Mars Colonization
with a fusion-fission hybrid spacecraft

22.63 Fall 2018
Final Design Presentation
13th December 2018

PSFC
Plasma Science and Fusion Center
Massachusetts Institute of Technology

22.63 Principles of Fusion Engineering

Teaching goals

- Have students use/develop modern design tools, mostly computational
- Attack integrated design issues in a multi-team format

Focus on applying recent tech and science advances

- High temperature superconductors
- Discovery of substantial water on Mars (plus thorium)
- Improved performance of stabilized mirrors (Te ~ keV) in Russia

My goals/constraints to the class

- Power "core" and propulsion for travel to and colonizing Mars
- D-T mirror + sub-critical fusion/fission blanket
- Reduce astronaut radiation dose during transit to more acceptable levels

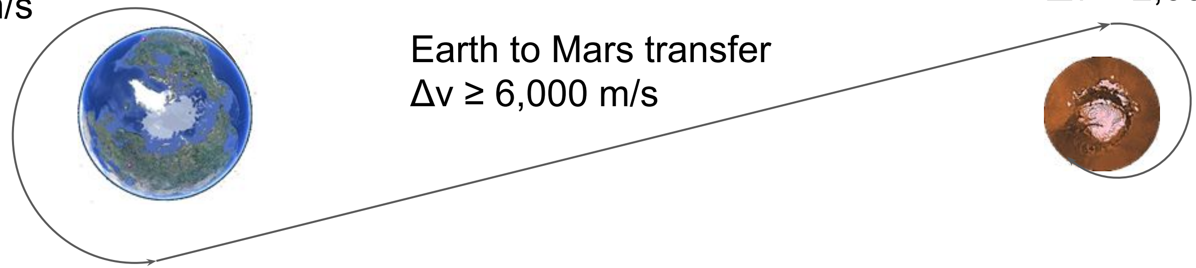
Overview

1. Going to Mars
2. Fusion core
3. Fission blanket
4. Power generation system
5. Propulsion system
6. Radiation shielding
7. System optimization

Going to Mars is hard

Mars is (at least) 55 million km away

Space missions have a certain “Δv” requirement - a measure of impulse change required for the maneuver, which corresponds to propellant requirement



Mars *colonization* with chemical propulsion seems unlikely

The rocket equation governs any “reaction engine”:

$$\frac{m_{final}}{m_{initial}} = e^{-\Delta v/v_e}$$

m_{final}

$m_{fuel} = m_{initial} - m_{final}$

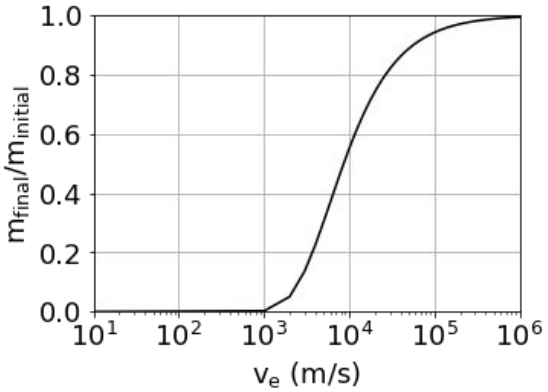
v_e

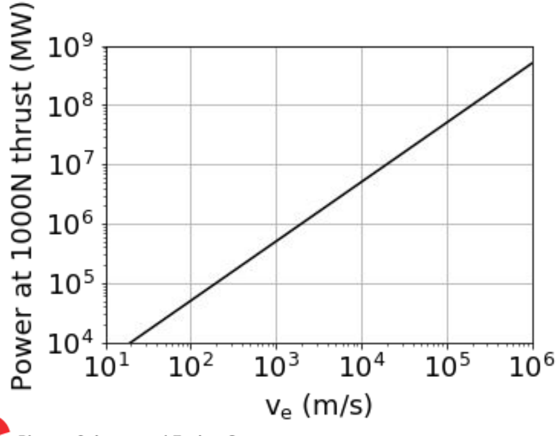
- Most efficient Earth-to-Mars trajectory requires Δv of 6000 m/s
- Highest v_e achievable by a chemical rocket is 4500 m/s (LH_2/LO_x), limited by energy content of fuel

$$\frac{m_{final}}{m_{initial}} = e^{-6000/4500} = 26.3\%$$

- ~10% of launchpad mass ends up in Earth orbit ⇒ ~3% of launch mass ends up on Mars
- This seems marginally feasible for small scale Mars missions, but **not feasible for colonization** or deep space missions

Electric propulsion could be a viable alternative





Need a very high v_e for any sort of large payload or deep space mission

⇒ **electric propulsion**

Need a source of electrical power that has high power density

⇒ **nuclear fission**

But there are problems

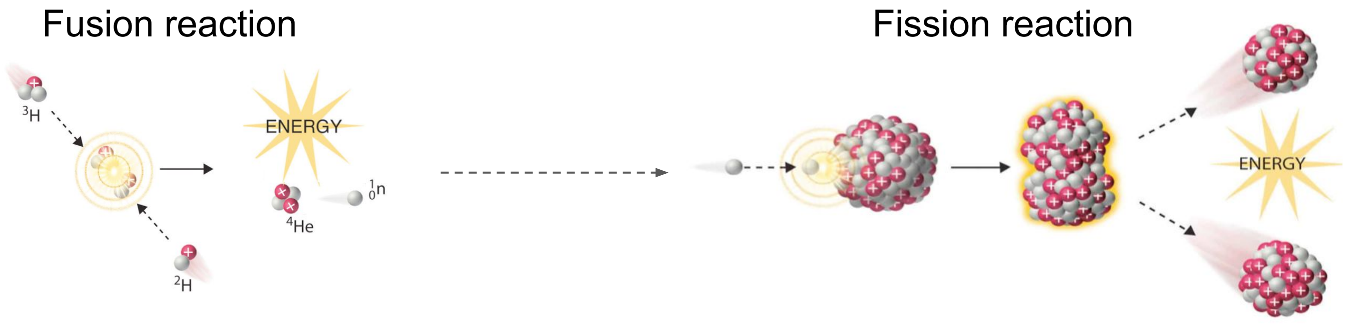
Safety and regulatory concerns of launching critical fission systems

Critical fission systems need **refuelling** for long term operation and colonization

Other types of electrical generation have **low specific power**

Cosmic radiation harms astronauts in long duration space missions

A fusion-fission hybrid could solve some of these problems



Safety

- Fusion-fission hybrid is a “driven” system - simpler control
- Fission fuel is never in a critical configuration - inherently safe

Suitable as long term power supply

- Ability to operate with substantial fission product inventories
- Ability to breed fissile fuel *in-situ*

A high power density fusion-fission hybrid does not exist yet

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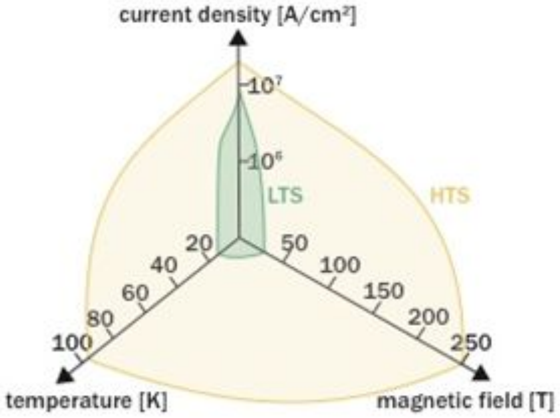
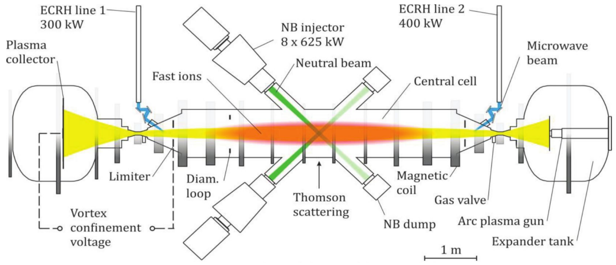
New technologies might be game changers

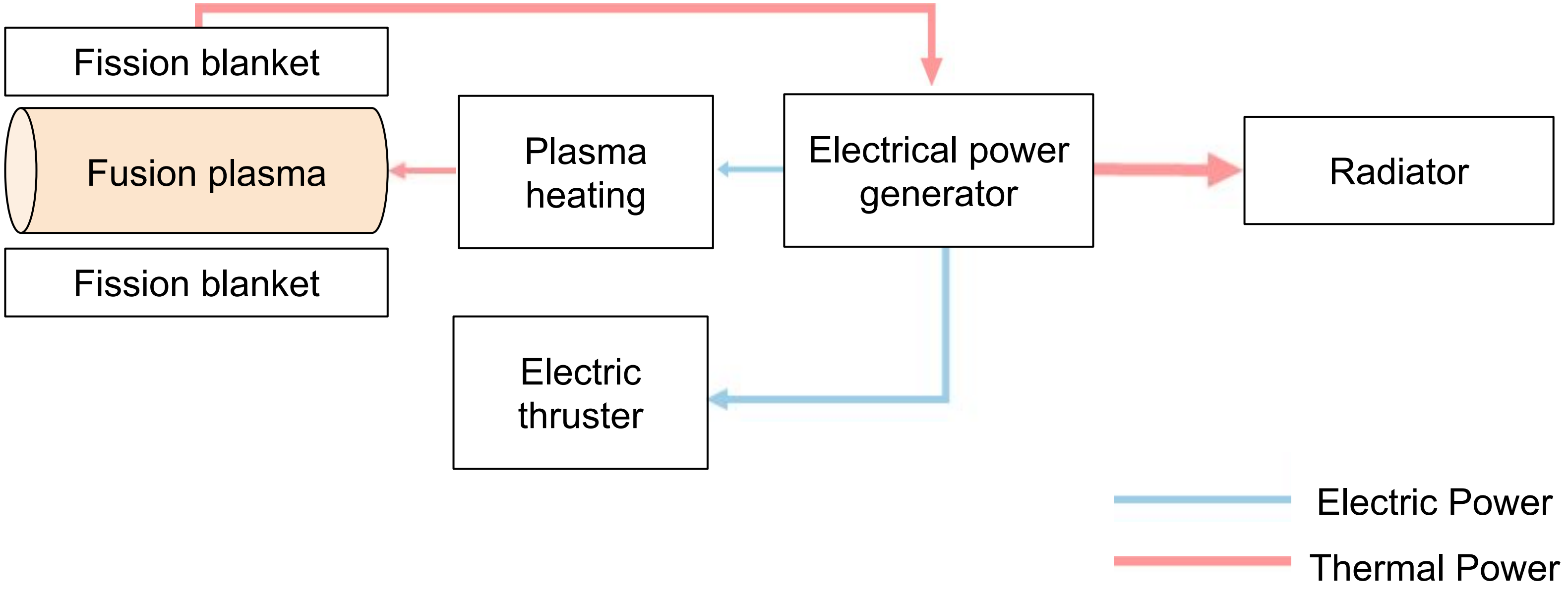




Novosibirsk mirror device (Ivanov et al., 2017)

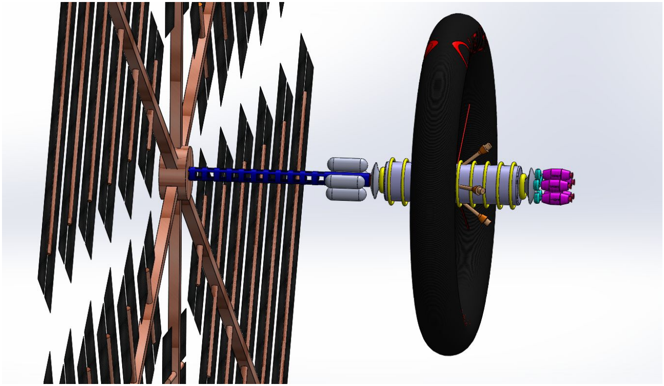
1. High temperature superconducting (HTS) **magnets**
   a. Lighter, smaller, higher-field magnets for fusion core
   b. Practical magnetic shielding with reasonable mass
   c. Opportunities in magnetohydrodynamic (MHD) power generation
2. New demonstrated **fusion mirror** performance capabilities
   a. Improved energy confinement ⇒ fusion energy gain (Q_{fusion}) on the order of unity
   b. Stability at high plasma pressure ⇒ power density could be high

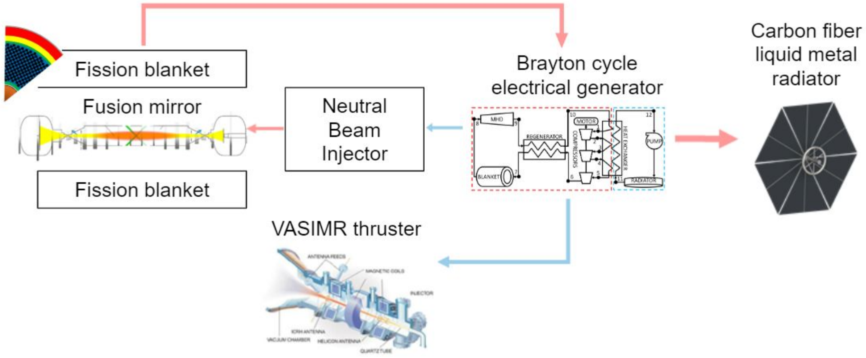
The fusion-fission spaceship concept



Question: can we design a fusion-fission spacecraft to colonize Mars?

Yes





We have designed a spacecraft which can transport very heavy payloads to Mars, suitable for colonization missions

System mass	363	mt
Travel time	414+	days
Payload capacity	500+	mt
Thermal power	33	MW
Electrical power	12	MW

How did we design the spacecraft?

Requirements and constraints:

- Enable the transport of **large payloads to Mars** (e.g. for human colonization)
- Reduce **radiation exposure** to colonists during the trip to levels which will not cause long-term genetic damage
- Spacecraft and payload to require launch of less than **1000 mt to Earth orbit** (same as SpaceX BFR)
- Use where possible **existing demonstrated technology**

Objective:

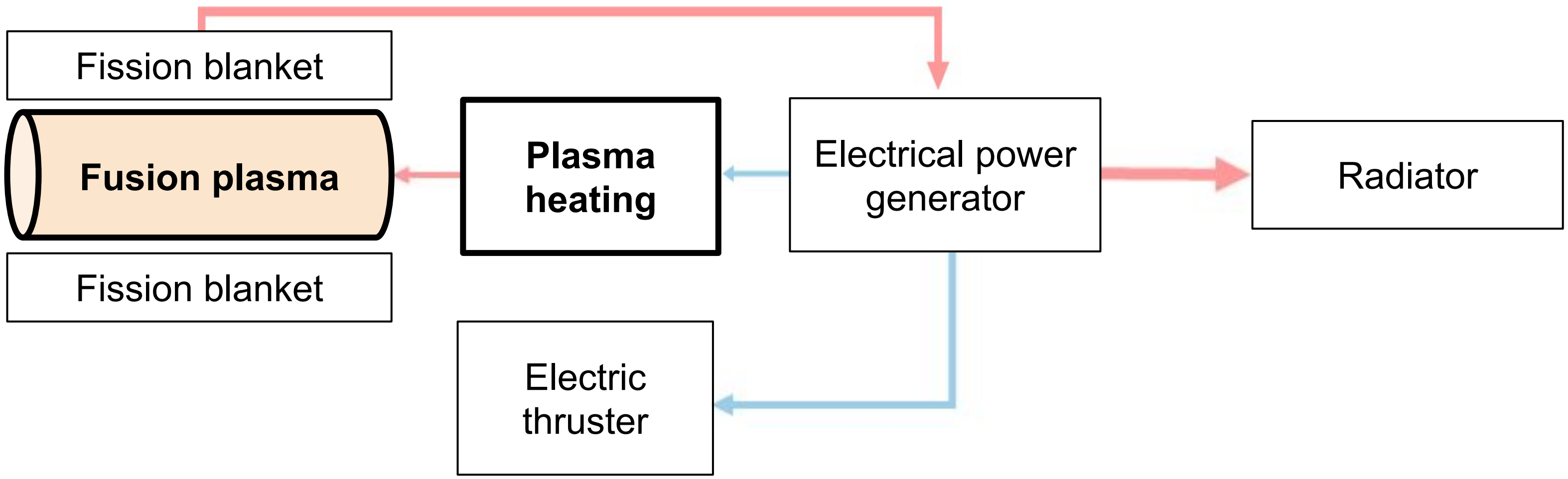
Transport a large payload quickly to mars:

1. Maximize payload
2. Minimize travel time

For a fixed system power/thrust, the objective is to **minimize mass**. Design process:

1. Quantify mass-performance trade-offs during subsystem design
2. Use numerical optimization to find optimum overall design (later)
3. Repeat until satisfied

The fusion mirror system



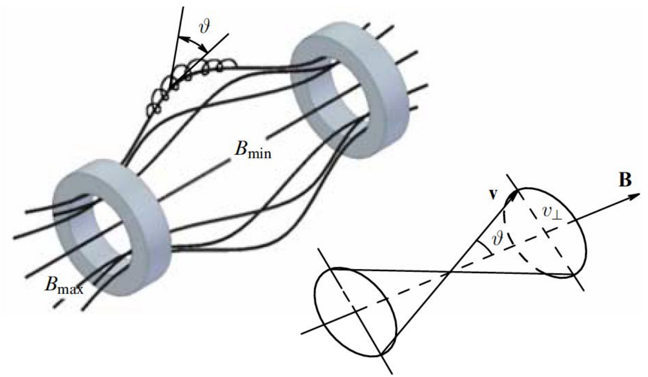
The fusion mirror core

Requirement:

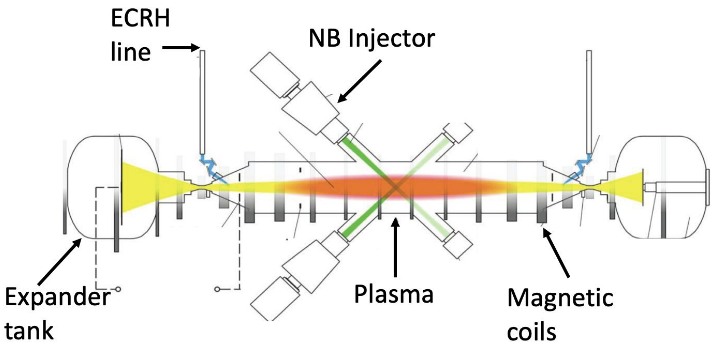
- Heat and confine fusion plasma

Design:

- Open, trap-based fusion reactor
- Plasma confined by transverse magnetic field, longitudinal flow reflected at the high-field magnetic mirrors
- Plasma heated by neutral beam injection (NBI) and electron cyclotron resonance heating (ECRH)
- Stability enhanced by novel methods (expander, plasma rotation etc)
- Extrapolation of performance achieved experimentally at Novosibirsk



Schematic of mirror trapping



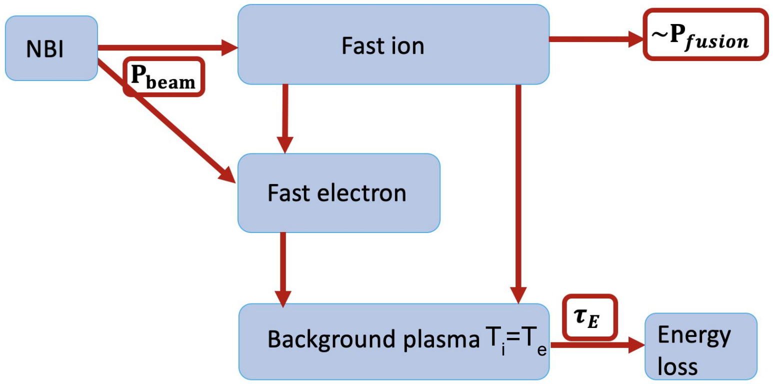
Novosibirsk mirror device (Ivanov et al., 2017)

Estimating fusion performance

- First principles physics models
  - Three monoenergetic populations
  - Power balance between three populations determines temperature and particle densities
- Energy confinement time rescaled from Novosibirsk experiment results

$$\tau_E = \tau_{E,0} \frac{R}{R_0} \frac{L}{L_0} \left(\frac{T_0}{T} \right)^{\frac{1}{2}}$$

  - Confinement determined by geometry and background particle properties



Schematic of the three-population model
Red arrows representing energy flow

- Extrapolation to the 99% fast particles regime
  - Beam-beam fusion dominant
  - Fusion performance mainly determined by fast particle properties

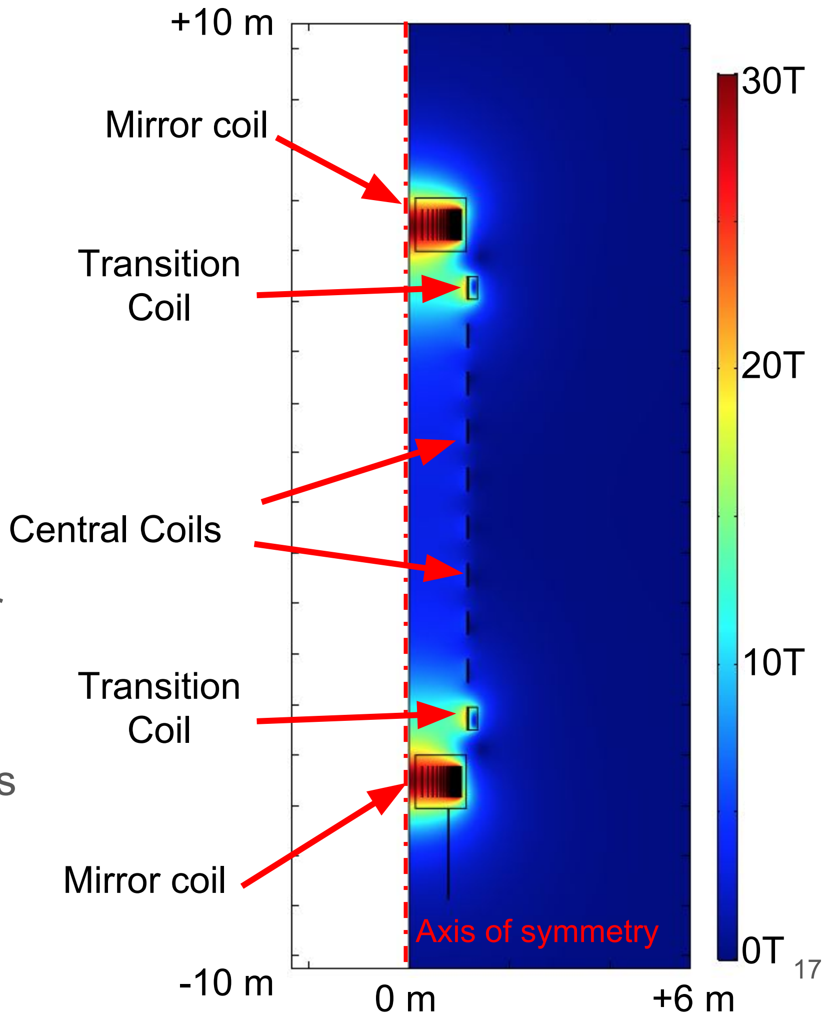
HTS magnets for the mirror

Physics requirements:

- Central confinement coils to contain plasma and trap charged fusion products
- Two transition coils for field shaping
- Two high-field mirror coils to trap particles at two ends

Engineering constraints:

- Strains not above 0.4% on the superconductor
- Stresses not above 1 gigapascal in the structural material
- Reduce neutron flux to extend magnet lifetimes
  - Total lifetime fluence: 1e19 neutrons/cm^2



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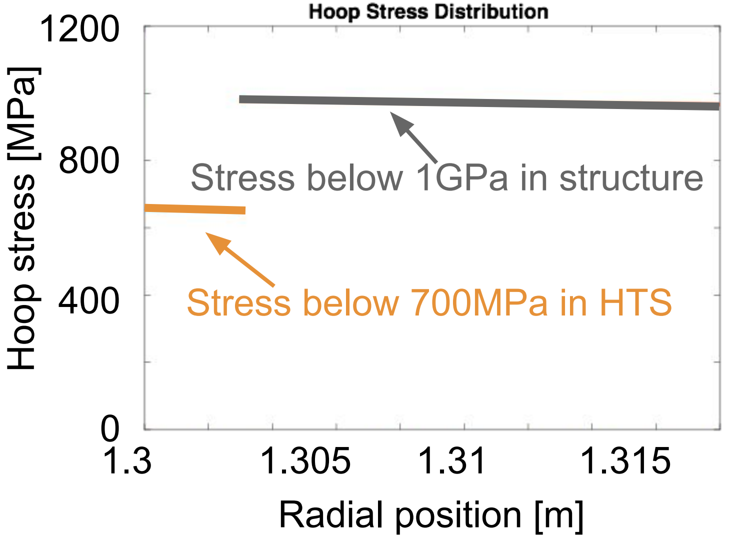
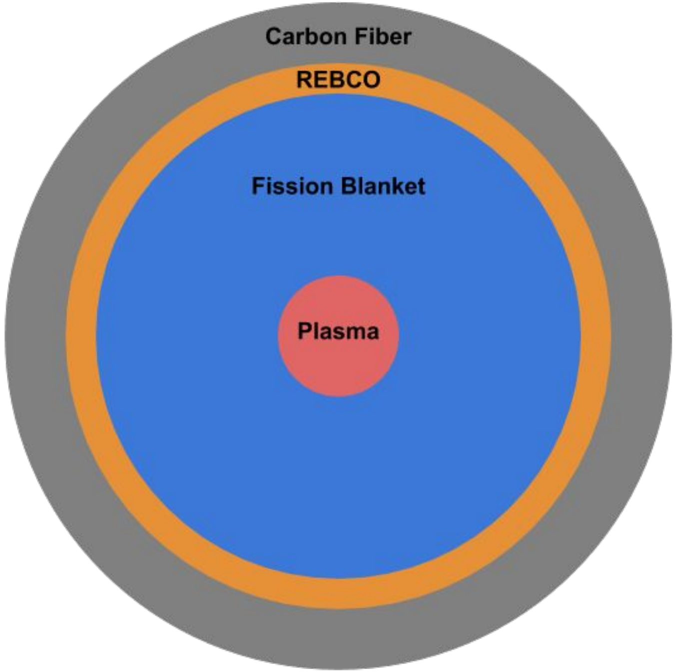
Central magnets use a simple design and analysis

- Lower field coils were modeled using a 2D analytical calculation of stress in an infinite solenoid.



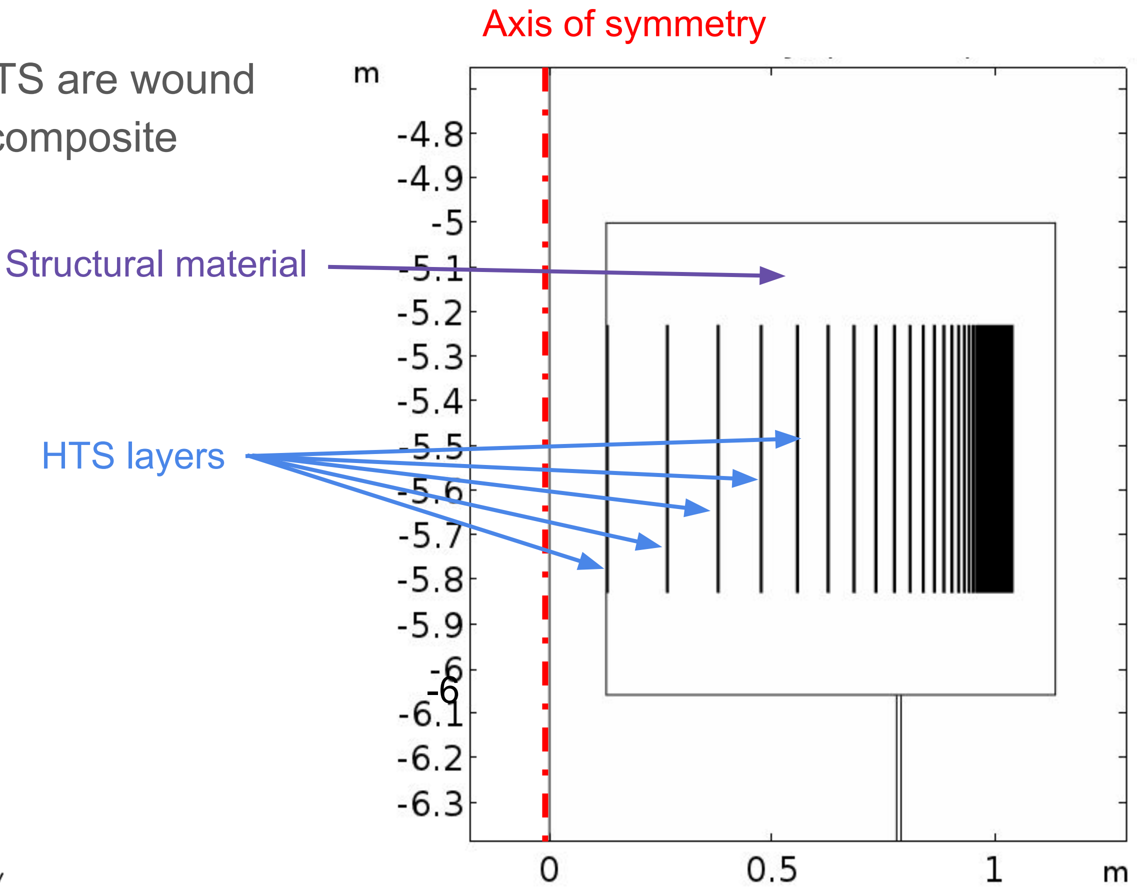
$$\frac{1}{\rho}\nabla \cdot \sigma = -\mathbf{f}$$



- Each of the 8 central coils weighs approx ⅓ mt

Mirror coils use graduated spiral wind to reduce stress

Graduated layers of HTS are wound between carbon fiber composite structure.



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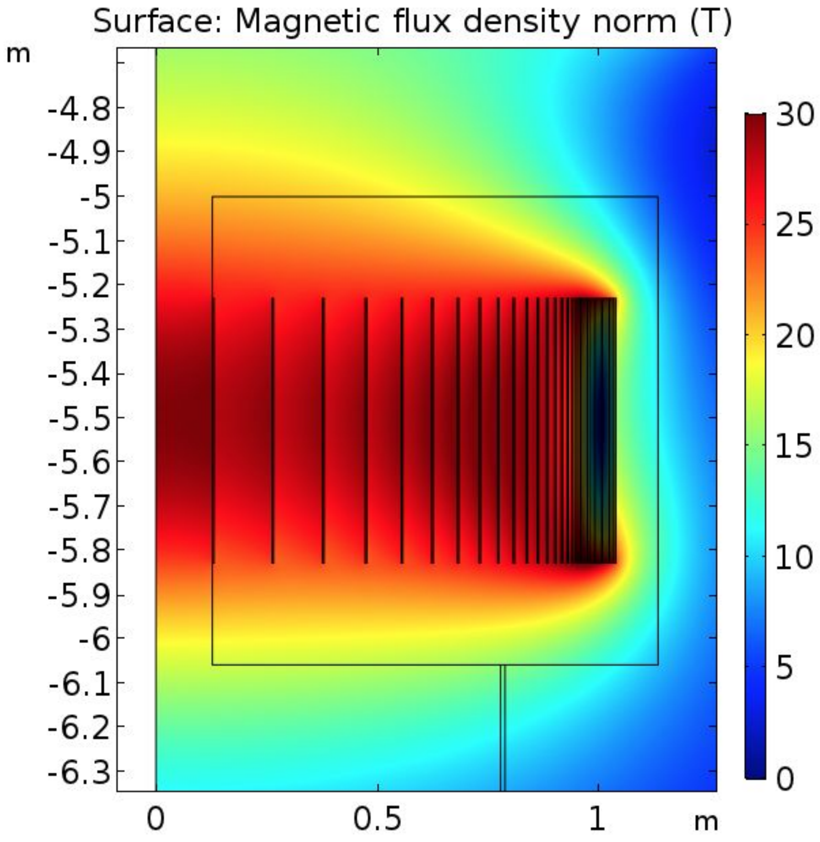
Graduated layers of HTS are wound between carbon fiber composite structure.

The magnetic field near the axis of symmetry is much higher, leading to significantly higher forces on the tape.



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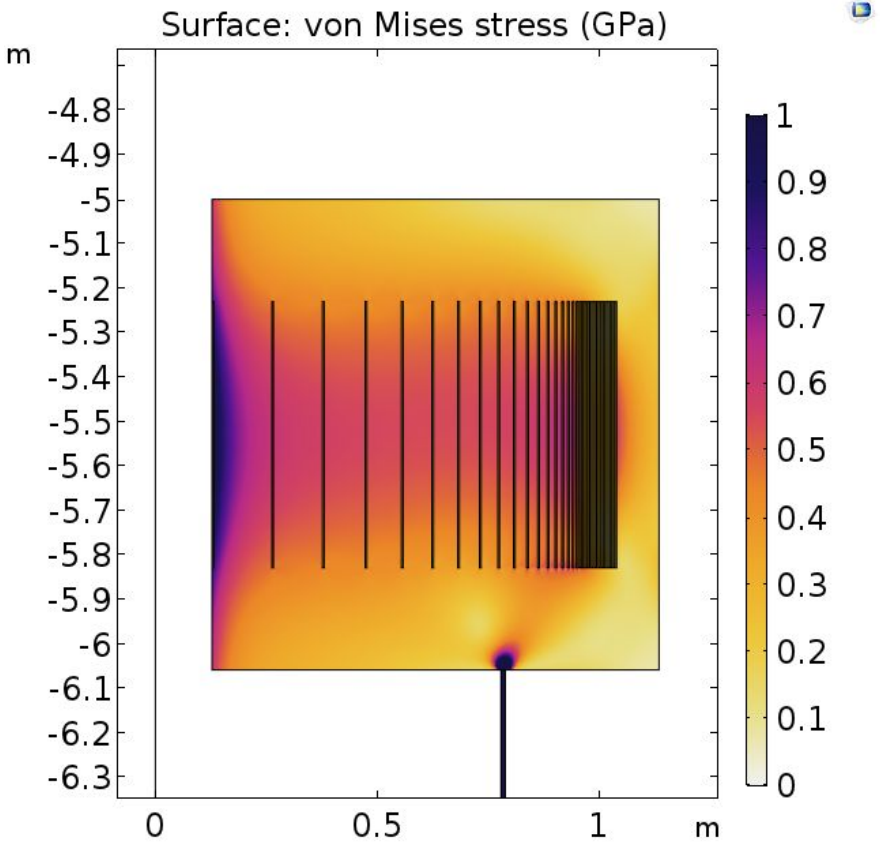
Mirror coils use graduated spiral wind to reduce stress

Graduated layers of HTS are wound between carbon fiber composite structure.

The magnetic field near the axis of symmetry is much higher, leading to significantly higher forces on the tape.

By de-loading the inner tape layers we can achieve 1 GPa maximum von mises stress in the structure.



Mirror performance limits Q_{fusion} to ~0.5

Fusion energy multiplication

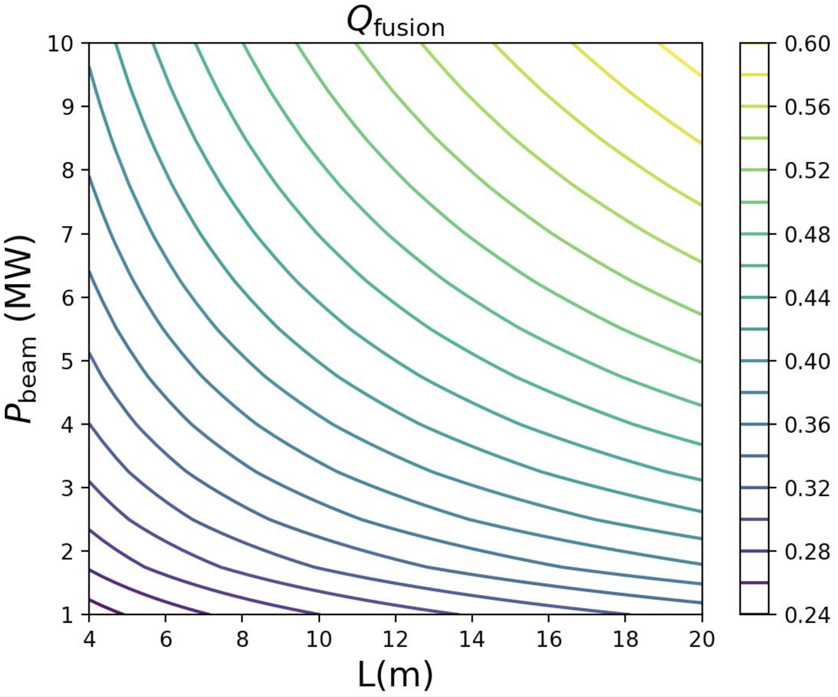
$$Q_{fusion} = \frac{P_{fusion}}{P_{beam}}$$

Increasing the length and the power of the mirror improves confinement, but increases mass

$$Q_{overall} = Q_{fusion} \cdot Q_{blanket} \cdot \eta_{elec}$$

$Q_{overall}$ must be greater than 1 for the system to produce any power for propulsion

Q_{fusion} ~ 0.5, η_{elec} ~ 0.3 ⇒ we need a fission blanket with high energy multiplication!



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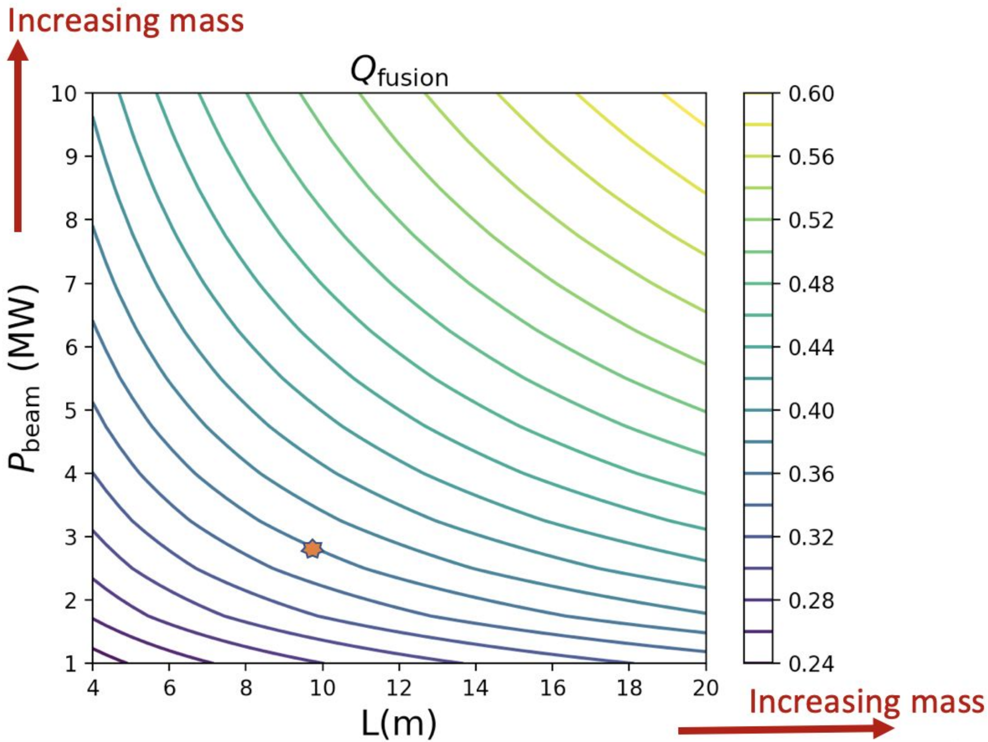
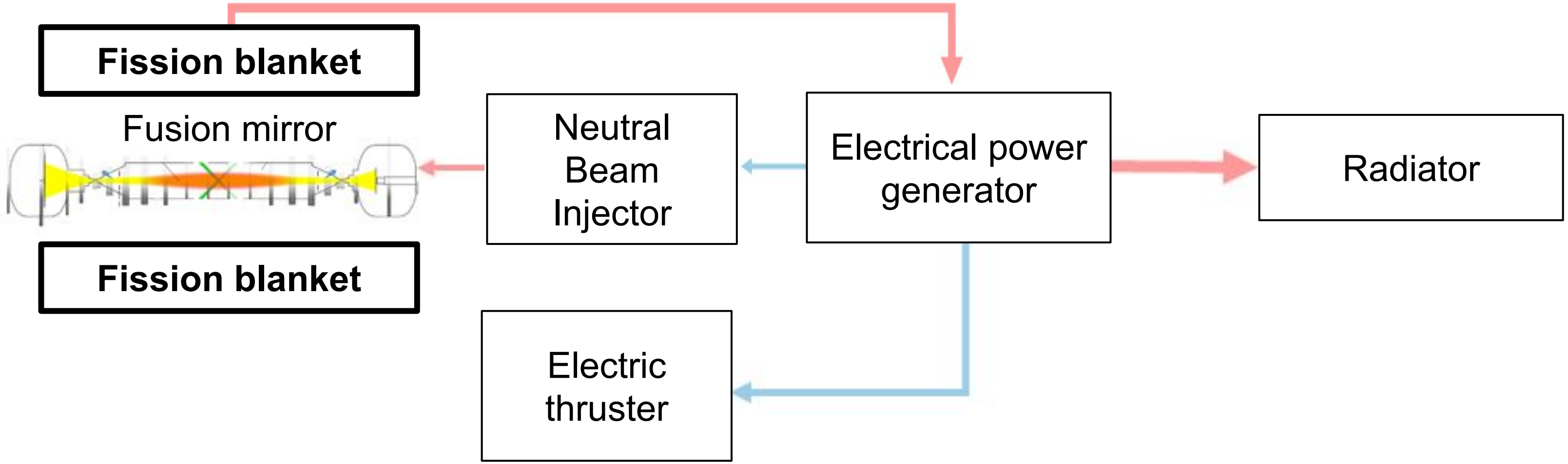


The fission blanket



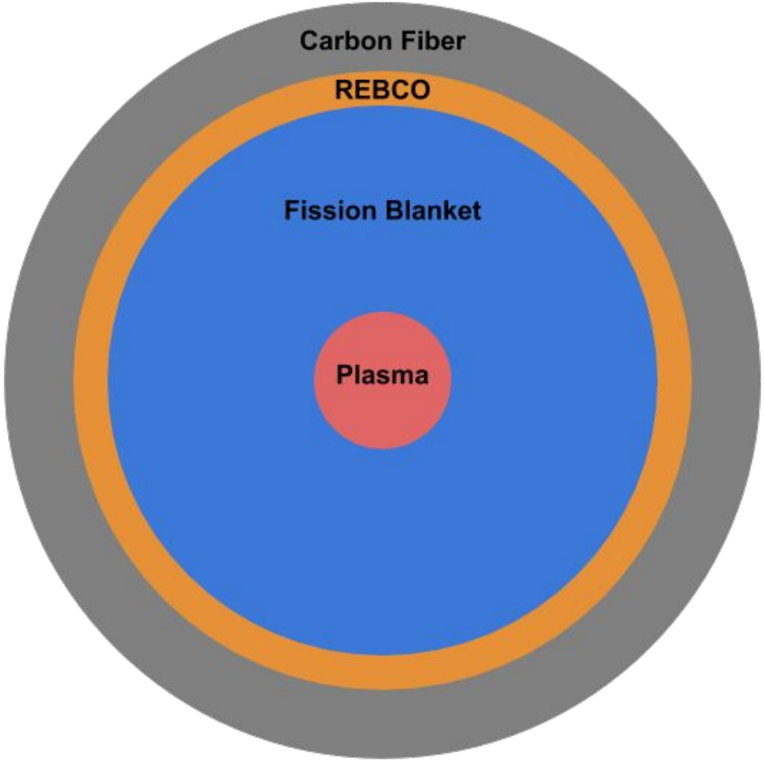
The subcritical fission blanket

Requirements:

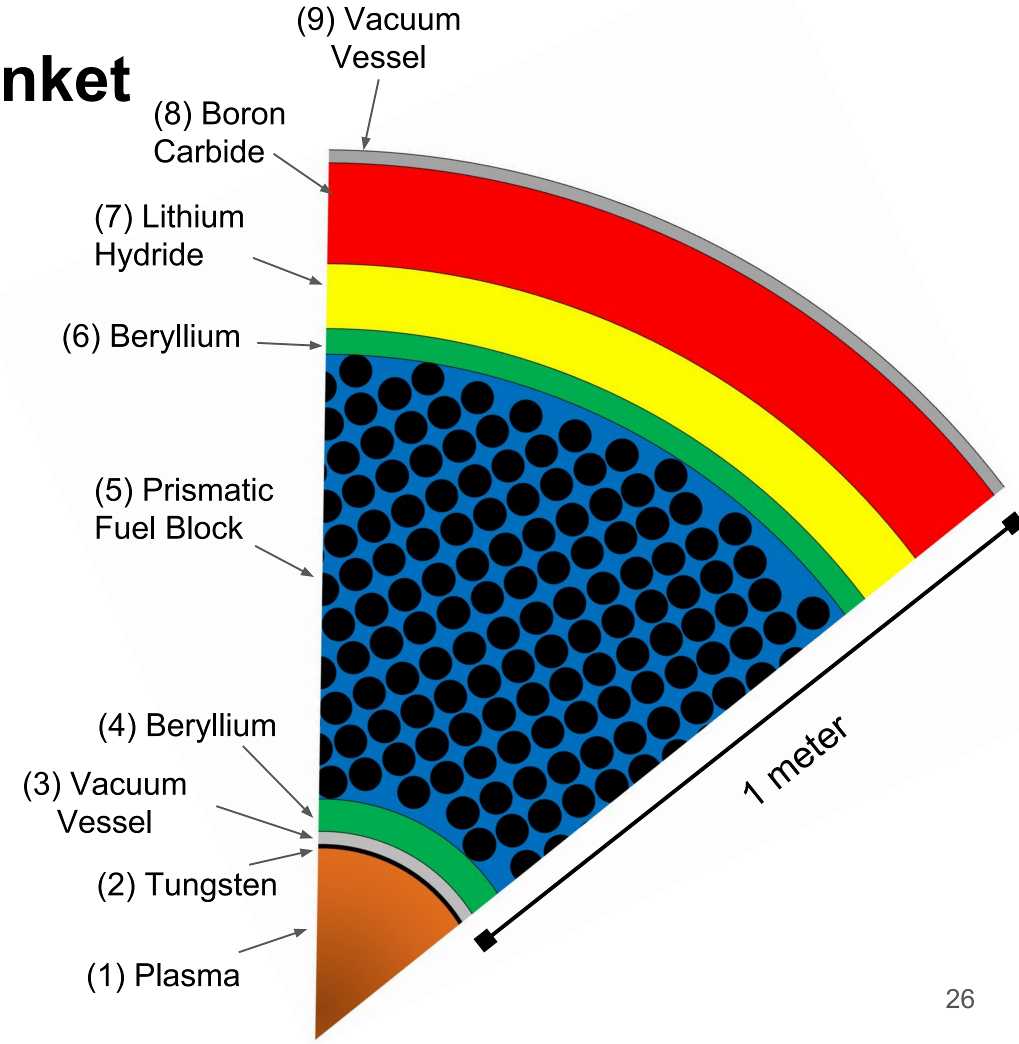
- High energy multiplication ($Q_{blanket}$ >> 1)
- Sufficient tritium breeding (TBR >1)
- Adequate shielding of magnets
- Low-enriched Uranium (LEU)

Also desirable:

- Long fuel lifetime
- High output temperature



The Subcritical Fission Blanket



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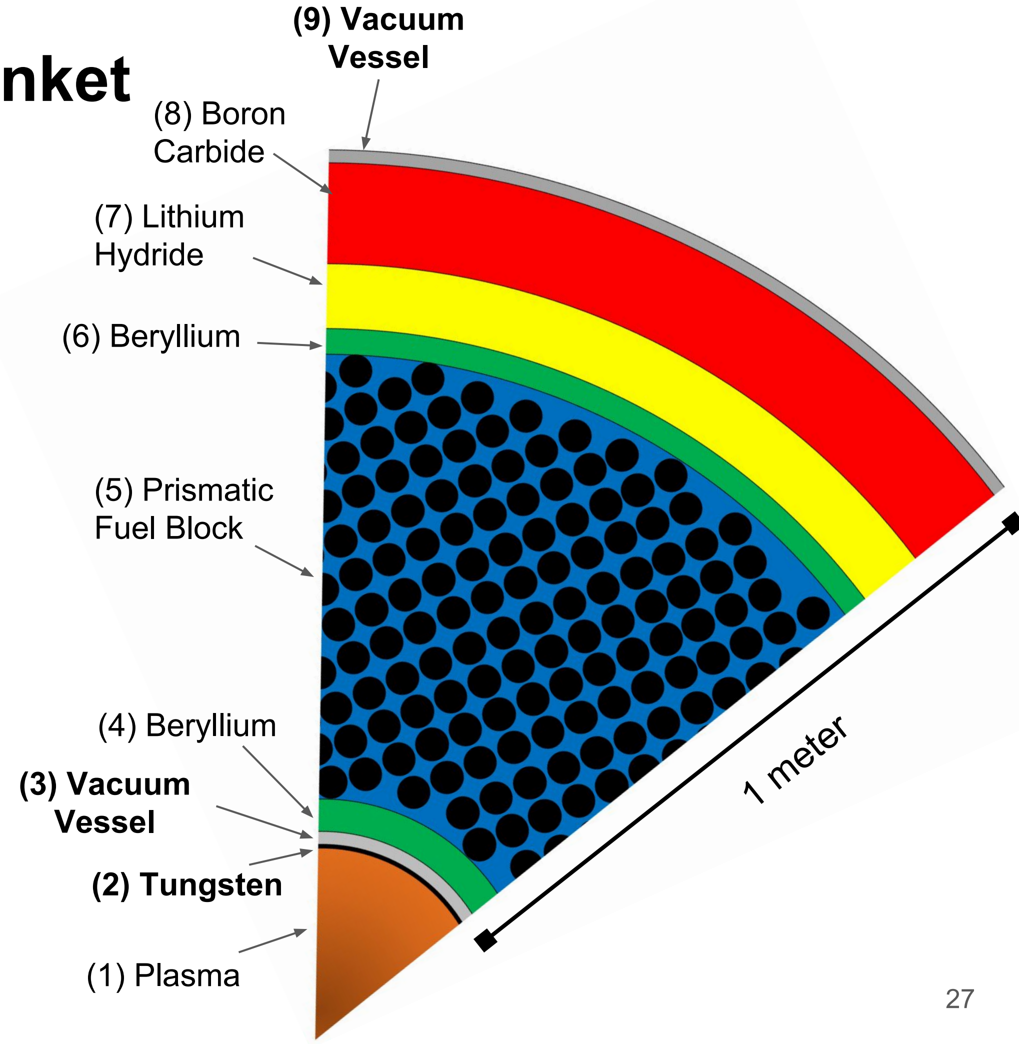
The Subcritical Fission Blanket

(2) Tungsten:

- Plasma first wall

(3), (9) Vacuum Vessel:

- Steel or Nickel alloy (Inconel)



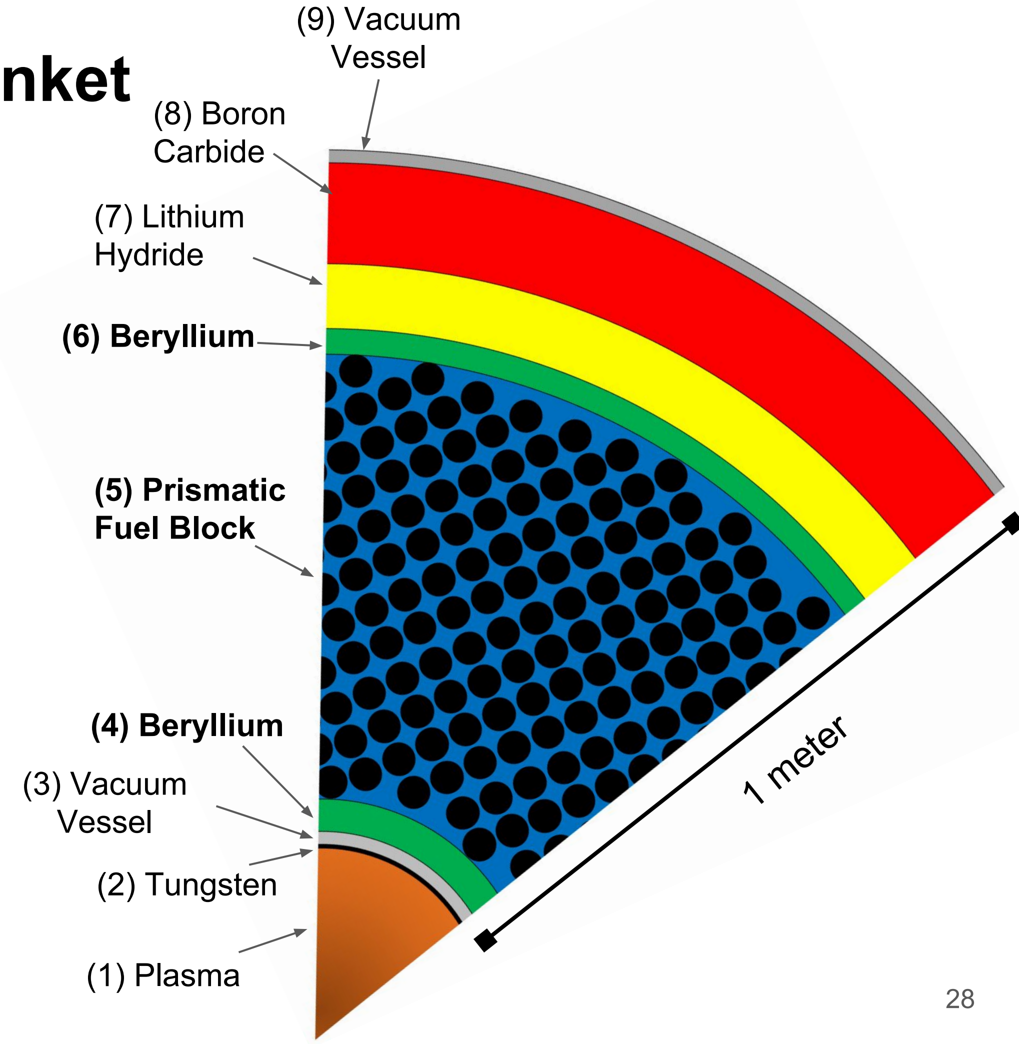
The Subcritical Fission Blanket

(4), (6) Beryllium:

- ^{9}Be is a prolific neutron multiplier.
- Also acts as a neutron reflector for the core.
- Significantly increases tritium breeding ratio.

(5) Prismatic Fuel Block:

- Proven fuel technology for fission high-temperature gas reactors
- Mixture of carbon and heavy metal
- Achieves high gas outflow temperature (Max Fuel temperature at 1600 K)
- Low-Enriched Uranium (max 20% ^{235}U)



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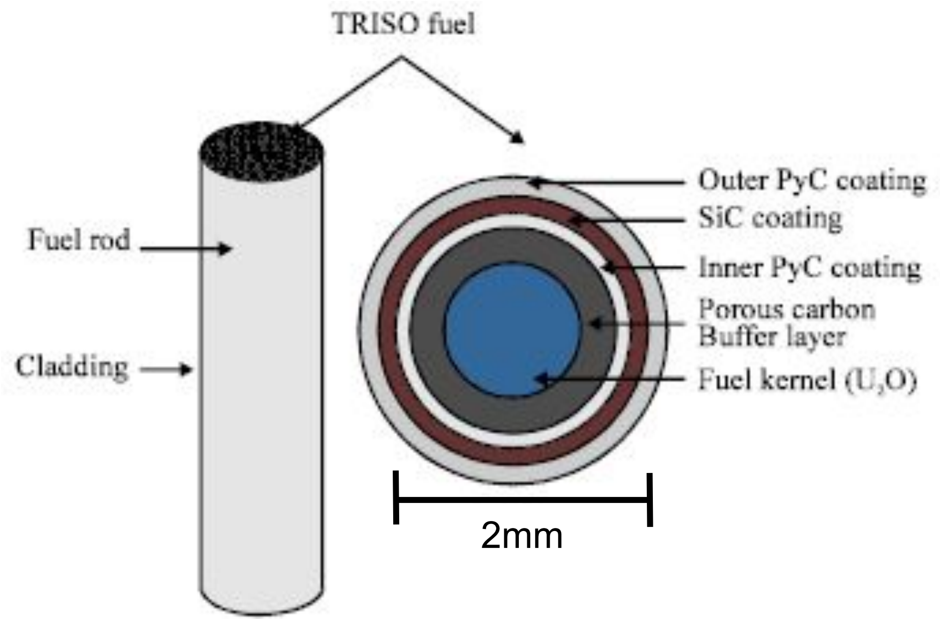


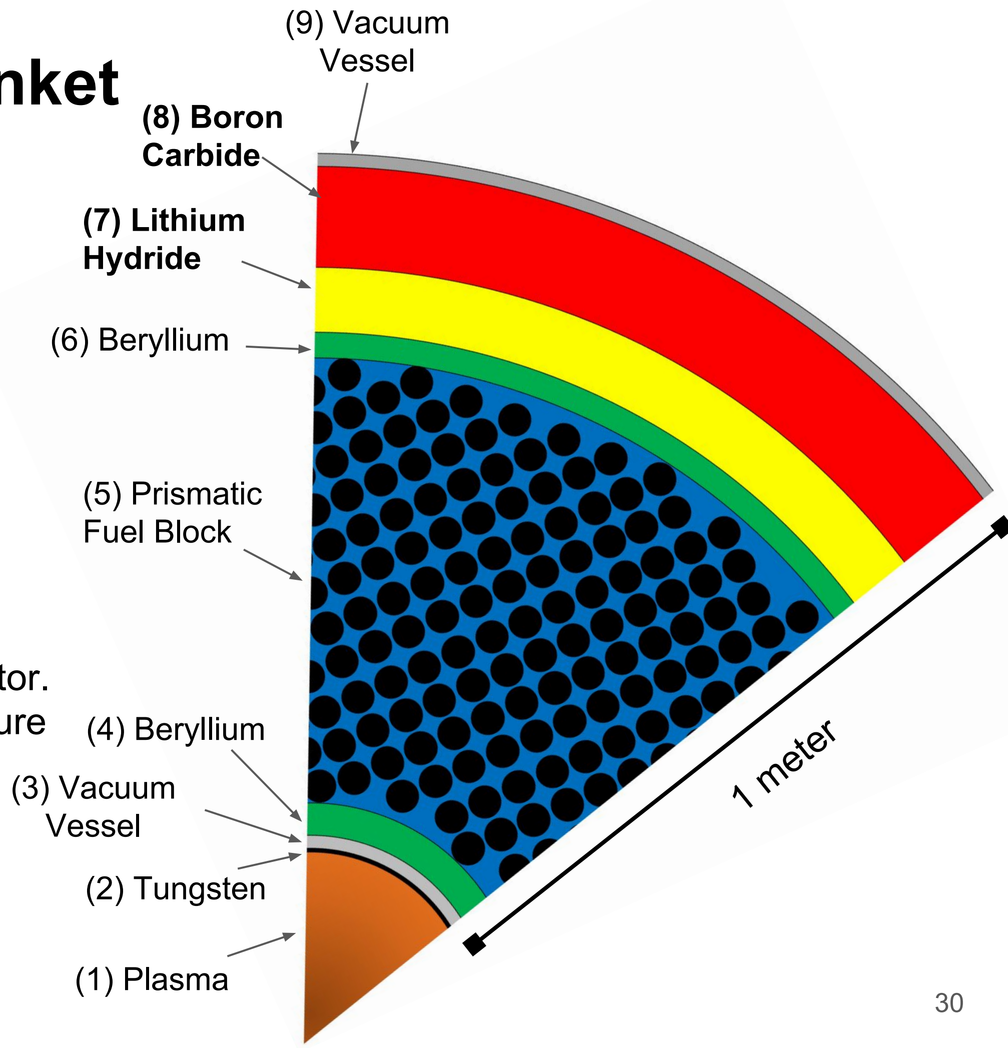
The Subcritical Fission Blanket

(7) Lithium Hydride:

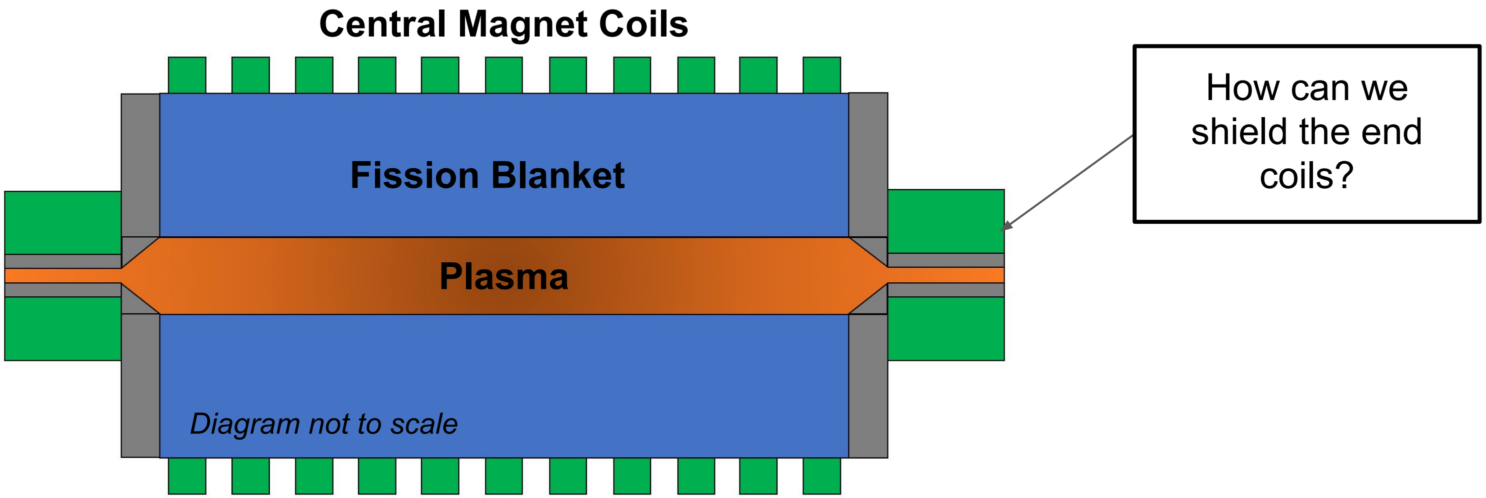
- Lithium required for tritium breeding.
- Natural Lithium.
- LiH chosen as Hydrogen is a superb neutron moderator.

(8) Boron Carbide:

- Additional shielding for magnets.
- Carbon is an effective neutron moderator.
- ^{10}B (enriched) has a high neutron capture cross section.

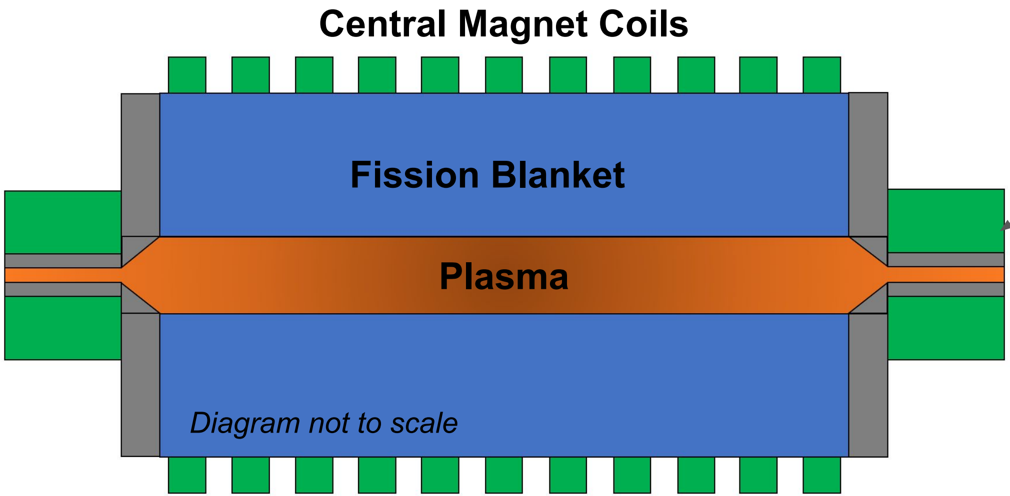


Modifying neutron profile for end coil shielding

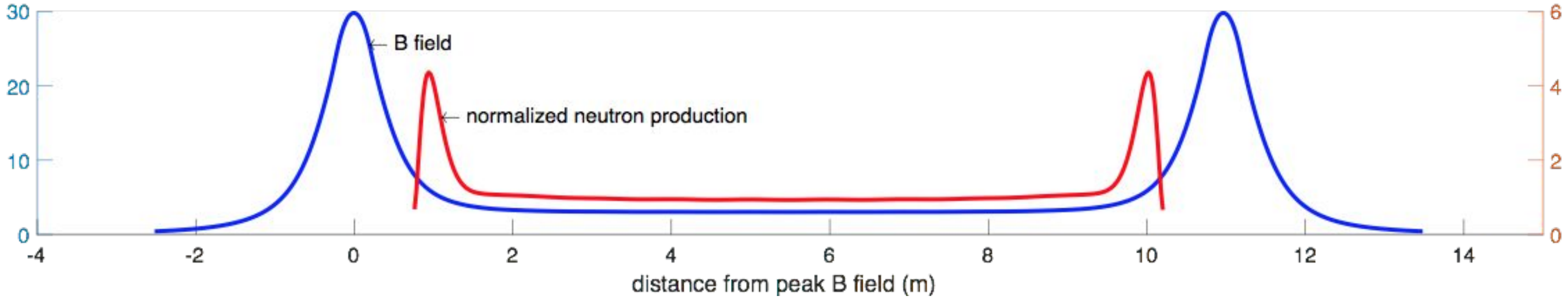


Modifying neutron profile for end coil shielding

Magnet damage is expected at neutron fluences above 1e19 neutrons/cm^2.



How can we shield the end coils?



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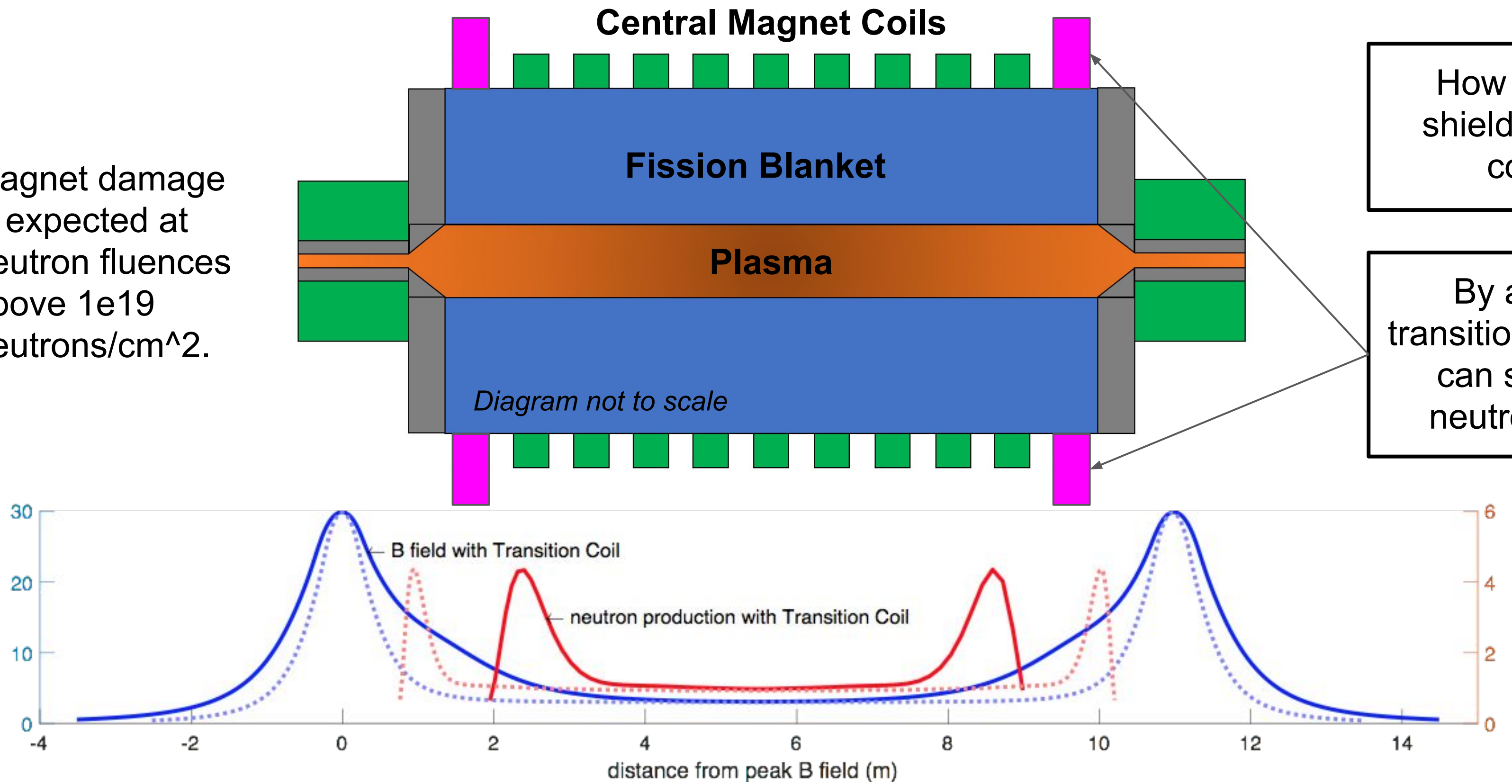


How can we shield the end coils?

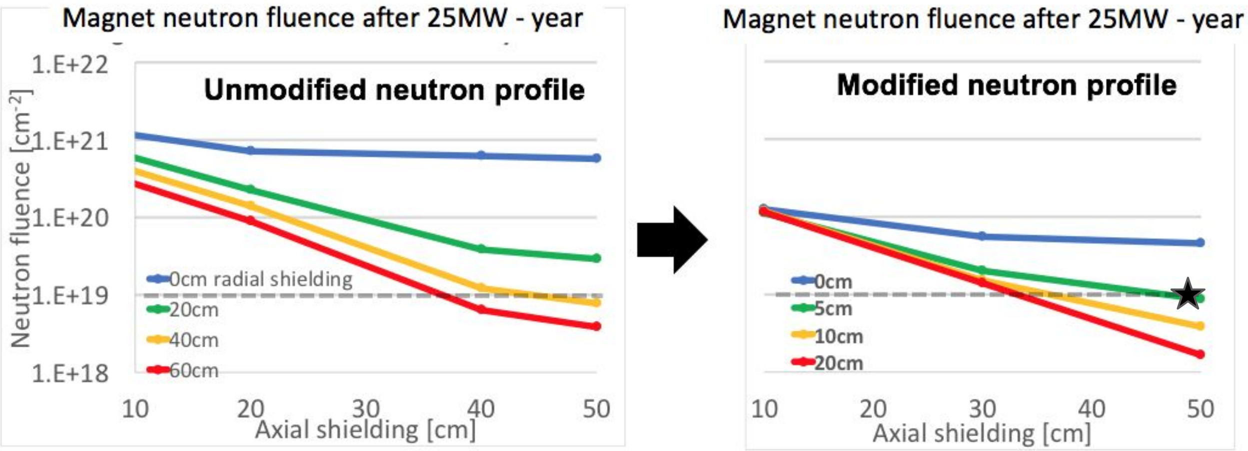
By adding transition coils, we can shift the neutron peak

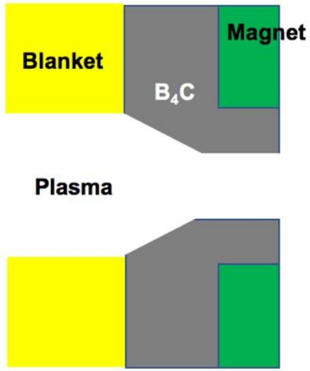
Modified neutron profile reduce magnet shielding requirements

Neutron fluence to end-coil magnets simulated using MCNP.

Radial and axial thickness of shielding varied.

Maximum lifetime fluence: 10^{19} neutrons/cm^2.





Shielding requirements:
5cm radial shielding
50cm axial shielding

Magnet dimensions:
12.7cm inner radius
110cm outer radius

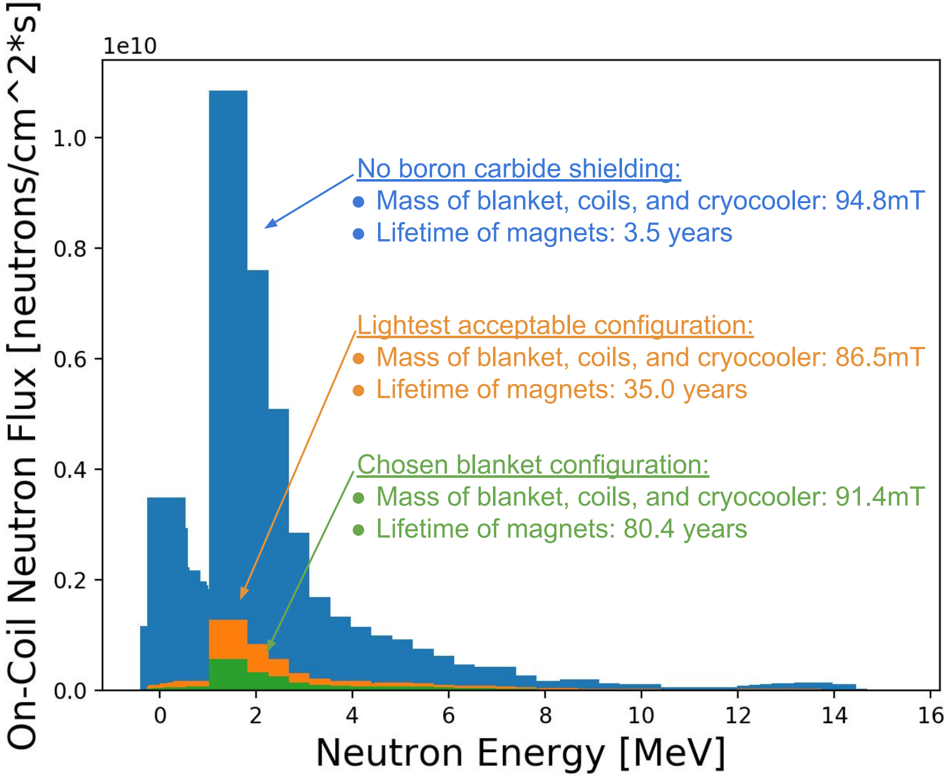
Neutron flux on magnets dictates shielding requirements

Goal: minimize total mass of blanket, coils, and cryocooler

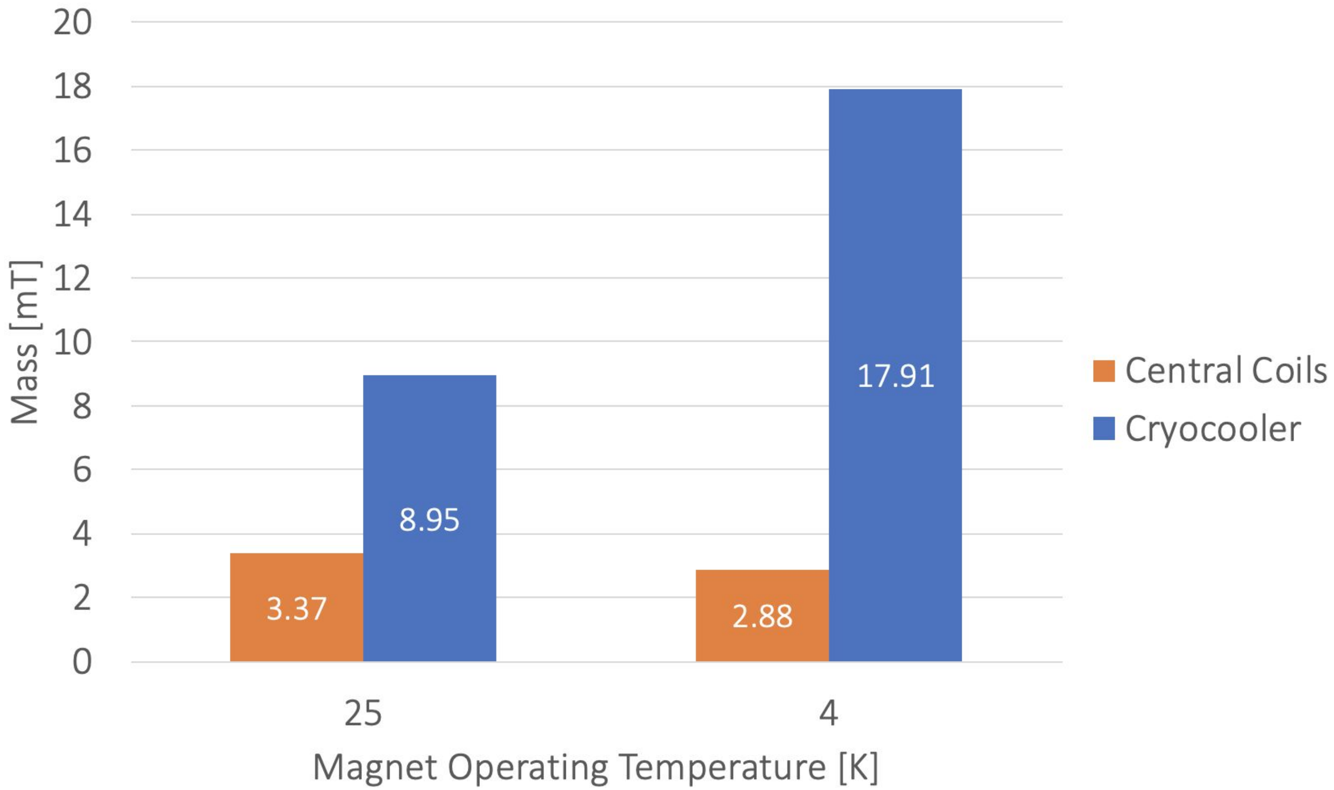
- Optimize over amount of shielding and operating temperature
- Must remain below REBCO fluence limit of 1e19 neutrons/cm^2

Final operating parameters:

- Magnet temperature: 25K
- Magnet coolant: liquid hydrogen
- Neutron heat load: 2kW
- Electric power needed for heat rejection: 193kW



Lower operating temperature doesn't decrease mass



Steady State: Blanket Thermal Design

Blanket Constraints:

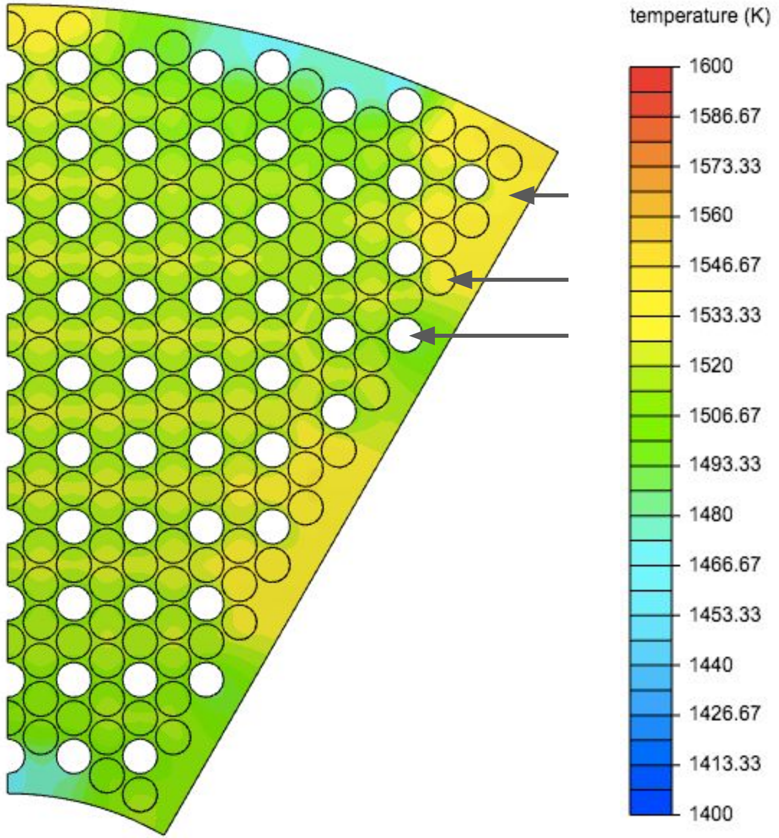
- Fuel Maximum Temperature: 1600 K
- Coolant: 900 K inlet, 1400 K outlet
- Goal: Maximize fuel to volume ratio
- Goal: Uniform blanket temperatures

Design Point Selected:

- 1788 fuel pins, 624 cooling channels
- 6-60° Blanket Core Sections

Blanket Performance:

- T_max = 1550 K
- Fuel_ratio = 48.5% fuel by volume



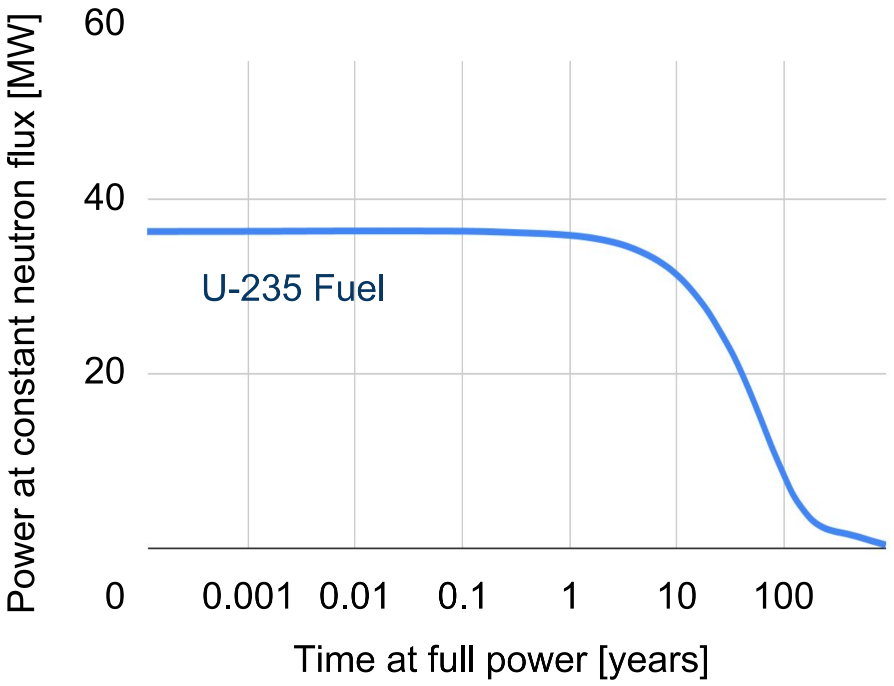
Fuel burnup manageable using low-enriched uranium

Design Constraint:

- Constant long-term thermal power output.

Controlled Variables:

- Amount of ^{9}Be
- Size of the fuel block
- Uranium Enrichment
    - Ratio of fertile material (^{238}U) and fissile material (^{235}U) can affect long-term energy production



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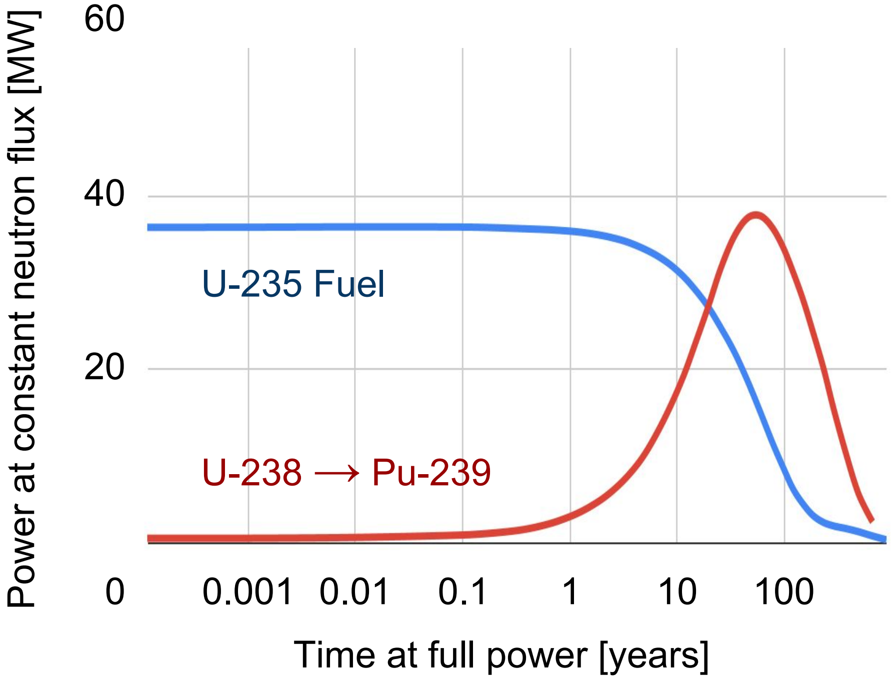

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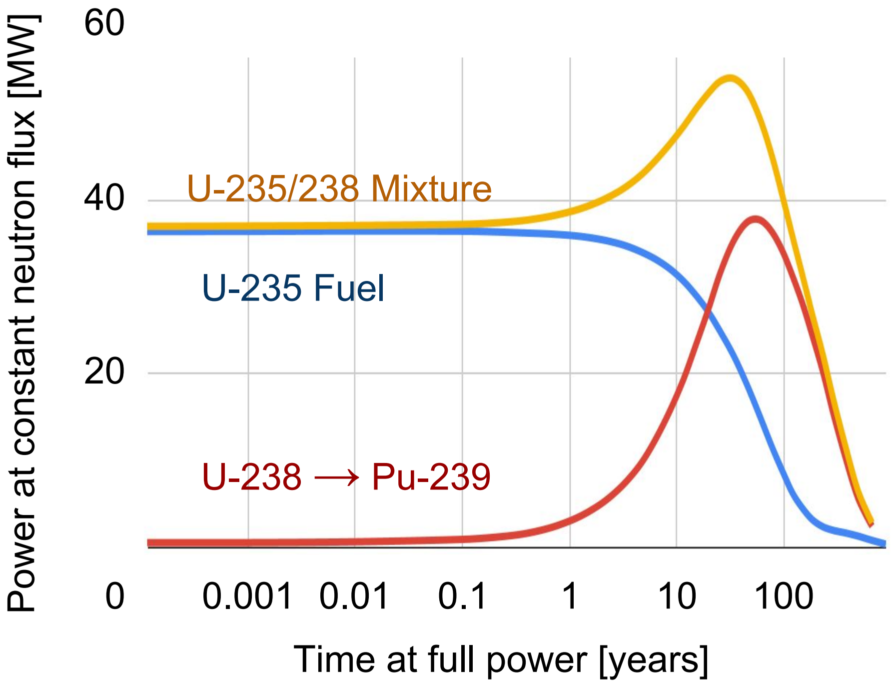


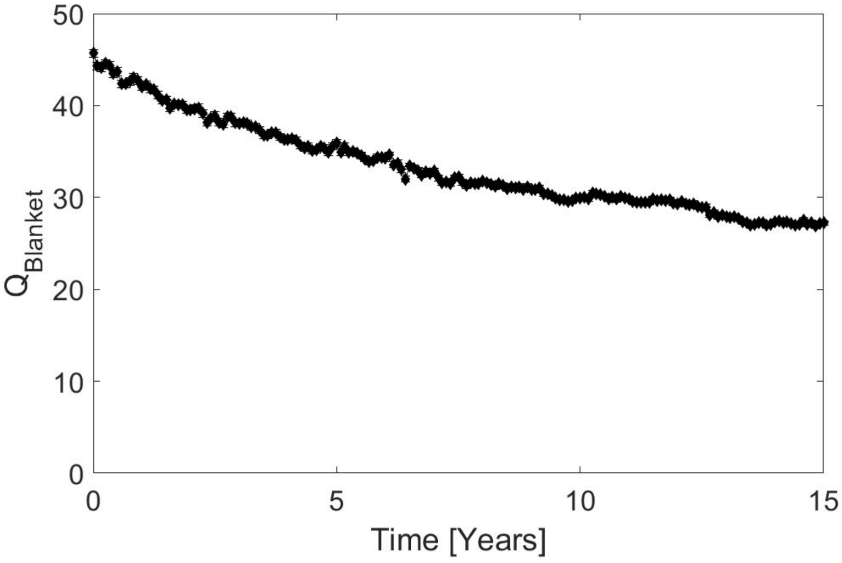
Blanket composition optimized for steady heat output

Design Constraint:

- Constant long-term thermal power output.

Result:

- Minimize the amount of ^{9}Be
    - Decreases neutron flux magnitude
    - Fuel region size controlled by $Q_{blanket}$
- Uranium Enrichment
    - Maximized the amount of ^{235}U (limited to high assay LEU, 20% enrichment)
    - FISPACT verified power production on relevant time-scale & validated specialized inventory code.

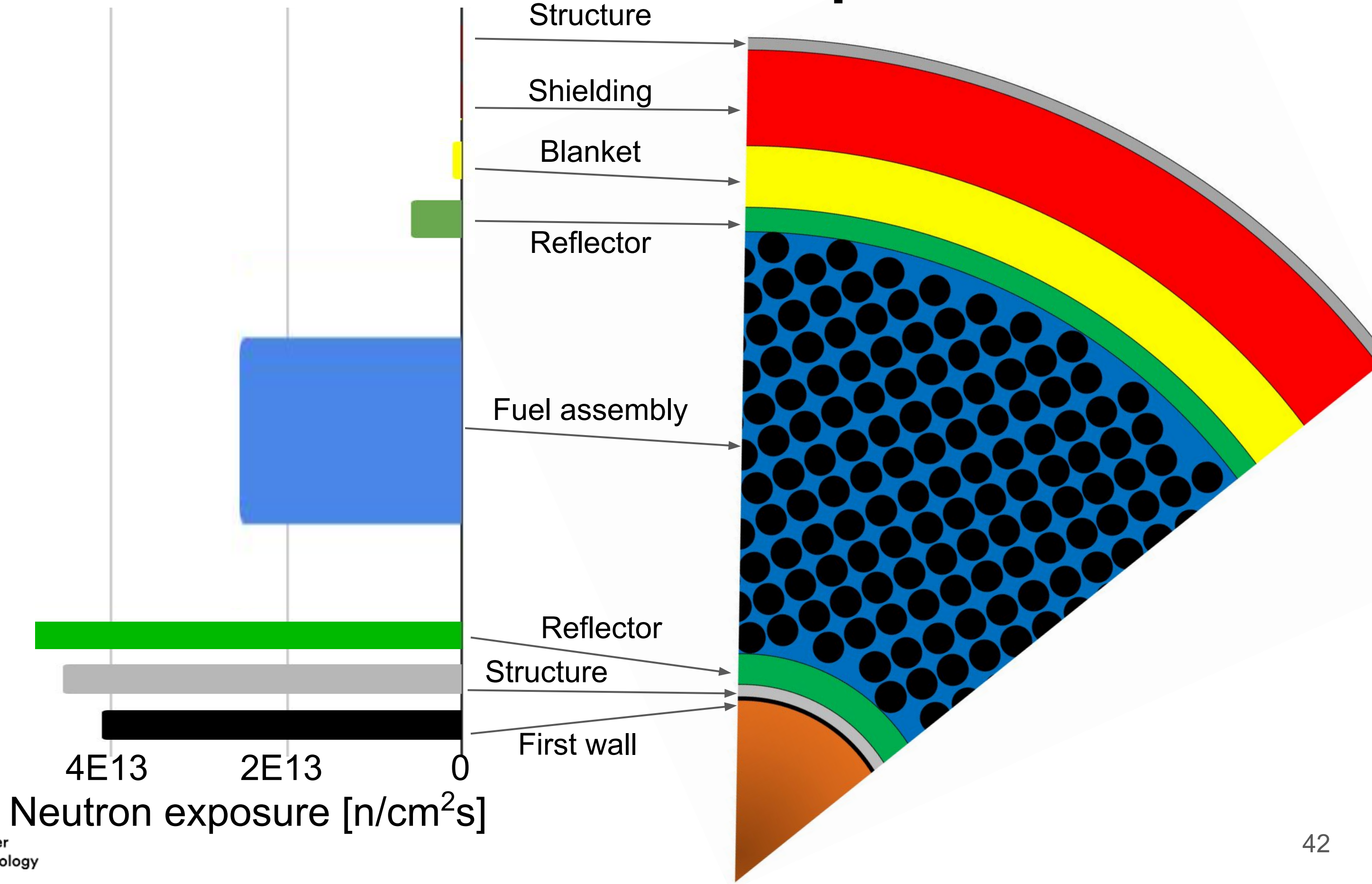


$Q_{blanket}$ time-dependence from a specialized nuclear inventory code coupled with MCNP.

X-5 Monte Carlo Team, i "MCNP - Version 5, Vol. I: Overview and Theory", LA-UR-03-1987 (2003).

J.C. Sublet, et al. FISPACTII: An advanced simulation system for activation, transmutation and material modelling, Nucl. Data Sheets 139 (2017)

Neutron exposure calculated in each component



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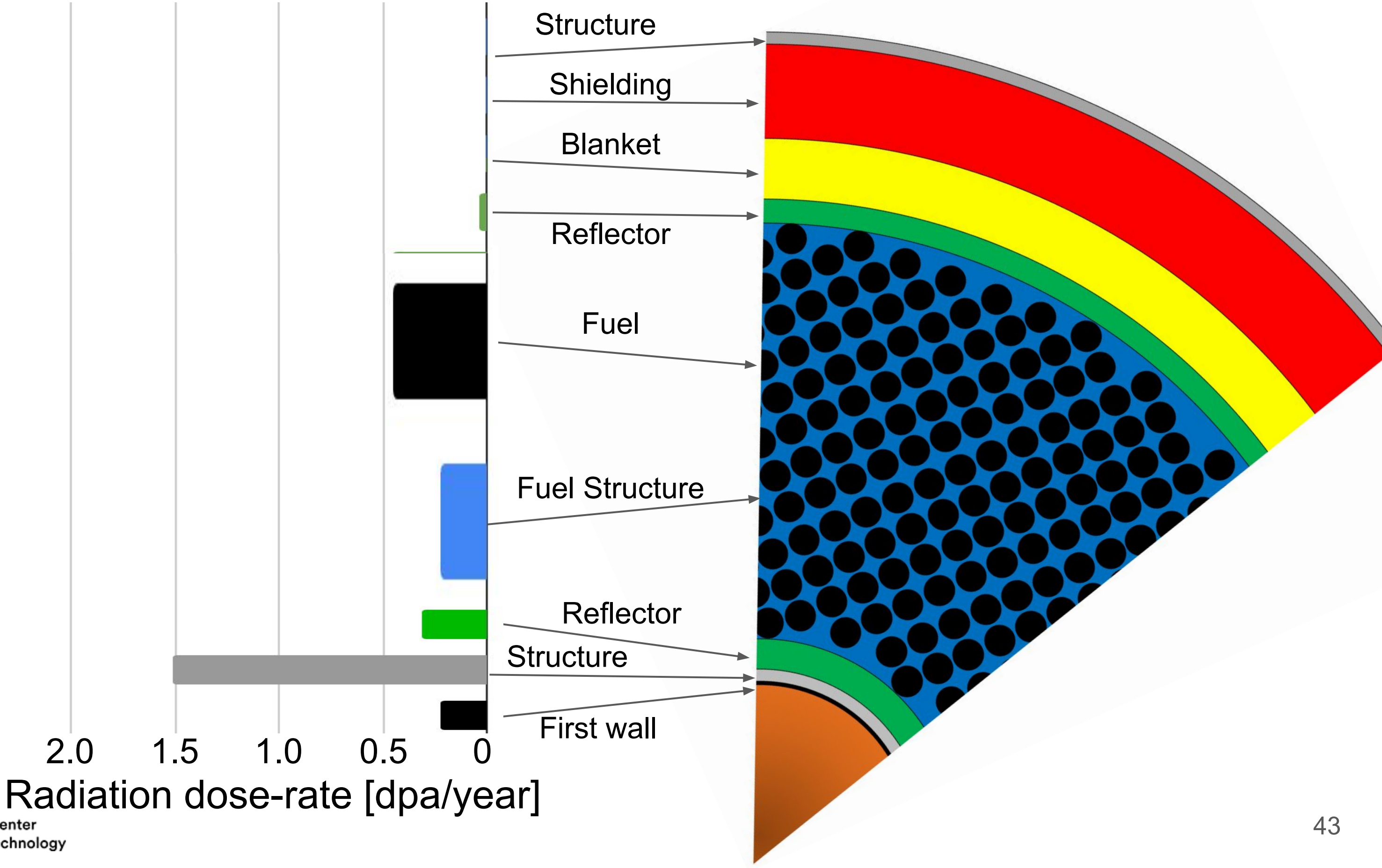
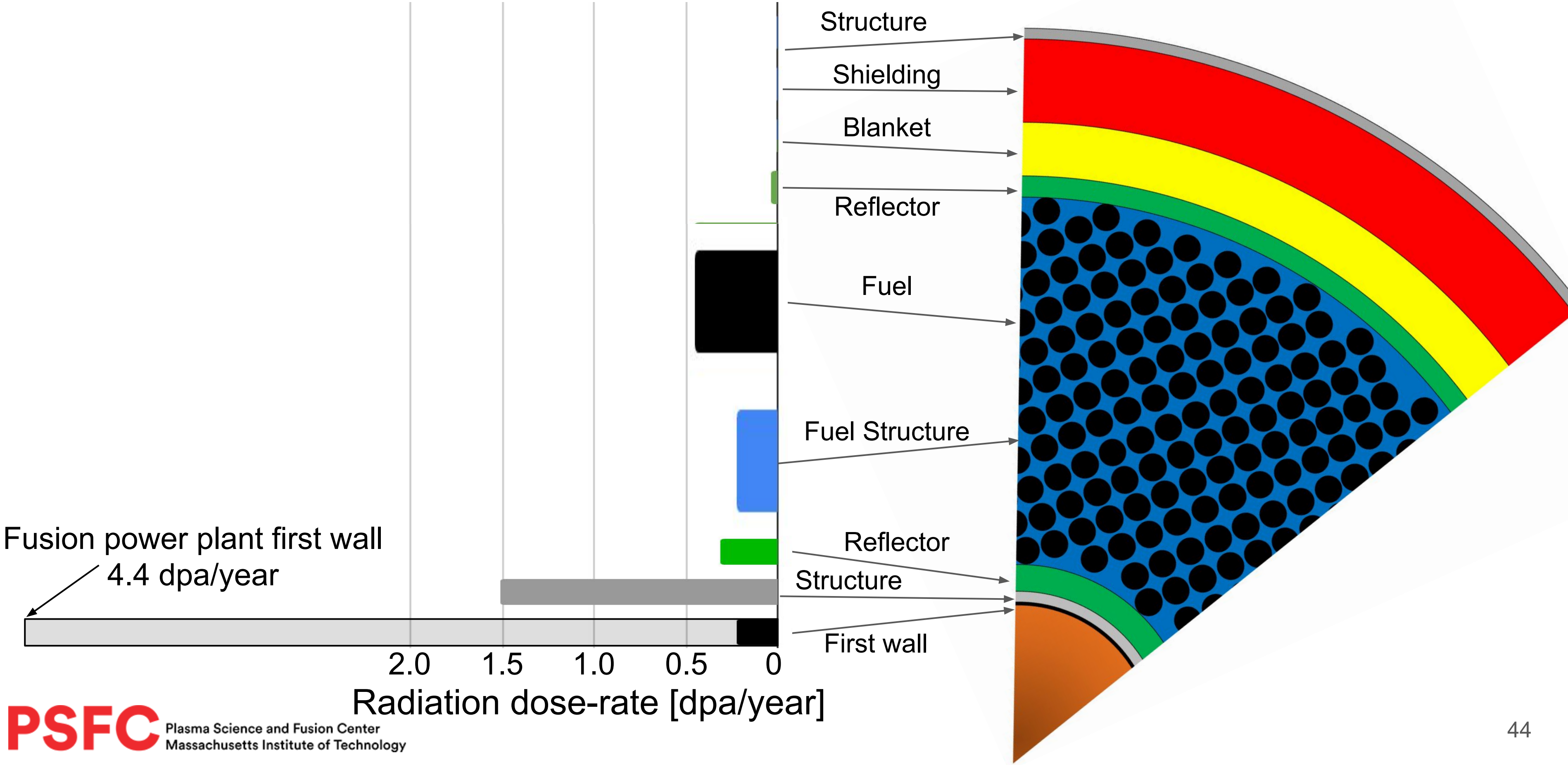
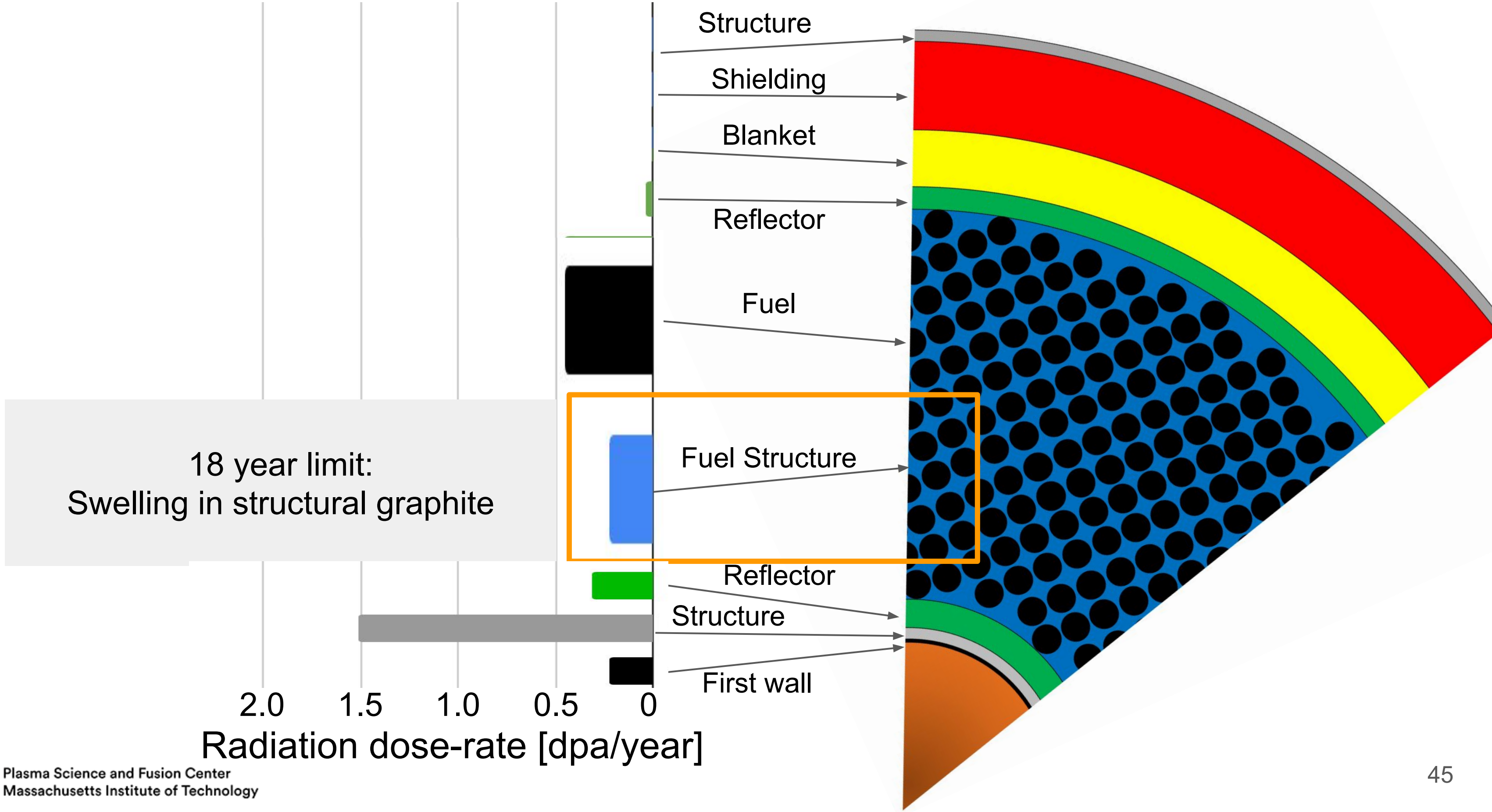
Moderate radiation damage in blanket components



Moderate radiation damage in blanket components



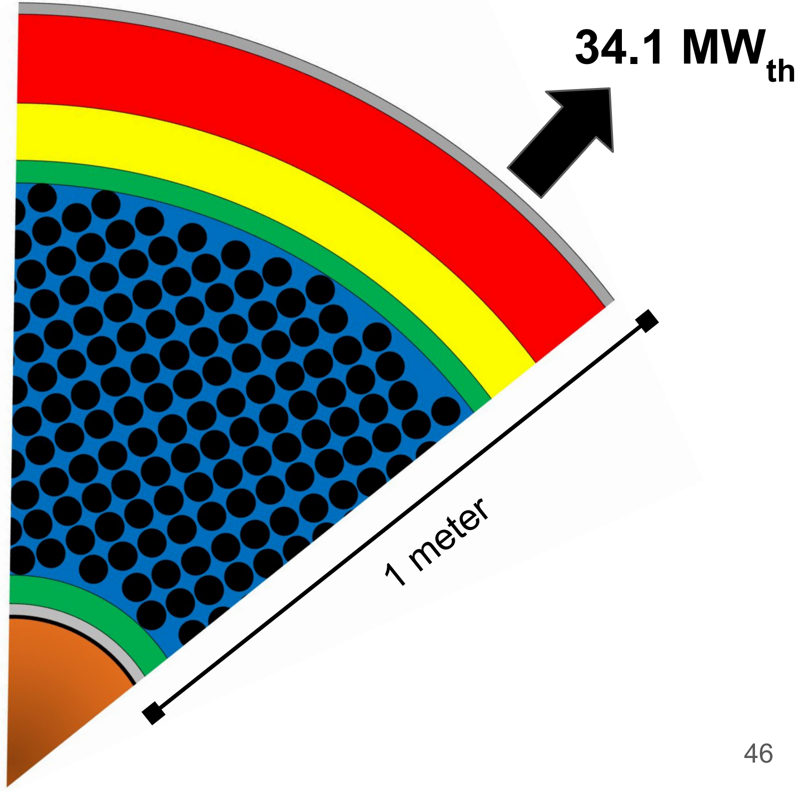
Moderate radiation damage in blanket components



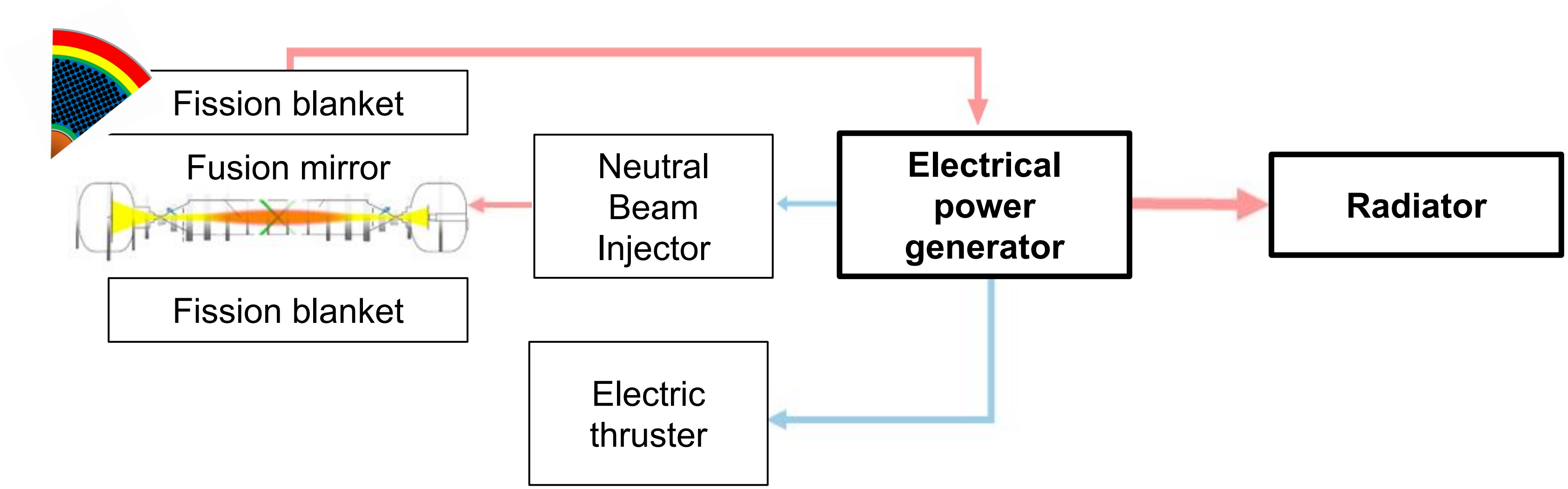
The Subcritical Fission Blanket

Metric	Success?
High $Q_{blanket}$	✅ Q=45
Subcritical	✅ $k_{eff} \cong 0.85 < 1$
TBR > 1	✅ 1.3 - 2.0
Proper Magnet Shielding	✅ Optimized for mass + power
High Output temperature	✅ 1400 Kelvin
Long lifetime	✅ 18 years

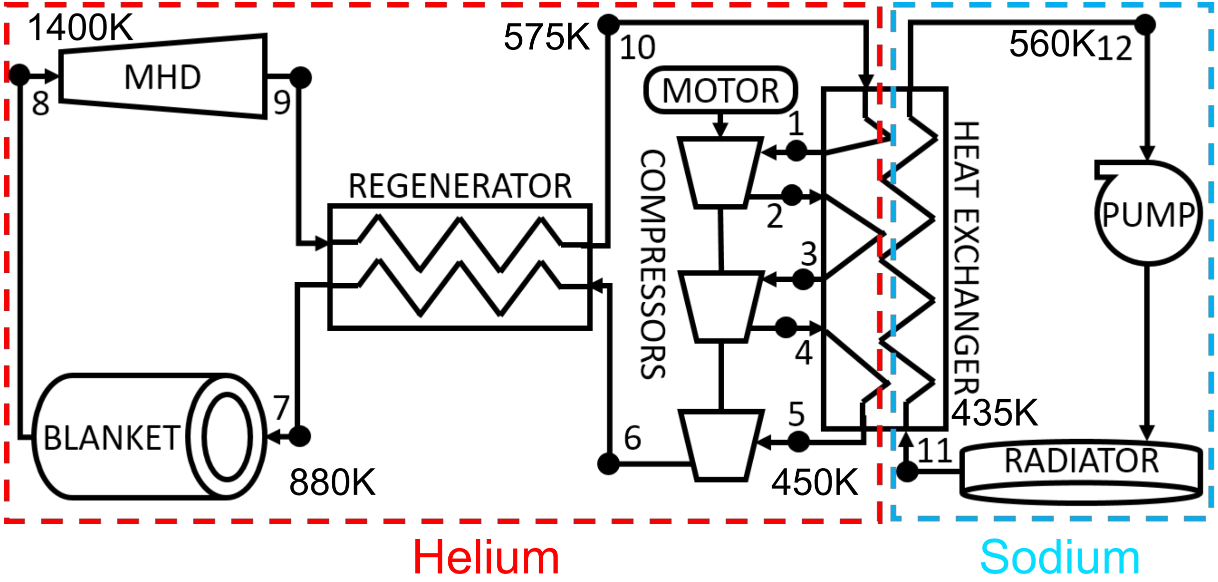
Mass/length: ~7 tons/m **Thickness**: ~1 m

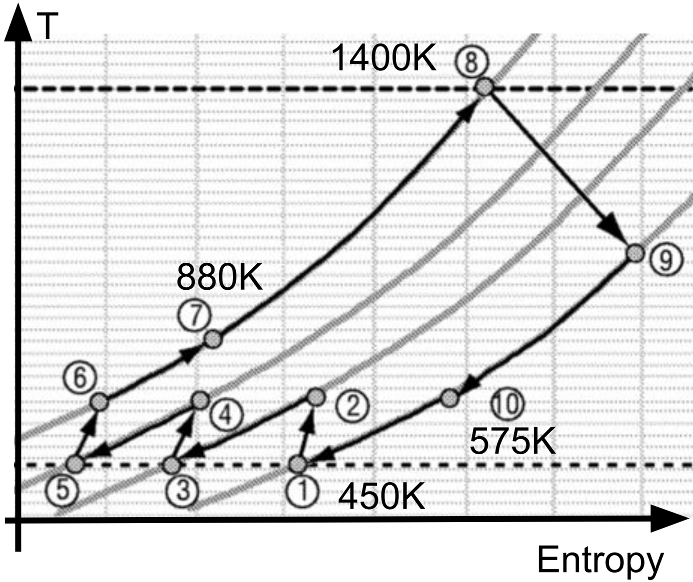


The electrical power generator and radiator



Feasible power generation system with He and Na

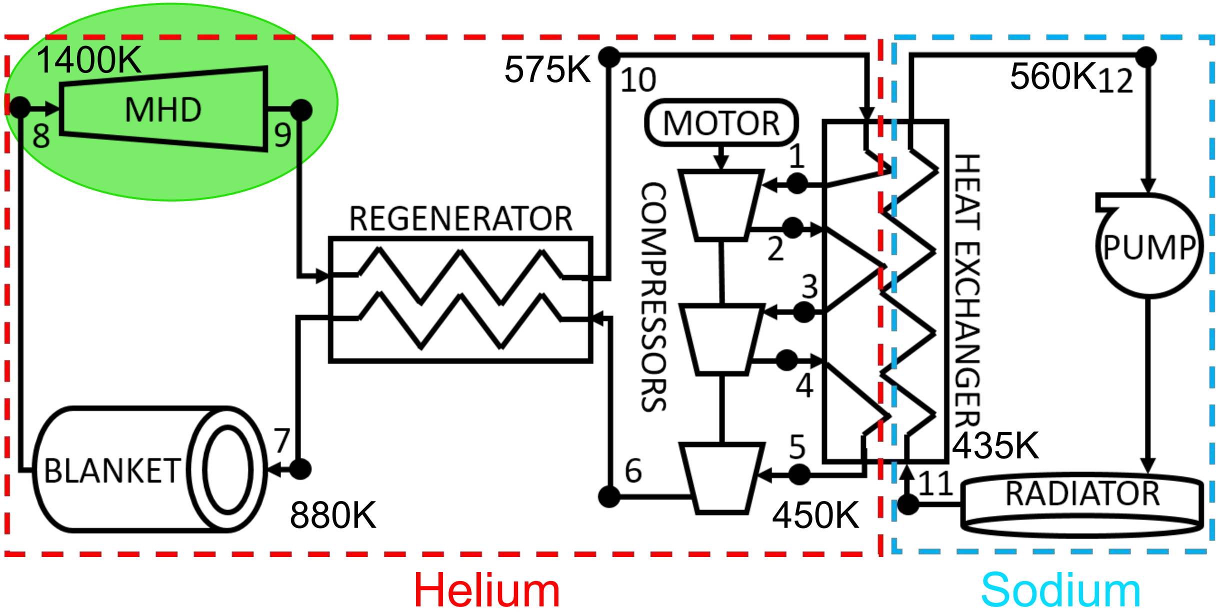


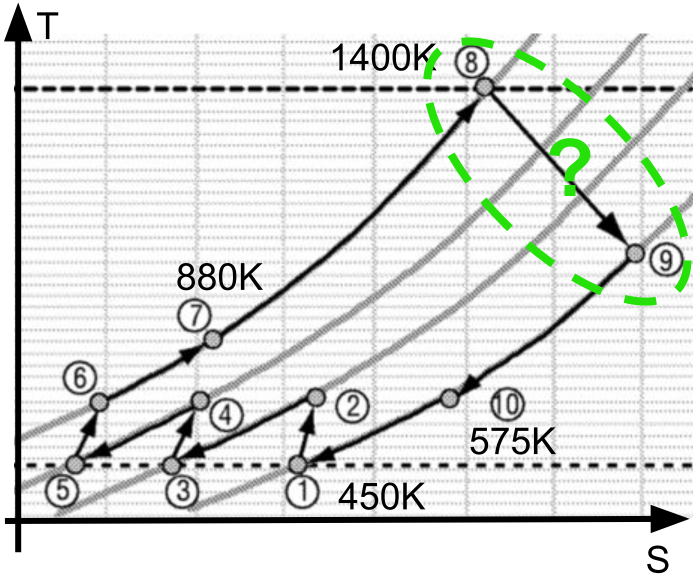


<u>Requirements:</u>

- Minimize system mass
- Make electric efficiency sufficiently high
- Accommodate thermal power up to 50 MW

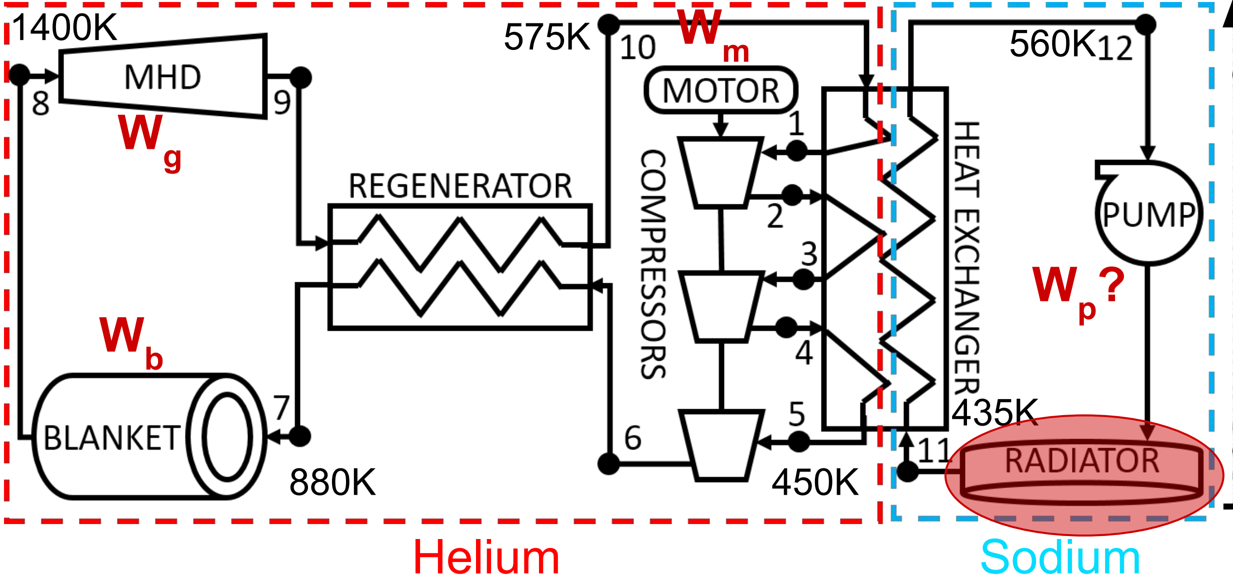
Two key components are missing: MHD generator

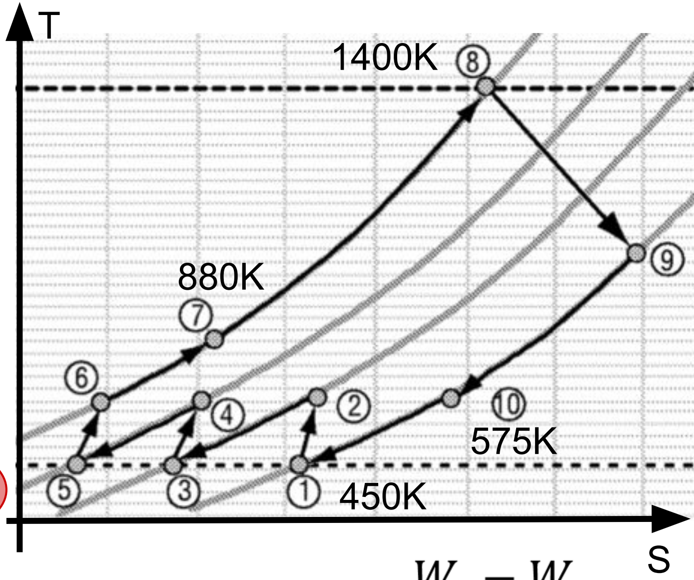




MHD generator requires modelling for thermodynamic cycle

Two key components are missing: Radiator





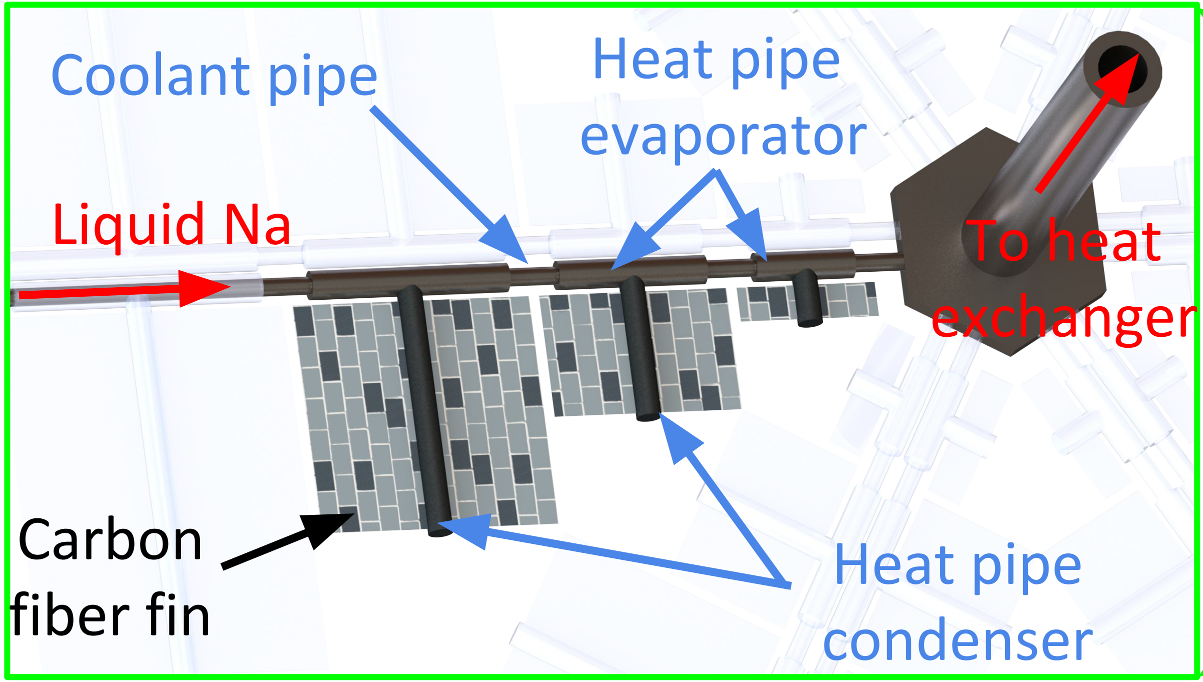
$$\eta_{th} = \frac{W_g - W_m}{W_b}$$

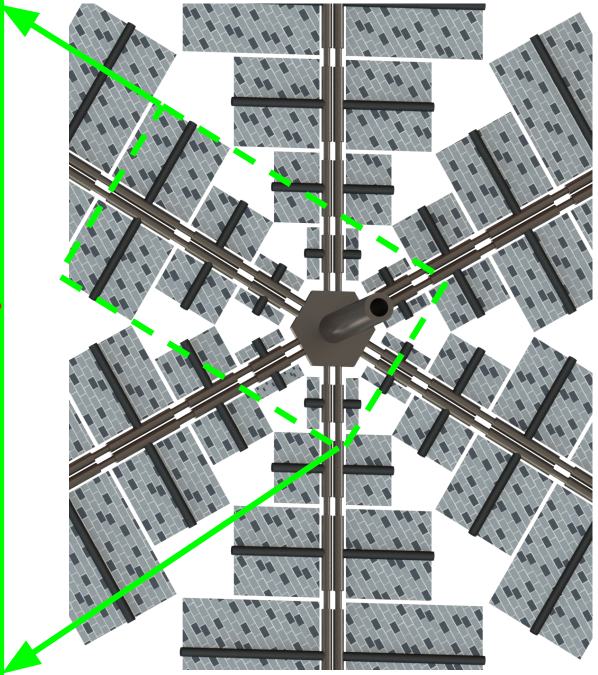
Why radiator matters?

- Accounts for a large fraction of power generation system mass
- May have substantial effects on the net electric efficiency

$$\eta_e = \frac{W_g - W_m - W_p}{W_b}$$

Rejecting multi-MW of heat in space is a challenge





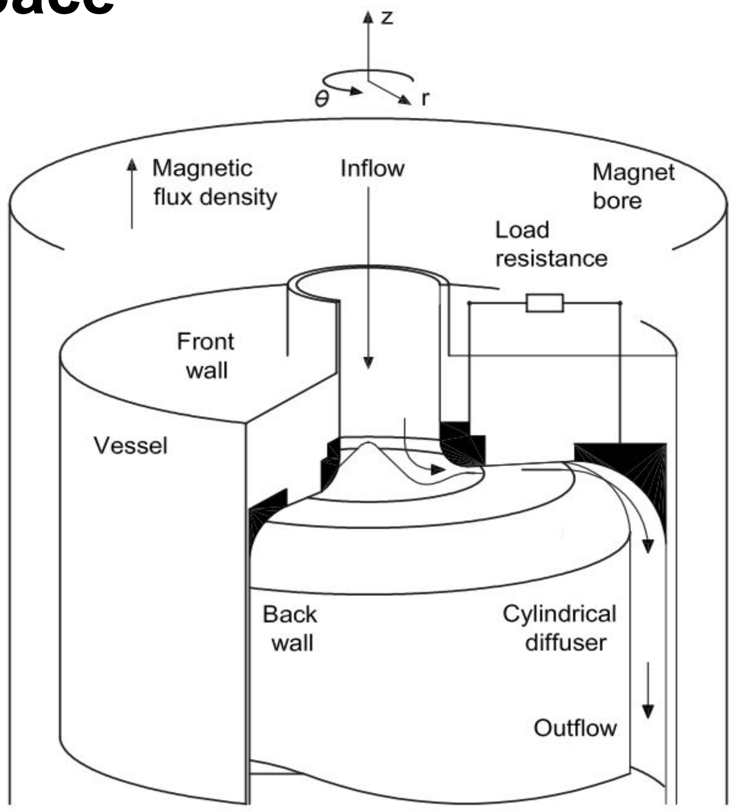
Semi-empirical iterative code to calculate the size and mass

To reject 30MW:
Area: ~15000 m^2 (3 American football fields)
Mass: ~40 tonnes (7 African bush elephants)

MHD generators scale well in space

- Hall disk MHD generator replaces turbine in standard Brayton cycle
- Seedless pre-ionization of helium gas avoids ionization instability
- Design with no moving parts can handle high T_{hot} → higher efficiency
- Requires sufficiently high β → HTS
- High power density (> 200 MWe/m^3) and low mass (~B^{-2}) → space travel

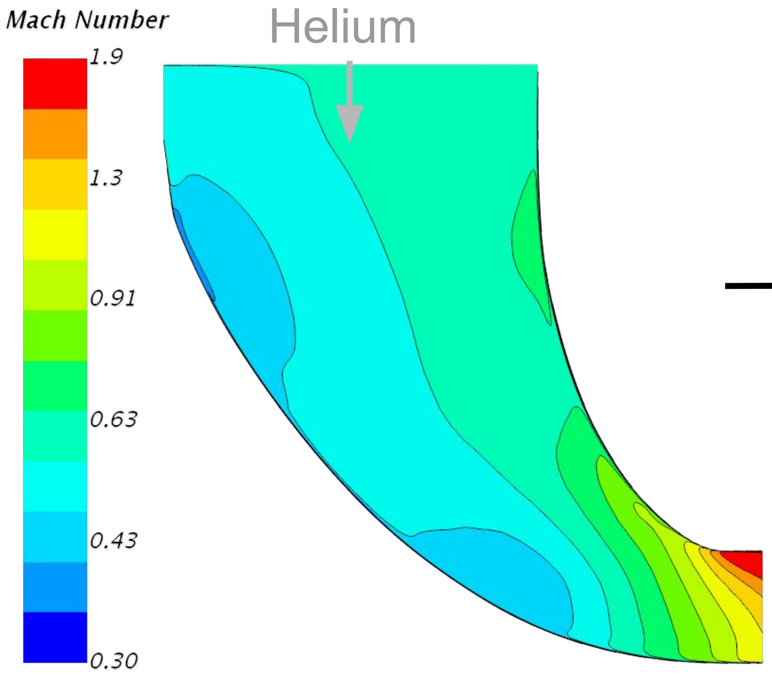
$$\vec{J} = \underbrace{\sigma(\vec{E} + \vec{v} \times \vec{B})}_{\text{Faraday current}} - \underbrace{\beta\left(\frac{\vec{J} \times \vec{B}}{|B|}\right)}_{\text{Hall current}}$$



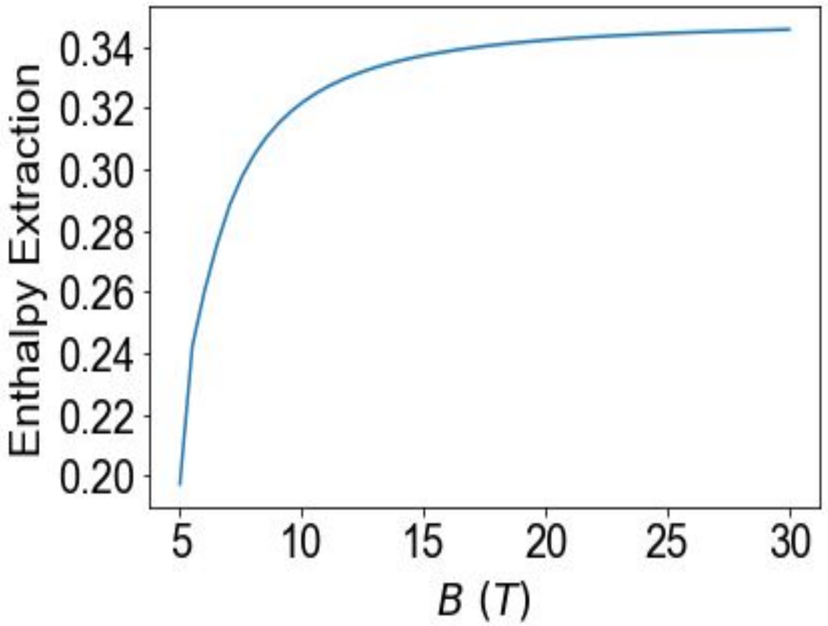
$$\beta = \frac{\text{gyrofrequency}}{\text{collision frequency}} \propto \frac{\text{B}}{\text{pressure}}$$

MHD generator simulation demonstrates saturation at 20 T

CFD Nozzle Simulation
(Boundary Condition)



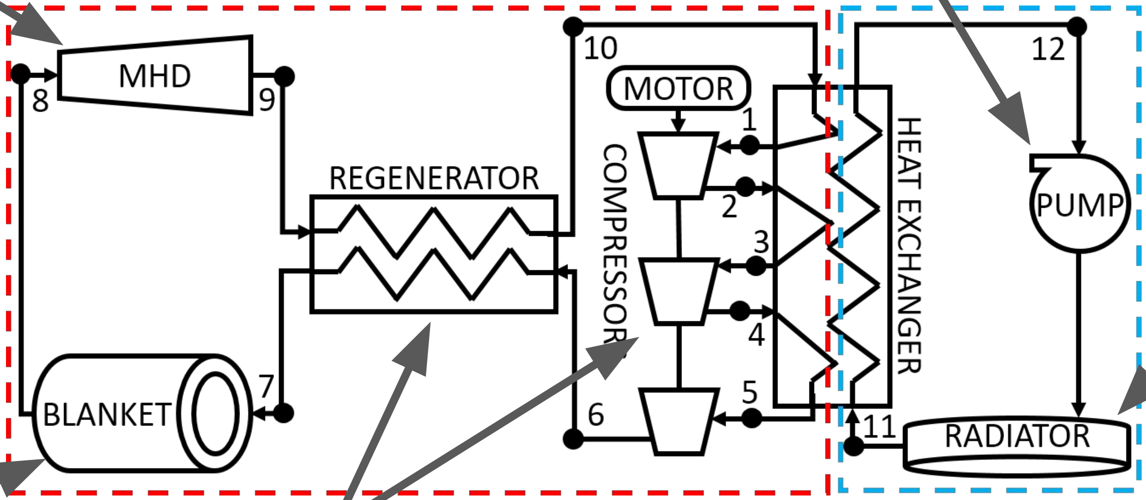
J.P. Freidberg Hall MHD Model
(Simulation of Generator)



Creation of an integrated model

J.P. Freidberg
1-D Physics Model

Semi-Empirical Power Consumption Model



Semi-Empirical Iterative Optimization Model

Blanket Group Results

Empirical Values & Scalings

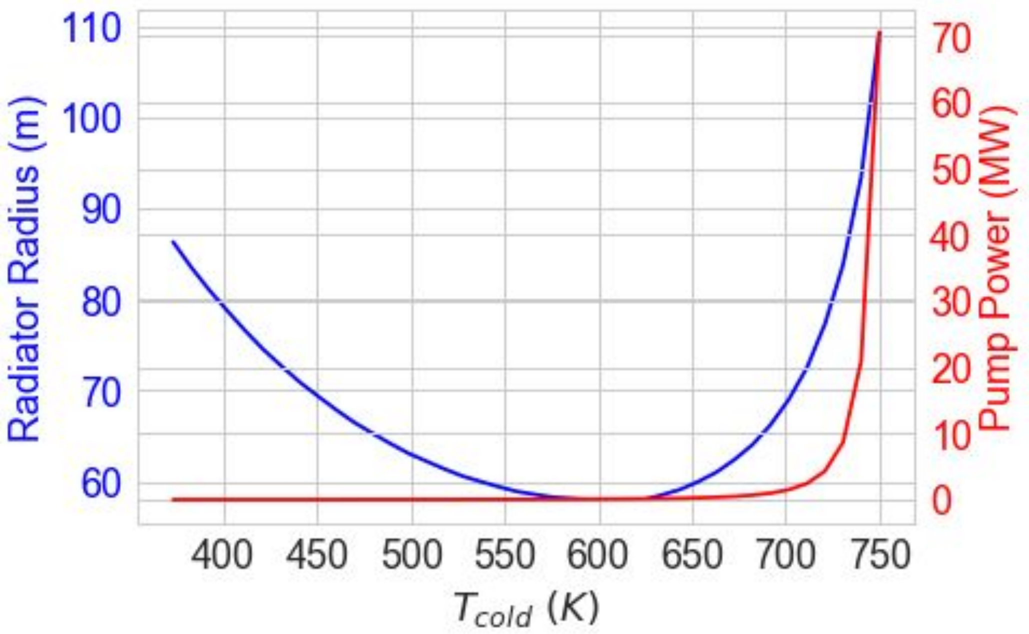
Combine all these modelling tools into one self-consistent thermodynamic model to optimize balance of plant systems

Set constraints on model to begin optimization

Need to find optimization point.
Constrained parameters:

- P_{ele}: 12.5 MW
- T_{hot} :1400 K (Blanket Max)
- Generator B-field: 20 T (Efficiency Saturation)
- $T_{cold} > T_{freeze} = 372$ K

Vary T_{cold} to find additional design limits

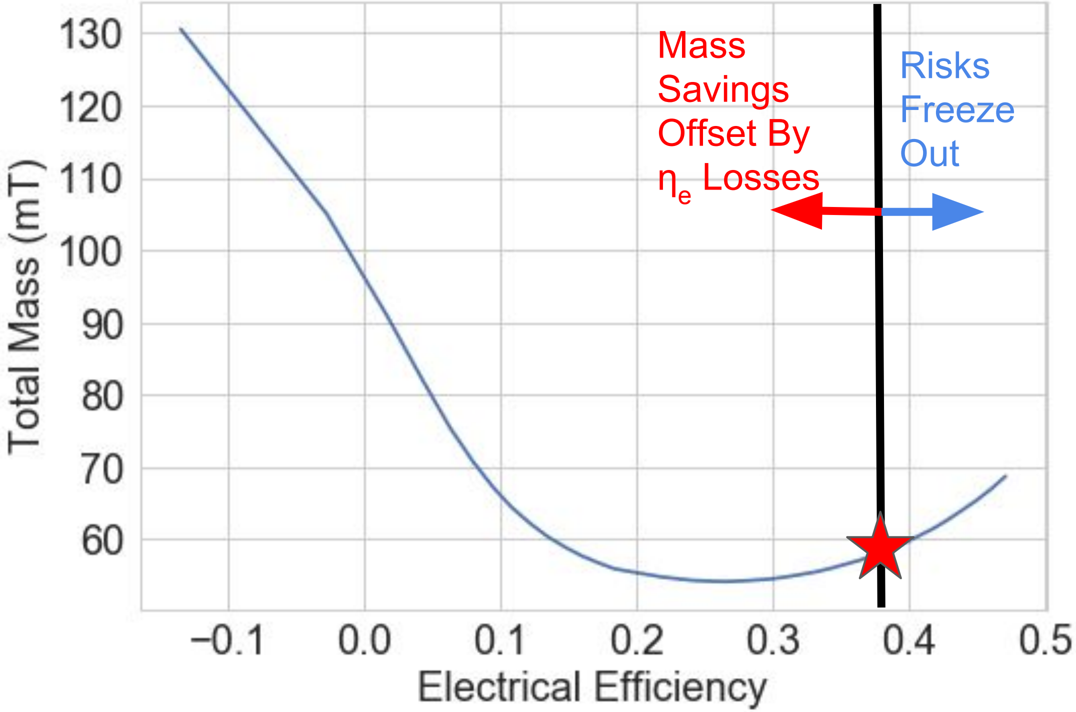


Radiator Size and **Pump Power** blow up at high T_{cold}!

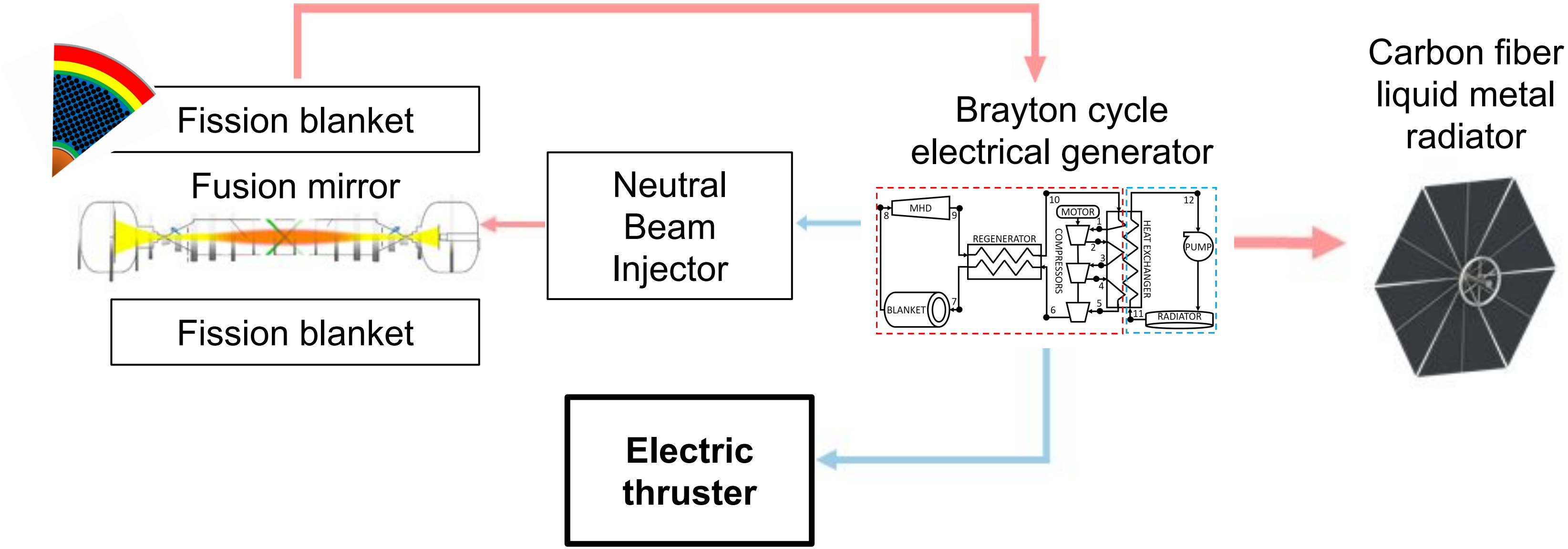
Obtain mass/efficiency curve and select design point

Design point near global minimum obtained that satisfies all system constraints:

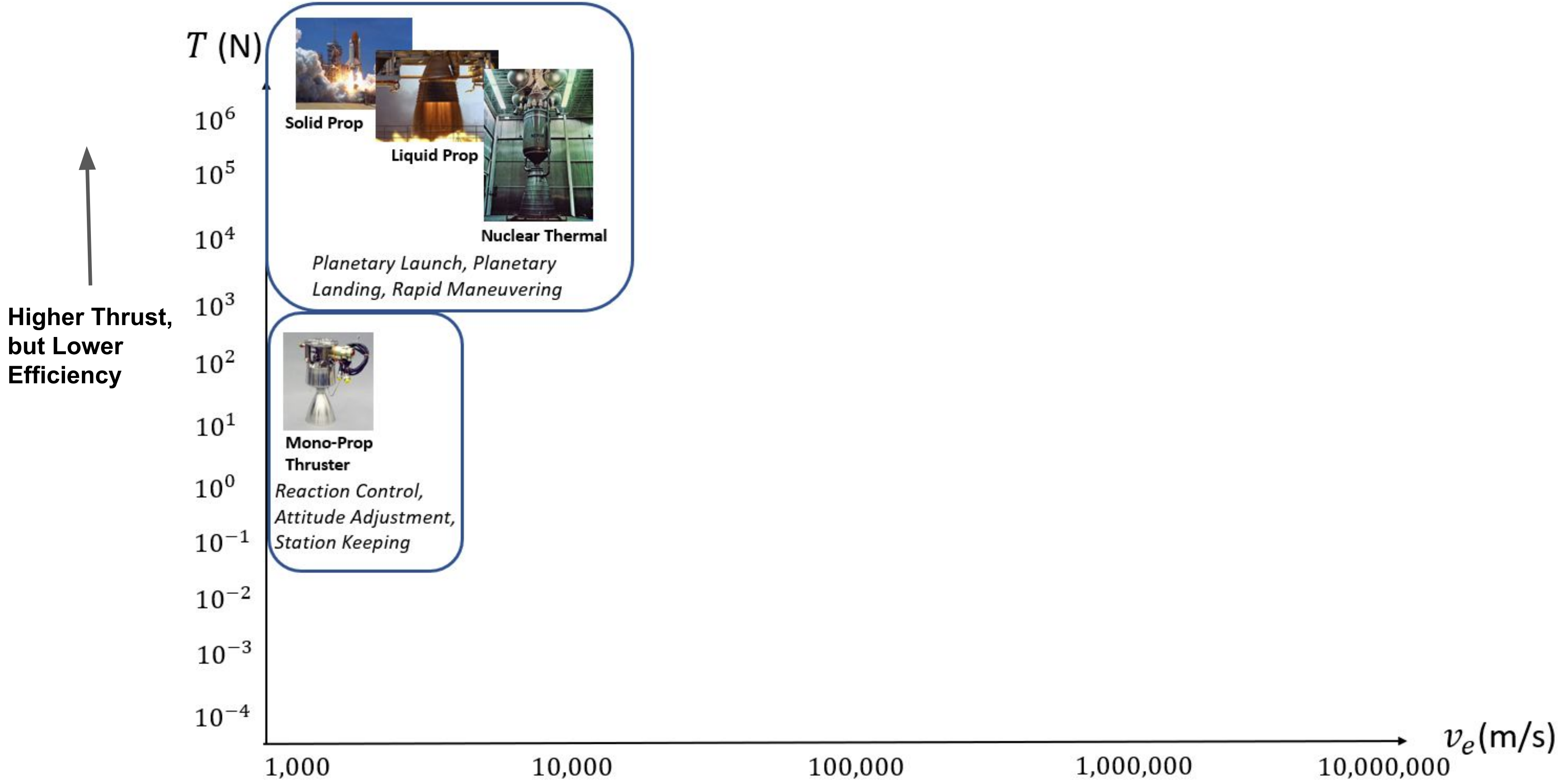
- **$P_{electric}$: 12.5 MWe**
- **T_{hot}: 1400 K**
- **T_{cold}: 450 K**
- **B-field: 20 T**
- **η_e: 0.37**
- **Mass: 59mT**



What propulsion do we use?



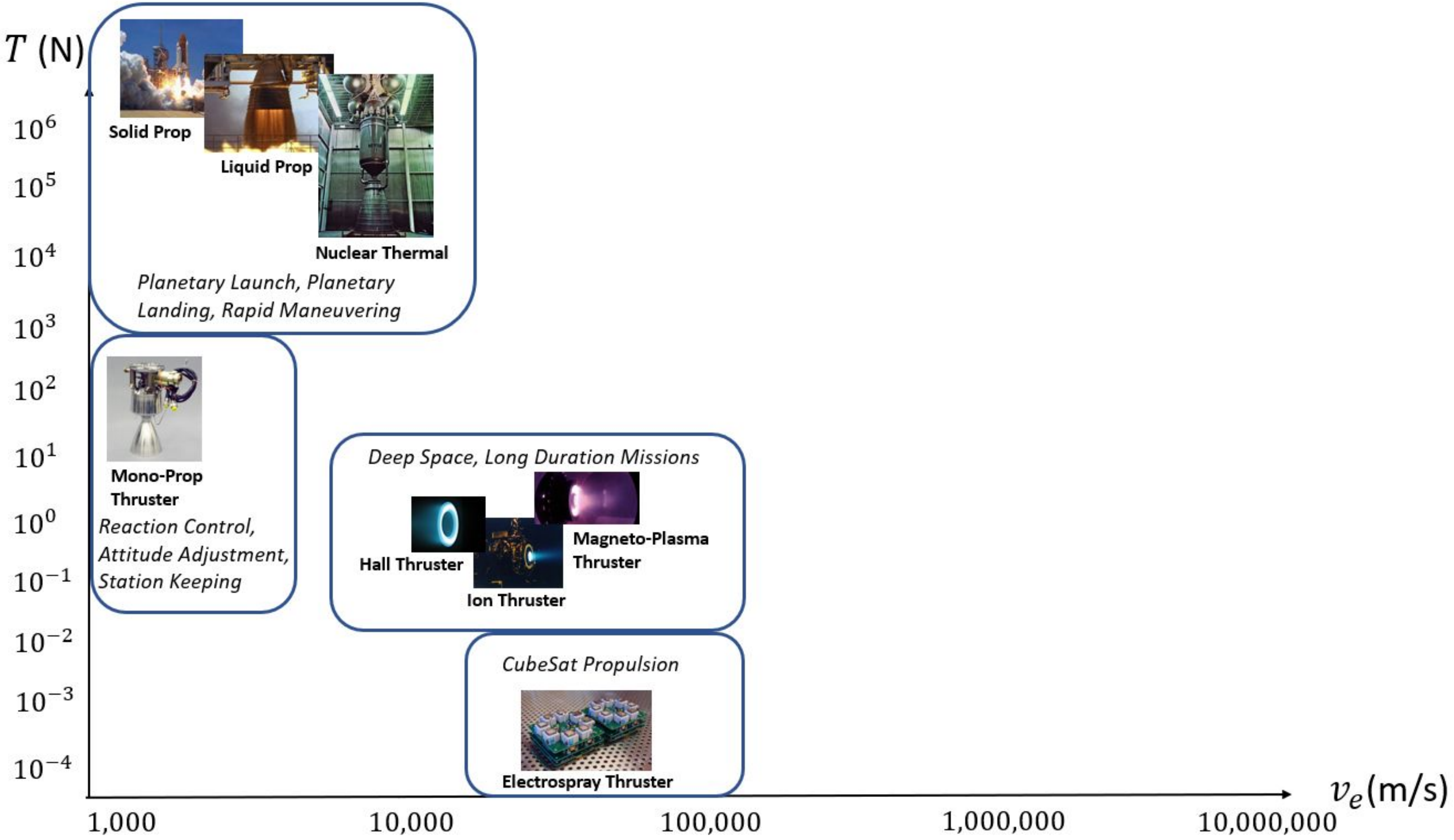
Finding the right propulsion system



Higher Efficiency, but Higher Power Requirement

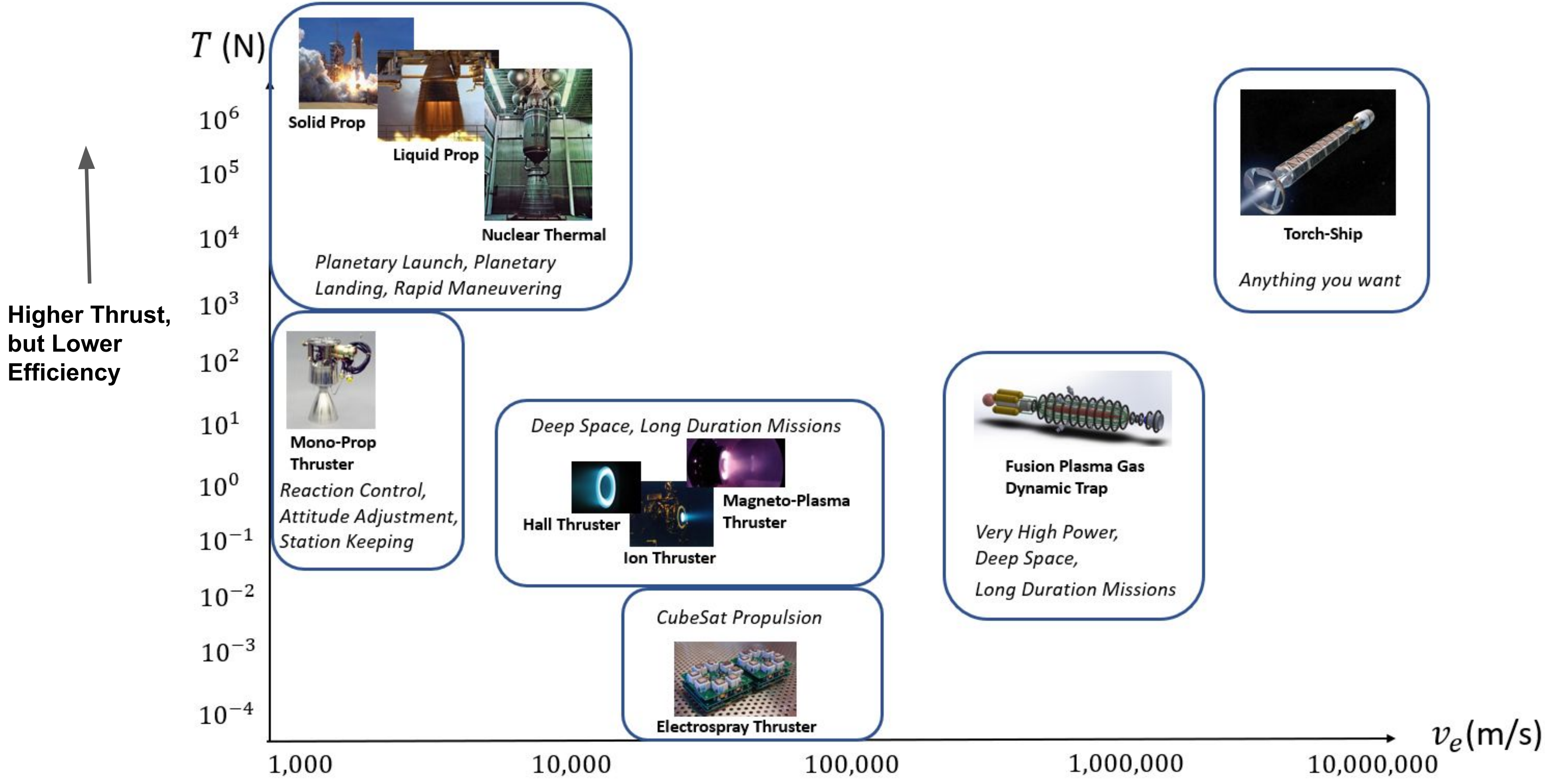
Chemical is out, but traditional plasma thrusters are too small

Higher Thrust, but Lower Efficiency



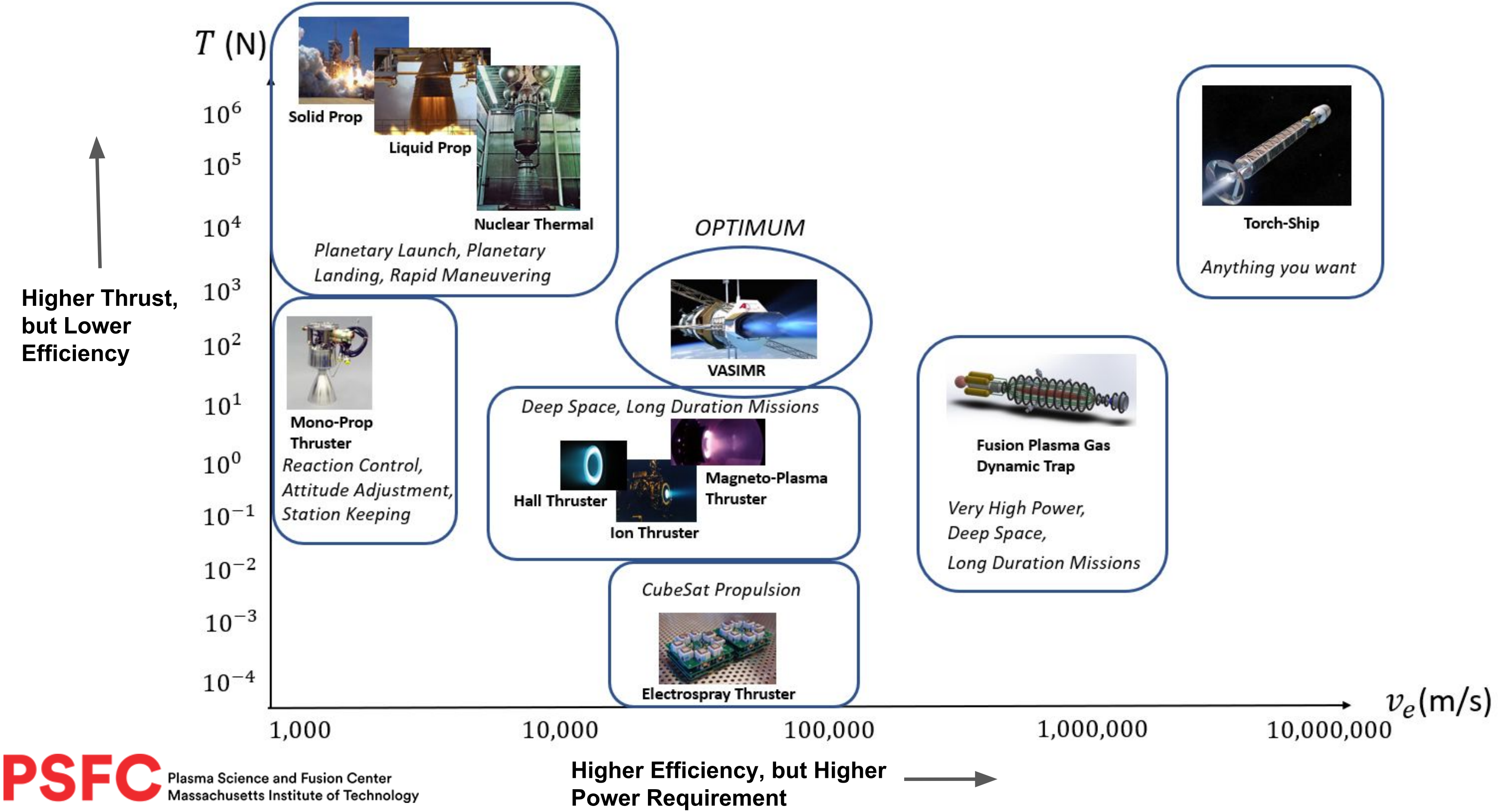
Higher Efficiency, but Higher Power Requirement

Too much power - Can’t launch a GW+ power plant into space



Higher Efficiency, but Higher Power Requirement →

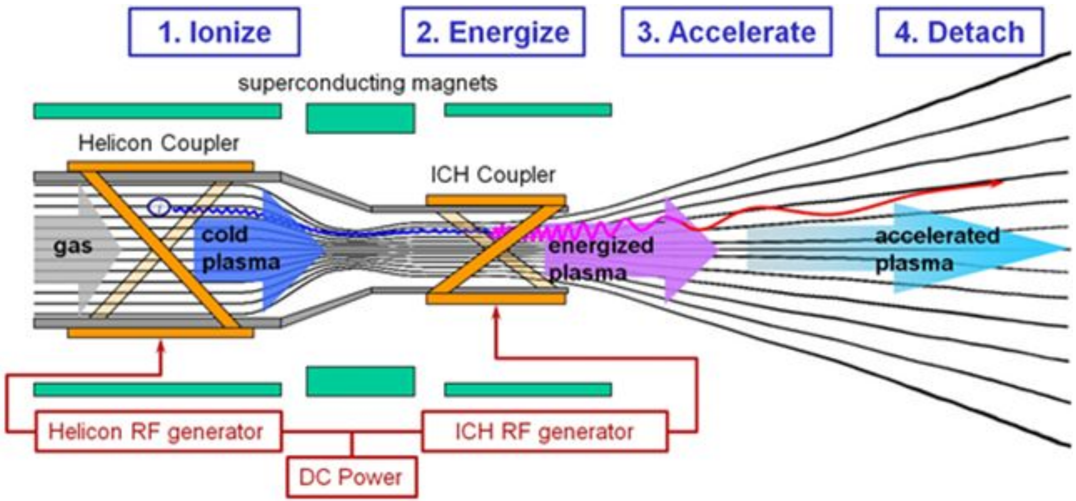
VASIMR is the right choice



Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

Electromagnetic Thruster with **no electrodes** and **variable v_e**

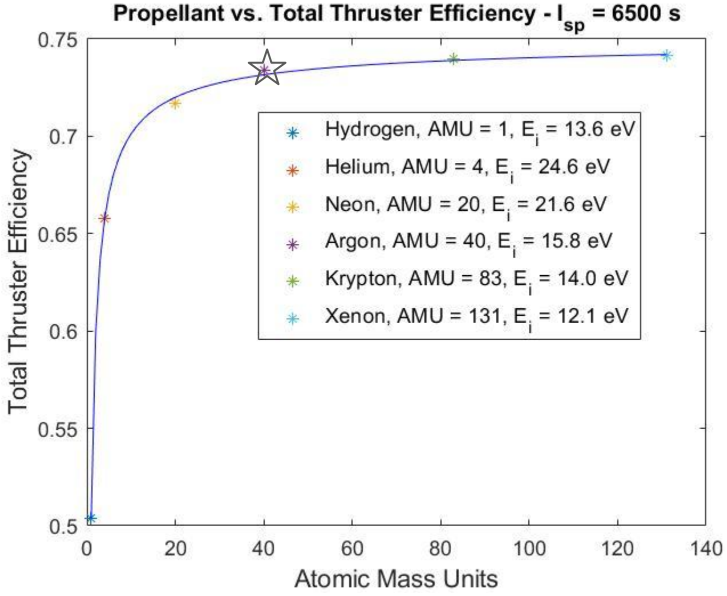
- **Stage 1:** Helicon Coupler to create plasma discharge
- **Stage 2:** ICRH Coupler to heat plasma
- **Stage 3:** Expand through magnetic nozzle

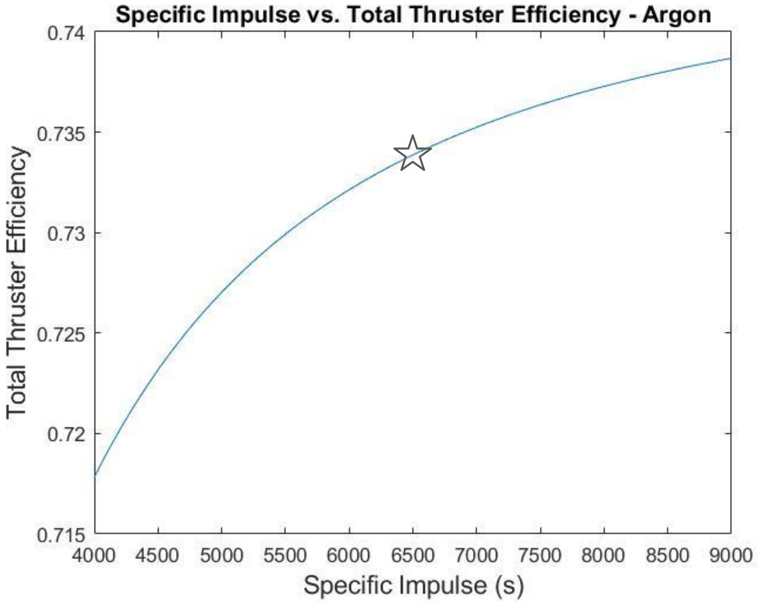


VASIMR® operation diagram. Credit & Copyright: Ad Astra Rocket Company © all rights reserved

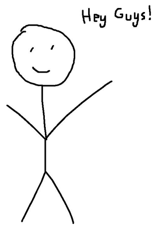
VASIMR Meets Performance Requirements

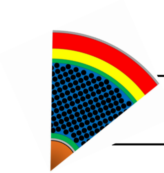
Mass [mT]	Number of Thrusters	Magnetic Field [T]	Propellant	RF Coupling Efficiency	Nozzle Efficiency	Overall Thruster Efficiency	Total Power [MW]	Thrust Power [MW]
10.8-12.2	2-5	2	Argon	0.74	0.93	0.73	8.3	6





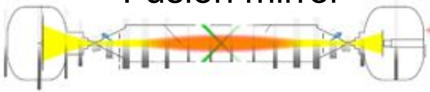
What about the humans?





Fission blanket

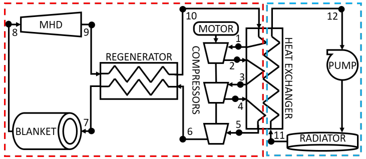
Fusion mirror



Fission blanket

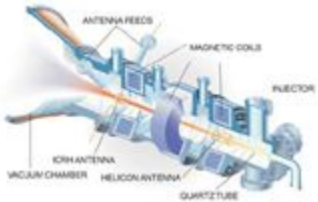
Neutral Beam Injector

Brayton cycle electrical generator



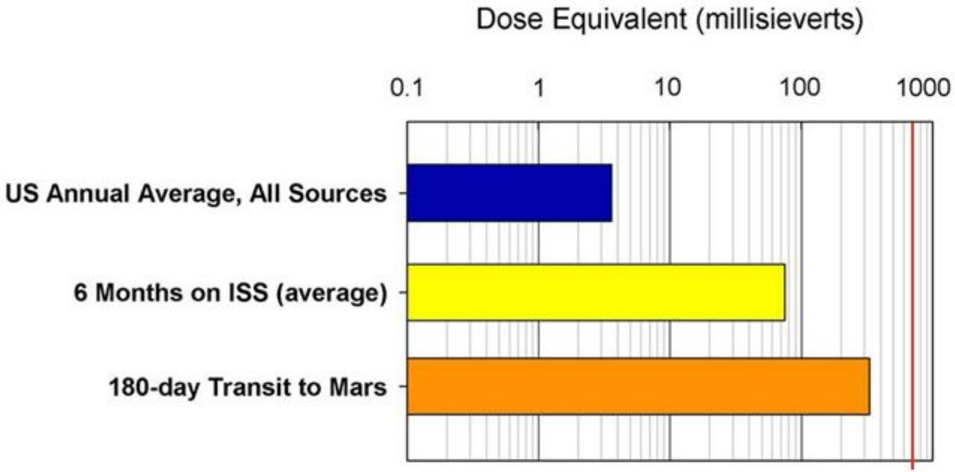
Carbon fiber liquid metal radiator

VASIMR thruster



Radiation hazards in space

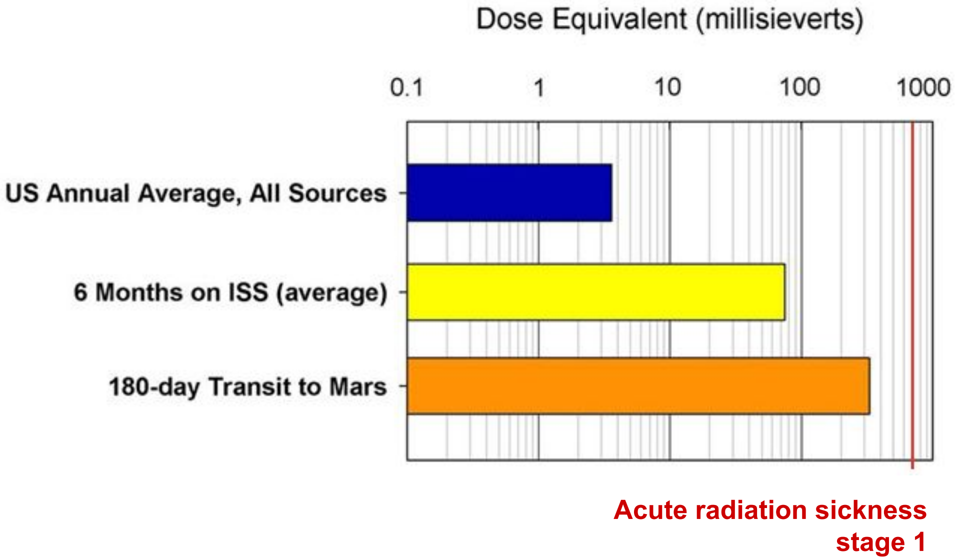
- Average annual radiation dose to a US citizen is 6.2 mSv.
- One year in space will give dose of 609 mSv. **A factor of 100 more dose!**



Acute radiation sickness stage 1

Radiation hazards in space

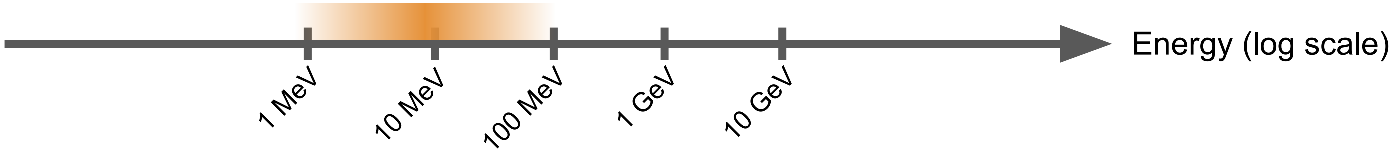
- Average annual radiation dose to a US citizen is 6.2 mSv.
- One year in space will give dose of 609 mSv. **A factor of 100 more dose!**
- NASA places a Career Dose limit for a 25 year old woman astronaut at **550 mSv**.
- Acute Radiation Sickness onsets at **700 mSv**. Using as a secondary limit, but low dose rate should prevent this anyways.



Radiation hazards in space

Solar energetic particles

- Dangerous ones occur ~4 times/year
- Unshielded 1-day dose is fatal



Radiation hazards in space

Solar energetic particles

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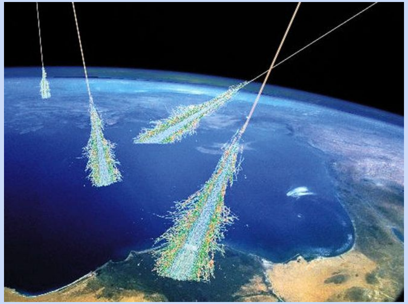
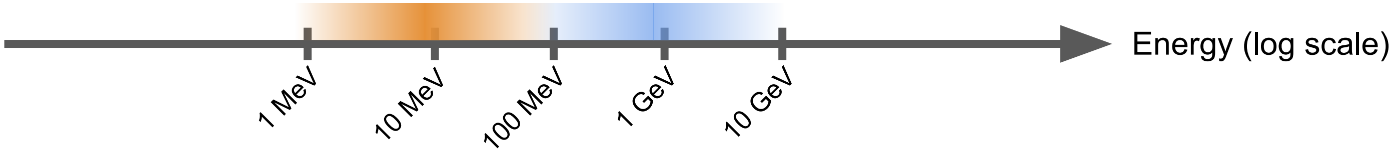
- Unshielded 1-day dose is fatal

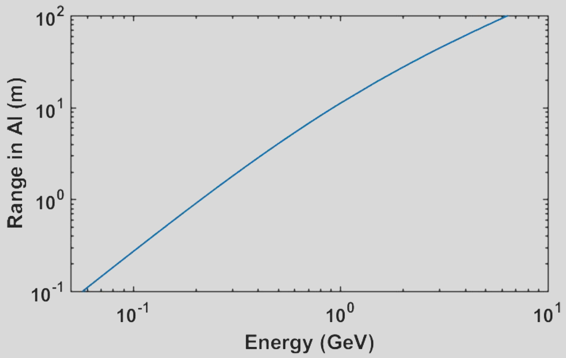
Galactic cosmic rays



- Relatively constant flux
- Unshielded 1-year dose is near max permissible



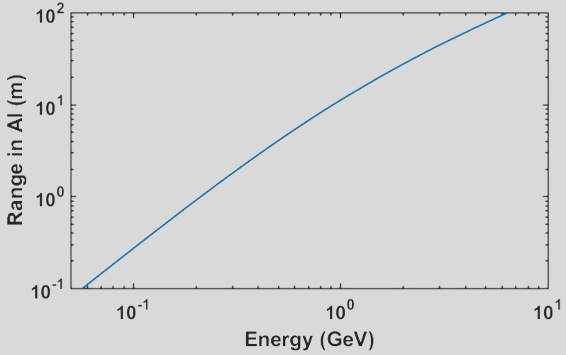
Materials alone can't shield crew from high-energy ions



Mass shielding

- Very large masses required
- Dangerous secondary particles produced during passage through shielding

Materials alone can't shield crew from high-energy ions



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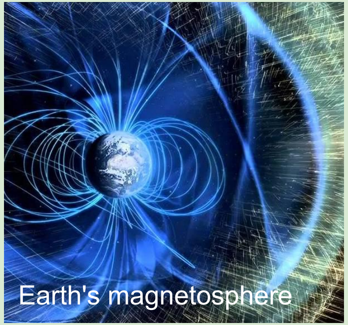
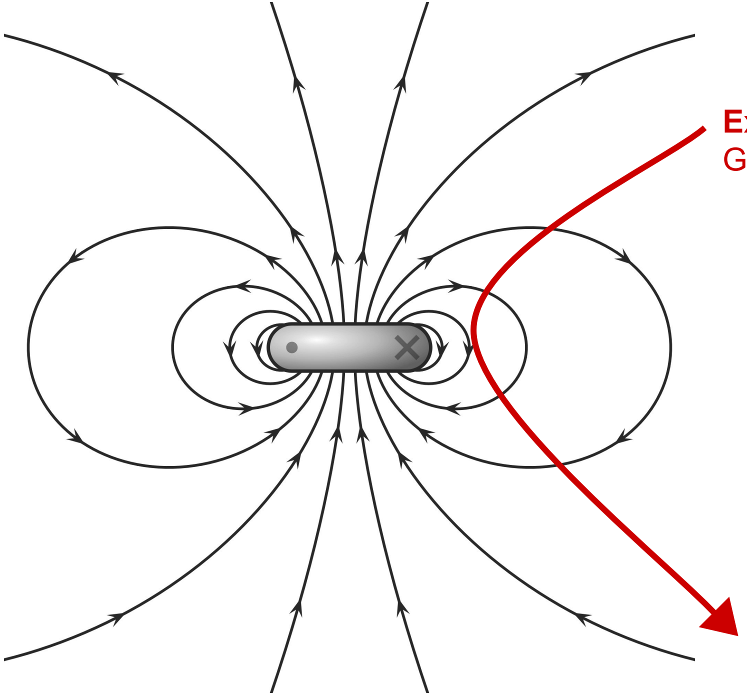


Magnetic shielding

- Deflect high-energy ions to avoid dangerous secondary particles
- High fields using HTS may be beneficial

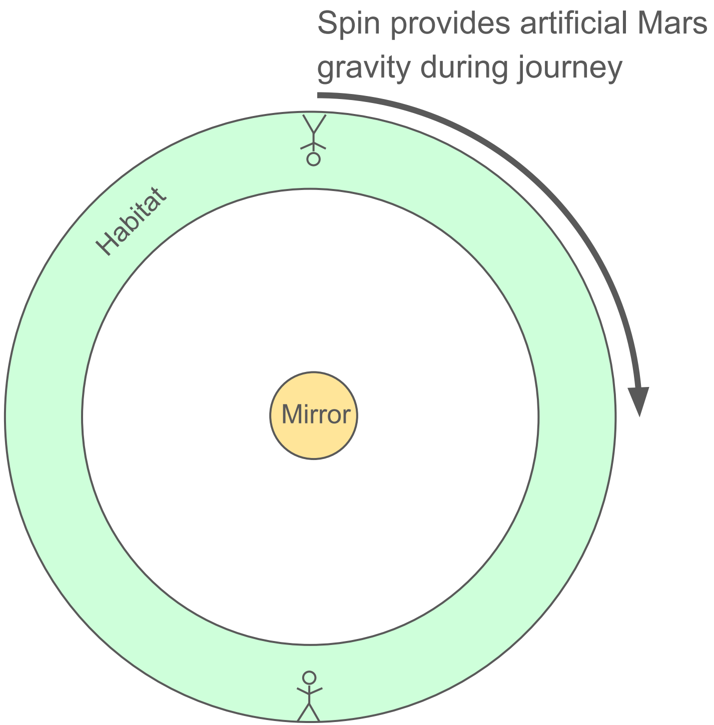
A dipole field using HTS could shield from cosmic ions



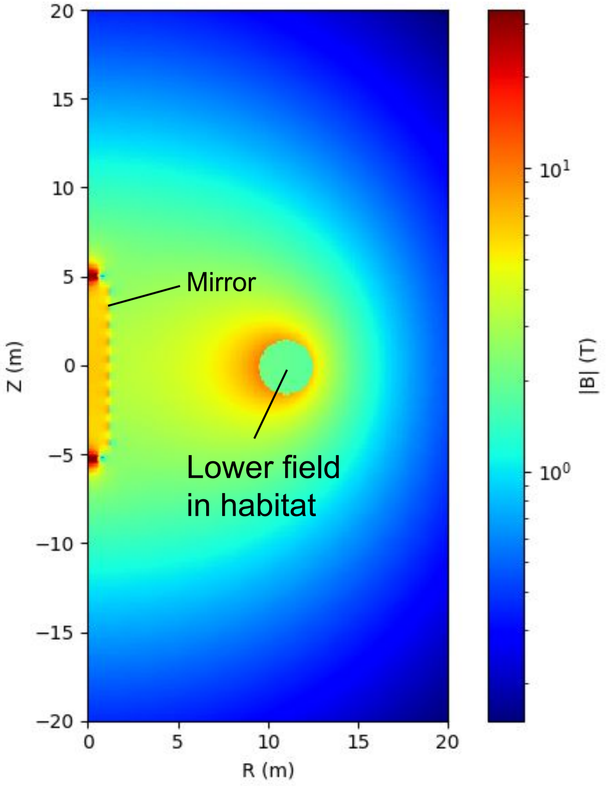
Dipole magnetic field

A toroidal habitat is good for astronaut health

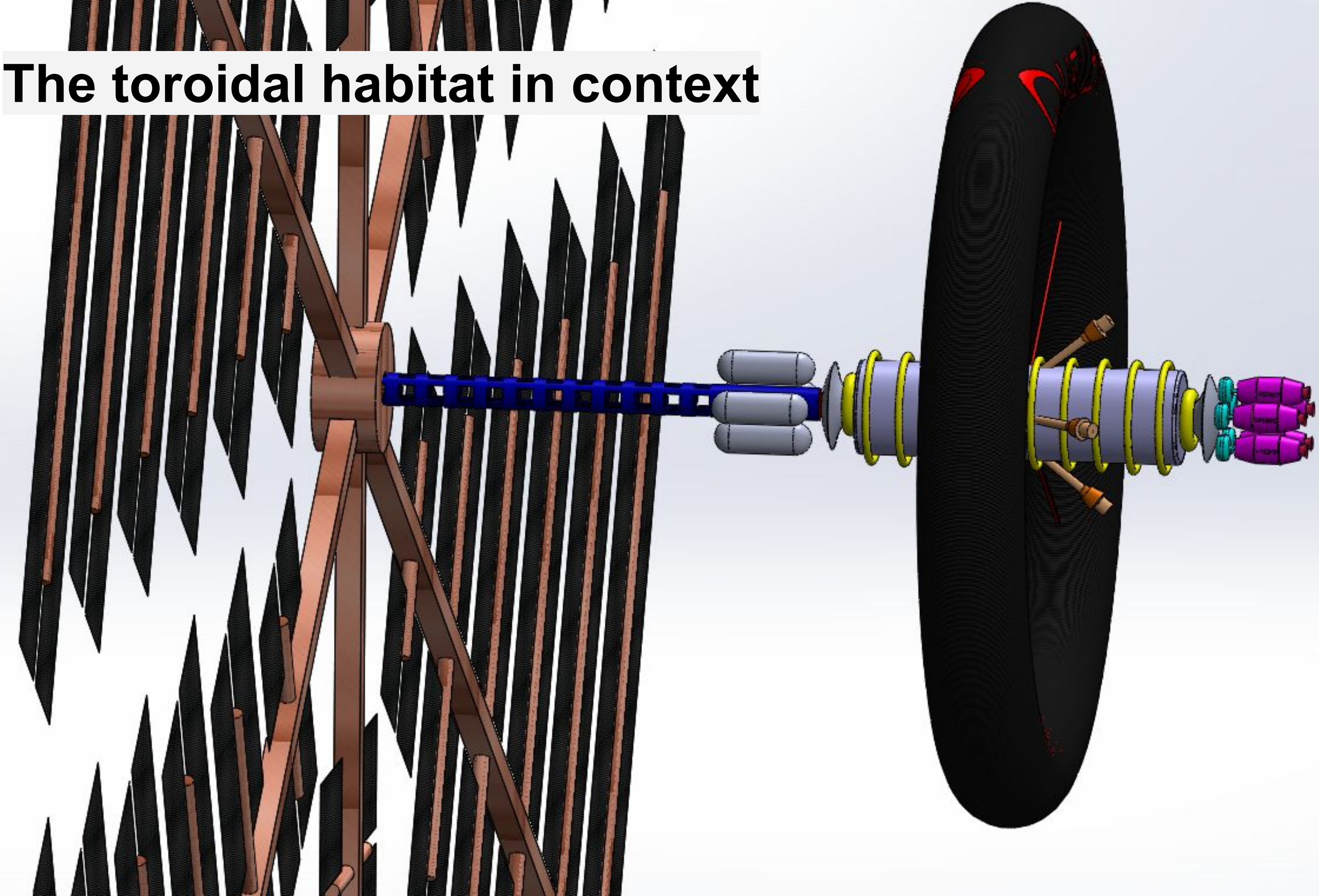
Top view



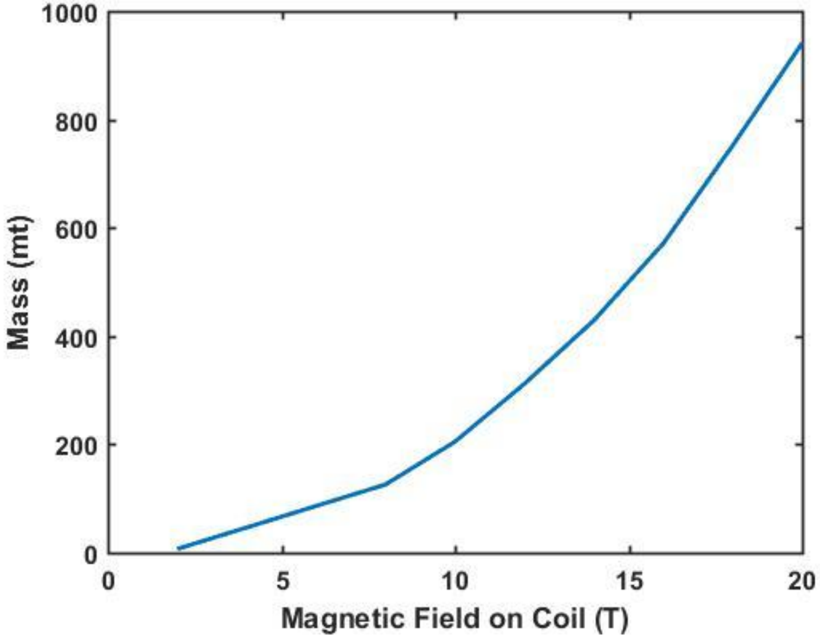
Cross section



The toroidal habitat in context



Magnetic shielding can be heavy

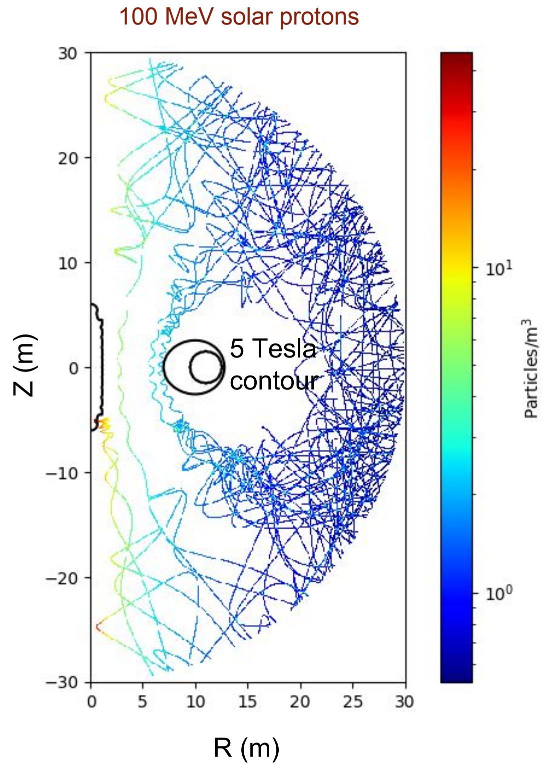


- Magnetic field is created by HTS wound toroidally around the habitat.
- Carbon Fiber support structure layered on top of HTS.

Magnetic shielding will protect from solar protons

Created a Monte Carlo simulation of ions approaching the dipole magnetic field (no material interactions included in simulation)

Effect of 10 Tesla habitat magnets on particle fluxes



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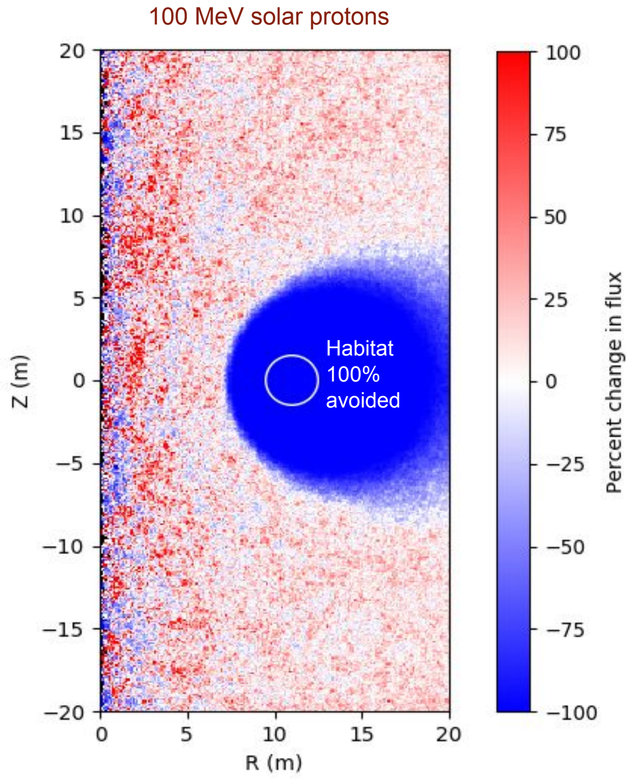
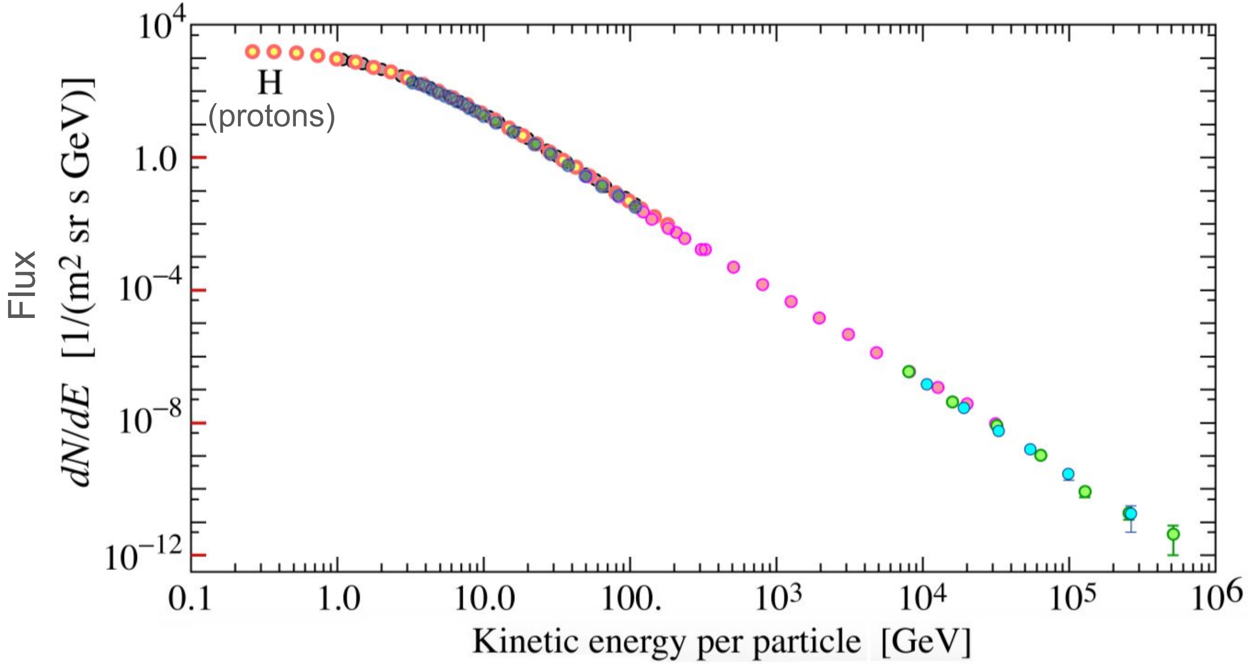


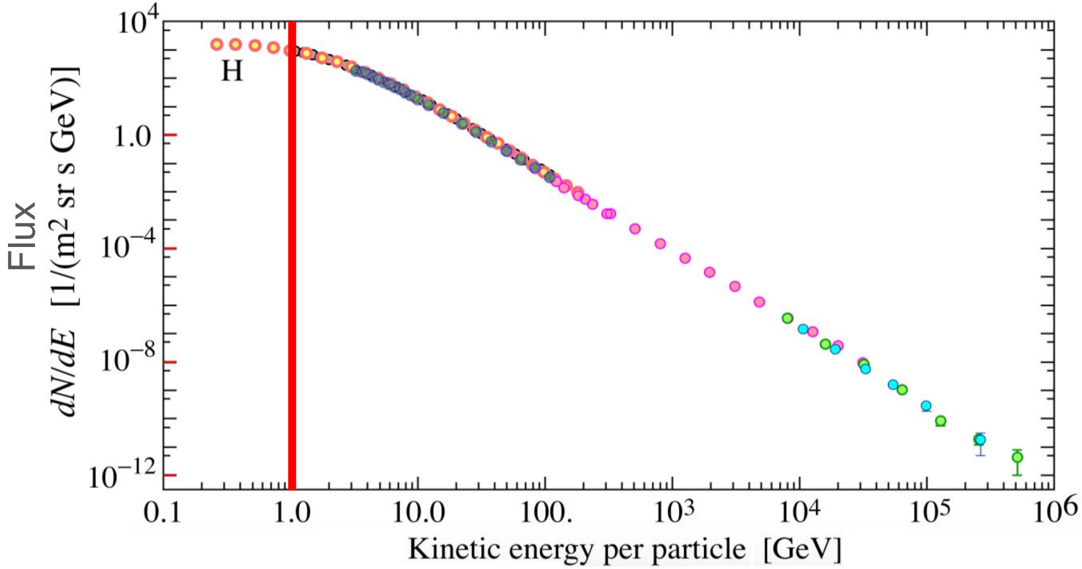
Cosmic protons can be highly energetic

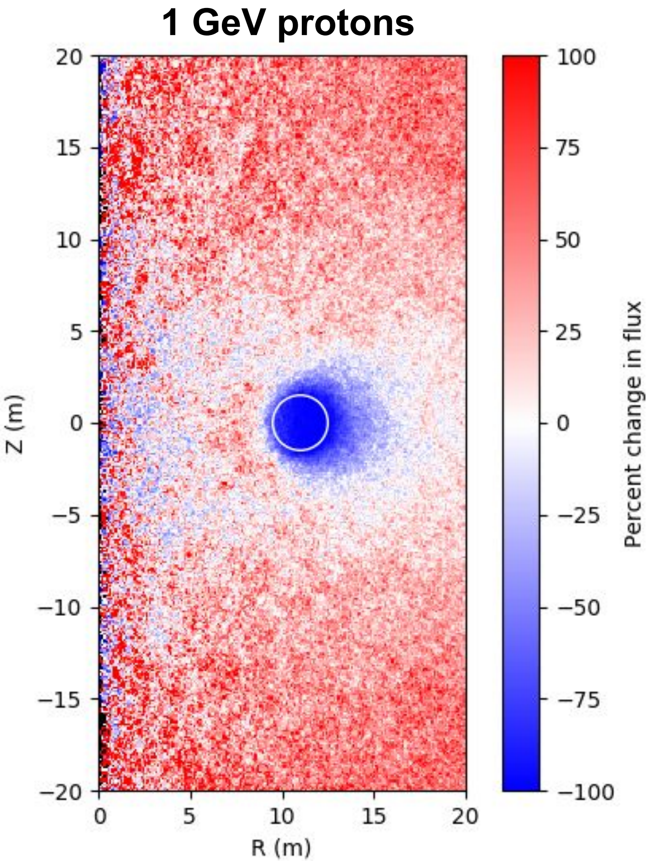
And our simulations are sensitive to details of the energy spectrum.



Heavier nuclei up to iron are also present in lower quantities.

>1 GeV protons aren't shielded as well





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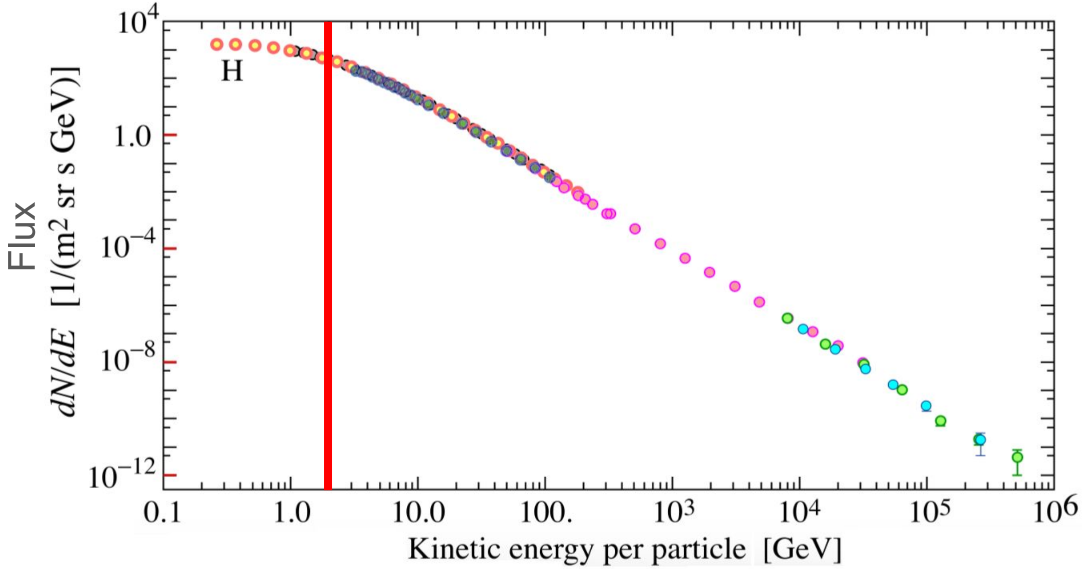
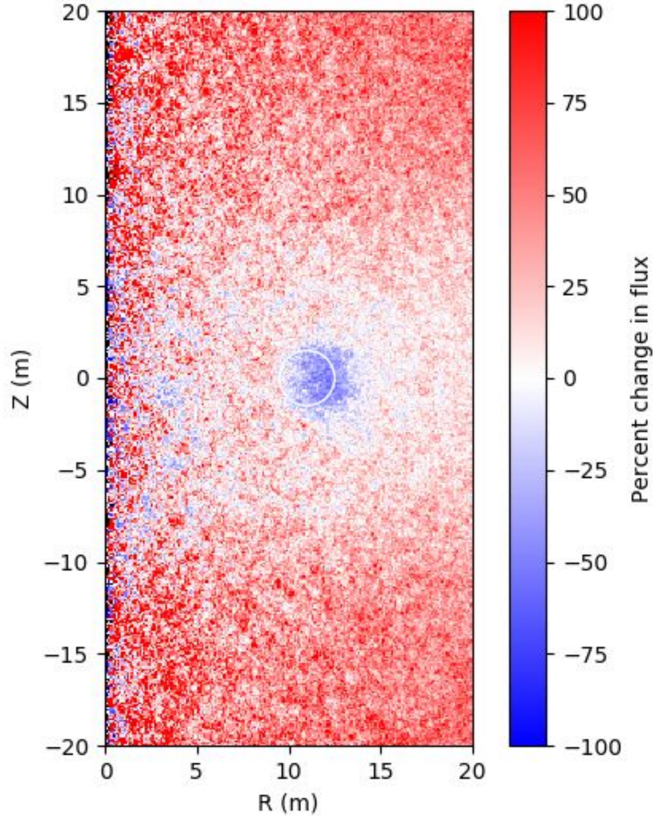
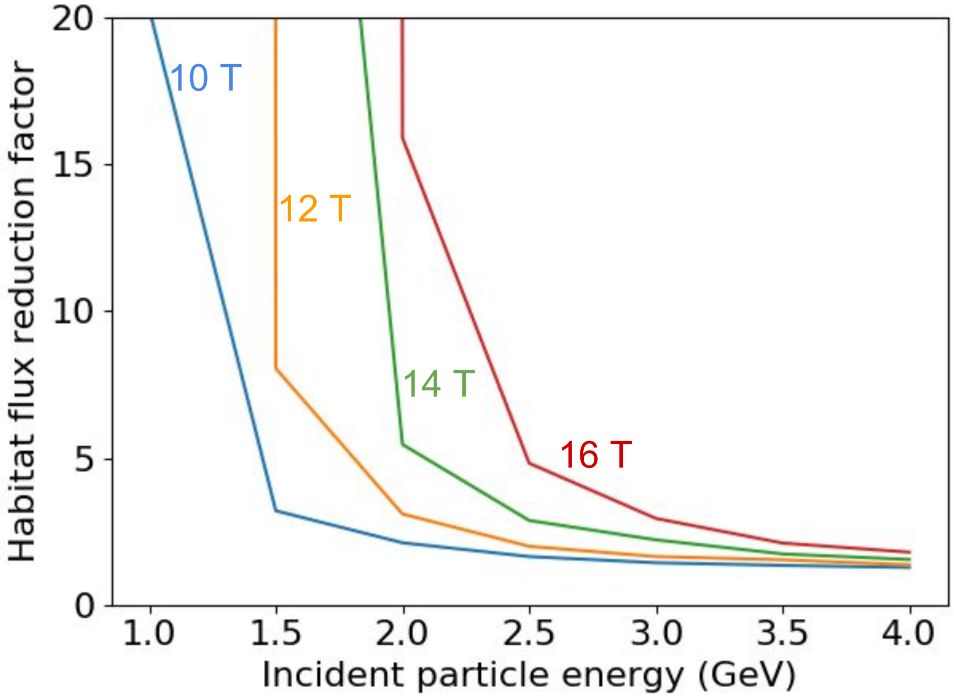


2 GeV protons



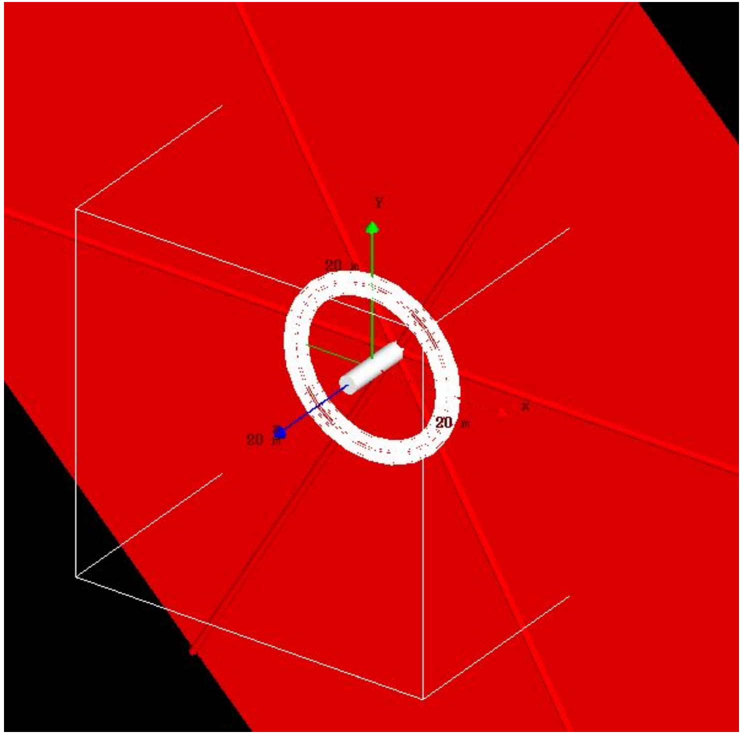
Shielding from high-E protons should be possible with higher magnetic fields



Good

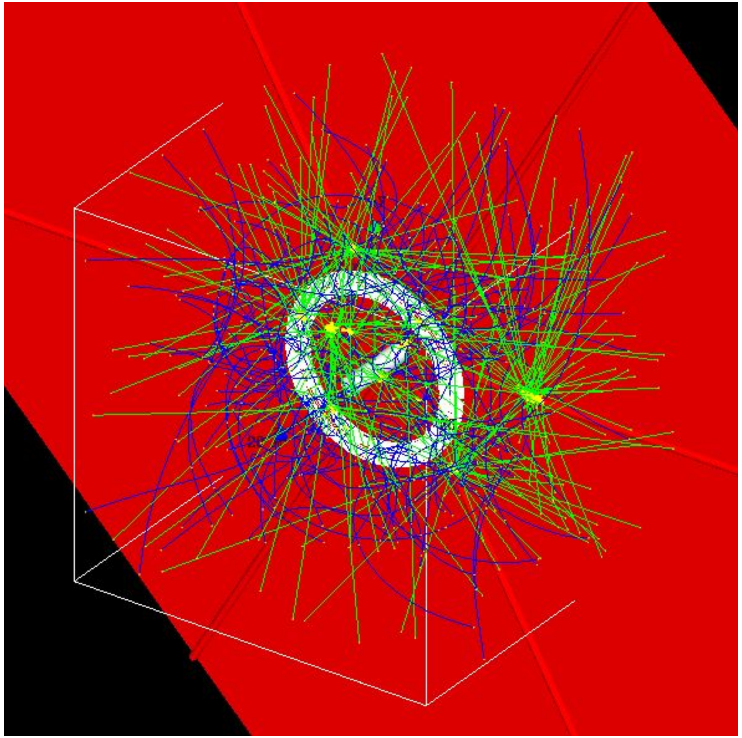
Bad

GEANT4: magnetic effects with material interactions



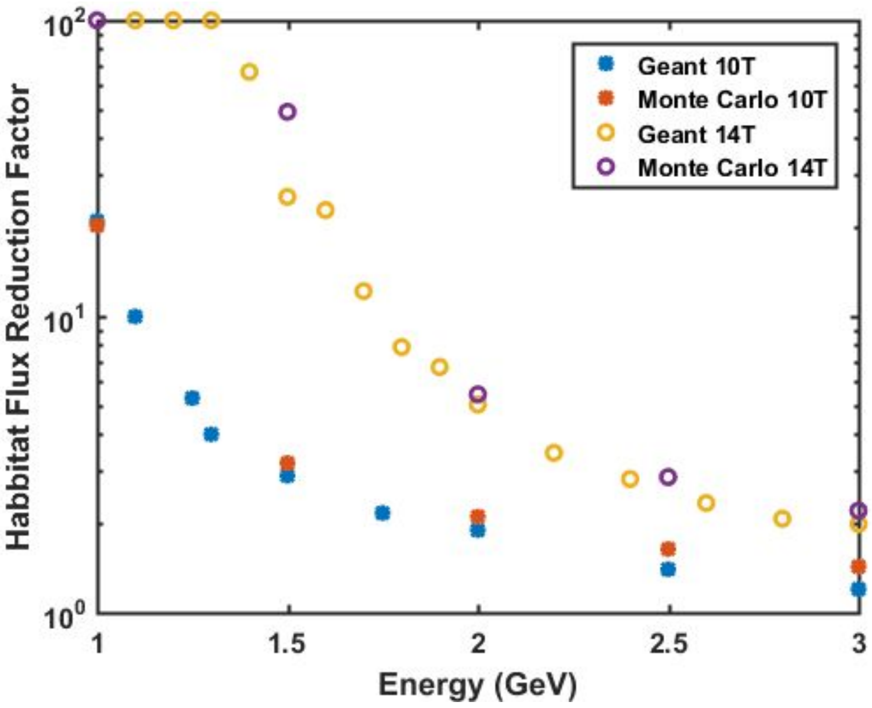
- Geant is a radiation interaction code similar to MCNP, but designed to deal with charged particles.
- Build up a physical and magnetic geometry, including dose detectors.

GEANT4: magnetic effects with material interactions



- Geant is a radiation interaction code similar to MCNP, but designed to deal with charged particles.
- Build up a physical and magnetic geometry, including dose detectors.
- Launch particles towards habitat and measure dose to passengers.

GEANT4 monoenergetic vacuum flux



- No physical structure.
  - Same as Monte Carlo.
- Launching monoenergetic protons.
- Good agreement between codes.

Different energy spectra produce significantly different shielding results

Case	Flux Reduction Factor at 10T	Flux Reduction Factor at 14T
Geant4	3	4.5
Monte Carlo	20	37

- No physical structure
  - Same as Monte Carlo
- Launching particles from a spectrum.
- Poor agreement!

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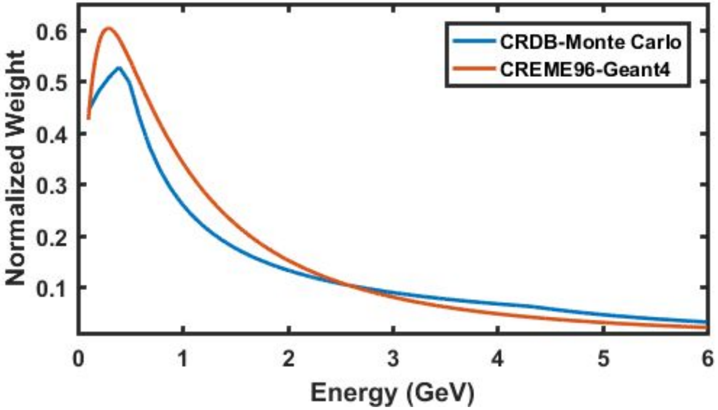

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  - Same as Monte Carlo
- Launching particles from a spectrum.
- Poor agreement!

- The only difference is the simulations are sampling similar but different spectra.

Calculating dose reduction factors

Geometry	Flux Reduction Factor at 14T	Dose Reduction Factor at 14T
ISS-eq	1	1
14T Structure	--	.9
14T Field	4.5	1.23

- Take the pessimistic case in Geant
- Do full geometry simulations of
    - ISS equivalent habitat: Kevlar layered on aluminum, no magnetic field.
    - Structure for 14T Magnetic field: Kevlar, layered on Carbon Fiber, layered on HTS, layered on Aluminum, with no magnetic field.
    - Full 14T Magnetic field and structure

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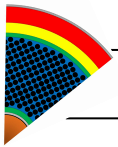
  - Full 14T Magnetic field and structure
- Violate NASA Limit After 407 days
- Violate secondary ARS limit after 519 days

Magnetic shielding takeaways

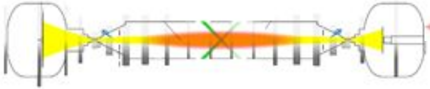
- Magnetic shielding is effective at shielding crew from 100MeV solar radiation!
- Order 10T fields can be used to shield against Cosmic Rays effectively depending on the details of the energy spectrum.
- Need better cosmic ray spectral data before optimization.

How do we pick the right design point?



Fission blanket

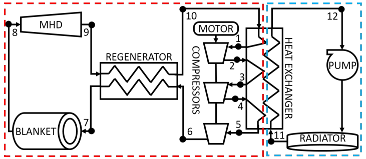
Fusion mirror



Fission blanket

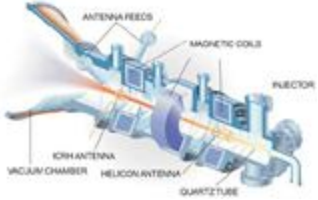
Neutral Beam Injector

Brayton cycle electrical generator

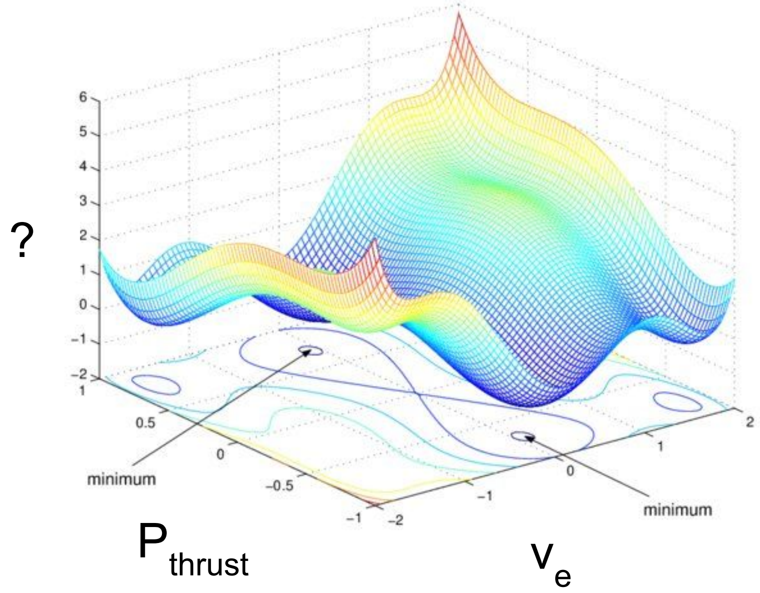


Carbon fiber liquid metal radiator

VASIMR thruster



Generalised optimization is hard

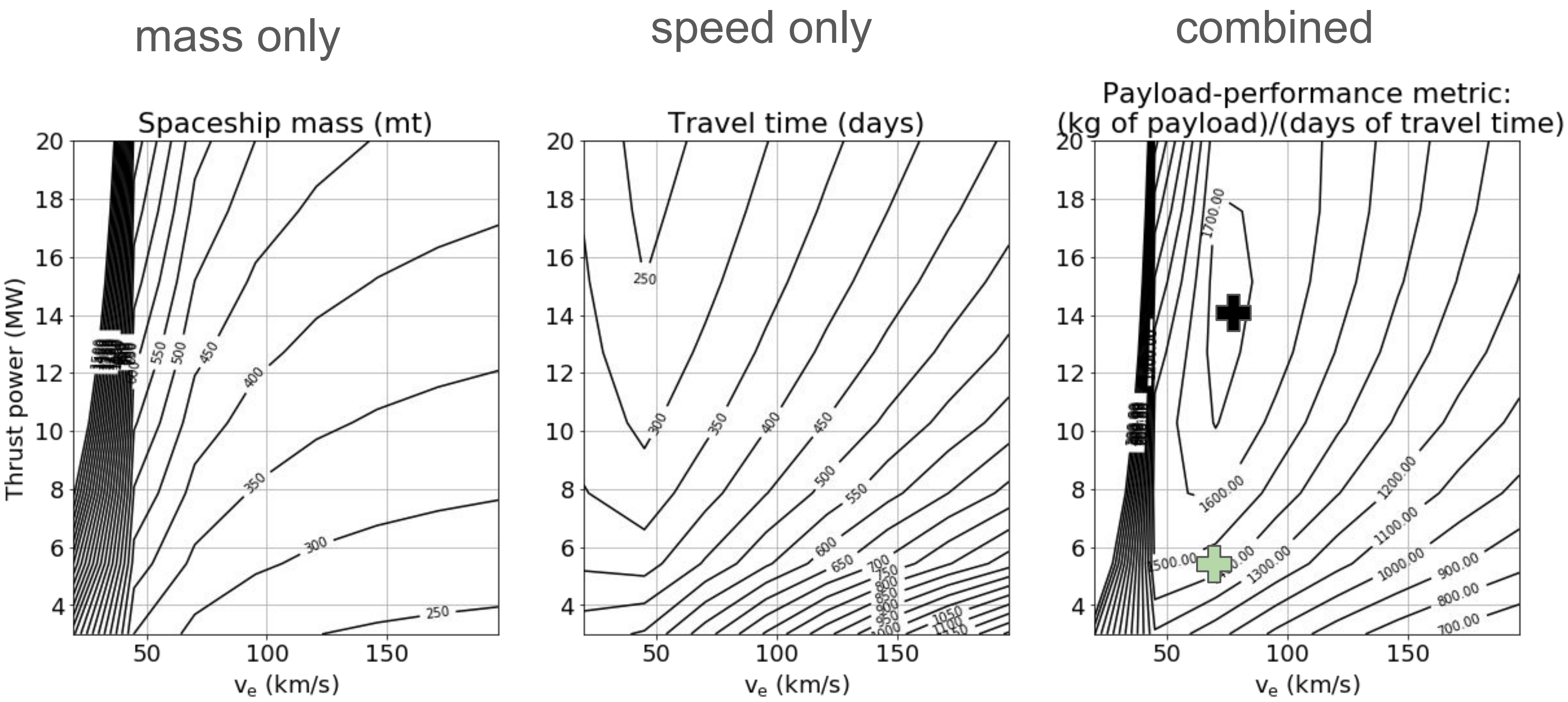


- Need to **minimize objective function** for many **design variables** subject to many **non-linear constraints**
- Need to trade off **fidelity** and **computational cost**

Geometric programming is novel solution emerging in Aerospace Engineering:

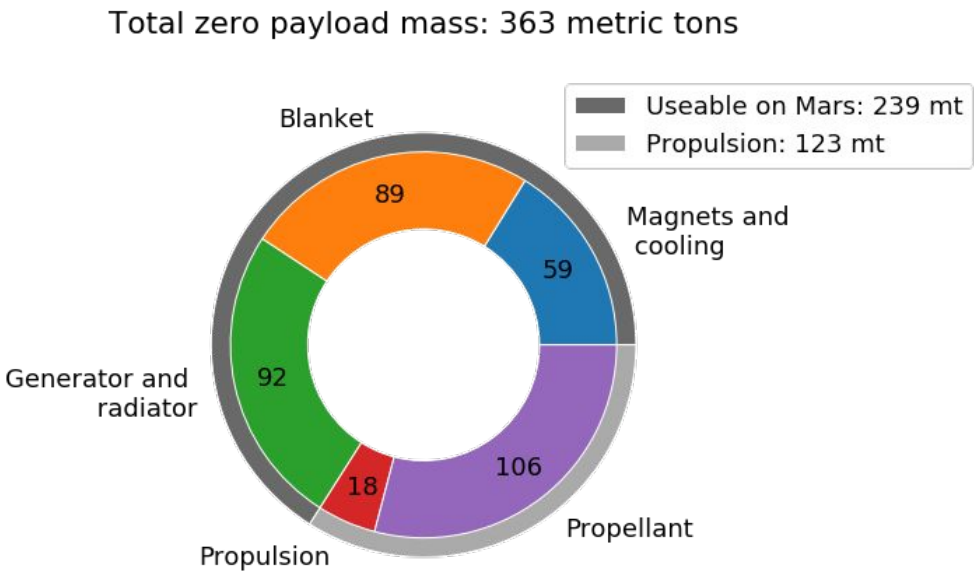
- Computationally efficient framework which guarantees global optimum
- Can cope with large number of design variables and constraints
- *But* restricted functional form of constraints

Optimizing for payload and speed



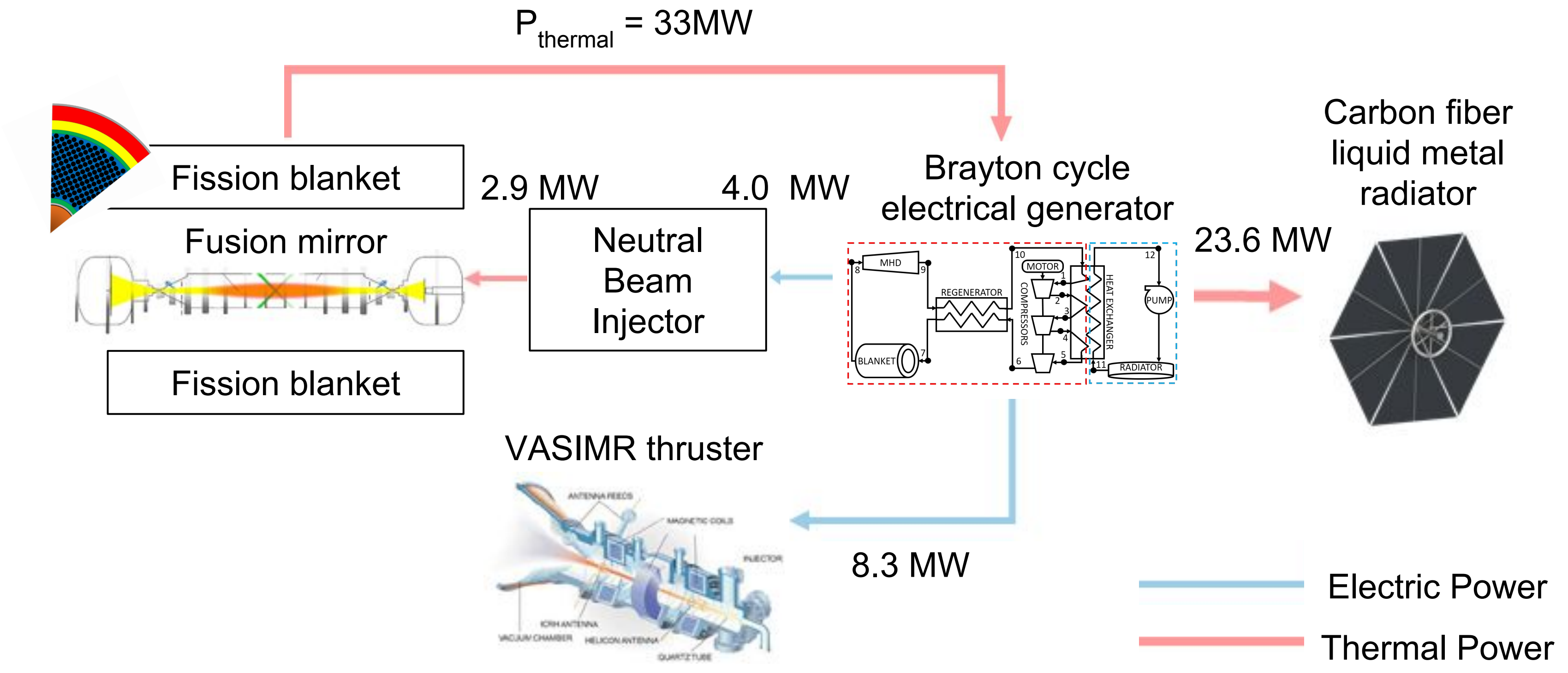
Our design point

Zero payload mass	363	mt
Zero payload travel time	414	days
500 mt payload travel time	900	days
$Q_{blanket}$	40	
Q_{fusion}	0.36	
Length of mirror	10	m
Propellant v_e	65	km/s



PSFC Plasma Science and Fusion Center
Massachusetts Institute of Technology

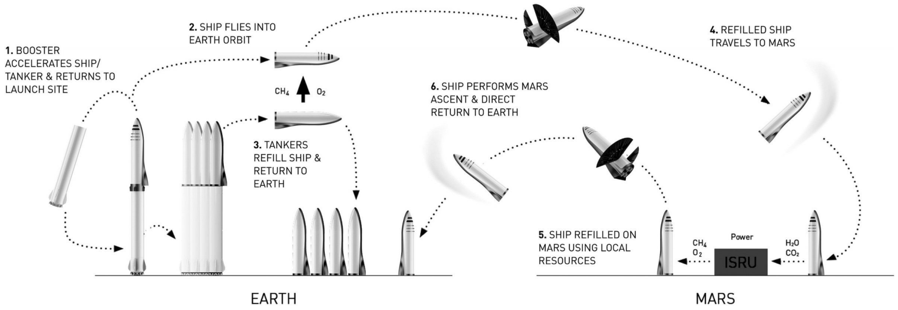
Our design point

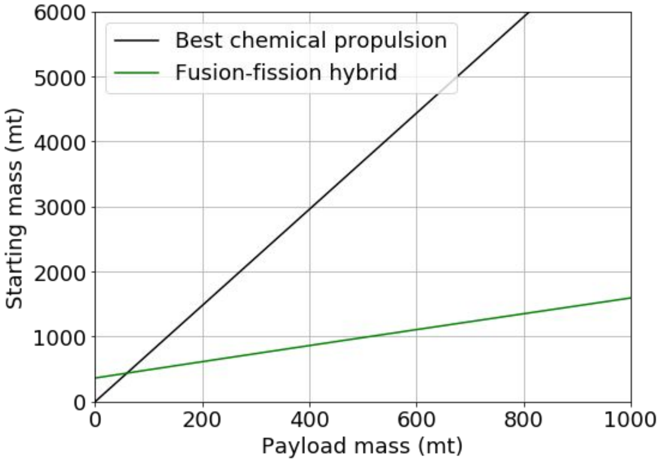


How do we stack up?

For a **same mass to low Earth orbit** of 1000 mt launched by chemical propulsion:

- SpaceX BFR is able to get **150 mt** payload to Mars orbit in **270 days** (0.55 mt/day)
- Fusion-fission hybrid is able to get **500 mt** payload to Mars orbit in **900 days** (0.55 mt/day)





Future research opportunities

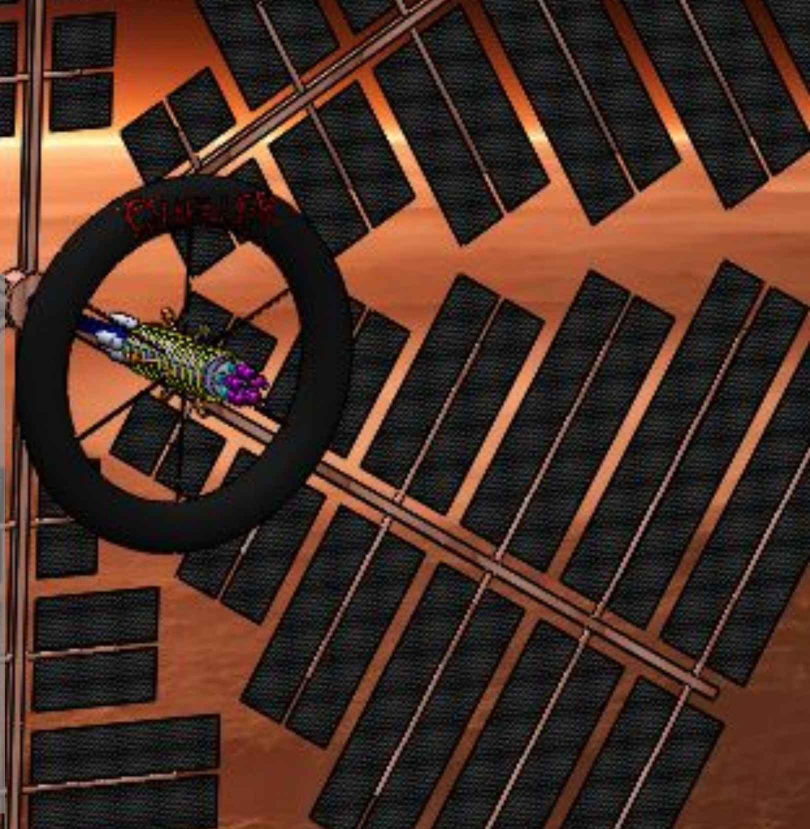
Feasibility: many of our systems have not been demonstrated at this scale

- Mirror confinement system (Is it stable? Can confinement be extrapolated?)
- Multi-MW power generation and radiation systems
- High power VASIMR thrusters
- Magnetic shielding
- Launching and assembling ~300 mt system in orbit (ISS is 417 mt)

Cost: what would be the cost of such a system? Would it be competitive vs. other architectures (even if they are less mass efficient)

THE Q.U.E.L.L.E.R. DRIVE

Q Uranium Enhanced Linear Long Endurance and Range



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TA’s: Norman Cao, Alex Creely, Alex Tinguely, Libby Tolman

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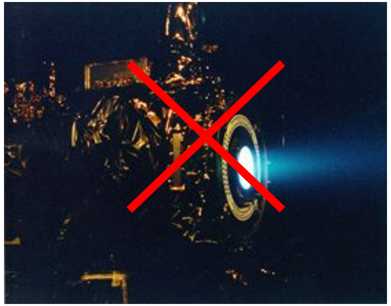
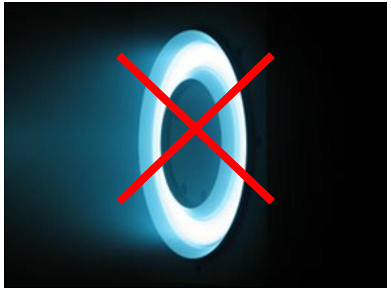
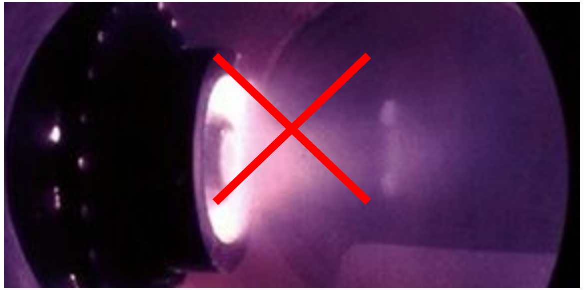
Appendix

It is clear we need plasma propulsion

What can satisfy our propulsion requirements?


Ion Thruster


Hall Thruster


MPD

- **Ion Thruster (Electrostatic)**: Space Charge Limited, Power/Thrust Density Limited
- **Hall Thruster (Electrostatic)**: Plasma Instabilities, Power/Thrust Density Limited
- **MPD (Electromagnetic)**: Operates at high power and thrust densities, **BUT** requires electrodes which are in contact with the plasma - **EROSION**
- But $\frac{B^2}{2\mu_0} > \frac{1}{2}\epsilon_0 E^2$ - Should operate in the electromagnetic regime