Beam Dynamics of the ESS Linac

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Introduction

Content

- Overview of accelerator
- ESS linac changes since TDR (2012)
- Beam Dynamics considerations
- Beam Dynamics Studies
- Outlook
Introduction

The ESS Linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Power</td>
<td>5</td>
<td>MW</td>
</tr>
<tr>
<td>Final Energy</td>
<td>2</td>
<td>GeV</td>
</tr>
<tr>
<td>Peak Current</td>
<td>62.5</td>
<td>mA</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>2.86</td>
<td>ms</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>14</td>
<td>Hz</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>4%</td>
<td>-</td>
</tr>
</tbody>
</table>
## Introduction

### The ESS Linac

<table>
<thead>
<tr>
<th>Source</th>
<th>LEBT</th>
<th>RFQ</th>
<th>MEBT</th>
<th>DTL</th>
<th>Spokes</th>
<th>Medium β</th>
<th>High β</th>
<th>HEBT &amp; Contingency</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 keV</td>
<td>3.6 MeV</td>
<td>90 MeV</td>
<td>216 MeV</td>
<td>571 MeV</td>
<td>2000 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Energy, Modules, Cavity per Module, Beta γ, Temperature, and Length

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy [MeV]</th>
<th># modules</th>
<th>cav./mod.</th>
<th>βγ</th>
<th>Temp. [K]</th>
<th>Length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>0.075</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>≃ 300</td>
<td>-</td>
</tr>
<tr>
<td>LEBT</td>
<td>0.075</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>≃ 300</td>
<td>2.5</td>
</tr>
<tr>
<td>RFQ</td>
<td>3.62</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>≃ 300</td>
<td>4.6</td>
</tr>
<tr>
<td>MEBT</td>
<td>3.62</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>≃ 300</td>
<td>4.0</td>
</tr>
<tr>
<td>DTL</td>
<td>90.0</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>≃ 300</td>
<td>38.9</td>
</tr>
<tr>
<td>Spokes</td>
<td>216</td>
<td>13</td>
<td>2</td>
<td>-</td>
<td>≃ 2</td>
<td>55.9</td>
</tr>
<tr>
<td>Med.-β</td>
<td>571</td>
<td>9</td>
<td>4(6C)</td>
<td>0.67</td>
<td>≃ 2</td>
<td>76.7</td>
</tr>
<tr>
<td>High-β</td>
<td>2000</td>
<td>21</td>
<td>4(5C)</td>
<td>0.86</td>
<td>≃ 2</td>
<td>178.9</td>
</tr>
<tr>
<td>HEBT</td>
<td>2000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>≃ 300</td>
<td>239.5</td>
</tr>
</tbody>
</table>

### Diagram Details:

- **Frequency Bands:**
  - LEBT: 352.21 MHz
  - RFQ: 704.42 MHz

### June, 2018

**HB2018**
Changes Since the TDR

What has changed?
Changes Since the TDR

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- Longer RFQ (3 → 3.6 MeV)
- Longer DTL (78 → 90 MeV)
Changes Since the TDR

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- Shorter elliptical cavity sections (medium/high β)
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- Increased SRF gradients by $\sim 11\%$
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- Increased beam intensity
- Contingency space maintains same upgrade possibilities
Changes Since the TDR

Modular cryomodules + LWUs in the Cold Linac

Spokes

Medium-β

High-β

8520 mm
Beam Dynamics Considerations

Boundary conditions

- Unprecedented loss control $\rightarrow$ 1 W/m loss limit
- Main cause of losses is connected to halo creation
  - mismatches
  - high space charge and tune depression
  - non-linear fields
  - escape of particles from the accelerating bucket
  - errors (misalignment, machining, construction, ...)

June, 2018
Beam Dynamics Considerations

Design Main Choices

- The zero current phase advance per period in all the planes must be less than 90 deg
- The phase advance per meter (average phase advance) variation should be smooth and continuous
- At ESS on top of this the average phase advance changes monotonically
- The tune depression, $k_{sc}/k_0$, must stay above 0.4 in all the planes during acceleration
Beam Dynamics Considerations

Tune Depression

...Phase Advance <90 degrees...

....Smooth Transitions...

...Avoid strong tune depression...

...Equipartition vs Equi-Tune-Depression...
- IS and LEBT built by our in-kind partners in INFN Catania
- Microwave Discharge Ion Source
- High reliability and long mean time between failure (MTBF)
- Up to 3 ms long pulse at flat top
- 75 keV energy
Beam Dynamics Studies

Sections: IS+LEBT

- IS and LEBT built by our in-kind partners in INFN Catania
- LEBT 2.5 m long with two solenoids
- Iris to adjust the current
- Chopper removes low quality head and tail of beam
- Diagnostics to characterise and monitor the beam
- Design space-charge compensation (SCC) of 95%
- Capability to inject $H_2$ and $N_2$ to enhance SCC
Example - Solenoid Transmission Scan

\[ B_2 [T] \]

\[ B_1 [T] \]

Transmission [%]

Courtesy A. Ponton
RFQ built by our in-kind partners in CEA Saclay
- 4-vane structure, 4.55 m long, accelerates to 3.62 MeV
- 60 tuners, 4 coupler ports, 36 vacuum ports, 28 pick-up ports, 80 cooling connectors
- Designed to minimize RF power losses, and ease machining
- Aperture profile at entrance optimized for minimal convergence of input beam
- Final focal section at end provide slight divergence to optimise matching into MEBT
Solenoid Transmission Scans: LEBT+RFQ

- Best transmission is 92% for \((B_1,B_2) = (0.235, 0.1975)\)
- Simulations taking into account aperture limitations.

Courtesy A. Ponton
Beam Losses in the RFQ

Very good transmission, majority of losses in the beginning of acceleration phase
Beam Dynamics Studies

Study on RFQ errors and non-conformity

From A. Ponton, TUPAF067 IPAC’18
Beam Dynamics Studies

Sections: MEBT

• MEBT built by our in-kind partners at ESS-Bilbao
• Match and transport the beam into DTL, characterise the beam from the RFQ
• 4.0 m long (check)
• 11 quadrupoles, 3 buncher cavities
• Fast chopper to clean mismatched head of the pulse
- No periodic structure $\rightarrow$ non-trivial to match
- Cannot focus as strongly as RFQ or DTL $\rightarrow$ emittance growth unavoidable
• DTL built by our in-kind partners at INFN-LNL
• 5 tanks of around 8 m length
• Energy 3.6 MeV → 90 MeV
• 2.8 MW klystron for each tank, 2.2 MW needed for acceleration field assuming 50 % ohmic losses
• Increased input energy simplifies first drift tubes
• Transverse focusing by permanent magnets in every 2nd DT
• RF phase & amplitude corrected tank-by-tank
Beam Dynamics Studies

Sections: DTL

- Commissioning of 1st tank particularly challenging
- 15 BPM’s planned, at least 2 per tank (tank distribution is 6, 3, 2, 2, 2)
- The positions of BPM’s and steerers are optimised for trajectory correction
Beam Dynamics Studies

Sections: Spokes

- Spoke cavities built by our in-kind partners at IPN Orsay
- DTL-Spoke transition to superconducting (LEDP)
- 2 spokes per cryostat, 13 cryostats
- Max gradient 9 MV/m
- Larger aperture compared to NC structures

Courtesy S. Bousson
The electric (left) and magnetic (right) field maps of the spoke cavity
Beam Dynamics Studies

Linac Warm Units (LWU)

- All quadrupoles and corrector magnets after DTL built by our in-kind partners at Elettra
- Between each cryomodule there is one Linac Warm Unit (LWU)
- 2 quadrupoles, 1 BPM, 1 dual-plane corrector, central slot for diagnostics
6-cells $M\beta$ almost same length as 5 cells $H\beta$
4 cavities per cryostat, cryostat 5.6 m long
9 $M\beta$ and 21 $H\beta$ cryostats
Accelerating field
The frequency jump is a challenging point for beam dynamics and require soft longitudinal transition between Spoke - Med. $\beta$.

352 MHz vs. 704 MHz

Lower frequencies are favoured due to looser tolerances in manufacturing cavity components. Lower frequencies also have the advantage of reducing RF losses in superconducting cavities, decreasing beam losses through larger apertures, and ameliorating higher order mode (HOM) effects from the high-current beams. Higher frequencies are encouraged by the desire to keep the size of the superconducting cavities small, making them easier to handle and reducing manufacturing costs. The cryogenic envelope and power consumption are also reduced at higher frequencies.
The frequency jump is a challenging point for beam dynamics. Require soft longitudinal transition between Spoke - Med. $\beta$ We see losses originating from this region in end-to-end studies.

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• Distribution of losses along the ESS linac

• The energy distribution of the particles lost from the start of the medium-$\beta$ and a few periods into the high-$\beta$ section. Almost no losses from the upstream linac are seen.
Considering the cells of the same cavity as independent gaps is an unrealistic approach.

Mechanical error in a cell influences the accelerating field in all the cavity and not only in that cell.
Averages of the normalised RMS emittances and power loss at 100% (red) and 99% (blue) confidence levels.
Beam Dynamics Studies

Sections: Contingency, Dumpline, A2T

- HEBT beam physics design by our in-kind partners at Aarhus University
- Contingency of 130 m, for future upgrades, 15 lattice periods
- Dipole brings beam up to target level at a 4° angle
- Achromatic dogleg
- Dipole off → beam to dump
- H+V rastering at up to 40 kHz vertical and 29 kHz horizontal paint the beam onto the rectangular target area
- Phase advance between raster centre and the cross over point is set to 180 deg.
Beam Dynamics Studies

Sections: Contingency, Dumpline, A2T

15 linac contingency periods
UHB, 128 m

4°

10 RMS, X, Y

DMPL, 49 m

5 MW Target

A2T, 45 m

Dipole

Quadrupole

Vertical displacement from target [mm]

Courtesy H. Thomsen
Beam Dynamics Studies

Target Painting

$<J>_{\text{max}} = 53.3 \, \mu\text{A/cm}^2$

Courtesy H. Thomsen
Beam Dynamics Studies

Target Painting

Courtesy H. Thomsen
• The beam dynamics design of the ESS linac has advanced since the TDR
• The strict requirement on losses and halo control together with reliability and cost drives the design optimisations
Thank you!