The FNAL Booster 2nd Harmonic Cavity

Robyn Madrak for the 2nd Harmonic Cavity task group

61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams

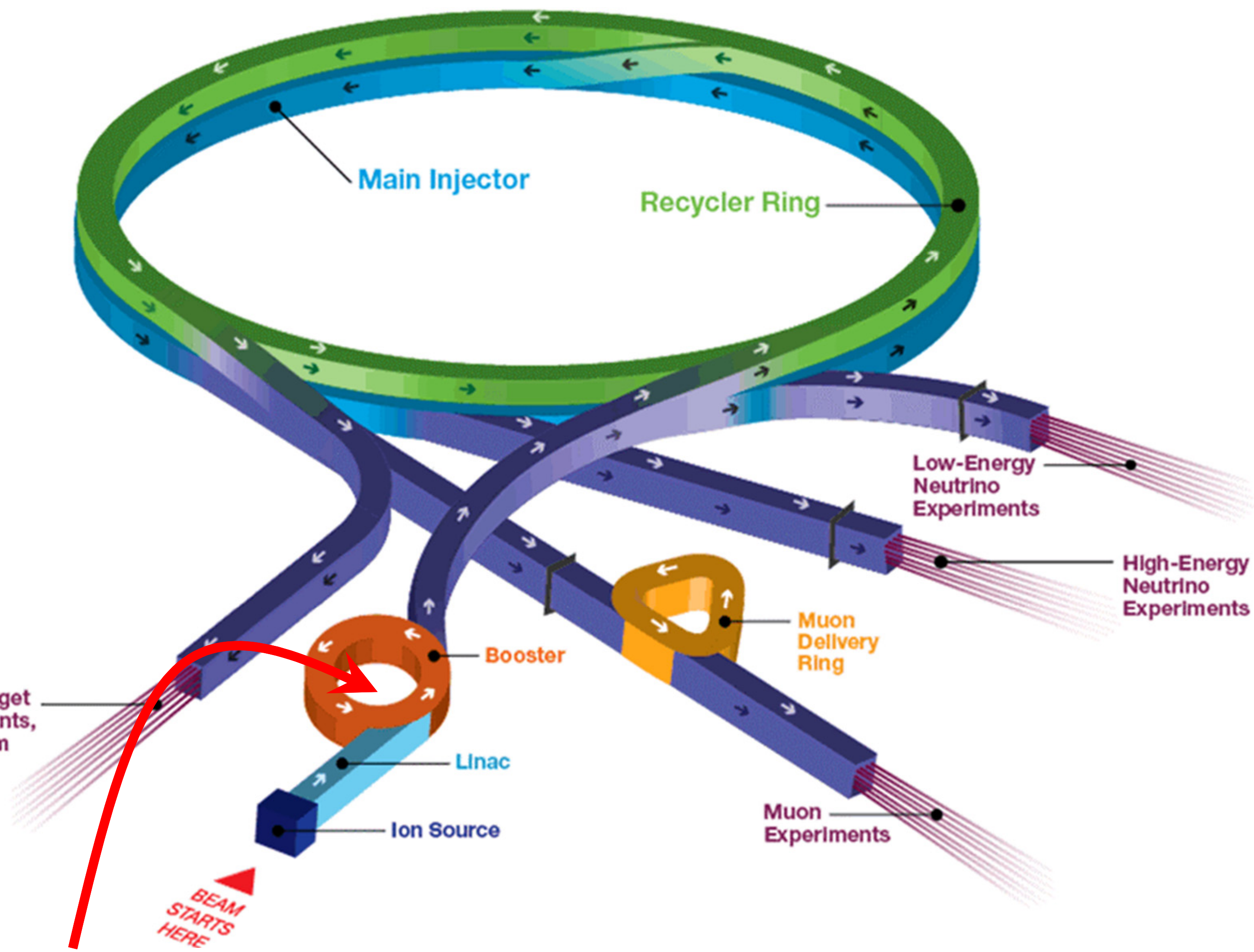
21 Jun 2018

People Involved

- John Kuharik (Accelerator Division, Masters Student)
- C. Y. Tan, Bill Pellico (Accelerator Division, Proton Source)
- Gennady Romanov, Yuri Terechkine, Sasha Makarov (Technical Division)
- Kevin Duel, Matt Slabaugh (Accelerator Division, Mechanical)
- Joe Dey, Robyn Madrak, Rene Padilla, John Reid, Ding Sun, Matt Kufer (Accelerator Division, RF)
- Technicians, to name a few: Daren Plant, Bob Scala, Ryan Montiel, En Sukkert, Gerik Wysocki, Ken Klotz, Rocky Rauchmiller, Jeff Larson, Drew Feld, Ken Koch, Mike Henry

- ***Many thanks to National Magnetics for the manufacture of our garnet and the assembly of the tuner rings with our required consistency and precision***.

Fermilab Accelerator Complex



- Booster: accelerates beam from 400 MeV to 8 GeV
- Has 22 accelerating cavities operating at ~38 – 53 MHz

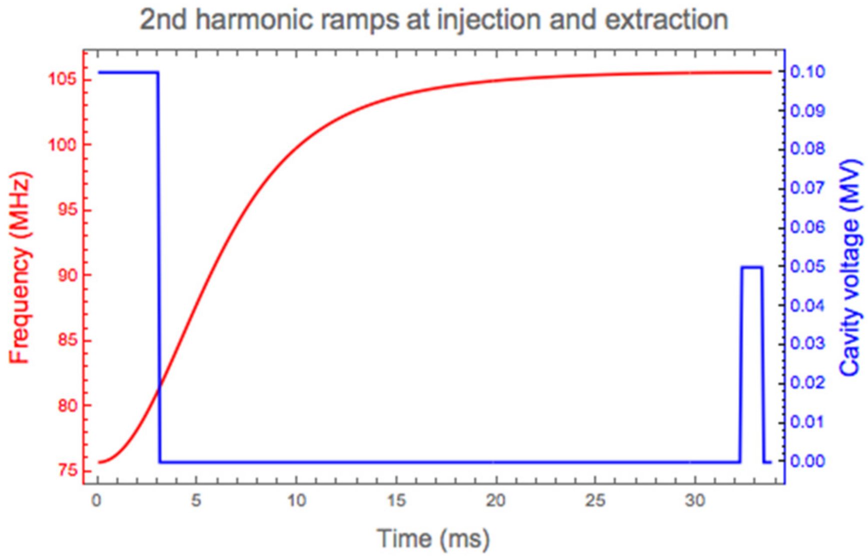
2^{nd} Harmonic Cavity: ~ 76 – 106 MHz

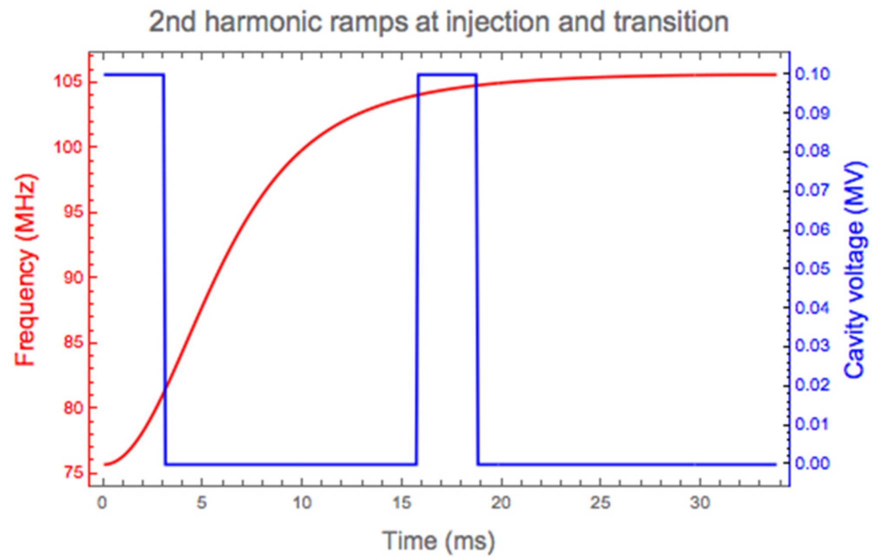
Works at double the frequency of the fundamental cavities

- Purpose – to reduce losses
  - First and foremost: increase capture at injection by flattening the RF bucket
    - Must have at least 100 kV gap voltage (one cavity)
  - Can also be used at transition and extraction

- Unlike the fundamental frequency accelerating cavities 2^{nd} harmonic will be turned on only for a few ms of the 33 ms Booster ramp
  - Only necessary to be on at these times to achieve the goal
  - This decreases duty factor and helps with any cooling issues

Example (possible) ramps



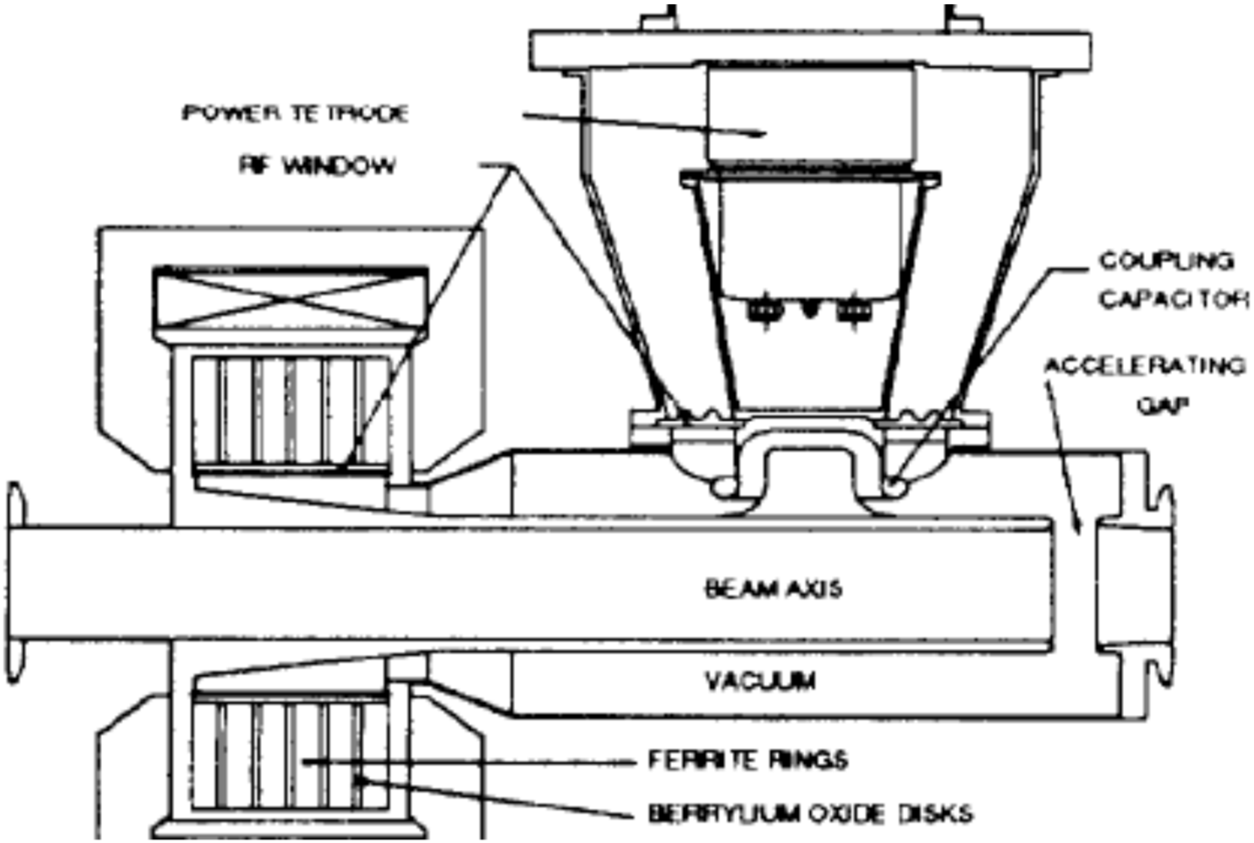


- Red = frequency ramp (left axis)
- Blue = gap voltage (right axis)

Perpendicular Bias

- Many wideband cavities tune using parallel biased ferrite
  - The bias magnetic field is parallel to the RF magnetic field
- Prototype cavities have been developed showing that the perpendicular bias method is advantageous due to lower losses
  - (LANL, TRIUMF, SSC Low Energy Booster)
  - Lower losses – higher shunt impedance
- This comes down to choice of material.
  - In general, the higher the bias, the lower the losses
  - “newer” materials (garnet) have a lower saturation magnetization (M_s) and can be biased into saturation (low losses) with a reasonable field
    - But in order to maintain tuneability, bias must be perpendicular
    - When the bias is perpendicular, μ varies as B/H instead of dB/dH (parallel case), which is small when the ferrite is near saturation

Early Perpendicular Bias Cavity with tuner on-axis (LANL/TRIUMF)



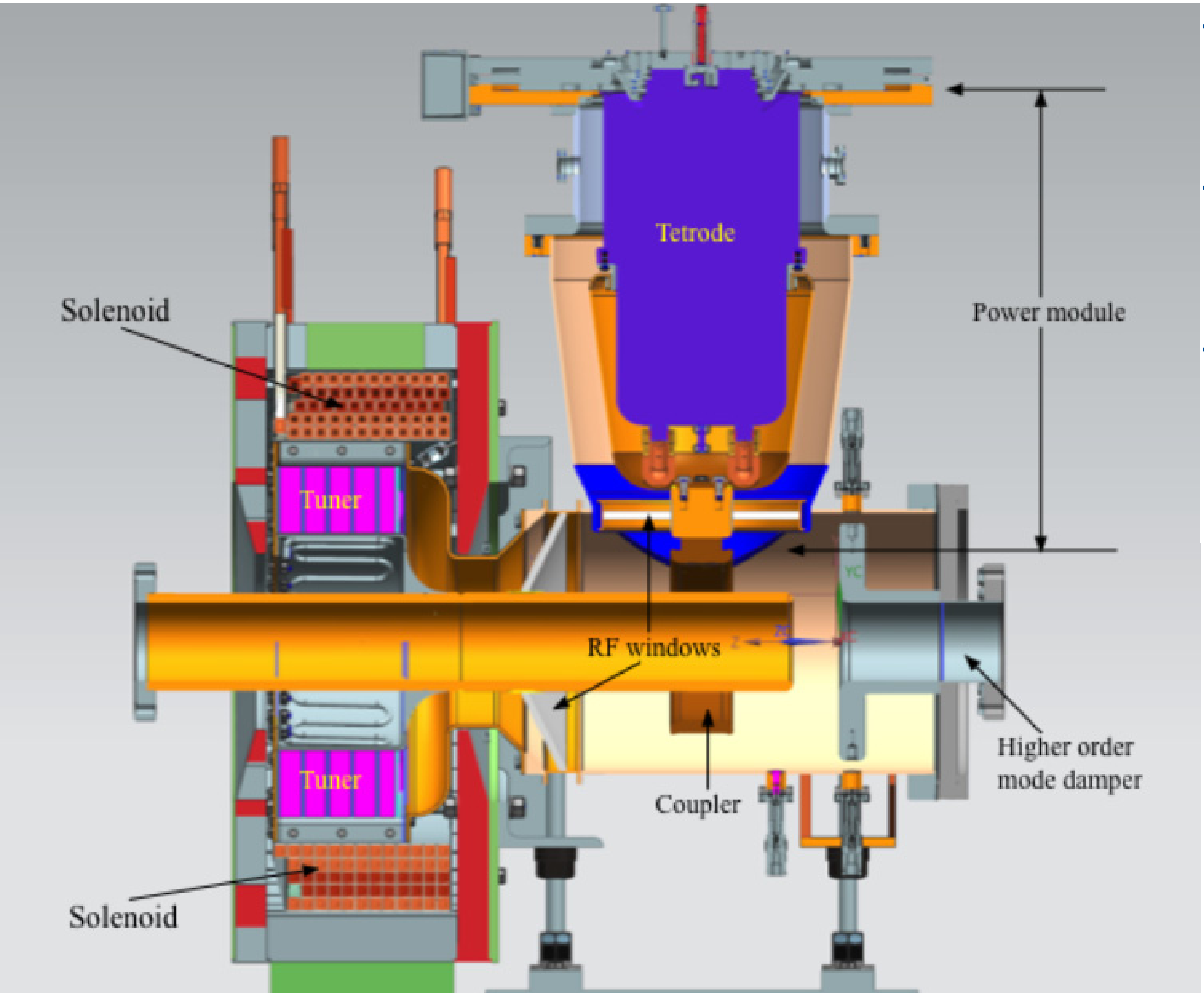
From R. L. Poirier, "Perpendicular Biased Ferrite-Tuned Cavities"

Various parameters of tuners with perpendicular bias

	TRIUMF Booster	SSC LEB	FNAL cavity
Min f(MHz)	46.1	47.5	75.7
Max f(MHz)	60.8	59.8	105.6
Peak Gap V (kV)	62.5	127.5	100
Accelerating time (ms)	10	50	33*
Rep Rate (Hz)	50	10	15
Ferrite Material	TT-G810	TT-G810	NM-AL-800
~ Min μ(ferrite)	1.48	1.4	1.2
~ Max μ(ferrite)	3.94	3.2	3.2
Cavity Q	2200 - 3600	2800 - 3420	3200 - 5700

* Cavity is turned on for only a few ms

Cavity Model



- Length flange-to-flange:
  844 mm
- Aperture:
  76 mm
- $P = V^2/2\ R_{sh}$
  76 MHz, R_{sh} = 96 kΩ
  106 MHz: R_{sh} = 180 kΩ

Challenges

- Achieving the large tuning range with realistic magnetic field
- Keeping the magnetic field in the tuner as uniform as possible
  - In transition region from garnet to air, field in garnet is low
  - When field is low, local values of permeability are large => losses are large
  - Even if average Q is good, there can be local hot spots
- Transfer and removal of heat with non-toxic materials
  - BeO was used in the past; transfers heat well but is a toxicity concern
  - Oil cooling generates mixed waste
- Eddy current mitigation
  - 15 Hz bias Ramping induces eddy currents in cavity shell - can distort field without proper design
- Including the power tube in the RF model
  - Strong coupling affects cavity frequency

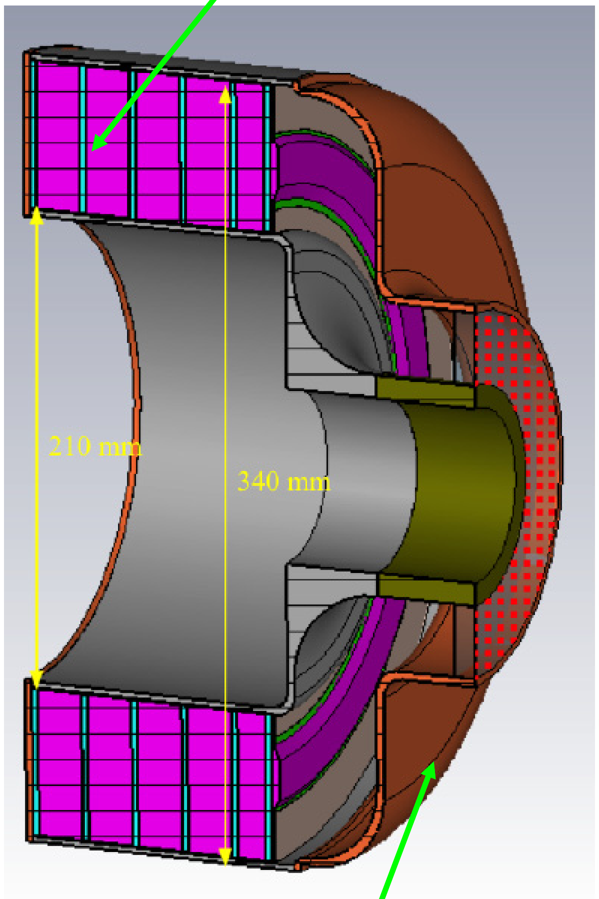
Tuner

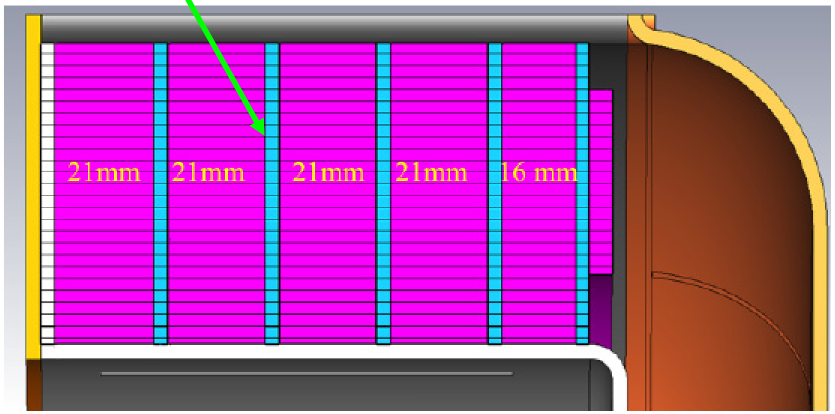
- Garnet rings (OD, ID = 340 mm, 210 mm) are constructed by epoxying together 8 sectors
  - Oven size limitation at vendor
- Each garnet ring is epoxied to an $Al_2 0_3$ ring which transfers heat to tuner outer shell, which is water cooled
  - Garnet has poor thermal conductivity
- Outer shell is stainless steel (to reduce eddy currents) Cu plated on the inside (RF)
  - Also divided into 4 azimuthal segments to reduce eddy currents
- Specially shaped shim ring at the end of the tuner improves magnetic field uniformity where it is most non-uniform
  - Transition from garnet filled section to air
  - Flux return cannot be right next to it (inside RF volume)
  - With shim, minimum field is increased to being comfortable above the level at which losses become large (gyromagnetic resonance)

Tuner

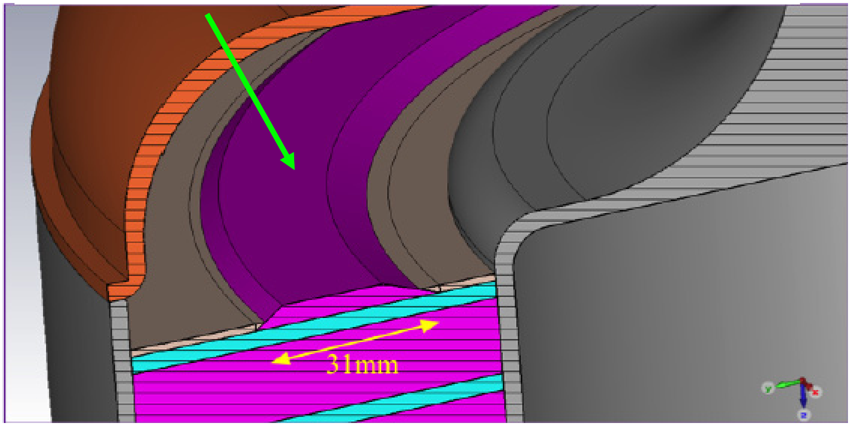
Garnet rings

Al_2O_3 rings epoxied to garnet





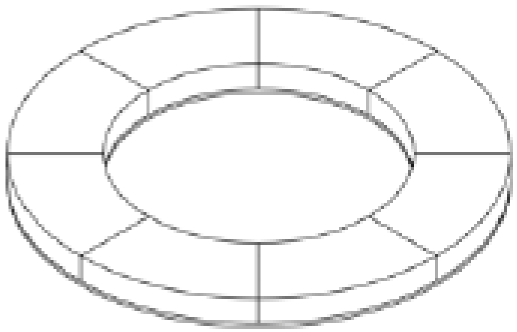
Magnetic shim at end



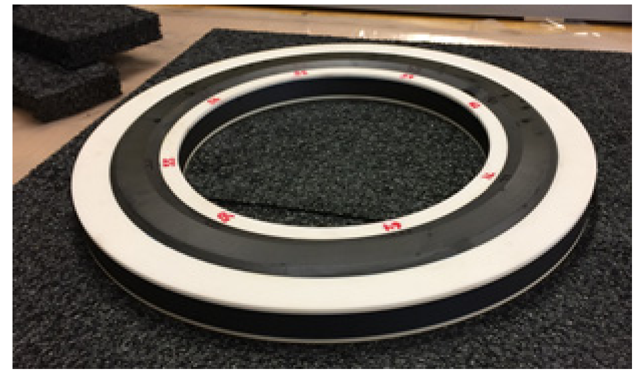
Cu plated (inside) stainless steel shell

Garnet Rings

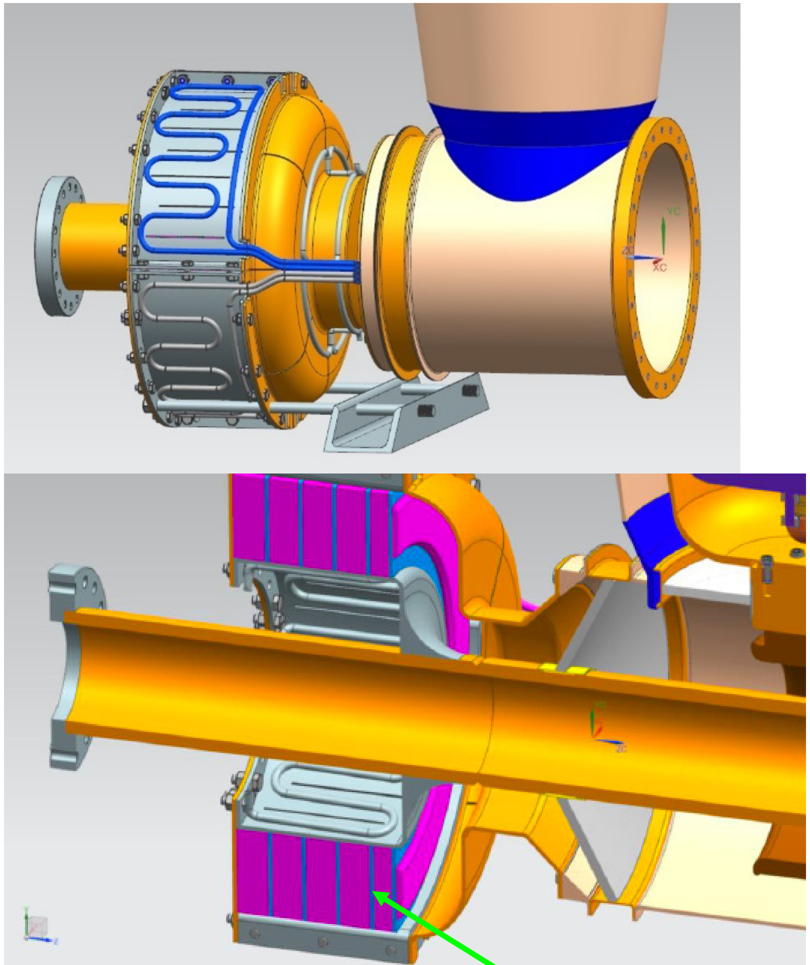
Standard Rings (4)



Shim (End) Ring (1)

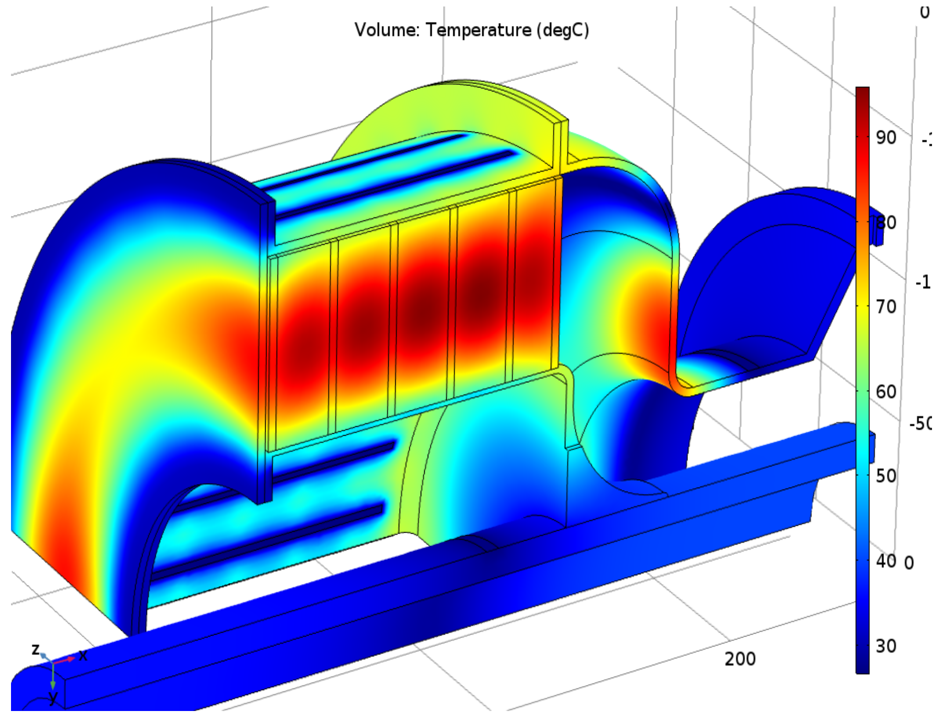


Cooling

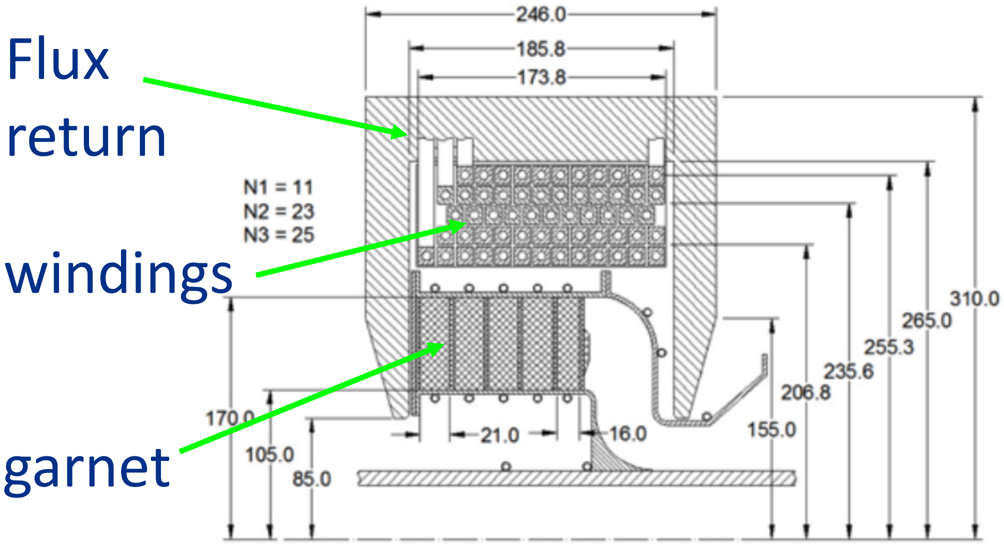


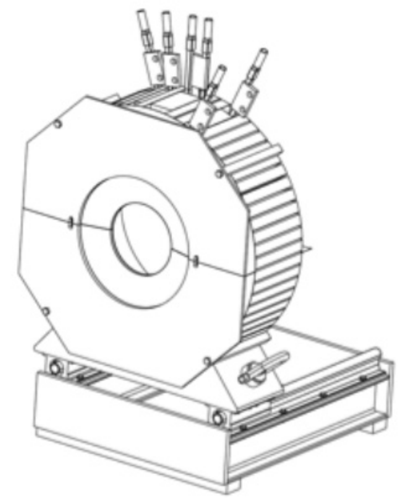
alumina

- RF power loss: ~ 3 kW
  - Eddy current loss ~ 600W
- Max temp ~ 100 ° C
- Curie temp 200° C



Bias Solenoid



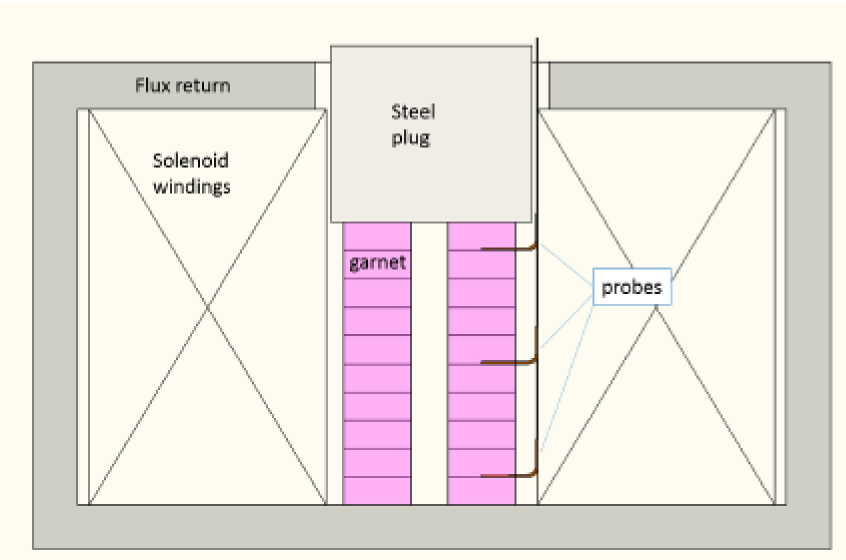


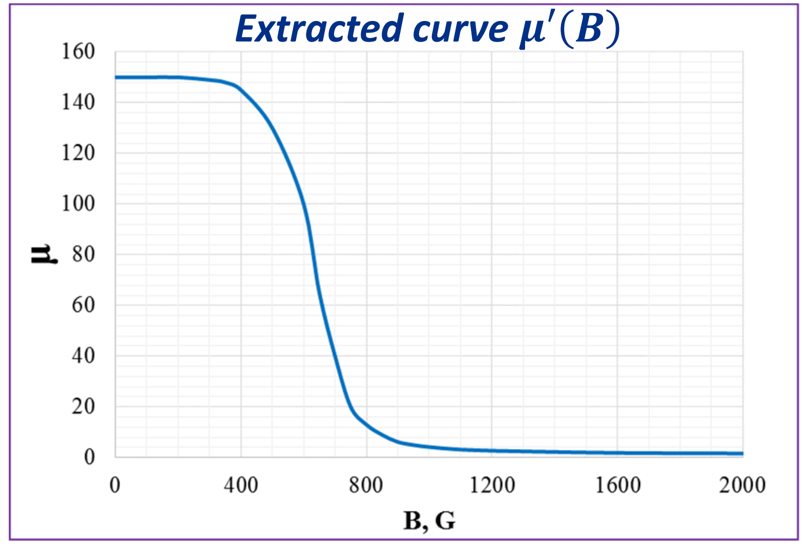
- Booster cycle 15 Hz -> solenoid yoke made from laminations to reduce eddy currents
- Three separate coils, total of 59 turns. Will be connected in series
- Bias current is 139 A at injection to ~600 A at extraction
- Coil inductance varies between ~3.5 and 4.7 mH

Garnet Properties

- To accurately model the cavity, need to understand the garnet properties:
  - μ' vs bias field for frequency
  - μ'' vs bias for losses
  - need to know these at each point in the cavity for each value of the magnetic field
- No published data existed
- Measurements subject to uncertainties and nonuniformity of magnetic field in the material
- Performed measurements by assembling sample garnets
  - Stack of ten 0.5" thick garnets with 3" OD, 0.65" ID
  - Used a spare solenoid on-hand from another project

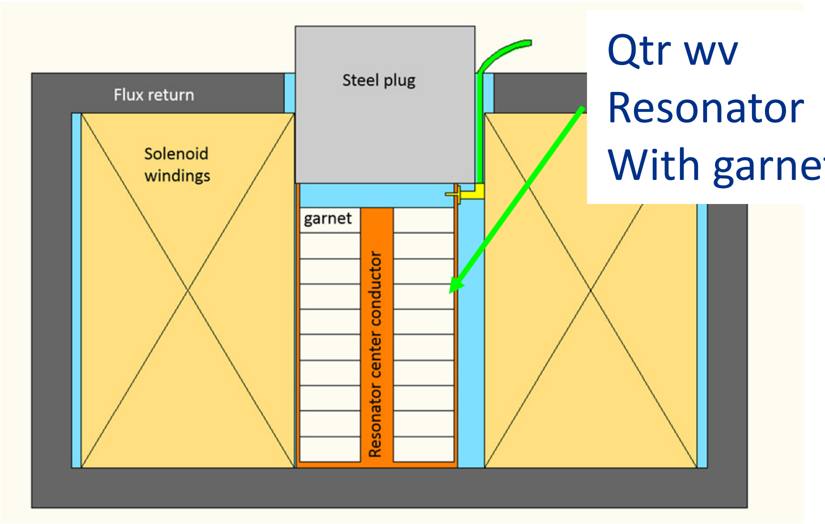
Permeability measurements: $\mu'(B)$



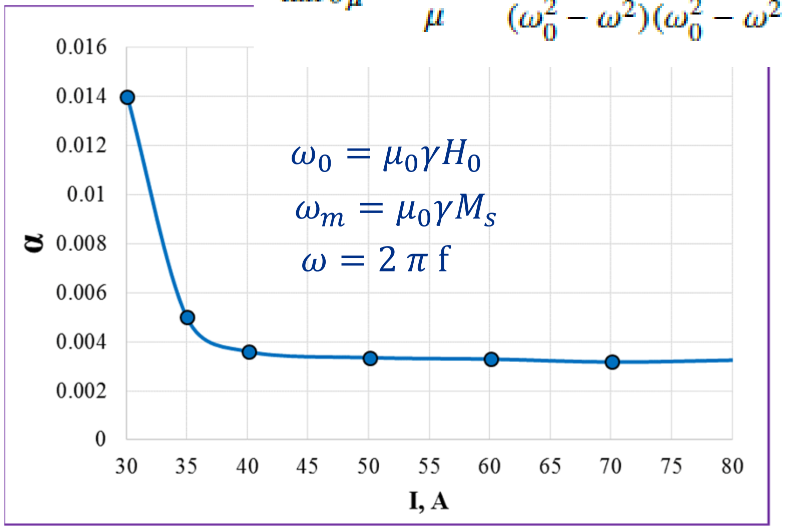


- Measured B vs. solenoid bias using Hall probes at 3 locations
- Model setup in simulation with an initial assumption for $\mu'(B)$
  - initial assumption based on vendor data for initial permeability (~50), and a theoretical calculation for large B.
- Iteratively adjust $\mu'(B)$ in the simulation starting with low bias current and moving up
- adjusted curve accepted as the actual curve when simulation matched data, for B vs. I.

Permeability measurements: $\mu''(B)$ ($\tan\delta_\mu$)



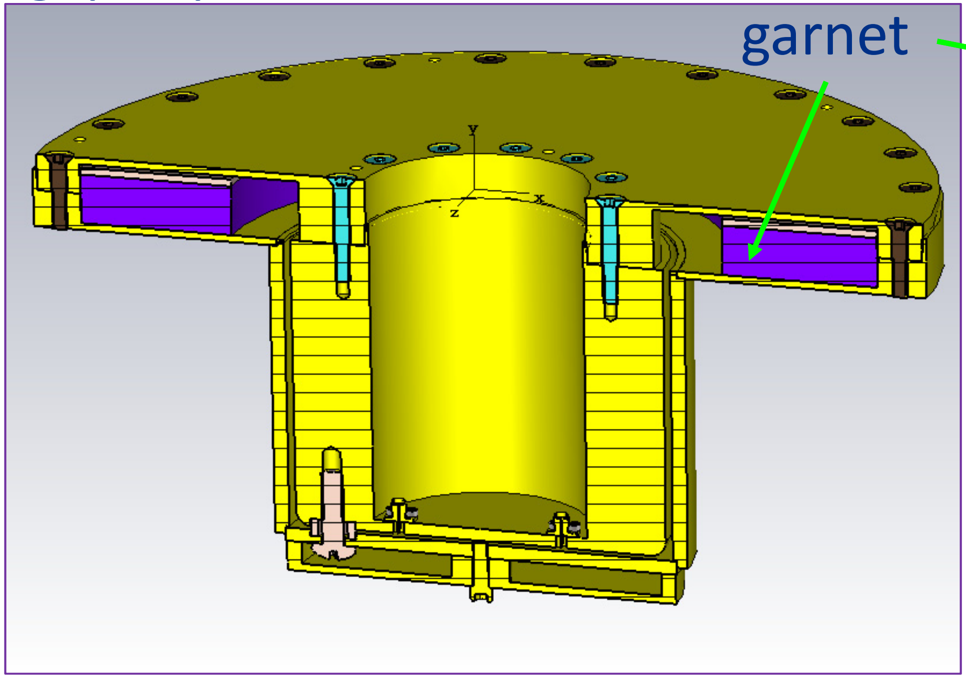
$$\tan\delta_\mu = \frac{\mu''}{\mu} = \frac{\alpha\omega\omega_M(\omega_0^2+\omega^2)}{(\omega_0^2-\omega^2)(\omega_0^2-\omega^2+\omega_M\omega_0)}$$



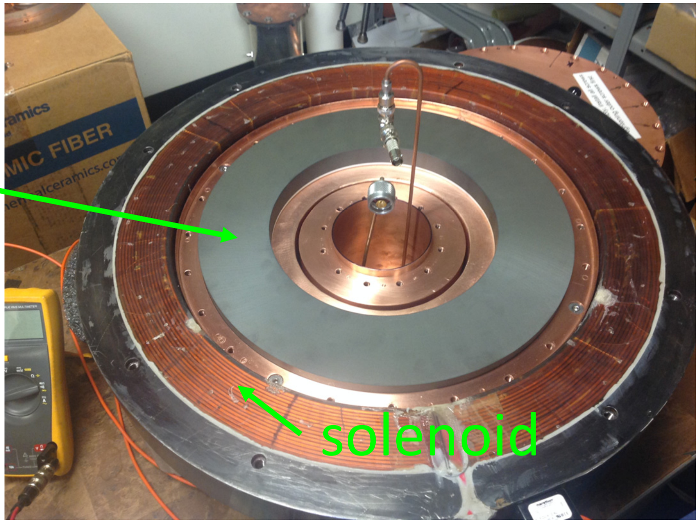
- Measure *Q* in *λ/4* resonator for several bias settings
- Simulate the setup with previously extracted curve $\mu'(B)$
- For each bias current setting, α was adjusted in the simulation until measured and predicted values of Q agreed
- For $\alpha \ll 1$ can extract $\tan\delta_\mu = {}^{\mu''}/_{\mu'}$

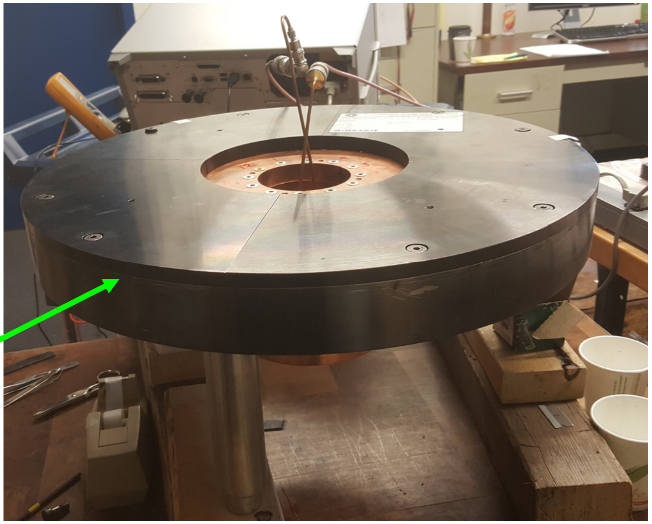
QC fixture for actual rings

RF volume: $\lambda/4$ resonator with large gap capacitance



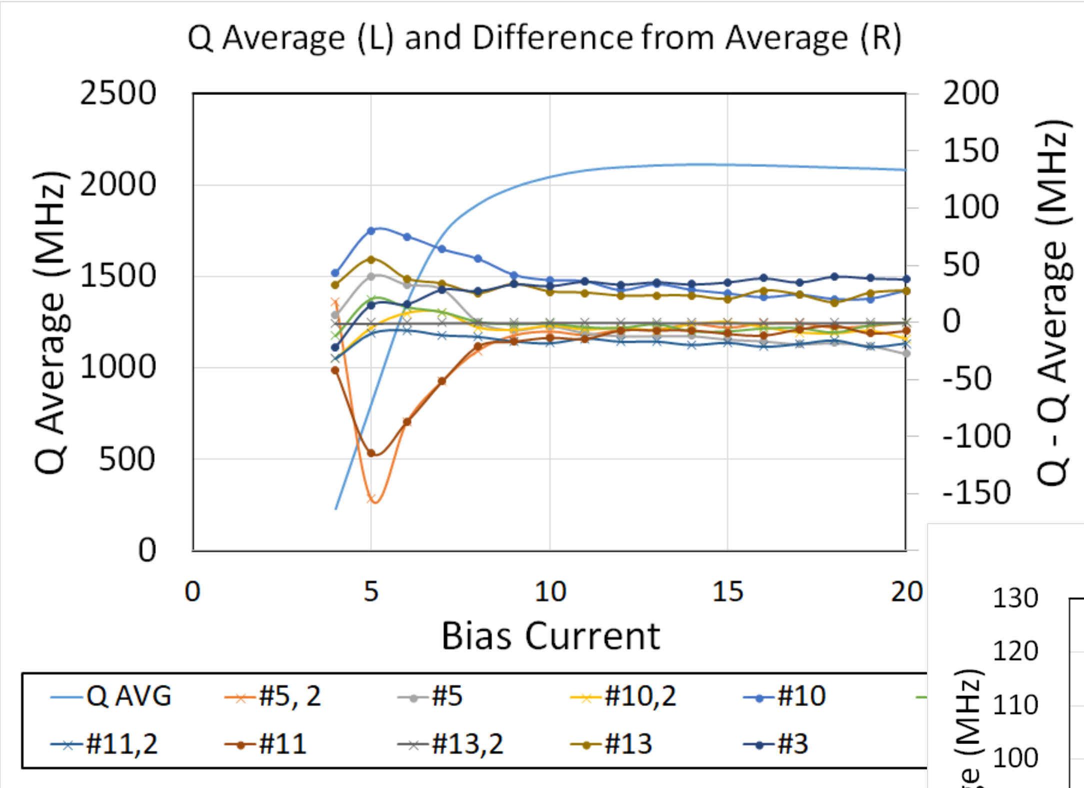
Fixture with top removed and solenoid shown

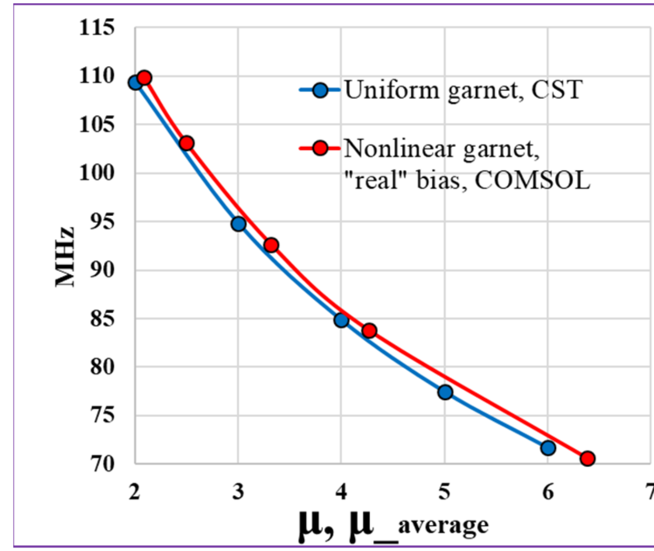


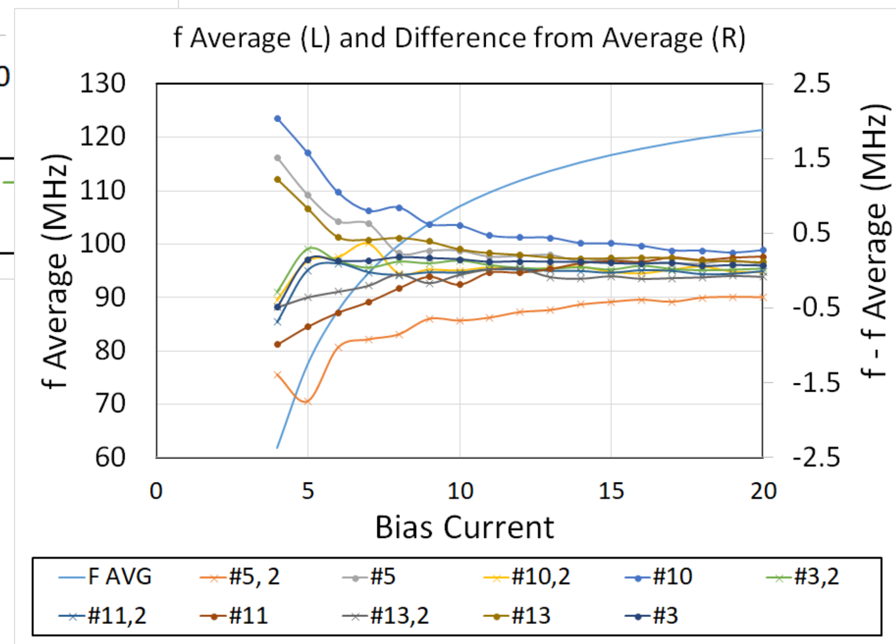


Fixture with top on and flux return shown

Results for Five cylindrical rings





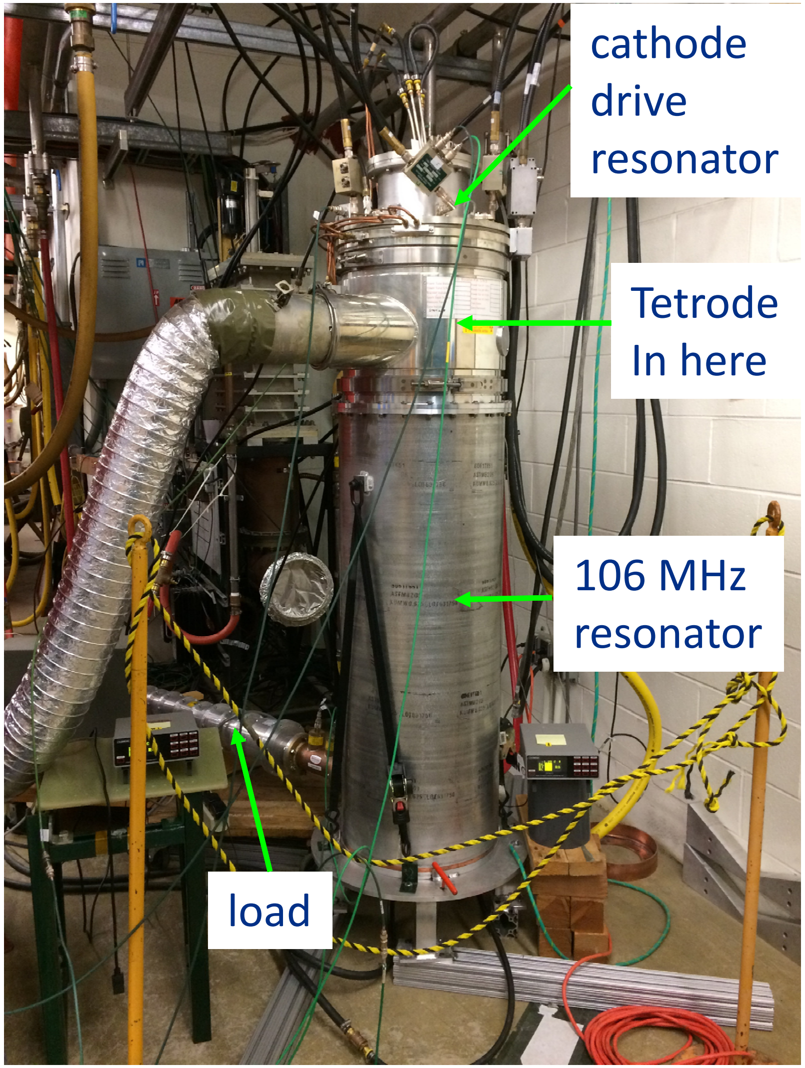


- Within measurement accuracy, rings are uniform in frequency (μ’) and Q (μ’’)

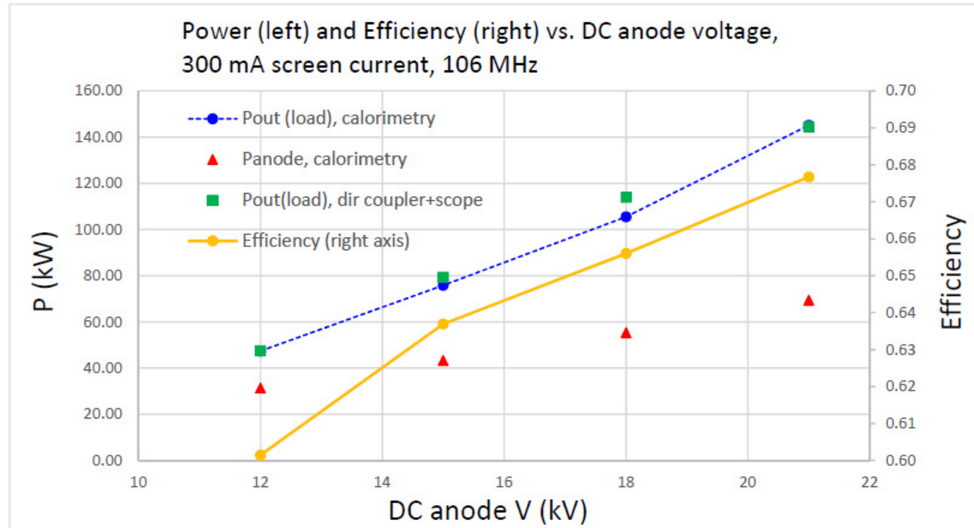
Power Amplifier tests

- We will use the Y567B (Fermilab version of Eimac 4CW150000) power tetrode
  - Rated to 150 kW anode dissipation, to 108 MHz
- We only expect to need ~55 kW at 76 MHz, even less at higher frequency
- Still needed to test at 76 and 106 MHz to verify operation at these higher frequencies
- Redesigned fundamental Booster PA cathode drive resonator to work at higher frequency
- Tetrode exceeded 100 kW output at both 76 and 106 MHz

Power Amplifier tests



Pload = output power



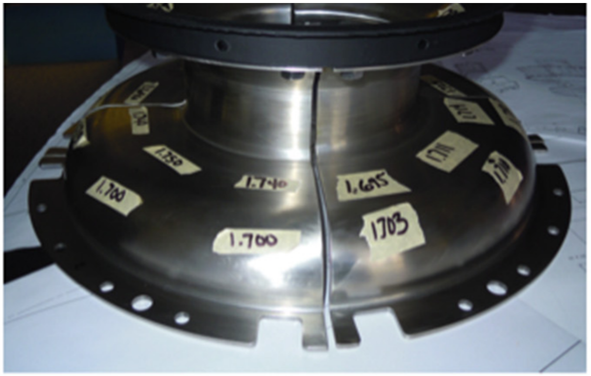
Fermilab

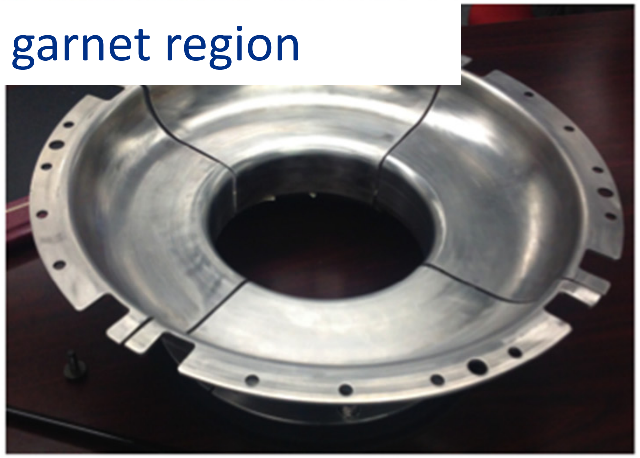
Status

- Design was finalized in September
- All parts on hand
- Solenoid is finished, currently being set up for initial tests with the bias supply
- We are building the cavity
  - Windows are welded
  - PA input welded
  - One remaining weld for a complete (garnet free) cavity – inner conductor to outer can

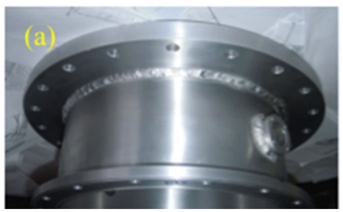
Cavity Parts

Outer conductor vacuum-> garnet region



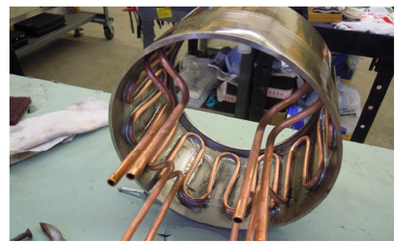


outer conductor garnet region

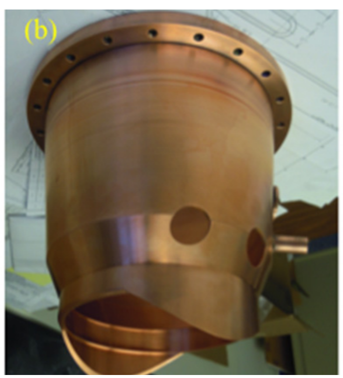


PA outer, top

Coupling ring

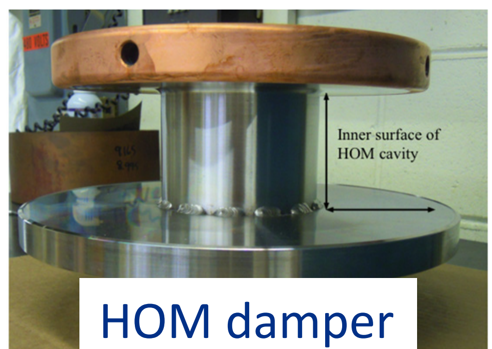


inner conductor garnet region,
before Cu plating



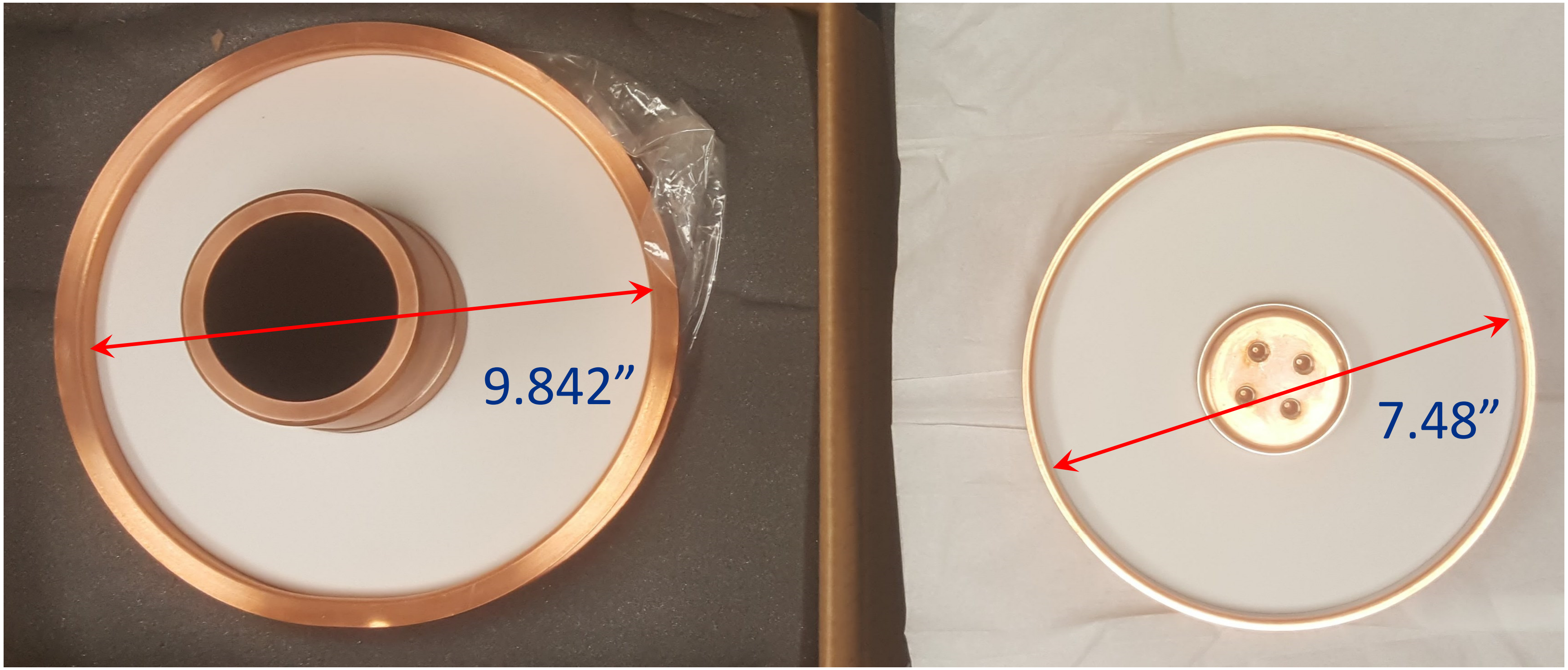
PA outer, bottom

Tetrode connection



HOM damper

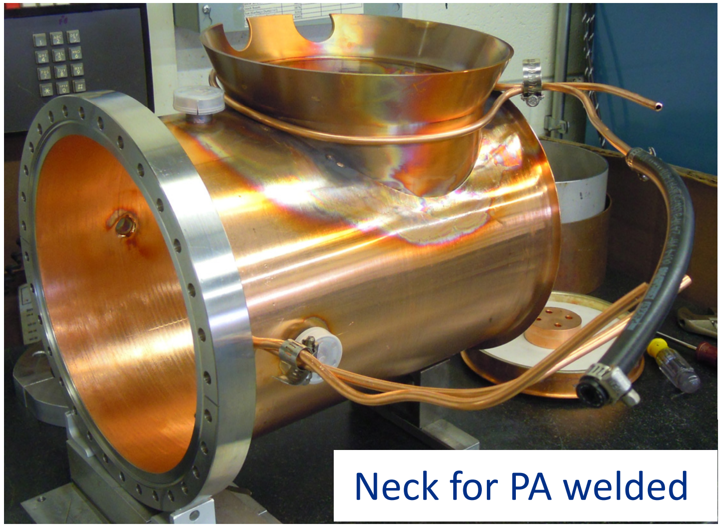
Windows



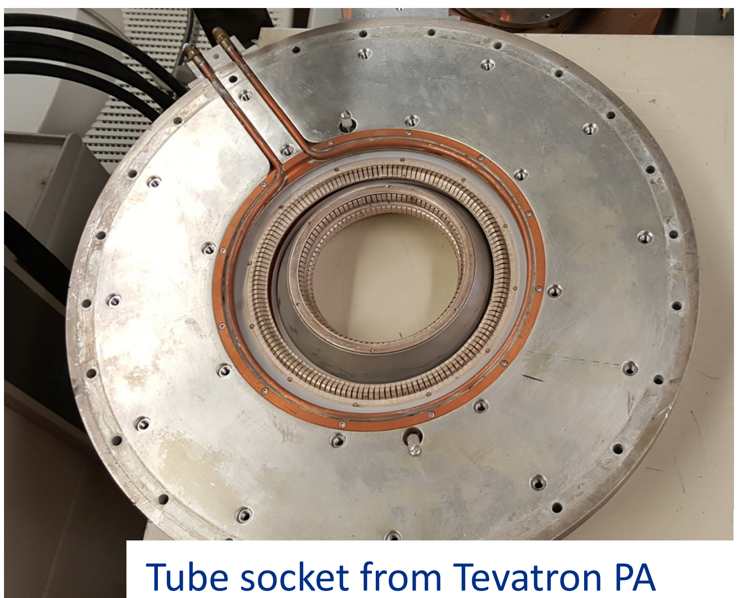
Conical tuner window

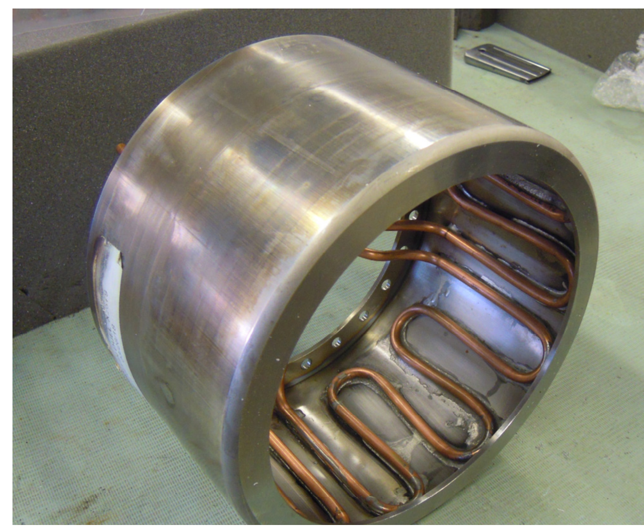
Flat PA window

Cavity Parts and Initial Construction


Neck for PA welded

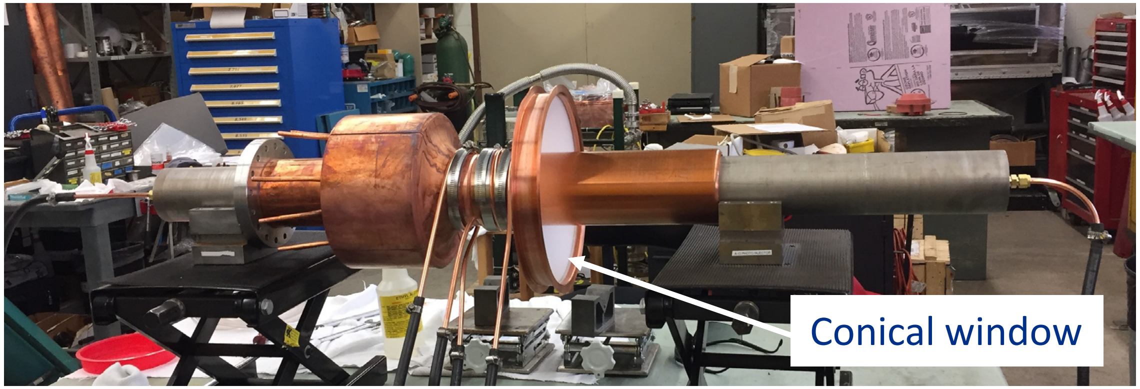

Flat window welded in


Tube socket from Tevatron PA

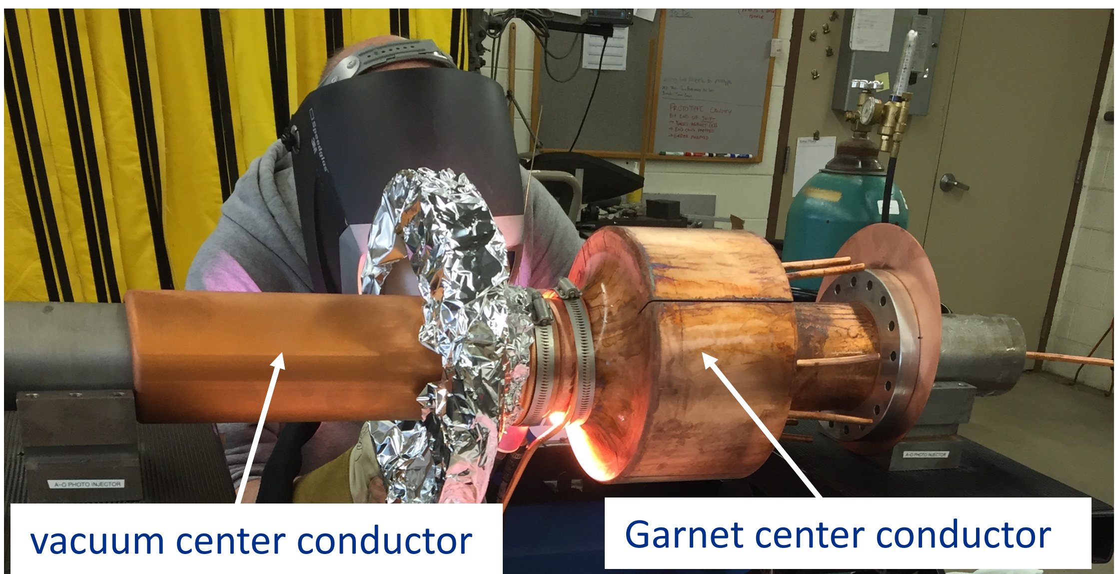

Garnet center conductor before Cu plating

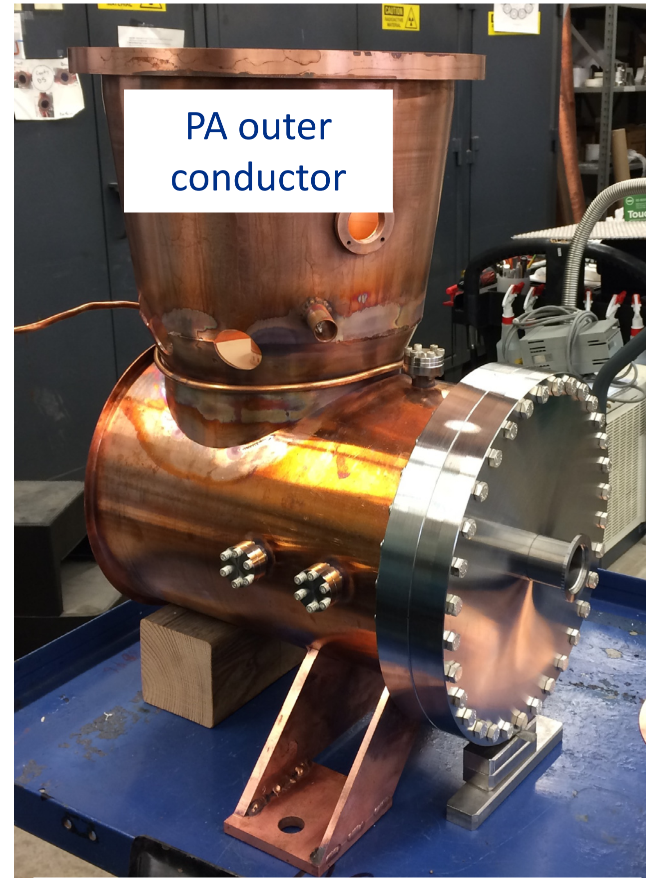
Further along

Setup for welding cavity center conductor



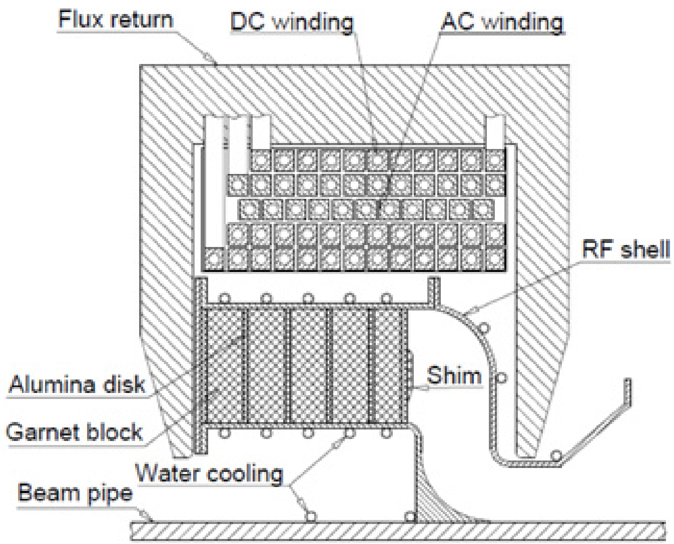
welding cavity center conductor

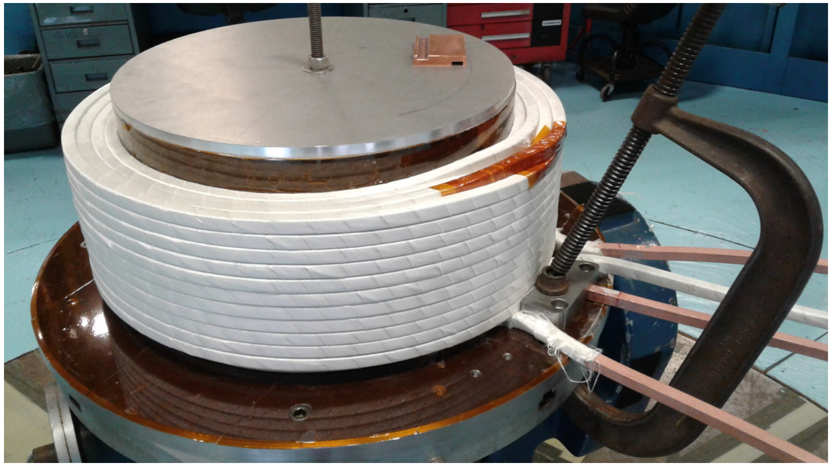


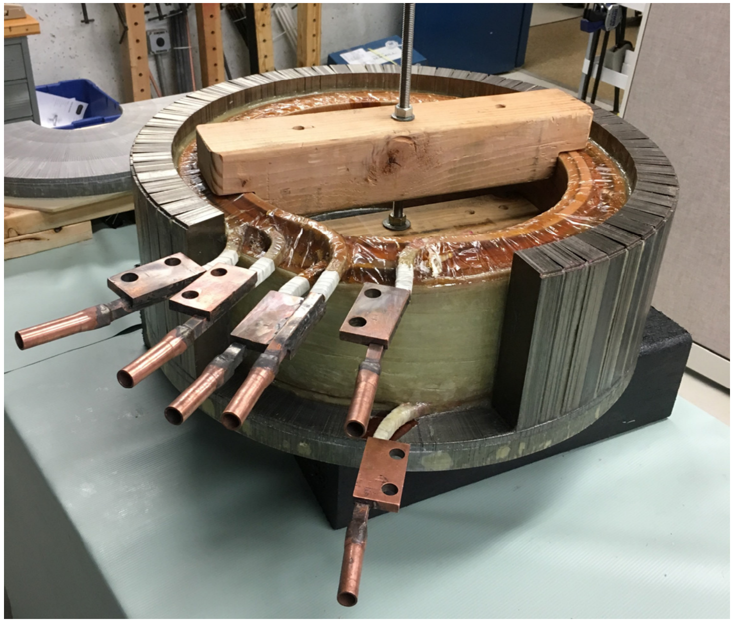


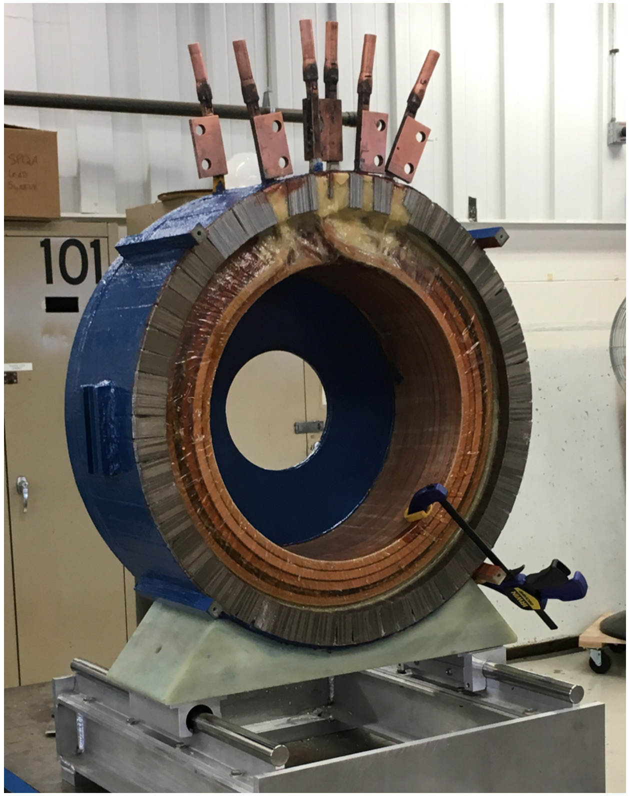
Cavity outer conductor – vacuum section (no garnet)

Solenoid


Flux return
DC winding
AC winding
RF shell
Shim
Alumina disk
Garnet block
Water cooling
Beam pipe





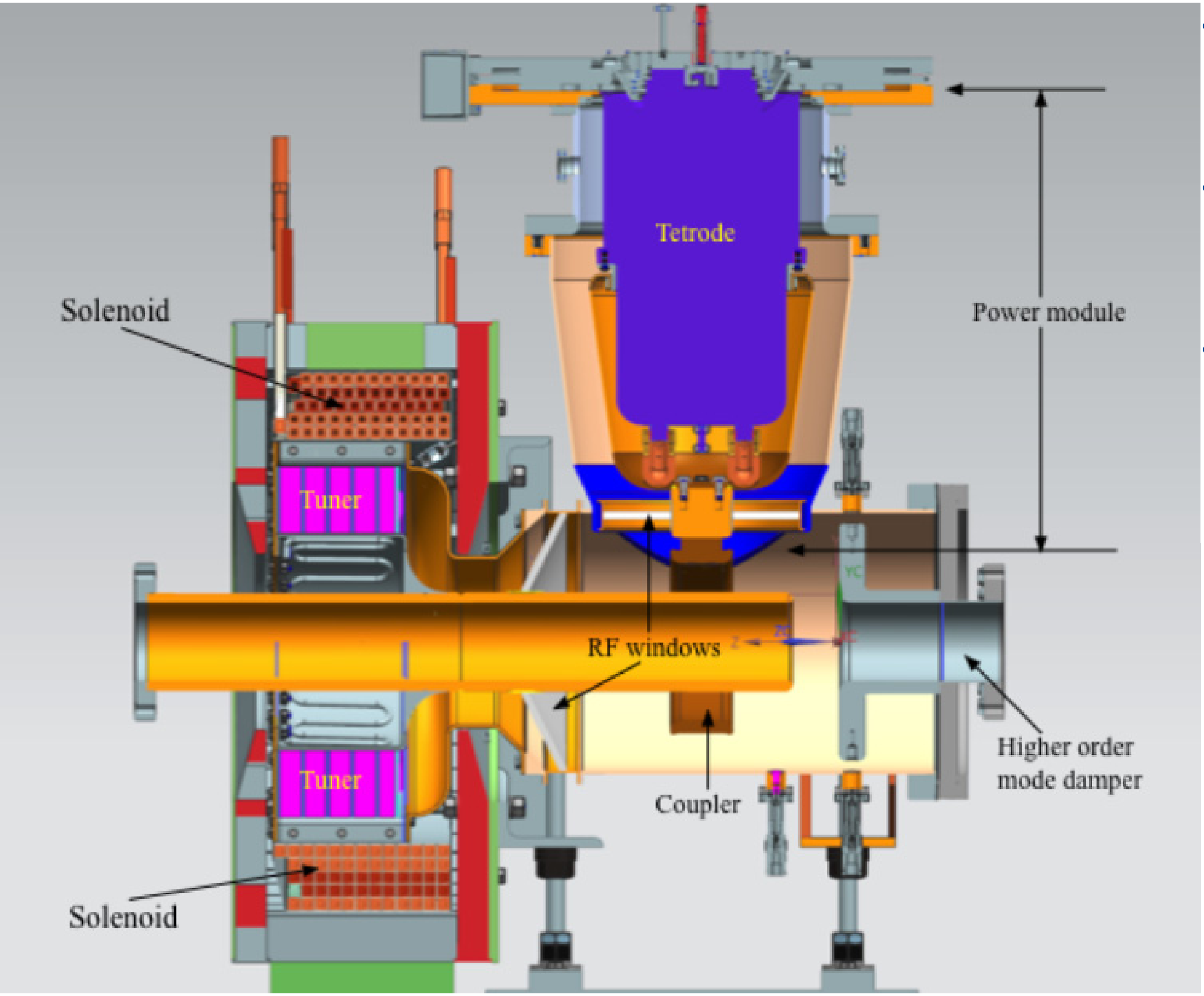

101

Status/Conclusions

- Still need to do some welding/leak checking/weld cleanup
- Then measure cavity f and add garnet
- Plan to install in summer shutdown
  - Will high power test the cavity first
- Initial operation will be only at injection due to lack of a powerful enough bias supply; bias supplies will be upgraded later
- A description of the work done so far may be found at: http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=6113

- Questions?

Cavity Model



- Length flange-to-flange: 844 mm
- Aperture: 76 mm
- $P = V^2/2\,R_{sh}$
  76 MHz, R_{sh} = 96 kΩ
  106 MHz: R_{sh} = 180 kΩ