Tokamak Energy

Design of magnet and shielding systems for compact fusion machines

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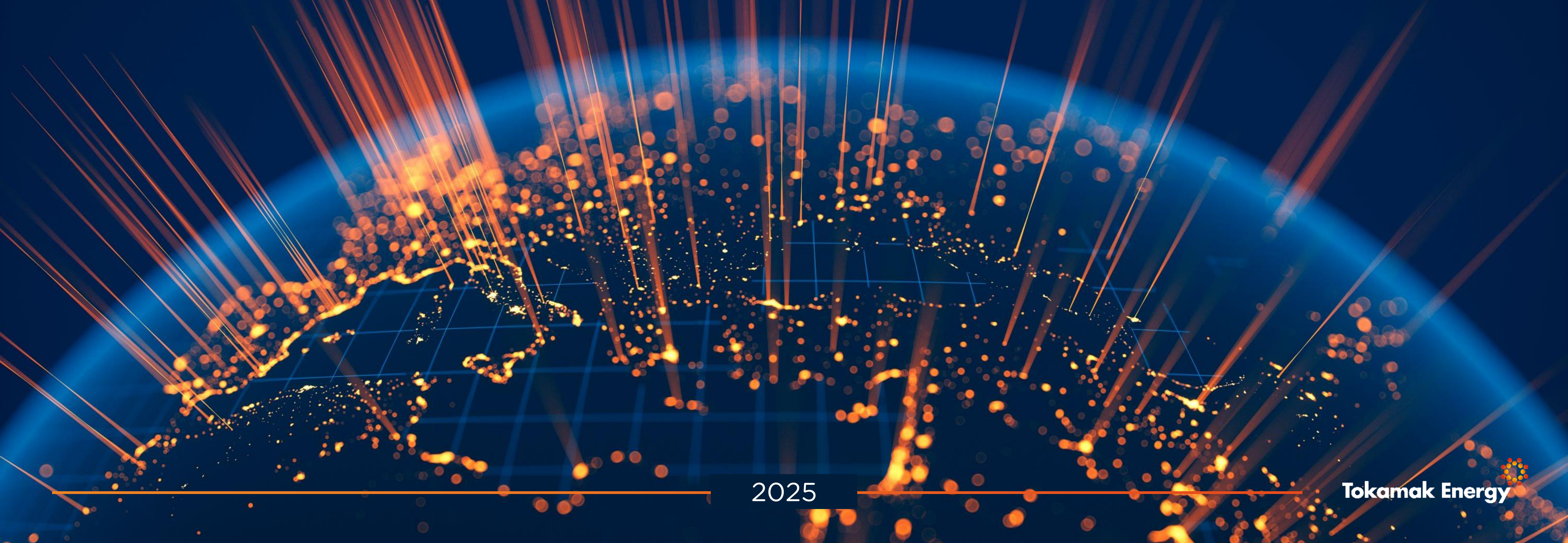
Jonathan Naish

Tokamak Energy

DELIVERING FUSION POWER AND TRANSFORMATIVE SUPERCONDUCTING MAGNET TECHNOLOGY



2025

Tokamak Energy

WE ARE TOKAMAK ENERGY

- THE LEADING GLOBAL FUSION ENERGY COMPANY
- THE LEADING HIGH TEMPERATURE SUPERCONDUCTING MAGNETS COMPANY

🇺🇸 **PRINCETON, NJ**
U.S. SUBSIDIARY

🇬🇧 **OXFORD, UK**
GLOBAL HEADQUARTERS

🇯🇵 **TOKYO, JP**
JAPANESE SUBSIDIARY

260 people worldwide

$335 million raised

Partnering with:

Department of Energy United States of America

Oak Ridge National Laboratory

University of Illinois Urbana-Champaign

ATI

General Atomics

PPPL

UK Atomic Energy Authority

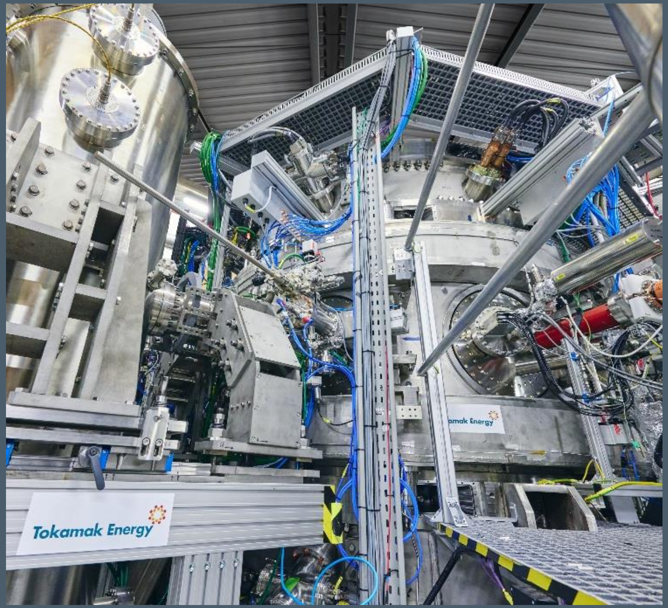
Sumitomo Corporation

Kyoto Fusioneering

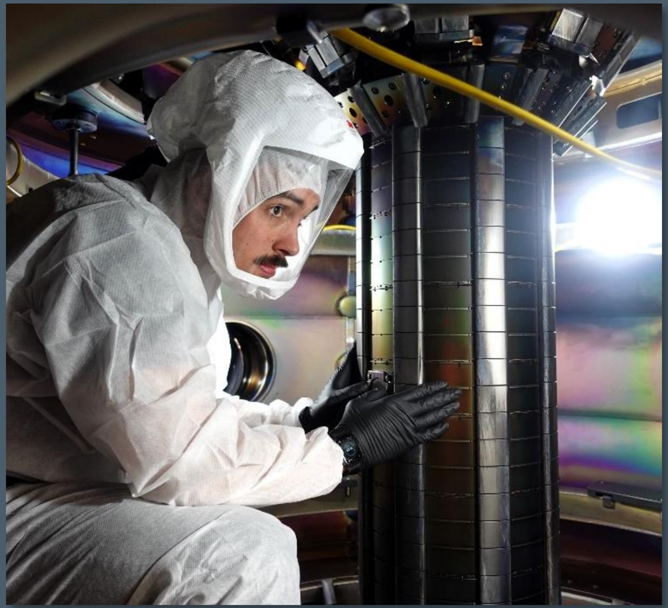
東京大学 The University of Tokyo

Furukawa Electric Group

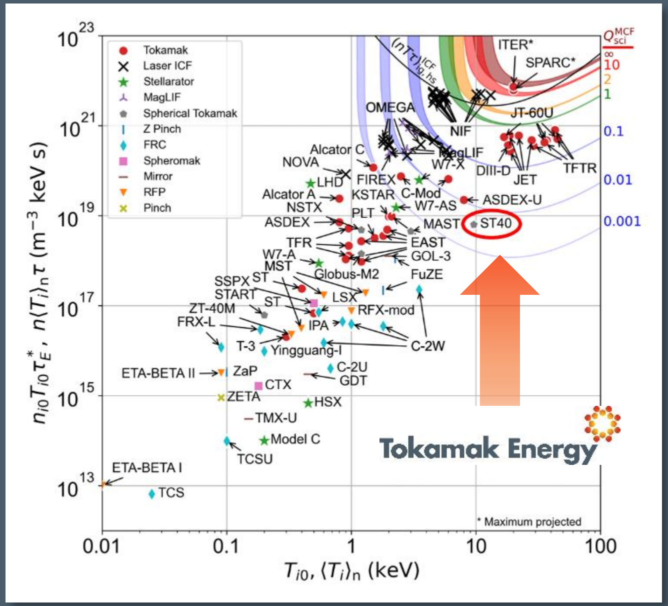
OUR RECORD



Only company with 10+ years’ experience designing and building tokamaks and HTS magnets



Unrivalled experience commissioning, operating and upgrading tokamaks



Peer reviewed highest ‘triple product’ in a privately funded tokamak

6 x 10^18 keV.s/m³

OUR FUSION TECHNOLOGY

Spherical tokamak with High Temperature Superconducting (HTS) magnets

Spherical tokamak

- High efficiency (high bootstrap current)
- Stable plasma
- Steady state running
- Requires 50% less magnet material*

HTS magnets

- Quench-safe, robust magnets
- Ultra-high magnetic field (20 Tesla +)
- Operate at 20K (no liquid cryogens)

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* Compared to a conventional tokamak (CT)

SPHERICAL TOKAMAK:
ENGINEERING REQUIREMENTS

The advantages of the spherical tokamak come with some specific engineering challenges associated with the low aspect ratio and slim centre column:

Magnet shielding

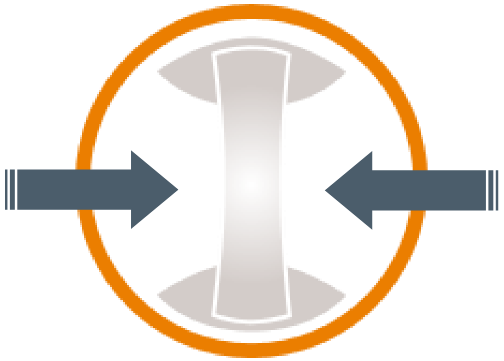
Reduced space for neutron and thermal shielding of the magnets, given fixed linear dimensions, means that novel shielding materials will be required to ensure the HTS magnets can operate for the lifetime of a power plant. *NOTE: These materials are likely to have many commercial applications.*

Outboard breeder blankets

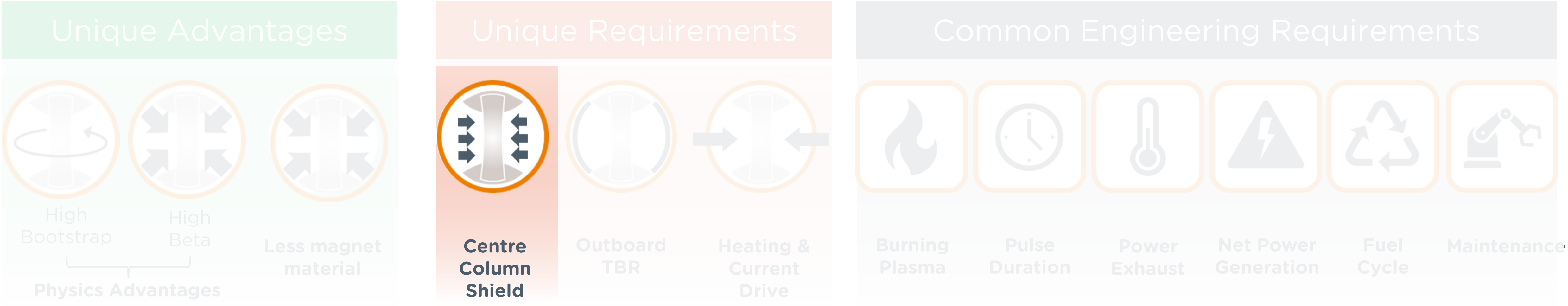
Insufficient space to accommodate an inboard tritium breeder blanket means that only outboard breeder blankets are available, with the same tritium breeding ratio (TBR) required for tritium self-sufficiency. *NOTE: The spherical geometry is favourable for outboard blankets.*

Heating and current drive

Reduced space for a large solenoid to be used for inductive current drive means the plasma heating and non-bootstrap current drive must be driven by non-inductive means such as radio frequency (RF). *NOTE: The high bootstrap fraction helps reduce the amount of RF heating needed.*



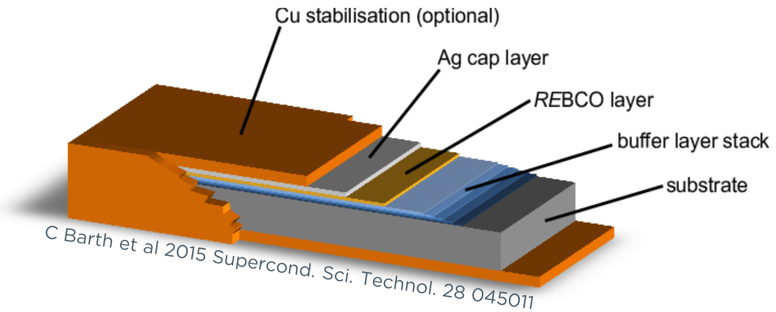
SPHERICAL TOKAMAK:
THE PATH TO DEMONSTRATION



Our path to fusion focusses on validating the physics advantages and resolving the engineering requirements.

By doing so, we are demonstrating that the HTS Spherical Tokamak provides the most commercially viable fusion energy solution.

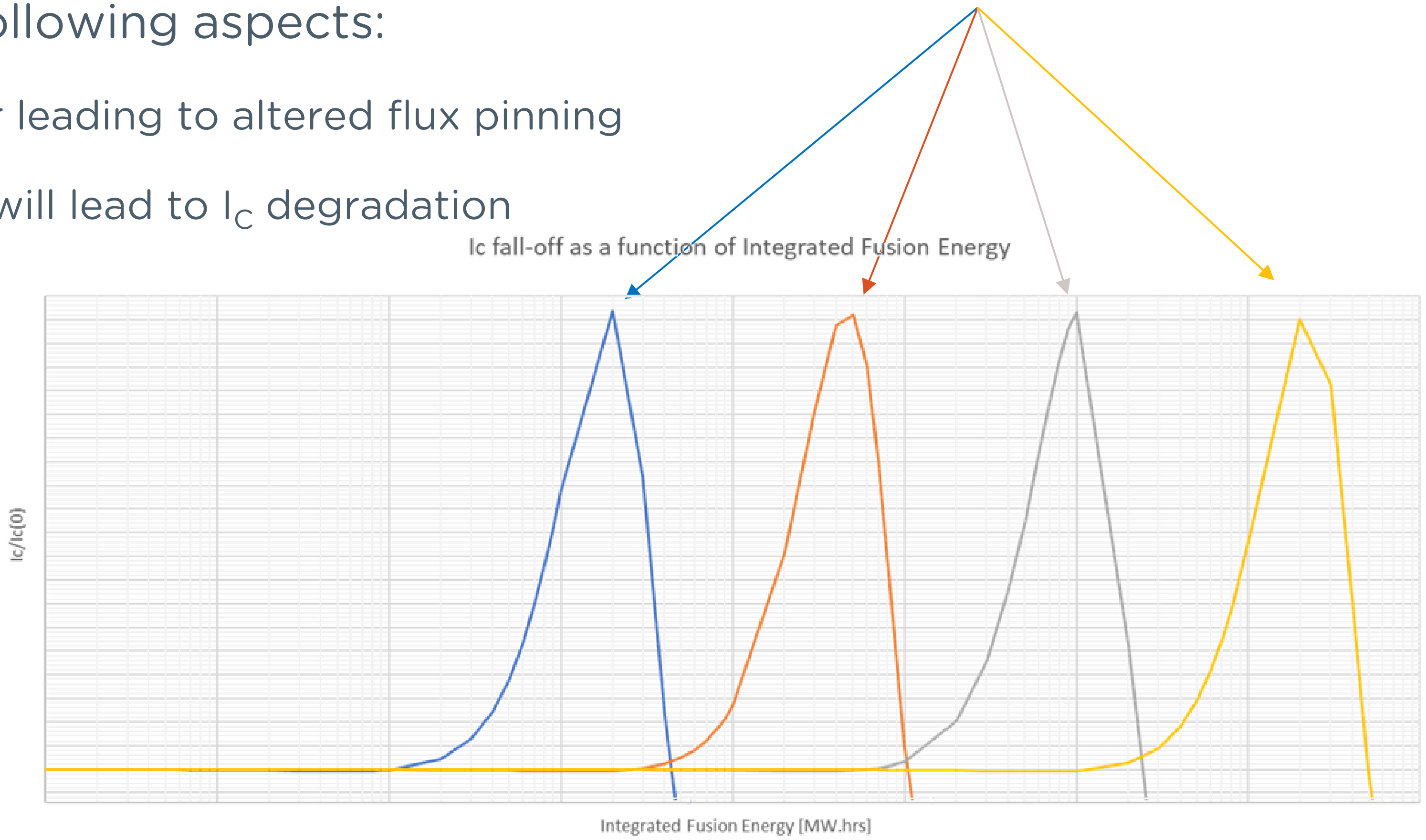
HTS Tapes Must Be Resilient To Radiation Damage



C Barth et al 2015 Supercond. Sci. Technol. 28 045011

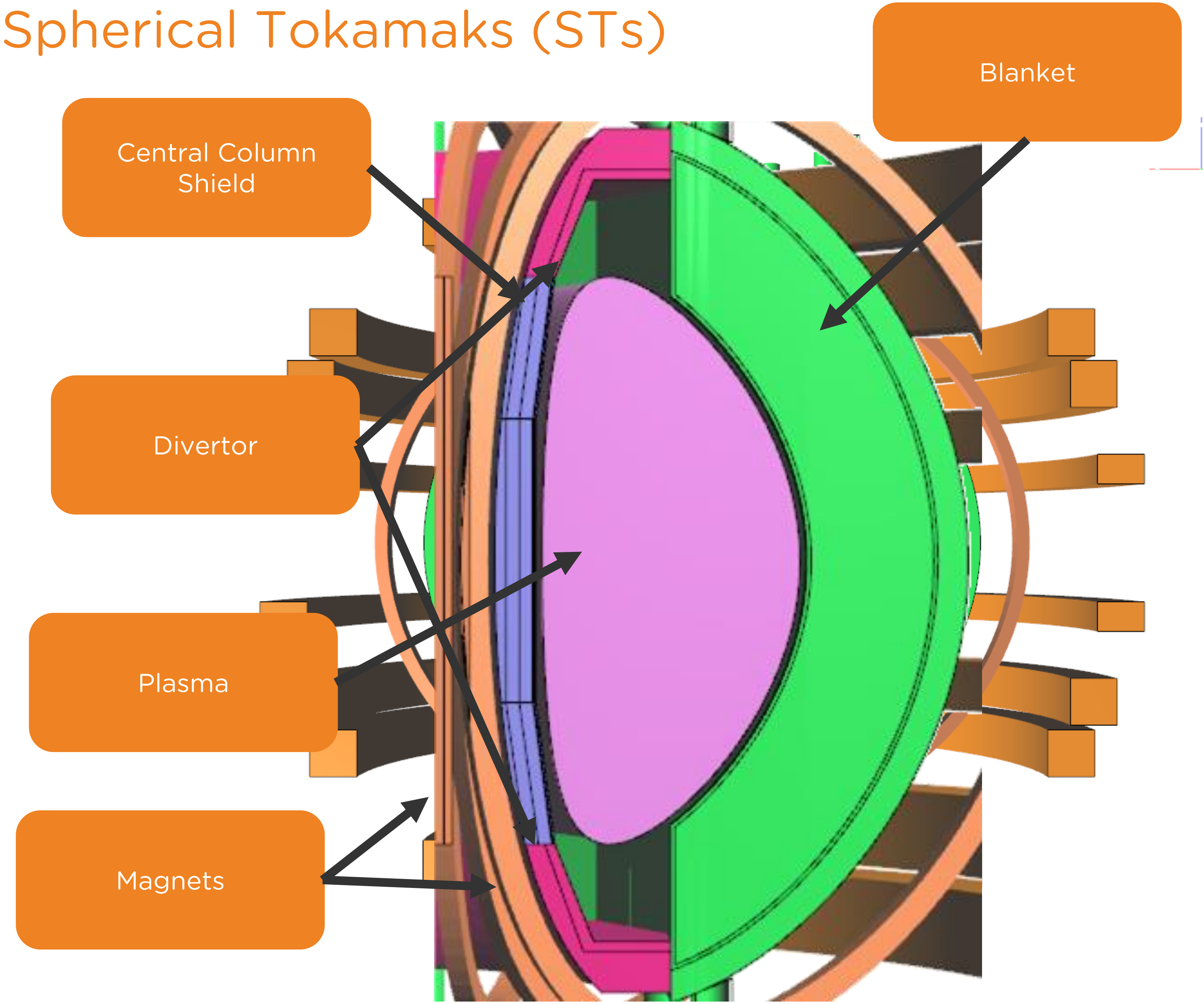
- Our commercial HTS tape technology utilises a REBCO superconducting layer
- HTS tape can evolve due to the following aspects:
  - Neutron Damage of the REBCO layer leading to altered flux pinning
  - Bombardment of the REBCO lattice will lead to I_C degradation
- Additionally,
  - The HTS tape will activate causing additional damage
  - The REBCO will transmute potentially forming into something non-superconducting

Various Shielding Tactics can help with reduction of HTS tape degradation



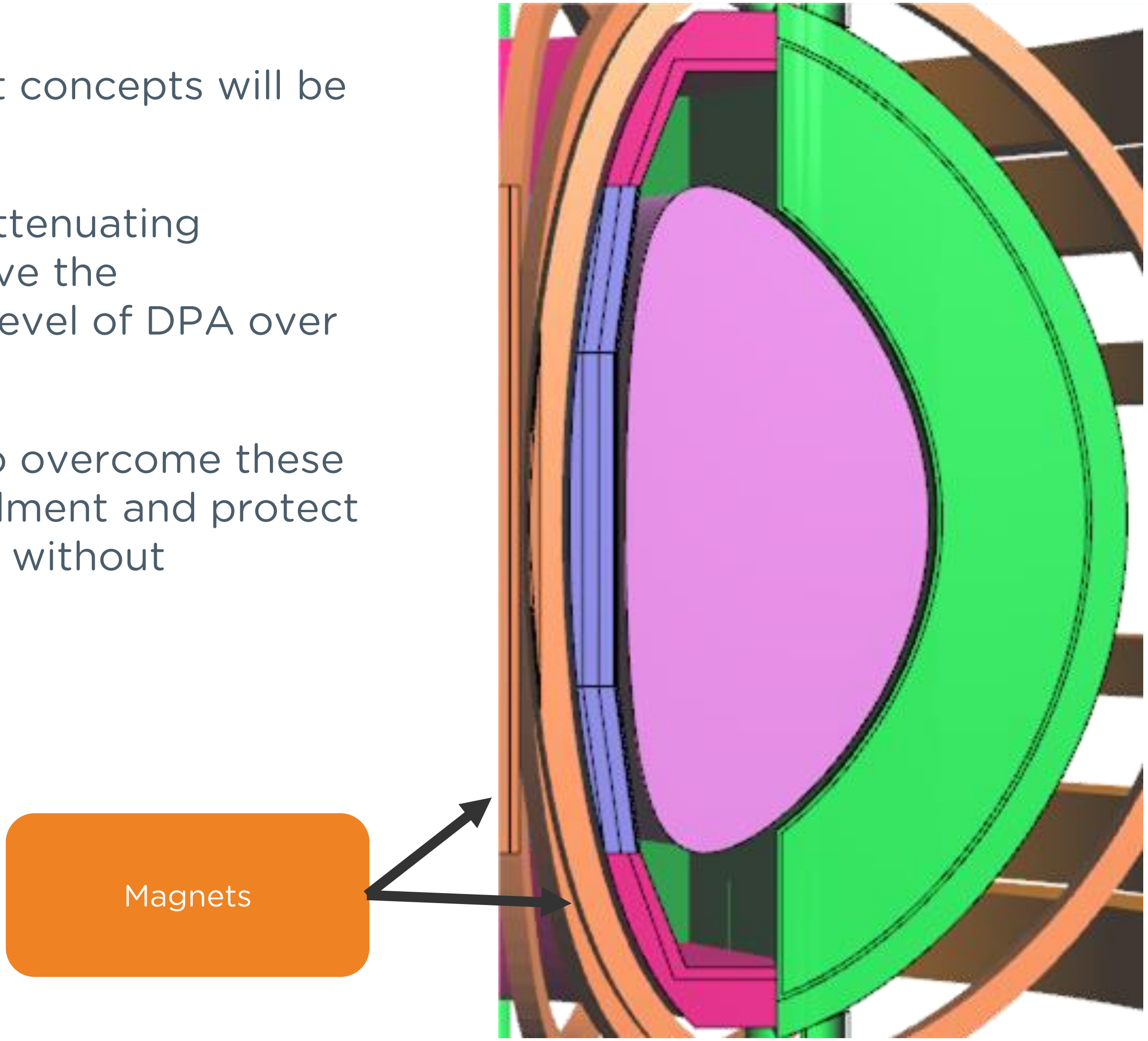
Shielding Space Is Limited In Spherical Tokamaks (STs)

- The space available between the central column and the plasma is limited due to the compactness of a ST.
- The use of efficient shielding is necessary in order to protect the fusion plant by:
  - Reducing the instantaneous, local, heat to the magnets so they do not go above operational temperatures.
  - Reducing overall heat to the magnets so they do not impose significant cooling requirements on the cryogenic systems.
  - Reducing the dose to the magnets so they remain functional throughout the proposed lifetime (Activation & Dose).

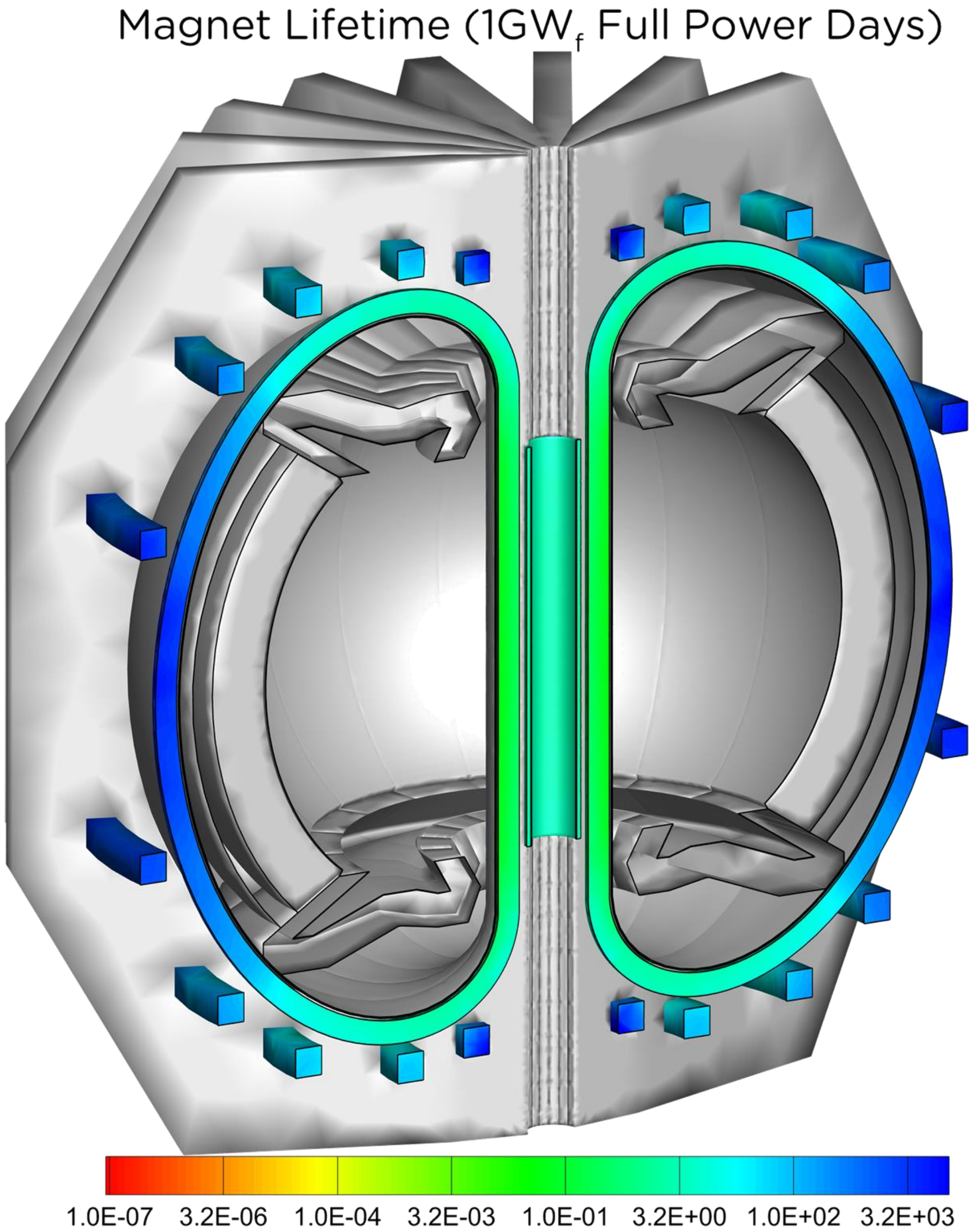


Shielding Space Is Limited In Spherical Tokamaks (STs)

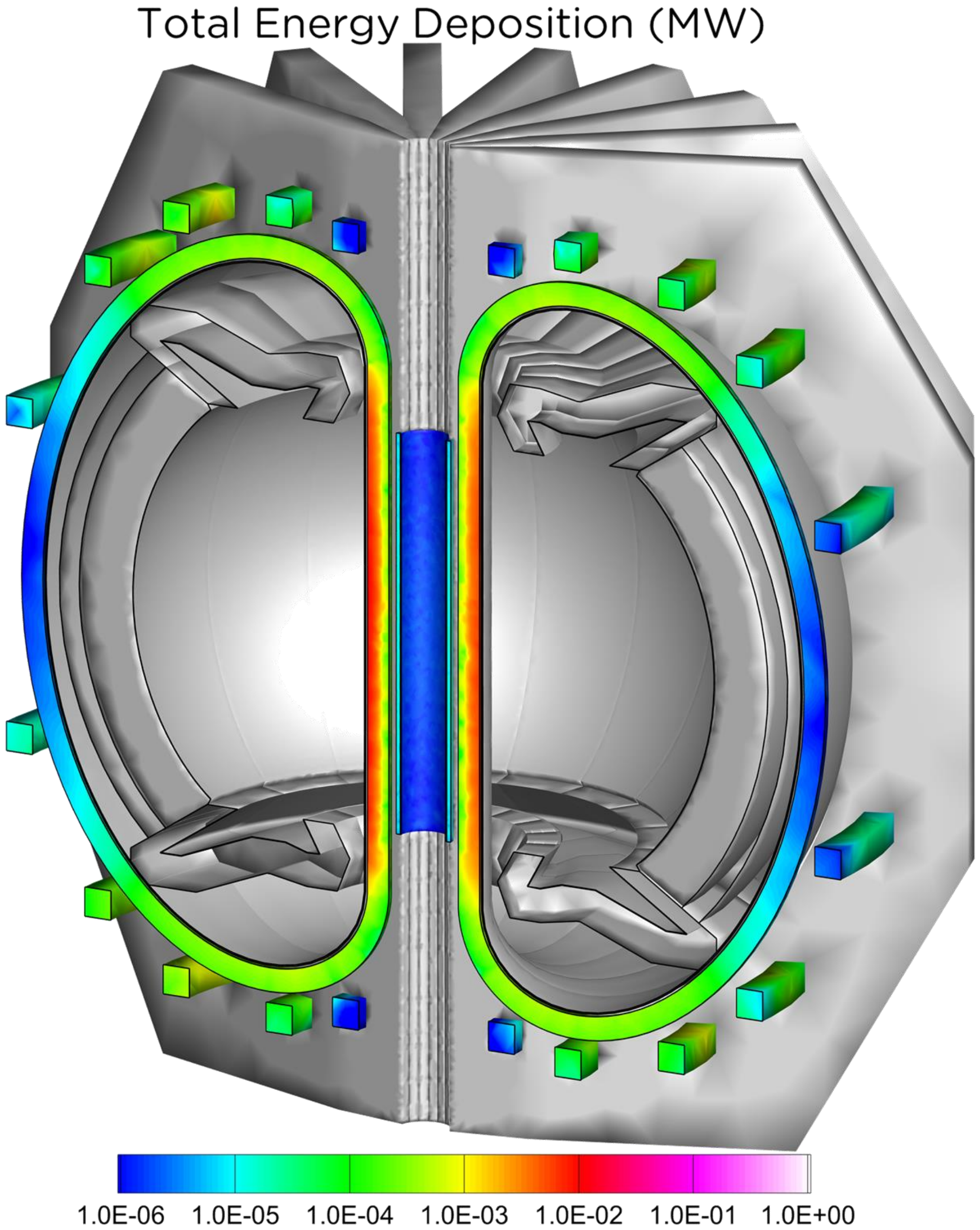
- The magnet lifetime with a typical blanket concepts will be less than 10 days for STs.
- “Traditional” shielding materials are not attenuating enough or are not robust enough to survive the environment of a tokamak; including the level of DPA over a reasonable duty cycle.
- Advanced shields are therefore needed to overcome these challenges; survive the radiation bombardment and protect the magnets over the determined lifetime without significantly increasing the size of the ST.



Consequences Of No Shielding



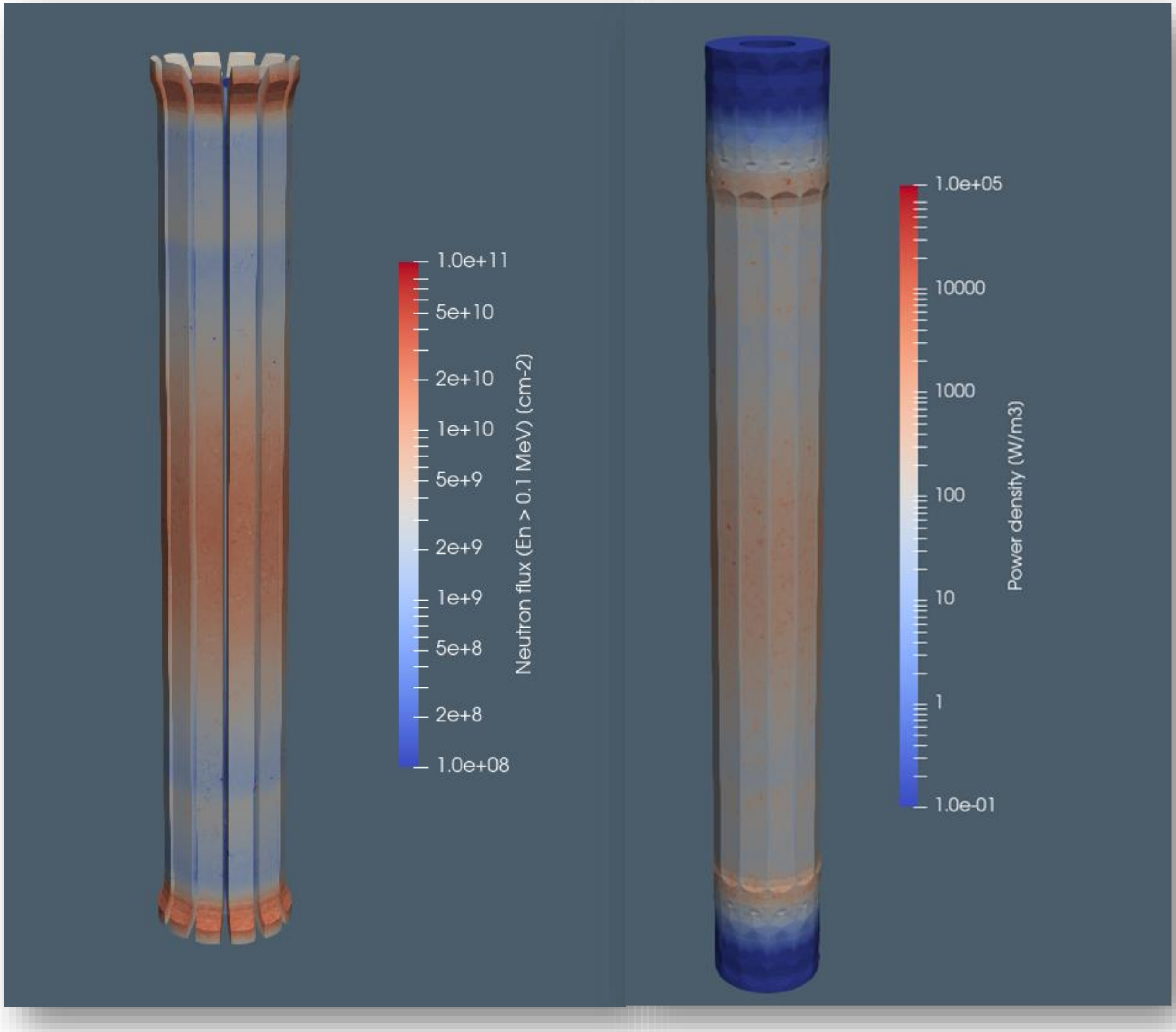
Magnet Lifetime ($1GW_f$ Full Power Days)



Total Energy Deposition (MW)

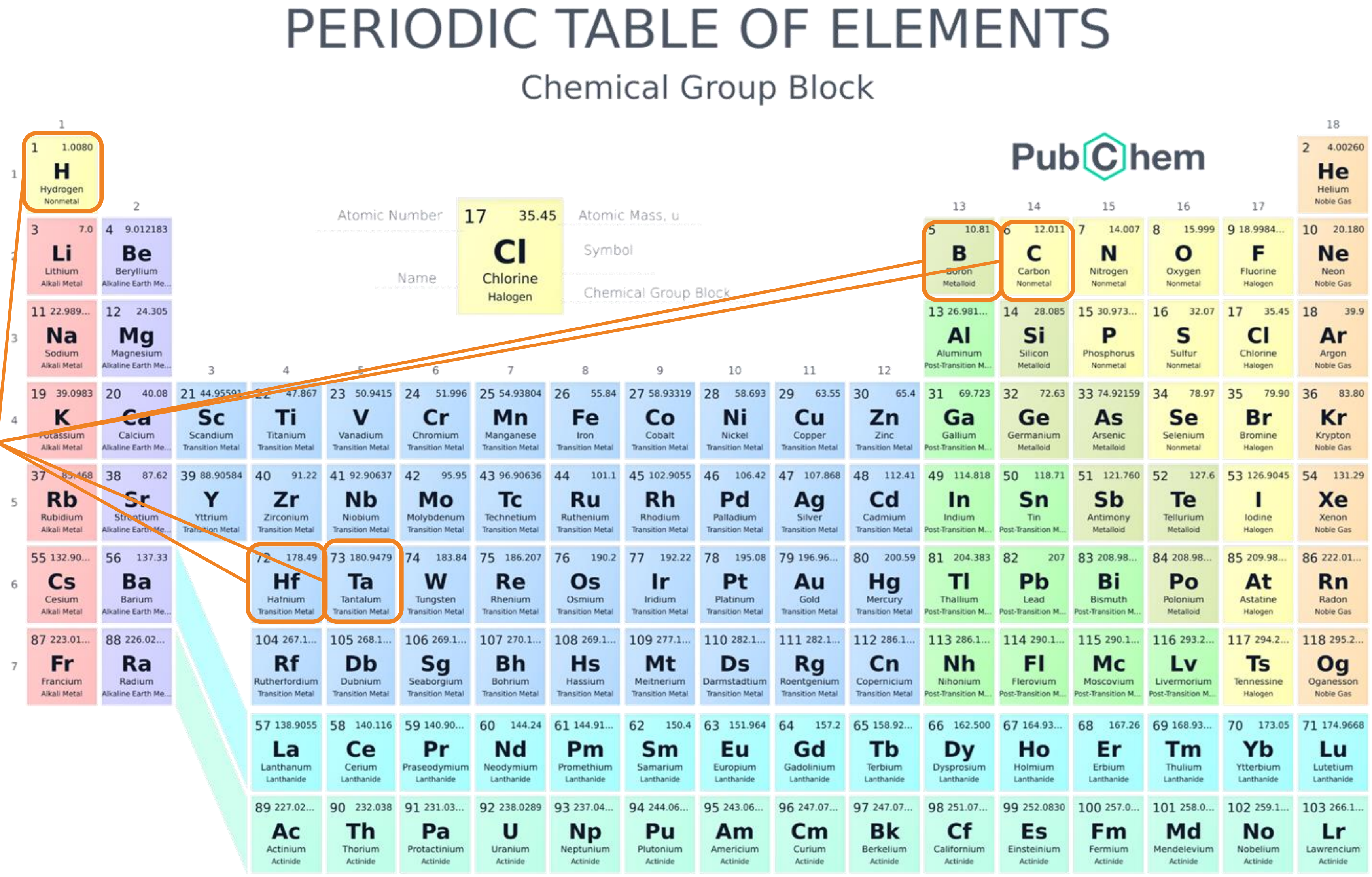
Considerations Beyond Magnet Lifetime

- From a recent study, the fast neutron flux in the toroidal field windings, within the centre column, shows acceptable shielding performance for commercial fusion concept
- However, the total nuclear power in the cold mass was ~50 kW which would require significant cryo-plant capacity, with heavy cost and recirculating power implications.
- Protecting the magnets from the fast neutrons is not sufficient to protect them from high heat load, and the entire cold mass has to be well shielded to reduce the capacity of the cryo-plant and the associated plant recirculating power.



Search For Advanced Material For Radiation Shielding

- Tungsten and hafnium have good scattering cross section and density.
- Carbon and hydrogen has good neutron moderation, and boron has excellent neutron absorption capabilities.
- Other elements are also good but come with economic/supply-chain/Material-stability issues:
  - Metallic Hydrogen
  - Re + Os based alloys
  - NiH_2



PERIODIC TABLE OF ELEMENTS

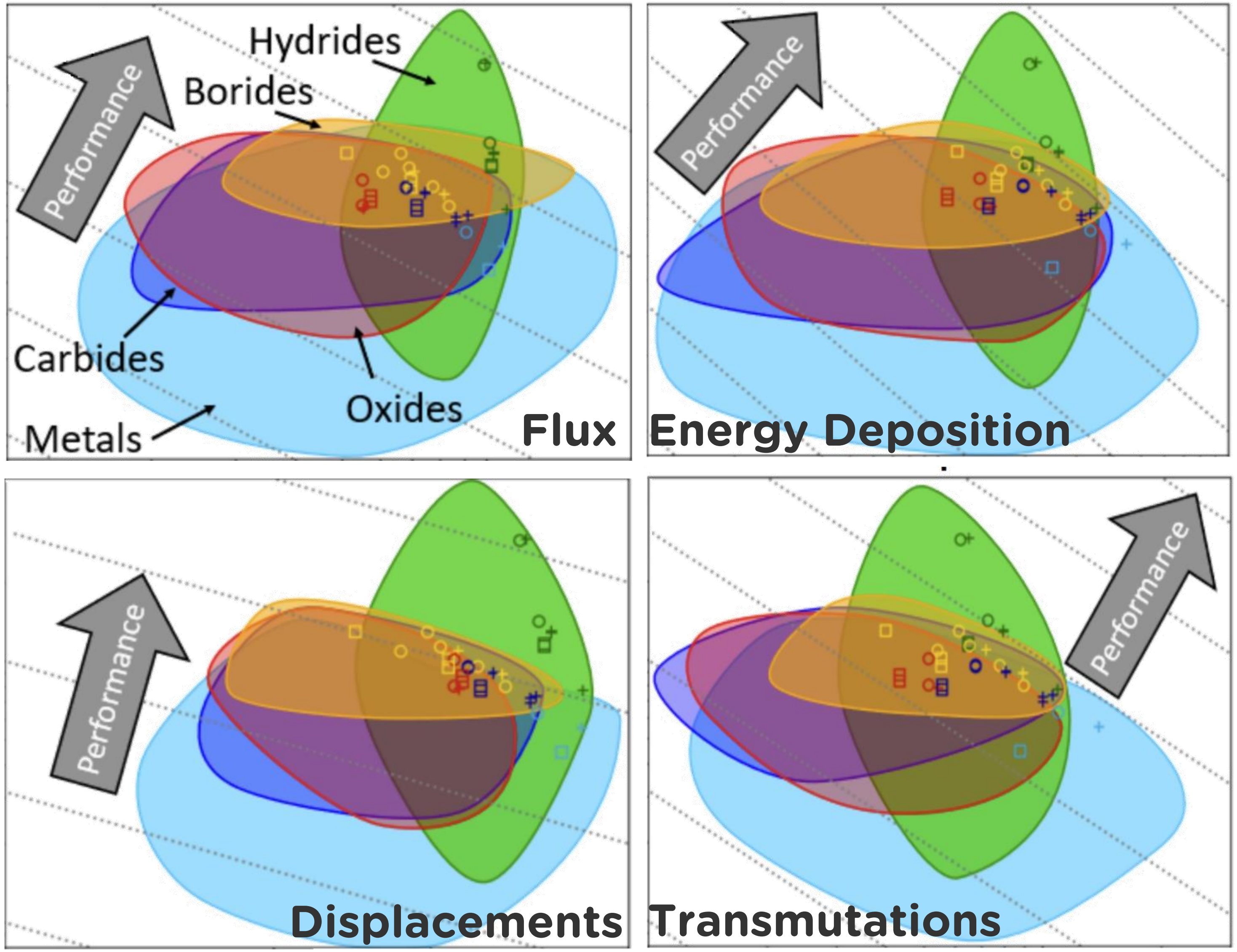
Chemical Group Block

17 35.45
Cl
Chlorine
Halogen

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 1.0080 H Hydrogen Nonmetal																	2 4.00260 He Helium Noble Gas
2	3 7.0 Li Lithium Alkali Metal	4 9.012183 Be Beryllium Alkaline Earth Me...											5 10.81 B Boron Metalloid	6 12.011 C Carbon Nonmetal	7 14.007 N Nitrogen Nonmetal	8 15.999 O Oxygen Nonmetal	9 18.9984... F Fluorine Halogen	10 20.180 Ne Neon Noble Gas
3	11 22.989... Na Sodium Alkali Metal	12 24.305 Mg Magnesium Alkaline Earth Me...											13 26.981... Al Aluminum Post-Transition M...	14 28.085 Si Silicon Metalloid	15 30.973... P Phosphorus Nonmetal	16 32.07 S Sulfur Nonmetal	17 35.45 Cl Chlorine Halogen	18 39.9 Ar Argon Noble Gas
4	19 39.0983 K Potassium Alkali Metal	20 40.08 Ca Calcium Alkaline Earth Me...	21 44.95591 Sc Scandium Transition Metal	22 47.867 Ti Titanium Transition Metal	23 50.9415 V Vanadium Transition Metal	24 51.996 Cr Chromium Transition Metal	25 54.93804 Mn Manganese Transition Metal	26 55.84 Fe Iron Transition Metal	27 58.93319 Co Cobalt Transition Metal	28 58.693 Ni Nickel Transition Metal	29 63.55 Cu Copper Transition Metal	30 65.4 Zn Zinc Transition Metal	31 69.723 Ga Gallium Post-Transition M...	32 72.63 Ge Germanium Metalloid	33 74.92159 As Arsenic Metalloid	34 78.97 Se Selenium Nonmetal	35 79.90 Br Bromine Halogen	36 83.80 Kr Krypton Noble Gas
5	37 85.468 Rb Rubidium Alkali Metal	38 87.62 Sr Strontium Alkaline Earth Me...	39 88.90584 Y Yttrium Transition Metal	40 91.22 Zr Zirconium Transition Metal	41 92.90637 Nb Niobium Transition Metal	42 95.95 Mo Molybdenum Transition Metal	43 96.90636 Tc Technetium Transition Metal	44 101.1 Ru Ruthenium Transition Metal	45 102.9055 Rh Rhodium Transition Metal	46 106.42 Pd Palladium Transition Metal	47 107.868 Ag Silver Transition Metal	48 112.41 Cd Cadmium Transition Metal	49 114.818 In Indium Post-Transition M...	50 118.71 Sn Tin Post-Transition M...	51 121.760 Sb Antimony Metalloid	52 127.6 Te Tellurium Metalloid	53 126.9045 I Iodine Halogen	54 131.29 Xe Xenon Noble Gas
6	55 132.90... Cs Cesium Alkali Metal	56 137.33 Ba Barium Alkaline Earth Me...		72 178.49 Hf Hafnium Transition Metal	73 180.9479 Ta Tantalum Transition Metal	74 183.84 W Tungsten Transition Metal	75 186.207 Re Rhenium Transition Metal	76 190.2 Os Osmium Transition Metal	77 192.22 Ir Iridium Transition Metal	78 195.08 Pt Platinum Transition Metal	79 196.96... Au Gold Transition Metal	80 200.59 Hg Mercury Transition Metal	81 204.383 Tl Thallium Post-Transition M...	82 207 Pb Lead Post-Transition M...	83 208.98... Bi Bismuth Post-Transition M...	84 208.98... Po Polonium Metalloid	85 209.98... At Astatine Halogen	86 222.01... Rn Radon Noble Gas
7	87 223.01... Fr Francium Alkali Metal	88 226.02... Ra Radium Alkaline Earth Me...		104 267.1... Rf Rutherfordium Transition Metal	105 268.1... Db Dubnium Transition Metal	106 269.1... Sg Seaborgium Transition Metal	107 270.1... Bh Bohrium Transition Metal	108 269.1... Hs Hassium Transition Metal	109 277.1... Mt Meitnerium Transition Metal	110 282.1... Ds Darmstadtium Transition Metal	111 282.1... Rg Roentgenium Transition Metal	112 286.1... Cn Copernicium Transition Metal	113 286.1... Nh Nihonium Post-Transition M...	114 290.1... Fl Flerovium Post-Transition M...	115 290.1... Mc Moscovium Post-Transition M...	116 293.2... Lv Livermorium Post-Transition M...	117 294.2... Ts Tennessine Halogen	118 295.2... Og Oganesson Noble Gas
				57 138.9055 La Lanthanum Lanthanide	58 140.116 Ce Cerium Lanthanide	59 140.90... Pr Praseodymium Lanthanide	60 144.24 Nd Neodymium Lanthanide	61 144.91... Pm Promethium Lanthanide	62 150.4 Sm Samarium Lanthanide	63 151.964 Eu Europium Lanthanide	64 157.2 Gd Gadolinium Lanthanide	65 158.92... Tb Terbium Lanthanide	66 162.500 Dy Dysprosium Lanthanide	67 164.93... Ho Holmium Lanthanide	68 167.26 Er Erbium Lanthanide	69 168.93... Tm Thulium Lanthanide	70 173.05 Yb Ytterbium Lanthanide	71 174.9668 Lu Lutetium Lanthanide
				89 227.02... Ac Actinium Actinide	90 232.038 Th Thorium Actinide	91 231.03... Pa Protactinium Actinide	92 238.0289 U Uranium Actinide	93 237.04... Np Neptunium Actinide	94 244.06... Pu Plutonium Actinide	95 243.06... Am Americium Actinide	96 247.07... Cm Curium Actinide	97 247.07... Bk Berkelium Actinide	98 251.07... Cf Californium Actinide	99 252.0830 Es Einsteinium Actinide	100 257.0... Fm Fermium Actinide	101 258.0... Md Mendelevium Actinide	102 259.1... No Nobelium Actinide	103 266.1... Lr Lawrencium Actinide

National Center for Biotechnology Information (2023). Periodic Table of Elements. Retrieved June 12, 2023, from https://pubchem.ncbi.nlm.nih.gov/periodic-table/.

Search For Advanced Material For Radiation Shielding

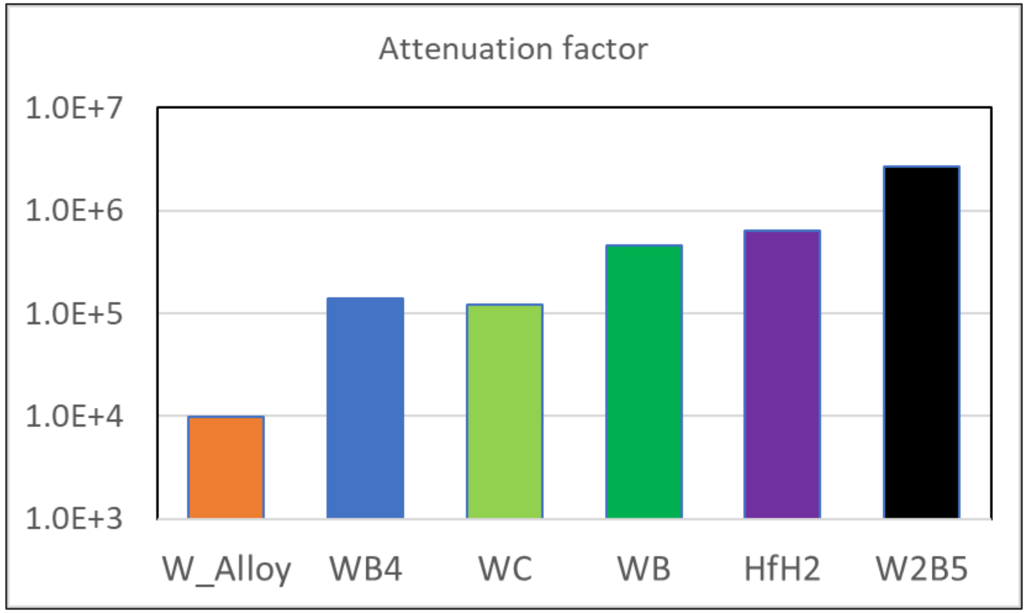


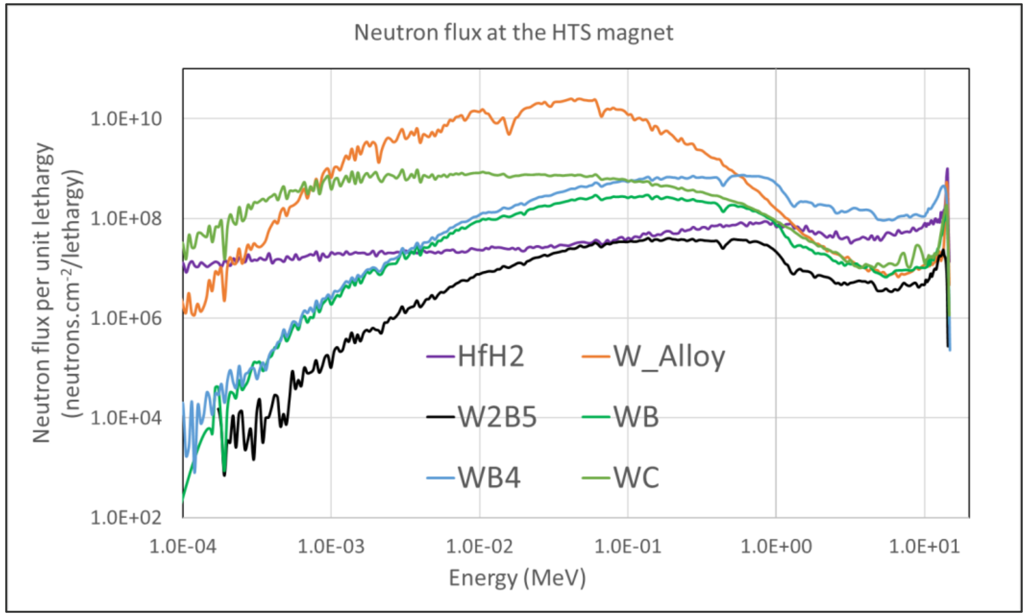
Material Selection Charts for Optimised Radiation Shielding, M. Brand et al Materials Today (submitted)

- The possibility of materials which contain one or more of the elements can increase drastically when scouting for shielding material candidates
- Material selection charts can assist in visually understanding the material types and their potential for a minimal thickness shield of REBCO
- Light blue shows metals, dark blue shows carbides, red shows oxides, green shows hydrides. Materials containing W (hollow circles), Hf (hollow squares) and Ta (pluses) are shown as points

Our Advanced Shielding Materials Of Consideration

- Hydrides, carbides, and borides are shown to be good neutron shields for both, fast and slow neutrons.
- Tungsten boride's performance is superior when compared to the other advanced shield materials
- Neutron energies above 0.1 MeV are considered fast for the purposes of this presentation as these are considered the threshold to magnet degradation



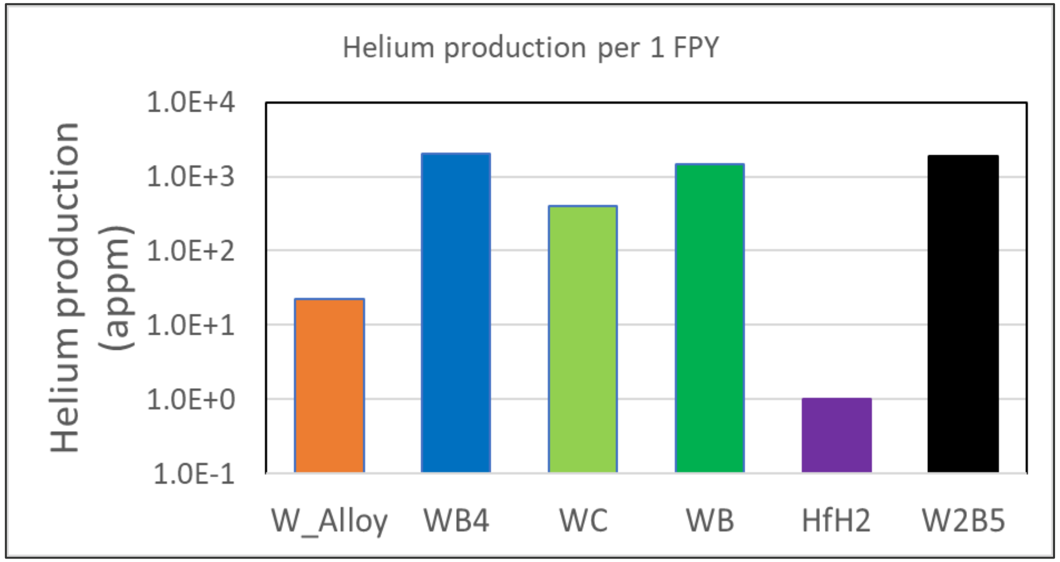


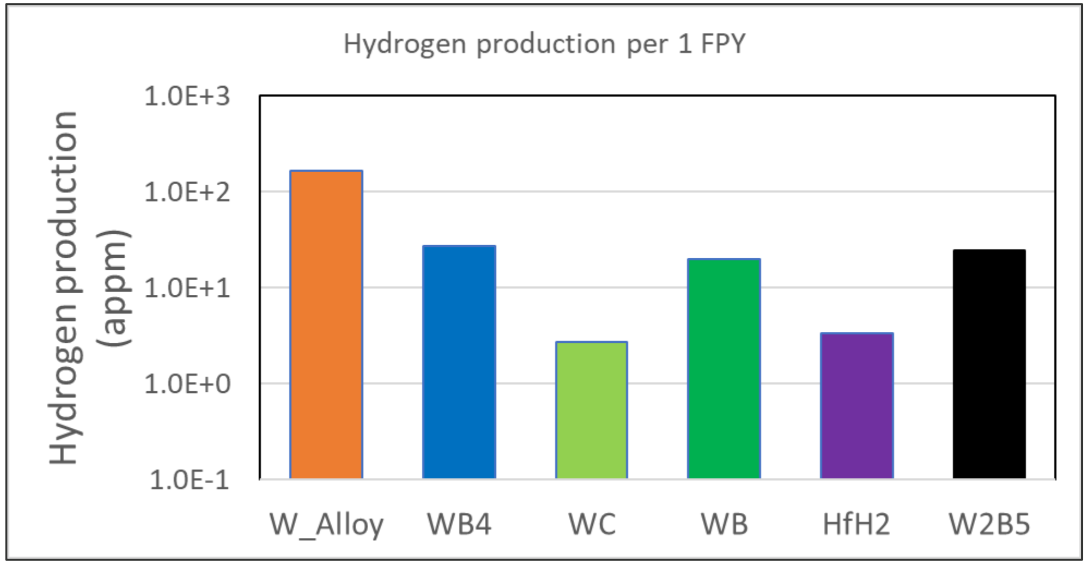
Material Considerations In Advanced Shield Materials

Borides and Carbide produce high amounts of helium due to the alpha production reaction channel in Boron and carbon;

$^{10}B(n,a)^{7}Li$ $^{12}C(n,n'\alpha)2\alpha$

Tungsten alloy produces a large amount of hydrogen when compared against carbides and hydrides.





Magnet Lifetime With These Advanced Materials

WC, WBs, and HfH2 come out as the preferred shielding solutions in monolithic form.

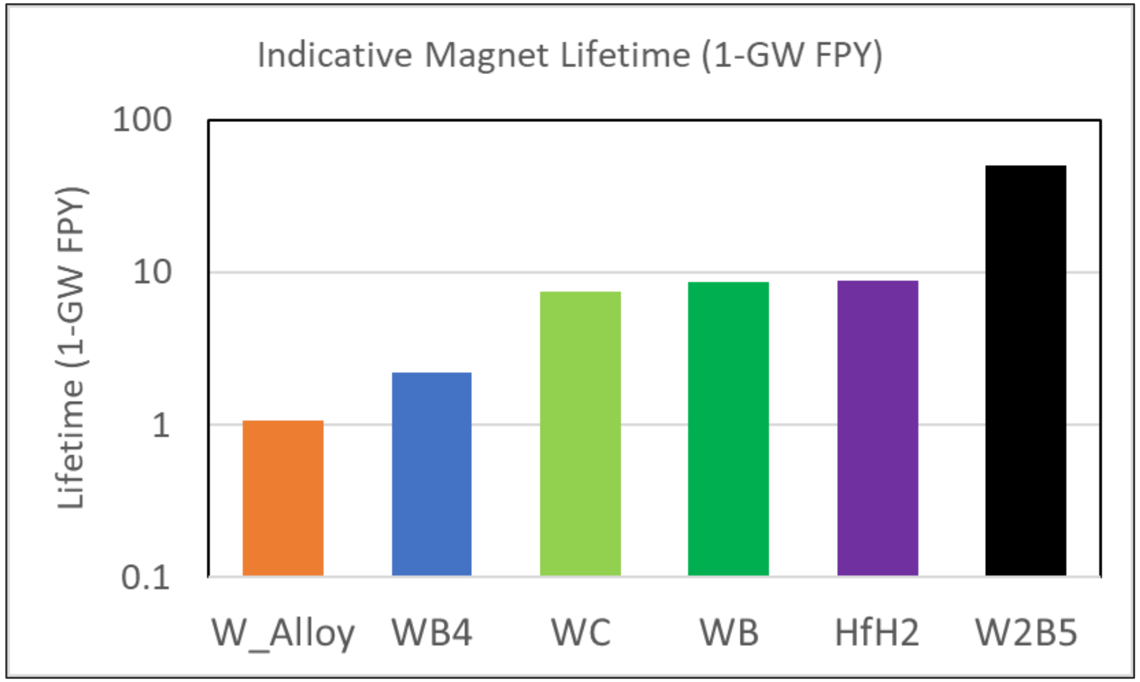
Some of these materials are at such low Technology Readiness Levels that significant work is needed for them to be realised.

Additional concerns of these materials are as follows:

Thermomechanical and structural compatibility of these materials at elevated temperatures

Thermomechanical and structural changes as a function of dose uptake.

Their compatibility with coolant materials



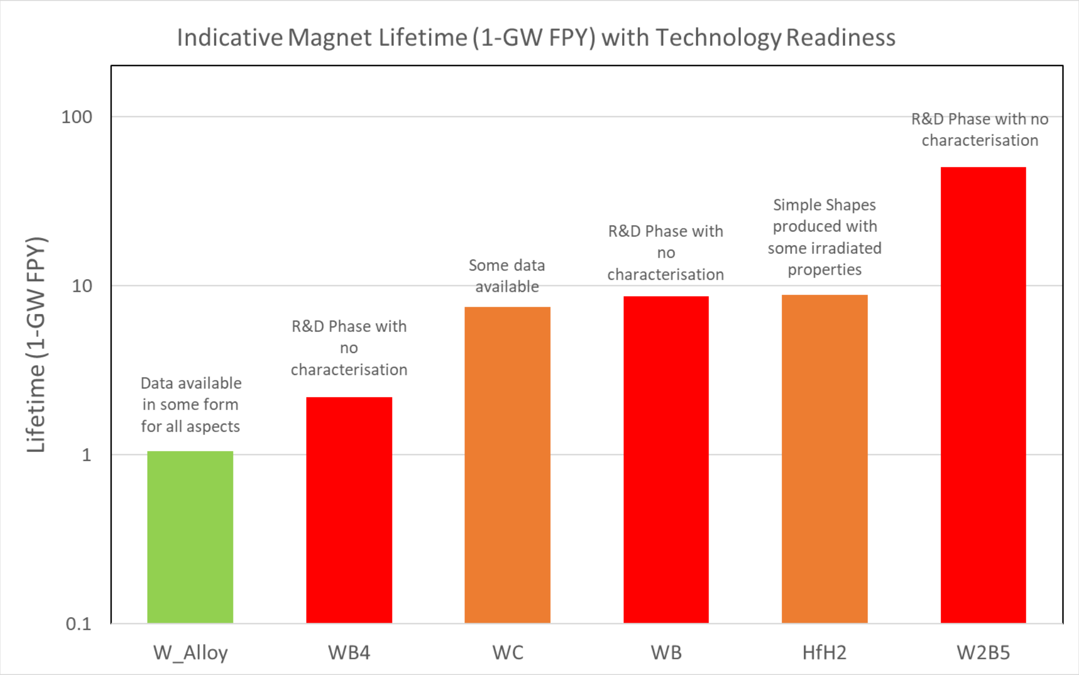
D X Fischer et al 2018 Supercond. Sci. Technol. 31 044006

Various Material Challenges To Overcome For These Materials

The performance of shielding materials is heavily dependent on the isotopic composition and density of the material, all of which can drastically change during the realisation process with our materials experts.

These considerations are:

- Possible tolerances in specific shape production
- Supply chain to support the tonnes of material needed
- Non-irradiated characteristics such as thermal conductivity and hardness
- Irradiated characteristics such as thermal expansion and swelling
- Transmutation and maintenance considerations



Impact Of Alloying Materials On The Radioactive Waste Production

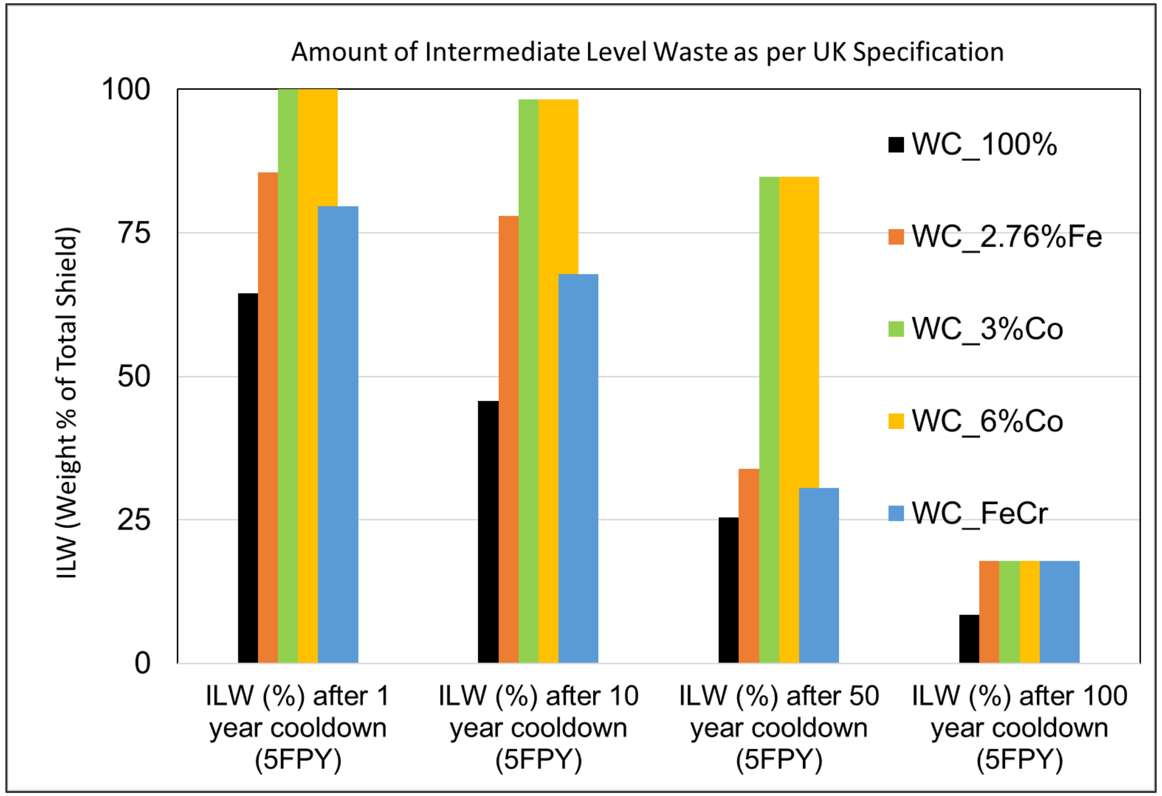
WC has a binder material to enhance its thermomechanical properties, but this causes additional concerns:

- Generation of radiological waste.
- Biological dose during maintenance.
- Degradation of binder following transmutation over time.

Radiological waste assessment of WC with different binders justifies avoiding Co as a binder.

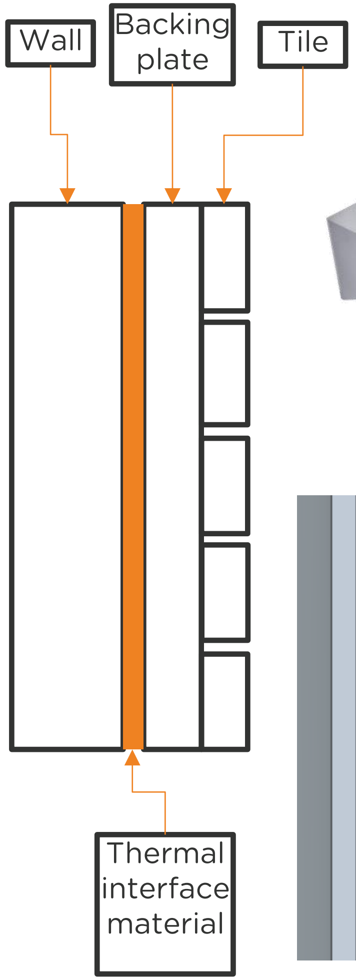
Binder-less Carbides would be preferable but at what cost?

Work is needed on the ALARP justifications for activated shielding materials.



Thermomechanical Properties Are Important!

- The radiation shield will experience a volumetric heating load in the region of 10s of MW/m^3.
  - A high performing shield candidate will result in an exponential reduction in volumetric heating through its depth
- Cooling solutions will be required to ensure shielding materials remain within their operating window, but cooling pipes will degrade the shielding performance!
- Material Irradiation response will change as a function of temperature changing material properties in multiple ways
- High thermal conductivity will elevate some burden of cooling structures but the thermophysical properties need to be understood holistically. This will then produce an overall shielding solution.
- Properties like thermal expansion, coolant compatibility, strength will result in gaps reducing the overall volume of shielding material available

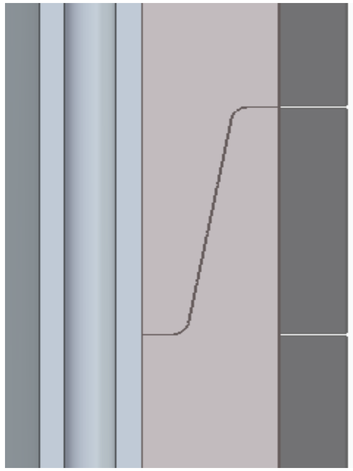


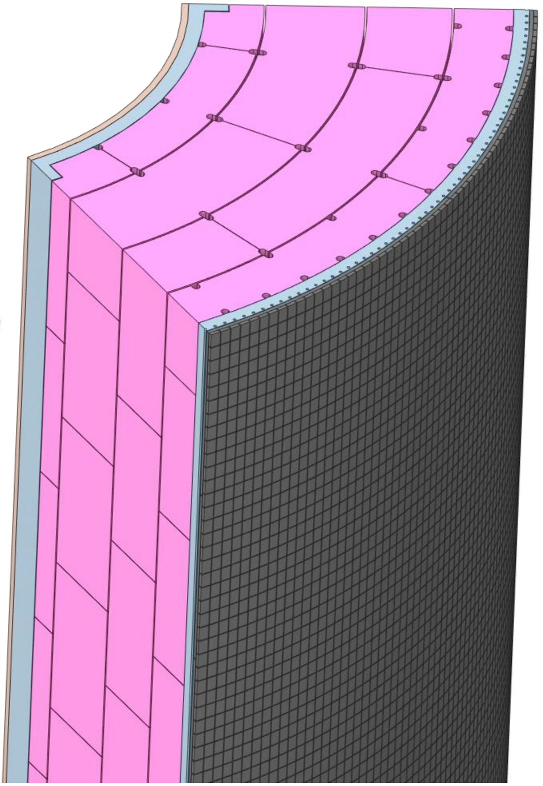
Wall

Backing plate

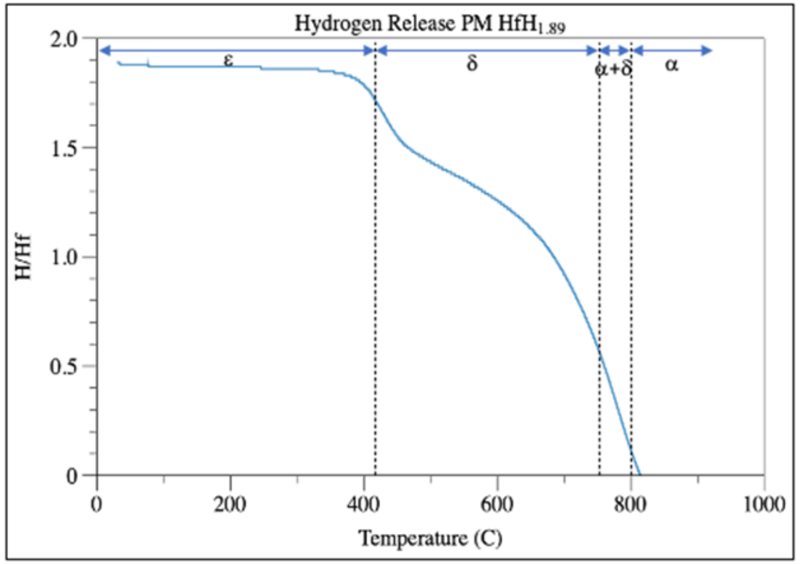
Tile

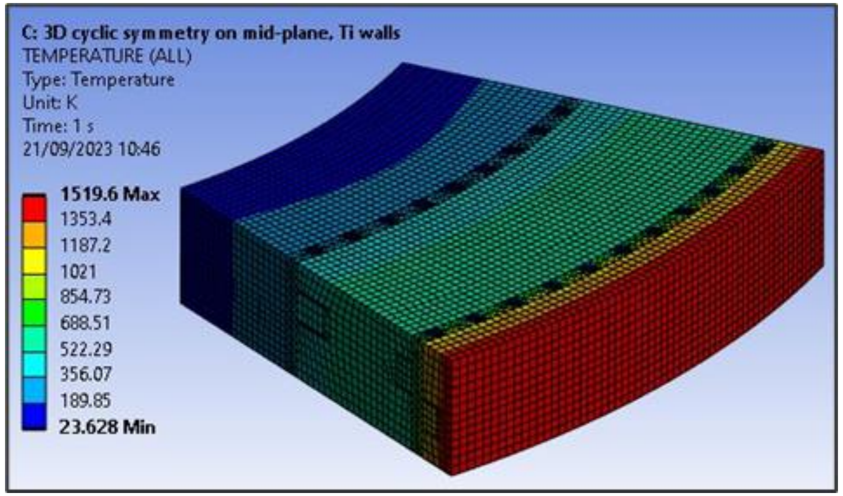
Thermal interface material

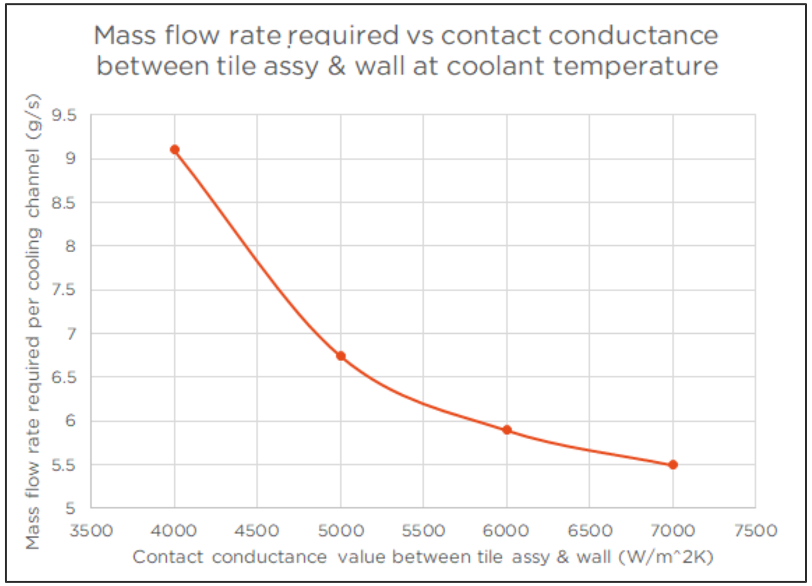


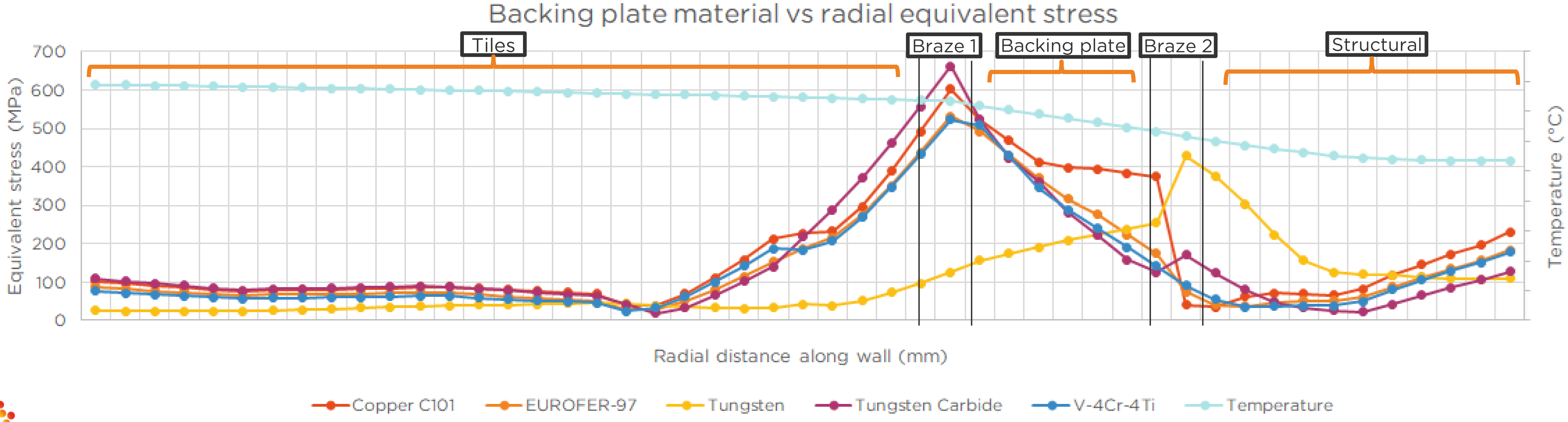


Thermomechanical Properties Are Important!



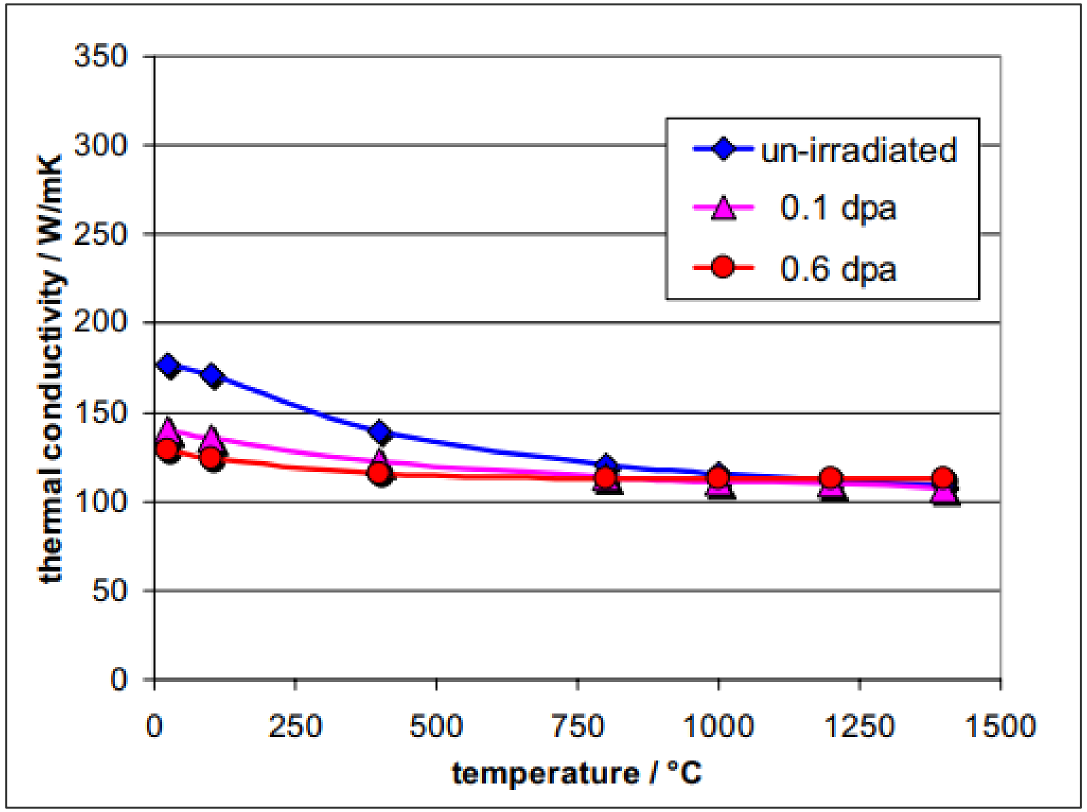






Thermomechanical Properties Are Important!

- To account for volumetric heating and structural loads. the shield material must have:
  - High strength to weight ratio
  - Good thermal conductivity
  - Good fatigue and creep rupture properties
  - Small modulus of elasticity
  - High electrical resistivity and heat capacity
  - Low coefficient of thermal expansion
  - A good compatibility with the coolant
  - High workability and good weldability
  - Commercial availability
  - Magnetic compatibility



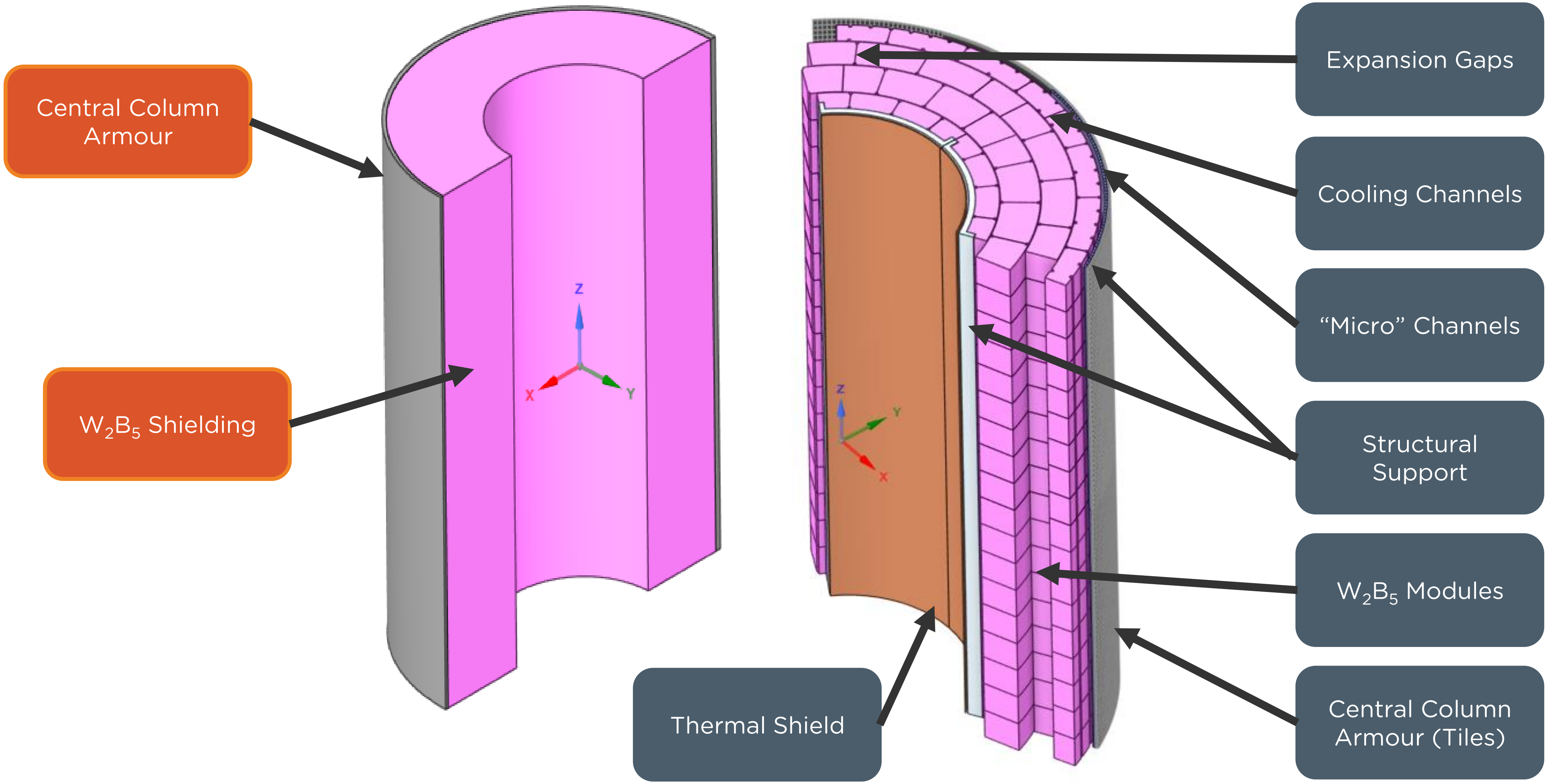
M. Scheerer et al Physica Scripta T91, 98 (2001)

Thermal conductivity of Tungsten before and after irradiation

Thermomechanical Properties Are Important!

Neutronics Pre concept Model
Magnet Life = 80 FPY [1-GW_f]

Multiphysics Concept Model
Magnet Life = 12 FPY [1-GW_f]



Central Column Armour

W_2B_5 Shielding

Expansion Gaps

Cooling Channels

“Micro” Channels

Structural Support

W_2B_5 Modules

Central Column Armour (Tiles)

Thermal Shield

Tokamak Energy

Thank you

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