MEBT Rebunching cavity simulations

October 2013

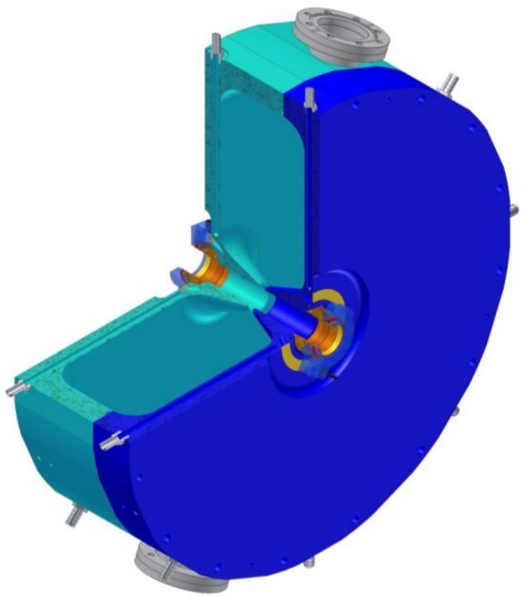

Figure n, ¾ section view of MEBT rebunching cavity based on CERN design

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1. Results Summary – using 8x power input

NB: The results below are incorrect. The power values used were 8x too large.

The FETS MEBT rebunching cavity is designed to run at 324MHz. Various factors will cause the frequency to move away from the design value, including:

- Thermal expansion
- Vacuum deformation
- Plating thickness variation
- Machining deviations

These factors can be divided into those that can be predicted and taken account of at the design stage and those that must be compensated for dynamically by the tuner.

Thermal: The cavity will start off a room temperature and must have a frequency of 324MHz. Once up to operating temperature and full thermal expansion it must remain at 324MHz. This expasnion must therefore be compensated for by the dynamic tuner.

1) Nose gap reduction = 0.026mm, @4.177 MHz/mm = **-0.11 MHz**

[CHECK: DECREASED GAP = CAPACITANCE UP = FREQUENCY DOWN**]**

2) Diameter growth = 0.2mm, @-0.369 MHz/mm = **-0.074 MHz**

[CHECK: LONGER CURRENT PATH = INDUCTANCE UP = FREQUENCY DOWN**]**

3) Length increase = negligible

4) Total frequency shift from thermal expansion = **-0.184 MHz**

NB: These results were obtained by recording the deformations shown in ANSYS Workbench and applying them to the results obtained in SuperFISH.

Vacuum loading: The cavity will only be operated under vacuum and the deformation due to vacuum is known and can be designed for.

5) Nose gap reduction = 0.08mm, @4.177 MHz/mm = **-0.33 MHz**

6) Length change (approximated to be half the nose gap change)

= 0.04mm, @0.751 MHz/mm = +**0.03 MHz**

[CHECK: SHORTER CURRENT PATH = INDUCTANCE DOWN = FREQUENCY UP**]**

7) Total frequency shift from vacuum deformation = **-0.30 MHz**

Plating thickness: We will ask the plating company for a minimum plating thickness which we can design for. In some regions there will be up to 30% over-thickness **(value needs comfirming)** and this we cannot design for. We will ask whether the nose tip region can be the most tightly controlled for plating thickness because it is in this region that the cavity is the most sensitive to size deviation. Over-thickness of plating can be measured using a CMM and compensated for by altering the tuner (fixed) length.

8) Max over plating = 15 microns, @ 0.00765 MHz/micron = **-0.11 MHz**

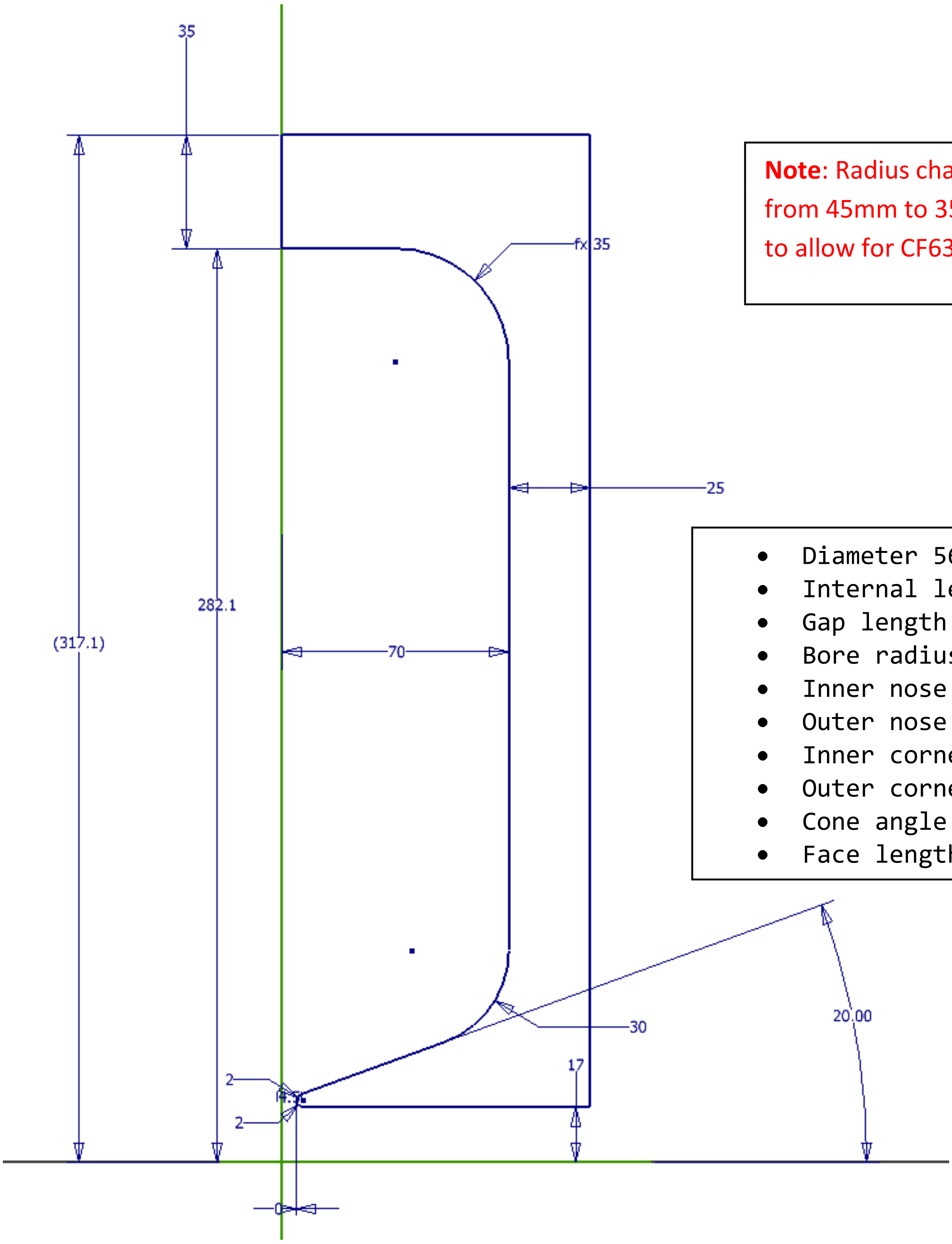
Machining deviations: We will measure the completed cavity prior to plating using a CMM. The cavity can be designed such that it can be re-machined if size or form deviations are unacceptable.

Conclusion: The frequency change due to temperature rise must be compensated for using the dynamic tuner. The total frequency change is in the region of:

Total frequency shift from thermal expansion = **-0.184 MHz**

The tuning range is 0.64 MHz over the full 50mm range. The results shown here indicate that the total frequency shift due to temperature change and plating variation could be tuned with 14mm of travel.

2. Cavity geometry & dimensions



Note: Radius change from 45mm to 35mm to allow for CF63 port

- Diameter 564.2 mm
- Internal length 140mm
- Gap length 9mm
- Bore radius 17mm
- Inner nose radius 2mm
- Outer nose radius 2mm
- Inner corner radius 30mm
- Outer corner radius 45mm
- Cone angle 20 deg
- Face length 0mm

Figure n, Underlying sketch for rebunching cavity

3. One-eighth 3D model

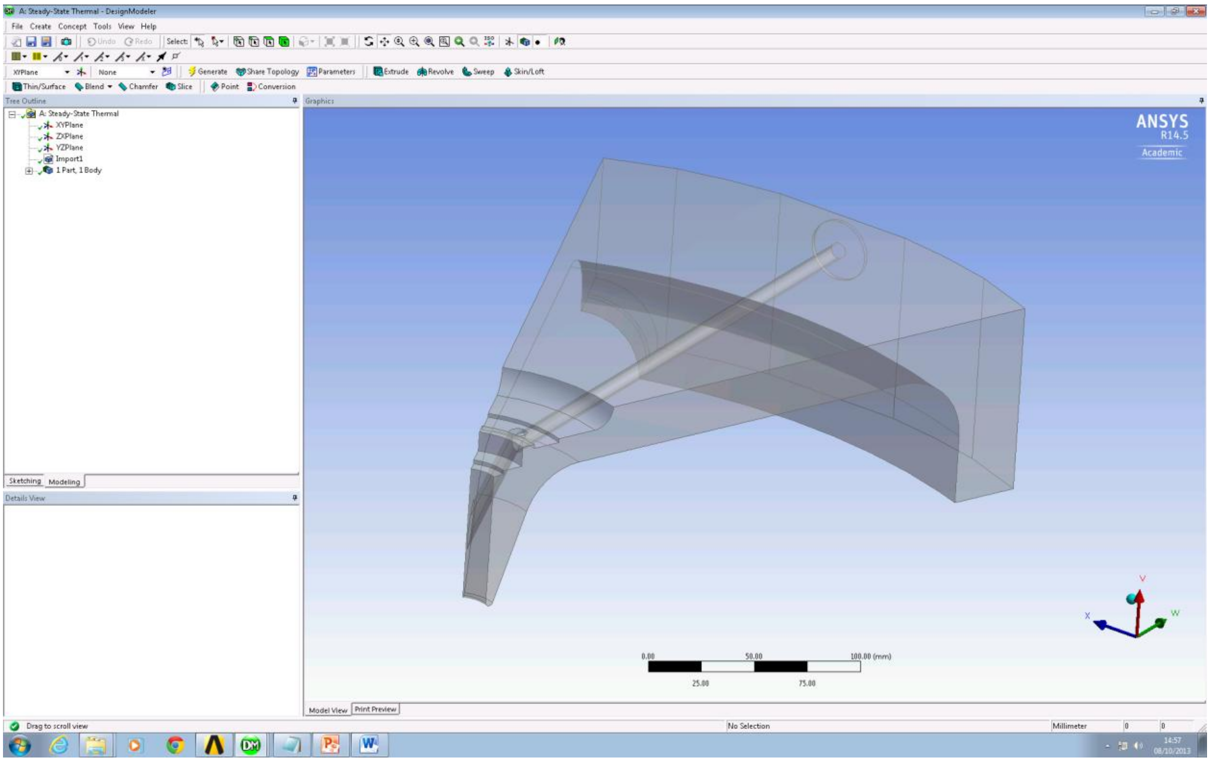


Figure n, Imported IGES file from CAD to be used for simulations

4. Cavity thermal modelling

Material: Structural Steel

Thermal conductivity: 60.5 w/m/C (may be a bit high - **CHECK**)

The values refer to peak power in watts for 100 kV effective voltage. The average powers are 10% of these values.

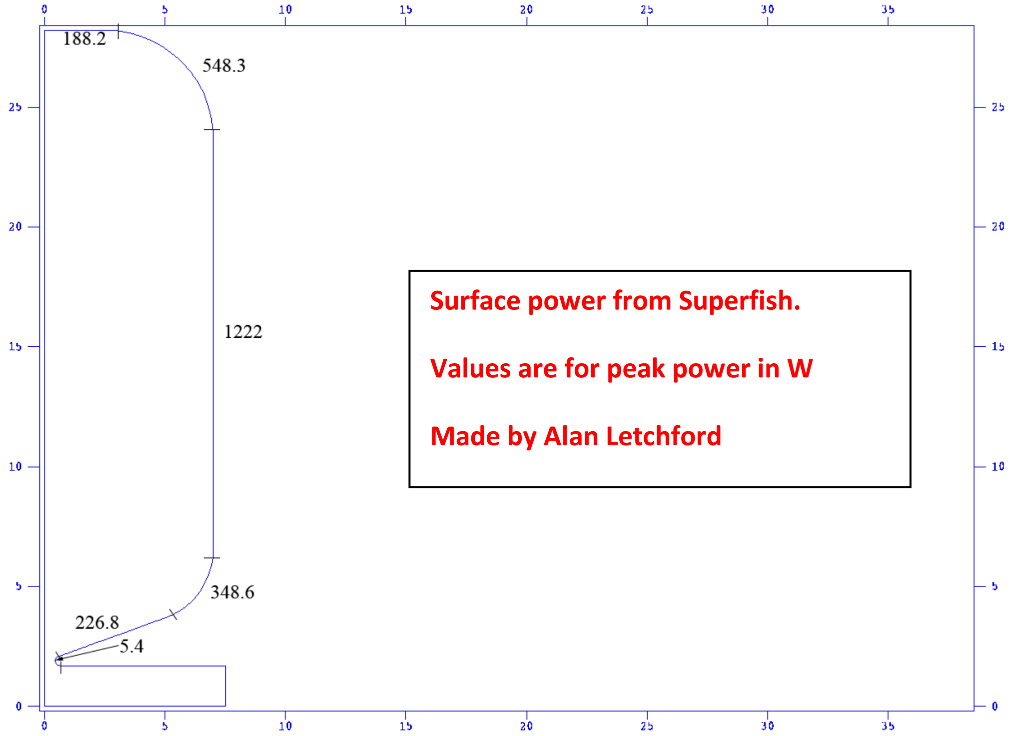


Figure n, Power on inner surfaces

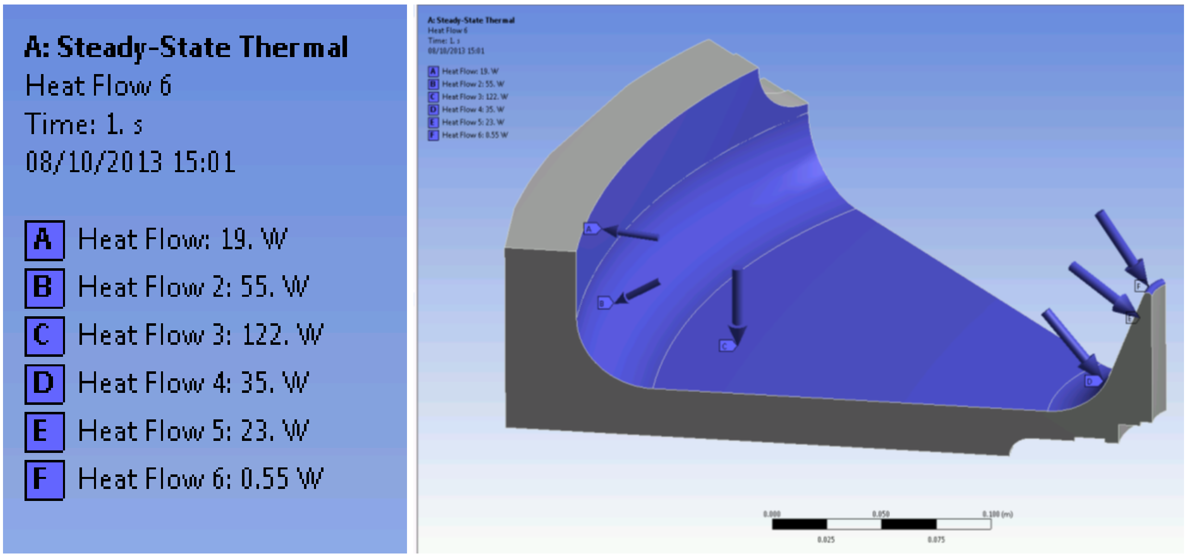


Figure n, Average power on inner surfaces

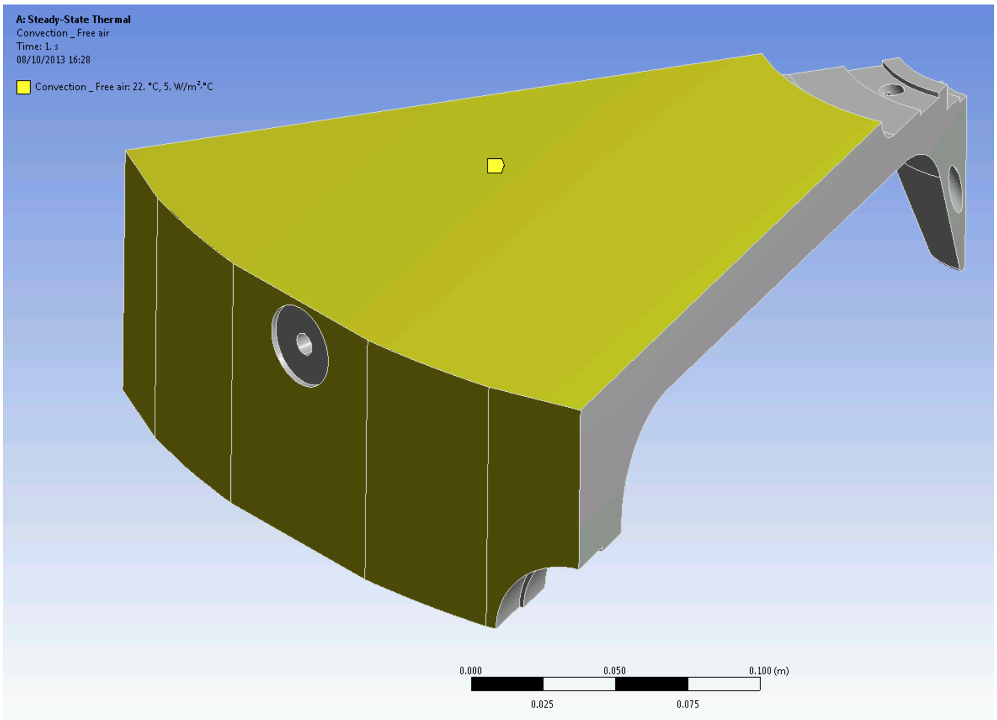


Figure n, Free air convection on outer surfaces, 5 $W/m^2.^0C$

[Free Convection - Air : 5 - 25 (W/m2K)]

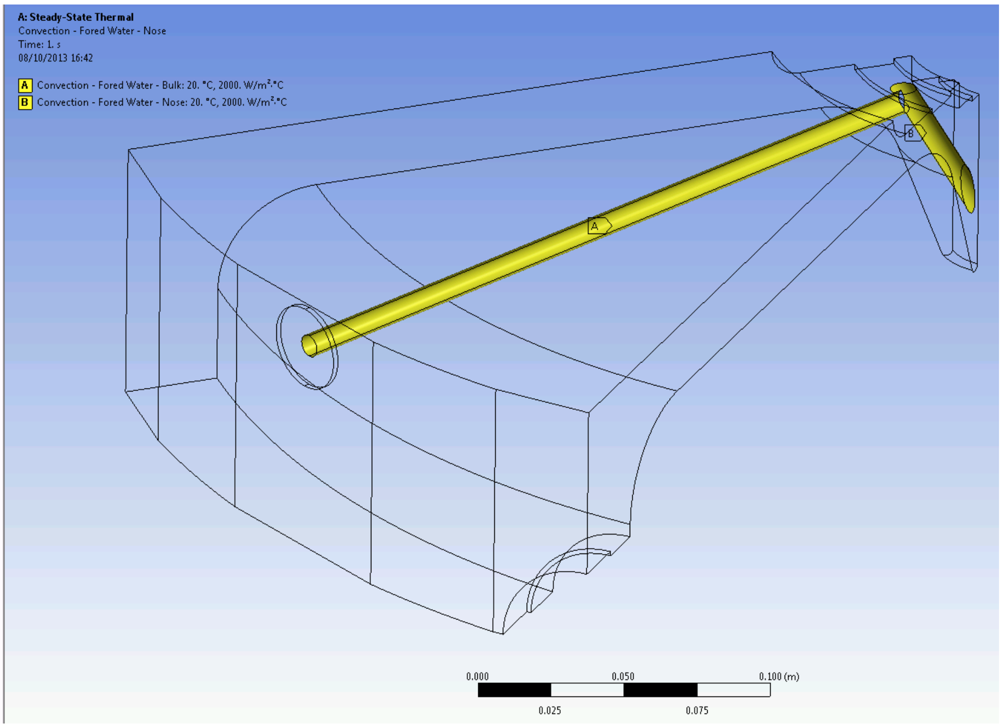


Figure n, Forced water convection on hole surfaces, 2000 $W/m^2.^0C$

[Forced Convection - Water: 50 - 10.000 (W/m2K)]

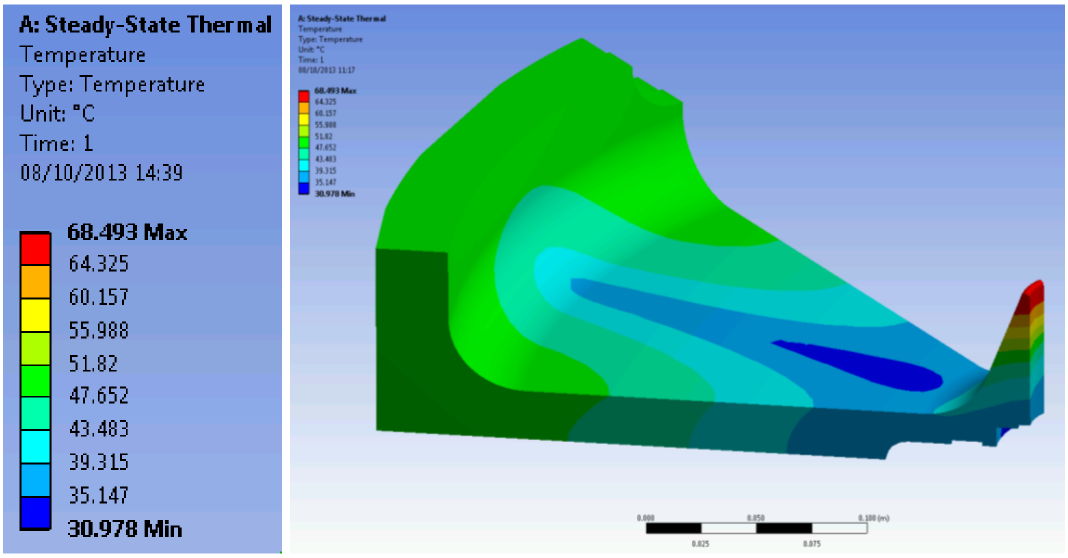


Figure n, Cavity temperatures

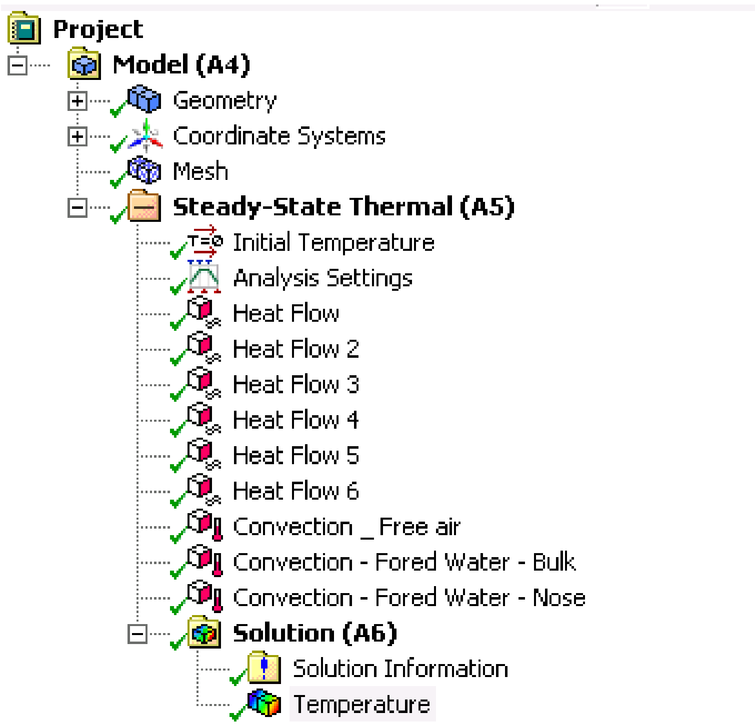


Figure n, Model setup in ANSYS Workbench

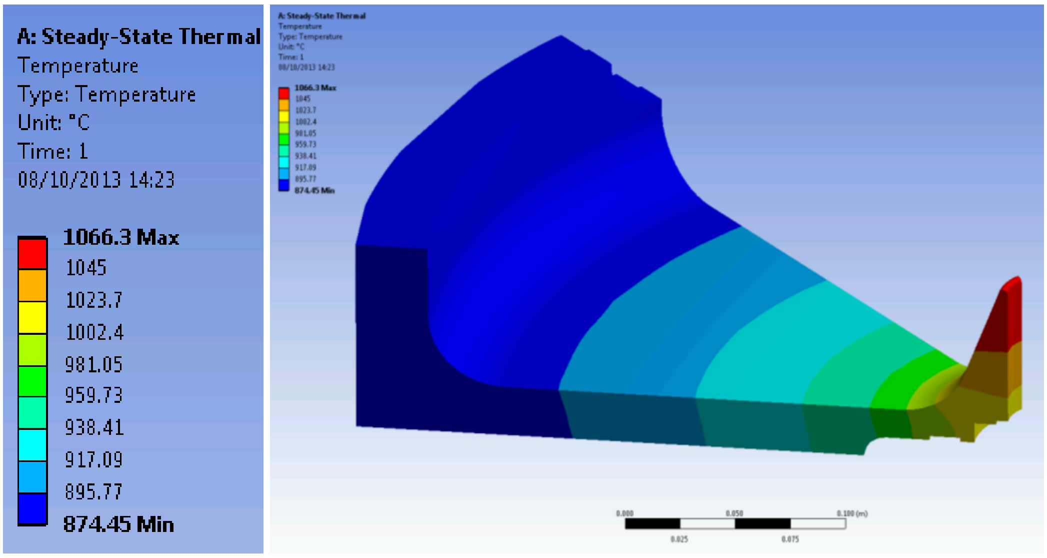


Figure n, Water cooling turned off. Only air cooling on outer surfaces.

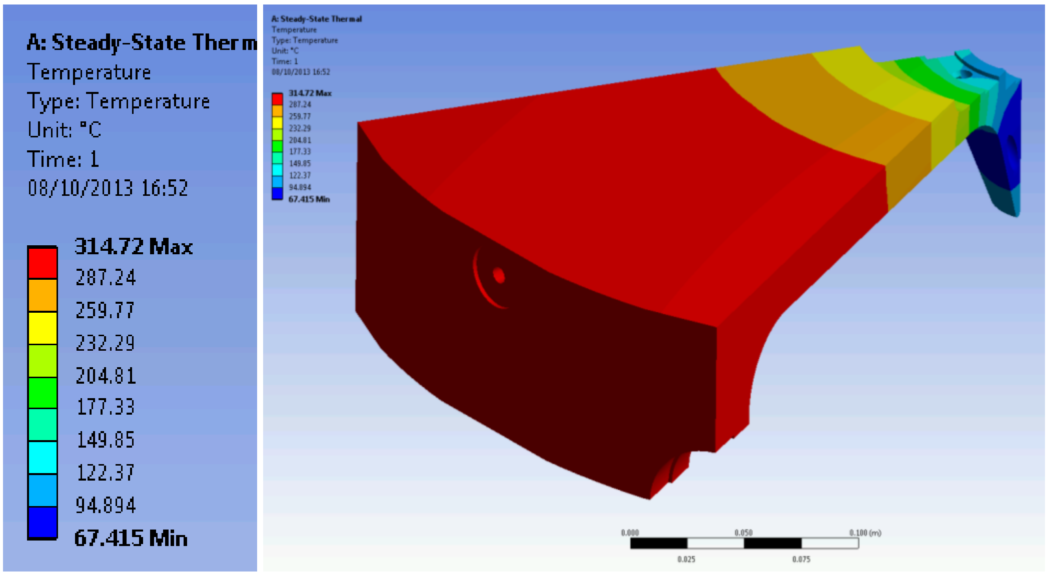


Figure n, Water cooling at the nose region only.

A question has been asked: Can we cool the cavity at the nose only to avoid the expense of gun drilling to create the radial cooling channels?

ANSWER: **No.** The radial channels are needed. The thermal expansion of the cavity at 300 C would be beyond the tuning range.

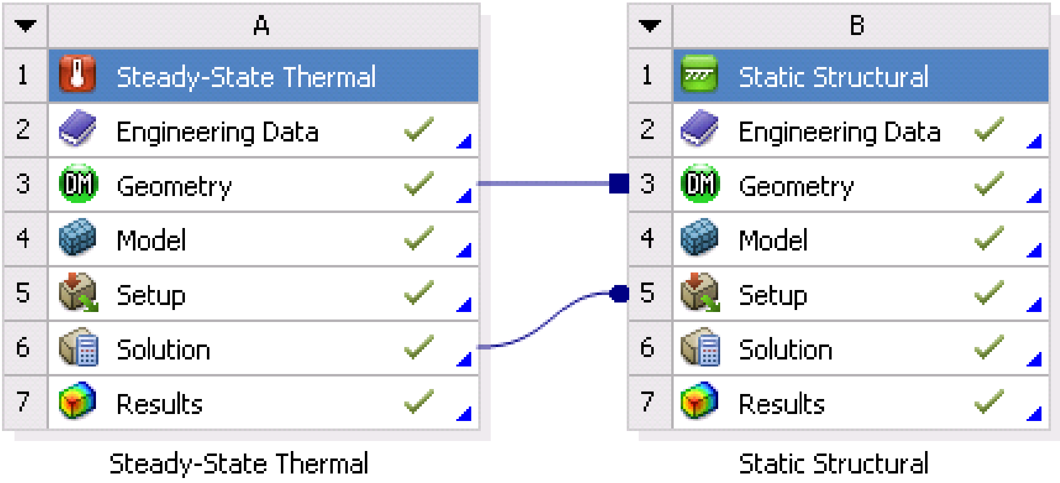


Figure n, ANSYS Workbench 14,5 Project Schematic

Showing how to create a thermal expansion analysis (Static Structural) using the **Geometry** and the **Temperature distribution** from the steady-state thermal simulation.

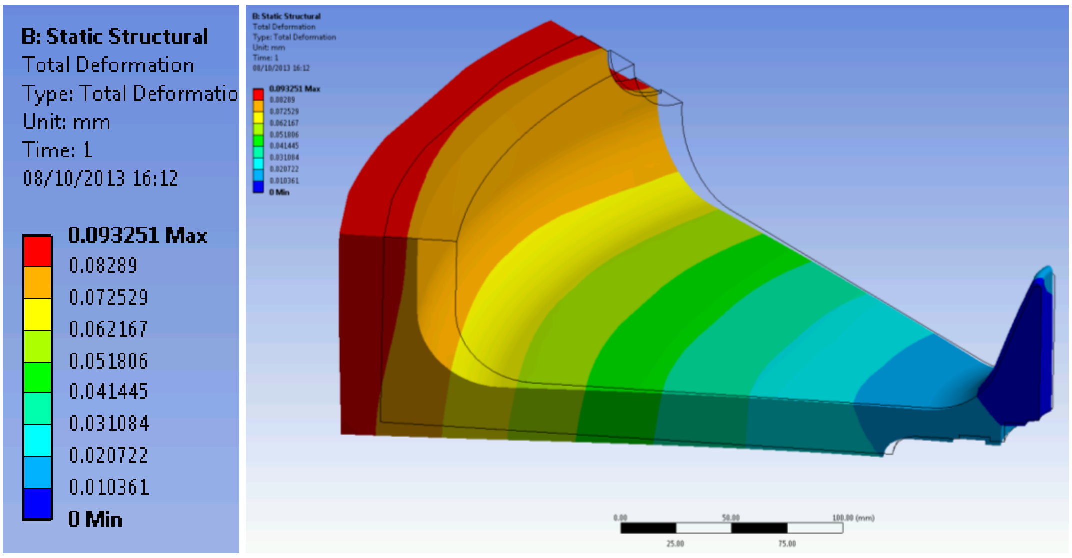


Figure n, Total displacement due to temperature rise.

Note that the constraints used in this model are not totally accurate. However, they are sufficient to provide a feeling for the displacement values which are as follows:

Outer radius growth = 0.1 mm, **diameter growth = 0.2mm**

Would recommend that **quarter models** are used for future models instead of **eigth**. This allows the symmetry planes to be constrained as friction free which allows the cavity to grow, effectively fixed at the beam axis. The eigth model is under-constrained with just the symmetry planes made friction free, an extra constraint is needed and for the purpose of this model I fixed one edge of the inner bore.

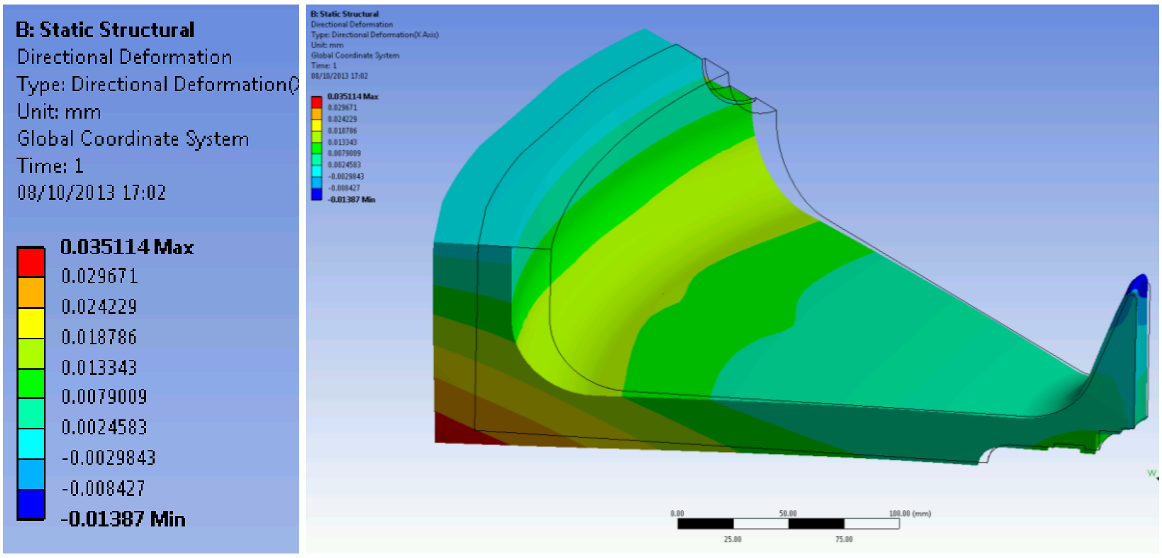


Figure n, Displacement in X due to temperature rise

Wall separation = negligible

Nose tips move together each by 0.013mm i.e. the **nose to nose gap reduces by 0.026mm**

5. Deformation due to vacuum loading

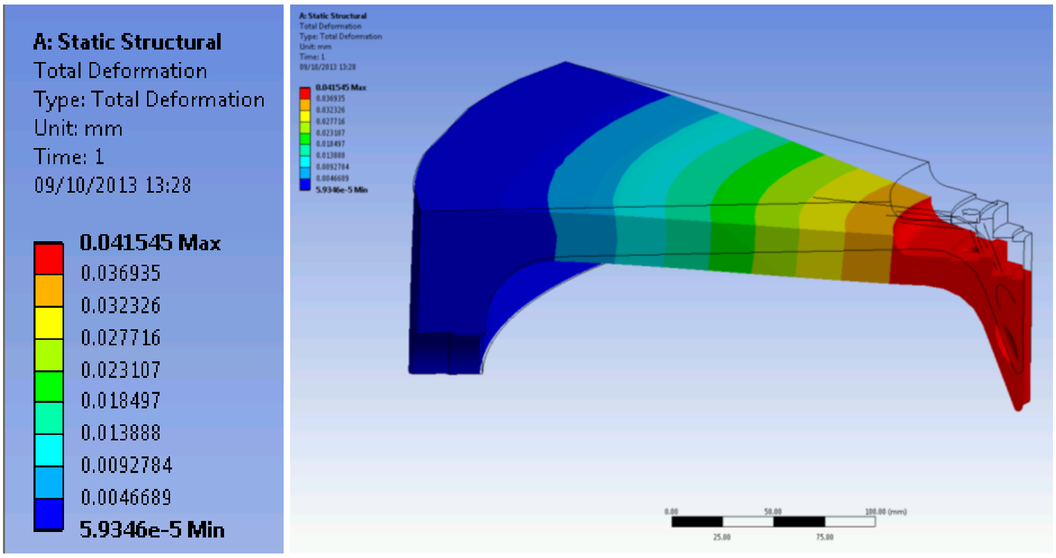


Figure n, Total displacement due to vacuum loading

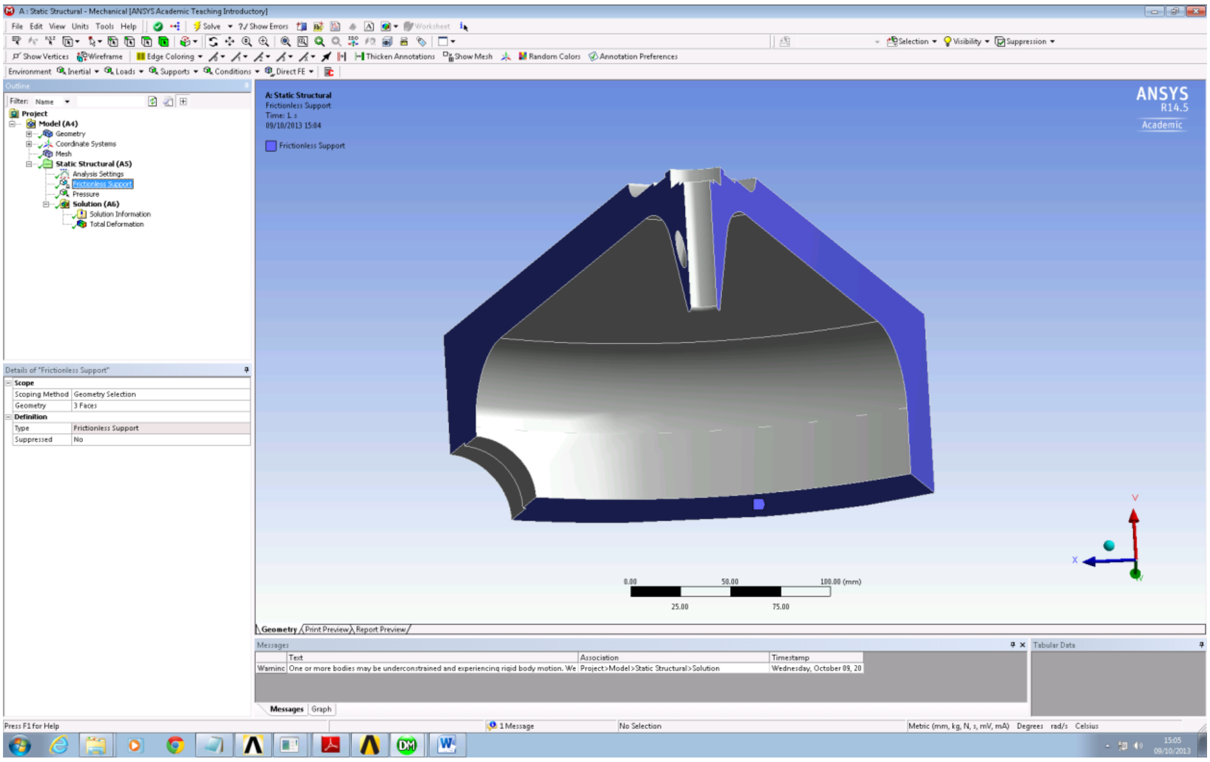


Figure n, Constraints - frictionless surfaces

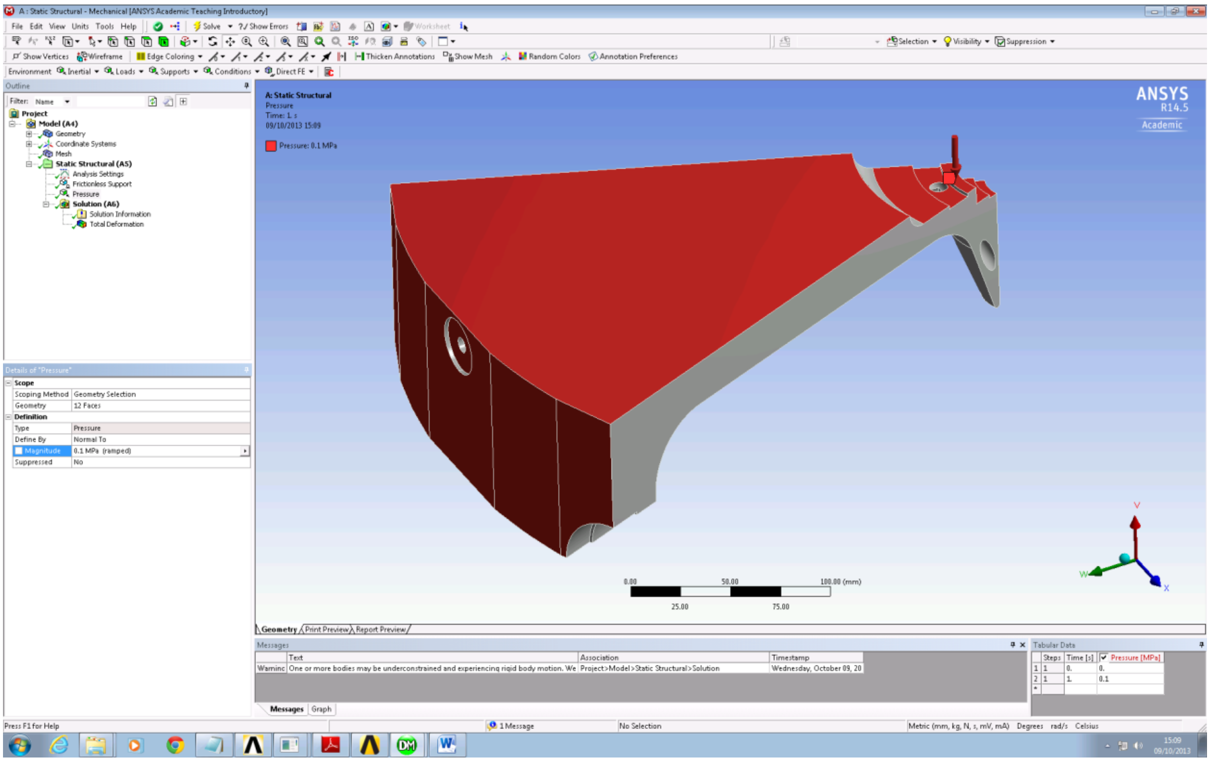


Figure n, Vacuum loading – pressure 100,000 Pa

NB: Previous vacuum deformation calculations made in Inventor showed a deformation of 0.06mm at the nose tips while here 0.04mm I showing. The difference may be due to the smaller diameter and larger radius used in this cavity, both of which add stiffness.

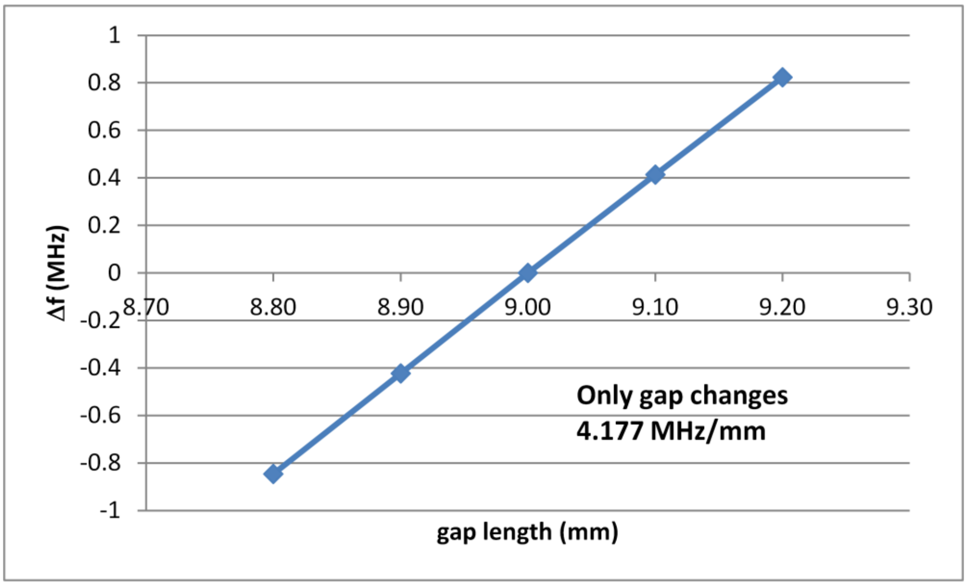
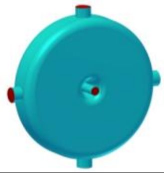
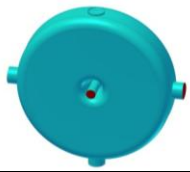
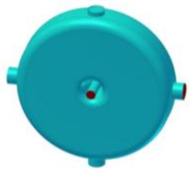
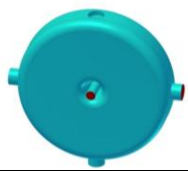
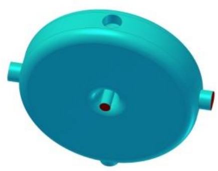


Figure n, Change of frequency versus gap length (source: Alan)

For a gap length reduction from 9.00mm to 8.92mm we would expect a frequency change of -0.33 MHz.

6. Frequency modelling

Table n, Morteza's frequency results from COMSOL

#	Date	Model (.sat)	Frequency (MHz)	Image
0	18th Oct 2013	RBC_v7_D564.2	**323.85**	
1	9th Oct 2013	RBC_v7_D559	**323.93**	
2	9th Oct 2013	RBC_v7_D559_Empty_Radial_Ports	**323.65**	
3	9th Oct 2013	RBC_v7_D559mm_TunerFlush	**323.69**	
4	9th Oct 2013	RBC_v7_D559mm_Tuner-10mm	**323.63**	
5	9th Oct 2013	RBC_v7_D559mm_Tuner+20mm	**323.97**	
6	9th Oct 2013	RBC_v7_D559mm_Tuner+40mm	**324.27**	
7	11th Oct 2013	RBC_v7_D559mm _0.015	**323.92**	
8	11th Oct 2013	RBC_v7_D559mm _0.030	**323.86**	
9	11th Oct 2013	RBC_v7_D559mm _0.060	**323.80**	

Model description:

#0: Original model geometry supplied by Alan

(**Superfish frequency for 3D model = 324.05 to 324.20 MHz**).

#1: No ports. Diameter reduced from 45mm to 35mm to make space for the DN63CF ports. Overall diameter reduced from 564.2mm to 559.0mm to compensate for extra volume due to decreased radius. Target frequency was 323.75MHz and 323.92MHz is considered close enough to continue the simulation studies.

#2: Empty radial ports added. Everything else kept constant.

[CHECK: LONGER CURRENT PATH = INDUCTANCE UP = FREQUENCY DOWN**]**

#3: Adding one tuner to one of the ports where the tuner face is flush with the inner cavity surface. Everything else kept constant.

[CHECK: SHORTER CURRENT PATH = INDUCTANCE DOWN = FREQUENCY UP**]**

#4: One tuner withdrawn 10mm into the tuner port. Everything else kept constant.

[CHECK: LONGER CURRENT PATH = INDUCTANCE UP = FREQUENCY DOWN**]**

#5: One tuner protruding into the cavity by 20mm. Everything else kept constant.

[CHECK: SHORTER CURRENT PATH = INDUCTANCE DOWN = FREQUENCY UP**]**

#6: One tuner protruding into the cavity by 40mm. Everything else kept constant.

[CHECK: SHORTER CURRENT PATH = INDUCTANCE DOWN = FREQUENCY UP**]**

#7: Model # 1 with 15 microns added to all inner surfaces. Result to be compared to model #1.

[CHECK: NOSE GAP REDUCED = CAPACITANCE UP, SHORTER CURRENT PATH = INDUCTANCE DOWN, RESULT = FREQUENCY DOWN – CAPACITANCE CHANGE IS DOMINANT**]**

#8: Model # 1 with 30 microns added to all inner surfaces. Result to be compared to model #1.

[CHECK: SAME AS #7**]**

#9: Model # 1 with 60 microns added to all inner surfaces. Result to be compared to model #1.

[CHECK: SAME AS #7**]**

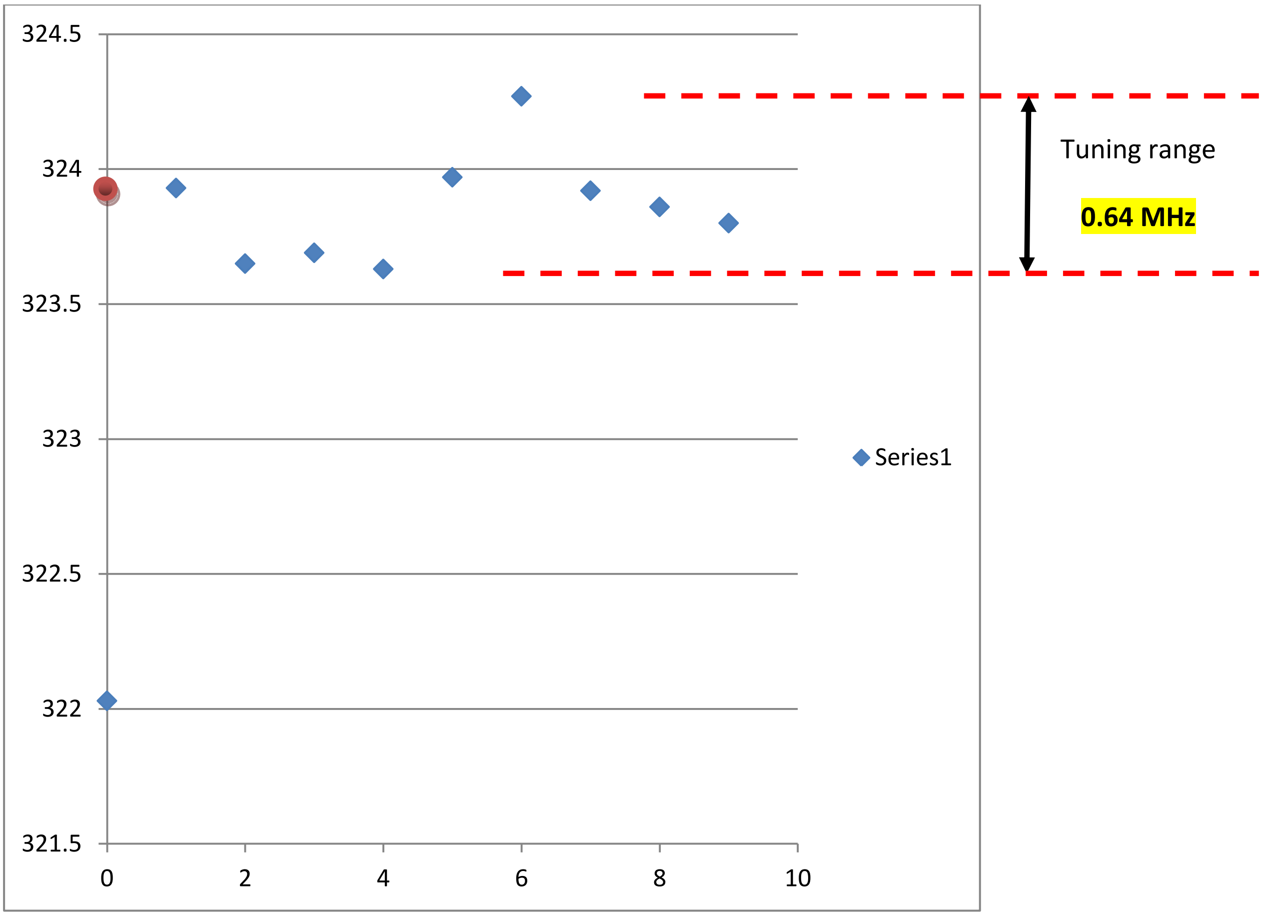


Figure n, Frequency for each model

Model #	Description
0	Alan's cavity geometry
1	Reduced outer radius and reduced overall diameter
2	4 empty ports
3	One tuner flush with inner surface
4	One tuner withdrawn into the port by 10mm
5	One tuner protruding into the cavity by 20mm
6	One tuner protruding into the cavity by 40mm
7	15 micron added to inner surfaces
8	30 micron added to inner surfaces
9	60 micron added to inner surfaces

7. Scale model

Plating thickness: at Imperial College we could build a scale model of half of a rebunching cavity to test the variation in plating thickness.

The maximum size for a **turned** model would be 284mm diameter.

The maximum size for a **milled** model would be 400mm diameter.

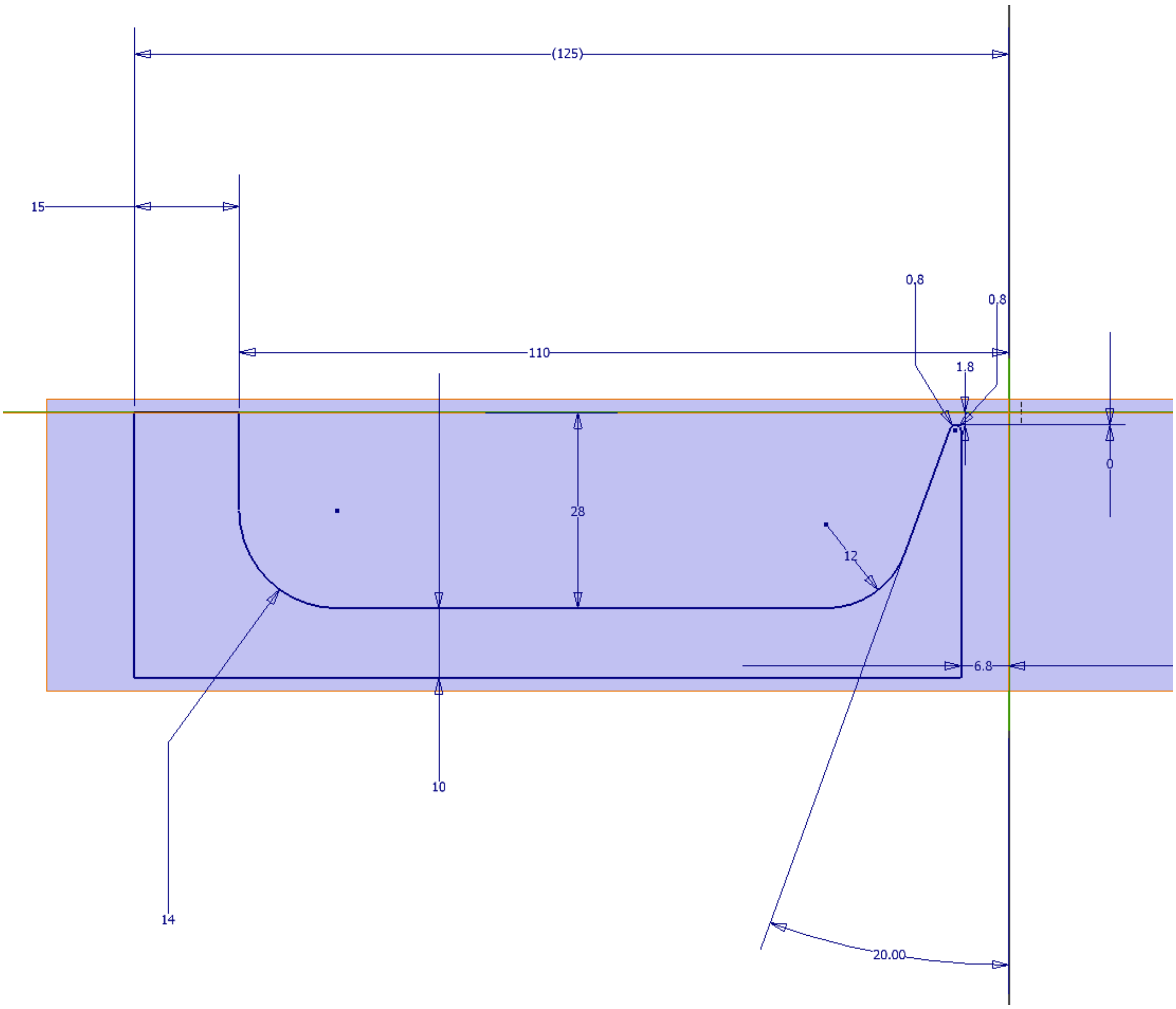


Figure n, The sketch for the **0.4 scale** cavity plating test model.

The outside diameter will be 250mm and the thickness will be 38mm.

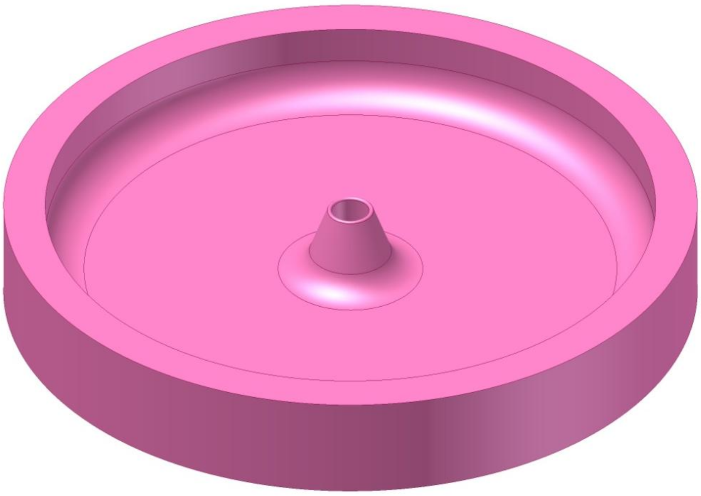


Figure n, Inside of scaled-down cavity

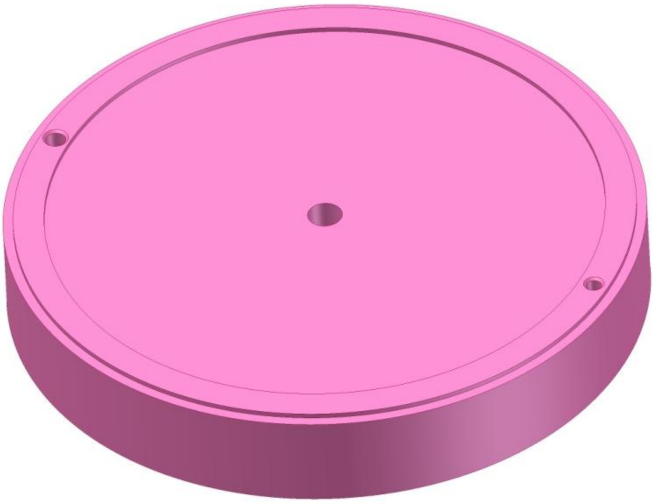


Figure n, Outside of scaled-down cavity showing alignment dowel holes in base

Plan:

1. Machine cavity to size.
2. Place on CMM jig plate – a flat plate with 2 dowel holes for location.
3. Measure interior with CMM and record results.
4. Plate interior with nickel and then copper, leaving the underside un-plated.
5. Re-locate the cavity on the CMM jig.
6. Repeat CMM measurements.
7. Plot the result and determine the plating thickness and distribution.
8. Measure frequency (if of value).
9. Use result to guide full sized cavity design.

8. Results from study of 110mm wide cavity

Model #	Date	Model	Frequency (MHz)	Description
1	3rd October 2013	**RBC_v6_D607mm.sat**	**324.95**	First frequency model, no ports, target = 323.75 MHz
2	3rd October 2013	**RBC_v6_D609.2mm.sat**	**324.10**	Increased O.D. by 0.37% to bring frequency down towards target
3	3rd October 2013	**RBC_v6_D609.9mm.sat**	**323.83**	Increased O.D. by 0.11% to bring frequency down. Result is close enough to target to start to model the tuning range.
4	7th October 2013	**RBC_v6_D609.9mm_Empty_Radial_Ports.sat**	**323.51**	Adding the empty ports has brought the frequency down by 0.32 MHz
5	7th October 2013	**RBC_v6_D609.9 mm_TunerFlush.sat**	**323.57**	Adding one flush tuner has increased the frequency by 0.06 MHz
6	7th October 2013	**RBC_v6_D609.9 mm_Tuner-10mm.sat**	**323.52**	One tuner withdrawn into the port by 10mm
7	7th October 2013	**RBC_v6_D609.9 mm_Tuner+20mm.sat**	**323.90**	One tuner protruding into the cavity by 20mm
8	7th October 2013	**RBC_v6_D609.9 mm_Tuner+40mm.sat**	**324.33**	One tuner protruding into the cavity by 40mm.

Figure n, Frequency and tuning results for 110mm wide cavity

Tuning range = **0.81 MHz**

Model #	Date	Model	Frequency (MHz)	Description
9	7th October 2013	**RBC_v6_D609.9mm_Empty_Radial_Ports_Plating_0.050**	**323.12**	Model #4 with 50 microns plating added
10	7th October 2013	**RBC_v6_D609.9mm_Empty_Radial_Ports_Plating_0.100**	**322.73**	Model #4 with 100 microns plating added
11	7th October 2013	**RBC_v6_D609.9mm_Empty_Radial_Ports_Plating_0.200**	**321.98**	Model #4 with 200 microns plating added

Figure n, Frequency results for varying plating thickness (for the 110mm wide cavity)

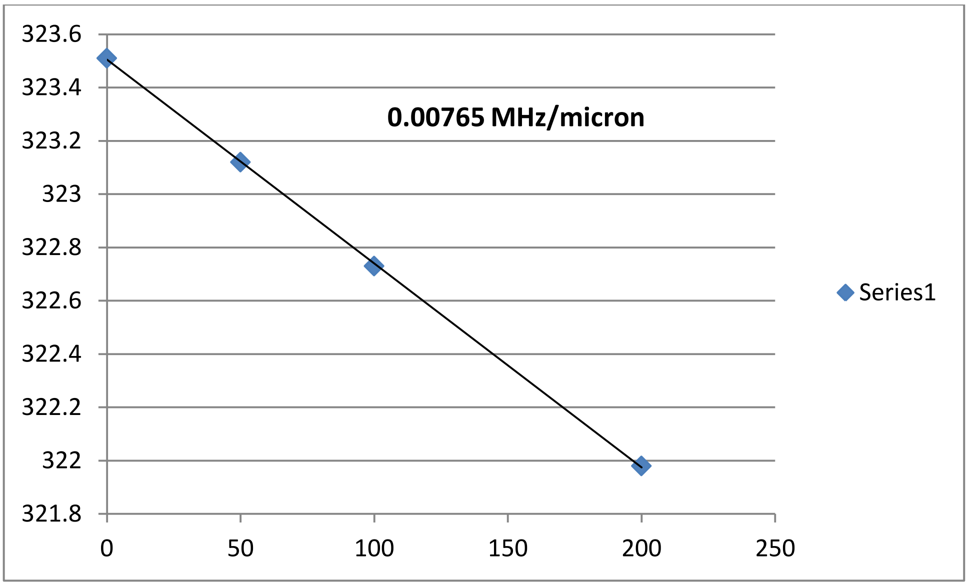
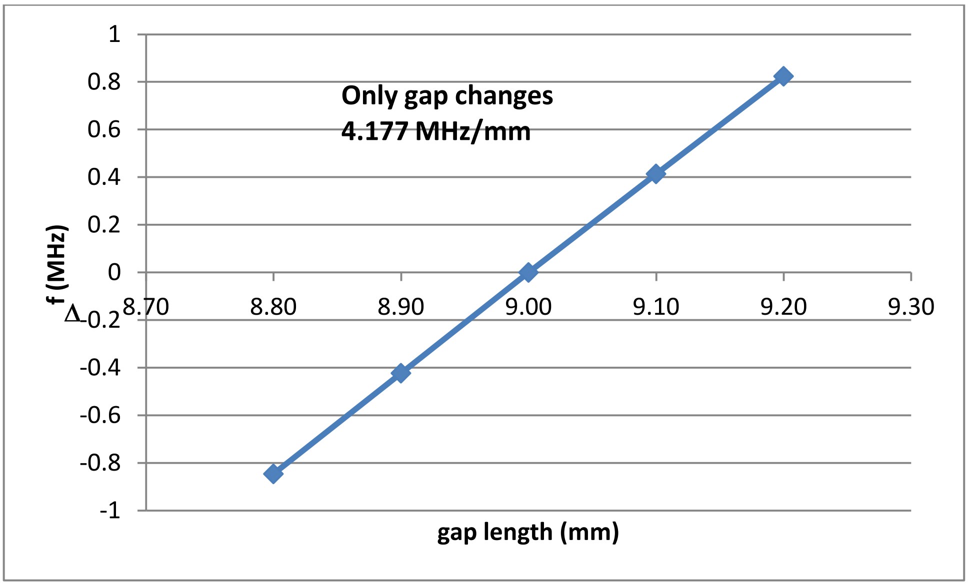
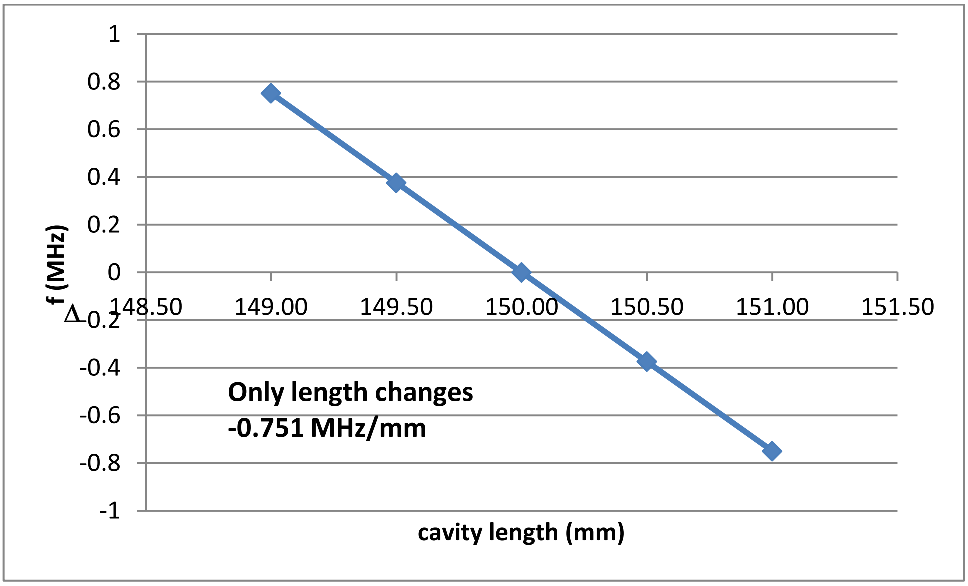
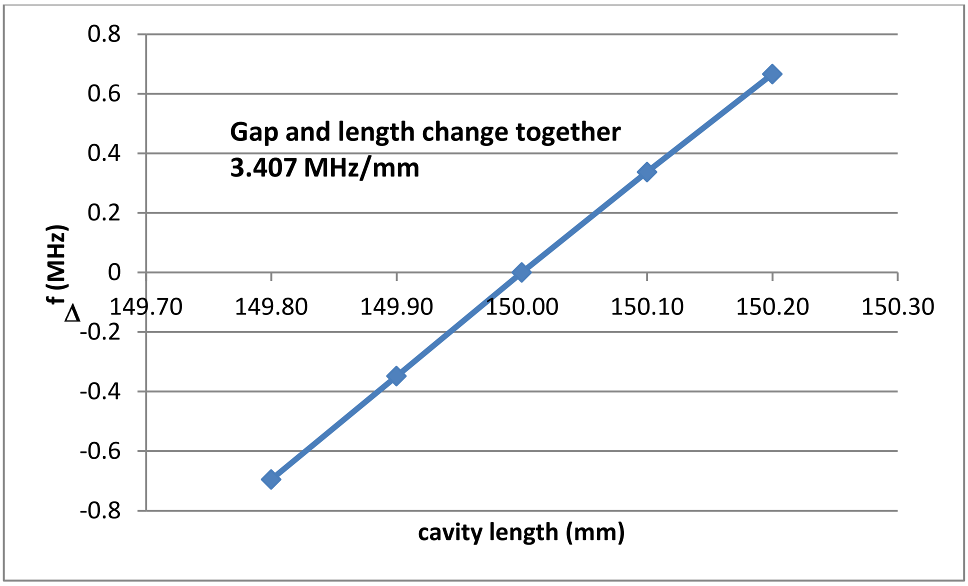


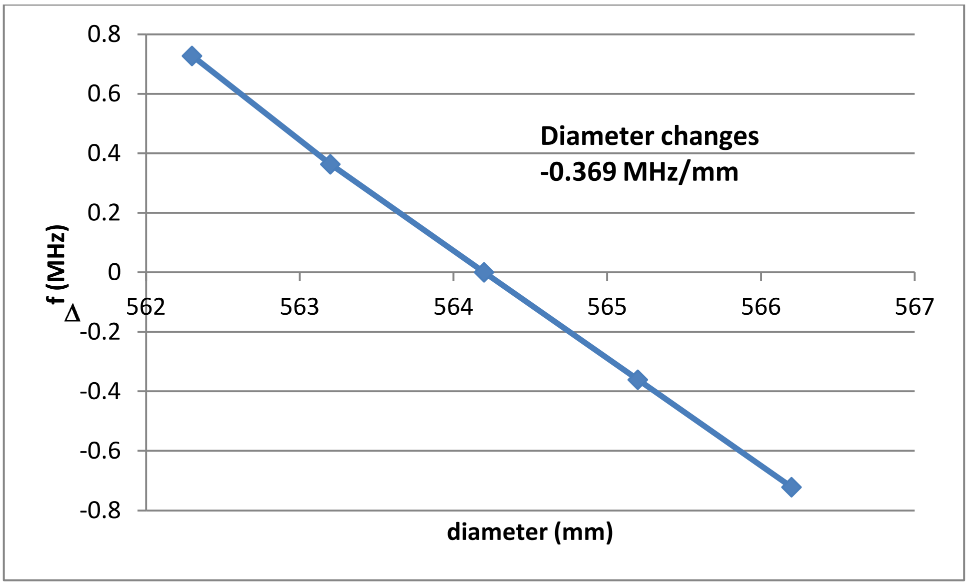
Figure n, Frequency results for varying plating thickness for 110mm wide cavity.

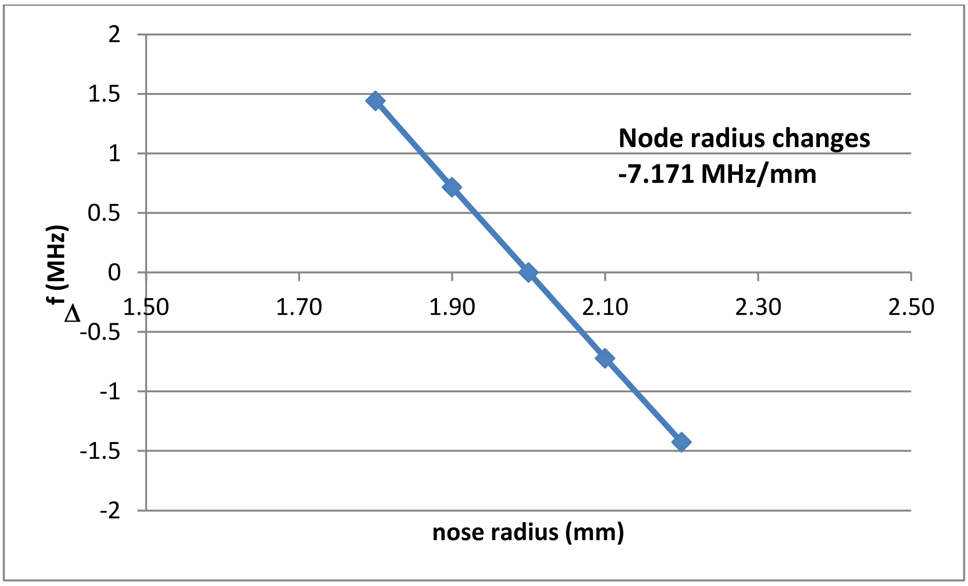
9. Alan's Results from Superfish






Gap and length change together
3.407 MHz/mm
Δf (MHz)
cavity length (mm)


Diameter changes
-0.369 MHz/mm
Δf (MHz)
diameter (mm)


Node radius changes
-7.171 MHz/mm
Δf (MHz)
nose radius (mm)

10. Updated results using corrected power values

The power values used for the previous simulations were **incorrect**.

The power values from Superfish were for a half cavity whereas an eighth of one half was modelled.

Alan has recalculated the power figures for the cavity with a reduced outer radius from 45mm to 35mm.

Table n, Power values for MEBT cavity

	Half cavity	Half cavity / 4	Half cavity /4	Half cavity /8
	Peak power	**Peak power**	**Average power**	**Average power**
	W	**W**	**W**	**W**
	263.9	66.0	6.6	3.30
	425.4	106.4	10.6	5.32
	1283	320.8	32.1	16.04
	348.4	87.1	8.7	4.36
	226.8	56.7	5.7	2.84
	5.4	1.4	0.1	0.07
Total	**2500**	**625**	**62.5**	**31.25**

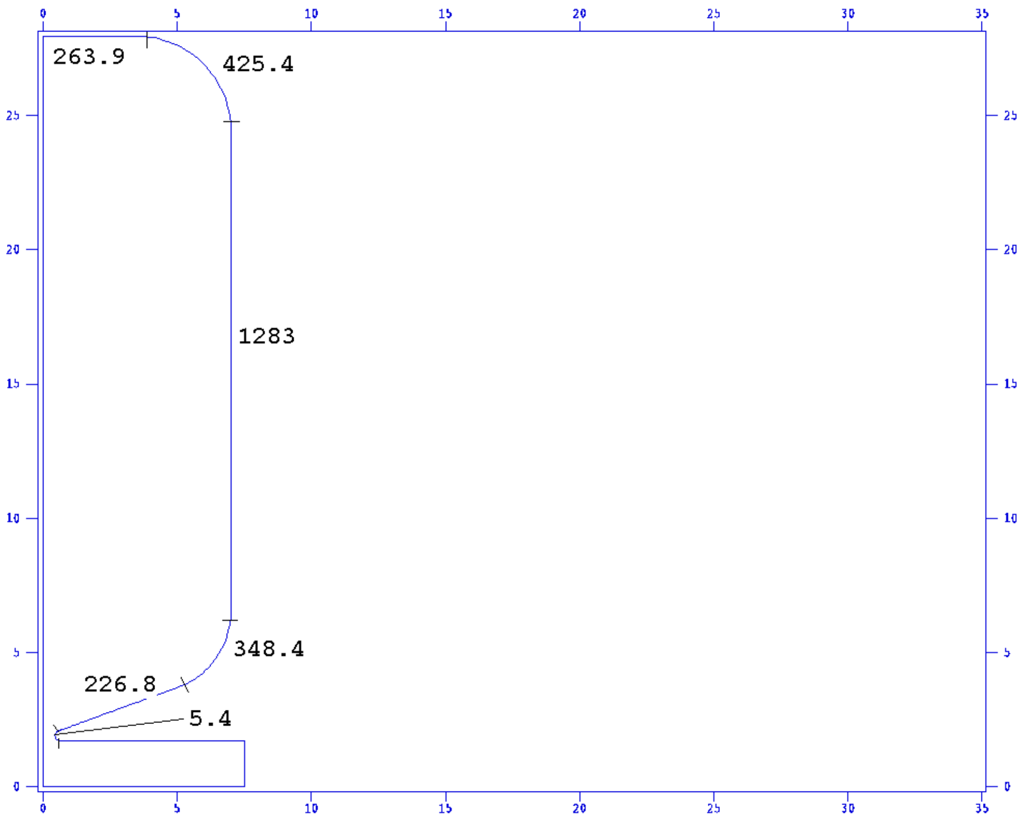


Figure n, Power values for smaller corner radius

Applying the correct power values to the 1/8 cavity model:

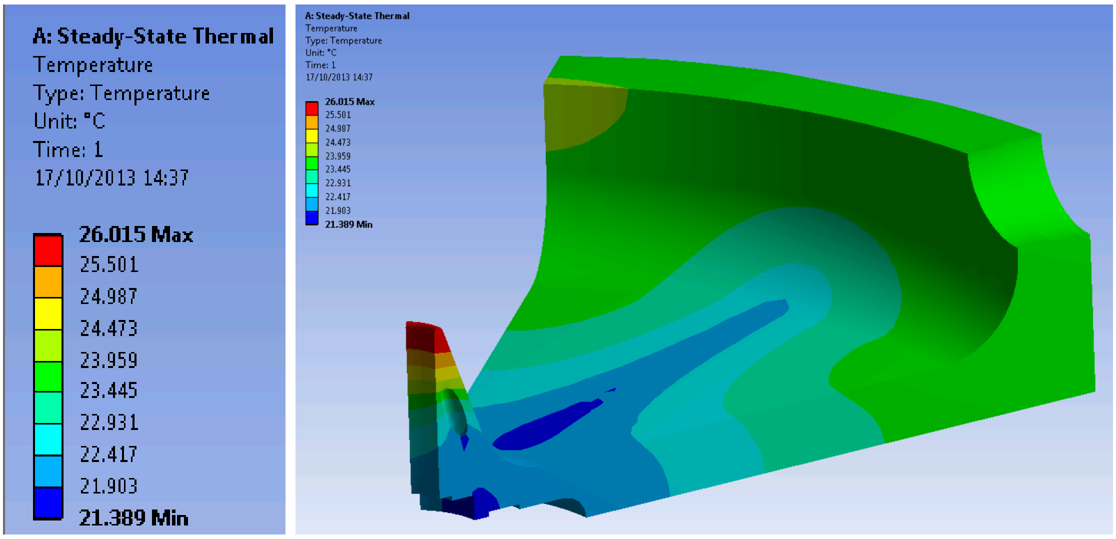


Figure n, Cavity temperatures using half cavity/8 average power values

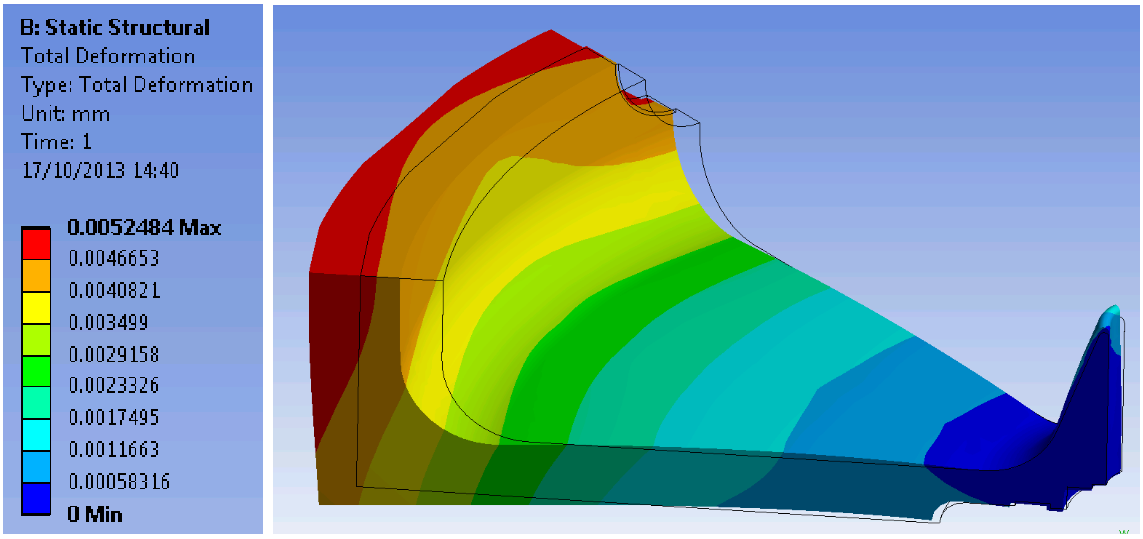


Figure n, Total deformation for cavity temperatures using half cavity/8 average power values

11. Circular cooling channel

Using the corrected lower power values should we consider using a simpler to machine circular cooling channel?

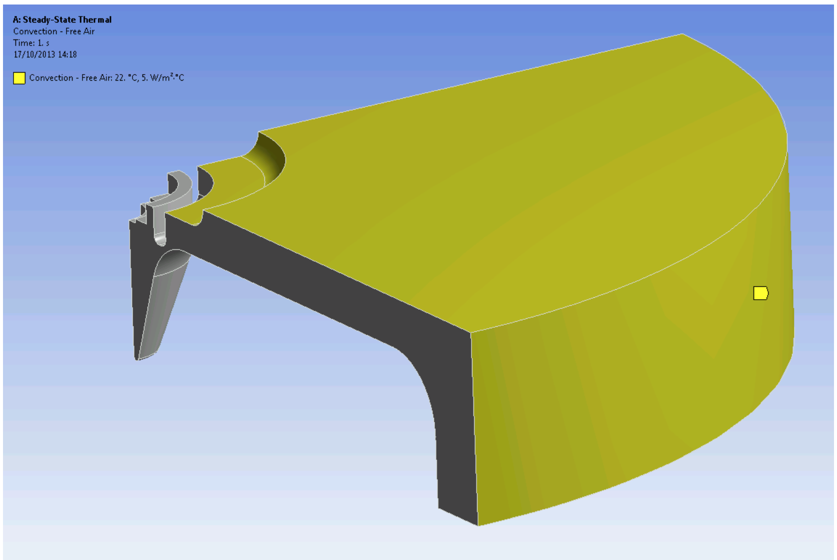


Figure n, Half cavity/8 with circular cooling channel.

Free air convection on outer surfaces, 5 $W/m^2.^0C$

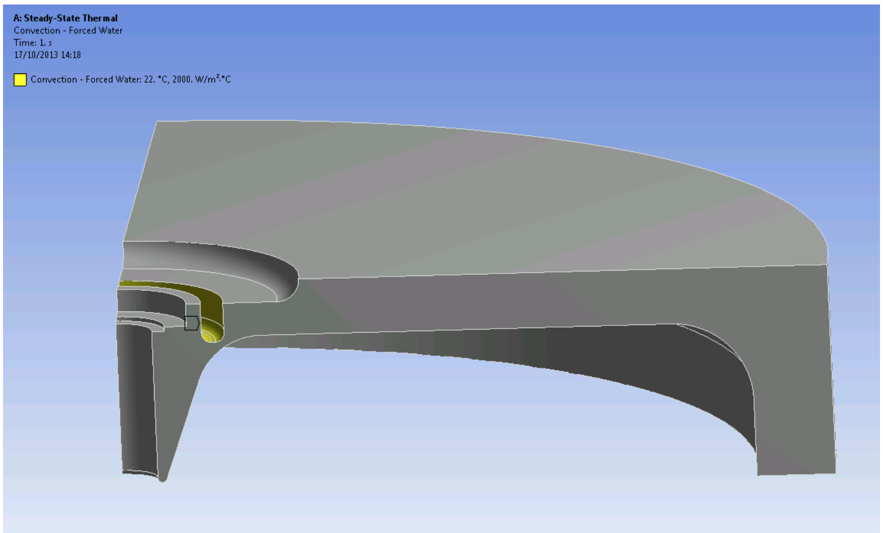


Figure n, Forced water convection in circular cooling channel, 2000 $W/m^2.^0C$

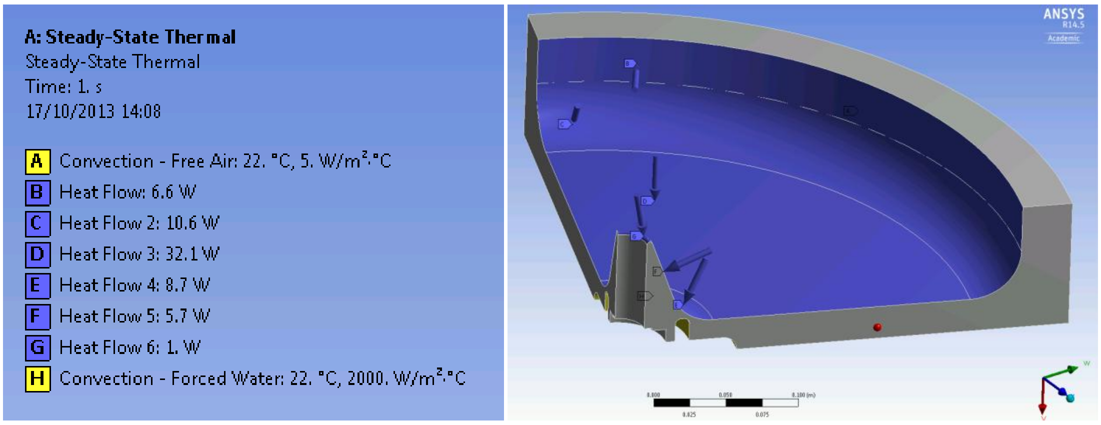


Figure n, Power applied to inner surfaces

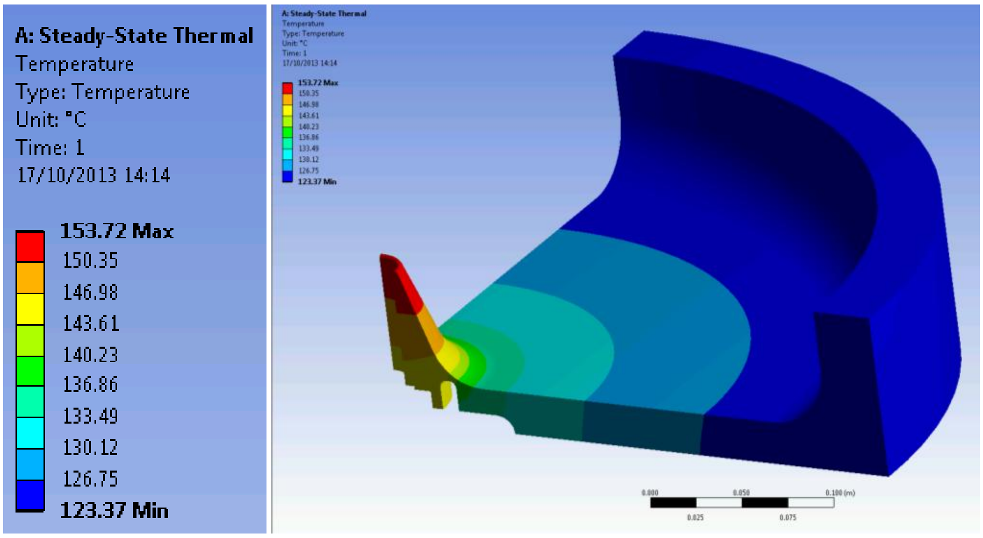


Figure n, Cooling channel not active. Free air convection to the outer surfaces only.

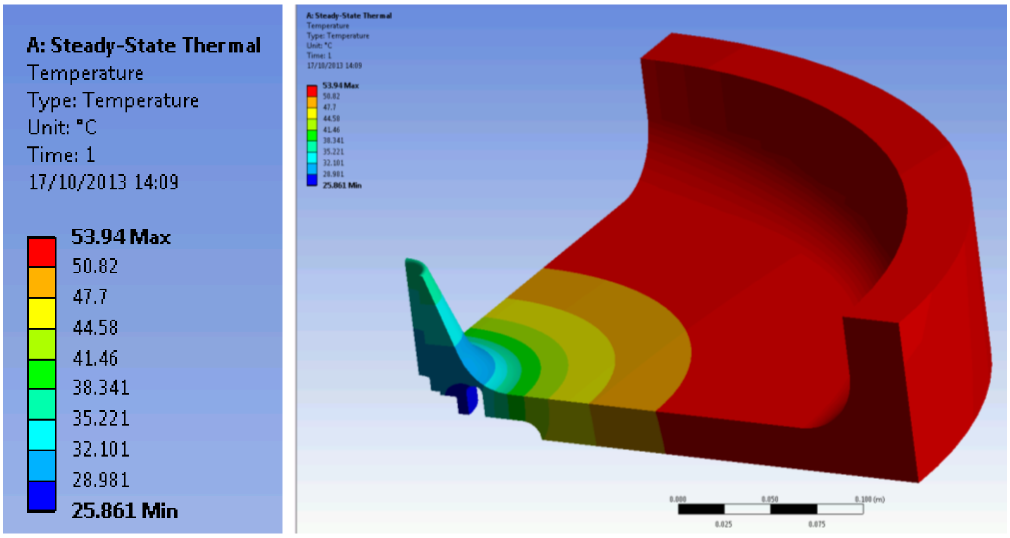


Figure n, Cooling in circular pocket.

12. Flow characteristics

Questions:

1. A value of 2000 W/m^2.^{0}C has been applied to the cooling channels. Is this reasonable?
2. For the gun-drilled channels, what is the flow velocity drop due to the sharp change in fluid direction?

- RFQ cooling: ~15 kW (per metre)
- MEBT Rebunching cavity power: ~5 kW (Peak power)

To determine a practical cooling flow rate let's start by aiming for a Reynold's number of 10,000.

Def: Reynold's number -how effective is the flow condition at cooling?

Using the flow calculations for the RFQ we'll assume an initial volume flow rate of 0.1 litres/sec.

First determine the flow velocity C:

- Volume flow rate **v = 0.1 l/s**
- Mass flow rate **m= 0.1 kg/s**
- Flow channel diameter **d = 0.008m**
- Flow channel cross-sectional area **A = 5 x 10^{-5} m^2**
- Density of water **ρ = 1000 kg / m^3**

Using $m = \rho A C$ $C = m / \rho A$ C = 0.1 / (1000) x (5x10^{-5})

Flow velocity per cooling hole inlet **C= 2.0 m/s**

Using Reynolds number $Re = \rho C d / \mu$

Dynamic viscosity **μ = 1 x 10^{-3} N.s/m^2** (for water at 20^{0}C)

Re = (1000)(2)(0.008)/1x10^{-3} = **Re = 16,000** (a bit high!)

Reduce the flow rate by a factor of1.6 to **v =0.0625 l/s**

C = 1.25 m/s

Re = 10,000

$$R_e = \frac{\rho v D_H}{\mu} \Rightarrow N_u = 0.023 R_e^{0.8} P_R^{0.4} \Leftarrow P_R = \frac{c_p \mu}{k}$$

$$\Downarrow$$

$$HTC = \frac{N_u k}{D_H}$$

We know the Reynold's number so, if we calculate the Prandtl number we can determine the Nusselt number which can be used to determine the heat transfer coefficient.

Nusselt number:
Given two parallel plates at different temperatures, the Nusselt number gives the ratio of actual heat transferred between the plates by a moving fluid to the heat transfer that would occur by conduction.

The Prandtl Number: is a dimensionless parameter of a convecting system that characterises the regime of convection.

$\mathbf{P_R = v / a}$ **or** $\mathbf{P_R = C_p\, \mu/k}$

where: *μ = absolute or dynamic viscosity (kg/m s)* = $1\text{x }10^{-3}$

c_p = specific heat capacity (J/kg K) = 4.18 x 10^3

k = thermal conductivity (W/m K) = 0.6 for water

$P_R = (4.18 \text{ x } 10^3)(1\text{x}10^{-3})/0.6$

$\mathbf{P_R = 7}$

Nusselt Number: Dittus-Boelter equation

The Dittus-Boelter equation (for turbulent flow) is an explicit function for calculating the Nusselt number. It is easy to solve but is less accurate when there is a large temperature difference across the fluid. It is tailored to smooth tubes, so use for rough tubes (most commercial applications) is cautioned. The Dittus-Boelter equation is:

$N_D = 0.023\ R_e^{0.8}\ P_R^{n}$

where: n = 0.4 for heating of the fluid and n = 0.3 for cooling of the fluid. The Dittus-Boelter equation is valid for:

$0.6 < P_R < 160$ **YES**

R_e ~ 10,000 **YES**

L/D > 10 **YES** (flow length/ diameter)

$N_D = 0.023\ (10000)^{0.8}\ (7)^{0.4} = 80$

$N_D = 80$ (bit low! Range is 100 – 1000)

Finally we can calculate the **heat transfer coefficient:**

HTC = $N_D\, k / d$ = 80 x 0.6 / 0.008

HTC = 6000 W/m^2 K (a practical maximum is 6000 W/m^2)

Conclusion:

In pratice we should easily exceed the

2000 W/m^2 used in the cooling calculations.

Cooling water temperature rise:

Using our flow rate of 1.25 m/s and knowing the power needed to be cooled we can calculate the water temperature rise using:

$Q = mCp\Delta T$

where Q = heat load in kW = 0.0625 kW (average power)

m = mass flow rate = 0.1 kg/s

Cp = specific heat capacity of water 4.18 kJ/kg/K *

ΔT = temperature rise

Temperature rise $\Delta T = 0.15^0$ C

** This means it takes 4.18 joules of energy to raise 1 gram of water by 1 degree Celsius*

13. Flow simulations

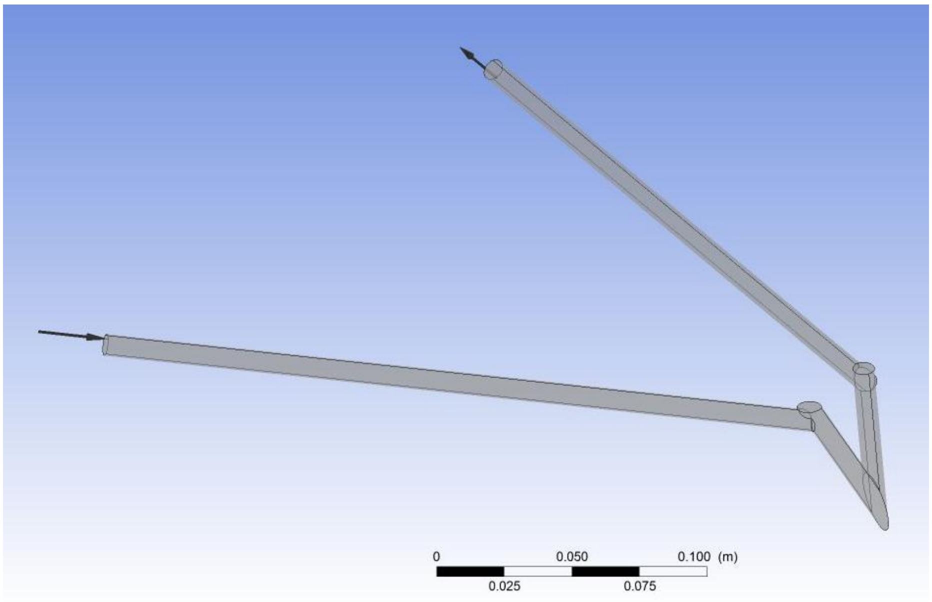


Figure n, Subtracting the cavity volume away from a bulk volume to leave behind a 3D model of the cooling holes. These will be used for the flow simulations.

Input flow velocity = **1.25m/s**

Outlet pressure = **0Pa**

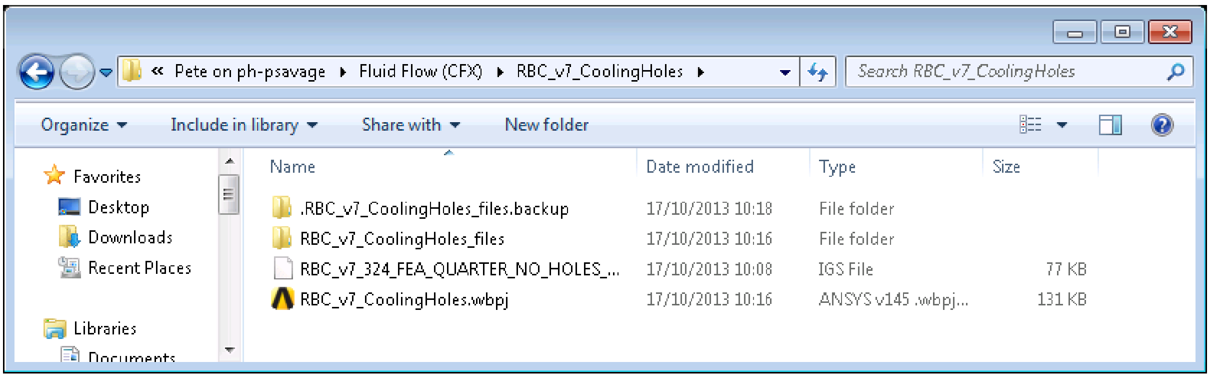


Figure n, FEA model location

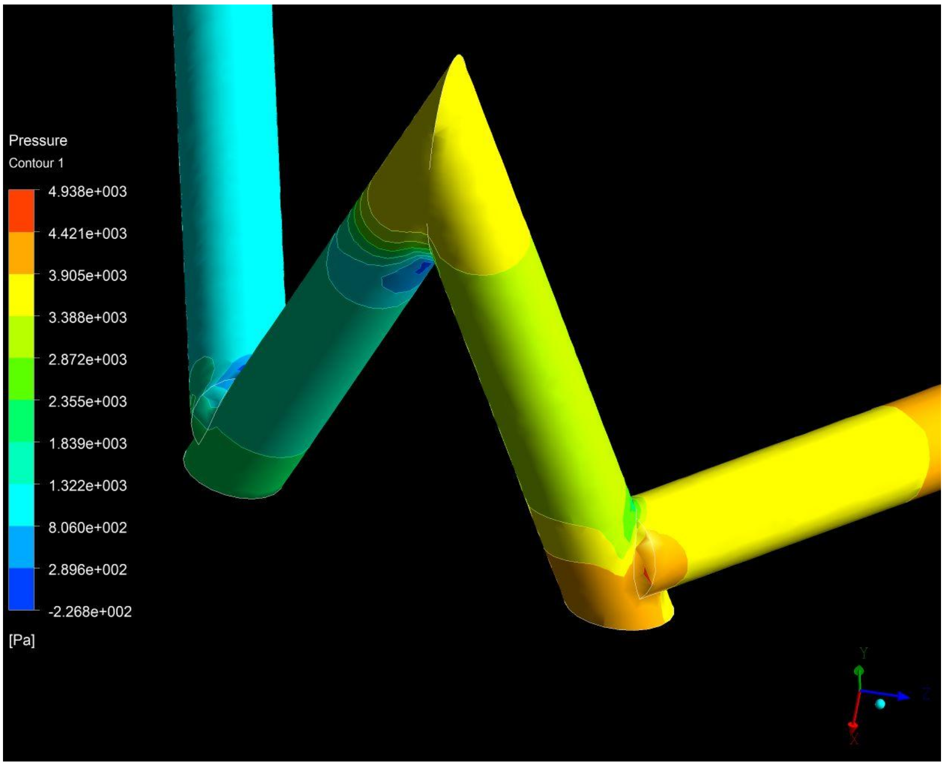


Figure n, Pressure contours

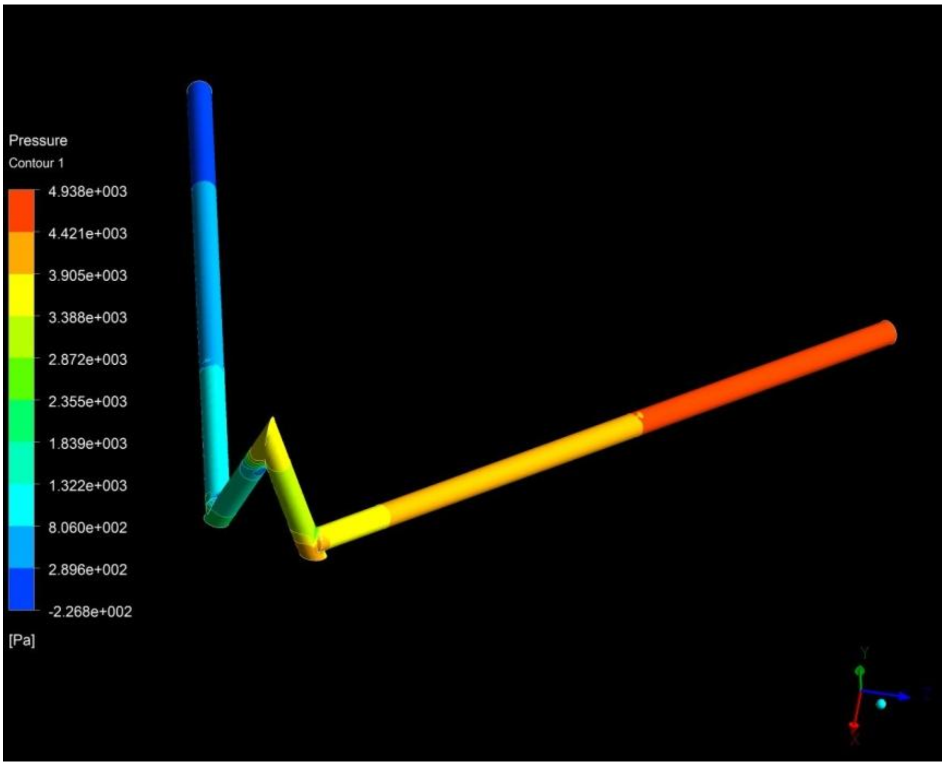


Figure n, Pressure contours

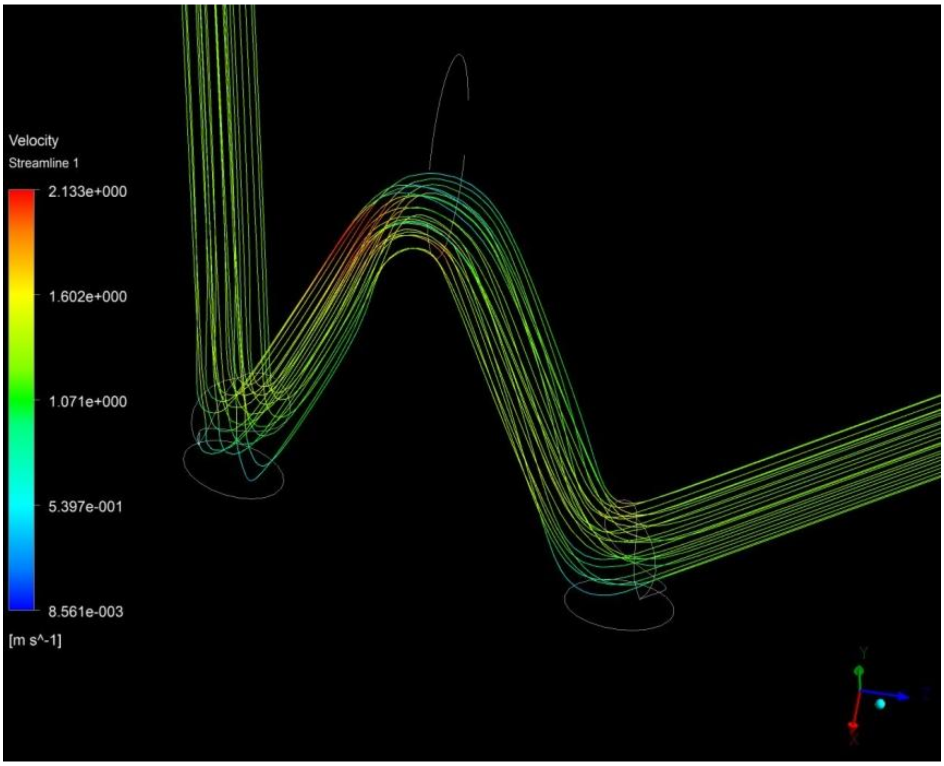


Figure n, Velocity streamlines showing that there is little flow at the apex where the two holes meet.

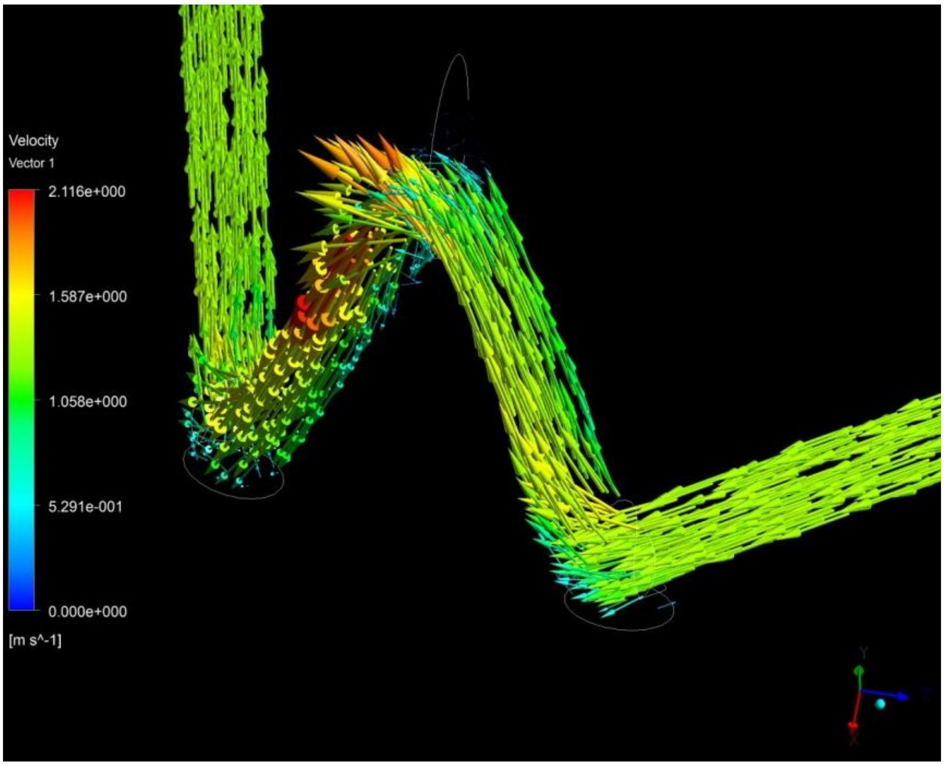


Figure n, Velocity vector

14. Frequency verification

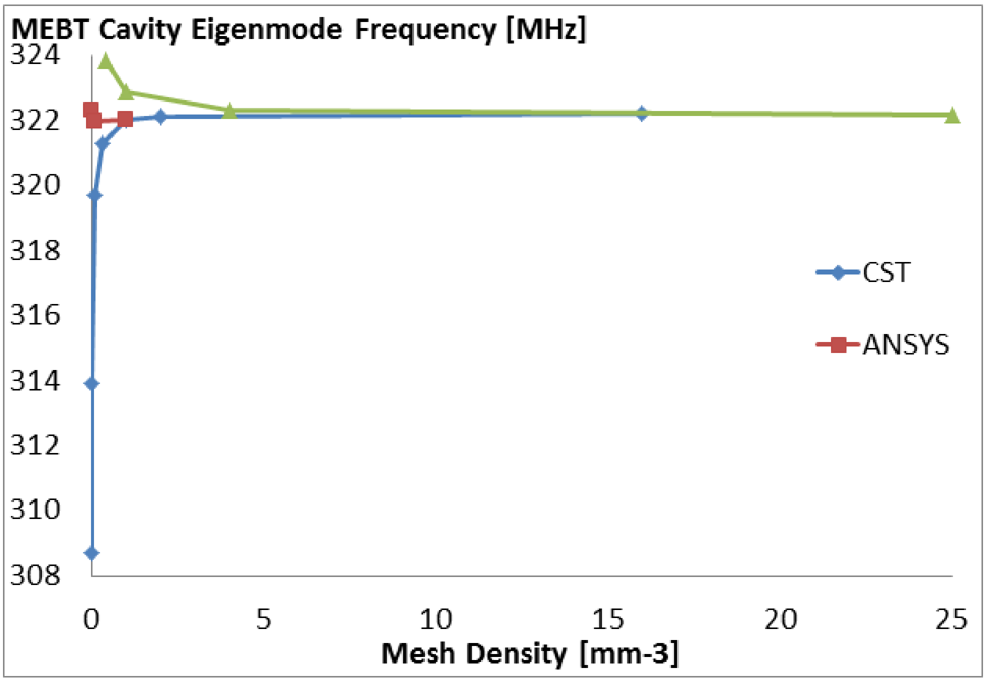


Figure n, Frequency simulations by Scott.

COMSOL (not shown on graph), Superfish (Green), CST and ANSYS confirm the result of 322MHz for the 564.2mm diameter cavity with a 45mm outer radius.

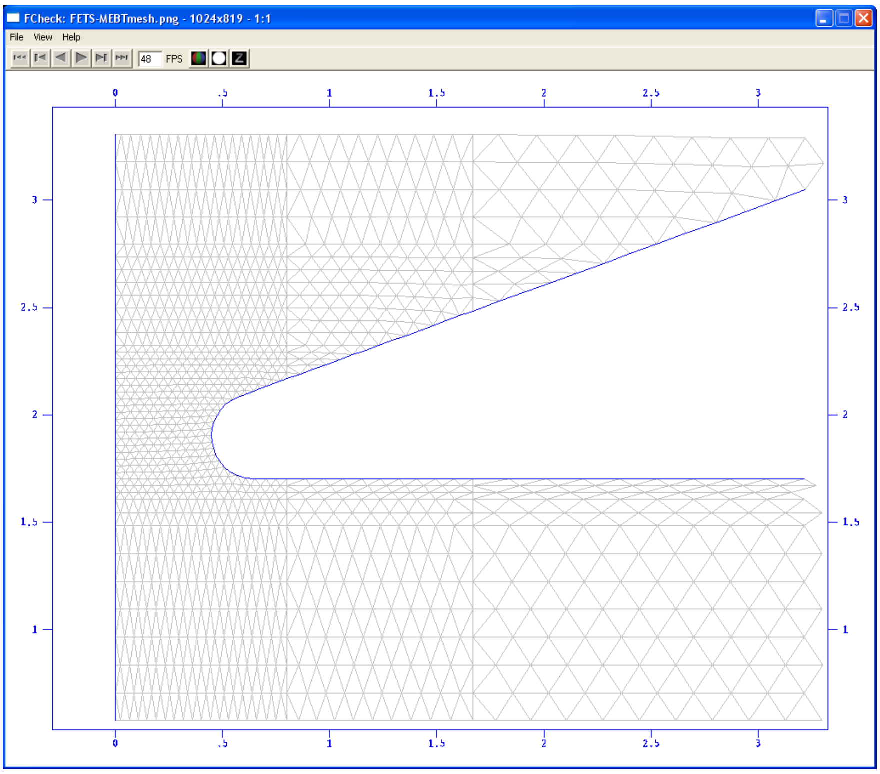


Figure n, Showing the mesh density used for Alan's Superfish simulations

15. Conclusion

As expected cooling the MEBT Rebunching cavities sufficiently will not present a challenge.

Using drilled radial holes for cooling channels will allow the cavity to run at little above ambient temperature with corresponding low thermal expansion.

These studies indicate that the cavity frequency is very sensitive to cavity geometry, especially in the nose tip region. We will use these results as a guide to tolerancing the engineering drawings and during inspection of the cavities.

The variation in plating thickness could be above the acceptable variation in cavity geometry. A scale model is proposed to measure actual plating thickness.

16. Extra

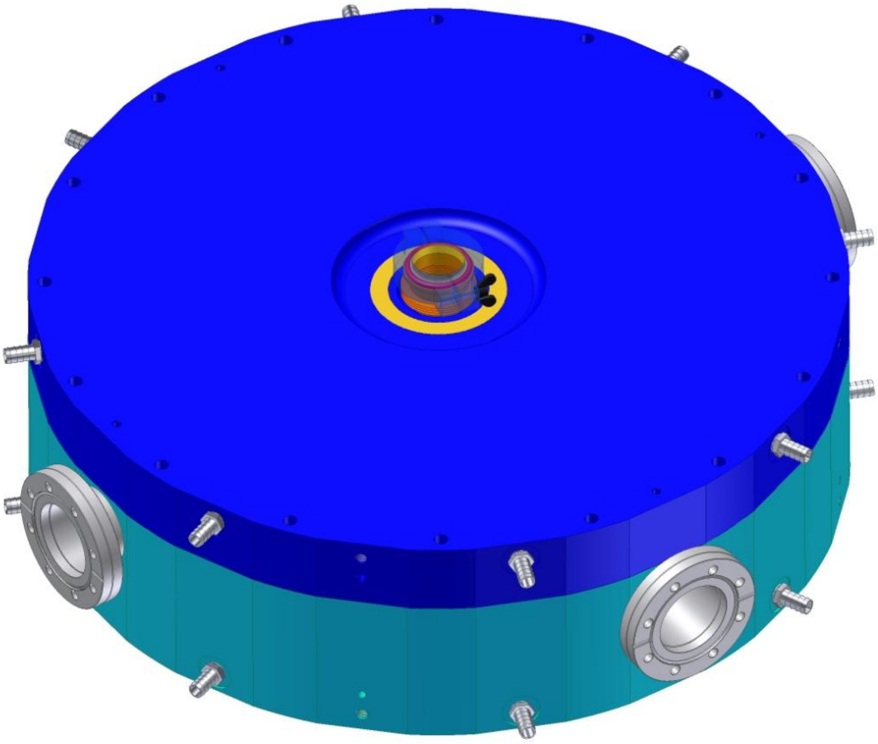


Figure n, 3D CAD model of cavity

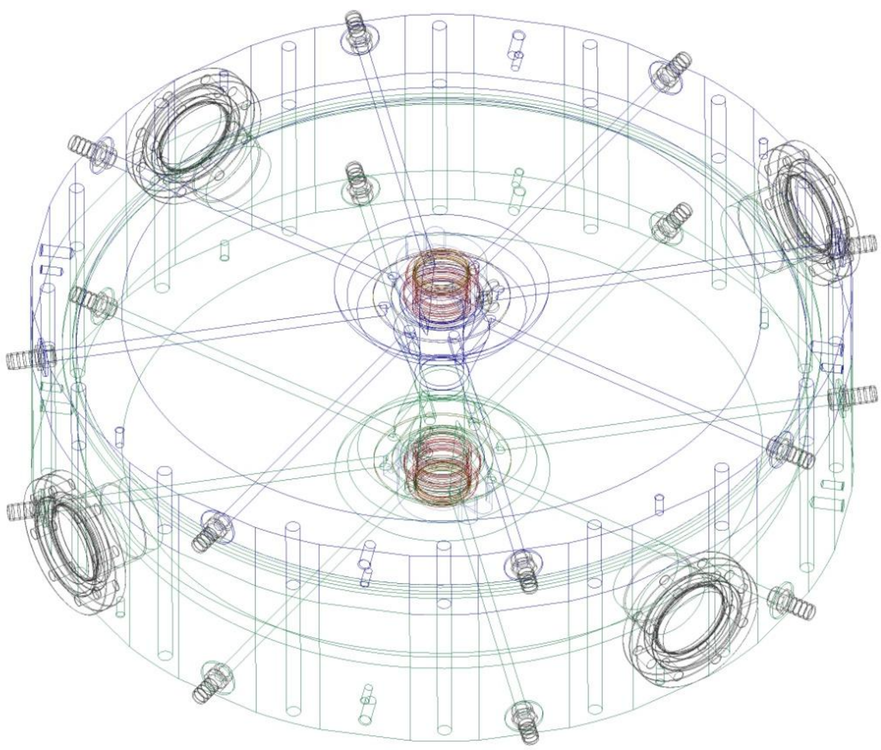


Figure n, 3D CAD model of cavity showing hidden detail

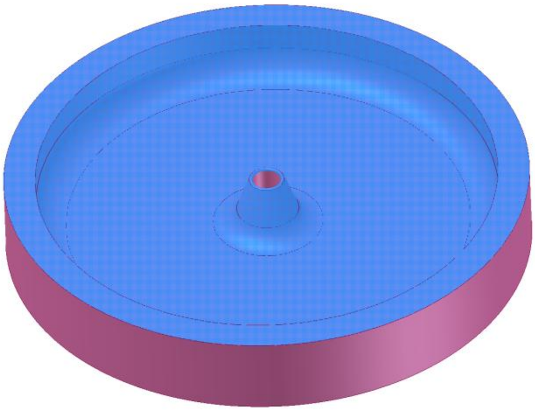


Figure n, 3D CAD model of scaled cavity for plating test. Blue region shows suggested plated faces. Should we leave inner beam pipe area plated with Nickel only?

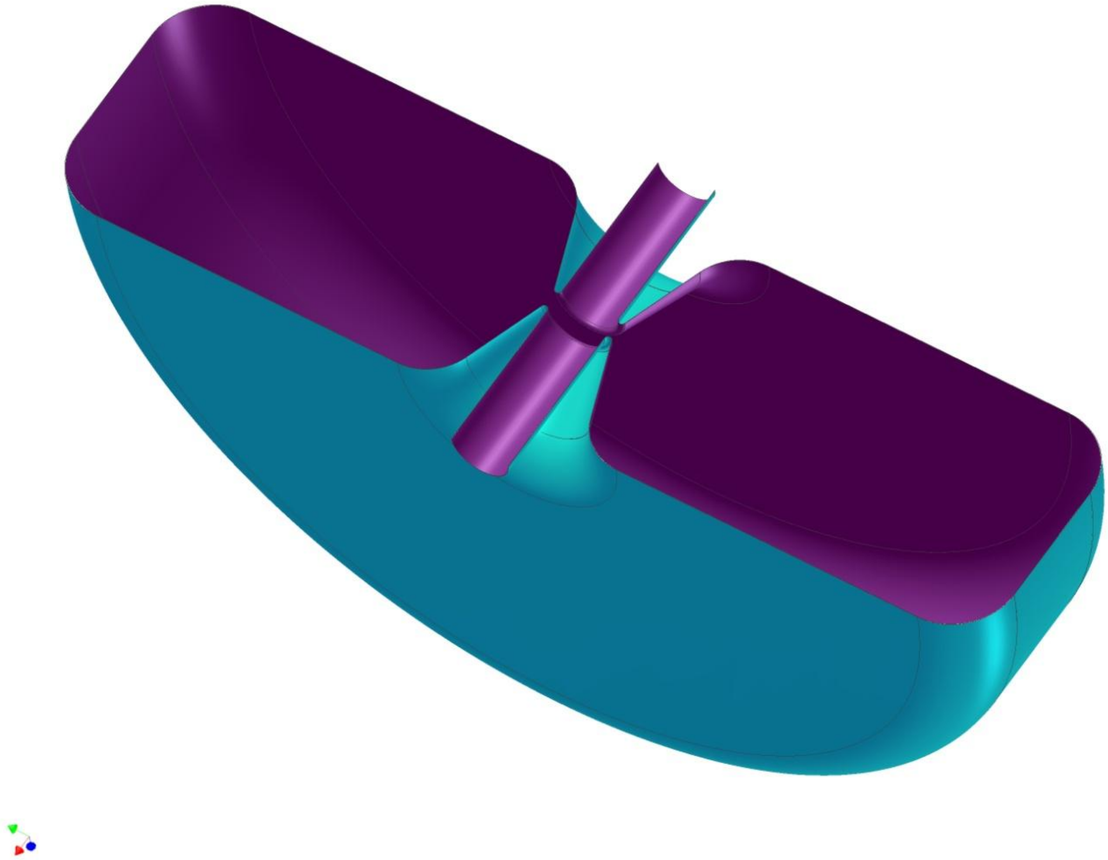


Figure n, Subtraction of extra 'plating' thickness layer. Used to prove that added plated layer was complete.

From: alan.letchford@stfc.ac.uk [mailto:alan.letchford@stfc.ac.uk]
Sent: 08 October 2013 11:35
To: p.savage@imperial.ac.uk; juergen.pozimski@stfc.ac.uk; m.aslaninejad@imperial.ac.uk; michael.dudman@stfc.ac.uk
Subject: RE: MEBT Cavity thermal expansion + more

Something to bear in mind is that the frequency shifts due to thermal expansion cannot be 'designed out' to put the cavity on resonance when hot. The reason is that we have to operate the cavity when it's cold too - namely when we first switch it on or if operating at reduced power or duty factor. This means that the tuning system has to be able to cover the whole of the thermally driven frequency shift plus the possible frequency errors due to manufacturing tolerances. Taking at face value the expansions given in Pete's note the frequency shift is almost -0.4 MHz and if the vacuum deformation is included too it gets close to -0.65 MHz which is most of the tuning range leaving very little for dimensional errors. Of course the calculated thermal expansion for a uniform 100C temperature is almost certainly very pessimistic so hopefully it won't be that bad but it is something to think about when deciding on the cold untuned frequency. Also the vacuum deformation will always be present so it may be acceptable to design this out. I'm just flagging up that we need to consider the dynamic range of frequency shift as well as the known and unknown static errors. I've attached a document where we looked at a similar problem to show the approach we took (although in this case the thermal effects were very small and the much longer gap made the vacuum deformation effects smaller too). I've also attached an updated spreadsheet of dimensional sensitivity which includes the effect of node radius (inner and outer changed together) which is the most sensitive single dimension and which I left out of the original version.

Regarding the plating variation, taking the numbers from my spreadsheet gives for a +50um change in thickness:

Length reduced by 100um gives +0.0751 MHz Diameter reduced by 100um gives +0.0369 MHz Gap reduced by 100um gives -0.4177 MHz Node radius increased by 50um gives -0.3586 MHz

The total frequency shift is -0.6643 MHz. This may be slightly inaccurate because the nose radius and gap length are quite closely coupled but it's still quite a big effect. However it's (virtually) all due to changes around the nose/gap area and a possible option would be to not plate the tip of the nose. From the figures I sent yesterday you can see that only 5W out of ~2500W is dissipated on the tip of the nose so even if it was bare steel and therefore more lossy it's unlikely to be a big problem. We'd have to think about if a step in the plating at that point is acceptable but it's certainly an option worth considering if the plating thickness cannot be well controlled.

Alan