Beam Instrumentation for High-Intensity, Multi-GeV Superconducting Linacs

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Outline

• High Beam Power SRF Linacs
• Beam Diagnostics Issues in SRF Linacs
• Fermilab’s “Project X”
• Beam Test Facilities at Fermilab
• First Beam Measurements
• Examples of Beam Diagnostics R&D
• Summary
**High Power SRF Linacs**

<table>
<thead>
<tr>
<th></th>
<th>SNS</th>
<th>SPL</th>
<th>ESS</th>
<th>Myrrha</th>
<th>Project X</th>
</tr>
</thead>
<tbody>
<tr>
<td>E [GeV]</td>
<td>1.3</td>
<td>5</td>
<td>2.5</td>
<td>0.6</td>
<td>3</td>
</tr>
<tr>
<td>P [MW]</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>2.4</td>
<td>3</td>
</tr>
<tr>
<td>$I_{\text{pulse}}$ [mA]</td>
<td>42</td>
<td>40</td>
<td>50</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>$I_{\text{ave}}$ [mA]</td>
<td>2.5</td>
<td>0.8</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>duty factor [%]</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>CW</td>
<td>CW</td>
</tr>
<tr>
<td>pulse lenght [ms]</td>
<td>1</td>
<td>0.4</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>rep. frequency [Hz]</td>
<td>60</td>
<td>50</td>
<td>20</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

- **Goals of existing and planned SRF proton / H- linacs**
  - not listed: J-PARC (not SRF yet), FRIB (heavy ions), and others(?)
- **In common: High beam power!**
  - Requires precise control, stability, and verification of the guide fields.
SRF Linac Beam Diagnostics

- Essential beam instrumentation:
  - Beam trajectory
    - Beam position monitors (BPMs)
  - Beam phase, time-of-flight (TOF)
    - BPMs, WCMs, EO methods
  - Beam intensity
    - Toroid, wall current monitor (WCM)
  - Beam losses
    - BLM (ion chamber), TLM (Heliax)
  - Beam profile / emittance & halo
    - SEM (multitwist), wire scanner, Allison scanner, slits, vibrating wire, laser diagnostics, e-beam scanner, IPM, etc.
  - Bunch profile & tails
    - Feschenko monitor, laser diagnostics, etc.

- SRF issues:
  - High beam power -> low losses
    - Rule of thumb: <1 W/m
    - Residual losses of invasive diagnostics
  - Requires non-invasive diagnostics
    - Cavities: cleanroom class 10
    - Contamination from dissociated wire material, etc.
  - Cryogenic temperatures
    - Avoid moving parts in the CM
  - Cryo-string sectioning
    - Warm diagnostics sections
  - In the cryo-modules (CM):
    just BPMs, no other beam diag.!
Fermilab’s Project X: A Multi-MW Proton Source

• Serves simultaneously (intensity frontier):
  – HEP rare processes (kaons, muons)
  – Nuclear physics & energy R&D
  – HEP neutrino physics
    • Pulsed 3-8 GeV SRF linac extension
    • Stripped H- injection in RR / MI

• Staged approach back to the HEP energy frontier
  – Neutrino factory
  – Muon collider

• Schedule
  – 2010…2015: R&D
  – 2015…2020: construction
  – 2020…+: operation, upgrades

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### Project X SRF CW Linac Baseline Configuration

**"Warm" diagnostics**

<table>
<thead>
<tr>
<th>Section</th>
<th>Freq (MHz)</th>
<th>Energy (MeV)</th>
<th>Cav/mag/CM</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSR0 ($\beta_G=0.11$)</td>
<td>325</td>
<td>2.5-10</td>
<td>26 / 26 / 1</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR1 ($\beta_G=0.22$)</td>
<td>325</td>
<td>10-32</td>
<td>18 / 18 / 2</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR2 ($\beta_G=0.42$)</td>
<td>325</td>
<td>32-160</td>
<td>44 / 24 / 4</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>LB 650 ($\beta_G=0.61$)</td>
<td>650</td>
<td>160-520</td>
<td>42 / 21 / 7</td>
<td>5-cell elliptical, doublet</td>
</tr>
<tr>
<td>HB 650 ($\beta_G=0.9$)</td>
<td>650</td>
<td>520-2000</td>
<td>96 / 12 / 12</td>
<td>5-cell elliptical, doublet</td>
</tr>
<tr>
<td>ILC 1.3 ($\beta_G=1.0$)</td>
<td>1300</td>
<td>2000-3000</td>
<td>64 / 8 / 8</td>
<td>9-cell elliptical, quad</td>
</tr>
</tbody>
</table>

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**Project X**

**Beam Test Facilities**

- **ILC Test Accelerator (ILCTA)**
  - Beam tests (electrons) of one or more ILC RF units, each consists out of 3 ILC//XFEL cryomodules, keeping eight 1.3 GHz $\beta=1$ elliptical TESLA-style cavities, plus quad package and cold button-style BPM.
  - Electron beam diagnostics, only partially applicable for Project X.

- **Project X Test Accelerator (PXTA)** – formally known as High Intensity Neutrino Source (HINS)
  - Beam tests (protons / H-) of a Project X “like” source
    - LEBT, RFQ, MEBT, 325 MHz SC spoke resonators, etc. up to some MeV
    - Ultra-broadband chopper
    - Beam optics, lattice optimization
    - Vector modulator concept (single klystron RF source on many cavities).
    - Various beam diagnostics
The PX test linac is equipped with a reconfigurable, movable diagnostics station at the end of the linac.
• Beam profiles at the RFQ output
  – 3 wire scanners
  – No focusing
  – Beam fills physical aperture
First Beam Measurements
Beam Intensity

- **LEBT beam pulse**
  - 18 mA (different charge states)
  - 500 μsec
- **MEBT beam pulse**
  - 4 mA (most H+), 50 μsec

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**RFQ Outputs VS RFQ Power**

- RFQ bunched & unbunched beam
  - Toroir & BPM signal levels vs. RFQ RF power
First Beam Measurements

Beam Energy

- Stability of the beam energy
  - Phase of BPMs I-Q signal
  - Q-signal tuned to $0^0$: phase

- MEBT beam energy: 2.5 MeV
  - TOF of the sparked RFQ between two button BPMs

- Energy Stability

- Time of Flight – Sparked RFQ
  - Toriod
  - Up BPM
  - Down BPM

- 2.5 MeV = 43.9 ns
- ~ 45 ns
- ~ 8 keV
Future Diagnostics Layout & Laser Emittance

T: Toroid
GV: Gate Value
Q: Quadrupole
LW: Laser Wire
SEM: Secondary Emission Monitor
BPM: Beam Position Monitor
WS: Wire Scanner
S: Horz and Vert Slits
BSM: Bunch Shape Monitor (Longitudinal)
FFC: Fast Faraday Cup
HM: Halo Monitor
FD: Faraday Cup/Dump
SM: Spectrometer Magnet
4-stage Chopper MEBT
Lattice Optimization

- Each kicker
  - 5 mrad
  - 750 volt
  - 0.5 m long
  - 150 mm gap
  - 1 nsec rise & fall time!
  - > 80 MHz rep. freq.

OFF

Tracking (Partran) results: 100k particles

ON

Tracking (Partran) results: 100k particles
Beam Diagnostics R&D: Beam Position Monitors

Cold button BPM

Stripline BPM
Beam Diagnostics R&D: Bunch Shape Monitor

Focus/Steering HV
Beam Port
Deflector RF and Single-Stub Matching
EMT
Beam Diagnostics R&D: Fast Faraday Cup (SNS)

- TD S21 transmission measurement
  - 4 psec risetime increase
  - 12% amplitude decrease

150 psec / div

Courtesy C. Deibele / SNS

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Beam Diagnostics R&D: Laser Diagnostics (LBNL)

- Narrow band lockin amp detects 1MHz modulated signal
- Laser reprise is locked to 325MHz from machine
- Galvo scan is triggered by macropulse event signal
- Upper components are in tunnel, lower are in a laser hutch

Courtesy R. Wilcox / LBNL
Beam Diagnostics R&D: Beam Halo Diagnostics

- Vibrating wire beam halo diagnostics

Courtesy S.G. Arutunian / J. Bergoz
Summary

• High power SRF linacs put additional constraints to beam diagnostics
• Test accelerators are important for hands-on experiments and beam studies
• Fermilab will test a large variety of proton / H- beam diagnostics, many in collaboration with other laboratories.