Board and system level testing in other RADSAGA facilities and beyond

Daniel Söderström
RADSAGA System Level Test Review
CERN, November 11-13, 2019
Outline

• Facility requirements for system level tests
• Example facilities
  / Heavy ions
  / Protons
  / Neutrons
• Summary
Facility requirements for system level tests

- High beam penetration
  - High energies
  - Projectile properties
- Large beam size
  - Large irradiation area
  - Dependent on system and test mode
Penetration of particles

- Ions
- For 10 cm range:
  - 200 MeV H
  - 400 MeV/n O
  - 600 MeV/n Ar
  - 900 MeV/n Kr

At very high energies, the particle range becomes limited by the inelastic interaction length.

https://www.bnl.gov/nsrl/userguide/let-range-plots.php
Penetration of particles

- Neutrons
  - Thermal: ~9 cm MFP in Si
  - 10 MeV: ~25 cm in water
  - Differs greatly with material, but generally long range

Penetration of particles

• **Gammas**
  
• $^{60}\text{Co }\gamma$ in Si: $\sim10$ cm MFP
  
  // $I(x) = I_0 e^{-\mu x}$
  
  // $MFP = \frac{1}{\rho\mu}$
  
  // (with suitable units)

Data from [https://www.nist.gov/pml/xcom-photon-cross-sections-database](https://www.nist.gov/pml/xcom-photon-cross-sections-database)
Penetration of particles

- Electrons
- Even if electrons are stopped, bremsstrahlung is present
- About 10 cm range in Si for 100 MeV electrons

Data from [https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html](https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html)
# Beam sizes – Heavy-ion facilities

<table>
<thead>
<tr>
<th>Heavy-ion facility</th>
<th>Beam size</th>
<th>Max energy (MeV/u)</th>
<th>Compliance with ESCC 25100</th>
<th>Cost of test per hour (ballpark)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSRL</td>
<td>60x60 cm² (typ. 20x20)</td>
<td>1500</td>
<td>Yes</td>
<td>~$5700</td>
</tr>
<tr>
<td>RADEF</td>
<td>5x5 cm² (3x3 in air)</td>
<td>16.3</td>
<td>Yes</td>
<td>~800 €</td>
</tr>
<tr>
<td>TAMU</td>
<td>4.5 cm diameter</td>
<td>40</td>
<td>Yes</td>
<td>~$1000</td>
</tr>
<tr>
<td>KVI</td>
<td>3x3 cm²</td>
<td>90</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>UCL</td>
<td>2.5 cm diameter</td>
<td>9.3</td>
<td>Yes</td>
<td>~800 €</td>
</tr>
<tr>
<td>GANIL</td>
<td>Few cm diameter, sweeping beam</td>
<td>60</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>LBNL</td>
<td>Few cm diameter</td>
<td>30</td>
<td>Yes</td>
<td>~$1600</td>
</tr>
<tr>
<td>GSI</td>
<td>1 cm diameter</td>
<td>2000</td>
<td>Yes</td>
<td>-</td>
</tr>
</tbody>
</table>
# Beam sizes – Proton facilities

<table>
<thead>
<tr>
<th>Proton facility</th>
<th>Beam size</th>
<th>Max energy (MeV)</th>
<th>Compliance with ESCC 25100</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSRL</td>
<td>60x60 cm² (typ. 20x20 cm²)</td>
<td>2500</td>
<td>Yes</td>
</tr>
<tr>
<td>KVI</td>
<td>12 cm diameter</td>
<td>184</td>
<td>Almost*</td>
</tr>
<tr>
<td>RADEF</td>
<td>10 cm diameter</td>
<td>55</td>
<td>Almost*</td>
</tr>
<tr>
<td>PSI PIF</td>
<td>9 cm diameter</td>
<td>230</td>
<td>Yes</td>
</tr>
<tr>
<td>LBNL BASE</td>
<td>8 cm diameter</td>
<td>55</td>
<td>Almost*</td>
</tr>
<tr>
<td>UCL</td>
<td>8 cm diameter</td>
<td>62</td>
<td>Almost*</td>
</tr>
<tr>
<td>TRIUMF PIF</td>
<td>7.5x7.5 cm²</td>
<td>480</td>
<td>Yes</td>
</tr>
<tr>
<td>TAMU</td>
<td>4.5 cm diameter</td>
<td>45</td>
<td>Almost*</td>
</tr>
<tr>
<td>GSI</td>
<td>1 cm diameter</td>
<td>4500</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*Protons should be delivered in the energy range 20-200 MeV
Beam sizes

• Bigger fields
  / Point sources, $^{60}$Co
  / CHARM
  / Reactors

Image from *Research Nuclear Reactor TAPIRO information sheet*, ENEA. 40 cm diameter Grand Horizontal irradiation channel. It has also the Grand Vertical Channel with 80-90 cm diameter.
NSRL – NASA Space Radiation Laboratory

Located in USA at Brookhaven National Laboratory

Much used for radiobiology testing

High-energy heavy ions and protons

Large beam size
Ion species

- Many ions from BNL booster
  - Almost any ion possible, table present used ions so far
- Switching time 1.5 – 2 minutes
  - (When pre-tuned for the new energy)
- Fluxes $10^6$-$10^{11}$ ions per spill

Time structure

- Spills and microstructure
- 300 ms every 2.8 - 6.6 s

Beam size and monitoring

- **Large field size**
  - Typically 20 x 20 cm²
  - Up to 60 x 60 cm²
- **Uniformity typically ± 3 %**
- **Monitoring**
  - Digital beam imager
  - Large ion chamber for high flux
  - Plastic scintillators for low flux
TRIUMF

Located in Vancouver, Canada
Protons (PIF)
Neutrons (NIF)
Proton Irradiation Facility, PIF

BL1B protons

- **Standard Test Energies**: 350 or 480 MeV (480 MeV preferred)
- **Some other energies with a degrader**
- **Extracted Intensity**: 0.1 to 3 nA
- **Flux**:
  - Standard location: $10^6$ to $4 \times 10^7$
  - Upstream location: $7 \times 10^6$ max
- **Spot Size**:
  - Standard location: 3x3 cm to 7.5x7.5 cm
  - Upstream location: 1 to 2 cm diameter
- **Spot Homogeneity**: Standard location: +/- 5%
- **Dose Rate**:
  - Standard location: 10 to 20 mGy/s
  - Upstream location: up to 500 mGy/s
- **Beam Counting and Monitoring System**: Ion Chamber or Scintillator
- **Device-Positioning System**: Remote-controlled X-Y platform with laser alignment
- **Access Conditions**: 20 m cable length to Control Area
- **https://www.triumf.ca/pif-beam-specifications**

BL2C protons

- **63 or 105 MeV**
- **Other energies available with a degrader or by changing the cyclotron extraction energy**
- **Extracted Intensity**: 0.1 to 7 nA
- **Flux**:
  - Standard location: $10^6$ to $1 \times 10^8$
  - Upstream location: $2 \times 10^6$ max
- **Spot Size**:
  - Standard location: 1x1 cm to 5x5 cm or 7.5 cm diameter
  - Upstream location: 0.5 to 2 cm diameter
- **Spot Homogeneity**: Standard location: +/- 5%
- **Dose Rate**:
  - Standard location: 50 to 100 mGy/s
  - Upstream location: up to 1000 mGy/s
- **Beam Counting and Monitoring System**: Ion Chamber, Scintillator, or Faraday Cup
- **Device-Positioning System**: Remote-controlled X-Y platform with laser alignment
- **Access Conditions**: 20 m cable length to Control Area

A 480 MeV proton has 58 cm range in Si (SRIM2013)
Neutron Irradiation Facility, NIF

- Spallation neutrons
- TNF
  - TRIUMF Neutron Facility
  - Target down BL1A
- BL1B and BL2C
  - Targets in PIF

https://www.triumf.ca/nif-beam-specifications
NIF, TNF area

https://www.triumf.ca/neutron-irradiation-facility
NIF, TNF area

- High flux but limited space
  - Fixed beamspot size, 5 cm x 15 cm (vertical x horizontal)
  - Narrow access channel, 15 cm in beam direction x 27 cm perpendicular to beam
  - Typical flux of >10 MeV neutrons: ~3x10^6 n/cm^2/s
NIF, BL1B area

• Large area for setting up and testing equipment in PIF
• Ability to change beam size and flux
  / Flux of >10 MeV neutrons: $10^3$ to $10^5$ n/cm$^2$/s
  / Circular beamspot, 5 to 75 cm diameter
• Collimated protons available at the same location (PIF) to confirm errors from a specific sensitive chip.
• Variety of stands and support tables with vertical positioning capability.
### NIF Beam data

<table>
<thead>
<tr>
<th>Energy</th>
<th>Thermal to 400 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flux</strong></td>
<td>2x10⁶ to 3x10⁶ above 10 MeV, 5x10⁵ thermal energies</td>
</tr>
<tr>
<td><strong>Spot Size</strong></td>
<td>5x12 cm</td>
</tr>
<tr>
<td><strong>Spot Homogeneity</strong></td>
<td>+/- 10%</td>
</tr>
<tr>
<td><strong>Beam Counting and Monitoring System</strong></td>
<td>BF₃ Counter and Activation Foils</td>
</tr>
<tr>
<td><strong>Device-Positioning System</strong></td>
<td>Movable Trolley with positive stop</td>
</tr>
<tr>
<td><strong>Access Conditions</strong></td>
<td>6 m cable length to Control Area</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BL1B neutrons</th>
<th>BL2C neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/E spectrum to 480 MeV</td>
<td>1/E spectrum to 120 MeV</td>
</tr>
<tr>
<td>10³ to 5x10⁵ above 10 MeV</td>
<td>10³ to 5x10⁴ above 10 MeV</td>
</tr>
<tr>
<td>5 to 75 cm diameter</td>
<td>30 to 150 cm diameter</td>
</tr>
<tr>
<td>+/- 10%</td>
<td>+/- 10%</td>
</tr>
<tr>
<td>BF₃ Counter and Activation Foils</td>
<td>BF₃ Counter and Activation Foils</td>
</tr>
<tr>
<td>Remote-controlled X-Y platform with laser alignment</td>
<td>Remote-controlled X-Y platform with laser alignment</td>
</tr>
<tr>
<td>20 m cable length to Control Area</td>
<td>20 m cable length to Control Area</td>
</tr>
</tbody>
</table>

Systems can be irradiated.

[https://www.triumf.ca/nif-beam-specifications](https://www.triumf.ca/nif-beam-specifications)
High energy accelerators in Europe: GANIL, GSI and KVI

European high-energy heavy-ion beams
GANIL – Caen, France
GSI – Darmstadt, Germany
KVI – Groningen, Netherlands
GANIL

• Small beam that can be swept over a region
  / Can cover 4x50 cm²
• Energies up to 60 MeV/u for ⁸⁶Kr
  / 1223 µm range in Si
• Might not be able to cover whole system
• Not able to penetrate packaged components
• One ion per campaign
GSI SIS18 beam

- Energies up to 2 GeV/u
  - From p to U
  - Lower for heavier elements
- Beam size 1 cm diameter
  - Beam sweeping 20x20 cm²
- Not commonly used for electronics testing
- One ion per campaign

https://www.gsi.de/en/researchaccelerators/accelerator_facility.htm
KVI

- Energies up to 90 MeV/u
  - He, C, O, Ne
- Up to 30 MeV/u
  - O, Ne, Ar, Kr, Xe
- Beam size 3x3 cm²
- cm range in Si for 90 MeV/u, and mm range for 30 MeV/u

Small part of system possible to irradiate. Some beam penetration.

AGOR cyclotron https://www.rug.nl/kvi-cart/research/facilities/agor/agorfirm/
European high-energy proton irradiation facilities

KVI continuation

PIF at PSI – Villigen, Switzerland
Proton beams

- PIF and KVI provide high energies
- UCL and RADEF have only lower energies available

<table>
<thead>
<tr>
<th></th>
<th>PIF</th>
<th>KVI</th>
<th>UCL</th>
<th>RADEF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>6 – 230</td>
<td>10 - 184</td>
<td>10 - 62</td>
<td>0.4 – 55</td>
</tr>
<tr>
<td>Beam size (cm diameter)</td>
<td>9</td>
<td>12</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Max. range in Si (mm, SRIM2013)</td>
<td>176</td>
<td>120</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>Flux (p/cm²/s)</td>
<td>&lt; 2x10⁹</td>
<td>&lt; 10⁹</td>
<td>&lt; 5x10⁸</td>
<td>&lt; 3x10⁸</td>
</tr>
</tbody>
</table>

Proton system level testing information: S. M. Guertin, Board Level Proton Testing Book of Knowledge for NASA Electronic Parts and Packaging Program
Summary

• Facilities where irradiation of whole 3D structures is possible are scarce
• Testing systems at other facilities would require some imagination, but is possible
• Testing with many particle types possible
  / Neutrons provide high penetration
  / NSRL heavy ion testing facility for 3D systems
Thank you for your attention!

• Daniel Söderström
  – daniel.p.soderstrom@jyu.fi

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 721624.
Bonus and old slides
### NIF vs ChipIr

<table>
<thead>
<tr>
<th></th>
<th>TNF neutrons</th>
<th>BL1B neutrons</th>
<th>BL2C neutrons</th>
<th>ChipIr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>Thermal to 400 MeV</td>
<td>1/E spectrum to 480 MeV</td>
<td>1/E spectrum to 120 MeV</td>
<td>(1/E) spectrum to 800 MeV</td>
</tr>
<tr>
<td><strong>Flux</strong> (neutrons/cm²/s)</td>
<td>2x10⁶ to 3x10⁶ above 10 MeV</td>
<td>10³ to 5x10⁴ above 10 MeV</td>
<td>10³ to 5x10⁴ above 10 MeV</td>
<td>10⁷ above 10 MeV</td>
</tr>
<tr>
<td><strong>Spot Size</strong></td>
<td>5x12 cm diameter</td>
<td>4 to 60 cm diameter</td>
<td>30 to 150 cm diameter</td>
<td>Up to 70x70 mm² (Planned up to 1 m² for future)</td>
</tr>
<tr>
<td><strong>Homogeneity</strong></td>
<td>+/- 10%</td>
<td>+/- 10%</td>
<td>+/- 10%</td>
<td></td>
</tr>
<tr>
<td><strong>Beam Counting and Monitoring System</strong></td>
<td>BF₃ Counter and Activation Foils</td>
<td>BF₃ Counter and Activation Foils</td>
<td>BF₃ Counter and Activation Foils</td>
<td></td>
</tr>
<tr>
<td><strong>Device-Positioning System</strong></td>
<td>Movable Trolley with positive stop</td>
<td>Remote-controlled X-Y platform with laser alignment</td>
<td>Remote-controlled X-Y platform with laser alignment</td>
<td></td>
</tr>
<tr>
<td><strong>Access Conditions to Control Area</strong></td>
<td>6 m cable length</td>
<td>20 m cable length</td>
<td>20 m cable length</td>
<td></td>
</tr>
</tbody>
</table>

**Diagram Description:**

- **TRIUMF Neutron Spectra:**
  - TNF for atmospheric spectra.
  - BL1B and BL2C for data from the neutron converter.

- **Graph:**
  - Neutron flux vs energy.
  - Comparison of atmospheric and ChipIr 2016 measurements.

- **Intensity vs E* graph:**
  - Log-log scale for intensity and E*.
  - Data points at E* values from 1 to 1000 MeV.
Electronic systems testing example

- A. de Bibikoff et al. RADECS 2019
- Irradiation of one PCB with components on both sides
- Considerations for SEL in system
  - IR camera to detect SEL
- Considerations for LET span of ion through the system
Electronic systems testing example

- A. de Bibikoff et al.
- Irradiation of one PCB with components on both sides
- Considerations for SEL in system – IR camera
- Considerations for LET span of ion through the system

A. de Bibikoff, Method for System-level testing of COTS electronic board under High Energy Heavy Ions, RADECS 2019
CERN facilities

CHARM already discussed
IRRAD – high-energy protons
Gamma ray facilities
Sometimes very high-energy ions
CHARM and IRRAD

- 24 GeV protons from PS in spills
- Sometimes 5-6 GeV/n ions
- Beam sizes
  - CHARM about 10x10 cm$^2$
  - IRRAD up to about a cm diameter
LANSCE

Los Alamos Neutron Science Center
Proton linac and neutron spallation targets
Industrial research at the Weapons Neutron Research facility (WNR)
Neutrons at LANSCE

- Electronic systems and ICs testing at the Irradiation of Chips and Electronic (ICE) Houses (ICE-I and ICE-II)
- 800 MeV protons on a tungsten spallation target
- Atmospheric neutron spectrum up to about 600 MeV
  / At ICE-II, see image
  / At ICE-I, lower energies

Los Alamos High-Energy Neutron Testing Handbook, Steve Wender, LANL
Radiobiology

- Facility used mainly for radiobiology, e.g. how astronauts are affected by space radiation
- Different irradiation routines
  / E.g. GCR simulation

# Proton Irradiation Facility, PIF

**BL1B protons**

<table>
<thead>
<tr>
<th><strong>Standard Test Energies</strong></th>
<th>350 or 480 MeV (480 MeV preferred)</th>
</tr>
</thead>
</table>

**Extracted Intensity** 0.1 to 3 nA

<table>
<thead>
<tr>
<th><strong>Flux (protons/cm²/s)</strong></th>
<th>Standard location: 10⁶ to 4x10⁷ (10⁶ possible)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream location: 7x10⁶ max</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Spot Size</strong></th>
<th>Standard location: 3x3 cm to 7.5x7.5 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream location: 1 to 2 cm diameter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Spot Homogeneity</strong></th>
<th>Standard location: +/- 5%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream location: +/- 10%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Dose Rate</strong></th>
<th>Standard location: 10 to 20 mGy/s (1 to 2 rads/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream location: up to 500 mGy/s (50 rads/s)</td>
</tr>
</tbody>
</table>

**Beam Counting and Monitoring System**

- Ion Chamber or Scintillator
- Remote-controlled X-Y platform with laser alignment

**Access Conditions** 20 m cable length to Control Area

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**BL2C protons**

<table>
<thead>
<tr>
<th><strong>Energies</strong></th>
<th>63 or 105 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Other energies available with a degrader or by changing the cyclotron extraction energy</td>
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</tbody>
</table>

<table>
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<tr>
<th><strong>Extracted Intensity</strong></th>
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</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Flux (protons/cm²/s)</strong></th>
<th>Standard location: 10⁶ to 1x10⁸ (10⁶ possible)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream location: 2x10⁶ max</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Spot Size</strong></th>
<th>Standard location: 1x1 cm to 5x5 cm or 7.5 cm diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream location: 0.5 to 2 cm diameter</td>
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<thead>
<tr>
<th><strong>Dose Rate</strong></th>
<th>Standard location: 50 to 100 mGy/s (5 to 10 rads/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream location: up to 1000 mGy/s (100 rads/s)</td>
</tr>
</tbody>
</table>

**Ion Chamber, Scintillator, or Faraday Cup**

**Remote-controlled X-Y platform with laser alignment**

**Access Conditions** 20 m cable length to Control Area

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A 480 MeV proton has 58 cm range in Si (SRIM2013)

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https://www.triumf.ca/pif-beam-specifications

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https://www.triumf.ca/proton-irradiation-facility
NIF, BL1B area

- Irradiation in the PIF area