A generic study on the design and operation of high power spallation targets

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Abstract

With the move towards beam power in the range of 1–10 MW, a thorough understanding of the response of target materials and auxiliary systems to high power densities and intense radiation fields is required. This paper provides insight into four major aspects related to the design and operation of high power solid targets: thermal stresses, coolant performance, radiation damage and neutron economy. Where appropriate, a figure-of-merit approach is followed to facilitate the comparison between different target or coolant candidates. The section on radiation damage reports total and spatial variations of DPA and helium production levels in different target materials, while the neutron economy section aims to refine the optimisation process of spallation target designs.

- Introduction
  - Work done under PASI Targets Work Package 1
    - M1.3 candidate target materials.
  - Submitted to
    - Physical Review Special Topics: Beams and Accelerators (Oct 13)
- Aim
  - Assist us to design and operate solid high power targets in a safe way.
  - Tool to assist us in identifying candidate target materials
  - Using the Figure of Merit approach to assist in design process
- Focus on four main areas
  - Thermal stresses - FoM
  - Coolant performance - FoM
  - Radiation damage
  - Neutron economy
- Used ISIS TS1 target and beam parameters where required

- Thermal stresses
  - Time varying energy deposition even for so called CW targets!
  - Rapid rates of temperature rise during a beam pulse
  - Different rates of thermal expansion
  - Different rates of thermal diffusion
  - Thermal shock from pulse – not sonic
  - Useful to compare the thermal stress resistance capability of different materials hence:
- FoM (flat plate)

$$FoM_{stress} = \frac{YS(1-\nu)k}{YM\alpha\rho C_p}$$

where k is thermal conductivity, ρ is density and C_p is heat capacity.

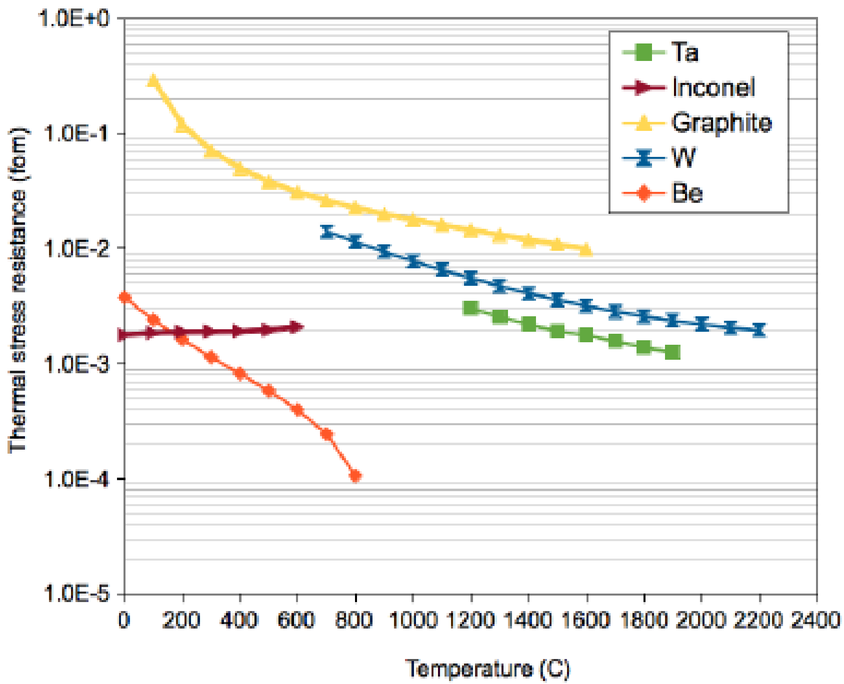


FIG. 1. Thermal stress resistance figure-of-merit in different target materials at different operating temperatures

- Additional issues:
  - Fatigue
  - Brittle/ductile materials
  - Material QA

- Coolant performance
  - The ideal
    - Good heat transfer and transport with minimal neutron absorption
    - Looking for efficient forced convection
  - Based on reactor coolant FoM work
- FoM

$$FoM_{coolant} = \frac{C_p^{2.8}\rho^2}{\mu^{0.2}}$$

Addition of k discussed!

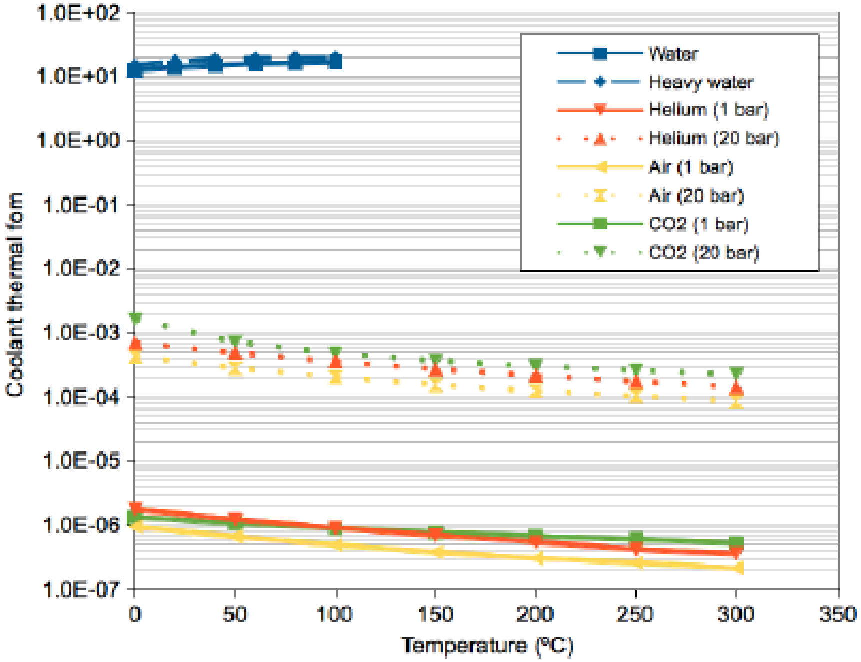


FIG. 2. Thermohydraulic figure-of-merit for different target coolants at different operating temperatures and pressures

- Coolant neutronic performance
  - The ideal
    - minimal neutron absorption
  - Used well known source ENDF database
  - Then developed the absorption macroscopic cross-sections
  - Results:

i	Energy group (i)	$w(i)$
1	[1 eV, 300 eV]	3.52E-05
2	[300 eV, 1 MeV]	5.53E-01
3	[1 MeV, 20 MeV]	3.88E-01
4	[20 MeV, 800 MeV]	5.93E-02

TABLE I. Spallation spectrum energy groups and their corresponding weighting factors

where σ is the 'effective' microscopic cross-section found using Eq. (11) and ρ' is the atomic density.

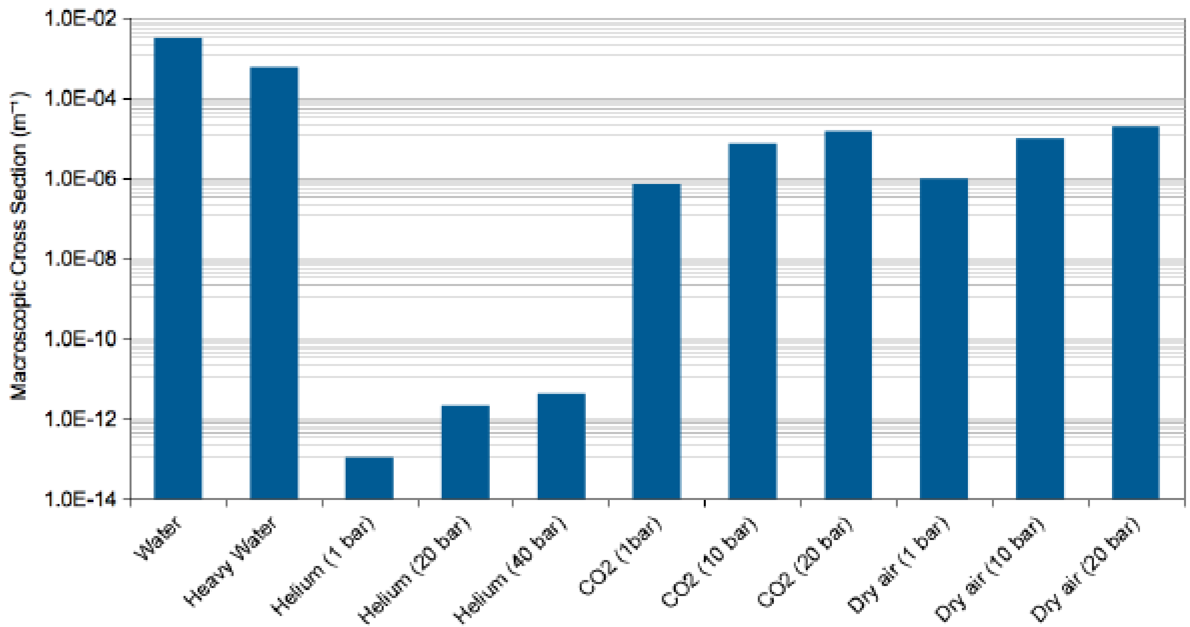


FIG. 3. Neutron absorption in different target coolants at different operating conditions

- Notes on radiation damage in high power targets
  - Damage due to displacement and transmutation
  - Spallation harsher than fission environment?
  - Complex mechanisms at work
  - Use Monte Carlo simulation codes (FLUKA)to estimate:
    - Dpa
    - He production

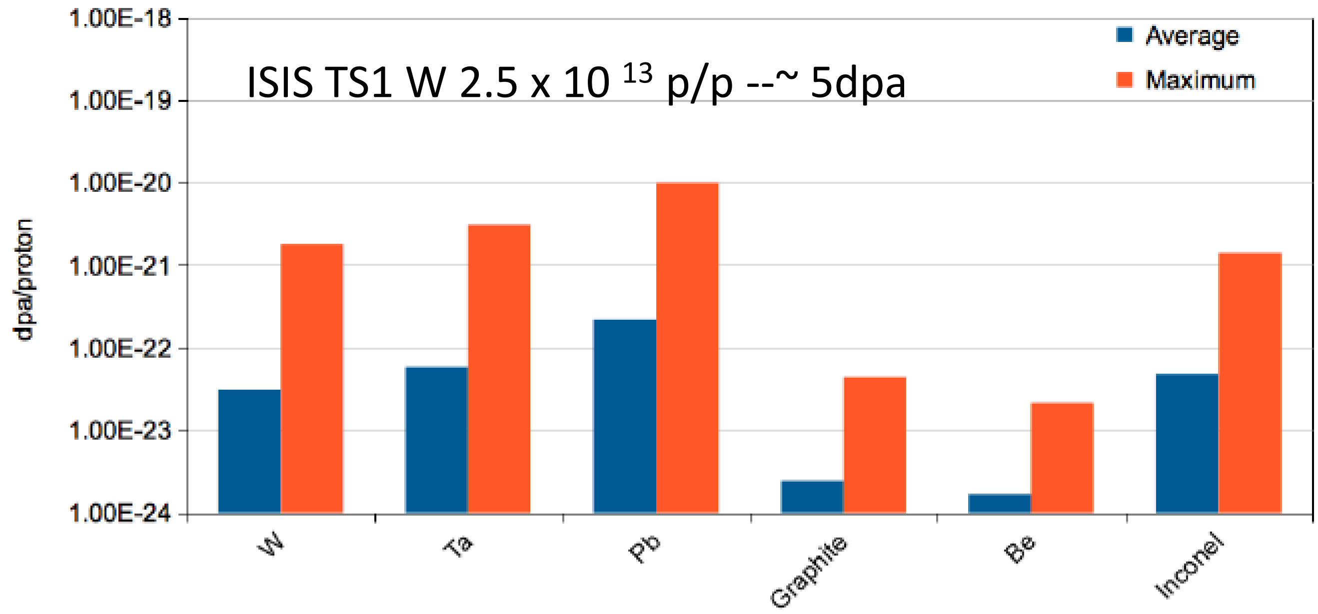


FIG. 4. DPA values per incident proton of 800 MeV kinetic energy for different target materials

Parameter	Value	Unit
Target dimensions	$10 \times 10 \times 36$	cm
Beam kinetic energy	800	MeV
Beam profile	Gaussian (σ=1.7)	cm
Displacement damage threshold		Value (eV)
W		90
Ta		53
Pb		25
Graphite		30
Be		31
Inconel		40

TABLE II. Simulation parameters of radiation damage case

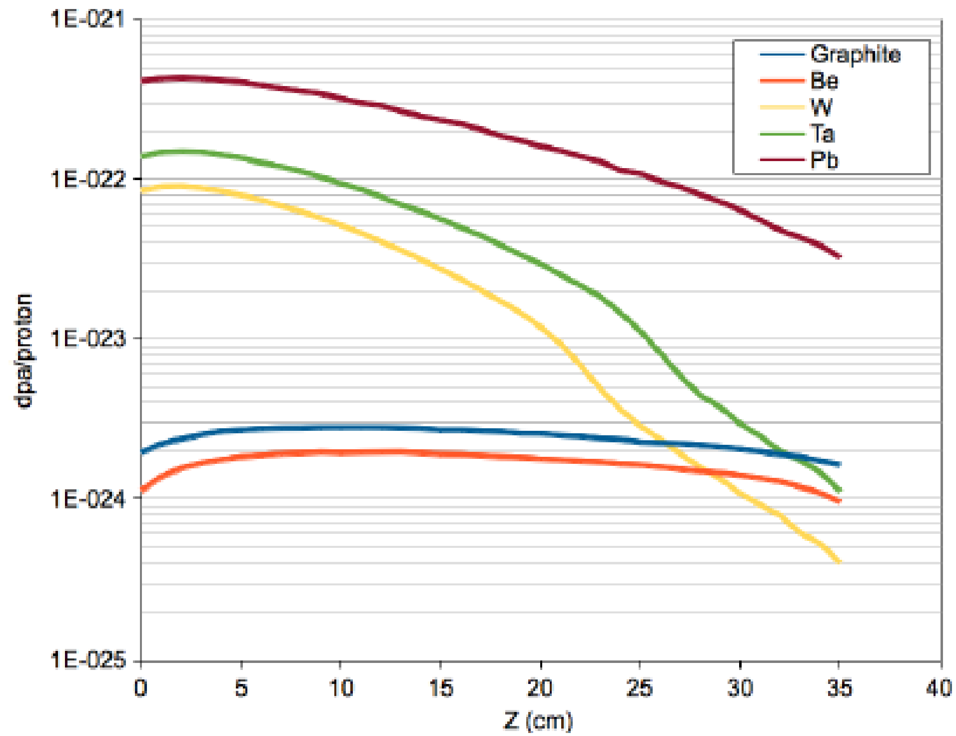


FIG. 5. DPA variations with target depth for different target materials

appm?

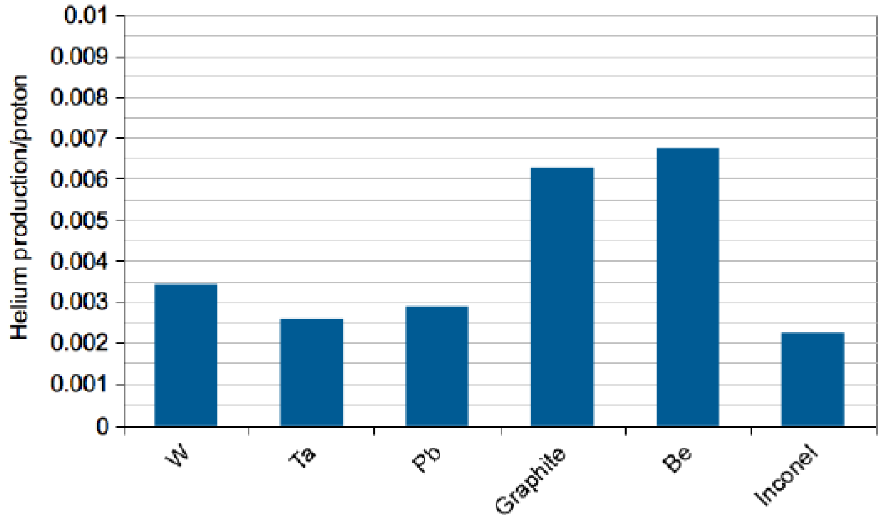


FIG. 6. Total helium production in different target materials

Remember varying
diffusion rates

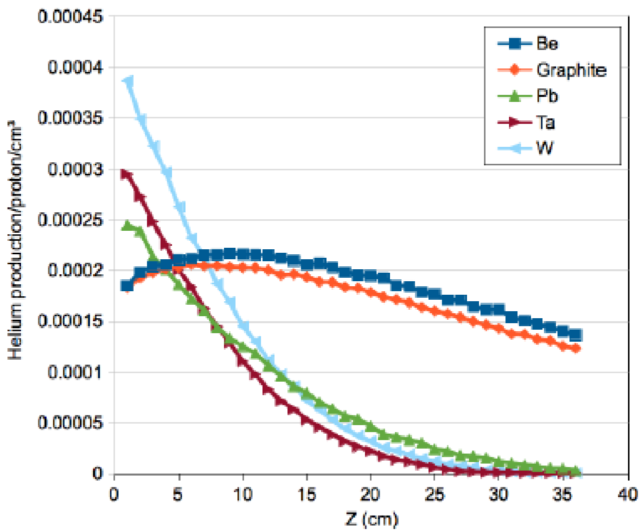


FIG. 7. Variations of the total helium production with target depth for different materials

- Neutron economy for a spallation neutron source
  - High neutron production in specific energy ranges
  - Useful neutrons at instrument!
  - Solid targets preferred over liquid ones
  - Issues with some materials for instance Uranium
  - Importance of pulse shape

The neutronic modelling of TS1 has been done using the MCNPX Monte Carlo code [17].

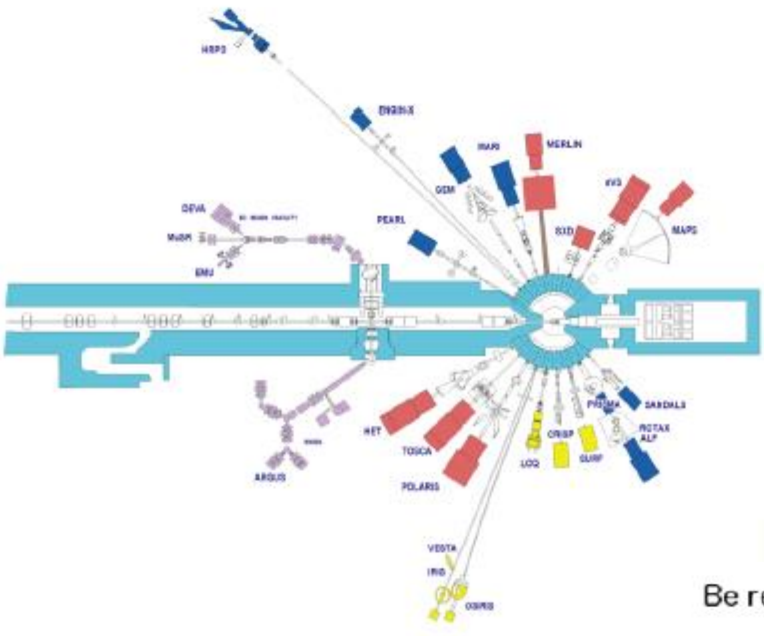
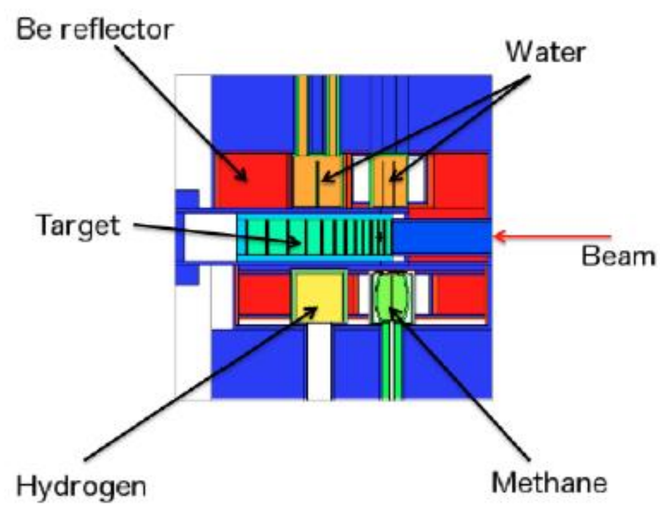


FIG. 8. Layout of ISIS TS1



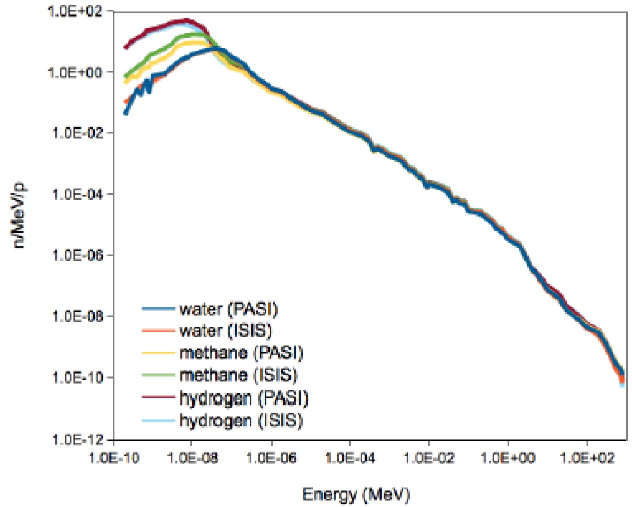


FIG. 10. Neutron flux comparison between ISIS and PASI MCNPX models

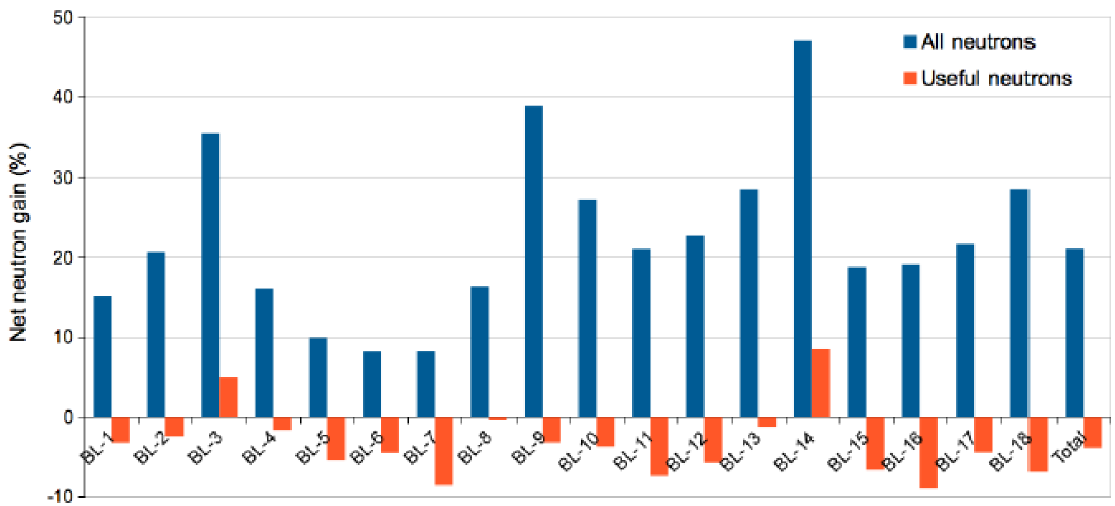


FIG. 11. Comparison of the net neutron gain in a steel-free concept of ISIS TS1

- Conclusion

In this paper, we studied four major aspects related to the operation and design of high power targets. A figure-of-merit approach was used to compare the resistance of target materials to thermal stresses as well as the thermohydraulic performance of candidate target coolants. The figure-of-merit analysis showed that there are some gaps in the materials' data, particularly in regards to tantalum. The coolant performance analysis showed that, although water has superior heat transfer efficiency, it absorbs too many neutrons compared to other candidate coolants. Pressurised helium seems to be a good coolant option, as it offers negligible neutron absorption and good thermal properties compared to other gaseous coolants.

On the issue of radiation damage, the total and spatial variations of DPA and helium production were reported for different target materials in a fixed target geometry. Heavy and light elements showed different spatial variations due to the effects of other factors, such as electronic energy losses and the spatial distribution of primary and secondary particles. The final section of the paper introduced the concept of neutron economy for optimising the neutronic needs defined by the physics and applications supported in a spallation target station. A steel-free concept based on the current design of ISIS TS1 was studied, as an example, and to support ongoing work by the authors to optimise neutron production in the target station.