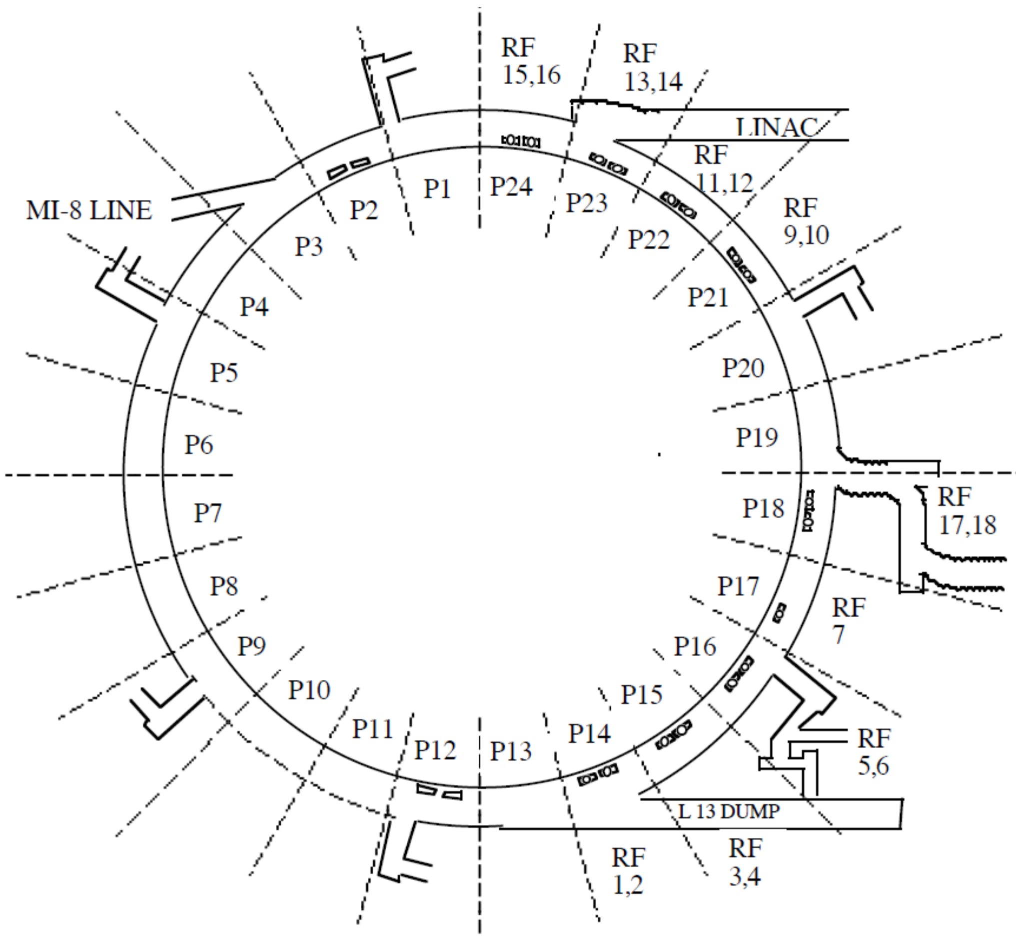
Progress in the RF/Thermal Modeling Effort of the Booster Cavity

Mohamed Hassan, John Reid, Vyacheslav Yakovlev, Valeri Lebedev, and Mark Champion

January 18th 2012

Booster Parameters



Booster Parameters

Circumference..............................2π x 74.47 meters
Injection energy............................400 Mev (kinetic)
Extraction energy..........................8 Gev (kinetic)
Cycle time..................................1/15 sec
Harmonic number, h........................84
Transition gamma..........................5.45
Injection Frequency........................37.77 Mhz
Extraction Frequency......................52.81 Mhz
Maximaum RF voltage....................0.86 MV
Longitudinal emittance...................0.25 eV sec
Horizontal β max...........................33.7 meters
Vertical β max.............................20.5 meters
Maximum dispersion.....................3.2 meters
Tune $\upsilon x = \upsilon y$...............................6.7
Transverse emittance(normailized).....12π mm rad
Bend magnet length.......................2.9 meters
Standard cell length.......................19.76 meters
Bend magnets per cell 4
Bend magnets total........................96
Typical bunch intensity..................3 x 10e10
Phase advance per cell....................96 degs
Cell type.......................FOFDOOD (DOODFOF)

- The Fermilab Booster is a synchrotron that accelerates protons from 400 MeV to 8 GeV
- The Booster circumference is 474.2 meters, the magnetic cycle is a biased 15 Hz sinusoid, and the RF operates at harmonic 84 of the revolution frequency

Problems with the Current Cavity

Activation Problem

- Current beam pipe (2.25”) is vulnerable to activation
- Need to increase the beam pipe size (3”)

Heating Problem

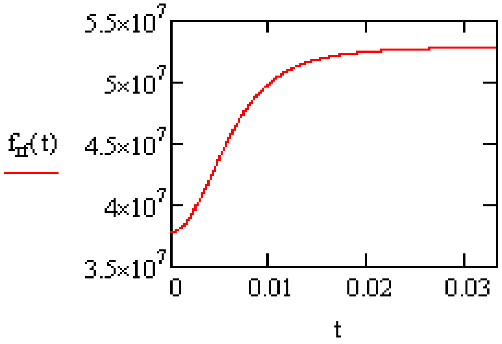
- Need to double the repetition rate to
- Current cooling mechanism may not tolerate the additional heating in tuners

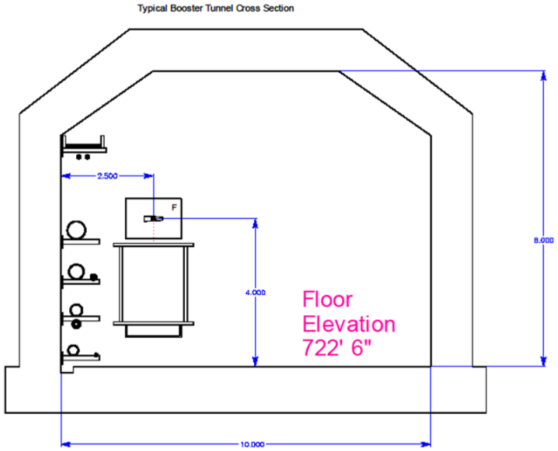
Breakdown Problem

- Need to increase the current Gap Voltage
- Weak points of max fields in Vacuum and Air will be more susceptible to break down

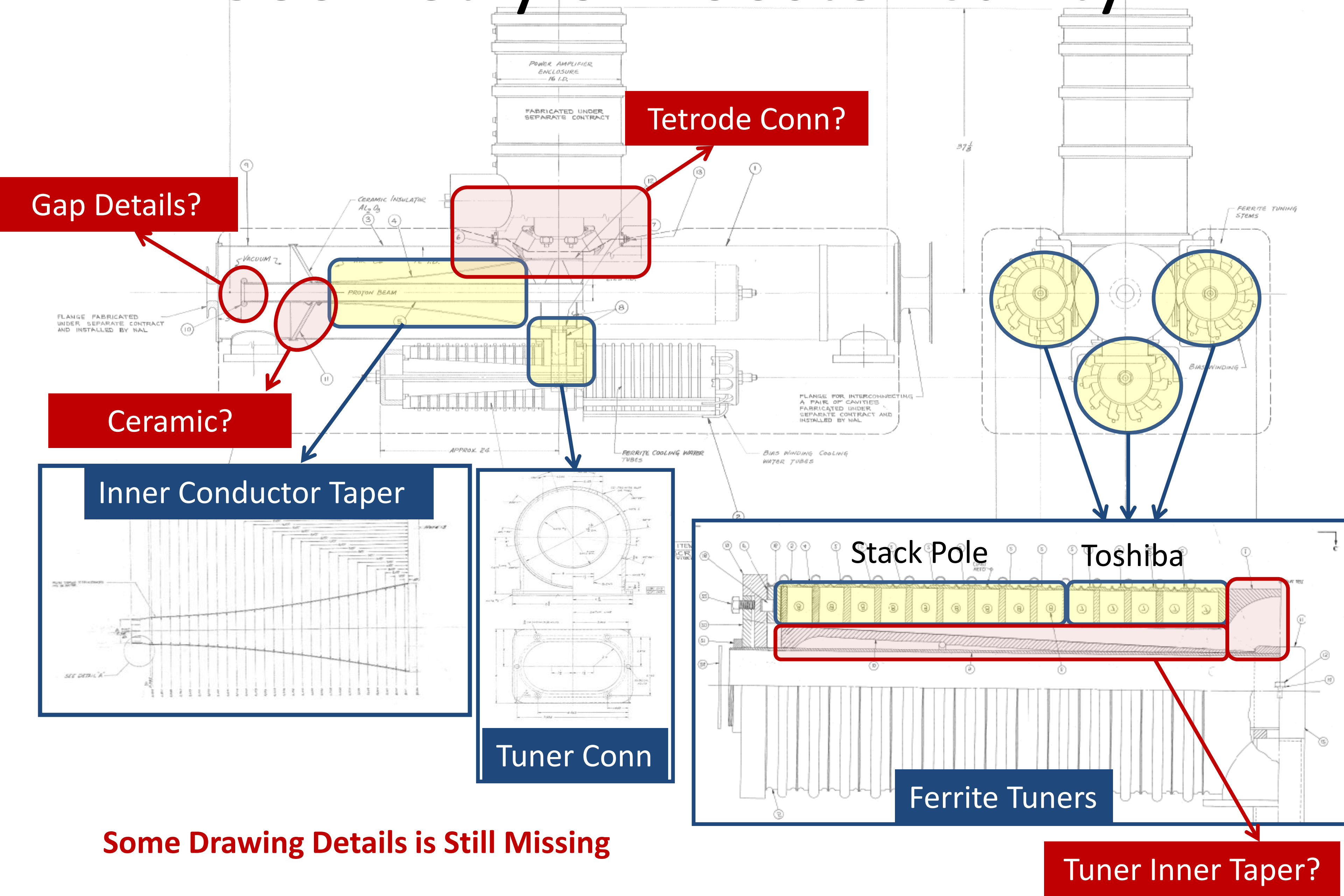
Specifications for Design of New Accelerating Cavities for the Fermilab Booster

	Current	Modified
Frequency Range	37.80-52.82 MHz	Same
V_{acc}	55 KV	60 KV
R/Q	~50	~50
Duty Cycle	Effectively 25%	50%
Repetition Rate	Effectively 7 Hz	15 Hz
Cavity Tuning	Horizontal Bias	Same
Beam Pipe Diameter	2.25”	>3”
Higher Order Mode Impedance	<1000 Ohm	<1000 Ohm
Cooling	LCW at 95 F, Water flow up to 21 gpm	Same





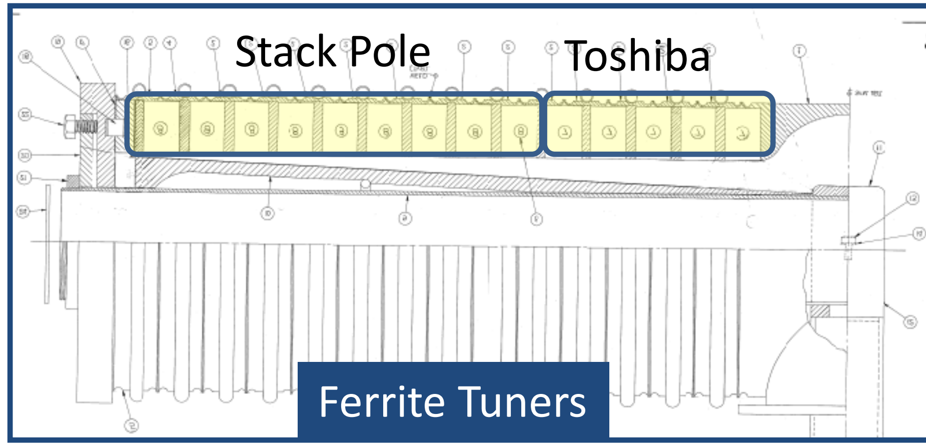
Geometry of Booster Cavity

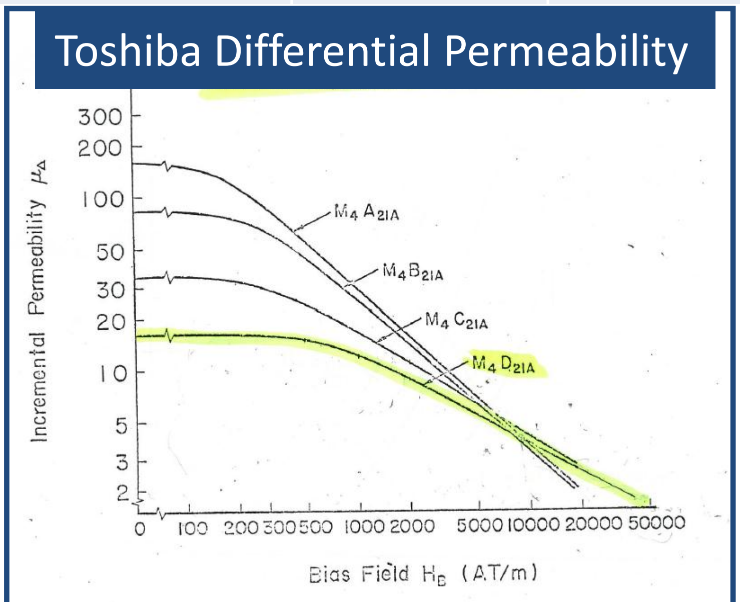


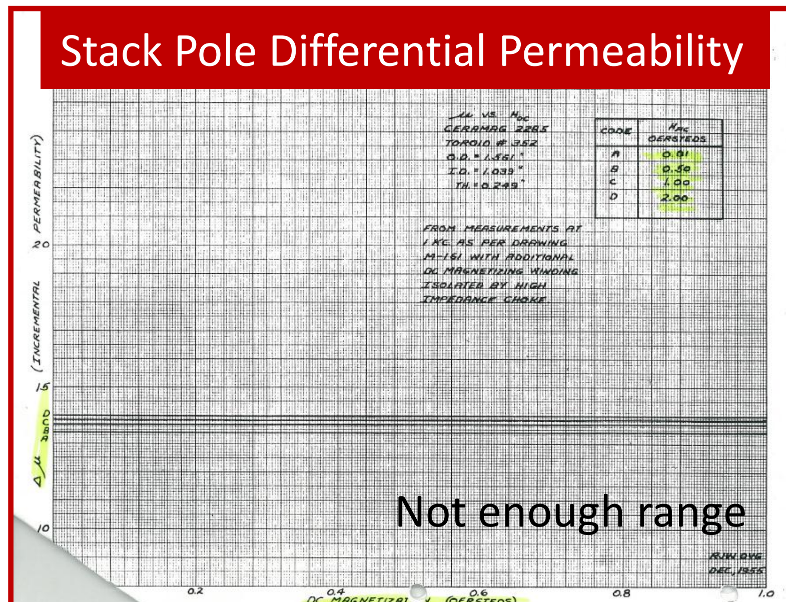
Some Drawing Details is Still Missing

Material Properties

	Stack Pole	Toshiba
μ_{max}	12.5	20
Magnetic Loss Tangent @ 50 MHz	0.005	0.007
Dielectric Const	10.5	12
Dielectric Loss Tangent @ 50 MHz	0.005	0.005







Some Material Properties are Still Missing

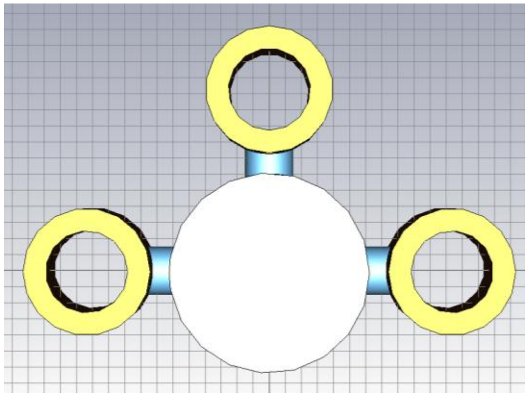
Thermal Properties

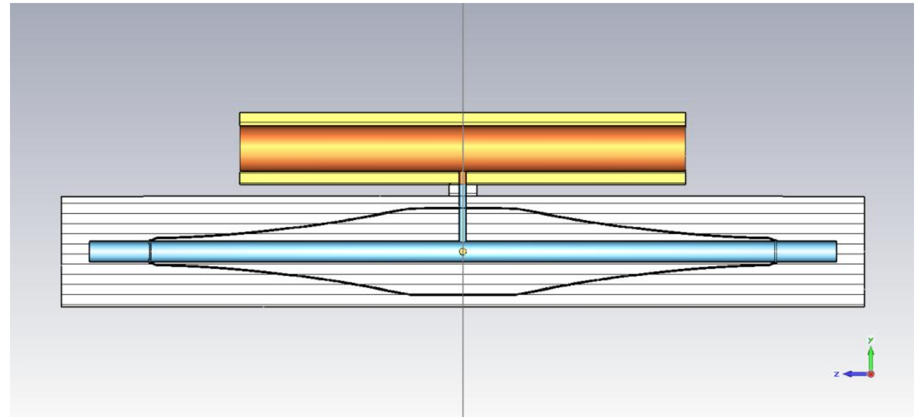
- Due to the lack of available material info, typical properties of Ni-Zn are assumed

Typical mechanical and thermal properties

Property	MnZn ferrite	NiZn ferrite	Unit	Datasheets
Young's modules	(90 to 150) × 10^{+3}	(80 to 150) × $10+^{3}$	N/mm^2	
Ultimate compressive strength	200 to 600	200 to 700	N/mm^2	
Ultimate tensile strength	20 to 65	30 to 60	N/mm^2	sfmatgra_frnt.pdf
Vickers hardness	600 to 700	800 to 900	N/mm^2	
Linear expansion coefficient	(10 to 12) × 10^{-6}	(7 to 8) × 10^{-6}	K^{-1}	
Specific heat	700 to 800	750	Jkg^{-1} × K^{-1}	
Heat conductivity	(3.5 to 5.0) × 10^{-3}	(3.5 to 5.0) × 10^{-3}	$Jmm^{-1}s^{-1}$ × K^{-1}	

Simplified EM Model

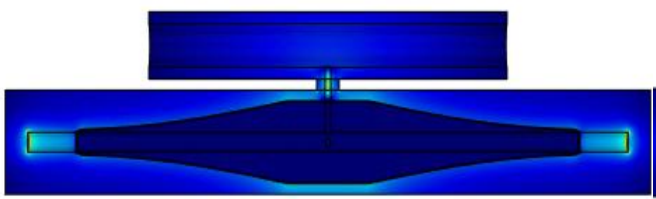


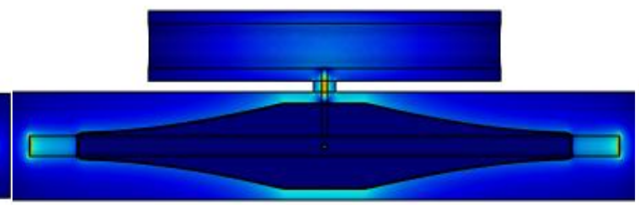


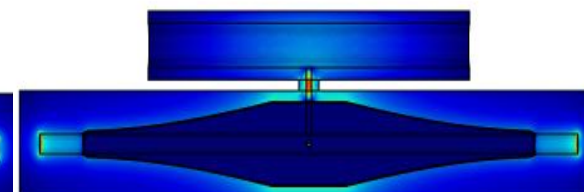
μ=1.5
56.2 MHz

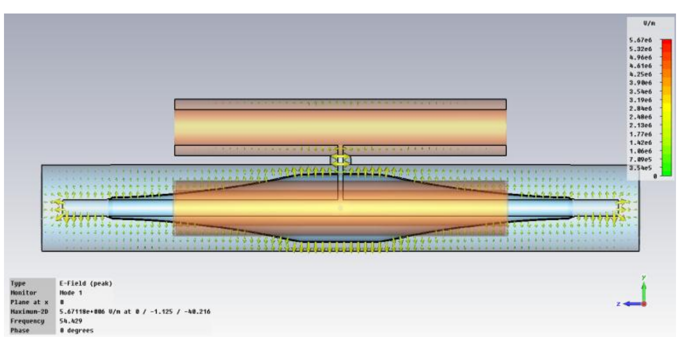
μ=3
42.9 MHz

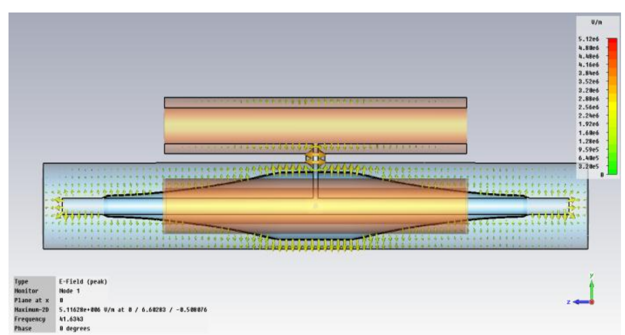
μ=5
34.3 MHz

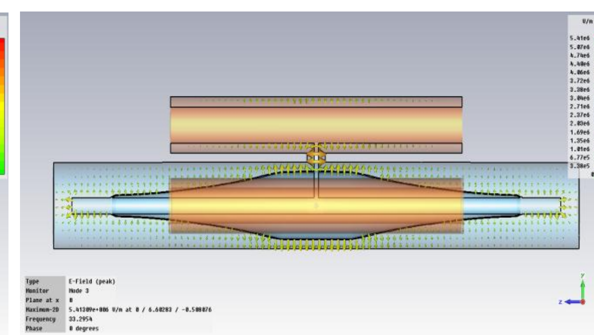






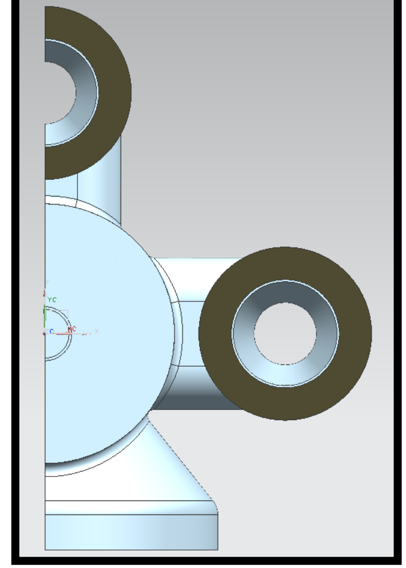


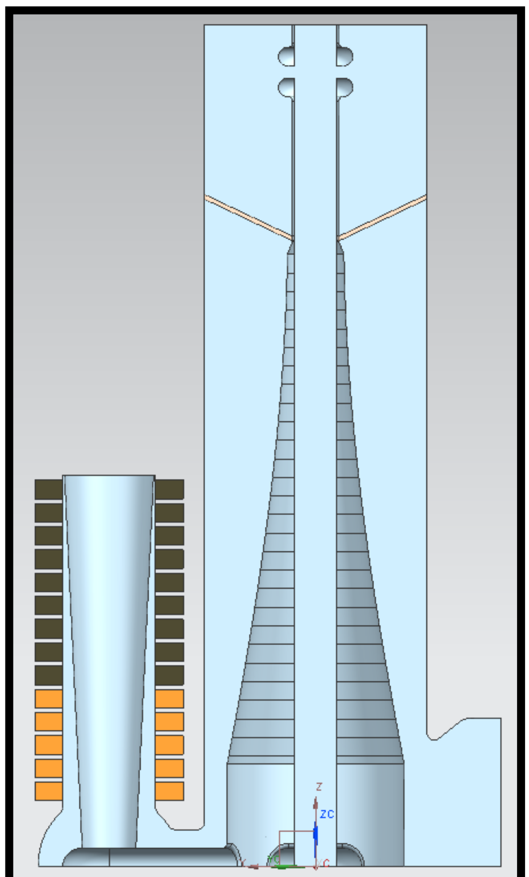


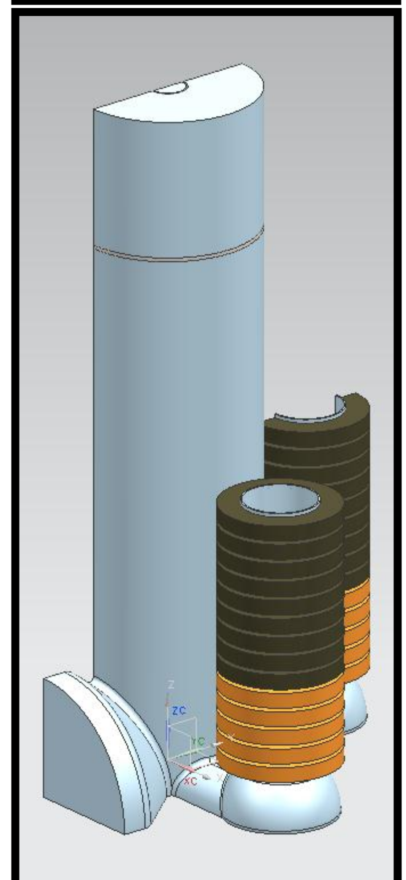


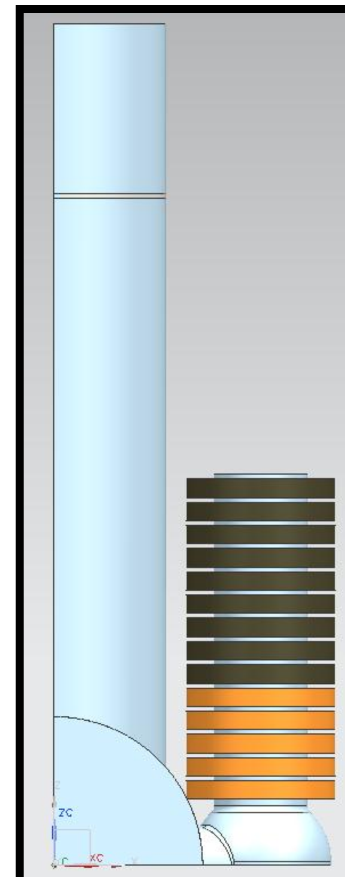
Latest Model

- Realistic Tuner with all the fine details
  - 5 Toshiba Ferrites
  - 9 Stackpole Ferrites
  - Flared Inner Conductor
- Realistic Tuner Connection



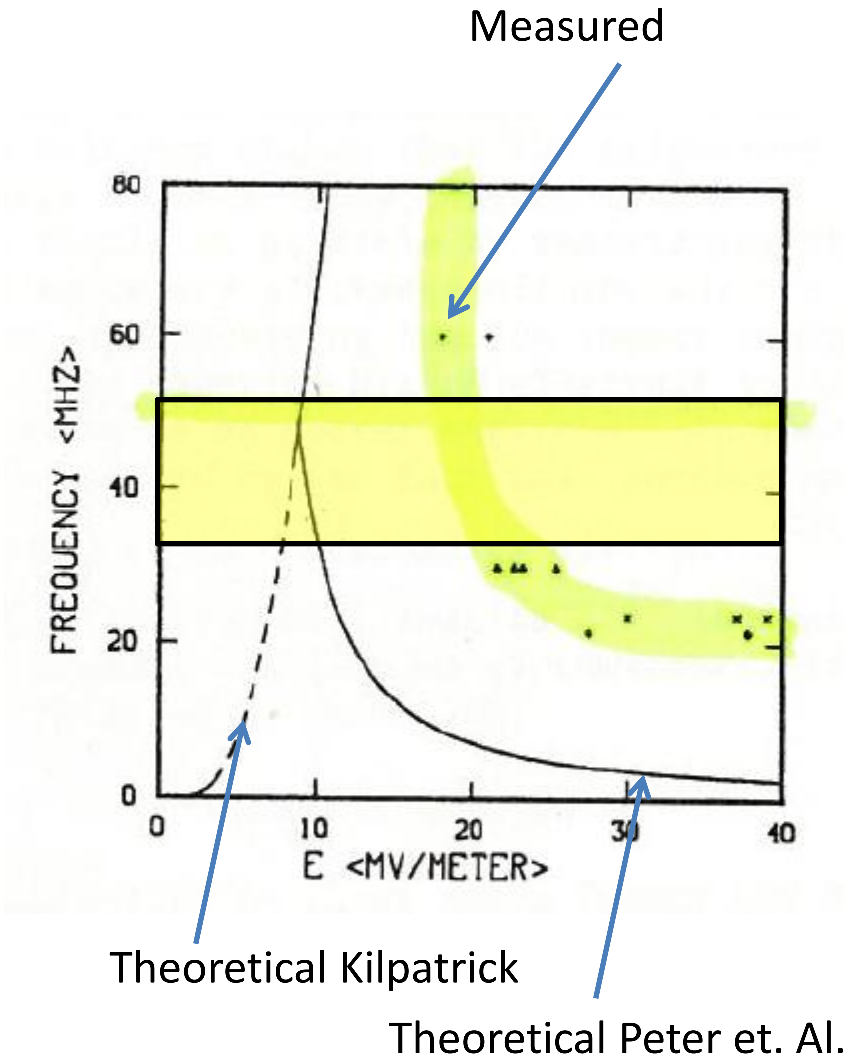






Voltage Breakdown

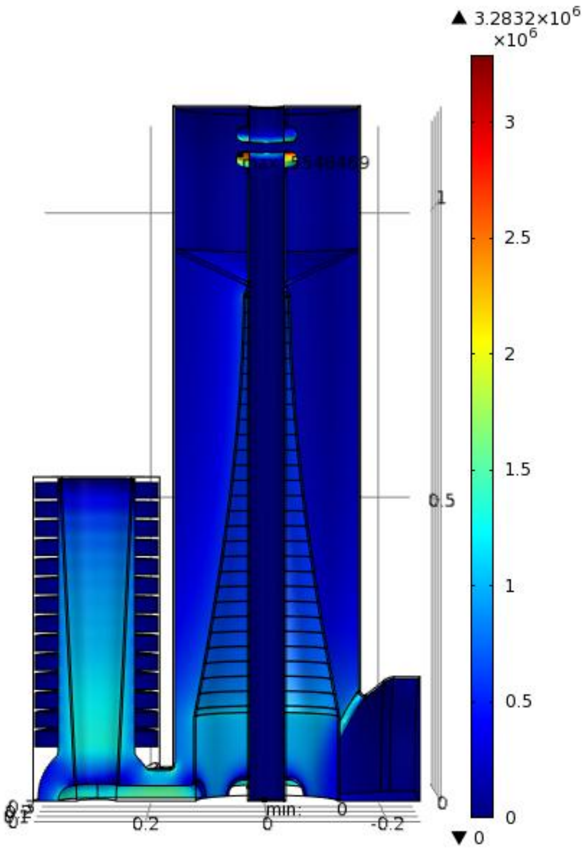
- In Air ~ 3 MV/m (30 KV/cm)
- In Vacuum (according to Kilpatrick) is ~ 10 MV/m (theoretical) 18 MV/m (measured)

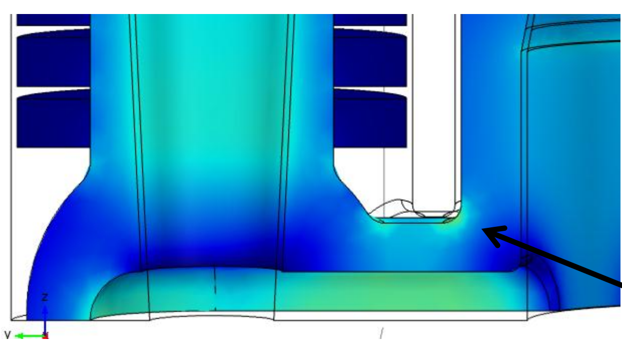


W. Peter, R. J. Fael, A. Kadish, and L. E. Thode, "Criteria for Vacuum Breakdown in RF Cavities," IEEE Transactions on Nuclear Science, Vol. Ns-30, No. 4, Aug 1983

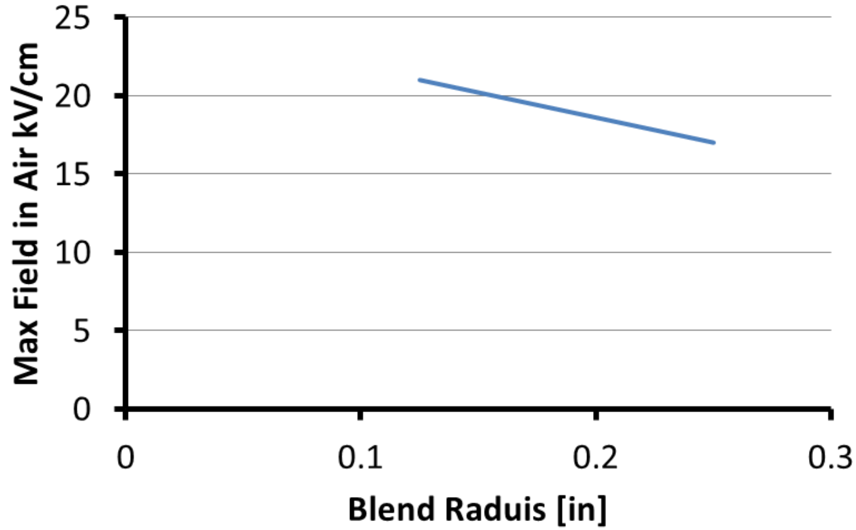
Max Field in Air

Electric Field for 55KV





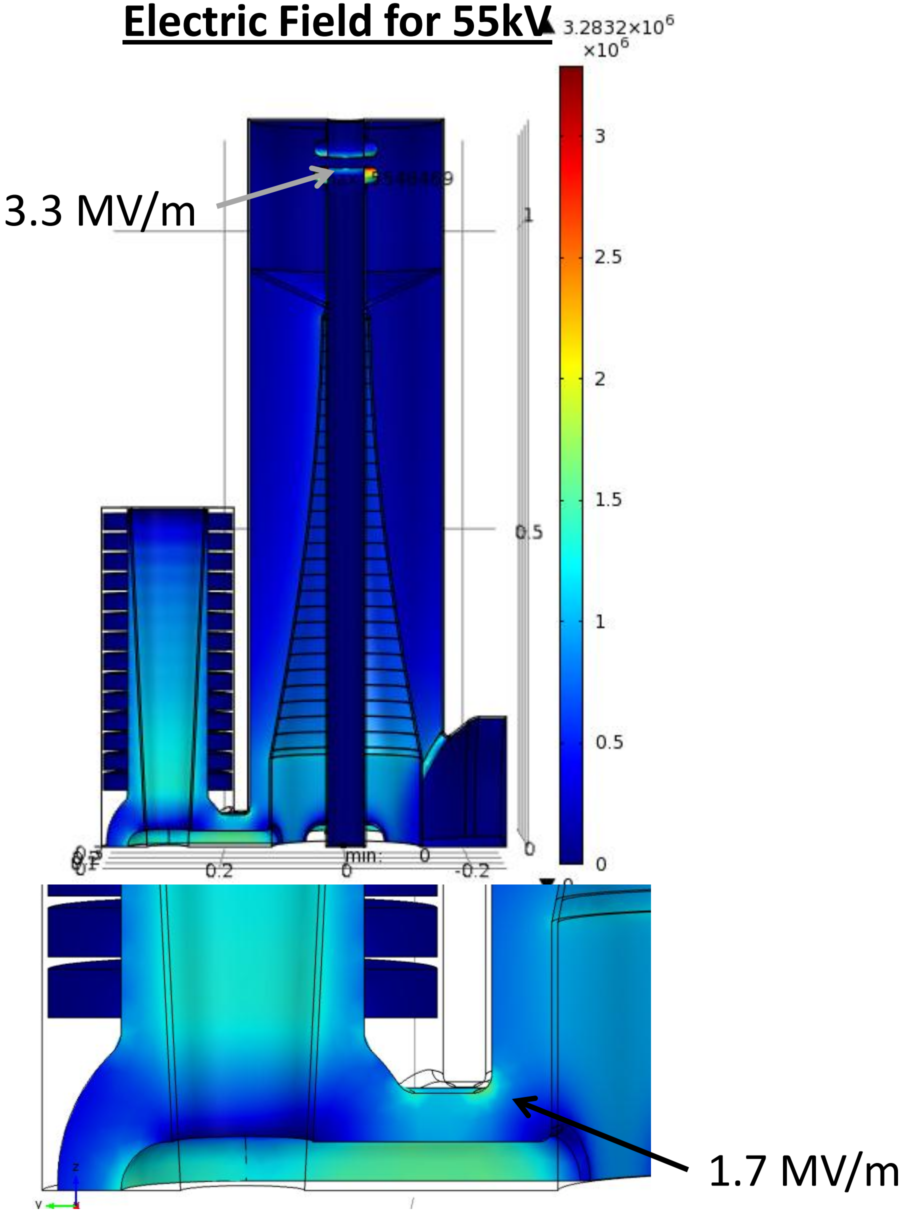
1.7 MV/m



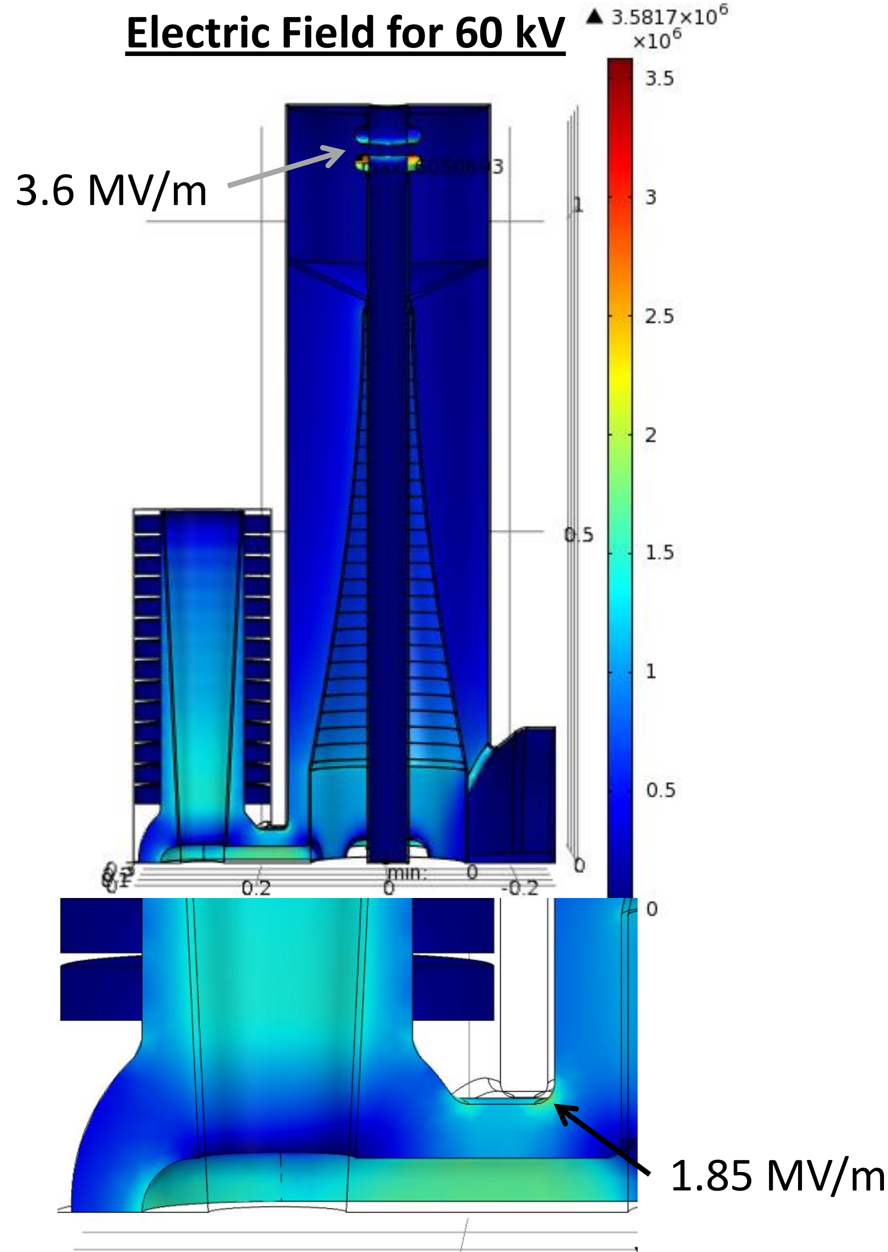
Assumed 0.25” Blend Radius upon John Reid’s recommendation

Max Electric Field

Electric Field for 55kV



Electric Field for 60 kV

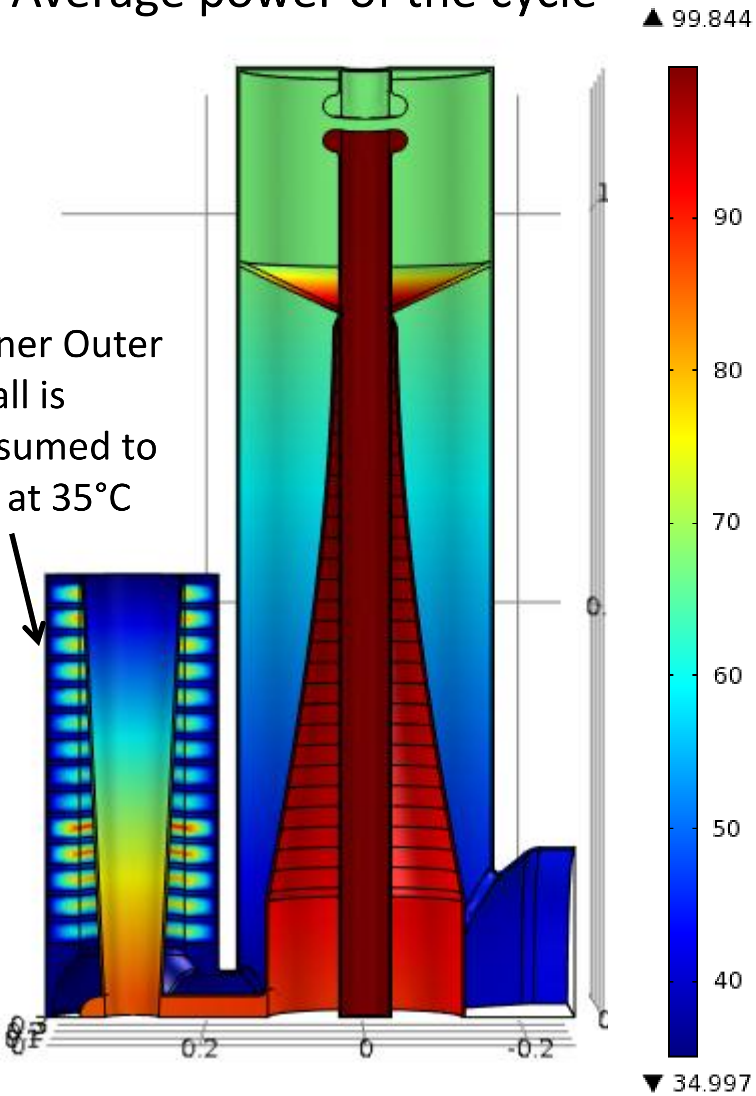


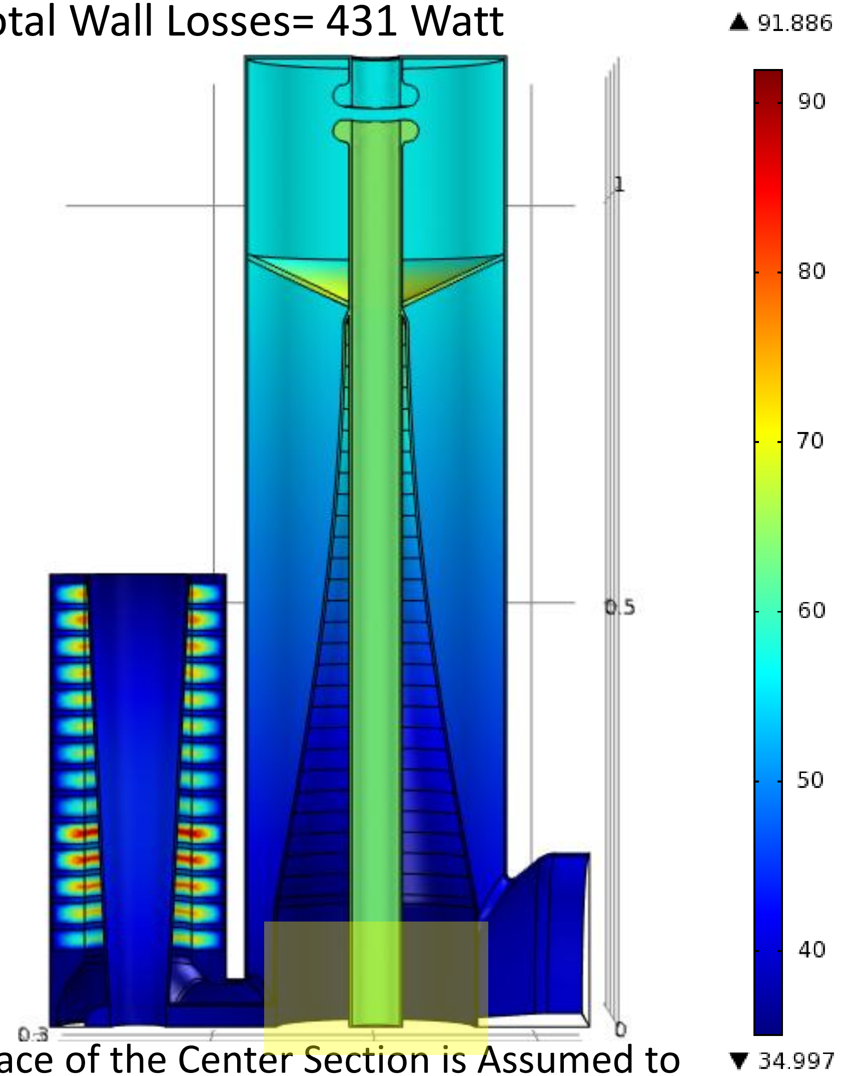
Thermal Heating – Preliminary Trials

Assuming Duty Cycle ¼ -- 7Hz
Average power of the cycle

Total Magnetic Power Loss = 63.7 KWatt
Total Eclectic Power Loss= 1.4 KWatt
Total Wall Losses= 431 Watt

Tuner Outer Wall is Assumed to be at 35°C



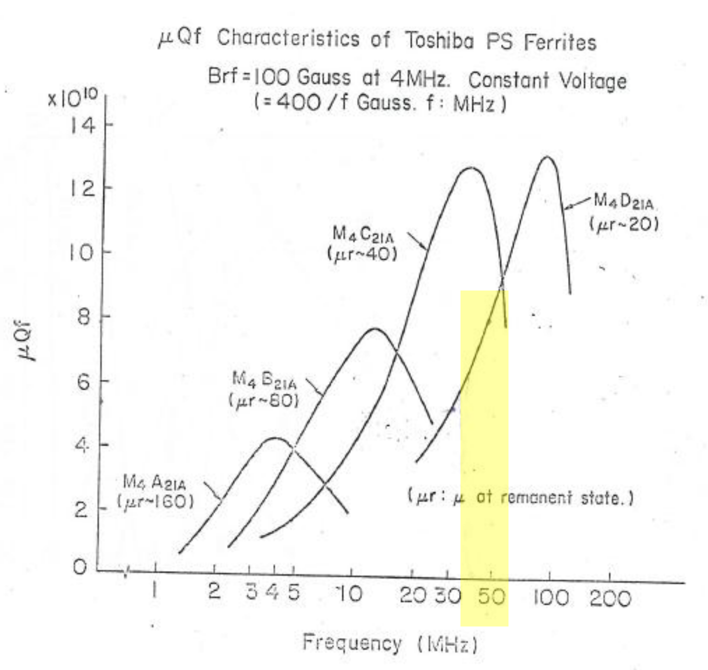


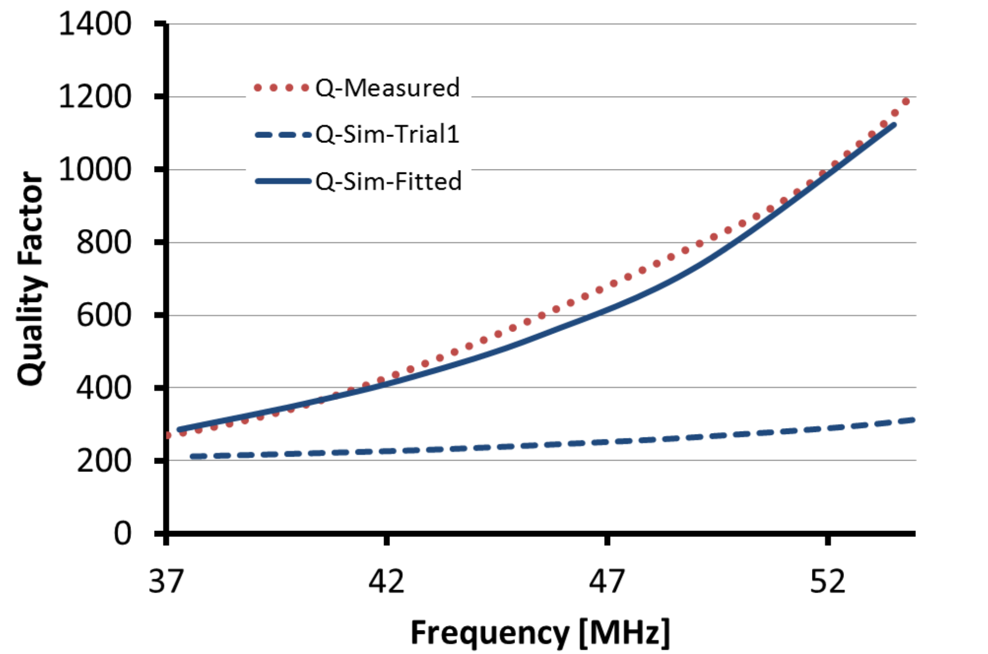
Surface of the Center Section is Assumed to be at 35°C (John's Sugg.)

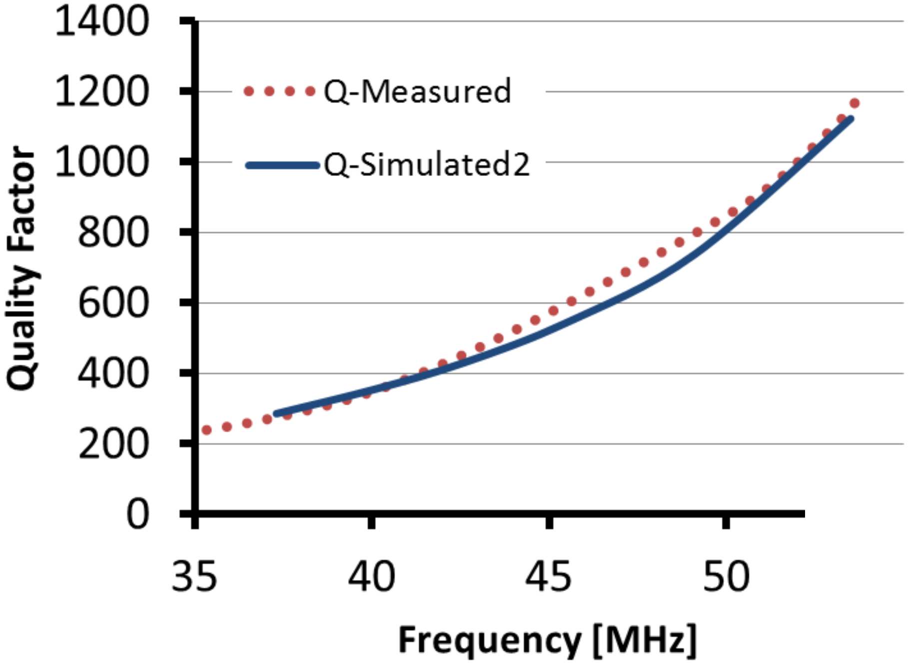
Adjusting the Simulated Q-curve

- Total power loss is a higher than expected mainly because the Simulated Q is Lower than expected
- Losses of the Ferrites are strongly dependent on frequency
- Simulated Q has been fitted to the measured one by adjusting the magnetic loss tangent with frequency

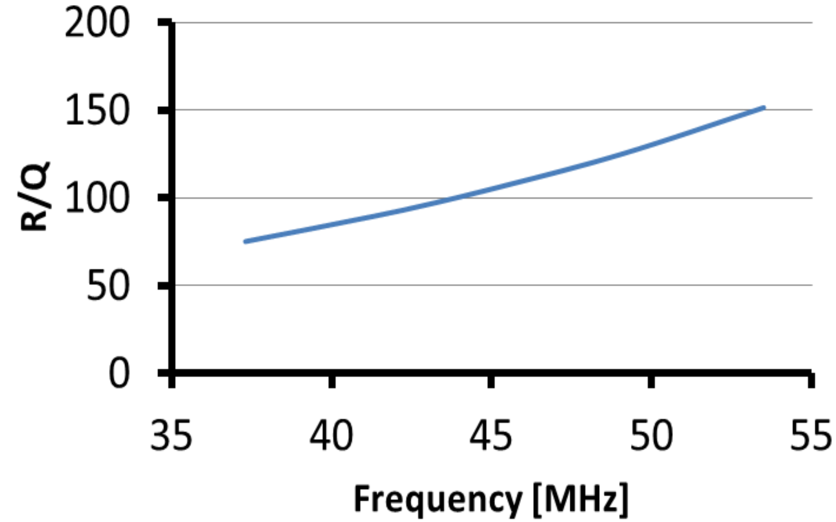
- $\mu_{toshiba}$=8.4
- $\mu_{stackpole}=\mu_{toshiba}*12.5/20$
- $\delta_{m\text{-}toshiba0}$=0.007
- $\delta_{m\text{-}stackpole0}$=0.005
- $\delta_{m\text{-}toshiba}=\delta_{m\text{-}toshiba0}*\mu_{toshiba}/11.5$
- $\delta_{m\text{-}stackpole}=\delta_{m\text{-}stackpole0}*\mu_{stackpole}/(11.5/20*12.5)$



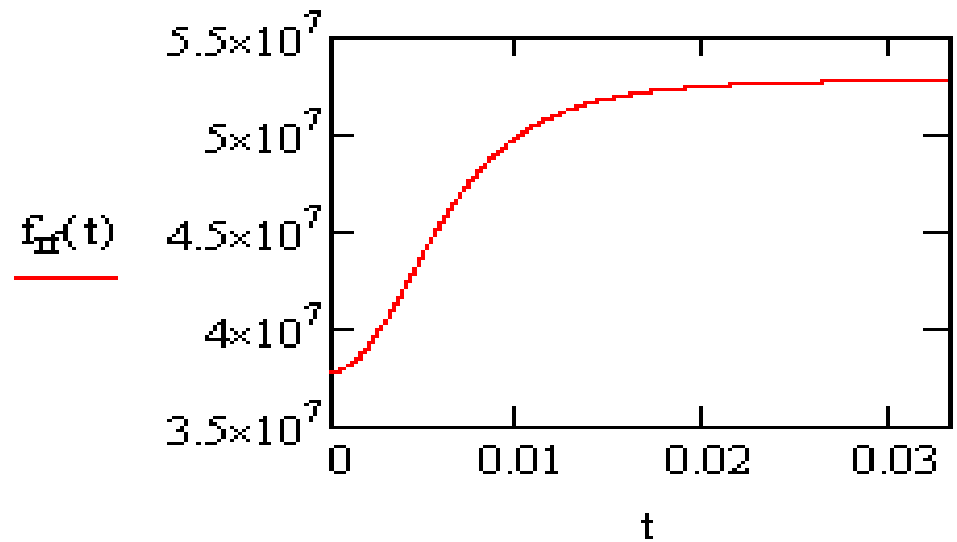




Quality Factor
1400
1200
1000
800
600
400
200
0
Q-Measured
Q-Simulated2
35
40
45
50
Frequency [MHz]



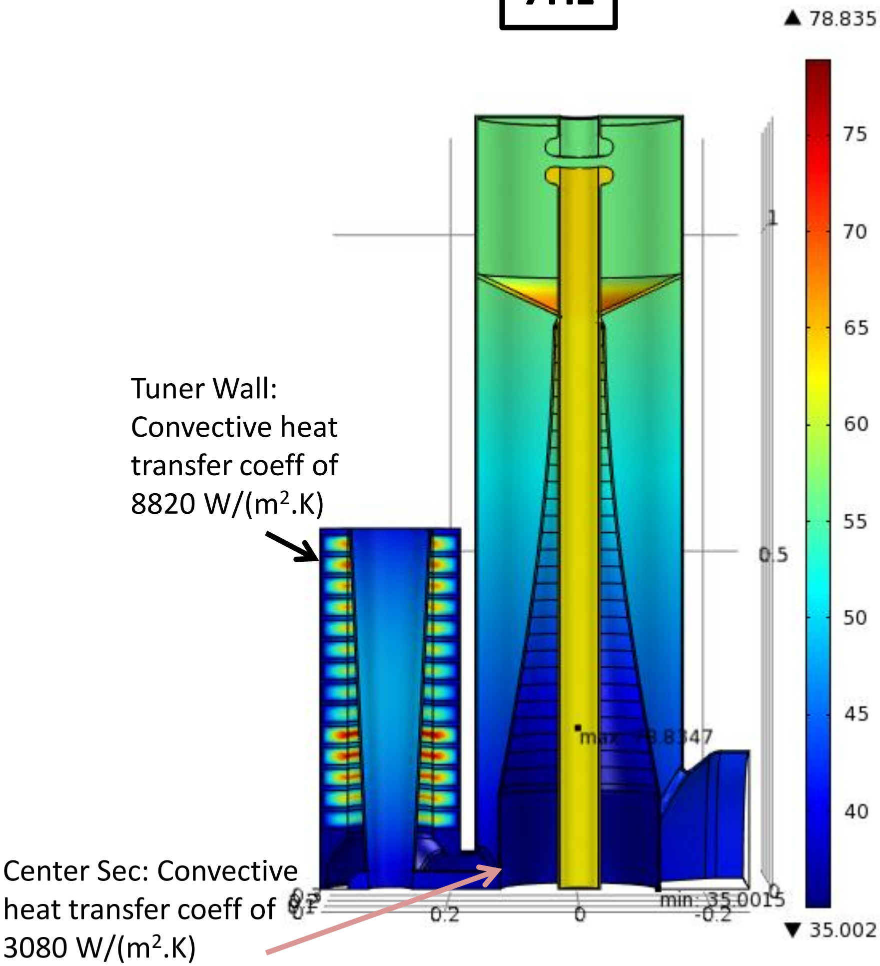
R/Q
200
150
100
50
0
35
40
45
50
55
Frequency [MHz]



5.5×10^7
5×10^7
4.5×10^7
4×10^7
3.5×10^7
0
0.01
0.02
0.03
t

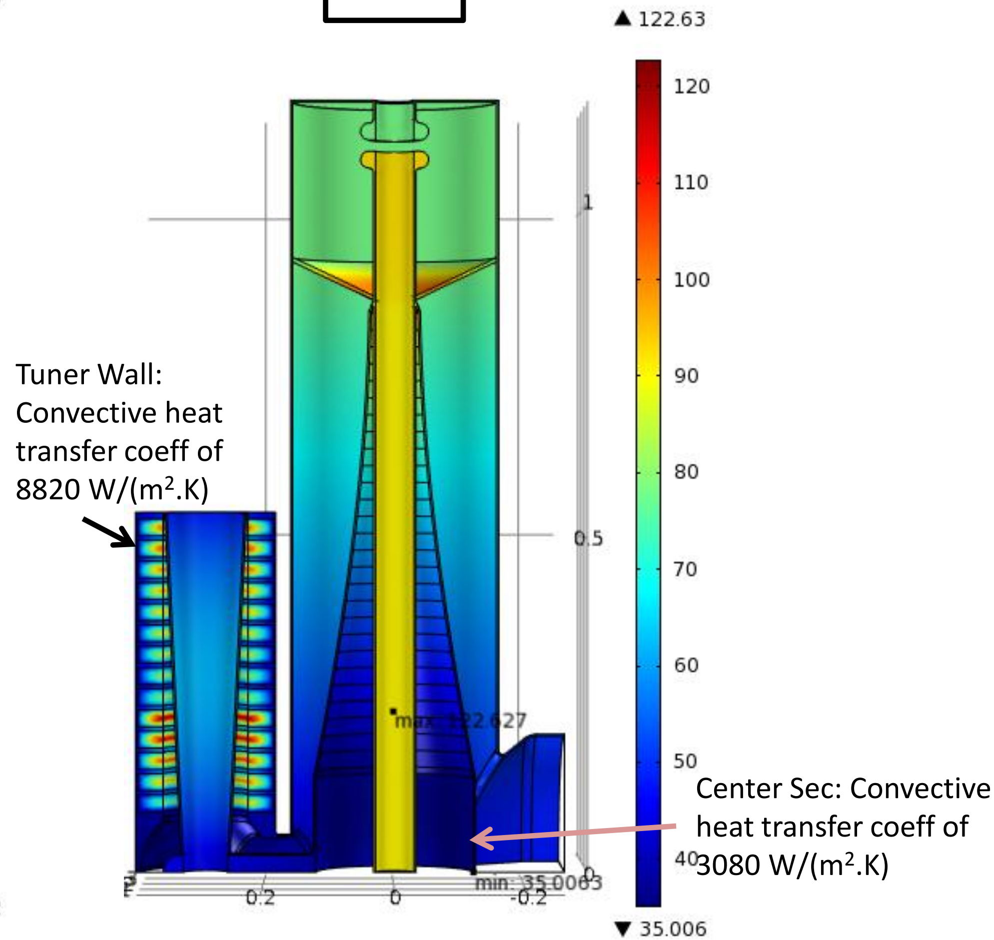
After Adjusting the Q-curve

7Hz



- **Loss/Tuner ~ 7.6 KWatt**

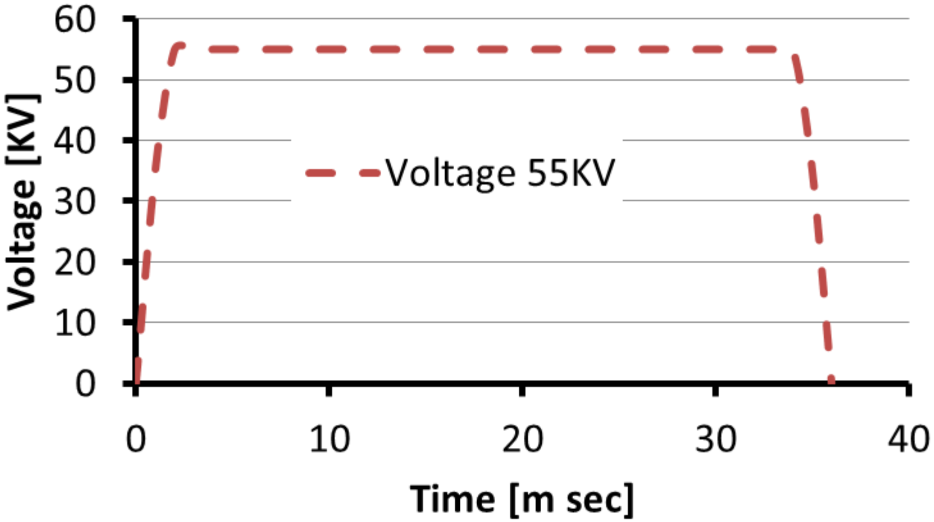
15Hz

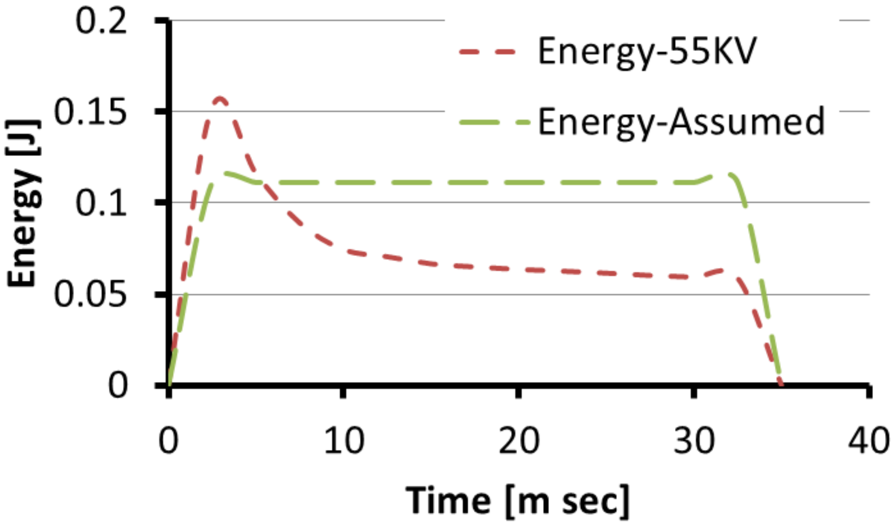


- **Loss/Tuner ~ 15.2 KWatt**

Averaging over the Frequency Cycle

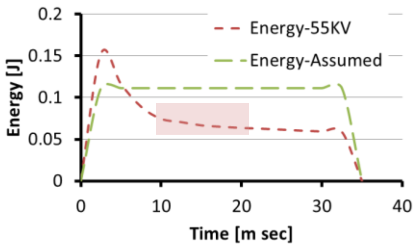
- The losses still higher than expected
- The losses of the cavity need to be averaged properly by integrating the power over the frequency cycle





Area-Red/Area-Green= 0.69

55 KV Waveform – Corrected Results

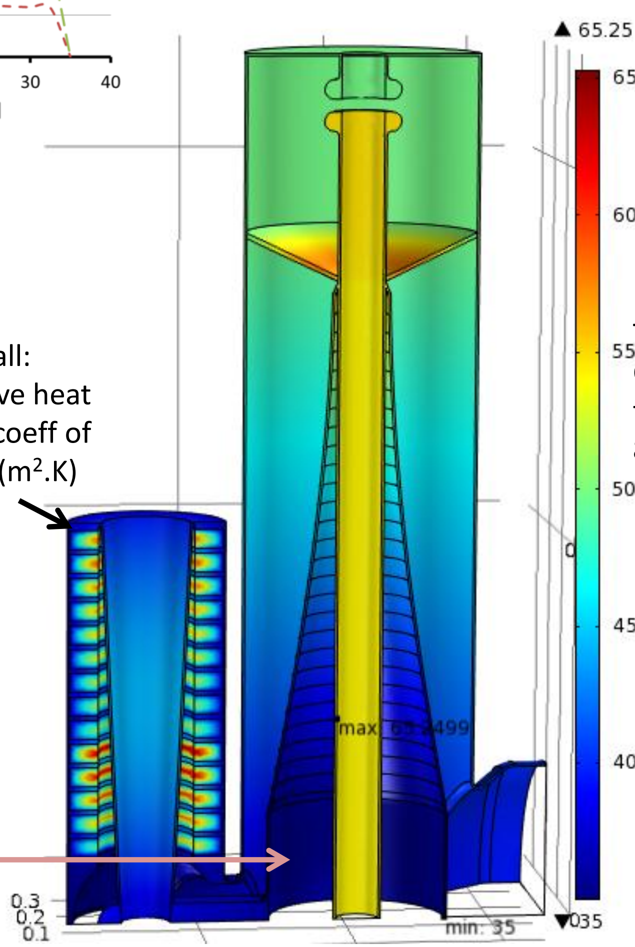


7Hz

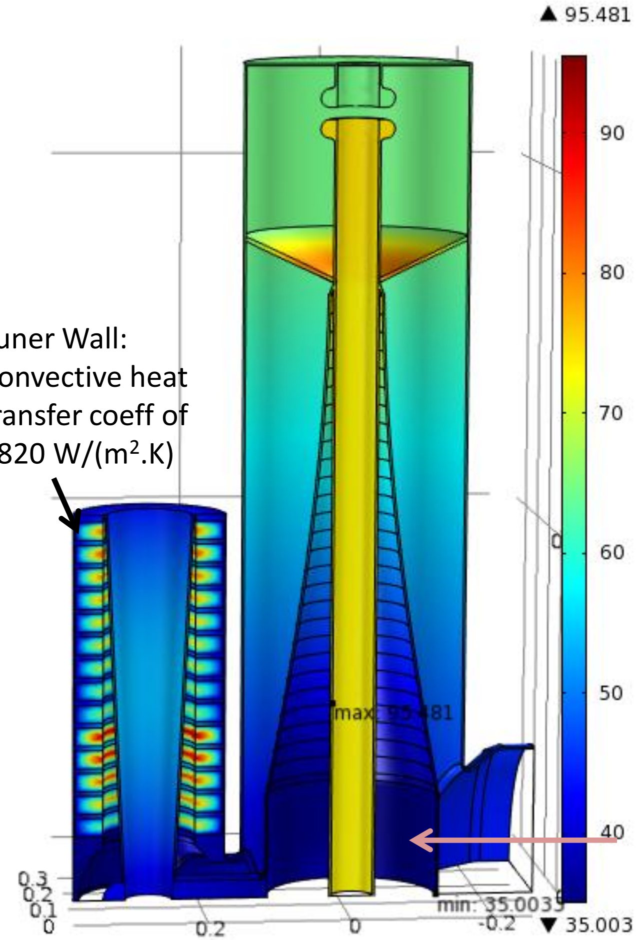
15Hz

Tuner Wall: Convective heat transfer coeff of 8820 W/(m^2.K)

Center Sec: Convective heat transfer coeff of 3080 W/(m^2.K)



Tuner Wall: Convective heat transfer coeff of 8820 W/(m^2.K)

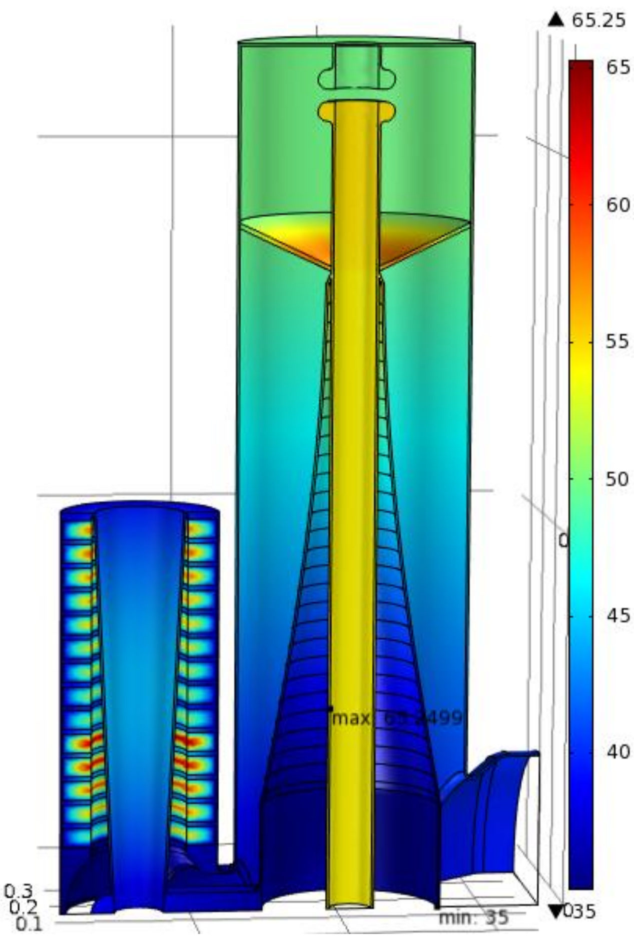


Center Sec: Convective heat transfer coeff of 3080 W/(m^2.K)

- **Loss/Tuner ~ 5.3 KWatt**
- **Loss/Tuner ~ 10.5 KWatt**

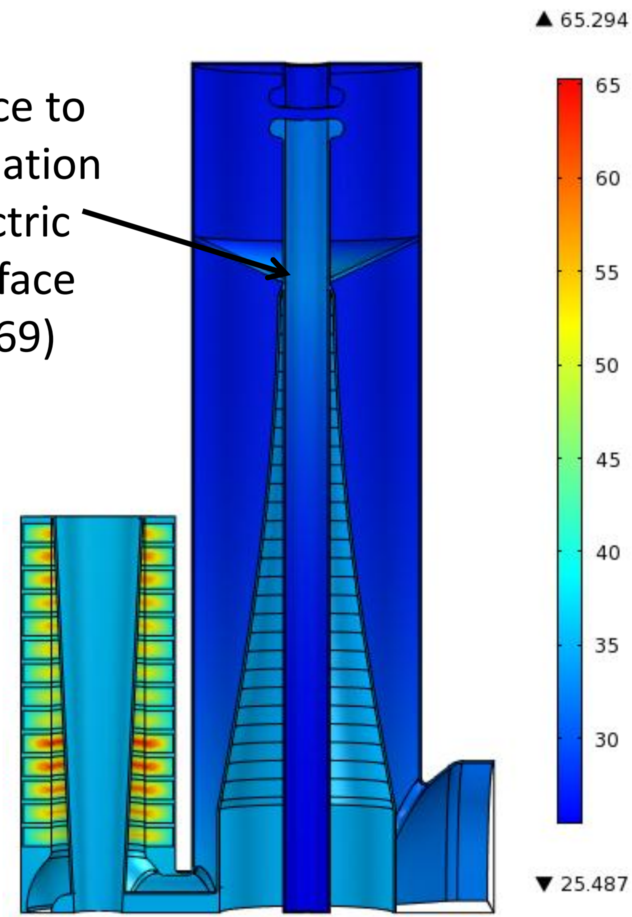
Inner Conductor of the Cavity is Warmer than Expected !

55 KV, 7Hz



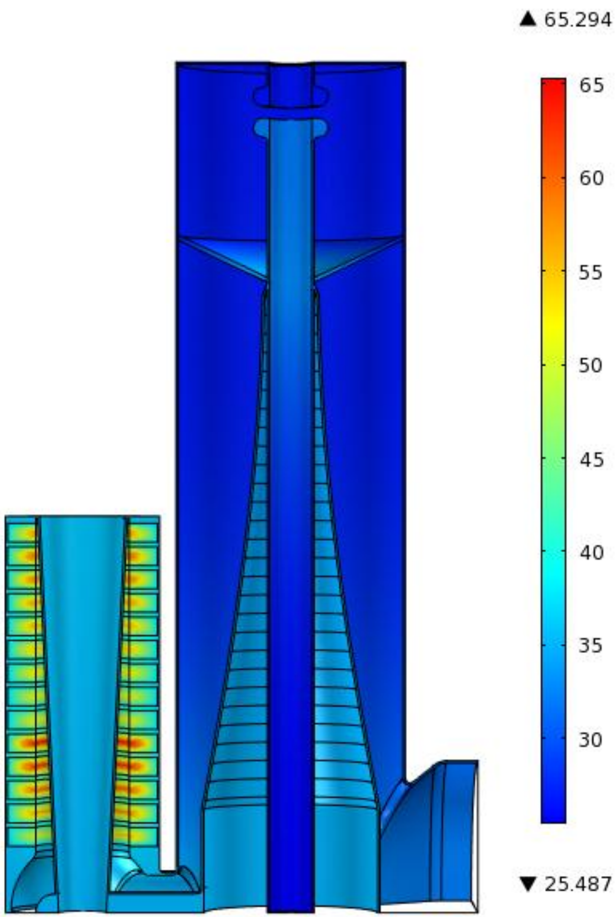
55 KV, 7Hz

Added surface to ambient radiation on the dielectric window (surface emissivity 0.69)

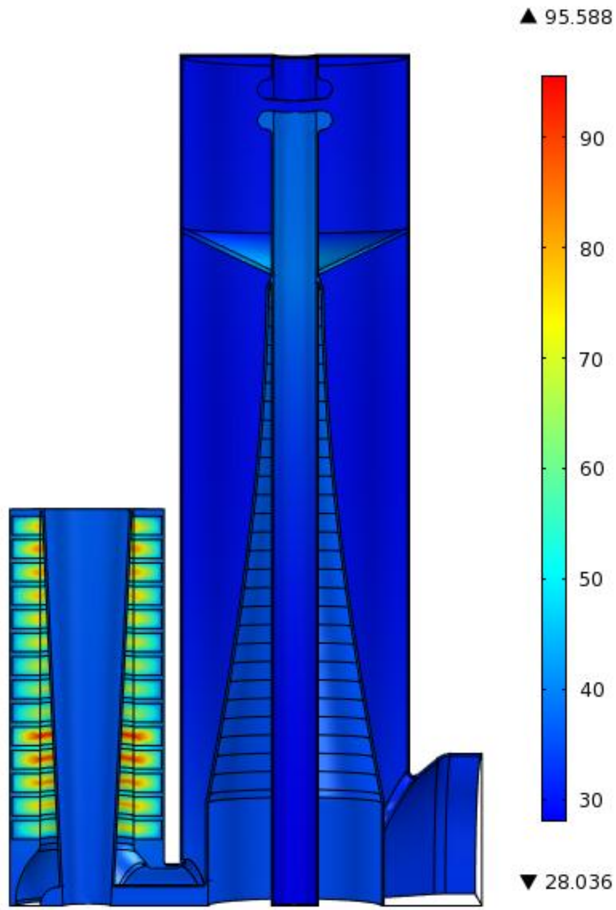


Latest Results

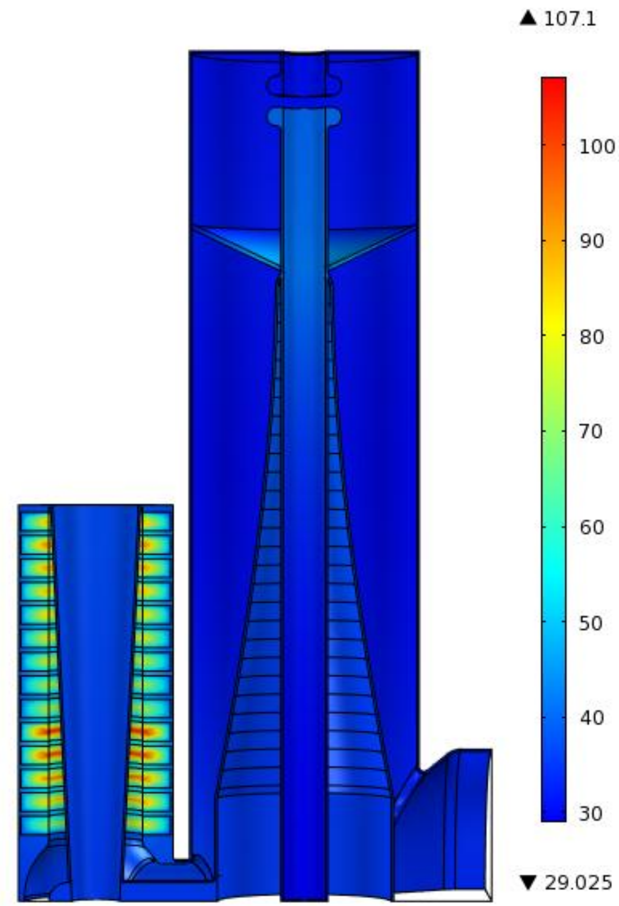
55 KV, 7Hz



55 KV, 15Hz



60 KV, 15Hz



Summary

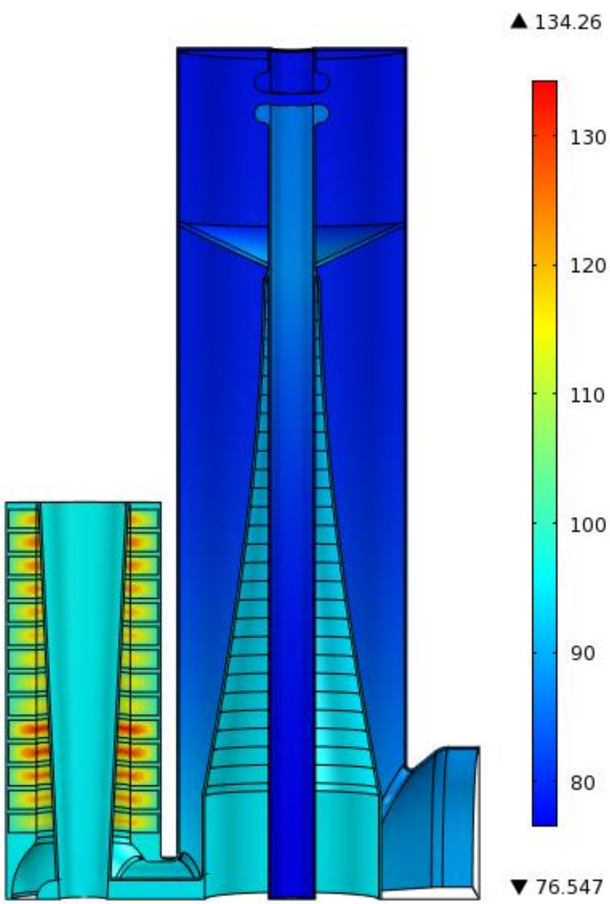
	55 KV, 7 Hz	55 KV, 15 Hz	60 KV, 15 Hz	Units
Max Field in Vacuum	3.3	3.3	3.6	MV/m
Max Field in Air	17	17	18.5	kV/cm
Electric Loss/Tuner	146	300	348	W
Magnetic Loss/Tuner	5.1	10.2	12.2	kW
Cavity Inner Cond Losses	39	79	93	W
Tuner Cone Losses	30.5	61	73	W
Ceramic Losses	22	45	54	W
Wall Losses	0.65	1.3	1.6	kW
Loss/Tuner	5.3	10.5	12.5	kW
Total Losses	16.6	32.8	39.1	kW

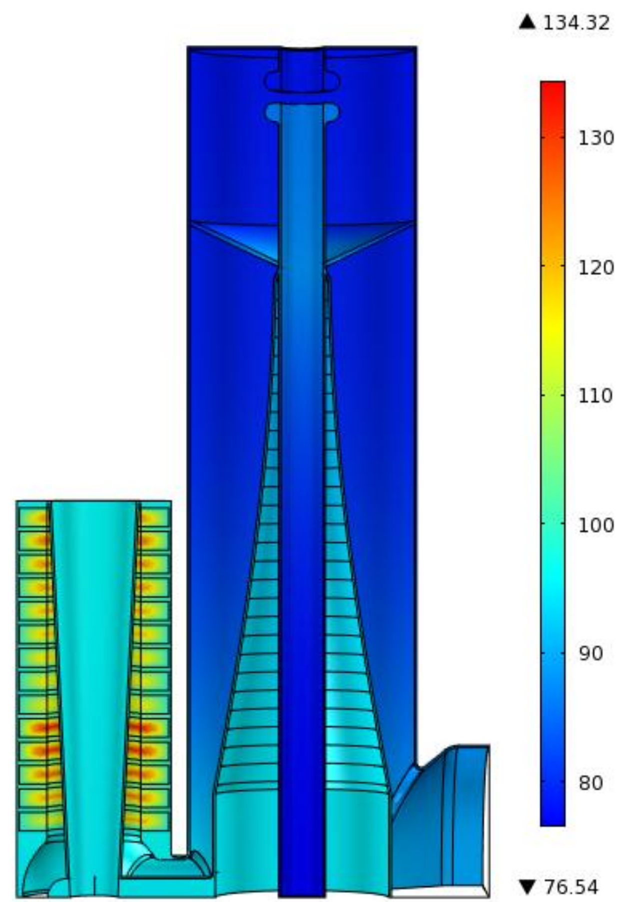
Comparison to John Reid's Measured Temperatures at 33 KV, 15 Hz

33 kV, 15 Hz

Measured Values on Stem ~124 F, 110 F

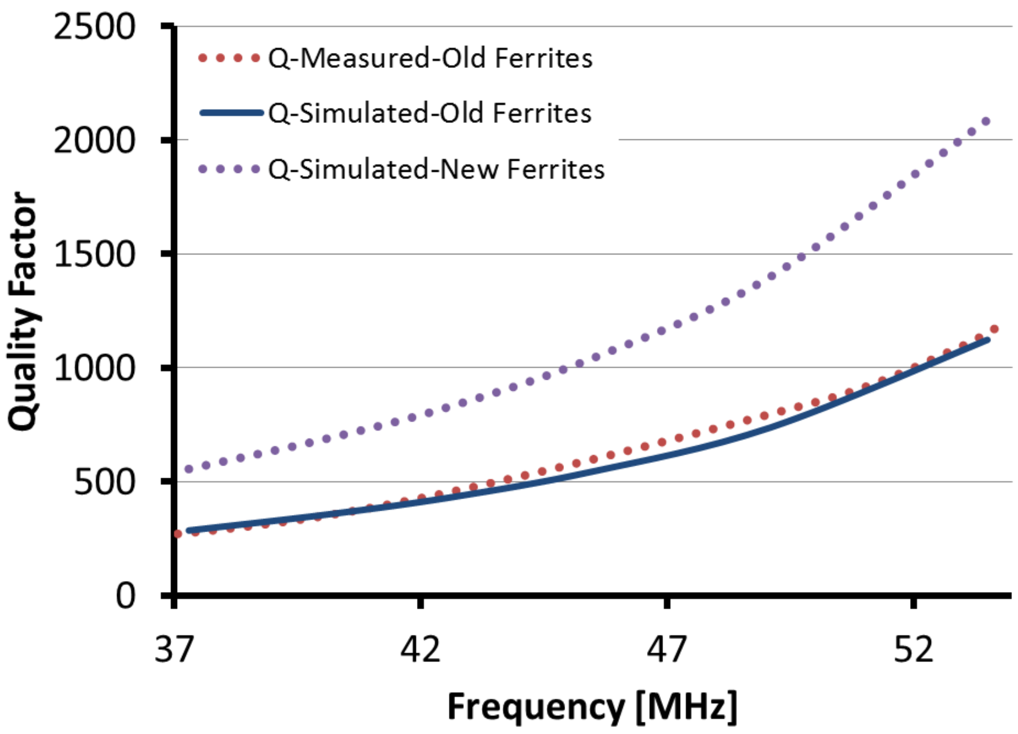
Temperature in deg F



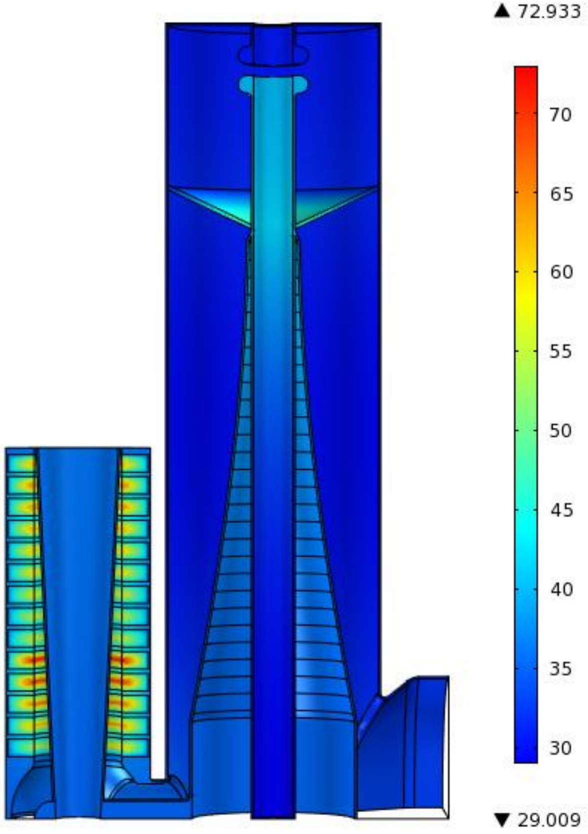


New Ferrites

- Assuming that the new ferrites would be better in Quality factor (double)



New Ferrites, 60 KV, 15Hz



Conclusion

- If there a problem of field breakdown in Air, it could be resolved by properly blending the stem connecting edges to the cavity
- 0.25” Blend radius seems to work fine even if we increased the gap voltage to 60 kV (18.5 kV/cm)
- Losses of the cavity at 7 Hz operation with 55 kV is about 16.6 kW inducing heating in the tuners of max temperature 65° C (149° F)
- Losses of the cavity at 15 Hz operation with 55 kV is projected to increase to 32.8 kW inducing heating in the tuners of max temperature is 96° C (205° F)
- Losses of the cavity at 15 Hz operation and with 60 kV is projected to increase to 39 kW inducing heating in the tuners of max temperature is 107° C (224° F)
- Better ferrites with higher Q’s would definitely help to reduce the losses and so mitigate the increased RF heating with 15 Hz operation