A Four Rod Compact Crab Cavity for LHC

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Cavity Design Team

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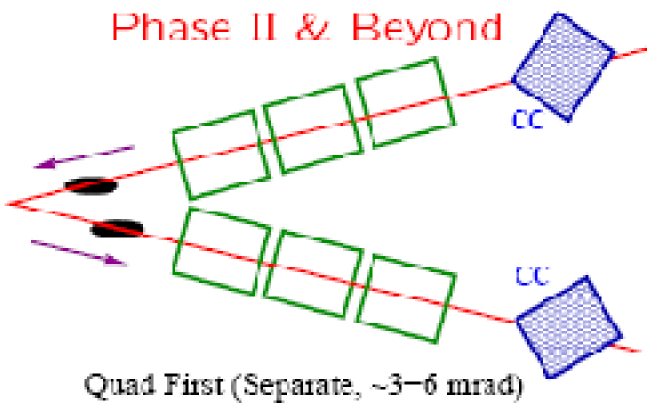
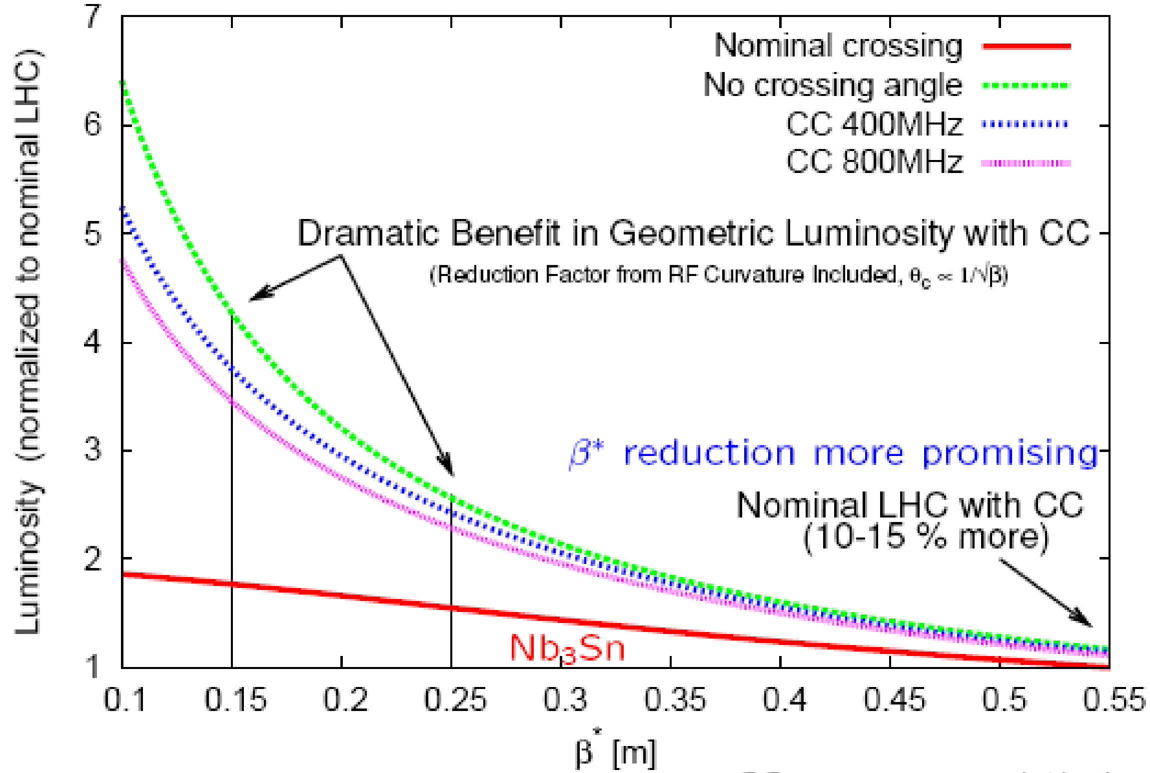
- H Wang (JLab)
- B Rimmer (JLab)

+ CERN (Jochim Tuckmantel, Erk Jensen and Ed Ciapala) on cavity integration

+ A Dexter and I Tahir on LLRF

LHC Luminosity Upgrades





X-Angle Reduction Factor: $\frac{L}{L_0} \approx \left[1+\left(\frac{\sigma_z}{\sigma_x^*}\tan\left(\theta_c/2\right)\right)^2\right]^{1/2}$

Par	Unit	Nominal [G]		Upgrade [L]	
$IP_{\{1,5\}}\ \beta^*$	[cm]	55		25 (8_{ES})	
β_{CC}	[km]	0.13	0.38	3.0	4.5
CC Volt	[MV]	2.0	5.8	5.4 (9.5)	3.7 (6.4)

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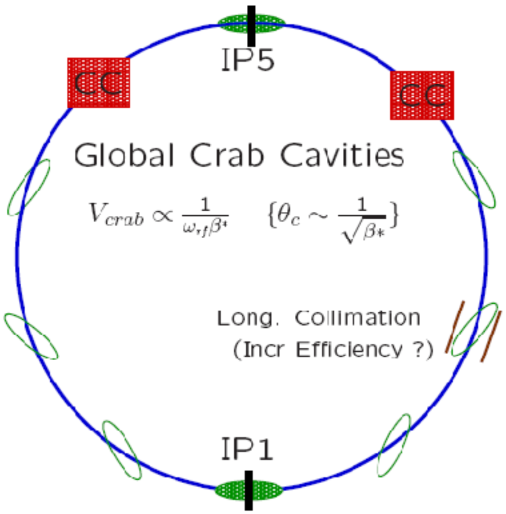
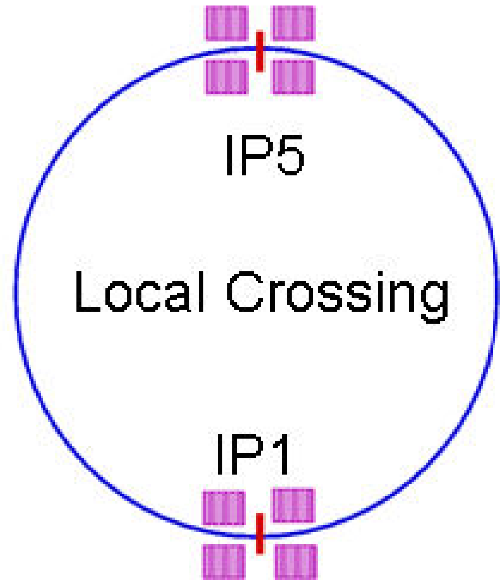
LHC-CC Local vs Global



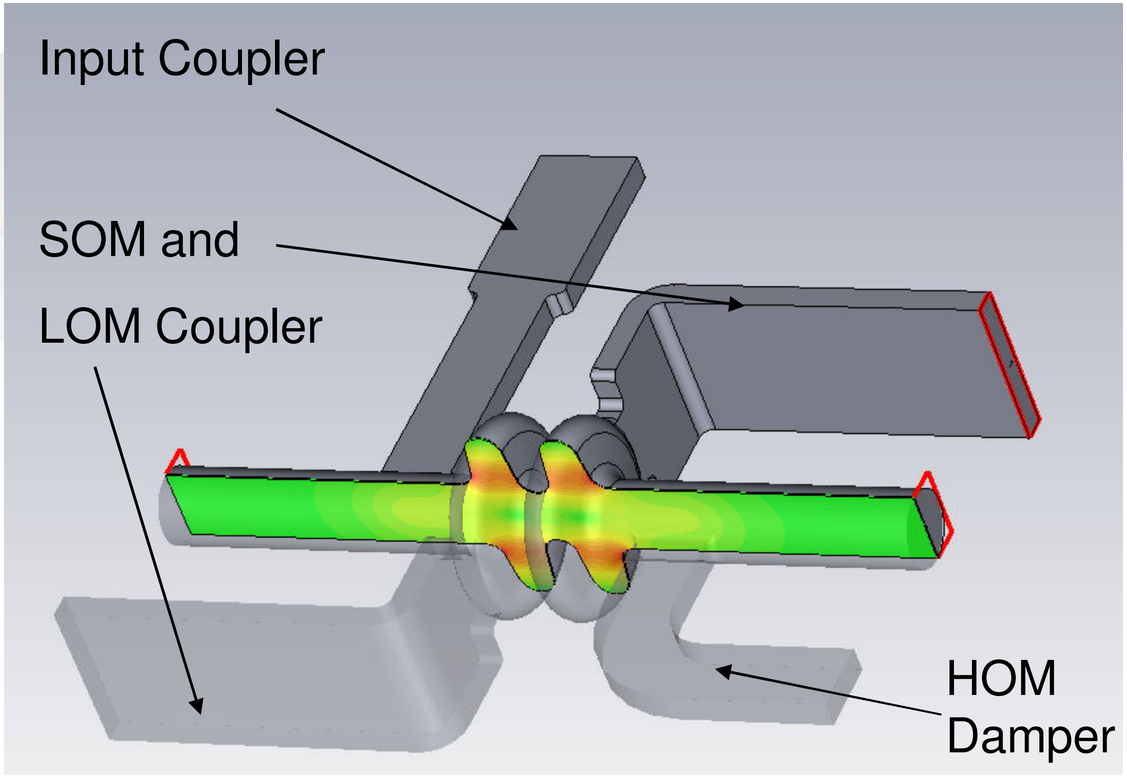
- Local crab crossing preferable (**Phase-II**):
  - Independent control at IPs,
  - Avoid collimation/impedance issues.
- Need compact cavities to fit in the IR region of the ring.
- Lower frequency hopefully!

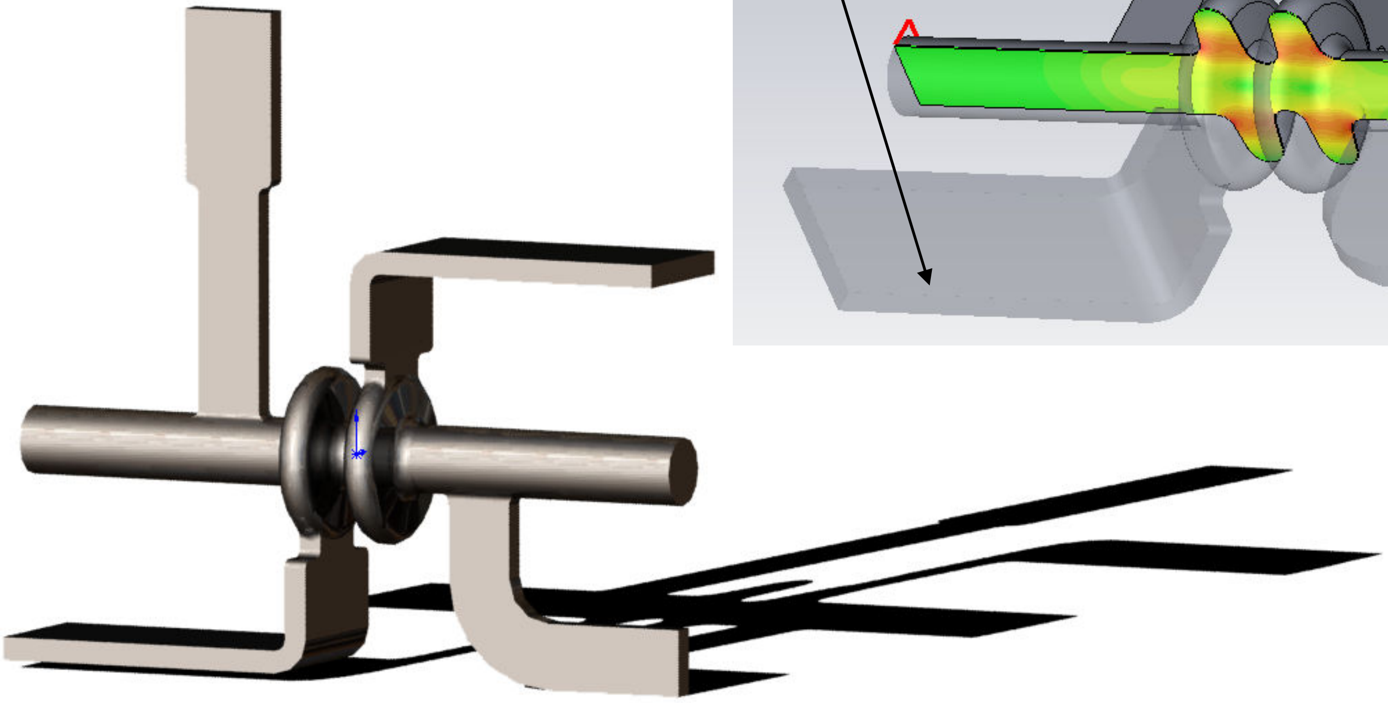


- Small crossing angle (~0.5 mrad):
- Global crab scheme is ideal choice for prototype **Phase-I**:
  - Test feasibility of crab crossing in hadron colliders,
  - Address all RF and beam dynamic issues,
  - Small orbit excursion and tune shifts,
  - Compatible with nominal and upgrade options to recover the geometric luminosity loss,
  - Collimation optimisation!
  - These cavities are feasible using available technology and the gradient requirements are within reach of current technology.

On-Cell Damping LHC

Waveguides are directly coupled to the cavities to provide significant damping. The coupling slots are placed at the field nulls of the crabbing mode to avoid high fields.





Vertical couplers only to meet the tight horizontal space requirements.

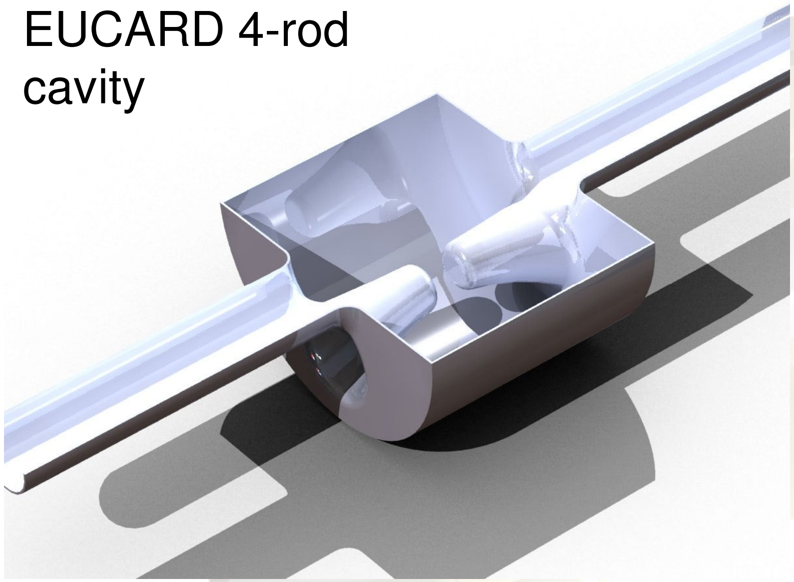
LHC-CC09 CERN: 16-18 Sept 09

- After the success of KEKB, **CERN must pursue crab cavities for the LHC**; the potential luminosity increase is significant.
- **Machine protection is possible show stopper**. Effect of fast cavity changes to be looked at with high priority. Impedance is concern as LHC (and SPS) revolution frequency changing during acceleration, and detuning of the cavity may be more difficult than for KEKB, strong damping of the dipole mode might need to be examined.
- **Demonstration experiments** with beam should focus on the **differences between electrons and protons** (e.g. effect of crab-cavity noise with beam-beam, impedance, beam loading) and on reliability & machine protection which are critical for the LHC;
  - beam test with a (KEKB?) crab cavity in another proton machine (SPS?) may be useful and sufficient.
- Both “global” and “local” crab schemes retained as options. **Future R&D focus should be on compact cavities**, which can be installed in the IR regions of IP1 and 5 as local cavities for the LHC upgrade phase II.
- Modifications of IR4 during the 2013/14 shutdown should be looked at; the **IR4 region could be used for the installation** and test of compact crab-cavity prototypes and for accommodating a possible global crab-cavity scheme.
- The crab cavity infrastructure should be kept in mind for all other LHC upgrades.

Steve Myers (CERN Director of Accelerators) conclusions

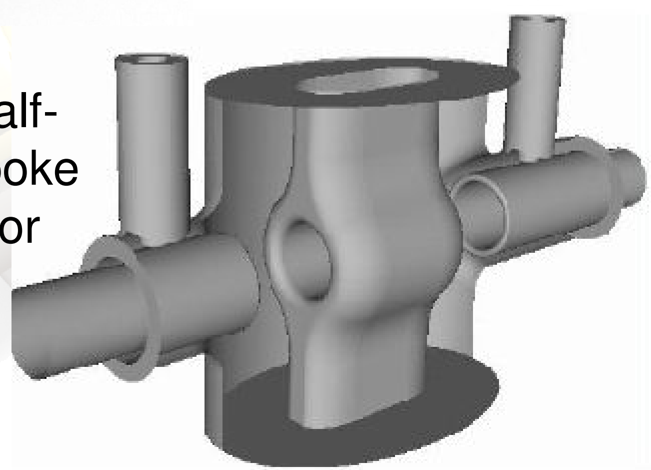
Compact Cavity Designs

EUCARD 4-rod cavity

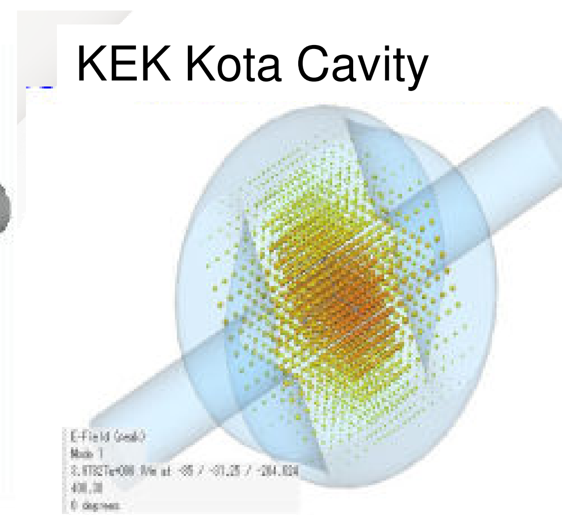


ODU Parallel Bar Cavity

SLAC Half-wave Spoke Resonator



KEK Kota Cavity



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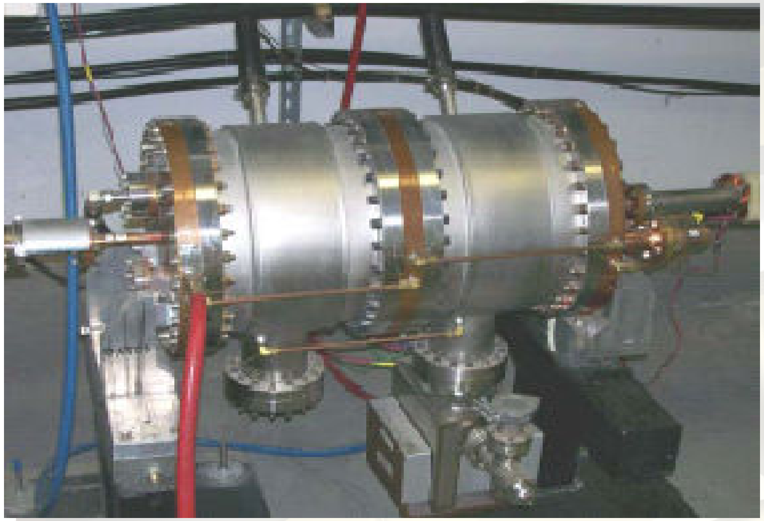
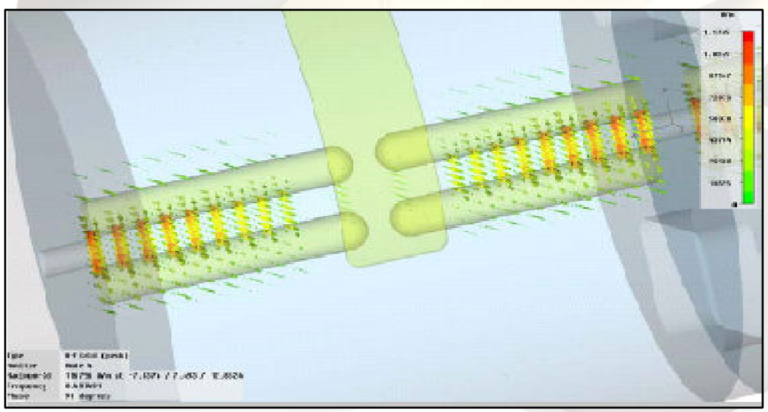
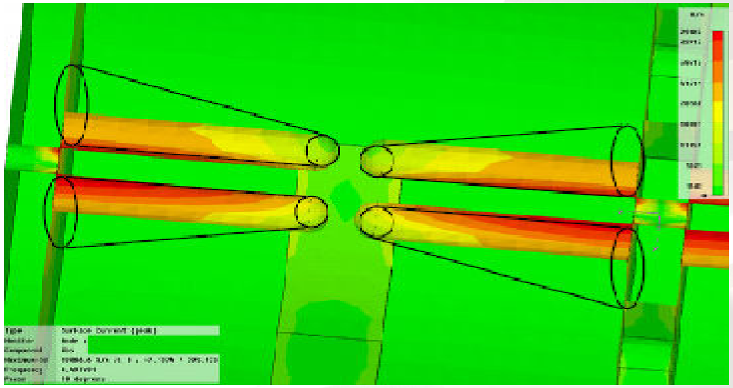
Initial Studies for a Compact CC





- CEBAF separator cavity is:
  - 499 MHz,
  - 2-cell, 8 rods
  - ~λ long
  - ~0.3 m diameter,
  - can produce 600kV deflecting voltage (on crest) with 1.5kW input RF power.
- Q_{cu} is only ~5000 (structure wise), the stainless steel cylinder only takes less than 5% of total loss.
- The maximum surface magnetic field at the rod ends is ~8.2 mT.
- Water cooling needed on the rods.
- If Nb used for this type of cavity, the $V_{\perp}$ is ≈ KEKB CC.
- Microphonics and fabrication issues to be resolved.

JLab Rod Cavity (SRF)



- **There are both magnetic and electric fields providing deflecting kick, $E_{\perp} \approx B_{\perp}$.**
- **The cavity tuner is in low field region. No field enhancement there.**
- **As rod separation increases, the B_x and E_y fields drop quickly.**

- Use "π" mode for separating three beams in CEBAF.
- Can a SRF version be made to work?
- Need to reduce the surface magnetic field at the rod ends.
- Need high B/E field near the beam path.
- Using cone shape electrodes can certainly reduce rod vibration and microphonics.
- Since there is a low loss on the cylinder can:
  - could make cavity cylinder in low RRR Nb, with rods in high RRR Nb?

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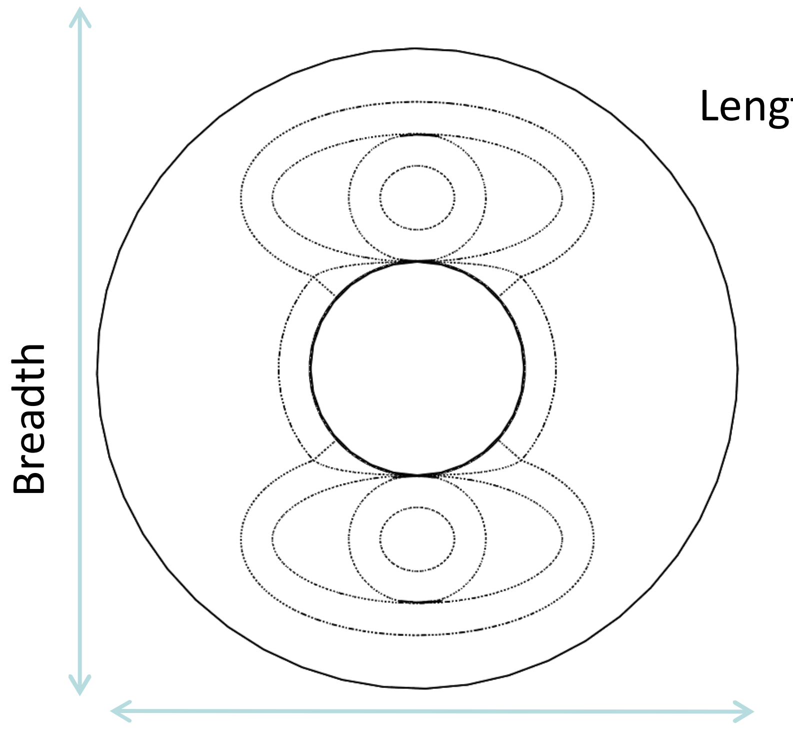
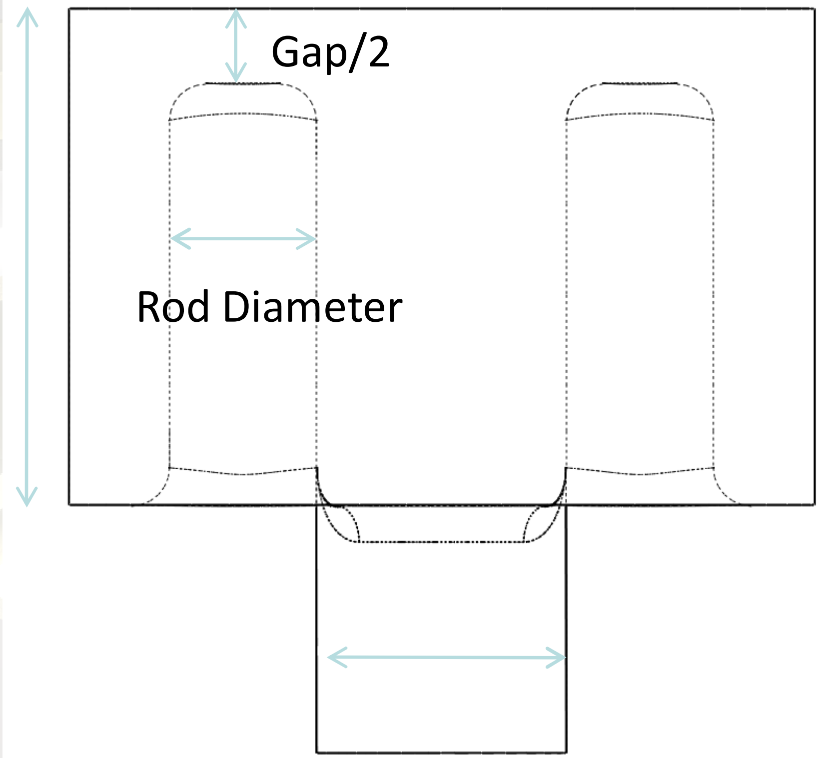
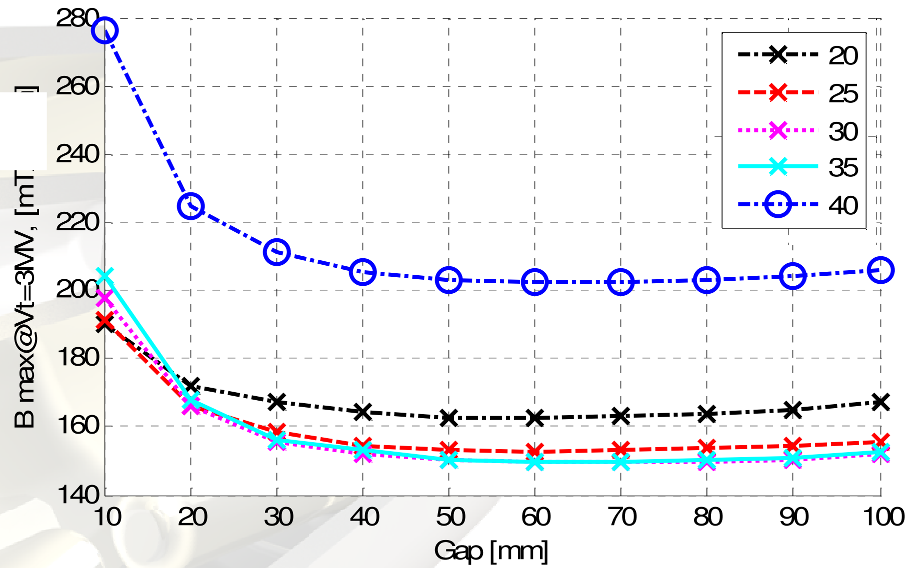
Initial Cavity shape

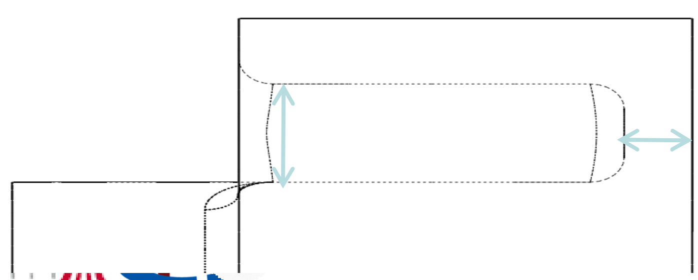


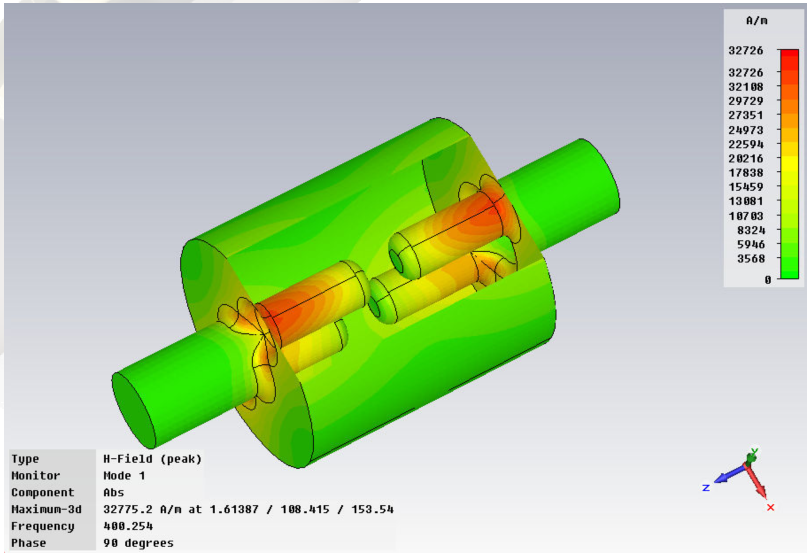


B_{max} vs. Rod gap and Rod radii

- Both Rod radius and gap play a fairly critical role.
- The rod gap has a faily broad minima as long as the rods are not too close.
- The rod radius also has a broad minima as long as the rod isn't too close to the outer can.
- When the rod gets close to the outer can the magnetic field spikes.

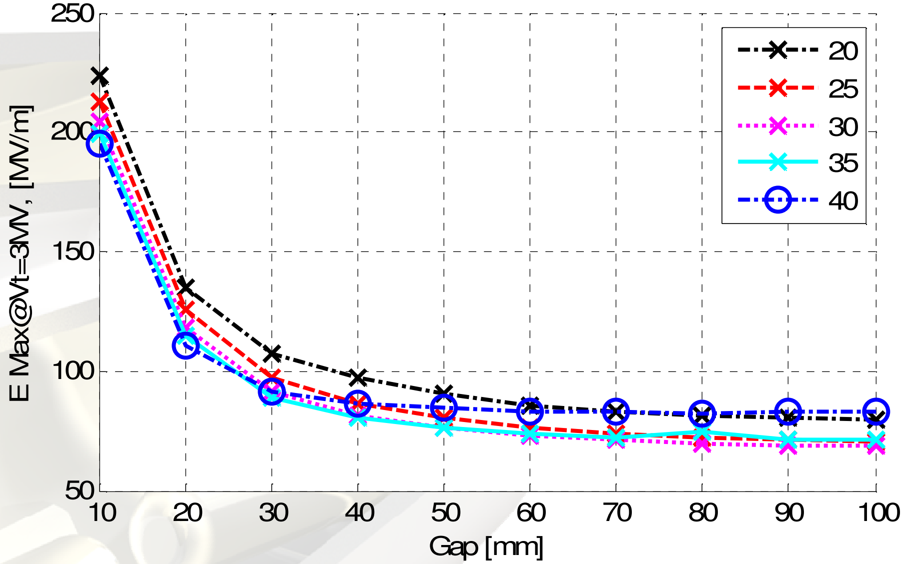


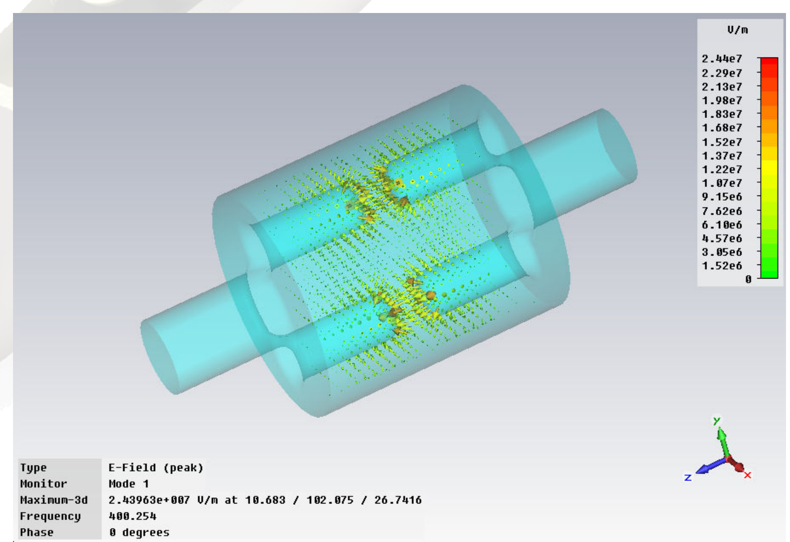


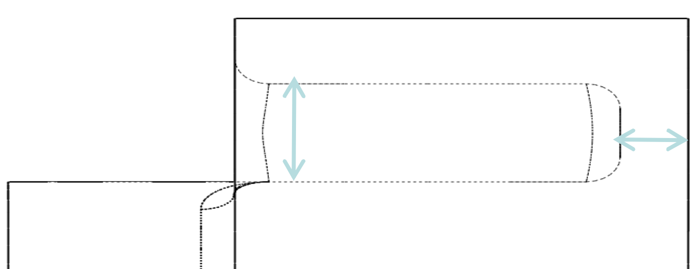


E_{max} vs. Rod gap and Rod radii

- Unlike other crab designs, the 4 rod cavity has high electric fields.
- Cavity rod shape has been optimised to keep surface E and B field within tolerable limits.
- Rod radius has a small effect on peak surface electric field.
- The surface electric field also has a broad minima as long as the gap isn't too small.







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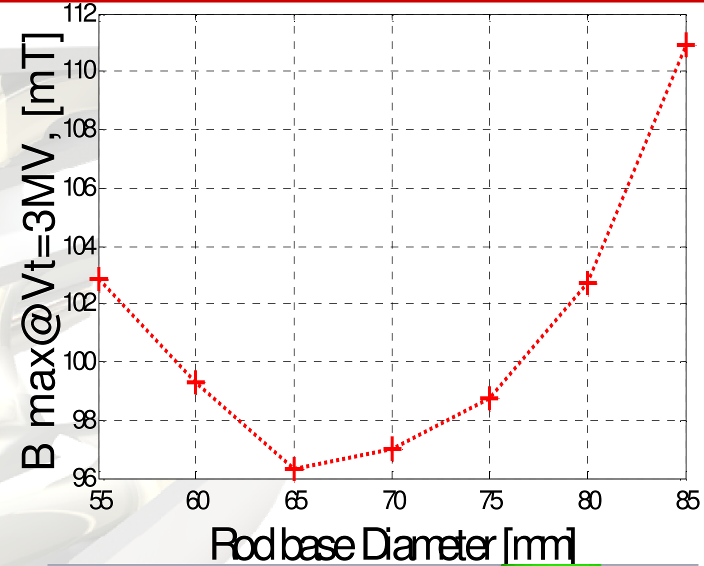
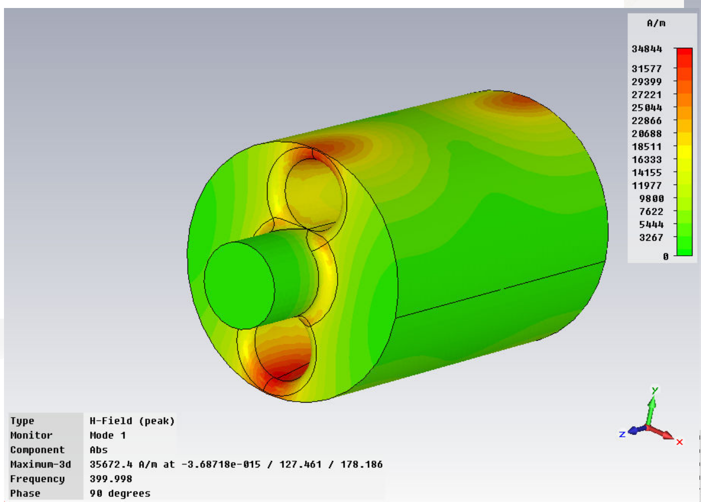
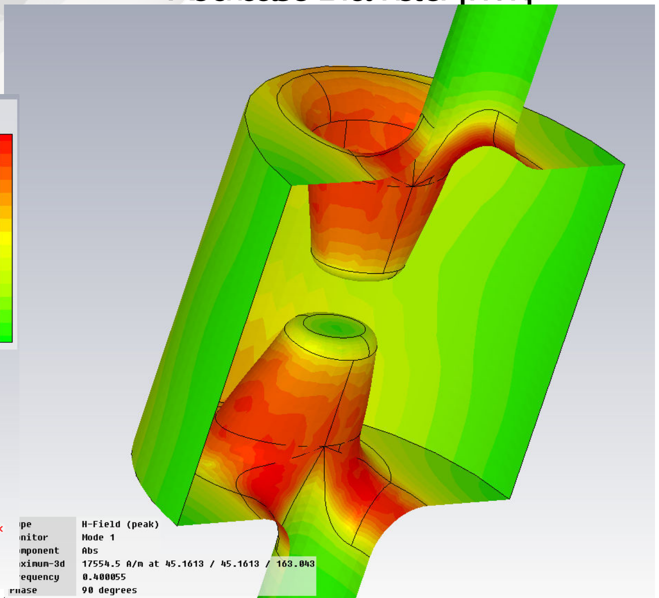
Cone shaped rods

- The magnetic field is very sensitive to the base of the rod and the electric field is sensitive to the tip hence conical rods make sense.
- Base of the rods concerned almost entirely with surface magnetic field
- Increased size interacts with outer wall of can
- Decreased size causes concentration of magnetic field around beam pipe.
- Hence the rod base has a narrow minima.







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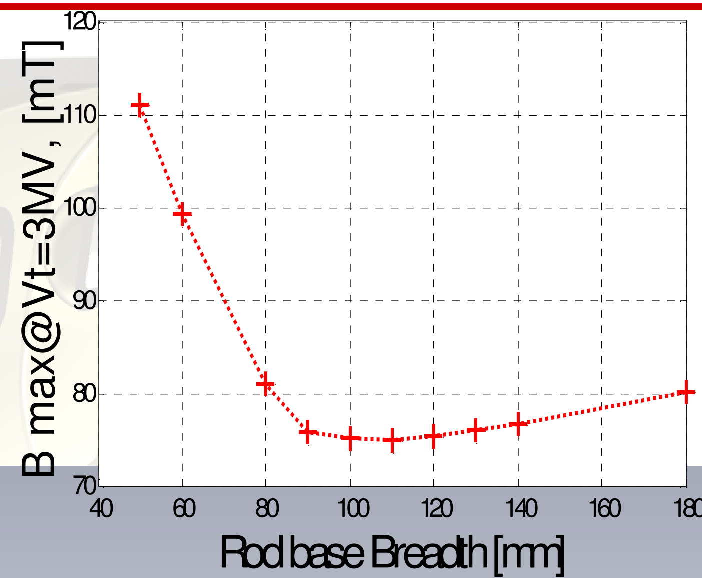
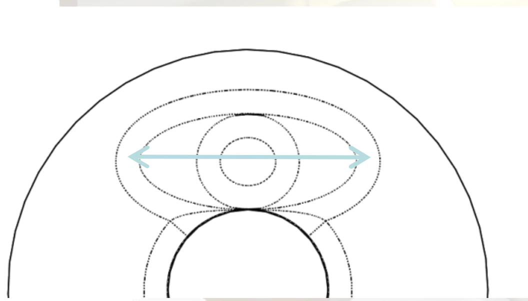
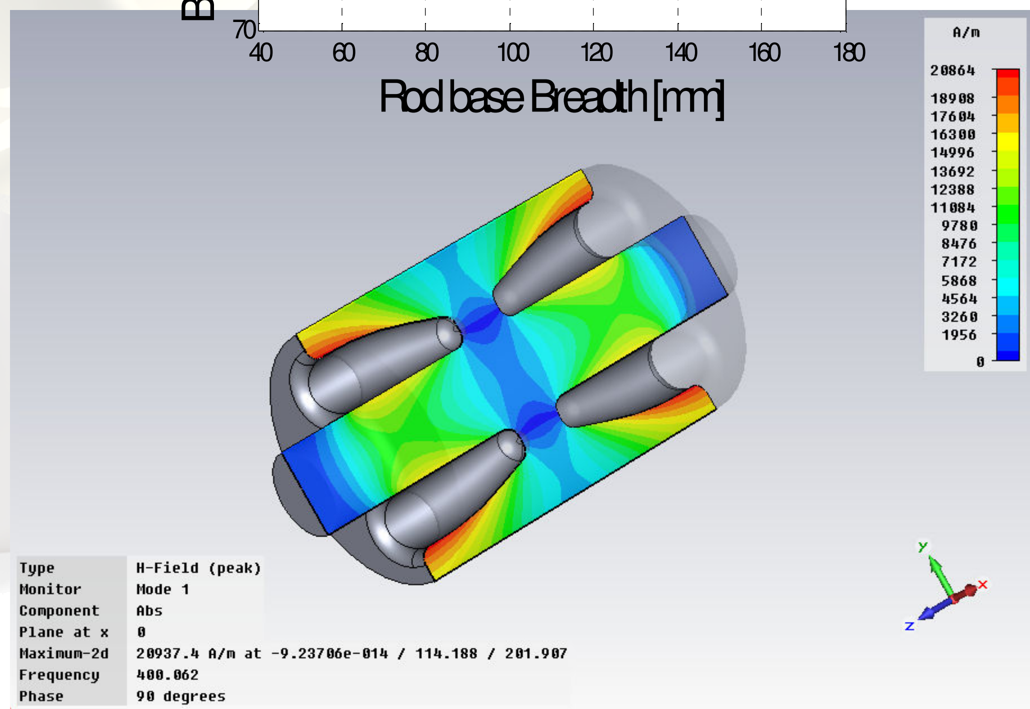
Elliptical Base

- Further decreases in surface magnetic field can be made by using an elliptical base.
- Oval breadth allows increase in rod base size without disproportionate increasing interaction with outer can
- Small breadth leads to previous issues with beam-pipe







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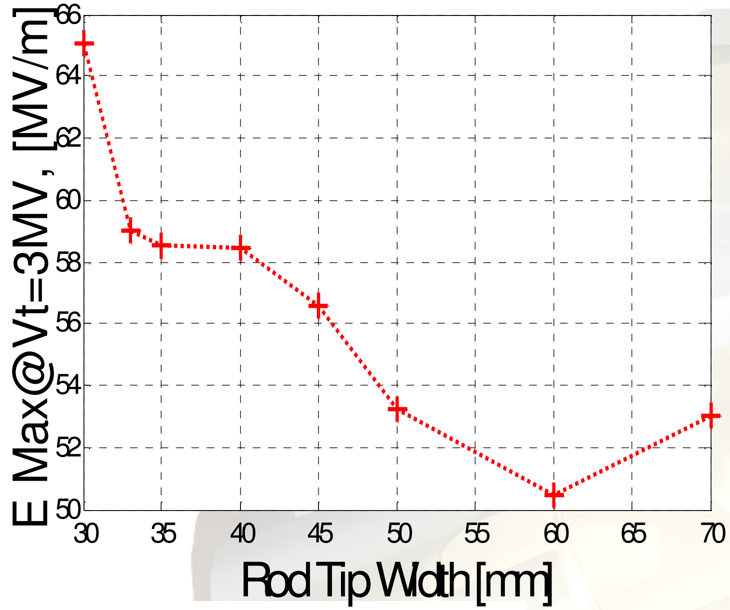
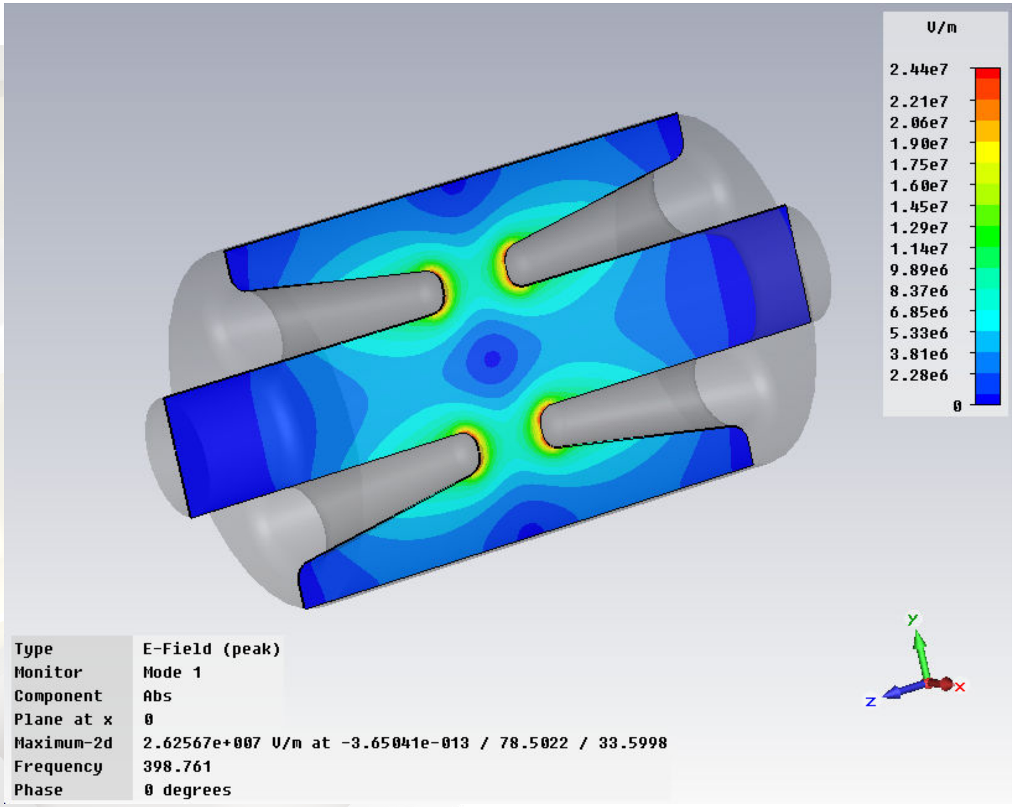
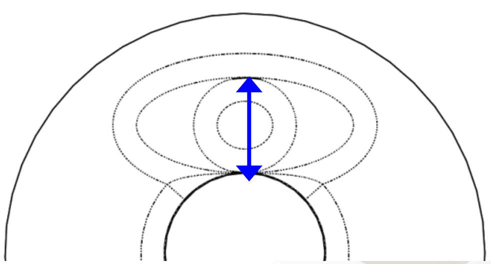
E_{max} vs. Tip width







- Tip mostly concerned with electric field.
- A sharp tip will cause field enhancement.
- Increased tip width decreases peak surface electric field but also will decrease deflecting field.

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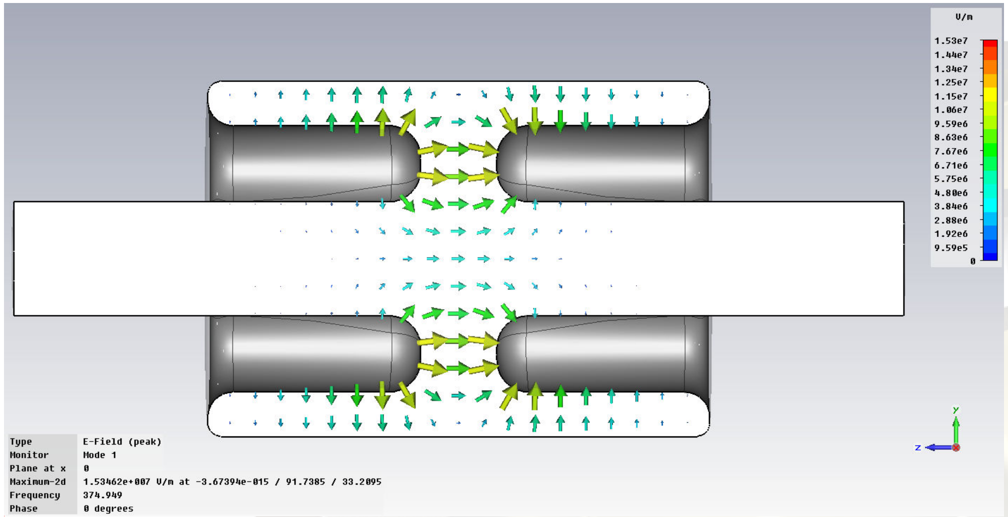
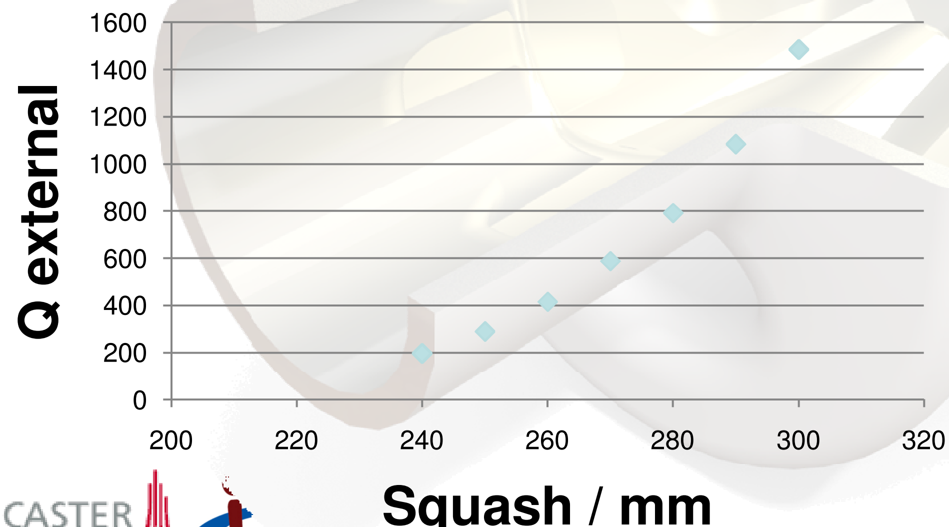
Lower Order mode





- The four-rod cavity also has a lower order mode (LOM).
- This mode has an azimuthal magnetic field flowing around the outer can which is ideal for waveguide coupling.
- The fields are weaker far from the rods so a squashed can shape enhances coupling.

LOM Frequency	374.95 MHz
R/Q	121 Ohms

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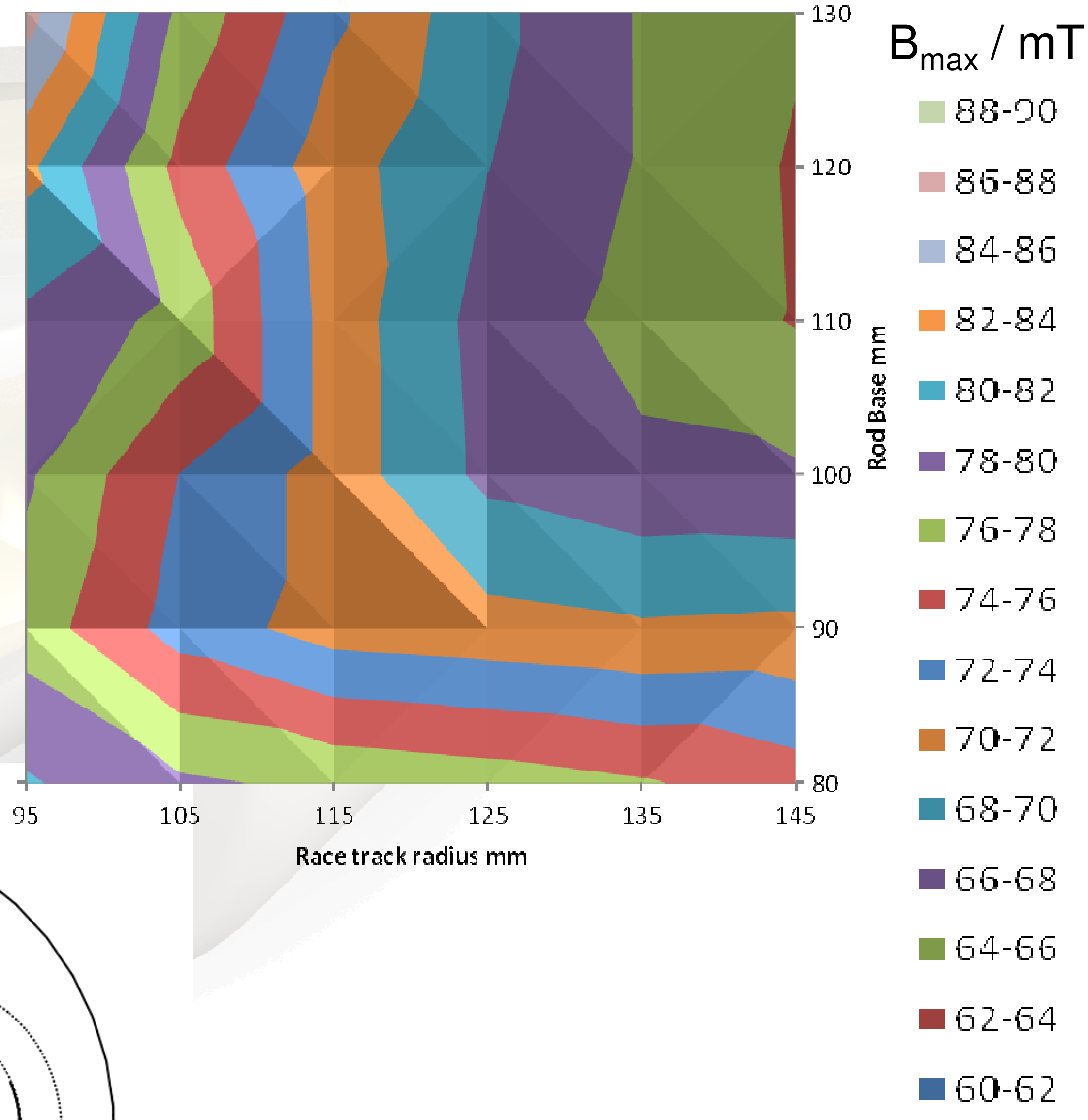
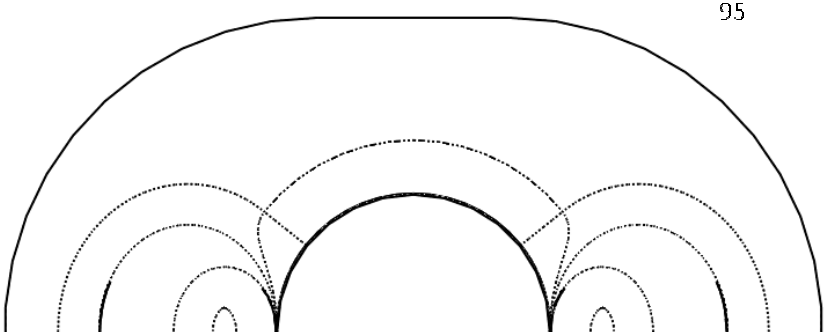
Racetrack

- A racetrack cross section has been shown to be superior to an elliptical shape as it causes less magnetic field enhancement.



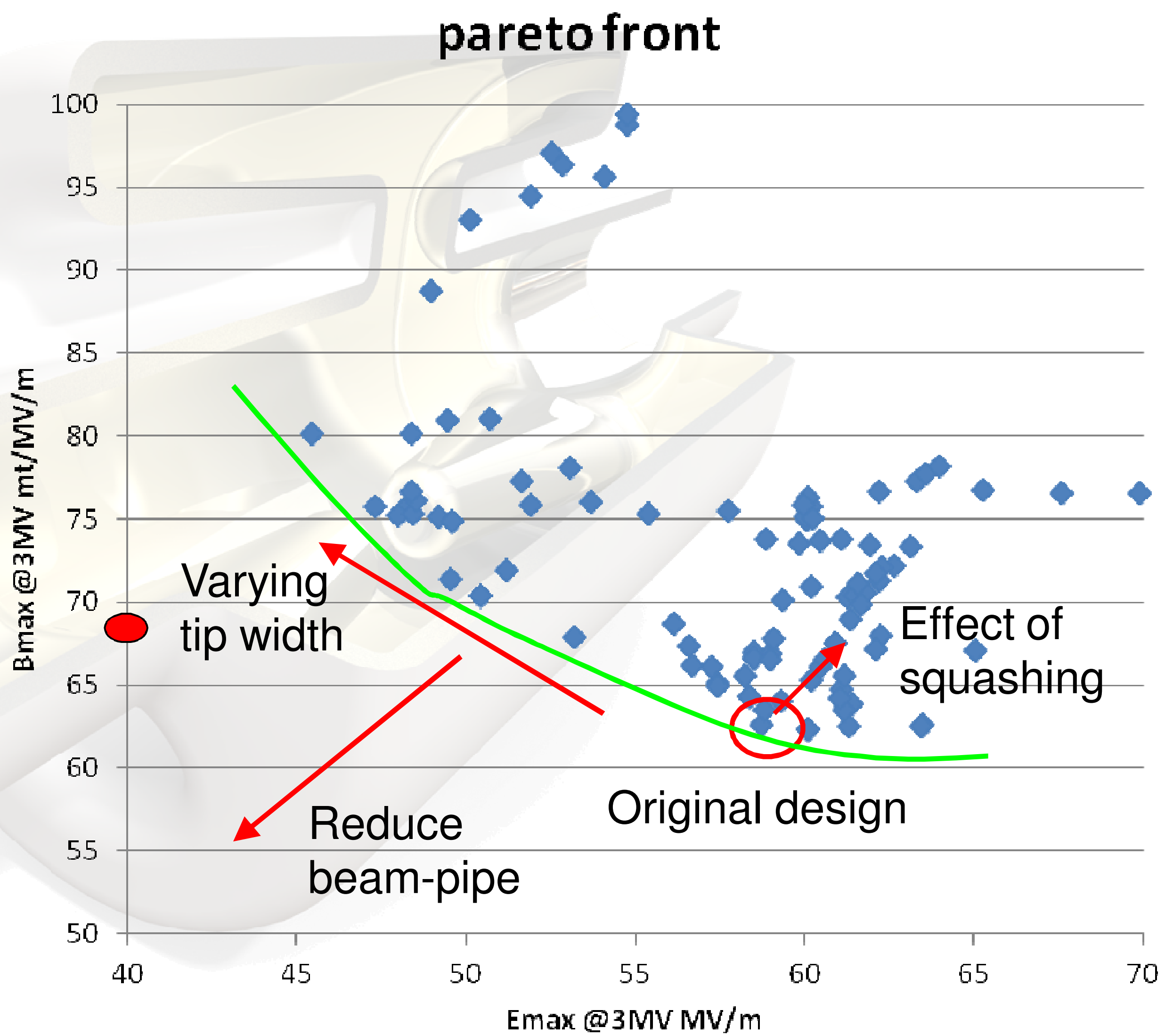


Pareto cavity optimisation

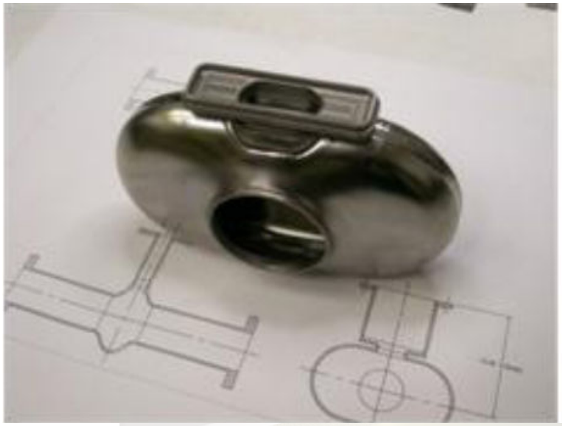
A pareto plot is a standard way of analysing optimisations.

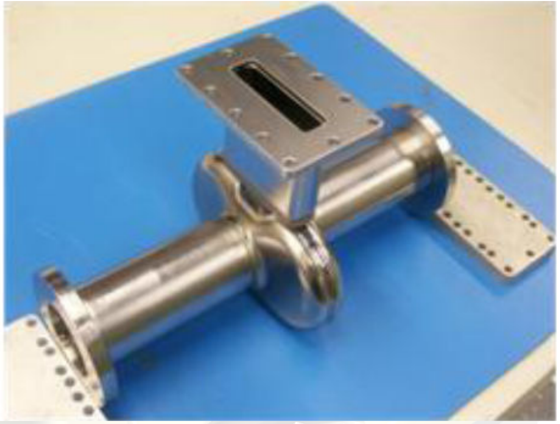
Optimum designs lie on the outer surface.

Our design lies on the knee of the curve indicating an optimum design (for 50 mm beam-pipe).

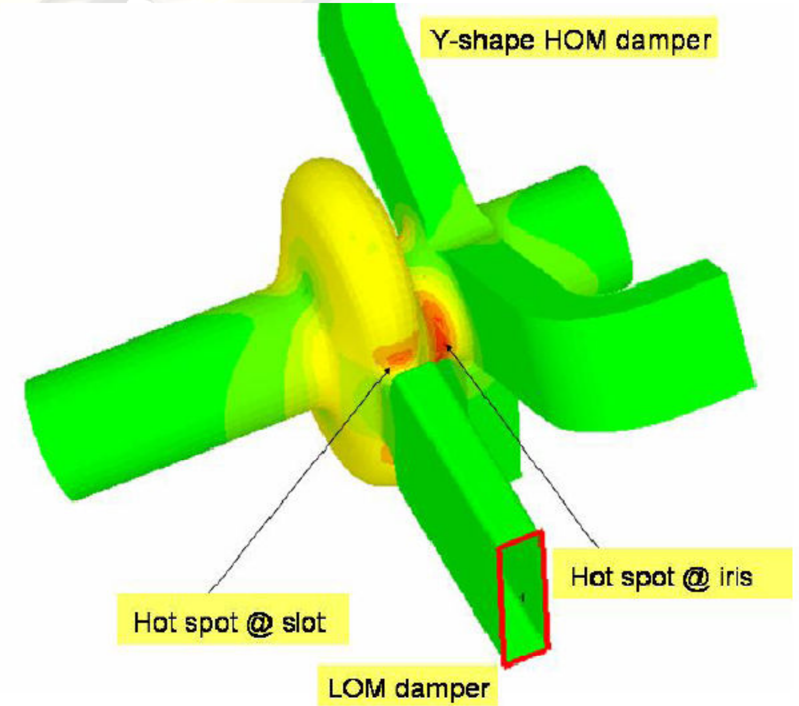


On-Cell damping





- A prototype of cavity utilising this scheme has been developed at TJNAF, using the ALS crab cavity design.
- The first ANL on-cell damper structure was made directly by machining the equators' slot to match a "saddle" adapter in a 3-D contour.
- Three pieces were EB-welded both from the outside and inside through isises.
- A second adapter joining the "saddle" and waveguide was made for the sequenced EB-welds.



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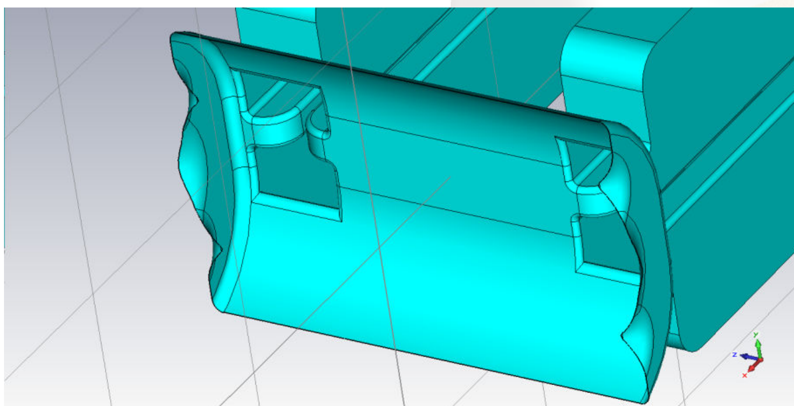
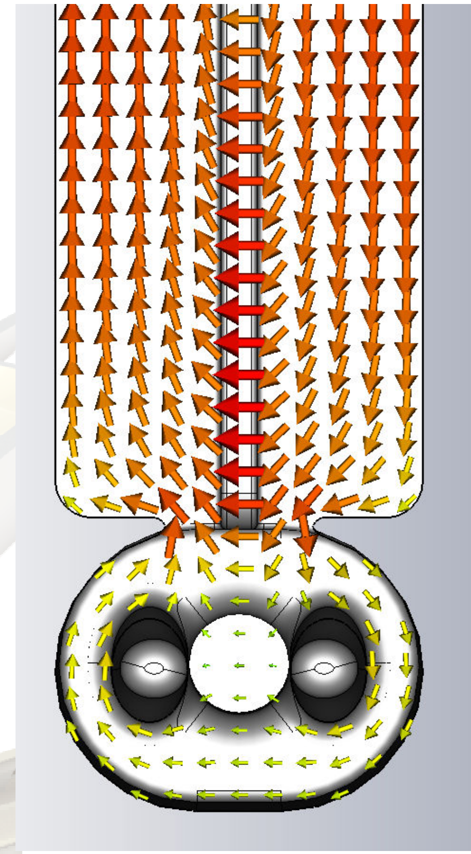
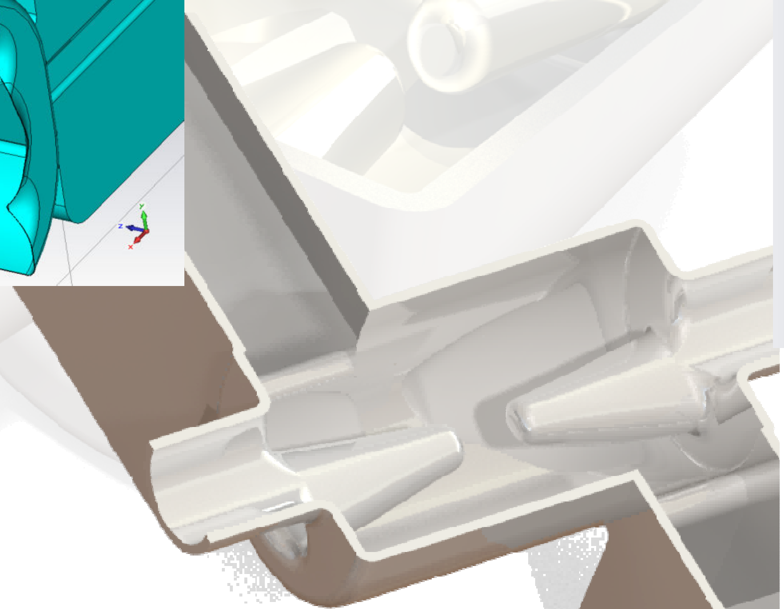
On-cell Waveguide coupling

- Waveguide magnetic coupled to the LOM.
- The magnetic field of the crabbing mode is zero at right angles to the rod polarisation.
- Large aperture required for strong coupling.
- Ridged waveguide can reduce waveguide size.







LOM Qe – ~100

Crab Qe – 10^9

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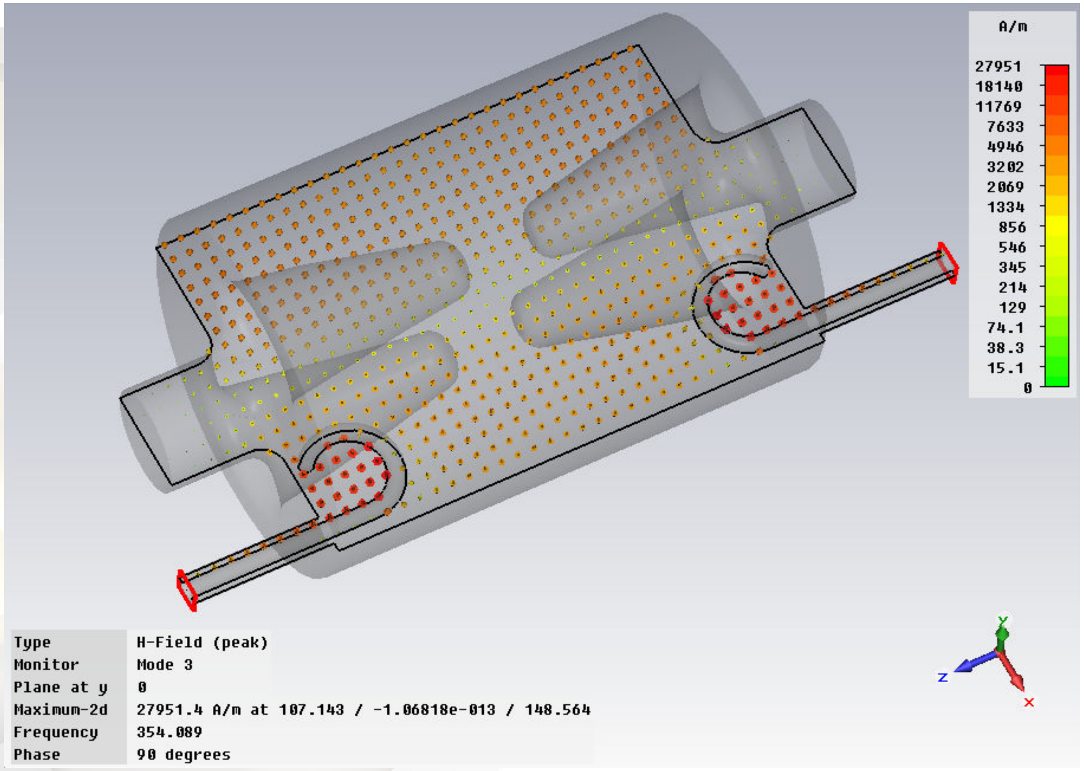
On-cell Coaxial coupling

- The magnetic field is relatively strong close to the outer can surface so a loop coaxial coupler could be an option.
- Large loop area is required for good coupling.
- Easily couples to operating mode if slight variation in angle.
- This can be rectified with a notch filter.



LOM Qe– 70
Crab Qe– 10^7

Few degree twist
LOM Qe– 68
Crab Qe– 2300

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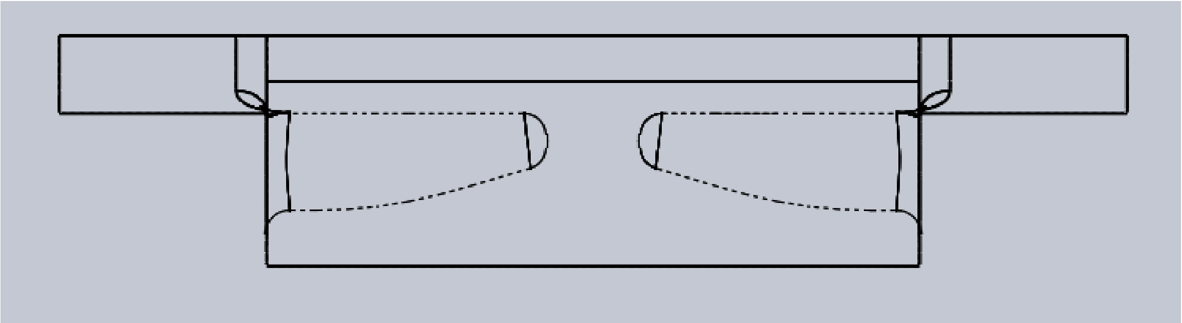
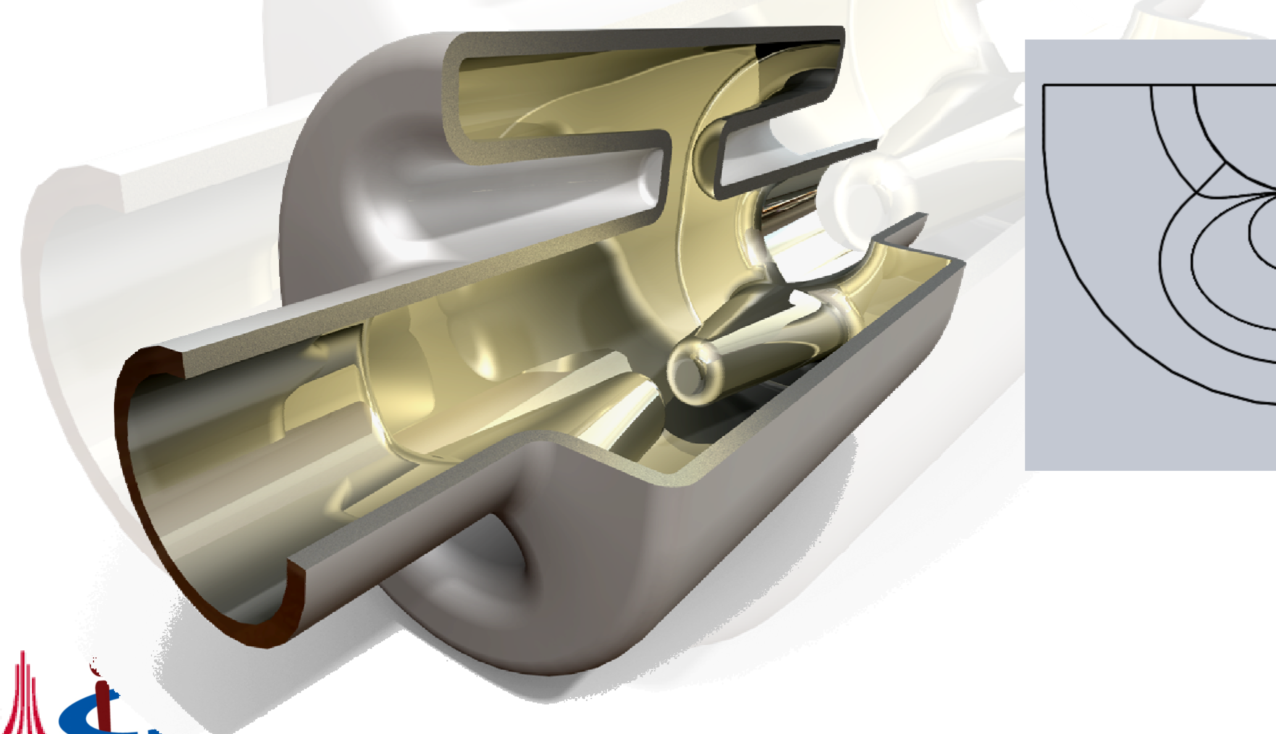
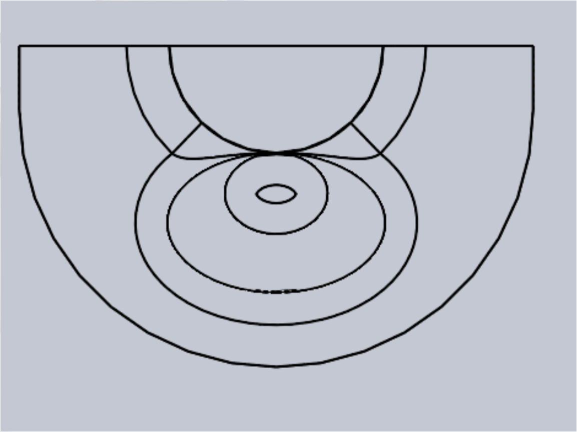
Final Cavity Design







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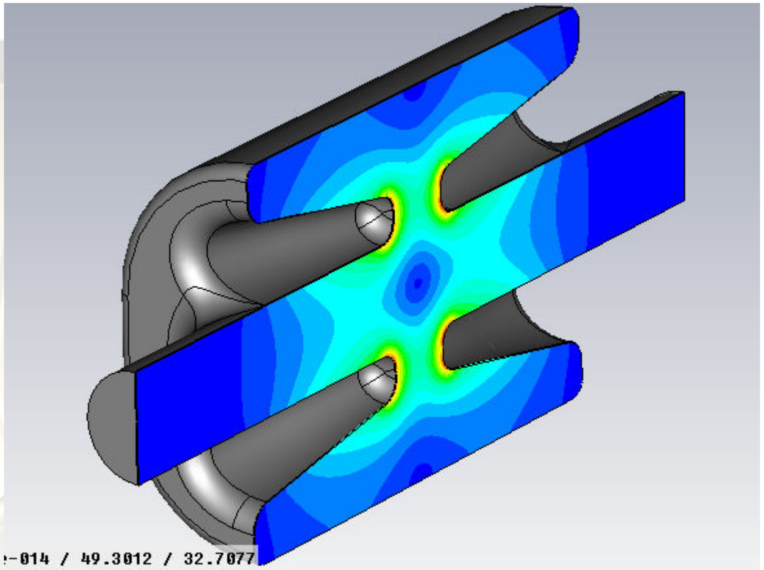
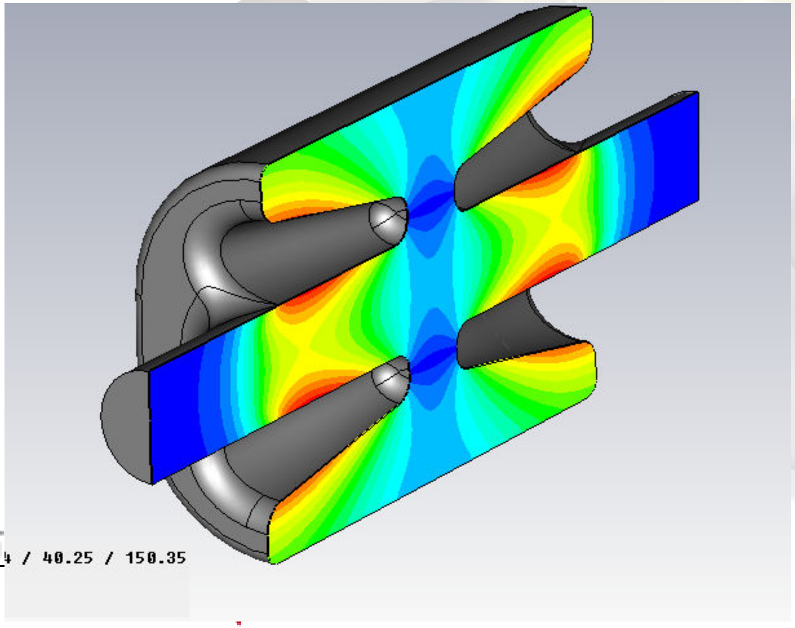
Final Cavity Shape

The cavity design includes a 280mm / 230 mm diameter squashing to increase coupling to the LOM when a coupler is included.

Cavity fits in all LHC scenarios (90mm aperture) and meets design gradient.



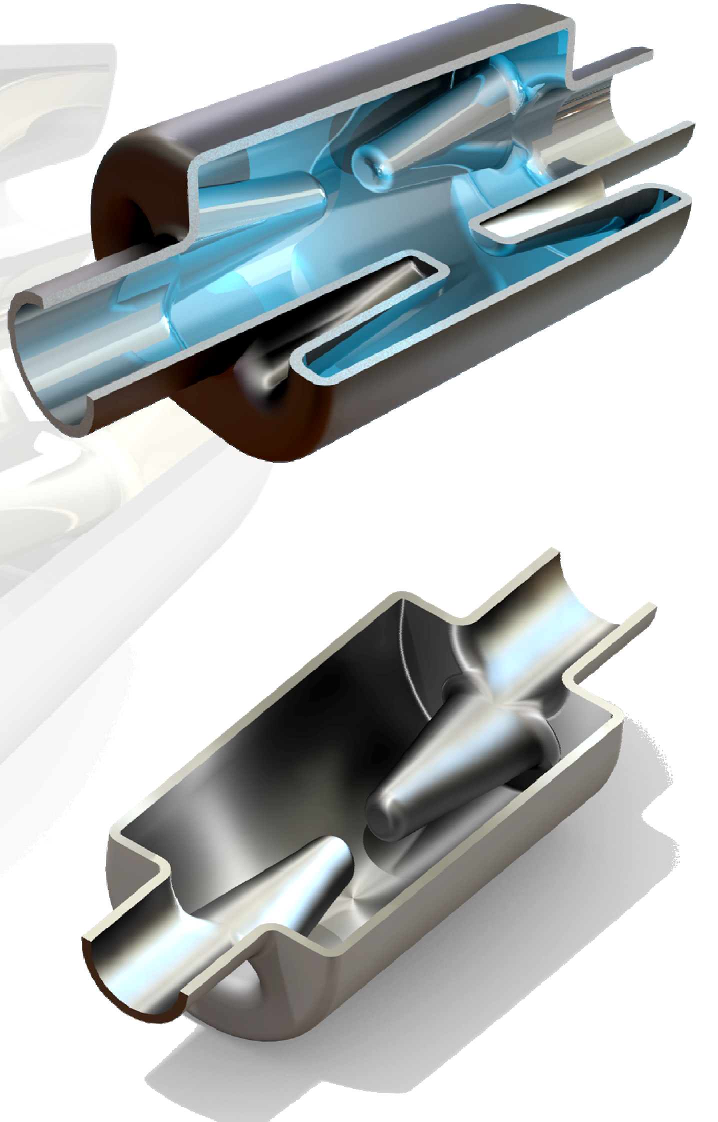


Emax @3MV*	37.0 MV/m
Bmax @3MV	68.2 mT
Cavity Q [pert]	11562
Transverse R/Q	802 Ohms

*Note: Emax significantly lower for new design than presented on Wednesday by Rama for older design

Cavity Prototype

- UK have some funding for a cavity prototype.
- UK and Jlab have significant expertise in cavity measurements and verification.
- Beadpull and wire tests could be performed, as well as coupler verification and possibly even microphonic studies.
- The funding is likely to stretch to a Niobium cavity without couplers.



Conclusion

- A new cavity shape is proposed for the LHC.
- The crabbing TEM mode allows a very transversely compact design.
- The compact size does not impact of the cavity fields greatly.
- Coupler designs are under investigation.
- A prototype is expected to be constructed this year.