Research supported by the High Luminosity LHC project

Low Impedance Collimators for the HL-LHC

N. Biancacci, C. Accettura, S. A. Antipov, G. Arduini,
L. Barraud, A.Bertarelli, X. Buffat, F. Carra, L. Carver, I. L. Garcia,
A. Mereghetti, E. Métral, D. Mirarchi, S. Redaelli, B. Salvant,
J. Guardia Valenzuela, D. Valuch, W. Vollenberg (CERN, Geneva, Switzerland),
D. Amorim (CERN and Université Grenoble-Alpes, Grenoble, France),
G. Mazzacano (Università di Roma "La Sapienza", Rome, Italy)

9th International Particle Accelerator Conference,
Vancouver, Canada, 2nd May 2018

Outline

- Introduction to the HL-LHC project
- The HL-LHC impedance and stability model
- Experience with LHC
- Low impedance collimators for HL-LHC
- Tests with TCSPM prototype
  - Impedance measurements with beam
  - Impedance measurements with wire
  - Jaw material resistivity studies
- TMCI threshold in LHC/HL-LHC
- Conclusion and outlook

Outline

- Introduction to the HL-LHC project
- The HL-LHC impedance and stability model
- Experience with LHC
- Low impedance collimators for HL-LHC
- Tests with TCSPM prototype
  - Impedance measurements with beam
  - Impedance measurements with wire
  - Jaw material resistivity studies
- TMCI threshold in LHC/HL-LHC
- Conclusion and outlook

The HL-LHC project

HL-LHC is an approved CERN project:

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{peak\ ult}$ $\cong$ **7.5 10^{34} $cm^{-2}s^{-1}$** and **Ultimate Integrated $L_{int\ ult}$ ~ 4000 fb^{-1}**

LHC should not be the limit, would Physics require more…

From L.Rossi, "HL-LHC baseline and operational scenario", LHC Performance workshop – Chamonix 2018

Main parameters

	HL-LHC nominal	HL-LHC ultimate
$L_{peak}\ [10^{34}\ cm^{-2}s^{-1}]$	5	7.5
$L_{tot}\ [fb^{-1}]$	3000	4000
β^* before collision [cm]	64	41
β^* stable beams [cm]	15	15

Enhanced effect of long ranges

- Beam parameters:

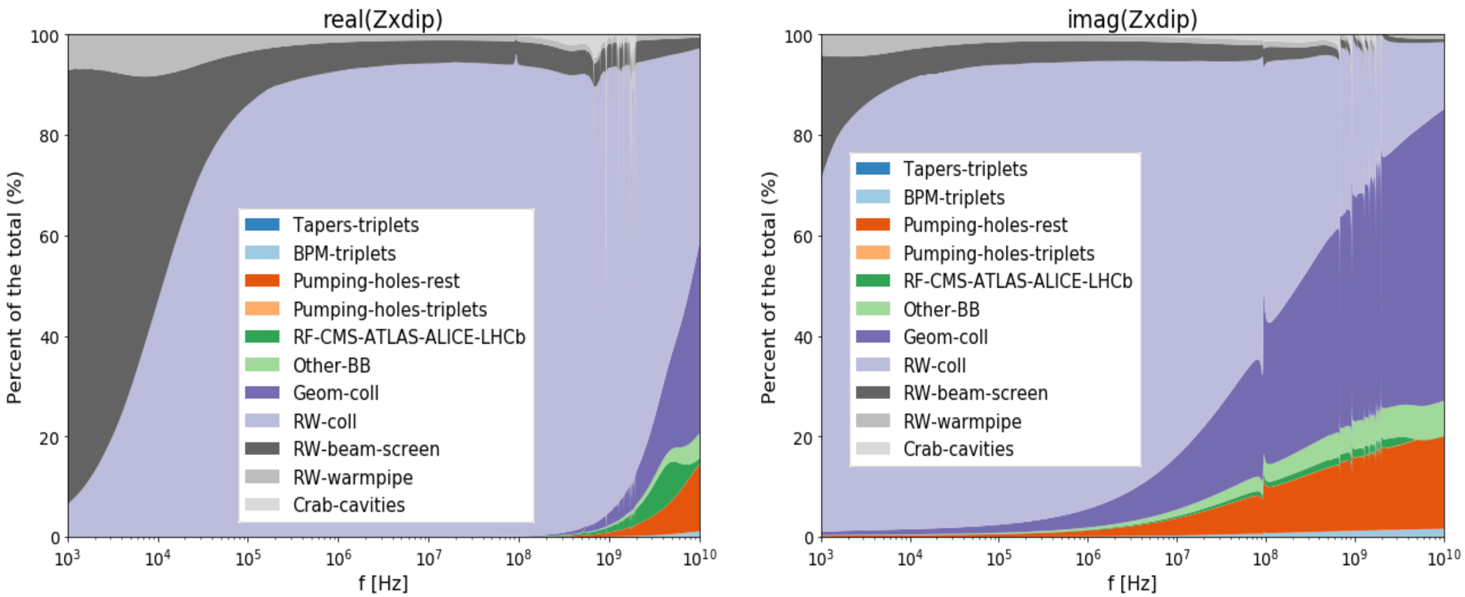
	HL-LHC standard	HL-LHC BCMS	LHC 2017
Energy [TeV]	7	7	6.5
# of bunches	2760	2748	2544
$N_b\ [10^{11}ppb]$	2.3	2.3	1.2
$\varepsilon_{x,y}^{rms}$ [μm]	2.1*	1.7	2.5
σ_z^{rms} [cm]	9	9	9

Ultimate scenario + BCMS → **challenging for beam stability**!

Outline

- Introduction to the HL-LHC project
- The HL-LHC impedance and stability model
- Experience with LHC
- Low impedance collimators for HL-LHC
- Tests with TCSPM prototype
  - Impedance measurements with beam
  - Impedance measurements with wire
  - Jaw material resistivity studies
- TMCI threshold in LHC/HL-LHC
- Conclusion and outlook

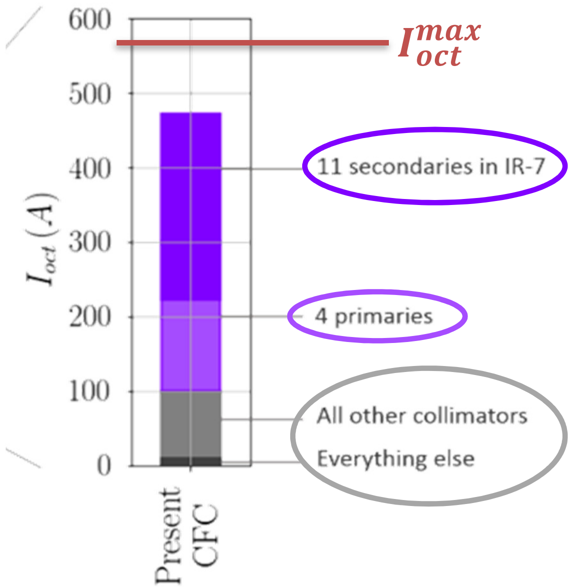
The HL-LHC impedance model

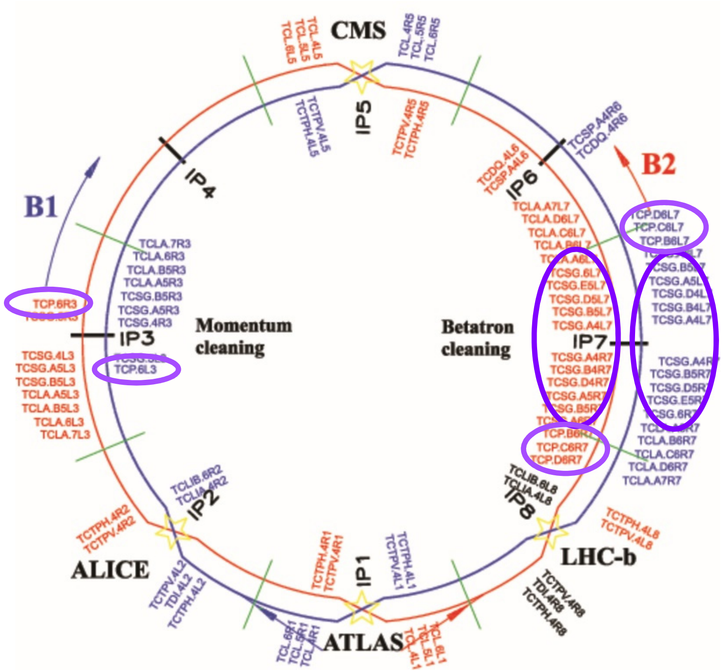


- As the LHC, the HL-LHC impedance **would be dominated by collimators**' impedance:
  - Large number (54/beam)
  - Tight gaps (< 2mm in IP7 betatron cleaning)
  - Highly resistive jaw material: majority made of Carbon Fiber Composite (CFC)
  - Not negligible impact of geometrical transitions

- **Lowering the collimators impedance** -> **gain on stability and operation margins**.

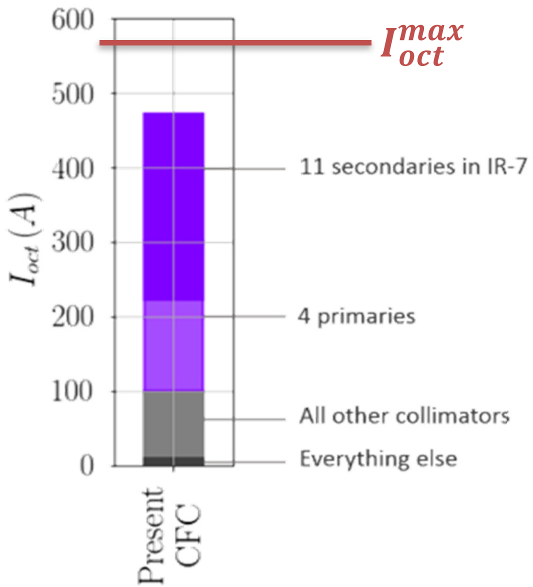
The HL-LHC stability model

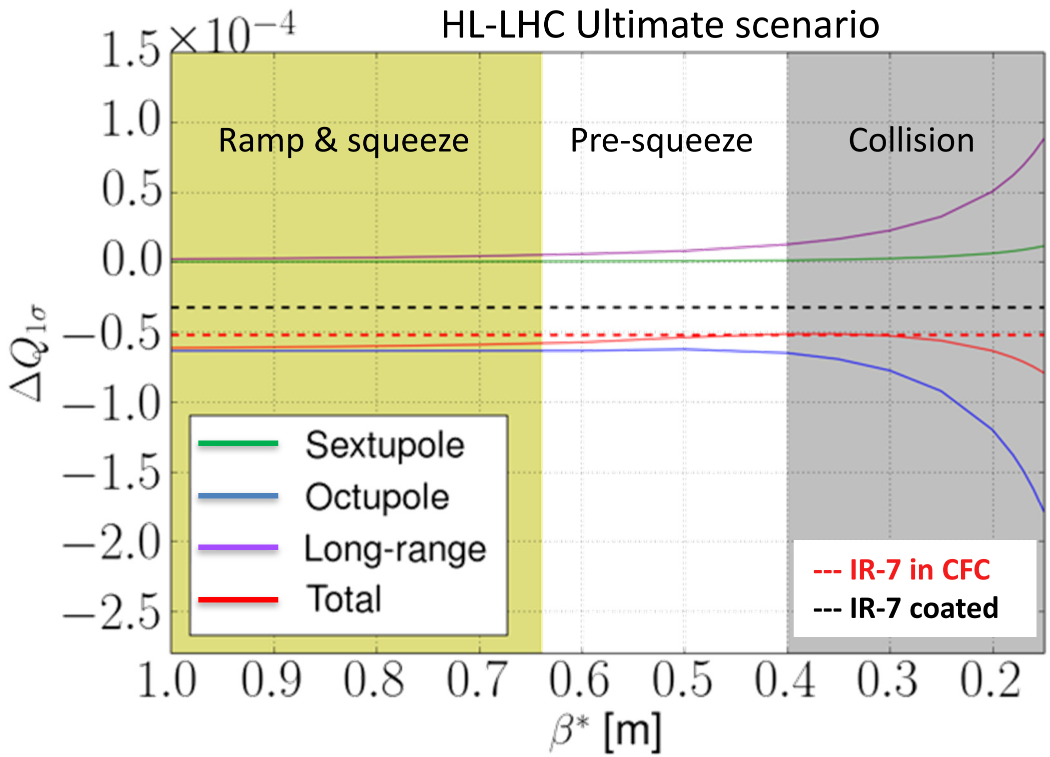




- HL-LHC with LHC collimators: tight margins for **BCMS beam**
- Impedance: 480 A out of 570 A for **Ultimate scenario** at $\beta^* = 41cm$.

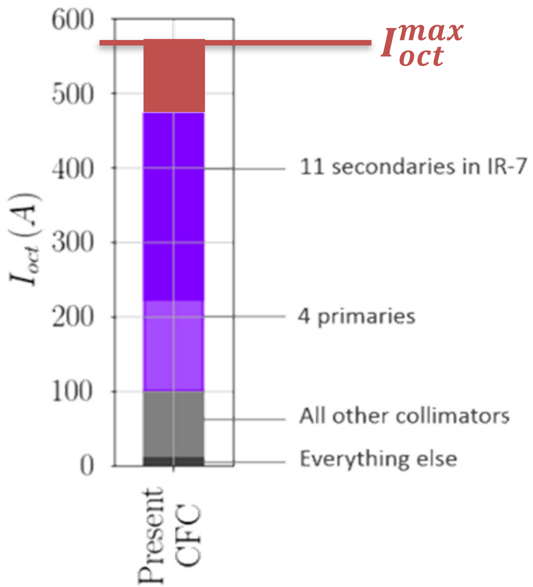
The HL-LHC stability model

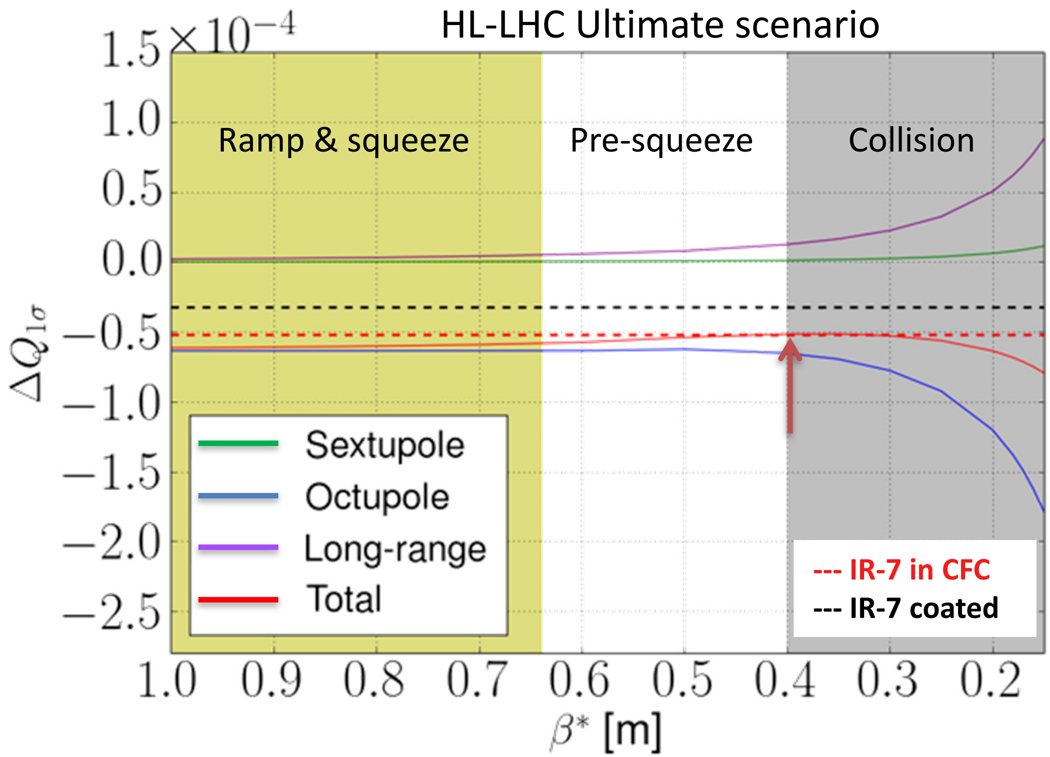




- HL-LHC with LHC collimators: tight margins for **BCMS beam**
- Impedance: 480 A out of 570 A for **Ultimate scenario** at $\beta^* = 41cm$.
- Considering **long ranges** effect:

The HL-LHC stability model



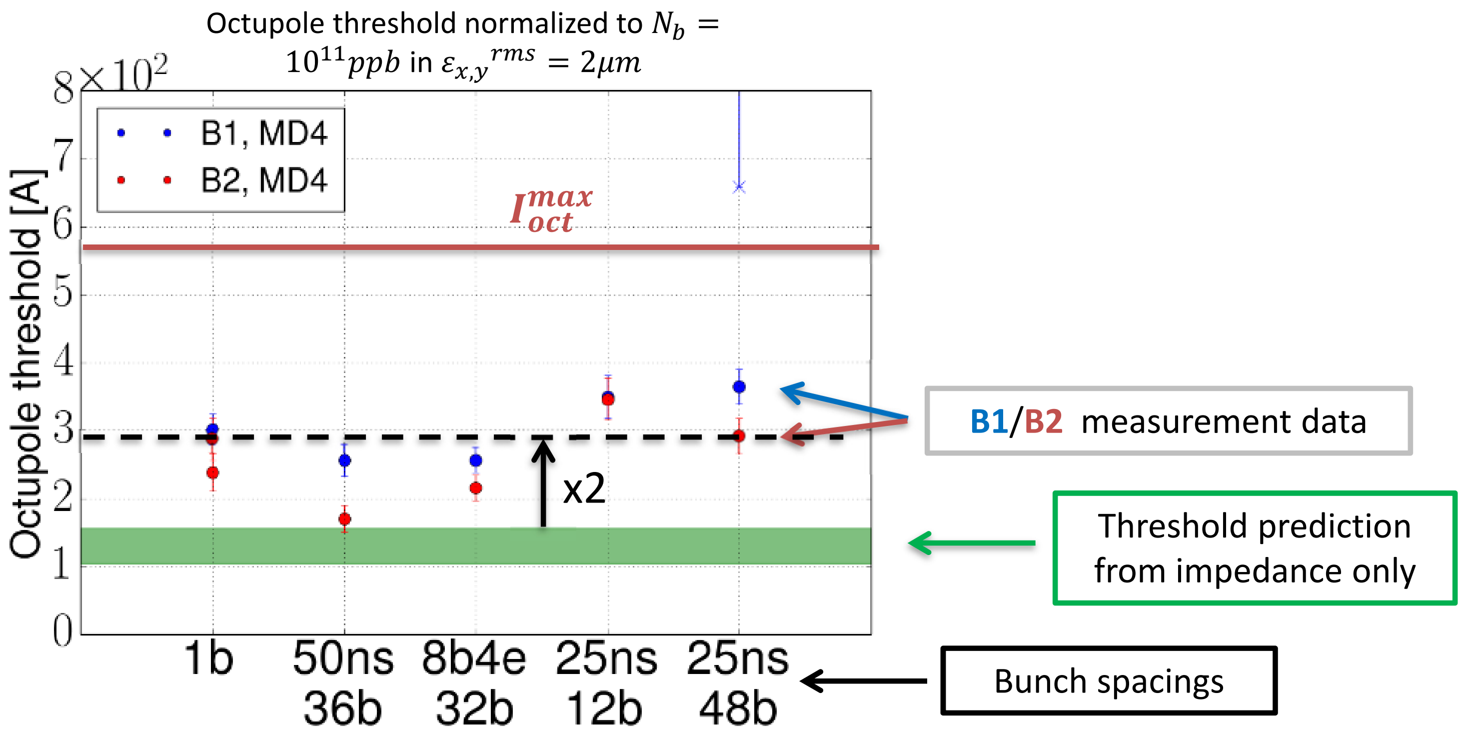


- HL-LHC with LHC collimators: tight margins for **BCMS beam**
- Impedance: 480 A out of 570 A for **Ultimate scenario** at $\beta^* = 41cm$.
- Considering **long ranges** effect: **no margin** for **Ultimate scenario.**

Outline

- Introduction to the HL-LHC project
- The HL-LHC impedance and stability model
- Experience with LHC
- Low impedance collimators for HL-LHC
- Tests with TCSPM prototype
  - Impedance measurements with beam
  - Impedance measurements with wire
  - Jaw material resistivity studies
- TMCI threshold in LHC/HL-LHC
- Conclusion and outlook

Experience with LHC

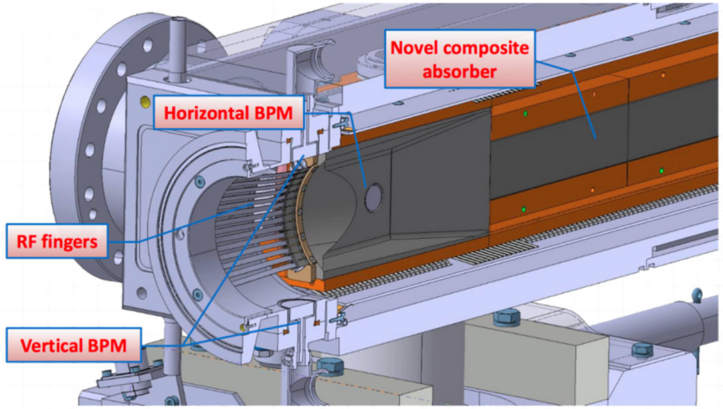


- 2017 LHC operational evidence: **needed x2 higher octupole** current than expected.
- Destabilizing mechanisms under investigation (damper noise, coupling, optics errors, long range beam-beam, tail distributions, …)
- **Need at least factor 2 margin also in HL-LHC → Collimator impedance reduction**

Outline

- Introduction to the HL-LHC project
- The HL-LHC impedance and stability model
- Experience with LHC
- Low impedance collimators for HL-LHC
- Tests with TCSPM prototype
  - Impedance measurements with beam
  - Impedance measurements with wire
  - Jaw material resistivity studies
- TMCI threshold in LHC/HL-LHC
- Conclusion and outlook

Low impedance collimators

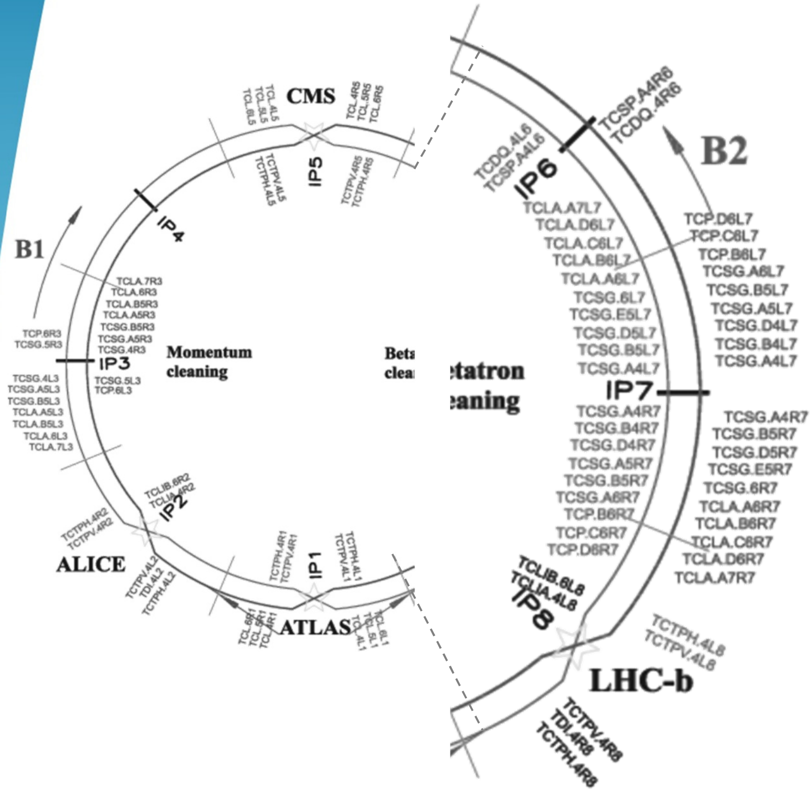


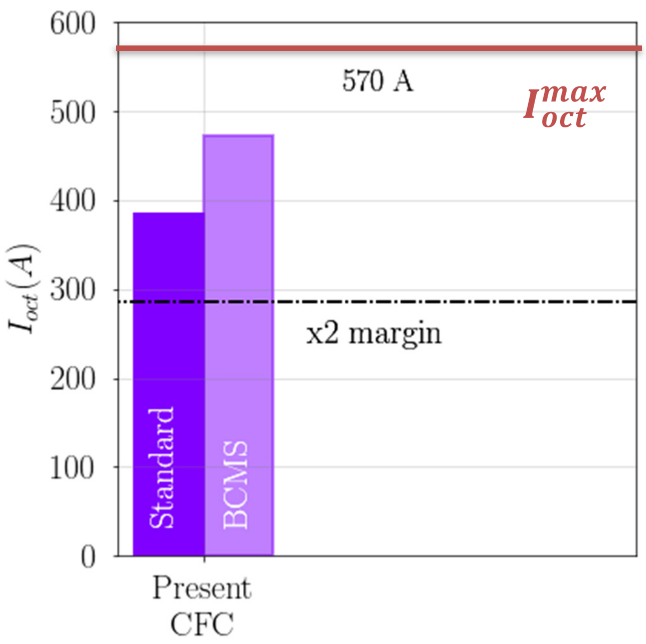
- Investigated new jaw absorber materials for HL-LHC to:
  - ✓ Cope with larger power deposition
  - ✓ Reduce beam impedance
- Main options:

Material	Resistivity [$n\Omega\mathrm{m}$]	Purpose
CFC	5000	Present in LHC
MoGr	1000	Baseline bulk
Mo	53	Baseline coating
TiN	400	Alternative coating
Cu	19	Alternative coating

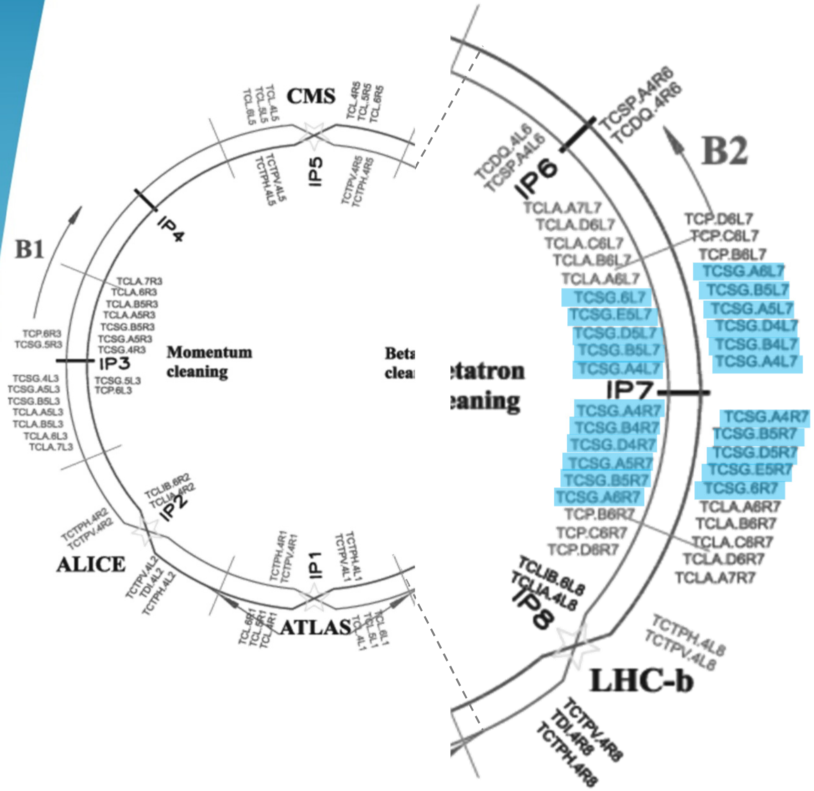
HL-LHC baseline (MoGr, Mo)

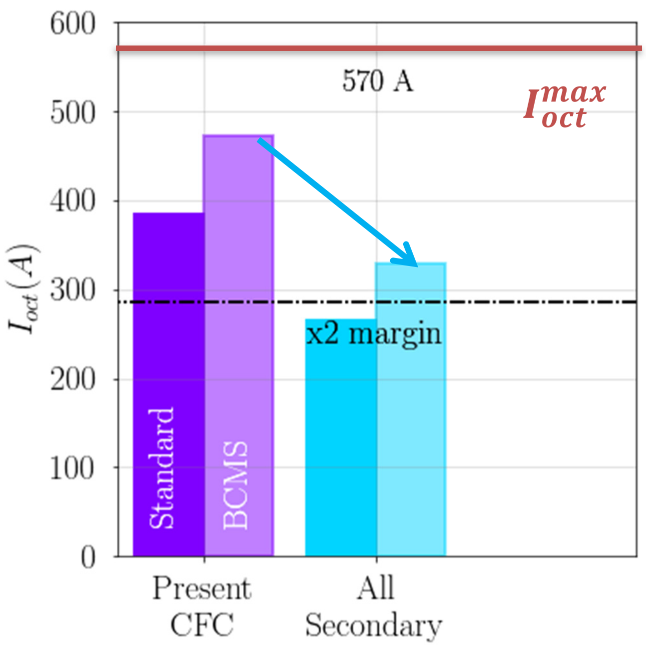
Low impedance collimators





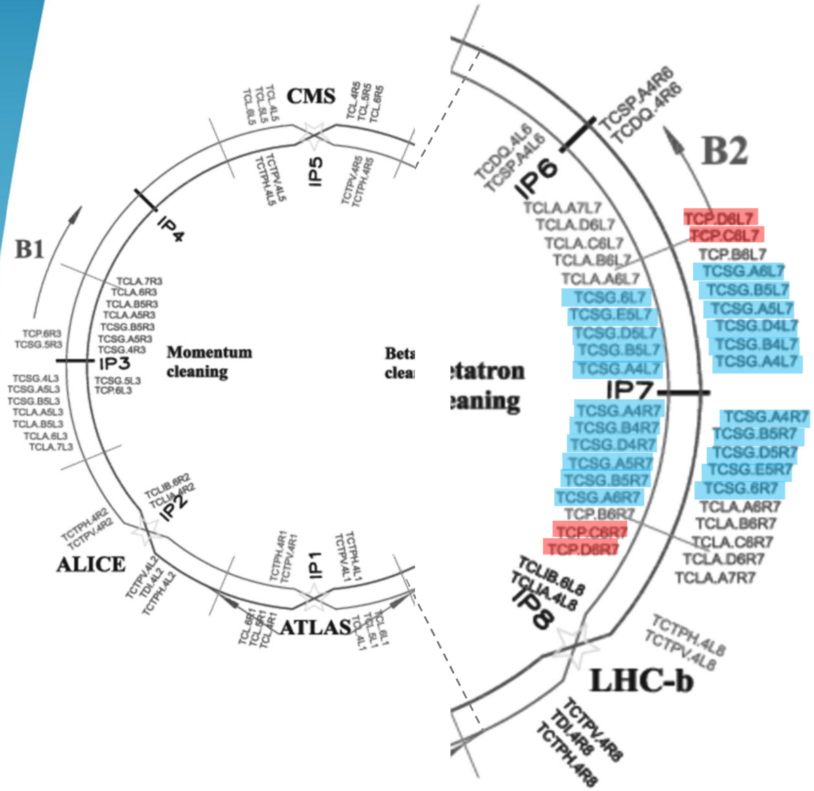
Low impedance collimators

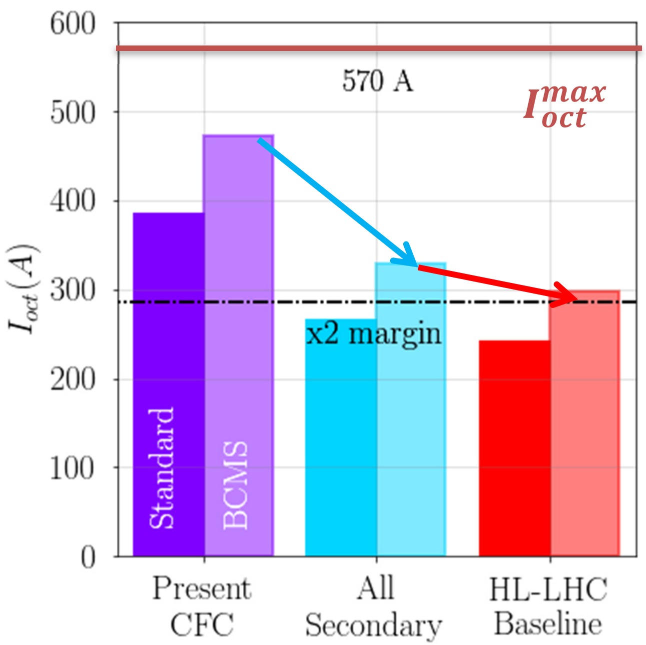




- Coating all secondaries in IP7 will reduce the octupole threshold by ~150 A.

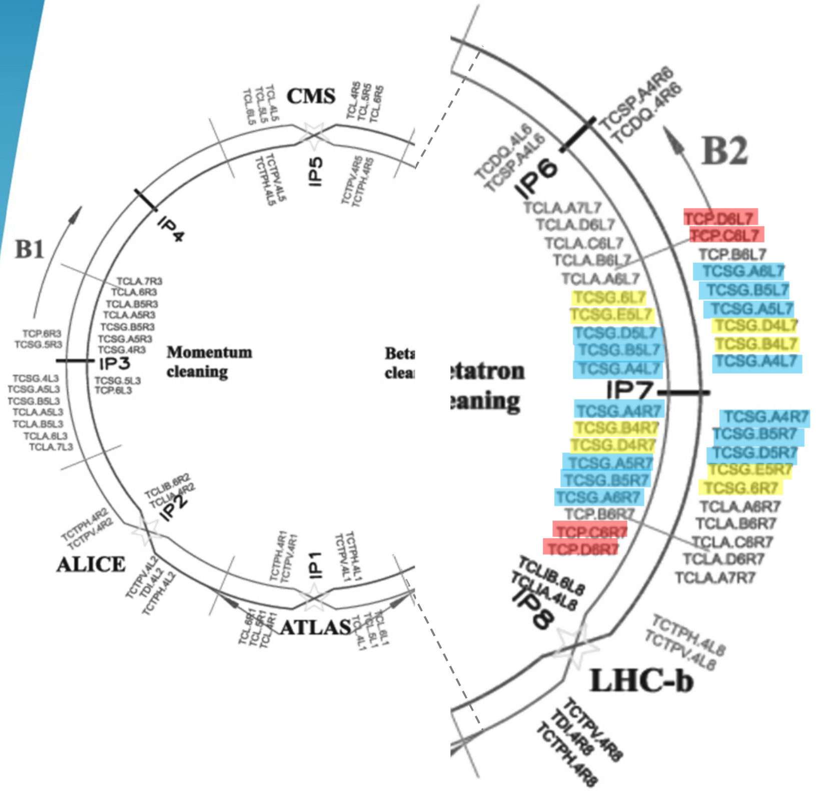
Low impedance collimators

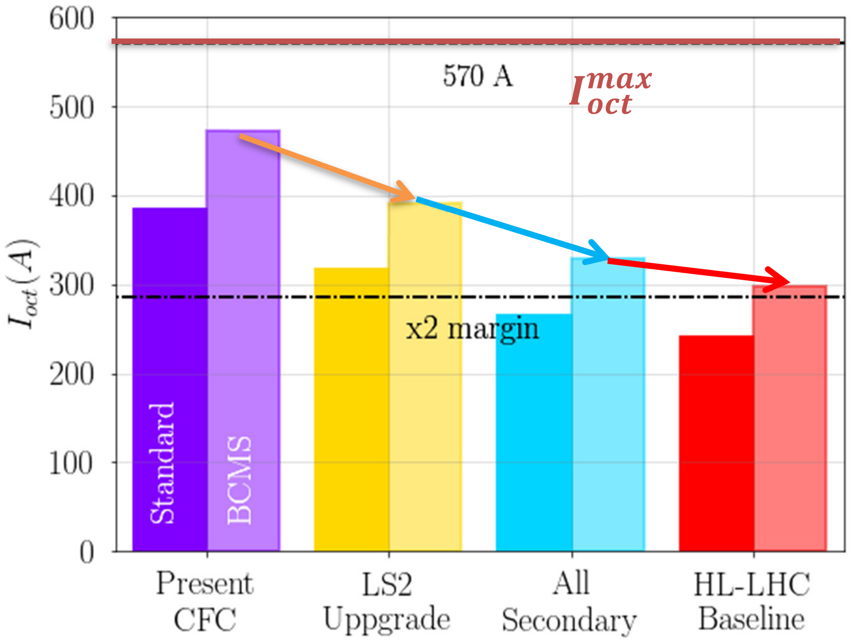




- Coating all secondaries in IP7 will reduce the octupole threshold by ~150 A.
- With 2 primaries in MoGr (HL-LHC baseline): x2 margin for operation (- 30 A).

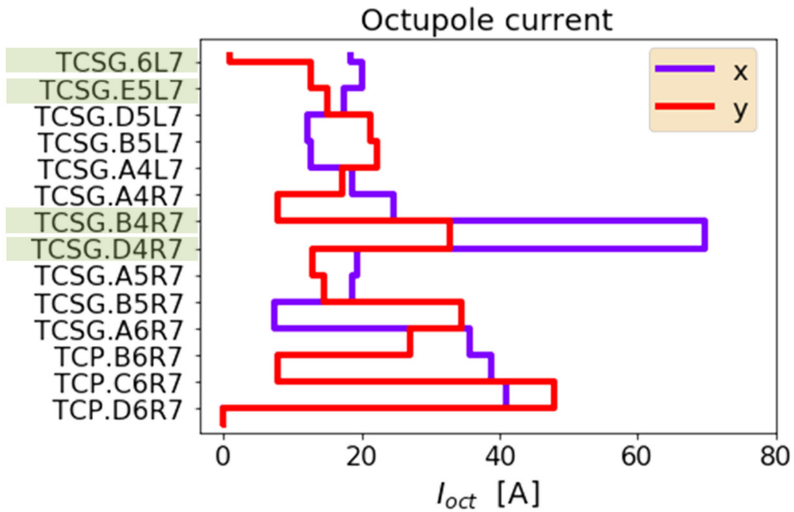
Low impedance collimators

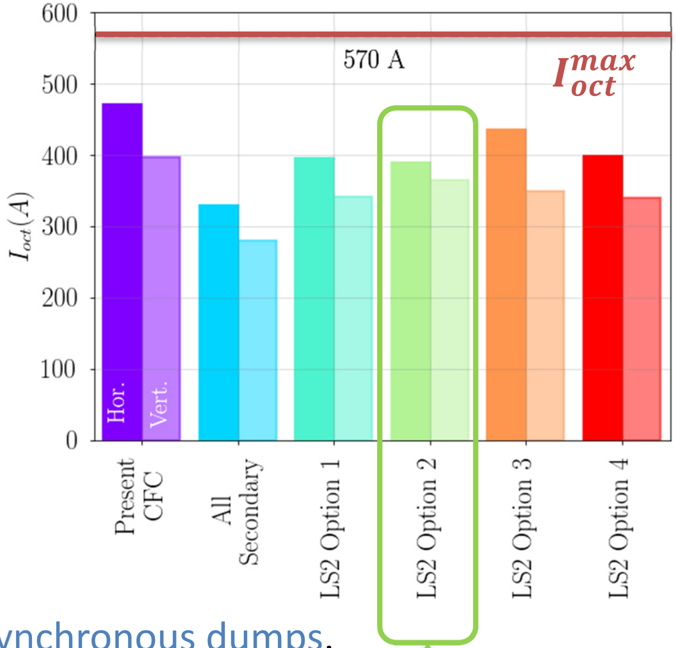




- Coating all secondaries in IP7 will reduce the octupole threshold by ~150 A.
- With 2 primaries in MoGr (HL-LHC baseline): x2 margin for operation (- 30 A).
- Staged implementation foreseen (4/11 secondaries/beam) during next LHC Long Shutdown (LS2)

Staged installation of low impedance collimators





- Selection constraints:
  1. Gain in impedance reduction.
  2. Rate of injection/extraction failures or asynchronous dumps.
  3. Amount of exposure to steady beam losses.

- Selected set:
  - 1 Vertical: D4L/R7
  - 1 Horizontal: B4L/R7
  - 2 Skews: E5L/R7 and 6L/R7

Outline

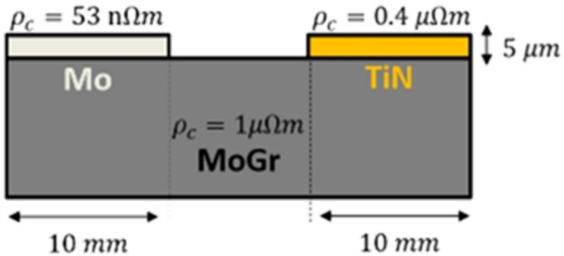
- Introduction to the HL-LHC project
- The HL-LHC impedance and stability model
- Experience with LHC
- Low impedance collimators for HL-LHC
- Tests with TCSPM prototype
  - Impedance measurements with beam
  - Impedance measurements with wire
  - Jaw material resistivity studies
- TMCI threshold in LHC/HL-LHC
- Conclusion and outlook

TCSPM: the three stripe collimator

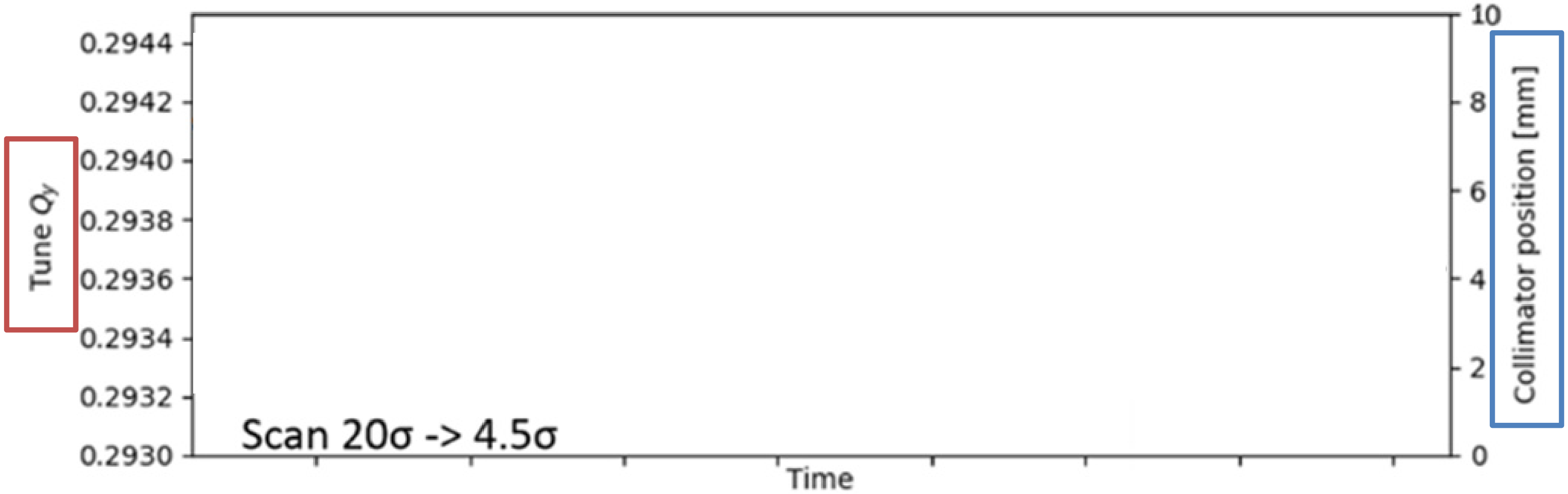
The TCSPM is a three stripe vertical collimator prototype installed during the 2016-2017 LHC winter shutdown (thanks to all the team involved!) with aim to quantify experimentally the gains in terms of coating impedance reduction.

Materials exposed to the beam:

1. Mo coating on MoGr bulk
2. MoGr uncoated bulk
3. TiN coating on MoGr bulk

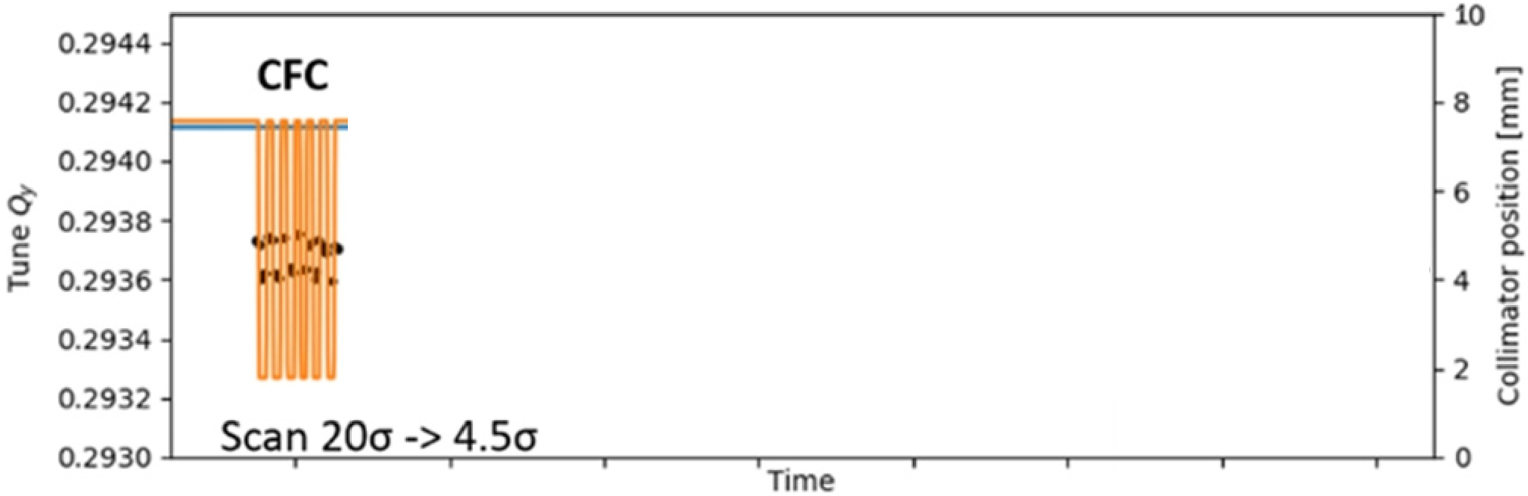


Probing HL-LHC collimator impedance



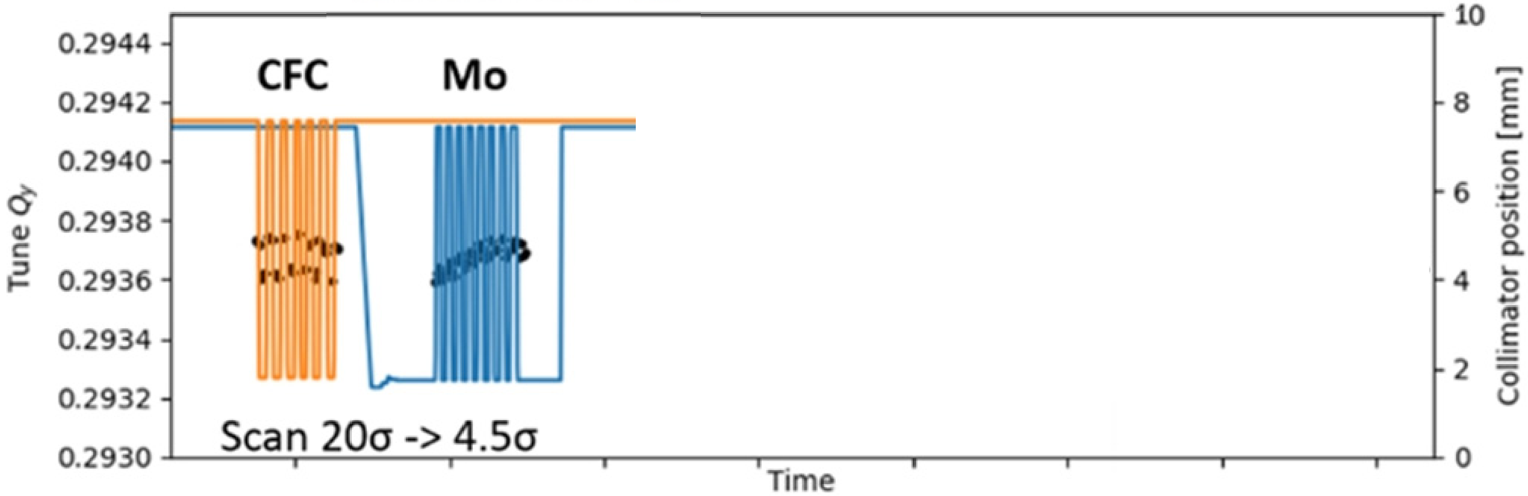
- Studied **tune** change Vs **gap** movement for TCSPM and adjacent CFC collimator.

Probing HL-LHC collimator impedance



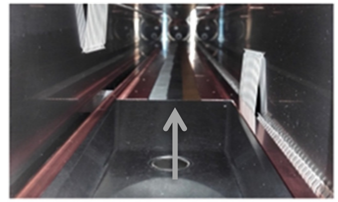
- Studied **tune** change Vs **gap** movement for TCSPM and adjacent CFC collimator.
- Sequence of fast collimator gap cycling + kick → 10^{-5} **accuracy reached thanks to ADT team!**

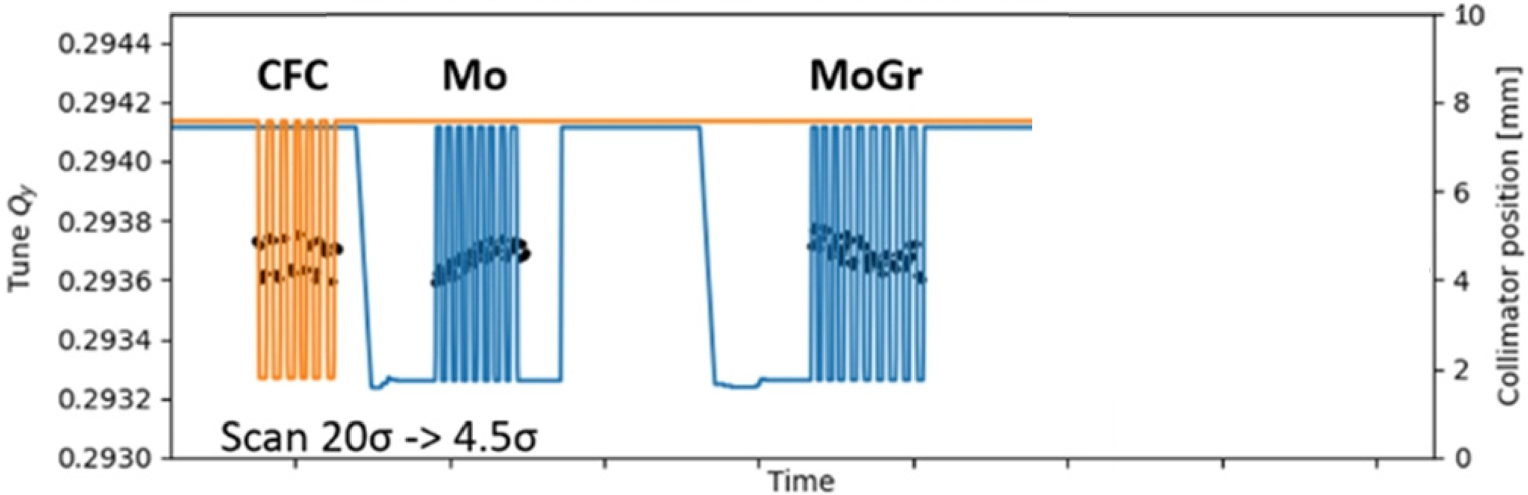
Probing HL-LHC collimator impedance



- Studied **tune** change Vs **gap** movement for TCSPM and adjacent CFC collimator.
- Sequence of fast collimator gap cycling + kick $\rightarrow$ **10^{-5} accuracy reached thanks to ADT team!**

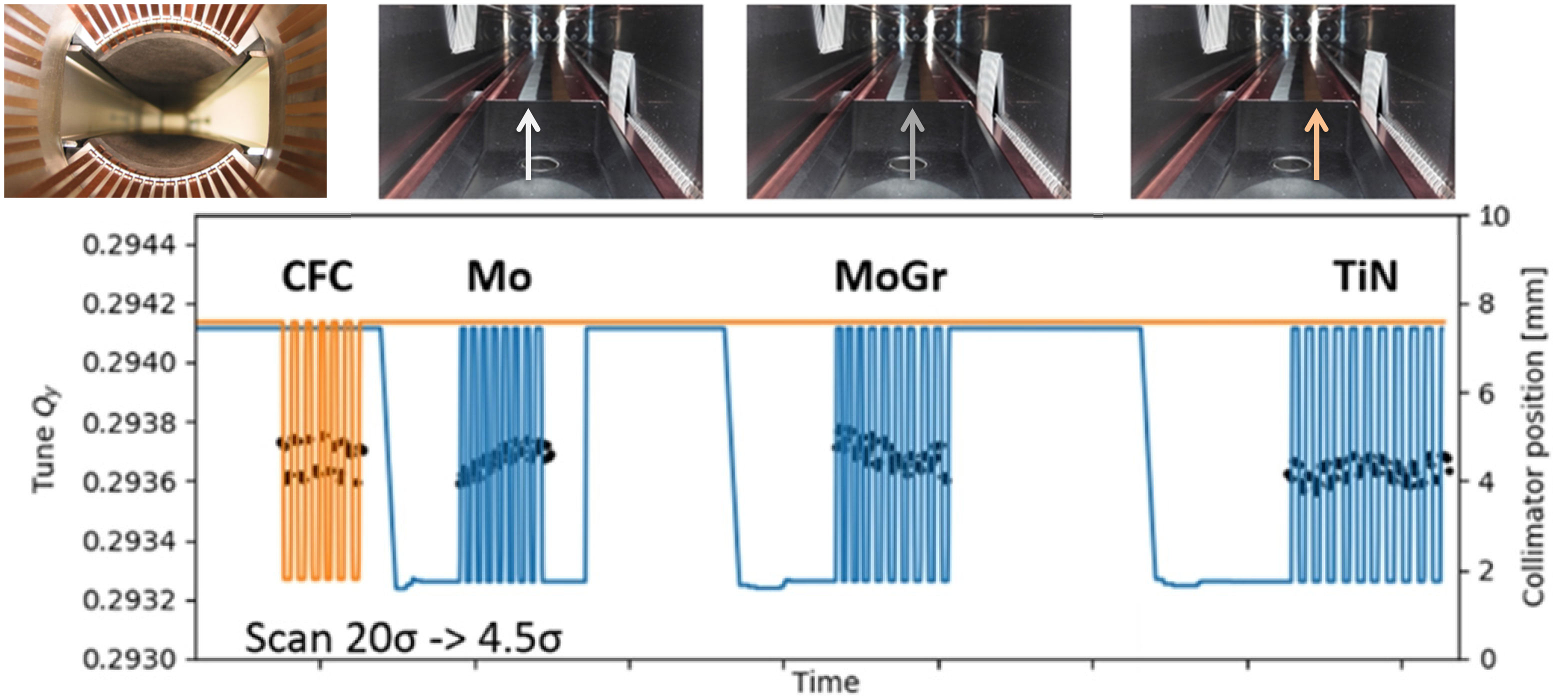
Probing HL-LHC collimator impedance





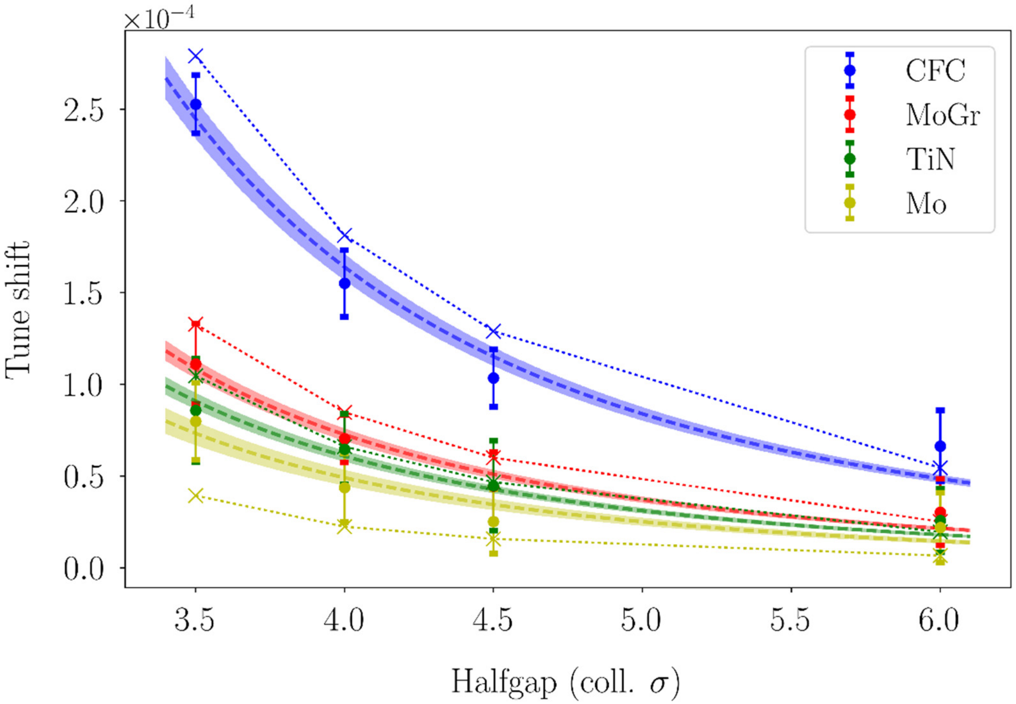
- Studied **tune** change Vs **gap** movement for TCSPM and adjacent CFC collimator.
- Sequence of fast collimator gap cycling + kick → **10^{-5} accuracy reached thanks to ADT team!**

Probing HL-LHC collimator impedance



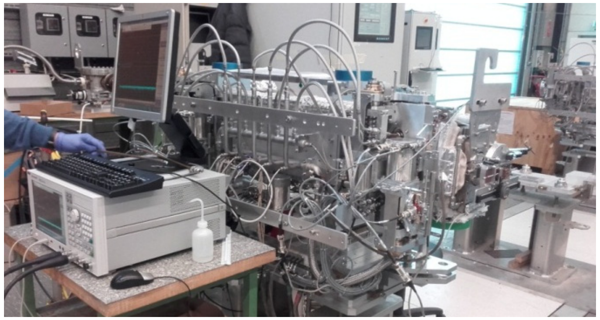
- Studied **tune** change Vs **gap** movement for TCSPM and adjacent CFC collimator.
- Sequence of fast collimator gap cycling + kick → $\mathbf{10^{-5}}$ **accuracy reached thanks to ADT team!**

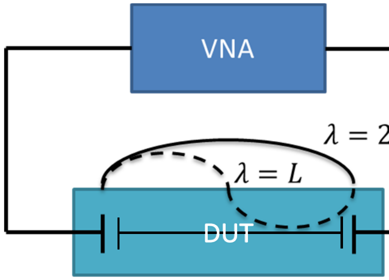
Probing HL-LHC collimator impedance

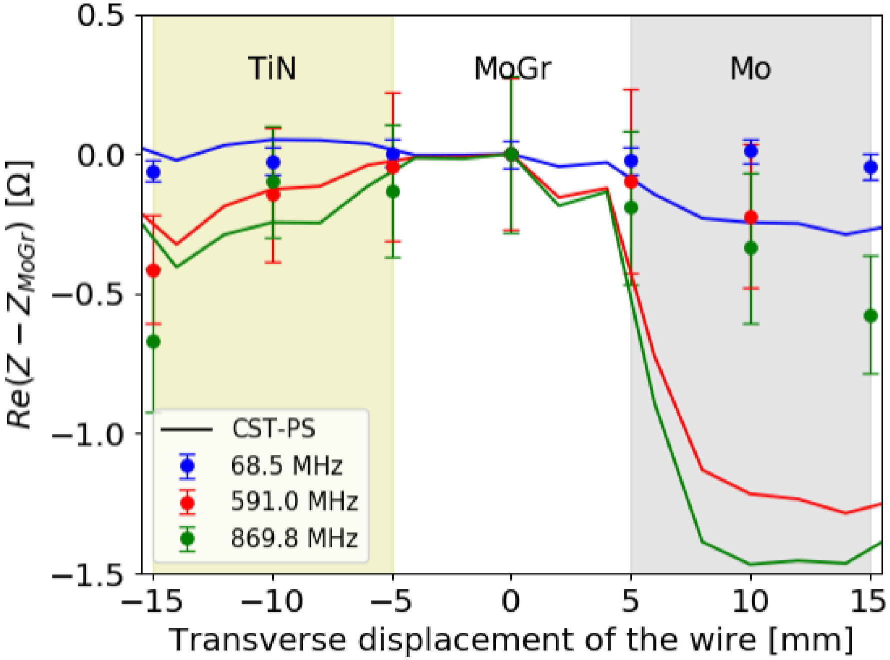


- Clear gain with respect to CFC collimators.
- Factor x2 higher tune shift on Mo stripe → 250$n\Omega m$ resistivity (expected ~53$n\Omega m$).

Bench RF measurements





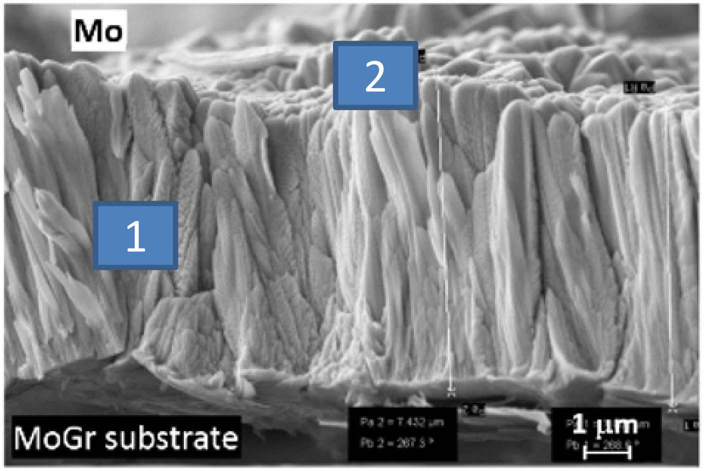


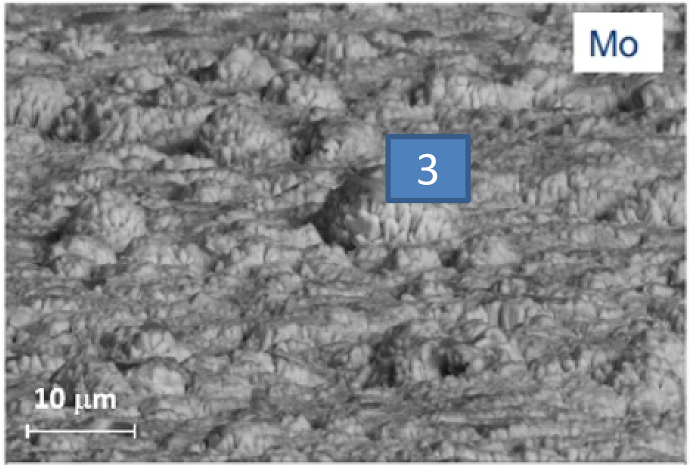
- Resonant wire measurements performed:
  - Wire capacitive coupled → the collimator is made resonant
  - Change in Q-factor → Real part of longitudinal impedance.

- Agreement within errorbars on TiN stripe.

- Lower impedance reduction measured on Mo stripe → Compatible with $\sim 300 n\Omega m$ Mo resistivity (expected $53 n\Omega m$).

Surface studies



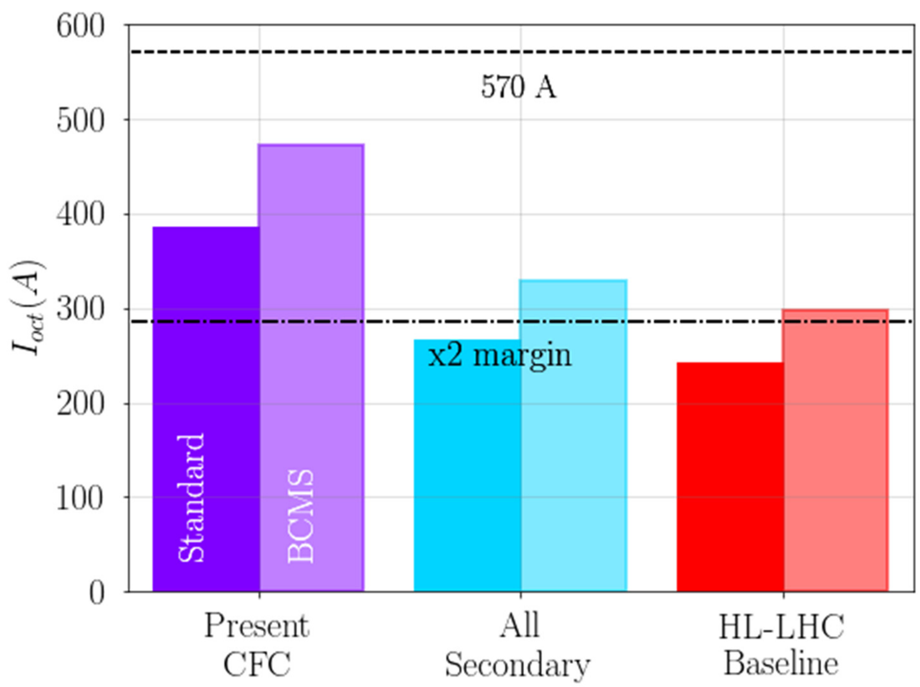


- Higher Mo resistivity could be related to:
  1. Coating grain size and number of boundaries.
  2. Coating surface roughness.
  3. Presence of large ($< 10\mu$m) bumps on the surface.

- Surface impurities could also increase effective resistivity.

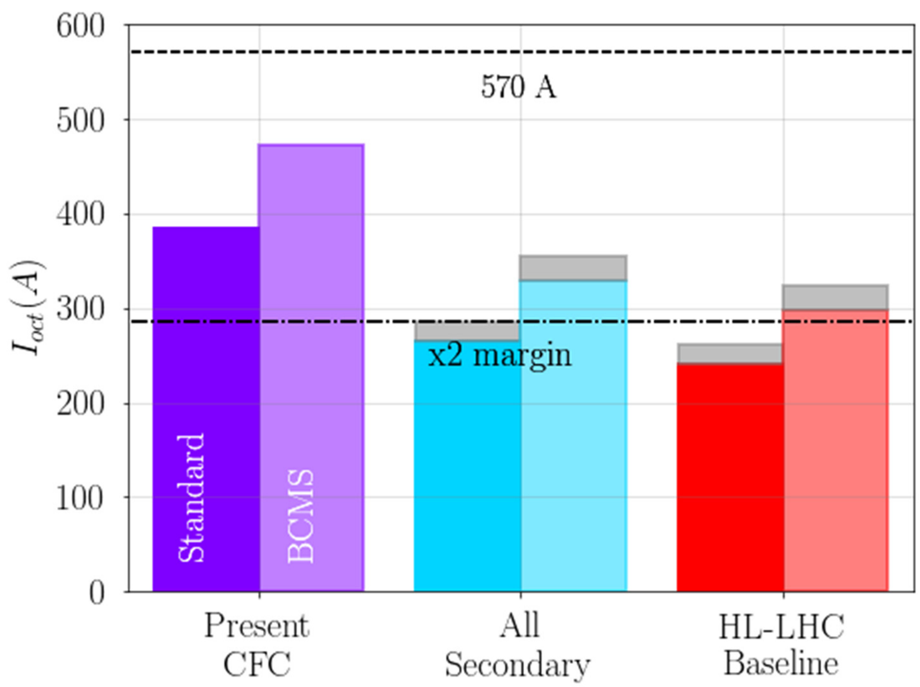
- Investigations ongoing on specific coating procedures:
  - Ultra-sound,
  - Surface polishing,
  - CO2 blasting,
  - …

Impact of Mo resistivity on stability



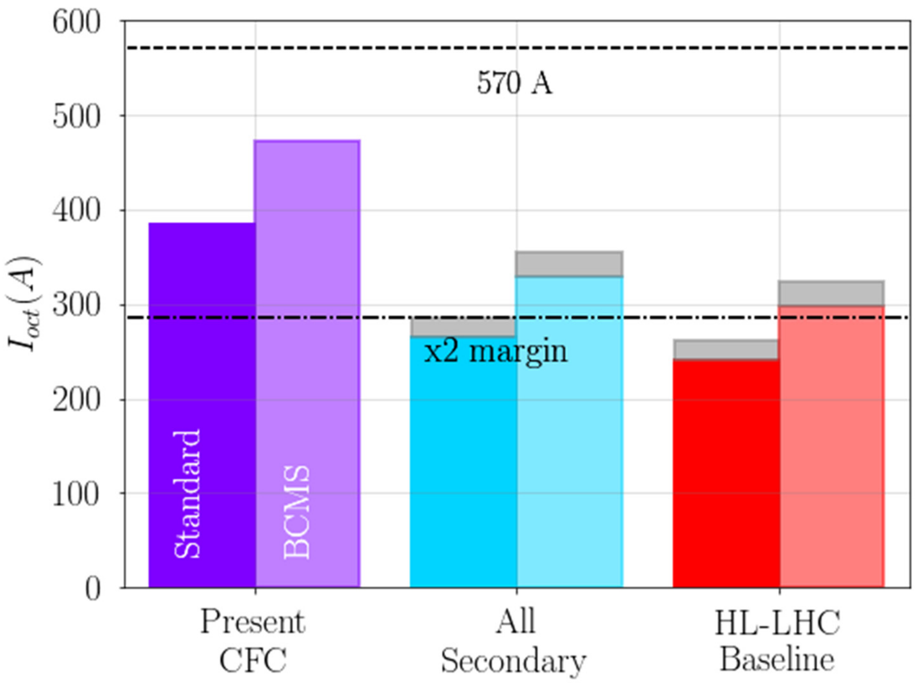
- What is the impact of the measured Mo resistivity (250 nΩm instead of 53 nΩm) on the HL-LHC baseline?

Impact of Mo resistivity on stability



- What is the impact of the measured Mo resistivity (250 nΩm instead of 53 nΩm) on the HL-LHC baseline?
    - -25 (20) A reduction in margin for BCMS (Standard) beam

Impact of Mo resistivity on stability



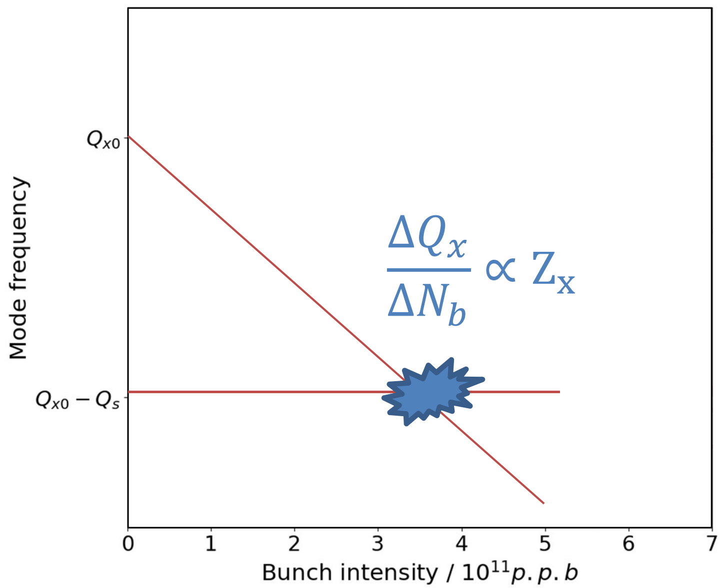
- What is the impact of the measured Mo resistivity (250 nΩm instead of 53 nΩm) on the HL-LHC baseline?
  - -25 (20) A reduction in margin for BCMS (Standard) beam

- Still close to operation margin for HL-LHC Standard and BCMS beams.

Outline

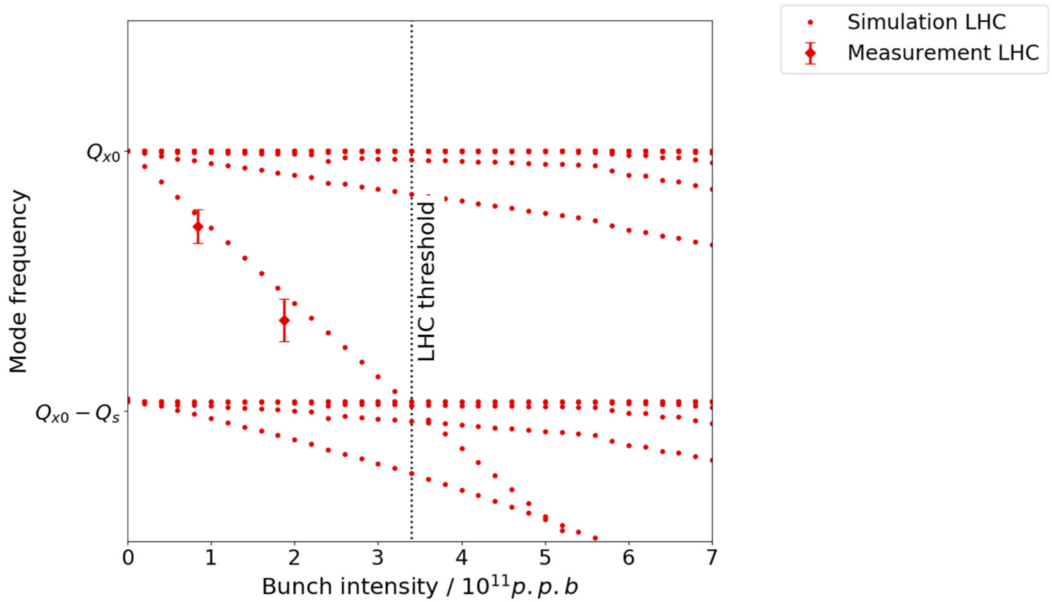
- Introduction to the HL-LHC project
- The HL-LHC impedance and stability model
- Experience with LHC
- Low impedance collimators for HL-LHC
- Tests with TCSPM prototype
  - Impedance measurements with beam
  - Impedance measurements with wire
  - Jaw material resistivity studies
- TMCI threshold in LHC/HL-LHC
- Conclusion and outlook

Probing HL-LHC TMCI threshold



- Measurement of **tune shift versus intensity** gives information on :
  - Transverse impedance of the machine
  - Maximum reachable intensity before TMCI (coupling of Q_x with $Q_x - Q_s$)

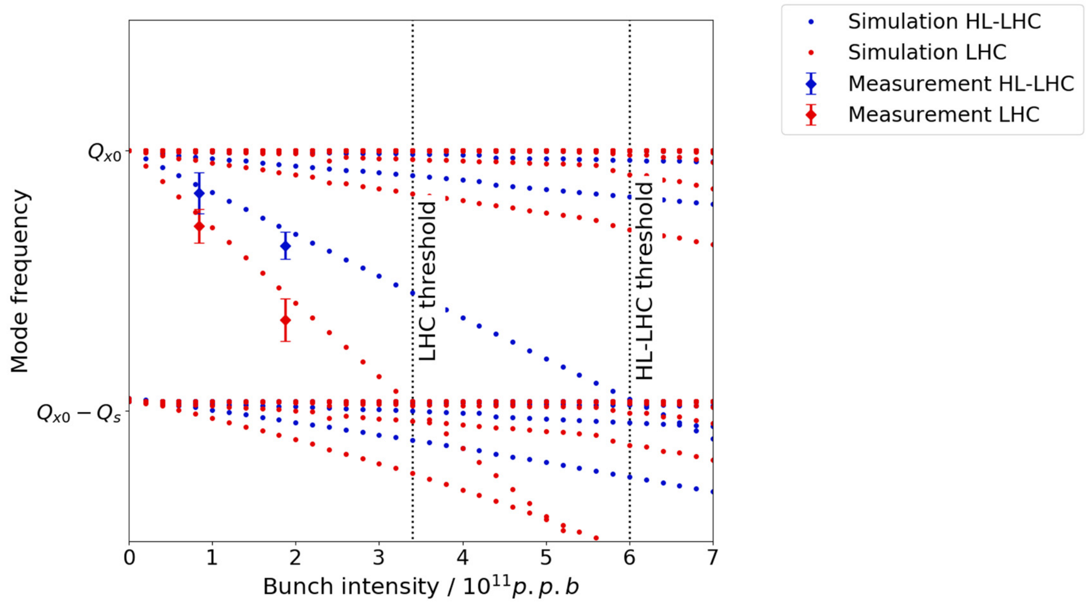
Probing HL-LHC TMCI threshold



- Measurement of tune shift versus intensity gives information on :
  - Transverse impedance of the machine
  - Maximum reachable intensity before TMCI (coupling of Q_x with $Q_x - Q_s$)

- Performed in **LHC**: threshold close to expected $\mathbf{3.5 \cdot 10^{11}}$**ppb**

Probing HL-LHC TMCI threshold



- Measurement of tune shift versus intensity gives information on :
  - Transverse impedance of the machine
  - Maximum reachable intensity before TMCI (coupling of Q_x with $Q_x - Q_s$)

- Performed in **LHC**: threshold close to expected $\mathbf{3.5 \cdot 10^{11}}$**ppb**

- HL-LHC low impedance collimators were *imitated* by opening the LHC collimator gaps.

- **HL-LHC TMCI threshold** close to expected $\mathbf{6 \cdot 10^{11}}$**ppb** (factor x2 higher than LHC)

Conclusions and outlook

- Beams brightness will more than double in the HL-LHC → **challenge for beam stability**.

- New materials have been studied for collimation upgrade and impedance reduction.

- Dedicated machine tests confirmed:
  - Reduction of collimators' impedance with Mo coating.
  - Increase of TMCI threshold by a factor of 2.

- Discrepancies remain between measured Mo resistivity and the expected value.
  - Surface observations on going to identify the cause.
  - Different coating procedures and materials being tested.

- Even accounting for worse Mo resistivity, HL-LHC stabilizing octupole current **is close to the operational margin** to account effects other than impedance.

See also poster of S.Antipov THPAF035

Thanks for your attention!