Why do we need coated collimators?

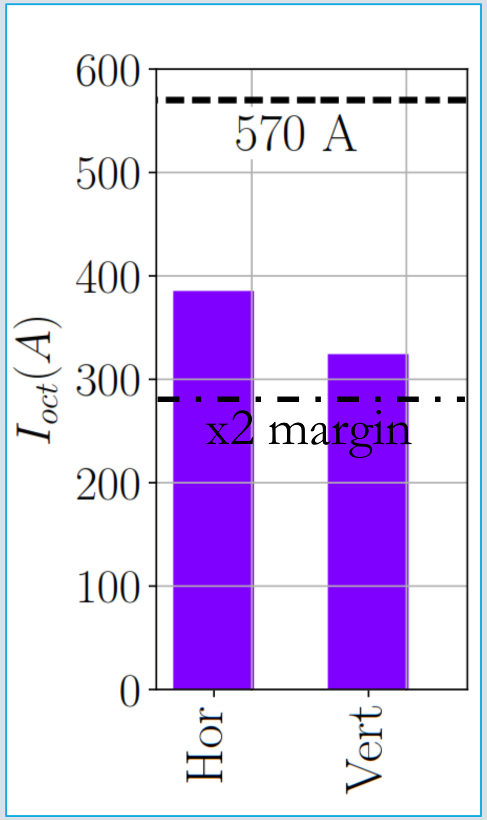
S. ANTIPOV, D. AMORIM, N. BIANCACCI, X. BUFFAT, E. CARIDEO,
J. GUARDIA, E. METRAL, N. MOUNET, B. SALVANT

HL-LHC WP2 MEETING, 28.08.18

What is the motivation for collimator impedance reduction?

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

Octupole current close to threshold



- Linear coupling
- Magnet imperfections
- Feedback noise
- Optics errors
- Uncertainty of beam distribution

Current study:

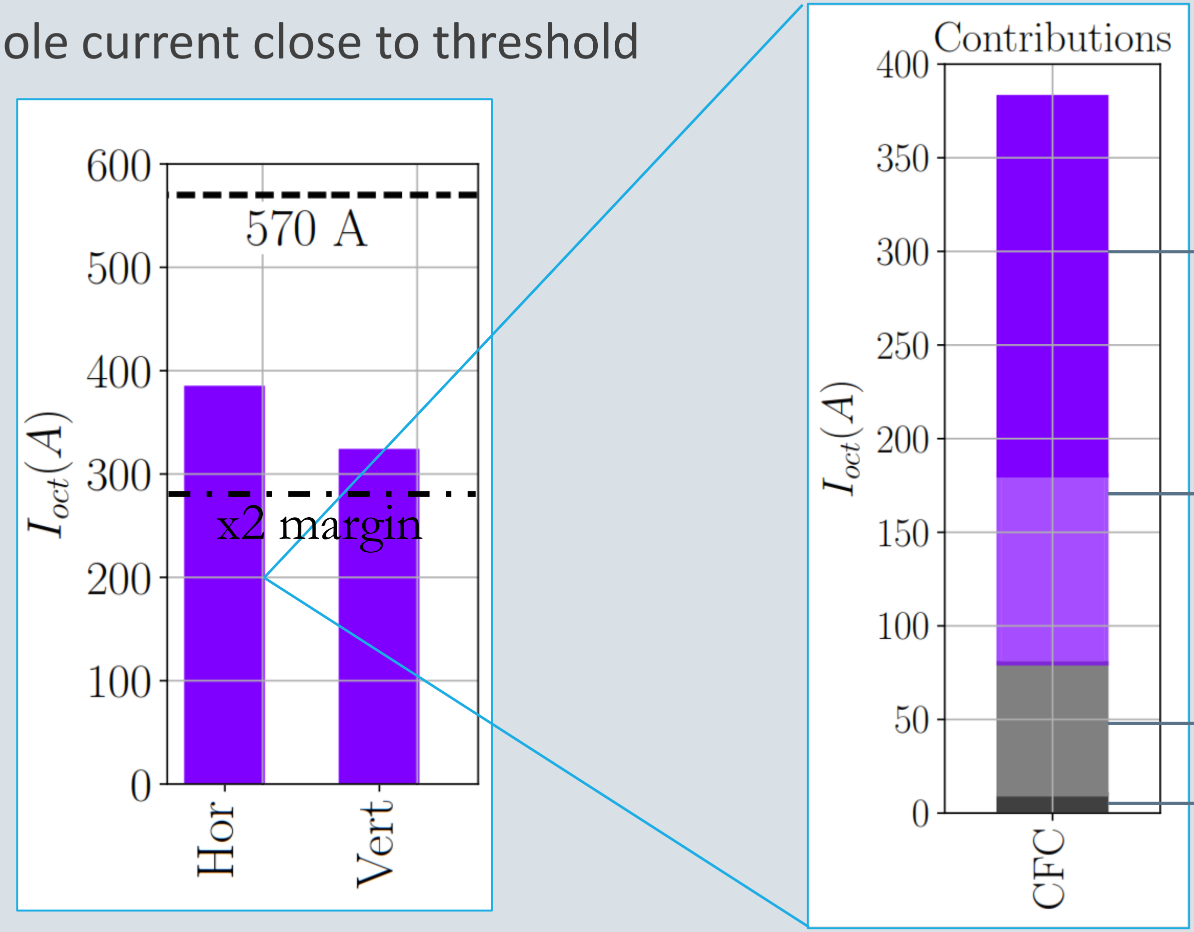
- Ultimate OP scenario
- Right before collision
- No beam-beam
- No help from ATS

Present operational experience:

- Need a factor 2 margin at least
- Compared to pure impedance

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

Octupole current close to threshold



Dominant component is the collimator impedance

11 secondaries in IR-7 - 200 A

- To be upgraded
- 4 to be replaced during LS 2

4 primaries - 100 A

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

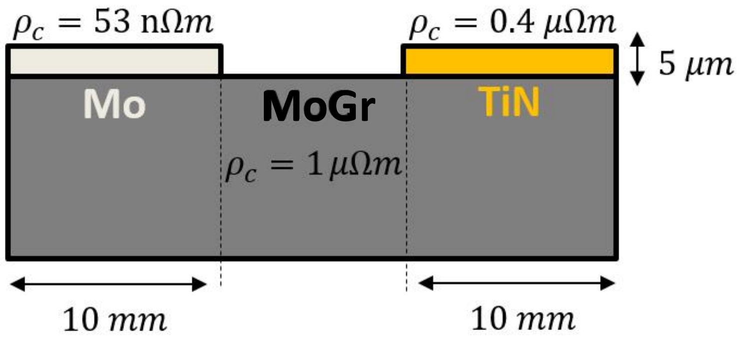
All other collimators - 70 A

Everything else - < 10 A

* 2 approved at the moment

Study of the low impedance collimator in LHC

Currently, both primary and secondary collimators have CFC jaws (ρ_c = 5 μΩm)



N. Biancacci

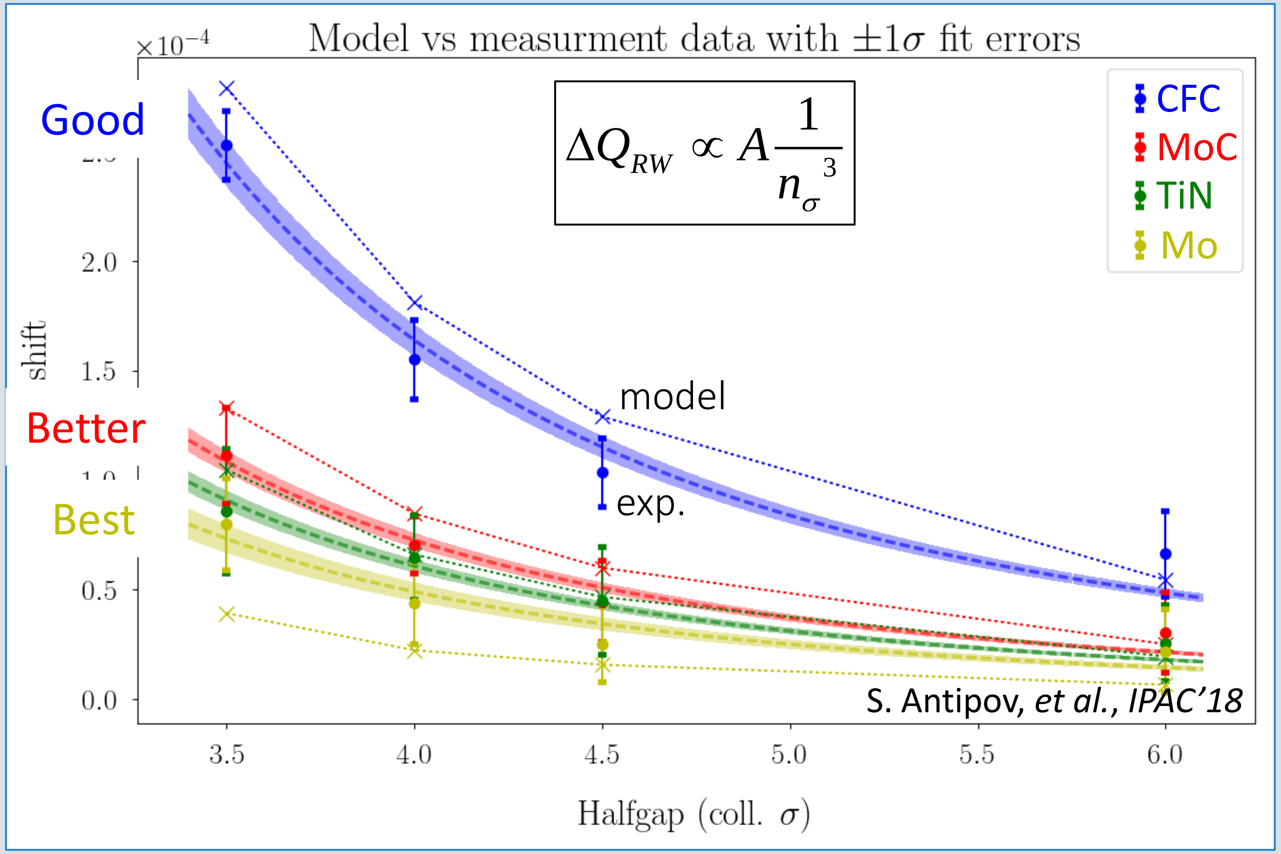
Primary collimators:

- MoGr to replace CFC

Secondary collimators:

- MoGr jaw
- Low-resistivity coating

The largest reduction of the resistive wall tune shift measured for Mo coating

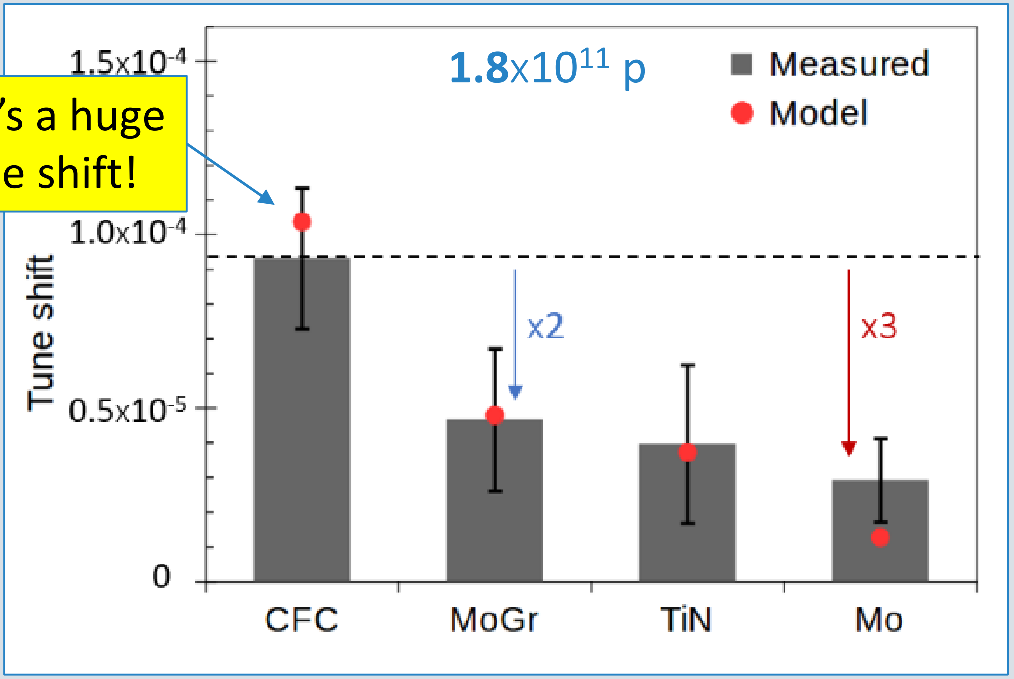


$$\Delta Q_{RW} \propto A \frac{1}{n_\sigma^{\ 3}}$$

S. Antipov, *et al.*, *IPAC'18*

IR-7 Secondary collimators are the right target for impedance reduction

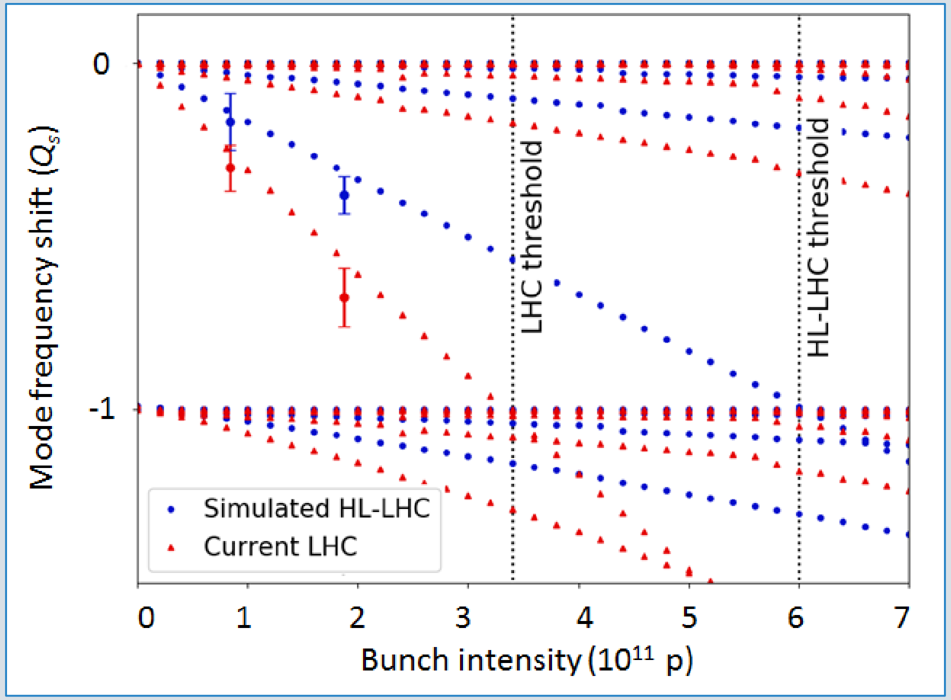
COLLIMATOR TUNE SHIFT GOES DOWN



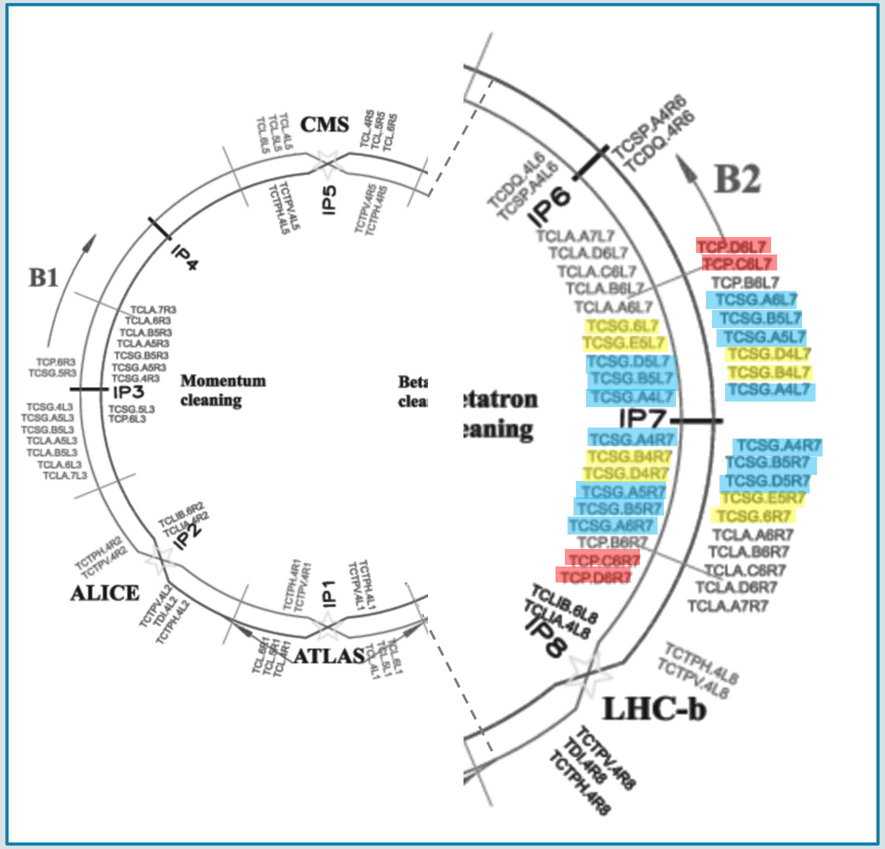
That's a huge tune shift!

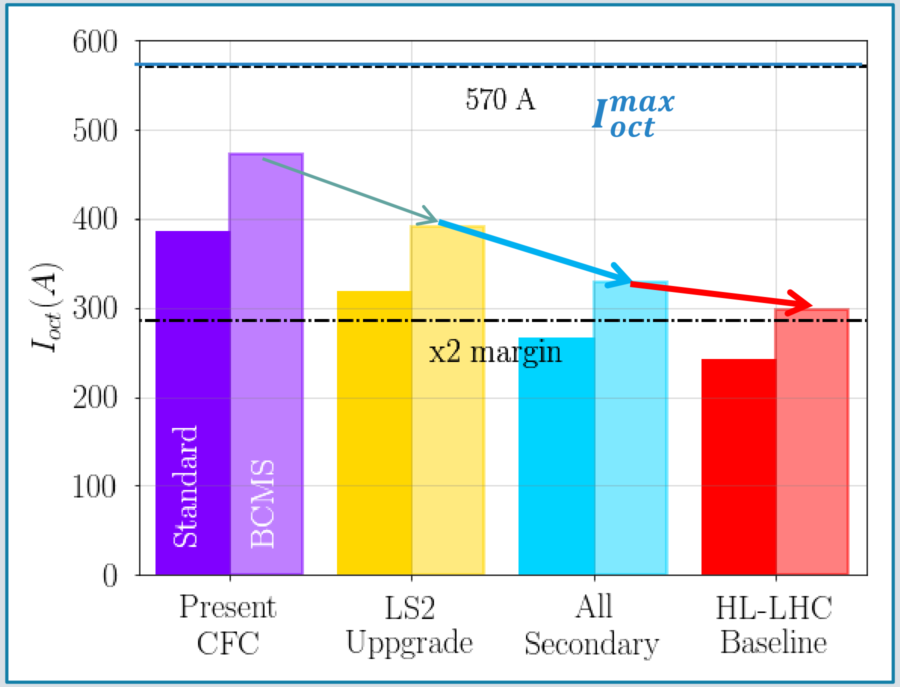
Measured tune shift of 1 collimator: TCSG.D4, TCSPM

SIGNIFICANT REDUCTION IN IMPEDANCE WAS MEASURED IN THE TMCI MD



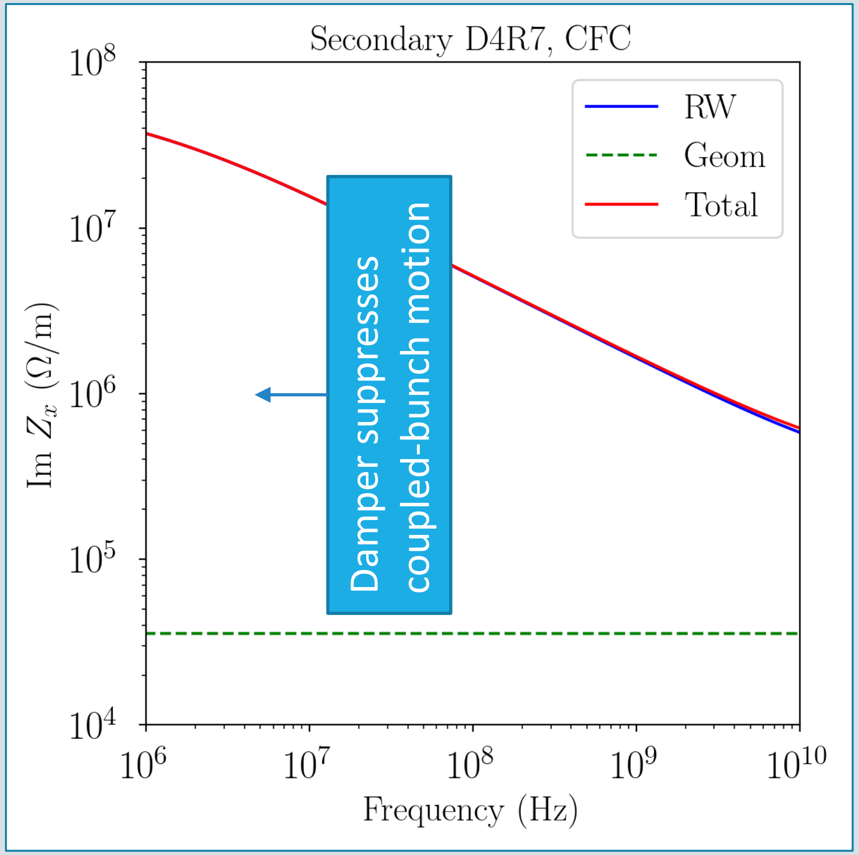
Low impedance collimators



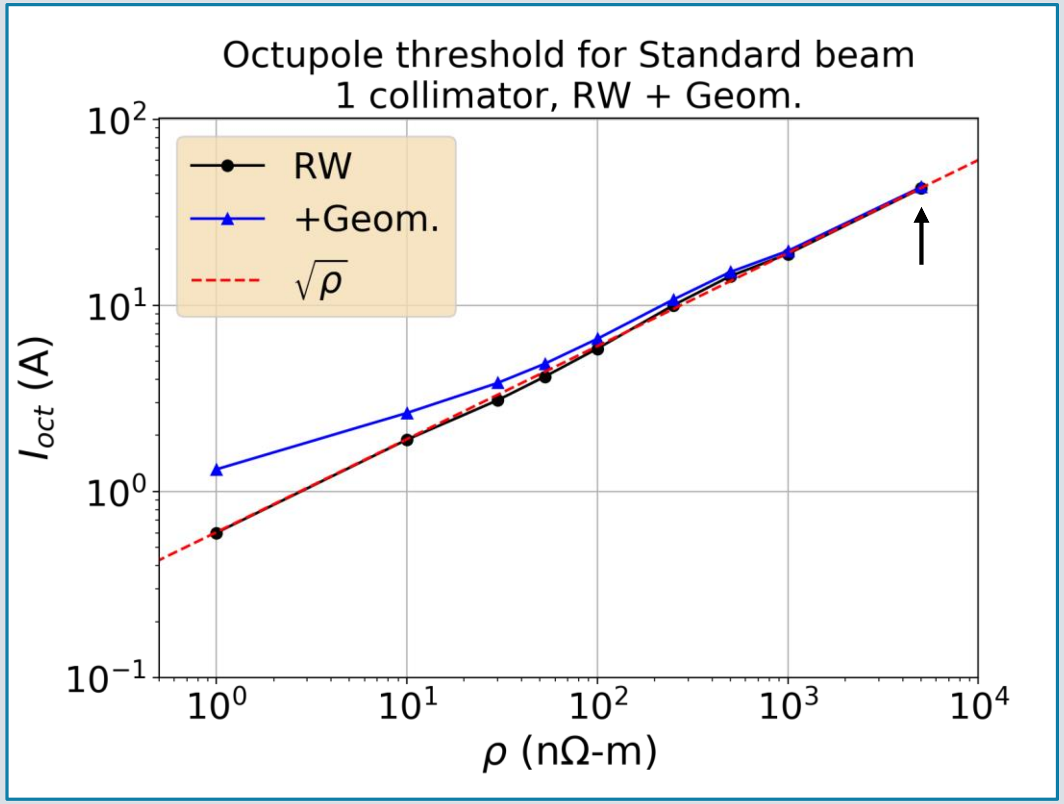


How does the gain scale with coating resistivity?

One collimator, closer to the beam: Coating is very efficient

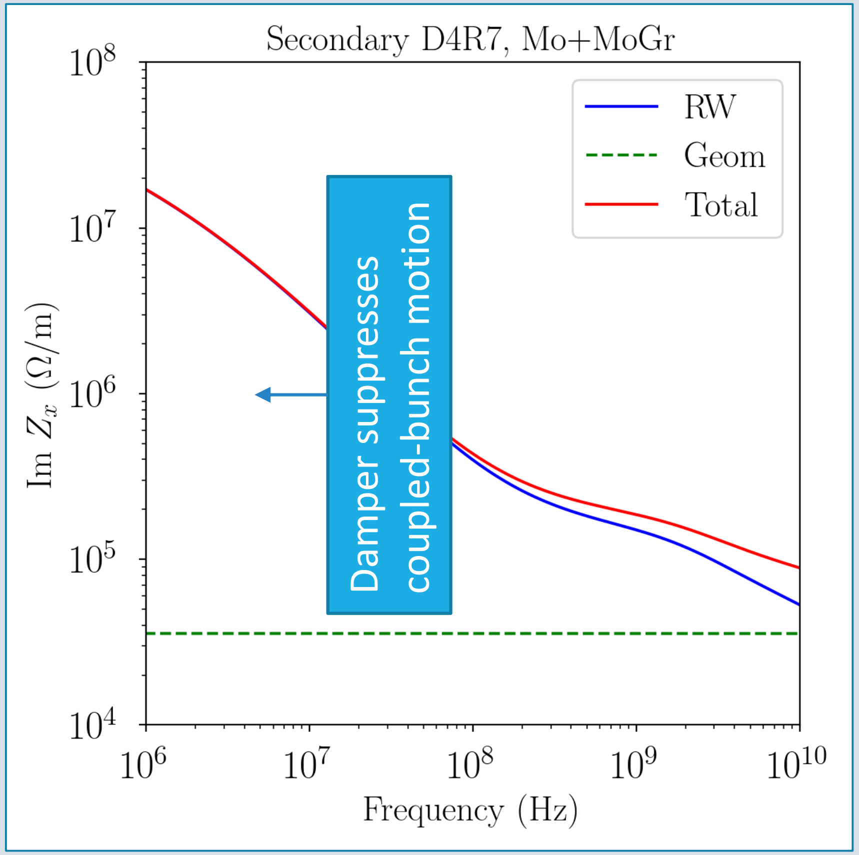


Damper suppresses coupled-bunch motion



Vertical collimator, Halfgap: 1.4 mm

One collimator, closer to the beam: Coating is very efficient



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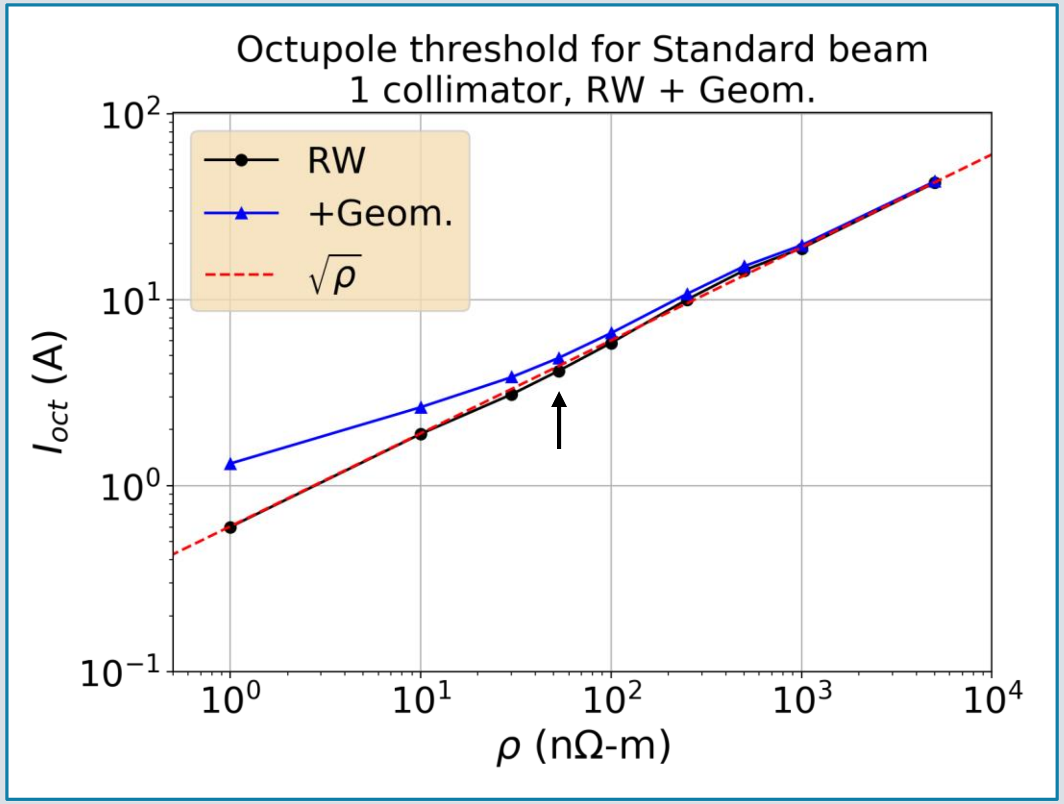
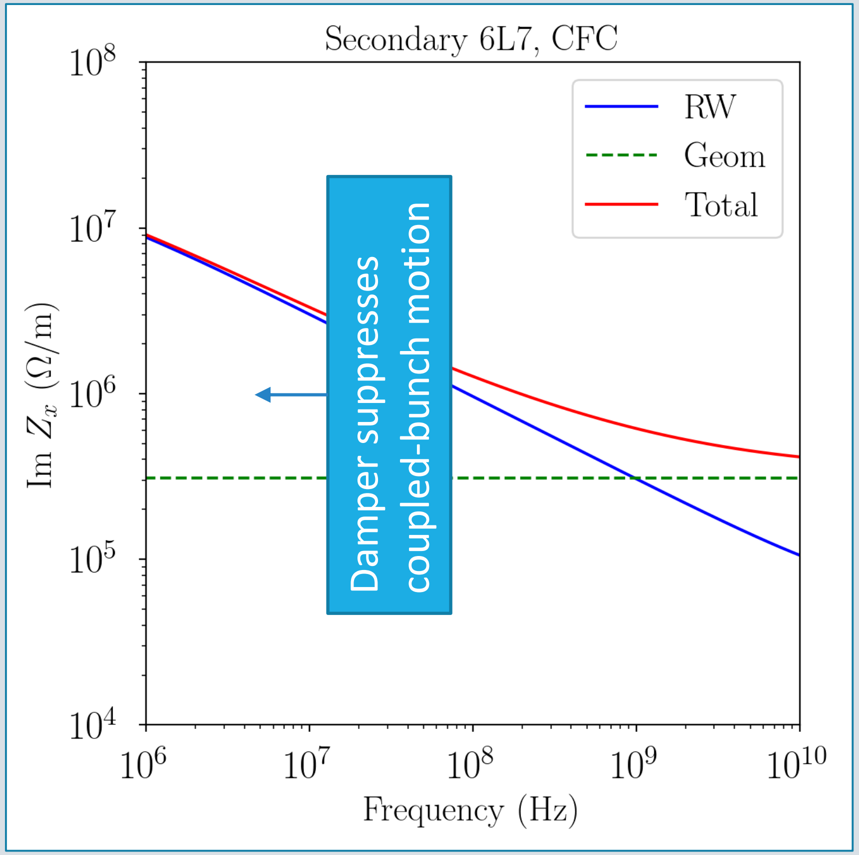
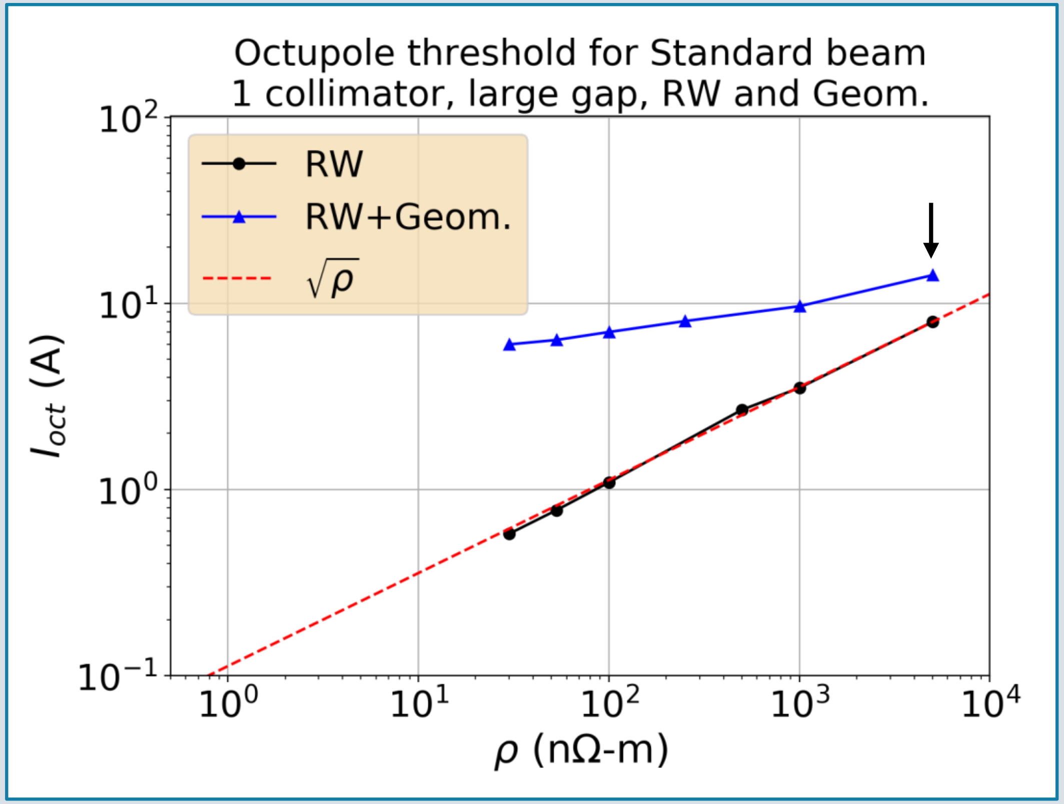


Vertical collimator, Halfgap: 1.4 mm

Coating is less efficient when other sources of impedance take part

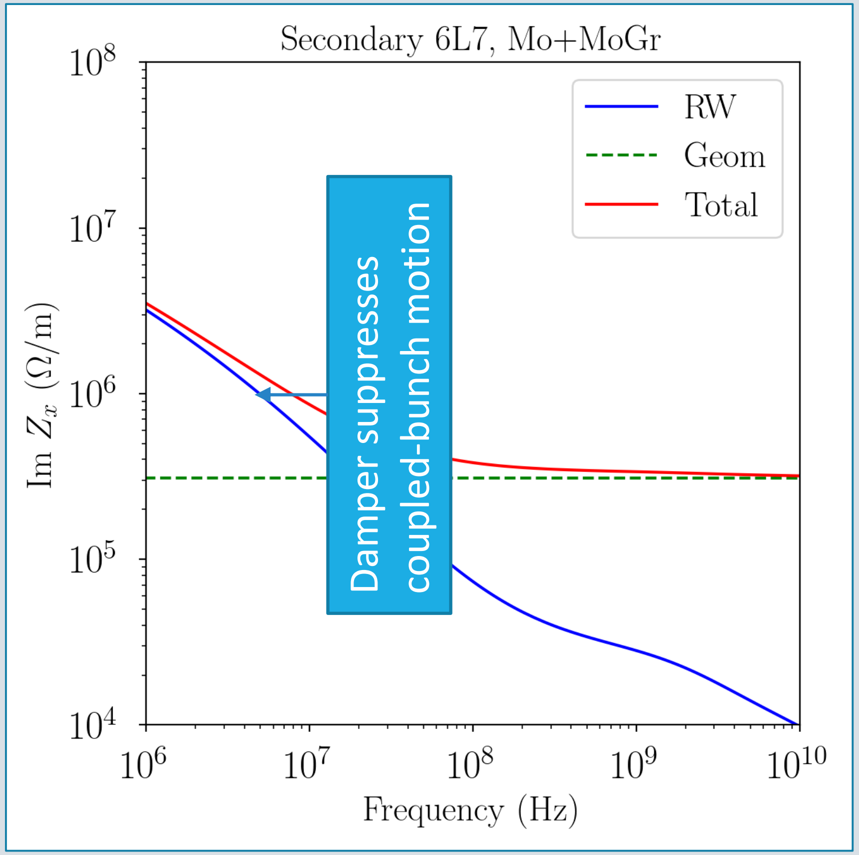


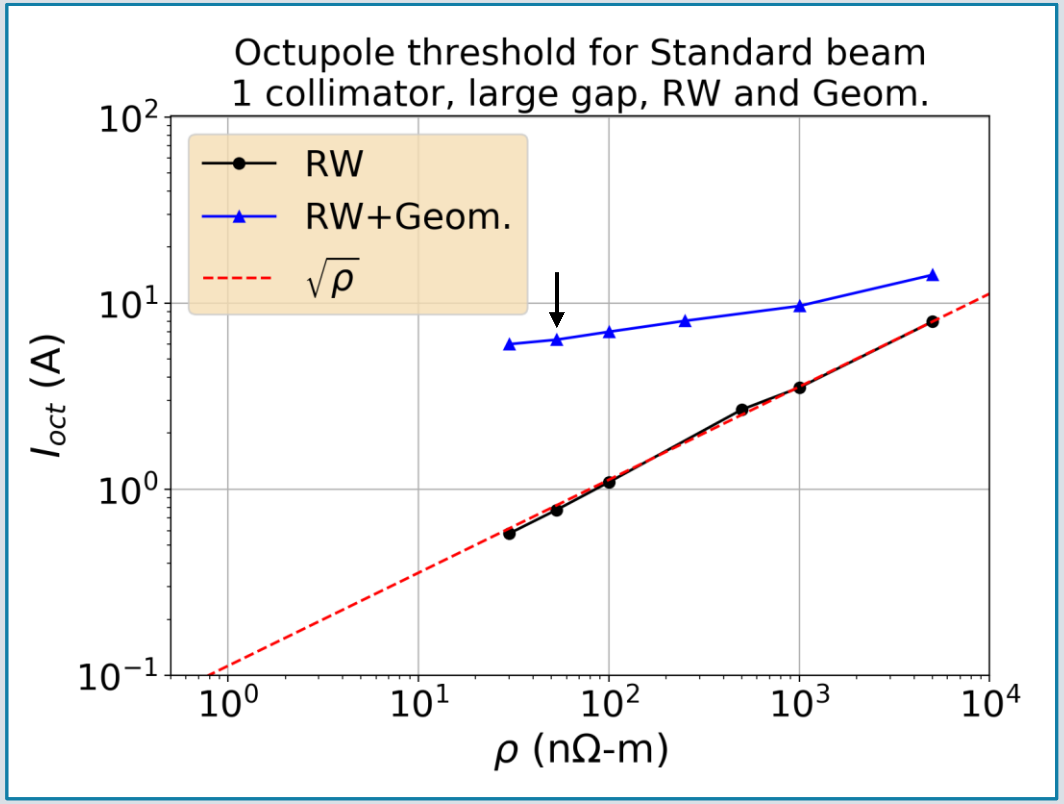
Damper suppresses coupled-bunch motion



Horizontal collimator, Halfgap: 3.1 mm

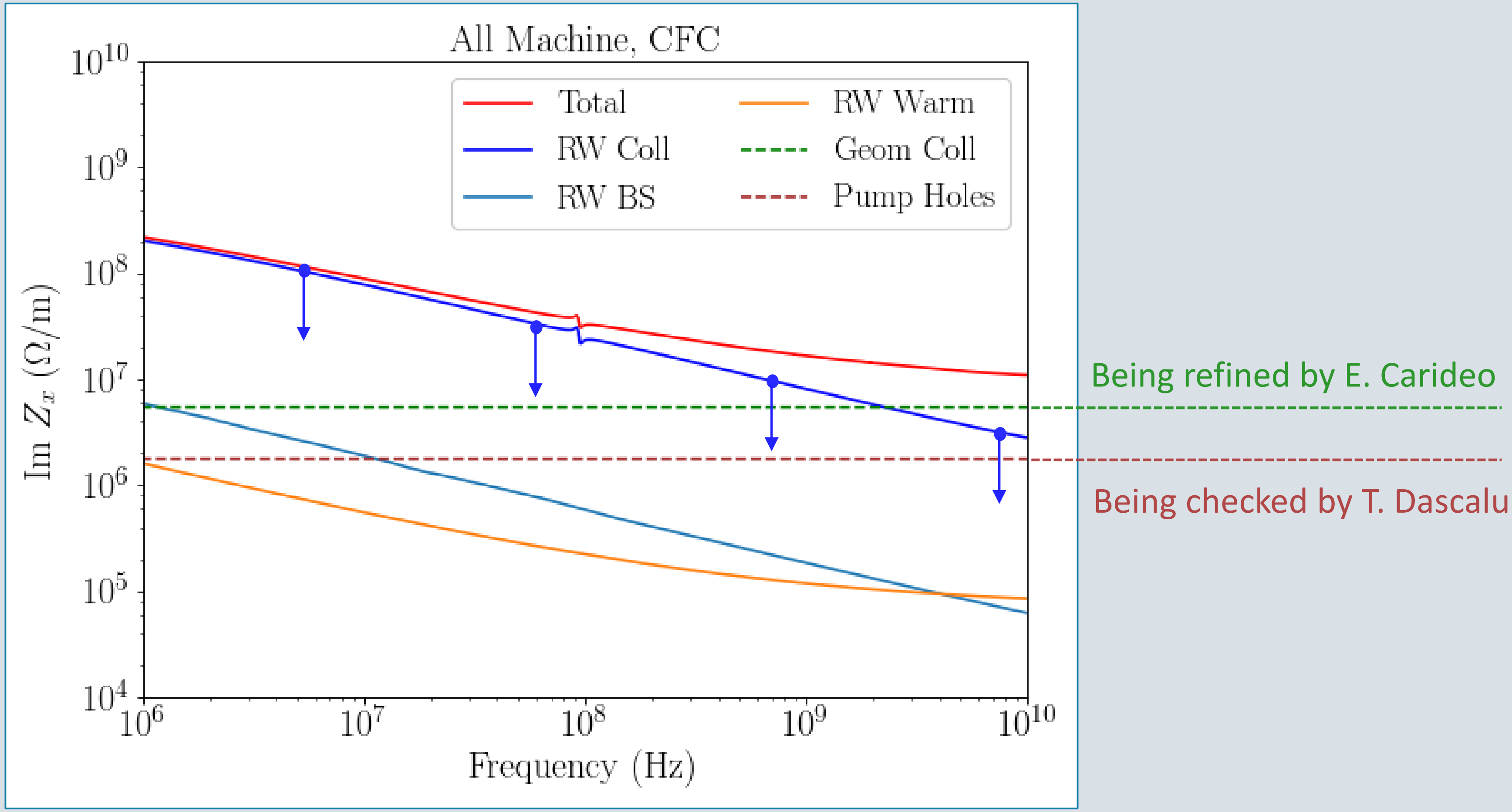
Coating is less efficient when other sources of impedance take part





Horizontal collimator, Halfgap: 3.1 mm

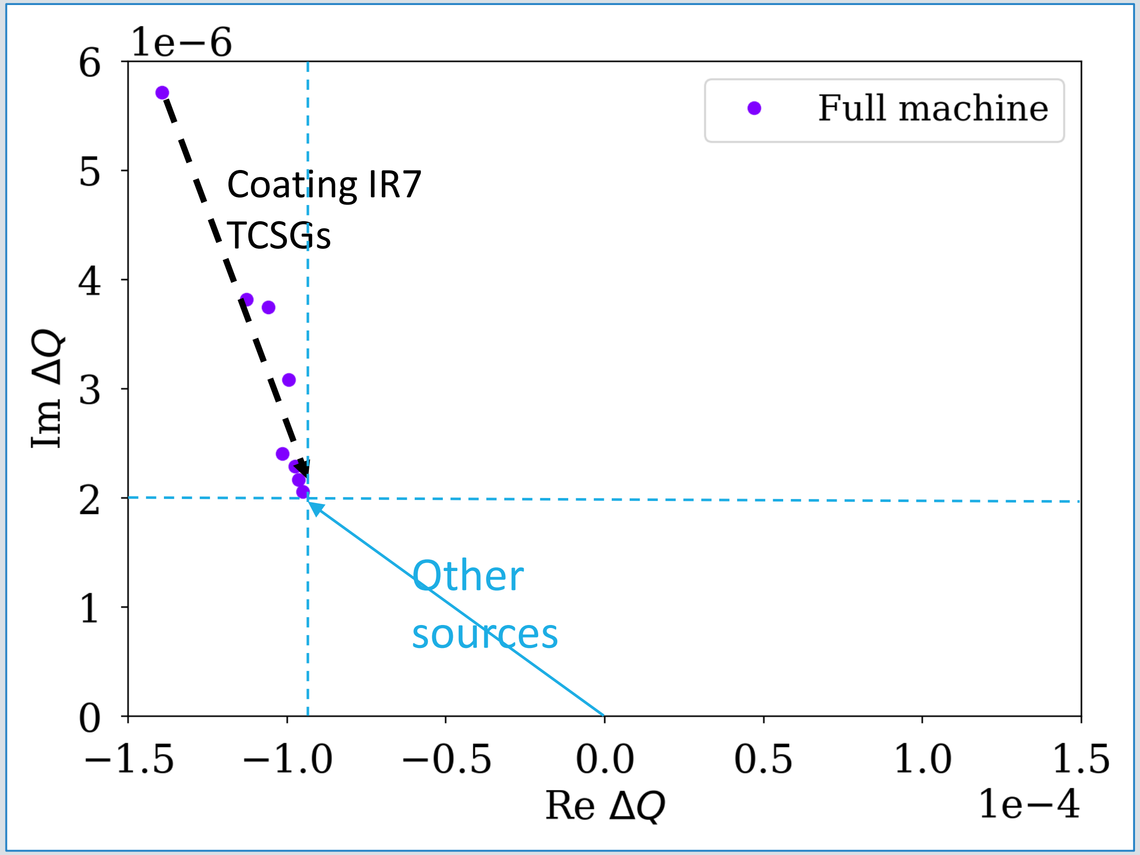
Broadband components of impedance limit how much the total can be reduced



Being refined by E. Carideo

Being checked by T. Dascalu

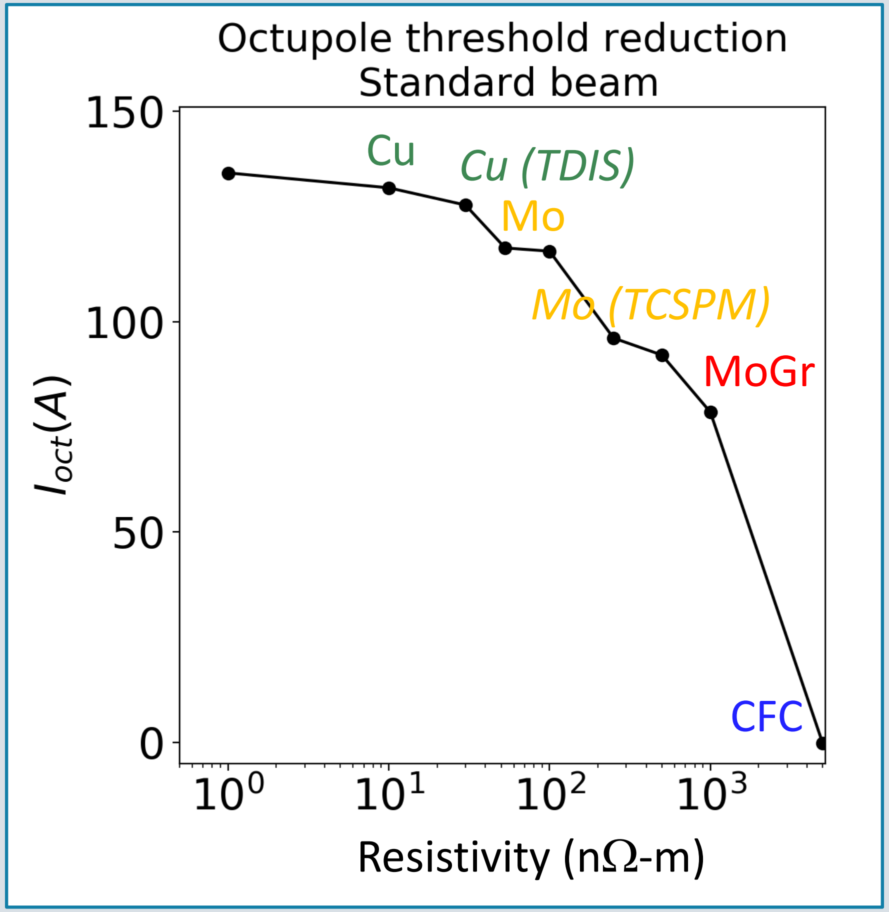
Stability diagram: Full machine



Coating IR7 TCSGs

Other sources

Further reducing the resistivity gets less effective as one goes to better conductors



What could be different (go wrong)?

Need tighter collimator settings for machine protection

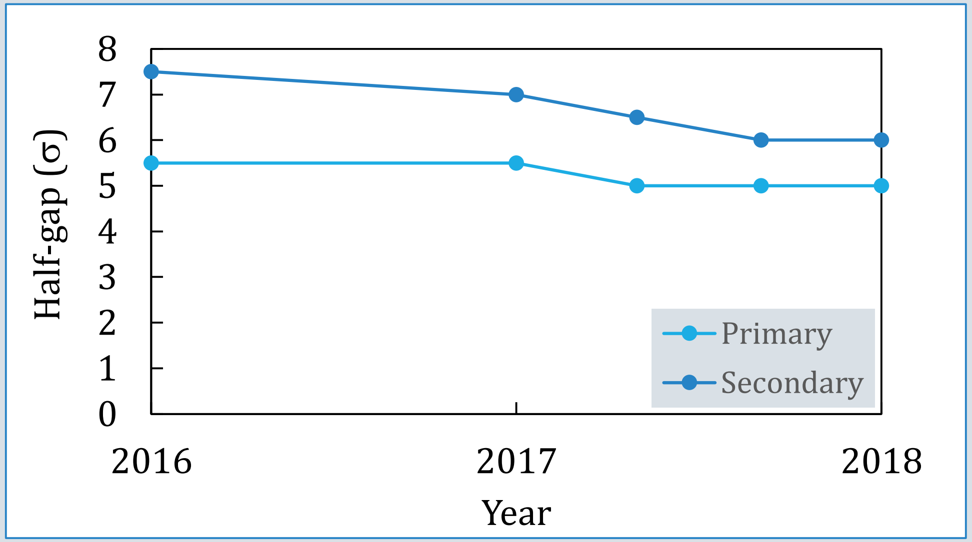
Mo coating does not perform as expected

Have to settle for uncoated secondary collimators

Something left unaccounted for in the model

- Refining the model of geometric impedance
- Noise leading to instabilities with large latency times
- Beam-beam interaction reducing the Stability Diagram

LHC keeps tightening the collimator gaps during its operation



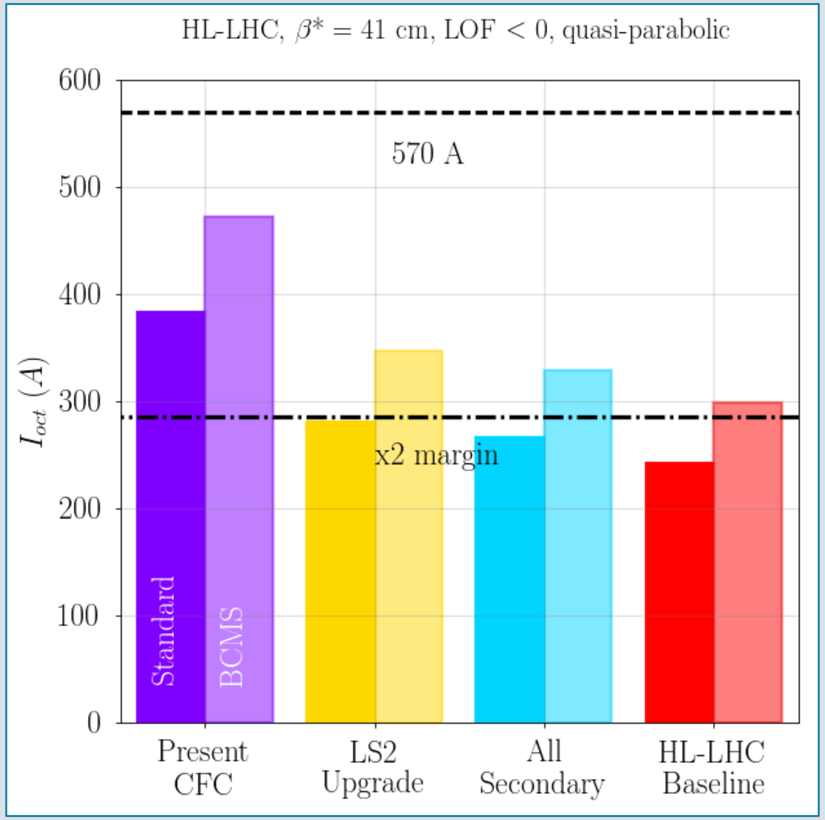
Originally, there were three collimator scenarios for HL-LHC:

- 1.0 σ: TCP – 6, TCS – 7 (for 3.5 μm ref. emittance, “Nominal” design report)
- 1.5 σ: TCP – 5, TCS – 6.5
- 2.0 σ: TCP – 5.7, TCS – 7.7 ← Ultimately became the baseline

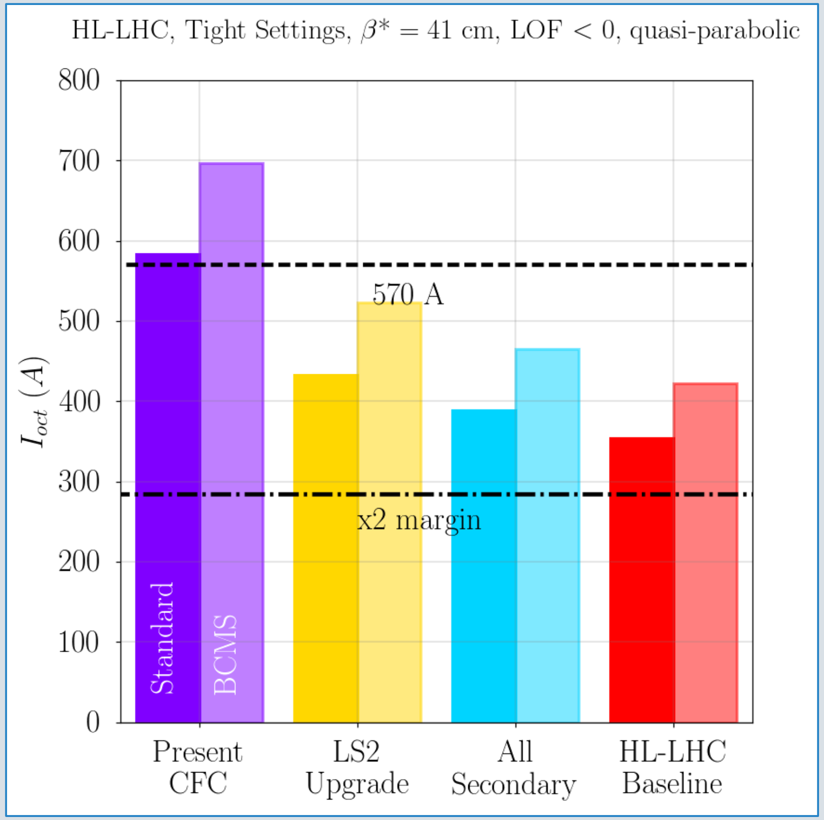
Are we sure the settings are not going to change in the future?

Little or no safety margin for tighter settings if the full impedance reduction is not done

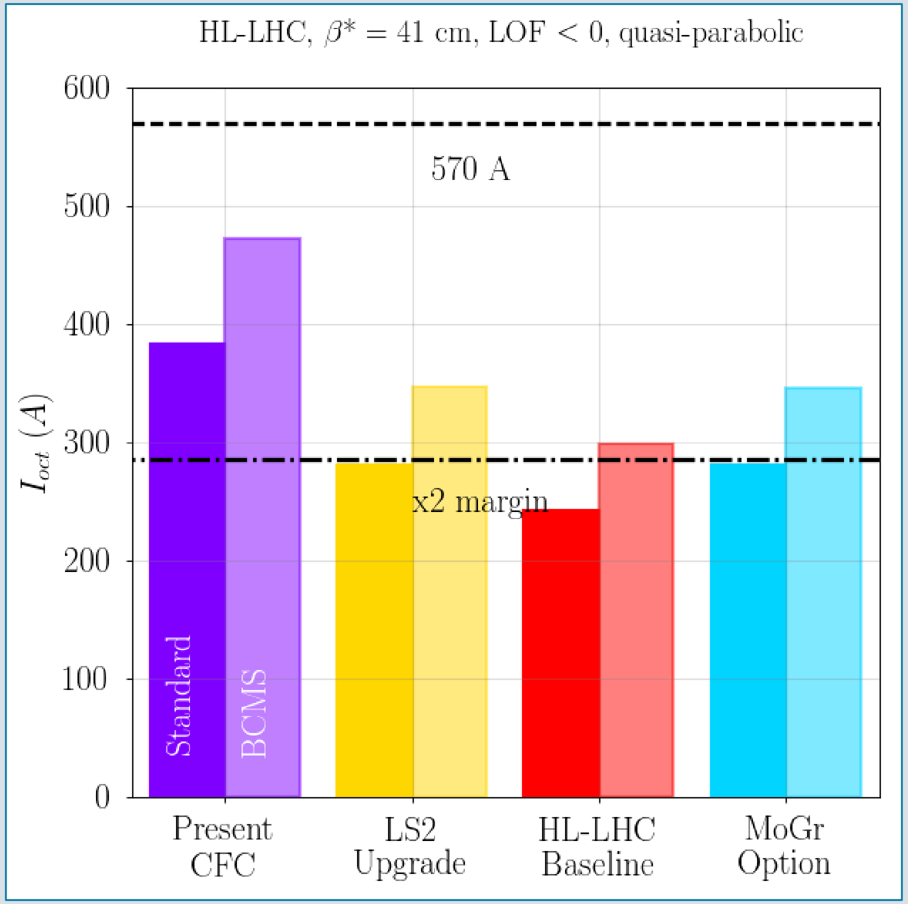
Nominal settings



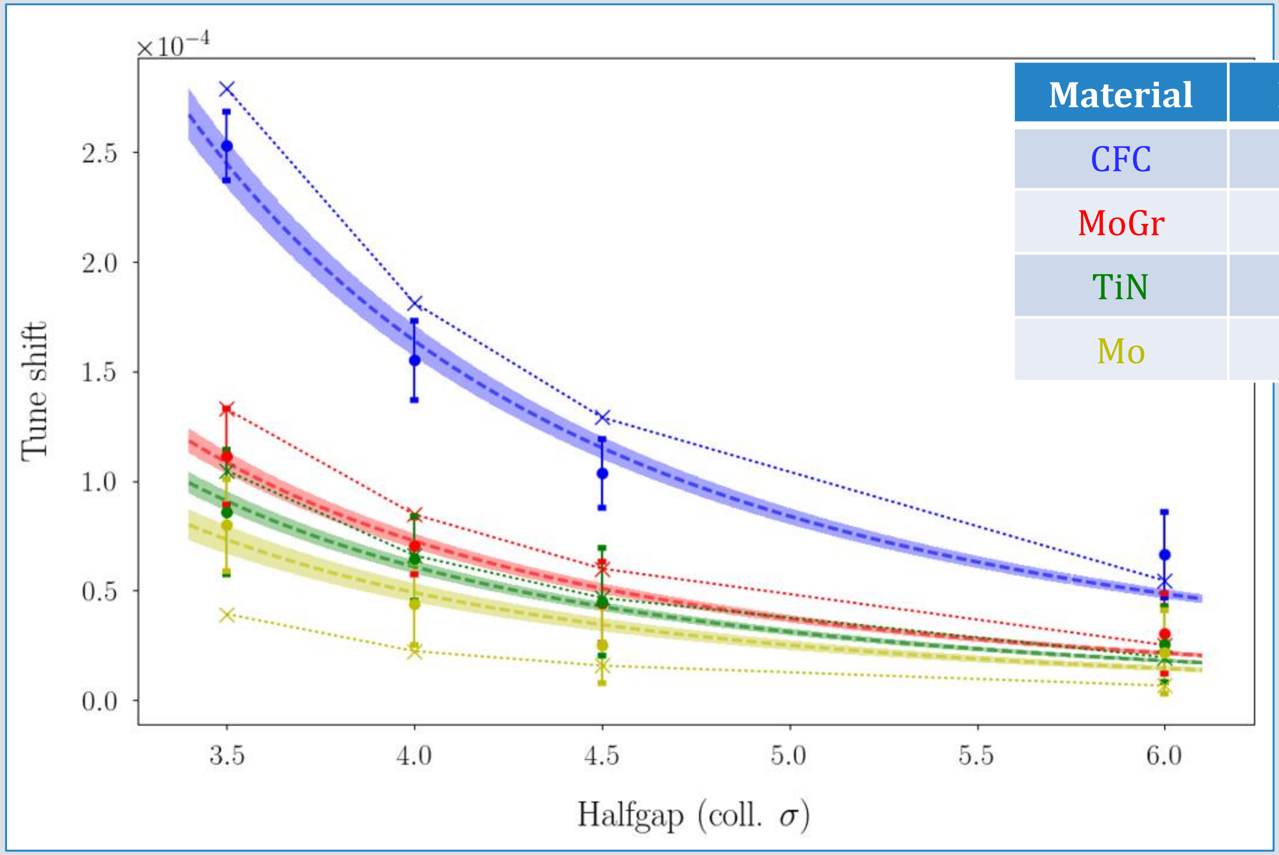
Tight (non-baseline) settings



Not coating the secondary collimators: Octupole current threshold – similar to post-LS2



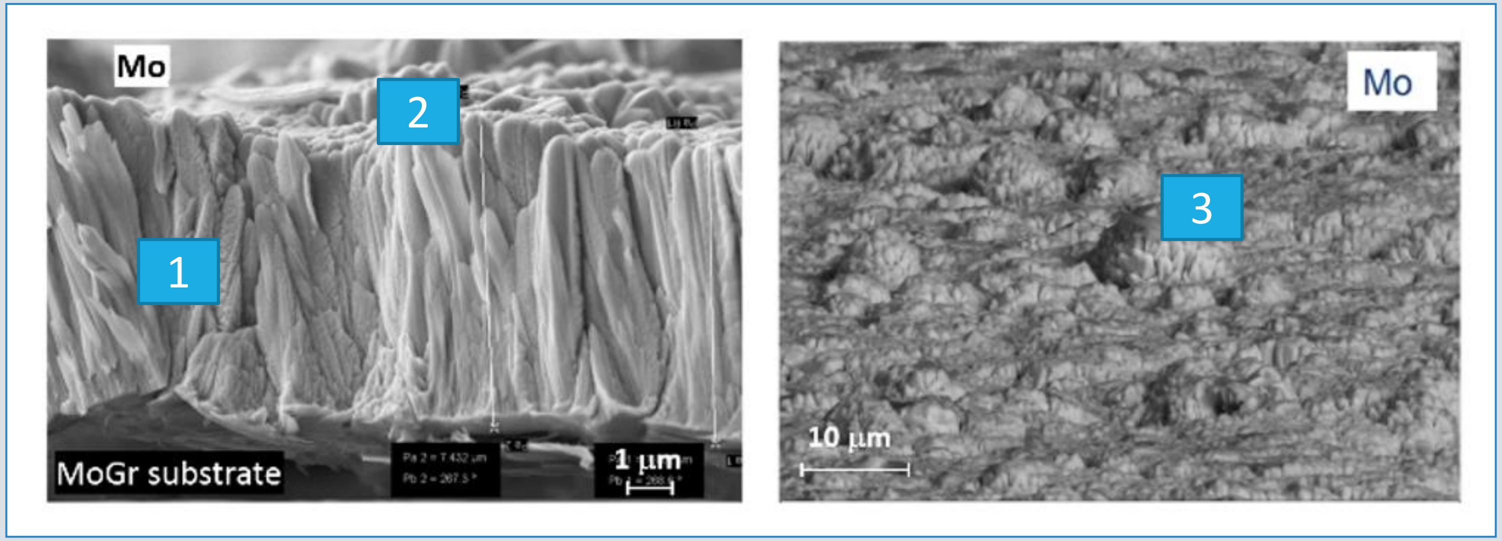
The actual resistivity of Mo coating might be higher than the model value



Material	Model	Beam	Lab: DC	Lab: RF
CFC	5000	4030 ± 380	5000 – 6000	-
MoGr	1000	760 ± 60	900 ± 100	-
TiN	400	340 ± 40	-	~400
Mo	53.5	250 ± 50	100 – 300	~300

S. Antipov, *et al.*, *IPAC’18*

Surface studies



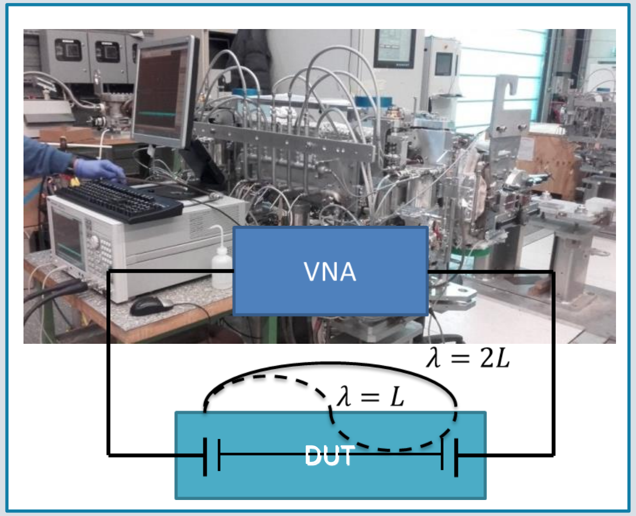
- Higher Mo resistivity could be related to:
  1. Coating grain size and number of boundaries – affect the resistivity
  2. Coating surface roughness – affect the imaginary impedance
  3. Presence of large ($< 10\mu m$) bumps on the surface – affect the imaginary impedance

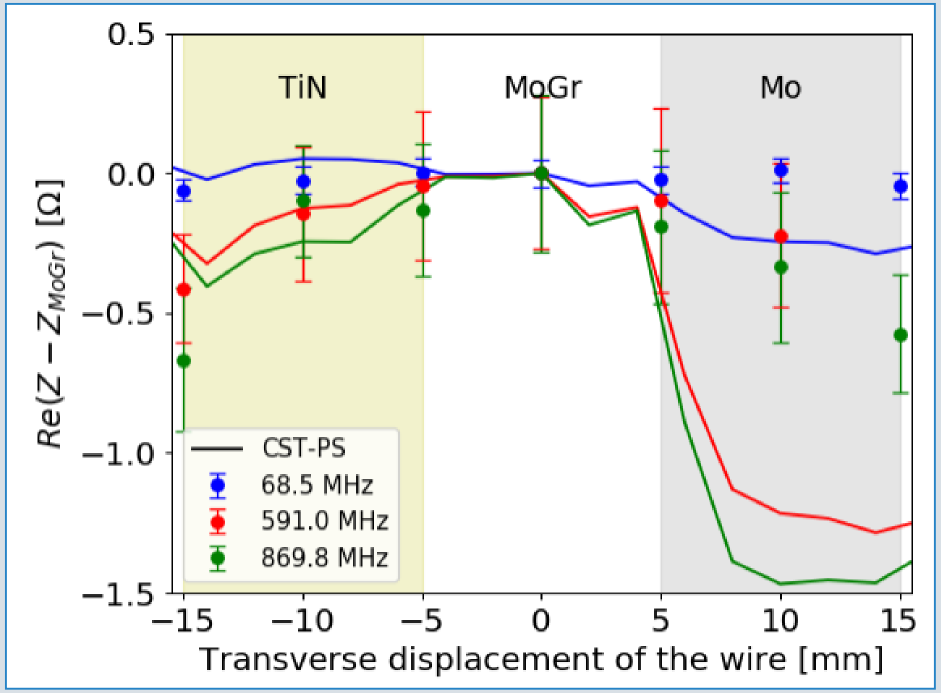
- Surface impurities could also increase effective resistivity

N. Biancacci, *et al.*, *IPAC'18*

Bench RF measurements suggest the importance of the microstructure

Resonant wire measurement setup

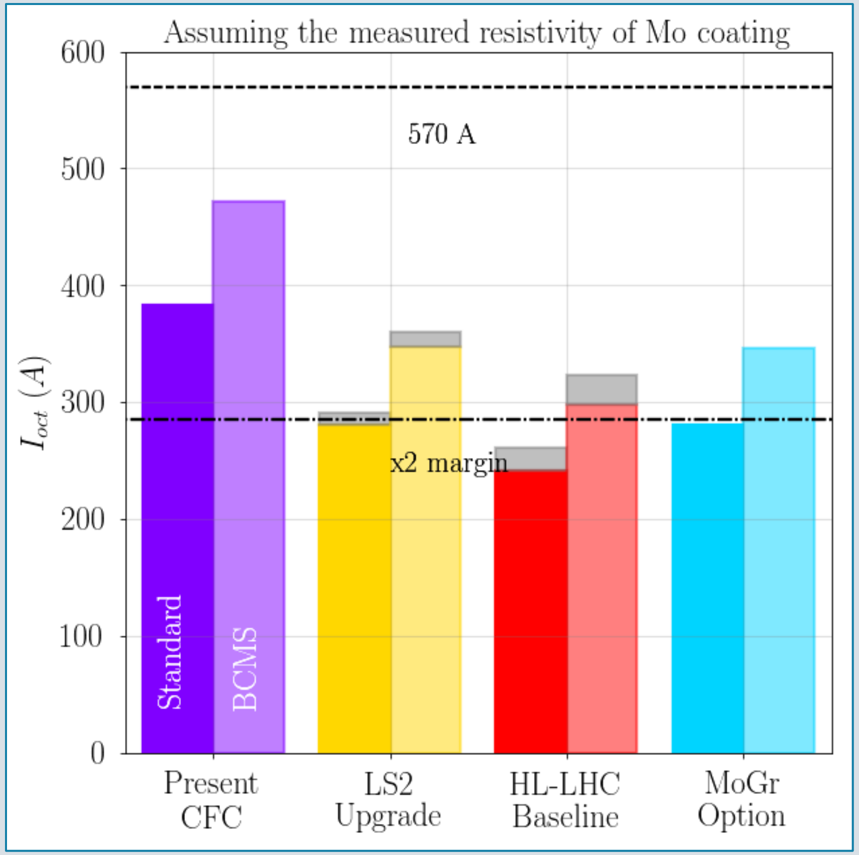




- Change in Q-factor → Real part of longitudinal impedance
- Agreement within error bars on TiN stripe
- Lower impedance reduction measured on Mo stripe → $\sim 300 n\Omega m$ Mo resistivity (expected $53 n\Omega m$)

N. Biancacci, *et al.*, *IPAC'18*

Impact of higher than expected Mo resistivity



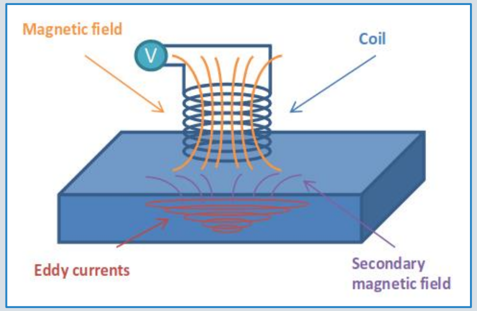
Assuming measured Mo resistivity (250 vs 54 nΩ-m): 25 (20) A reduction in margin for BCMS (Standard) beam

Latest Mo-coated samples show good electrical conductivity

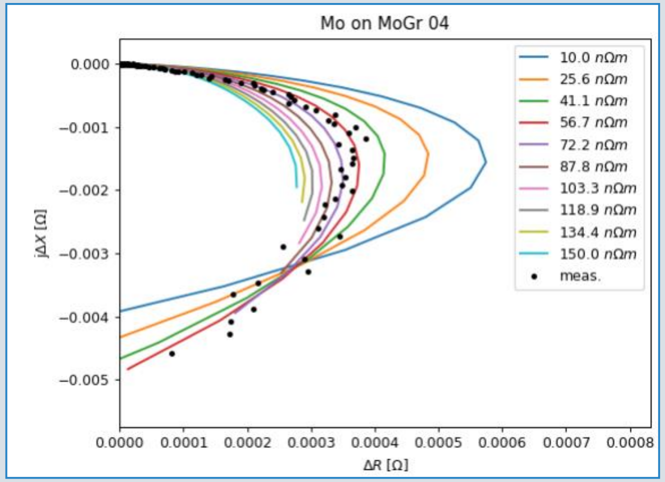
Eddy current measurement is required to qualify the coating

- DC not enough – not 'beam' frequency, does not account for surface roughness

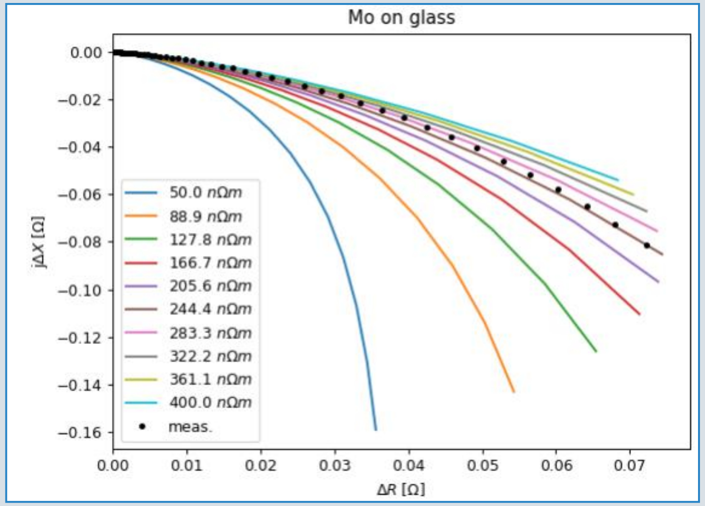
N. Biancacci, Update on Mo coating resistivity, 18.05.18



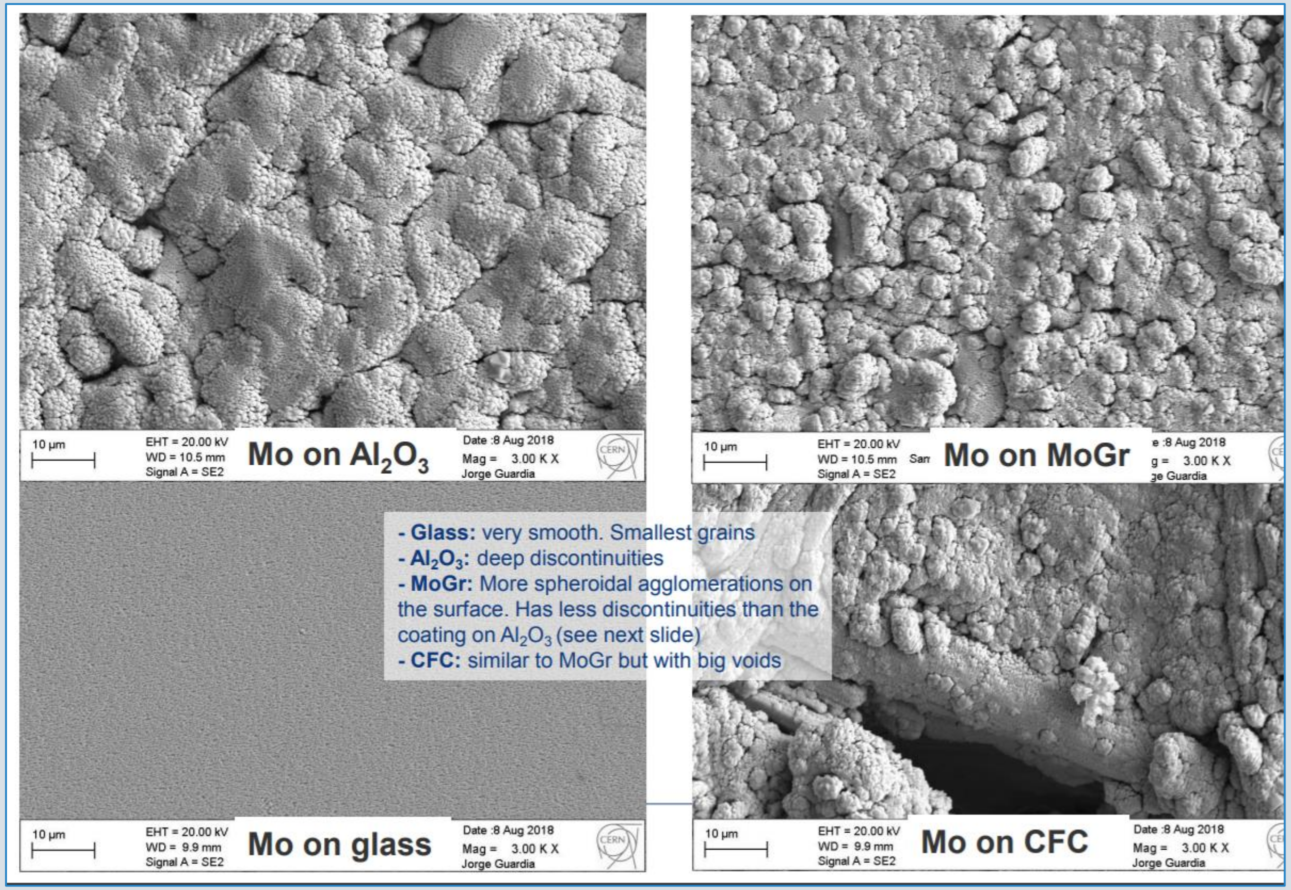
Newer coatings show 60-70 nΩ-m



Some (older ones) feature up to 300 nΩ-m



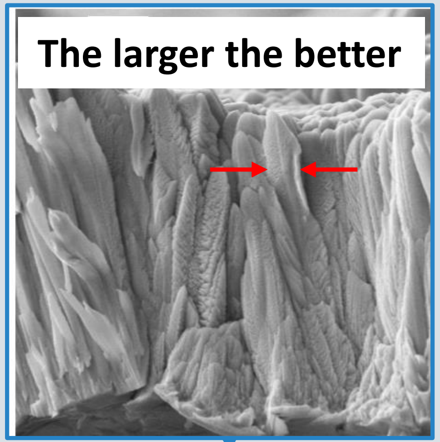
The increase in Mo resistivity is likely to be governed by its microstructure

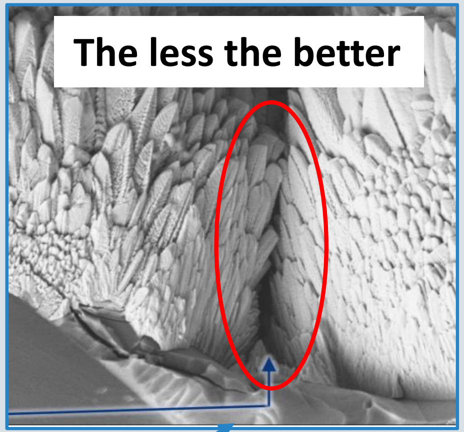


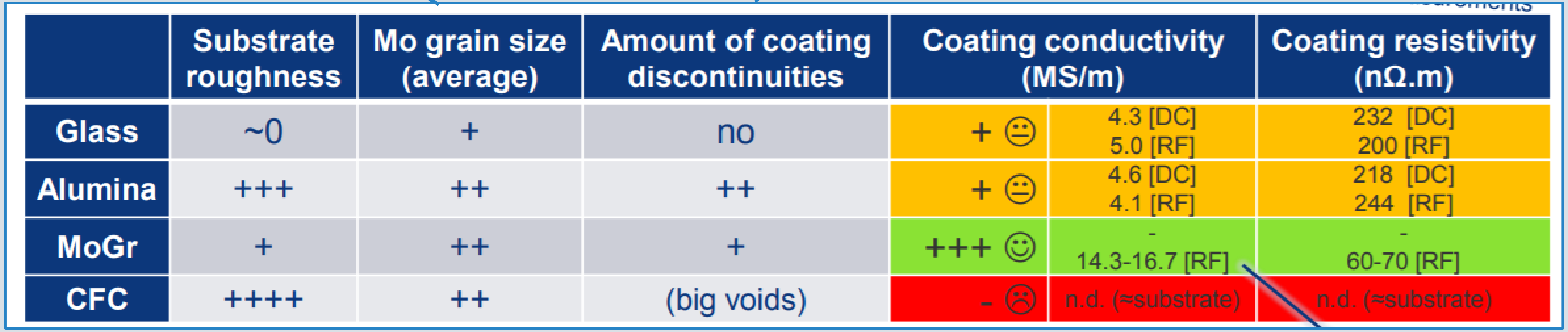
- **Glass:** very smooth. Smallest grains
- **Al_2O_3:** deep discontinuities
- **MoGr:** More spheroidal agglomerations on the surface. Has less discontinuities than the coating on Al_2O_3 (see next slide)
- **CFC:** similar to MoGr but with big voids

J. Guardia, Impedance Meeting, 24.08.18

The increase in Mo resistivity is likely to be governed by its microstructure



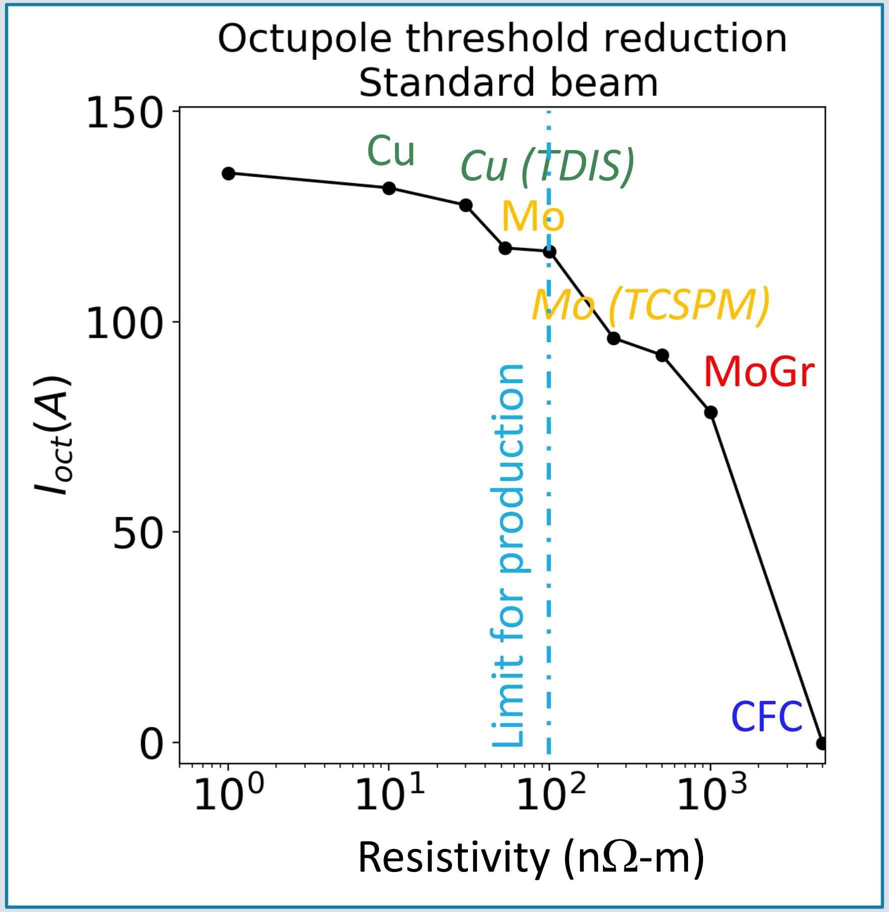




	Substrate roughness	Mo grain size (average)	Amount of coating discontinuities	Coating conductivity (MS/m)		Coating resistivity (nΩ.m)
Glass	~0	+	no	+ 😐	4.3 [DC] 5.0 [RF]	232 [DC] 200 [RF]
Alumina	+++	++	++	+ 😐	4.6 [DC] 4.1 [RF]	218 [DC] 244 [RF]
MoGr	+	++	+	+++ ☺	- 14.3-16.7 [RF]	- 60-70 [RF]
CFC	++++	++	(big voids)	- ☹	n.d. (≈substrate)	n.d. (≈substrate)

J. Guardia, Impedance Meeting, 24.08.18

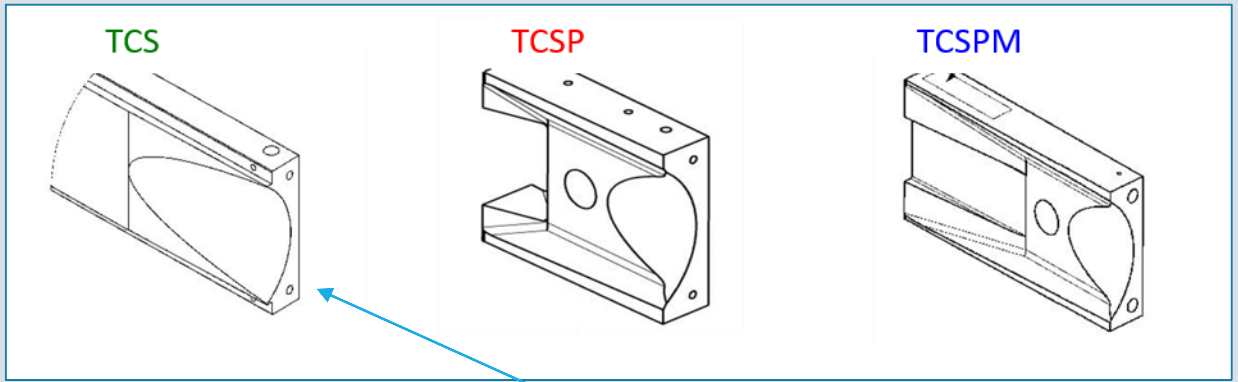
Propose to set the limit for production such that a degradation of the octupole current is < 10%



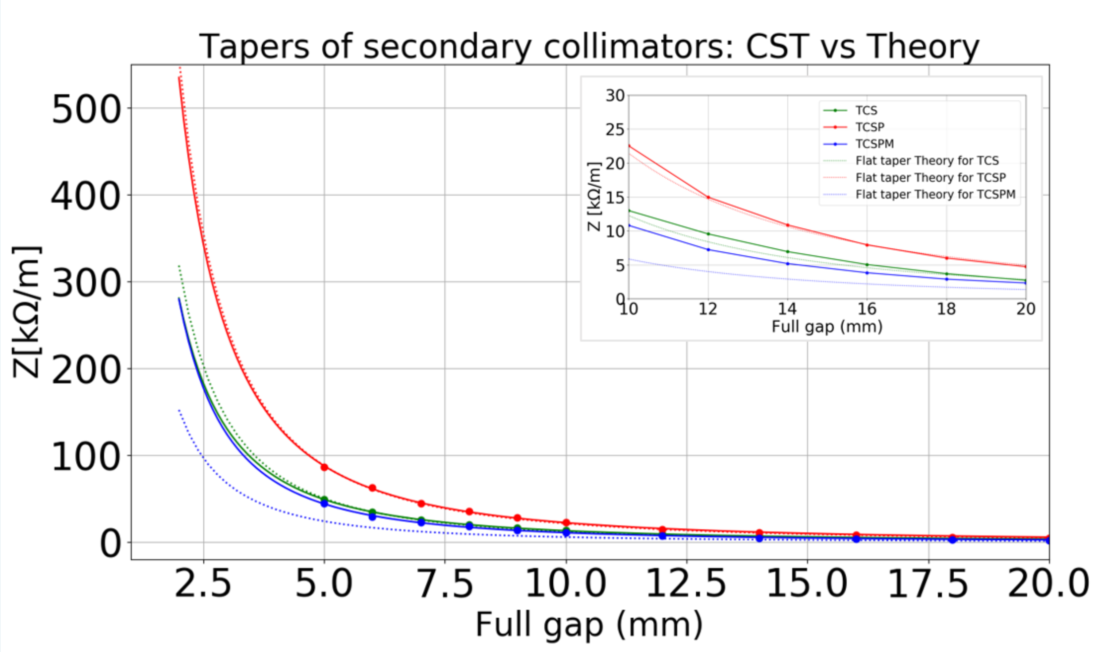
Changes in geometric impedance: New taper geometries

TCS	**TCSP**	**TCSPM**
11,6°	16°, 16,5°	16,5°, **5°**
97 mm	37 mm, 27 mm	36 mm, 80 mm

Optimized for Imp.

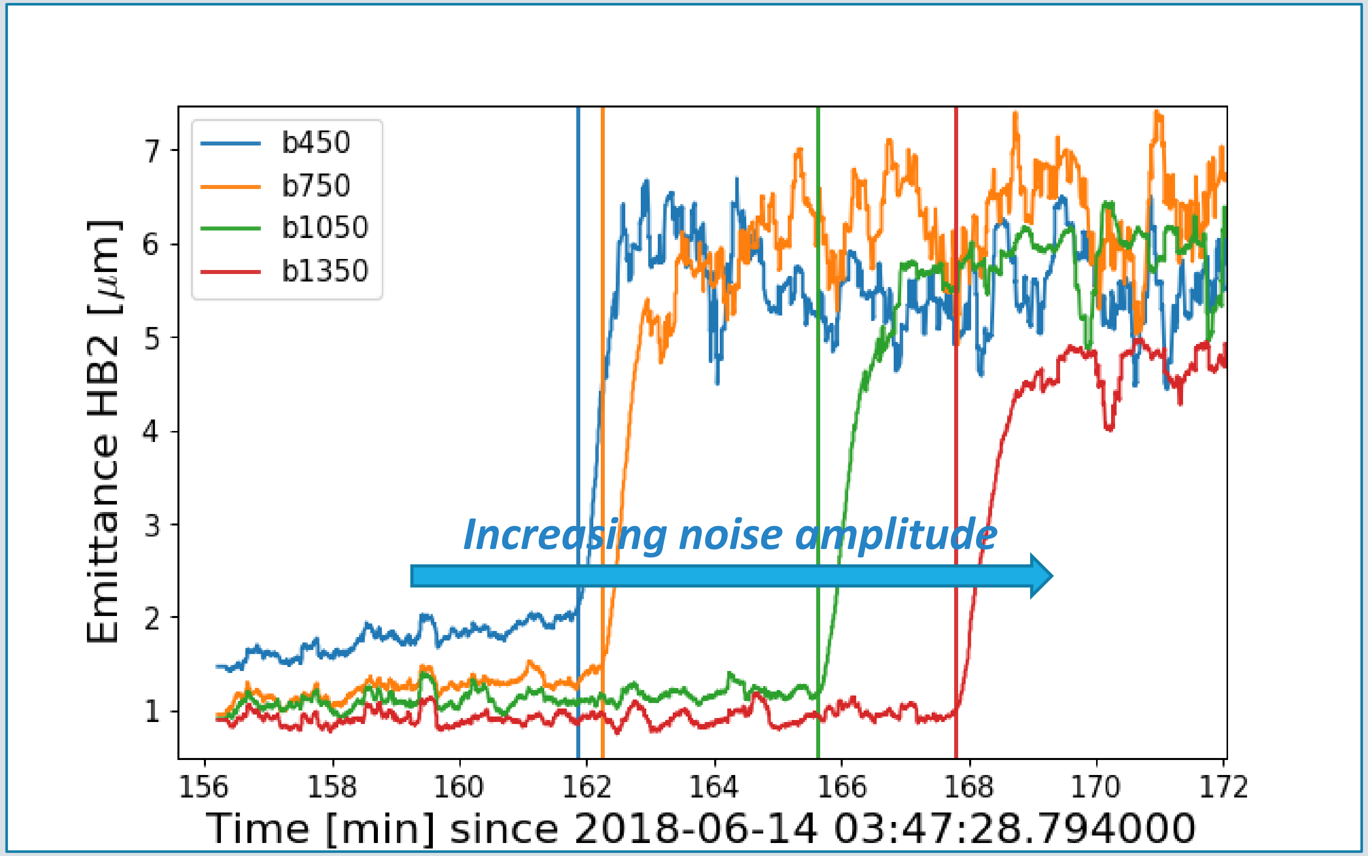


This is the only geometry in the model at the moment
Simulated as a broadband flat taper impedance



E. Carideo

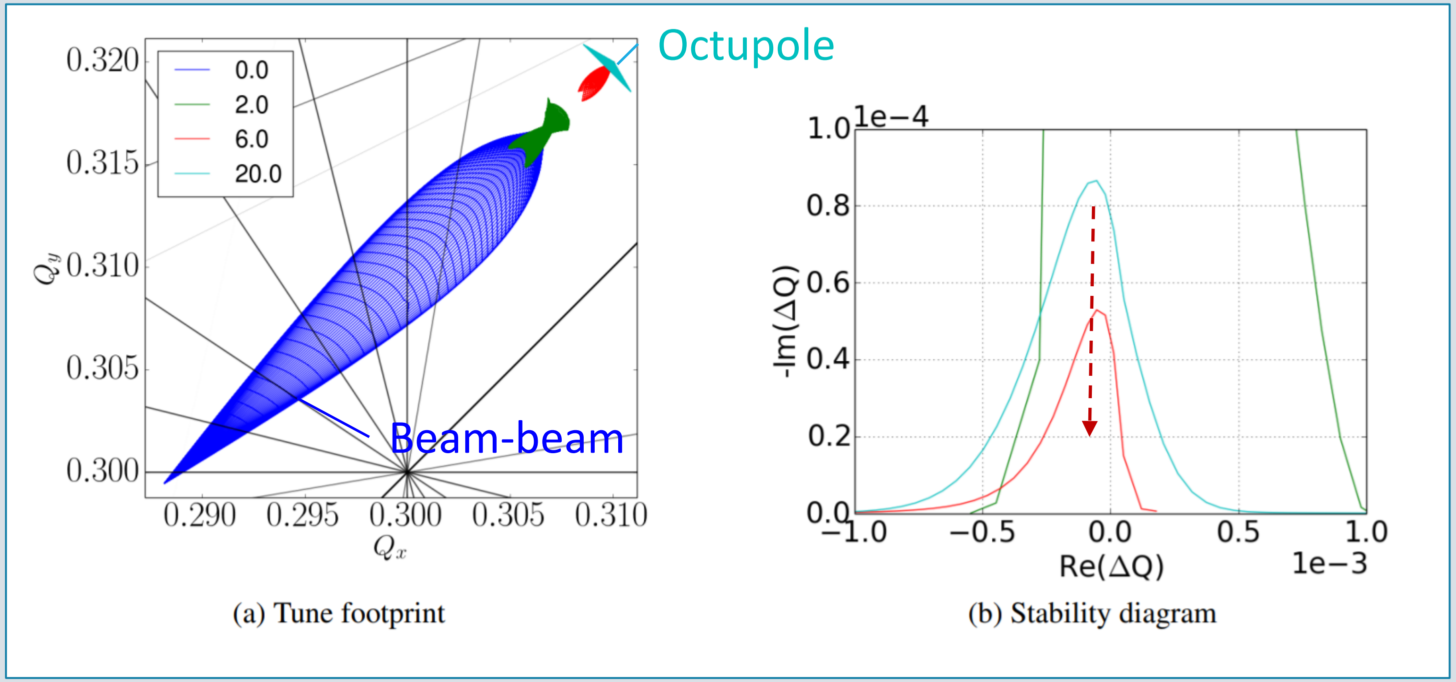
Noise triggers an instability with high latency time at Flat-Top



Stability diagram collapses as the beams are brought into collision

Minimum at a certain beam separation

Predicted theoretically and observed in a dedicated MD



(a) Tune footprint

(b) Stability diagram

X. Buffat *et al.*, CERN-ACC-NOTE-2018-0036, 2018

Conclusions

IR-7 primary and secondary collimators are the right target for impedance reduction

- From the past operational experience, a x2 margin in octupole threshold is required
- Mo coating on MoGr offers the largest reduction of impedance and octupole current in HL-LHC
- For the ultimate scenario one gains up to 150 A (BCMS beam) by coating all the secondaries in IR-7
- Additional 30 A (BCMS) can be gained by replacing the 2 primary collimators with MoGr
- 1/2 the gain with LS2 upgrade (2 primary + 4 secondary) or with uncoated MoGr secondaries

A collimator resistive wall component of the octupole threshold scales as $\rho^{-1/2}$

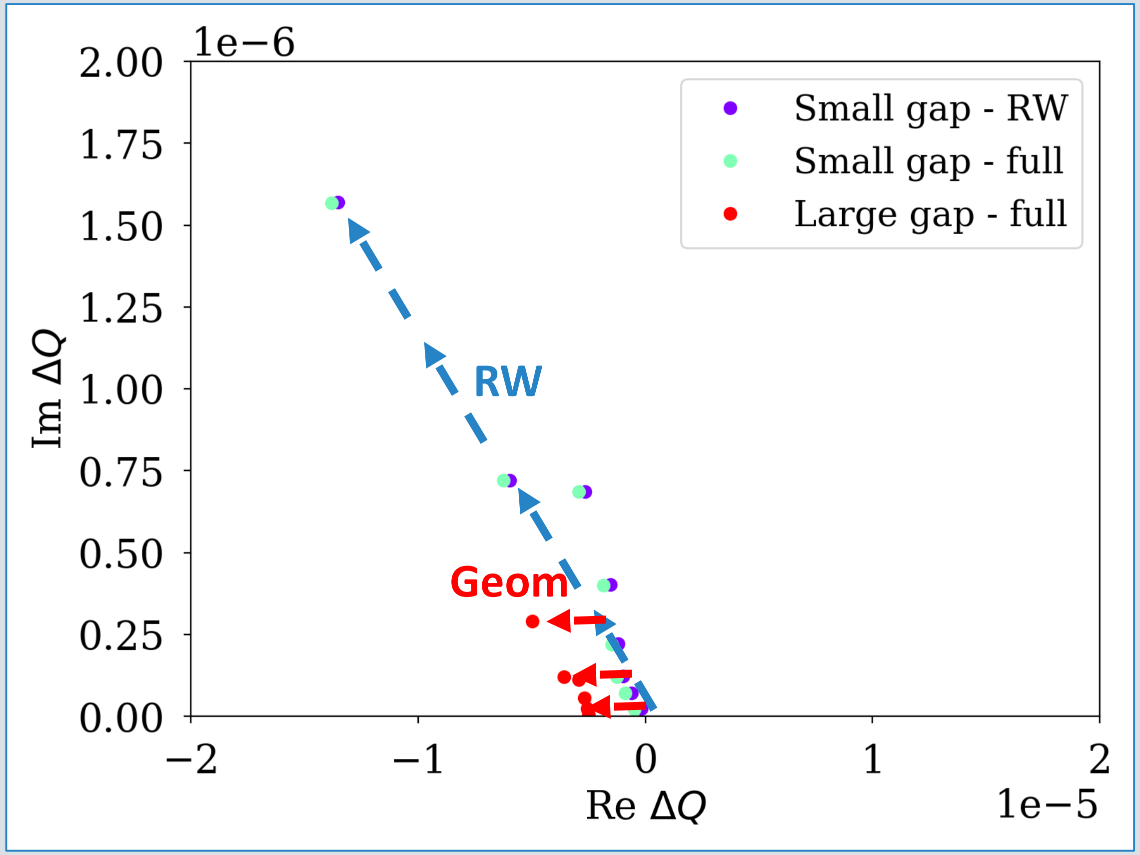
- Coating provides a large gain $\left(\rho_{Mo} / \rho_{CFC}\right)^{-1/2} \sim 10$
- Only for the collimators that are close to the beam; further away – the taper geometry plays a role

In a realistic accelerator the scaling is worse than $\rho^{-1/2}$

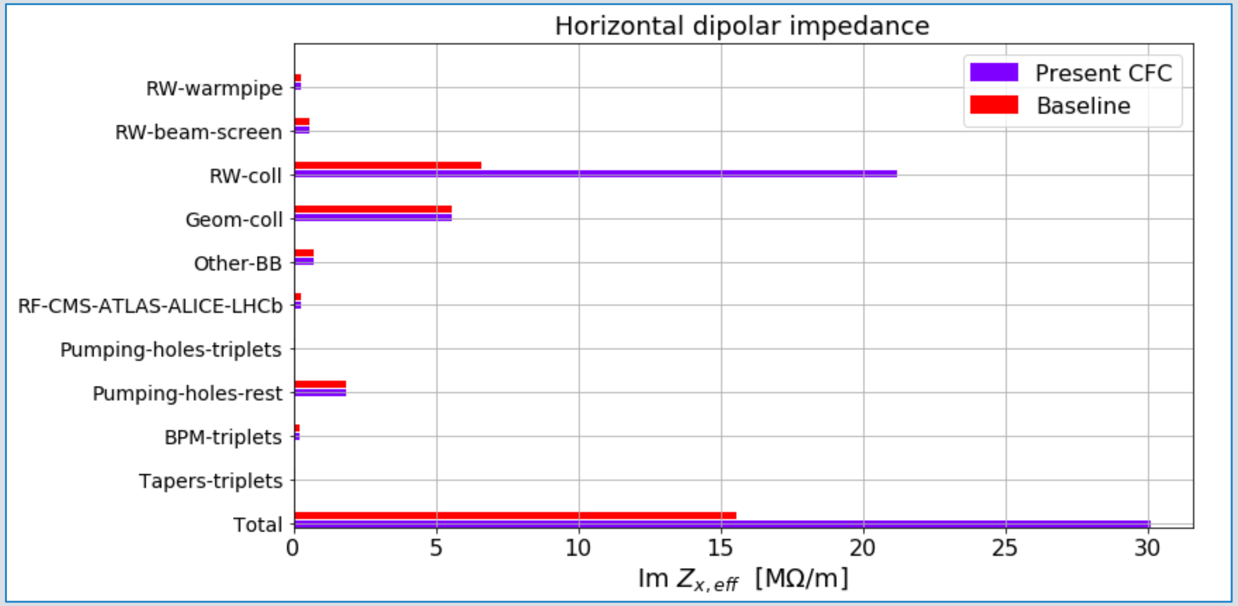
- Other sources of impedance: beam screen, tapers, etc. Act on 50% of effective beam impedance
- At small resistivities, a further reduction is less effective
- Can set a limit of 100 nΩ-m for the production Mo coatings

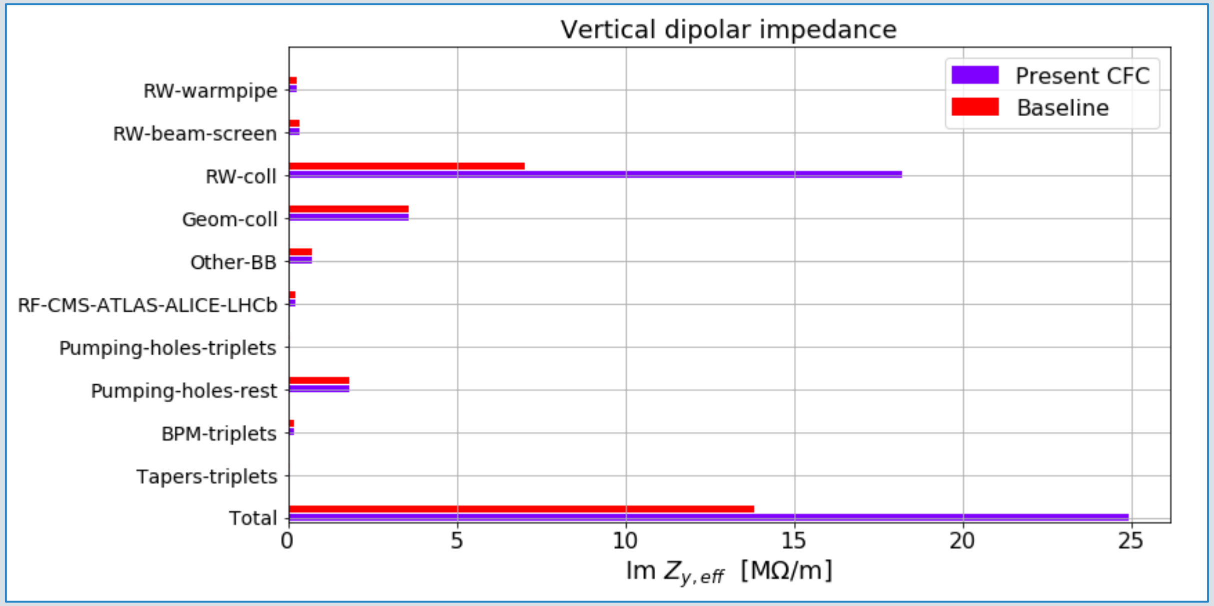
Back-up

Stability diagram: 1 Collimator

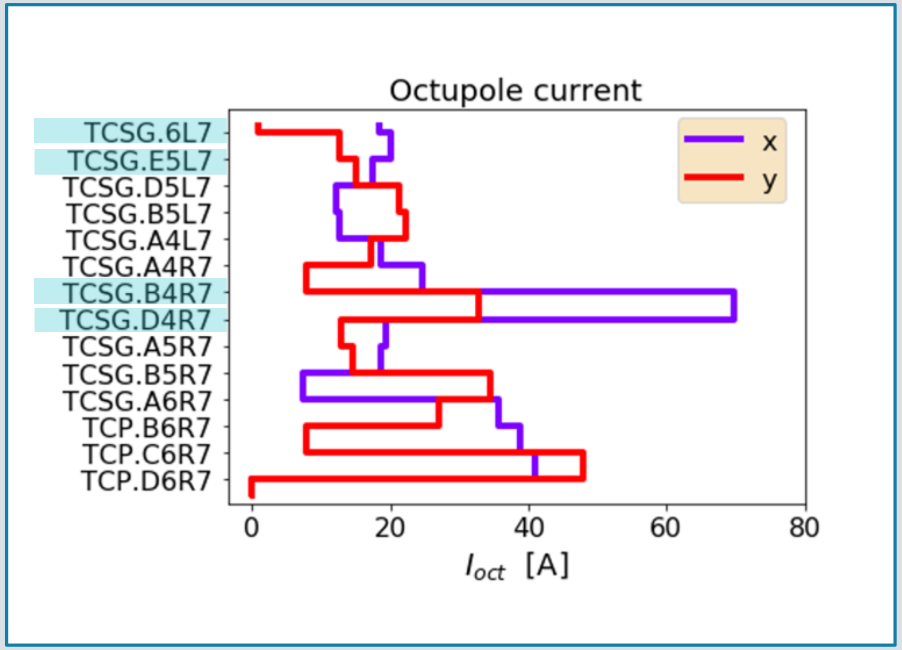


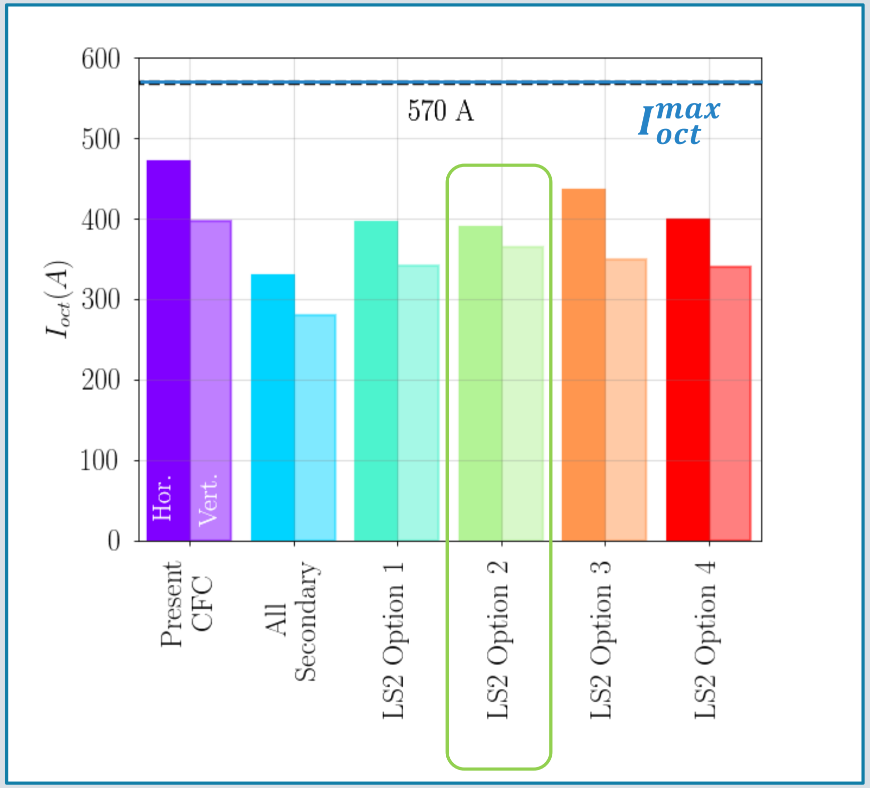
Geometric component of collimator tapers is comparable to resistive wall after the upgrade





Staged installation of low impedance collimators in LS2: Maximizing reduction in the most critical, horizontal plane

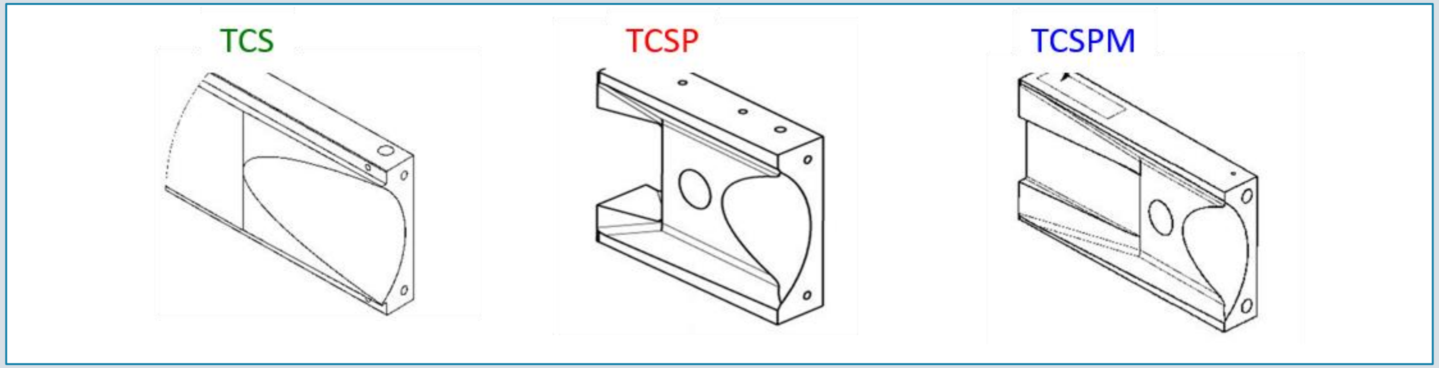




- Impedance reduction
- Injection/extraction failure events or asynchronous dumps
- Steady exposure to beam losses

Fitting the taper impedance: $Z[\mathrm{Omh/m}] = A * g[\mathrm{m}]^{-\alpha}$

Name	A	α
TCS	$2{,}07*10^{-3}$	1.9
TCSP	$2{,}57*10^{-3}$	2.0
TCSPM	$1{,}02*10^{-3}$	2.0



The model can be used to refine the prediction for HL-LHC

- Work ongoing

E. Carideo

TMCI Threshold for different coating scenarios

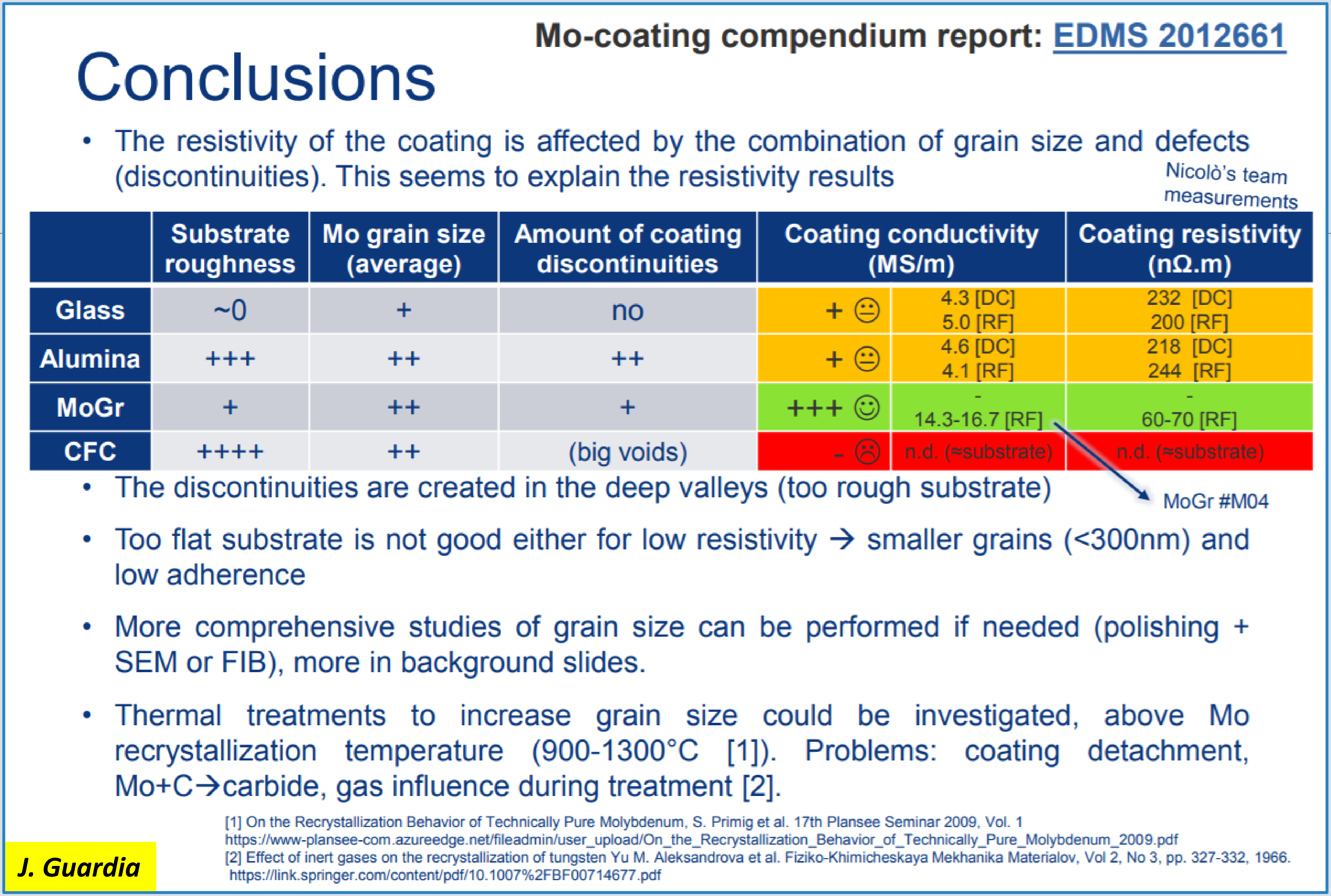
Simulated Measured

Simulated

	TCPs	TCSGs	TMCI threshold (DELPHI)$[10^{11} p.p.b]$
LHC ft 2017	-	-	2.6
LHC ft 2017, TCSGs at $14\sigma_{coll}$	-	-	5.0
HL-LHC LS2.2 uncoated TCSGs	2 in MoGr	4 in MoGr	5.7
HL-LHC LS2.2 coated TCSGs	2 in MoGr	4 in MoGr with Mo coating	6.3
HL-LHC full upgrade uncoated TCSGs	2 in MoGr	All in MoGr	6.7
HL-LHC full upgrade (baseline)	2 in MoGr	All in MoGr with Mo coating	8.7

Looser settings

D. Amorim



Mo-coating compendium report: EDMS 2012661

Conclusions

- The resistivity of the coating is affected by the combination of grain size and defects (discontinuities). This seems to explain the resistivity results

Nicolò's team measurements

	Substrate roughness	Mo grain size (average)	Amount of coating discontinuities	Coating conductivity (MS/m)		Coating resistivity (nΩ.m)
Glass	~0	+	no	+ 😐	4.3 [DC] 5.0 [RF]	232 [DC] 200 [RF]
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CFC	++++	++	(big voids)	- ☹	n.d. (≈substrate)	n.d. (≈substrate)

MoGr #M04

- The discontinuities are created in the deep valleys (too rough substrate)
- Too flat substrate is not good either for low resistivity → smaller grains (<300nm) and low adherence
- More comprehensive studies of grain size can be performed if needed (polishing + SEM or FIB), more in background slides.
- Thermal treatments to increase grain size could be investigated, above Mo recrystallization temperature (900-1300°C [1]). Problems: coating detachment, Mo+C→carbide, gas influence during treatment [2].

[1] On the Recrystallization Behavior of Technically Pure Molybdenum, S. Primig et al. 17th Plansee Seminar 2009, Vol. 1 https://www-plansee-com.azureedge.net/fileadmin/user_upload/On_the_Recrystallization_Behavior_of_Technically_Pure_Molybdenum_2009.pdf

[2] Effect of inert gases on the recrystallization of tungsten Yu M. Aleksandrova et al. Fiziko-Khimicheskaya Mekhanika Materialov, Vol 2, No 3, pp. 327-332, 1966. https://link.springer.com/content/pdf/10.1007%2FBF00714677.pdf

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