HL-LHC Impedance model and stability

S. ANTIPOV, D. AMORIM, N. BIANCACCI, L. CARVER, G. MAZZACANO,
A. MEREGHETTI, E. METRAL, S. REDAELLI, B. SALVANT

MANY THANKS TO: R. BRUCE, R. CALAGA, F. GIORDANO, R. DE MARIA, D. MIRARCHI, J. MITCHELL, D. VALUCH

31.10.17

Goal of the talk: review the beam stability from impedance for the most challenging OP scenario

What is the maximum required octupole strength?

How do different components contribute to the threshold?

What are the ways to further attack the impedance?

Structure of this talk:

- First, consider the impedance model focusing on the collimation system
- Then, estimate the impact of the crab cavities

Studying the most challenging cases

ULTIMATE

Energy, β^*	E = 7 TeV, β^* = 46 cm
Beam intensity	M = 2748, $N_b = 2.3\times10^{11}$ p
Beam emittance Bunch length	ε_n = 2.0 μm (injection) σ_z = 9.0 cm, rms, Gaussian
Damper, chroma	d = 100 turns, Q' = 10
Octupole SD	Negative polarity Tails cut at 3 rms beam size
Collimator settings	Tight settings (3.5 μm ref. ε): TCP – 5σ TCSG – 6.5σ

BCMS

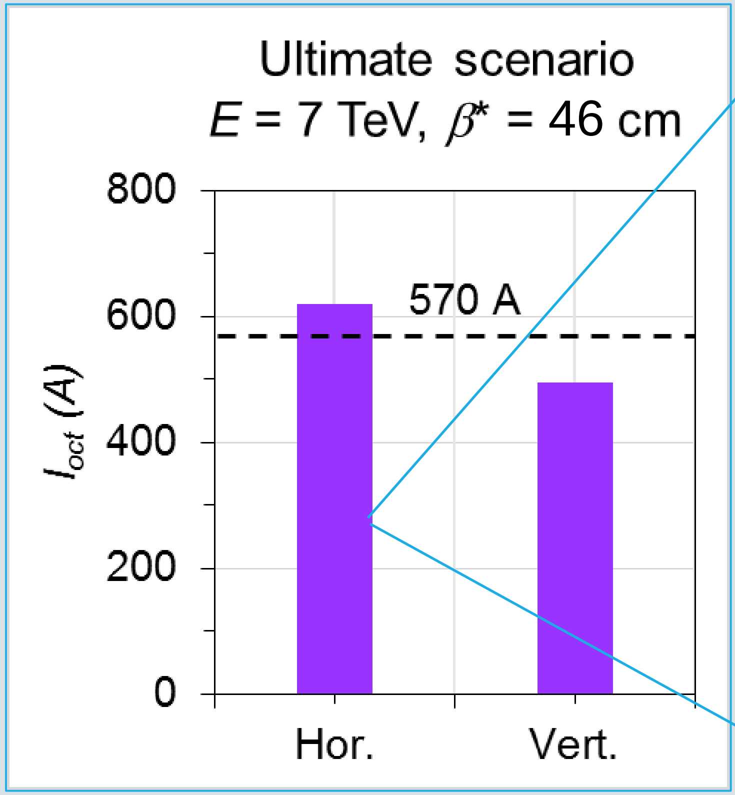
Energy, β^*	E = 7 TeV, β^* = 46 cm
Beam intensity	M = 2604, $N_b = 2.3\times10^{11}$ p
Beam emittance Bunch length	ε_n = 1.7 μm (injection) σ_z = 9.0 cm, rms, Gaussian
Damper, chroma	d = 100 turns, Q' = 10
Octupole SD	Negative polarity Tails cut at 3 rms beam size
Collimator settings	Tight settings (3.5 μm ref. ε): TCP – 5σ TCSG – 6.5σ

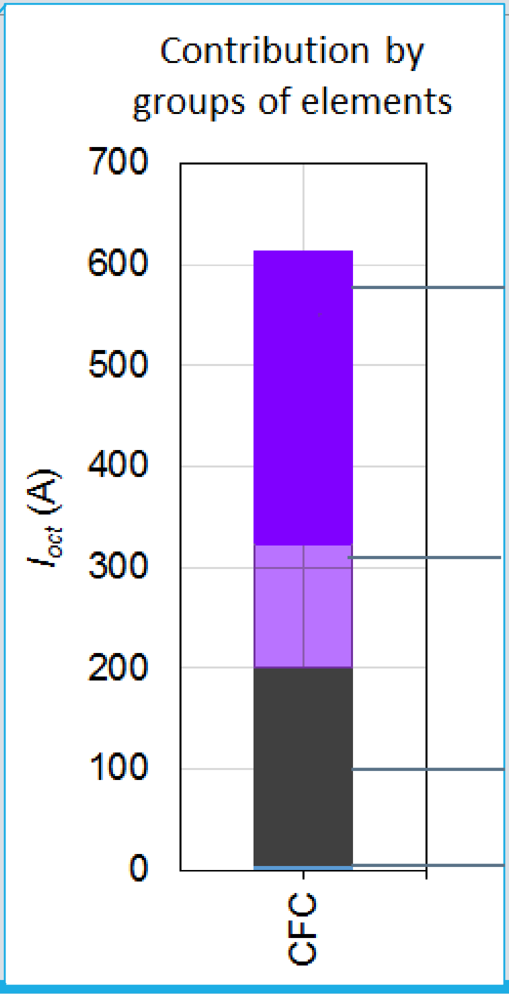
R. Tomas, L. Medina, "Parameter update for the nominal HL-LHC", HLLHC-TC, 16.03.17

- To be updated with the new OP scenarios (E. Metral, WP-2 Meeting, 24.10.17)

Impedance of LHC collimators has to be reduced for the Hi-Lumi upgrade

Octupole current above the threshold





11 secondaries in IR-7 - 290 A

- To be upgraded with Mo+MoGr
- 4 replaced during LS 2

4 primaries - 120 A

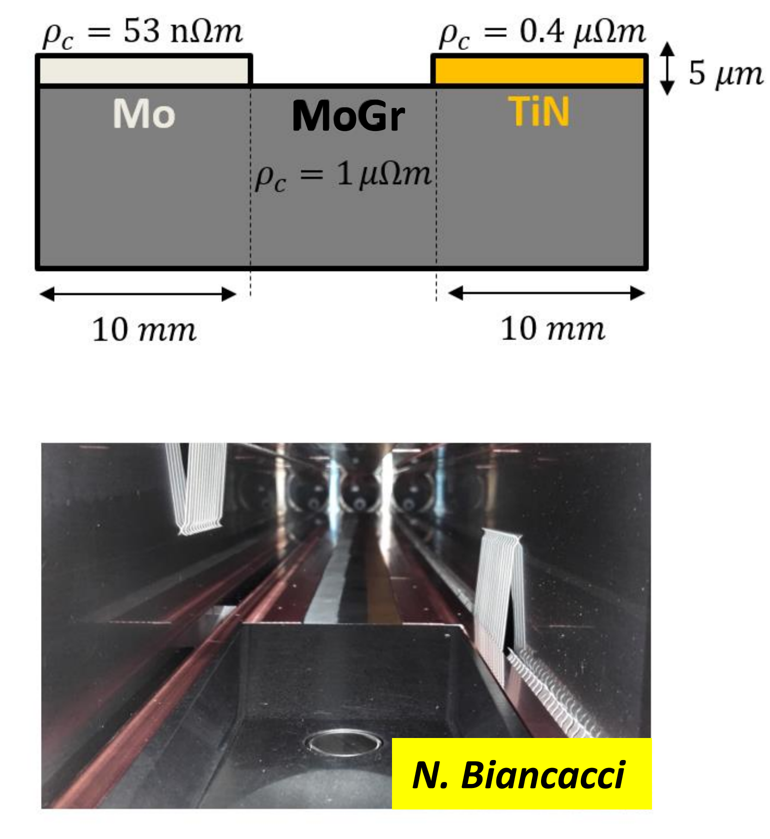
- To be upgraded with MoGr*
- 2 to be replaced during LS 2

All other collimators - 200 A

Everything else - < 10 A

* Only 2 approved at the moment

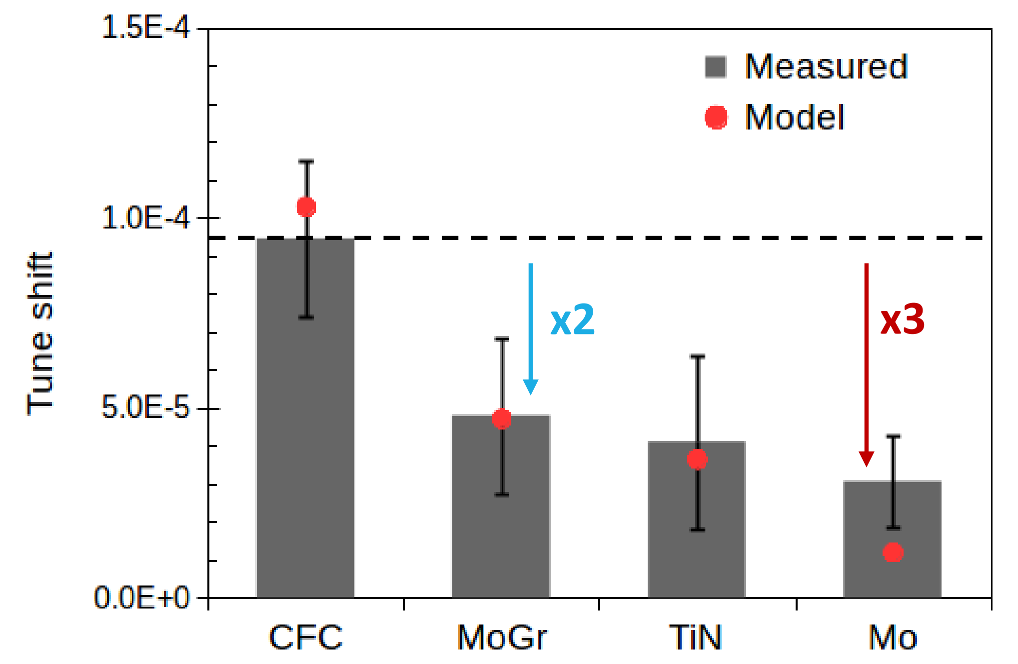
Study of the low impedance collimator in LHC



N. Biancacci

Novel coatings provide a significant reduction of the resistive wall tune shift at HL-LHC intensity

Shift for 6σ and 1.9×10^{11} p



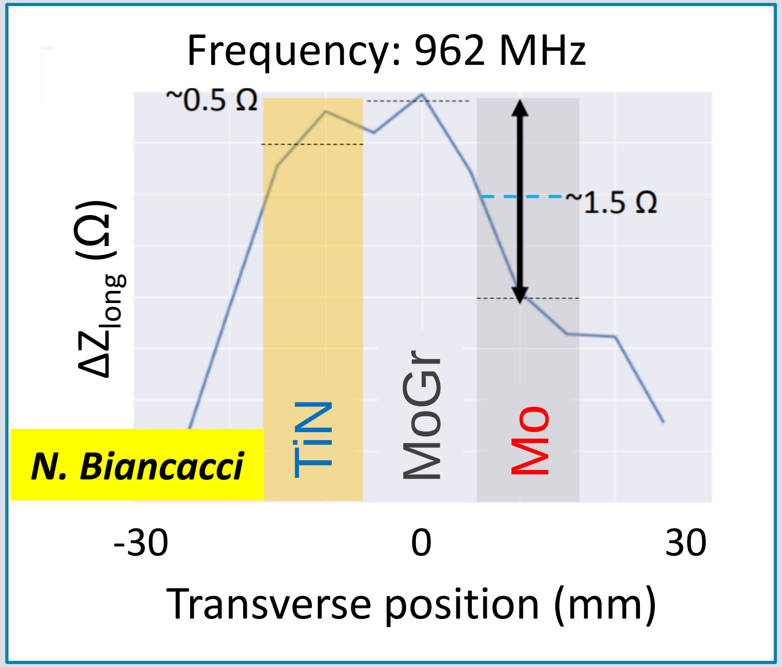
Tune shift: measured vs IW2D model

Material	Measured ($\times10^{-5}$)	Expected ($\times10^{-5}$)
CFC	9.3 ± 2.0	10.4
MoGr	4.7 ± 2.0	4.8
TiN	4.0 ± 2.3	3.7
Mo	2.9 ± 1.2	1.3

S. Antipov, *et al.*, “TCSPM Results for HL-LHC Intensity”, 93rd ColUSM, 22.09.17

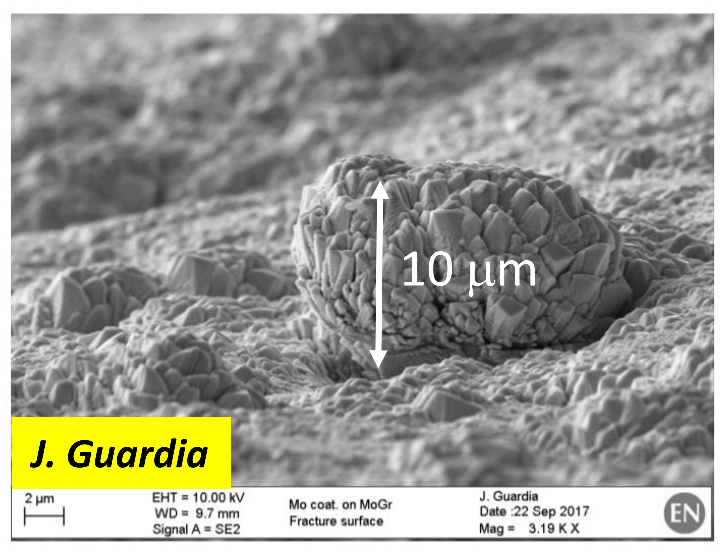
Possible source of discrepancy in Mo resistivity: Roughness of the Mo surface

Wire measurement is in agreement with the expectations



Suggesting the extra impedance is **purely inductive**

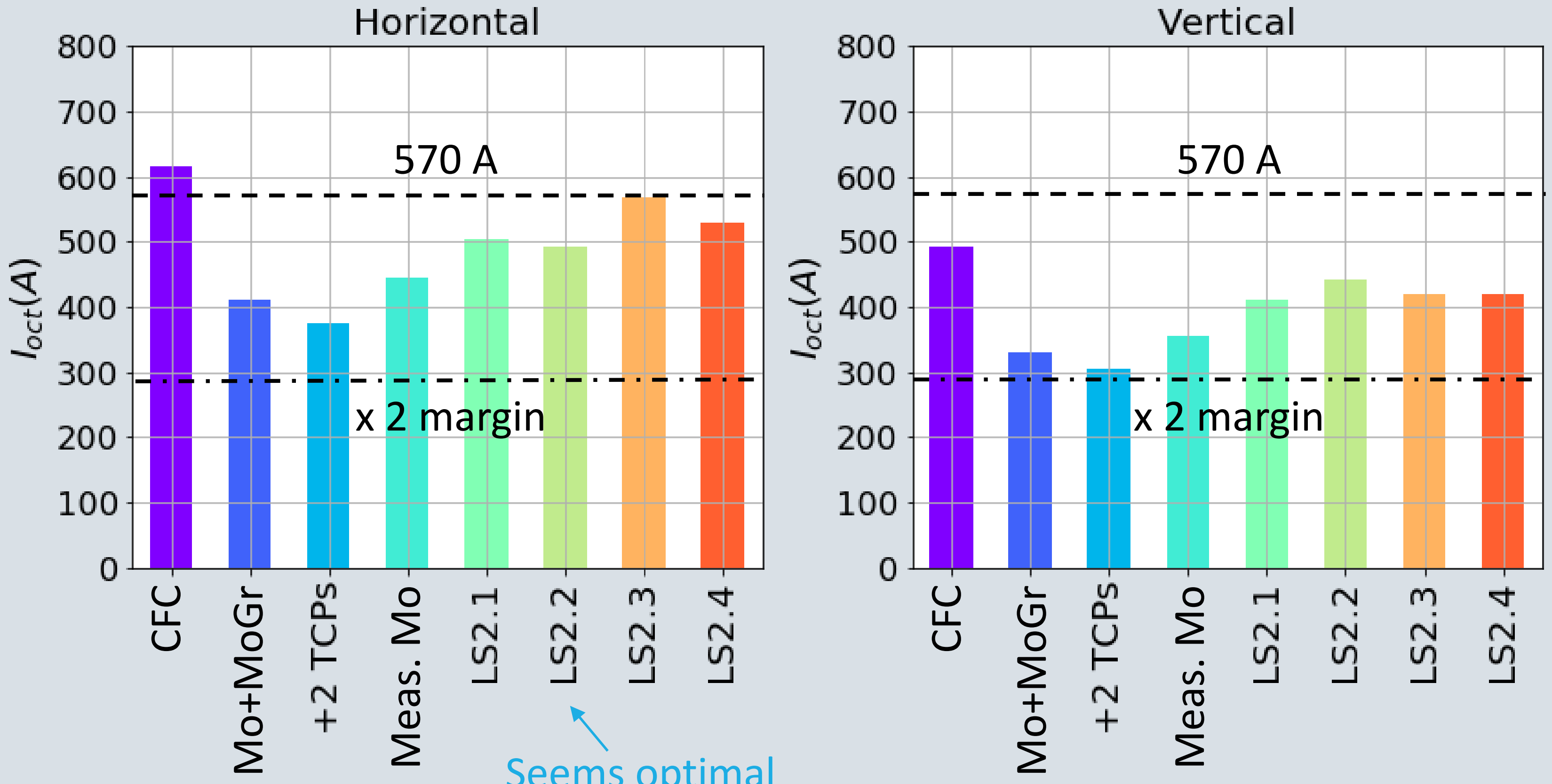
SEM image of the coating



Effect of surface roughness is being investigated:

- G. Mazzacano, *et al.*, Impedance Meeting, 25.09.17

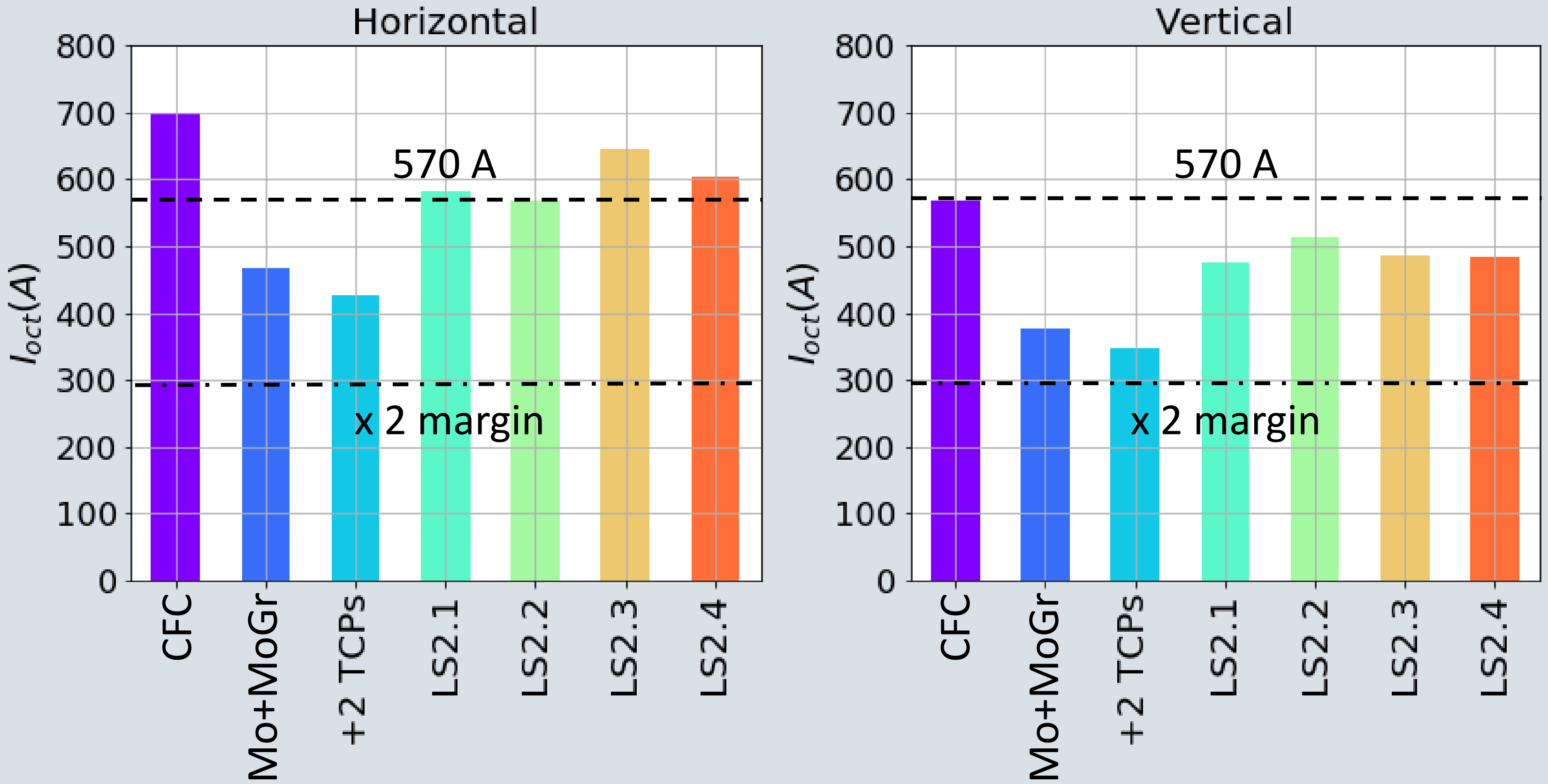
New coating decreases the octupole threshold by up to 200 A for the ultimate scenario



Seems optimal

β^* = 46 cm
$N_b = 2.3 \times 10^{11}$ p
M = 2748
ε_n = 2.0 μm
σ_z = 9.0 cm
d = 100 turns
Q' = 10
Negative polarity
Tight coll. settings

For the BCMS beam the new coatings can reduce the octupole threshold by 220 A



β^* = 46 cm
$N_b = 2.3 \times 10^{11}$ p
M = 2604
ε_n = 1.7 μm
σ_z = 9.0 cm
d = 100 turns
Q' = 10
Negative polarity
Tight coll. settings

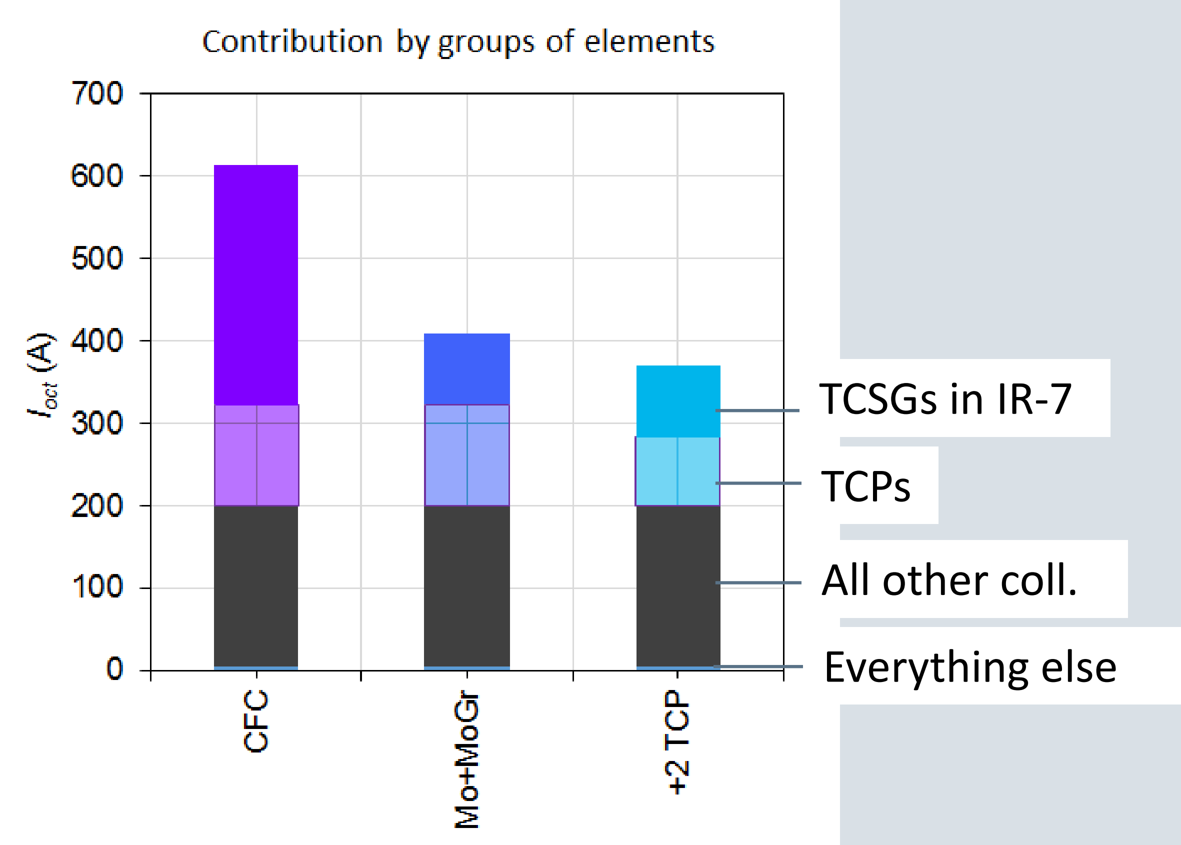
Potential for improvement: low-resistivity coatings

The two remaining TCPs can utilize MoGr jaws

- Upgrading the first two gives 40 A

Further upgrade of TCSGs with the low-resistivity coatings might help

- Could Cu+CFC be an option for the least exposed ones?

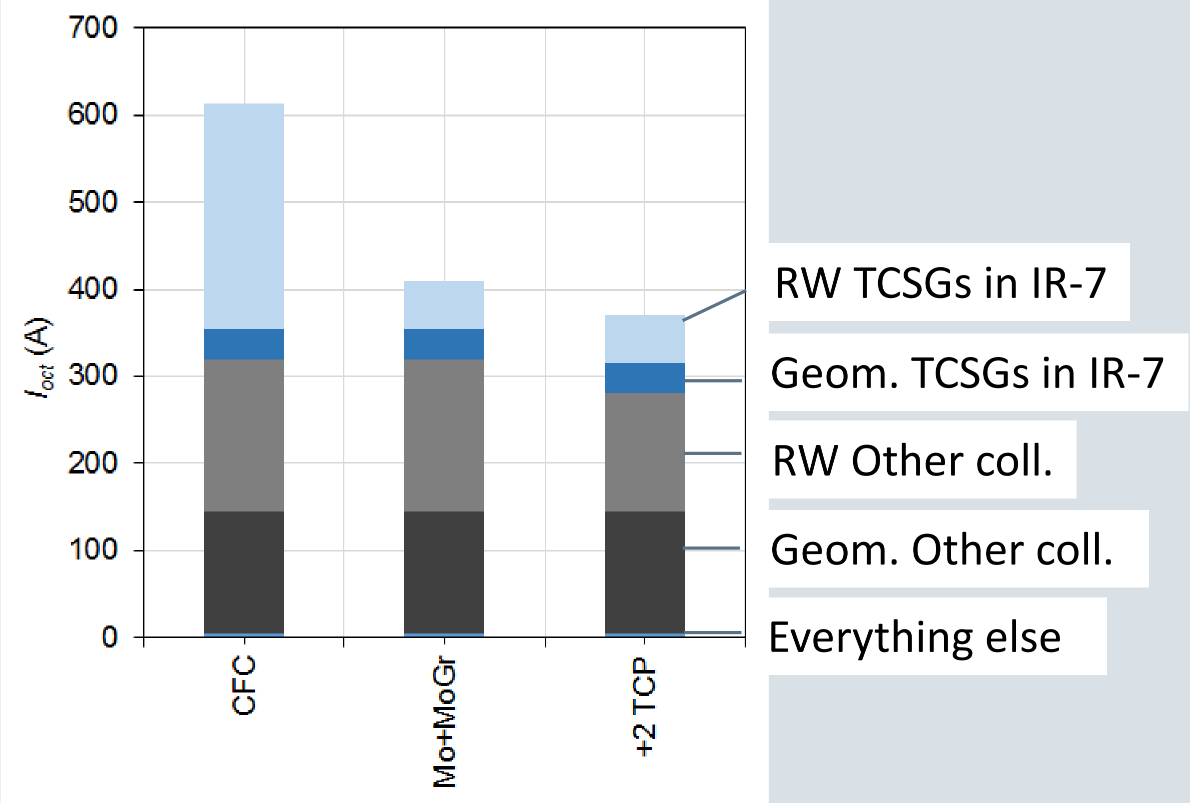


Potential for improvement: reducing the geometric impedance

After the collimator upgrade the geometric impedance accounts for

- 30% of the contribution of the TCSGs in IR-7
- Nearly 50% of the rest

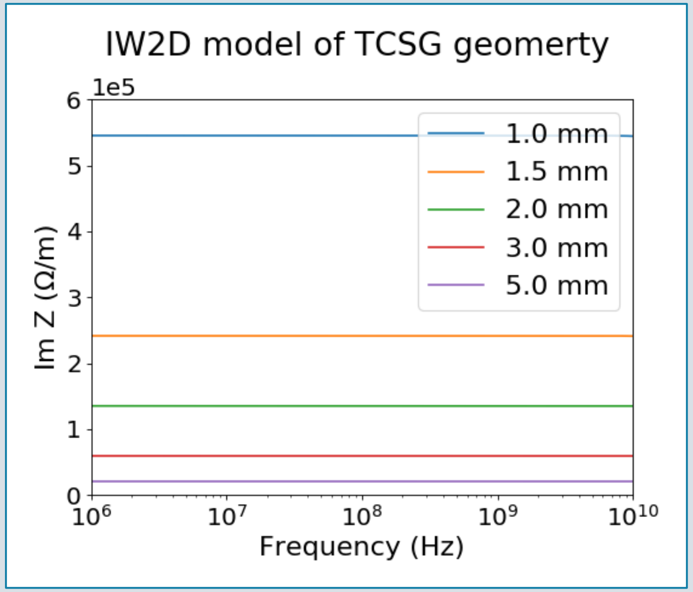
Without the geometric contribution the octupole threshold would have been almost 200 A lower



Potential for improvement: better understanding the geometric contribution

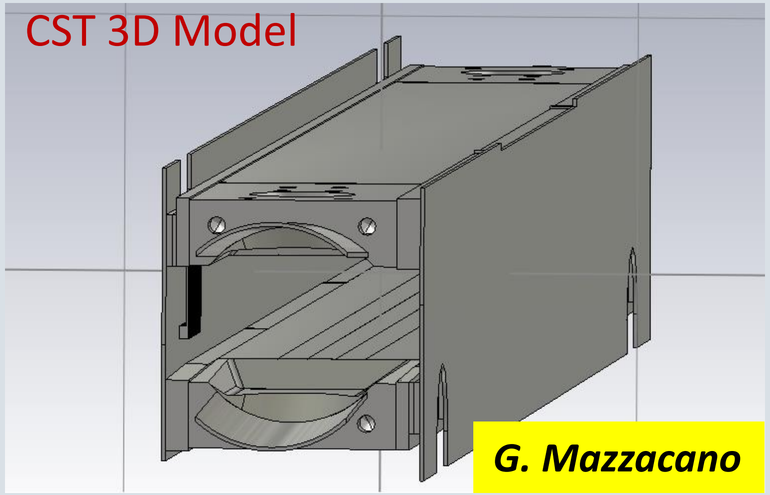
The geometric impedance is modelled by two Stupakov flat tapers

- This might not be extremely accurate for the TCSPM design

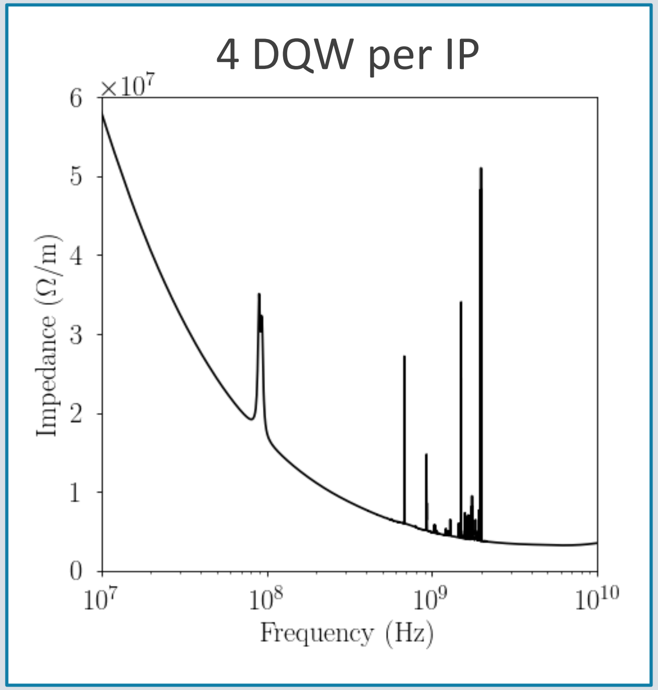


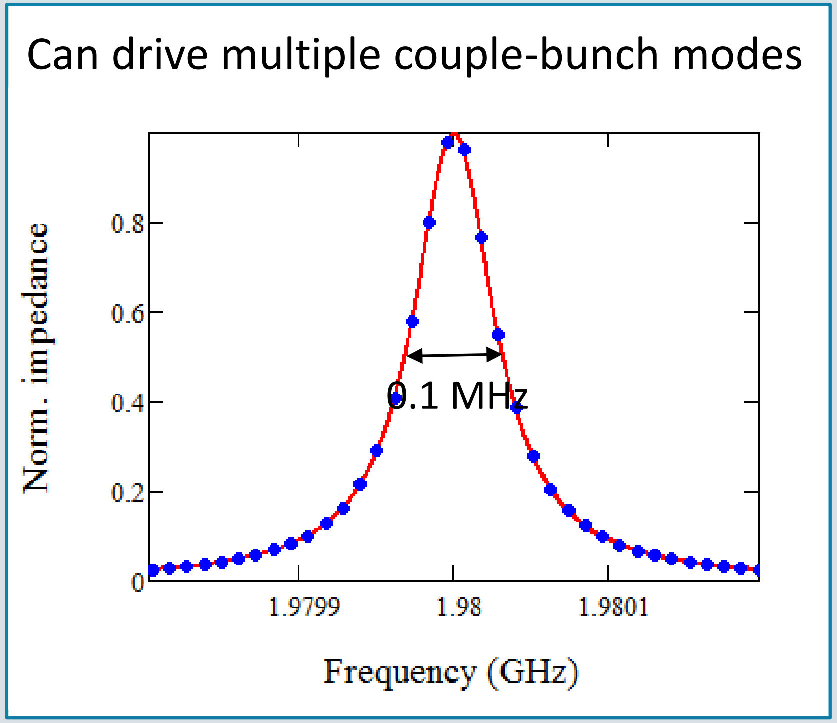
CST simulation could be more precise

- Need to overcome numerical noise, learn to interpolate data between the simulated gaps
- Integrating with IW2D
- B. Salvant and G. Mazzacano are looking into the feasibility of the approach



Crab HOMs dominate the impedance at the frequencies around 1 GHz


4 DQW per IP

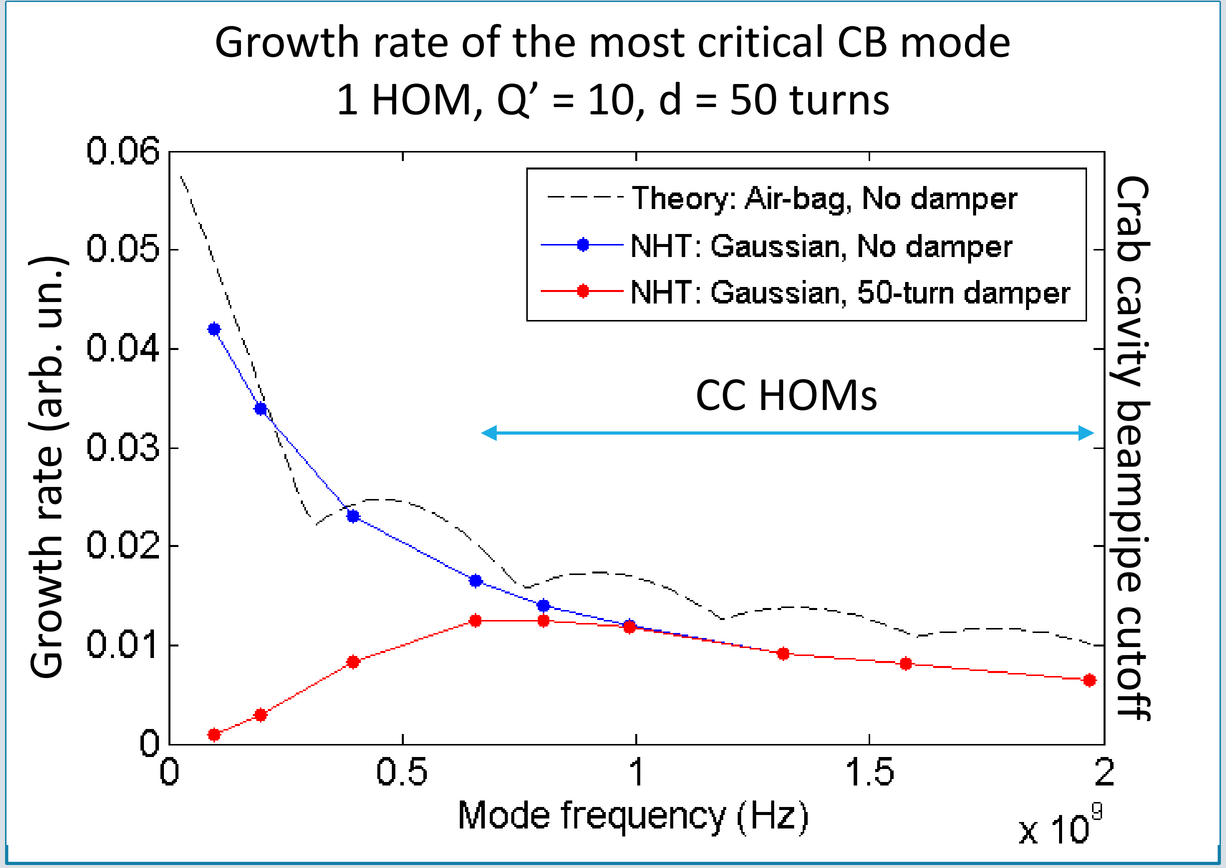

Can drive multiple couple-bunch modes

It is important to keep the HOMs under control to ensure beam stability

E. Metral, *et al.*, Beam intensity limitations, 4th Joint HiLumi LHC-LARP Annual Meeting, KEK, 2014

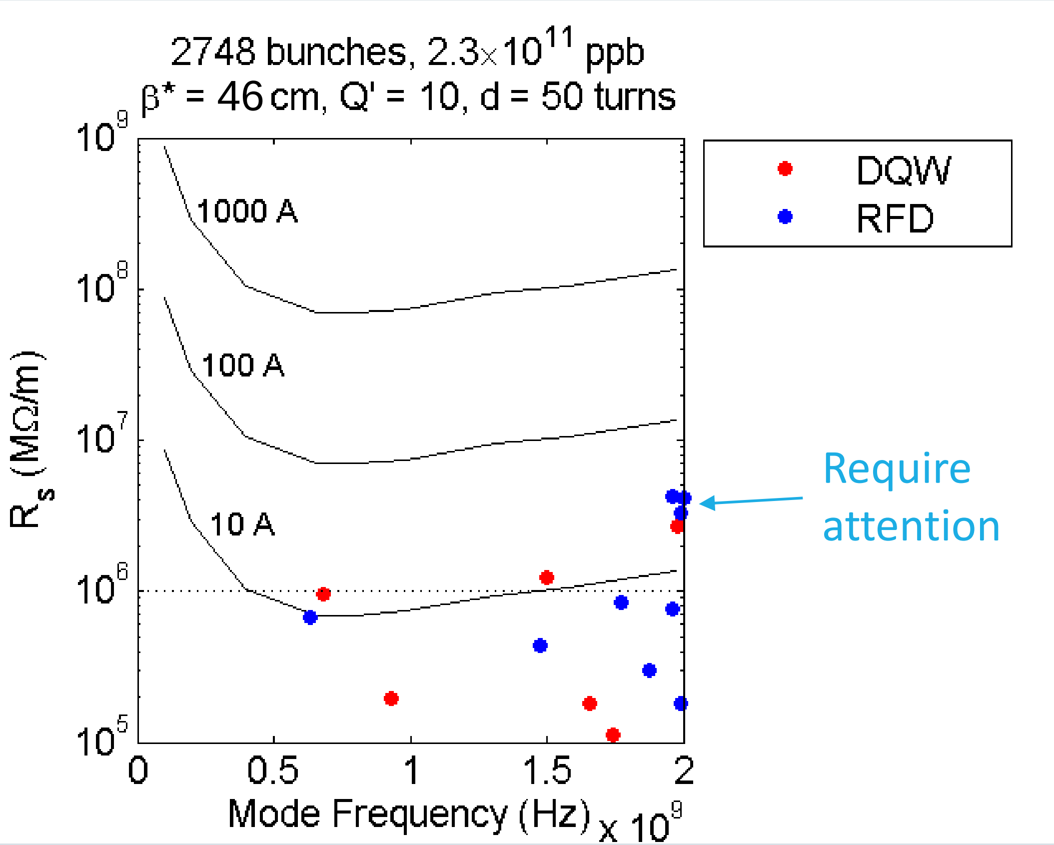
N. Biancacci, *et al.*, HL-LHC impedance and stability studies, HiLumi Workshop, FNAL, 2015

Transverse feedback is inefficient above 1 GHz



Most HOMs require negligible octupole current, even if fall on the couple-bunch line

No other sources of impedance

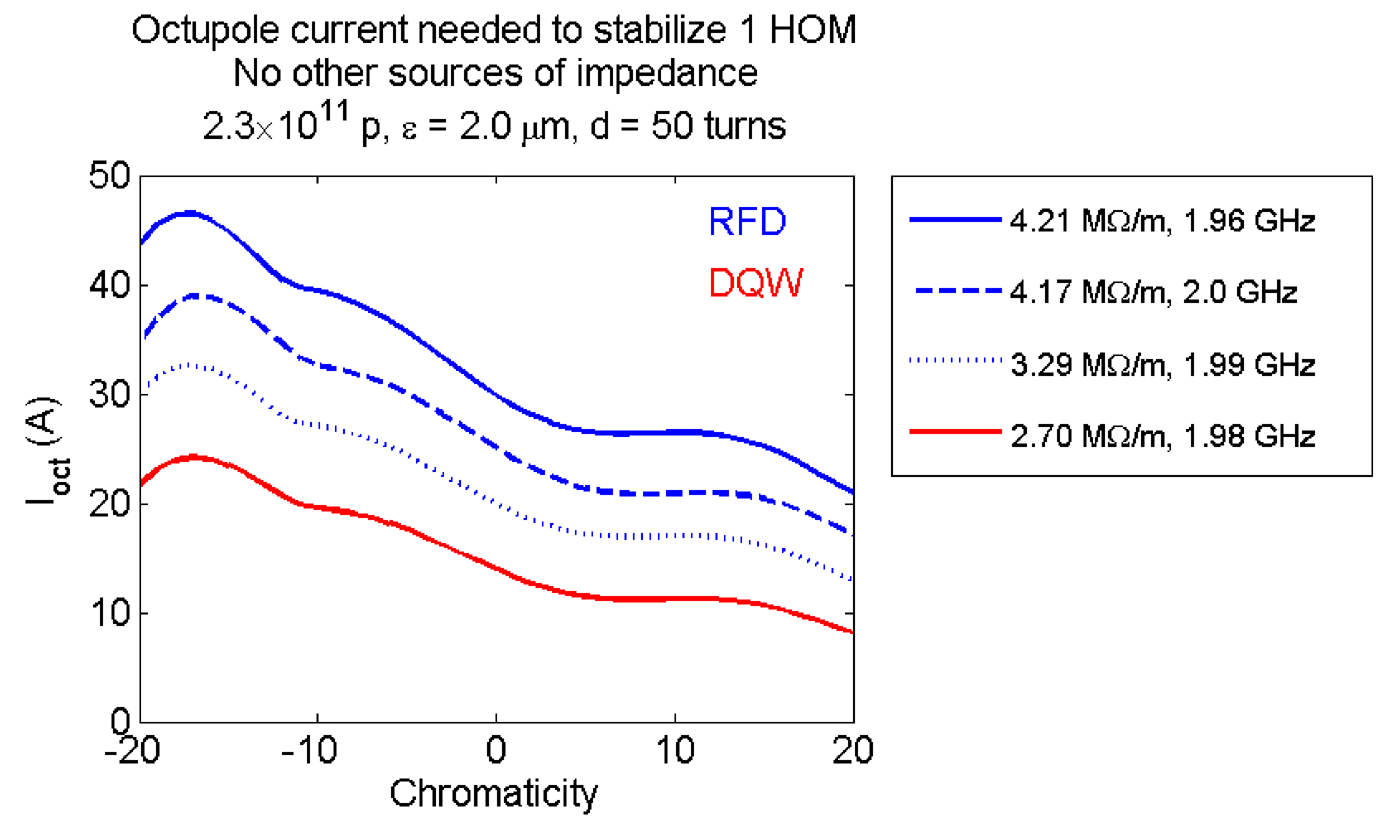


Require attention

DQW: update of 2016.10.21

- A more advanced HOM filter design by J. Mitchell offers better suppression.
- To be finalized and uploaded into EDMS

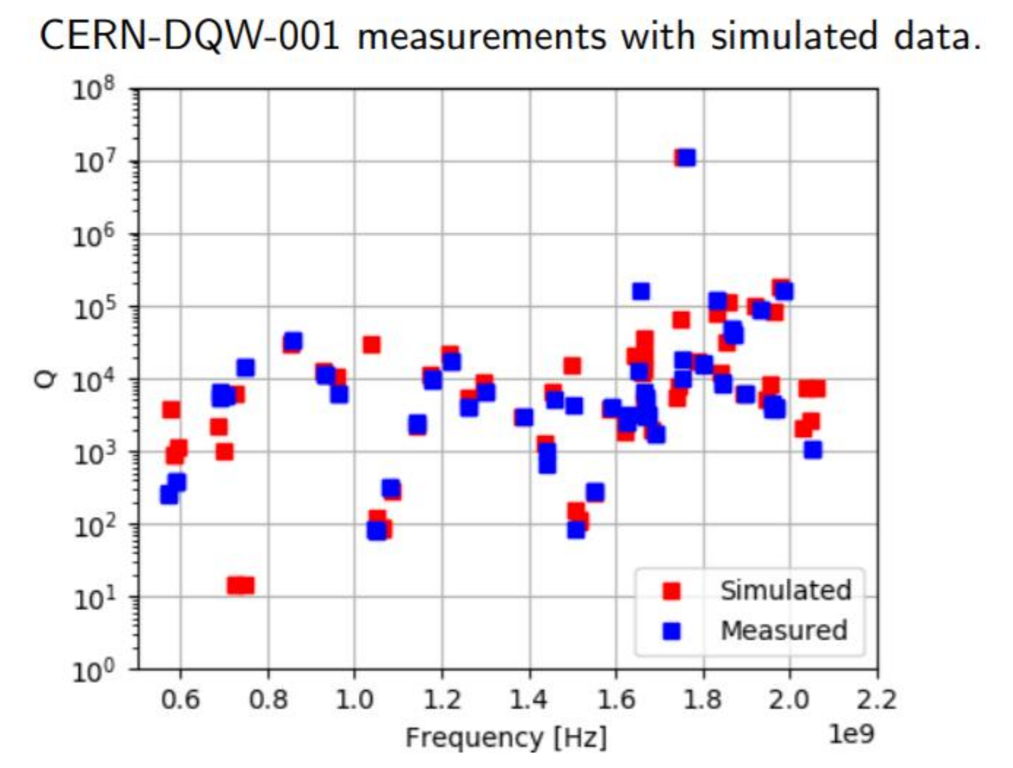
~ 10 A needed to stabilize the most critical modes



The HOMs are likely to have a higher shunt impedance

Simulated and real modes might differ

- *Q* (R_s) can be higher by up to **x3**
- *f* can vary by up to **4 MHz**

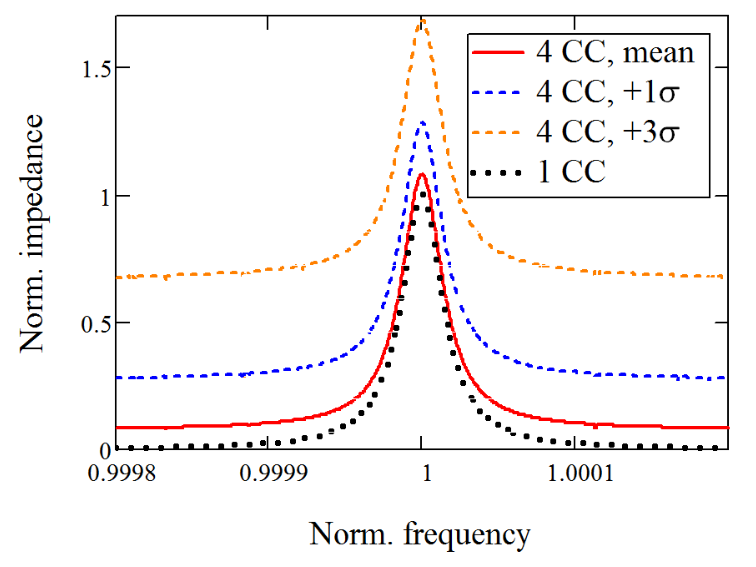

CERN-DQW-001 measurements with simulated data.

J. Mitchell, HOM Impedance Simulations and Measurements for the DQW Crab Cavity, Impedance Meeting, 14.09.17

The modes of different cavities are unlikely to overlap

Uncertainties of HOM frequencies are much larger than their width

Assuming an HOM of one cavity hits a couple-bunch line,
the mean expected increase due to 3 other cavities is marginal

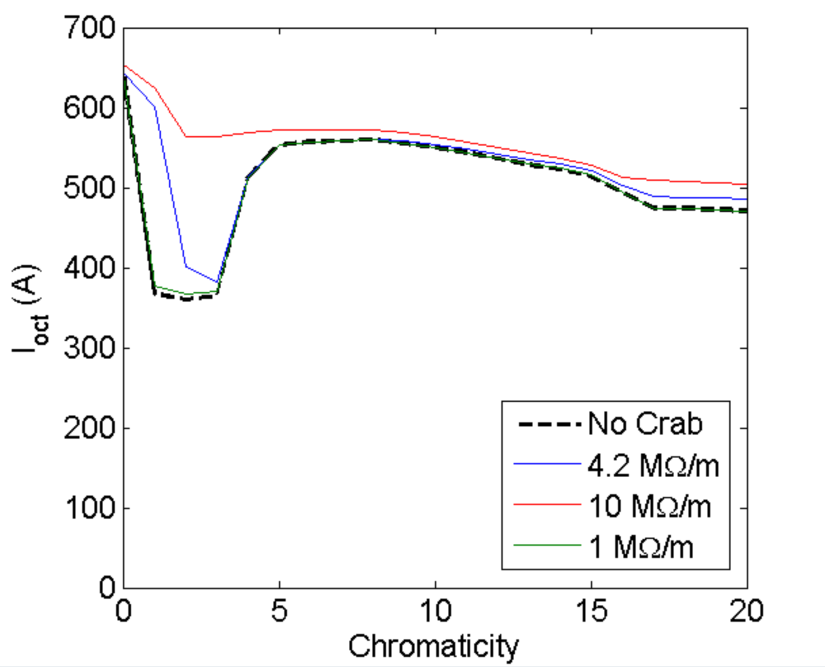


f = 1.98 GHz
Q = 31 000
$3\sigma_f$ = 4 MHz

In order not to affect the operational scenarios we need to keep the CC HOMs below 1 MΩ/m

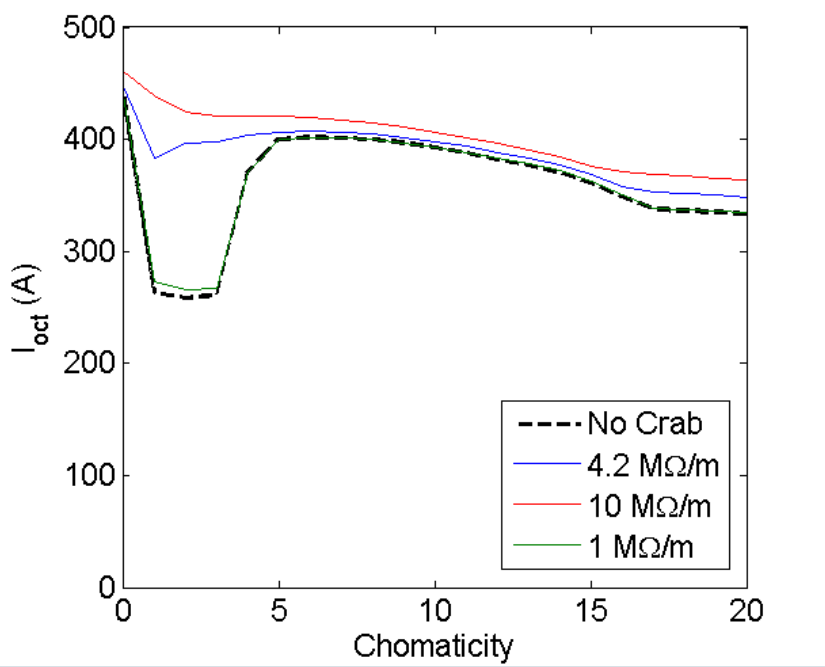
“ULTIMATE”

2748 b, 2.3x10^{11} ppb, β^* = 46 cm



“NOMINAL”

2748 b, 2.3x10^{11} ppb, β^* = 64 cm



Summary

Mo coating on MoGr offers the largest reduction of impedance and octupole threshold in HL-LHC

- For the tight collimator scenario one can gain 200 A by coating all the secondaries in IR-7
- Up to 100 A by coating a subset of 4 collimators

Still, the required current is too close to the limit of 570 A

- In the real machine the impedance can only be worse than in the idealistic model
- Based on the past operational experience, it would be beneficial to have at least factor of 2

Further improvement can be achieved by reducing the geometrical part of the collimator impedance

- Accounts for up to 1/2 of the total current when using the low-resistivity coatings

Crab cavity HOM might affect couple-bunch stability

- Transverse mode shunt impedance below 1 MΩ/m is required for the HOMs not to increase the octupole threshold significantly

An update for the actual OP scenarios is under way

- Octupole thresholds are expected to be lower due to less challenging collimation settings

Back up slides

Differences between the studied scenario and OP Note (to be shown in Madrid)

CURRENT

Energy, β^*	**E = 7 TeV, β^* = 46 cm**
Beam intensity	M = 2748, $N_b = 2.3\text{x}10^{11}$ p
Beam emittance Bunch length	ε_n = 2.0 μm (injection) σ_z = 9.0 cm, rms, Gaussian
Damper, chroma	d = 100 turns, Q' = 10
Octupole SD	Negative polarity Tails cut at 3 rms beam size
Collimator settings	Tight settings: TCP – 5.9σ (5) TCSG – 7.7σ (6.5) 2.5 (3.5 μm) ref. ε

"MADRID"

Energy, β^*	**E = 7 TeV, β^* = 46 cm**
Beam intensity	M = 2760, $N_b = 2.3\text{x}10^{11}$ p
Beam emittance Bunch length	ε_n = 2.0 μm (injection) σ_z = 9.0 cm, rms, Gaussian
Damper, chroma	d = 100 turns, Q' = 10
Octupole SD	Negative polarity Tails cut at 3 rms beam size
Collimator settings	Nominal settings: TCP – 6.7σ TCSG – 9.1σ 2.5 μm ref. ε

Octupole thresholds for different coating scenarios

Coating / Op. Scenario		**Ultimate Hor (Vert)**	**BCMS Hor (Vert)**	**Comment**
Secondaries IR-7	**Primaries**			
CFC	CFC	620 A (490 A)	660 A (540 A)	“As is”
Mo+MoGr	CFC	410 A (330 A)	440 A (350 A)	Based on expected bulk conductivity of Mo
Mo+MoGr (Meas.)	CFC	440 A (350 A)	–	Worst possible case for Mo coating
Mo+MoGr	2 in MoGr 2 in CFC	370 A (300 A)	400 A (330 A)	
Partial coating: Option 1	CFC	500 A (410 A)	550 A (450 A)	Choosing the highest contributors in both planes
Partial coating: Option 2	CFC	490 A (440 A)	540 A (490 A)	Avoiding the most exposed to steady losses
Partial coating: Option 3	CFC	570 A (420 A)	610 A (460 A)	Avoiding hor. and vert. ones for protection reasons
Partial coating: Option 4	CFC	500 A (420 A)	570 A (460 A)	Optimizing protection at the top energy

Summary of the resistivity measurements

Material	Beam Meas. [nΩ-m]	Lab Meas. (AC) [nΩ-m]	IW2D Model [nΩ-m]	Lab Meas. (HF)
CFC	4030 ± 380	–	5000	–
MoGr	760 ± 60	800 – 1200	1000	Close to expected
TiN	340 ± 40	Not measurable	400	Close to expected
Mo	250 ± 50	20 – 100	50	Close to expected

A factor **5** higher resistivity than expected!

See also: G. Mazzacano’s, Master Thesis, Oct. 2017

Preliminary results for the latest OP scenario