DQW HOM Coupler for LHC

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   - HOM Coupler Re-Design

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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 $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.
- 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.](image-url)
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.

![Crab Cavities Diagram](image)

**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).

**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](image)

**Wakefield Simulation Parameters**

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Mesh cells (tetrahedrons)</td>
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<tr>
<td>Wake length [km]</td>
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<tr>
<td>Longitudinal direction</td>
<td>$z$</td>
</tr>
<tr>
<td>Crabbing direction</td>
<td>$y$</td>
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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).

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

**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
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.
Figure 12: Assembly of SPS DQW HOM couplers on L-bend transmission test-box.
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 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 $Q_{ext}$ 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.
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?


Research

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<td>LHC Crab Cavity Coupler Test Boxes</td>
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<td>Method to Calculate the Longitudinal Impedance from a Partial Wakefield Simulation</td>
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