HOM Damping and SPS Measurements

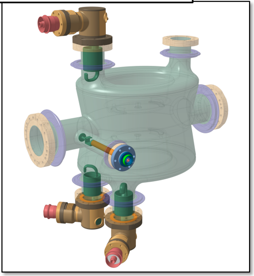
J. Mitchell
with significant contribution from
BNL, CERN, Lancaster University, FermiLab, JLAB and SLAC (Z. Li).

CERN, BE-RF-PM

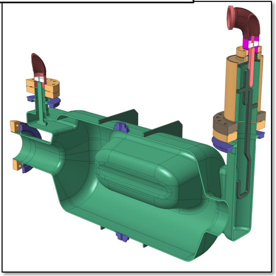
20/06/2019
International Review of the Crab Cavity system design and production plan for the HL-LHC

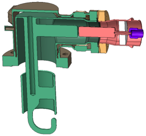
Crab cavity HOM damping: 2018 (1st QTR)

Double Quarter Wave (DQW)



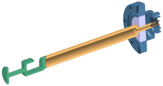
Radio Frequency Dipole (RFD)





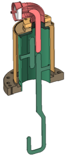
3 x HOMC

- Damp HOMs



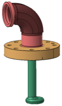
1 x Hybrid field antenna

- 1 W: f = f_0, $V_\perp$ = 3.34 MV
- Damp several high frequency HOMs (1.75 GHz horizontal mode)



1 x H-HOMC

- Damp horizontal HOMs



1 x V-HOMC

- Damp vertical HOMs

Changes due to HOMs

- Impedance thresholds: $Z_{\parallel}$ and $Z_{\perp(x,y)}$ as $200\,\mathrm{k\Omega}$ and $1\,\mathrm{M\Omega/m}$.
- Each cavity had several modes over the threshold.
- Each cavity had one **high power HOM**.

Cavity	Mode frequency [MHz]	Nearest bunch spacing harmonic [MHz]	$Z_{\parallel}$ [kΩ]	P[1 2] [kW]
DQW	958.87	961.92 (24^{th})	100	**10**
RFD	760.94	761.52 (19^{th})	29	**9**

- Methods of reducing high power:
  - HOM impedance (Q-factor) should be decreased.
  - Detune mode frequency.

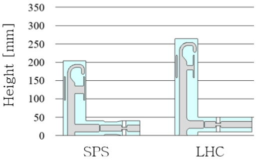
[1] Threshold is 1 kW.

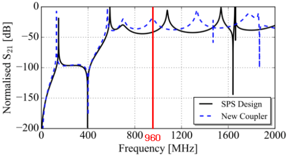
[2] Power calculated at the frequency of the bunch spacing harmonic only and assuming that the mode fully aligns with this frequency.

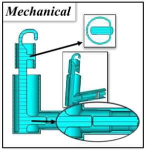
Changes due to HOMs

DQW

- Altered HOM coupler's equivalent circuit.
- Square profile, flat section on capacitive jacket and lifted output line.

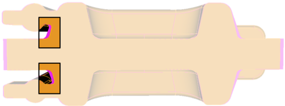






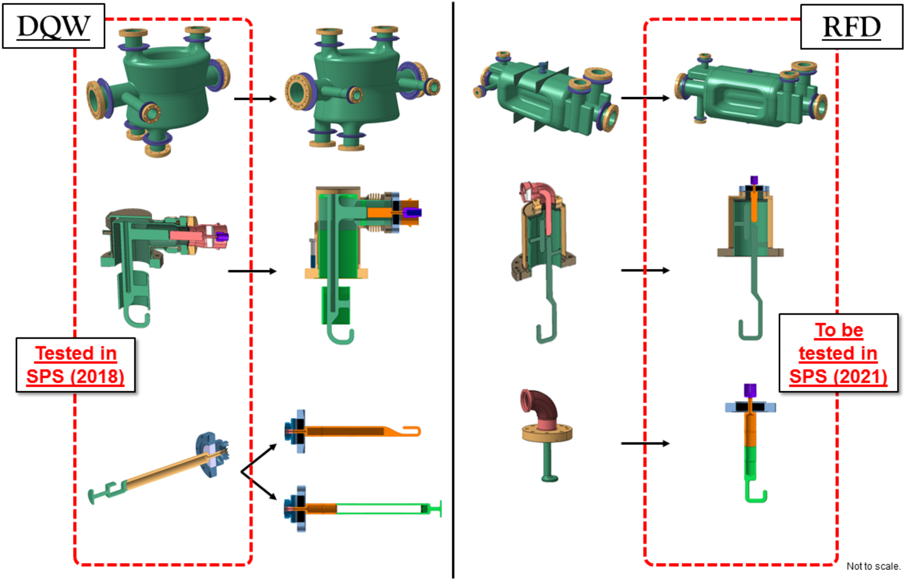
RFD

- Detune high power HOM and alter ancillaries.

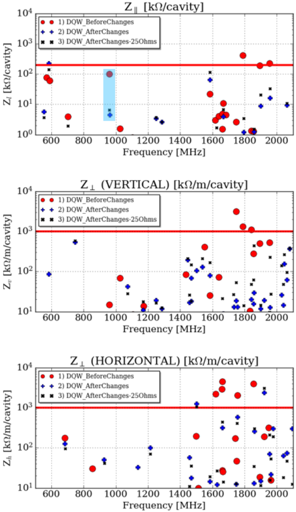


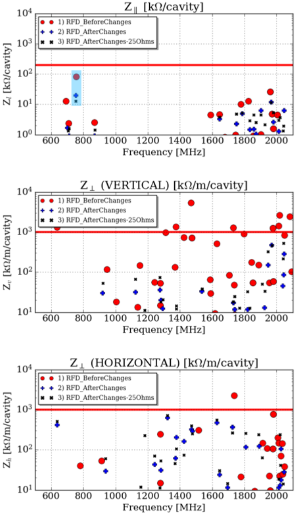
- -9 MHz detuning of mode using cavity geometry.
- H-HOMC: larger waveguide stub, rotation, hook changes.
- V-HOMC: 'electric' to 'electric and magnetic coupling'.

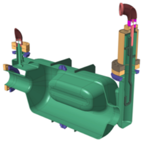
Changes due to HOMs



HOM Impedances

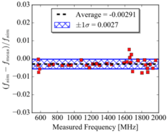




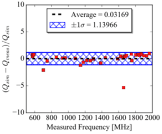


- $25\,\Omega$ matching verified ✓

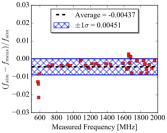
- Measured mode parameter deviation from simulations.



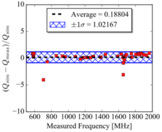
(a) Cavity 1 - Frequency.



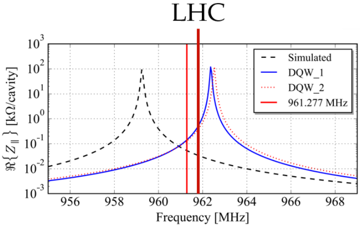
(b) Cavity 1 - Q_L.



(c) Cavity 2 - Frequency.



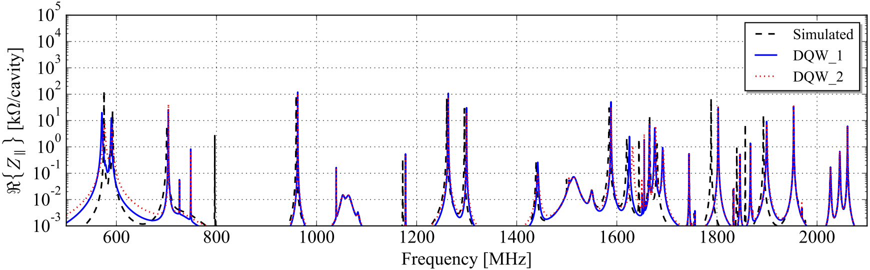
(d) Cavity 2 - Q_L.



- f-range: -0.9% → +1.0%, Q-range: -50% → +100%
- 959 MHz mode
  - Frequency: + 3.31 MHz and + 3.47 MHz
  - Q-factors: - 15% and - 30%
- **Mode could align with 24th bunch spacing harmonic: confirms further damping needed.**

SPS Measurements: Pre-Installation

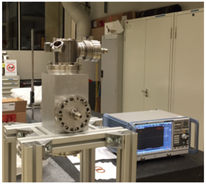
- Measured frequencies and Q-factors used to modify simulated impedance table and produce 'measured' impedance spectra.

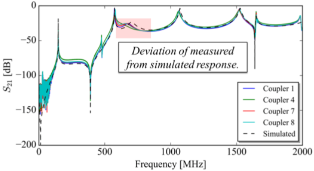


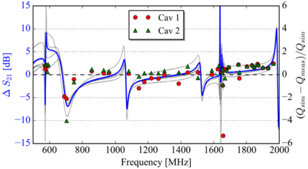
- Intra-cavity mode spread analysed.

Coupler Measurements: Predicting damping

- Individual coupler measurements on ‘test-boxes’ pre-assembly to compare transfer function to simulations.







- Areas of decreased damping identified: correlate with Q-factor deviations.
- Coupler-port location unknown.
- In the future
  - Record coupler mounting location.
  - Acceptance criterion.
  - Coupler installation location choice.

SPS test: HOM measurements

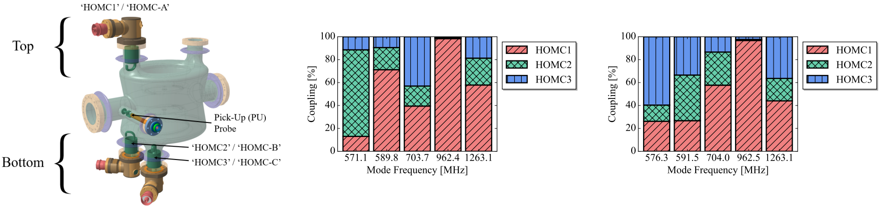
Measurement goals

- Identify **unforeseen issues** arising from HOMs.
- Quantify **effect of geometric deviations** from manufacture on HOMs.
- Ensure HOM performance with proton beam is **predictable**.

Measurements: HOM Power

- The power from each of the HOM couplers was measured with single and multi-bunch beams.

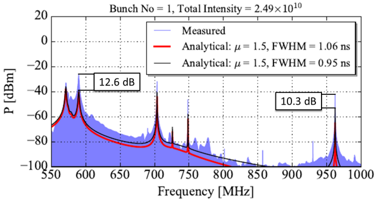
- High longitudinal impedance modes couple differently to each coupler.
- This was measured to quantity the difference from simulation.



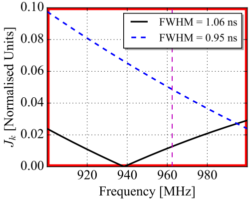
- High power mode (960 MHz) only couples to top HOM coupler.
- → **This means the high power will only be on the top HOM coupler.**

SPS test: Single Bunch

- Single bunch coast (one bunch for many hours).
- Measurements from each coupler compared to analytical calculations (impedance spectra altered with measured frequencies and Q-factors).



(a) Analytical and measured (average from 3 couplers) HOM power for single bunch.

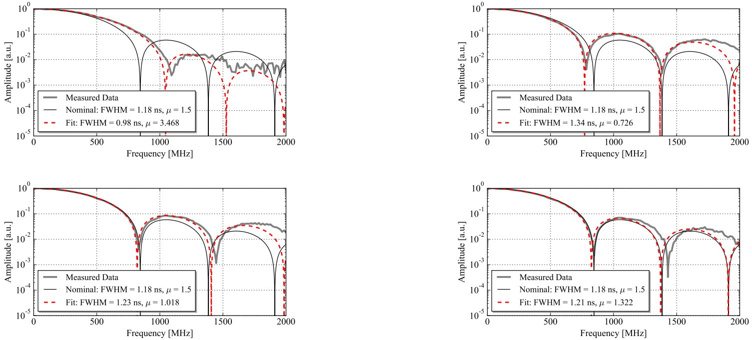


(b) Normalised bunch profile (form of current source).

- General form matches well (HOMs seen where predicted).
- Analytical power under-estimated.
  - **Misrepresentation of proton bunch distribution.**
  - Underestimation of impedance spectra.
  - Error in the measurement signal.

SPS test: Profile measurements

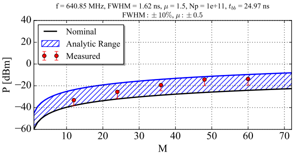
- Bunch represented by binomial formula (dependant on σ and μ).
- 4 bunch coast used to measure profile of proton bunches.

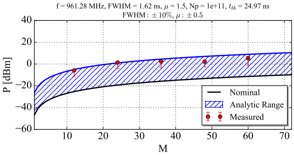


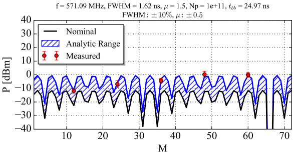
- Bunch length spread $\pm$ 10%, μ error $\pm$ 0.5 from SPS nominal (1.5).
- First bunch is close to Gaussian.
- Also oscillations on bunch profile as a function of time. Frequency of oscillations much faster than sweep time on analyser $\rightarrow$ **very difficult to compare broad-band response.**

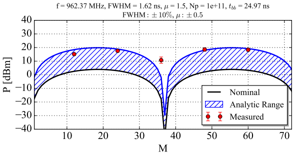
SPS test: Multi-bunch

- Power at different bunch numbers measured.
- Both at the frequencies of the high $Z_{\|}$ modes and multiples of the bunch spacing harmonics (t_{bb}).









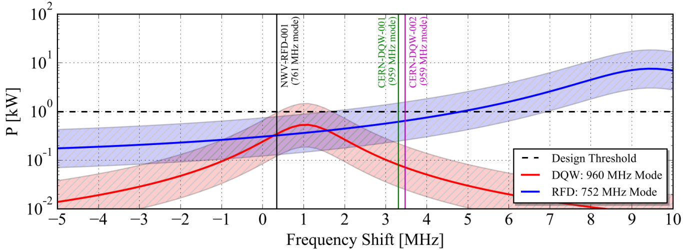
- <u>**Highest power region predictable.**</u>

Overall Conclusions

- Both DQW and RFD crab cavities have changed from last review to **mitigate high power HOMs**.
  - DQW
    - HOM coupler damping improvement.
    - Geometric to ease manufacture.
  - RFD
    - Cavity geometry altered.
- Mode parameter deviation measured and quantified.
  - 960 MHz mode could align with 24^{th} bunch spacing harmonic.
  - Under/over damping predictable from test box measurements.
- DQW HOM measurements in the SPS
  - Coupling ratios: high power more only couples to top HOM coupler.
  - Single bunch broad band measurements
    - Difficult to compare to analytic because of bunch **profile deviations and bunch instabilities**.
    - More information needed on bunch form.
  - Multi-bunch measurements agree with analytic near to the bunch spacing harmonics **and agree for highest powers.**

Moving forward

- Study the effect of bunch profile variations in further detail.



- Re-designed ancillaries for 25 Ω matching for larger inner conductors (see E. Montesinos' talk).
- RFD SPS HOM measurments.
  - Better record the bunch profile during MDs.
  - Combine HOMC signals and have them continually logged to timber or equivalent.

Appendix

LHC Crab Cavities
Impedance and Multipole Update

J. A. Mitchell[1, 2]

[1]Engineering Department
Lancaster University

[2]BE-RF Section
CERN

29/01/2019 - 140th HL-LHC WP2 Meeting

- SPS DQW antenna was dual function: HOM damper and fundamental mode antenna.
- Functions split because damping geometry coupled to beam (perturbing LLRF signal).

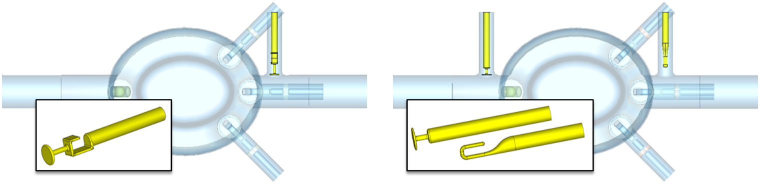
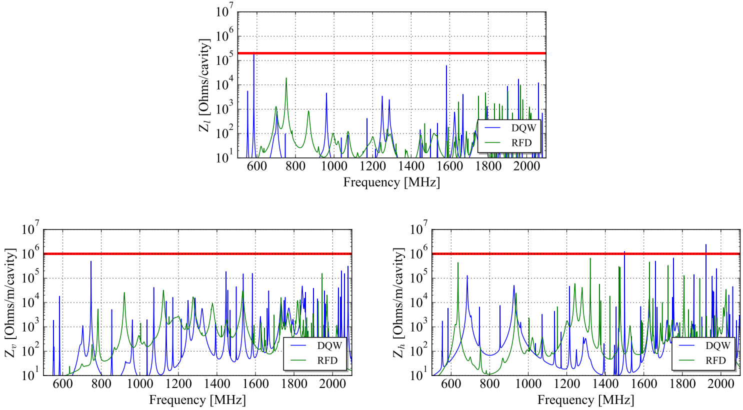


Figure 1: SPS (left) and LHC (right) DQW crab cavities with beampipe ancillaries highlighted.

Crab Cavity Impedance



- DQW model: EDMS No. 2009911 - Alumina ceramics, Nb HF-Damper, Cu Antenna.
- RFD model: EDMS No. 1347072
- RFD was benchmarked with ACE3P results from Z. Li.

Concerning Modes

- Limits: $\perp = 1\,\mathrm{M\Omega/m/cavity}$, $\parallel = 200\,\mathrm{k\Omega/cavity}$.

f [MHz]	Qe	R_v [kΩ/m]	R_h [kΩ/m]	R_l [kΩ]	Notes
583.59	4381	-	-	243.00	Far from bunch spacing harmonic
960.87	507	-	-	4.70	Close to bunch harmonic. Al_2O_3: R_l + 27% Al_2O_3: Frequency + 0.75 MHz
1500.20	23200	-	2009	-	
1754.40	8522	-	751	-	
1921.98	60600	-	2505	-	Not mesh converged.

Table 1: DQW

f [MHz]	Qe	R_v [kΩ/m]	R_h [kΩ/m]	R_l [kΩ]	Notes
752.06	217	-	-	19.4	9.4 MHz from bunch harmonic. Not simulated with HOM coupler ceramics.

Table 2: RFD

19^{th} and 24^{th} bunch spacing harmonics: 761.52 MHz and 961.92 MHz

HOM Power

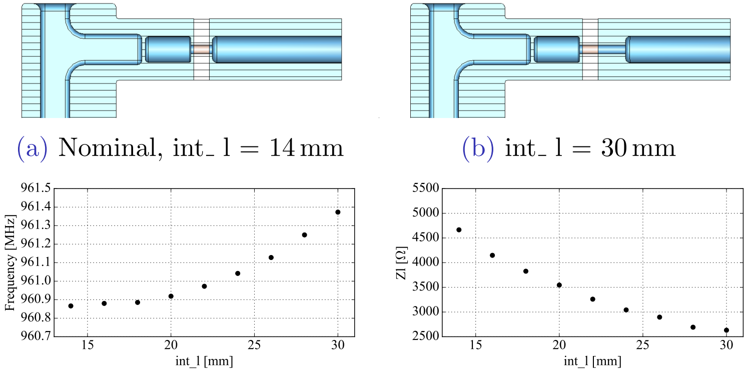
- HL-LHC beam parameters from [1].
- Mode frequency and Q varied: 1000 stochastic variations.
- Limits from SPS DQW measurements.
- Q: factor 0.5→2.0, f: -0.1→0.9%

Cavity	P_{max} (Gaussian) [W]	P_{max} (Binomial) [W]	Mode
DQW	1000	1000	961 MHz
RFD	8500	8200	752 MHz

Table 3: Maximum HOM power values.

Average DQW 960 MHz shifts
f: +0.35%, Q: $0.77\times Q_{sim}$
From measured RFD HOM deviations [Berrutti et. al.]
f: +0.342 MHz, Q: $1.26\times Q_{sim}$

DQW Feedthroughs - Tuning



(a) Nominal, int_ l = 14 mm

(b) int_ l = 30 mm

(c) Frequency

(d) Longitudinal Impedance

Multipole Components

- Last meetings: Questions about b_4 magnitude.
- Re-visited: Issues with CST field export and convergence

  Panofsky Wenzel method did not converge. Lorentz Force does.
- Solved. Benchmarked with K. Papke's code.

SPS DQW (Dressed)					
		b1	b2	b3	b4
LF	Re	33	6	1498	1026
	Im	0	-2	19	-383
LHC DQW (Dressed)					
		b1	b2	b3	b4
LF	Re	33	6	1488	1048
	Im	0	-2	21	-292
LHC RFD (Dressed)					
		b1	b2	b3	b4
LF	Re	34	0	-458	128
	Im	0	0	-74	55

Table 4: Evolution of b_n in units of $\mathrm{mT/m^{n-1}}$. Values correspond to a transverse deflecting voltage of 10 MV and are evaluated with 64 points around the azimuth at a radius of 30 mm.

- TDR: Limit of b_4 was 1000 units.
- TDR: Limits pending for higher components.

Conclusions

- DQW HOMs: two horizontal modes 2.5 times over threshold.

- Worst case HOM Power in DQW (1000 W - very pessimistic) is more likely. But it is manageable.
- Heat load in RFD could be problematic (8 times threshold), f-shift is unlikely - measure during upcoming manufacture.
- Damping and tuning method for DQW 960 MHz mode.

- Multipoles: b4 are now more realistic $\rightarrow$ in limits. Limits for b5?

Appendix

960 MHz Mode Shift

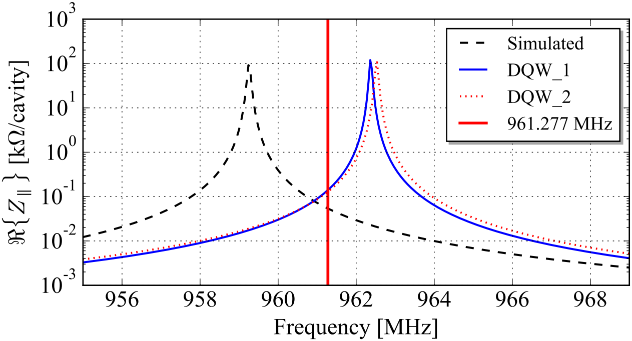


Figure 4: Measured impedance spectra in SPS.

Multipole Components

J. Mitchell

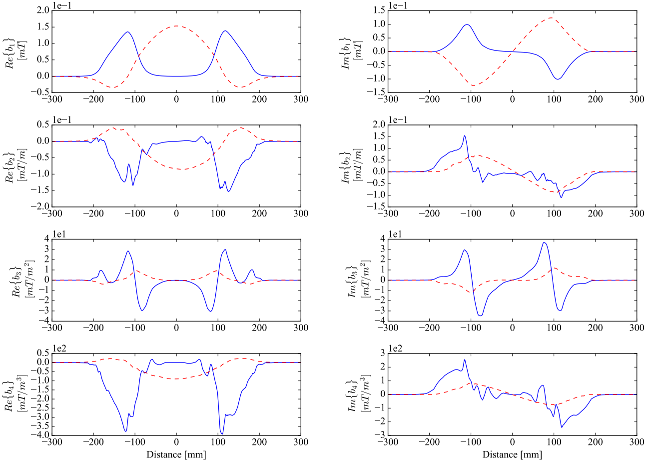
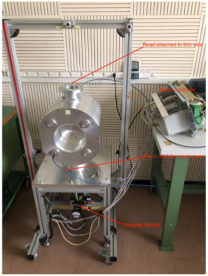


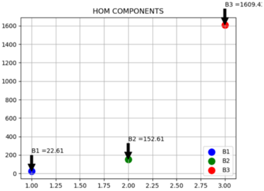
Figure 5: Multipole coefficients as a function of longitudinal position. Panofsky-Wenzel and Lorentz Force decomposition methods shown in blue and red dashed lines respectively.

Multipole Measurements

- Measurement technique developed on aluminium prototype (PoP design).
- TDR: Limits pending for higher components.



α_{radius}	b_1	b_2	b_3
20mm	31.97	0.18	1049.03
30mm	32.08	2.87	1184.75



- Work from and detailed in the summer student report by P. Gapais.

Horizontal Modes

- 1500 MHz mode Q can be reduced using a more complex HOM damper.
- Probe material still under investigation - if copper can bring down by 25%.

- 1920 MHz mode is under investigation. I see a decrease in Q with mesh convergence, beam-pipe length and without ports.
- There are also big differences between broadband and narrow band solvers.

References

J. Mitchell

R. Tomas, Presentation: Parameter update for the nominal HL-LHC : Standard , BCMS , and 8b + 4e Current HL-LHC Parameters table, in *26th HL-LHC TCC*, 2017.