HOMs for HL-LHC Crab Cavities
RF-Mechanical Aspects

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IET-STFC RF-Mechanical Workshop
Daresbury Laboratories, Warrington, UK, 13 September 2018

Presentation Aim

"… is therefore critical that combined RF and Mechanical studies are performed as part of RF device development"

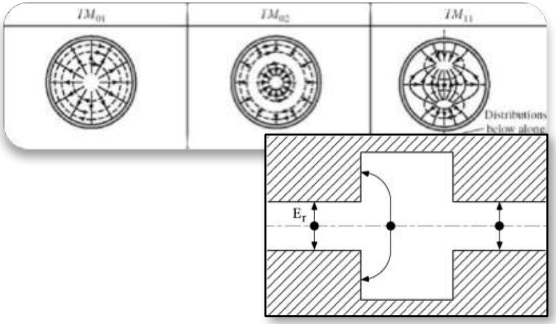
IET event description

I will present **DQW HOM coupler development**, design decisions and problems associated with **RF design and mechanical engineering.**

Outline

1) Theory

- HOMs, Excitation and Damping
- HOM Coupler



2) DQW HOM Coupler

- Operation
- RF-mechanical
  - Thermal, multipacting, design advantages
- Evolution to LHC
  - Lessons – Manufacture
  - Lessons – Power lines and feedthroughs
  - RF thresholds
- New Design

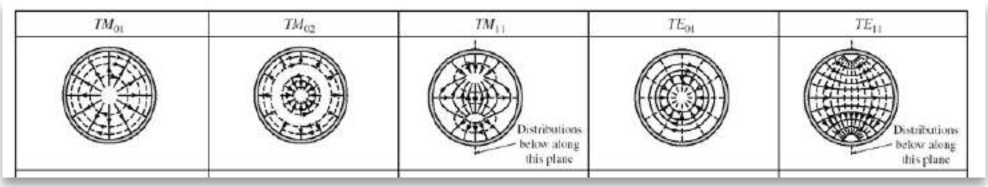
3) Alternative Design

4) Future concepts

HOMs

HOMs

- Higher Order Modes
- Resonances (eigenmodes) at frequencies higher than the fundamental.



Why are HOMs Undesirable?

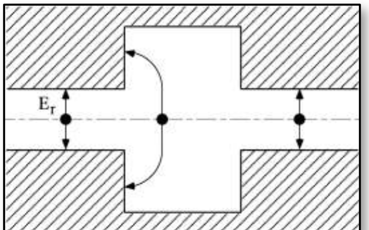
1. Beam instabilities and emittance growth.
2. Power generation.

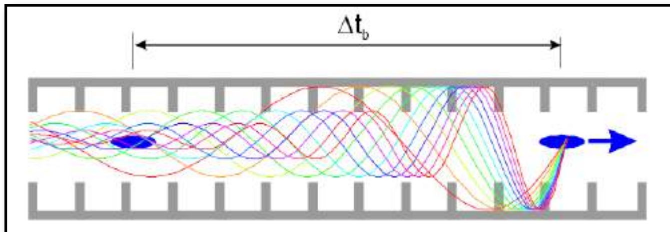
Which mode types cause which problems?

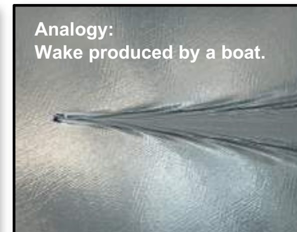
- **Longitudinal (e.g. TM_{010})**: Longitudinal emittance growth, energy spread and power generation.
- **Transverse (e.g. TE_{110})**: Transverse emittance growth and beam motion instabilities.

HOM Excitation

- The fundamental mode is excited from an **<u>external RF source</u>**.
  - Modulator, klystron, gridded tubes, magnetrons, solid state etc…
- The HOMs are excited from the **<u>charged particle beam</u>**.







Particles enter cavity

↓

Image charges cannot travel as fast as bunch (longer path)

↓

RF energy left behind: this is the <u>WAKEFIELD</u> and is an EM wave

↓

The energy is deposited in each excitable mode (need e-field along axis of beam propagation)

HOM Damping

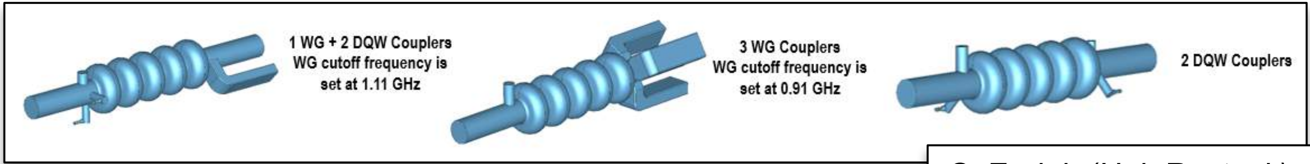
- HOM damping: providing a **power flux** away from the cavity resonator at the HOM frequency.
- Reduces the Q_e of the mode.

$$Q_e = \frac{\omega_0 U_{st}}{P_e} \qquad \frac{1}{Q_l} = \frac{1}{Q_0} + \frac{1}{Q_e}$$

- Mechanisms:

Note, for superconducting cavities, the Q0 is so large that we can assume Ql=Qe.

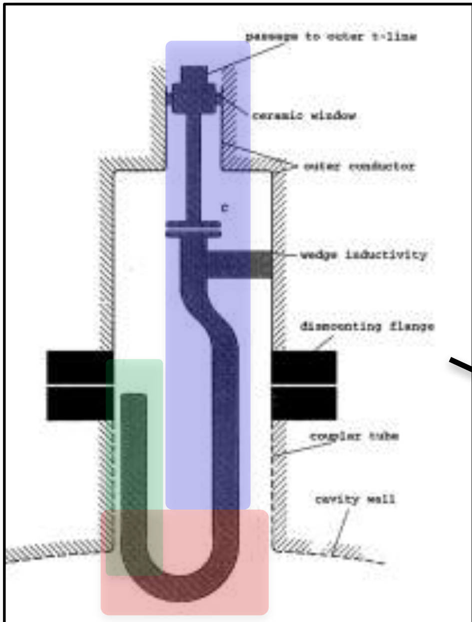
Coaxial dampers (on beam pipe), waveguide dampers (on beam pipe), absorbers, Fundamental Power Coupler (FPC), **<u>on-cell dampers.</u>**



<u>S. Zadeh (Uni. Rostock)</u>

The HOM Coupler: RF operation

- Taking the LHC HOM coupler as an example:



1) Couple to the field
- **'Hook' coupling mechanism.**
- **Preferentially magnetic coupling but also electric.**

2) Reject fundamental mode
- **L-C notch filter at 400 MHz.**

3) Provide power flux to HOMs
- **Coaxial transmission line to load.**

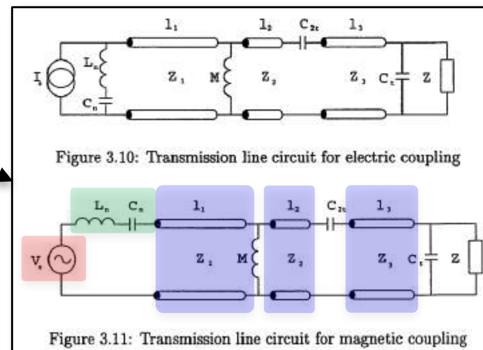


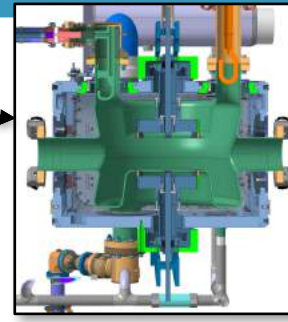
Figure 3.10: Transmission line circuit for electric coupling

Figure 3.11: Transmission line circuit for magnetic coupling

F. Gerigk
Design of Higher Order Mode Dampers for the 400 MHz LHC Superconducting Cavities

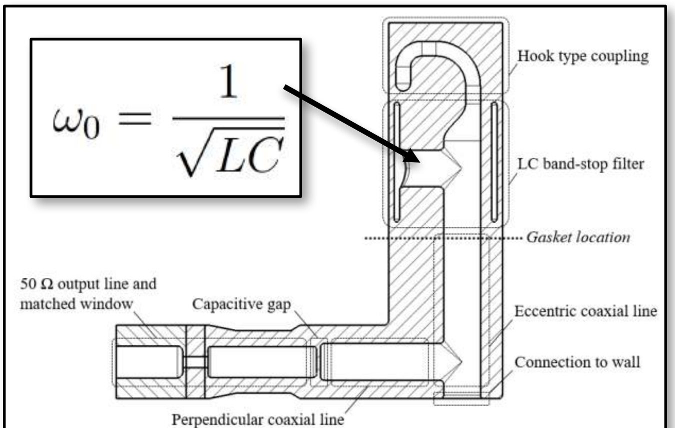
DQW HOM Coupler: RF Operation

- DQW: Double Quarter Wave
  - Superconducting crab cavity for HL-LHC.
  - Currently being tested in the SPS (7 km proton synchrotron at CERN)

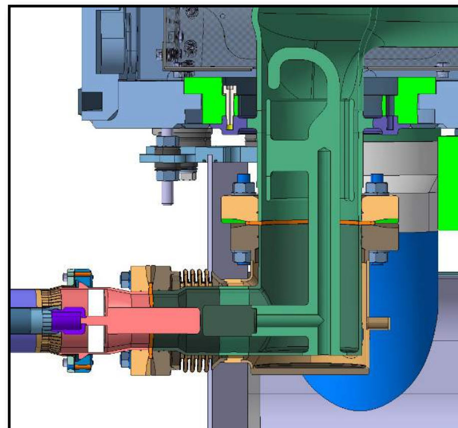


- DQW HOM Coupler: SPS version

Vacuum model



CAD model

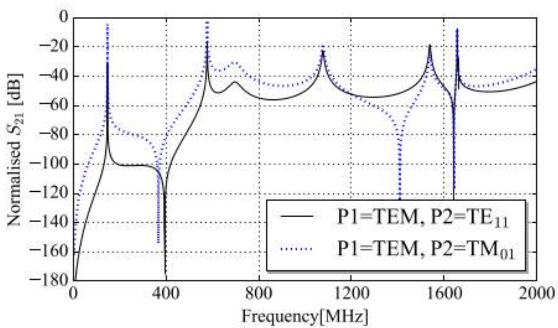


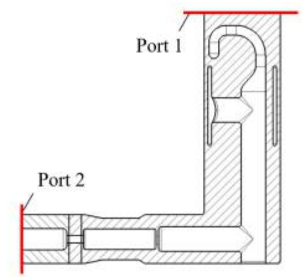
DQW HOM Coupler: Eqiv. Circuit

- **Equivalent circuit** modelling can **reproduce the transmission response** of the coupler very well.
- The circuit simulations are **many order of magnitudes faster** than the 3D FEA simulations.

3D electromagnetic simulation

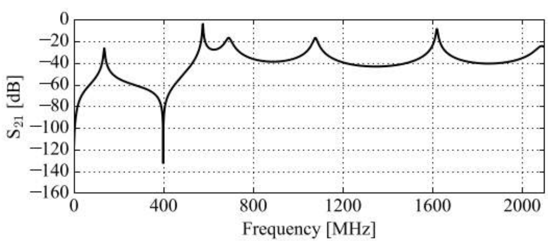
CST MWS

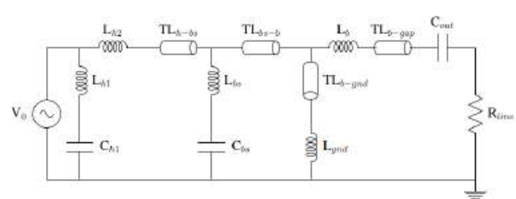




Equivalent circuit response

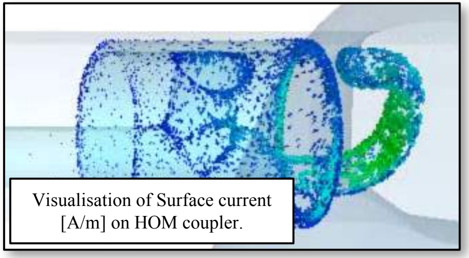
AWR





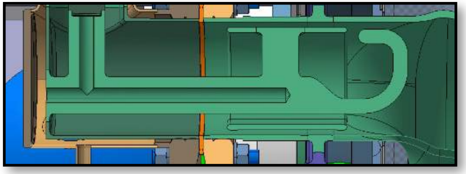
RF-Mech: *Thermal*

- Magnetic field on coupler → Ohmic losses → Heating
- The heating is a function of:
  1. Amplitude of the magnetic field.
  2. Heat transfer coefficient.
- Coupler is internally cooled by 2 K SUPERFLUID Helium.
  - Frictionless flow of liquid through channel.
  - Heat energy deposited in helium bath.
  - Note(!): **1 W/cm²** limit.



Visualisation of Surface current [A/m] on HOM coupler.

Both of these are a function of to material properties and temperature.



Hook is the most at risk from heating!

- Highest H-field
- Large distance from cooling channel.

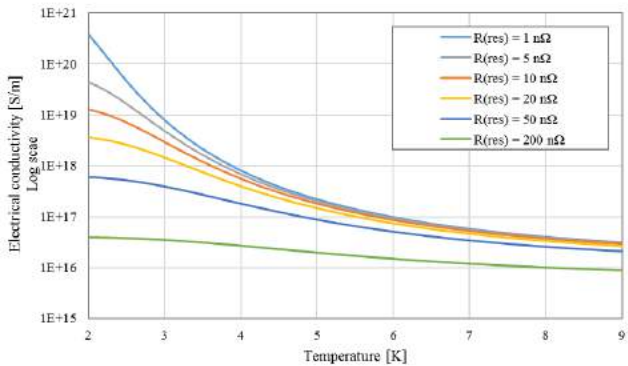
RF-Mech: *Thermal*

Electrical Conductivity

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

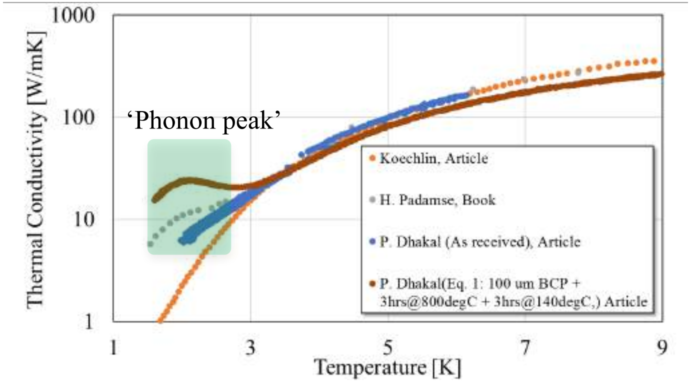
$$R = R_{BCS} + R_{residual}$$

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



Thermal Conductivity

- Varies with literature.
- Phonon peak varies dramatically with chemical processing [T1].
- I use a pessimistic approach (orange curve).



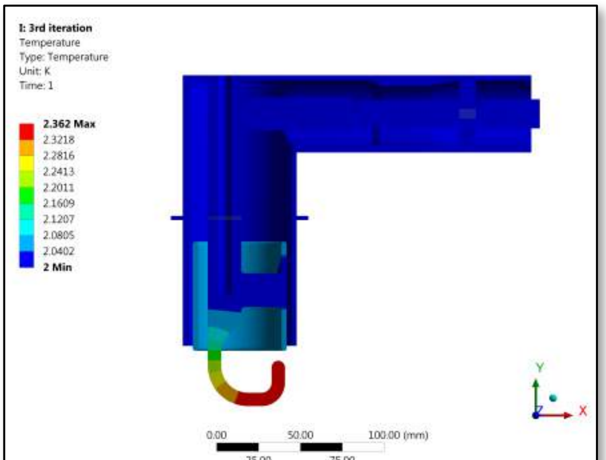
[T1] P. Dhakal, Superconducting DC and RF properties of Ingot Niobium. Thomas Jefferson National Accelerator Facility, CA 23606, US.

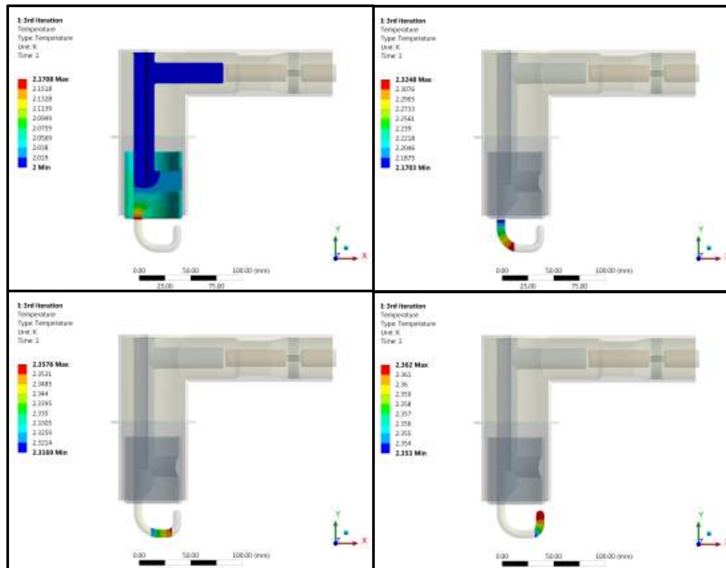
RF-Mech: Thermal

Iterative Simulation Technique:

1. Simulate electromagnetic fields in cavity structure for given **temperature and residual resistance** (CST) and scale to $\mathbf{V_T = 3.4}$ **MV**.
2. Simulate heating using thermal conductivity at that temperature.
3. Iterate until temperature convergence.

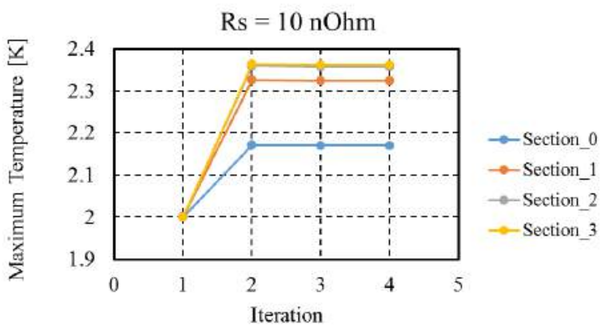
Note: We split into sections and pessimistically take the maximum temperature.

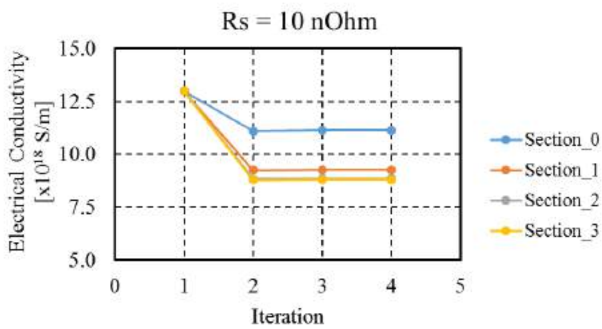




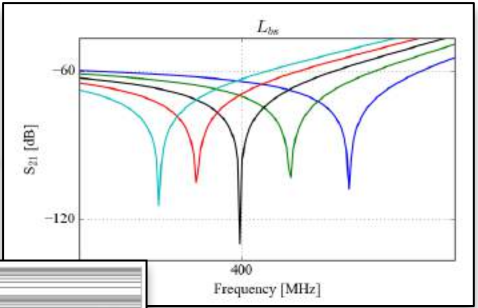
RF-Mech: *Thermal*

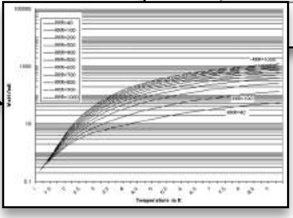
- **Results for Rs = 10 nOhm, K = 57.3 W/K/m**





- Converged temperature < 2.4 K
- Tc of Niobium ~ 9 K
- Other things to study
  - Effect of heat transfer coefficient (K)
  - HOMC Notch detuning – higher field
  - RRR of material – change in thermal conductivity

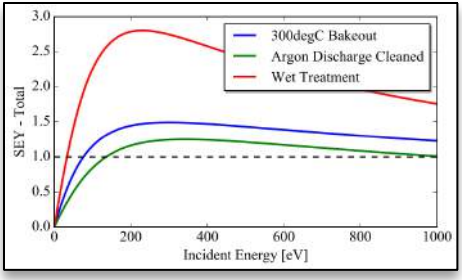




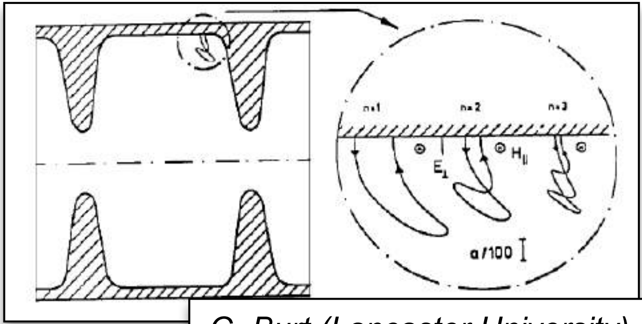
RF-Mech: Multipacting

Resonant electron instability

1. Electron strikes surface (with certain energy).
2. Generates (on-average) more than one secondary particle.

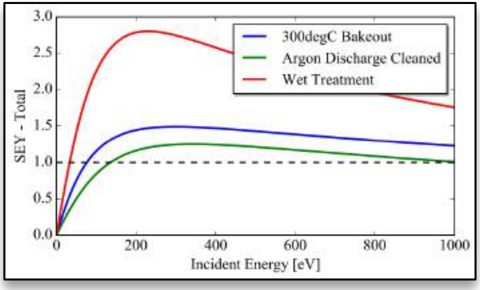


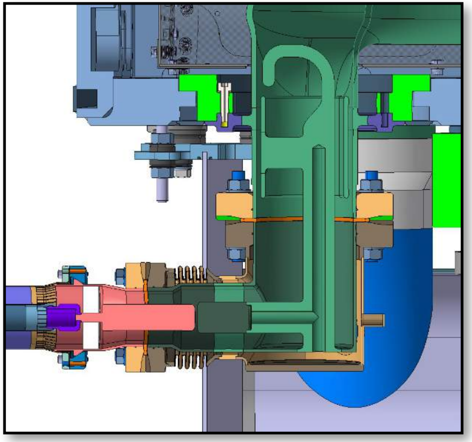
- If secondary returns with same RF phase and energy – avalanche effect – exponential electron growth.
- The electrons are a well for RF power – limiting the cavity from increasing in voltage.



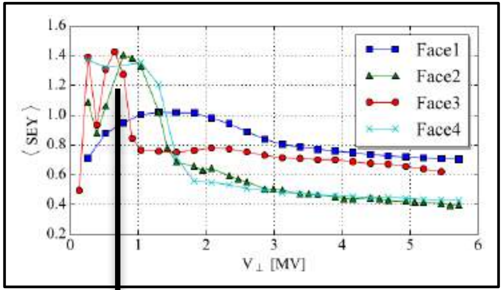
G. Burt (Lancaster University)

RF-Mech: Multipacting (…double point)

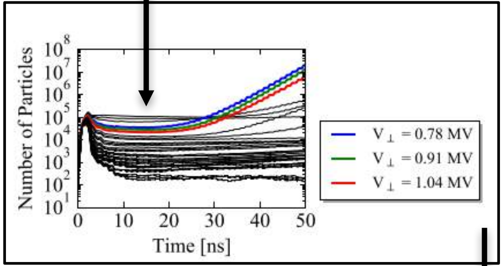




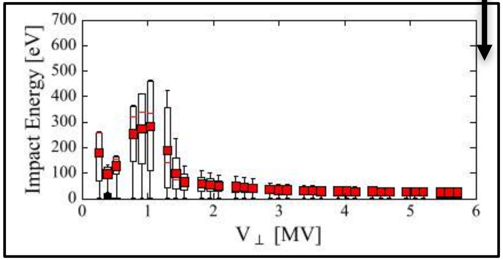
Average secondary electron yield
Highlights voltages at which multipacting could occur.



No. of particles Vs time
Shows avalanche effect over time.



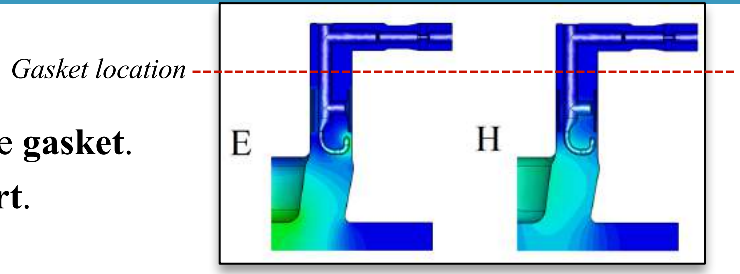
Impact energy at different field levels
Highlights incident energies with field level.



Note, the results are for a modified coupler, but present multipacting sims. conceptually.

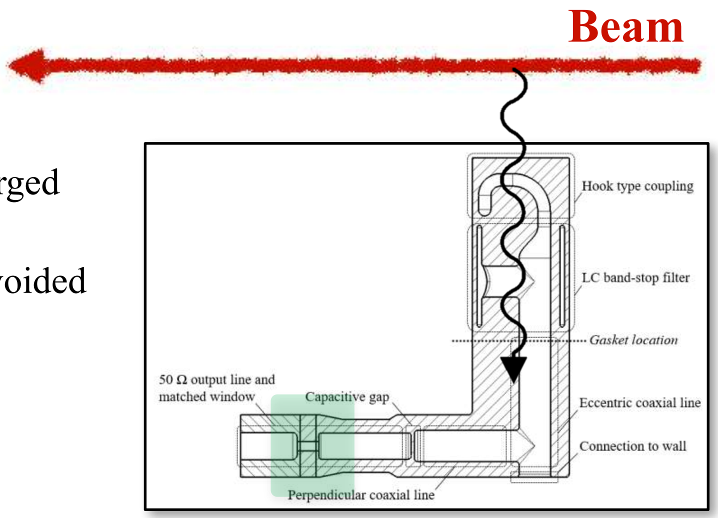
RF-Mech: Mech. Advantages

1. Gasket heating
   - The **LC band-stop** is <u>before</u> the **gasket**.
   - This acts like an **electrical short**.



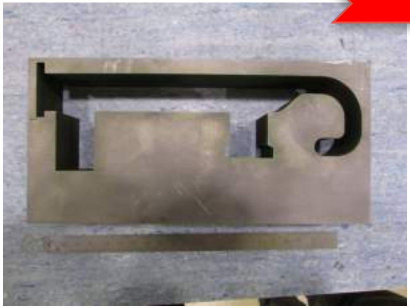
   - Very little dynamic heat load on the copper gasket (~ mW)!
   - CRYOMODULE HAS DYNAMIC HEAT LOAD LIMIT (~ 20 W).

2. Window location
   - Window is perpendicular to charged particles ejected from beam.
   - Screening current on window avoided
   - WINDOW BREAKS → CRYOMODULE DOWN!

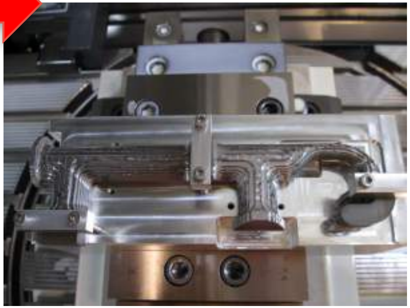


Evolution: Mech. Difficulties #1

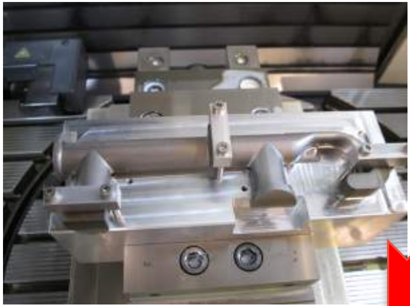
Machining

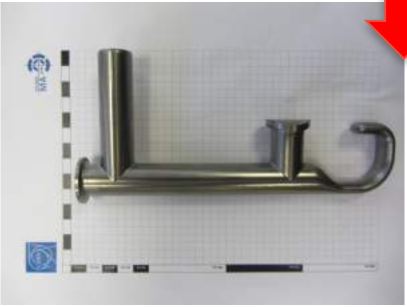


Wire cut from bulk Nb.



Machined from flat to round cross section.



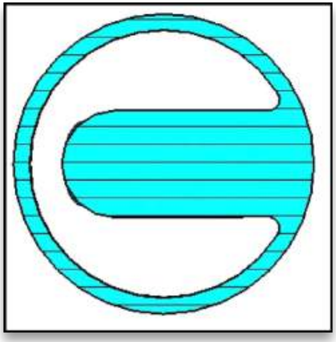


- Machining time is very expensive.
- Circular cross-sections are the bottle-neck.
- For 6*4+spares this represents a significant cost.

Solution: rectangular profile.

Welding of Capacitive Jacket





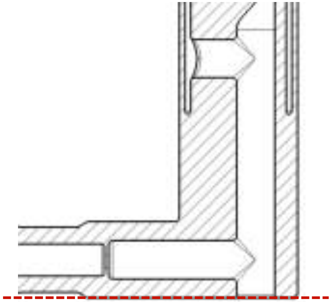
- Difficult to weld on curved surface.
- Could result in alignment issues and notch detuning.

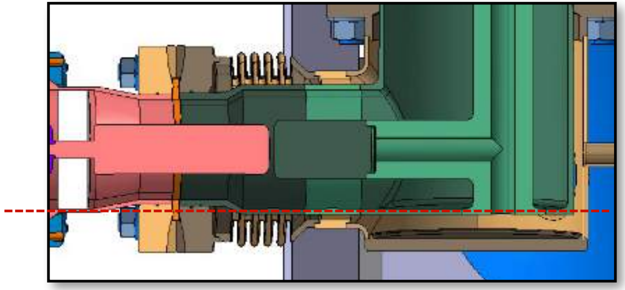
Solution: Weld on flat surface.

Evolution: Mech. Difficulties #3

Manufacture of Outer Conductor

- Perpendicular coax line is ‘flush’ with coupler base.





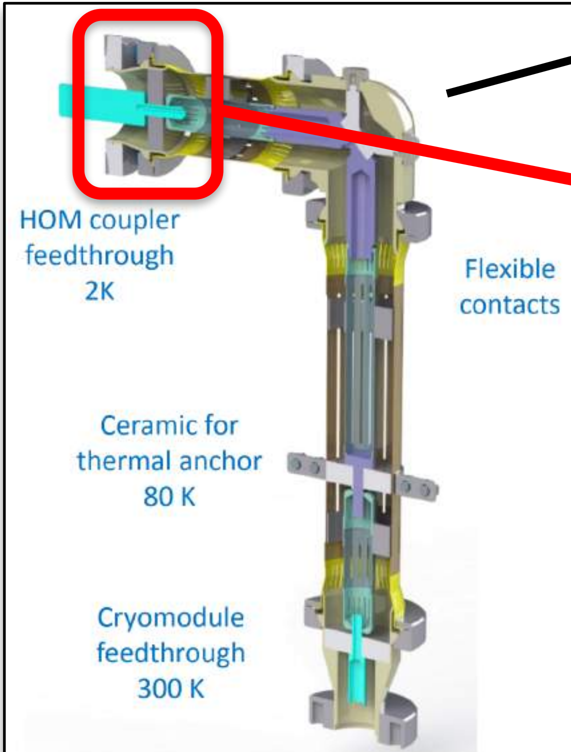
- Hence → Machined from bulk which is very expensive with large ‘wastage’.

Solution: Raise output line from base.

Evolution - Feedthroughs

Content from E. Montesinos (CERN)

HOMC power lines



Rated to:
16 kW pulsed 1ms – 1Hz
4 kW CW during 8 hours

- Vertical test – feedthroughs leaked!

… in parallel

LEP type feedthrough and field antenna feedthrough have been assemble onto a vacuum leak detection system
After five cycles 60 seconds in cold nitrogen(-190 C) + 60 seconds in hot water (+ 80 C), both designs were qualified

Evolution - Feedthroughs

Content from E. Montesinos (CERN)

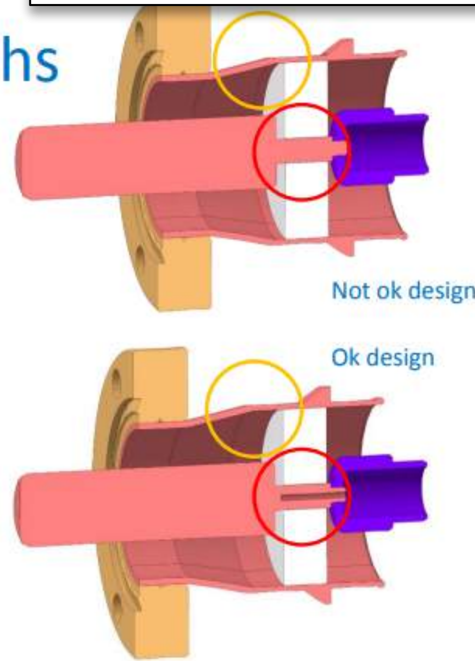
HOM coupler feedthroughs

Points of failure of the feedthroughs that we identified

Inner line must be a tube

Outer line impedance step must be farer from the ceramic

New feedthroughs will be built and validated with stressing cold/hot cycles

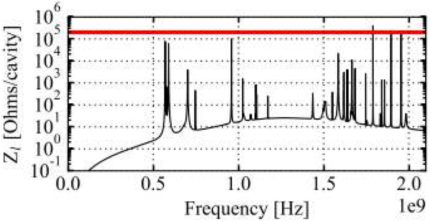


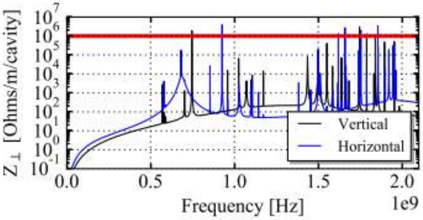
Now only 200 W capability
- Fine for SPS test
- Need to be modified for HL-LHC

Evolution: RF Issues

IMPEDANCE

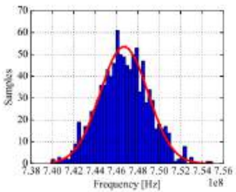
- Some modes are above the impedance threshold.



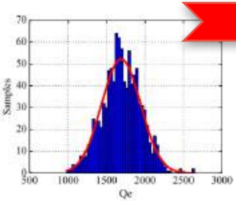


POWER

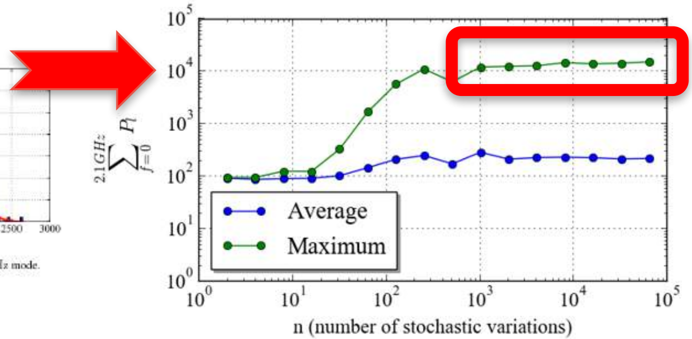
- I measured the deviation in frequency and Qe for the manufactured cavities.
- Applying the variation observed stochastically… worst case HOM power for HL-LHC…



(a) Frequency samples for the 747 MHz mode.



(b) Q_e samples for the 747 MHz mode.



Worst case power 10 x max threshold!

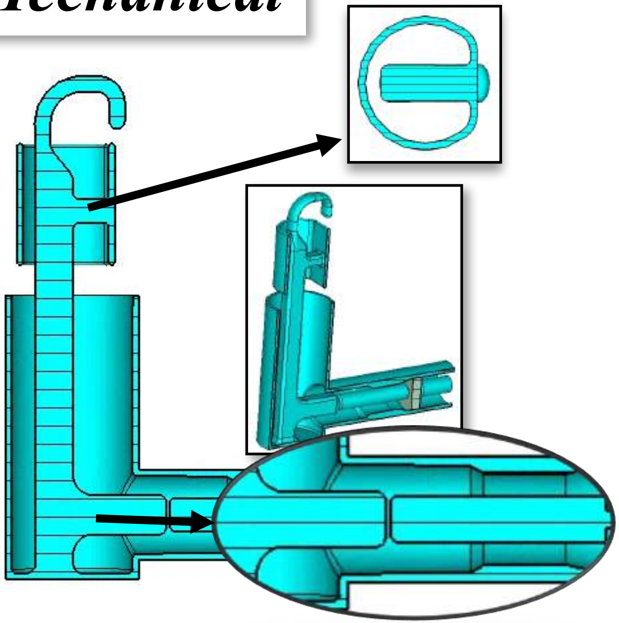
Result of mode at 960 MHz

DQW HOMC: Design Goal

1. Incorporate solutions to manufacturing issues
2. Reduce all modes to below impedance thresholds.
3. Reduce impedance of 960 MHz mode to < 1e4 Ohms/cavity

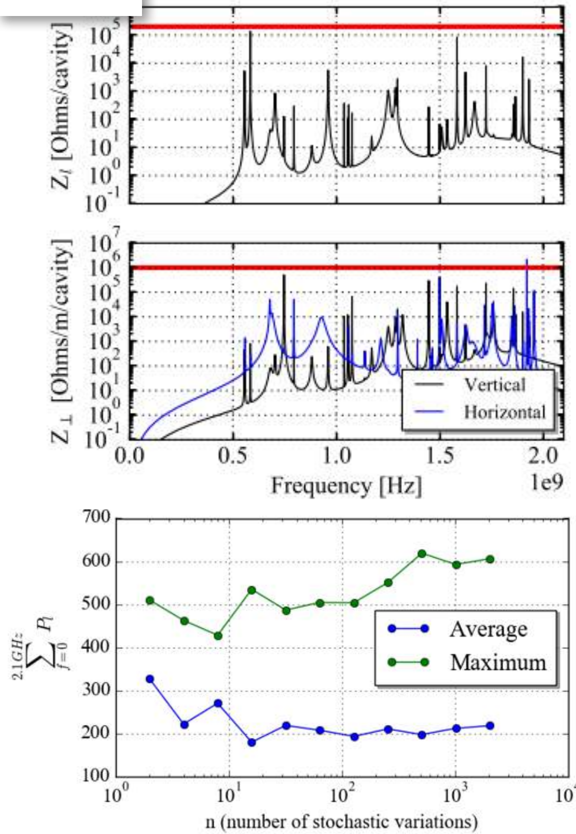
DQW HOMC: Solution

Mechanical



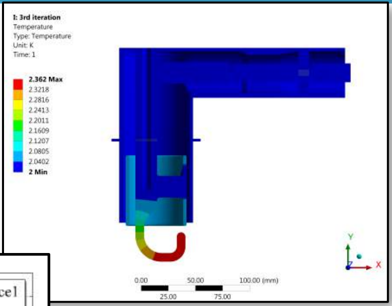
1. Flat section on capacitive jacket.
2. Square profile throughout.
3. Lifted output line for extruded 'can'.

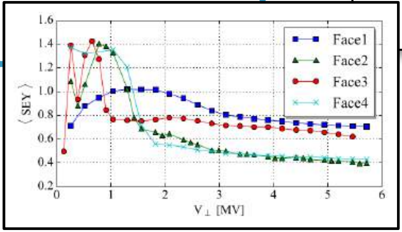
RF



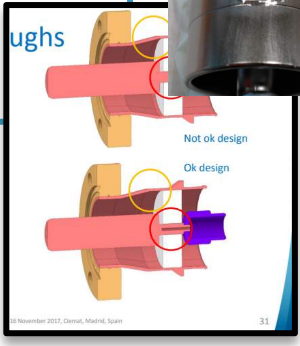
Conclusion

- RF design stage should incorporate mechanical engineering ideals.
    - Thermal, multipacting, operational advantages.





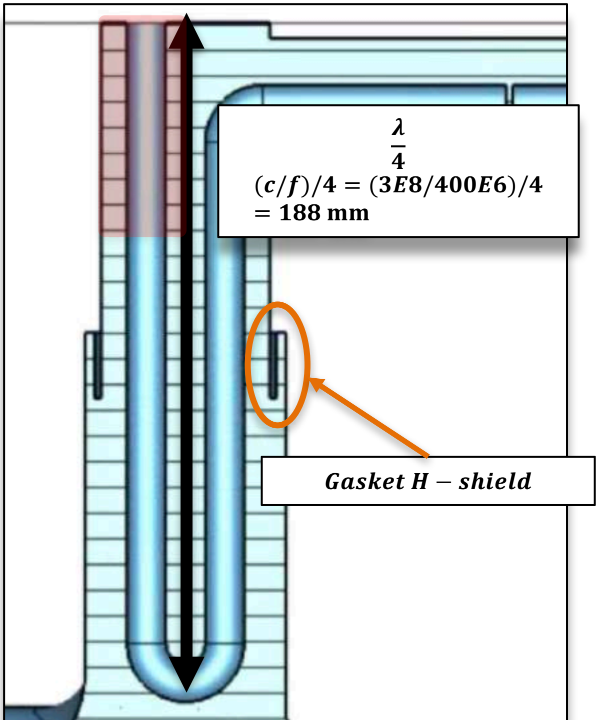
- SPS tests have given many lessons which will improve development of LHC infrastructure.

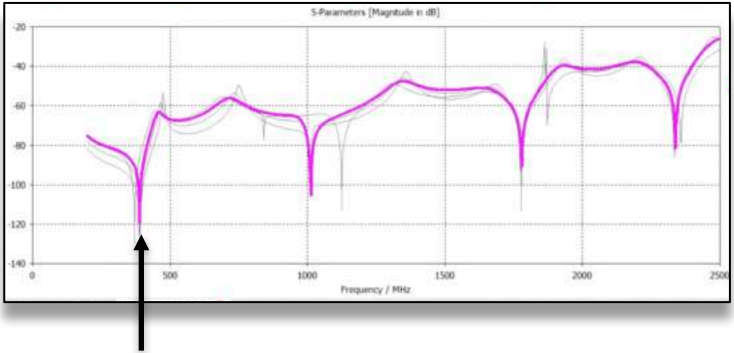


Thanks for Listening!

Back-Up Slides

DQW HOMC: Alternative



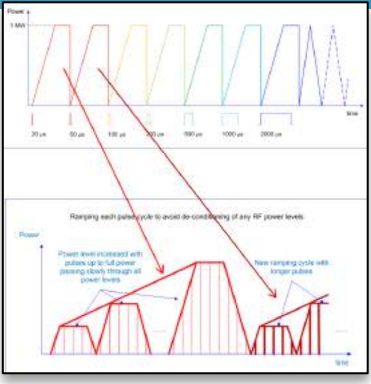


- **Quarter wave rejection filter – centered at fundamental mode.**
- **Harmonics reject also.**

- Advantages
- Loop type coupling – magnetic coupling to HOMs – good broad-band damping.
- High H-Field on cooled section – no ΔT to He.
- Very easy to manufacture - mass produce.

- Disadvantages
- Gasket heat-load – 1000 x higher than LC stopband.
- Harmonics can be moved slightly but will always be present.

Future Ideas – HOMC Conditioning



FPC's are conditioned before installation:

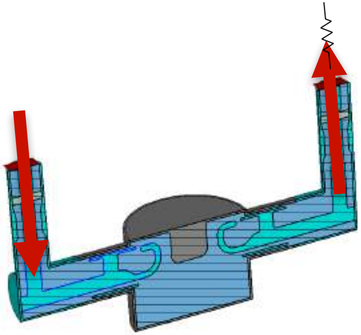
- Acceptance test, desorption of absorbed gasses, ensuring required power level (without RF breakdown), training ceramic…

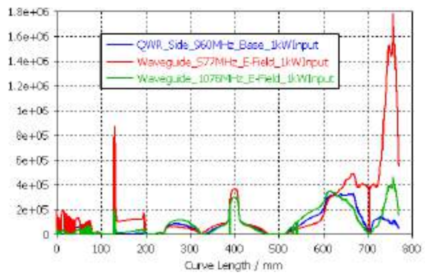
Technique

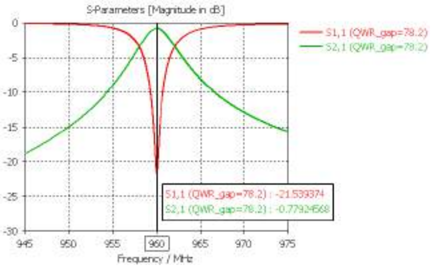
- Power, pulse length, duty cycle: Low → High (with FM and AM)
- Using 'test-box' in travelling wave mode.

HOM couplers are becoming higher and higher in power

- **Do not see high power at high frequency until beam!**







RF-Mech: Test Boxes