>
<td>98.00</td>
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</table>
Summary

• The Front-end and DTL1-4 have been fully commissioned, the primary design goals of $I_{pk}$ & $I_{avg}$, transverse emittance and beam energy have been achieved.

• The DTL output energy, measured by phase scan method, agrees well with that measured by time-of-flight method.

• Beam transmission efficiency and beam loss are well optimized. More work needs to be done on halo's formation mechanism and inhibition method.
Beam of 50kW

Beam Transport Efficiency

Beam Loss Monitors
**Beam of 80kW**

### Beam Transport Efficiency

<table>
<thead>
<tr>
<th>值班</th>
<th>CT Display</th>
<th>2019-09-24 14:22:59</th>
</tr>
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<tbody>
<tr>
<td>LEBT CT01</td>
<td>41.96</td>
<td>mA/E12 RTBT CT01 13.02 E12</td>
</tr>
<tr>
<td>MEBT CT01</td>
<td>6.19</td>
<td>mA/E12 RDBT CT01 12.82 E12</td>
</tr>
<tr>
<td>MEBT CT02</td>
<td>6.19</td>
<td>mA/E12 DTL Trans 99.93 %</td>
</tr>
<tr>
<td>LRBT CT01</td>
<td>6.19</td>
<td>mA/E12 LRBT Trans 100.7 %</td>
</tr>
<tr>
<td>LRBT CT03</td>
<td>6.23</td>
<td>mA/E12 EXT Trans 101.7 %</td>
</tr>
<tr>
<td>DCCT-INJ</td>
<td>1066.0</td>
<td>mA/E12 DCCT Trans 98.8 %</td>
</tr>
<tr>
<td>SCT-INJ</td>
<td>1091.8</td>
<td>mA/E12 SCT Trans 98.8 %</td>
</tr>
<tr>
<td>DCCT-EXT</td>
<td>2504.7</td>
<td>mA/E12 RDBT Trans 98.5 %</td>
</tr>
<tr>
<td>SCT-EXT</td>
<td>2563.8</td>
<td>mA/E12 Beam Power 82.214 kW</td>
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</table>

### Beam Loss Monitors

![Beam Loss Monitors Chart]
Beam of 100kW

Beam Transport Efficiency

<table>
<thead>
<tr>
<th>CT Display</th>
<th>2020-05-25 08:06:29</th>
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<tbody>
<tr>
<td>LEBT CT01</td>
<td>32.63 mA</td>
</tr>
<tr>
<td>LEBT CT02</td>
<td>0.83 mA</td>
</tr>
<tr>
<td>MEBT CT01</td>
<td>6.56 mA</td>
</tr>
<tr>
<td>MEBT CT02</td>
<td>6.58 mA</td>
</tr>
<tr>
<td>LRBT CT01</td>
<td>6.55 mA</td>
</tr>
<tr>
<td>LRBT CT02</td>
<td>6.54 mA</td>
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<tr>
<td>LRBT CT03</td>
<td>6.57 mA</td>
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<tr>
<td>DCCT-INJ</td>
<td>1.608 E13</td>
</tr>
<tr>
<td>DCCT-EXT</td>
<td>1.584 E13</td>
</tr>
<tr>
<td>RTBT CT01</td>
<td>1.591 E13</td>
</tr>
</tbody>
</table>

Beam Loss Monitors

- MEBLM01: 121.09
- MEBLM02: 39.65
- MEBLM03: 27.93
- T01BLM01: 8.56
- T01BLM02: 15.28
- T01BLM03: 172.28
- T02BLM01: 36.4
- T02BLM02: 46.94
- T02BLM03: 80.39
- T03BLM01: 64.65
- T03BLM02: 43.4
- T03BLM03: 96.38
- L04BLM01: 218.81
- L04BLM02: 57.83
- L04BLM03: 88.73
- L05BLM01: 41.74
- L05BLM02: 172.23
- L05BLM03: 8.16
- L05BLM04: 10.87
- L05BLM05: 1.66
- L05BLM06: 13.13
- L05BLM07: 22.91
- L05BLM08: 3.44
Thanks For Your Attention!