Acknowledgement

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Thank you very much for your help and support!
A trial of a definition

**TARGET**

A target is an assembly of material(s) that intercept accelerated particle beams to produce secondary particles (in large amounts). Created secondary particles are either used as probes to investigate other object(s) for their (physical) properties (behavior under irradiation) or themselves (or their decay products) are objects of interest. In some cases produced secondary particles are again used to create other species at so called secondary targets.
Aim of Targets

Particle Production

Boundary conditions/constraints:

- Geometrical situation
- Thermo-mechanical stability
- Material damage (Lifetime)
- Compactness (conflicting with dissipation of energy)
- Availability
- Safety
- Handling

Information for Target Design

Crucial information for Target Design

- Particle production performance
- Energy density distribution → Energy density Limits of Material(s)
- Radioactive inventory → Handling of used Targets and Beam Dumps
- Material and irradiation properties → Radiation damage Limits, Erosion/Corrosion Limits, Fatigue …
- Safety issues → Accident scenarios (Licensing)
Design is a complex and iterative process which has to satisfy multiple requirements with usually incomplete data

Frequent sources of problems include:
- Incomplete or unknown requirements at the start
  - Performance
  - Safety
  - Reliability/Maintainability/ Inspectability
- Initial cost and schedule estimates used to get project approval overly optimistic

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Beam parameters

Most key design parameters for the target scale with the peak intensity (protons/unit area).

For the same total number of protons, the peak can vary significantly depending on the profile.

Initial scoping calculations frequently use

**Gaussian.**
\[ I = I_0 \cdot e^{-(x^2/2\sigma_x^2 + y^2/2\sigma_y^2)} \]
- \( I_0 = N_p/(2\pi\sigma_x\sigma_y) \)

**Parabolic.**
- \( I = I_0 \cdot (1-(x/a)^2)(1-(y/b)^2) \)
- \( I_0 = 9 \cdot N_p/(16ab) \)

or **Flat** beam profiles (beam painting)
- \( I = I_0 \)
- \( I_0 = N_p/(4ab) \)
  - \( N_p = \) number of protons per pulse, \( I_0 = \) peak number of protons per unit area per pulse
**Beam Parameters**

**Power** = \( N_p \cdot f \cdot E \cdot 1.6021 \times 10^{-13} = I(\mu A) \cdot f \cdot E \ [\text{MeV}] \ [\text{W}] \)

Where \( N_p \) = protons per pulse, \( f \) = frequency (Hz), \( E \) = beam energy in MeV

**Current (A)** = \( N_p \cdot f \cdot 1.6021 \times 10^{-19} \)

**Peak current density (A/mm\(^2\))** = \( I_0(p/mm^2) \cdot f \cdot 1.6021 \times 10^{-19} \)

For a proton energy loss of \( C \ [\text{eV/mm}] \) the volumetric heating would be

\[
Q''(\text{MW/m}^3) = I(p/mm^2) \cdot f \cdot C(\text{MeV/mm}) \cdot 10^9 \cdot 1.6021 \times 10^{-19}
\]

for thin windows at ~ 1 GeV

\( C = 0.7 \text{ MeV/mm} \) – aluminum
\( C = 1.85 \text{ MeV/mm} \) – Inconel

Example 2.9 \( \times \) \( 10^{10} \) p/mm\(^2\) @ 60 hz, 1 GeV Inconel window

Current density = 0.28 A/m\(^2\) \quad Q'' = 515 MW/m\(^3\)

---

**Targets and Beam Dumps**

And many more applications
Repetition of some physics

Energy loss in a medium

By Ionization/excitation - Bethe Bloch formula

\[-\frac{dE}{dx} = 4 \cdot \pi \cdot N_A \cdot r_e^2 \cdot m_e \cdot c^2 \cdot z^2 \cdot \frac{Z}{A} (1/\beta^2) \times \left[ \ln \left( \frac{2 \cdot m_e \cdot c^2 \cdot \gamma^2 \cdot \beta^2}{I} \right) - \beta^2 - \delta \right] \]

\[I = 16 \cdot Z^{0.9} \text{[eV]} \text{ for } Z>1\]

I=15 eV for atomic hydrogen, I=19.2 eV for molecular hydrogen and I=21.8 eV for liquid hydrogen

\[\begin{align*}
N_A & \text{ - Avogadro const (} \approx 6.023 \times 10^{23} \text{ mol}^{-1}) \\
r_e & \text{ - classical electron radius (} \approx 2.82 \times 10^{-13} \text{ cm}) \\
m_e & \text{ - electron rest mass (} \approx 0.511 \text{ MeV}/c^2) \\
z & \text{ - projectile charge} \\
I & \text{ - atomic number of medium} \\
A & \text{ - atomic weight of medium (g/mole)} \\
\gamma & \text{ - Lorentz factor (} \approx \frac{E}{mc^2}) \\
\beta & \text{ - (} \gamma \text{)} \\
\delta & \text{ - density correction (shielding effects of electrons)}
\end{align*}\]
Energy loss in a medium

Bremsstrahlung
Interaction of charges particles with the Coulomb field of nuclei of the medium \( \rightarrow \) de-acceleration \( \rightarrow \) part of kinetic energy emitted in form of photons \( \rightarrow \) Bremsstrahlung

\[
-d\frac{E}{dx} = 4 \cdot \alpha \cdot N_A \cdot \frac{Z^2}{A} \cdot z^2 \left( \frac{1}{4\pi \varepsilon_0} \frac{e}{mc^2} \right) \cdot E \cdot \ln \left( \frac{183}{Z^{1/3}} \right)
\]

In addition, at high energies, pair production as well as energy loss due to photonuclear effects also contribute to the total energy loss of a particle. These losses are \( \sim \) to the incident particle energy \( (E) \) and become important at sufficient high energies.

\( \alpha \) - fine structure constant \( (\alpha = \frac{1}{137.035}) \)
\( N_A \) - Avogadro const. \( (= 6.023 \times 10^{23} \text{ mol}^{-1}) \)
\( Z \) - atomic number of medium
\( A \) - atomic weight of medium \( (\text{g/mole}) \)
\( z \) - atomic number of projectile
\( m \) - mass of projectile
\( E \) - energy of projectile

Range of particles

The range \( (R) \) of particles is defined as the mean free distance that a particle travels before it comes to rest:

\[
R \equiv \int_0^{x_{\text{max}}} dx(\beta) = \int_0^{\beta_{\text{max}}} \left[ -d\frac{E}{dx} \right]^{-1} dE \ d\beta
\]

Semi-empirical approximation by Carpenter for spallation source materials \( (Z > 10 \text{ and } 0.1 \leq E \leq 1 \text{ GeV}) \) – incident particle is a proton

\[
R = (\frac{1}{\rho}) \cdot 233 \cdot Z^{0.23} (E - 0.032)^{1.4} \ [\text{cm}]
\]
Temperature rise

The instantaneous temperature rise in a material – hit by a Gaussian beam – can be written as:

$$\Delta T = \frac{dE}{dx} \cdot \frac{N_p}{(2 \cdot \pi \cdot \sigma_x \cdot \sigma_y) \cdot \rho \cdot c_p}$$

The instantaneous temperature rise will be small if $\rho \cdot c_p$ is large.

The resulting cyclic thermal stress is proportional to:

$$\sigma_{cyclic} \propto \Delta T \alpha E$$

Coulomb scattering

The differential cross section for a charged particle scattered into the solid angle interval $d\Omega$, $\Omega + d\Omega$ can be written as

$$\frac{d\sigma}{d\Omega} = \frac{1}{4} \left( \frac{Z \cdot Z \cdot e^2}{\beta \cdot c \cdot p} \right) \cdot \frac{1}{\sin^4(\Theta/2)}$$

In general scattering at different scattering samples → stochastic → only statistical distribution can be given

$$\Theta_{\text{rms}} = \sqrt{\langle \Theta^2 \rangle} = \frac{13.6 \text{MeV}}{\beta \cdot c \cdot p} \cdot \sqrt{\frac{x}{X_0}} \cdot [1 + 0.038 \cdot \ln(x / X_0)]$$

With $X_0$ the radiation length

$$X_0 = \frac{A}{4 \cdot \alpha \cdot N_A \cdot Z^2 \cdot r^2 \cdot \ln(183 \cdot Z^{1/3})} \text{ (g/cm}^2\text{)}$$
Targetry and MC simulation codes

Targetry issues
- To get adequate „parameters“ for targets at any accelerator facility it is necessary to produce and collect a (very) large number of particle tracks/histories. For instance, at a spallation neutron source neutronic behavior has to be studied, for neutrino target the production of pions and kaons is necessary, rare isotope accelerators need information about the formation of residual nuclei in targets ...

Informations of interest:
- Production of particle of interests and their behavior inside complex geometries.
- Behavior of „unwanted“ particles which could create background → Adequate suppression in beam lines can be tailored.
- Information on the survivability and life time of the target and beam windows. Strongly depends on fatigue, stress limits, radiation damage, erosion....
- Activation of components → planning of remote handling and exchange procedures, radioactive waste issues ...
- Heat loads, activation and radiation damage in targets and surrounding structures; for instance in superconducting focusing devices at v-beam lines, moderators at spallation neutron sources and so on.
- Shielding issues for radiation protection, „spent“ beam handling, ground water activation ...
Most of these issues can be addressed by Monte-Carlo particle transport codes. Therefore, the predictive power and reliability of these computer codes is of crucial importance. This leads to requirements of the physics implemented in such code systems:

- Reliable description of cross-sections, particle production modes, particle yields in a large energy regime from (sub-)eV to several GeV even TeV, for hadrons, photons, composite particles and even nuclei.
- Adequate \( m^0 \) and \( K^0 \) production (\( \nu_e \)) and correct the modeling of electromagnetic showers (\( \pi^0 \rightarrow \gamma \gamma \)), photoproduction of hadrons, muons.
- Description of energy loss processes, e.g. charged hadrons, neutrons, muons …(ionization losses, knock-on electrons, and at high energies Bremsstrahlung, Pair production).
- Correct transport and moderation of neutrons at meV energies.
- Predictive powers for nuclide inventories, dpa, Helium and Hydrogen production.
- Accurate transport of all particle species from microns to meters.
- Inclusion of effects of magnetic fields, gravity (cold and ultra-cold neutrons).
- User interface.

### Code packages

<table>
<thead>
<tr>
<th>Monte Carlo Codes</th>
<th>Event Generators</th>
<th>Developed at</th>
<th>Available through</th>
<th>Main developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLUKA</td>
<td>PEANUT / DPMJET</td>
<td>INFN (Italy)</td>
<td><a href="http://www.fluka.org/fluka.php">http://www.fluka.org/fluka.php</a></td>
<td>Alfredo Ferrari</td>
</tr>
<tr>
<td>GEANT4</td>
<td>QMD</td>
<td>CERN (Switzerland / France)</td>
<td><a href="http://www.geant4.org/geant4/">http://www.geant4.org/geant4/</a></td>
<td>Collaboration</td>
</tr>
<tr>
<td>MCNPX</td>
<td>BERTINI, CEM, FLUKA89, INCL, ISABEL, LAOGSM</td>
<td>Los Alamos National Lab (USA)</td>
<td><a href="https://mcnpx.lanl.gov/officialversions">https://mcnpx.lanl.gov/ official versions OECD/NEA or RSICC</a></td>
<td>MCNP(X) team</td>
</tr>
<tr>
<td>PHITS</td>
<td>JAM / QMD</td>
<td>JAERI (Japan)</td>
<td><a href="http://phits.jaea.go.jp/">http://phits.jaea.go.jp/</a></td>
<td>Koji Niita</td>
</tr>
</tbody>
</table>

IAEA benchmark for different codes and event generators where Results as well as experimental data are provided:

[http://nds121.iaea.org/alberto/mediawiki-1.6.10/index.php/Main_Page](http://nds121.iaea.org/alberto/mediawiki-1.6.10/index.php/Main_Page)
## Spallation Targets

### Spallation Sources - operating or shut down

<table>
<thead>
<tr>
<th>Facility</th>
<th>Status</th>
<th>Time Structure</th>
<th>Coolant</th>
<th>Target Material</th>
<th>Power</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPNS</td>
<td>De-commissioned</td>
<td>X</td>
<td>X</td>
<td>Depleted U</td>
<td>7kW</td>
<td>Short life</td>
</tr>
<tr>
<td>IPNS</td>
<td>De-commissioned</td>
<td>X</td>
<td></td>
<td>Mercury</td>
<td>7kW</td>
<td></td>
</tr>
<tr>
<td>ISIS 1</td>
<td>Operated</td>
<td>X</td>
<td>X</td>
<td>Depleted U</td>
<td>100 kW</td>
<td>Short life</td>
</tr>
<tr>
<td>ISIS 1</td>
<td>Operated</td>
<td>X</td>
<td>X</td>
<td>Tantalum</td>
<td>250 kW</td>
<td>High decay heat</td>
</tr>
<tr>
<td>ISIS 1</td>
<td>Running</td>
<td>X</td>
<td></td>
<td>3% Ta clad</td>
<td>150 kW</td>
<td></td>
</tr>
<tr>
<td>LANSCE</td>
<td>Running</td>
<td>X</td>
<td>X</td>
<td>Tungsten</td>
<td>100 kW</td>
<td></td>
</tr>
<tr>
<td>KENS</td>
<td>De-commissioned</td>
<td>X</td>
<td>X</td>
<td>W-Ta clad</td>
<td>3 kW</td>
<td></td>
</tr>
<tr>
<td>SINQ</td>
<td>Operated</td>
<td>X</td>
<td></td>
<td>Zircalloy rods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SINQ</td>
<td>Operated</td>
<td>X</td>
<td>X</td>
<td>Pb in SS rods</td>
<td>800 kW</td>
<td></td>
</tr>
<tr>
<td>SINQ</td>
<td>Test run completed</td>
<td>X</td>
<td>X</td>
<td>Pb-Bi</td>
<td>-800 kW</td>
<td>Target removed</td>
</tr>
<tr>
<td>SNS</td>
<td>Operated</td>
<td>X</td>
<td>X</td>
<td>Pb in Zr rods</td>
<td>2.5 MW</td>
<td>Optimized target</td>
</tr>
<tr>
<td>ISIS 2</td>
<td>Running</td>
<td>X</td>
<td>X</td>
<td>3% Ta clad</td>
<td>46 kW</td>
<td>Very optimized</td>
</tr>
<tr>
<td>SNS</td>
<td>Running</td>
<td>X</td>
<td>X</td>
<td>Mercury</td>
<td>7 kW</td>
<td>PWR design</td>
</tr>
<tr>
<td>SNS</td>
<td>Running</td>
<td>X</td>
<td>X</td>
<td>Mercury</td>
<td>1 MW design</td>
<td></td>
</tr>
</tbody>
</table>
## Selected Design Studies

### Design studies – not (yet) built

<table>
<thead>
<tr>
<th>Facility</th>
<th>Status</th>
<th>Time Structure</th>
<th>Coolant</th>
<th>Target Material</th>
<th>Power</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSNS</td>
<td>Preliminary Design</td>
<td>X X</td>
<td>Mercury</td>
<td>W-Ta clad</td>
<td>250 kW</td>
<td></td>
</tr>
<tr>
<td>SNS-STS</td>
<td>Pre Conceptual Design</td>
<td>X</td>
<td>Mercury</td>
<td>1.0 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SNS-STS</td>
<td>Pre Conceptual Design</td>
<td>X</td>
<td>Mercury</td>
<td>1.0 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SNS Upgrade</td>
<td>Conceptual Design</td>
<td>X</td>
<td>Mercury</td>
<td>1.0 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Los Alamos Next Generation</td>
<td>Conceptual Design</td>
<td>X</td>
<td>Mercury</td>
<td>1.0 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SNS</td>
<td>Conceptual Design</td>
<td>X</td>
<td>Mercury</td>
<td>1.0 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eurisol</td>
<td>Conceptual Design</td>
<td>X</td>
<td>Mercury</td>
<td>4 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTS</td>
<td>Conceptual Design</td>
<td>X</td>
<td>Mercury</td>
<td>1.0 MW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Physics

Evaporation competing with high energy Fission

- Intra-Nuclear Cascade
- Excited nucleus Evaporation
- Fission products
- Spallation residue α, β, γ decay

\[ \text{time} \sim 10^{-22} \text{s} \]

\[ \text{time} \sim 10^{-18} \text{s} \]
Physics

Existing spallation neutron sources are driven by proton accelerators operating in an energy regime from 0.5 – 3 GeV.

- Minimum ionisation approached at 0.8 – 1.0 GeV → more energy into neutron production
- Slow fall off towards higher energies due to increasing production of π
- Other high-Z materials (e.g. Hg) show similar behavior as Pb

Target material choice for Spallation Sources

- High Z → high neutron production rate
- High density → high luminosity
- Radiation stability → long lifetime, availability
- Low neutron absorption → high neutron intensities (for pulsed sources not so much of an issue)
- Low activity & after-heat → service and decommissioning
## Target Materials for Spallation Sources

<table>
<thead>
<tr>
<th>Composition</th>
<th>Pb</th>
<th>Bi</th>
<th>LME</th>
<th>LBE</th>
<th>Mg</th>
<th>W</th>
<th>Ta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Z</td>
<td>82</td>
<td>83</td>
<td>~82.5</td>
<td>80</td>
<td>74</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>11.35</td>
<td>9.75</td>
<td>-</td>
<td>-</td>
<td>19.3</td>
<td>16.65</td>
<td></td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>10.7</td>
<td>10.07</td>
<td>10.6</td>
<td>10.5</td>
<td>13.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coeff. of thermal expansion (K⁻¹)</td>
<td>2.91*10⁻⁵</td>
<td>3.75*10⁻⁵</td>
<td>-</td>
<td>-</td>
<td>6.1*10⁻⁵</td>
<td>4.4*10⁻⁶</td>
<td>6.6*10⁻⁶</td>
</tr>
<tr>
<td>Contraction on solidification (%)</td>
<td>3.32</td>
<td>-3.35</td>
<td>-3.6</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>217.13</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific heat capacity (J/g/K)</td>
<td>24</td>
<td>25</td>
<td>-</td>
<td>-</td>
<td>32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal neutron absorption (barn)</td>
<td>0.17</td>
<td>0.34</td>
<td>0.37</td>
<td>-</td>
<td>0.11</td>
<td>0.309</td>
<td>0.185</td>
</tr>
</tbody>
</table>

## Comparison of n production

<table>
<thead>
<tr>
<th>Nuclear Process</th>
<th>Neutron Production yield (neutrons/reaction)</th>
<th>Energy deposition (MeV/neutron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 keV D on T in Ti-matrix</td>
<td>4•10⁵ (neutrons/D)</td>
<td>10⁴ MeV/n</td>
</tr>
<tr>
<td>35 MeV D on liquid Li (stripping)</td>
<td>3•10³ (neutrons/D)</td>
<td>10⁴ MeV/n</td>
</tr>
<tr>
<td>100 MeV e⁻ on ²³⁵U</td>
<td>5•10² (neutrons/e)</td>
<td>2•10³ MeV/n</td>
</tr>
<tr>
<td>²³⁵U(n,f) (thermal fission)</td>
<td>3 neutrons/fission</td>
<td>1.9•10² MeV/n</td>
</tr>
<tr>
<td>1 GeV protons on thick Hg target</td>
<td>~ 30 neutrons/proton</td>
<td>5.5•10¹ MeV/n</td>
</tr>
<tr>
<td>CTR (controlled thermonuclear reaction) (D,T) fusion by laser beam</td>
<td>1 neutron/fusion</td>
<td>8 MeV/n</td>
</tr>
</tbody>
</table>
SINQ – Schweizer Intensive Neutronen Quelle

- SINQ is the only existing CW spallation source
- Medium size reactor
- Advantage compared to reactor
  - No chain reaction
  - Energy deposition
- Low neutron absorbing materials
- Coolant/Moderator D$_2$O
- Cold Moderator D$_2$O @25 K
- Optimum Target Materials (low $\sigma_{\text{abs}}$)
  - Lead Bismuth Eutectic (LBE), Pb, Zr, Al

- Vertical alignment → Proton beam from below
- 360° access → cylindrical shape of the target
- Fully coupled system
- Beam Energy $E_p=575$ MeV
- Beam current 1.5 mA
- 2/3 of beam power deposited in target
- SINQ Target lifetime 2 years → limit: embrittlement of AlMg3 BEW

Proton beam:
- CW
- 575 MeV
- ~ 1.5 mA → 0.9 MW
- Gaussian beam shape ($\sigma_x=2.14 \text{ cm}$, $\sigma_y=2.96 \text{ cm}$)
- Peak current density 25 $\mu$A/cm$^2$/mA
**Lifetime Limiting Component**

AlMg3 proton beam window (integrated into the Safety Hull of the SINQ targets)

**SINQ Target Safety Hull:**

Tensile tests after one year of irradiation

γ-mapping of the beam footprint

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**Target Development History**

Target Development History – a very short overview

- 1996/97: Start-up of SINQ with a solid Zircalloy rod target (Target 1, Mark II)
- 1998/99: Operation with a solid Zircalloy rod target (Target 3, Mark II)
- 2000/01: Use of Steel-cladded Lead rods „Cannelloni Target“ (Target 4, Mark III)
- 2002/03: „Cannelloni Target“ as in previous operation cycle (Target 5, Mark III)
- 2004/05: Again Lead-filled Steel tubes „Cannelloni Target“ (Target 6, Mark III)
- 2006: Liquid Lead Bismuth Eutectic Target – MEGAPIE
- 2007/08: Mix of Lead-filled Steel and Zircaloy tubes - „Cannelloni Target“ (Target 7, Mark III)
- 2009/10: Improved solid target, still „Cannelloni Target“, only Zircaloy used as cladding material (Target 8, Mark IV)
- 2011: Slightly modified Mark IV „Cannelloni Target“: start of operation April 2011 (Target 9, Mark IV)
**Target Evolution at SINQ**

1997-1999: SINQ Target Mark 2  
Water-cooled Zircaloy rods

2000 - 2009: SINQ-Target Mark 3:  
Lead rods, with steel clad  
42% increase in neutron yield

Aug-Dec 2006: MEGAwatt Pilot Experiment:  
- Joint international initiative to design, build, licence, operate and explore a liquid metal spallation target for 1 MW beam power

2010 – present: SINQ-Target Mark 4:  
Lead rods, with Zr clad, blanket

**Validation of MC-model**

Calculated flux maps of MEGAPIE, Target 7 and the improved SINQ target (target 8).  
Simulated differences to Target 6 are: MEGAPIE (~1.80), Target 7 (~1.20*), Target 8 (~1.60).  
*if STIP samples are included (1.10)

Good agreement with measured data!
Calculation of energy depositions for stress analysis

Inversion of the Beam Entrance Window (BEW)

- Original BEW designed for minimum mechanical stress → hemispherical shape
- Water head between BEW and Target Array ~ 10 cm → ~ 10 MeV energy loss & only spallation on light nuclei (Oxygen of D₂O), see circle
- Inversion of BEW: energy loss minimized, mechanical stress slightly higher. Neutron Flux gain → 10%
- Temperatures of safety shroud between 65 – 75°C

Von Mises Stresses. D₂O flow.

Mis-Steering of the beam

Stresses in the beam entrance window due to off center beam

Stresses found in this abnormal conditions are between 1.7 and 4.2 MPa, which are well below the yield strength of AlMg3 → maximum deformation 0.1 mm

Temperatures in Blanket/Reflector

Also in the new Blanket/Reflector temperatures and resulting stresses are found to be in a regime were no damage is to be expected.
**The SINQ Mark 4 Target**

**Increasing the Lead content in the Cannelloni target:**
- Compact the Target array
- Decreasing the cladding thickness

**Compact the Target array**

The outlet gap (gap2) was reduced to 1.2 mm → Pitch 10.11 mm → 5 % neutron gain

**Decreasing the cladding thickness**

Attempts have been made to decrease the Zr cladding thickness from 0.75 mm to 0.5 mm by drilling. However, during fabrication temperatures are high, so that Zr crystal structure might have changed. Moreover, quality not always the same.

---

**Conceptual design of SINQ Mark 4 Target**

**Optimization between coolant and spallation material**

![Diagram of the SINQ Mark 4 Target](image-url)
The new Zr-Pb cannelloni target for SINQ

Status:
Operated @ 0.9 MW
April 2009 – Dec. 2010

Neutron flux gain:
54% compared to Target Mark 3
(2004 / 2005)

Accident – beam focus: Target temperature recording

Temperatures during an unintended beam focussing, October 2004

-990 µA
-1260 µA
Zr-clad rod: visual inspection after 2 years in SINQ (>10Ah of accumulated proton charge):

Neutron tomography: Zr-clad test rod

strongly neutron attenuating spots:
spot location outside of cladding wall
Metallographic investigation: Zr-rod 06-3

Accident: Searching for the object of failure

....adjacent steel-clad rod
Neutron radiographs from damaged (steel-clad) target rods

ISIS TS1 Targets
**ISIS Target moderator and Reflector Assembly**

**Beam Parameters**
- 800 MeV
- 50 Hz – short pulse ( < 10^{-6} s)
- 200 mA → ~ 160 kW

**ISIS TS1 Targets**

- ISIS started with Uranium (depleted) plate Targets → additional neutrons due to fission
- Target plates thickness inversely proportional to energy deposition (7.7 – 26.5 mm)
- U-plates clad with Zircalloy to prevent corrosion (similar materials as in reactors)
- D_2O cooled
**ISIS TS1 Targets**

**ISIS TS1 Uranium Target**

- U (depleted) plates (thickness 7.7 - 26.5 mm, Ø 90mm) cladded with Zircalloy (by isostatic pressing @850°C) cooling channels 1.75 mm
- High neutron output
- Higher heat production due to fissioning (max. 0.77 kW/cm³)
- Surface cooled with D₂O
- All U-Targets failed ~250 mAh
- Reason for failure unclear (thermal cycling, phase transition, H-,He-production …)
- Failure mode: Crack in the cladding Zr → release of FP to D₂O

<table>
<thead>
<tr>
<th>Target</th>
<th>Thermal cycles</th>
<th>Proton beam power</th>
<th>Total heat deposited</th>
<th>Peak power deposited</th>
</tr>
</thead>
<tbody>
<tr>
<td>U#1</td>
<td>3.1</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U#2</td>
<td>40000</td>
<td>1.8</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>U#3</td>
<td>10389</td>
<td>5.8</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>U#4</td>
<td>4147</td>
<td>4.6</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>U#5</td>
<td>5074</td>
<td>9.9</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>U#6</td>
<td>2628</td>
<td>4.2</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>U#7</td>
<td>1805</td>
<td>3.6</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>U#8</td>
<td>Not Used</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U#9</td>
<td>815</td>
<td>3.8</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Ta#1</td>
<td>73378</td>
<td>58.4</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Ta#2</td>
<td>37734</td>
<td>40.8</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Ta#3</td>
<td>45860</td>
<td>58.8</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Ta#4</td>
<td>23000</td>
<td>45.8</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>W#1</td>
<td>87.0</td>
<td></td>
<td>180</td>
<td></td>
</tr>
</tbody>
</table>

**ISIS TS1 Tungsten Target**

- 12 Ta cladded W plates (high corrosion of W in water, APT experience)
- Surface cooled with D₂O

Proton beam power 160 kW
Total heat deposited 95 kW
Peak power deposited 0.25 MW/l

Cooling system D₂O cooled
- Inlet pressure 6.2 bar
- Pressure drop 0.25 bar
- Inlet temperature 35 C
- Temperature rise 4 C
- Flow rate 350 l/min
- Peak plate temperature 380 C

**ISIS Targets**

- Ta-Target used as a replacement for U-targets
- Change in HTC as fct. of protons on target
  - Peak temp. of target 320°C in last run period, peak temp. 180°C in first run period
  - High afterheat → significant release of Tritium in storage (500 MBq/day)!!

**ISIS TS1 Tungsten Target**

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The ISIS Tungsten Target Construction

Target Pressure Vessel

Target Module and Cooling Manifolds

Side Manifold

Target Module

ISIS Target moderator and Reflector Assembly
SNS mercury target

- SNS Ultimate Parameters
  - 1 GeV protons
  - 2 MW average beam power
  - Pulse duration ~ 0.7 µs
  - 60 Hz rep rate

- Pulsed spallation Source
  - Shape of target rather thin and broad → allows for moderators near to target
  - Target material Hg → liquid at room temperature (no heating for liquification)
  - Hg is target material and coolant

- Shape of target rather thin and broad allows for moderators near to target
- Target material Hg liquid at room temperature (no heating for liquification)
- Hg is target material and coolant
### Mercury Loop Parameters @ 2 MW

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power absorbed in Hg</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>Nom Op Pressure</td>
<td>0.3 MPa</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>340 kg/s</td>
</tr>
<tr>
<td>$V_{\text{max}}$ (In Window)</td>
<td>3.5 m/s</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>• Inlet to target</td>
<td>60°C</td>
</tr>
<tr>
<td>• Exit from target</td>
<td>90°C</td>
</tr>
<tr>
<td>Total Hg Inventory</td>
<td>1.4 m$^3$</td>
</tr>
<tr>
<td>Centrifugal Pump Power</td>
<td>30 kW</td>
</tr>
</tbody>
</table>

SNS Hg Target operates at low temperature and pressure.

Peak power density in mercury ~ 800 MW/m$^3$ @ 2 MW.

### Target Service Bay

- Stainless-steel lined
- 4 window workstations
- 8 through-the-wall manipulators
- 7.5 ton crane
- Pedestal mounted manipulator
- Shielded transfer bay

[Image of Target Service Bay with Hg Pump, 7.5 Ton Crane, Telerob Manipulator, and Dual Arm Telerob Manipulator on extended pedestal.]
SNS Power Ramp-Up

• Currently operating at ~ 1 MW

Target Status @ SNS

• 1st Target ran until July 2009 (more than 5 dpa – the design goal)
• 2nd Target replaced July 2010
• Plan: Run Targets till end-of-life, i.e. mercury leaks from primary container to its water-cooled shroud (or 10 dpa)
• 3rd Target reached end-of-life on April 3rd 2011 (10 dpa reached in summer) → replaced in 14 days → PIE on Target 3 → location and characterization of leak → confirmation for cavitation erosion (pitting)

Three spare target modules on-site; five more by 2012
Mercury target module lifetime remains uncertain

1250 hours corresponds to goal of 4 target replacements/year

Results Post-Irradiation Examination Target Module #1

- Target #1:
  - Cavitation damage phenomenon confirmed on inner wall at center of target
  - Outer wall fully intact; inner wall at off-center location shows little or no damage
  - Damage region appears to correlate with regions of low Hg velocity, but not such a clear distinction on Target #2

Demonstrated power limit is now > 900 kW
Target #2 survived through planned operating period but **inner wall** suffered more damage

**JSNS mercury target**
**JSNS Hg Target**

- Proton Beam (design parameters):
  - 3 GeV, 25 Hz rep rate, 0.33 mA ⇒ 1 MW
- Hg Target:
  - Cross-flow type, with multi wall vessel
  - Hg leak detectors between walls
  - All components of circulation system on trolley
  - Hot cell: Hands-on maintenance
  - Vibration measuring system to diagnose pressure wave effects

**Beam power on JSNS target**

![Graph showing beam power and cumulative beam power.]

- Beam Power (kW): 20 kW, 120 kW, 220 kW
- Cumulative Beam Power (MWh): 0, 20, 120, 220 kW
Confirmation of target system design

- Temperature rise of mercury vessel for 120 kW & 300 kW beam power agreed with estimates
- Confirmed operation of the mercury circulation system, EM pump, heat exchanger, etc.

Max. calculated power dep.: 430 W/cm³ @ 1MW

Bubble Injection to Mitigate Cavitation Damage

3 mechanisms for each region
- Center of thermal shock: A
  - Absorption
- Propagation path: B
  - Attenuation
- Negative pressure field: C
  - Suppression

Absorption: Bubble<50 μm

Absorption, Attenuation, Suppression: bubble mitigation by compressive pressure emitted from gas-bubble expansion.
Gas supply system for bubblers

Component tests are being carried out in water and mercury loops.
Conceptual design is being made by a company.

- Surge tank
- Remove bubbles > 100 µm
- Heat exchanger and high points
- Evaluate effects of remaining bubbles or gas layers on mercury flow

Strong Collaboration Between JSNS and SNS

Facilities for cavitation damage characterization and mitigation tests:
- Off-line tests
  - JAEAs impact testing apparatus (MIMTM)
  - ORNLs full-scale Hg loop (TTF)
- In-Beam Tests at LANLs WNR facility
  Characterize bubbles, measure mitigation effects, etc.
Conclusion Spallation Targets

- High power targets (solid and liquid) are operated in the 1 MW regime.
- Target lifetime is mostly limited by following effects
  - Radiation damage  →  Embrittlement, fatigue or more general change of material properties due to irradiation
  - Cavitation Erosion (Pitting) in case of LMT
- All laboratories do extensive Post Irradiation Examination (PIE) of spent Targets  →  knowledge data base growing
- At power levels > 1 MW the biggest problems are:
  - Dissipation of energy densities (liquid targets, rotating targets …)
  - Shock waves  →  search for new structural materials.mitigation
- Personal opinion: In the regime of 1 MW it is not clear which target concept (Liquid Metal Target or Solid Target) is advantageous.
- New projects aiming for higher beam powers (2 MW+) need know-how from existing sources  →  intensive collaborations

Meson and Neutrino targets
Basic parameters

- 590 MeV proton cyclotron with maximum current of 2.2 mA (~1.3 MW)
- 2 meson production targets:
  - Target „M“ (mince, 5 mm graphite)
  - Target „E“ (epaisse, 4 cm graphite)

History of meson targets at PSI

- Mainly graphite targets
- Targets radiation cooled
- Operated in continuous mode (no pulses)
- Target M: $\sigma_x=0.8 \text{ mm} \sigma_y=0.9 \text{ mm}$
- Target E: $\sigma_x=0.75 \text{ mm} \sigma_y=1.3 \text{ mm}$
Design of "p-Kanal", Target E, collimators & beam dump

High dose rates at beam level shielded → working platform moderate dose

Measured dose rate > 500 Sv/h!!

Meson production Target E
**Meson production Target E**

**TARGET CONE**
- Mean diameter: 450 mm
- Graphite density: 1.8 g/cm³
- Operating Temperature: 1700 K
- Irradiation damage rate: 0.1 dpa/Ah
- Rotational Speed: 1 Turn/s
- Target thickness: 60 / 40 mm
- 10 / 7 g/cm²
- Beam loss: 18 / 12 %
- Power deposition: 30 / 20 kW/m²

**SPKES**
To enable the thermal expansion of the target cone.

**BALL BEARINGS *)**
- Silicon nitride balls
- Rings and cage silver coated
- Lifetime: 2 y

*) GfN, Nürnberg, Germany

---

**Target E – latest design**

The gaps allow unconstrained dimensional changes of the irradiated part of the graphite.

In operation since 2003
- Integrated beam current: ~2E Ah
- Irradiation damage rate: ~2.5 dpa
Target E – Temperatures & Stresses

\[ Q \left( \frac{W}{m^2} \right) = \varepsilon \cdot \sigma_{SB} \cdot T^4 \]

- \( \varepsilon \) ... emissivity
- \( \sigma_{SB} \) ... Stefan-Boltzmann Konstante (= 5.67 \times 10^{-8} \frac{W}{m^2 \cdot K})
- \( T \) ... Temperature [K]

**Radiation cooling**

- Very effective at high temperatures.
- Cool surrounding instead of target.
- High emissivity necessary.

Neutrino Production Targets
Production principle

Production scheme of Neutrino beam

- 1 meter long graphite target, water cooled
- 120 GeV proton beam $N_p=4 \times 10^{13}$ (f=0.53 Hz, pulse length 10 µs, gaussian shape $\sigma_x=0.7$ mm $\sigma_y=1.4$ mm)
- $p+A \rightarrow \pi$ ($T=2.6033 \times 10^{-8}$ s) emerge from target $\rightarrow$ decay in long tunnel $\rightarrow \pi \rightarrow \mu + \nu_\mu$ (99.987%)
- Intense $\nu_\mu$ neutrino beam (contamination due to $\mu + \nu_e + \nu_\mu$)

Neutrino Target (LE option)

- Long (2-3 interaction lengths),
- thin structures $\rightarrow$ fast escape of mesons ($\pi, K$)
- Shape governed by magnetic focusing system (horns) $\rightarrow$ inside horns
- Highly focussed beam $\rightarrow$ large energy densities
- Current targets $\rightarrow$ low Z materials (C, Be)
- Future targets $\rightarrow$ high Z foreseen (Hg, W ...)
NuMi Target (LE option)

Experience with the NuMI Target

1st Target took beam for over a year, 820 MWhr integrated beam power. Two problems:
- water leak soon after turn-on, back-pressure with Helium to keep water out
- target motion drive shaft froze up after year of operation – stack in H.E. focus

2nd Target is running (no leak)

<table>
<thead>
<tr>
<th>Target Design specification</th>
<th>Max. Proton/spill</th>
<th>Max. Beam Power</th>
<th>Integrated Protons on Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st target Before leak</td>
<td>25e12 p.p.p.</td>
<td>69 kW</td>
<td>0.7 e18 p.o.t.</td>
</tr>
<tr>
<td>2nd target</td>
<td>40e12 p.p.p.</td>
<td>320 kW</td>
<td>201 e18 p.o.t.</td>
</tr>
</tbody>
</table>
**Neutrino Targets**

<table>
<thead>
<tr>
<th>Neutrino targets</th>
<th>Laboratory</th>
<th>Energy/momentum</th>
<th>Target material</th>
<th>Length</th>
<th>Water Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNGS</td>
<td>CERN</td>
<td>400 GeV/c protons 2.4·10^{13} ppp 512 kW</td>
<td>Carbon</td>
<td>≥2 m</td>
<td>Air Cooling</td>
</tr>
<tr>
<td>NuMi</td>
<td>Fermi National Laboratory</td>
<td>120 GeV/c protons f=0.53 Hz</td>
<td>Carbon</td>
<td>≤1 m</td>
<td>Water cooling</td>
</tr>
<tr>
<td>MiniBoone</td>
<td>Fermi National Laboratory</td>
<td>8 GeV protons 5·10^{12} ppp f=5 Hz</td>
<td>Beryllium</td>
<td>≤</td>
<td>Air Cooling</td>
</tr>
<tr>
<td>T2K</td>
<td>J-Parc</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Conclusion Neutrino Targets**

- High energy densities and resulting thermal shocks currently set limit for (solid) neutrino targets → cyclic stresses → fatigue limits

- New target concepts for ν-Production targets address following issues:
  - Dissipation of energy due to rotating/moving targets
  - Liquid metal targets (as e.g. MERIT)
  - High Z materials → higher neutrino production
  - Extensive tests of materials
Beam Dumps

• Used during beam development and set-up of accelerators
  – Generally not used during normal operation (except for colliders)
• Parts of accelerators can be optimized → other parts do not see beam
• Have to absorb and stop primary beam particles → secondary particles in general shielded by a so-called biological shield (concrete, earth …)
• Essentially the same requirements as targets (not for particle production) → same assessment
  – Beam often defocussed to reduce peak current densities → reduction of power densities
• High Z materials favored
  – Often medium Z materials such as Steel or Copper used
3 GeV Extraction
Beam Dump
JSNS

Y. Kasugai and H. Kogawa
JAERI

Specification

Maintenance free and passive cooling
Maximum proton beam power: 4 kW
Configuration
• Steel: 3.5 m × 3.0 m × 3.0 m, type 304-SS liner.
• Concrete: 2.0 m in thickness.
• Beam duct
Technical requirement
- Radiation dose limit at boundary of concrete and soil is set to be less than 11 mSv/hr.
- Safety margin of factor 2 should be considered for calculation.
- That means less than 5 mSv/hr is required for shielding calculation.

Calculation
- NMTC/JAM + DORT
- Calculation Model: R-Z
Radiation Dose

Calculation results
• Concrete with 2 m thickness is sufficient.

Thermal Distribution

Technical requirement
• Temperature of concrete should be kept less than 60°C in order to keep the structural strength.

Calculation
• Heat deposition: NMTC/JAM
• Thermal conduction: ABAQUS
• Continuous operation for 48 hours is assumed.
Thermal Distribution at 48 hours

Concrete Max. 36°C

SS Max. 220°C

4kW

Output Set: Step 1-8, 172800.
Contour: Temperature

Temperature History

SS Temp. history

Concrete Temp. history

Max: 37.5°C @ 66h
PSI 590 MeV beam dump

590 MeV Beam Dump: side view

Material: copper  water cooled

local shielding
590 MeV Beam Dump: front view

Beam envelope from Target E (6 cm) to Beam Dump

\[ \sigma_x = 104 \text{ msr} \]

\[ \sigma_y = 70.5 \text{ msr} \]
Temperature distribution for 6 cm C-target E

![Temperature Distribution Diagram]

Key parameters on beam dump

<table>
<thead>
<tr>
<th>size (cm)</th>
<th>slices</th>
<th>power deposit (kW/mA)</th>
<th>water flux (l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.section: 30 x 44</td>
<td>6</td>
<td>220</td>
<td>4.2</td>
</tr>
<tr>
<td>2.section: 35 x 26</td>
<td>7</td>
<td>180</td>
<td>4.2</td>
</tr>
<tr>
<td>3.section: 35 x 14</td>
<td>7</td>
<td>30</td>
<td>4.2</td>
</tr>
<tr>
<td>4.section: 30 x 50.5</td>
<td>6</td>
<td>- (= shielding)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Local shielding: 30-60 l/s

- Designed for:
  - 2 mA with 6 cm C-Target E → 40% beam loss → 1.2 mA on beam dump
  - 1.6 mA → 30% → 1.12 mA

- Total max. power deposit: 500 kW
- Highest power density: 350 W/cm³
- Highest temperature: 380 °C for 2 mA, 6 cm C-Target E
  < 405 °C (allowed limit due to recrystallisation of Cu)

- Energy deposit: 425 MeV/mA
- Proton range: 23 cm
Thank you for your attention.