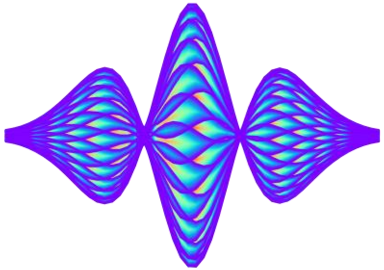

Impedance models, operational experience and expected limitations
(20 + 10 min, 17 slides)

Elias Métral for the impedance and instability team
(BE-ABP-HSC and BE-ABP) in close collaboration with collimation team
Many thanks to many HL-LHC colleagues!

International Review of the HL-LHC Collimation System, CERN, 11-12/02/2019

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Introduction (1/4)

- Collimators => Impedance => Beam instabilities => 3 main mitigation methods for both LHC and HL-LHC
  - Landau Octupoles (**LO**) => Possible boost from **ATS** optics
  - Chromaticity (**Q'**)
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- Collimators => Impedance => Beam instabilities => 3 main mitigation methods for both LHC and HL-LHC
  - Landau Octupoles (**LO**) => Possible boost from **ATS** optics
  - Chromaticity (**Q'**)
  - Transverse Damper (**TD**)
- Trade-off with Dynamic Aperture (**DA**) and beam lifetime
  - **LO**: value and sign to be optimised
  - **Q'**: value and sign to be optimised
  - **TD**: gain / bandwidth / noise to be optimised => Important for HL-LHC

Introduction (2/4)

- LHC from design report (2004) at 7 TeV => **LO** stability diagram (**TCBI**)

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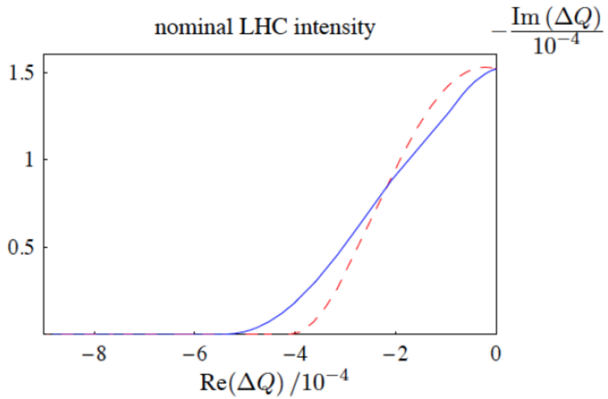

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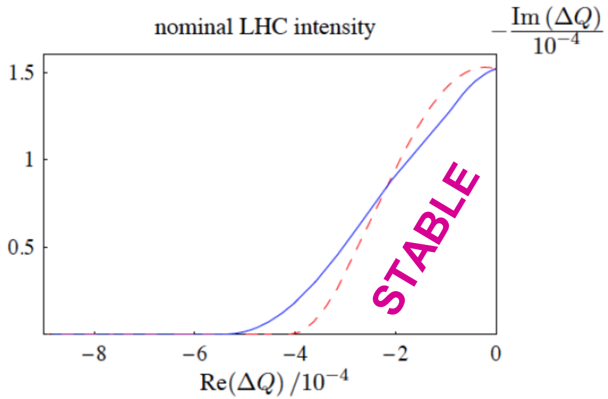

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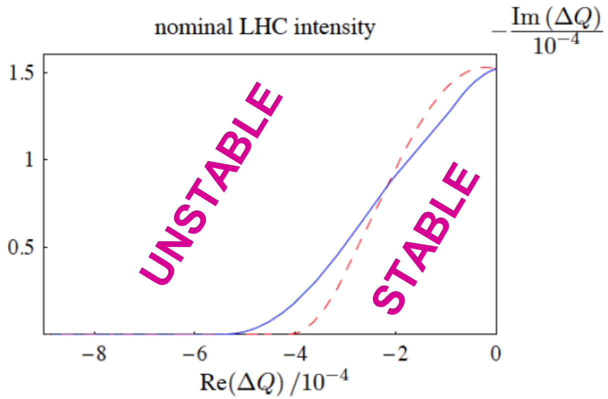

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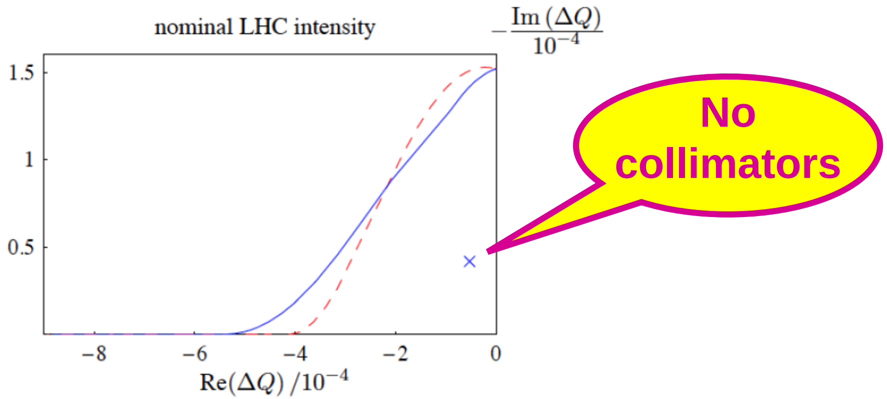

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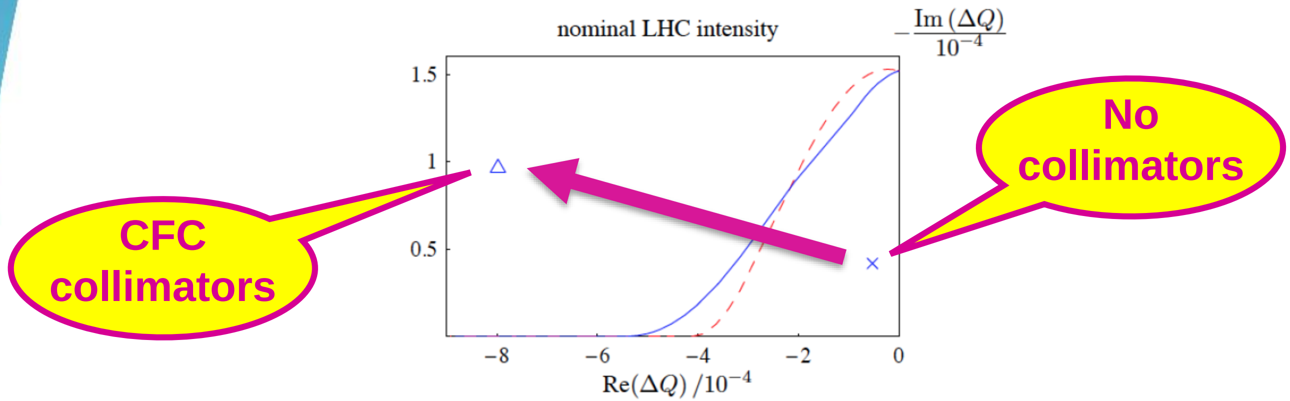

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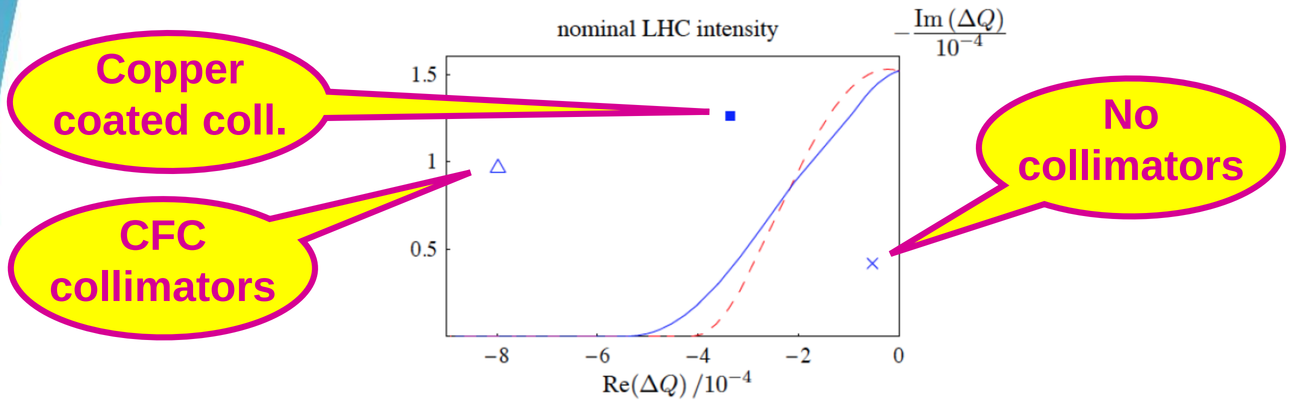

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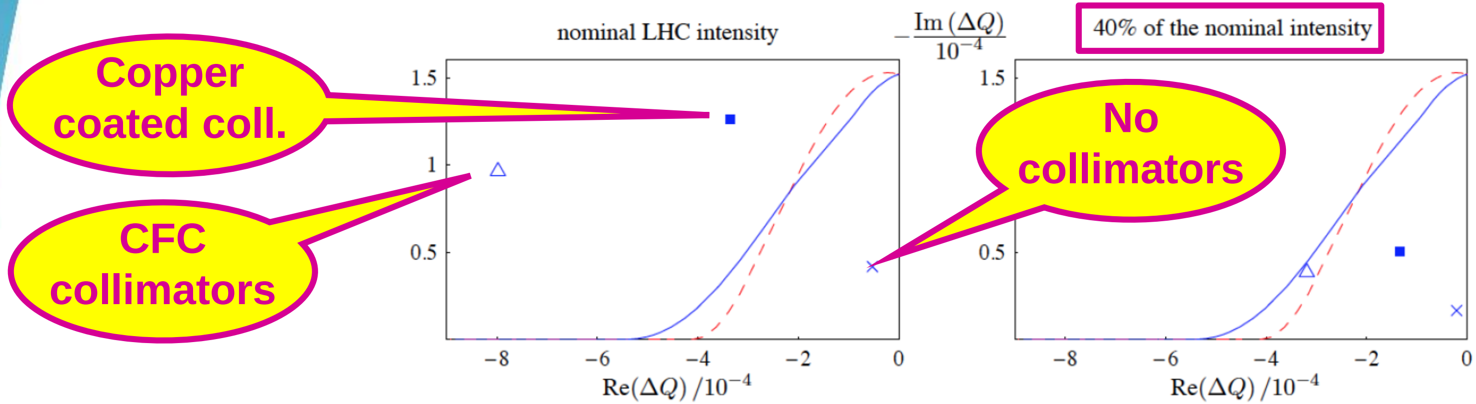

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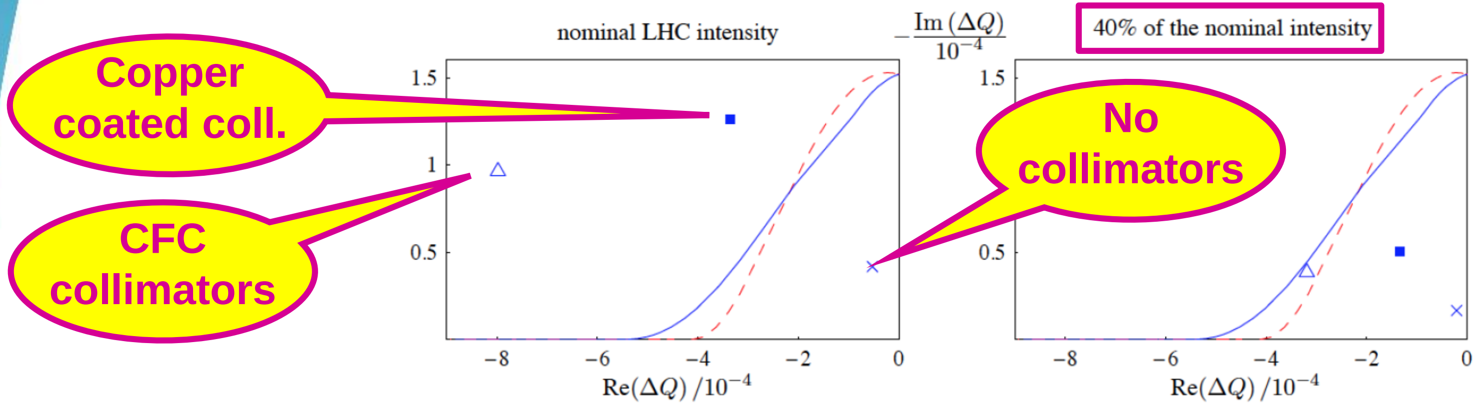

- **LO**: maximum current (550 A) => N.B.: 570 A for HL-LHC
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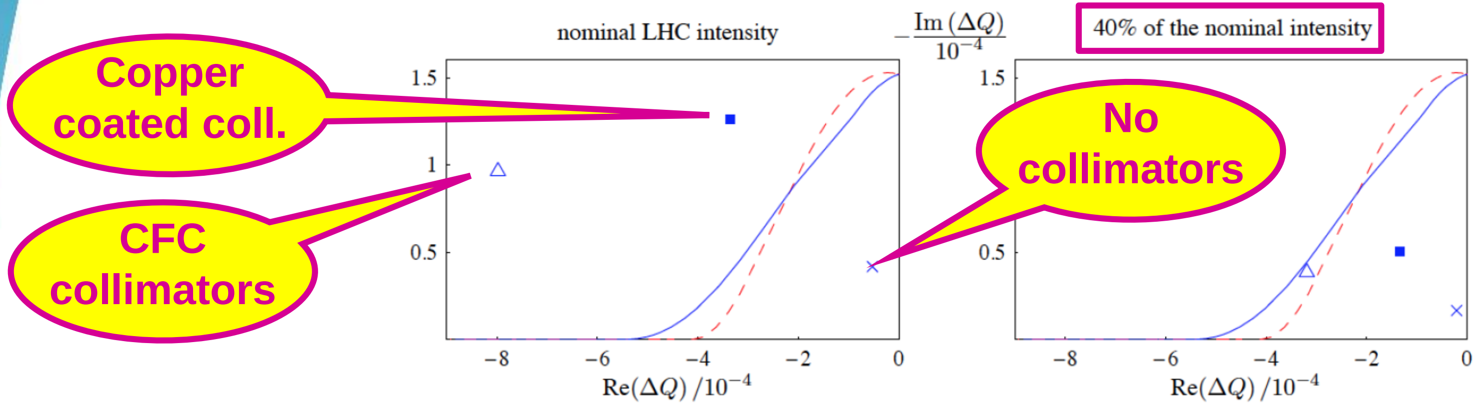

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=> **TD** and/or **Q'** absolutely needed to reach beam stability (due to collimators)!

Introduction (3/4)

- LHC in 2018 at 6.5 TeV => Predicted **effect of TD**

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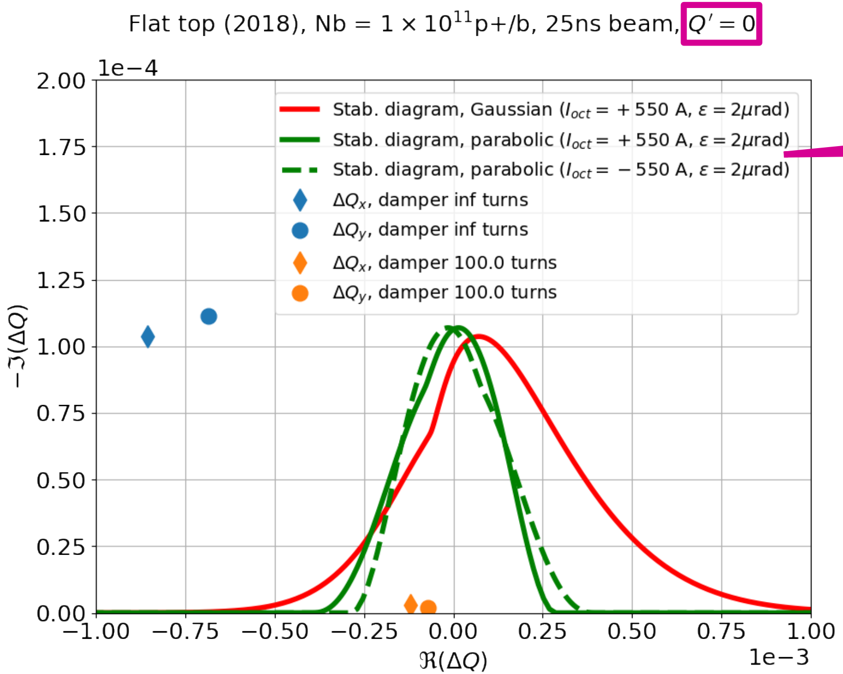

Tails cut at ~ 3 σ

N. Mounet et al.
(DELPHI Vlasov Solver, 2014)

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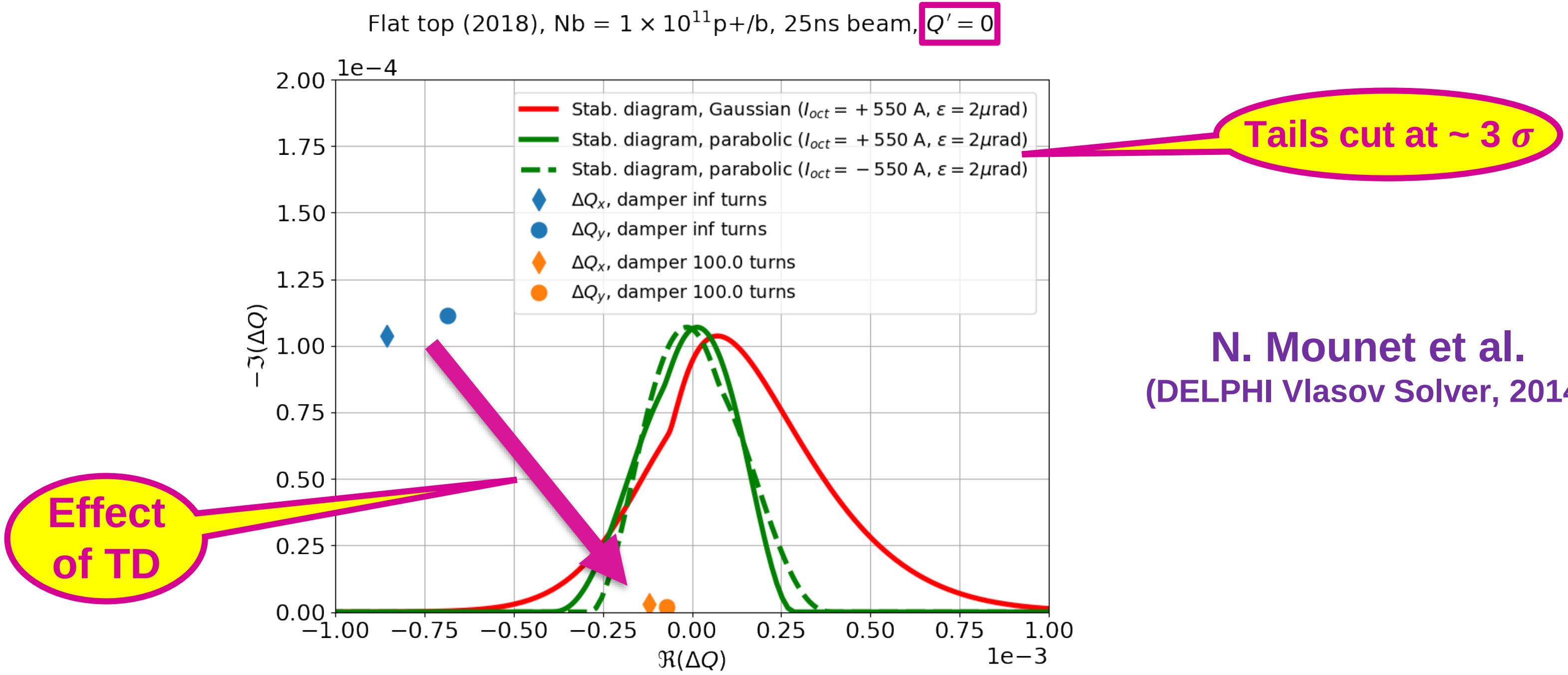

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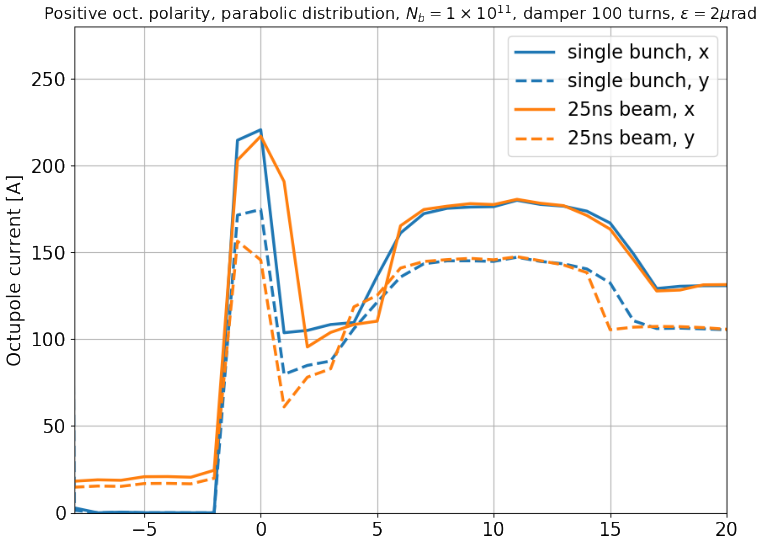
With **TD**



Q'

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Introduction (4/4)

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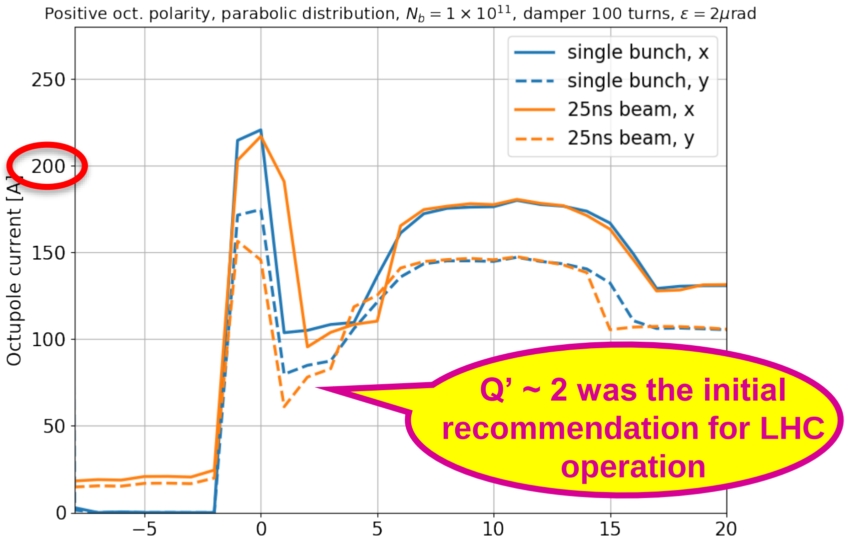

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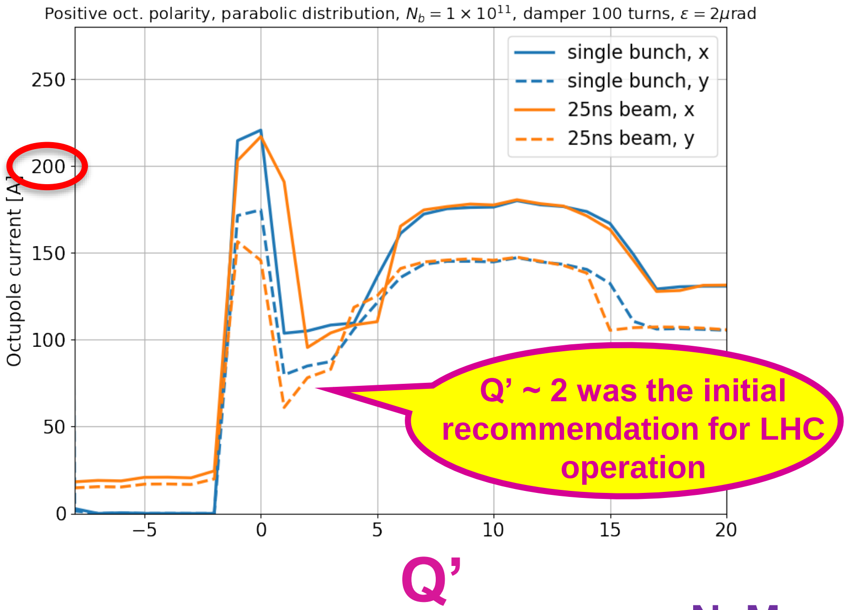

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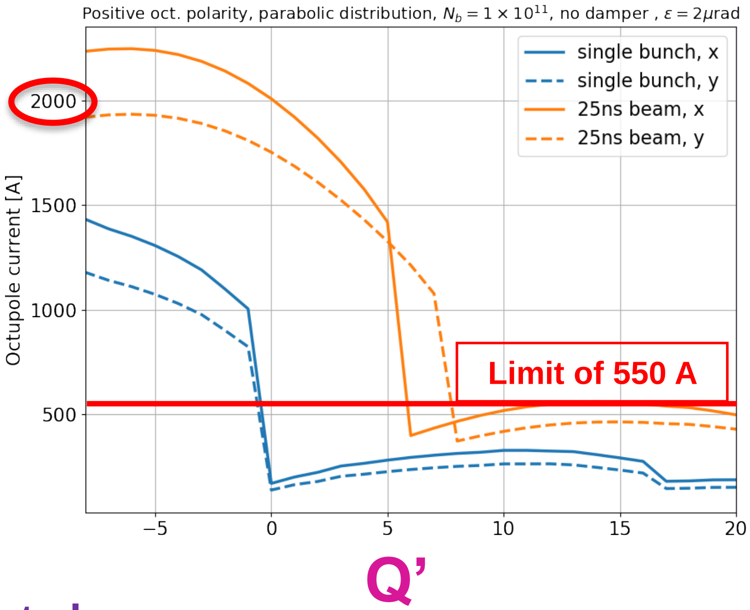

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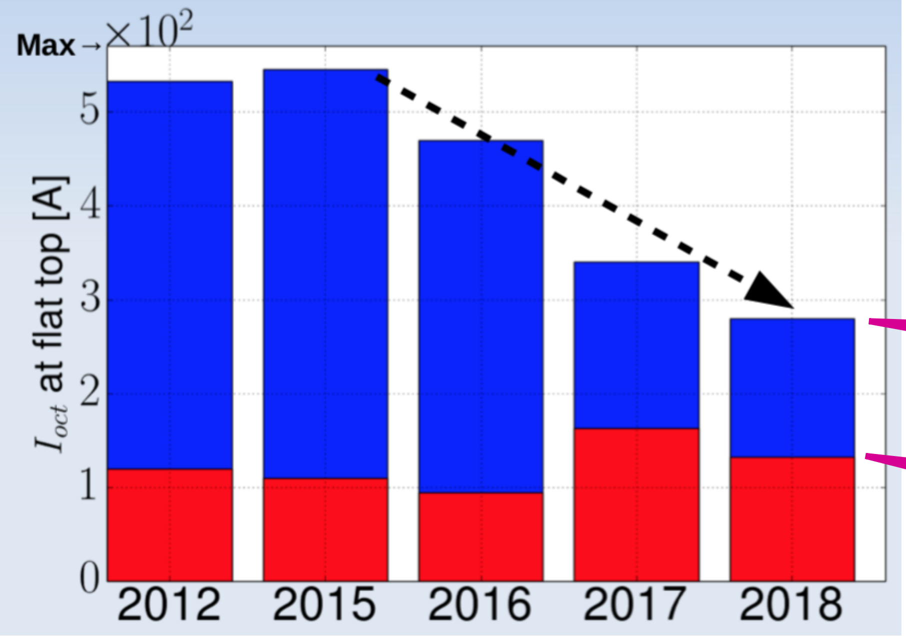
Experience from Run 1 and Run 2 (1/3)

- LHC is now running closer to the **LO** limit (factor ~ 2) with a better control of the machine year after year



X. Buffat et al.

Measured

Predicted

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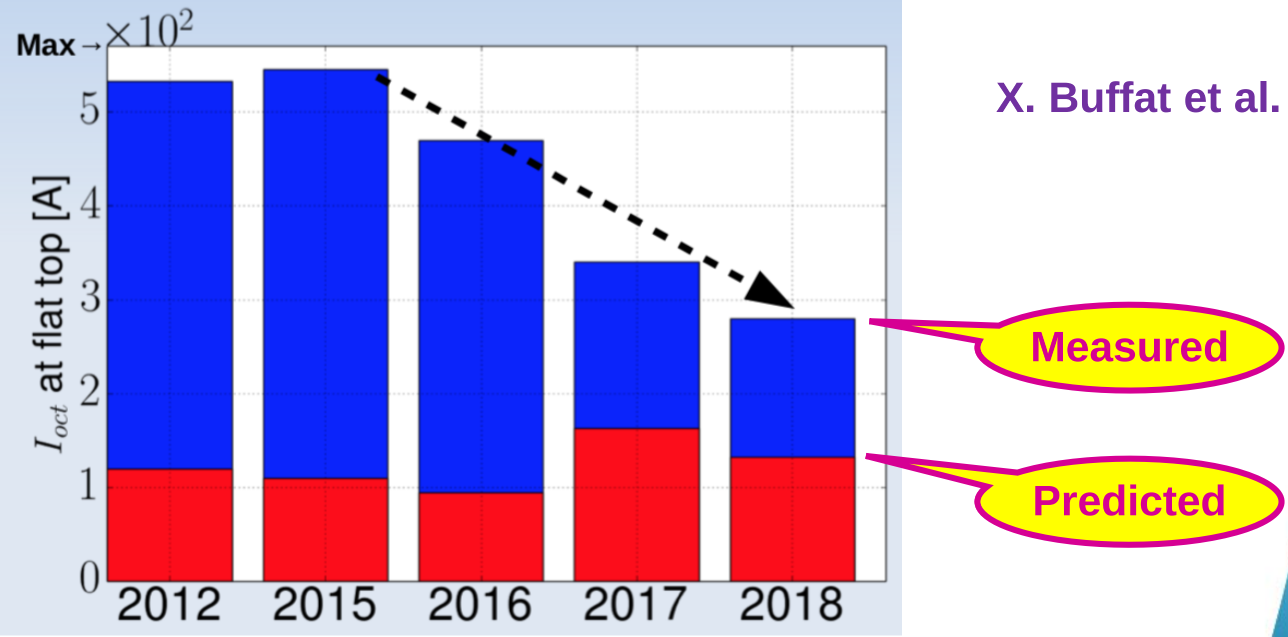

X. Buffat et al.

- **Q'**: ~ + 15
- **TD**: ~ 50-100-turn damping

Experience from Run 1 and Run 2 (2/3)

- **Lessons learned** => In a machine like the LHC, not only all the mechanisms have to be understood separately, but (ALL) the possible interplays between the different phenomena need to be analysed in detail => To highlight only few of them

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  - *N.B.: E-cloud effects not discussed here (issue for stability mainly at injection after scrubbing, while impedance and Beam-Beam effects mainly at high energy)*

Experience from Run 1 and Run 2 (3/3)

- Best estimate of transverse impedance (B1H, B1V, B2H, B2V): larger than predicted by factor ~ 1.5 as an upper limit

B. Salvant et al.

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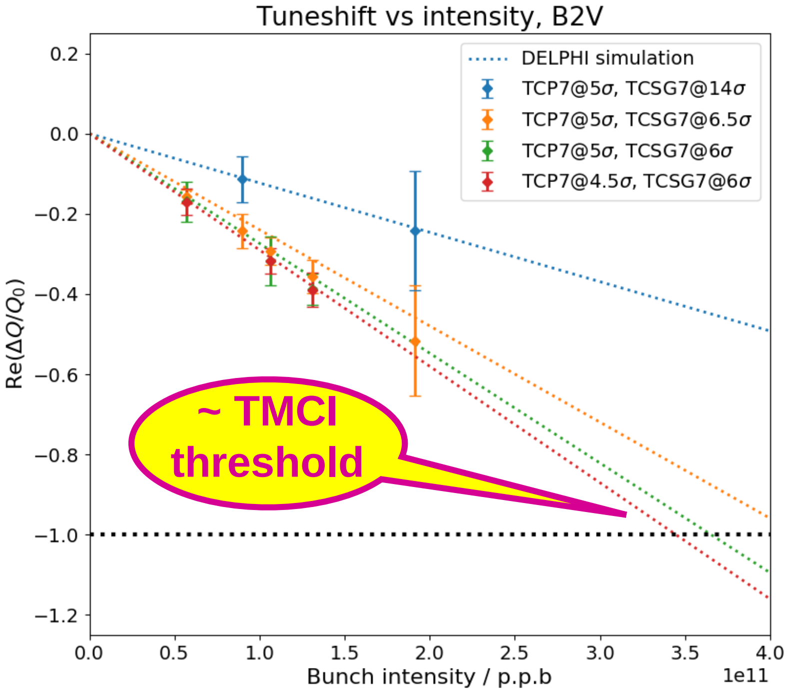

D. Amorim et al.

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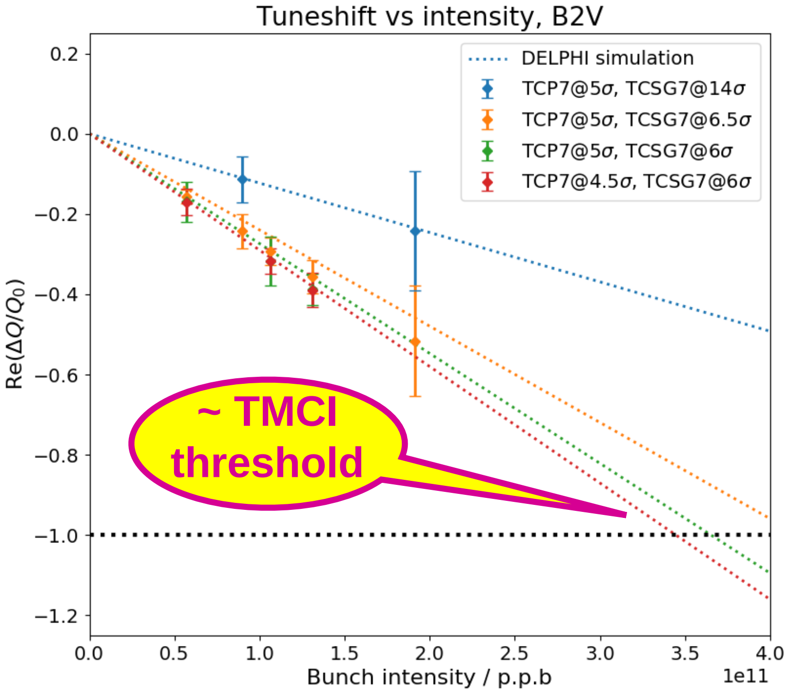

Factor well < 1.5 in this example

D. Amorim et al.

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Considering the (~ LHC) factor 2 in required LO current

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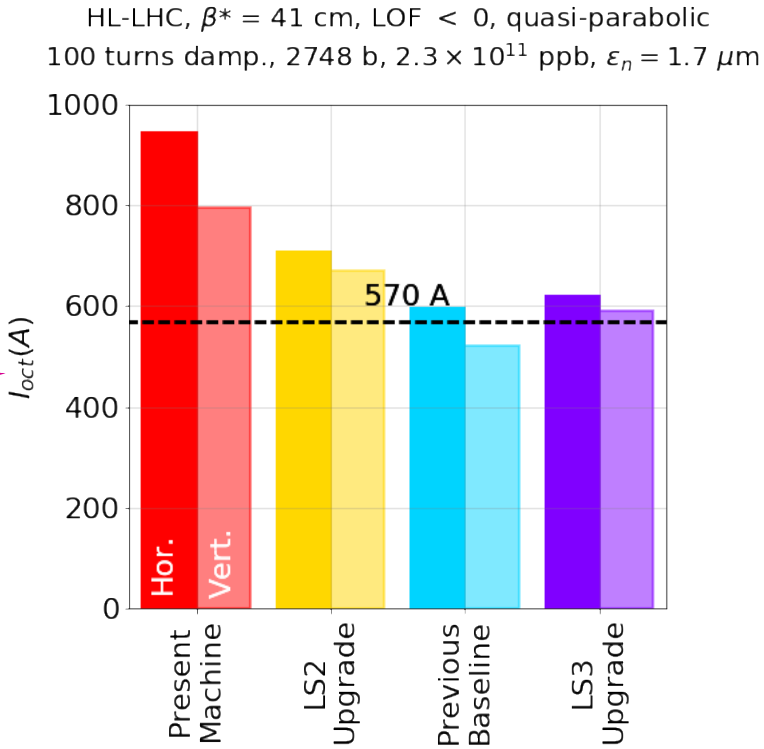
LOF (Focusing) < 0 and > 0 similar as the tails are cut at ~ 3 σ



S. Antipov et al.

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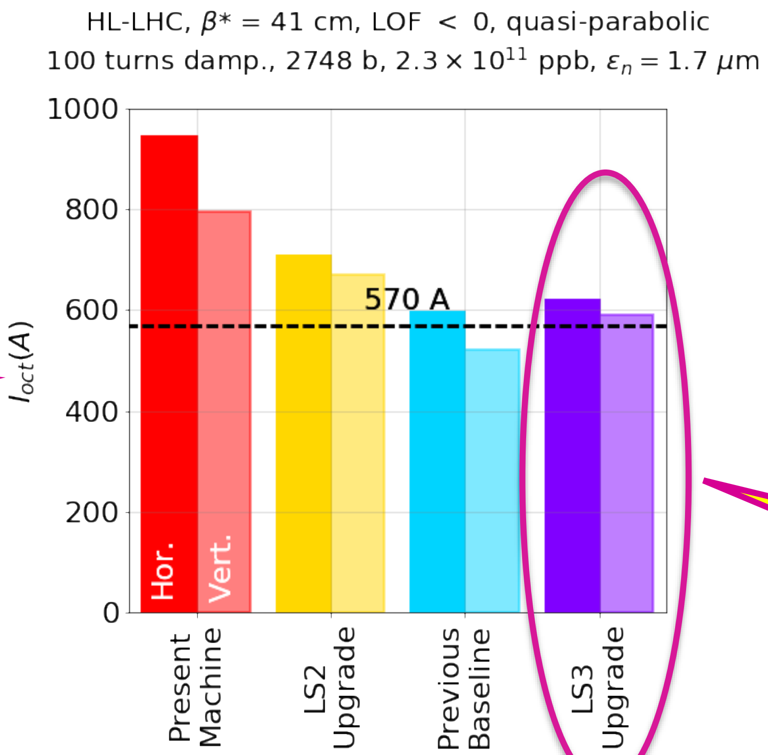

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S. Antipov et al.

AT THE LIMIT!

Expectations for HL-LHC (2/3): 2-beam stability

Considering the
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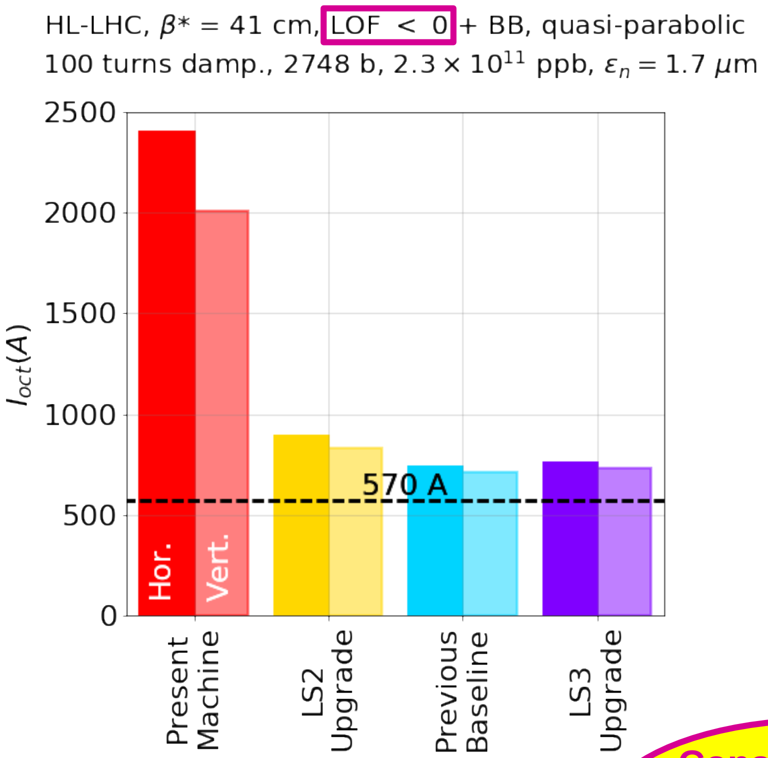
required LO current

Expectations for HL-LHC (2/3): 2-beam stability



X. Buffat & S. Antipov et al.

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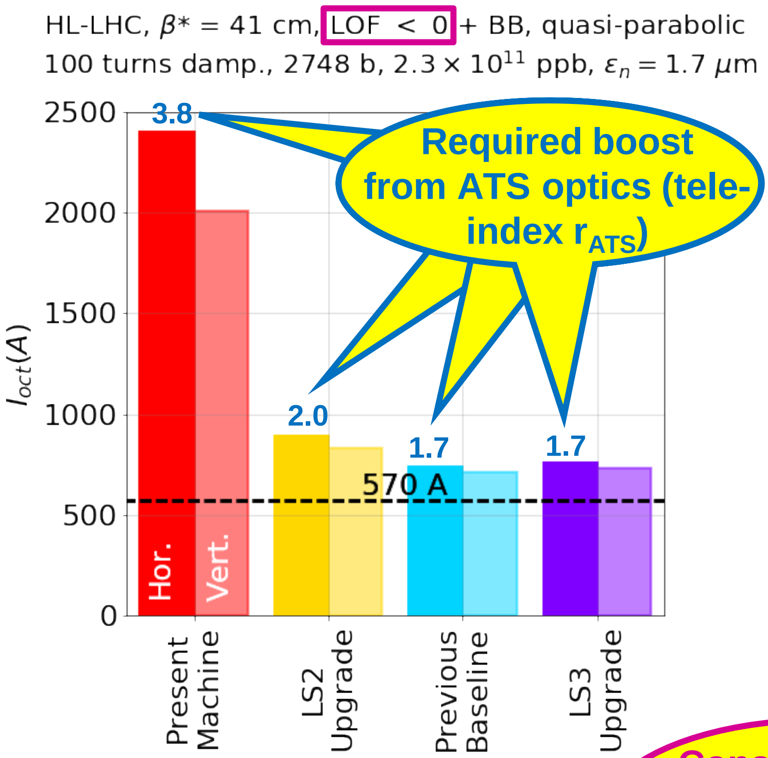

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X. Buffat & S. Antipov et al.

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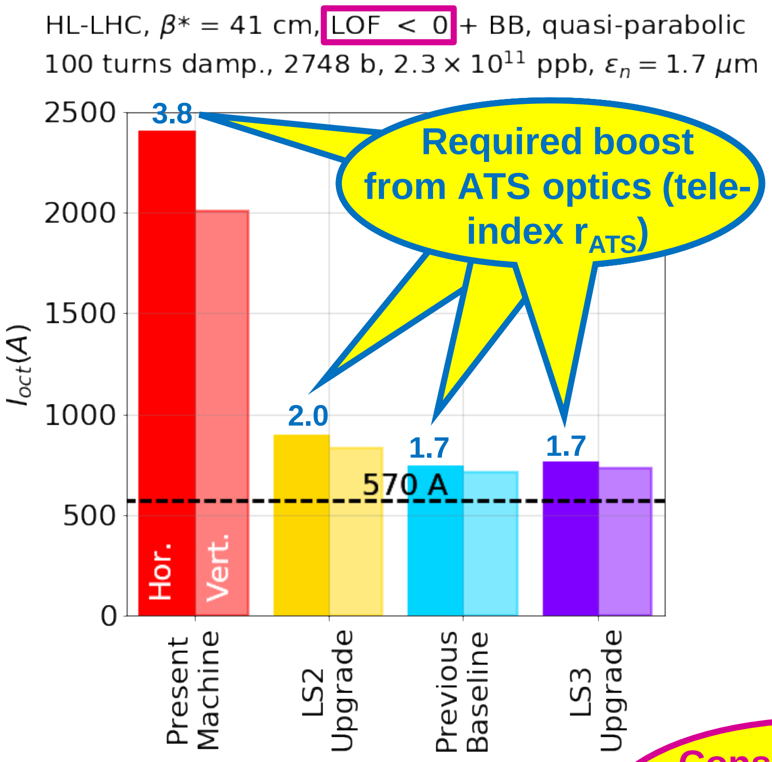

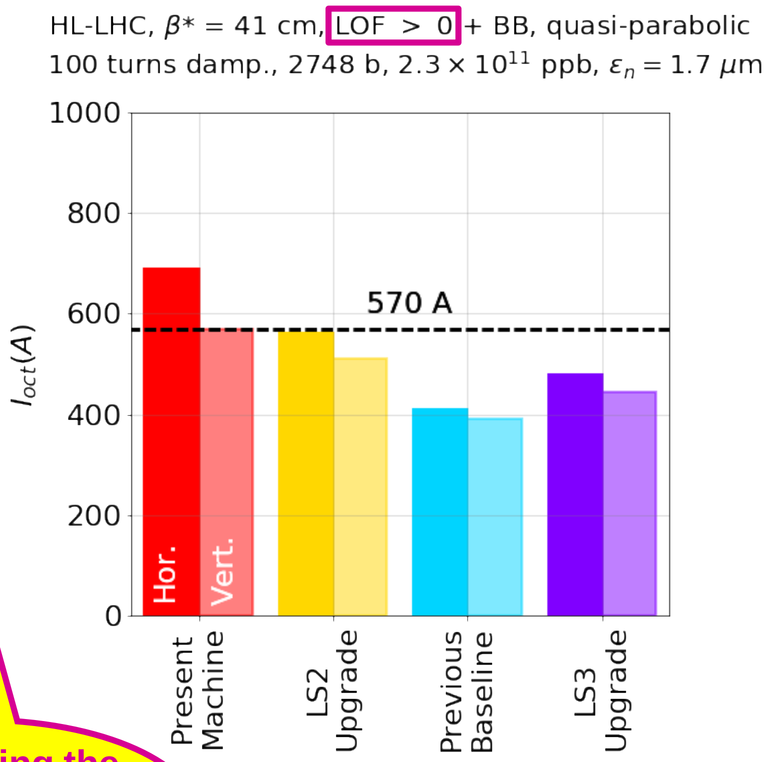

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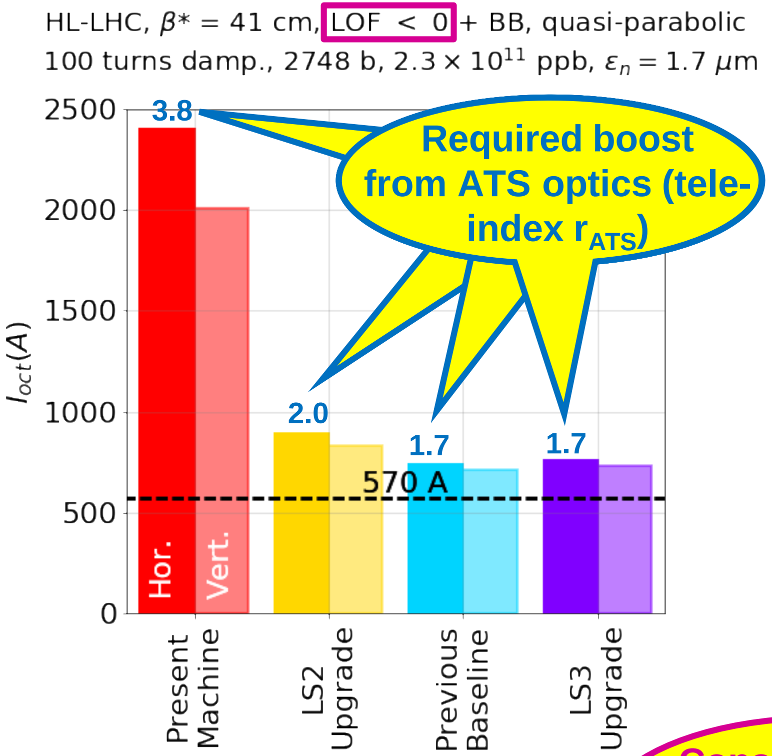

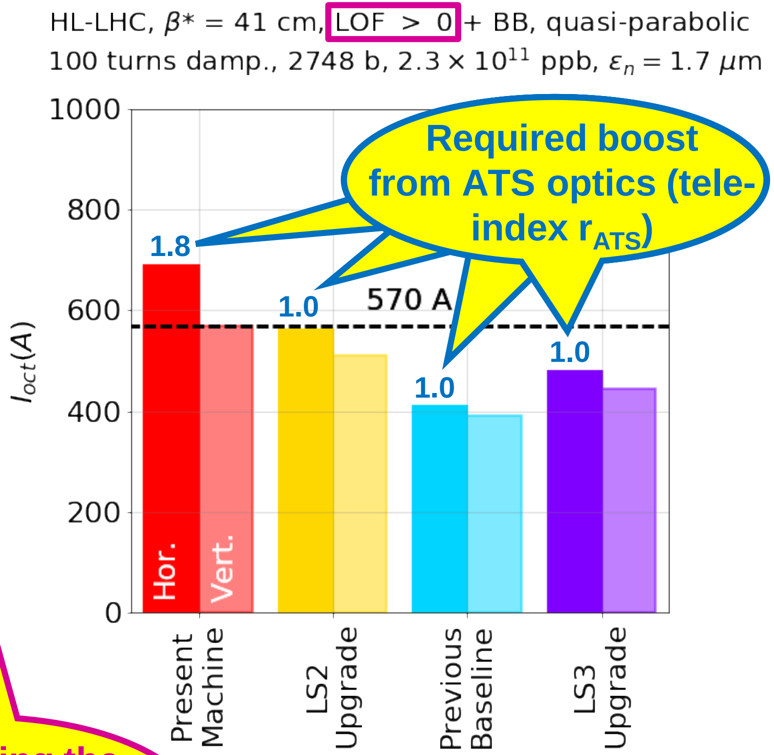

X. Buffat & S. Antipov et al.

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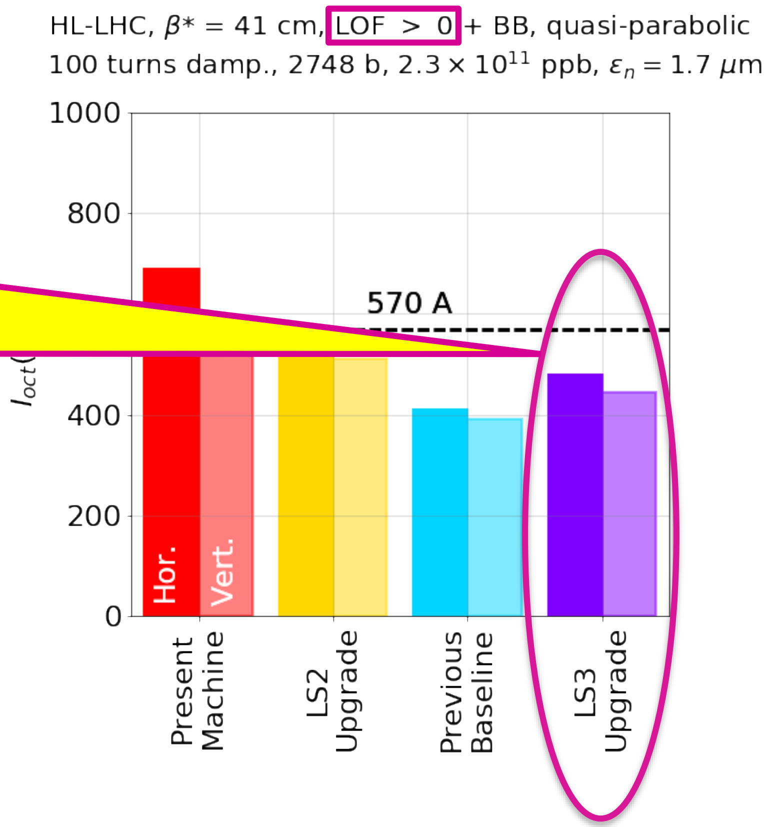

YES!

With a little bit of margin for operational aspects, optics correction, e-cloud?, etc. (see also DA results)

X. Buffat & S. Antipov et al.

Expectations for HL-LHC (3/3): DA => OK

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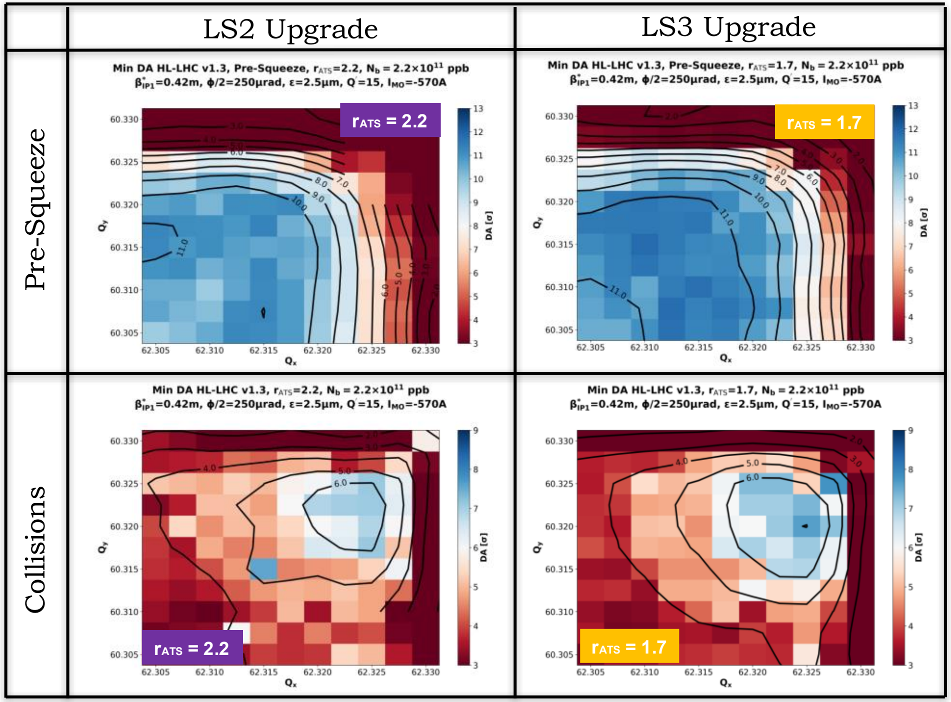
LOF < 0 => Slightly preferred



N. Karastathis et al.

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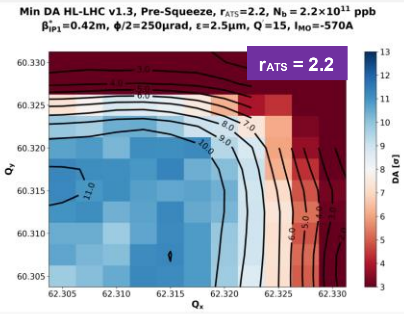
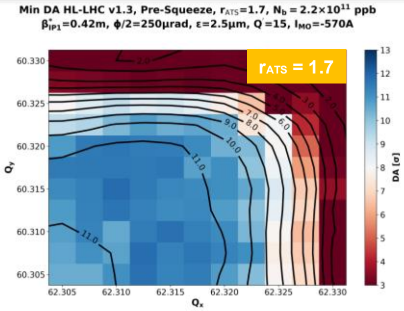
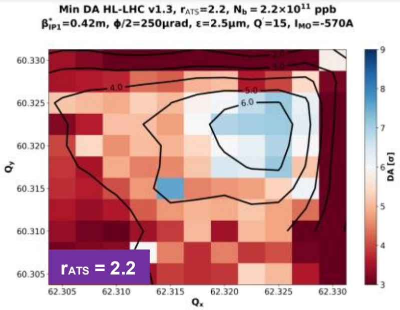
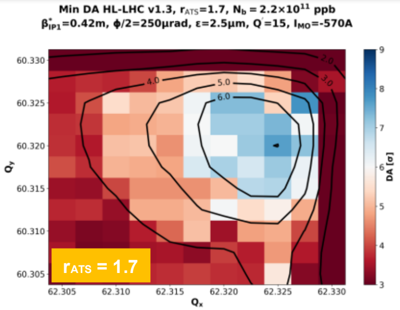
	LS2 Upgrade	LS3 Upgrade
Pre-Squeeze		
Collisions		

But LOF > 0 also OK (no margin & w/o errors)

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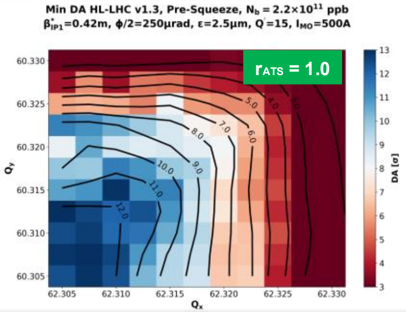
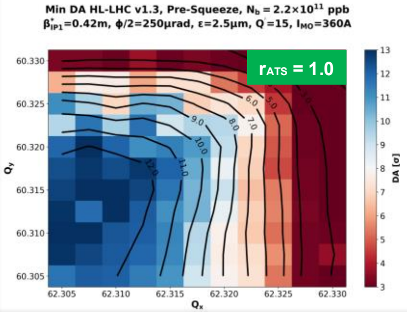
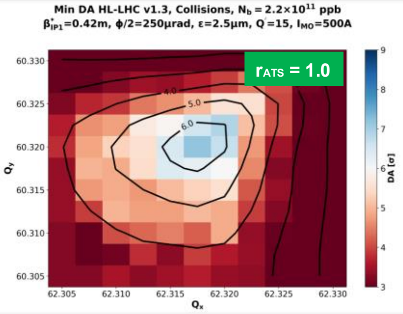
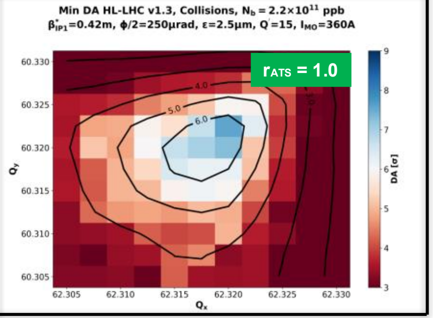
Pre-Squeeze		
Collisions		

N. Karastathis et al.

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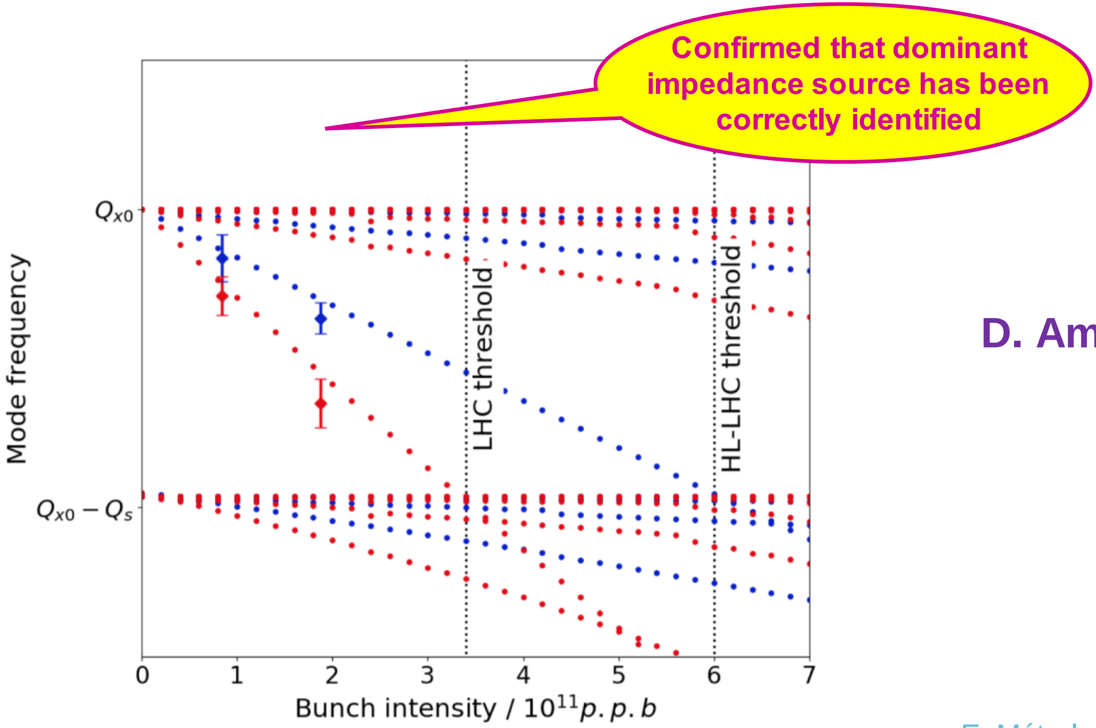
Impedance reduction tests (1/4)

- Mimicking HL-LHC impedance reduction by opening the collimators (B1H)

Impedance reduction tests (1/4)

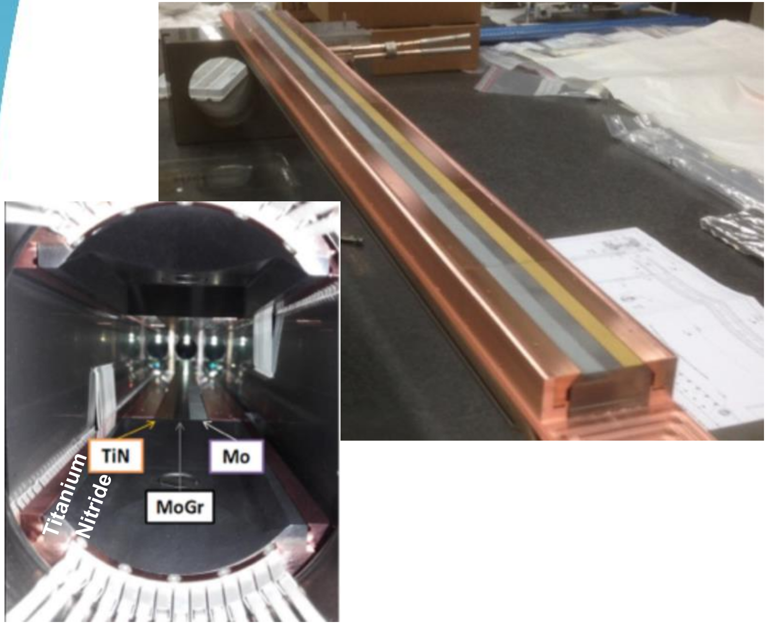
- Mimicking HL-LHC impedance reduction by opening the collimators (B1H) => Significant increase of **TMCI** threshold



D. Amorim et al.

Impedance reduction tests (2/4)

- Low-impedance prototype installed in LHC => Many lab and beam-based studies



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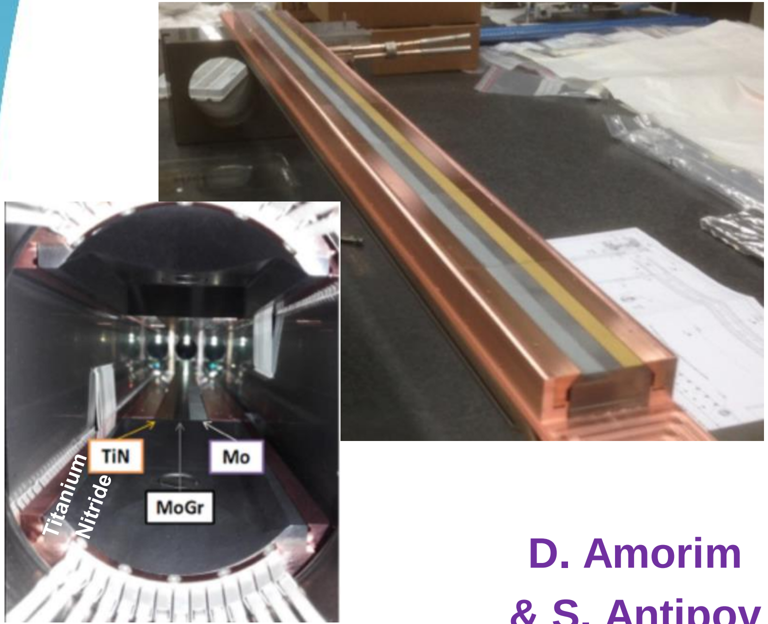

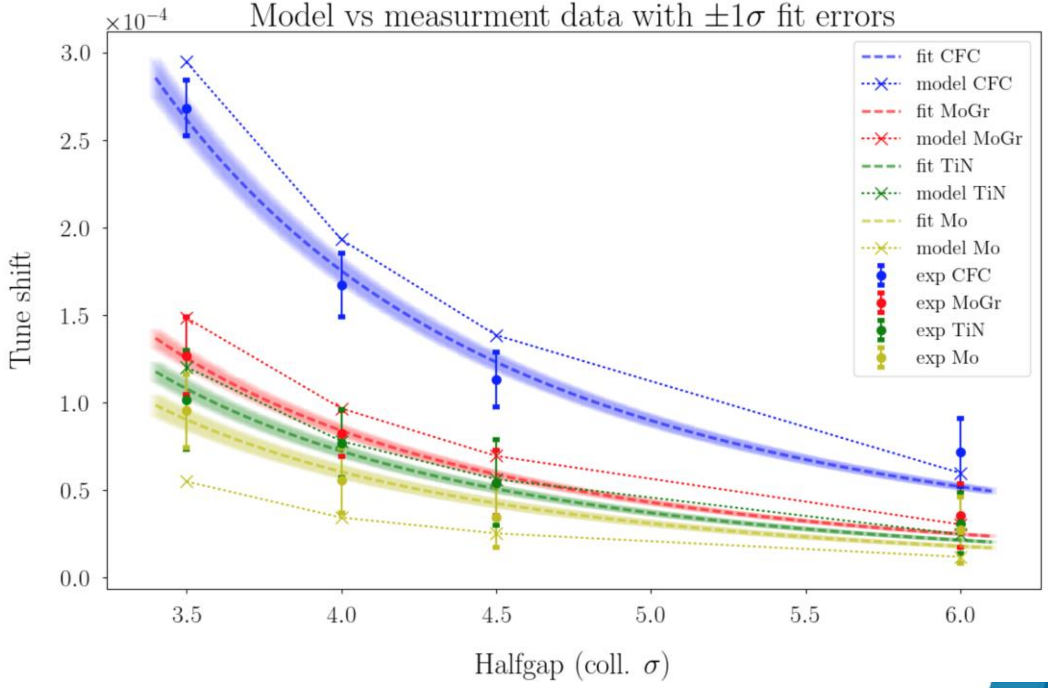

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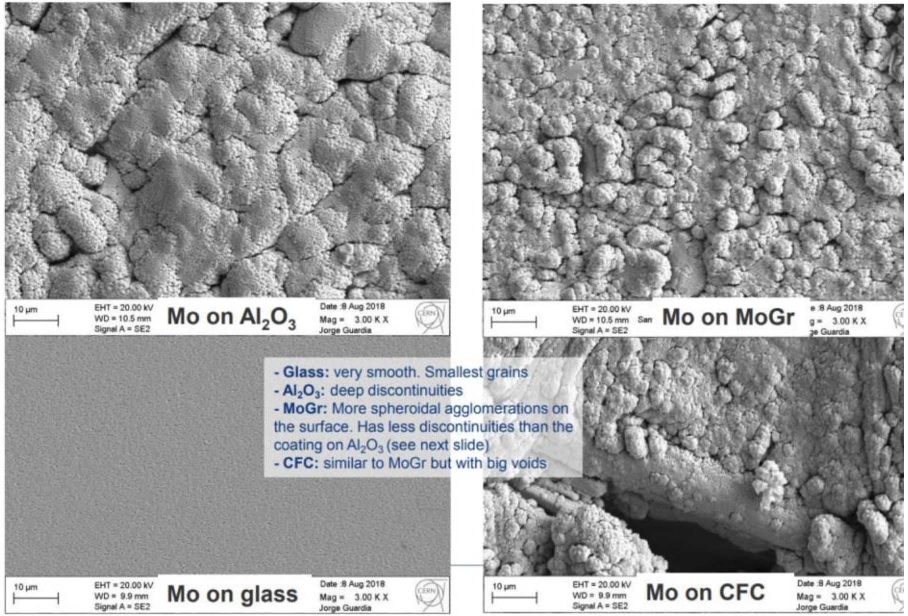
Impedance reduction tests (3/4)

- **Mo resistivity** seemed to be a factor ~ 5 higher than expected (~ 250 instead of ~ 50 nΩ.m) => Bench RF measurements suggested importance of microstructure (N. Biancacci et al.)



J. Guardia et al.

Impedance reduction tests (4/4)

- Measurement of coating resistivity on **Mo** coated samples with H011 cavity after Eddy current method (N. Biancacci et al.)

Impedance reduction tests (4/4)

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	RF	DC
Measured Mo (DTI)	~54 nOhm.m [1]	100 nOhm.m [2]
Measured Mo (CERN)	~523 nOhm.m [1]	210 +/- 20 nOhm*m [3]
Measured Mo (Politeknik)	~418 nOhm.m [1]	Not done by the company
Requirements	~<100nOhm.m	~<250nOhm.m

N. Biancacci & A. Kurtulus et al.

Impedance reduction tests (4/4)

- Measurement of coating resistivity on **Mo** coated samples with H011 cavity after Eddy current method (N. Biancacci et al.)

Cavity w/o end cap | Cavity w/ end cap | Cavity w/ DUT end cap

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N. Biancacci & A. Kurtulus et al.

- Measured resistivity consistent with microstructure observation
- DTI company OK and chosen for production

Contents

ACRONYMS

LO = Landau Octupoles
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Mo = Molybdenum
MoGr = Molybdenum Graphite
MD = Machine development

- Introduction
- Experience from Run 1 and Run 2
- Expectations for HL-LHC
- Impedance reduction tests
- Further ways to reduce impedance effects
- Conclusion and outlook

HiLumi HL-LHC PROJECT CERN

Further ways to reduce impedance effects

Further ways to reduce impedance effects

- Why studying this?
  - Previous estimates for HL-LHC based on (~ LHC) factor 2 more **LO** current required in 2018 => What will it really be for HL-LHC?
  - Importance of noise revealed in **MD** in 2018 => Scaling wrt main parameters?
  - Plans to reduce noise from **TD** and possibly power converters but…

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R. Bruce et al.

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R. Bruce et al.

A. Mereghetti et al.

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  - **Optics** => To optimise β–functions at collimators — **R. Bruce et al.**
  - **Asymmetric collimation** => To reduce impedance of collimators — **A. Mereghetti et al.**
  - **ATS optics** => To boost the **LO**: tele-index r_{ATS} = 3.1 already successfully tested in 2018 during MDs with bunch trains (with both **LO** polarities) — **S. Fartoukh et al.**

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Conclusion and outlook

- Baseline scenario provides stability with margin dictated by present experience compatibly with sufficient **DA**
- Impedance reduction with **Mo**-coated **MoGr** tested and validated with lab and beam-based measurements
- Measurements during Run 3 after LS2 installation and additional investigations key to confirm estimates and fully validate further impedance reduction during LS3
- Investigations ongoing to further reduce uncertainties (noise, impedance estimate, why **Q'** ~ 0 seems much more critical than predicted, etc.) and potential mitigation paths (optics, asymmetric collimation, **ATS** optics)

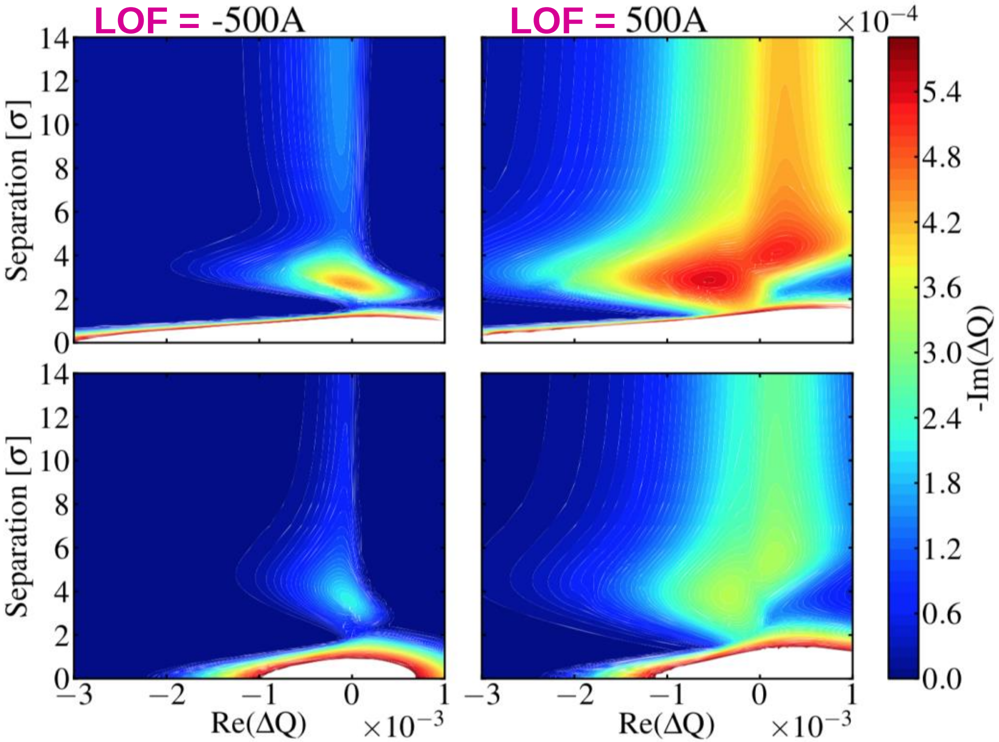
Thank you for your attention!

Appendix

Landau octupoles and beam-beam

2012

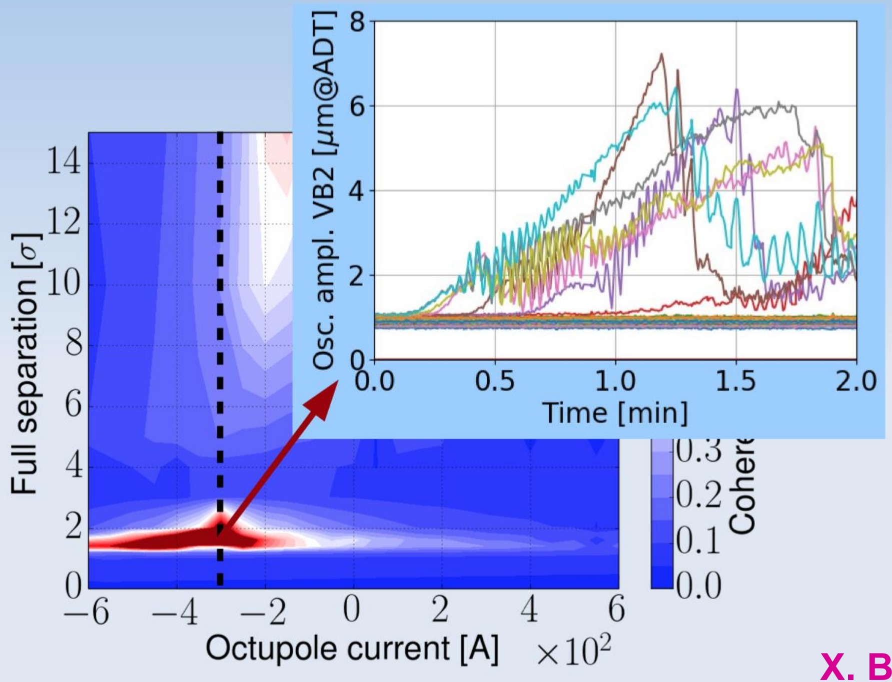
Nominal



X. Buffat et al.

(PRAB 2014)

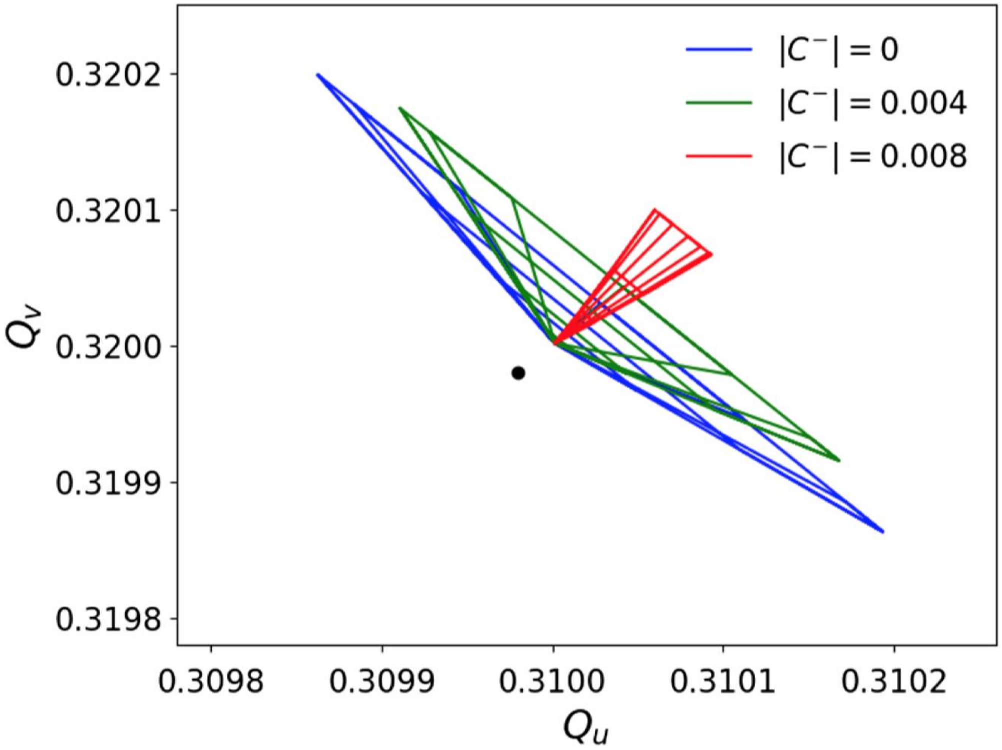
Landau octupoles and beam-beam



- The instability expected with offset beams could be well reproduced in controlled conditions with the negative polarity (and Q'~15)
  → No beam dumps *à la 2012*, even with 733b, rather a slow instability, **slow enough not to occur when collapsing the separation in one go**

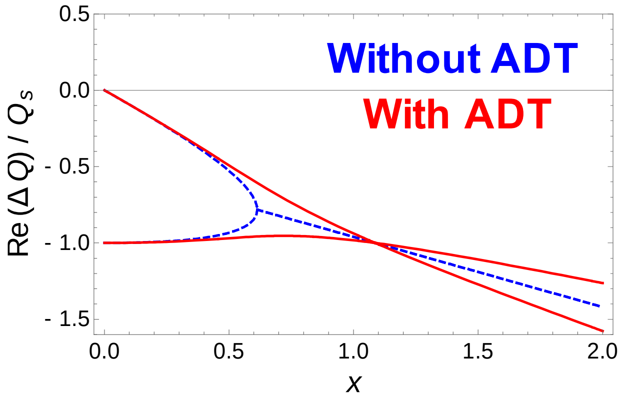
X. Buffat and S. Fartoukh et al. (ATS MD, 2018)

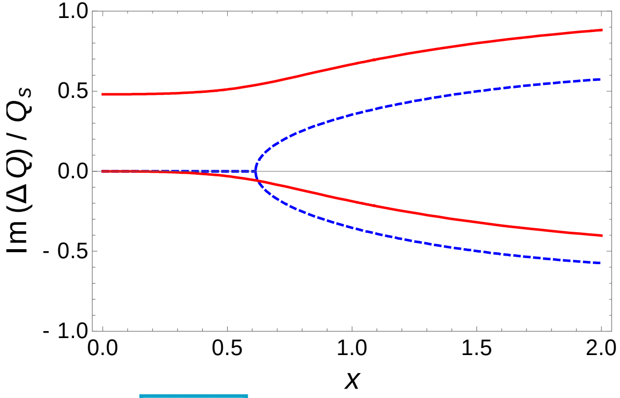
Destabilising effect of linear coupling

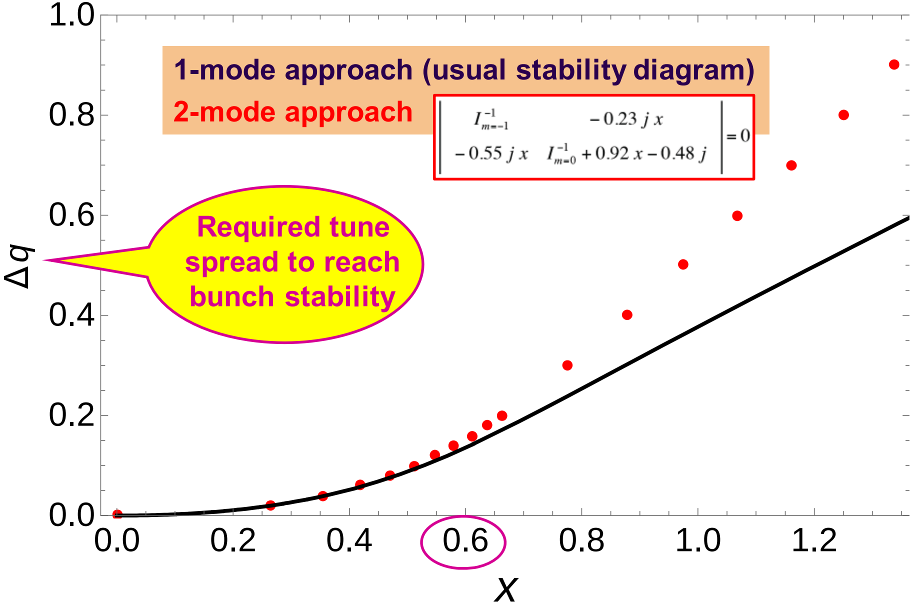


L.R. Carver et al. (PRAB 2018)

Destabilising effect of TD

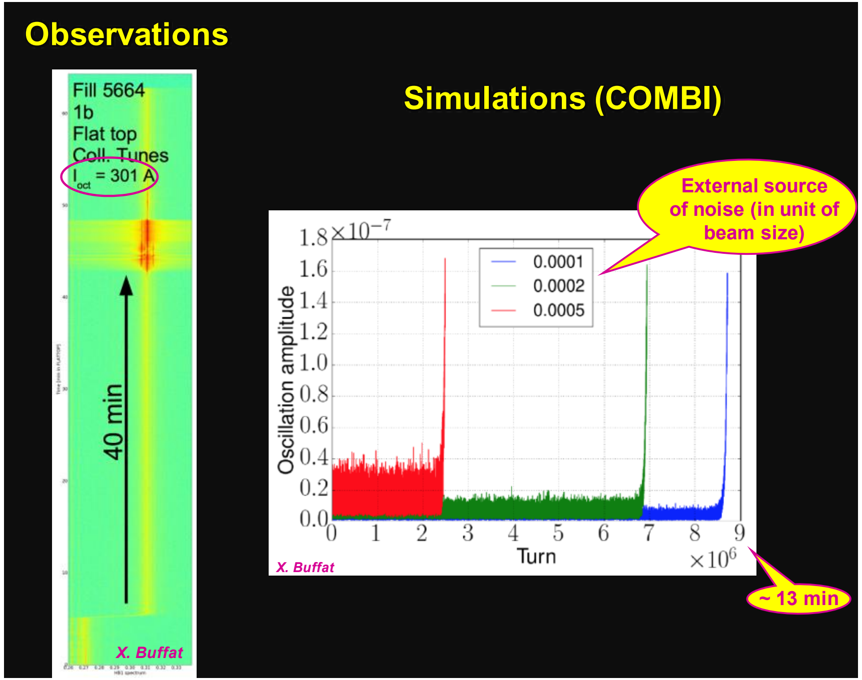




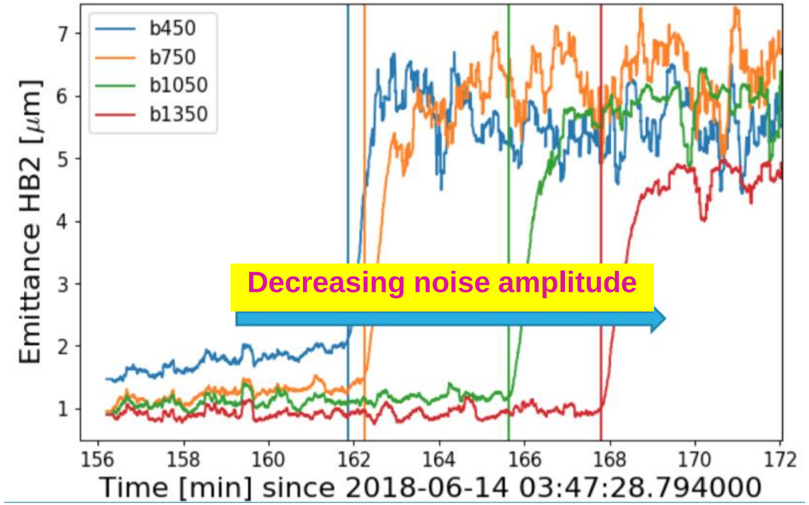


E. Métral et al. (IPAC'18)

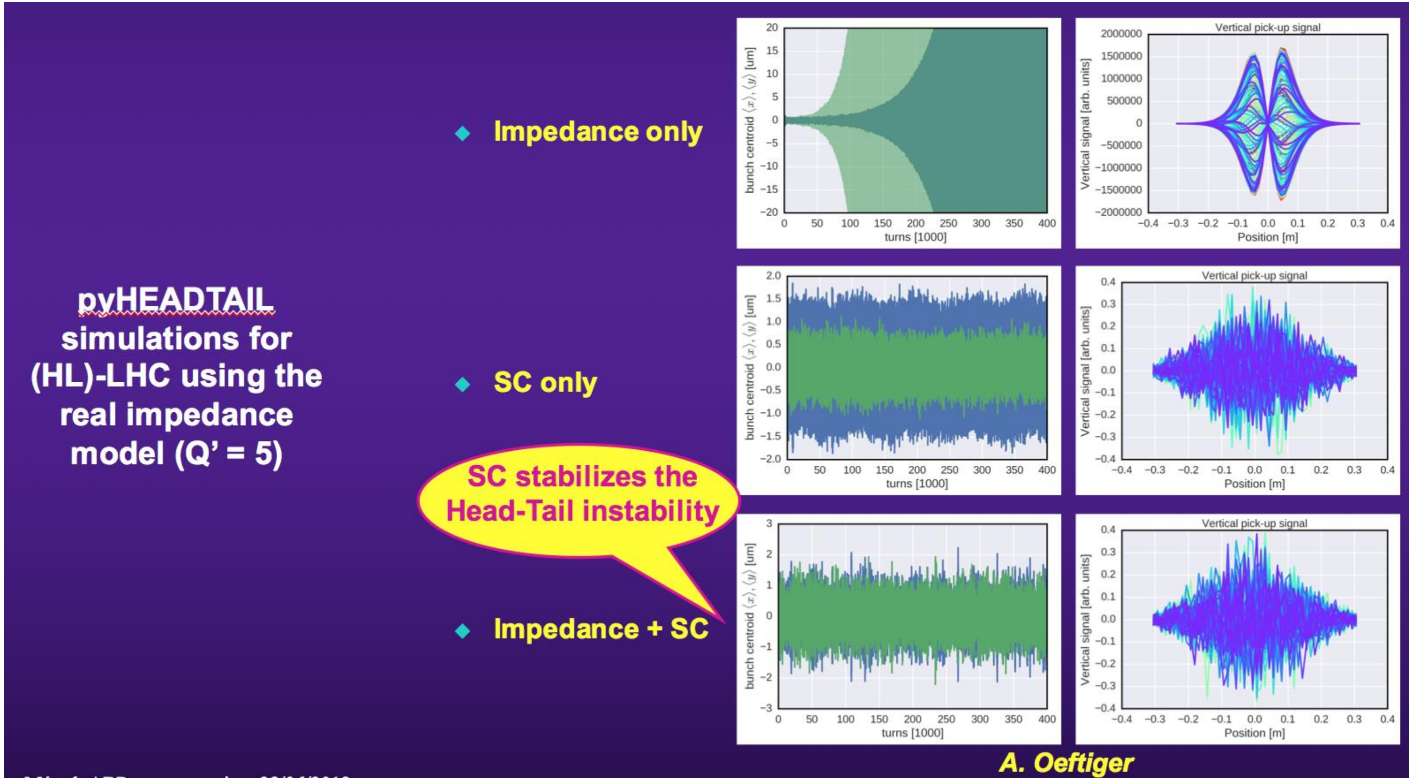
Destabilising effect of noise



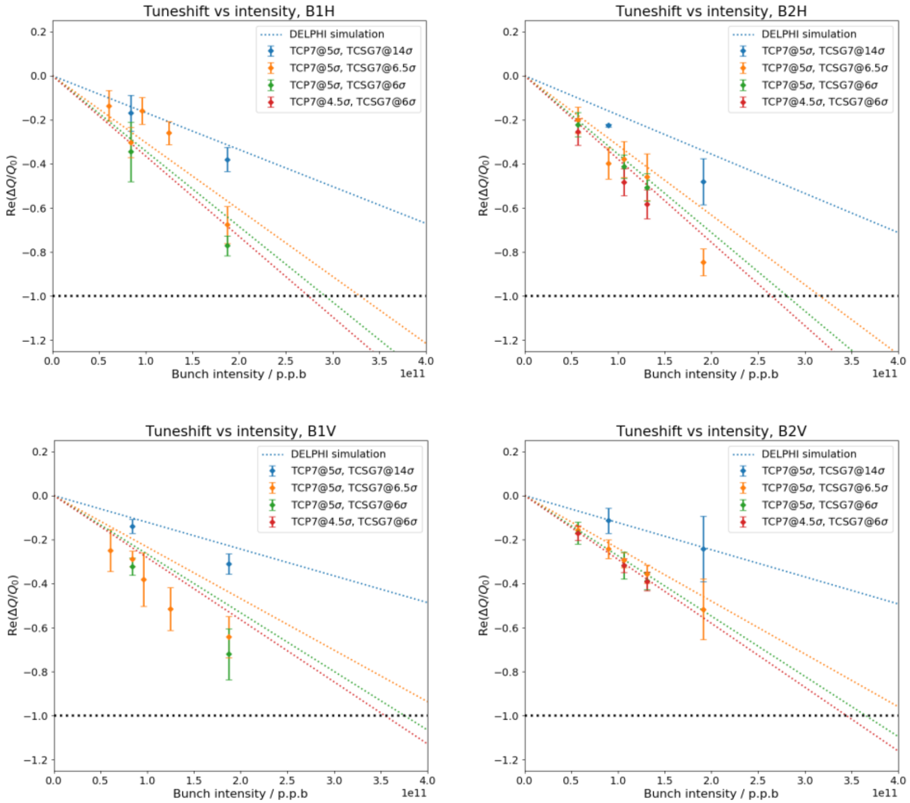
MD in 2018 (X. Buffat et al.)



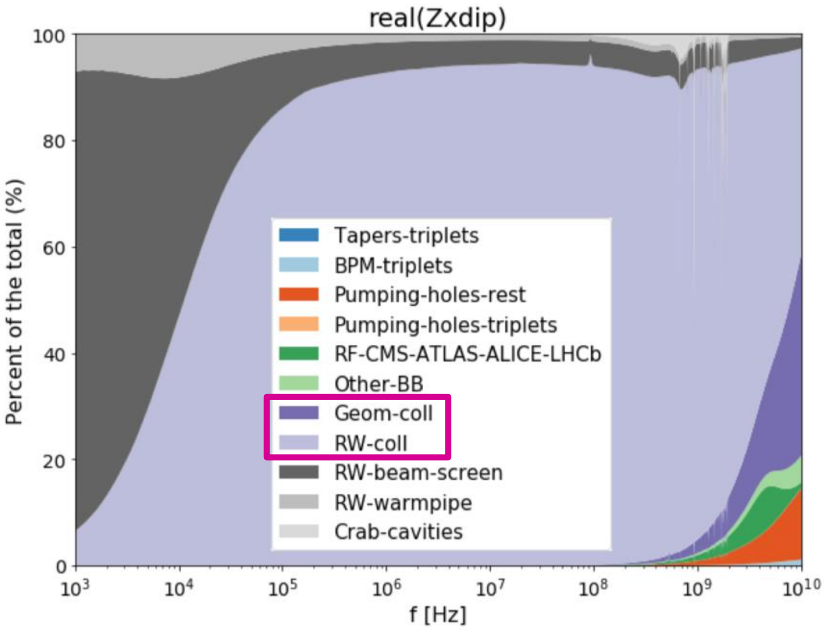
Stabilising effect of space charge at low energies

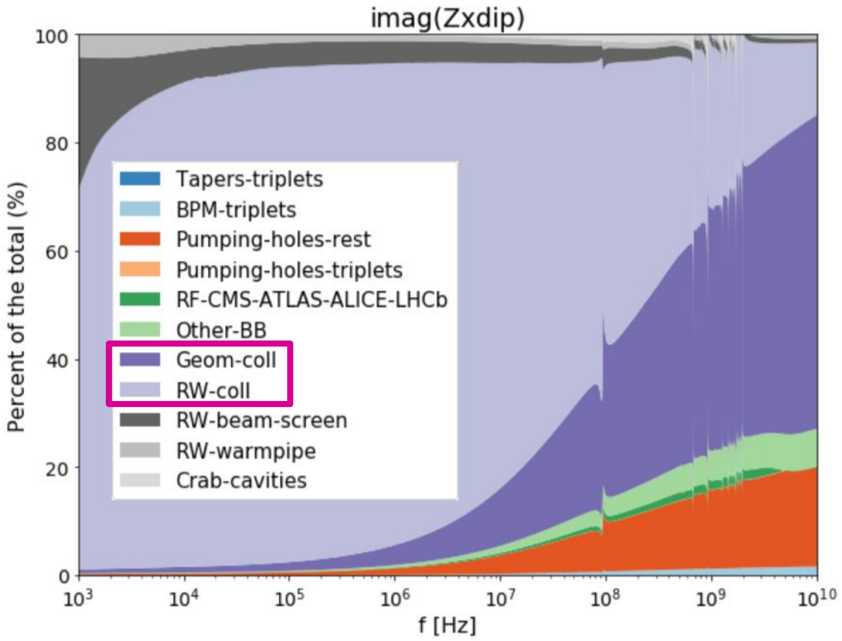


TMCI studies (D. Amorim et al.)

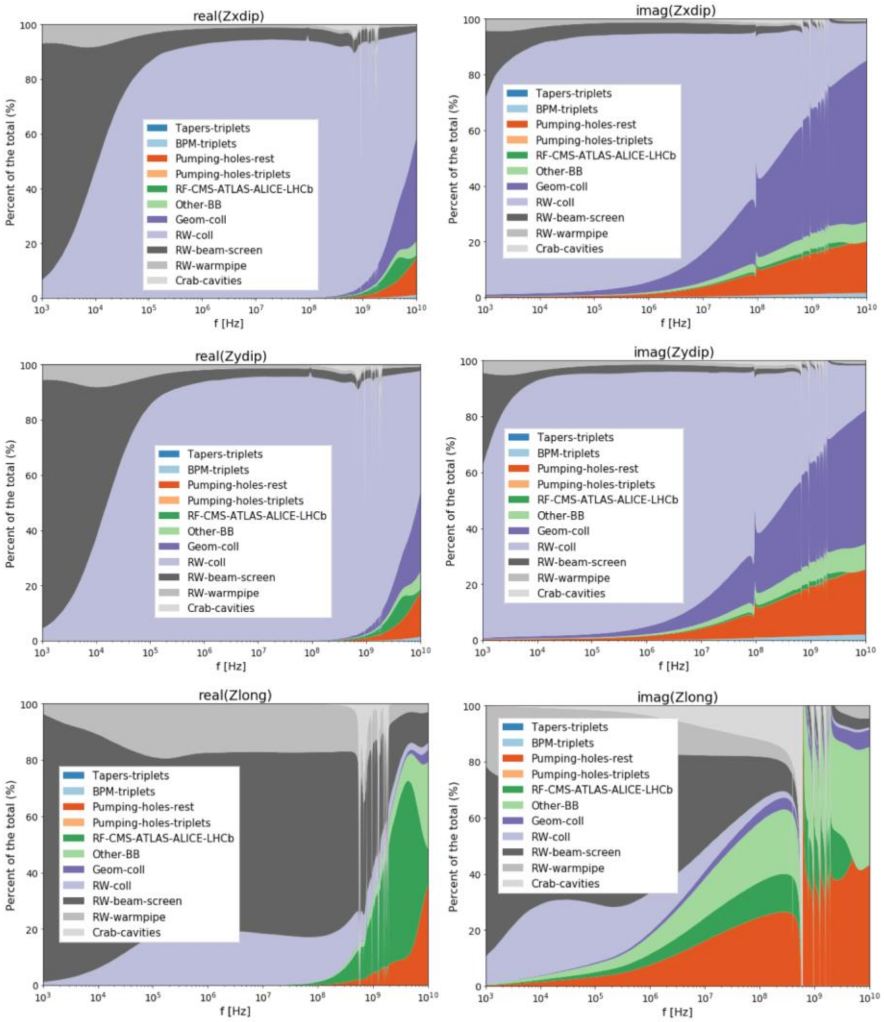


HL-LHC impedance model at 7 TeV ($\beta^* = 50$ cm)



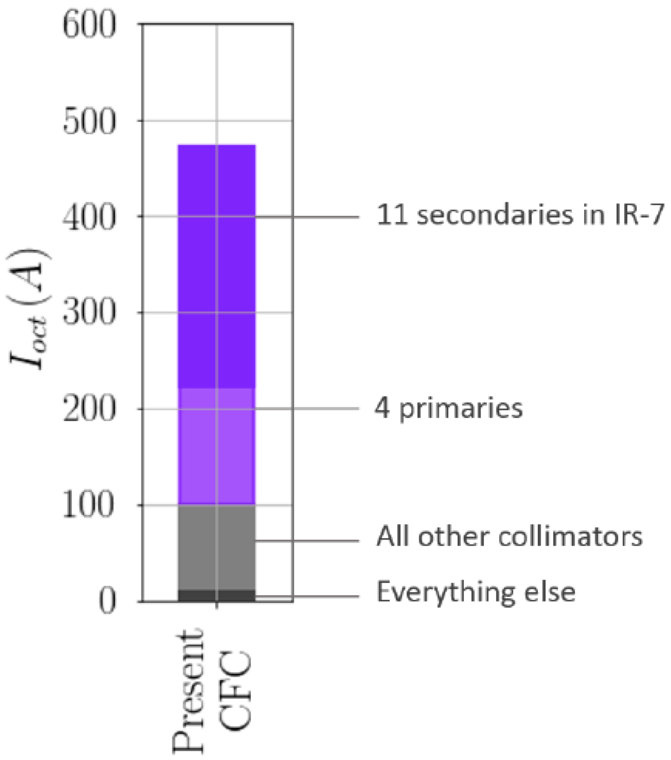


D. Amorim et al.



D. Amorim et al.

Impedance contributors (BCMS, without factor 2)



S. Antipov et al.

Collimation upgrade in LSS7

- Phase 1 (LS2 Upgrade)
  - Replacement of 2 primary collimators/beam with TCPPM low impedance collimators (MoGr)
  - Replacement of 4 secondary collimators/beam with TCSPM low impedance collimators (Mo-Coated MoGr collimators)
  - Construction of 2 spare TCPPM (MoGr)
  - Construction of 2 spare TCSPM (Mo-coated MoGr)
- Phase 2 (LS3 Upgrade) and pending results of the first part of Run 3
  - Replacement of 5 (was 7 for previous baseline) secondary collimators/beam with low impedance collimators (Mo-coated MoGr collimators *or Cu-coated graphite collimators*)
  - Construction of 2 spare TCSPM (Mo-coated MoGr collimators *or Cu-coated graphite collimators*)

LS3 Upgrade (new baseline): keep 2 CFC collimators

Two options to choose from

MINIMIZE HORIZONTAL IMPEDANCE

Horizontal plane – most critical from operation (*X. Buffat*)

Greater octupole current in the Vertical plane

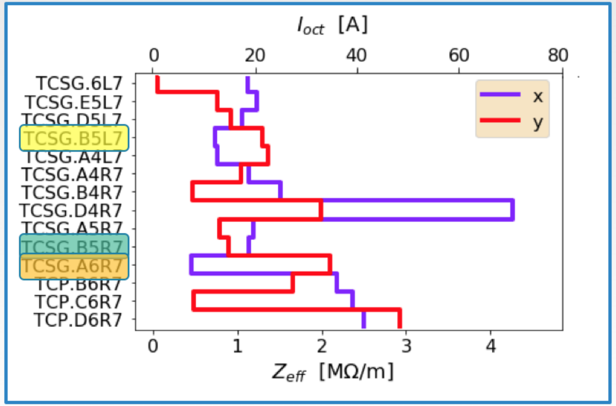
ATTACK BOTH PLANES

Collimator tune shift measurements show higher shift than expected (*D. Amorim*)

Slight increase in both planes

B5L7

A6R7



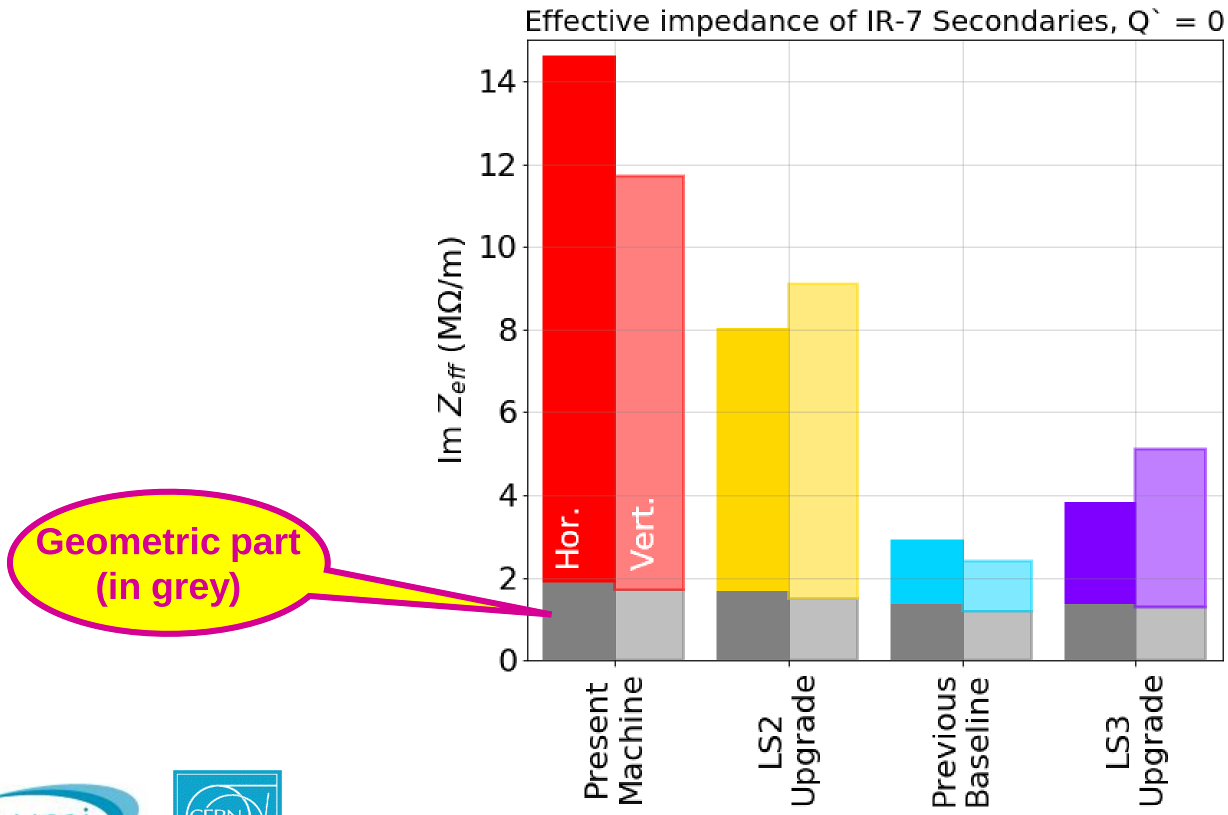
B5L7

B5R7

This scenario chosen

S. Antipov et al.

Resistive-wall impedance vs. geometric



S. Antipov & E. Carideo et al.

2-beam stability: LOF < 0 vs. LOF > 0

X. Buffat

Scenario	$I_{oct} < 0$ Asynchronous collapse $\phi_{CC} = 0$ $\beta^* = 41cm$	$I_{oct} < 0$ Asynchronous collapse $\phi_{CC} = -180$ $\beta^* = 41cm$	$I_{oct} < 0$ Synchronous collapse $\phi_{CC} = 0$ $\beta^* = 41cm$	$I_{oct} < 0$ Synchronous collapse $\phi_{CC} = -180$ $\beta^* = 41cm$	$I_{oct} > 0$ Either $\phi_{CC} = 0$ $\beta^* = 41cm$	$I_{oct} > 0$ Either $\phi_{CC} = -180$ $\beta^* = 64cm$	$I_{oct} > 0$ Either $\phi_{CC} = -180$ $\beta^* = 41cm$
CFC	-2400 (3.8)	<-2750 (>4.1)	<-2750 (>4.1)	-2600 (4.0)	>2750 (>5.7)	690 (1.8)	620 (1.5)
LS2 upgr.	-890 (2.0)	-1640 (3.1)	-1500 (2.9)	-1250 (2.6)	>2750 (>5.7)	560	500
Full upgr.	-740 (1.7)	-1230 (2.5)	-1230 (2.5)	-1100 (2.3)	>2750 (>5.7)	410	360

Tele-index required using the formula from StephaneF => To be confirmed once the optics are available

HL-LHC bunch brightness

- The HL-LHC bunch brightness has already been reached! => In 2016 at 6.5 TeV, bunches of ~ 1.4 times higher brightness than for HL-LHC were brought into collision with very good lifetime (burn-off dominated)

Parameter	***LHC***	**HL-LHC**	**LHC 2016**	**Delta [%]**
Energy [TeV]	*7*	7	6.5	- 7
Bunch population [10^{11}]	*1.15*	2.2	**1.9**	- 14
Transv. emittance [μm]	*3.75*	2.5	**1.5**	- 40
Brightness [10^{11} / μm]	*0.31*	0.88	1.27	**+ 44**

Factor 4.1!

Studies on alternative mitigation strategies ongoing (S. Redaelli et al.)

- New IR7 optics (proposal by N. Mounet) allowing larger physical collimator gaps being studied (R. Bruce)
- Reducing number of jaws at the beam => Asymmetric settings or fewer secondaries (A. Mereghetti & R. Bruce)
  - Impact on cleaning being studied
  - **MDs** in 2018 being analysed
  - Clearly, some scenarios only feasible if one can "trade" some cleaning performance (potential conflicts with the new Dispersion Suppressor layouts to be assessed)

Further considerations on ATS optics (S. Fartoukh)

- For **LO**F < 0, requested tele-index strongly dependent on choice of Xing angle function in ramp (essentially end of ramp)
  - From instability perspective, Xing angle shall be maximised (possible because one has plenty of aperture)
  - From other perspectives, it may have to be minimised
- Combined ramp and squeeze: OP mechanics was already demonstrated with up to ~ 800 nominal (and 8b4e) bunches in **MD** in 2018
- Budget of tele-index is limited in relative (typically from 1 to 4)
  - If already eaten substantially in ramp, then β^* – levelling in tele-mode in collision will not be possible
  - Strategy worked out for Run 3: deploy instead an anti-telescopic optics in ramp (and cross a tele-index of 1 later on but when beams are colliding)
  - Anti-telescopic optics are sensibly less flexible compared to telescopic optics (especially IR6), which in practice will limit the (effective anti-)tele-index to 2-2.5

Some reminders from the 2009 collimation review

The transverse feedback system should be able to damp instability rise-times of (We take a safety margin of a factor 2 compared to what was computed in the previous slides)

Strategy for the stabilization of the transverse coupled-bunch instab.

- Transverse feedback: at injection and top energy (seems OK)
- If pb $\Longrightarrow$ Landau octupoles (up to a certain intensity limit)

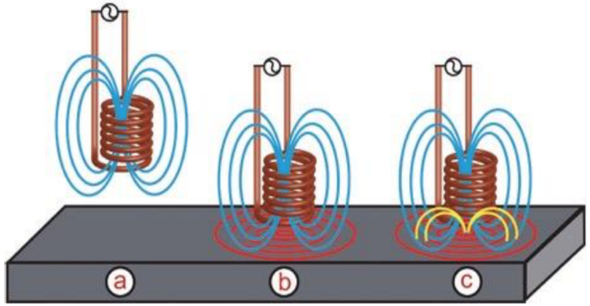
Phase 2: Copper and copper coated ceramics collimators are studied

The best way to reduce the collimator impedance remains to open the gaps and reduce the total length of the collimators!

Eddy current method (to measure resistivity)

Introduction on Eddy Current Testing

- Method based on variation of a magnetic field in a coil, in reaction to magnetic or electric conductive materials in its vicinity.
- Coil of conductive wire excited with AC produces a (primary) magnetic field around itself. When the coil approaches a conductive material, this (primary) magnetic field induces electrical currents (eddy currents) in the conductive material.
- In practice it is like an electric transformer, where the coil acts as the primary winding and the conductive material acts as the secondary winding.
- Depending on the material, one can correlate the change in coil input impedance to the material characteristic.

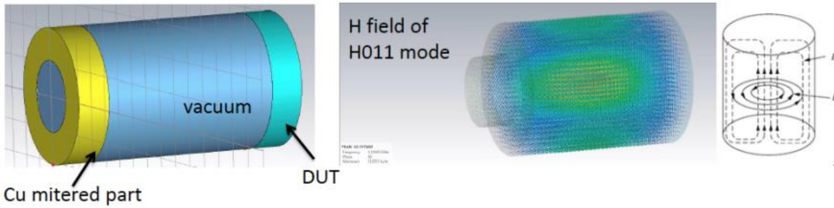


N. Biancacci et al.

H011 cavity method (to measure resistivity): ~ 16.5 GHz

- Accurate measurement of coating surface resistance is needed to characterize the production process of HL-LHC baseline collimators jaws made of 5um Mo coated MoGr.
- Extensive characterization studies done in the past by means of eddy current coils at low frequency (10kHz – 2MHz).
- 2 companies called for large production (DTI, Politeknik) and compared to CERN production.
- Measurements of resistivity was done on small blocks based on eddy current testing (see https://indico.cern.ch/event/773228/contributions/3219381/attachments/1754354/2843771/Outcome_of_recent_Mo_coating_resistivity_measurements.pdf) with good outcome for DTI.
- Attempted measurement also on real (thicker and larger) blocks: more sensitivity to bulk not homogeneity affected the results and triggered the study of an alternative method (161th HSC meeting https://indico.cern.ch/event/775773/)
- Alternative approach quickly developed and based on the application of a pillbox cavity optimized for H011 mode operation -> huge transversal team work!

- DUT placed as end cap: wall resistivity change -> Q change
- Frequency of operation: mode H011 (most insensitive to cap contacts)
- Mitered internal part to separate adjacent E modes.
- Known methodology to make frequency meters (e.g. [1,2,3])



N. Biancacci &
F. Caspers et al.

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