Study of the Transverse Mode Coupling Instability in the CERN Large Hadron Collider

D.Amorim, S.Antipov, N.Biancacci, X.Buffat, L.Carver, E.Métral

Many thanks to:
T.Levens, A.Mereghetti, B.Salvant, M.Soderen,
D.Valuch, LHC and Injectors Operations

61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams

Daejeon, South Korea

18/06/2018

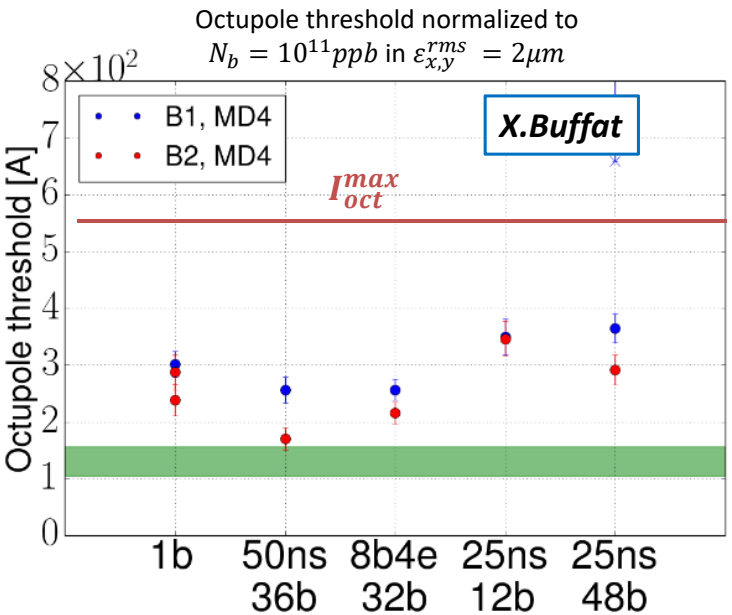
Outline

- Context and challenges
- The transverse mode coupling instability in the LHC
  - The transverse mode coupling instability
  - TMCI in the LHC era
  - TMCI in the HL-LHC era
- Conclusion and perspectives

Outline

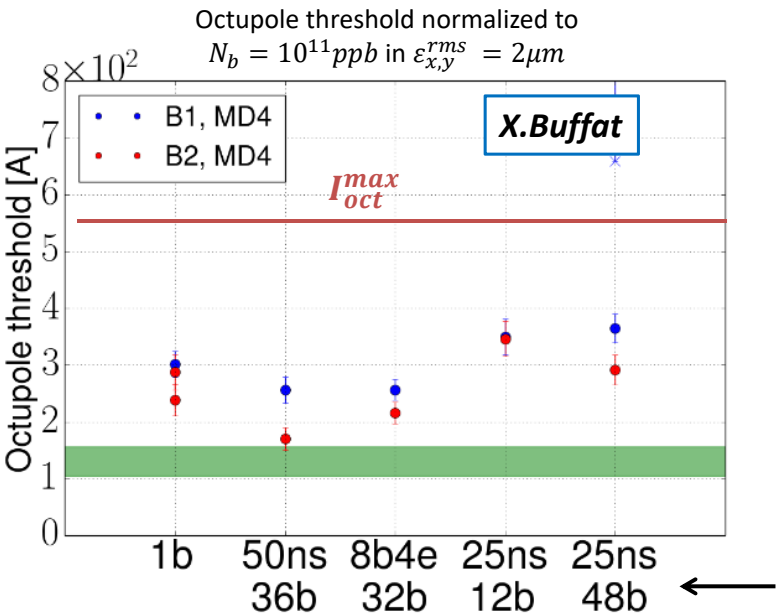
- Context and challenges
- The transverse mode coupling instability in the LHC
  - The transverse mode coupling instability
  - TMCI in the LHC era
  - TMCI in the HL-LHC era
- Conclusion and perspectives

LHC Beam stability in 2017



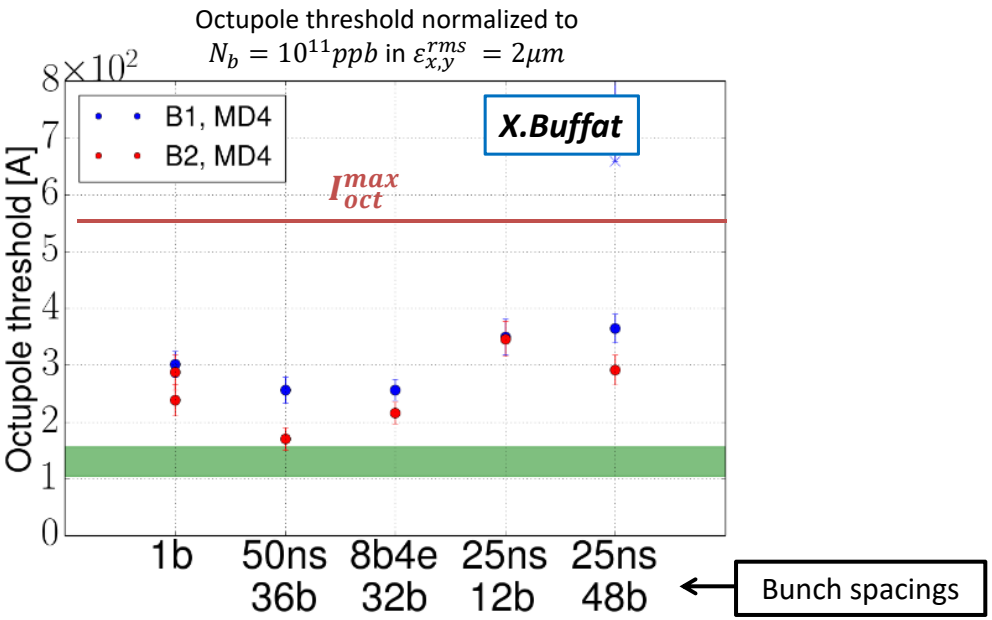
See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



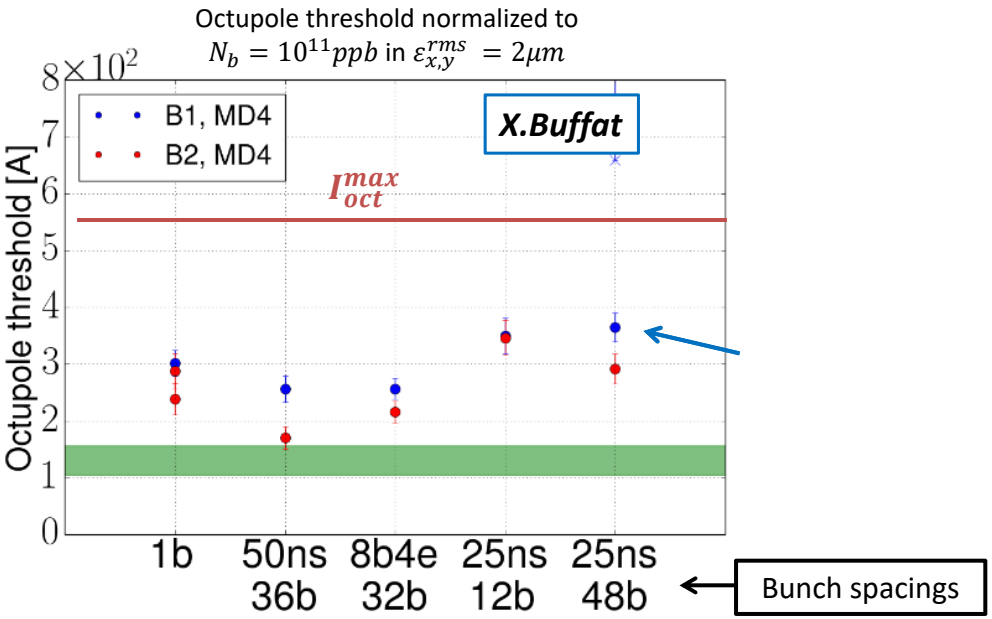
See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



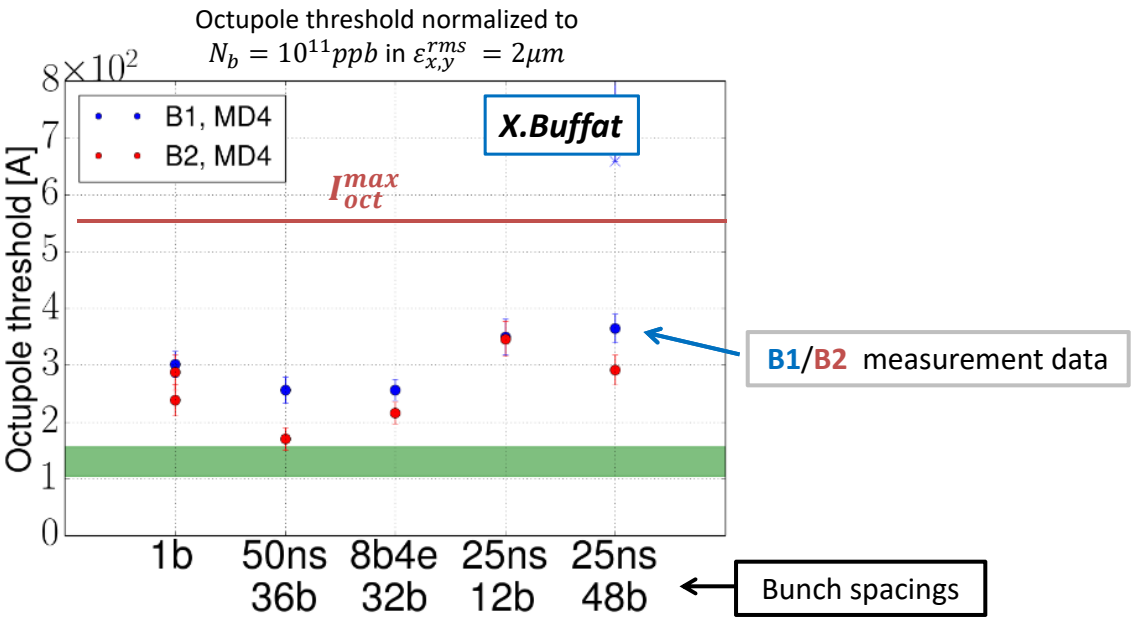
See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



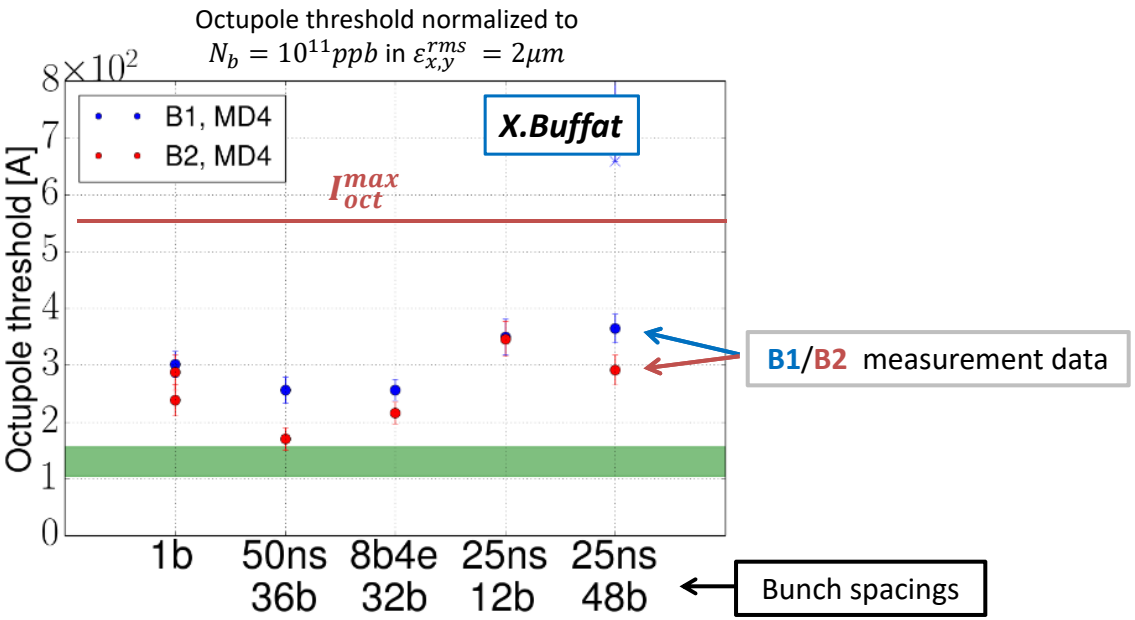
See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



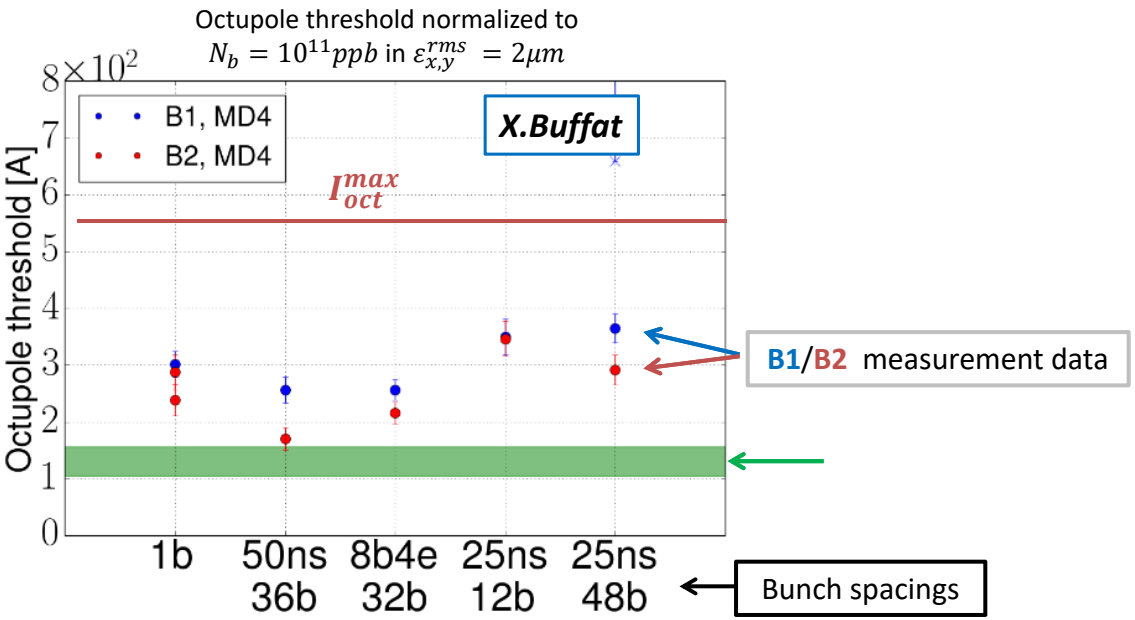
See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



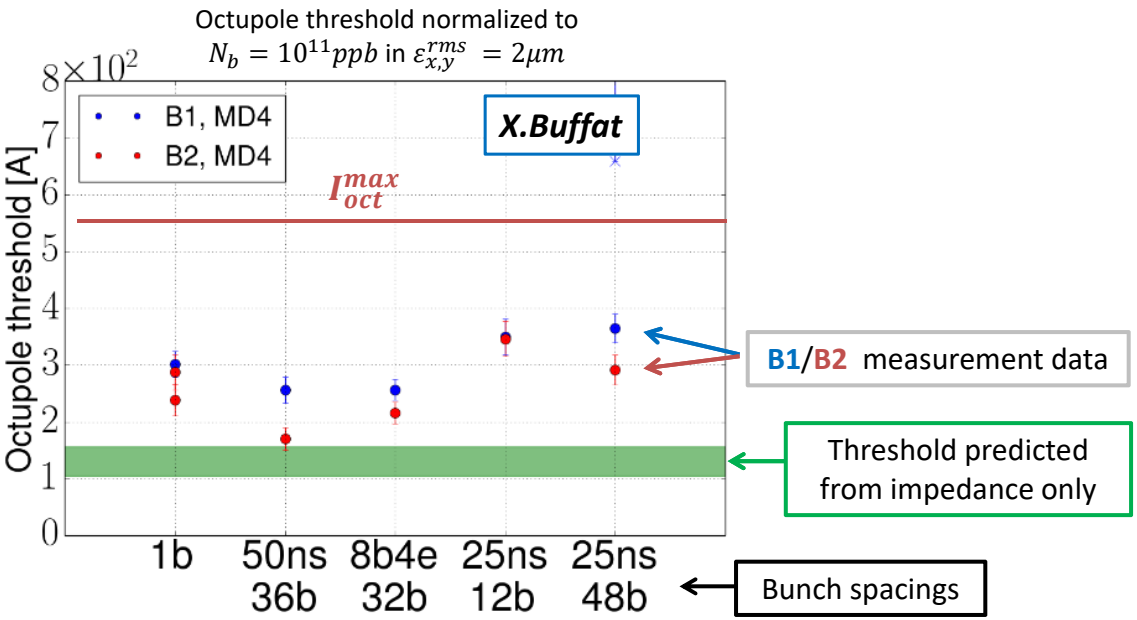
See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



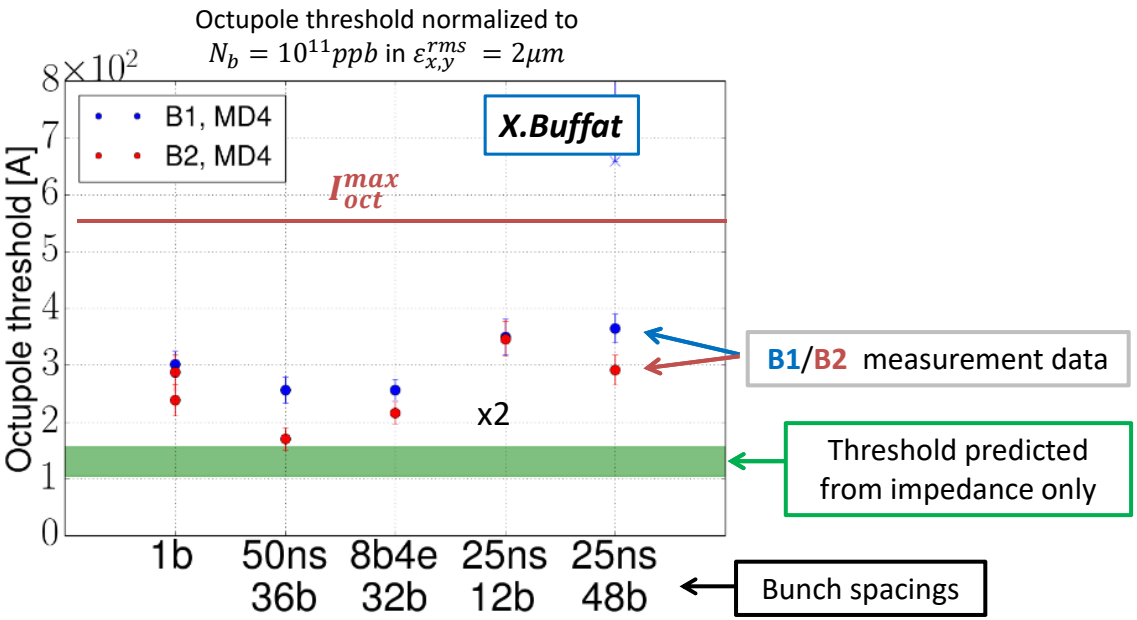
See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



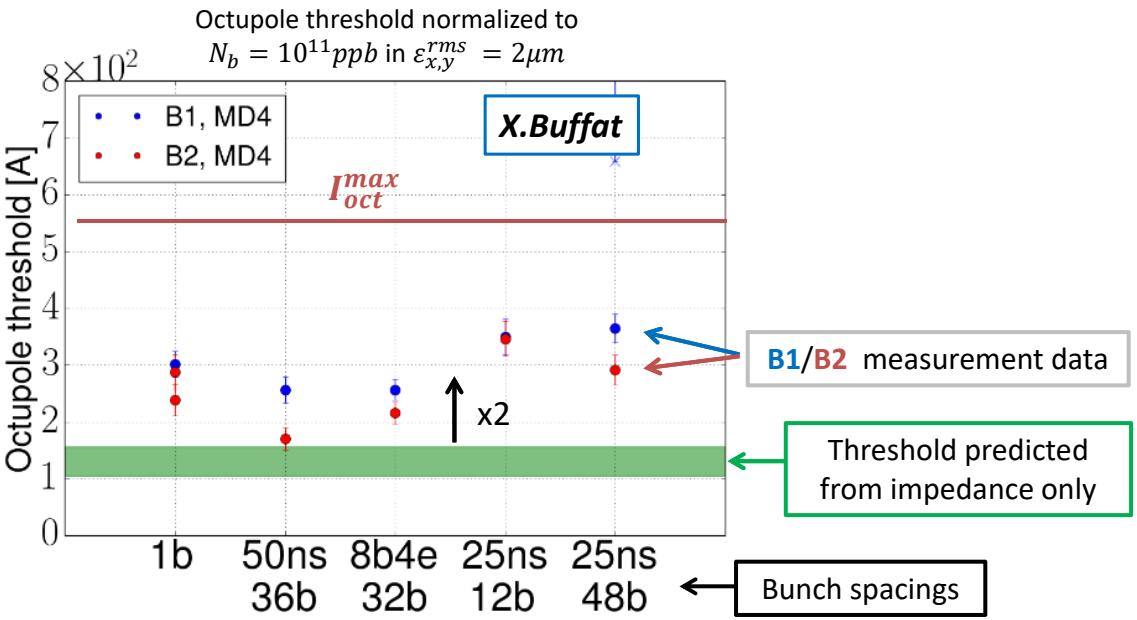
See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



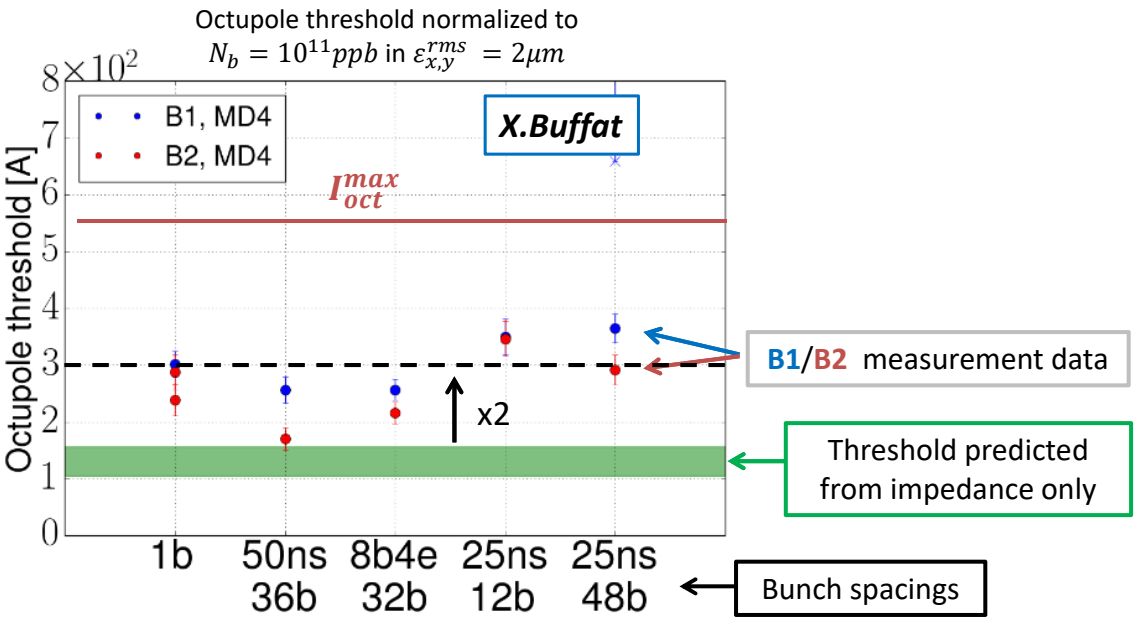
See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



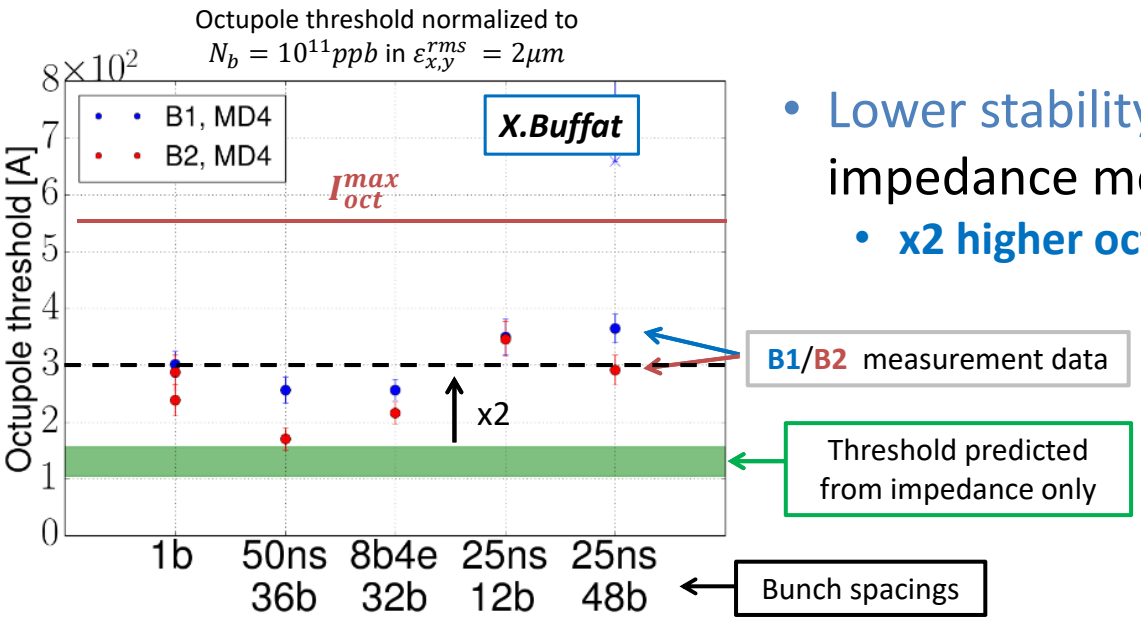
See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



See also ***N.Biancacci, IPAC18, WEYGBE4***

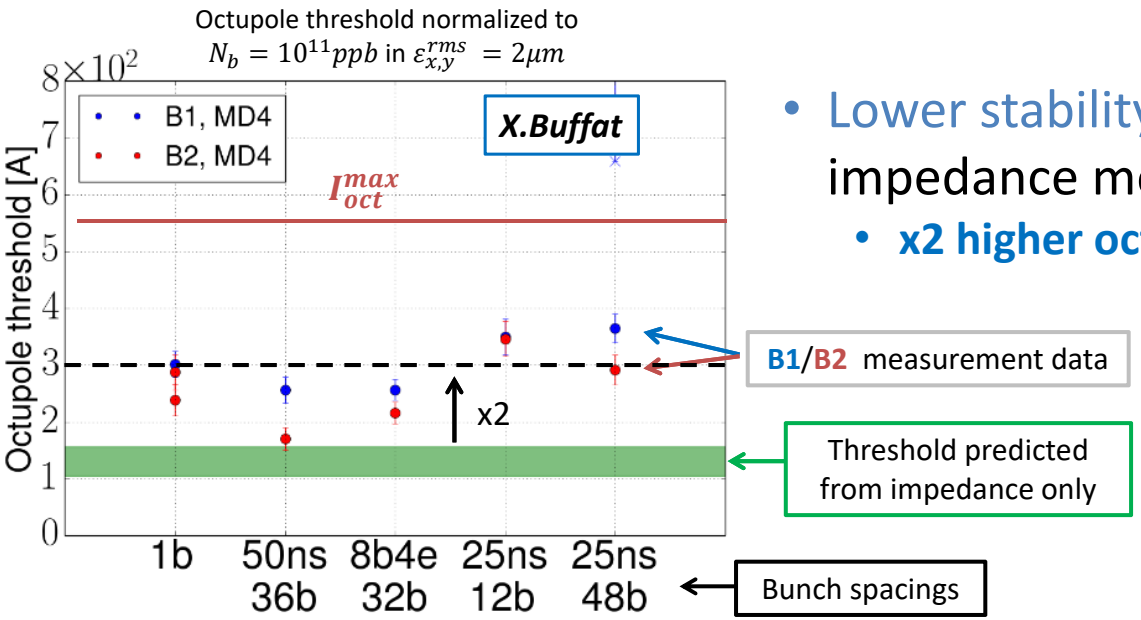
LHC Beam stability in 2017



- Lower stability margins than predicted from impedance model
  - **x2 higher octupole current needed**

See also ***N.Biancacci, IPAC18, WEYGBE4***

LHC Beam stability in 2017



- Lower stability margins than predicted from impedance model
  - **x2 higher octupole current needed**

See also ***N.Biancacci, IPAC18, WEYGBE4***

- More critical situation at lower chromaticities
- Different destabilizing mechanisms under investigation
  - Damper noise, coupling, optics errors, long range beam-beam, tail distributions…

The High Luminosity-LHC project

- More than a factor 2 peak luminosity compared to LHC

	LHC	HL-LHC nominal	HL-LHC ultimate
L_{peak} / 10^{34} $cm^{-2}s^{-1}$	2	5	7.5
L_{int} / fb^{-1}/y	50	262	325

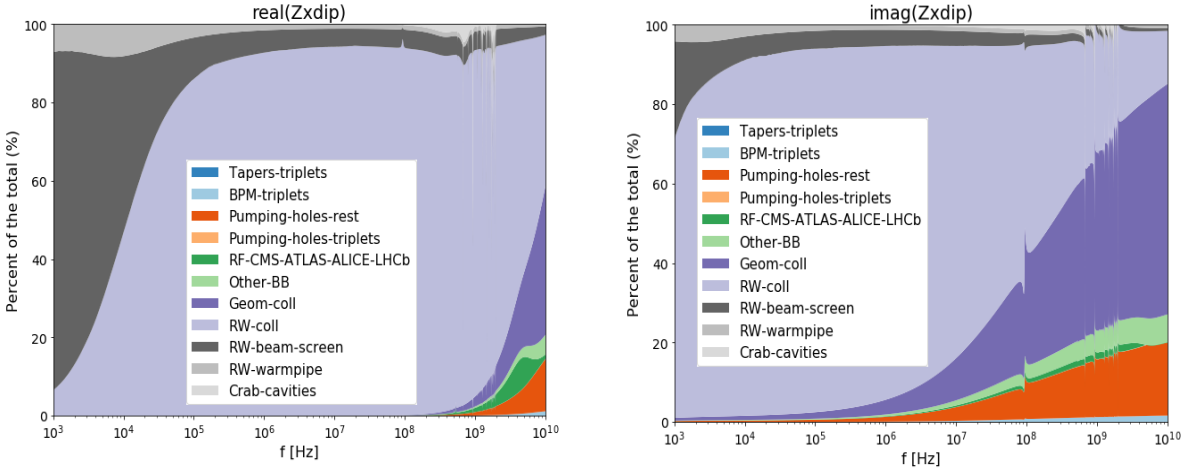
- Increased bunch intensity, decreased beam emittance

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

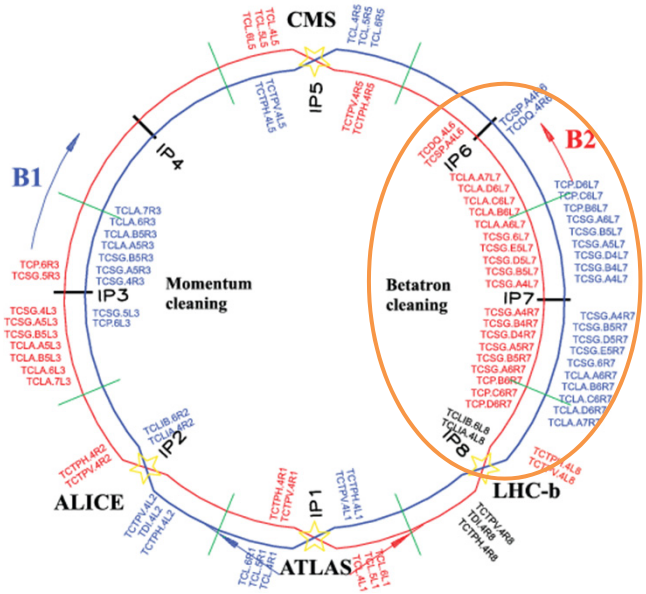
- Brighter beams will be a challenge for beam stability
  - Need to **keep a factor 2 margin** in HL-LHC

Stability in the HL-LHC era

- At top energy, the collimators are the main contributors to the impedance
  - 54 per beam, 11 in IR7 betatron cleaning region
  - In IR7: made of resistive materials (Carbon Fiber Composite), tightest gaps (<2mm)
- Low resistivity collimators will be implemented in HL-LHC



HL-LHC impedance budget at top energy



LHC collimation system

TMCI threshold in LHC / HL-LHC

TMCI threshold in LHC / HL-LHC

- Need to know the single bunch stability limits
  - Transverse Mode Coupling Instability could be a single bunch intensity limitation
  - It could help understand the tighter stability margins at low chromaticities
  - HL-LHC situation could be more critical because of higher brightness beams

- Measurement of the tune-shift as a function of intensity to assess it
  - Simulations using the LHC and HL-LHC impedance models
  - Measurement in the machine: need to work with LHC operational constraints

- Can help understand the discrepancies between predictions and measurements

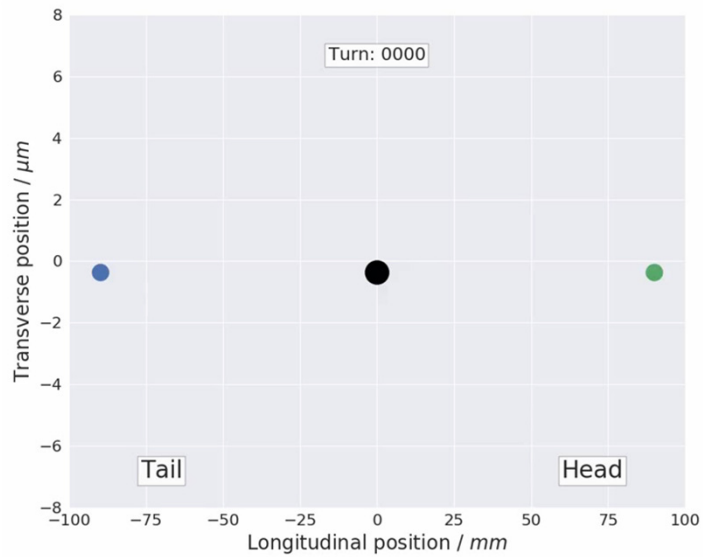
- Showcase the benefice of the impedance reduction for HL-LHC

Outline

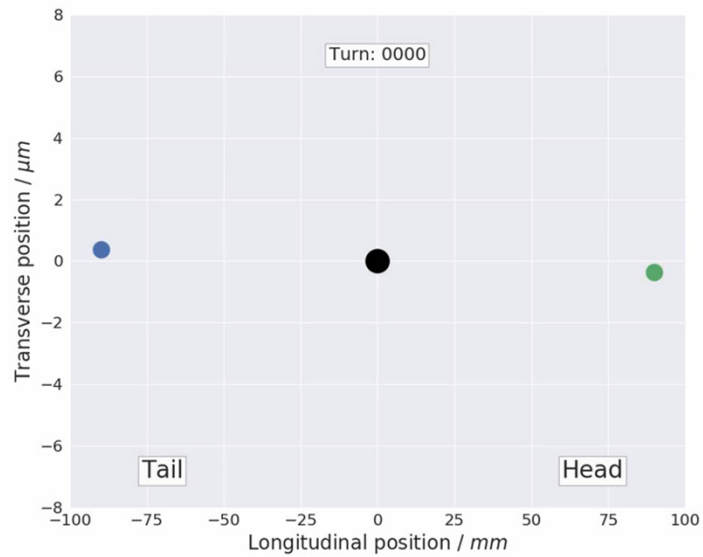
- Context and challenges
- The transverse mode coupling instability in the LHC
  - The transverse mode coupling instability
  - TMCI in the LHC era
  - TMCI in the HL-LHC era
- Conclusion and perspectives

Two particle model of TMCI

- As the bunch intensity increases, two oscillation modes can couple
- The beam becomes unstable



Mode 0

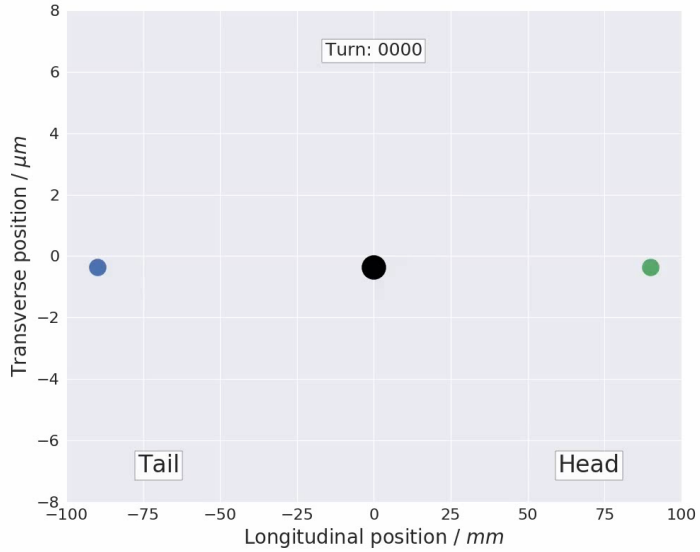


Mode -1

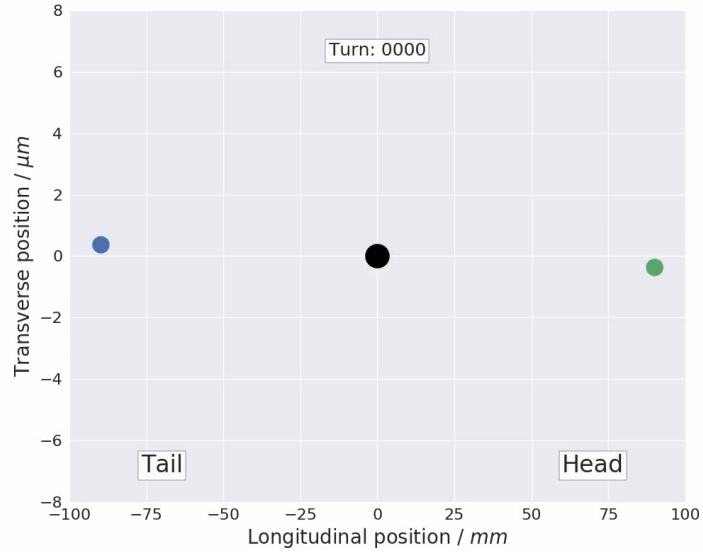
https://github.com/PyCOMPLETE/PyHEADTAIL
https://nbviewer.jupyter.org/github/PyCOMPLETE/PyHEADTAIL-playground/blob/master/Transverse_Mode_Coupling_Instability/TMCI_2particle_model.ipynb

Two particle model of TMCI

- As the bunch intensity increases, two oscillation modes can couple
- The beam becomes unstable



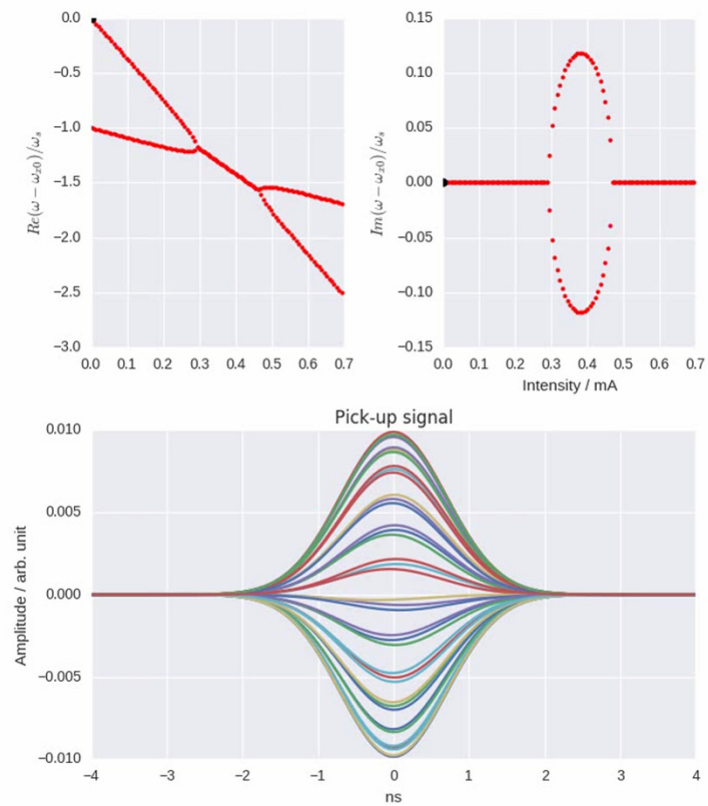
Mode 0



Mode -1

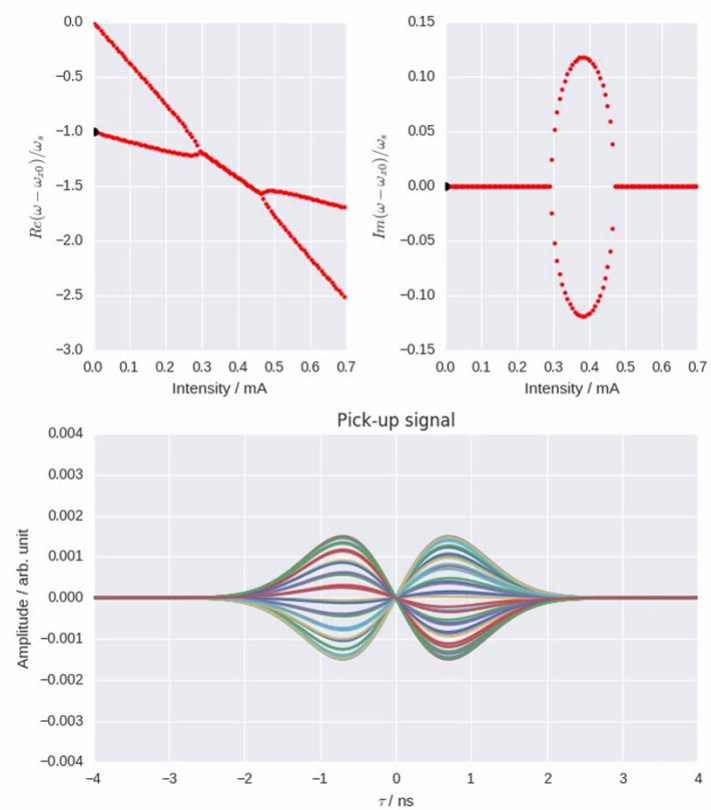
https://github.com/PyCOMPLETE/PyHEADTAIL
https://nbviewer.jupyter.org/github/PyCOMPLETE/PyHEADTAIL-playground/blob/master/Transverse_Mode_Coupling_Instability/TMCI_2particle_model.ipynb

Head-tail signal in mode coupling



Bunch length

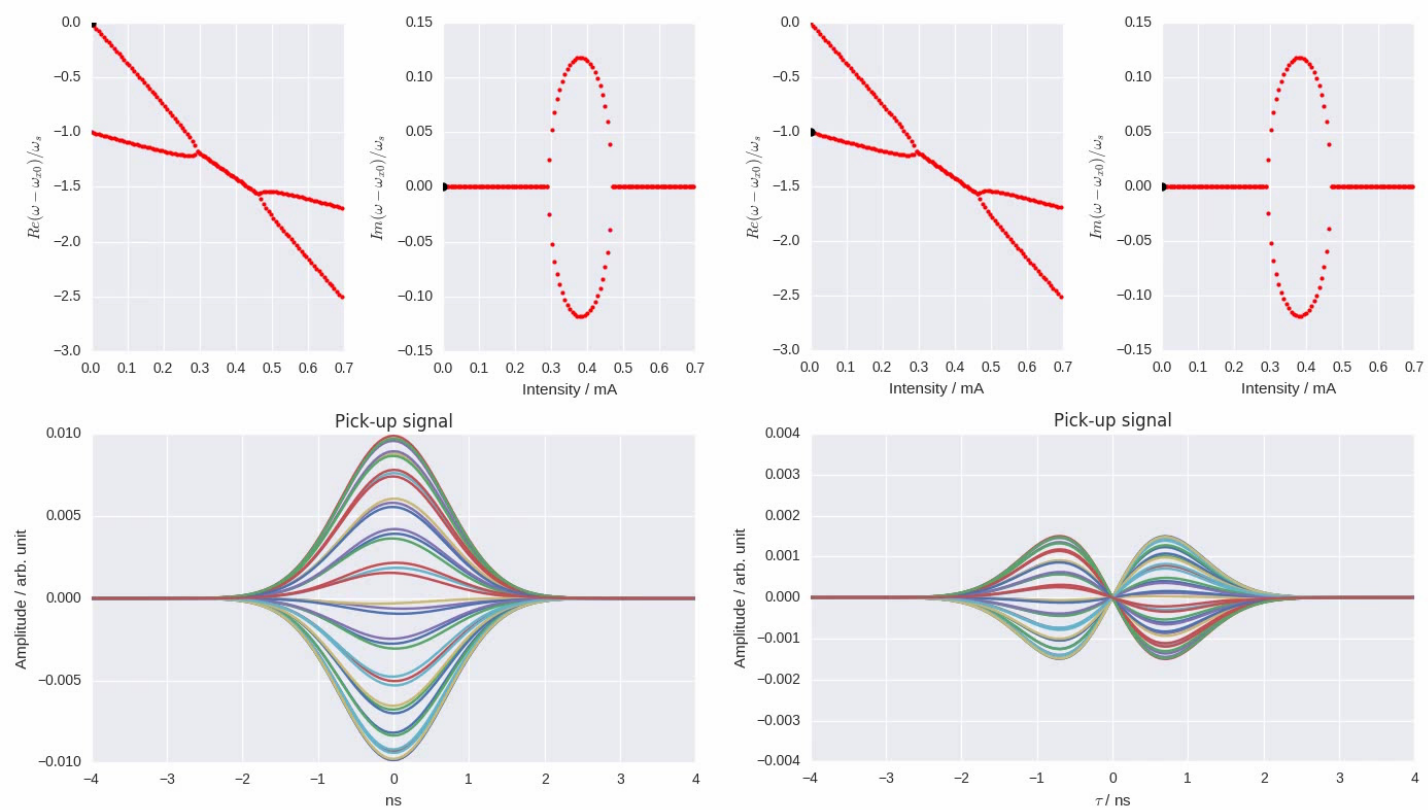
Mode 0



Bunch length

Mode -1

Head-tail signal in mode coupling



Bunch length

Mode 0

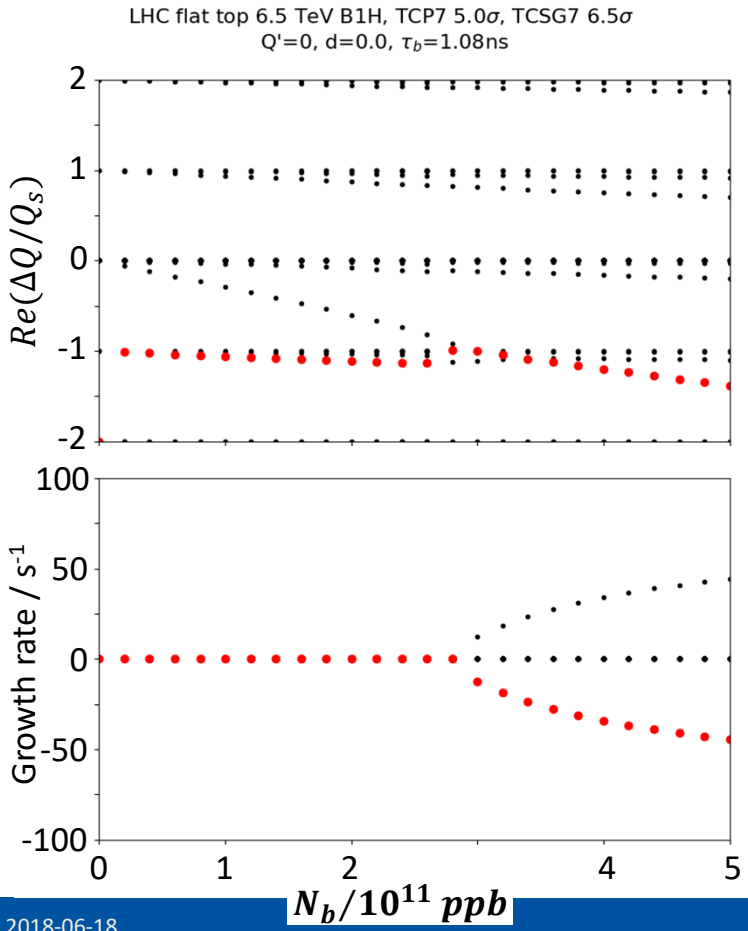
Bunch length

Mode -1

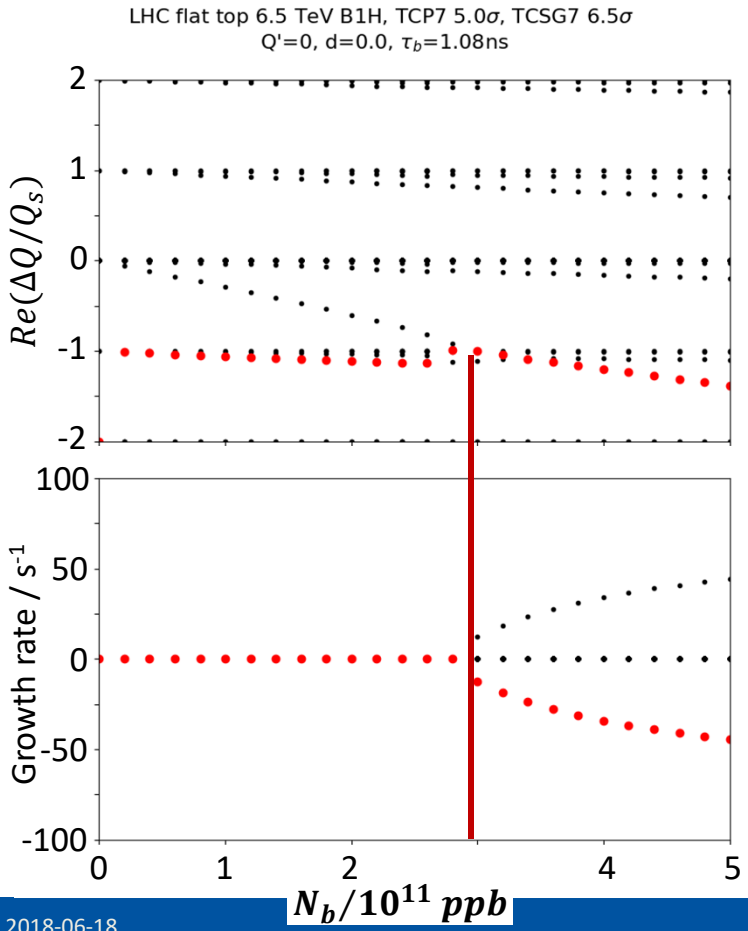
Outline

- Context and challenges
- The transverse mode coupling instability in the LHC
  - The transverse mode coupling instability
  - TMCI in the LHC era
  - TMCI in the HL-LHC era
- Conclusion and perspectives

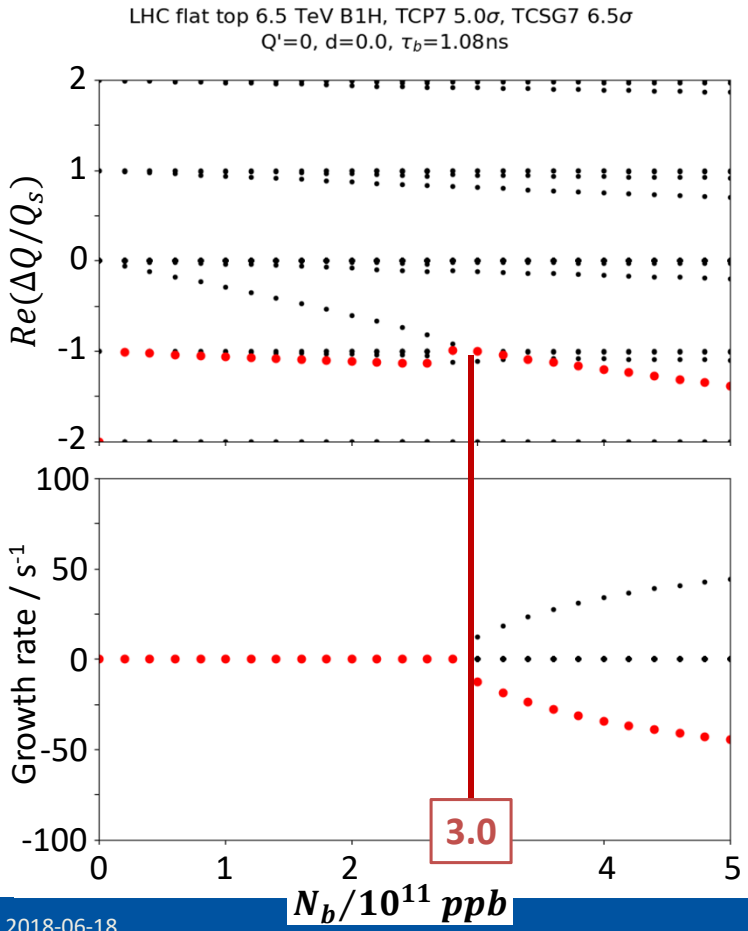
Simulation of TMCI in the LHC



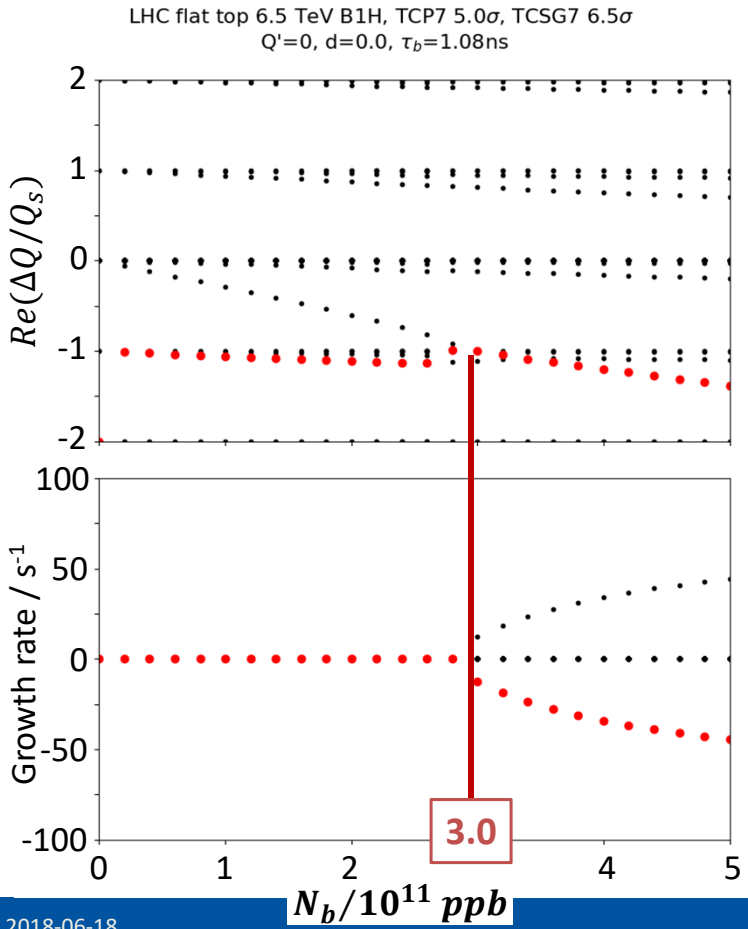
Simulation of TMCI in the LHC



Simulation of TMCI in the LHC

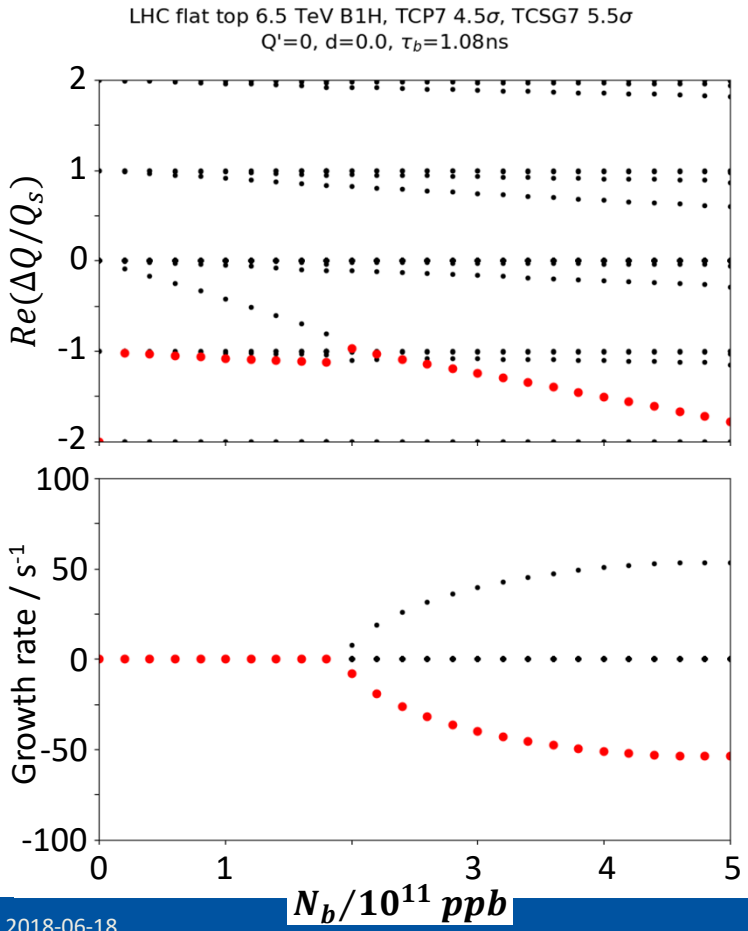


Simulation of TMCI in the LHC

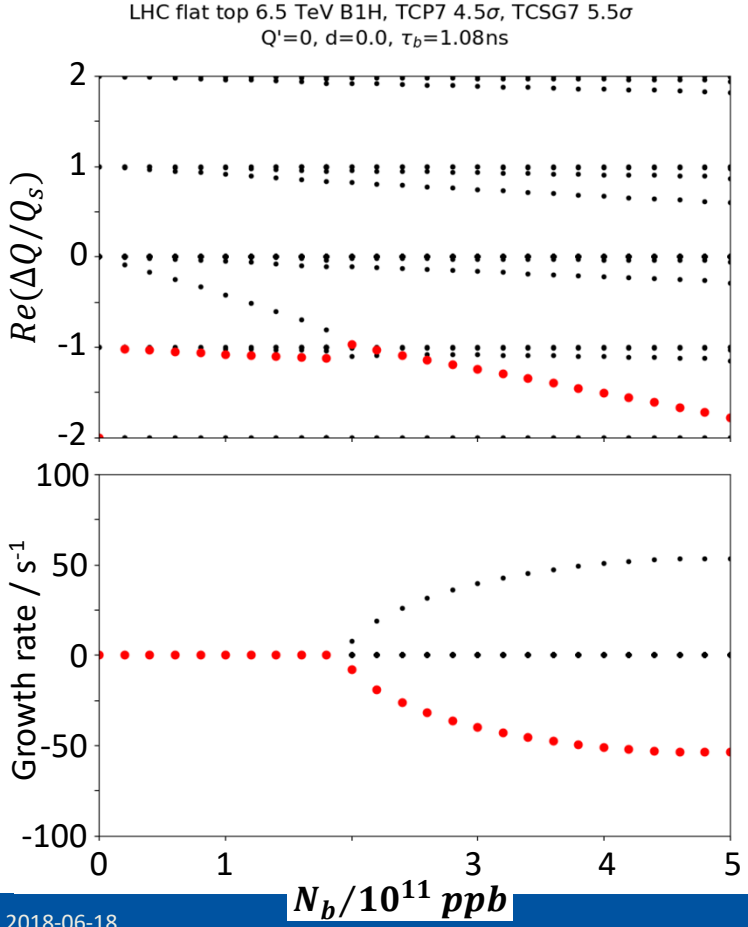


- Simulations with the Vlasov solver DELPHI
  - Eigenvalues: mode frequency shift and growth rate
  - Eigenvectors: mode head-tail signal
- Operational collimators settings
- TMCI intensity threshold at $3 \cdot 10^{11} p.p.b$
  - Not currently reachable in LHC
- Increase the machine impedance to try reaching the threshold

Simulation of TMCI in the LHC

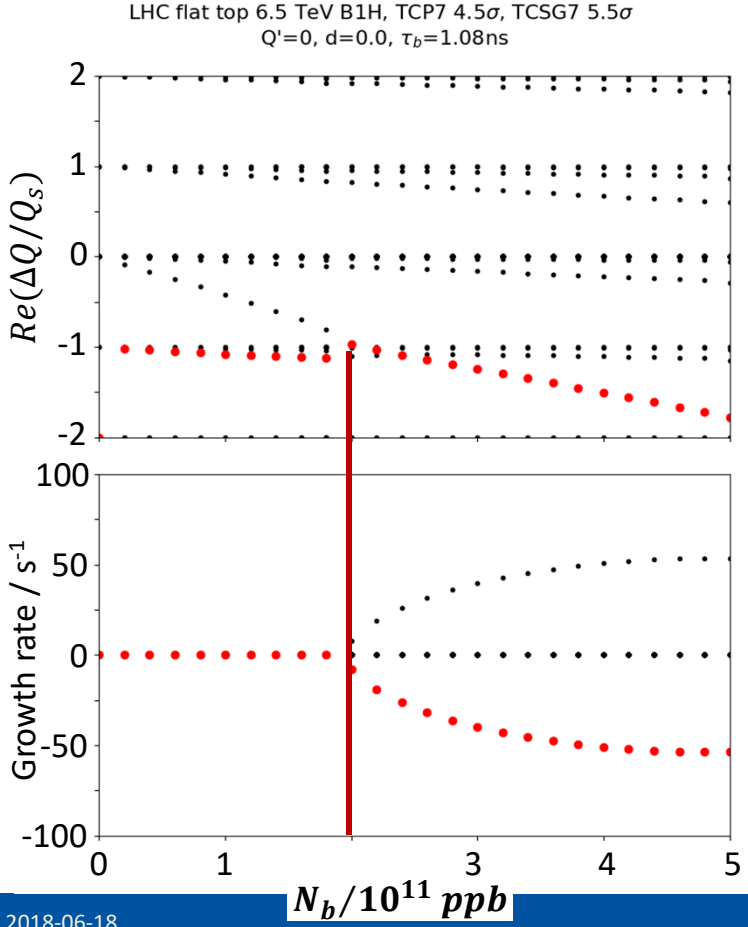


Simulation of TMCI in the LHC



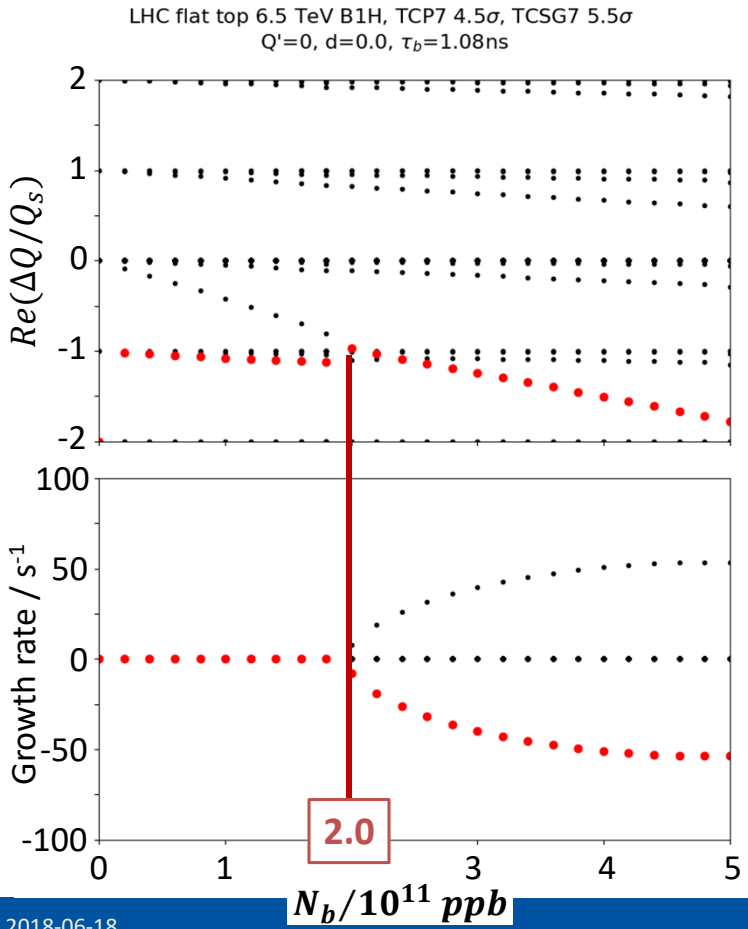
- Increase the machine impedance
  - Bring in closer selected betatron cleaning collimators
- TMCI intensity threshold at $2 \cdot 10^{11} p.p.b$
  - Intensity reachable in the LHC
- Machine chromaticity can only be controlled in a ± 2 units range

Simulation of TMCI in the LHC



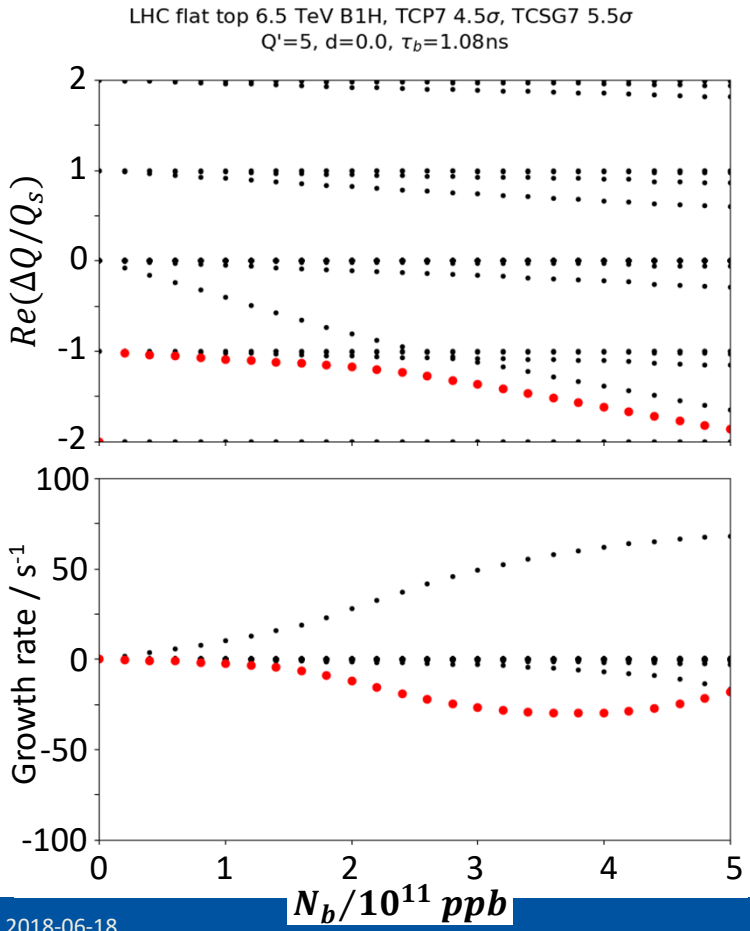
- Increase the machine impedance
  - Bring in closer selected betatron cleaning collimators
- TMCI intensity threshold at $2 \cdot 10^{11} p.p.b$
  - Intensity reachable in the LHC
- Machine chromaticity can only be controlled in a ± 2 units range

Simulation of TMCI in the LHC

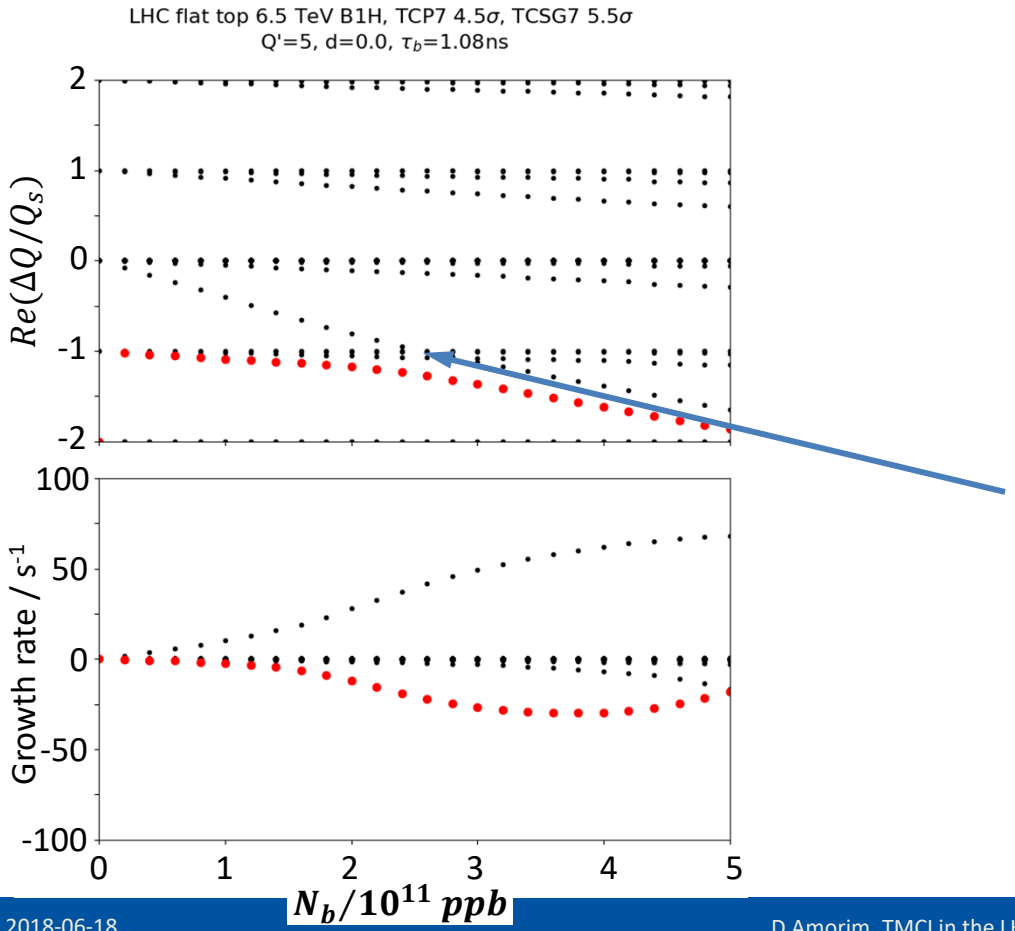


- Increase the machine impedance
  - Bring in closer selected betatron cleaning collimators
- TMCI intensity threshold at $2 \cdot 10^{11} p.p.b$
  - Intensity reachable in the LHC
- Machine chromaticity can only be controlled in a ± 2 units range

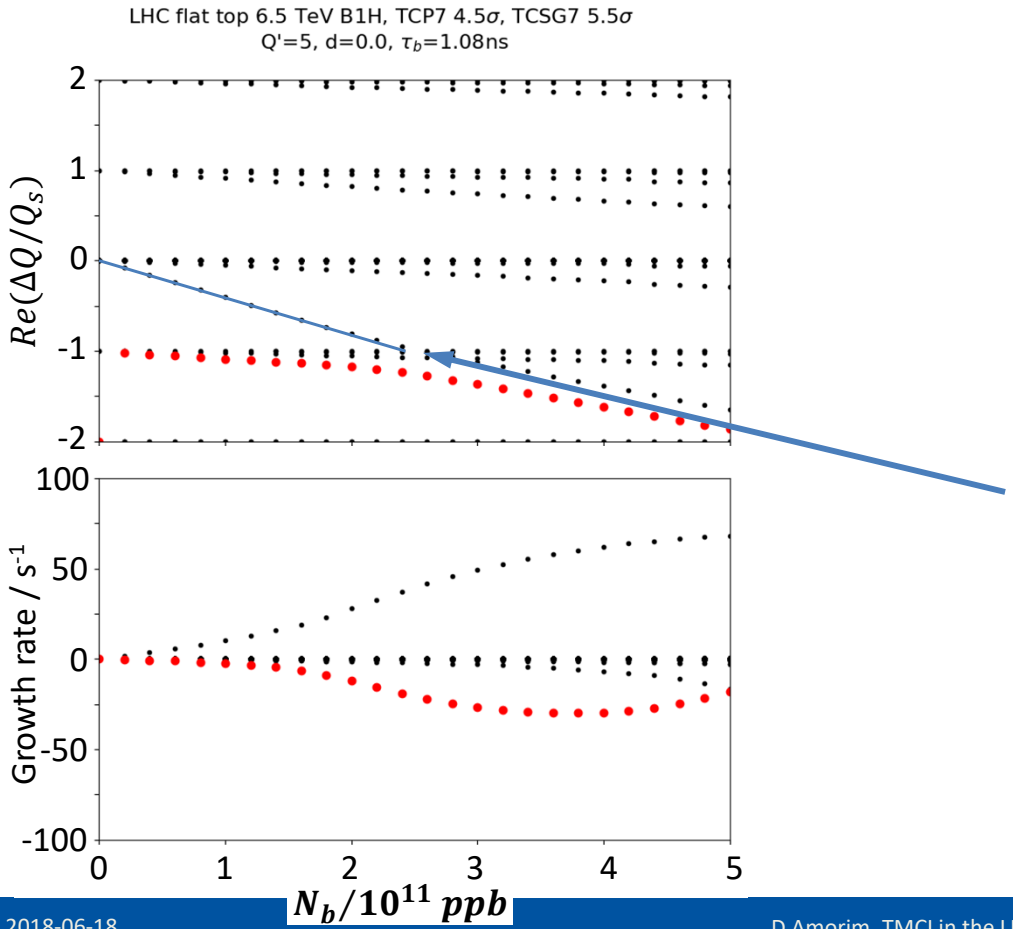
Simulation of TMCI in the LHC



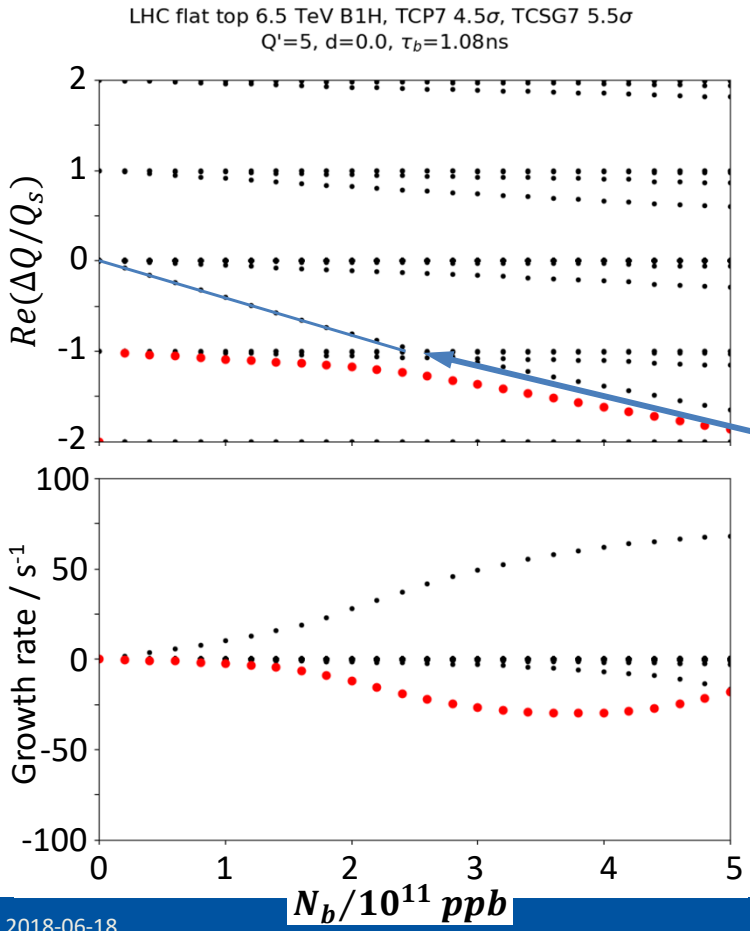
Simulation of TMCI in the LHC



Simulation of TMCI in the LHC



Simulation of TMCI in the LHC

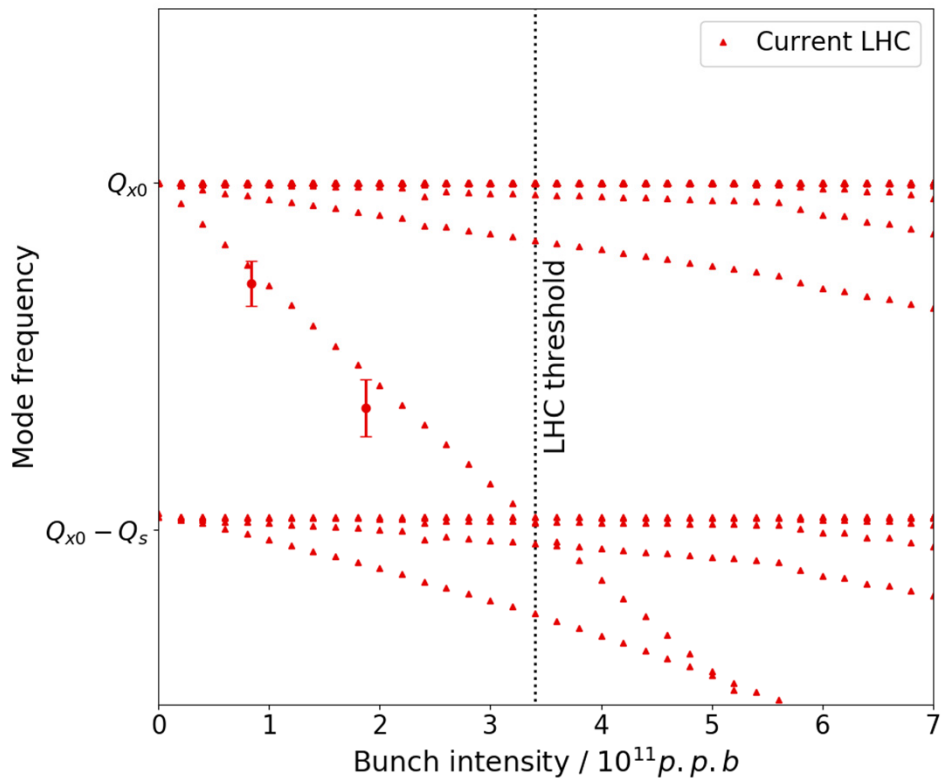


- Use a slightly positive chromaticity
  - Ensure stability of mode 0
- No clear mode coupling between modes 0 and -1 anymore
- But tune-shift vs intensity slope is preserved

LHC tune shift vs intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC

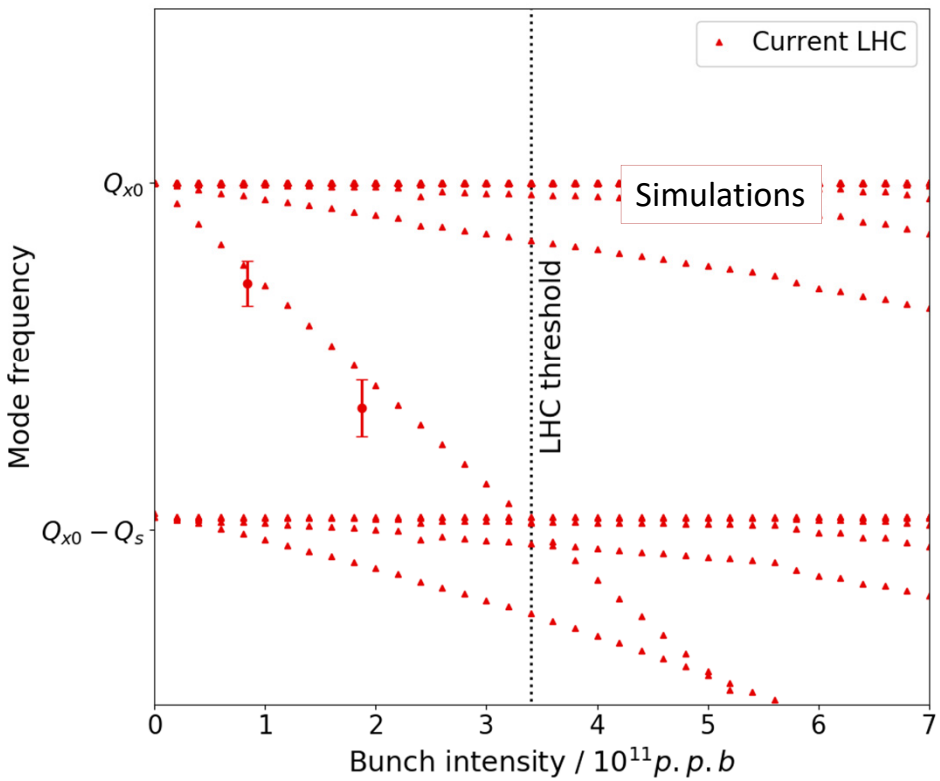


- Measurement with 2 or 3 bunches per beam
  - Number limited by machine protection constraints
- Bunch-by-bunch tune measurement
  - High precision measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
- Tentative to observe mode coupling by closing further the collimators

LHC tune shift vs intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC

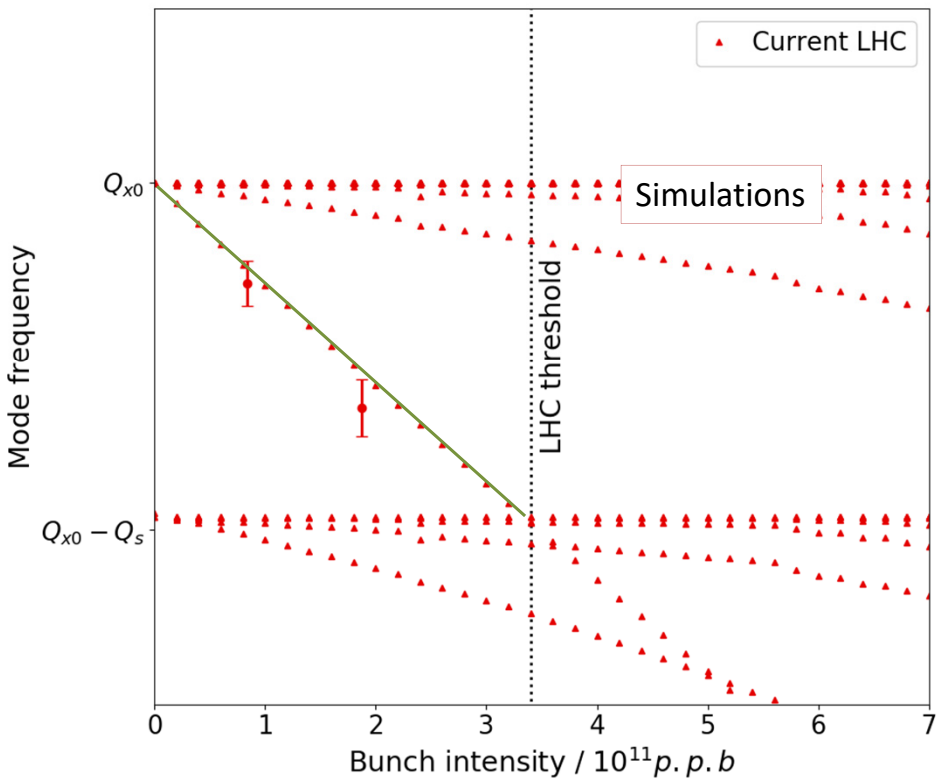


- Measurement with 2 or 3 bunches per beam
  - Number limited by machine protection constraints
- Bunch-by-bunch tune measurement
  - High precision measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
- Tentative to observe mode coupling by closing further the collimators

LHC tune shift vs intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC

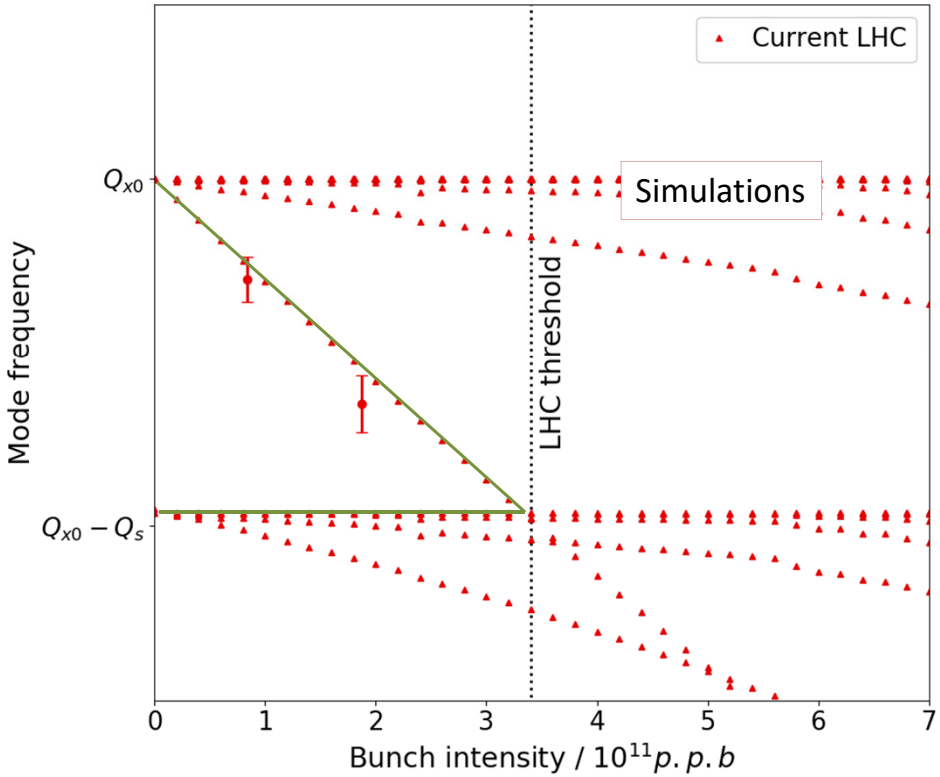


- Measurement with 2 or 3 bunches per beam
  - Number limited by machine protection constraints
- Bunch-by-bunch tune measurement
  - High precision measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
- Tentative to observe mode coupling by closing further the collimators

LHC tune shift vs intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC

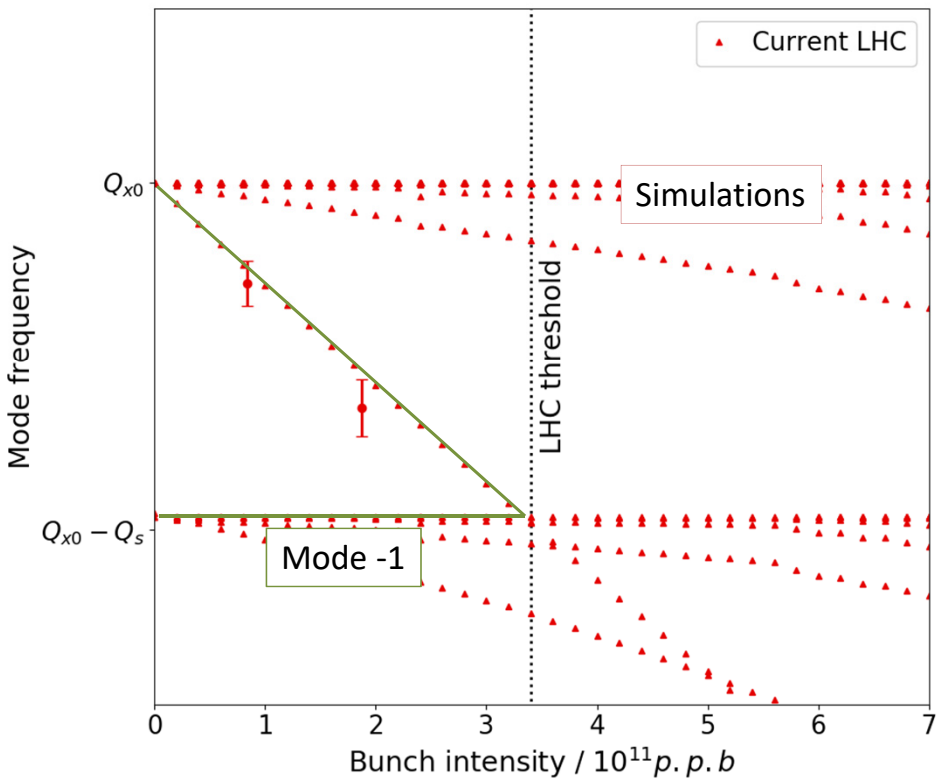


- Measurement with 2 or 3 bunches per beam
  - Number limited by machine protection constraints
- Bunch-by-bunch tune measurement
  - High precision measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
- Tentative to observe mode coupling by closing further the collimators

LHC tune shift vs intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC

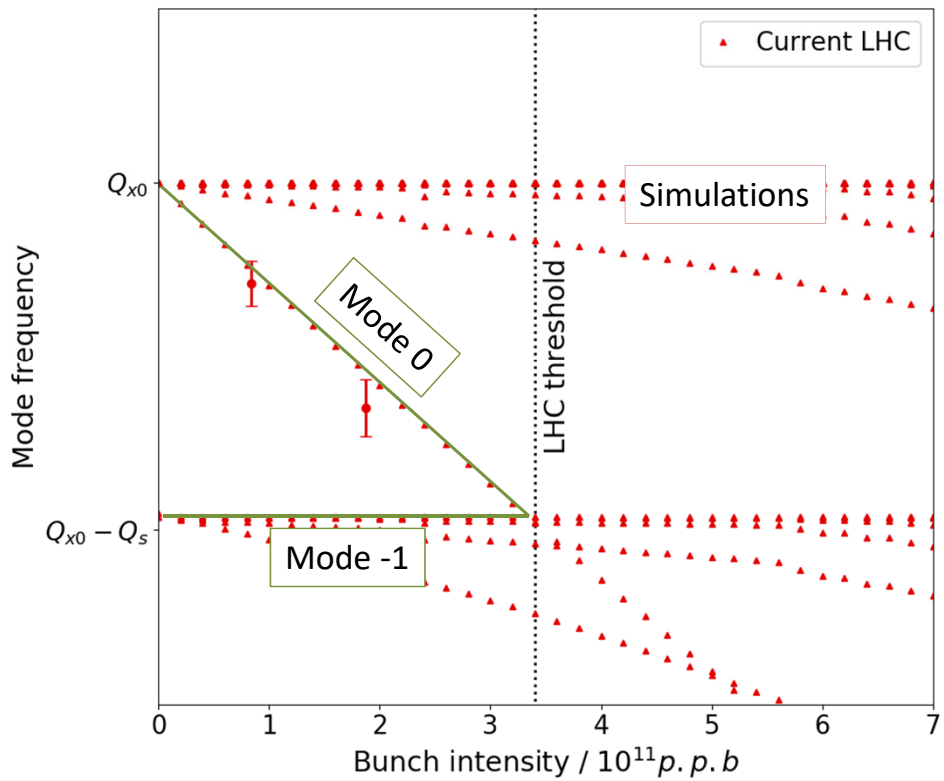


- Measurement with 2 or 3 bunches per beam
  - Number limited by machine protection constraints
- Bunch-by-bunch tune measurement
  - High precision measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
- Tentative to observe mode coupling by closing further the collimators

LHC tune shift vs intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC

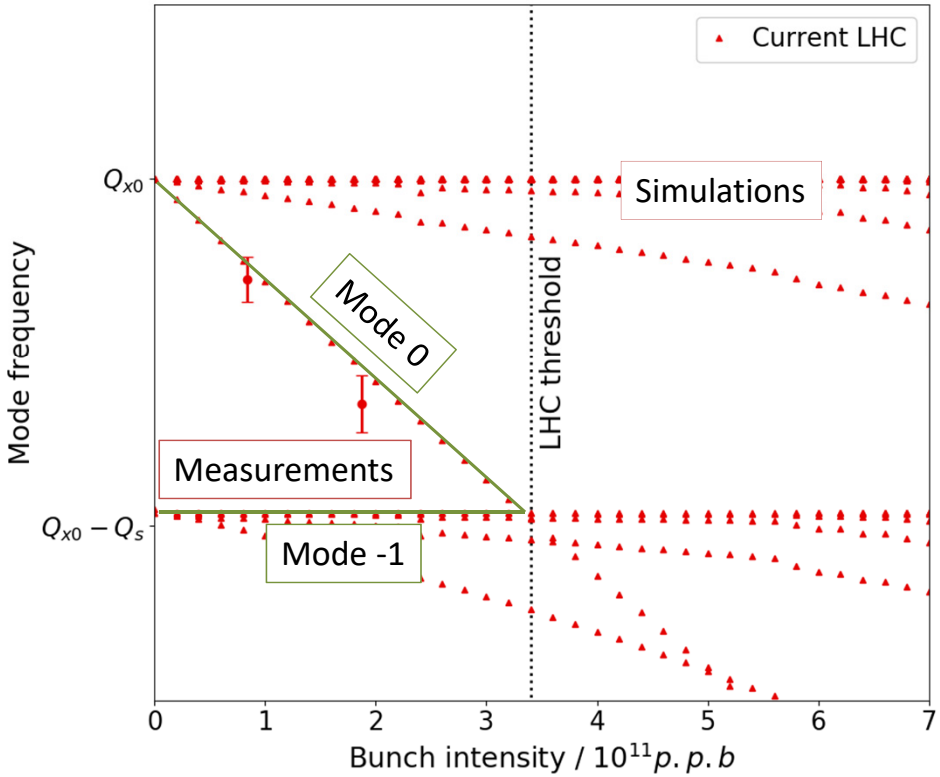


- Measurement with 2 or 3 bunches per beam
  - Number limited by machine protection constraints
- Bunch-by-bunch tune measurement
  - High precision measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
- Tentative to observe mode coupling by closing further the collimators

LHC tune shift vs intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC

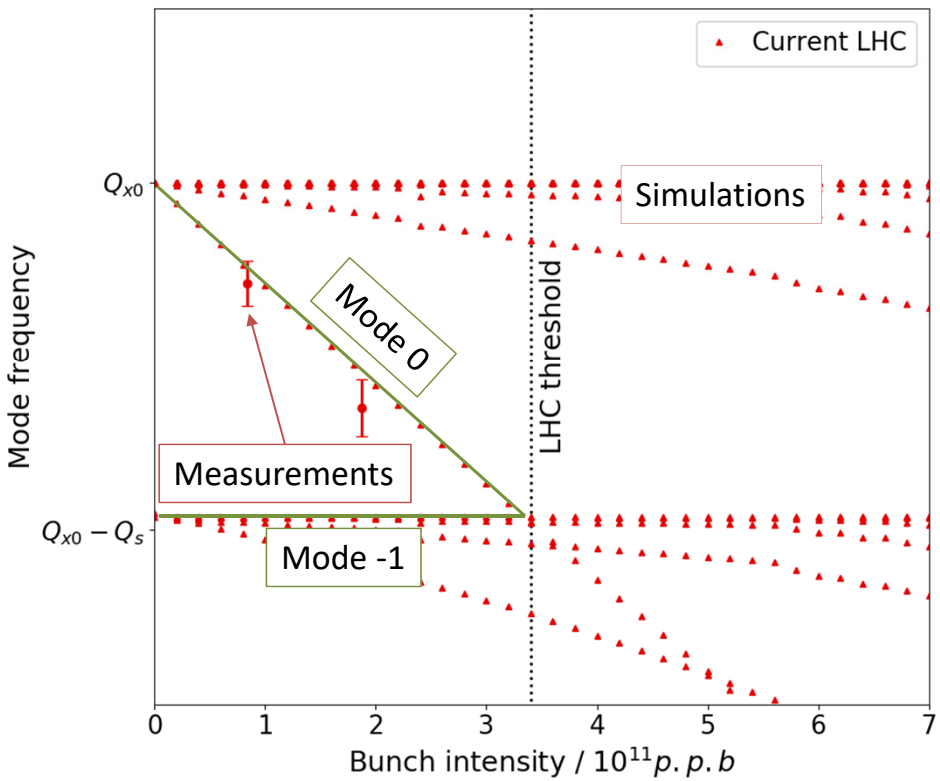


- Measurement with 2 or 3 bunches per beam
  - Number limited by machine protection constraints
- Bunch-by-bunch tune measurement
  - High precision measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
- Tentative to observe mode coupling by closing further the collimators

LHC tune shift vs intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC

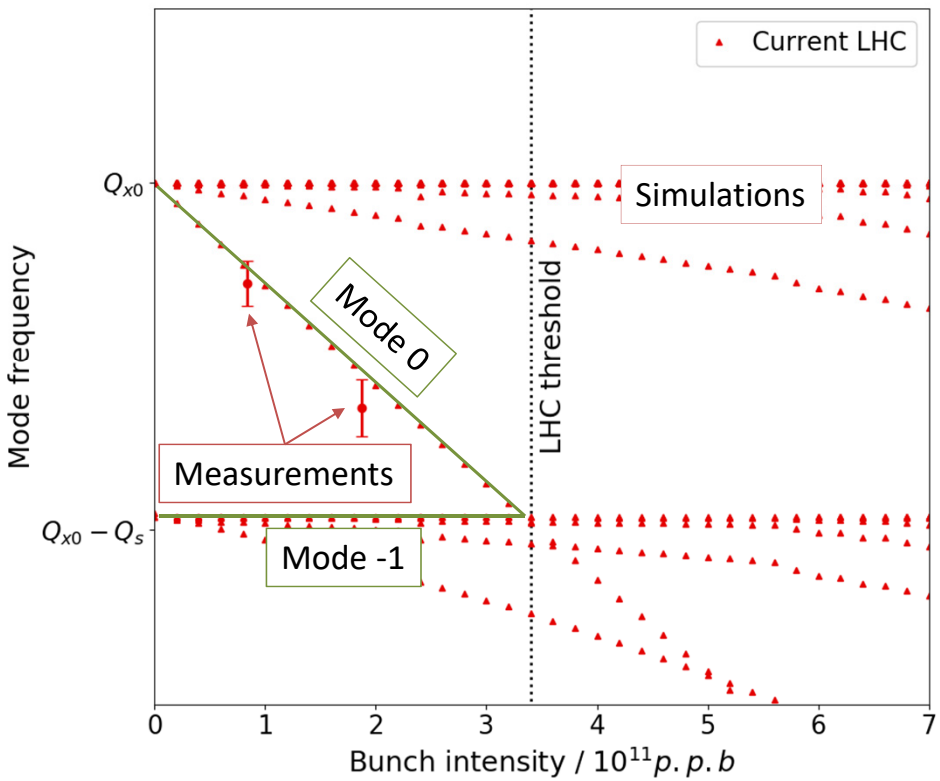


- Measurement with 2 or 3 bunches per beam
  - Number limited by machine protection constraints
- Bunch-by-bunch tune measurement
  - High precision measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
- Tentative to observe mode coupling by closing further the collimators

LHC tune shift vs intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC

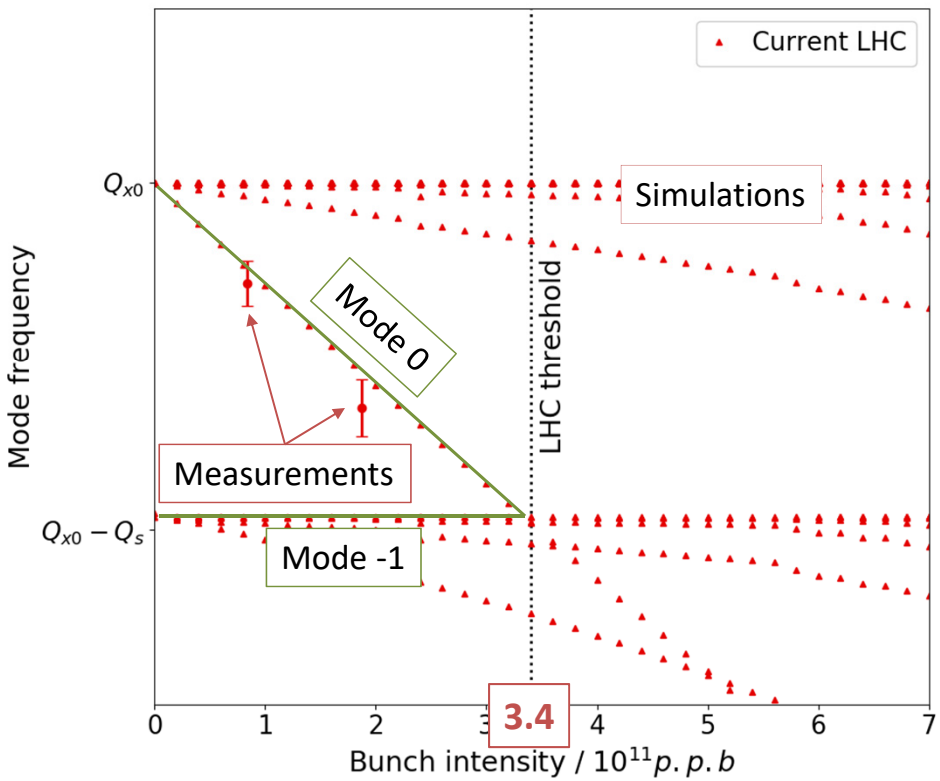


- Measurement with 2 or 3 bunches per beam
  - Number limited by machine protection constraints
- Bunch-by-bunch tune measurement
  - High precision measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
- Tentative to observe mode coupling by closing further the collimators

LHC tune shift vs intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC



- Measurement with 2 or 3 bunches per beam
  - Number limited by machine protection constraints
- Bunch-by-bunch tune measurement
  - High precision measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
- Tentative to observe mode coupling by closing further the collimators

Outline

- Context and challenges
- The transverse mode coupling instability in the LHC
  - The transverse mode coupling instability
  - TMCI in the LHC era
  - TMCI in the HL-LHC era
- Conclusion and perspectives

HL-LHC tune-shift vs. intensity

HL-LHC tune-shift vs. intensity

- Show the benefits of low resistivity coatings for the betatron cleaning collimators

- Collimators resistive wall impedance scale as $\sqrt{\rho}/b^3$
  - Cannot replace all the collimators with low resistivity materials
  - Instead open the gaps to reproduce an equivalent HL-LHC impedance

HL-LHC tune-shift vs. intensity

- Show the benefits of low resistivity coatings for the betatron cleaning collimators

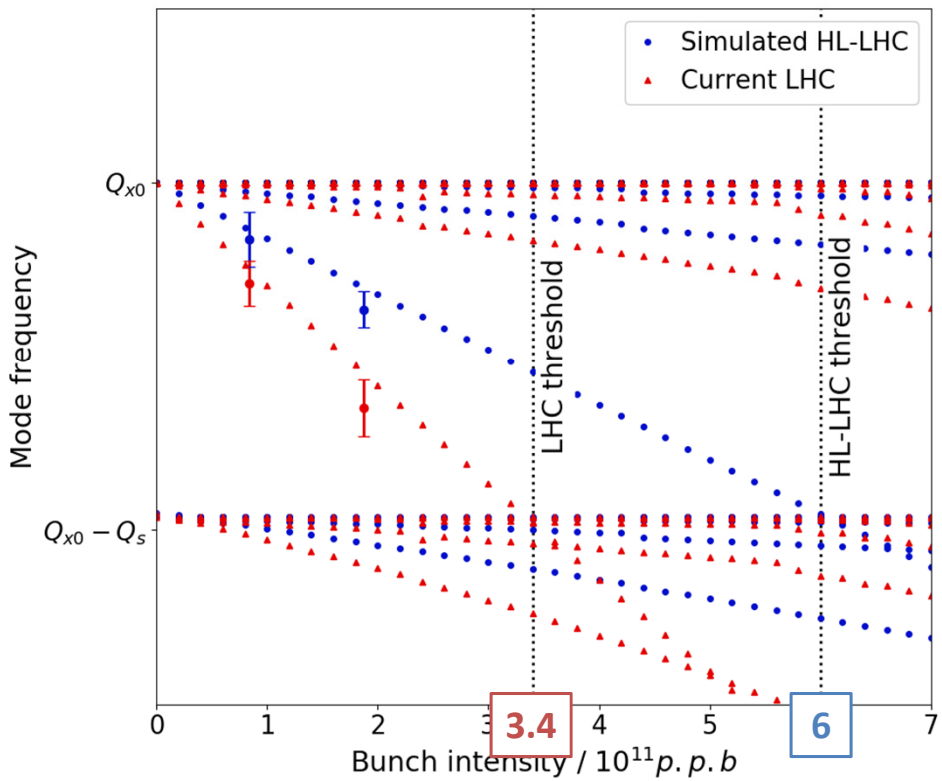
- Collimators resistive wall impedance scale as $\sqrt{\rho}/b^3$
  - Cannot replace all the collimators with low resistivity materials
  - Instead open the gaps to reproduce an equivalent HL-LHC impedance

ρ: resistivity in $\Omega \cdot m$
b: gap in m

HL-LHC tune-shift vs. intensity

Tune-shift vs. intensity, Beam 1, horizontal plane

Transverse mode coupling instability in LHC



Outline

- Context and challenges
- The transverse mode coupling instability in the LHC
  - The transverse mode coupling instability
  - TMCI in the LHC era
  - TMCI in the HL-LHC era
- Conclusion and perspectives

Conclusions

Conclusions

- The LHC TMCI threshold was investigated with simulations and measurements
  - Measurement useful to assess the LHC impedance and stability model at low chromaticities
- Direct measurement in the machine is challenging because of operational and safety constraints
  - The TMCI threshold can be inferred by measuring the tune-shift versus bunch intensity
  - Simulations were performed to find a good parameters set for the measurement
- Highlighted the beneficial effect of low resistivity collimators for HL-LHC
  - Reproduced an equivalent HL-LHC impedance by changing the collimators gaps
  - Clear tune-shift reduction and inferred a TMCI threshold two times higher than for LHC

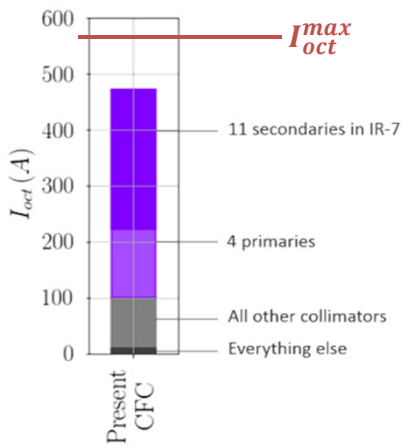
- Other effects that can act on the mode coupling are being investigated
  - Effect of the transverse damper
  - Landau damping in the mode coupling regime

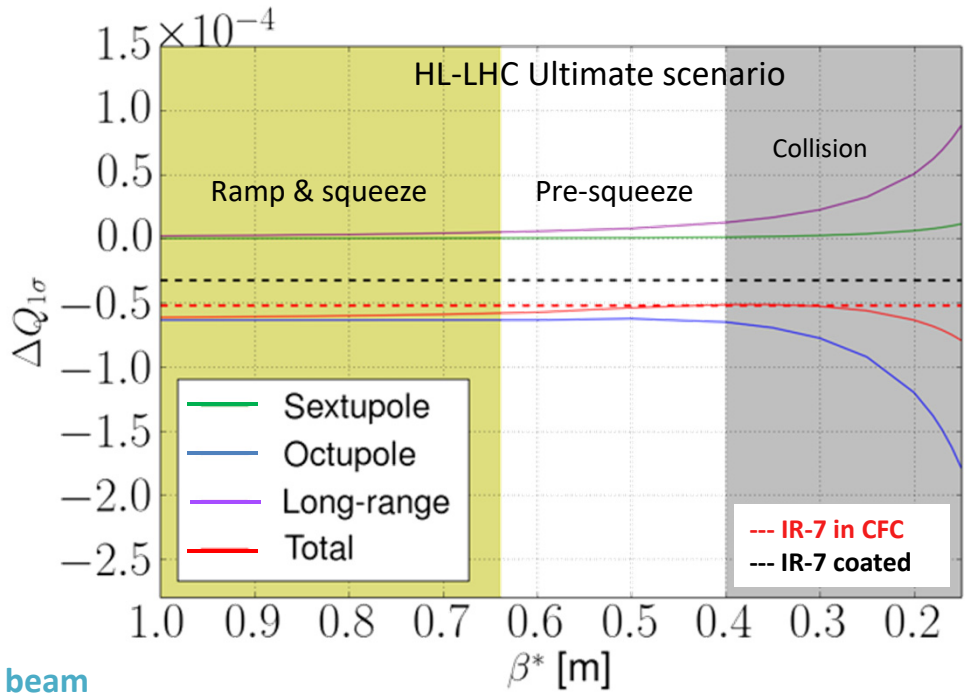
Thank you for your attention

Backup

The HL-LHC stability model

N.Biancacci, IPAC18, WEYGBE4

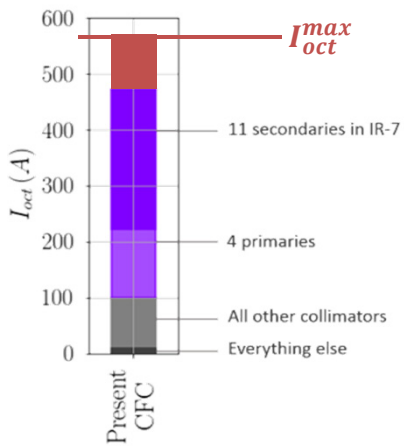


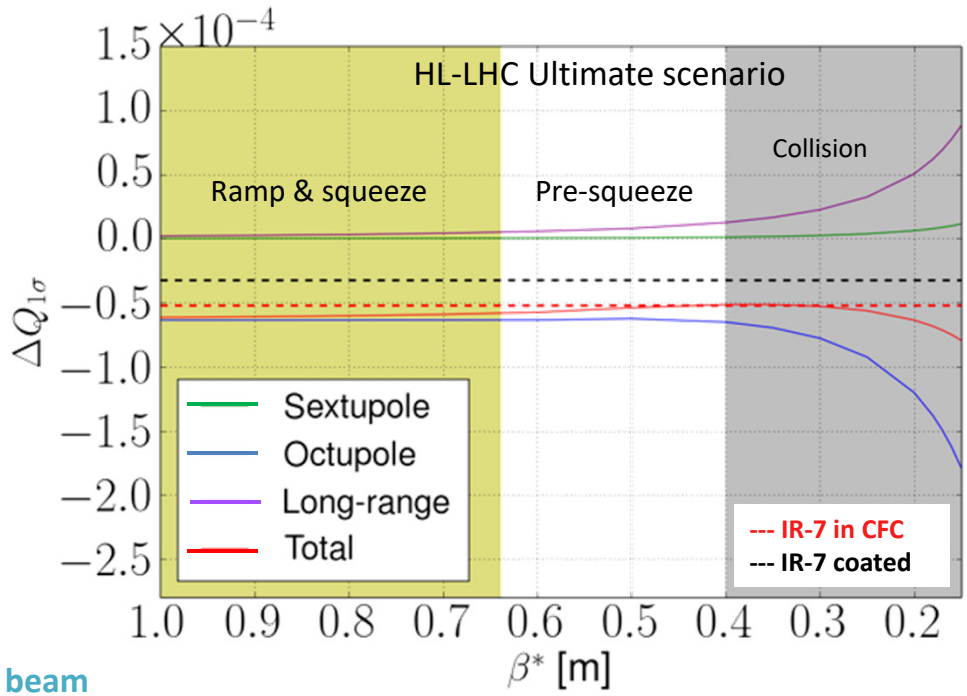


- HL-LHC with LHC collimators: tight margins for **BCMS beam**
- Impedance: 480 A out of 570 A for **Ultimate scenario** at $\beta^* = 41cm$.
- Considering **long ranges** effect: **no margin** for **Ultimate scenario**

The HL-LHC stability model

N.Biancacci, IPAC18, WEYGBE4

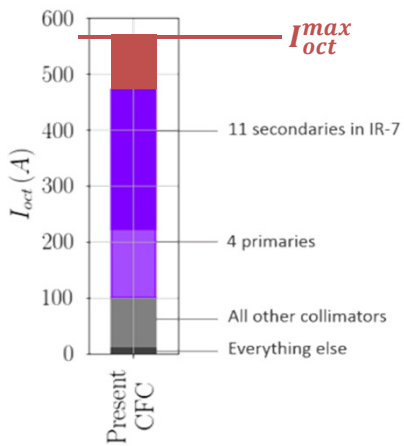


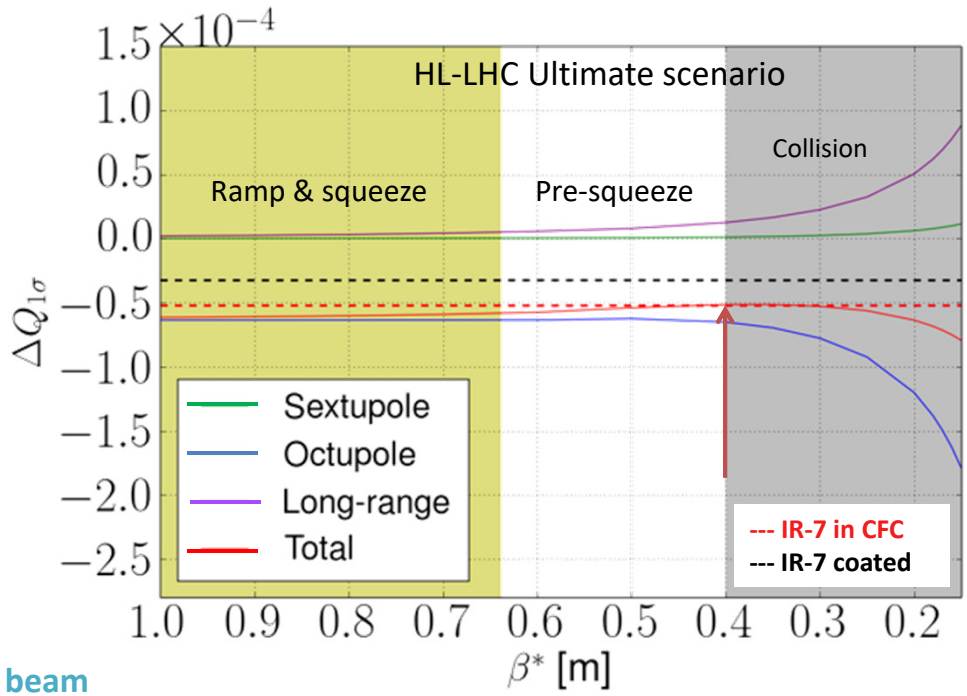


- HL-LHC with LHC collimators: tight margins for **BCMS beam**
- Impedance: 480 A out of 570 A for **Ultimate scenario** at $\beta^* = 41cm$.
- Considering **long ranges** effect: **no margin** for **Ultimate scenario**

The HL-LHC stability model

N.Biancacci, IPAC18, WEYGBE4





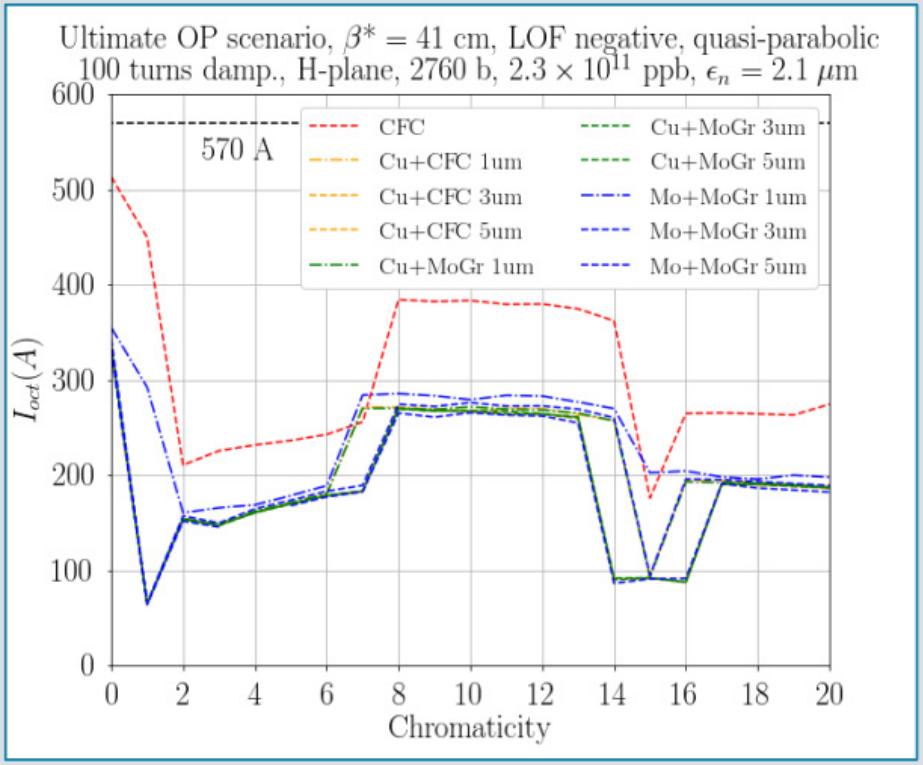
- HL-LHC with LHC collimators: tight margins for **BCMS beam**
- Impedance: 480 A out of 570 A for **Ultimate scenario** at $\beta^* = 41cm$.
- Considering **long ranges** effect: **no margin** for **Ultimate scenario**

Octupole threshold increases for thinner coatings

Mo: +20 A for Q' ~ 8-12

Cu: no significant difference for Cu around Q' ~ 10

The effect may be large at some chromaticities



S. Antipov

TMCI in the LHC: measurement procedure

- Measurement goals
  - Infer the TMCI threshold by measuring the tune-shift vs intensity
  - Try to observe a mode coupling instability in the LHC

- 8h time slot on Sep. 15th to 16th 2017 night to perform the measurement

- Machine safety: each beam can not contain more than $3 \cdot 10^{11} p.p.b$

- Measurement procedure:
  1. Inject 2/3 bunches of different intensities, and ramp to top energy
  2. Bunch-by-bunch tune measurement: high precision tune measurement with the transverse damper stripline pickup (tune resolution: 10^{-5})
  3. Close the collimators to increase the machine impedance and repeat the measurement

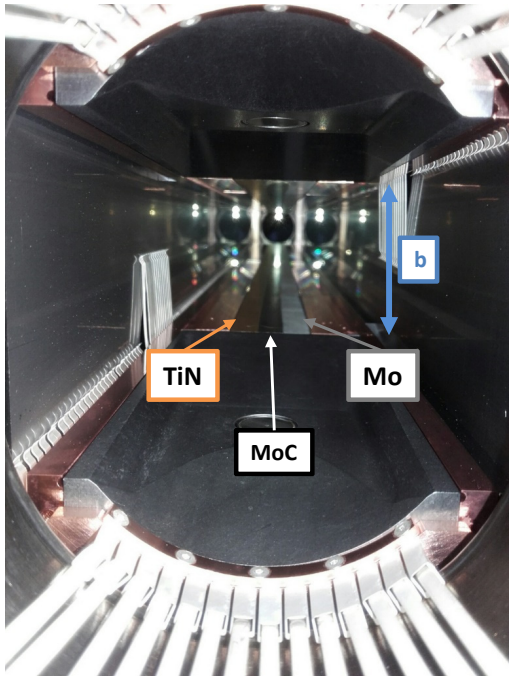
- Tentative to observe mode coupling by closing further the collimators

TCSPM: low resistivity collimator prototype

- Collimator impedance scales as $\sqrt{\rho}/b^3$
  - ρ: resistivity in $\Omega \cdot m$
  - b: gap in m

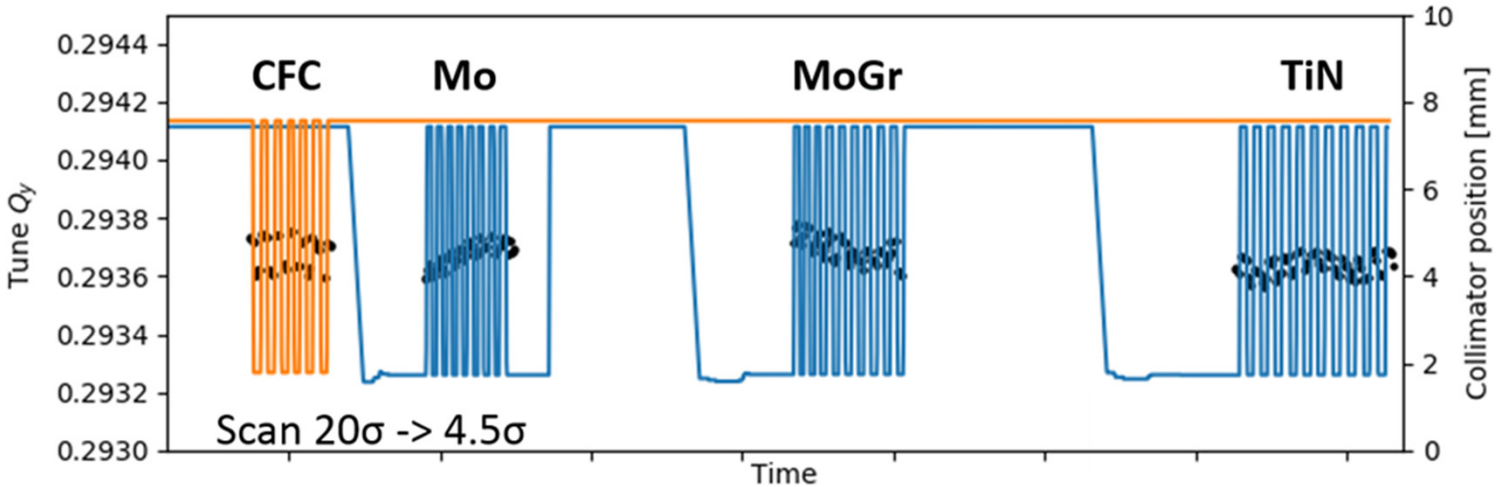
- To reduce the impedance
  - Decrease the resistivity
  - Increase the gaps

- A prototype collimator was installed in the LHC to test three different materials



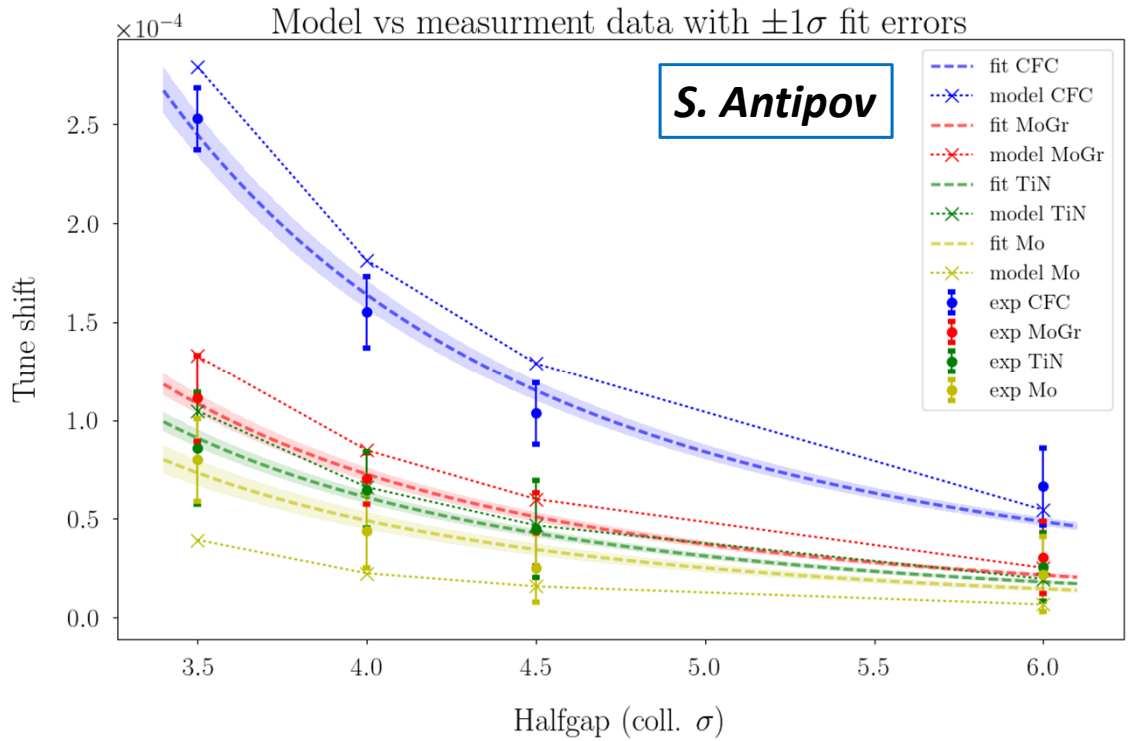
TCSPM: tune shifts measurement

- On-line analysis of the tune-shifts for the three materials
- State of the art transverse damper control allowed to measure shifts of the order of 10^{-5}

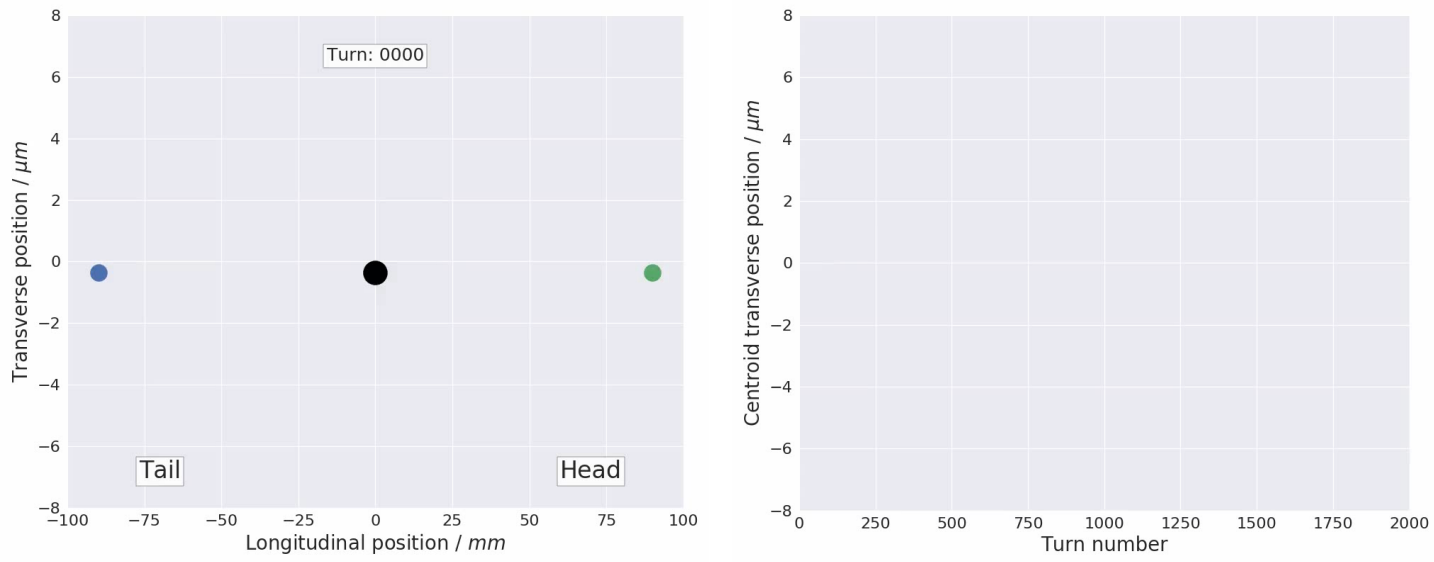


TCSPM: tune shifts measurement

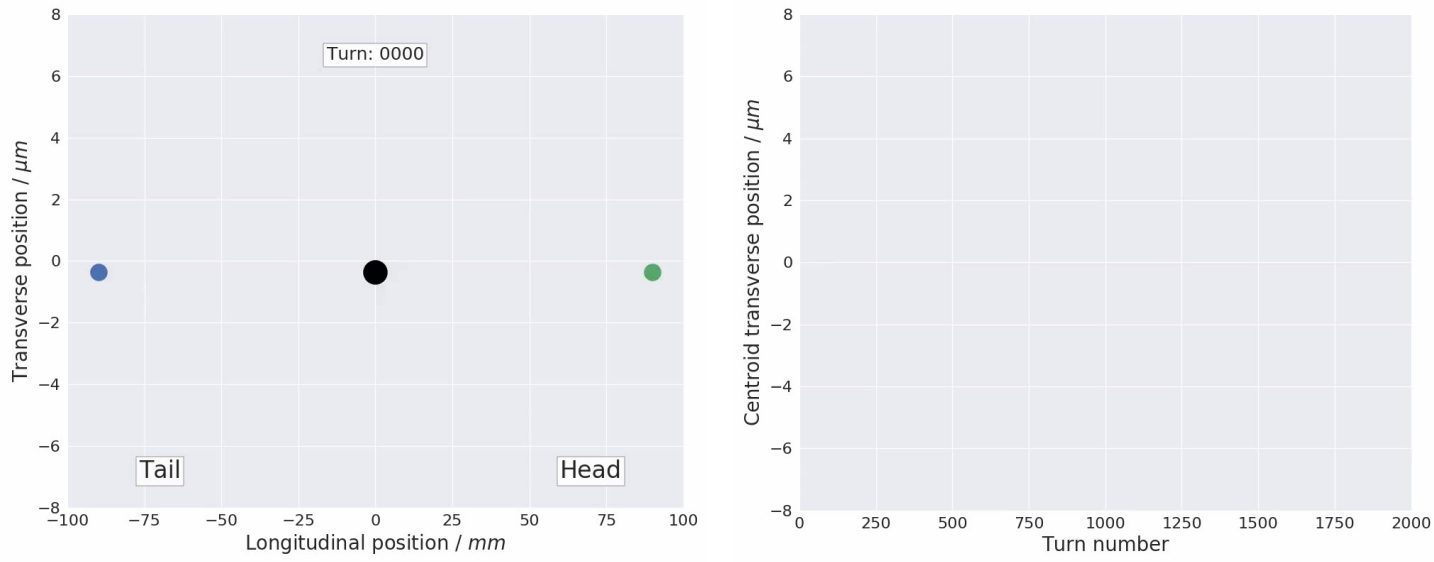
- The post-processing highlighted discrepancies with the impedance model used



Beam dynamics without collective effects

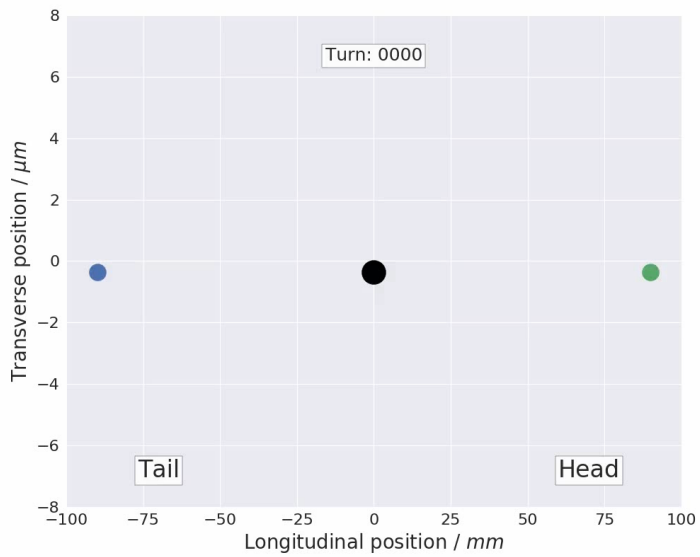


Beam dynamics with impedance effects

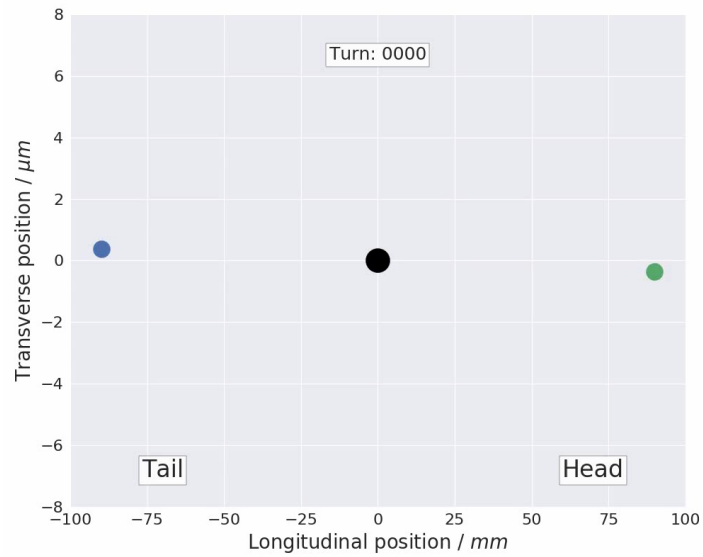


Transverse mode coupling instability

- For low bunch intensity, the oscillation modes are independent



Mode 0



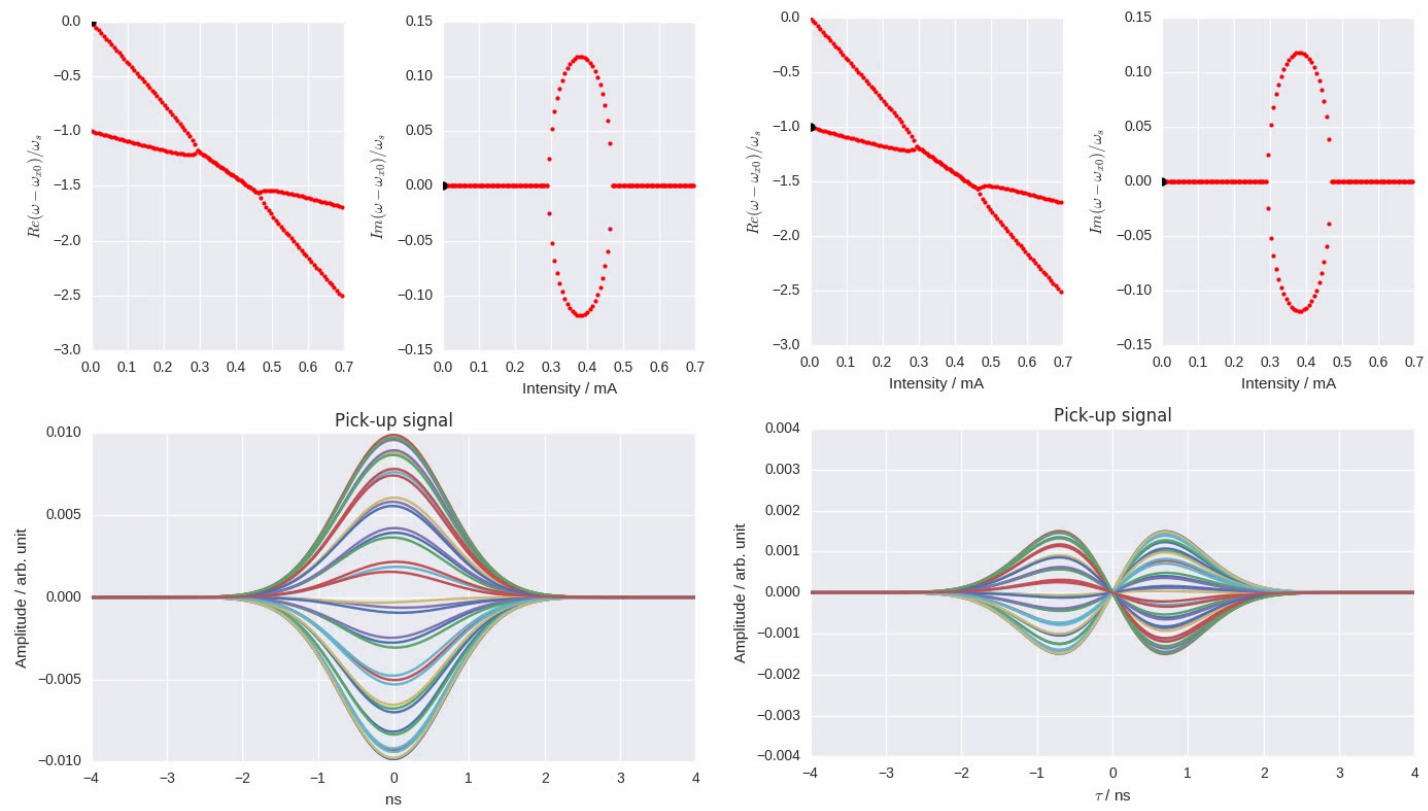
Mode -1

Effect of the transverse damper

SPS Q26, Resonator impedance

Q'=0, $f_r \tau_b = 2.8$

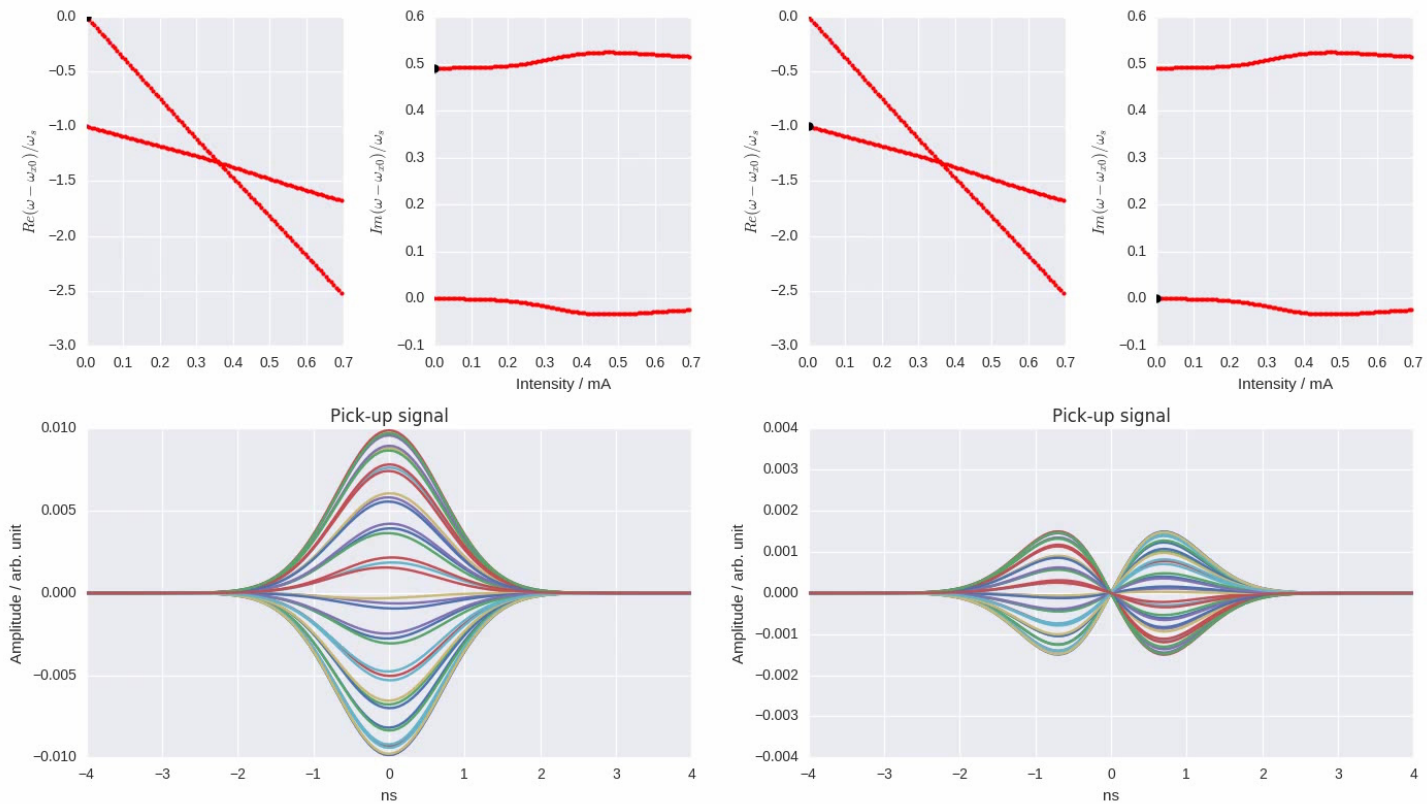
No damper



SPS Q26, Resonator impedance

Q'=0, $f_r \tau_b = 2.8$

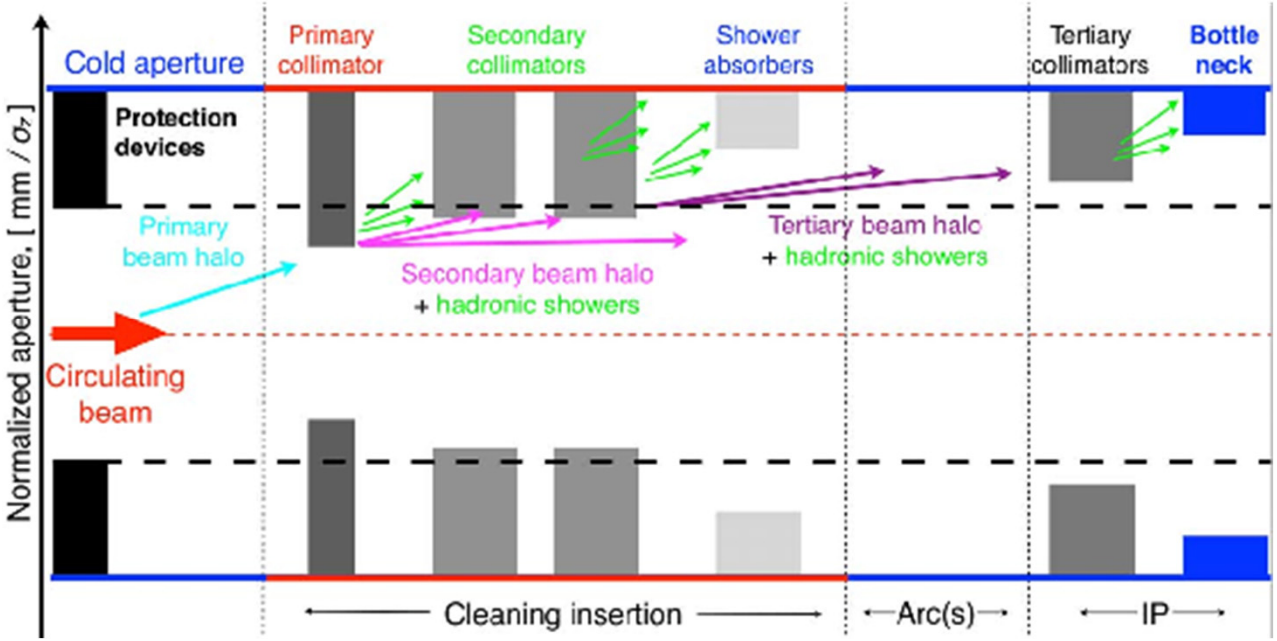
100 turns damper, resistive



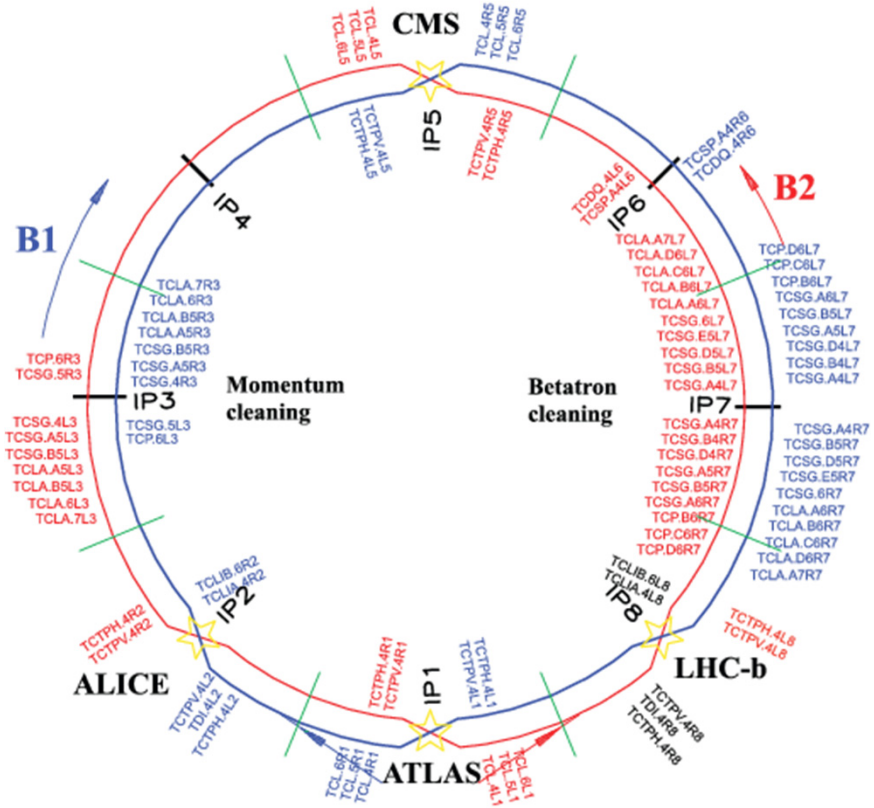
LHC Collimation system

LHC collimation system principle

- A superconducting magnet can quench if $\sim 10^9$ particles hit it
- The collimators are here to intercept stray protons
- Because of their high energy, the intercepted protons create particle showers that need to be intercepted as well



LHC collimation system layout



LHC collimation system