Neutron Shielding of a Levitated Dipole Reactor Power Plant

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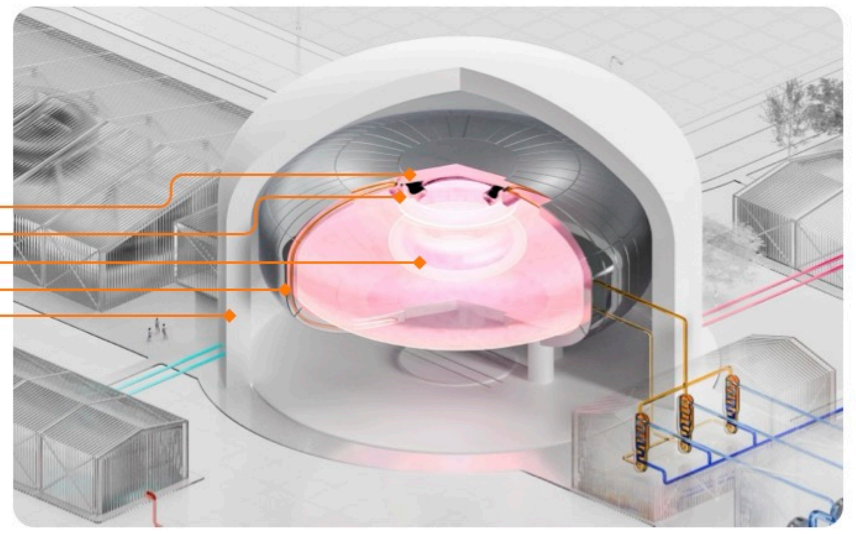
1. System Overview

A Levitated Dipole Power Plant

The fusion island of a Levitated Dipole Reactor (LDR) Fusion Power Plant will have the following main components:

- Low field top magnet
- Divertor
- High field core magnet
- Tritium Breeding Blanket
- Concrete Vacuum Vessel Structural Support

In a DT reactor, the core magnet assembly will need significant neutron shielding to sufficiently protect the cryogenic HTS magnet.



Levitated Dipole Confinement Physics

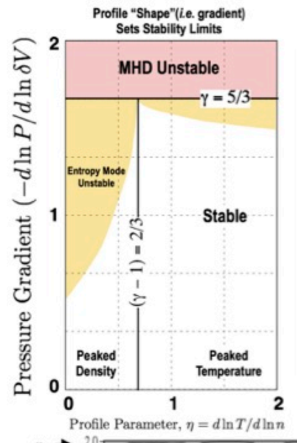
Rosenbluth and Longmire [1] showed that the stability of dipole plasmas occurs when an exchange of flux tubes causes internal plasma energy (work + compressibility) to increase:

$$\Delta E = \delta S \frac{\delta V}{V^{\gamma}}$$

$V = \oint dl/B$ is the differential flux tube volume
$S = pV^{\gamma}$ is the entropy density
$\gamma = 5/3$ is the ratio of specific heats

For $\delta S > 0$, an exchange of flux tubes increases plasma energy and damps perturbations. Marginal stability occurs when $\delta S = 0$ which gives a relation between peak pressure and edge pressure based on the size of the reactor.

[1] Annals of Physics **1**, 120-140 (1957); 10.1016/0003-4916(57)90055-6.



Self-organised stationary profiles

Profiles are stable below critical values:

$$-\frac{d\ln p}{d\ln V} < \gamma \quad (1); \quad -\frac{d\ln n}{d\ln V} < \frac{5}{7-3\eta} \quad (2), \quad \eta = \frac{d\ln T}{d\ln n}.$$

MHD *Entropy Mode*

Condition (2) drives a drift frequency "entropy" mode, which moves the system towards $\eta = 2/3$ and the pressure profile to marginal stability $\delta(pV^{\gamma}) = 0$.

When stability limit (1) is violated, large-scale convective cells form which reduce profiles back to critical values.

Levitated Dipole Plasma Benefits

High β Plasmas

Large stable plasmas allow for β to exceed unity locally. This reduces the cost of the overall system and could allow for the use of advanced fuels.

Fuel Recycling

Convective cells transport particles, but not their energy, to the outer edge of the plasma. This allows for the easy removal of plasma ash.

No Disruptions

Lack of driven currents makes disruptions impossible and greatly simplifies chamber design.

Levitated Dipole Engineering Benefits

The core magnet is decoupled from the vacuum vessel, giving LDRs some desirable engineering benefits:

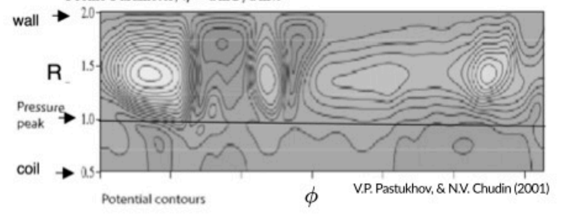
Replaceable Core Magnet

- Any maintenance on the core magnet can be performed ex-situe with a replacement swapped in to minimise downtime.
- The magnet can be designed to have replaceable portions, reducing design pressure on other parts of the system.

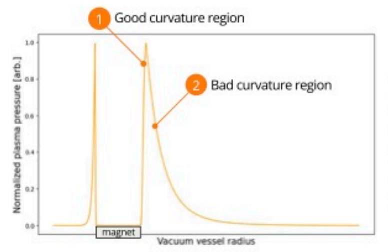
Un-coupled Vacuum Vessel

- There are no spatial requirements on the first wall and breeder blanket, giving more design freedom and easier maintenance access.
- The divertor can be made large, either allowing for more favourable edge conditions or lower PFC loadings.

These advantages would make LDRs quick to deploy and cheap to run. However, heating and damage from high energy fusion neutrons can easily negate these benefits if not handled properly.

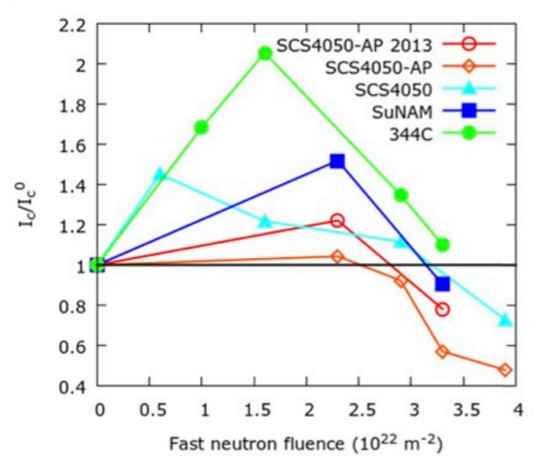


Simulated electric potential fluctuations in a levitated dipole plasma showing the convective cell formation in the bad curvature region where the marginally-stable interchange profiles are present.



Pressure profile in the z = 0 midplane showing the steep pressure gradients of the marginally stable profile. The location of the pressure peak in a reactor will be self-consistently determined by the energy transport inwards towards the magnet and outwards towards the first wall.

2. Design Requirements



[2] Supercond. Sci. Technol. **31**, 044006 (2018); 10.1088/1361-6668/aaadf2.

Performance Requirements

The neutron shield in a LDR has two goals:

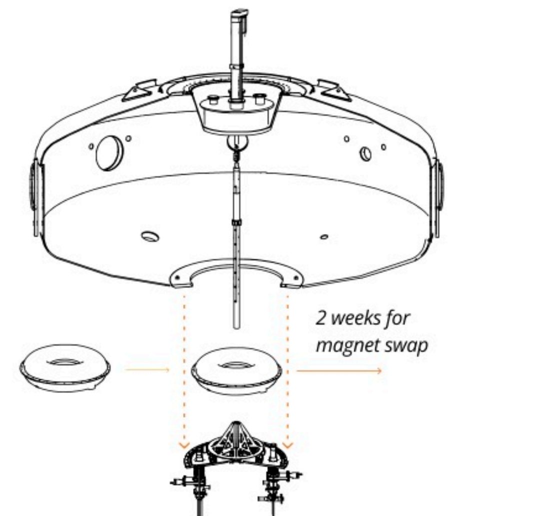
- **Nuclear Heating Reduction:** The heating in the cryogenic portion of the core magnet must be low enough to allow for power positive operation.
- **Irradiation Damage Prevention:** The residual neutron flux after shielding must be low enough to allow for reasonable magnet lifetimes.

We have shown previously that designing a neutron shield to reduce nuclear heating to acceptable levels is trivial.

Preventing damage is the more stringent requirement. Experimental results [2] show that REBCO coated conductor (2G HTS) can withstand a fluence of $\Psi_{max} = 3\times10^{18}$n/cm^2 at an energy of ~1 MeV.

The ease of maintenance of LDR core magnets can be leveraged to make 20% of the HTS expendable, allowing the "lifetime" of the magnet to be as low as 3 years. This sets an upper limit on the residual flux:

$$\phi_r = \frac{\Psi_{max}}{\tau_{cm}} = 3.1\times10^{10}\ \text{n cm}^{-2}\ \text{s}^{-1}$$

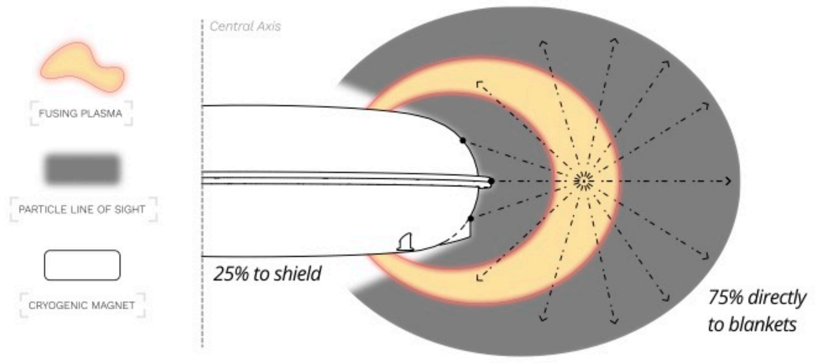


Thermal Requirements

Heat cannot be actively extracted from the shield during operation, leaving two options:

- **On board thermal storage:** Store the deposited neutron energy in a thermal reservoir to then be extracted later. Appropriate choice of the reservoir material would allow for energy recovery, maintaining overall plant efficiency.
- **Radiative cooling:** Let the shield reach temperatures sufficient to radiate the deposited power out to the first wall.

For most cases, relying solely on an on board thermal reservoir is not feasible due to the coolant volume needed to achieve adequate float times. For this reason **the shield will be primarily radiatively cooled**, with a small reservoir for structural reasons



3. Performance Impact

Shield Thickness

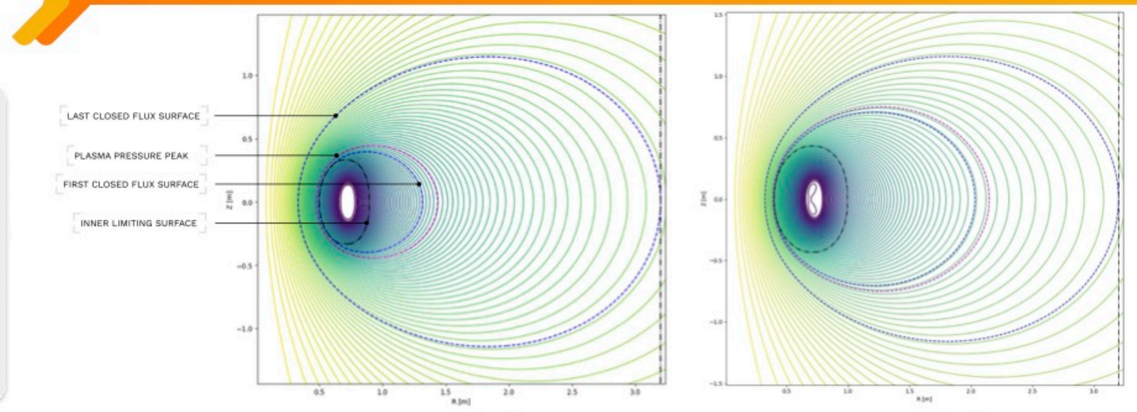
The marginally stable profile results in the following relation:

$$\frac{p_{core}}{p_{edge}} = \left(\frac{V_{core}}{V_{edge}}\right)^{\gamma} \implies p \sim r^{-20/3}$$

Which makes LDRs extremely sensitive to neutron shield thickness.

Additionally, the shield thickness is also amplified by flux expansion on the outboard side.

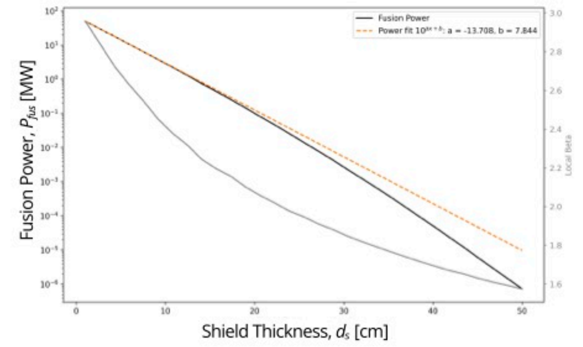
➤ Maximize shielding effectiveness per unit thickness.



Shield Temperature

In a radiatively balanced shield, the maximum operating temperature of the shield material implicitly limits the compactness of the plant. Higher fusion power densities result in higher wall loadings, which require both thicker shields and higher surface temperatures to radiate away the power over a reduced area. **Using materials with operating temperatures <1500K result in reactors too large to be practical for their power output.**

➤ Chose shielding materials with operating temperatures >2000K



4. Material Selection

Layered Shielding

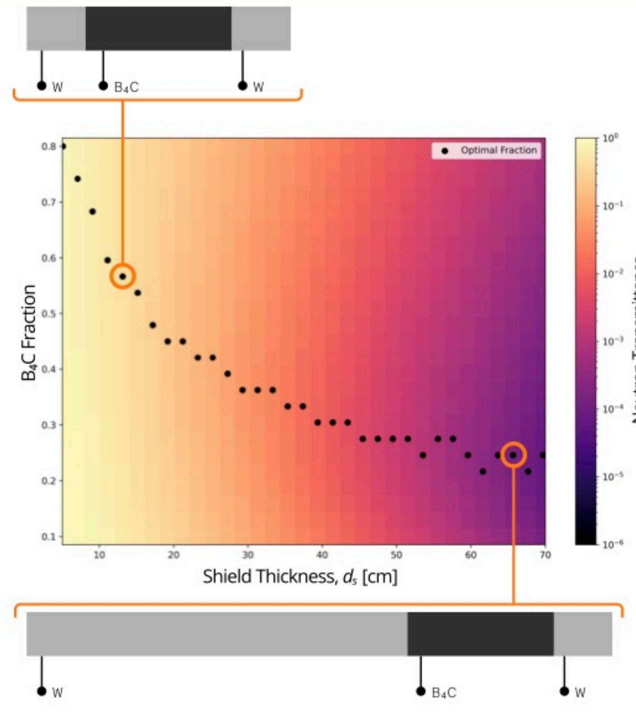
The high operating temperatures make metal hydrides not suitable for LDRs as they typically have a maximum temperature of ~800K before they begin to decompose.

The only viable materials that meet the temperature requirement are boron and tungsten containing compounds. Of the two groups, tungsten containing compounds are more volume efficient due to their higher scattering cross section at high energies.

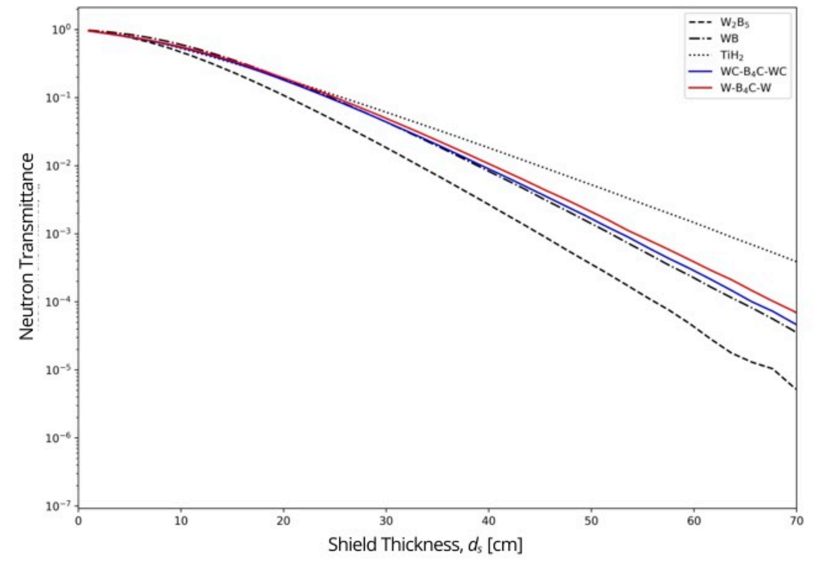
The best performing shield material is W_2B_5 however there is relatively little literature on its temperature stability and it has a significantly reduced thermal conductivity in comparison to pure tungsten.

By using a layered X-B_4C-X shielding construction, a large part of the performance of Tungsten Borides can be retained while using materials with higher operating temperatures and thermal conductivities.

➤ A shielding composition of **W-B_4C-WC** was chosen to maximize both surface temperature and space efficiency.



The optimal proportion of Boron Carbide is not constant with shield thickness, instead the absolute thickness is.



Using layered Tungsten Carbide or Tungsten shields with Boron Carbide gives the same shield performance as Tungsten Boride while either reducing cost or increasing operating temperature.

5. Shield Design

Design Methodology

Design Point

$P_{fus} = 500\ \text{MW} \quad \min(d_{shield}) = 550\ \text{mm} \quad t_{float} = 1\ \text{hr}$

Reactor Optimisation

The Differential Evolution algorithm was used to minimise the reactor size:

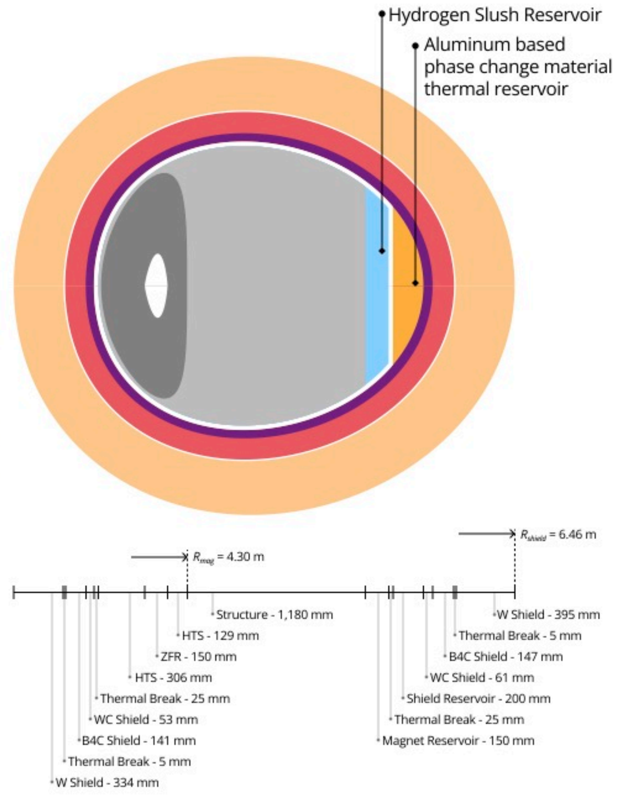
Parameters:	Constraints:
$\vec{u}$: Magnet Outer Profile	Magnet Current Density: $J_{op} < 100\ \text{A mm}^{-2}$
$\vec{v}$: Zero Field Region Profile	Homogeneous Hoop Stress: $\sigma_{\varphi\varphi} < 600\ \text{MPa}$
R_{m2}: Magnet Outer Radius	Plasma Outer Edge Pressure: $p_{edge} < 500\ \text{Pa}$
R_c: Chamber First Wall Radius	Plasma Outer Edge Temperature: $T_{edge} < 800\ \text{eV}$
p_{edge}: Plasma Outer Edge Pressure	
T_{edge}: Plasma Outer Edge Temperature	➤ Minimize FCFS Volume

Neutron Wall Loading Calculation

Using the output of the optimisation step, the full spatially dependant fusion reaction rate was calculated. OpenMC was then used to calculate the effective neutron wall loading on the FCFS, which acts as the outer surface of the neutron shield.

Neutron Shield Generation

Using the shielding performance calculated in the previous section and the neutron wall loading on the FCFS, the shield and all its layers can be generated.



Shield Structural Integrity

To preserve structural integrity of the shield, a small thermal reservoir is incorporated into the design to keep the temperature of the inner surface <1000K. This requires a thermal break between the outer W layer and the B_4C to ensure the majority of the thermal energy is radiated away, keeping the volume of the reservoir small.

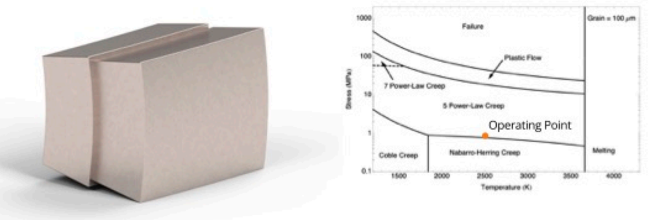
Aluminum based phase change materials have desirable properties [3]:

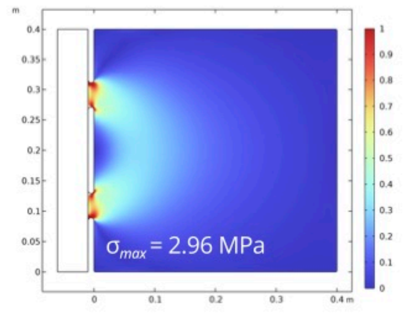
$$T_{melt} = 500 - 600\ ^{\circ}\text{C} \quad L_{fus} = 400 - 500\ \text{kJ kg}^{-1} \quad \rho = 2000 - 3000\ \text{kg m}^{-3}$$

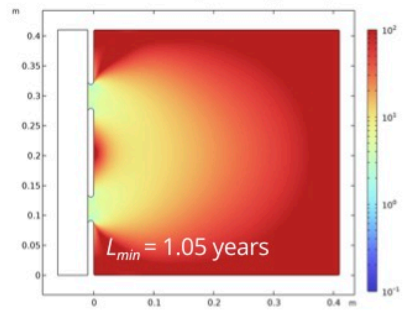
The exact material will be selected considering activation effects and chemical reactivity.

[3] Applied Energy **258**, 113955 (2020); 10.1016/j.apenergy.2019.113955

6. Shield Lifetime







Thermal Creep

At temperatures >2000 K, failure due to mechanical creep will occur unless the shield is designed to minimise stress. For this reason, the outer W layer is broken up into interlocking tiles to minimize stress and improve manufacturability. In general creep behavior is a function of three parameters: Temperature, *T*; grain size, *d*; and stress, *σ*. For this study the following values are used:

$$T = 2500\ \text{K} \qquad d = 100\ \mu\text{m}$$

Nabarro-Herring Creep [4]

This is the dominant creep model at the provided operating point, defined as:

$$\dot{\varepsilon} = 40\frac{\Omega D_l^0 e^{-Q_l/RT}}{d^2 k_B T}\sigma$$

Where:
$\Omega = 1.59\times10^{-29}\ \text{m}^3$
$Q_l = 520\ \text{kJ mol}^{-1}$
$D_l^0 = 8\times10^{-6}\ \text{m}^2\text{s}^{-1}$

For the presented tile, this gives a **lifetime of 1.1 years before replacement**.

[4] International Journal of Refractory Metals and Hard Materials **82**, 69-80 (2019); 10.1016/j.ijrmhm.2019.03.022

Other Damage and Recycling

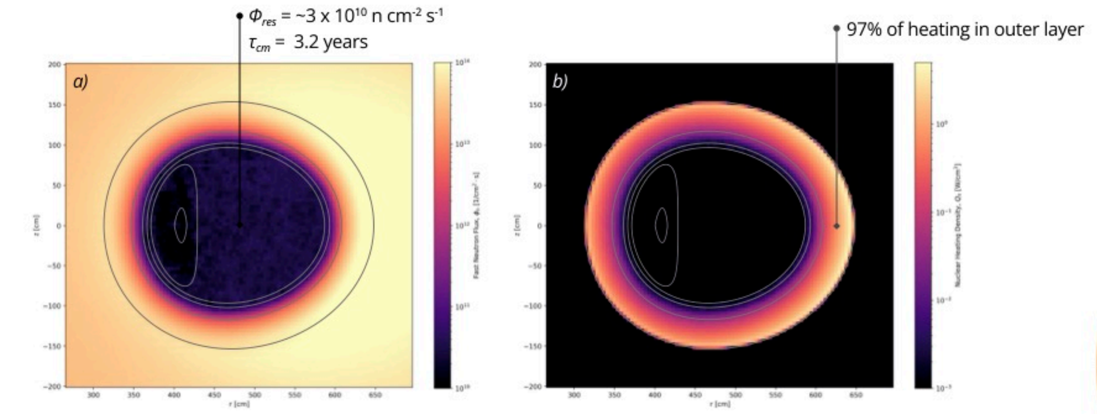
Radiation Damage

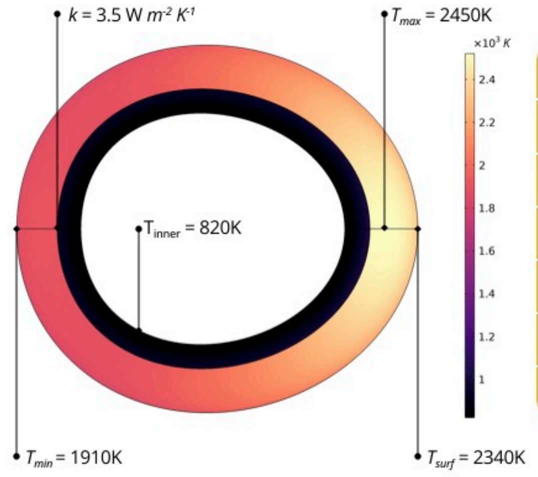
Using a standardised limit of 1 MW-year m^{-2} [5] and the wall loadings presented earlier, the W tiles will have a **lifetime of 1.8 years.**

Shield Recycling

LDRs can leverage the replaceability of the core magnet and its shield to minimize the impact of these short lifetimes. Since both of the damage mechanisms mentioned above are mechanical in nature, the shield tiles can be reprocessed without wasting any material. A shield replacement can occur during scheduled maintenance of the core magnet without incurring any additional downtime.

[5] "Bringing Fusion to the U.S. Grid" (2021); 10.17226/25991





Shield Spec		
Q_{mag}	2.25	kW
Q_{shield}	73.6	MW
q_{out}	0.562	MW m^{-2}
q_{in}	0.211	MW m^{-2}
m_{shield}	2.19 x 10^6	kg
m_{tot}	2.83 x 10^6	kg

7. Effect on Tritium Breeding

Reflective Shielding

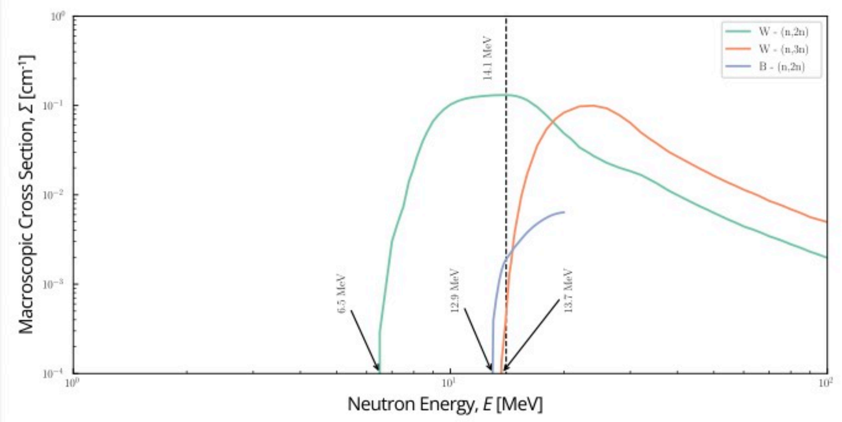
Tungsten has a significant cross section for neutron multiplication of 14.1 MeV neutrons. The effect is strong enough to account for all neutrons absorbed in the shield:

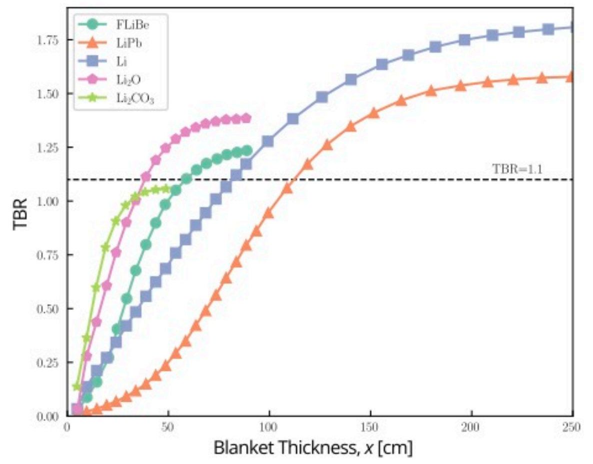
$$N_{fw} = 1.05 N_{fus}$$

Complete Freedom in Blanket Design

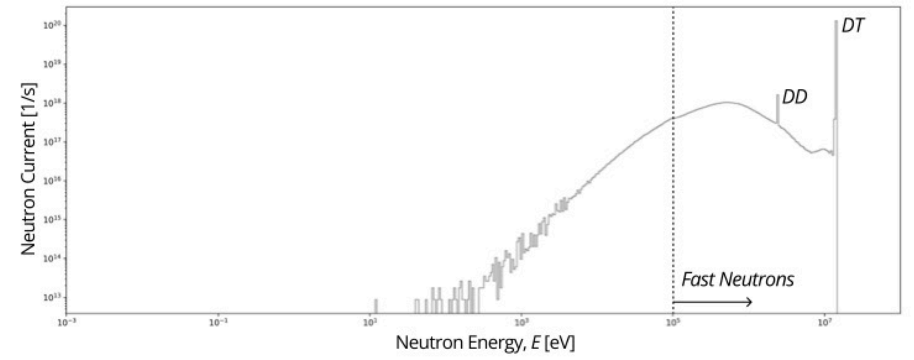
The design of a tritium breeding blanket for an LDR then becomes easier than other fusion concepts:

- **Space:** The cost of the vacuum chamber support structure does not scale rapidly with radius. The blankets and any associated maintenance space can be large.
- **No MHD:** Dipoles are effectively steady state devices.
- **Optimal Performance:** The good system neutron efficiency allows for materials with a wide range of TBRs to be considered.





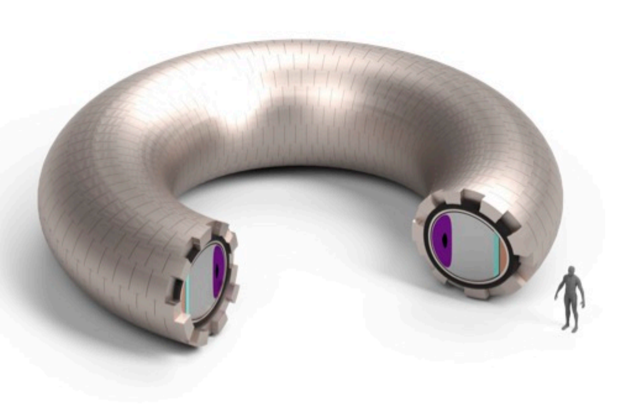
[6] Plasma Sci. Tech. **5**, 1995-2000 (2003); 10.1088/1009-0630/5/5/011

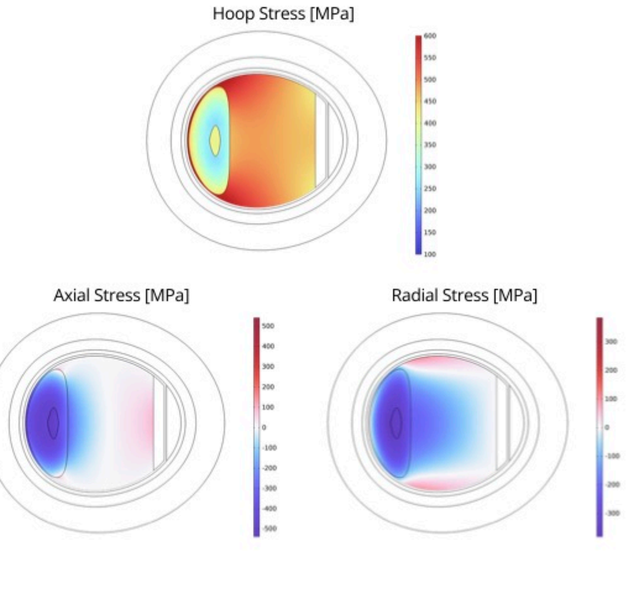


8. Reactor Specification

System Spec		
R_{mag}	4.30	m
R_{fw}	20.8	m
U_{mag}	22.7	GJ
I_{op}	30	kA
L_{HTS}	4061 (6mm)	km

Plasma Spec		
P_{fus}	503	MW
B_{max}	29.4	T
β_{max}	2.79	-
R_{core}	6.73	m
T_{core}	13.8	keV
n_{core}	1.5 x 10^{20}	m^{-3}
T_{edge}	770	eV
n_{edge}	2.03 x 10^{18}	m^{-3}
U_{plasma}	399	MJ
P_{brem}	10.6	MW





9. Conclusions

Physically Possible

With this shield design we present a possible 500MW$_{fus}$ LDR.

- ***Simple***, well proven materials have required shielding performance to keep reactor sizes manageable.
- Shield can reach radiative balance with first wall, maintaining ***high plant efficiencies***.
- Layered W-B_4C-WC shield design can ***withstand extreme temperatures*** with moderate lifetime.
- Enable ***high TBRs*** due to significant neutron multiplication and reflection.

Although not shown here, this shielding concept is applicable for many reactor scales

Economic Viability

This study made assumptions about component lifetimes that still allow for an economic fusion power plant. ***This still needs to be proven.***

OpenStar is currently working on a full LCOE model to evaluate the economic viability of different reactor designs. This model will then be used to inform the reactor design to create an "Economically Optimised" Reactor.

- Aiming for an LCOE of 100 USD/MWh for a FOAK plant

Future Work

There is still a lot to be done to improve and further understand the shield design

- ***Limiting Surface***
  This design does not include a plasma limiting surface on the outboard side. How the loading on this surface will effect the rest of the shield design needs to be understood. The impact of the partial pressure of tungsten also needs to be understood.
- ***Shutdown Dose***
  In order to effectively recycle the shielding material, the shutdown dose and cooldown time need to be modelled.
- ***Thermal Expansion***
  All shield components need to be designed with thermal expansion in mind. This study does not take this into account however future detailed engineering design studies should have this as a focus.
- ***Improved Tile Design***
  The presented shield tile design is not ideal. The interface between adjacent tiles needs to be designed to eliminate neutron shine-through while still leaving enough tolerance for assembly.
- ***Detailed Thermal Management Model***
  This study assumed a fully insulating inner boundary and an arbitrary thermal resistance between the B_4C and outer W layers. More work needs to be done on quantifying and designing these features.

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