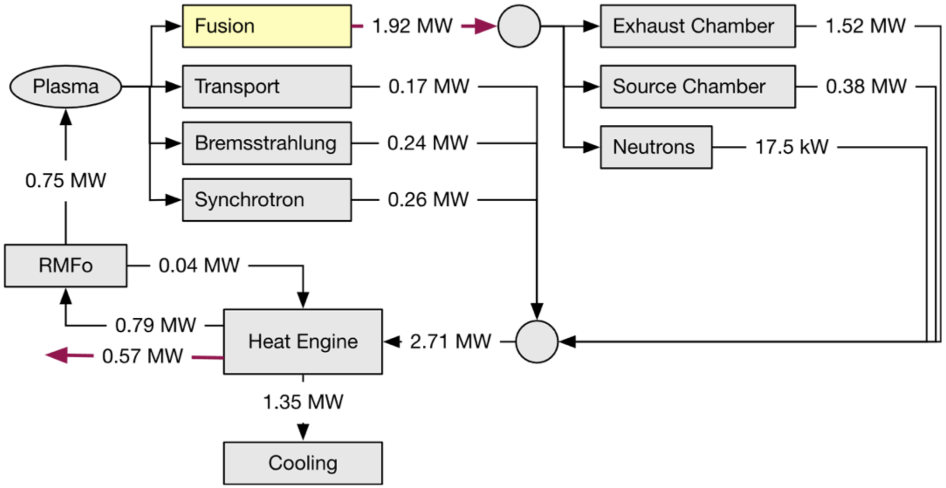
PFRC RMF Antenna modeling

Stephane Morel
Mason Bates

The core problem

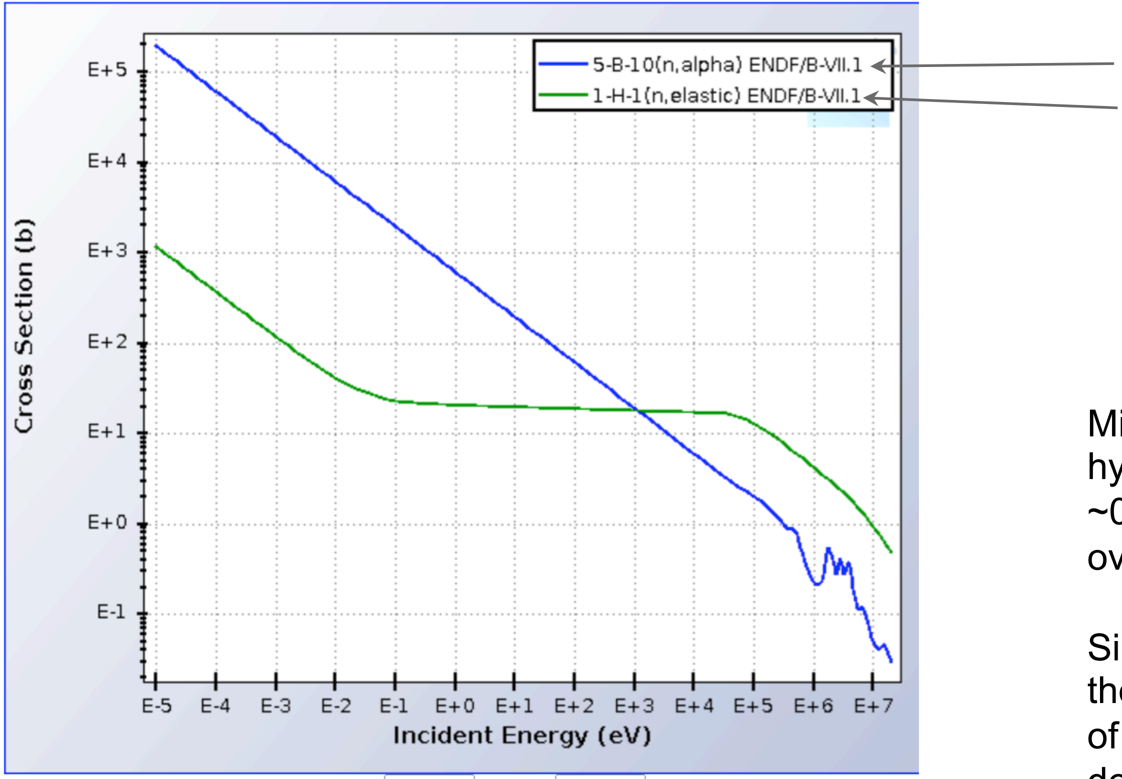


Galea et al. 2023

- Since a significant proportion of the energy is being used to heat the plasma, small changes to the heat engine's efficiency are extremely important.
- With the Brayton Cycle, you need high temperatures and high pressure ratios
  - Extremely hot gasses!! (~1500K)

Need hot gasses => Need hot shielding!

Why Boron?



Brookhaven NL NNDC

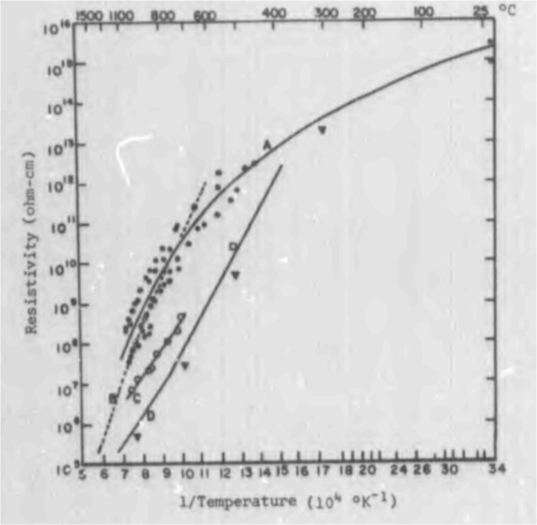
Miles Kim had a design that used lithium hydride to maintain density of hydrogen at ~0.07g/cm^3 at 1500K, which allowed for an overall thinner shield

Since high pressures are needed anyway for the Brayton Cycle, supercritical water may be of interest, since it can get to similar hydrogen densities. Supercritical water turbines already exist for natural gas power plants

Stainless steel at room temperature: ~10^-4Ω-cm

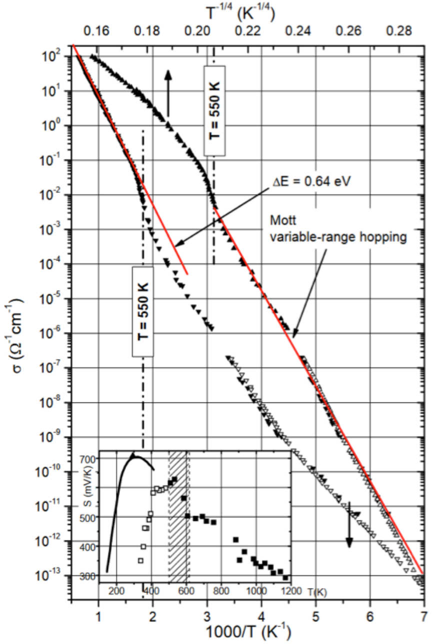
High temperature conductivities (1500K)

~10^4-10^5 Ω-cm



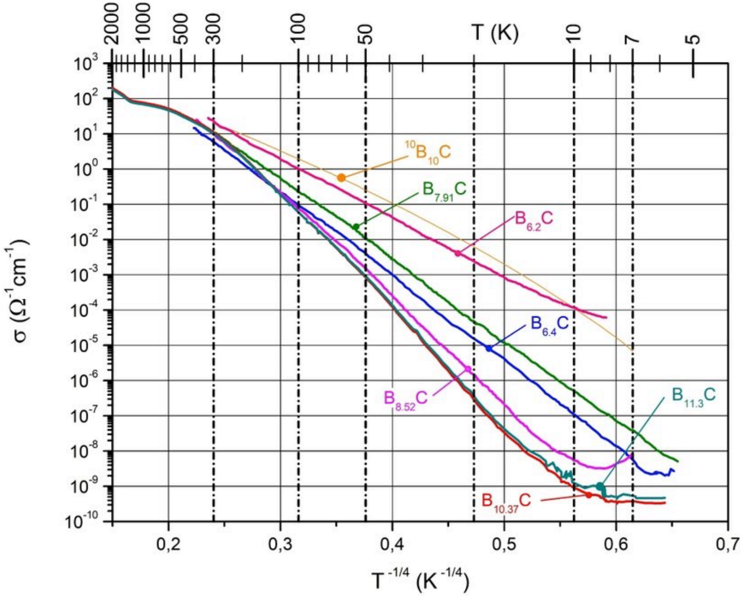
BN Conductivity:
Neuberger 1967

~10^-2 Ω-cm



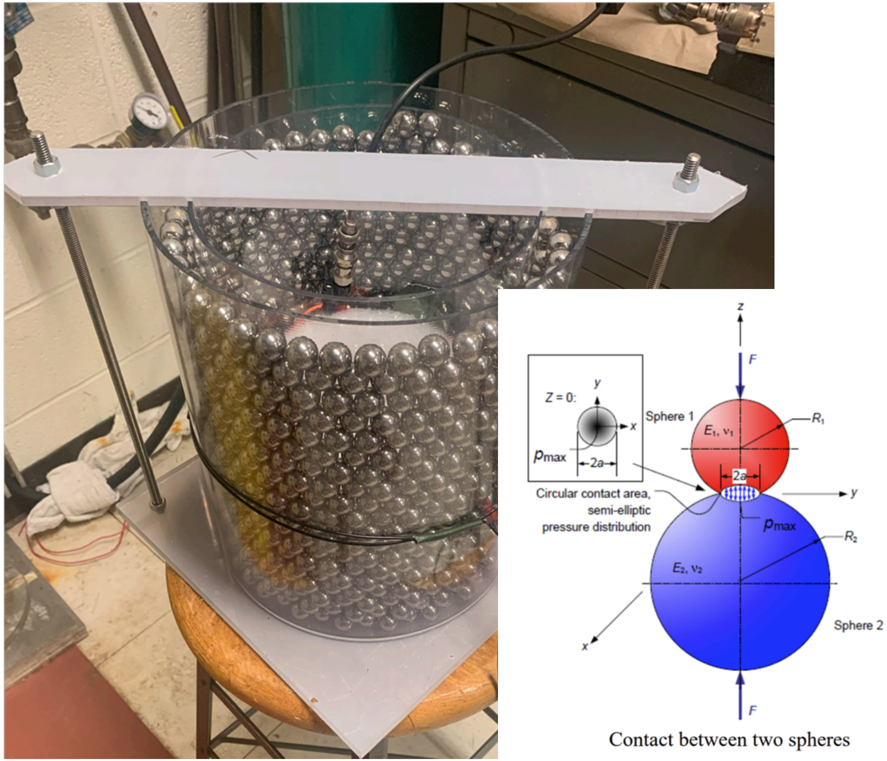
β-Boron Conductivity:
Helmut Werheit 2015

~10^-2 Ω-cm



BC Conductivity:
Helmut Werheit et al. 2022

Proposition: Boron Spheres



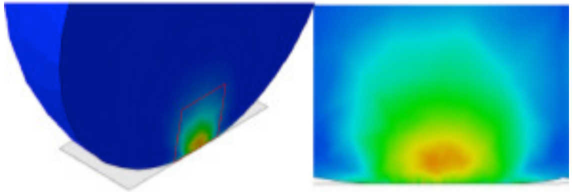
Contact between two spheres

The contact area between spheres is small

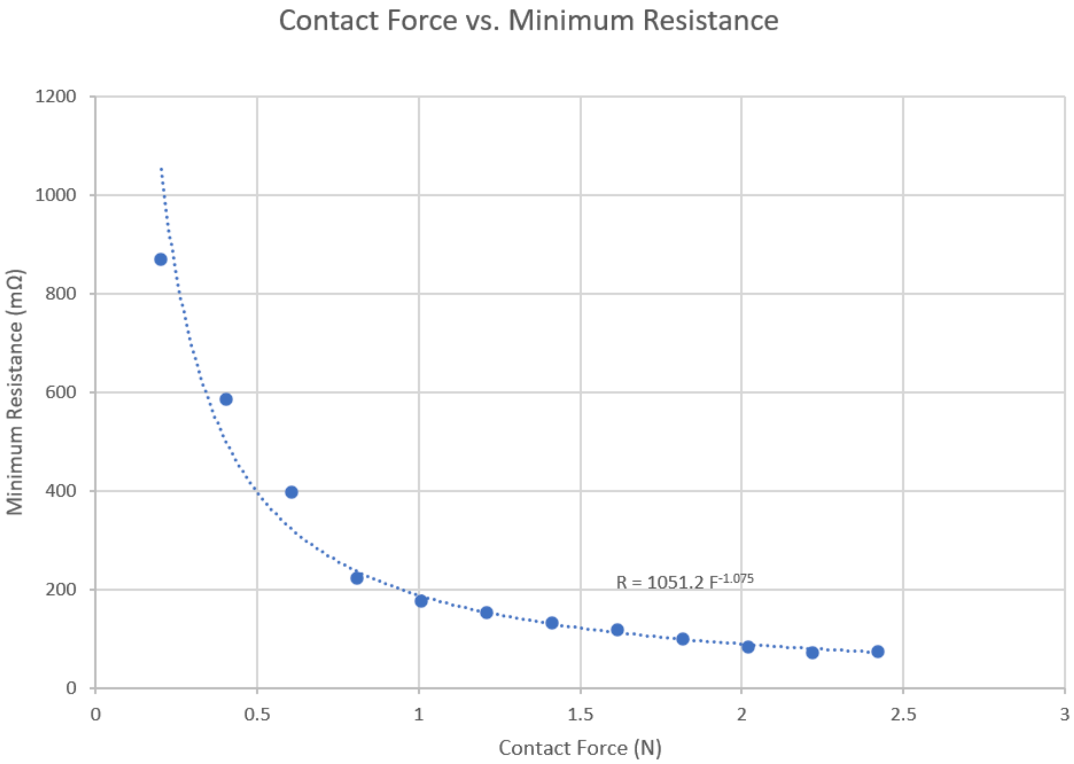
More difficult for current to pass across

Stainless Steel used as analog for conductivity of high temp Boron (1500K)

Contact Results



Single sphere:
Circular contact diameter 0.036mm



$$R \sim \frac{1}{F}$$

Hertzian theory suggests
$R \sim F^{-2/3}$

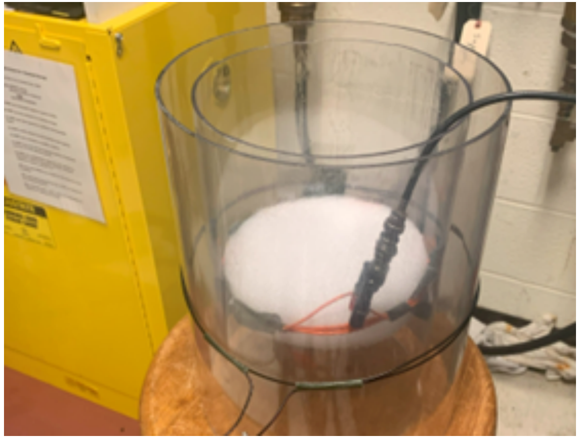
to experimentation. This experimentation showed that limitations[3] to the Hertz theory at smaller loads were

- That the area of contact was larger than predicted.
- The area of contact had a non-zero value even when the load was removed.
- There was strong adhesion if the contacting surfaces were clean and dry.

Brian, Taylor 2016

Compare

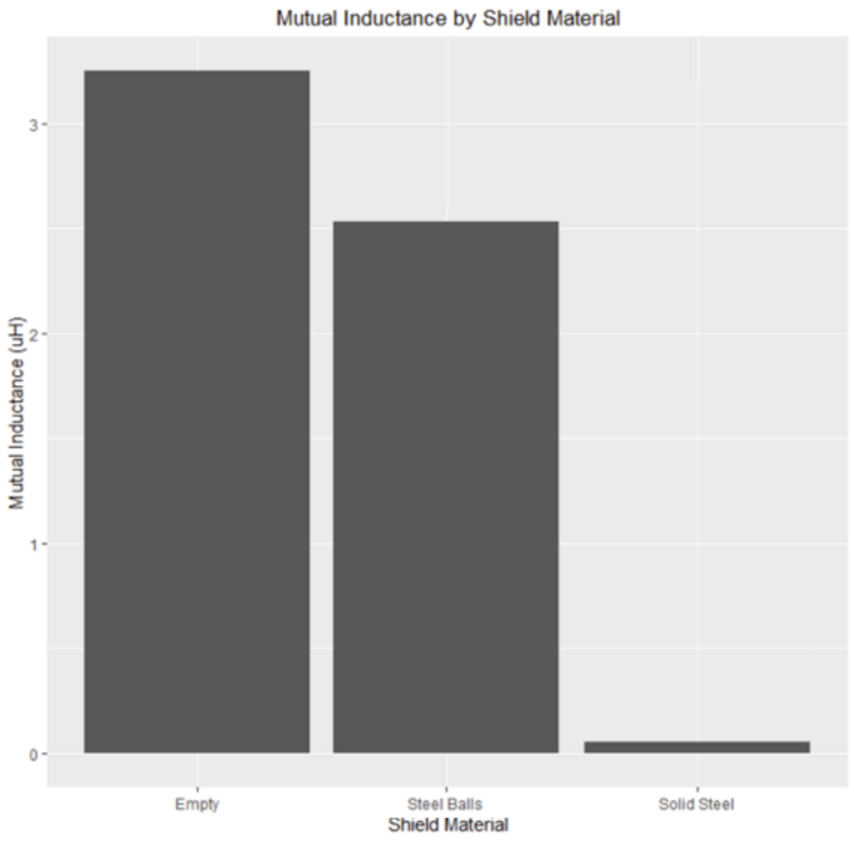
No Shield



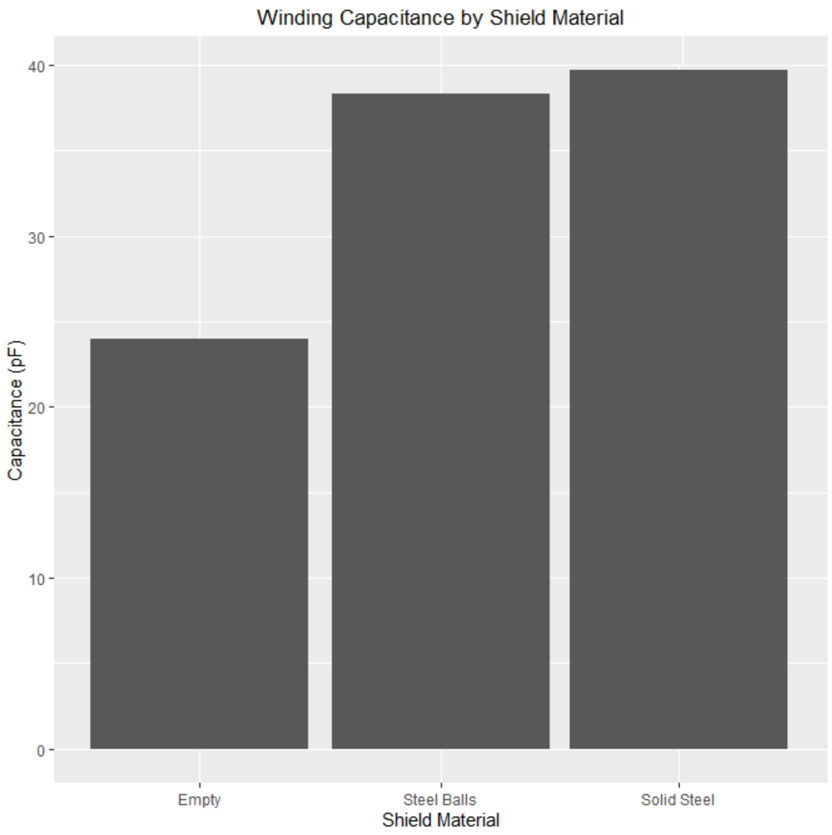
Spheres

Solid

Expect the spheres to allow greater RF passthrough than the solid steel, but less than no shield



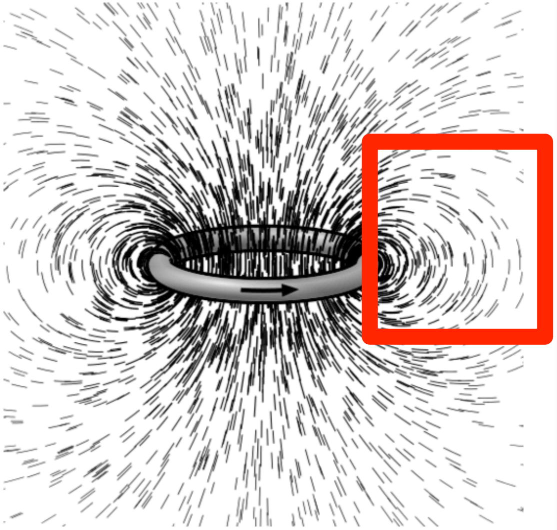
Mutual Inductance by Shield Material
Mutual Inductance (uH)
0
1
2
3
Empty
Steel Balls
Solid Steel
Shield Material



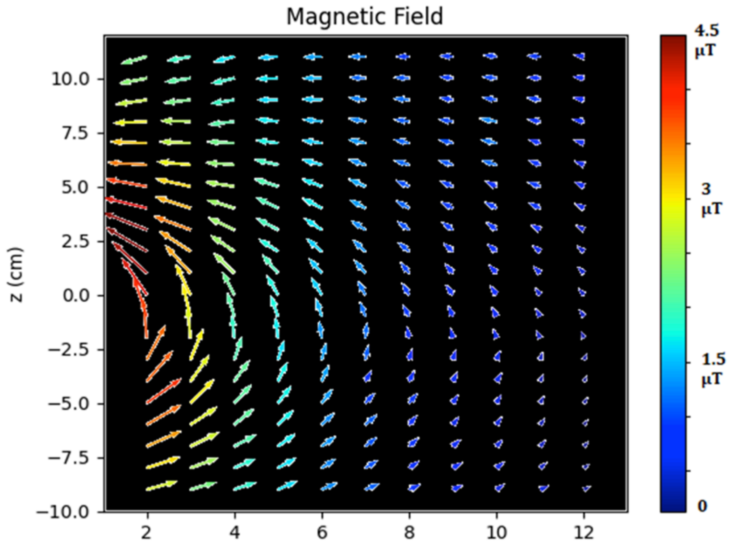
Winding Capacitance by Shield Material
Capacitance (pF)
0
10
20
30
40
Empty
Steel Balls
Solid Steel
Shield Material

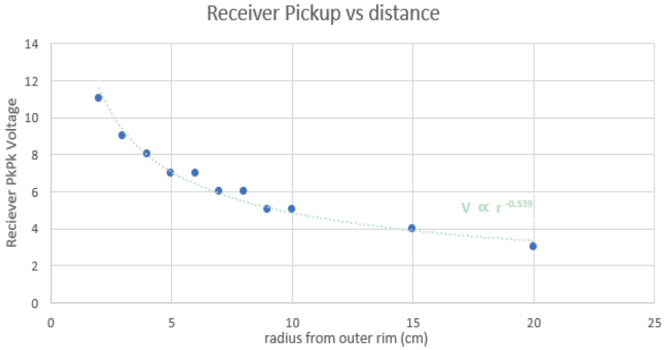
Field Mapping

No Shield

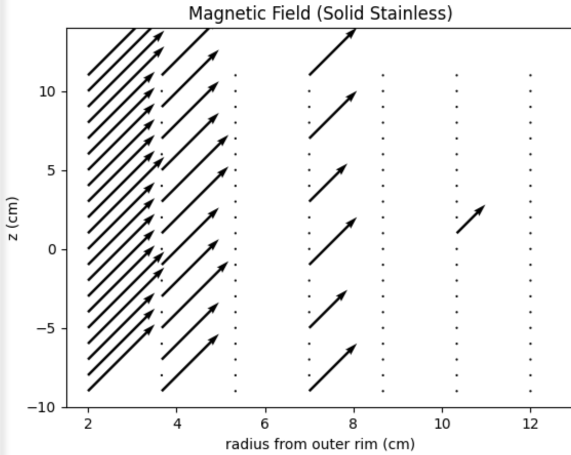


Spheres



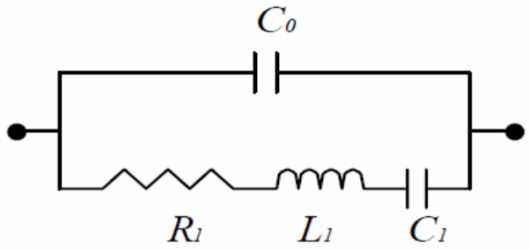


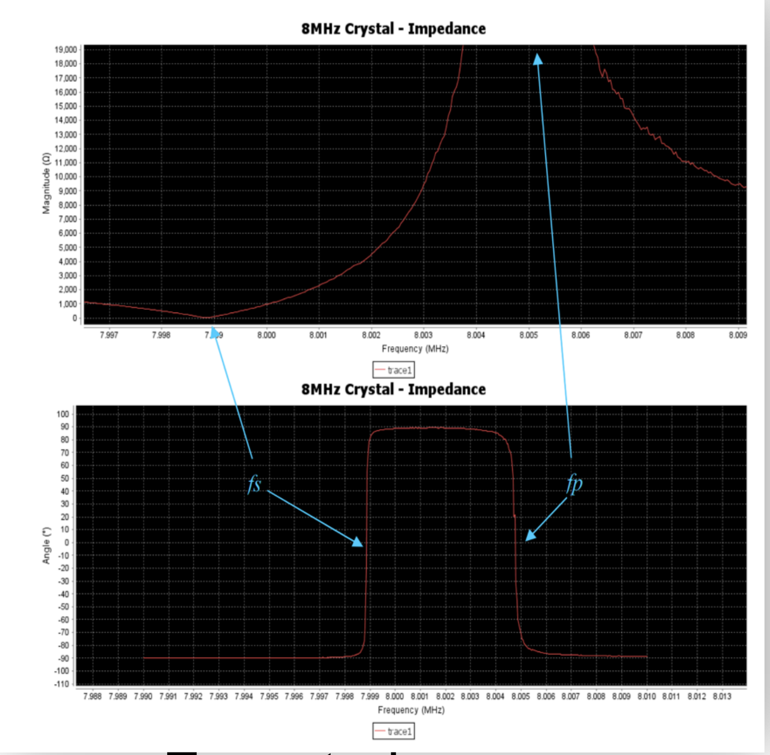
Solid



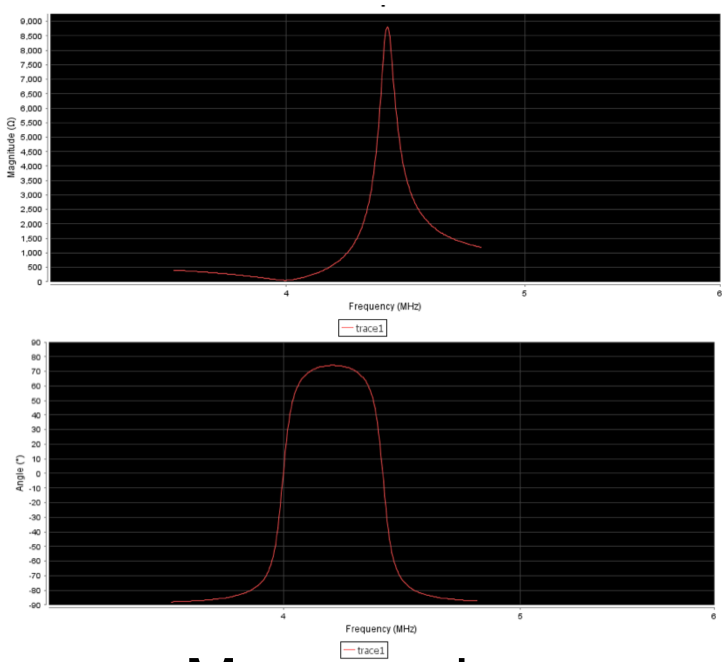
Grounding solid stainless plane lead to noise

Frequency Dependence





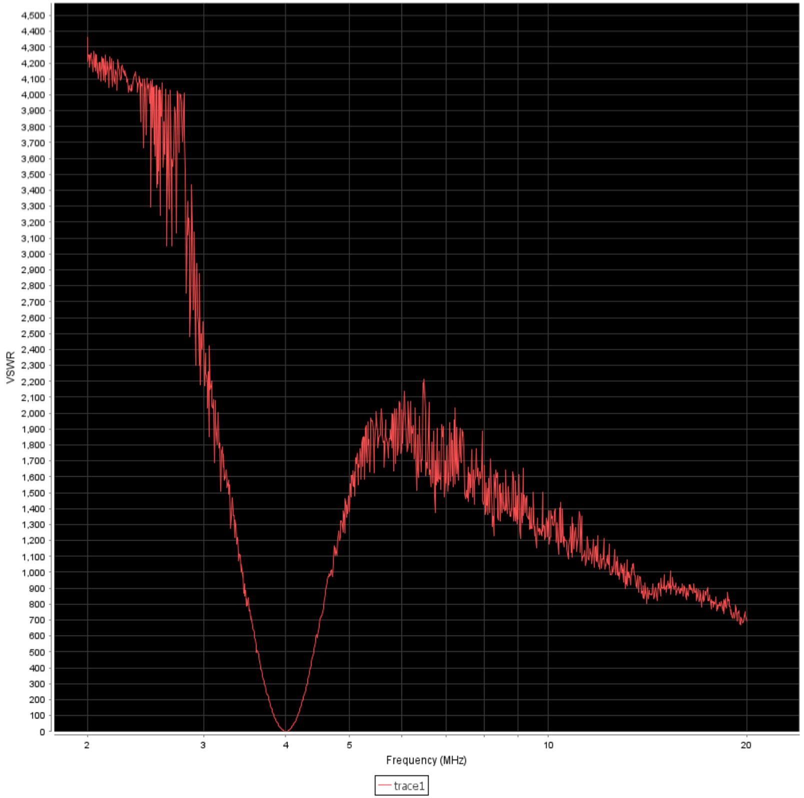
Expected



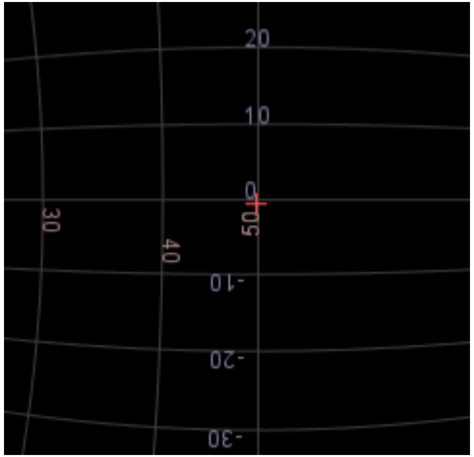
Measured

Frequency Dependence

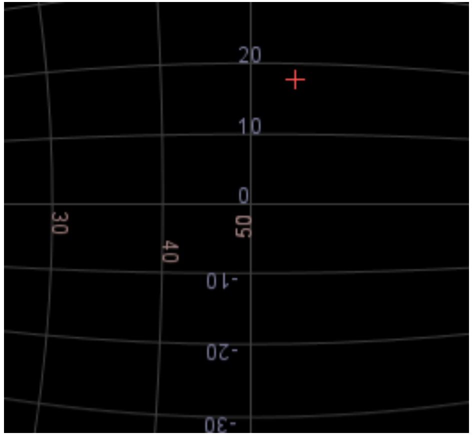
VSWR vs Frequency



Approaches 1 at resonance



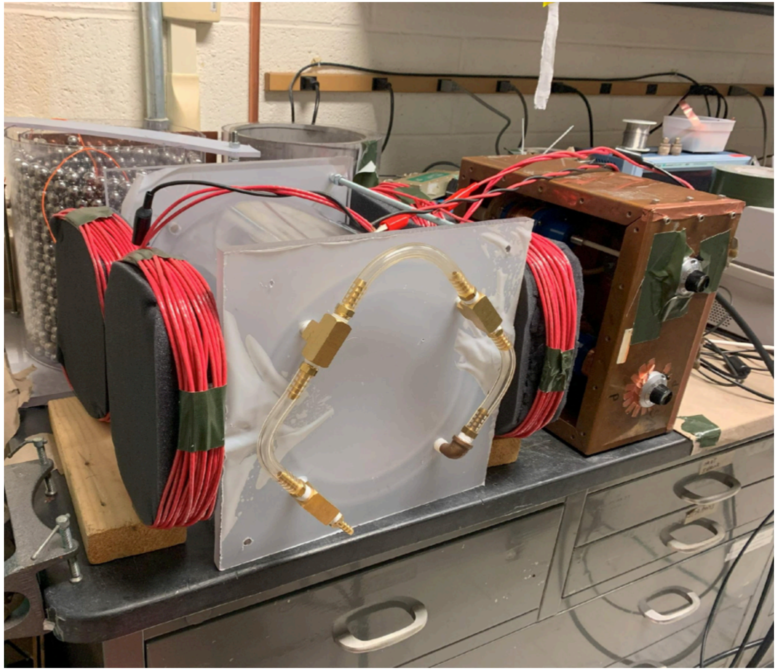
Isolated System



Human nearby (antenna)

As antenna's environment changes, Frequency Response Changes.

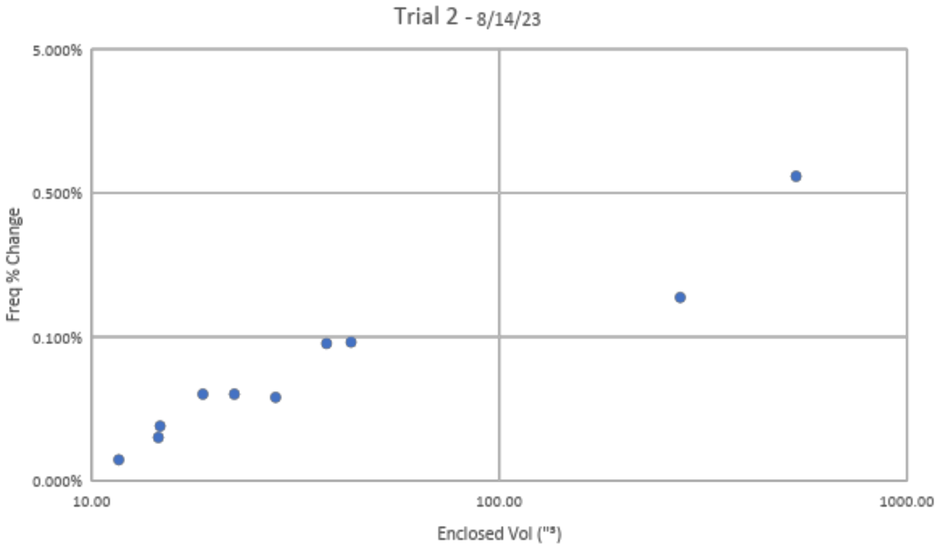
(Especially so in presence conductive material)



1. For reasonable plasma sizes, resonant frequency change < 1%, ~.1%

2. Change as a function of enclosed volume

d (")	l (")	t (")	Enclosed Vol	Material	Freq (MHz)	% Change	Cross-section A
				No pipe	2.00000	0.000%	
1.25	12	50m	14.73	Copper pipe	2.00024	0.012%	1.23
3.25	33.5	100m	277.91	Copper pipe	2.00188	0.094%	8.30
1.25	9.5		11.66	Solid Copper Rod	2.00014	0.007%	1.23
1.5	8.25		14.58	Solid Copper Rod	2.00020	0.010%	1.77
1.25	12		18.75	Solid Copper Square Prism (d=side)	2.00040	0.020%	1.56
1.25	18.25	75m	22.40	Steel Pipe	2.00040	0.020%	1.23
2	9	150m	28.27	Steel Pipe	2.00038	0.019%	3.14
2	12	250m	37.70	Steel Pipe	2.00090	0.045%	3.14
5.5	22.5	150m	534.56	Steel Pipe	2.01306	0.653%	23.76
10	12	300m	942.48	Steel Pipe			78.54
1.75	18		43.30	Solid Steel Rod	2.00092	0.046%	2.41



Do People Nearby Change resonant frequency

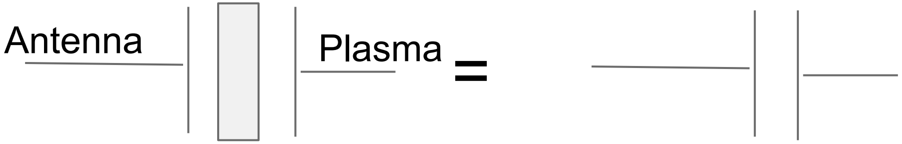
For analog? Yes: in worst case, by about -.05%

For the real PFRC (Top-down) antennas*? Negligible

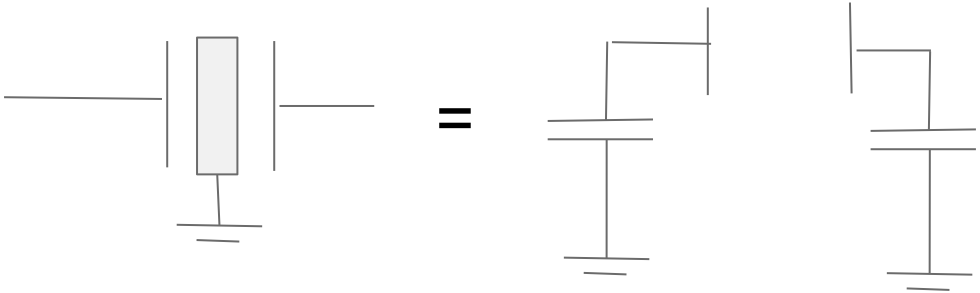
If it changes, change must be < 0.002%

Why different for the 2 setups?
Analog uses smaller capacitor, requires larger inductance (more loops 7x)

Capacitance



- Extremely strong electric field gradient near wall causes problems => want to minimize

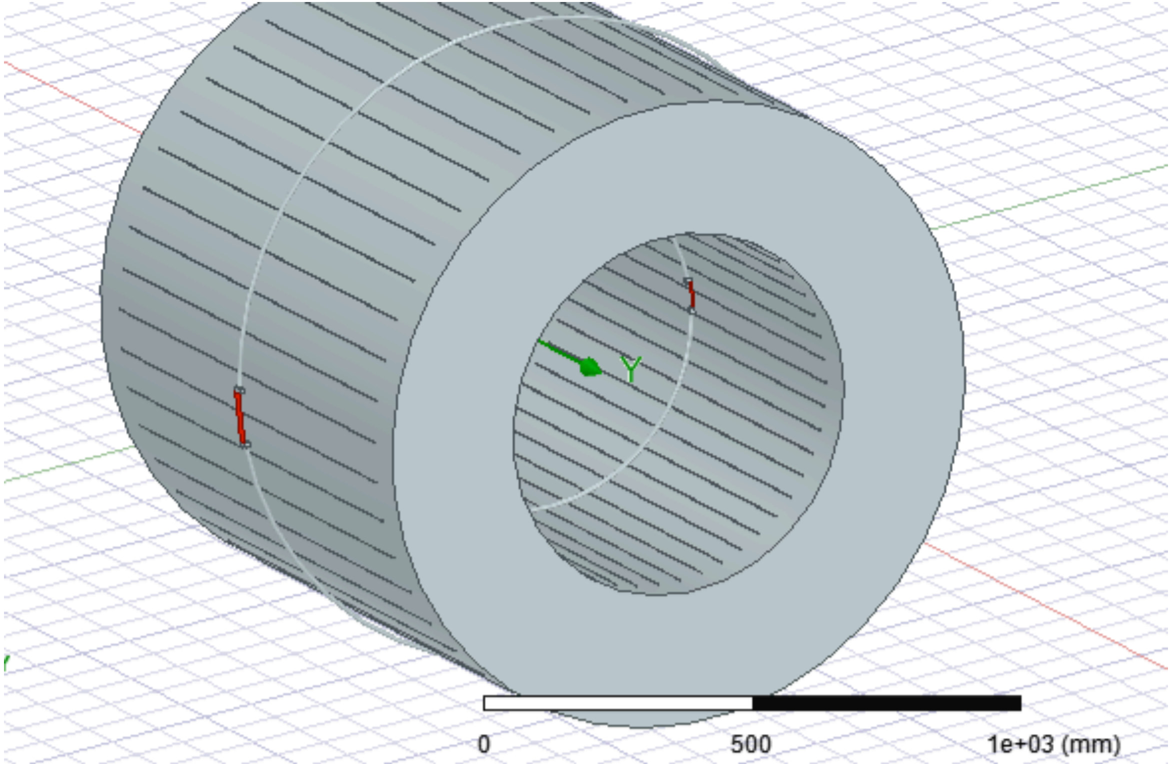


Grounding the shielding solves the problem

BUT effectiveness depends on the resistance between the shield and ground

Grounding each sphere would be impractical, precisely because they block the flow of current

The solution: A slit cylinder



Neutron Behaviour

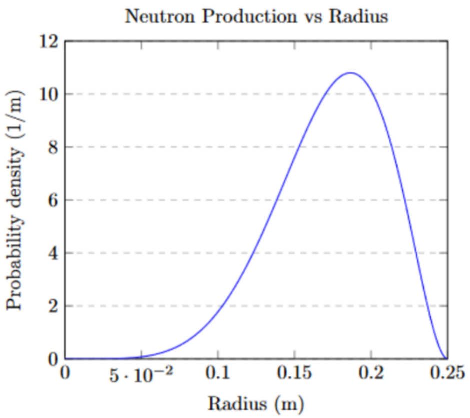
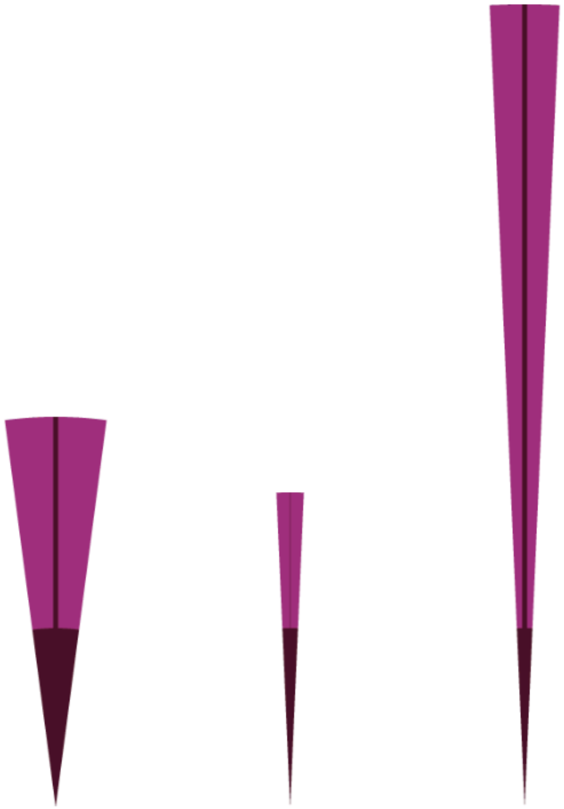


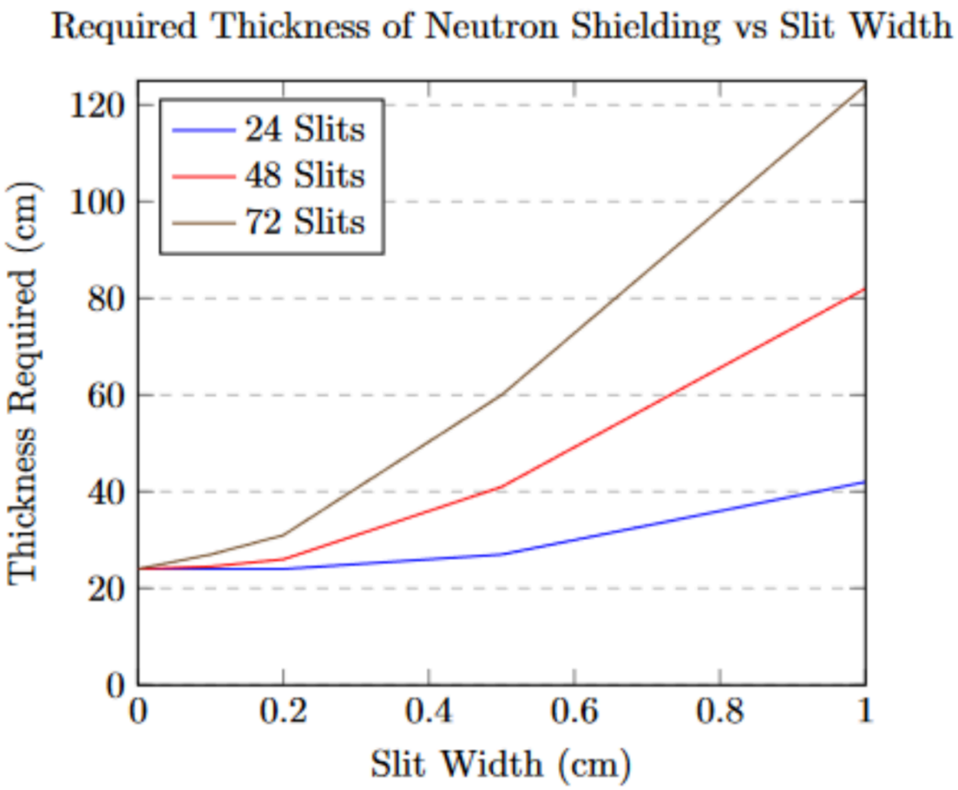
Figure 4: The probability density that a given neutron is created a distance R from the z-axis. Note that this accounts for the linearly increasing circumference of the rings, so a constant volume density would look linear on this plot



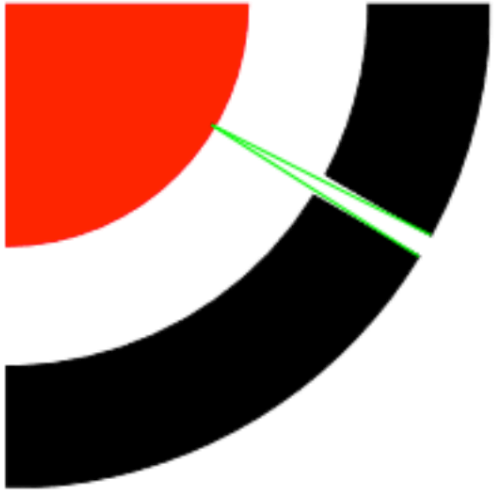
(a) 24/10mm (b) 72/1mm (c) 72/10mm

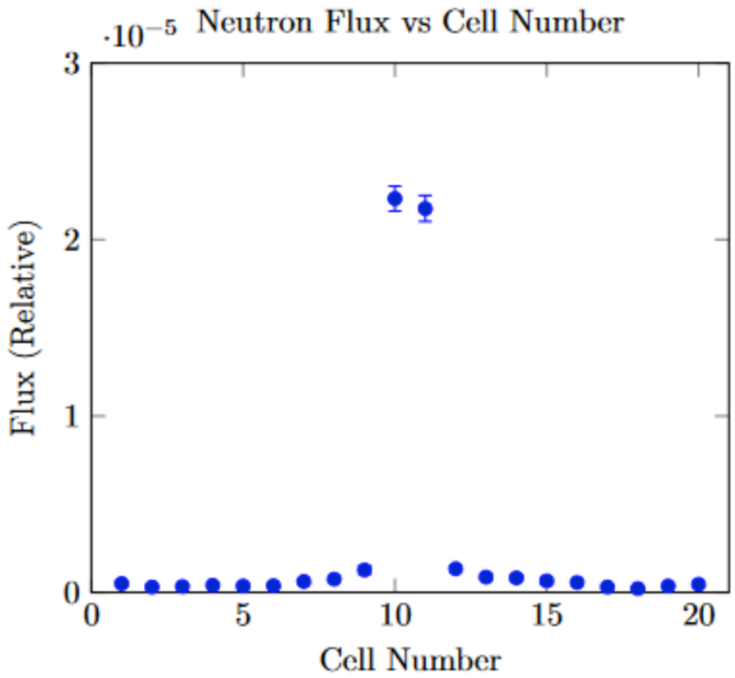
Figure 6: Visualizations from openMC showing variation in slit width, number, and radius. Radius was increased until flux was acceptable. Darker color represents a vacuum, with the lighter color being boron-10 shielding. Note that the neutrons are only produced up to 25cm, whereas the vacuum extends to 35.6cm

Neutron Behaviour



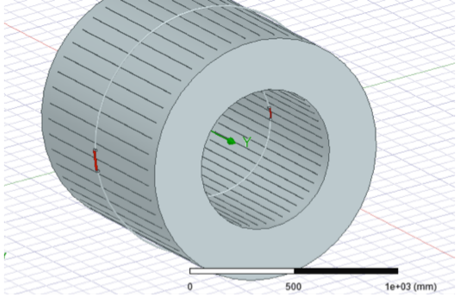
Problems with how I set it up

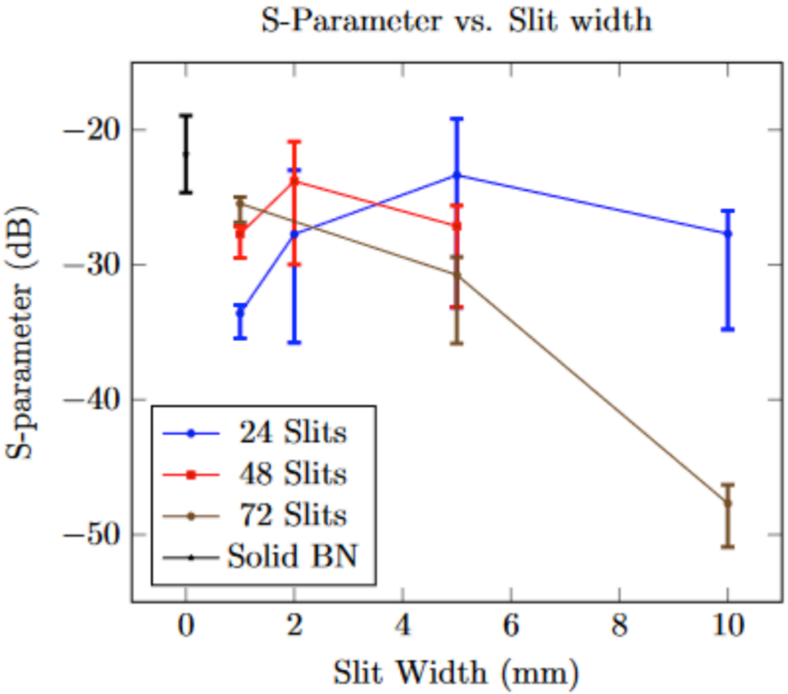




These thicknesses would go to infinity with enough cells….

Using these thicknesses from before,





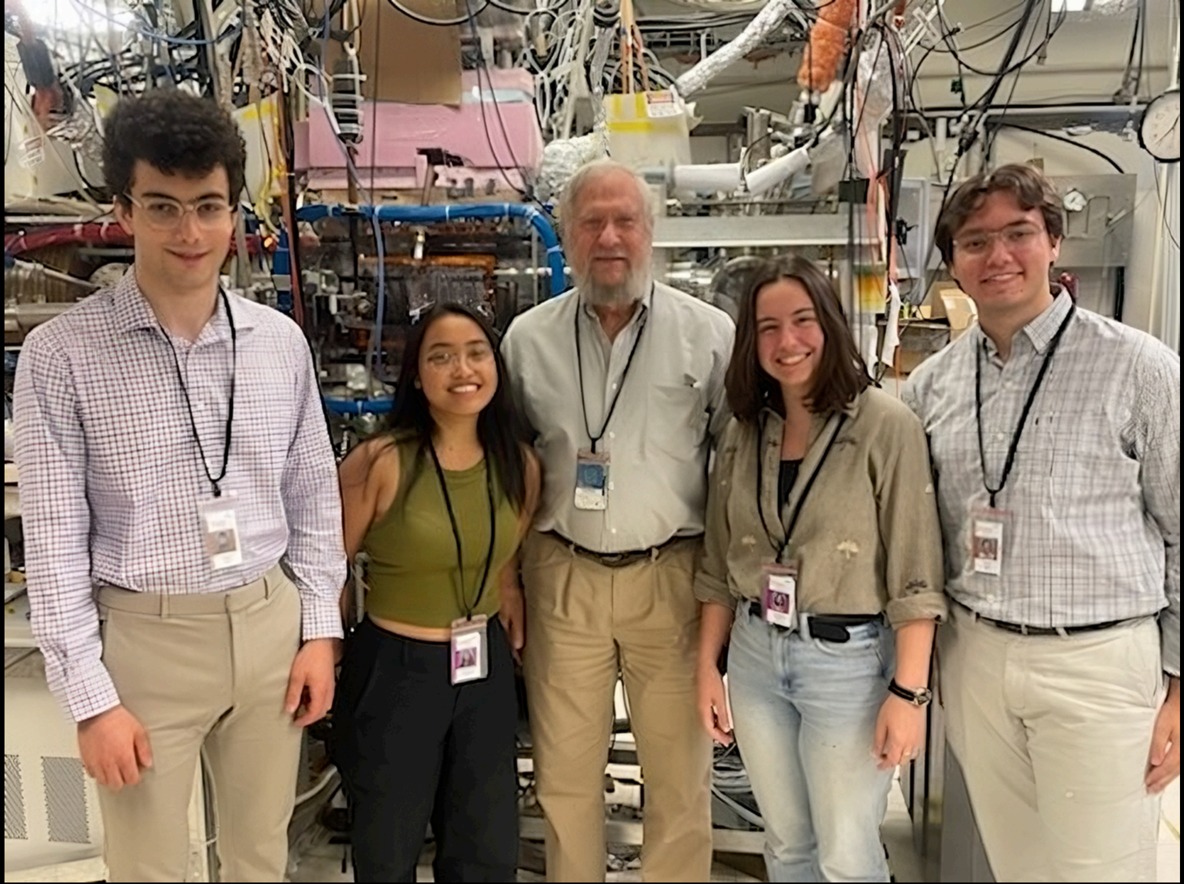
- Take with a grain of salt
- S-parameter isn't the correct measurement here, but I was unable to get the loss integral to converge in HFSS
- When using slits in BN, I would measure effectively zero losses, I didn't have time do a thorough study of it though

Top and bottom tick represent best/worst passthrough from 1-10MHz
Middle tick represents average

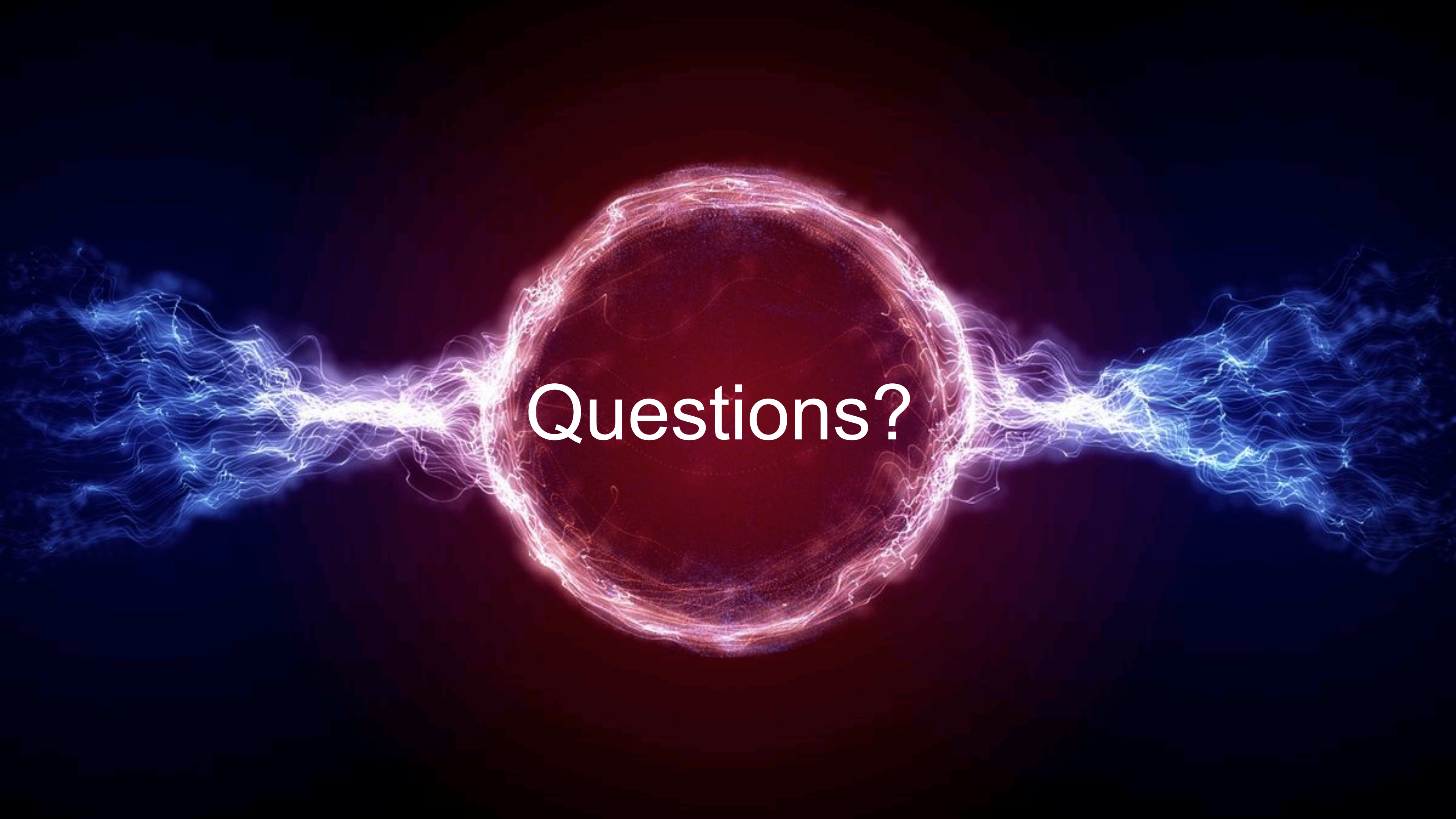
Solid BN isn’t actually good enough for 1500K

- Miles’ paper recommended BN @ 800K and calculated ~0.5% losses.
    - @ 1500K this would result in ~100x greater losses

- If I had to take a guess, the winning solution would be Boron Nitride diagonal slits with supercritical water, but this needs further investigation.
    - Diagonal slits may be unnecessary when water is acting as a scattering medium



Thank you to PPPL and PPST


Questions?