Pre-installation spectral response analysis of the HiLumi LHC crab cavity HOM couplers

Thermal simulations will also be presented for discussion

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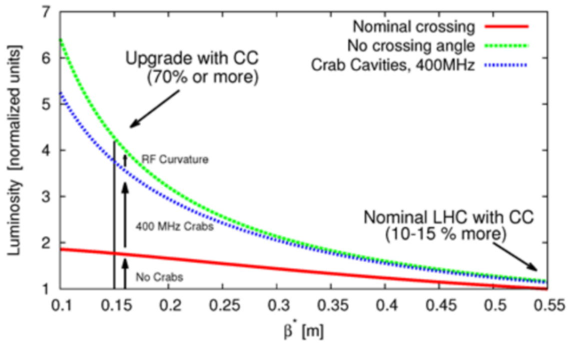
B2FiftyTwo Seminar: HOM Couplers for HiLumi LHC Crab Cavities

The HiLumi upgrade and WP4

HiLumi LHC goal

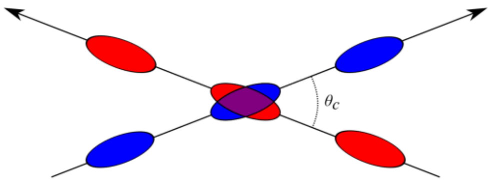
- Increase the luminosity and hence discovery potential of the LHC.
  - Peak luminosity from 2 x 10^{34} $cm^{-2}s^{-1}$ (2021 prediction) to 5 x 10^{34} $cm^{-2}s^{-1}$
- 19 work packages were launched to achieve this.
- Work package four (WP4) concerns the design and implementation of crab cavities.



Luminosity dependence on β^* for the LHC [1].

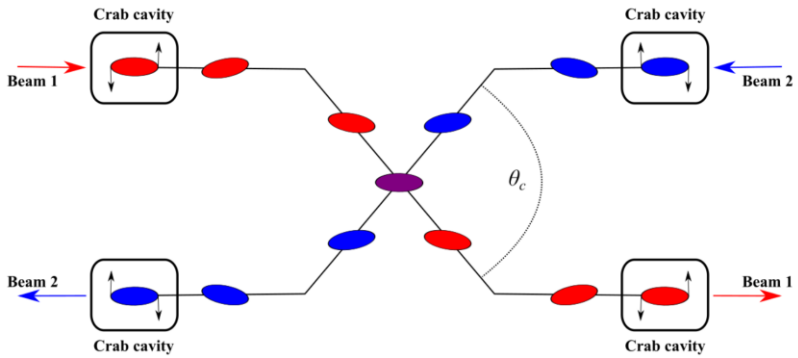
WP4 – Crab cavities

- Where there is a crossing angle in the collision scheme **luminosity is limited** due to an **incomplete overlap** of the bunches.
- By reducing the crossing angle, it is possible to achieve an effective head on collision and increase the luminosity.



$$L = \gamma \frac{n_b N^2 f_{rev}}{4\pi \beta^* \epsilon_n} R$$

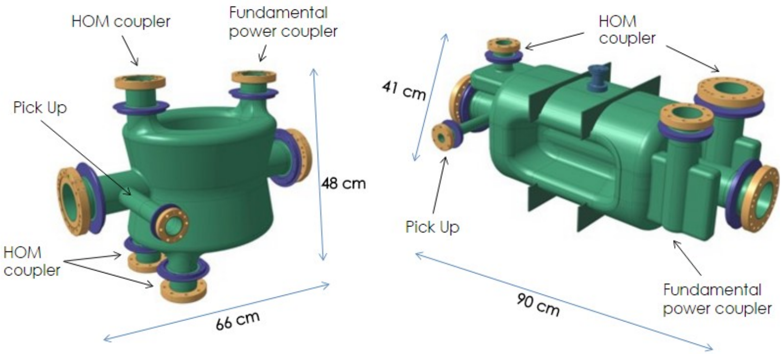
$$R = \frac{1}{\sqrt{1 + \frac{\theta_c \sigma_z}{2\sigma}}}$$



LHC crab cavities

LHC designs

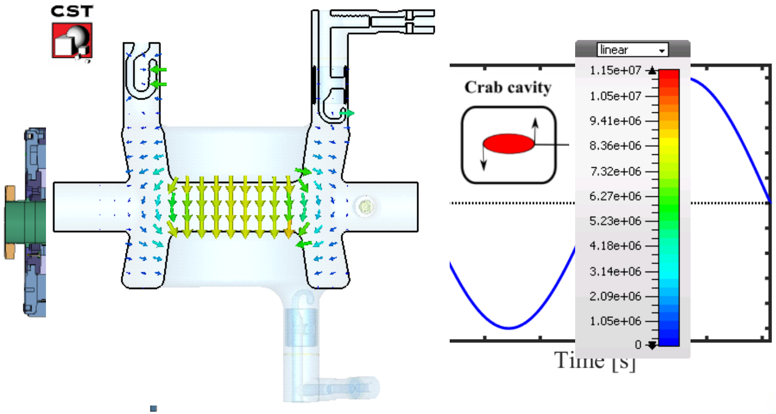
- The crab cavity designs selected for the HiLumi upgrade are the **Double Quarter Wave (DQW)** and **Radio Frequency Dipole (RFD)**.
- The cavities are made from Niobium (Nb) and are designed to operate in the superconducting regime at 2K.



DQW (left) and RFD (right) crab cavities for the HiLumi LHC upgrade [1].

Crab cavity operation

- Operate in the transverse dipole mode.
- **Phased at the zero crossing** to provide a rotation of the bunch.
- This is known as the crabbing regime.
- The DQW will be tested in the Super Proton Synchrotron (SPS) in 2018.



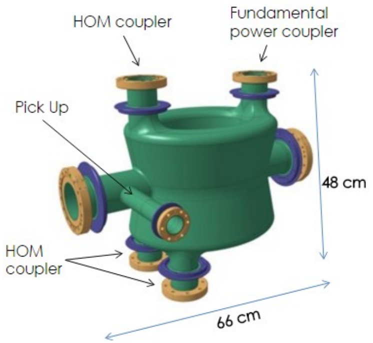
DQW crab cavity

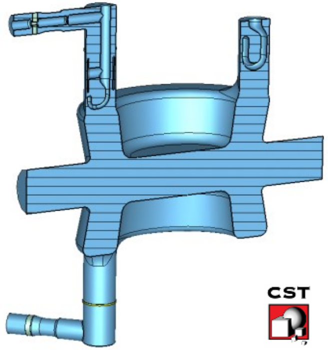
Cavity Details

- The DQW was developed at BNL and will be the first of two crab cavities to be tested in the SPS.
- In addition to the crabbing mode, there exists several **higher order modes (HOMs)**.

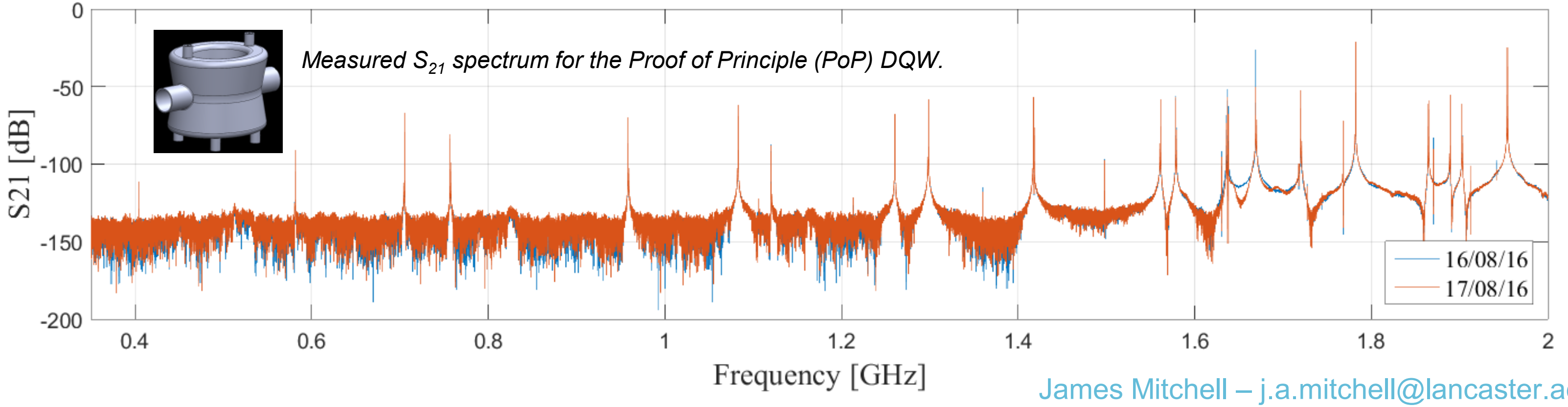
Higher Order Modes (HOMs)

- If excited by the beam, these HOMs alter the electromagnetic field within the cavity.
- This can have detrimental effects to the particle bunches by:
  - Accelerating/decelerating.
  - Adding energy spread.
  - Providing a kick/rotation.





CAD model (left) and vacuum model (right) for the DQW crab cavity.



Measured S_{21} spectrum for the Proof of Principle (PoP) DQW.

DQW Higher Order Mode (HOM) couplers

Development

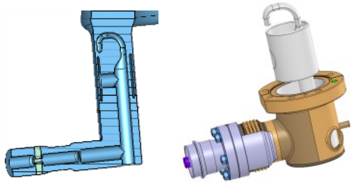
- The HOM couplers were originally designed for the Lancaster 4-Rod crab cavity and altered for the DQW.

EM Design

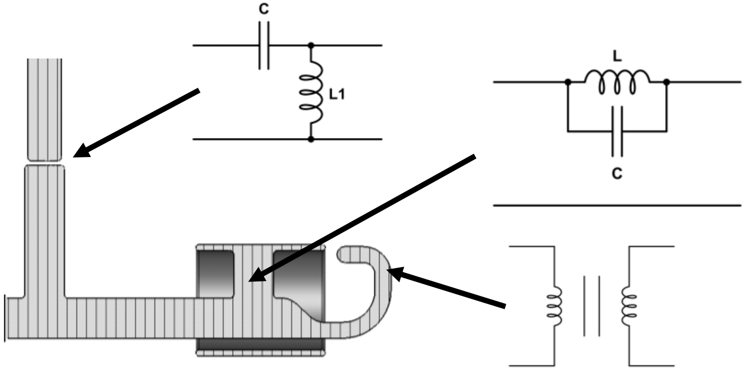
- Use an LC band-stop structure and an L-shaped high-pass filter to achieve the required filter response.
- Magnetically coupled to the electromagnetic field of the 400 MHz deflecting mode.
- On-cell couplers.
  - Better damping is achieved by this.
  - But the hooks are located in high field.

Mechanical design considerations

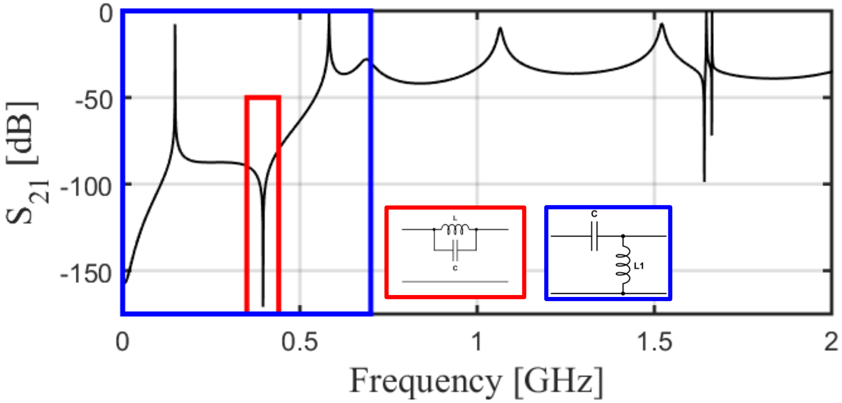
- LC band-stop filter is located near the hook so that there is no heating of the copper gasket.
- Cooled by immersion in the liquid helium – hollow inner conductor.



Vacuum model (left) and CAD model (right) for the DQWHOM couplers.



DQW HOM coupler schematic and the equivalent circuits for each of the main features.



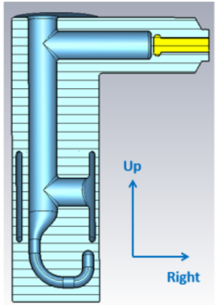
HOM coupler test boxes: MOTIVATION

HOM coupler defects

- Simulation studies show that the HOM couplers sensitive to manufacturing tolerances.
- Therefore small **geometric defects** can severely effect the **filter response**.
- Due to this, tight tolerance restrictions have been imposed for the manufacturing process.

Quantifying HOM coupler operation

- The HOM coupler's operational characteristics represent directly the accuracy of the manufacturing process.
- Therefore, techniques of analysing the spectral response of the HOM couplers were investigated with the idea being to create **TEST BOXES for the HOM couplers.**



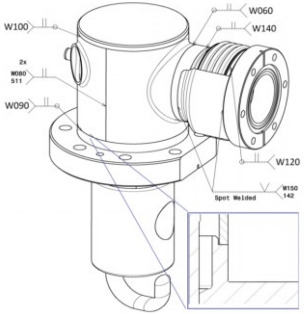
For error analysis of the hook, we need guidance on how the hook shape may change during machining.

Unit: mm

Parameter	Nominal	error	
Gap0	4	Left 0.4	Right 0.5
Gap1	3	Left 0.4	Right 0.5
Gap2	2	Left 0.5	Right 0.5
Rod1P	-9	Left 0.4	Right 0.5
Rod1L+Rod2P	125	Down 0.5	Up 0.5
Rod1L+Rod2P +Tube1P	128.5	Down 0.5	Up 0.5
Insertion	143	Down 0.5	Up 0.5
Rotation		Clockwise 1 degree	Counter clockwise 1degree

Explanation of the parameters are in the following slides. Please refer to the file "Parameterization of HOM filter_Dec102014". All parameters are at 2K after surface treatment.

Allowable mechanical errors corresponding to EM simulation parameters. Performed by B. Xiao.

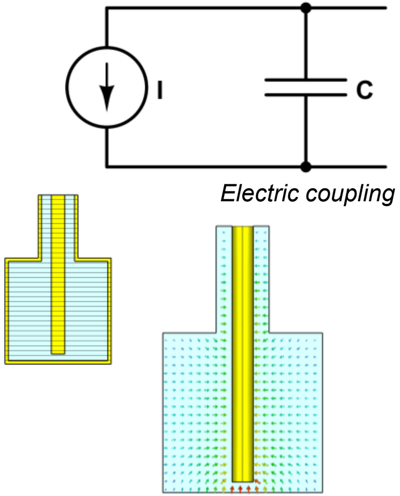


Example of mechanical tolerance specification. Specifically this drawing details the final weld tolerances.

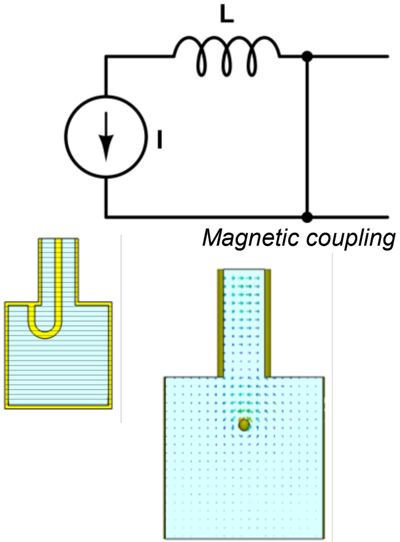
Coupling methods

Types of coupling

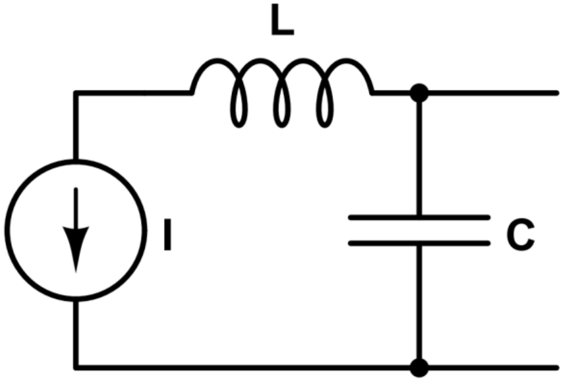
- The two types of field coupling are **electric** and **magnetic**.
- In reality, both types of coupling are always present, however it is possible to preferentially couple with once mechanism by designing the geometries such to excite electrically or magnetically.



Electric coupling



Magnetic coupling



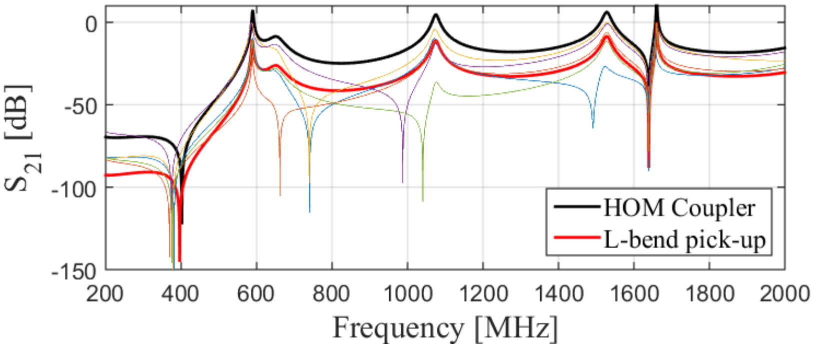
Electromagnetic coupling:

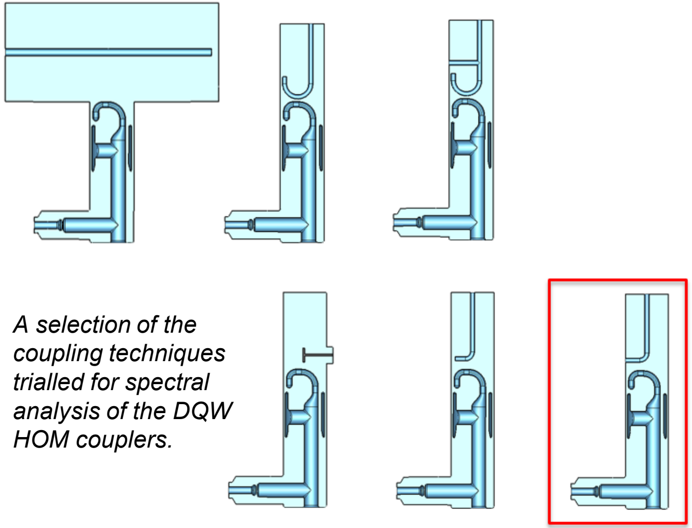
Changes in geometry shift the weighting of C and L.

Coupling to the DQW HOM couplers

Coupling trials

- In order to find the best method of measuring the spectral response of the couplers, several *coupling trials* were simulated in CST MWS.
- By comparing the S_{21} response of the HOM coupler with the transmission line set up it was possible to analyse the best coupling method.
- The best method was found to be the **bent probe connected to ground near to the HOM coupler's hook.**
- This method will be referred to as the **L-bend pick-up**.





A selection of the coupling techniques trialled for spectral analysis of the DQW HOM couplers.

L-bend pick-up

- Magnetic coupling provided by the L-shaped probe with bend.
- Path to ground situated as near as possible to the HOM coupler hook.

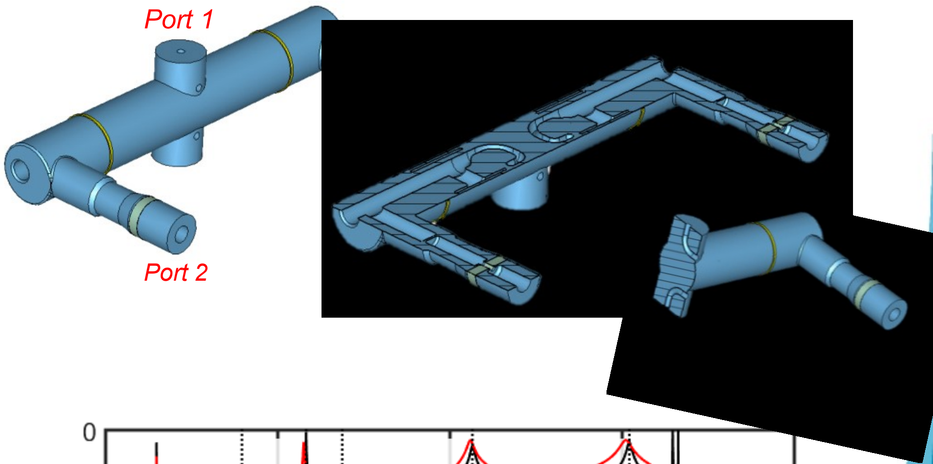
TEST BOX #1: L-bend transmission

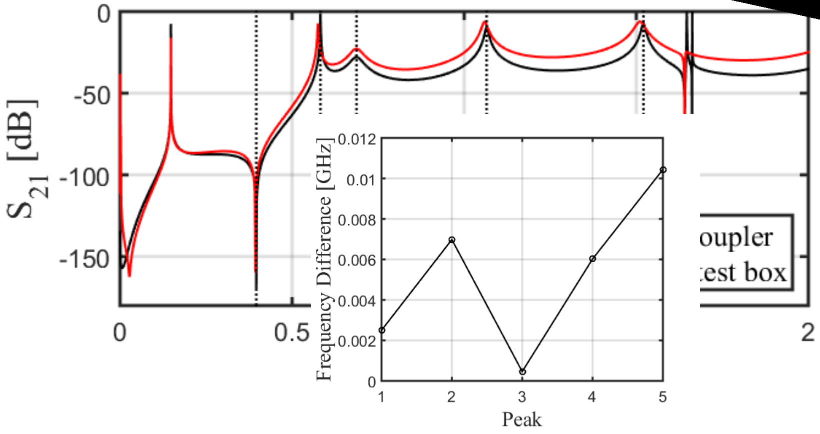
Design

- Test box designed using the L-bend pick-up connected to ground.
- Designed for **low power** spectral analysis.
- Designed to preferentially represent the stop-band at ~ 400 MHz.

Why a multiport system?

- Validation possible with multiple ports.
- Inherent symmetry improved response.
- Can still use one coupler – blanking plate.
- This design also allows **high power testing**, i.e. a transmission of power from HOM coupler port to the other.
  - Hence this *prototype* will act as a feasibility study for the high power testing.

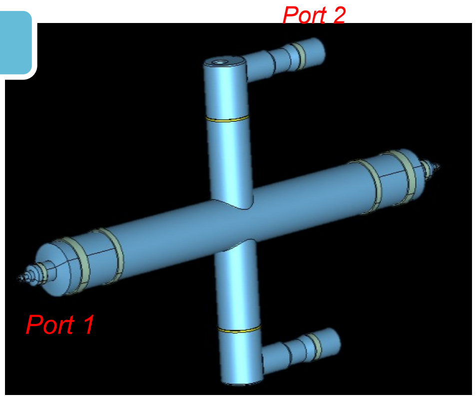


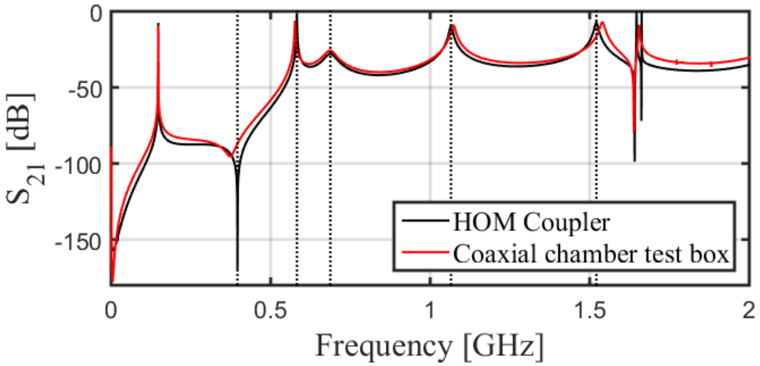


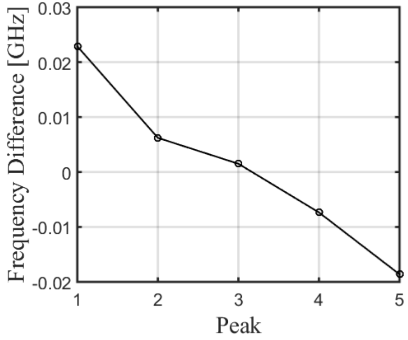
TEST BOX #2: Coaxial chamber

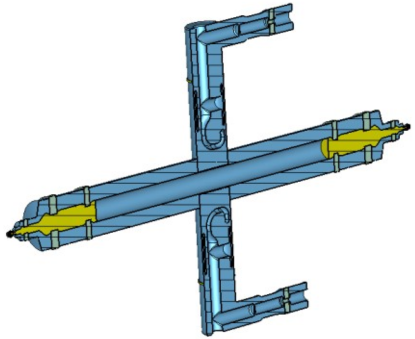
Design

- Like the L-bend transmission test box, four port symmetrical device.
- Uses a **procured** coaxial line with **procured** connectors which allow reduction to 7-16/N-type.
  - Quick assembly, little work needed in terms of machining.
- However this means that optimisation parameters are very limited.
  - Varying the insertion depth.
  - Mechanical system will allow two insertion depths.
- Worse representation of the deflecting mode frequency.



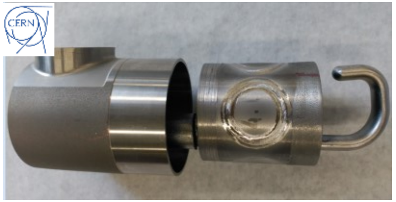


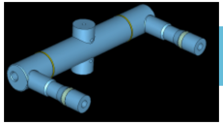




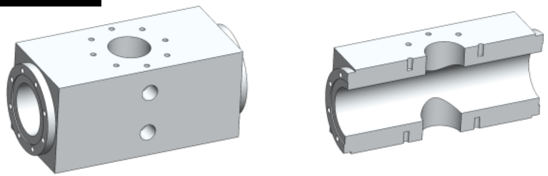
L-bend transmission mechanical design

HOM Coupler Manufacture

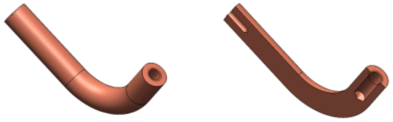




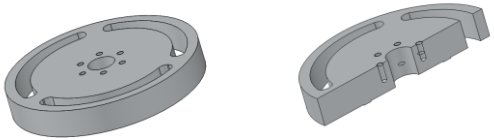
L-bend transmission components designed - CAD



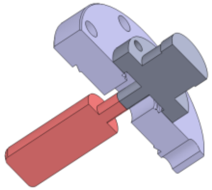
Aluminium body



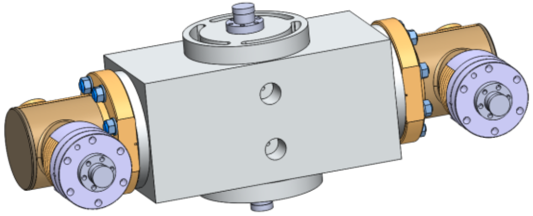
Copper pick-up probe

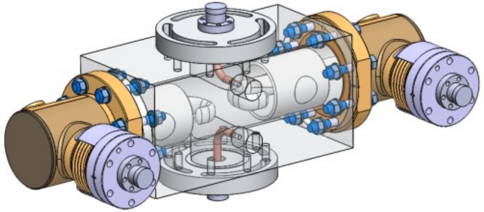


Custom rotatable flange
maintains correct orientation of pick-up



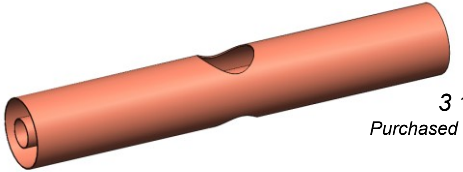
New high pass filter sections
termination to N-type



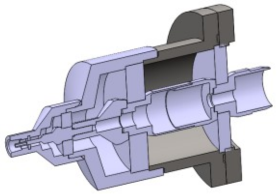


Coaxial chamber manufacture

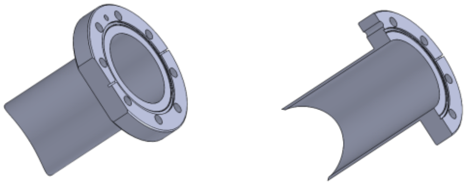
L-bend transmission components designed/purchased



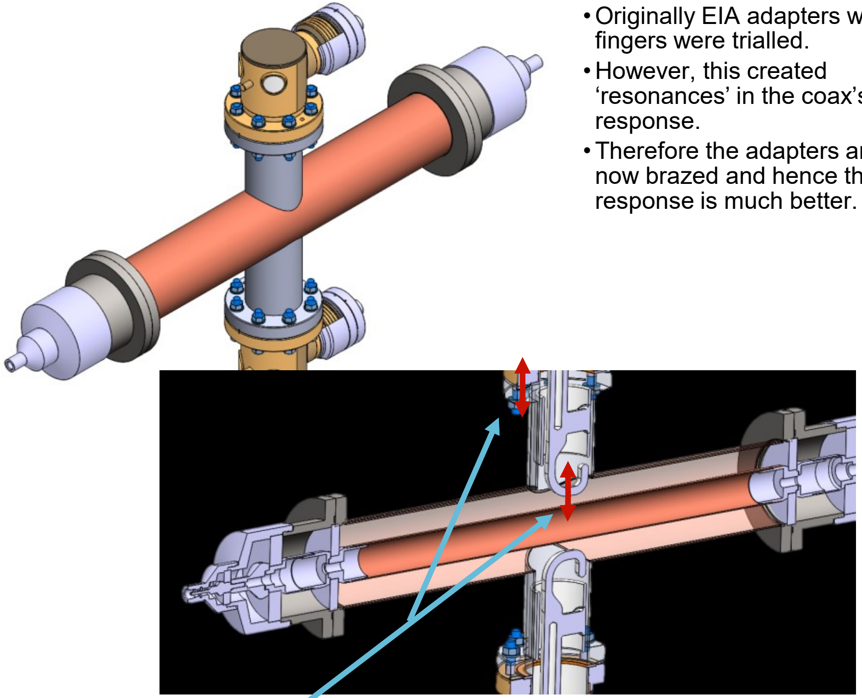
3 1/8" Coaxial line
Purchased with holes machined into the outer conductor



EIA to N-type adapters
Purchased



HOM coupler ports
Purchased

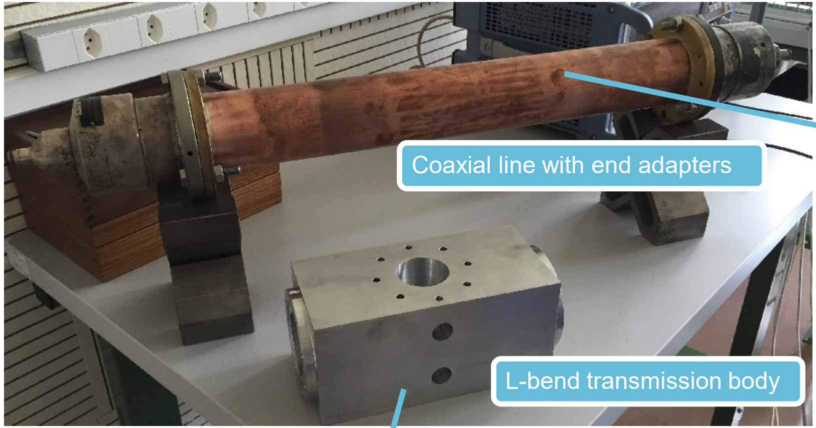


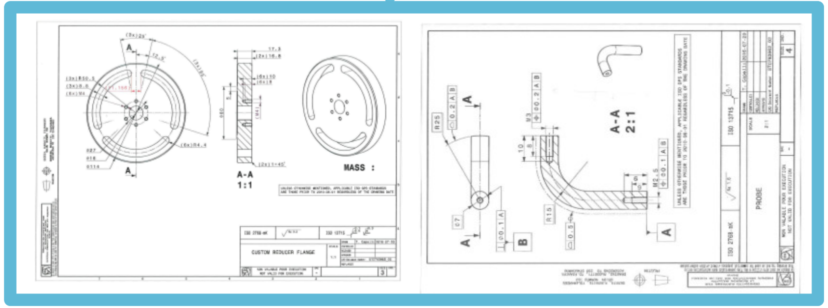
EIA adapters

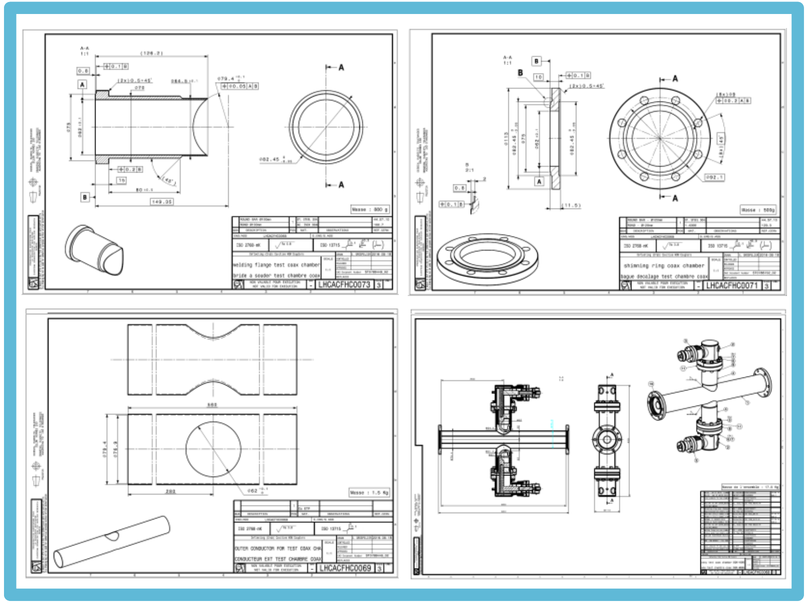
- Originally EIA adapters with RF fingers were trialled.
- However, this created 'resonances' in the coax's S_{21} response.
- Therefore the adapters are now brazed and hence the response is much better.

There will also be 'spacers' which will allow insertion depth variation.

Manufacture progress





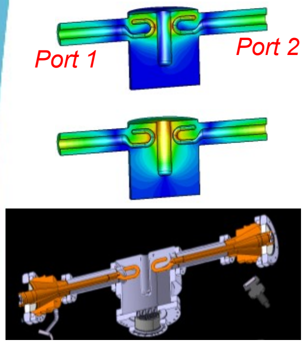


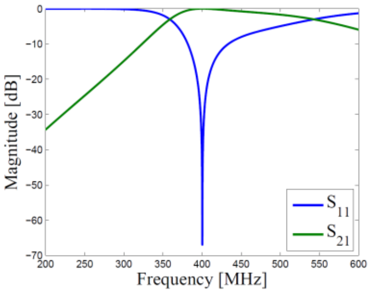
Currently all manufacturing drawings have been produced and the parts are waiting to be machined and welded.

FUTURE: High power conditioning

Fundamental Power Coupler (FPC) conditioning

- FPCs operate in areas of high field.
- If the surface is not smooth then the couplers will not operate under high power conditions without breakdown/vacuum activity.
- Therefore, a two port device is used which is able to transfer RF power (at the operating frequency) from one port to the next.
- Power is then applied according to documented procedures and this *conditions* the couplers for use at the operating conditions



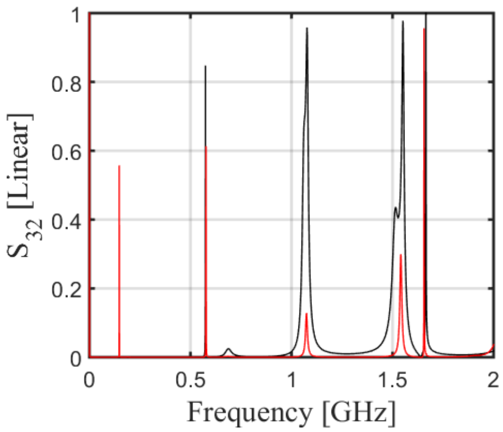


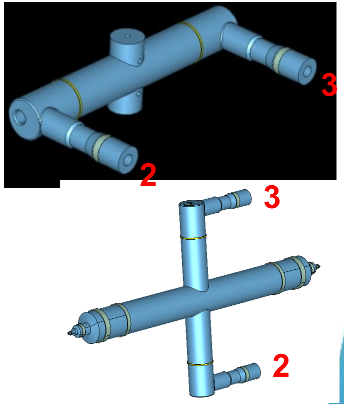
DQW FPC test box for high power conditioning.

Example of conditioning procedure [2]

HOM coupler conditioning

- Because the HOM couplers are on-cell couplers, the hooks are located in regions of high field.
- For this reason, conditioning of the couplers is seen as important to ensure no issues due to field breakdown on the rough surfaces of the couplers.
- Hence the test boxes were designed to have two coupler ports, with discrete frequencies where high power conditioning could take place.





THERMAL SIMULATIONS: DQW HOM couplers

Motivation

- Cavity system is designed to operate at 2K.
- Heating through conduction, radiation and due to the EM field could mean that the system raises in temperature.
- This would perturb the operation of the couplers.

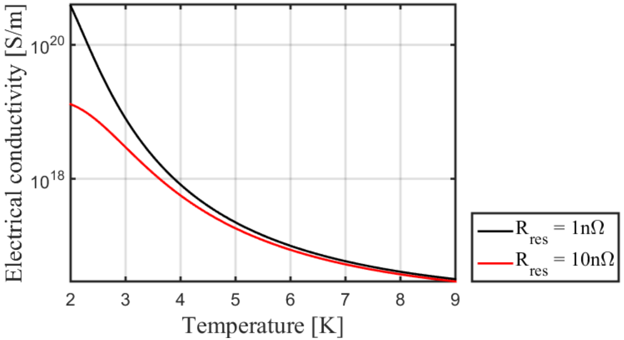
Why further simulations?

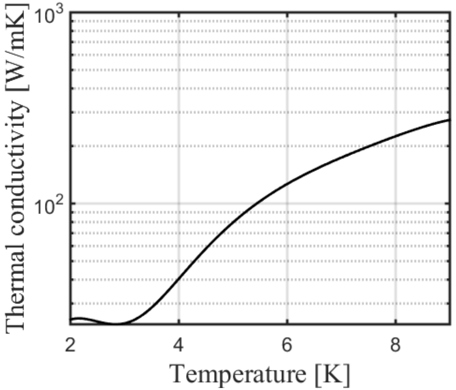
- The DQW HOM couplers have already been simulated thermally.
- However, the **temperature dependence of the electrical and thermal conductivities** of Niobium were analysed in post processing steps.
- Therefore, the ability to have an **all inclusive model** which iterates until temperature convergence was seen as a very powerful tool for this and future thermal simulations.

$$R_{BCS} = \frac{2\times 10^{-4}}{T} \times \left(\frac{f_{GHz}}{1.5}\right)^2 \times e^{\frac{-17.67}{T}}$$

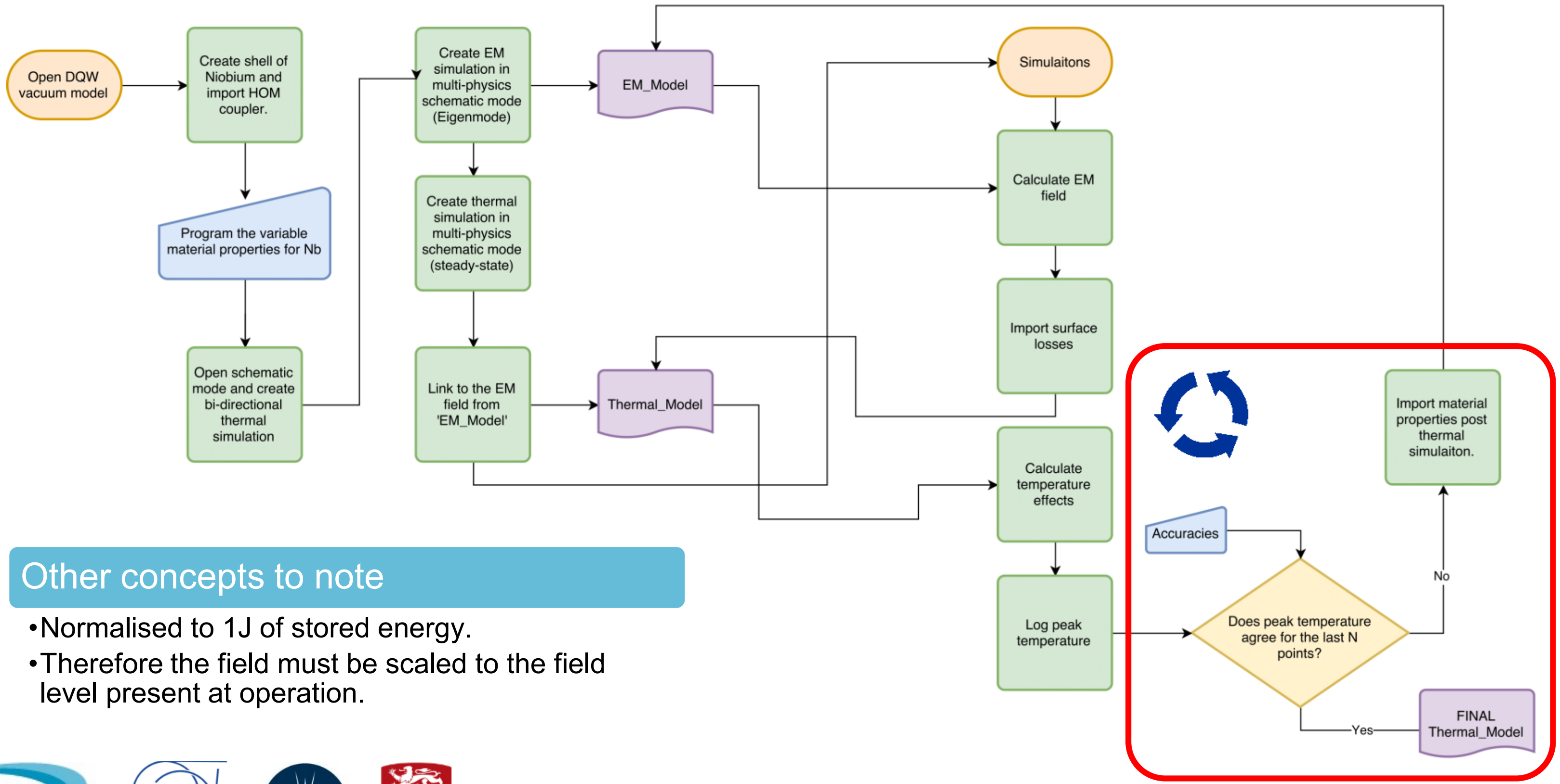
$$\sigma = \frac{\mu_0 \pi f_{Hz}}{R^2}$$

$$R = R_{BCS} + R_{residual}$$





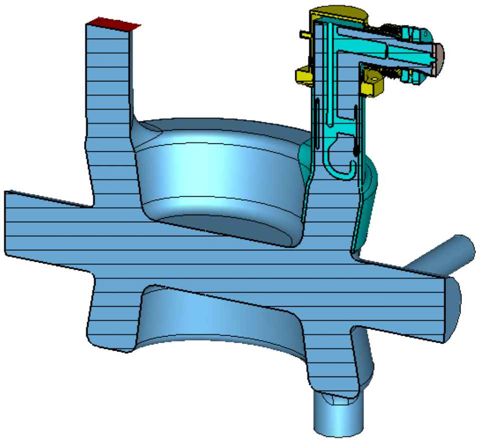
THERMAL SIMULATIONS: DQW HOM couplers

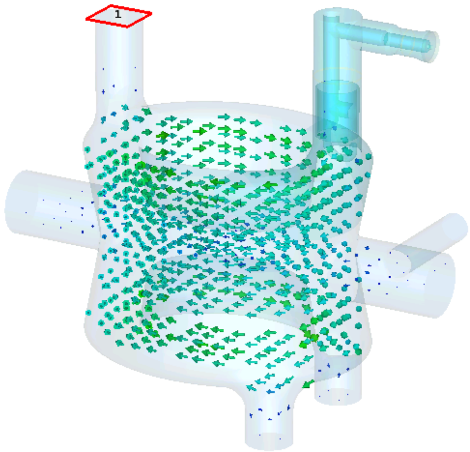


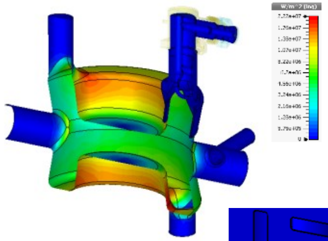
Other concepts to note

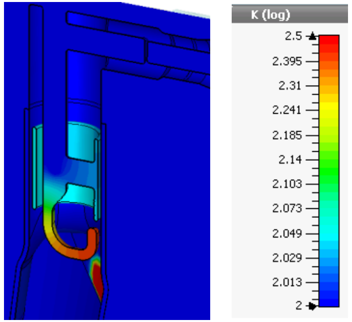
- Normalised to 1J of stored energy.
- Therefore the field must be scaled to the field level present at operation.

THERMAL SIMULATIONS: Results









Model build

- DQW crab cavity CST model.
- Imported CAD model of HOM coupler.
- Edited to solve meshing errors.
- Shelled to represent Niobium wall.

EM model

- Field map produced.
- Surface loss map inferred from EM field map (specifically magnetic field).

Thermal model

- Surface losses inferred from EM model.
- Initially, steady state simulation allows temperature to be calculated.
- **ITERATED THREE TIMES.**
- No feedback in the iteration, finding a way to log the peak temperature and evaluate until convergence is the next step.

THERMAL SIMULATIONS: Next stages

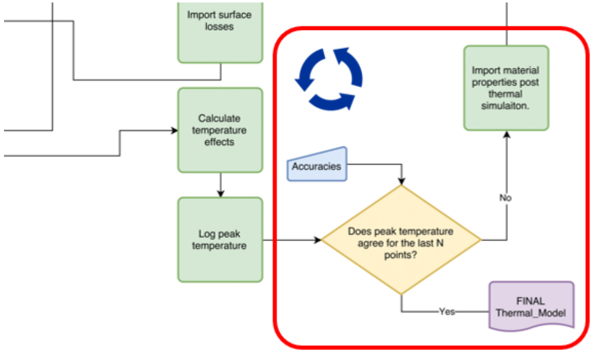
Next steps…

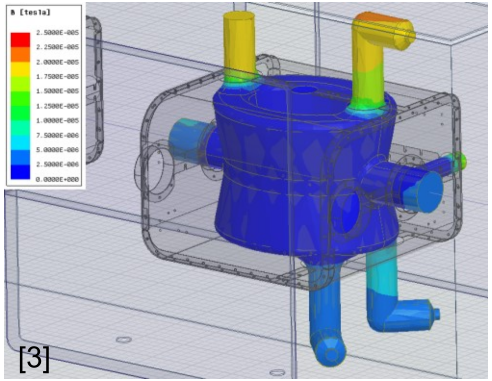
- No feedback in the iteration - find a way to log the peak temperature and evaluate until convergence.

- Take into account that there is a magnetic field present which **varies** due to the location of the **magnetic shield**.
- To do this, the coupler will be split into sections and the residual resistance of each section will be changed to correspond to the value of the external magnetic field.

Future

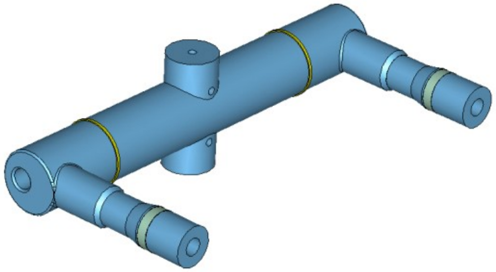
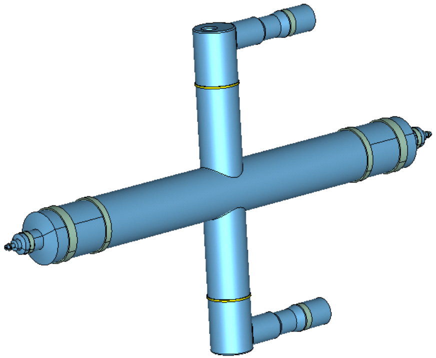
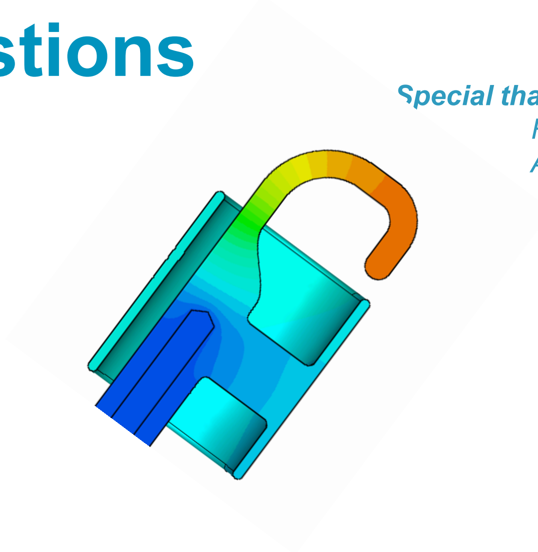
- HOM heating.
- Effect of material impurities on temperature and field.
- Conductive heat sources.
- Pick-up simulations.





[3]

Summary and Questions

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