Toroidal Axion Haloscope Development at CAPP

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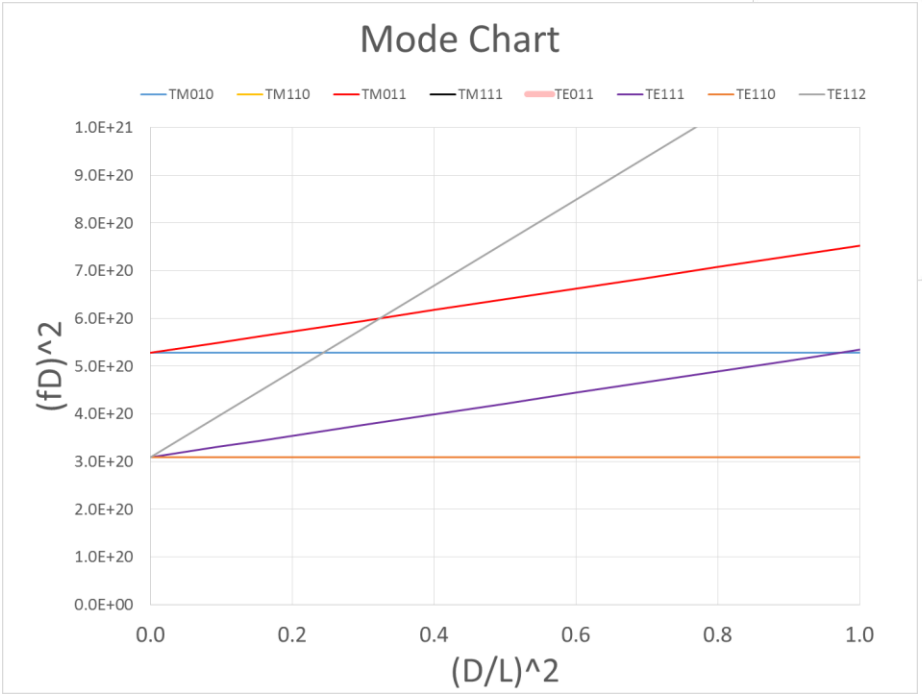
LLNL-Microwave Cavity Workshop 2017

Why Toroid?



Axion Power $P_a \propto QCB^2V$

- Larger cavities, higher field magnets, preserve Q & C
- Larger cavities -> problem at higher frequencies
  - Multiple Cavities (see SW Youn)
  - What about Toroids?
    - No endcaps, can I get something for nothing?
    - With a toroidal magnet the $\vec{B}$ field is, at least nominally, parallel to all conductive surfaces
    - Lends itself to superconductive films?

Toroid Modes

- No pure TM or TE modes
- Inverse toroid aspect ratio $\rho_0 = {}^{r}/_{R}$
- Bicycle tubes are better than truck tubes
- $\vec{E}$ field lines of desired mode similar to applied B field
- No mode crossings

478 IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. MTT-26, NO. 7, JULY 1978

Toroidal Resonators for Electromagnetic Waves

FERDINAND CAP AND RUDOLF DEUTSCH

Abstract—**The solution of Maxwell's equations for toroidal systems has been reduced to the solution of the scalar Helmholtz equation. The eigenfunctions and the corresponding electromagnetic fields have been calculated analytically. The dispersion relation was formulated. Three different types of eigenmodes were obtained for each frequency. The structure of the electromagnetic field of the $m=0,1,2$, and 3 modes is analyzed.**

I. Introduction

TO OUR KNOWLEDGE no exact solution of the Helmholtz equation is known for toroidal coordinates [1]. On the other hand, such a solution is of interest not only for microwave engineering, but also for the heating

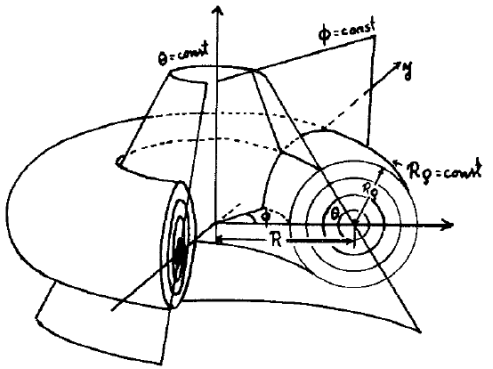
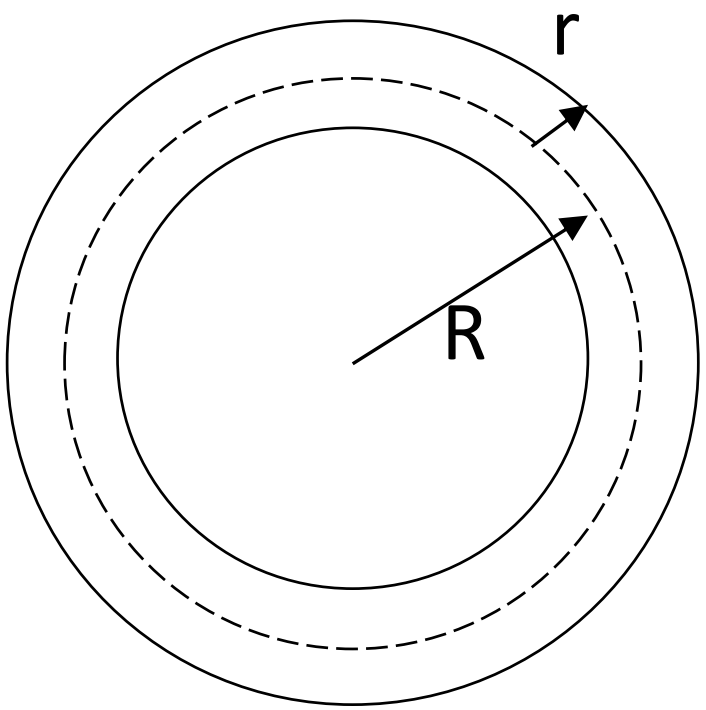


Fig. 1. The system of toroidal coordinates.

Analytic Modes



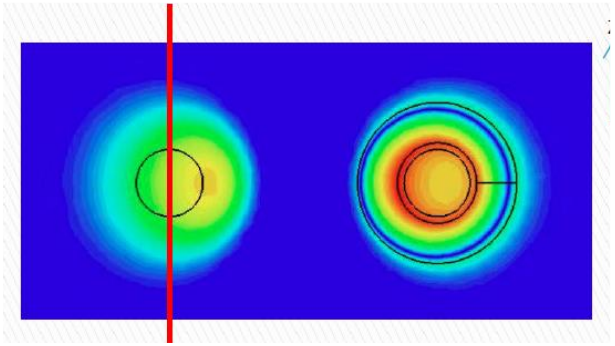
- Cap and Deutsch lEEE Transactions on Microwave Theory and Techniques Vol MTT-26,NO.7, JULY1978
- Janaki & Dasgupta IEEE Transactions on Plasma Science, VOL. I X . NO. I . FEBRUARY 1990
- Inverse toroid aspect ratio $\rho_0 = {}^{r}/_{R}$
- J & D expand in ρ_0
- $TM_{"like"} \propto \sum_{a=0}^{\infty} a_i \,\mathrm{TM} + \sum_{b=0}^{\infty} b_i \,\mathrm{TE}$
- As $R \to \infty$ $\rho_0 \to 0$ $TM_{"like"}$ $becomes$ TM
- For the dimensions contemplated there are no degeneracies, no crossings
- We used simulation to verify this

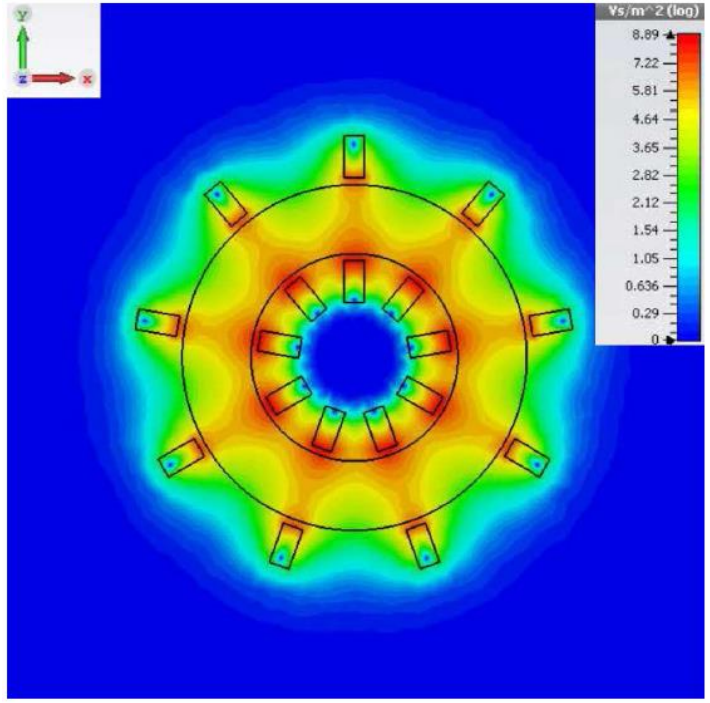
Effective Volume
B^2VC

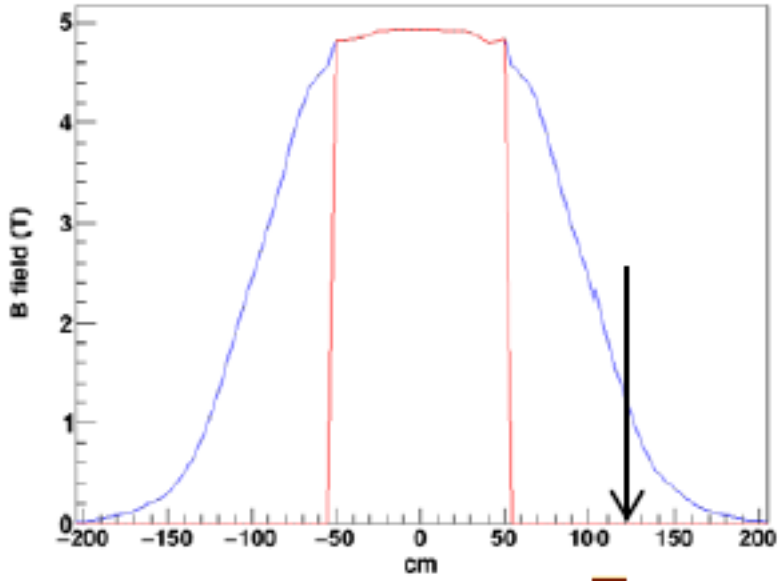
	B field (T)	$r_{cylinder}$ or r_{minor} (cm)	$h_{cylinder}$ or R_{Major} (cm)	Form Factor	B^2VC (T^2m^3)
ADMX solenoid	8	25	100	~0.5	~6.29
CAPP/IBS toroid	5	25	200	~0.6	~37.01

B. R. Ko; Axion Dark Matter Workshop, Stockholm

Low Fringe Fields





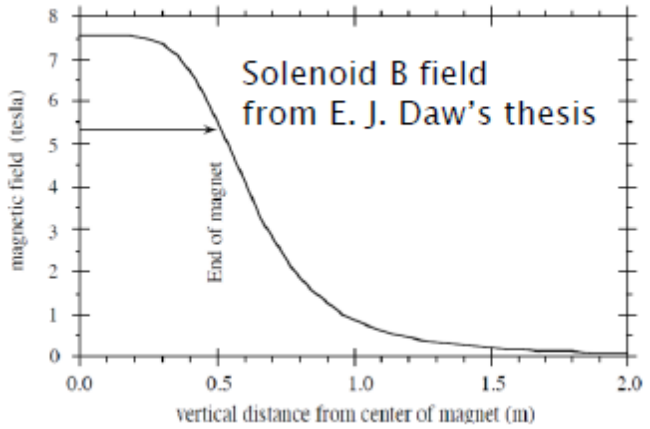


R = 200cm

R = 50cm

B_{avg} = 5T

9 coils



Q Factor

	B field (T)	$r_{cylinder}$ or r_{minor} (cm)	$h_{cylinder}$ or R_{Major} (cm)	Form Factor	Normalized Q factor	B^2VCQ (T^2m^3)
ADMX solenoid	8	25	100	~0.5	~1	~6.29
CAPP/IBS toroid	5	25	200	~0.6	~1.29	~47.74

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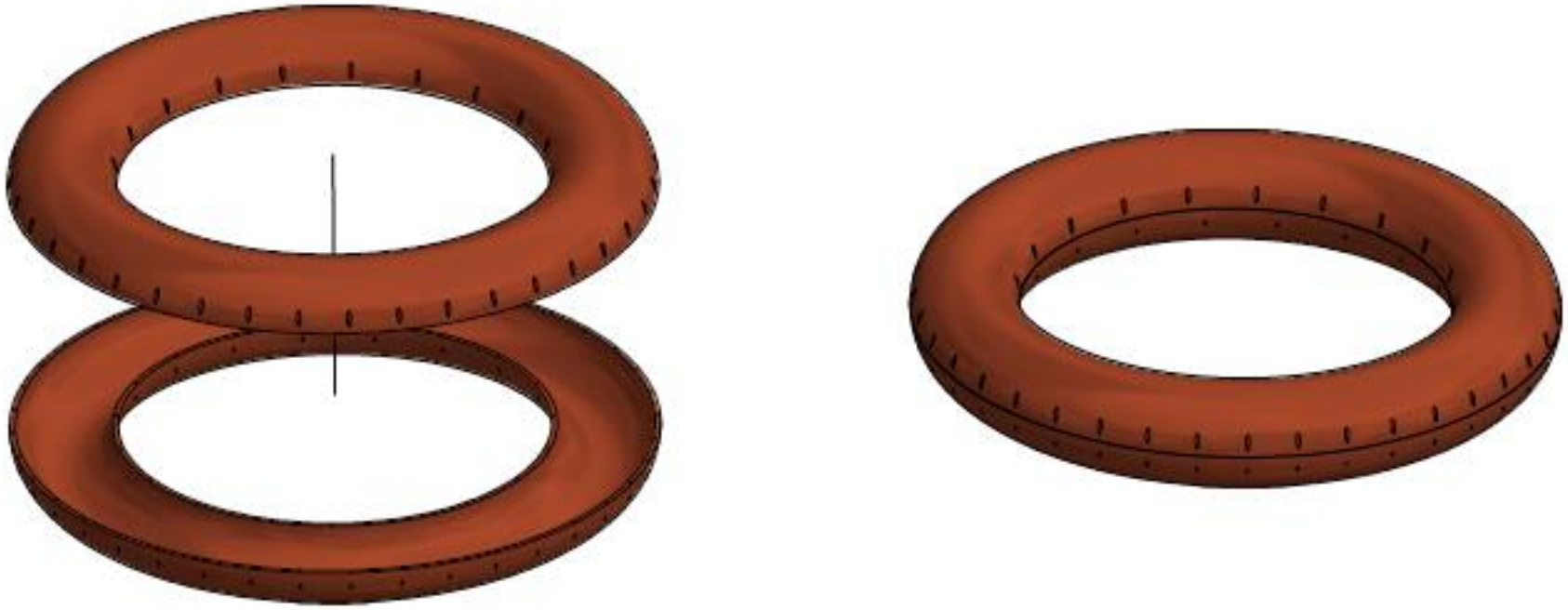
Assembly Concept



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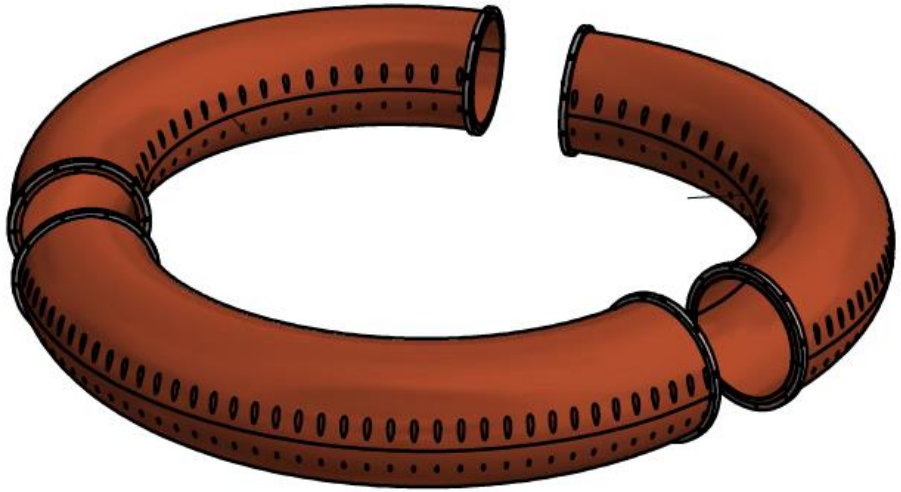

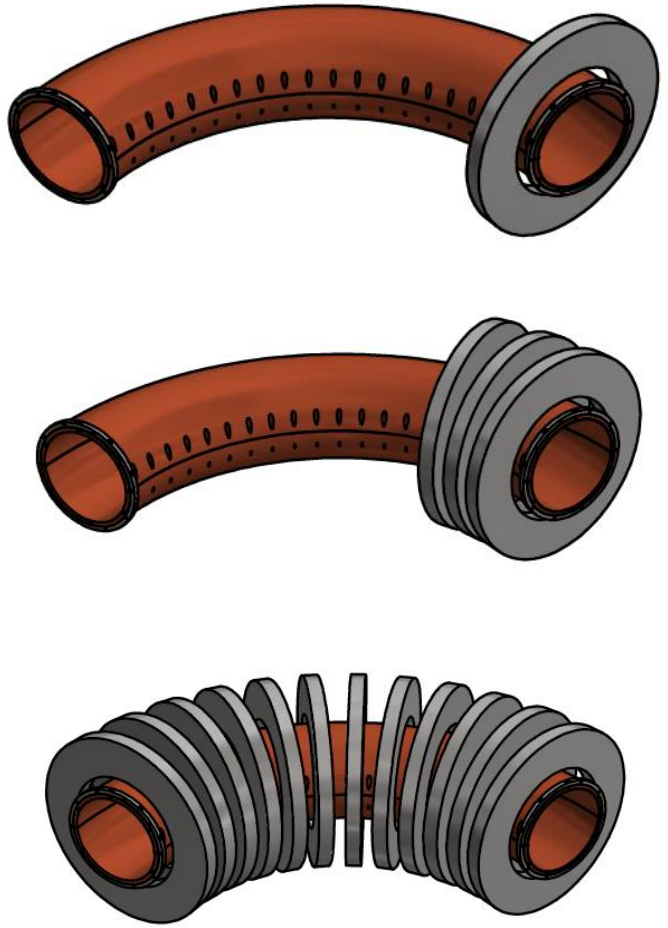

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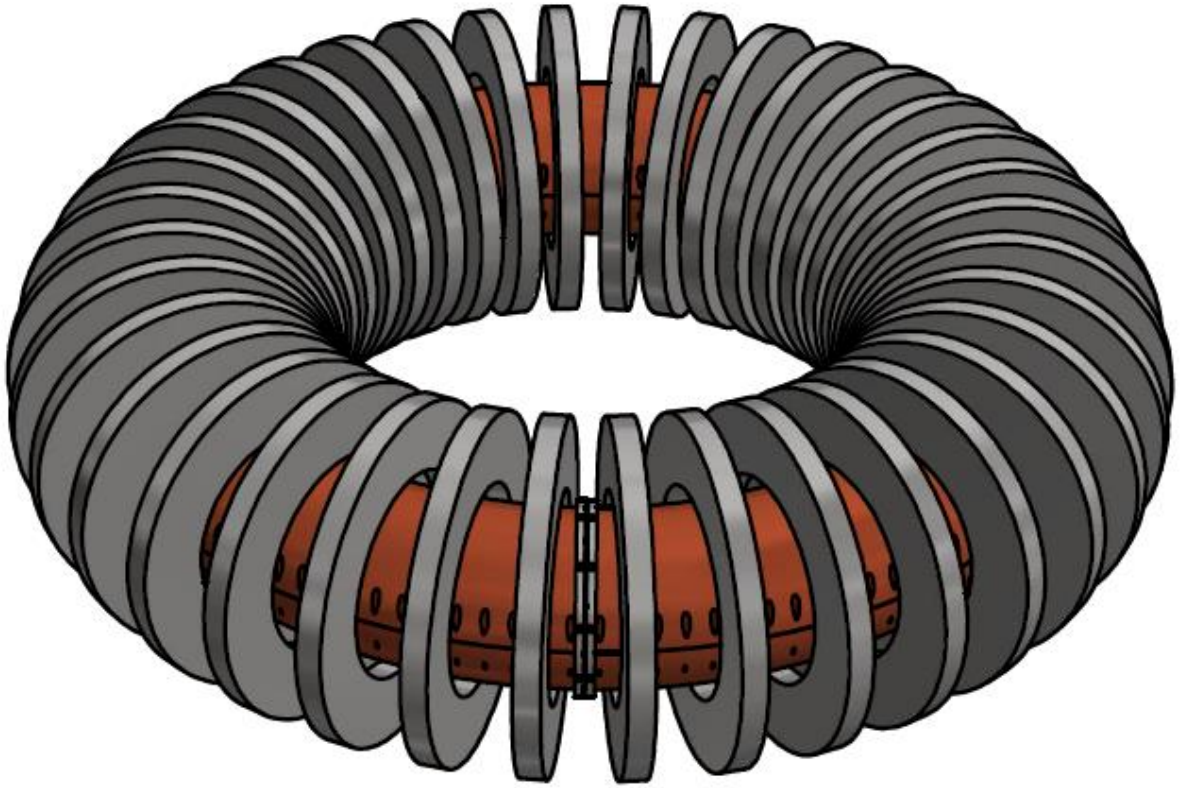
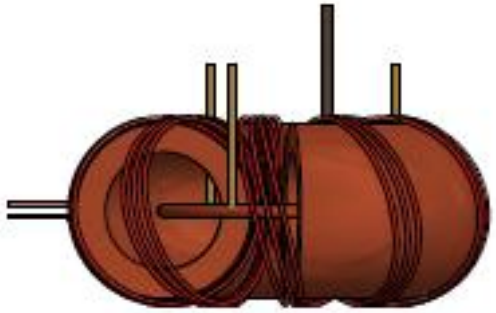
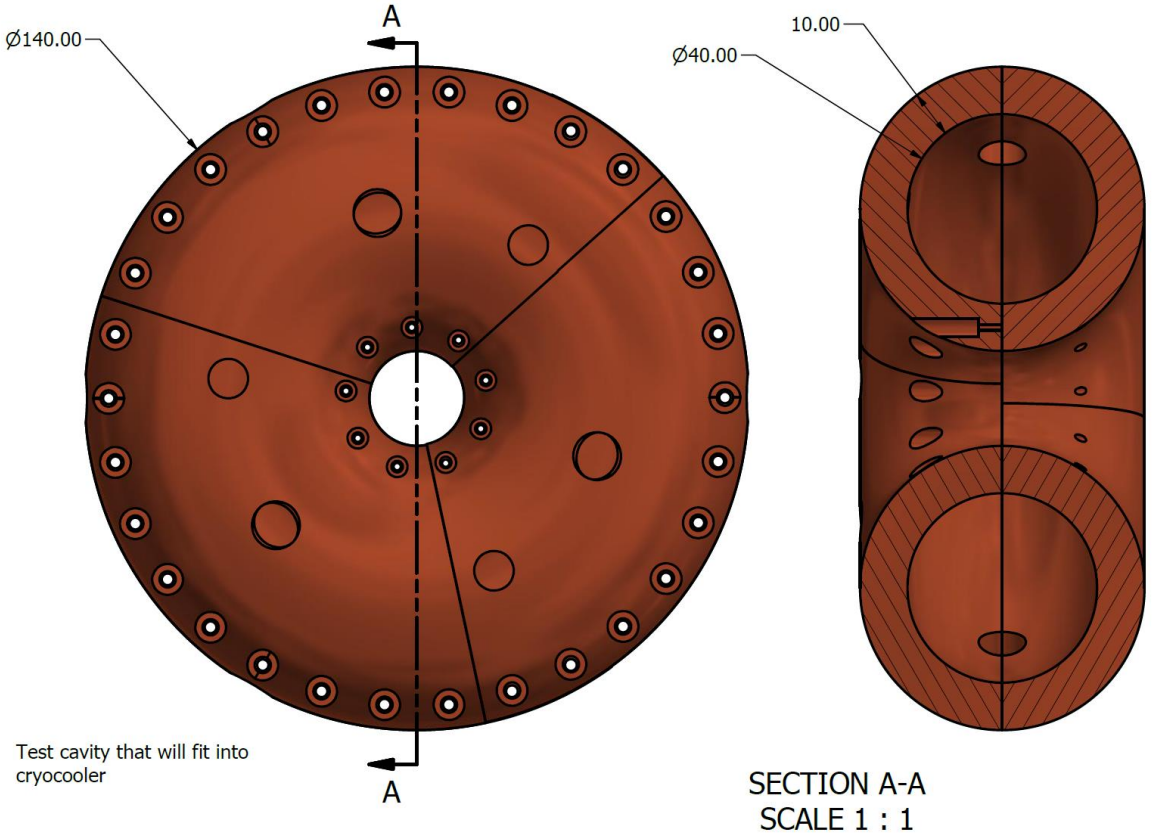




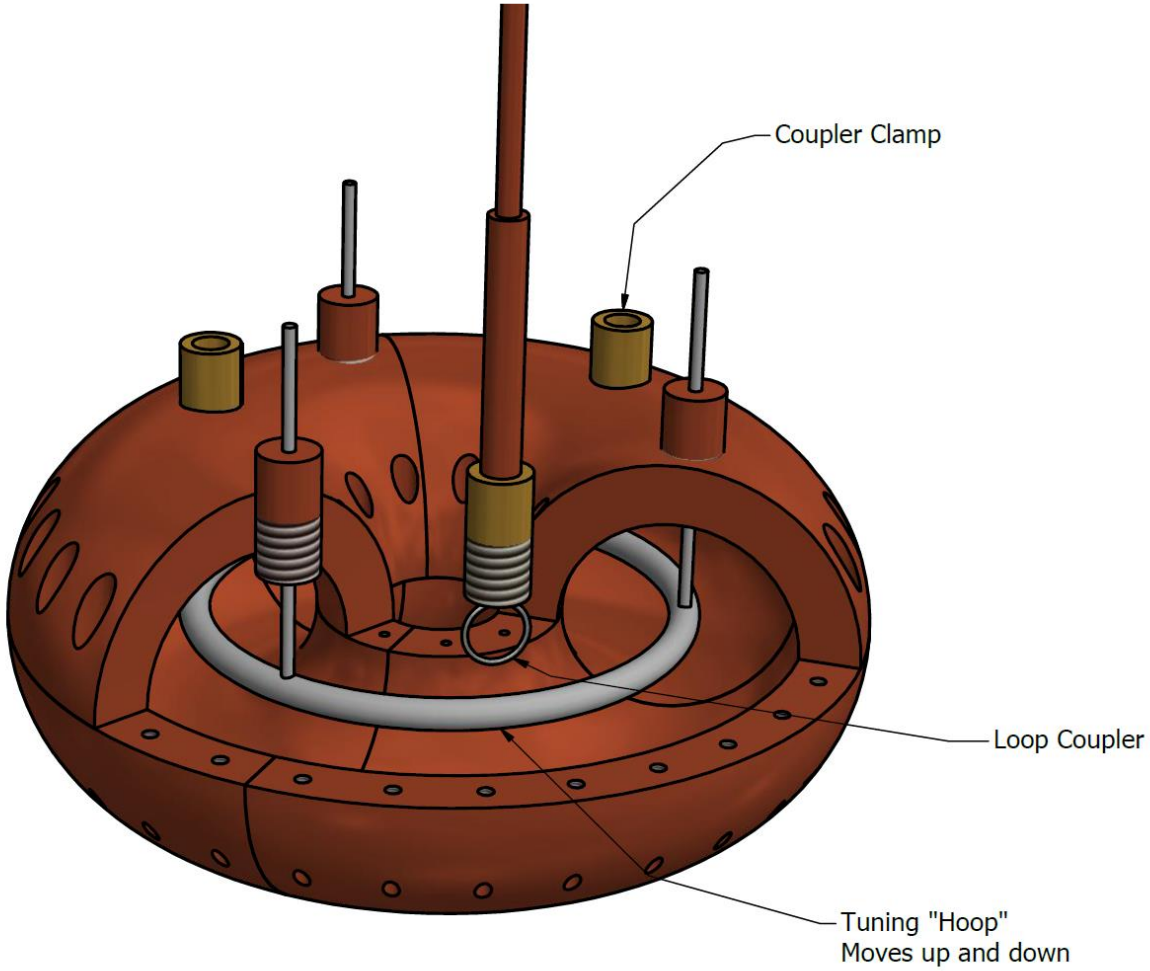
First Toroid “SUB”

- Driven by a desire to be able to mount in a cryocooler available to us
- R=4cm r=2cm $\rho_0 = 0.5$
- Simulation verifies no mode crossing



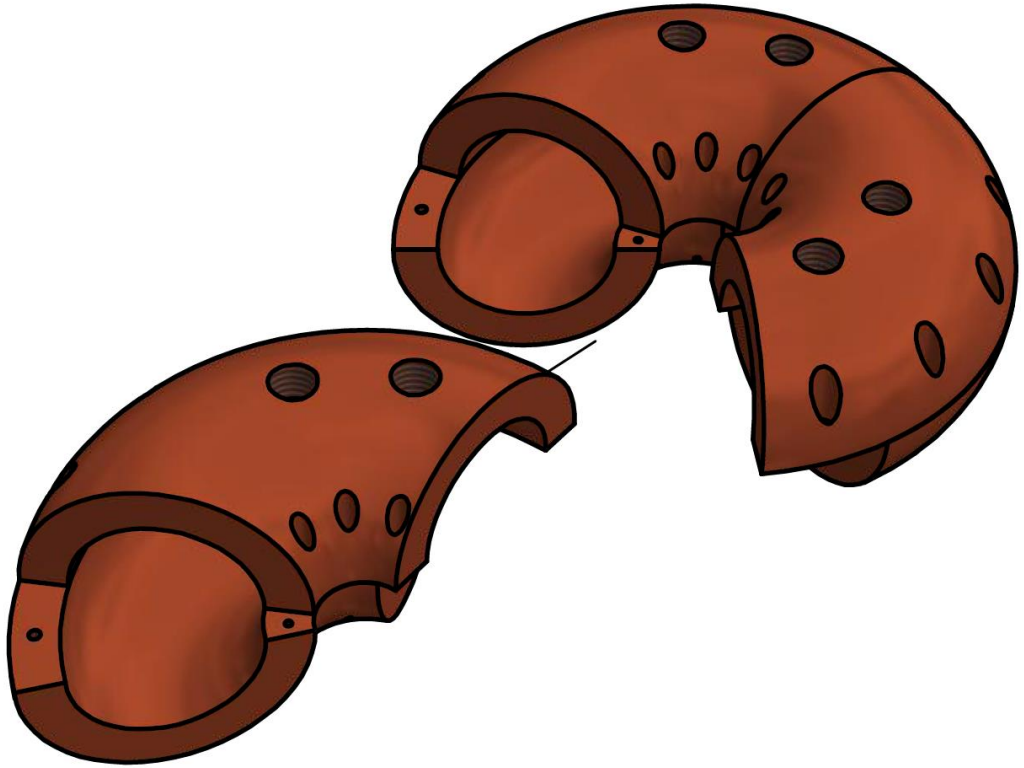
Cappuccino “SUB”

- Early iteration of design
- Simulation
  - Dimensions of SUB
  - Dimensions of tune hoop
  - Antenna sizes and shapes
  - Antenna placement (we had them at angles in the beginning)

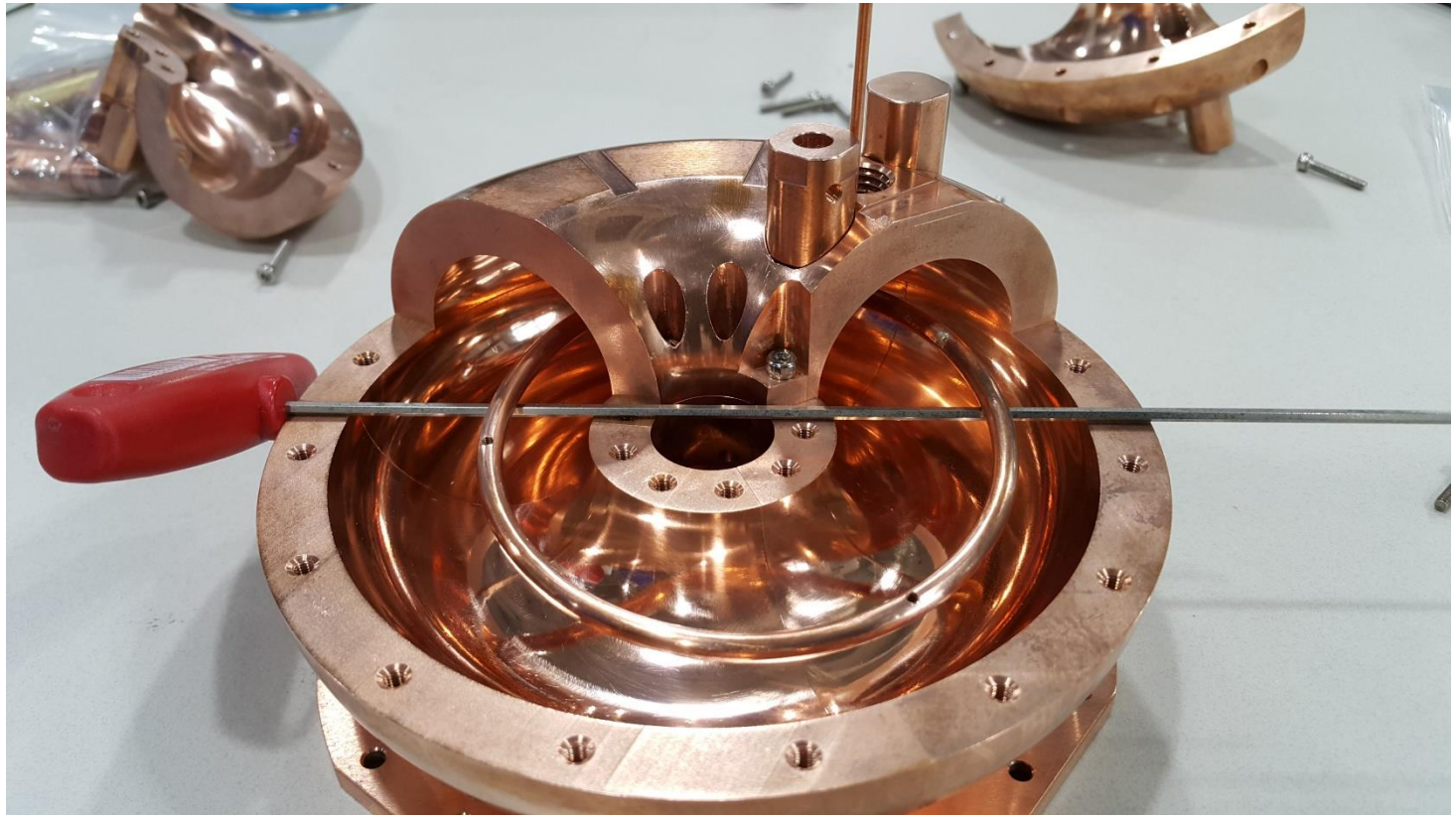


Design Challenges

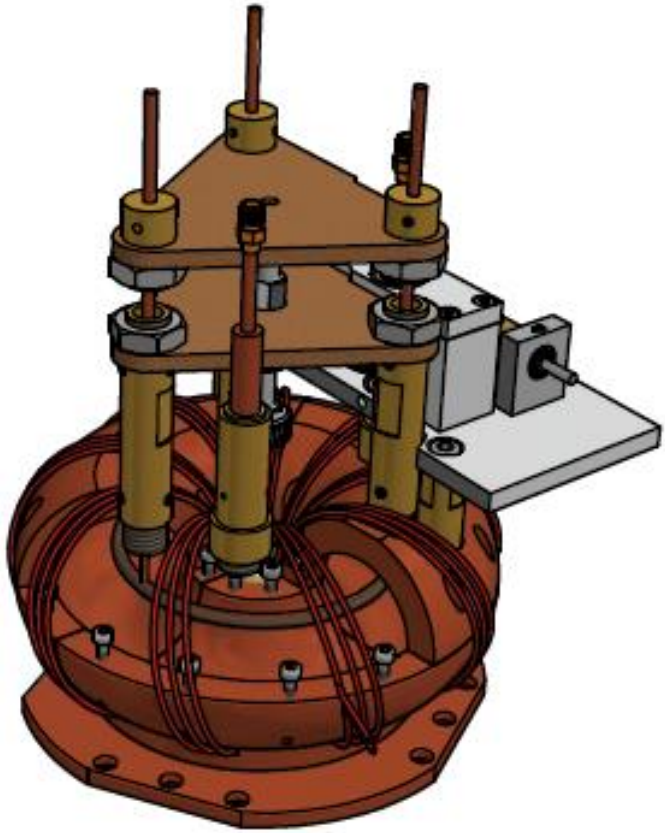
- Three sections not necessary for this model but we decided to have a learning experience
- One challenge was to exert force to push ends together

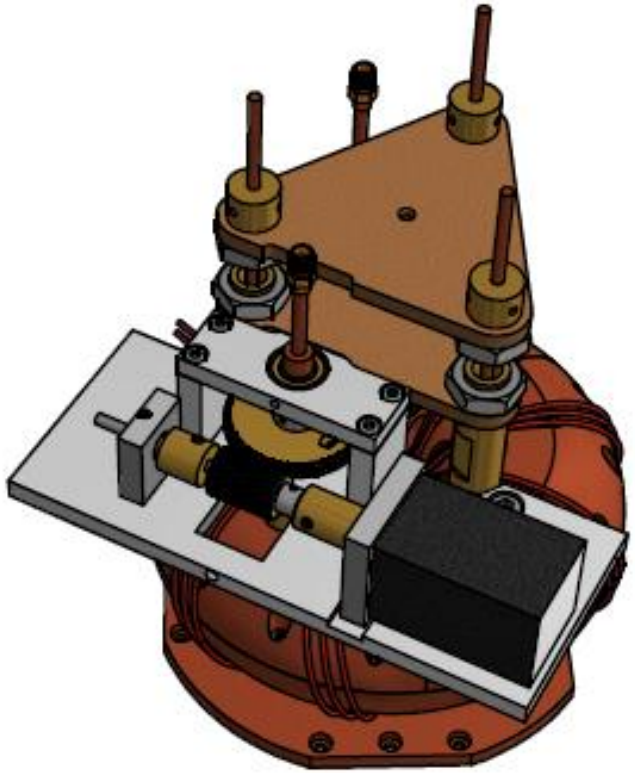


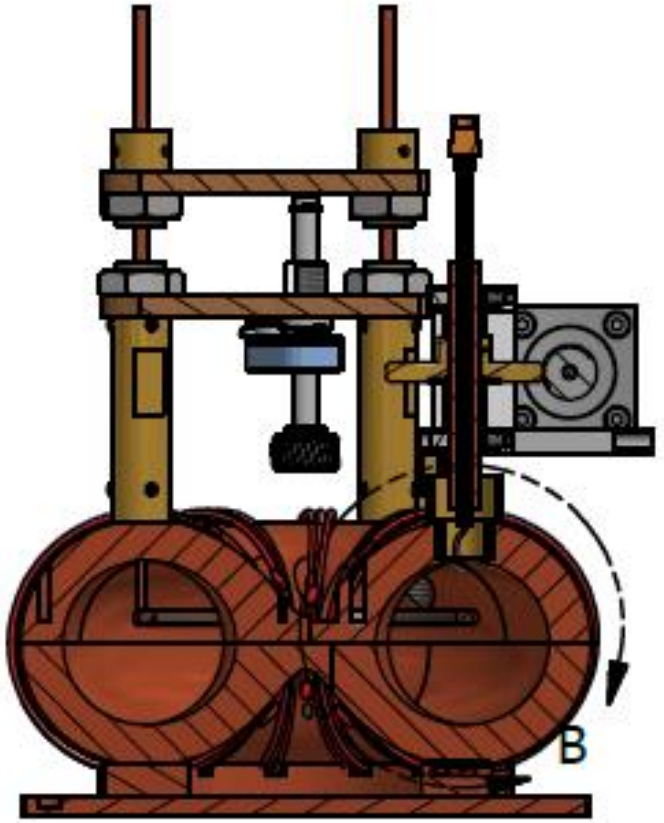
Photo



CAD Pictures

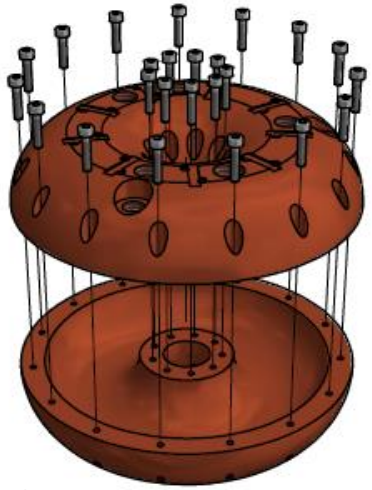


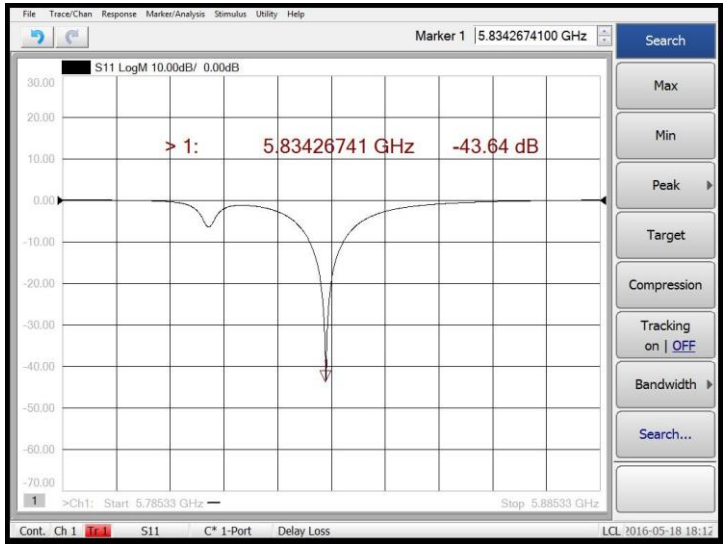




First Look

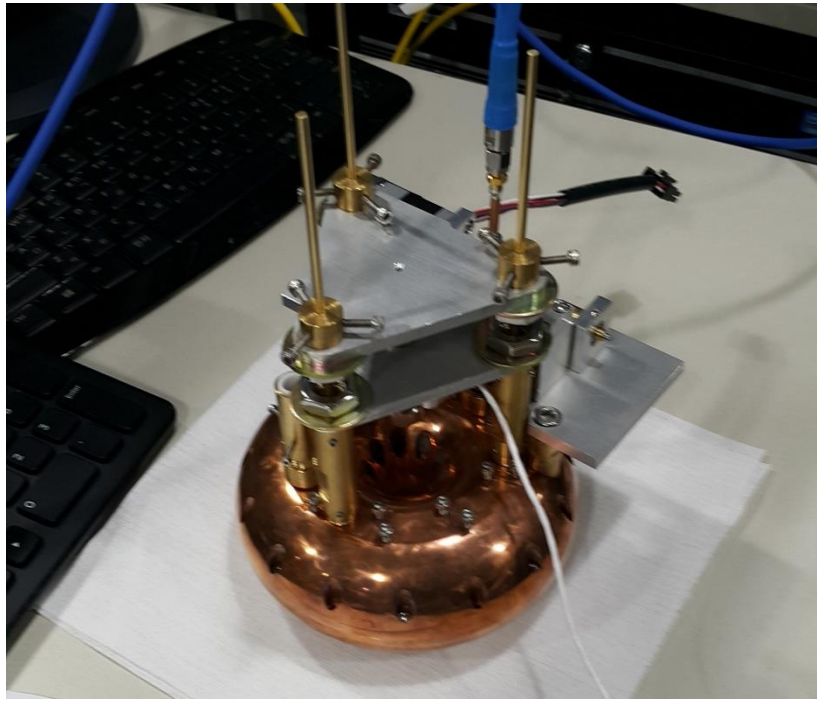
- Coupling issues, cross talk with each other with hoop, sim vs data
- Best antenna shape/size, reality vs simulation
- Q factor
  - Calculated 20 000
  - Alignment issues, best 6000
  - Indium “gaskets” were a failure
  - Bagel cut achieved 20 000 w/o hoop

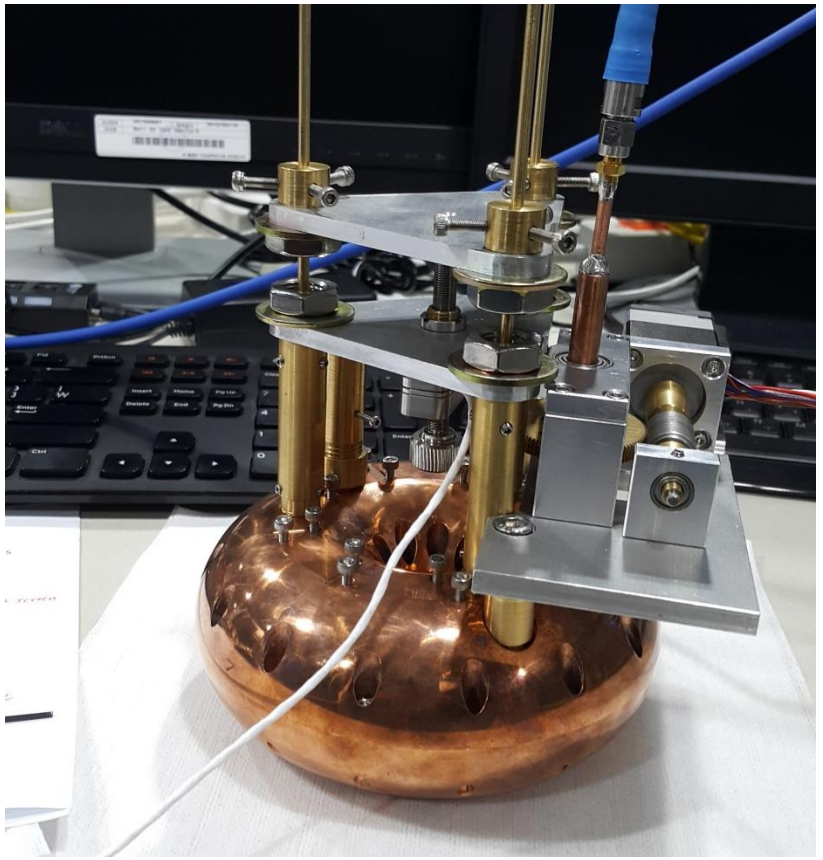


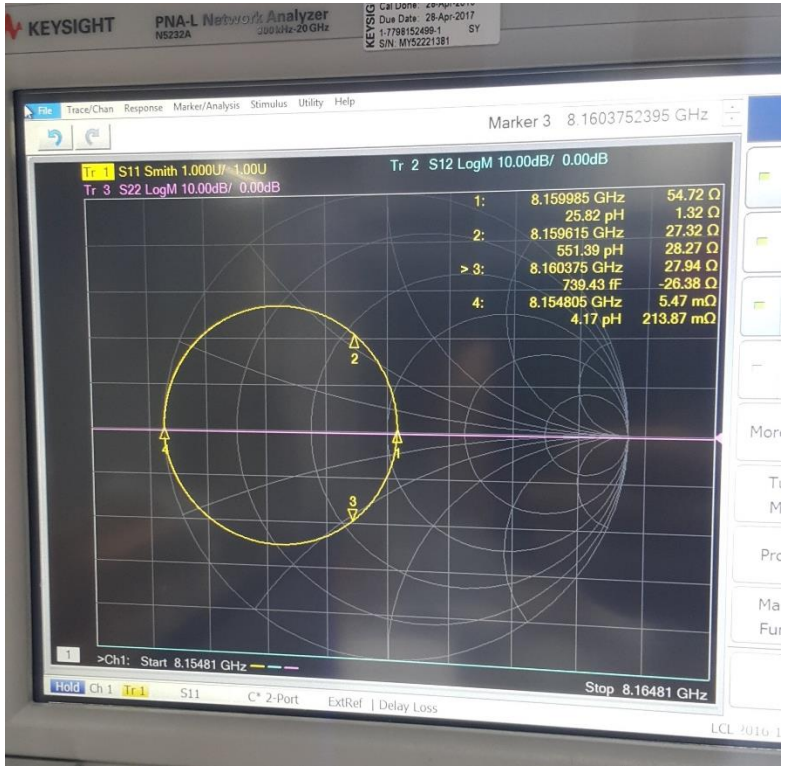


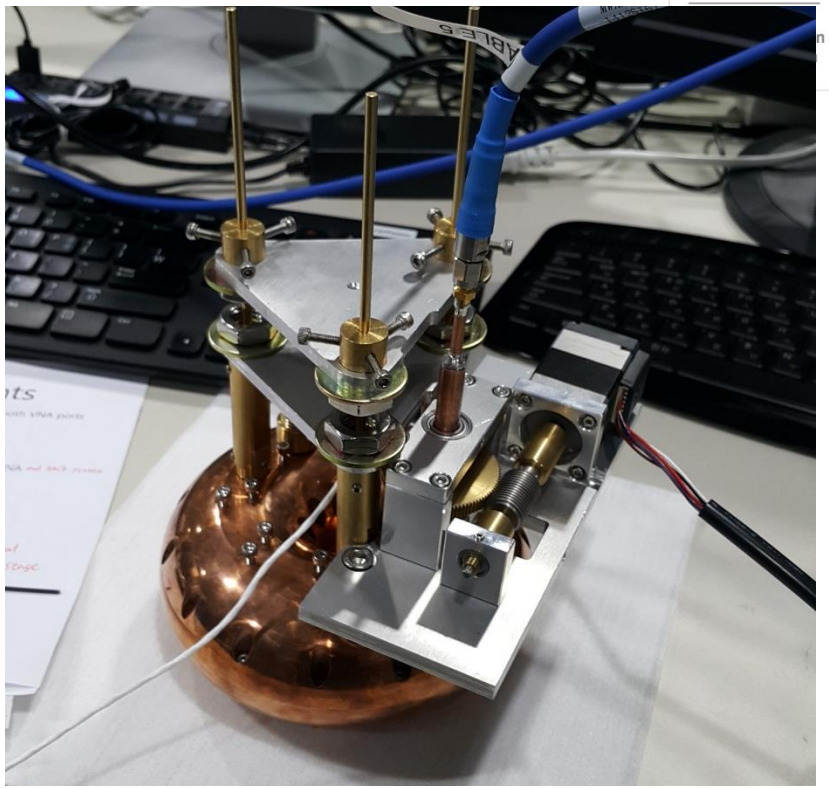
- The simulations predicted that the hoop must go upwards but doesn’t seem to matter

Finished Product







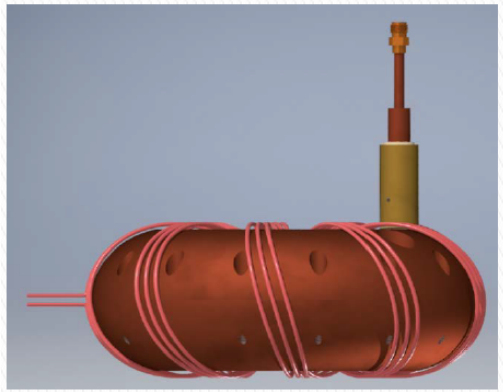


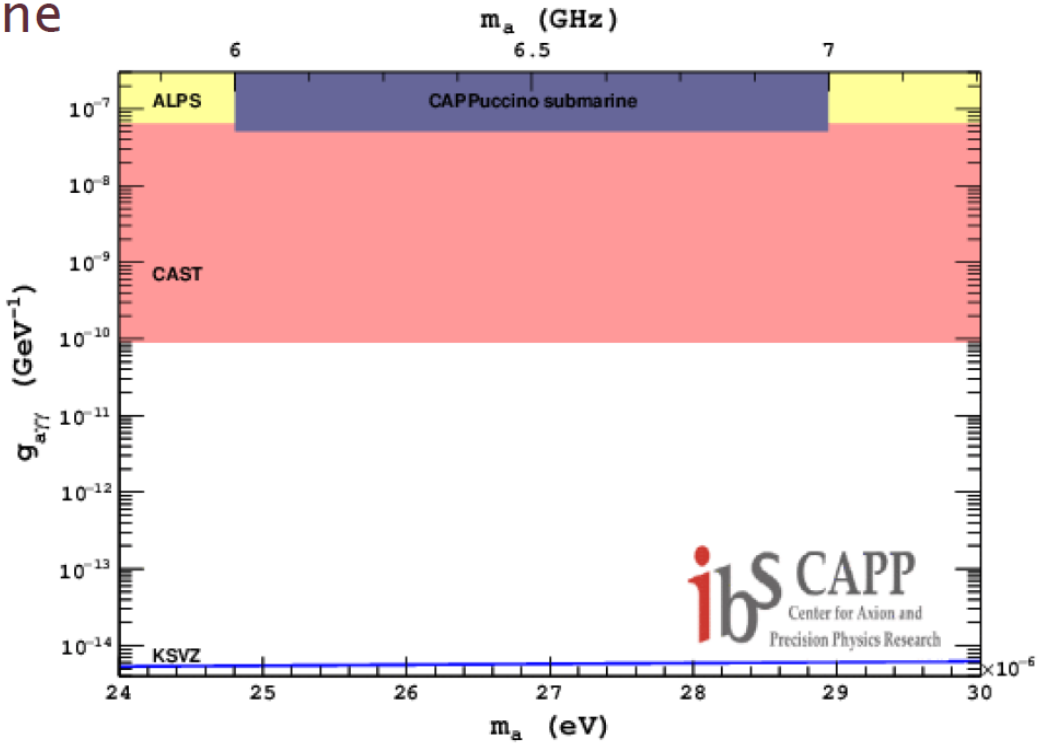
Q = 10,700

CF = 8.159GHz

Simplified toroidal system ; B_{avg} ~ 32 G, cavity with Major R=4 cm, minor r= 2cm

CAPPuccino submarine





Will be better than 2010 ALPS limit in 6~7 GHz

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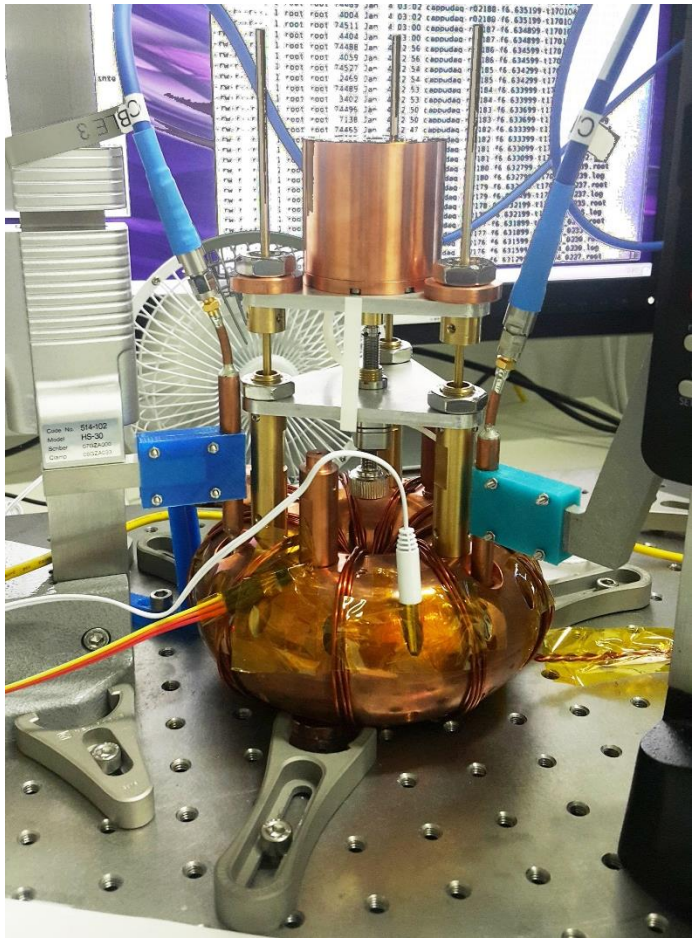
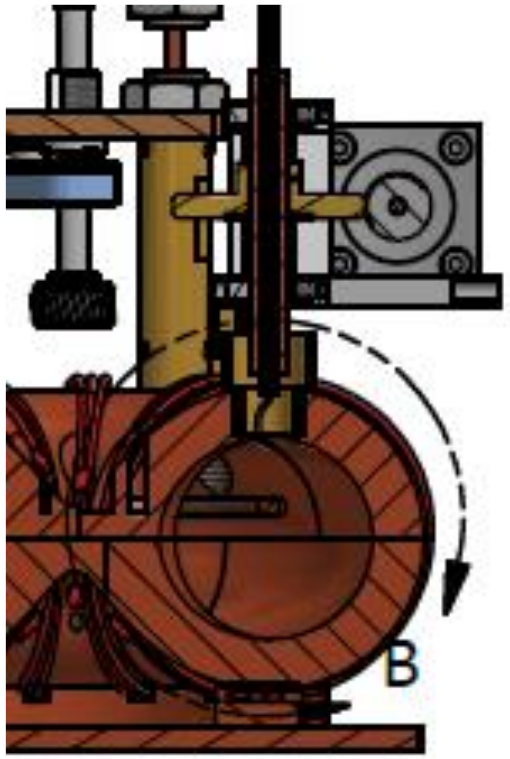
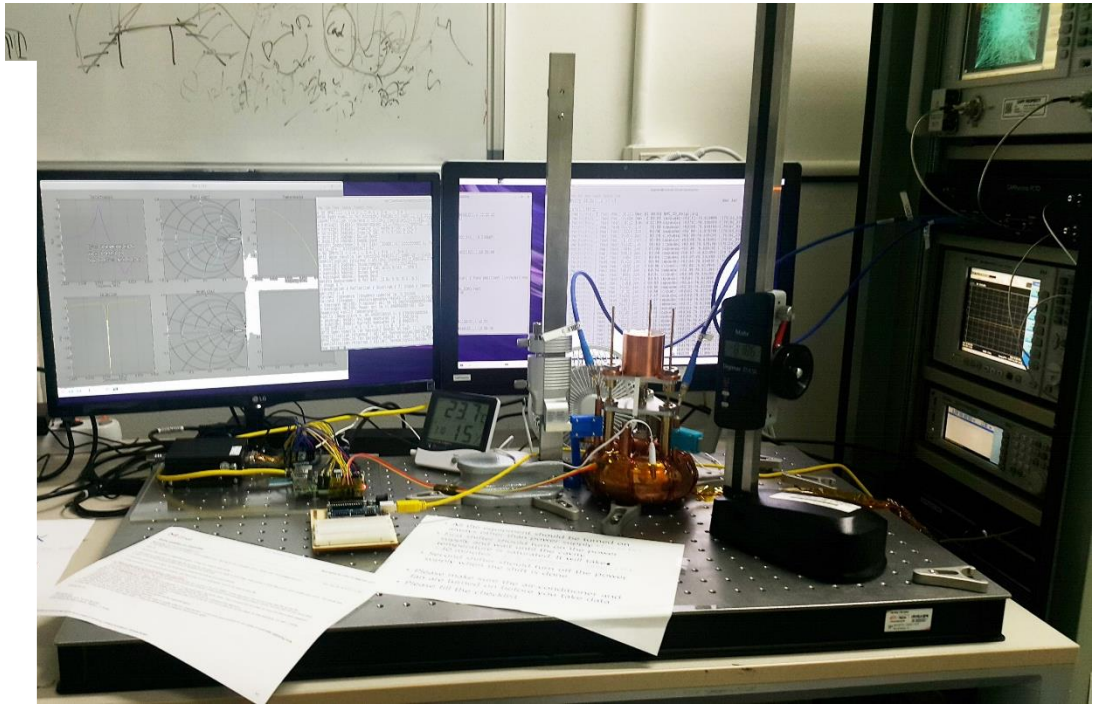
Pictures



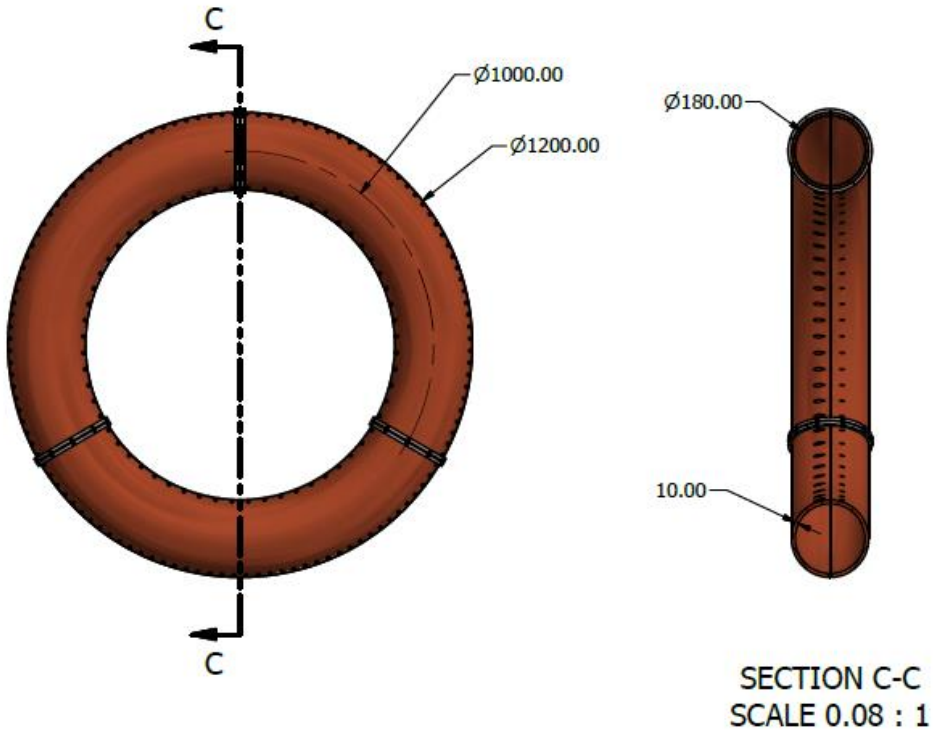




Future

500mm Major Radius

- Continue to develop flanging
- Scale up tuning
- Cryogenic ready
- Packaging
  - Physical placement
  - Placement WRT to cooling
  - Cable routing
  - Actuation routing

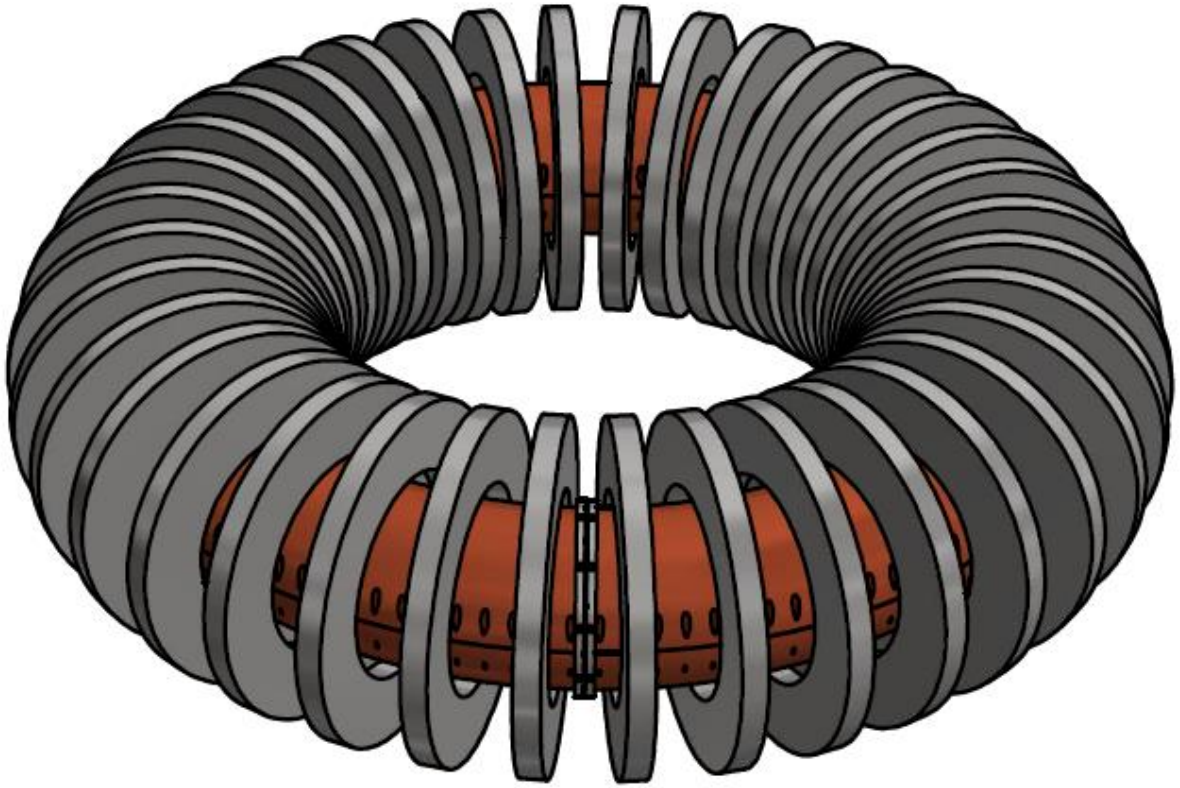


Conclusion

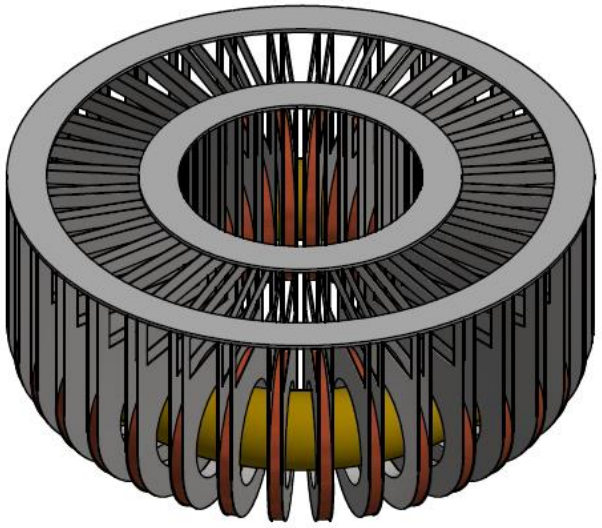
- We have a working toroidal cavity
- Learned a lot but this has also made us realize that there are some daunting challenges in front of us.
- CAPP LVP Hall is building momentum rapidly

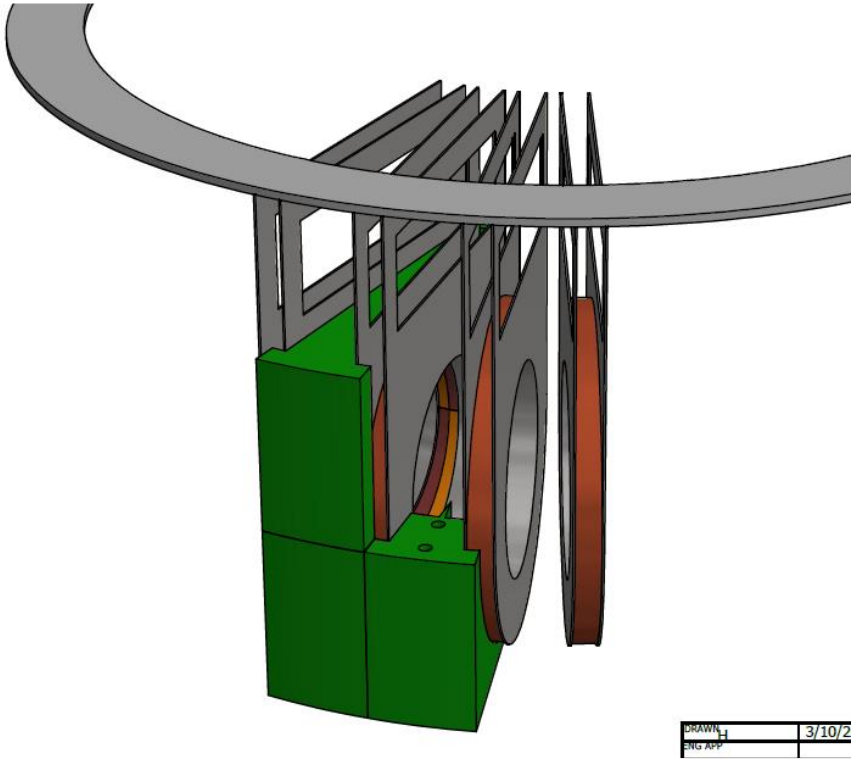
BACKUP

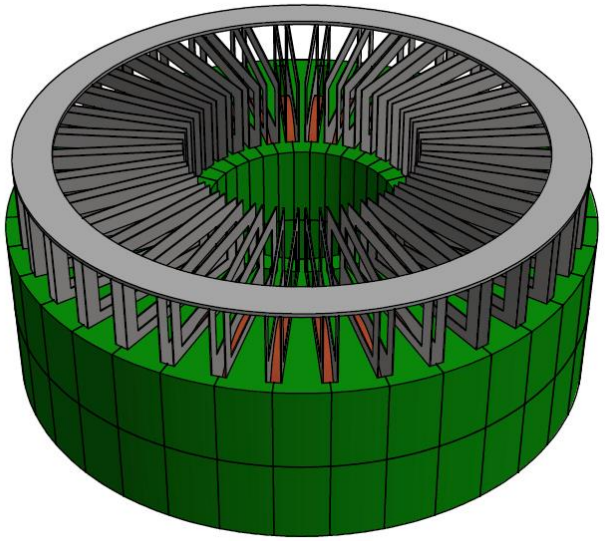
Assembly Concept

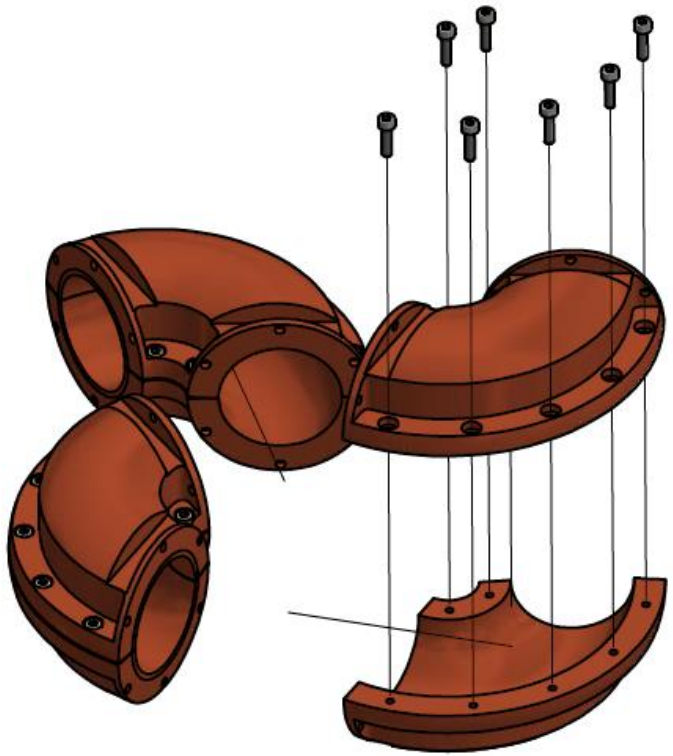


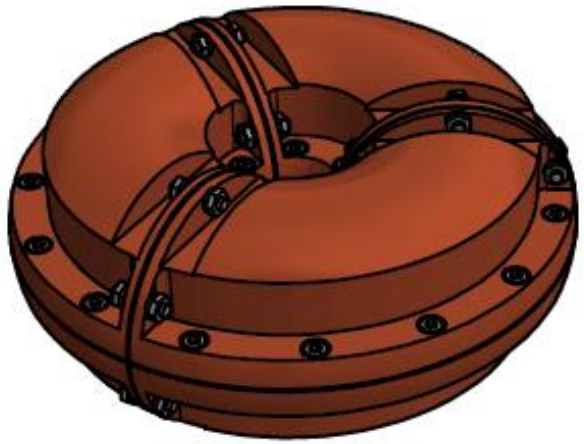
Challenges

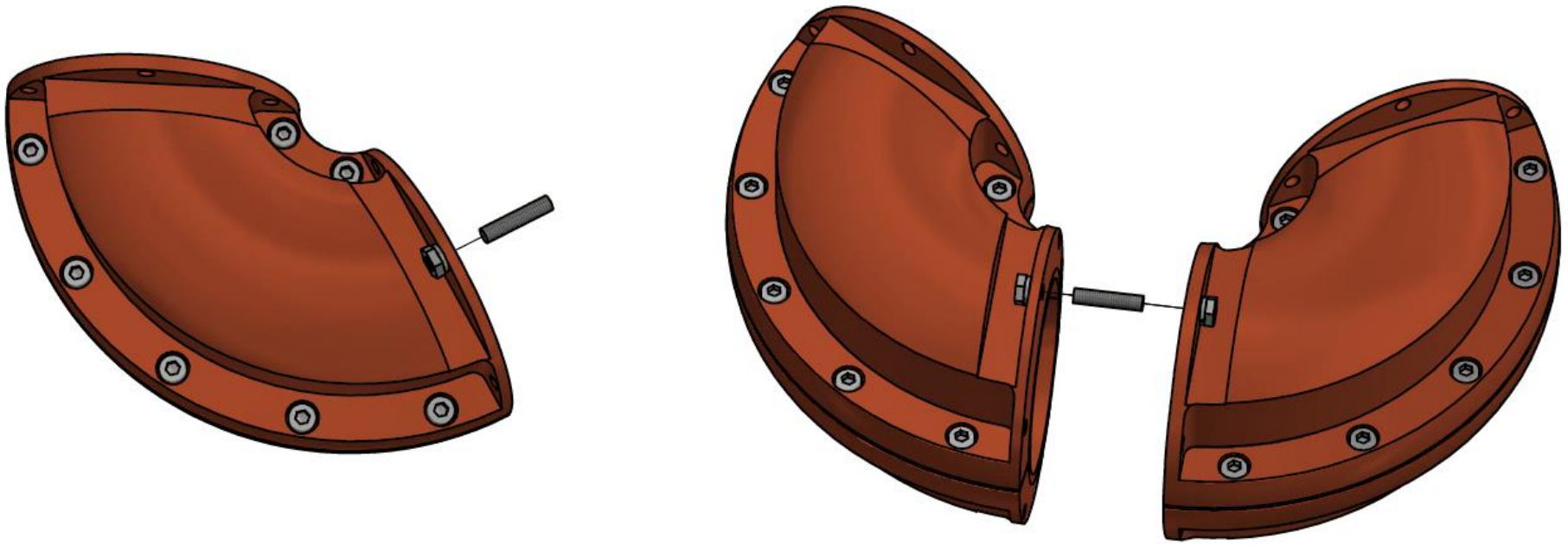


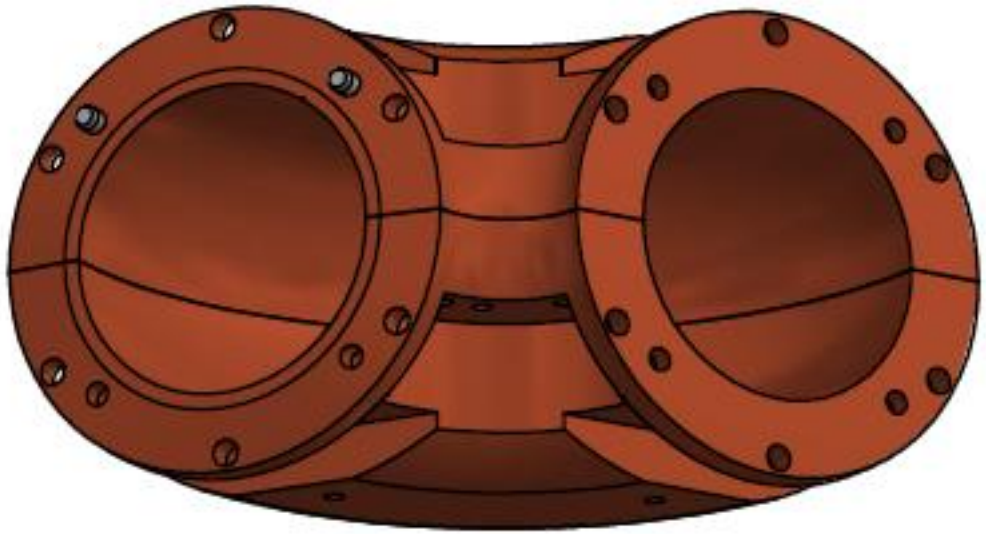


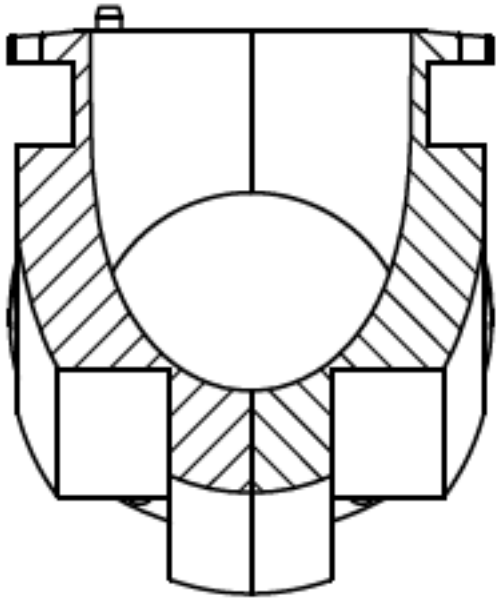












Axion Haloscopes at CAPP/IBS

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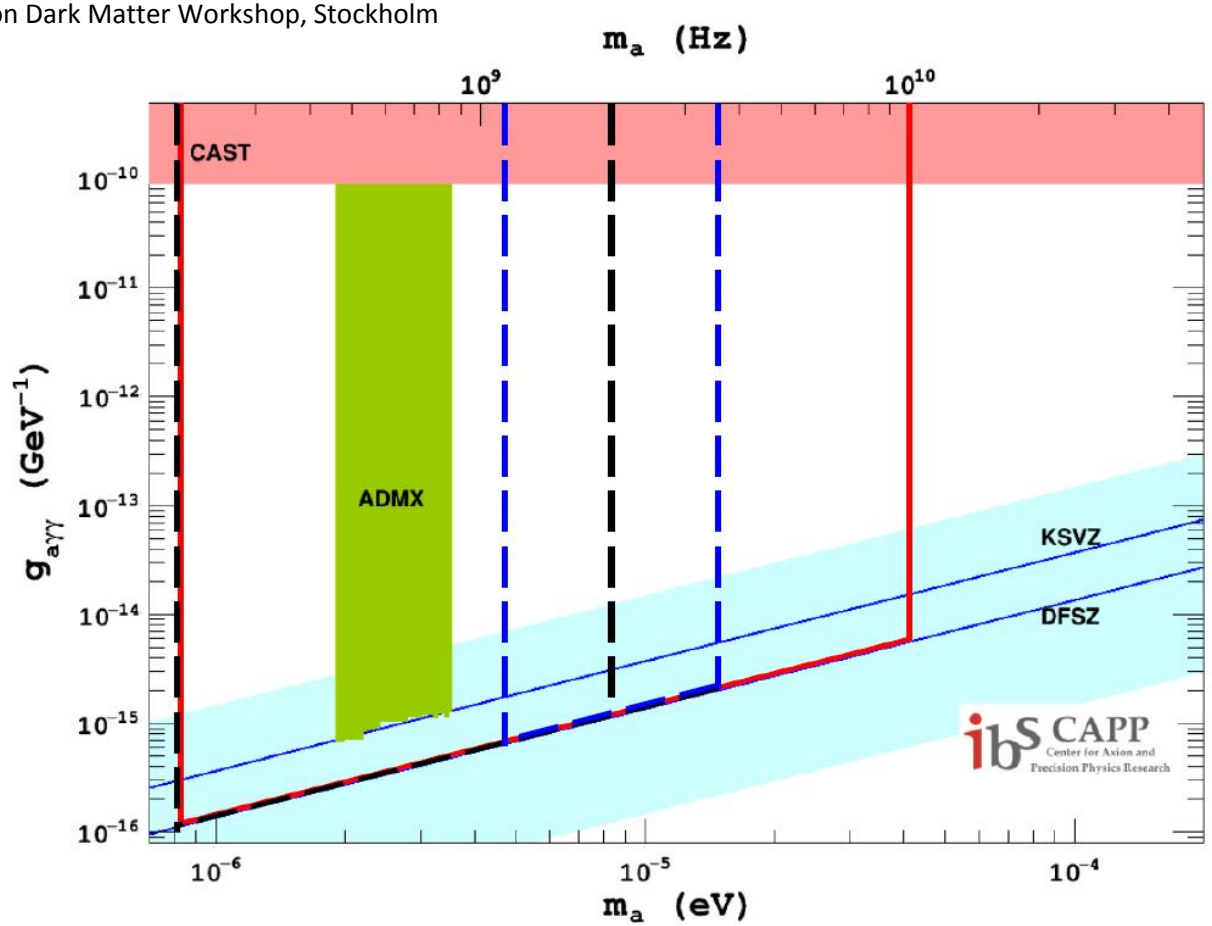

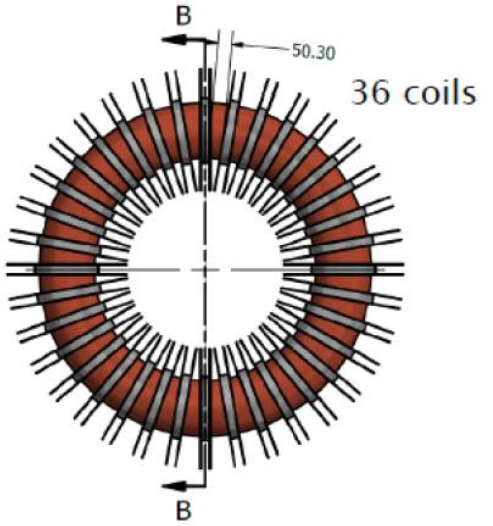

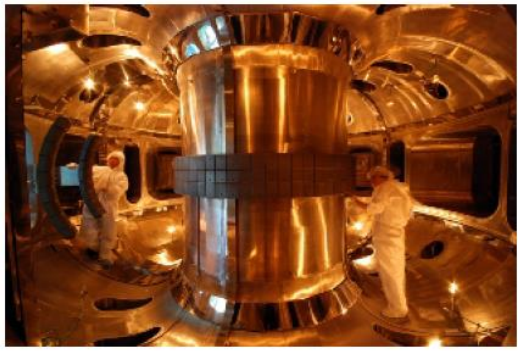

For [0.2, 3.6] GHz, larger volume from toroidal geometry;
80 L (blue) → ~9,900 L (black)