ADS Target Challenges

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Goal of ADS Target Systems

- Create lots of neutrons useful for some downstream purpose
- Many possible paths
  - Will focus here on waste transmutation
- Spallation is efficient for high efficiency neutron production

Process	Example	Energy cost-on target only
(D,T) fusion	400 keV on T	10,000 MeV/n
Li (D,n) breakup	35 MeV D on Li	14,000 MeV/n
U-238 (γ,n) photo-nuclear	20 MeV e^- on U-238	2000 MeV/n
^{9}Be (p,n;p,pn)	11 MeV proton on Be	2000 MeV/n
Spallation	800 MeV on Pb	55 MeV/n
	800 MeV proton on U-238	30 MeV/n

Table source: Nema, P. K. (2011). Application of Accelerators for Nuclear Systems: Accelerator Driven System (ADS). Energy procedia, 7, 597-608. doi:10.1016/j.egypro.2011.06.080

Targets Provide Neutrons for Amplification

- Beam power to target required depends on required power output and the surrounding core
- Burners may need >GW total power
- Optimal target designs could provide energy gain >100X with k_{eff}=0.98 cores
  - Gain isn't end goal in transmutation

$$\lim_{k_{eff} \to 1} \frac{k_{eff}}{(1 - k_{eff})} = \infty$$

$$Energy\ Gain = \chi \cdot \frac{\varphi * k_{eff}}{\nu \cdot (1 - k_{eff})} \cdot E_f$$

χ = Neutrons out from target per GeV beam in

φ = Neutron importance (factor > 1)

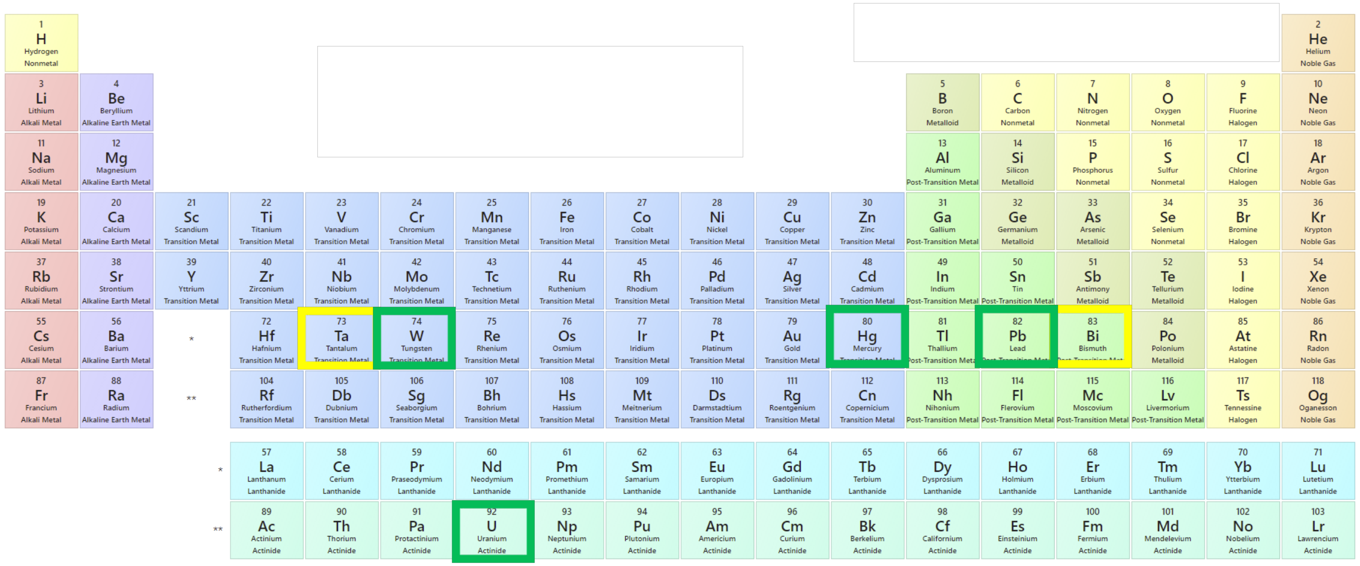
ν = Average neutrons released per fission

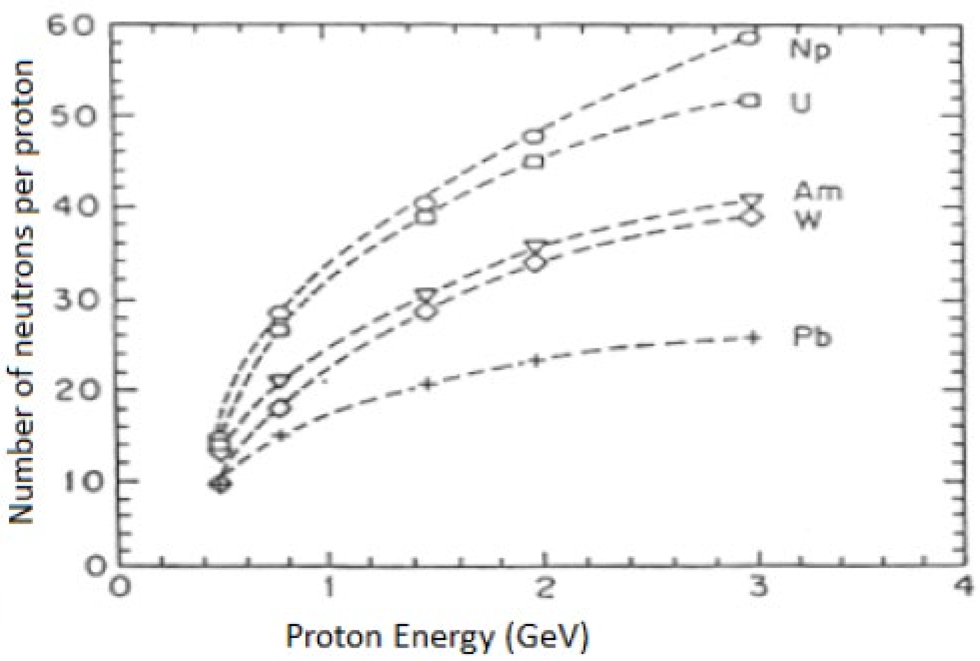
E_f = Useable energy per fission

Reference: Hashemi-Nezhad, S. R., Westmeier, W., Zamani-Valasiadou, M., Thomauske, B., & Brandt, R. (2011). Optimal ion beam, target type and size for accelerator driven systems: Implications to the associated accelerator power. *Annals of Nuclear Energy, 38(5), 1144-1155. doi:10.1016/j.anucene.2010.12.008*

High-Z Materials Are the Best for Spallation Targets

- Historically, tungsten (W), lead (Pb), uranium (U) and mercury (Hg) have been used for spallation target materials





Periodic table from https://pubchem.ncbi.nlm.nih.gov/periodic-table/
Figure from: International Atomic Energy, A. (2015). Status of accelerator driven systems research and technology development(IAEA-TECDOC-1766). Vienna : International Atomic Energy Agency.

Liquid Metal Options and Problems

- Mercury (used at the SNS)
  - Melting point −40°C
  - Boiling Point 350°C/ 670°F
- Lead
  - Melting point 330°C / 620°F
  - Boiling point 1,750°C / 3,200°F
- Lead bismuth eutectic (LBE)
  - Melting point 125°C / 260°F
  - Boiling point 1,670°C / 3,000°F

- All can cause liquid metal embrittlement and chemical incompatibility issues
- All are harmful to humans
- Lead and LBE require elevated temperatures for operation
- LBE has higher polonium production
- Mercury has higher vapor pressure

Fast Reactor Coolant ≈ Spallation Target Material

- Lead/LBE coolant can be used as a spallation target material
  - Planned approach for MYRRHA
- Lead/LBE works for fast reactor coolant
  - Blocks gamma, not neutrons
  - Good heat conductivity
- Removes separate cooling system for target

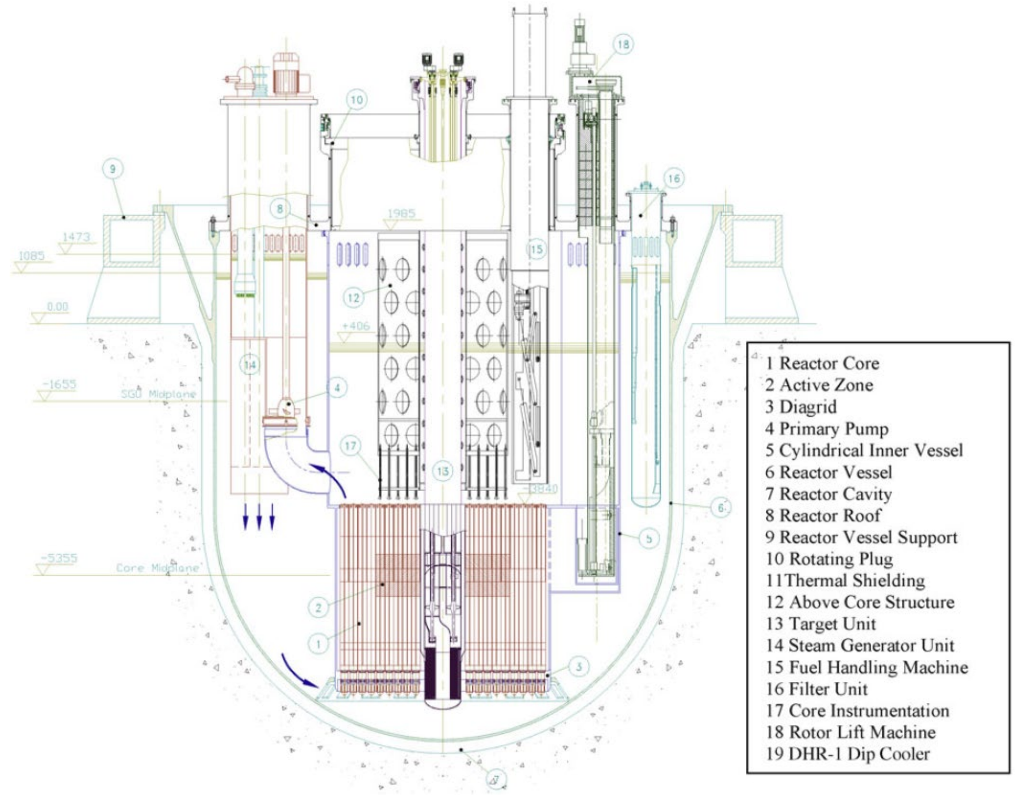
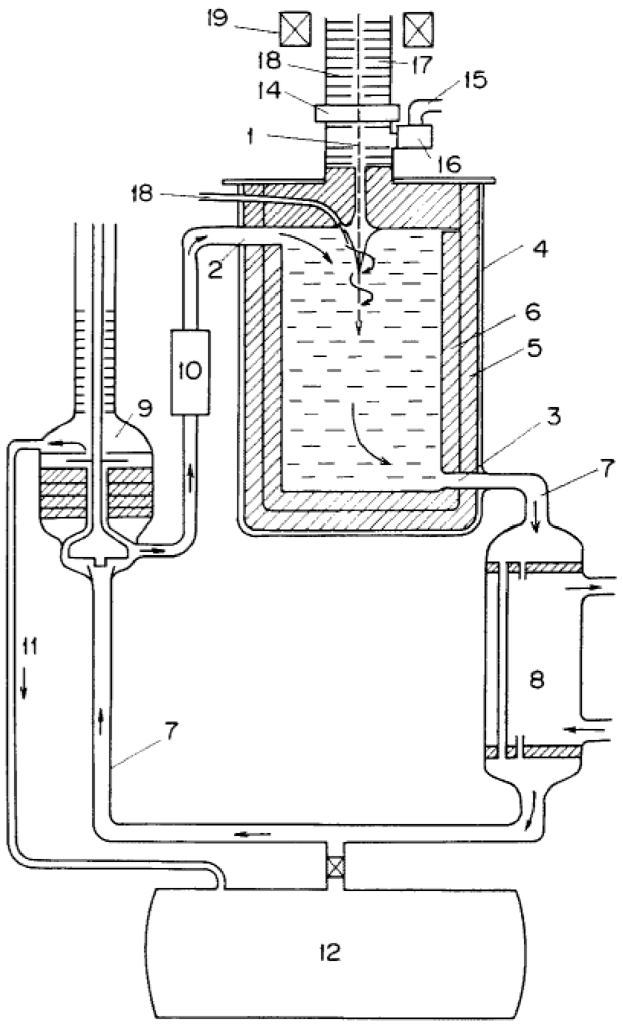


Image from: Mansani, L., Artioli, C., Schikorr, M., Rimpault, G., Angulo, C., & Bruyn, D. D. (2012). The European Lead-Cooled EFIT Plant: An Industrial-Scale Accelerator-Driven System for Minor Actinide Transmutation-I. *Nuclear Technology, 180(2), 241-263. doi:10.13182/NT11-96*

Reactor Fuel ≈ Spallation Target Material

- Shoot the beam directly at a solid core
- Use liquid fuel as spallation target
  - Molten salts can provide high-Z fissile or fissionable materials
  - Single fluid system simplicity
- Tradeoff in increased peak heat removal
  - Spallation heat + fission heat
  - Relatively short beam penetration concentrates beam energy near the impact area



1: Proton beam, 2: Salt inlet, 3: Salt outlet, 4: Reactor vessel, 5, 6: Graphite, 7: Primary loop, 8: Heat exchanger, 9: Main salt pump, 10: Throttle valve, 11: Overflow line, 12: Storage tank, 13: High-pressure salt outlet, 14: Gate valve, 15: Vacuum line, 16: Vapor trap, 17: Duct, 18: Orifice. 19: Focussing magnet

Image from: Furukawa, K., Tsukada, K., & Nakahara, Y. (1981). Single-Fluid-Type Accelerator Molten-Salt Breeder Concept. *Journal Of Nuclear Science And Technology, 18(1), 79-81. doi:10.3327/jnst.18.79*

High Beam Power + Normal Spallation Target Problems

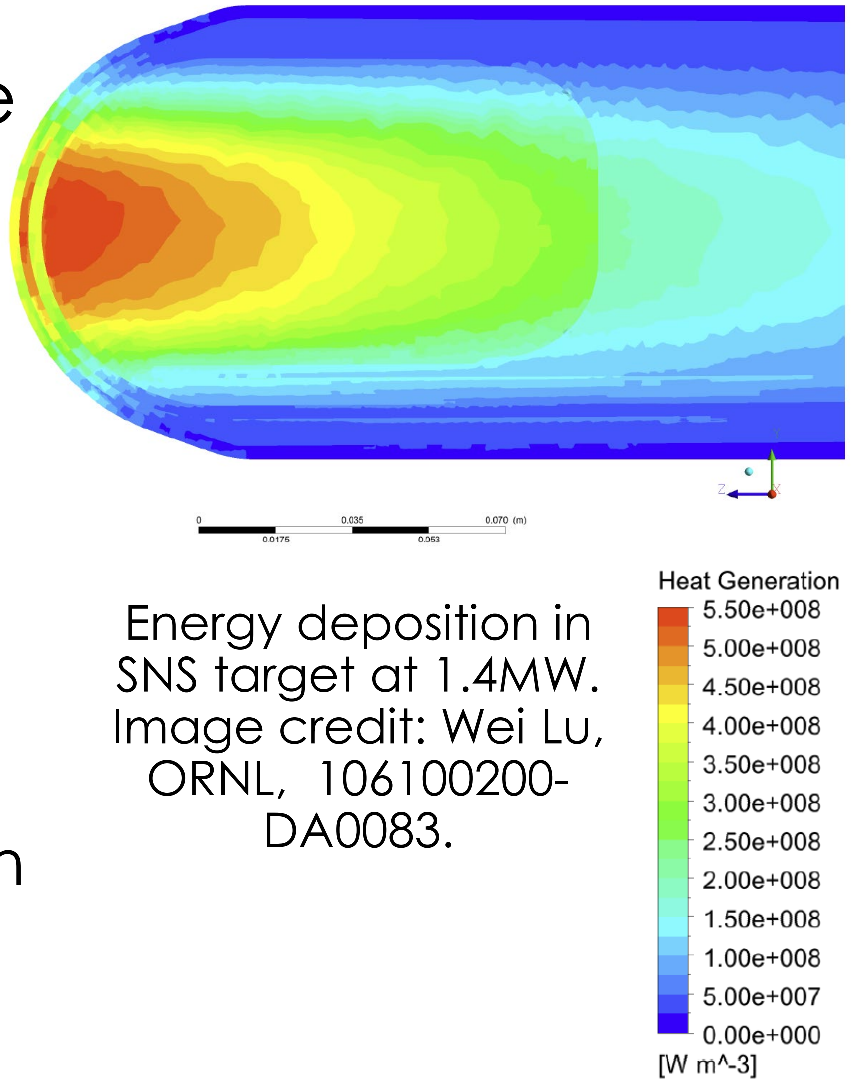
- Some solutions call for 10MW of beam power or more
  - Large compared to existing spallation sources
- Heat removal is a key driver
- Solutions
  - Liquid target material
  - Granular target material
  - Rotating through multiple targets
  - Spread beam across target(s)

Facility	Location	Power (MW)	Beam energy (GeV)
CSNS	IHEP, China	0.1	1.6
ISIS	RAL, UK	0.16	0.8
SINQ	PSI, Switzerland	0.9	0.6
JSNS	J-PARC, Japan	1.0	3
SNS	ORNL	1.4	1
ESS	Sweden	5 (planned)	2.5 (planned)

Table adapted from: Rummana, A. (2019). Spallation Neutron Source for an Accelerator Driven Subcritical Reactor. In: ProQuest Dissertations Publishing.

Compact Neutron Source = High Energy Intensity

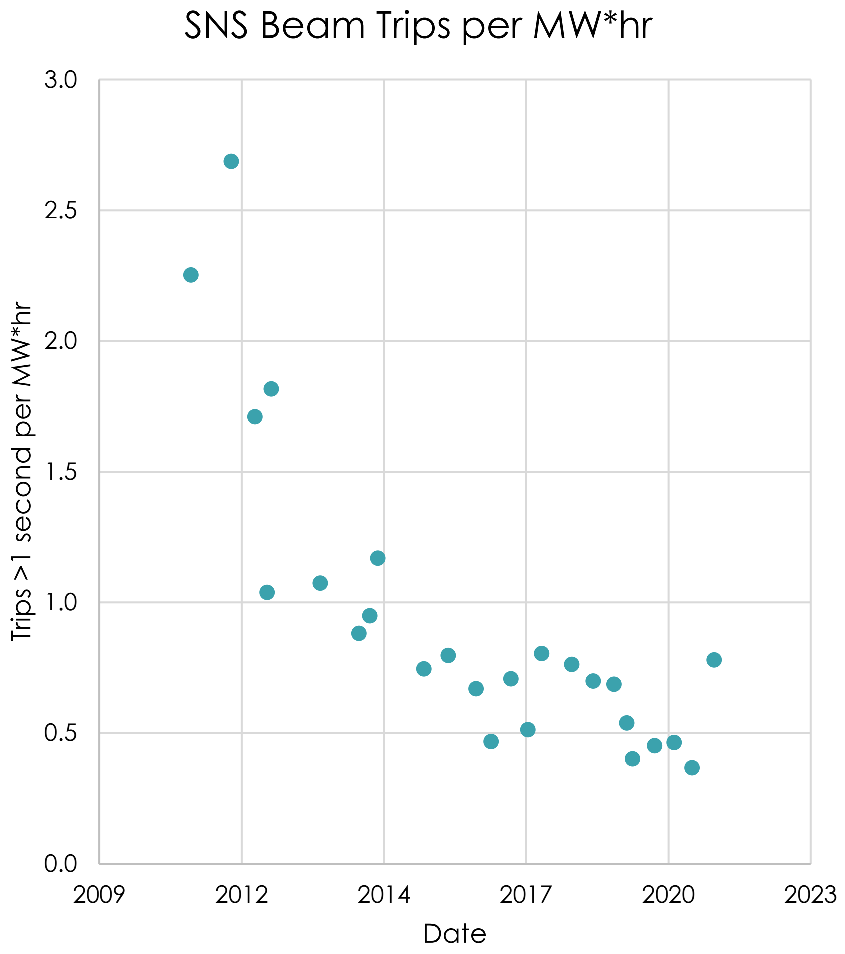
- Energy deposition can be high per volume
  - SNS target peak is ~560 MW/m^3 at 1.4 MW
- Length of energy deposition zone is a function of beam power
  - Relates to size of surrounding core to prevent neutron leakage
- Usefulness of the target for downstream function is related to size of beam
  - Tight beam gives bright source, but is harder on the area it hits



Energy deposition in SNS target at 1.4MW. Image credit: Wei Lu, ORNL, 106100200-DA0083.

Beam Transients Lead to Thermal Cyclic Stress

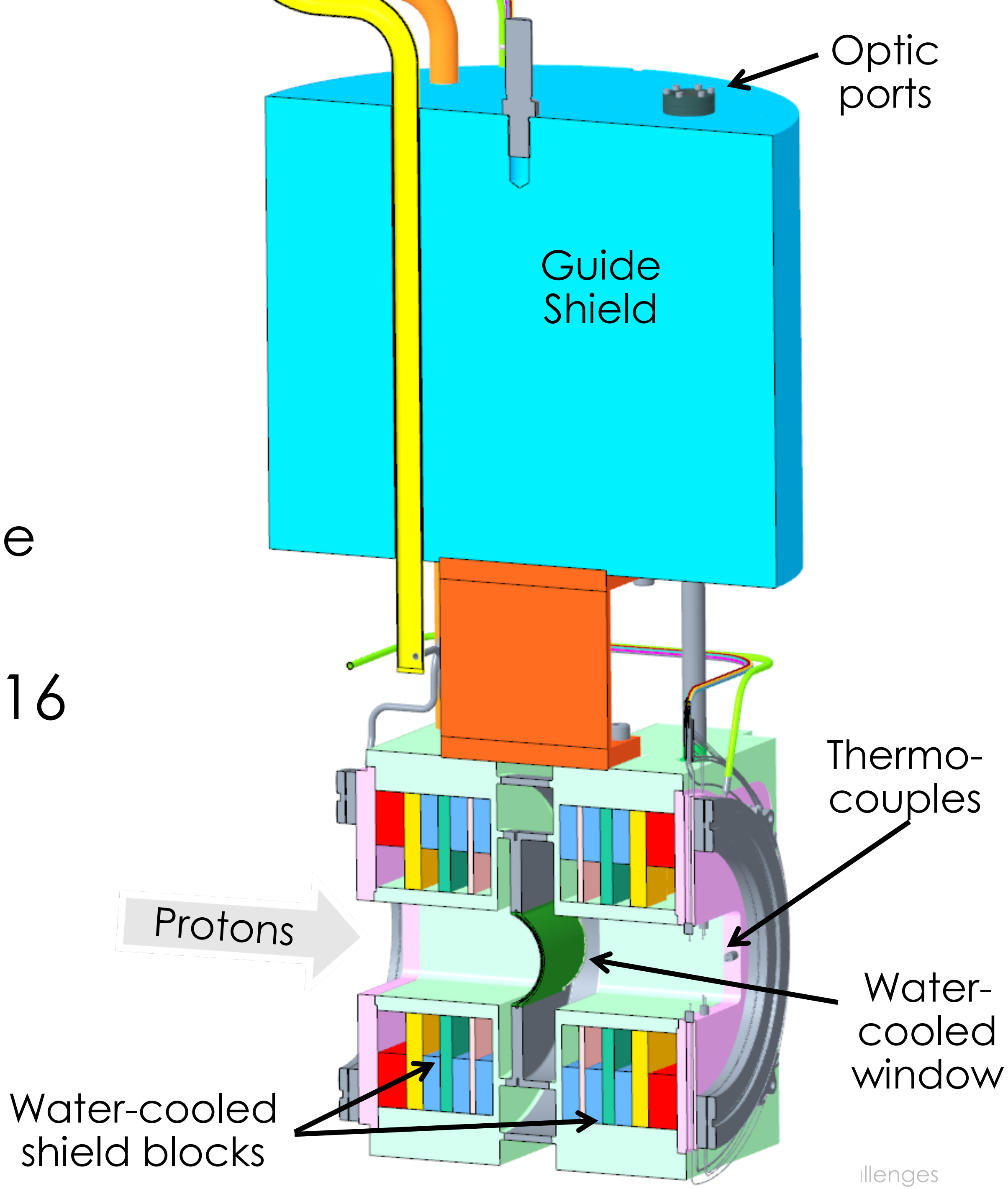
- Continuous wave (CW) beam eliminates pulse transient problem seen at short-pulse neutron scattering spallation sources
- High beam powers can lead to significant thermal transients during beam trips
  - Most concern driving accelerator reliability has been for fuel cladding
  - Thermal fatigue is also a concern for target components



Note: SNS accelerator is more complicated than a CW source

Challenges Surround Targets

- Surrounding structure may be an operational limit
  - Proton beam windows, other structures who experience high dose can become embrittled
- SNS proton beam windows last ~16 GW*hr of proton beam
  - ~2 months of continuous 10 MW operation
  - Will vary depending on the beam intensity



Target Design Choices Affect Challenges

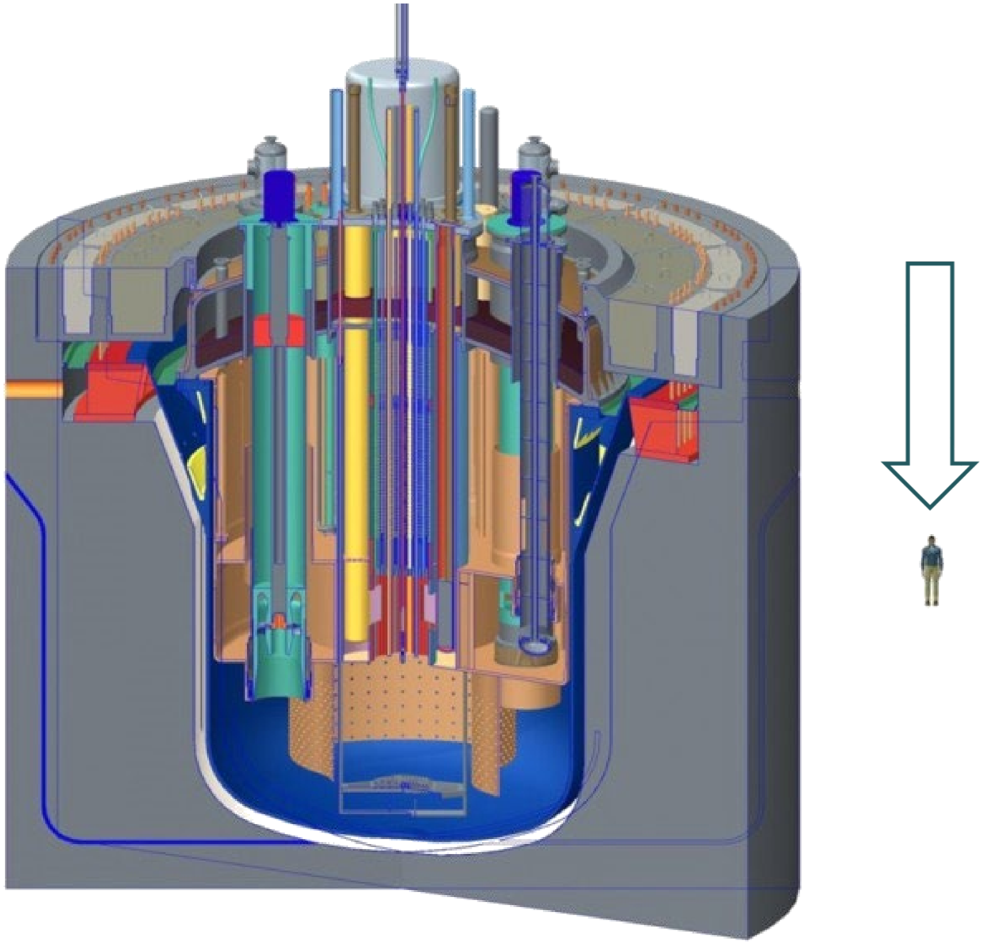
- Liquid and granular targets could operate without some structure
  - Proton beam windows
  - Target boundaries
- Reduces lifetime concerns due to
  - Radiation damage to materials
  - Fatigue damage
- Multi-use fluids (spallation/coolant or spallation/coolant/fuel) can simplify systems

Targets must serve the integrated system.

They are only a means to an end.

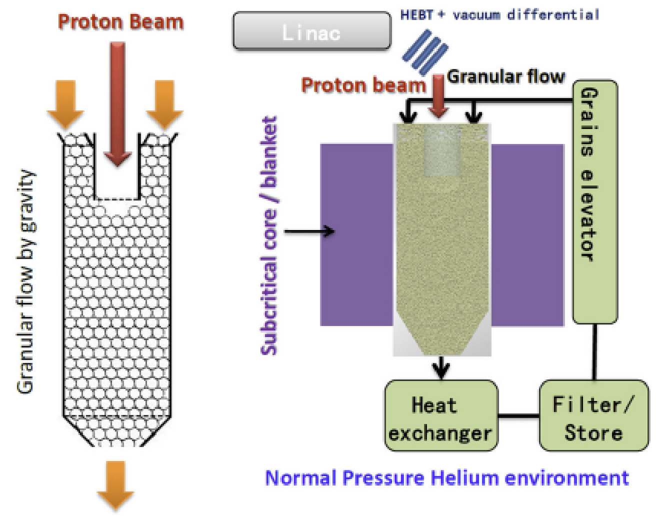
MYRRHA Target System Example

- LBE used as coolant and spallation target material
  - Would have beam window
- 0.6 GeV, 1.5 MW beam
- 50 to 100 MW_{th} output
- Want (amazingly) good beam reliability to reduce thermal cycles
  - ≤10 beam trips >3 seconds per 3 months

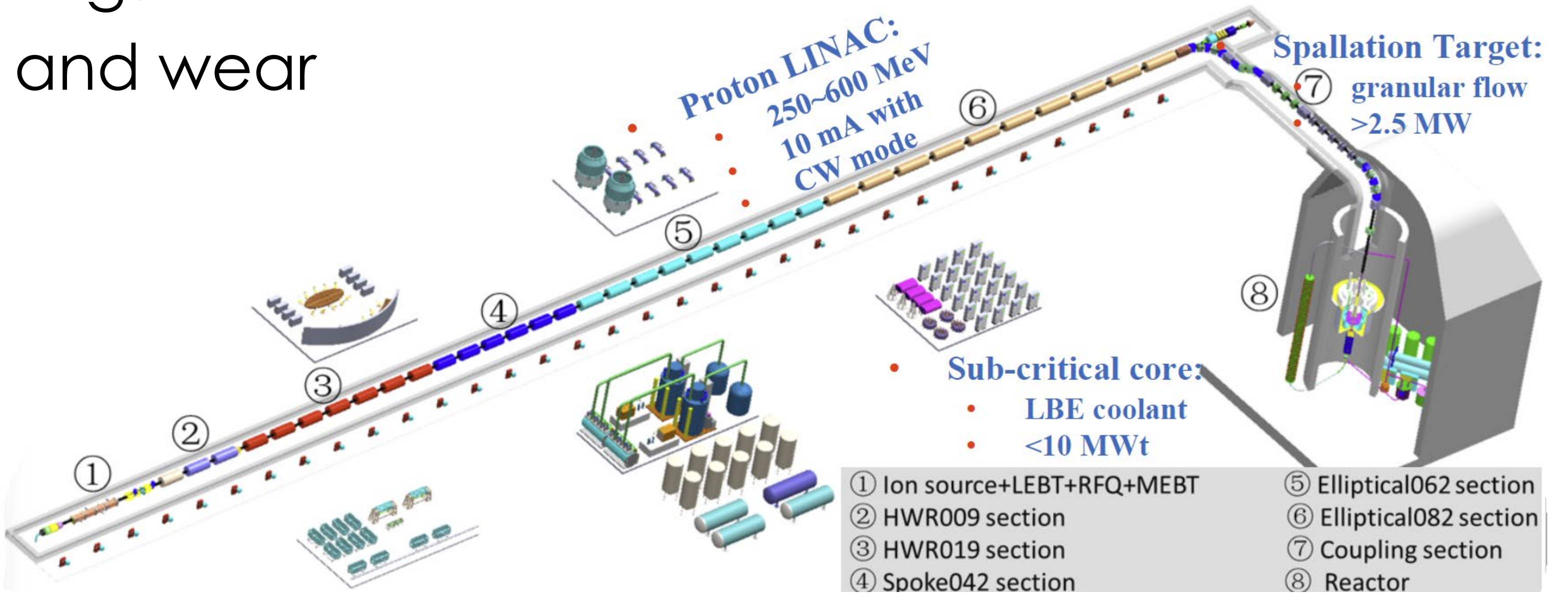


Adbderrahim, H. (2016, August 2016). *MYRRHA Project Status (06.2016). Paper presented at the 4th Workshop on ADS and thorium, Huddersfield, UK.*
Junquera, T. (2016, August 2016). *Accelerator Reliability Requirements for ADS: the MYRRHA project goals. Paper presented at the 4th International Workshop on ADSR systems and thorium, Huddersfield, UK.*
Image from:https://myrrha.be/myrrha-project/myrrha-reactor/

Chinese ADS Target (CIADS) Example



- Flowing granular target material
  - Liquid like without liquid metal problems
  - Tungsten grains with coatings
  - Potential issues with dust and wear
- Windowless design
- Up to 600 MeV, 6 MW



Images from: Han-Jie Cai, Fen Fu, Jian-Yang Li, Ya-Ling Zhang, Xun-Chao Zhang, Xue-Song Yan, Zhi-Lei Zhang, Jian-Ya Xv, Mei-Ling Qi & Lei Yang (2016) Code Development and Target Station Design for Chinese Accelerator-Driven System Project, Nuclear Science and Engineering, 183:1, 107-115, DOI: 10.13182/NSE15-59 and
He, Y., Zhan, W., Xu, H.-S., & Yang, L. (2016, August 2016). *Status and future plan of Chinese ADS project. Paper presented at the 4th International Workshop on ADSR systems and Thorium, Huddersfield, UK.*

Key Takeaways and Thoughts for Discussions

- Where goal is most neutrons per energy input, spallation is king
- Targets must be thought of as one part of an integrated ADS
  - A vital link in a chain to final product, not the main show
- ADS concept leverages beam power, but burners are hungry for neutrons
  - Large facilities will likely require multi-MW beam power
- Heat removal and material issues are major engineering problems and could limit large burner ADS reliability
  - High peak energy deposition, damage at proton beam path
  - Chemical compatibility