DQW HOM Coupler for LHC

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Engineering | Lancaster University

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Outline

The LHC

- Large Hadron Collider (LHC) is the largest particle accelerator in the world at 27 km in circumference.
- The maximum luminosity of the LHC is 2×10^{34} $cm^{-2}s^{-1}$.
- Where luminosity is the rate of particle-particle collisions and hence represents the discovery potential of the LHC.

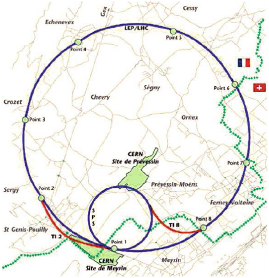


Figure 1: Map showing the location and size of the Large Hadron Collider (LHC)

[Figure extracted from "The Large Hadron Collider: Unravelling the Mysteries of the Universe", Martin Beech, 2010.]

The HiLumi Upgrade

- With upgrades to increase the machines luminosity, the crossing angle of the colliding charged particle bunches decreases.
- The figure below shows the ideal collision from a linear interaction of bunches followed by the same collision with an induced crossing angle.

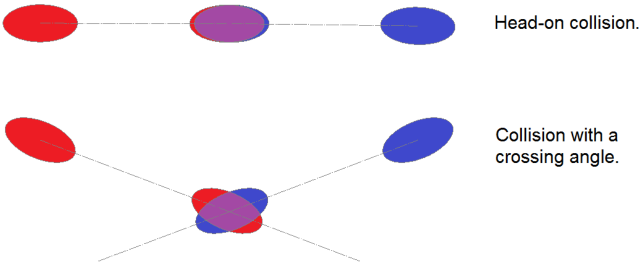


Figure 2: Ideal head-on collision and collision with an induced crossing angle for two charged particle bunches.

Crab Cavities - Correcting the Crossing Angle

- In order to correct for the induced crossing angle, the bunches need to be rotated to generate an effective head-on collision.
- **Crab Cavities** use an electromagnetic deflecting mode to rotate the bunches - this is known as the crabbing regime.

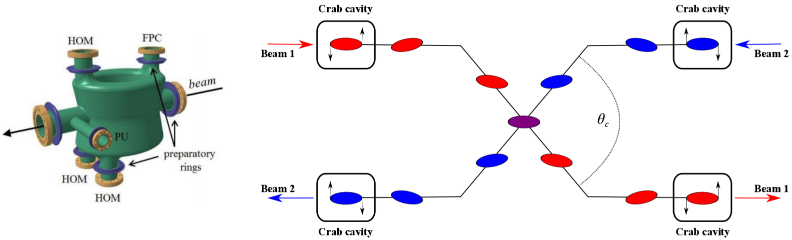


Figure 3: Double Quarter Wave (DQW) crab cavity and how its bunch rotation effects the collision regime.

The Double Quarter Wave (DQW) Crab Cavity

- DQW: crab cavity proposed for the HiLumi upgrade - will be tested in the Super Proton Synchrotron (SPS) in 2018.
- Niobium (Nb): Superconducting (low resistive losses) at 2 K.
- Sinusoidal transverse kick to the charged particle bunch. Zero phased with bunch - hence **rotation**.

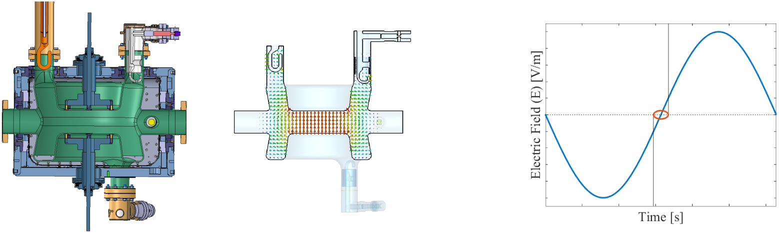
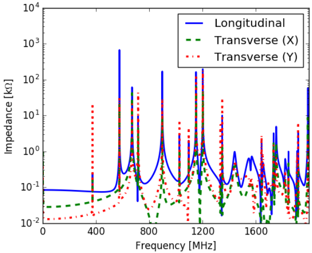


Figure 4: CAD and EM model of DQW crab cavity (left) and schematic showing the rotational effect of the sinusoidal transverse kick (right).

Higher Order Modes (HOMs)

- Crabbing regime uses dipole mode at $\sim$ 400 MHz.
- Other electromagnetic field configurations can resonate at discrete frequencies (modes) up to the beam-pipe cut-off frequency of 2 GHz.
- High impedance modes can, if excited by an external source, perturb cavity operation from that of the crabbing regime.



Wakefield Simulation Parameters	
Mesh cells (tetrahedrons)	7.57E+06
Wake length [km]	1
Longitudinal direction	z
Crabbing direction	y

Figure 5: Cavity impedance from wakefield simulation. Amplitude is not valid for such a high-Q cavity but frequencies of high impedance modes are correct. Some very high-Q modes may not be apparent if convergence has not been met.

HOM Couplers

- HOM Couplers act as a stop-band circuit at the fundamental frequency and a transmission path at the HOM frequencies.
- For the current version of the DQW (SPS version) there are three superconducting, on-cell HOM couplers.

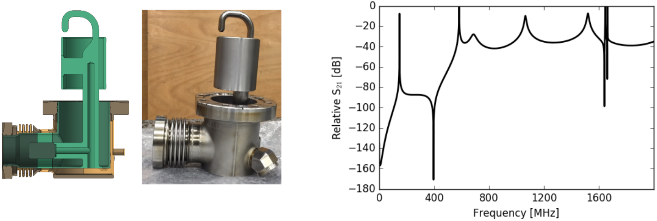
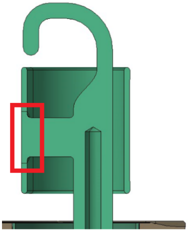


Figure 6: CAD HOM coupler cross-section (left), photograph of manufactured coupler (middle) and transmission characteristics (right).

HOM Coupler Re-design - Motivation

- Several manufacturing issues with the HOM coupler - main problem with the Electron Beam (EB) welding of the cylindrical jacket.
- RF performance should be improved to further damp the HOMs - especially the mode at 928 MHz.
- **RF engineer** with an understanding of **manufacturing processes**!



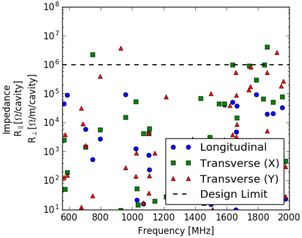
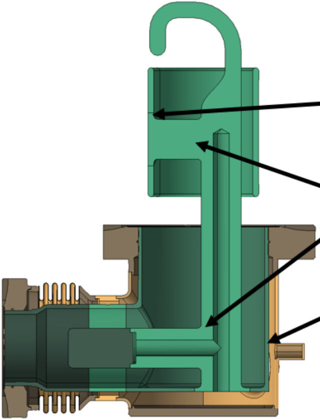


Figure 7: Image of one manufacturing problem for the SPS DQW HOM couplers (left) and impedance spectrum for the dressed SPS DQW crab cavity (right).

HOM Coupler Re-design - Manufacturing Problems



1. Weld between inductive stub and capacitive jacket is difficult due to curvature and thickness.
2. Circular cross-sections are more difficult to machine than rectangular.
3. Niobium 'shell' is made from one full piece of Niobium. This is costly.

HOM Coupler Re-design - Geometric Changes

- Several geometric changes were applied and their effect on the RF characteristics of the HOM couplers were quantified.

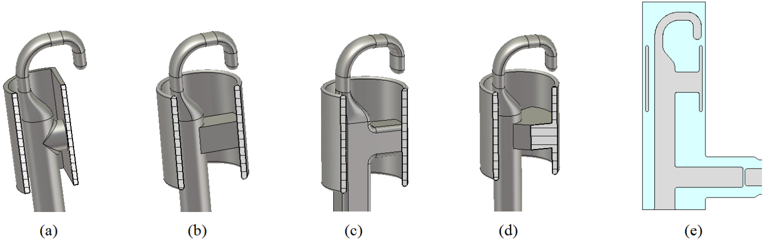


Figure 8: A selection of the geometric changes applied to the SPS DQW HOM Coupler to improve ease of manufacture.

HOM Coupler Re-design - New Design

- The chosen changes were then incorporated.
- Several parameters were then altered and the effect on various aspects of the coupler's transmission were tracked.
- Analysis in MatLAB and PYTHON logged the effect of the parameters on RF operation, quantifying these as **weighting factors**.

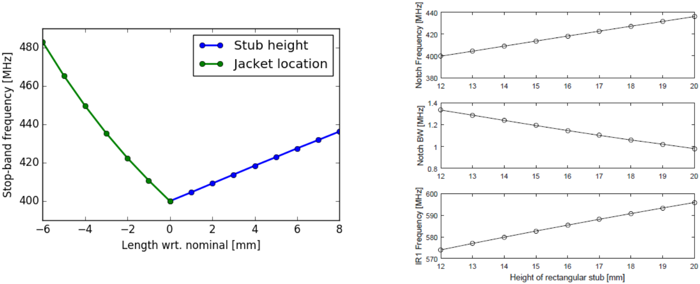


Figure 9: Examples of the monitoring of transmission parameters with geometric alterations of the HOM coupler.

HOM Coupler Re-design - Optimisation

- Optimisation theory used to tailor the HOM coupler's transmission response to the cavity's impedance spectrum.
- Simulated coupler on cavity and this process was iterated until...
- All modes were below 1 MΩ ('/cavity' for longitudinal and '/m/cavity' for transverse impedances) apart from one at $\sim$ 1920 MHz.

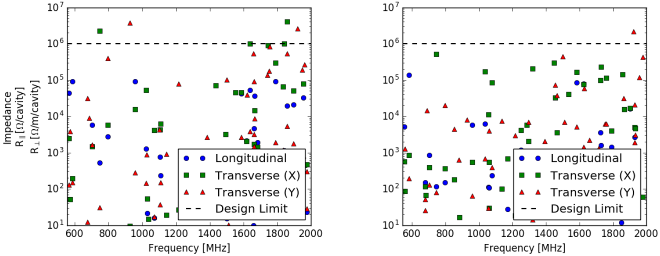
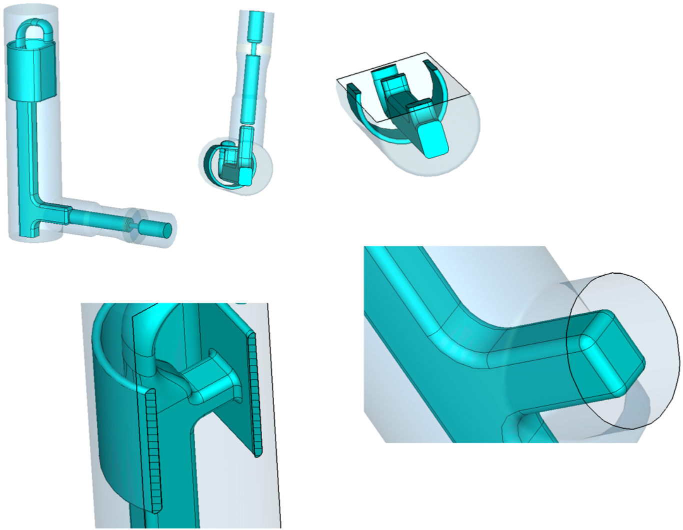


Figure 10: SPS DQW impedance spectrum with current HOM couplers (left) and re-designed HOM couplers (right).

HOM Coupler Re-design - Proposed HOM Coupler for HL-LHC



HOM Coupler Re-design - Proposed HOM Coupler for HL-LHC

Conclusions:

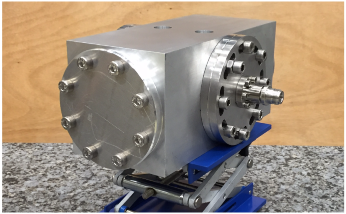
- Accepted by CERN's mechanical engineers as first step towards new design.
- Improved RF design with all modes but one high frequency mode below 1 MΩ.

Further work:

- Multipacting simulations - Started.
- Thermal analysis and improvements - Started.
- Benchmarking in second EM software.
- Copper coated rapid prototype.
- Copper and Niobium prototypes.

Test boxes for DQW HOM Couplers

- Novel methods of pre-installation spectral analysis of HOM couplers.
- Two devices designed in CST MWS.
- Both test-boxes built - assembly issue with one test-box.



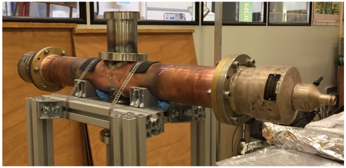


Figure 11: L-bend transmission (left) and coaxial chamber (right) test boxes for LHC HOM couplers.

Test boxes for DQW HOM Couplers - L-bend Transmission Measurements

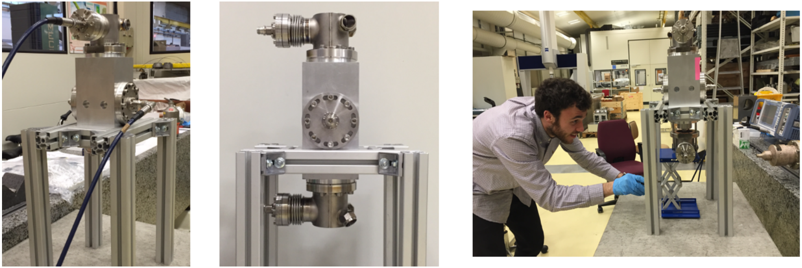


Figure 12: Assembly of SPS DQW HOM couplers on L-bend transmission test-box.

Test boxes for DQW HOM Couplers - L-bend Transmission Measurements

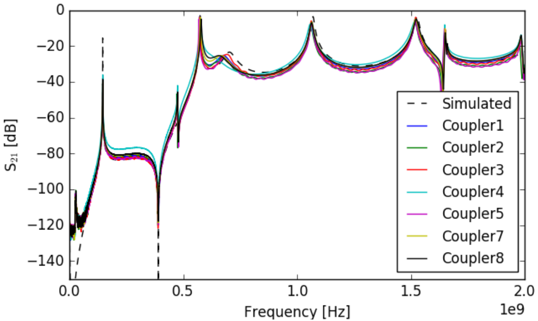


Figure 13: Full spectral measurements of the HOM couplers. Broadband calibration not applied for the first three couplers measured (Couplers 7, 8 and 2).

Test boxes for DQW HOM Couplers - L-bend Transmission Measurements

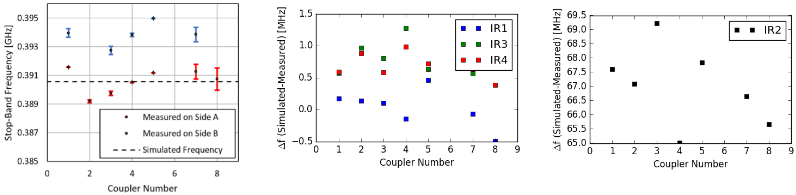


Figure 14: Change in frequency of the the notch and peak transmission areas of the HOM couplers.

- Measured and validated that one coupler has an abnormal broad-band spectral response.
- Quantified deviation of stop-band frequencies and transmission points.
- Can this data be used to predict the Qext deviation in the cavity ... ?

On-Cavity Measurements

- Thus far, two tests of the DQW with one or more HOM couplers.
- One at JLAB (VA, USA) and one at CERN (Geneva, Switzerland).
- In both cases detailed measurements carried out and damping efficiency compared to simulations For all HOMs.

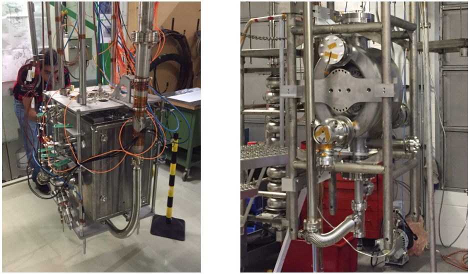


Figure 15: Partially dressed cavity tests at CERN (left) and single HOM coupler test at JLAB (right).

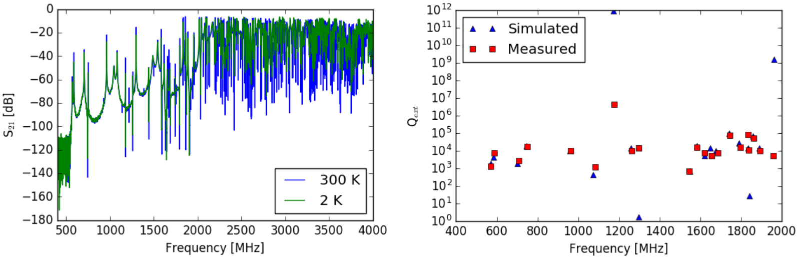


Figure 16: Spectral measurements (left - taken in 500 MHz bands and stitched) and comparison of simulated and measured Q_{ext} (right) for tests of single HOM coupler on NWV-DQW-001 at JLAB.

Measurement Examples - CERN

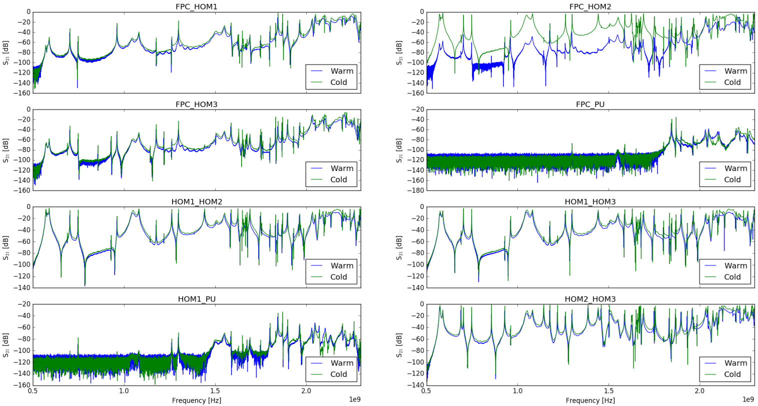


Figure 17: Spectral measurements of the CERN-DQW-001 partially dressed crab cavity.

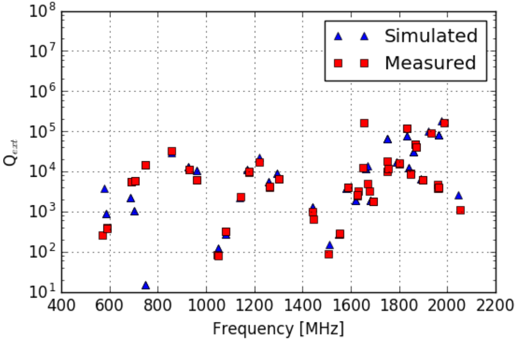
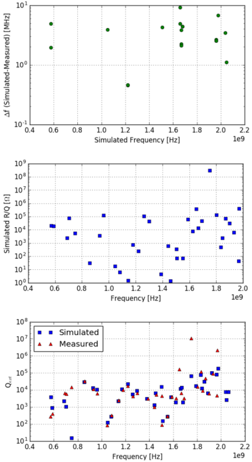
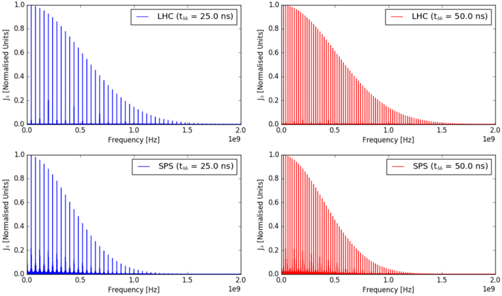


Figure 18: Comparison of simulated and measured Q_{ext} for the CERN-DQW-001 partially dressed crab cavity.

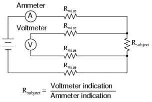
Future Work: Continuing from the Data Presented

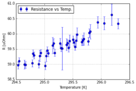
- Can we predict damping differences from the test-box data?
- Calculating the new HOM power down the couplers from frequency and Qext deviations measured.

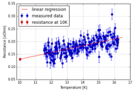




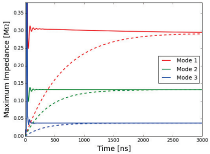
Other Work



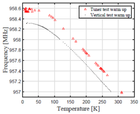


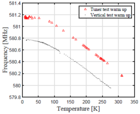


Cavity Bulk RRR Measurements

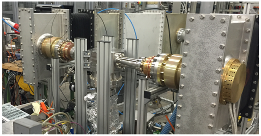


Impedence Extrapolation
- Wakefield Simulations

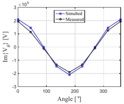




HOM Monitoring for
Material Performance



FPC Conditioning



Cavity Multipole Measurements

Conclusion

- SPS HOM coupler analysed in terms of designed RF performance and ease of manufacture.
- Several design changes applied to the HOM coupler to ease manufacture - effect on RF performance measured.
- Implemented chosen design changes,quantified parametric weighting on RF performance and optimised HOM coupler.
- Measurements from test-box and cold tests bring about potential problems, for which a new coupler can take account of.
- Other work showing the input of Lancaster University in CERN's HiLumi WP4.

Questions?

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Further reading available at www.jamesmitchellweb.com.

Research

Conference Paper	Conference	
ProTec - A Normal-Conducting Cyclinac for Proton Therapy Research and Radioisotope Production	IPAC'15	Download
VELA Photoinjector cavity RF investigations	IPAC'16	Download
LHC Crab Cavity Coupler Test Boxes	IPAC'16	Download
First RF Performance Results for the RF Crab Cavities to be Tested in the CERN SPS	IPAC'17	Download
Method to Calculate the Longitudinal Impedance from a Partial Wakefield Simulation	IPAC'17	Download

Journal Paper	Journal	
AWAKE, The Advanced Proton Driven Plasma Wakefield Experiment at CERN	Nuclear Instruments and Methods in Physics Research Section A	Download
A Path to AWAKE: Evolution of the concept	Nuclear Instruments and Methods in Physics Research Section A	Download