THE BEAM CONDITIONS ON THE TARGET
AND ITS OPERATIONAL IMPACTS
ON BEAM INTERCEPTING DEVICES AT ESS

Yong Joong Lee (ESS)
Heine Dølrath Thomsen (Aarhus University)
Ryoichi Miyamoto (ESS)
Thomas Shea (ESS)

www.europeanspallationsource.se
19 June, 2018
Building ESS: 45% Completion in June 2018
ESS Target Environment

Proton beam:
2 GeV/5 MW
Proton beam: 2 GeV/5 MW
Proton beam: 2 GeV/5 MW

Proton Beam Window (PBW)
ESS Target Environment

Proton Beam Window (PBW)

Proton beam: 2 GeV/5 MW
ESS Target Environment

Proton beam: 2 GeV/5 MW

Proton Beam Instrumentation Plug (PBIP)

Proton Beam Window (PBW)
ESS Target Environment

Proton beam: 2 GeV/5 MW

Proton Beam Instrumentation Plug (PBIP)

Proton Beam Window (PBW)
ESS Target Environment

Proton beam:
2 GeV/5 MW

Proton Beam Instrumentation Plug (PBIP)
Proton Beam Window (PBW)
Proton beam: 2 GeV/5 MW
Target Wheel
Proton beam:
2 GeV/5 MW

Proton Beam Instrumentation Plug (PBIP)

Proton Beam Window (PBW)

Proton beam: 2 GeV/5 MW

Target Wheel

ESS Target Environment
ESS Target Environment

Proton beam: 2 GeV/5 MW

Proton Beam Instrumentation Plug (PBIP)

Proton Beam Window (PBW)

Proton beam: 2 GeV/5 MW

Moderator-Reflector Plug (MR Plug)

Target Wheel
Proton beam: 2 GeV/5 MW

Proton Beam Instrumentation Plug (PBIP)

Proton Beam Window (PBW)

Proton beam: 2 GeV/5 MW

Moderator-Reflector Plug (MR Plug)

Target Wheel
Proton beam: 2 GeV/5 MW

Proton Beam Instrumentation Plug (PBIP)

Proton Beam Window (PBW)

Proton beam: 2 GeV/5 MW

Moderator-Reflector Plug (MR Plug)

Target Wheel

Neutron Beam Extraction
ESS Target Environment

- Proton Beam Instrumentation Plug (PBIP)
- Proton Beam Window (PBW)
- Proton beam: 2 GeV/5 MW
- Moderator-Reflector Plug (MR Plug)
- Target Wheel
- Neutron Beam Extraction
Generate spallation neutrons

ESS Target Station: High Level Functions

Eric Pitcher
Generate spallation neutrons

tungsten target produces about 60 neutrons per proton
≈ $10^{18}$ neutrons per second
Generate spallation neutrons
Beryllium reflects neutrons that might otherwise escape, boosting performance by a factor of 5.
ESS Target Station: High Level Functions
ESS Target Station: High Level Functions

Slow the neutrons to speeds useful for science

Liquid hydrogen moderator at 20 K

Eric Pitcher
ESS Target Station: High Level Functions

Liquid hydrogen moderator at 20 K

Cold neutrons

Eric Pitcher
ESS Target Station: High Level Functions

Liquid hydrogen moderator at 20 K

conversion efficiency $\sim 10^{-5}$
cold neutrons

neutron guide (start of the neutron scattering instrument)

Guide neutrons to neutron scattering instruments

Eric Pitcher
ESS Target Station: High Level Functions

Liquid hydrogen moderator at 20 K

cold neutrons

neutron guide
(start of the neutron scattering instrument)

Eric Pitcher
High Power Spallation Target

• The ESS target stops 5 MW beam
  – It’s like stopping a Mercedes-Benz S-Class (2000 kg in weight) driving at 255 km/h every second.
Beam on Target

- Conflicting requirements:
  - **Uniform beam spot**: Lower damage rate and thermal load
  - **Minimum beam loss**: Higher neutron yield and lower heat deposition in target monolith structure

- Beam expander options:
  - **Nonlinear magnets**: relatively higher beam loss and risk of beam focusing via H-V coupling
  - **Raster scanning magnets**: introduces a time structure for CW or long-pulse beam
Beam on Target

• Conflicting requirements:
  – **Uniform beam spot**: Lower damage rate and thermal load
  – **Minimum beam loss**: Higher neutron yield and lower heat deposition in target monolith structure

• Beam expander options:
  – **Nonlinear magnets**: relatively higher beam loss and risk of beam focusing via H-V coupling
  – **Raster scanning magnets**: introduces a time structure for CW or long-pulse beam

For more details on beam raster at ESS:
N. Milas, 14:00 Wed (WG-B)
Beam Dynamics of the ESS linac
ESS Beam Raster

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pulse length</td>
<td>2.86 ms</td>
</tr>
<tr>
<td>Sweep frequency - horizontal</td>
<td>39.55 kHz</td>
</tr>
<tr>
<td>Sweep frequency - vertical</td>
<td>29.05 kHz</td>
</tr>
</tbody>
</table>
# Proton Beam Window

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Al6061-T651</td>
<td></td>
</tr>
<tr>
<td>Raster deflection, horizontal</td>
<td>mm</td>
<td>47.4</td>
</tr>
<tr>
<td>Raster deflection, vertical</td>
<td>mm</td>
<td>15.8</td>
</tr>
<tr>
<td>Beamlet RMS, horizontal</td>
<td>mm</td>
<td>10.67</td>
</tr>
<tr>
<td>Beamlet RMS, vertical</td>
<td>mm</td>
<td>3.99</td>
</tr>
<tr>
<td>Peak current density</td>
<td>mA/cm²</td>
<td>1.66</td>
</tr>
</tbody>
</table>

\[<J>_{\text{max}} = 66.5 \, \mu\text{A/cm}^2\]
Multiwire Beam Profile Monitor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>SiC</td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>mm</td>
<td>0.1</td>
</tr>
<tr>
<td>Pitch</td>
<td>mm</td>
<td>2</td>
</tr>
<tr>
<td>Secondary electron yield</td>
<td>-</td>
<td>0.010</td>
</tr>
<tr>
<td>Delta-ray yield</td>
<td>-</td>
<td>0.013</td>
</tr>
<tr>
<td>Total electron yield</td>
<td>-</td>
<td>0.023</td>
</tr>
</tbody>
</table>

**$\delta$-ray Net Charge Deposition: Horizontal Wires**

**$\delta$-ray Net Charge Deposition: Vertical Wires**
# Spallation Target

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>2.0</td>
</tr>
<tr>
<td>Pulse length</td>
<td>ms</td>
<td>2.86</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>14</td>
</tr>
<tr>
<td>Raster deflection, horizontal</td>
<td>mm</td>
<td>60.0</td>
</tr>
<tr>
<td>Raster deflection, vertical</td>
<td>mm</td>
<td>20.0</td>
</tr>
<tr>
<td>Beamlet RMS, horizontal</td>
<td>mm</td>
<td>13.5</td>
</tr>
<tr>
<td>Beamlet RMS, vertical</td>
<td>mm</td>
<td>5.05</td>
</tr>
<tr>
<td>Peak current density</td>
<td>mA/cm²</td>
<td>1.16</td>
</tr>
</tbody>
</table>

$\langle J \rangle_{\text{max}} = 46.3 \, \mu\text{A/cm}^2$
Beam on Target: Target Area Definition

• Proton beam shall not hit the structural part of the target vessel:
• Maximum cross section area of spallation volume: $190 \times 70 \text{ mm}^2$.
• Maximum deviation of beam centroid:
  – Horizontal: $\pm 14.7 \text{ mm}$
  – Vertical: $\pm 3.0 \text{ mm}$
• Virtual target area: $160 \times 64 \text{ mm}^2$
Stepwise Beam Commissioning at ESS

- Phase 0: 571 MeV on the dump and/or target
  - Commissioning up to the medium-beta cryo-modules
- Phase 1: 1.3 GeV on the target
  - Commissioning up to half of the high-beta cryo-modules
- Phase 2: 2.0 GeV on the target
  - Full commissioning
Proton Scattering at PBW

<table>
<thead>
<tr>
<th>Beam Energy</th>
<th>Fraction landed on target area</th>
<th>Reference fraction on target area</th>
</tr>
</thead>
<tbody>
<tr>
<td>571 MeV</td>
<td>0.885</td>
<td>0.961</td>
</tr>
<tr>
<td>1.3 GeV</td>
<td>0.928</td>
<td>0.961</td>
</tr>
<tr>
<td>2.0 GeV</td>
<td>0.965</td>
<td>0.988</td>
</tr>
</tbody>
</table>

Proton flux per prim

Beam divergence at PBW
Maximum Beam Offset and Thermal Stress in Target Vessel

• Steel structure receives maximum 10 MJ/m³ for a 2 GeV/62.5 mA beam
• Additional stress of less than 10 MPa due to sudden thermal expansion
• **No risk** to structural integrity
Raster Failure and Beam Size

- The BEW and PBW shall not lose its mechanical properties during a full pulse in case of a total failure of beam raster.
  - **SA SS-316L**: Precipitation of chromium-rich carbides at grain boundaries at above 550 °C.
  - **Al6061-T6**: Thermal aging becomes an issue at the temperatures above 250 °C [RCC-MRx].

<table>
<thead>
<tr>
<th>Component</th>
<th>Max. temperature operation</th>
<th>Temperature limit during pulse</th>
<th>Max. dE/dz [MeV/cm]</th>
<th>Min. allowed RMSx * RMSy</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEW</td>
<td>160 °C</td>
<td>550 °C</td>
<td>18.5</td>
<td>33.5 mm²</td>
</tr>
<tr>
<td>PBW</td>
<td>60 °C</td>
<td>250 °C</td>
<td>5.3</td>
<td>32.6 mm²</td>
</tr>
</tbody>
</table>
Dynamic Stress Wave in Tungsten Bricks

- 30 Raster sweeps (0.38 ms, 13% of single pulse) were simulated.
- Dynamic stress amplifies with time.
- Resonance mode identified at 41.2 kHz which is only 4% off from the horizontal raster frequency (39.55 kHz)
- The raster frequency will be tuned away from the band-width of the resonance mode.

![Graph showing quasi-static and dynamic transient stresses during beam raster](image-url)
Beam Energies and Nuclear Heat Deposition

<table>
<thead>
<tr>
<th>Beam Energy</th>
<th>PBW (MeV/proton)</th>
<th>BEW (MeV/proton)</th>
<th>Tungsten (Max.) (MeV/proton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>571 MeV</td>
<td>1.41</td>
<td>3.98</td>
<td>8.1</td>
</tr>
<tr>
<td>1.3 GeV</td>
<td>1.24</td>
<td>4.38</td>
<td>10.8</td>
</tr>
<tr>
<td>2.0 GeV</td>
<td>1.22</td>
<td>5.01</td>
<td>14.5</td>
</tr>
</tbody>
</table>

At an early linac commissioning phase with a lower energy beam, attention should be paid to the higher heat load and associated higher thermal stress in the PBW.
Radiation Damage and Lifetime: PBW

- Helium embrittlement determines the lifetime
  - The SINQ target window at PSI doesn’t show much ductility at the accumulated helium production of 2400 appm.

<table>
<thead>
<tr>
<th>Beam energy</th>
<th>Lifetime at full beam current</th>
<th>Lifetime in accumulated beam power</th>
</tr>
</thead>
<tbody>
<tr>
<td>571 MeV</td>
<td>5780 hours</td>
<td>8.25 GWh</td>
</tr>
<tr>
<td>1.3 GeV</td>
<td>4110 hours</td>
<td>13.3 GWh</td>
</tr>
<tr>
<td>2.0 GeV</td>
<td>3580 hours</td>
<td>17.9 GWh</td>
</tr>
</tbody>
</table>


ISIS-TS2 PBW:
Picture courtesy by D. B. Lopez (ISIS)

SINQ safety hull made of AlMg3:
Picture courtesy by Y. Dai (PSI)
Radiation Damage and Lifetime: MWPM

- Both pure tungsten and SiC could be used for MWPM
- For a pencil beam, the beam diverges with:
  - SiC harp: 0.06 mrad => 0.01% of additional beam loss at the target
  - W harp: 0.25 mrad => 0.05% of additional beam loss at the target
- Radiation damage limited lifetime is 1 year at full beam current.

<table>
<thead>
<tr>
<th>Material</th>
<th>Secondary electron yield</th>
<th>Delta ray electron yield</th>
<th>Total Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>0.049</td>
<td>0.026</td>
<td><strong>0.075</strong></td>
</tr>
<tr>
<td>SiC</td>
<td>0.010</td>
<td>0.013</td>
<td>0.023</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tungsten</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-pulse max. temperature</td>
<td>1420 K</td>
</tr>
<tr>
<td>Post-pulse max. stress</td>
<td>77 MPa</td>
</tr>
<tr>
<td>Yield Stress/Flexural Strength</td>
<td>200 MPa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Max. DPA per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td><strong>64.8</strong></td>
</tr>
<tr>
<td>SiC</td>
<td><strong>5.4</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Material</th>
<th>Total Beam Energy/Charge</th>
<th>Accumulated Max. DPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORNL-SNS</td>
<td>W</td>
<td>41000 MWh</td>
<td>90</td>
</tr>
<tr>
<td>ISIS-TS2</td>
<td>SiC</td>
<td>0.985 Ah</td>
<td>2</td>
</tr>
</tbody>
</table>
Radiation Damage and Lifetime: Target Vessel

- **Lifetime criteria: DPA**
  - Decided maximum DPA dose limit: 8 DPA
    - Damage Rate: 1.6 DPA/ESS-year
    - Lifetime: 5 ESS-year
  - Conservatism is due to:
    - Different irradiation temperatures of STIP specimens and water cooled SNS beam entrance window
    - STIP specimen is SS 316 LN
    - Uncertainty in DPA estimates

D. A. McClintock et al., JNM 450 (2014) 130-140
Dose Limited Lifetime: Tungsten Bricks

• Tungsten is not subject to dose limited lifetime
  – It doesn’t carry structural load of target wheel
  – But, loss of mechanical integrity of tungsten bricks caused by thermal cycling could result in premature target failure

• Main concerns:
  – The radiation damage pushes the DBTT of tungsten bricks above the operation temperature of the ESS target
  – Uncertainty in setting fatigue limit for brittle materials

J. Habainy et al.
Tungsten Bricks: Radiation Damage

- Reduction of flexural stress => premature brittle failure
- Reduction of thermal conductivity => elevated thermal stress
- Increase of stiffness => elevated mechanical stress

8 mm samples, Ti: 60-140°C

Thermal diffusivity of Tungsten

J. Habainy et al.
Tungsten Bricks: Radiation Damage Effects

- Coupled CFD and Structural Analyses are made.
  - Thermal conductivity as irradiated was taken from recent STIP-V data [J. Habainy et al.].
  - Young’s modulus as irradiated was taken to be 20% higher than un-irradiated one [J. Habainy et al.].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Time</th>
<th>Un-irradiated</th>
<th>Irradiated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum temperature</td>
<td>Pre-pulse</td>
<td>321 °C</td>
<td>337 °C</td>
</tr>
<tr>
<td></td>
<td>Post-pulse</td>
<td>395 °C</td>
<td>411 °C</td>
</tr>
<tr>
<td>Maximum Quasi-static stress</td>
<td>Pre-pulse</td>
<td>27 MPa</td>
<td>50 MPa</td>
</tr>
<tr>
<td></td>
<td>Post-pulse</td>
<td>83 MPa</td>
<td>117 MPa</td>
</tr>
</tbody>
</table>
• Understanding beam and matter interaction is crucial for a reliable operation of the facility.
• Numerous Materials Research Program in Target Environments are in Progress.
• Acquired materials information is compiled in the ESS Materials Handbook.
Materials Research in Target Environment

- Spallation Materials
- PBW Materials
- Polymers and Lubricants
- Moderator Materials
- Beam Imaging Materials
- Irradiation Module
Thank you!