Space Charge Resonances in Linacs

Ciprian Plostinar
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Beam dynamics design guidelines (meta-criteria) for high intensity proton linacs (HB’10, 12, 14, etc.):

- Avoid the 90-degree stopband (i.e. zero current phase advance less than 90 degrees).
  - Envelope instability
  - Fourth order resonance ($4\sigma=360$)
- Good matching at the beginning and at transitions between structures.
- Smooth and continuous phase advance variation, regular lattice, adiabatic changes
- Tune depression control
- Tunes chosen to avoid radial-longitudinal coupling resonances
  - Hofmann Resonance Chart
  - Equipartitioning is not necessary to avoid exchange
  - Rate of exchange depends on the crossing speed
  - Individual analysis of coupling resonances, excitation level, etc.
Proton/Ion Linac Development
Beam Dynamics Design Approach

**SNS**

- Ion Species: H⁺
- Output Energy: 400 MeV
- Frequency: 324/972 MHz
- Pulse Length: 0.5 ms
- Peak Current: 30/50 mA
- Protons per Pulse: 9.4 x 10¹³ / 1.5 x 10¹⁴
- Repetition Rate: 25 Hz
- Duty Cycle: 1.25%
- Average Beam Power: 80/133 kW
- Accelerating Structures: RFQ, DTL, SDTL, ACS
- Accelerator Length: ~244 m

**J-PARC**

- Ion Species: H⁺
- Output Energy: 1 GeV
- Frequency: 402.5/805 MHz
- Pulse Length: 1.0 ms
- Peak Current: 38 mA
- Protons per Pulse: 1.5 x 10¹⁴
- Repetition Rate: 60 Hz
- Duty Cycle: 6%
- Average Beam Power: 1.4 MW
- Accelerating Structures: RFQ, DTL, CCL, SCL
- Accelerator Length: ~257 m

**Non-Equipartitioned**

**Equipartitioned**
Beam Dynamics Design Approach

**Linac4**

- **Ion Species**: H⁻
- **Output Energy**: 160 MeV
- **Frequency**: 352.21 MHz
- **Pulse Length**: 0.4 ms
- **Peak Current**: 40 mA
- **Protons per Pulse**: $1.0 \times 10^{14}$
- **Repetition Rate**: 2 Hz
- **Duty Cycle**: 0.08%
- **Average Beam Power**: 5.1 kW
- **Accelerating Structures**: RFQ, DTL, CCDTL, PIMS (*CCL)
- **Accelerator Length**: ~80 m

**ESS**

- **Ion Species**: Protons
- **Output Energy**: 2 GeV
- **Frequency**: 352.21/704.42 MHz
- **Pulse Length**: 2.86 ms
- **Peak Current**: 62.5 mA
- **Protons per Pulse**: $1.1 \times 10^{15}$
- **Repetition Rate**: 14 Hz
- **Duty Cycle**: 4%
- **Average Beam Power**: 5 MW
- **Accelerating Structures**: RFQ, DTL, SC Spokes/Elliptical
- **Accelerator Length**: ~365 m

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**Proton Source**

- **LEBT**

**Normal Conduction Linac**

- **RFQ**
- **MEBT**
- **DTL**
- **CCDTL**
- **PIMS**
- **HEBT**

**Accelerating Structures**

- RFQ, DTL, CCDTL, PIMS (*CCL)

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**Proton Source**

- **LEBT**

**Normal Conduction Linac**

- **RFQ**
- **MEBT**
- **DTL**
- **Spokes**
- **SCL Med $\beta_s$**
- **SCL High $\beta_s$**
- **HEBT**

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**Superconducting Linac**

- **704.42 MHz**

**Accelerating Structures**

- RFQ, DTL, SC Spokes/Elliptical

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**Equipartitioned**

**“Equitunes”**
But, does all this matter?

- Avoiding space-charge resonances and instabilities can require considerable efforts
  - Strict phase advance laws throughout the linac
  - Working point selection limit
- Design can be suboptimal and more costly
  - Particularly true for superconducting machines
- What is the figure of merit that we are aiming for?
- Can some emittance growth be tolerated?
The ISIS Experience

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Energy</td>
<td>70.4</td>
<td>MeV</td>
</tr>
<tr>
<td>Frequency</td>
<td>202.5</td>
<td>MHz</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>200-250</td>
<td>μs</td>
</tr>
<tr>
<td>Peak Current</td>
<td>25</td>
<td>mA</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Total Length</td>
<td>55</td>
<td>m</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>1-1.25</td>
<td>%</td>
</tr>
</tbody>
</table>
The ISIS Experience:

Typical user-run machine setup
The ISIS Experience: In an ideal world...

Emittance evolution - “Operational”

Emittance evolution - “Model”
The ISIS Experience

• ISIS simulation model tuning:
  – Avoid mismatches
  – Avoid resonances/instabilities
  – Minimise emittance growth

• ISIS Linac tuning
  – Real-life machine tuning has different aims
  – Reduce losses
  – Control activation to allow hands-on maintenance (crucial for an old machine)
  – In reality the beam core could be mismatched, but the transmission increased
Space-charge Resonances: Experimental evidence: UNILAC

- 2009 Experiment at UNILAC in GSI
- Linac lattice modified to investigate the 90 degree stop-band - $k_z/k_t=1$ resonance
- The resulting transverse emittance growth was measured thus giving an indication of a space-charge resonant effect.
- First experimental observation of emittance growth in a linac driven by the $k_z/k_t=1$ resonance.

Several key differences:
- A heavy ion was used rather than a proton/H- linac.
- Emittance ration $\varepsilon_t/\varepsilon_t$ closer to 10, which is much larger than those usually found in proton H- linacs where the ratio is closer to 1.
- Only transverse emittance was measured
Experimental evidence: SNS

• SNS Experiment
  – 90 degree stop-band
  – CCL lattice modified – phase advance kept constant for the test points
    • 4k=360 deg resonance
    • 2k_t-2k_z=0 coupling resonance

• Wire scanner profile measurements
  – “Beam shoulders” identified, characteristic for this resonance.

• Comparison with simulation
  – Very good agreement

• See D.-O. Jeon Talk/Paper THPM4X01
  – PRAB 19, 010101, 2016
Experimental Evidence: J-PARC

• Beam study campaign started in 2012
  – See THPWO087 – IPAC’13
• A wide variety of operating modes can be deployed
  – J-PARC uses EMQs throughout the machine
• Exploring tunes outside equipartitioning
• Testing alternative lattices to reduce intra-beam stripping losses
Experimental Evidence: J-PARC

- 2012 campaign: concentrated on SDTL
- 4 working points tested
- Both transverse and longitudinal beam parameters measured
Experimental Evidence: J-PARC

- **Procedure**
  - Full machine tuning for a 15 mA operating current. Front-end and DTL settings kept constant for all measurements.
  - New SDTL working point lattice deployed.
  - New DTL-SDTL transverse matching.
  - SDTL output measurement of transverse (wire scanners) and longitudinal (bunch shape monitors) parameters.
Experimental Evidence: J-PARC

- Phase advances for the four working points.
Experimental Evidence: J-PARC

- Simulation

![Graphs showing emittance over position for different times](image-url)
Experimental Evidence: J-PARC

- Measurement results

<table>
<thead>
<tr>
<th>Tt/Tz</th>
<th>εt (Pi.mm.mrad)</th>
<th>εz (Pi.mm.mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.216</td>
<td>0.269</td>
</tr>
<tr>
<td>0.9</td>
<td>0.229</td>
<td>0.233</td>
</tr>
<tr>
<td>0.7</td>
<td>0.253</td>
<td>0.223</td>
</tr>
<tr>
<td>0.5</td>
<td>0.293</td>
<td>0.161</td>
</tr>
</tbody>
</table>
Experimental Evidence: J-PARC

• 2012 campaign conclusions
  – Experimental observation of emittance exchange in a linac driven by the $k_z/k_t=2$ resonance.
  – First emittance exchange measurement in a linac with emittance ratios close to 1
  – Cases 1.0 and 0.9 consistent with simulation
    • Weak exchange for 0.9
  – Unexpected exchange for 0.7
    • Transverse mismatch at DTL-SDTL transition?
  – Unexpected transverse halo
Experimental Evidence: J-PARC

• 2015 - 2016 campaign
  – Several measurements performed with different configurations
  – Time consuming
  – A lot of data to analyse
  – Encouraging results
  – For more details see Y. Liu’s talk/paper – TUAM6Y01
Case 1 – 40 mA
Case 3 – 40 mA
Case 4 – 40 mA
Case 5 – 40 mA
Case 6 – 50 mA
Case 7 – 50 mA
Case 8 – 50 mA
Case 9, etc. – 40 mA
Preliminary Results (40 mA)
## Preliminary Results (40 mA)

<table>
<thead>
<tr>
<th>Tt/Tz</th>
<th>$\epsilon_t$ (Pi.mm.mr ad)</th>
<th>$\epsilon_z$ (Pi.mm.mr ad)</th>
<th>Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.36</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>0.39</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2k_z-2k_t=0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>0.37</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$k_z-2k_t=0$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing Normalised RMS Emittance (pi.mm.mrad)](image-url)
Pushing the intensity frontier

- Generic beam dynamics studies of ultimate intensity limits in proton linacs
- Industry-Oxford-STFC collaboration
- Parameters Space:
  - **Energy**: Up to 1 GeV
  - **Intensity**: Up to 1 A
  - **Power**: Hundreds of MW
- Several options developed
  - What are the limits/bottlenecks?
  - What is the parameter space?
  - Can technology be pushed?
- Details in MOPOY047 (IPAC16)
Pushing the intensity frontier

- 1 A, NC structures
- Design avoids $2k_z - k_t = 0$, $2k_z - 2k_t = 0$, $k_z - 2k_t = 0$
- Emittance growth: 30% (transv.), 10% (long)
- “No losses”, but small aperture to beam size ratio.
Pushing the intensity frontier

- 0.5 A, NC structures
- Design avoids $2k_z - k_t = 0$, $2k_z - 2k_t = 0$, $k_z - 2k_t = 0$
- Emittance growth: 20% (transv.), 5% (long)
- Better aperture to beam size ratio.
Pushing the intensity frontier

- 0.25 A, SC structures
- Design crosses $2k_z - k_t = 0$ and $2k_z - 2k_t = 0$
- Higher emittance growth: 40% (transv.), 100% (long)
- Best aperture clearance
Conclusions and Discussion

• Existing facilities show discrepancy between simulation models and machine operation
  – Halo matching vs. core matching
  – How can this be improved?
  – What is the figure of merit that we are aiming for?
  – Can some emittance growth be tolerated?

• A better understanding of space-charge resonances is emerging, but experimental evidence and impact remain limited.
  – A more robust experimental program needed
  – SNS, J-PARC?
    • Beam physics perhaps not a priority for running facilities
  – Machines under construction
  – Linac4 is an opportunity
  – Smaller experiments like IBEX (See WEAM6X01 – C. Prior) could bring interesting results