RECENT IMPROVEMENTS IN BEAM DELIVERY WITH THE TRIUMF’S 500 MeV CYCLOTRON

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Accelerator Systems Department Head,
On behalf of the Cyclotron Development Team
• Introduction
• Ion Source & Injection
• Intensity Stabilization
• Sr-82 Isotopes Production
• Extraction Foils
• Beam Losses
• Beam Rastering
• Outlook
Three simultaneous beams
- increased number of hours delivered per year
- new beam species
- increased beam development capabilities

ARIEL-I (complete)
- Electron linac
- Buildings

ARIEL-II (2016-2021)
- Beta-NMR
- Photo-fission
- CANREB
- BL4N
- High Power Photo-fission
What can cyclotron produce?

**3 Simultaneous Proton Beams:**

<table>
<thead>
<tr>
<th>BL1A: 120 µA @ 480 MeV or</th>
<th>Molecular &amp; Materials Science, µSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL1B: few nA @ 200-480MeV</td>
<td>Proton &amp; Neutron Irradiations</td>
</tr>
<tr>
<td>BL2A: 100 µA @ 480 MeV</td>
<td>ISAC (Nuclear &amp; Astro-physics)</td>
</tr>
<tr>
<td>BL2C4: 100 µA @ 100 MeV or</td>
<td>Medical Isotopes (Sr-82)</td>
</tr>
<tr>
<td>BL2C1: few nA @ 116 MeV or</td>
<td>Proton &amp; Neutron Irradiations</td>
</tr>
<tr>
<td>BL2C1: few pA @ 70 MeV</td>
<td>Proton Therapy (Ocular Melanoma)</td>
</tr>
</tbody>
</table>
Cyclotron High Intensity Capability

Present stable performance is limited to 300 μA

BL Capacity  Routine
- BL1A (150μA)  (120μA)
- BL2A (100μA)  (70μA)
- BL2C (100μA)  (95μA)

Future
- BL4N (100μA)  TBD
Cyclotron Annual Performance: – 10 years

Availability – 5000+ hours
Reliability – 90%
Charge – 900 mA·hours
• Increase reliability (>90%)
• Increase uptime (>5500 hours/year)
• Increase total intensity to 400 µA
• Increase beam stability
• Reduce beam interruptions (<50 per week)
• Reduce activation and contamination
• Reduce maintenance overhead
• Powerful and versatile H- source test stand established for hardware and beam studies:
  • Filament lifetime studies: 3 weeks ⇒ 4 months
  • High performance demonstration: 25 mA cw
  • New efficient source development for 500 MeV cyclotron (1 mA in 2 mrad·mm)
• Future: New operational source will be installed in the spare HV terminal
**Source Instability**

**Issue:** Strong dependence of beam steering at the output of the optics box on beam pulser setting (duty cycle)

**Reason:** Insulating coating layer on the electrostatic steering plate charged by beam provided deflecting field

**Resolution:** Aluminium steering plates replaced with stainless steel plates
**Issue:** Beam asymmetry out of acceleration column

**Reason:** Circular apertures with biased parallel plates act as a quadrupole

**Resolution:**
- Include field maps into simulations or
- balance opposite polarity bias on the plates or
- make rectangular slot apertures
Injection Beam Transport Modelling

- Electrostatic steerer quadrupole effects were removed
- Accurate model of beam optics from source to cyclotron was validated
- Good matching achieved
- High Level Application (HLA) of injection line was created and passed on to operations – first at TRIUMF!

Beam envelope from H- source to buncher
Squares represent measured beam size (2 rms)
Cyclotron transmission is 70-75%; increased by ~5%:
- New 12 m section of injection line (better matching to cyclotron)
- Curved electrostatic deflector at injection (added vertical focusing)
• 3 high intensity beams extracted simultaneously
• **Issue:** Intensity instabilities in all beamlines
• **Reason:** BL1A / BL2A split ratio variation caused by radial beam density oscillation induced by the $v_r = 3/2$ resonance at the energy 428 MeV [3, 4] due to residual 3-rd harmonic of the cyclotron magnetic field
• **Mitigation:**
  • Pulser modulated duty cycle feedback on BL2A intensity
  • 3-rd harmonic compensation with harmonic coils 12 and 13
  • Active feedback on radial beam position by regulating 1-st harmonic component with harmonic coil 12
• **Outcome:**
  • Intensity instabilities in BL1A and BL2A within +/- 1% - **solved!**
  • Intensity instabilities in BL2C +/- 5% - **still a problem**
Intensity Stabilization – Phase 2

- **Remained issue:** Intensity instabilities in BL2C (+/- 5%)
- **Reason:** Not understood yet
- **Observation:** With vertical mis-steering at injection there is vertical size/position fluctuation, causing variation of extracted beam at 100 MeV with partially dipped foil
- **Mitigation:** Extraction by a narrower foil fully dipped through the beam
- **Outcome:** Fast intensity instabilities in BL2C reduced down to +/- 1%

BL2C4 extracted current: left part - extraction with fully dipped foil; right part - with partially dipped foil
In 2013 Sr-82 Production Facility upgraded to 100 µA of protons

- **Need:** To run BL2C4 in a single user mode
- **Problem:** ~2% of beam bypassing widest extraction foil
- **Solution:** With 3 trim coils we made a field bump in $B_z$ to allow a 180 degree phase slip so that the whole beam of ~50 degree phase width turns around, gets decelerated back and passes through extraction foil again

**Future plans:**
- Increase Sr-82 production by 50% with elongated Rb target
- Reduce radioactive gas (O-15) release into nuclear ventilation with introduction of a delay/decay line
- Optimize target cooling
- Redesign BL2C4 (~5 m) to introduce beam rastering
<table>
<thead>
<tr>
<th>2005</th>
<th>2016</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Front side" /></td>
<td><img src="image2.png" alt="Front side" /></td>
</tr>
<tr>
<td>Used Pyrolytic Graphite foil (stainless steel frame).</td>
<td>Highly Oriented Pyrolytic Graphite at the end of the year (tantalum frame).</td>
</tr>
<tr>
<td><strong>Loose $^7$Be tank contamination around extraction 1A (in counts per min.):</strong></td>
<td></td>
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<tr>
<td>$4.10^5$</td>
<td>$2.10^4$</td>
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<tr>
<td><strong>Foil lifetime:</strong></td>
<td></td>
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<tr>
<td>~3 months, 50 mA hours</td>
<td>3+ years, 500 mA·hours</td>
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3 mechanisms leading to beam losses in the cyclotron:
1. Vertical effective emittance growth
2. Electromagnetic (Lorentz) stripping
3. Stripping on residual gas

**Mitigation:**
- Lorentz stripping was reduced from 5% to 3% by reducing extraction energy from 500 MeV to 480 MeV
- Cryo-pumping system upgrade: vacuum improved from $8 \times 10^{-8}$ to $2 \times 10^{-8}$ Torr.
- Studies of partial pressure of basic gases on the beam losses showed negligible impact on loss reduction beyond achieved vacuum

**Future plans:**
- Continue studies of beam vertical halo formation to reduce vertical tails losses down from 1.5%
Total Shutdown Dose for all TRIUMF Personnel
• Rotating a proton beam of reduced width (and smaller tails) on the ISAC targets would contribute to a more homogeneous temperature distribution across the target and enable operating at a higher average temperature.
  • Should allow a beam current increase of up to 50% of present levels
• The increased average temperature would enhance diffusion and effusion of the isotopes, and higher currents will boost production – both will contribute to higher yield of the radioactive ion beams.
Components and parameters:
- two magnets for X and Y movements
- two power supplies with adjustable frequencies: up to **400 Hz**.
- integral field up to 150 G-m

By adjusting the phases and amplitudes of the X and Y magnets a variety of rastering patterns can be achieved.
Non-intercepting Beam Position Monitor (BPM)
- Sensitivity ~2 µA
- Bandwidth ~10 kHz
New tune features:
- Beam is parallel in last drift
- 90 degree phase advance between raster magnets and target
- 4x4mm spot size
- Easy to steer
- Available diagnostics represents very well beam spot at the target
Beam Measurements

- $p^+ = 55 \mu A$
- Instant spot size = 4x4mm
- Rotating radius = 5.5 mm

Static beam profile

Rotating beam profile
Yield enhancement with rotating beam

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<tbody>
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<td>Li11</td>
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<td>Cs126</td>
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<td>1.29E+08</td>
<td>9.2E+07</td>
<td>70</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Cyclotron upgrade major objectives:

- Replace main magnet power supply (2017)
- Increase Sr-82 production by 50% (2017)
- Develop BL1A/BL1U beam sharing for Ultra Cold Neutrons program (2018)
- Build new BL4N with extracted 100 µA (4 years)
- Increase total extracted beam to 400 µA (5-7 years)
  - Build new efficient H- source
  - Replace old injection line
  - Solve space charge issues at injection
  - Increase Dee voltage by 5-7%
  - Develop stable extraction of 4 high intensity beams
- Reduce maintenance by switching to non-serviceable components (6-8 years)
  - New inflector
  - Cyclotron probes joints
- Extend running periods between major shutdowns to >1 year
Thank you!
Merci!

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