BEAM DYNAMICS DESIGN OF ESS WARM LINAC

Outline

- ESS Parameters
- SOURCE
- LEBT
- RFQ
- MEBT
- DTL
ESS parameters

Particle species: p
Energy: 2.5 GeV
Current: 50 mA
Average power: 5 MW
Peak power: 125 MW
Pulse length: 2.86 ms
Rep rate: 14 Hz
Max cavity surface field: 40 MV/m
Operating time: 5200 h/year
Reliability (all facility): 95%
Proton Source Requirements

- Proton Energy 75 keV
- Large currents (60-80 mA)
- Pulsed operation (2.86 ms - 14 Hz)
- Low emittance (0.2 to 0.3 \( \pi \) mm mrad)
- Short pulse rise time (100 ns)
- Long lifetime (>> 1 month)
- Robust extraction system
- High reliability (> 99%)
- LEBT optimization

**Issues:** experimental investigations planned to validate calculations
Proton source

Based on knowledge acquired with TRIPS, SILHI and VIS high intensity proton sources

<table>
<thead>
<tr>
<th>Status</th>
<th>TRIPS</th>
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</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>80 keV</td>
</tr>
<tr>
<td>Proton current</td>
<td>55 mA</td>
</tr>
<tr>
<td>Proton fraction</td>
<td>≈80%</td>
</tr>
<tr>
<td>RF power, Frequency</td>
<td>Up to 1 kW @ 2.45 GHz</td>
</tr>
<tr>
<td>Axial magnetic field</td>
<td>875-1000 G</td>
</tr>
<tr>
<td>Duty factor</td>
<td>100% (dc)</td>
</tr>
<tr>
<td>Extraction aperture</td>
<td>6 mm</td>
</tr>
<tr>
<td>Reliability</td>
<td>99.8% @ 35mA (over 142 h)</td>
</tr>
<tr>
<td>Beam emittance at RFQ</td>
<td>0.07πmmrad @ 32 mA</td>
</tr>
</tbody>
</table>

- Movable magnetic system composed by two solenoids
- Five electrodes extraction system
Flexible Magnetic field

1. "Simple Mirror"

2. "Off-Resonance"

3. "Magnetic Beach"

<table>
<thead>
<tr>
<th>current [A]</th>
<th>Inj</th>
<th>Med</th>
<th>Ext</th>
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<tbody>
<tr>
<td>Simple Mirror</td>
<td>400</td>
<td>-300</td>
<td>400</td>
</tr>
<tr>
<td>Off-Resonance</td>
<td>155</td>
<td>120</td>
<td>170</td>
</tr>
<tr>
<td>Magnetic Beach</td>
<td>260</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
PS-ESS beam extraction

**Itot= 98.55 mA**

*(H+=90%; H2+=10%)*
PS-ESS beam extraction

AXCEL Beam output @ 0.14 m has been used as input for TRACEWIN simulations.

**Alpha** = -10.2955
**Beta** = 1.9033

Proton beam emittance rms norm. @ 0.14 m = 0.126 pi mm mrad
The required for the ESS facility can be satisfied by means of conventional Microwave Discharge Ion Source (MDIS) based on the plasma direct absorption of the pumping electromagnetic waves through the Electron Cyclotron Resonance mechanism.

In PS-ESS design we merged the best solutions already tested in previous sources with a flexible magnetic system able to produce both standard and new magnetic profiles that will allow us to increase the current, increase the proton fraction, reduce the emittance and take under control the beam formation.
LEBT design

- **Solenoid assembled with steerer**
- **RFQ collimator used to dump the chopped beam**
- **Chopper assembled with TMP**
- **Cooling system will be sized for full beam power (300W)**
- **Repelling electrode**
LEBT configuration

Free space for diagnostics

Solenoid

160 mm flange

Solenoid

Total length = 2100 mm
Chopper plates were bent at $20^\circ$ to create a flat transversal electric field.

Electronics developed by INFN-LNS for the SPIRAL 2 project have already been tested at CEA-IRFU.

Low voltage control electronics is shown.

Measured performance @ 10kV:
- Rise and fall time of 13-15 ns (A,B)
- Up to 1.3 KHz of repetition rate (C)

ESS requirements:
- Beam rise and fall time of 100 ns
- 14 Hz repetition rate

Yellow = HV signal, Blue = TTL driver, Purple = pick-up signal.
Pulse beam formation

ESS requirements:
- 14 Hz repetition rate
- 2.86 ms beam width
- Emittance < 0.2 \( \pi \text{mm.mrad} \)
- 100 ns rise and fall time

Highly divergent beam during source startup must be stopped

Low emittance growth and Twiss parameters coupled to RFQ acceptance are required

- Estimate and reduce the rise time
- Estimate the charge that must be cut by MEBT-Chopper

Estimate the fall time

10 us needed to restore the space charge compensation
Steady state

Output of Axxel extraction system simulation

Optimum magnetic configuration have been found with TraceWin beam transport simulation...

...to match RFQ twiss parameters

Magnetic field

SCC=98%
Necessity of high SCC value

ESS requirement: Emittance $< 0.2 \pi \text{mm.mrad}$

<table>
<thead>
<tr>
<th>SCC</th>
<th>Chopped Current</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>98%</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>95%</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>93%</td>
<td>NO</td>
<td>NO</td>
</tr>
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</table>
Chopped beam

6.6 kV is enough to chopping the beam into the collimator

6.6 kV

SCC=98%

SCC=0%

Collimator
Chopping of not compensated beam

- SCC=0%
- During source start-up
- 65% Chopping Confinement (CC)
- 6.6 kV is also enough to chopping the not compensated beam
- Collimator
- OK

Diagram showing normalized particle density and current positions.
LEBT status

• To fulfill 100ns beam rise time requirement a MEBT CHOPPER is mandatory.
• It is necessary an high Space Charge Compensation, more than 95%, to avoid emittance growth and compensate LEBT Chopper effects.
• The SCC can be speed-up by injecting Argon.
RFQ
RFQ DESIGN EVOLUTION

Motivations for a shorter RFQ

Performance requirements

Previous design
- Initial operation at a peak beam current of 50 mA but upgradable at 75 mA
- Beam loss above 2 MeV limited to 1 W/m to limit activation
- Transverse and longitudinal emittances minimized to reduce potential for subsequent halo development
- No longitudinal tails as they are known to translate into transverse halo

Current design
- Peak operational beam current will not exceed 50 mA
- No limit to allowable beam loss below 3 MeV
- Halo development and beam loss in the high energy linac section traceable to the RFQ are minimized
- No longitudinal tails as they are known to translate into transverse halo
- Phase advances matched to adjacent sections

Benefits
- Fabrication and operational risk: less tuners, vacuum and RF seals, pumps, ...
- Cost in machining and brazing
- Alignment

Results
RFQ with 5 one-meter sections:
- High performance stand-alone structure
- Very long bunching section
- Slow rate of acceleration
- Fulfills all requirements

RFQ with 4 one-meter sections:
- Fully integrated in the linac
- Higher losses at high energy
- But very similar performances
- Fulfills all requirements
RFQ parameters

Figure 1: Main geometry parameters.

Figure 2: Voltage and 2D frequency shift.

Figure 3: Phase advances.

Emit rms = 0.13 MeVdeg

Figure 4: Beam portrait in longitudinal phase space.
RFQ status

- The transmission is very high and the longitudinal distribution is tailless.
- Significant improvements in the integration of the RFQ design have also been achieved in parallel with the consolidation of the ESS linac physical design.
- The new RFQ design is fulfilling all the updated performance requirements and the fabrication and operational risks as well as the cost have also been lowered substantially.
MEBT
From a short to long MEBT

From the May 2012 baseline, the MEBT was extended to include:

- Fast chopper
- Beam instrumentation
- Collimation

In CDR

1.2 meters

Actual

3.5 meters
MEBT envelopes
The RFQ simulation actually includes the un-captured particles.
Most of the un-captured particles seem lost by the end of the DTL. No loss in the SC part for both case but some difference in the HEBT.
Distributions out of the DTL w/ and w/o the cut

- Distributions become quite similar by the end of the DTL.
- The computation accurate for the un-captured particles?
How to decide collimator locations

- Sample particles in the normalized phase space:
  - $0.5\sigma$, $1.0\sigma$, ..., $4.0\sigma$
  - $30^\circ$, $60^\circ$, ..., $360^\circ$
- Space charge deforms the distribution

- Samples particles of $3\sigma$ and above at the end of the MEBT are left.
- Not all samples above $3\sigma$ at the entrance ends at above $3\sigma$ at the end.
- An effective collimation requires weights on specific angles even for a Gaussian distribution.
possible collimator locations for the MEBT

- Good locations found in the second space for BI.
- $6\text{kW} \times 0.25\% \ (\sim 3\sigma) = 15 \text{ W. (Feasible ??)}$
- The influence hardly seen on the halo if placed as far as $\sim 4\sigma$. 

Between quads possible?
Output distribution and halos w/ and w/o collimators

**W/o**

- Ele: 84 [3.53188 m]  NGOOD : 298206 / 298206
- X(mm) - X(mrad)
- Y(mm) - Y(mrad)
- P(deg @352.21 MHz) - W(MeV)
- Xmax = 4.757 mm  Ymax = 2.959 mm
- Po=0.118 deg  Wo=2.99853 MeV

**W/**

- Ele: 92 [3.531188 m]  NGOOD : 295673 / 295673
- X(mm) - X(mrad)
- Y(mm) - Y(mrad)
- P(deg @352.21 MHz) - W(MeV)
- Xmax = 4.760 mm  Ymax = 2.300 mm
- Po=0.113 deg  Wo=2.99854 MeV

**Halos**

- Position (m)
• Transverse emittances are slightly improved as well.
• The influence on the loss in the SC sections haven’t been studied yet.
MEBT status

• In the May 2012 baseline, the MEBT was extended from ~1.2 m to ~3.5 m to include the fast chopper, diagnostic devices, and collimators.

• Due to concern with the shape of the output distribution, the MEBT has been modified and one configuration with better beam dynamics property was found. It was seen that the modified MEBT improves the beam dynamics throughout the linac.

• Following the SNS experience, the MEBT collimation scheme has been studied. It is observed that the collimators could reduce the halo throughout the linac but their influence on the loss in the SC section haven’t been clarified yet.
Input energy of 3 MeV.
Maximum integrated field of 3.8T for PMQ.
Currents: 50 mA.
FODO PMQ Lattice.
PMQ law almost equipartitioned.
Input RMS emittance Tr. / Long. 0.22/0.28 mmmrad
### DTL Layout

<table>
<thead>
<tr>
<th>Tank</th>
<th>Length [m]</th>
<th>Cells</th>
<th>Total Power [kW]</th>
<th>Max Kp</th>
<th>Final Energy [MeV]</th>
<th>E0 [MV/m]</th>
<th>R bore [mm]</th>
<th>Flat length [mm]</th>
<th>Phase [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.953</td>
<td>66</td>
<td>2061</td>
<td>1.42</td>
<td>21.5</td>
<td>2.8 ÷ 3.2</td>
<td>10</td>
<td>0.7</td>
<td>-35 ÷ -24</td>
</tr>
<tr>
<td>2</td>
<td>7.628</td>
<td>36</td>
<td>2117</td>
<td>1.43</td>
<td>41.1</td>
<td>3.16</td>
<td>10</td>
<td>0.5</td>
<td>-24</td>
</tr>
<tr>
<td>3</td>
<td>7.762</td>
<td>29</td>
<td>2099</td>
<td>1.40</td>
<td>60.0</td>
<td>3.16</td>
<td>11</td>
<td>0.5</td>
<td>-24</td>
</tr>
<tr>
<td>4</td>
<td>7.724</td>
<td>25</td>
<td>2076</td>
<td>1.36</td>
<td>77.7</td>
<td>3.16</td>
<td>12</td>
<td>0.4</td>
<td>-24</td>
</tr>
</tbody>
</table>

**Graph:**
- **Y-axis:** Energy gain per meter (MeV/m)
- **X-axis:** Position (m)

The graph shows the energy gain per meter across different positions in the DTL layout.
Design Laws on E0 phase and surface field
Beam Density with Input distribution Gaussian 6σ

Ratio Bore/RMS from 9 to 6
Equipartitioning all along the DTL

High order resonances
Gradient High
Gradient Low
Uniform:
ET/E0T=1.05
EL/E0L=1.09

Gaussian:
ET/E0T=1.14
EL/E0L=1.18
Max transverse acceptance = 11.6 mmmrad norm.

Max Longitudinal acceptance = 10 degMeV

Acc/RMS Ratio:
- Transverse = 53
- Longitudinal = 91
Error study on the DTL

- All errors apply together with a Uniform input beam distribution
- with added a “halo” distribution with 3 times the emittance
- and 3\(\sigma\) as gaussian size distribution, 0.625% of the beam as halo,
- i.e. 1 kW.
- 100 random DTL generated.
- 1.6*10^5 particles i.e. 1 W for particle at 50 mA, 80 MeV.
- Separate X,Y Steerer used with max force of 1.6 mT*m.
- 4 Steerers and 2 BPM for each tank.
- Diagnostics BPM with 0.05 mm accuracy.
Gaussian 6σ

Uniform+Halo

With Uniform+Halo is increased the number of particles at large amplitude
Errors results on quad without correction Steerers

Step 1 ⇒ Maximum Quad shake of X,Y ±0.2 mm; ±1°; ±1%

Quad shake of X,Y ±0.1 mm; ±0.5°; ±0.5%  Total loss=42 Watts

Max emittance growth=40%
Errors results on quad with correction Steerers

Step 1 ≡ Maximum Quad shake of $X,Y \pm 0.2 \text{ mm; } \pm 1^\circ; \pm 1\%$

Quad shake of $X,Y \pm 0.1 \text{ mm; } \pm 0.5^\circ; \pm 0.5\%$

Max emittance growth=20%

Total loss=2 Watts
DTL status

• Complete definition of DTL parameters.
• Solution with 4 Tanks.
• With the steerers the losses are reduced by a factor 10 and the emittance growth by a factor 2.
Conclusion

The general rules used are:

• Smooth variation of the phase advance between sections.
• Equipartitioning law in the DTL, to avoid emittance exchange phenomena.
• Check the Halo formation and development from the RFQ up to the target.
• Use of collimators in the MEBT.
• Avoid tune depression below 0.4.

By using these laws, the design is more robust and less sensitive to any source of errors.
END