Coherent Instabilities

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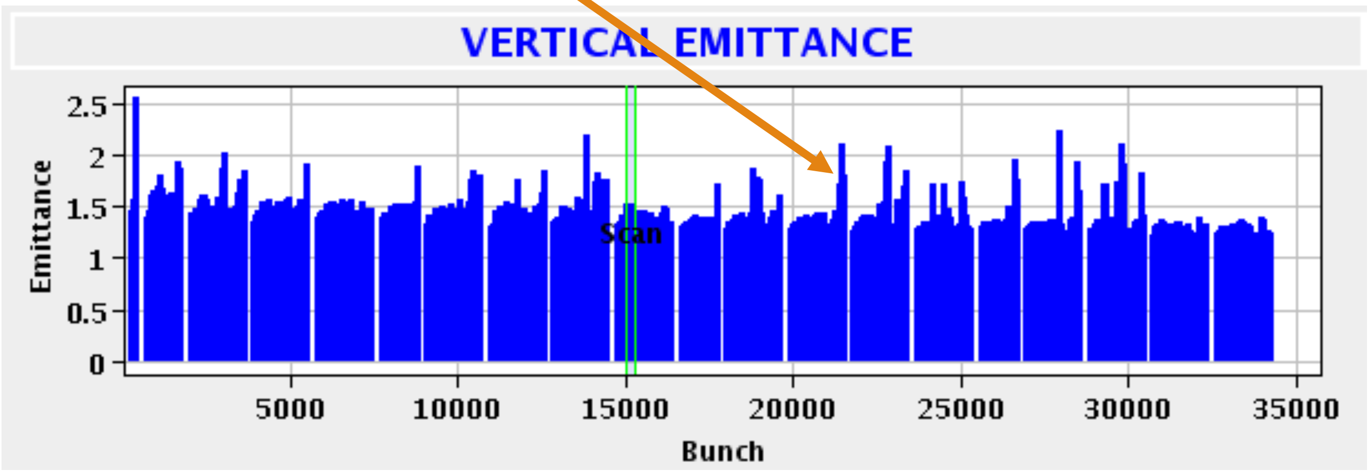
Introduction

- Beam stability in the LHC is related essentially to impedance and electron-cloud effects (see also talk by L. Mether).
- During operation, such coherent instabilities sometimes lead to beam dumps (mainly during Run 1) or beam blow-up, and are still one of the sources of brightness limitation in the LHC.
- Main evolutions since Run 2 affecting impedance-related stability:
  - ✓ low-impedance collimator upgrade (jaws of 2 TCPs and 4 TCSs in IR7 replaced by Mo-graphite ones, Mo-coated for the TCSs),
  - ✓ increased brightness from the injectors (post-LIU beams),
  - ✓ energy increase (6.5 $\longrightarrow$ 6.8 TeV),
  - ✓ transverse feedback (ADT) improvements (in particular in terms of noise from the pickups).
- Main modifications since Run 2 affecting e-cloud effects:
  - ✓ intensity increase (see later),
  - ✓ deconditioning (should disappear after scrubbing).

Injection - Lessons learned from Run 2

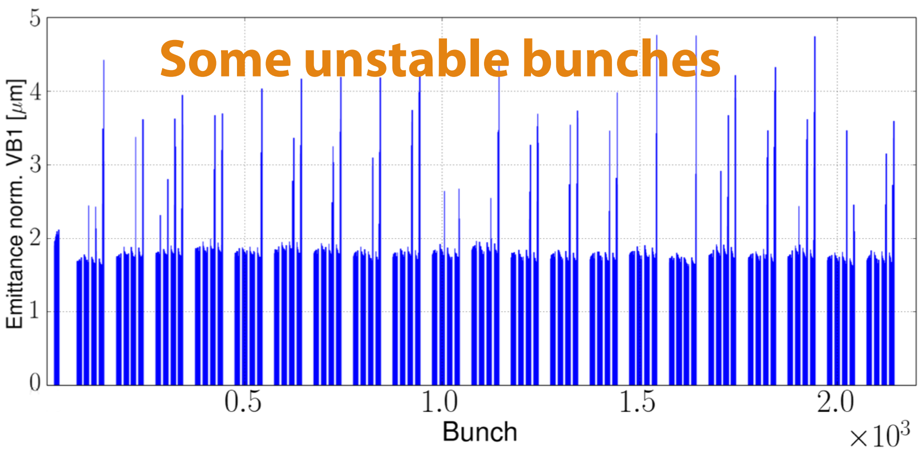
- Possible stability issues are related to electron-cloud.
- After scrubbing, instabilities at injection were well contained with a high chromaticity (15-20) and octupole current (~50 A)
  - Weak single bunch instabilities remained, with a marginal impact on the beam quality at flat top



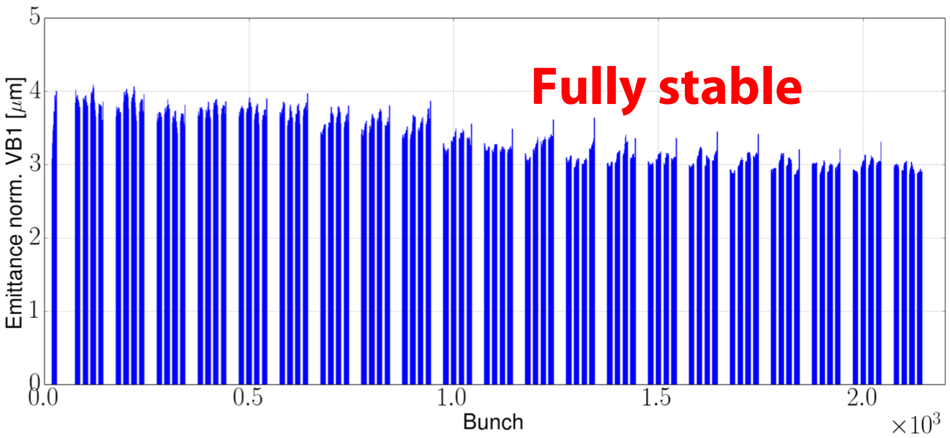
Injection - Recommendation

- Improvements are expected with higher bunch intensities, allowing for a reduction of the octupole current:

0.7e11 p+/b, **56 A** in octupoles (12b-trains)



1.8e11 p+/b, **0 A** in octupoles (12b-trains)



A. Romano et al., Phys. Rev. Accel. Beams 21, 061002 (2018)
G. Iadarola,et al., Chamonix 2018
L. Sabato et al., CERN-ACC-NOTE-2020-0050

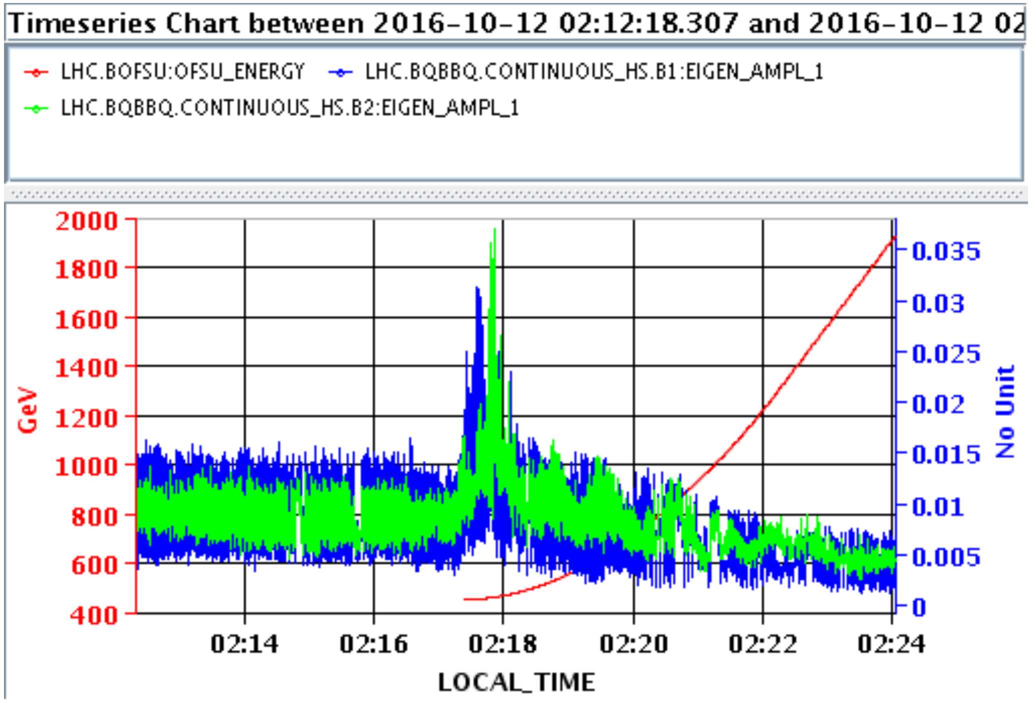
⟹ 50 A and Q'~15-20 (for 1.8 μm emittance) is a very safe starting point.

⟹ Possibility to relax these can be determined empirically.

- The octupole current should be scaled inversely proportional to the transverse emittance.

Ramp - Lessons learned and recommendations

- Weak single bunch instabilities were observed at the beginning of the ramp, similarly to those of injection (e-cloud).



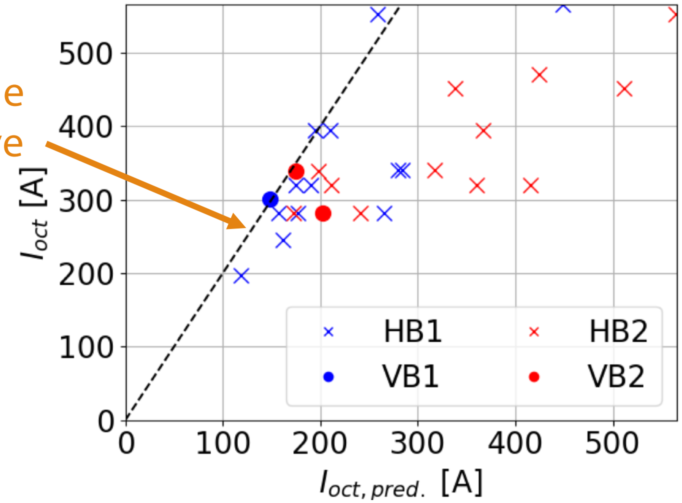
✓ Still well-contained if octupole and chromaticity starts at injection values (marginal impact on the beam quality at flat top).

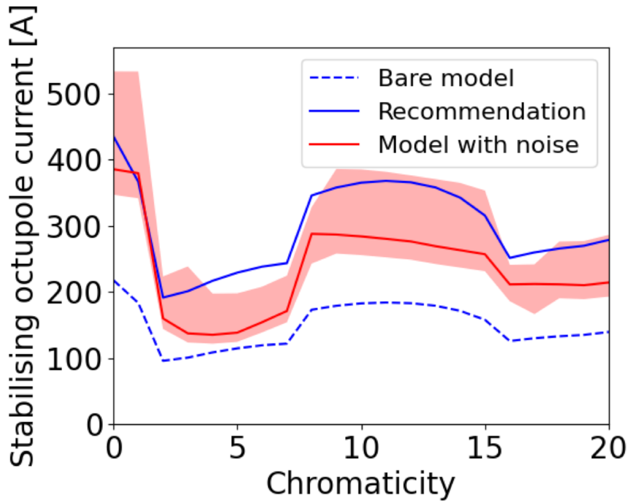
$\Longrightarrow$ Incorporate injection settings into the ramp – in particular octupoles & chromaticity. ADT gain can be reduced (50 turns).

Flat top - Lessons learned from Run 2

- Reliable recommendations provided, considering an **empirical factor 2** w.r.t. model (full machine impedance + ADT + Landau damping from arc octupoles).
  - Provided **linear coupling** is under control ($\frac{\Delta Q_{min}}{\Delta Q} < 0.1$) and **detuning from lattice non-linearities** is corrected / compensated

No unstable cases above this line





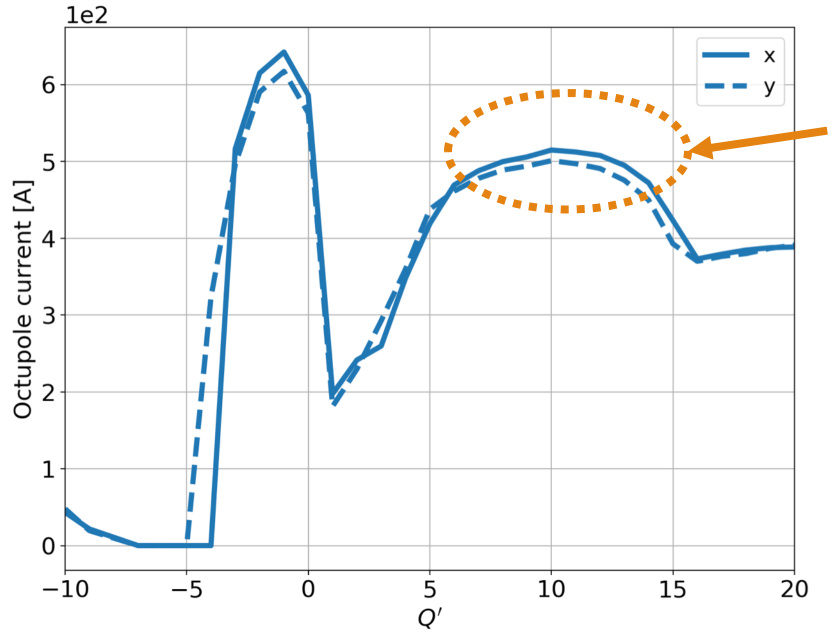
- Empirical factor 2 can be understood knowing the **impact of noise on Landau damping**, within uncertainties (noise amplitude, impedance, residual coupling, emittance measurement).
  - noise reduction in the ADT pickups beneficial (upgrade in LS2 – see talk by M. Soderen),
  - … but impact on stability at flat top remains marginal (residual noise in the machine).
- Currently the chromaticity is kept high (15) to avoid small (or even negative) values.

L. R. Carver et al., Phys. Rev. Accel. Beams 21, 044401 (2018)
X. Buffat et al., in proceedings of Evian 2019
S.V. Furuseth and X. Buffat, Phys. Rev. Accel. Beams 23, 11440 (2020)

Flat top prediction – octupole vs. Q'

- Regarding impedance-related instabilities, flat top is the most critical part of the cycle:
  - collimators (main impedance contributors) at the tightest settings,
  - we get only later the large, stabilizing effect from head-on tunespread (in stable beam, when collisions are established).
- The most critical stability threshold is in single-beam (long-range interactions have a beneficial effect with positive octupole polarity, but vary from bunch to bunch ⟶ we do not include them here).

Octupole threshold vs. chromaticity
(N=1.8e11 p+/b, ε=1.8μm, 25 ns, 6.8 TeV, single beam, 50 turns damper, factor 2 included, oct. > 0)



This is the « plateau » we usually consider « safe » (chromaticity uncertainty)

Flat top – recommendations

- Beam / machine conditions: 25 ns beam, 6.8 TeV (including impact on collimator settings / tune shifts / Landau damping due to 7 TeV → 6.8 TeV)
  - **Q' ~15** (see also MD plan) and **coupling corrected** ($\frac{\Delta Q_{min}}{\Delta Q} < 0.1$)
  - **ADT gain at 50 turns**, with **enhanced bandwidth**
  - **octupole current needed** (max for 10 ≤ Q' ≤ 20, include factor 2):

	Brightness [10^{11} p+/μm]	Oct. Threshold [A] 1.2 ns TeleIndex=1	Oct. Threshold [A] 1.2 ns **TeleIndex=0.5**	Oct. threshold [A] **1.4 ns** TeleIndex=1
	0.7	361	281	320
2022	0.8	**413**	321	367
(1.4e11 in 1.8 μm)	0.9	464	361	412
2023/2024	1.0	**516**	**401**	**458**
(1.8e11 in 1.8 μm)	1.1	568	441	504

Collision – lessons learned and recommendations

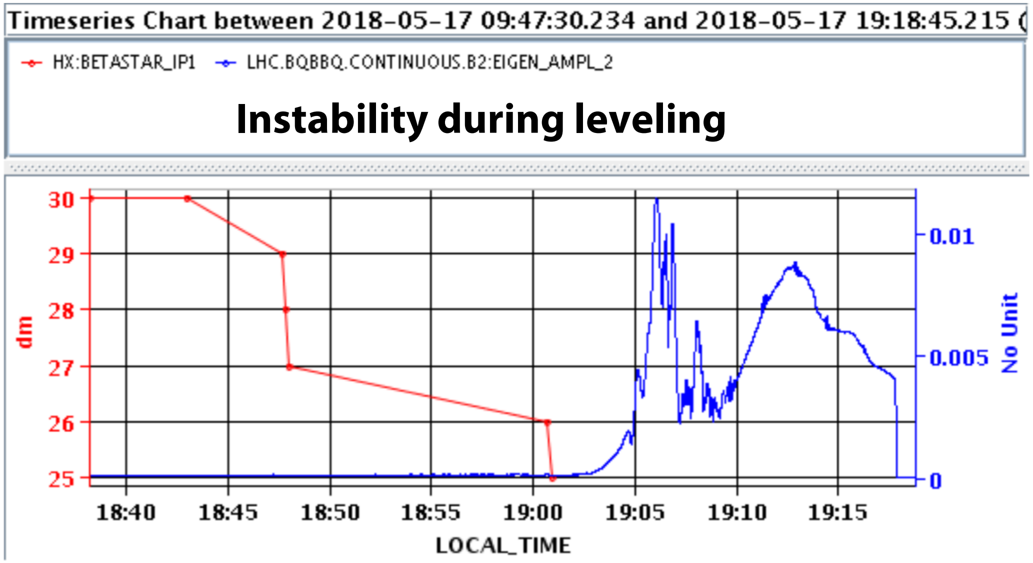
- Bunches colliding with an offset (1-2σ) can lose Landau damping
  - Keep one of the main IPs colliding during emittance / lumi scans
  - Avoid bunches colliding only at levelled IPs in the filling schemes
  - Design the VdM configurations with the instability team

- **Enhanced** ADT bandwidth (optimal for beam stability), should be maintained **from injection to start of collision**
  - **Once in collision** the **standard ADT bandwidth** reduces the emittance growth, and is enough since head-on tunespread stabilizes the beam.

X. Buffat et al., CERN-ACC-NOTE-2020-0059
S.V. Furuseth et al., Phys. Rev. Accel. Beams 24, 011003 (2021)
A. Ribes Metidieri and X. Buffat, CERN-ACC-NOTE-2019-0037
J. Wenninger et al, CERN-ACC-NOTE-2018-0026

Collision – lessons learned and recommendations

- Non-colliding bunches:
  - Perform coupling correction based with ADT-AC dipole on non-colliding bunches (bunch-dependent coupling).
  - Correct lattice non-linearities.
  - Reduce oct. in stable beams ONLY if brightness of non-colliding is reduced (HiLumi strategy).

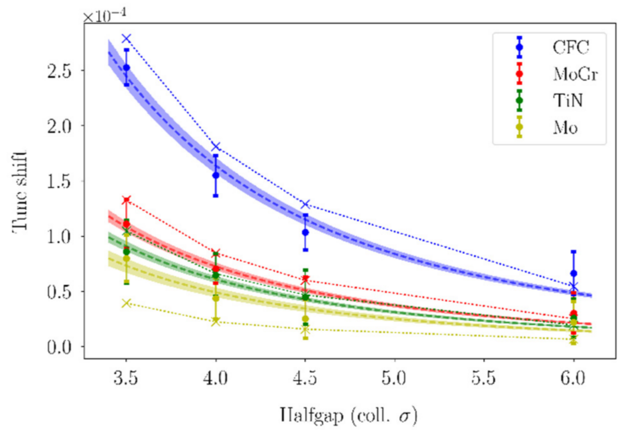


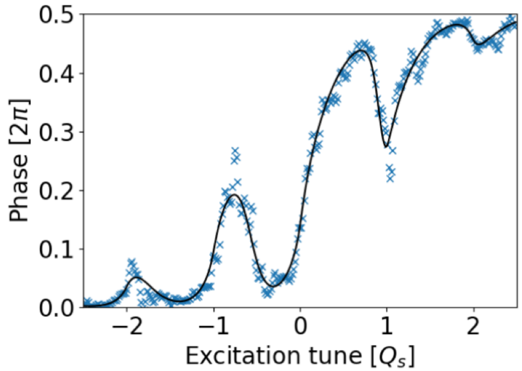
X. Buffat et al., CERN-ACC-NOTE-2020-0059
S.V. Furuseth et al., Phys. Rev. Accel. Beams 24, 011003 (2021)
A. Ribes Metidieri and X. Buffat, CERN-ACC-NOTE-2019-0037
J. Wenninger et al. CERN-ACC-NOTE-2018-0026

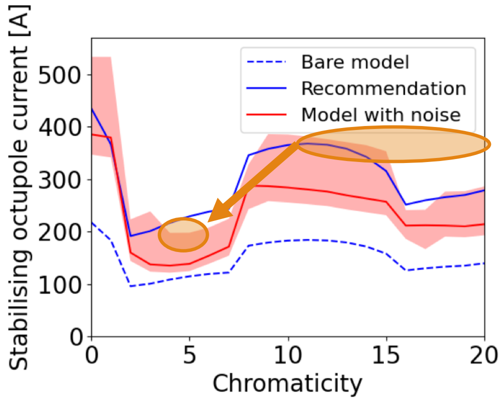
- Check for possible "pop-corn" instabilities (related to increased e-cloud effects with intensity decrease from burn-off)
  ⟶ high Q′ needed when machine not yet well conditioned.

MD plan

- Characterization of the machine and individual collimators' impedances with emphasis through tune shift measurements
  - Identification of non-conformities
  - Monitoring of the impact of radiation
  - Input for HL-LHC predictions (upgraded collimators)
  - Growth rates / octupole thresholds.
- Online chromaticity measurement based on Beam Transfer Function (BTF)
  - Accuracy demonstrated in simulations with non-linear fit / neural network
  - Test new BTF method based on noise injection with the ADT (single bunch kick) → could be used at every fill.





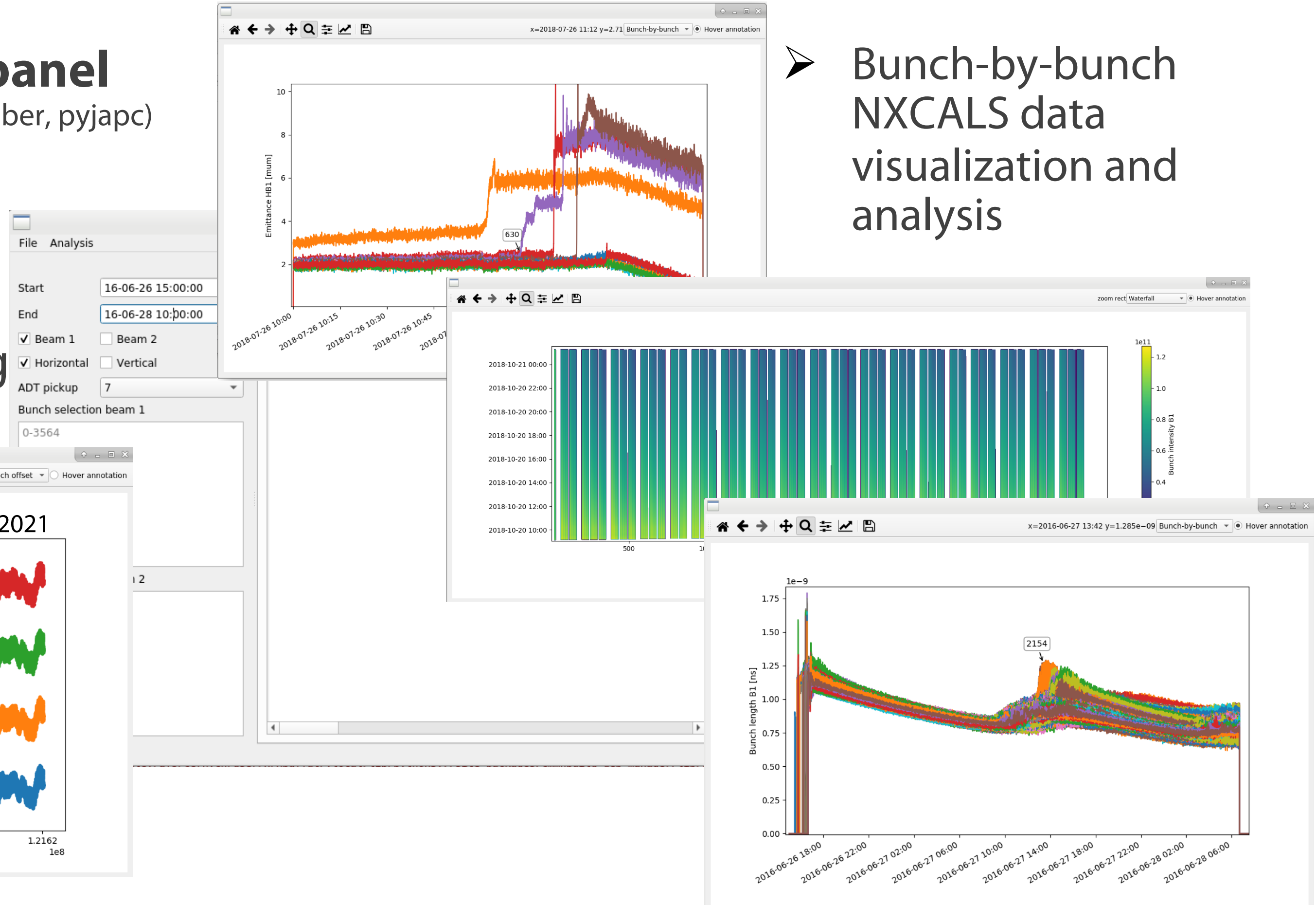


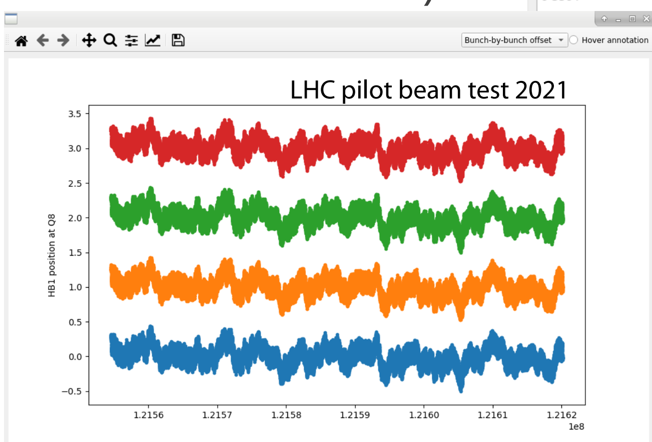
- Probe the accuracy of the stability model including noise
  - Validate the existence of a 'sweet spot' at lower chromaticity that would relax operational constraints (octupole current, coupling correction, NL correction)

S. A Antipov et al., IPAC'18, THPAF035
X. Buffat et al., in proceedings of HB2021

Operational tools and monitoring

- **New instability panel**
  based on acc-py (pyQt, pytimber, pyjapc)
- **ADTObsBox** data visualization and analysis (24h rolling buffer and LIST)
- Bunch-by-bunch NXCALS data visualization and analysis





- Online tools for Scrubbing and MDs
- ML based anomaly detection (L. Coyle)
- Up-to-date recommendation and communications (for OP and MDs):

https://cern.ch/lhcinstability

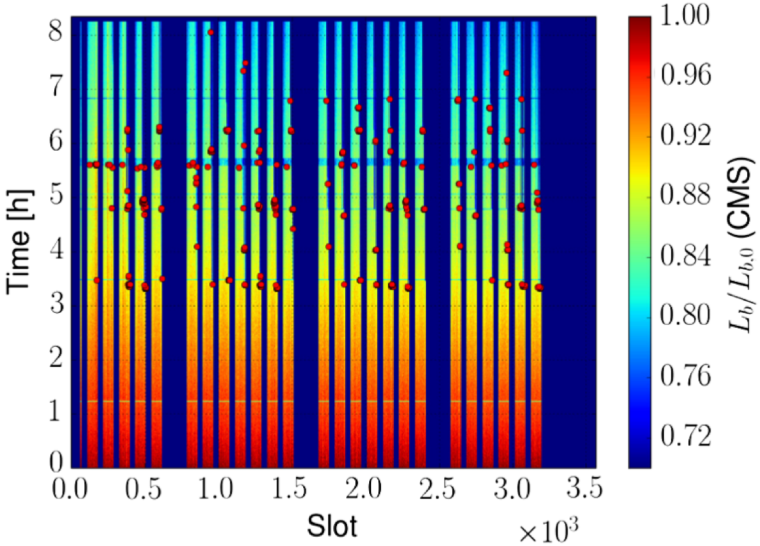
Summary of recommendations

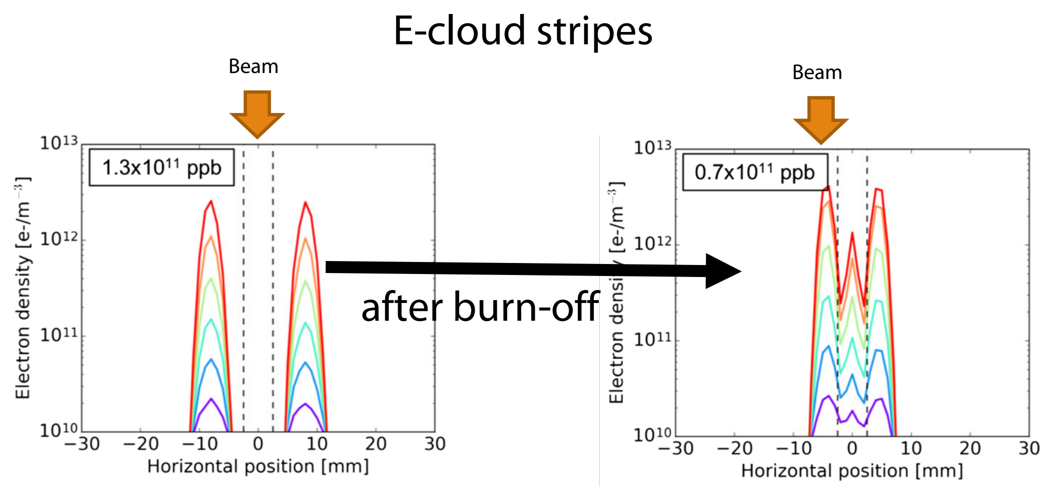
- In general: high chromaticity, correct linear coupling, use enhanced ADT bandwidth from injection until end of flat top.
- Injection: start with Run 2 settings (Q'~15-20, oct. ~50 A for 1.8 μm emit.), possibly relax step-by-step after scrubbing (when bunch intensities > Run 2).
- Ramp: start with injection settings in terms of Q' / octupoles.
- Flat top:
  - worst situation for impedance-related stability,
  - teleIndex=1, positive octupole polarity, brightness of 1.10^{11} p+/μm: oct. ~516 A,
  - teleIndex=0.5, positive octupole polarity, brightness of 1.10^{11} p+/μm: oct. ~401 A,
  - depending on new procedure to measure Q', decrease Q' from 15 to ~5.
- Collisions:
  - ADT settings to standard bandwidth,
  - Non-colliding bunches define the required octupole current, coupling correction and non-linear correction ⟶ reducing their brightness would relax these constraints.
  - "Pop-corn" (e-cloud) instabilities to consider carefully ⟶ start the run with high Q'.

Backup slides

DISCLAIMER: **values are not necessarily up-to-date** (in particular, **7 TeV** is always considered, instead of 6.8 TeV)

Collision – lessons learned and recommendations





- **Popcorn instabilities** during STABLE BEAM are caused by the increased central density of the electron cloud in the dipoles with low bunch intensity
  - They could re-appear due to deconditioning of the dipoles
- Proposed strategy: **Start the run with a high chromaticity in collision** (15 units), possibly reduce it in steps after few weeks of high intensity operation to optimize the beam lifetime

A. Romano, et al., Phys. Rev. Accel. Beams 21, 061002 (2018)

Run 3: Stability from impedance

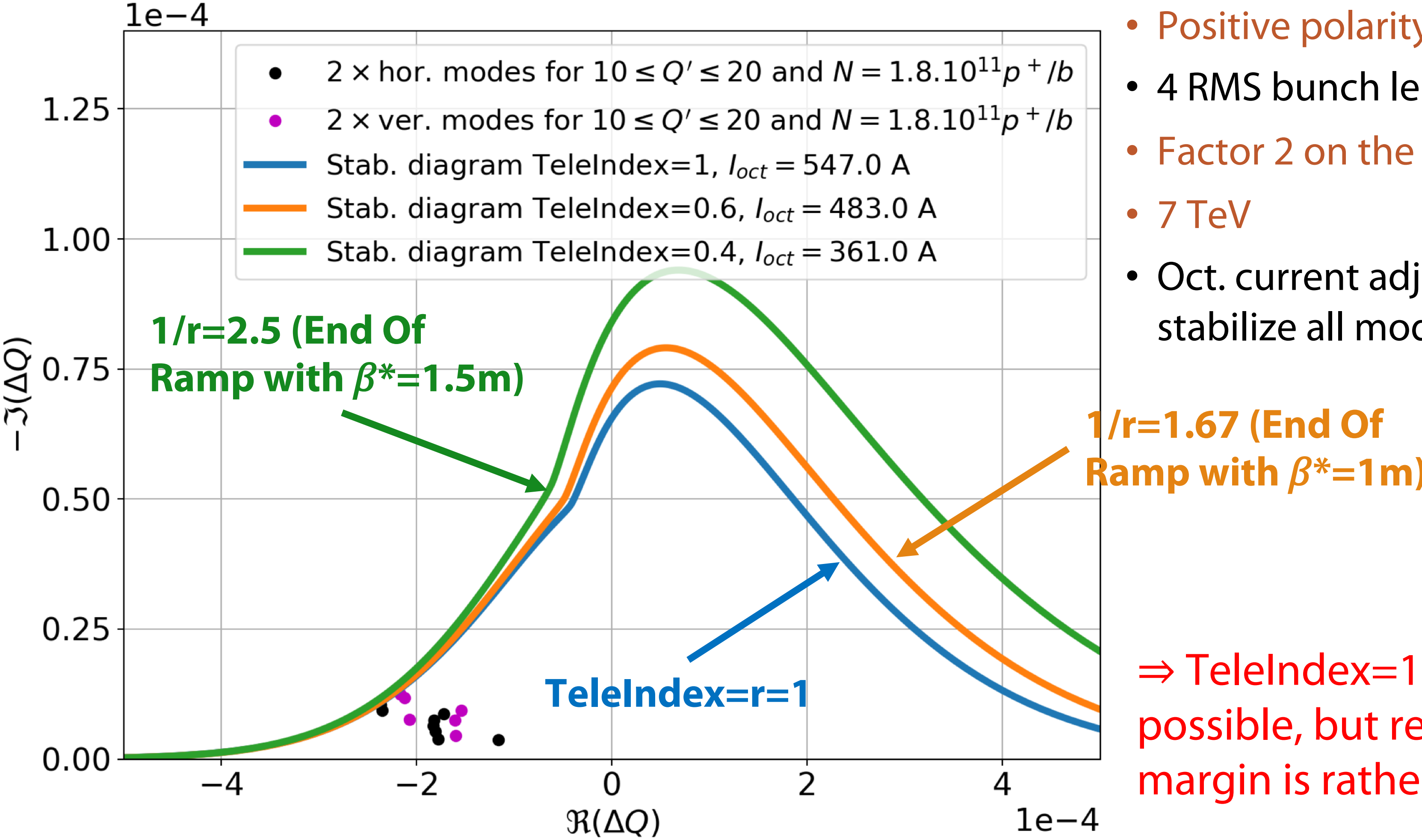
- Collimator scenario at top energy (expressed in σ computed with ε=3.5μm):

	« Tight » as in LHC Run II
TCP/TCS/TCLA(D) IR7	5 / 6.5 / 10 (10)
TCP/TCS/TCLA IR3	15 / 18 / 20
TCDQ/TCS IR6	7.3
TCT IR1/5	7.8
TCL (IR1/5) Q4/Q5/Q6	15 / 15 / parking
TCT IR2/8	37 / 15

Note: IR2 injection protection collimators are always in parking position.

Impact of (anti-)TeleIndex on stability

Octupole threshold depends on TeleIndex ⇒ different stability diagrams



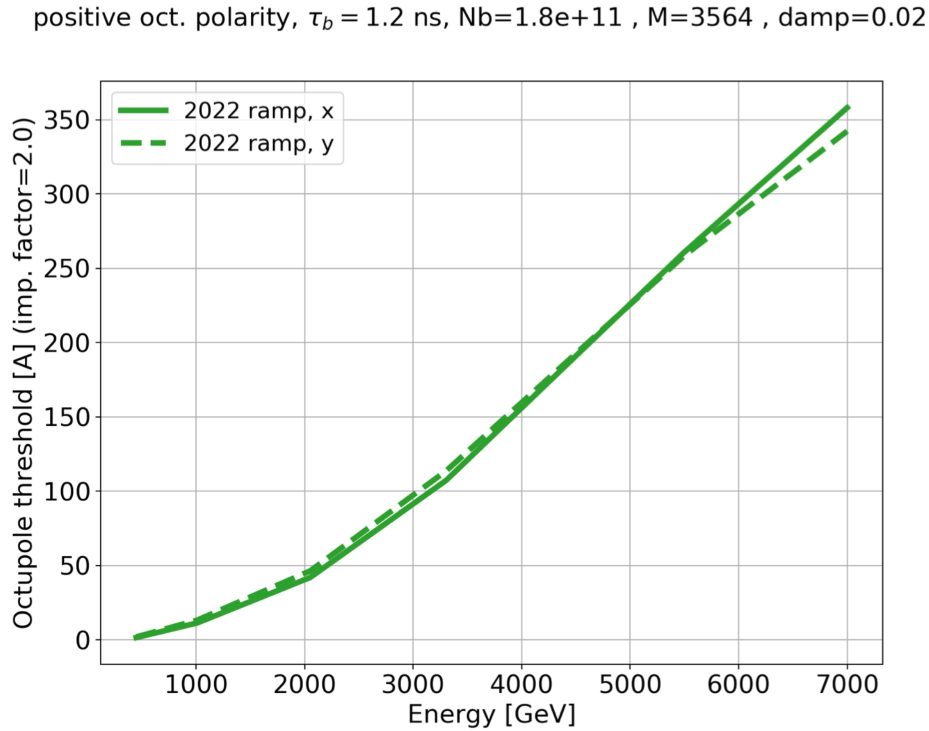
- Positive polarity, ε=1.8μm
- 4 RMS bunch length 1.2ns
- Factor 2 on the modes
- 7 TeV
- Oct. current adjusted to stabilize all modes.

⇒ TeleIndex=1 seems possible, but remaining margin is rather small.

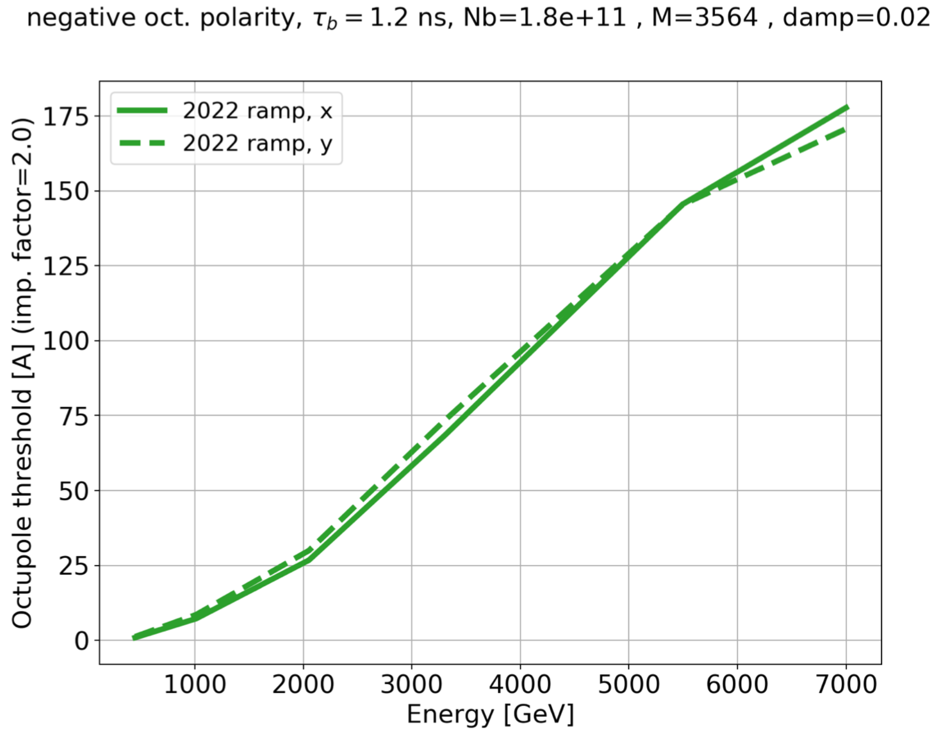
Single-beam stability

- Including factor 2, with Gaussian transverse distribution.

Positive polarity



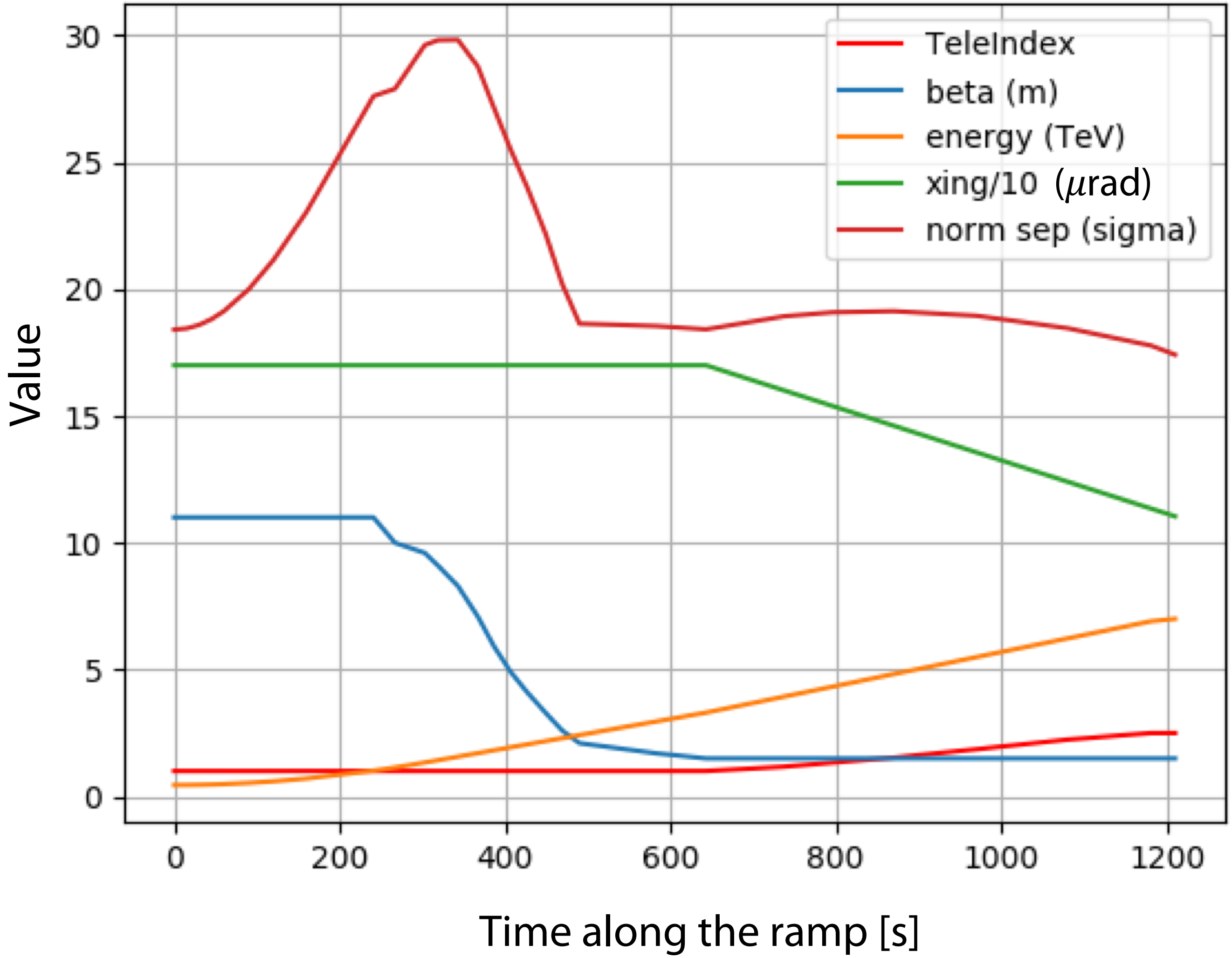
Negative polarity



$\Longrightarrow$ Negative polarity is twice more stable as positive one, in single-beam.

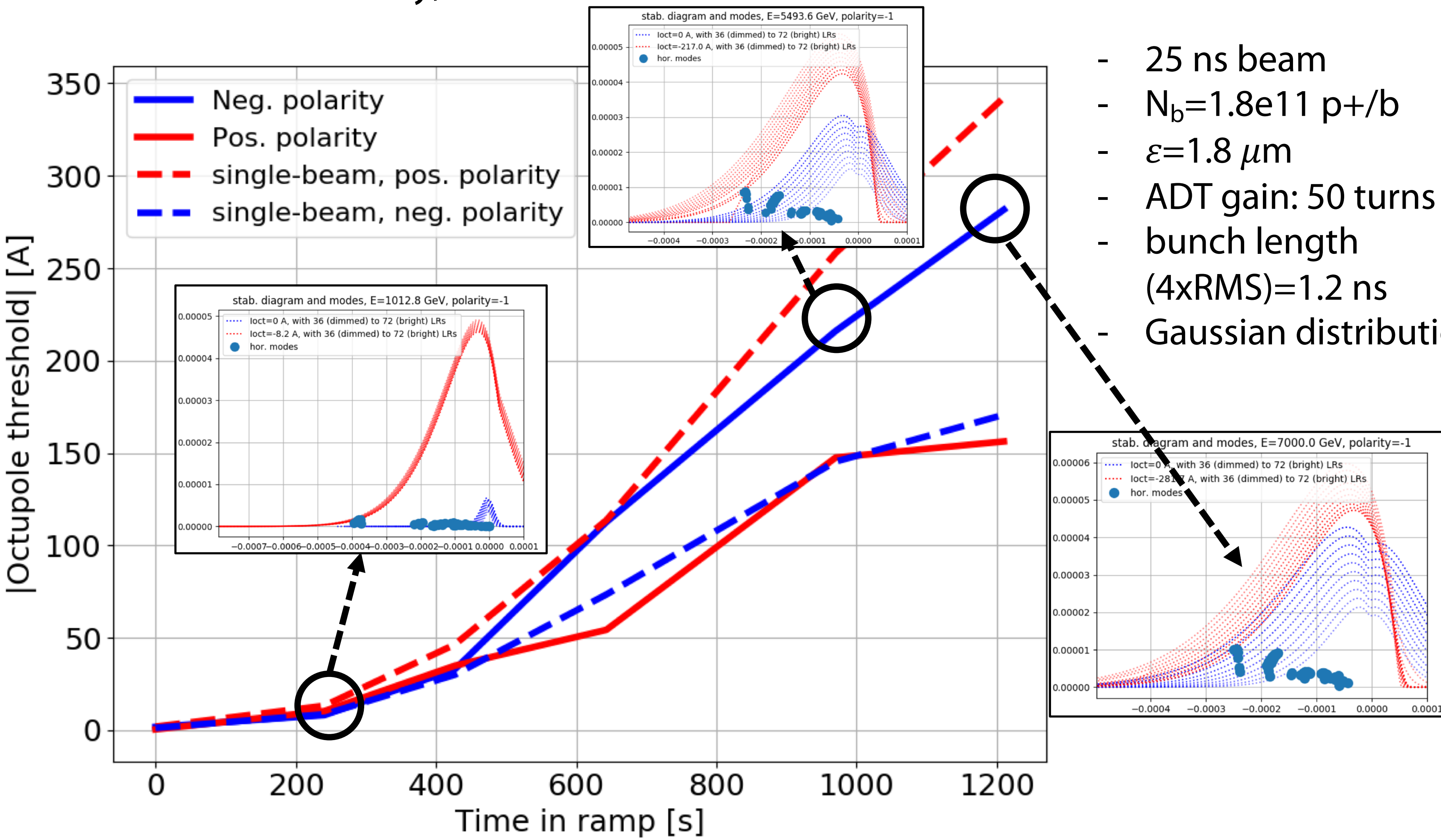
Ramp parameters

➢ Evolution of the parameters relevant to long-range effects, along ramp:



Stability with long-range beam-beam effects

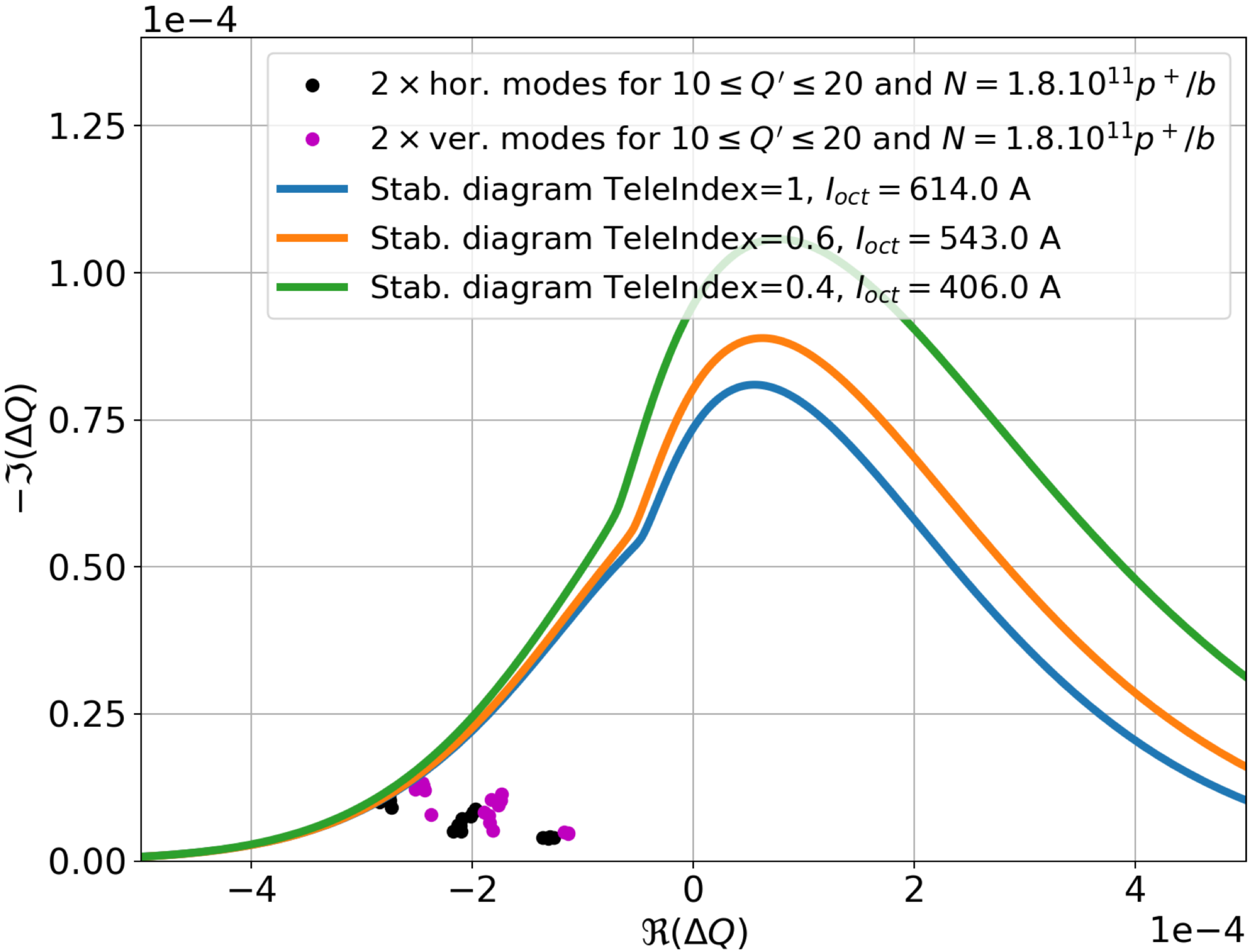
➢ Horizontal only, with factor 2 included:



- 25 ns beam
- N_b=1.8e11 p+/b
- ε=1.8 μm
- ADT gain: 50 turns
- bunch length (4xRMS)=1.2 ns
- Gaussian distribution

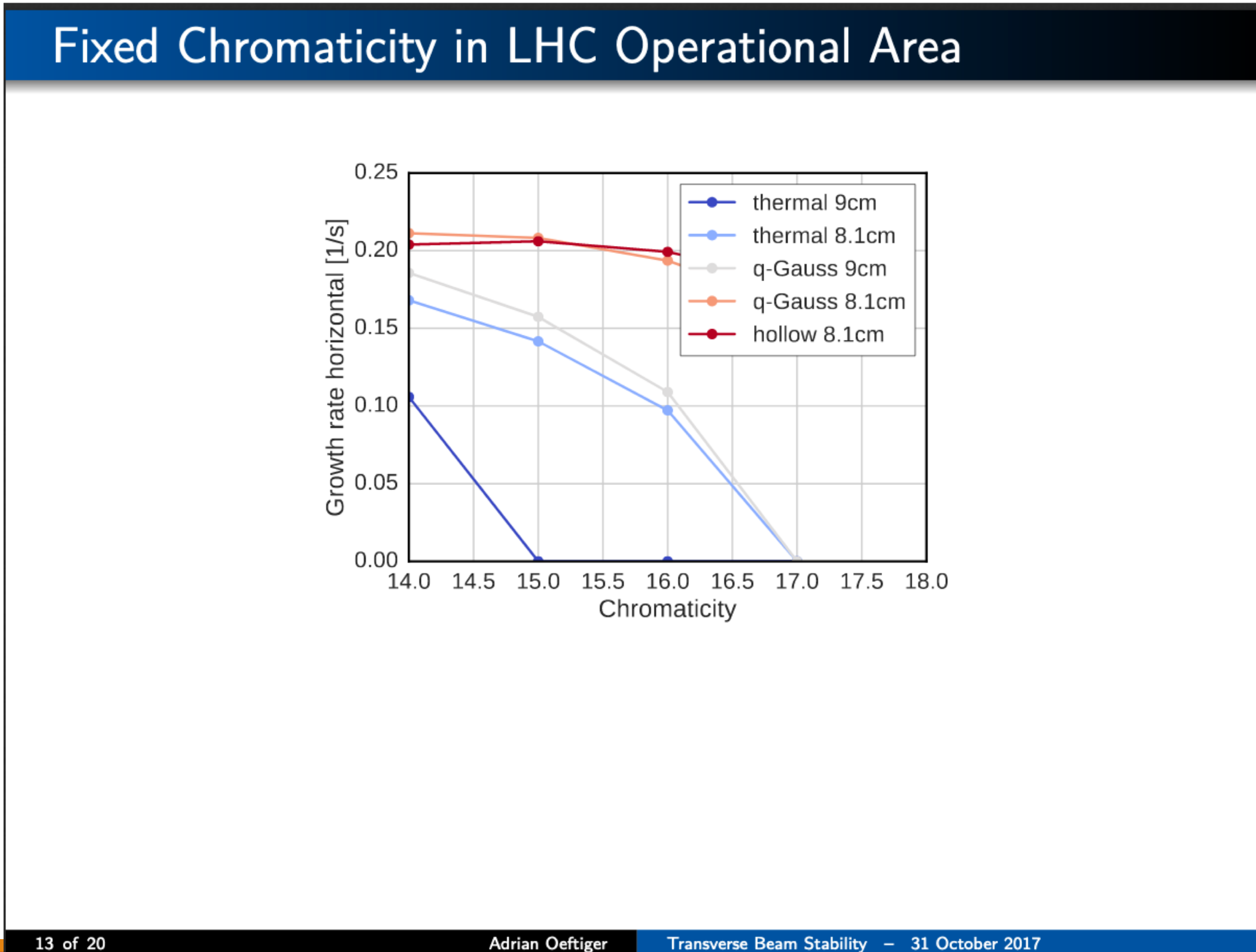
Impact of shorter bunch length on stability diagrams

With bunch length (full, i.e. 4*RMS) = 1ns, positive polarity, ε=1.8μm, 7 TeV



Dependency on longitudinal profile

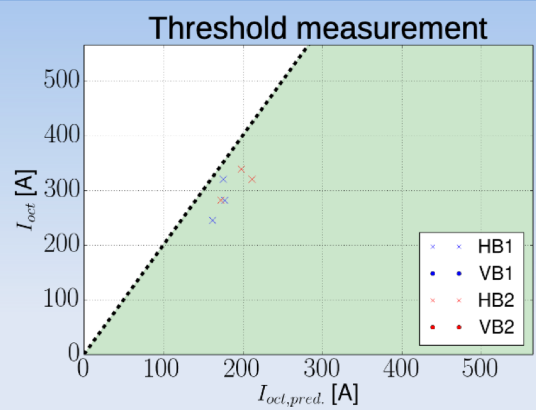
From **Adrian Oeftiger**, 109th WP2 meeting (31/10/2017)

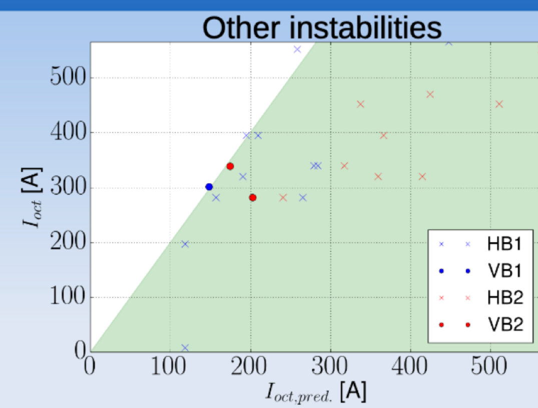


Factor 2 discrepancy

From **Xavier Buffat**, 9th LHC Operations Evian Workshop (01/02/2019):

2018 - Summary





Filtered :
- •Linear coupling
- •Offset beams
- •Reduced ADT gain
- •Pop corn

- All instabilities below the recommended margin occurred during MDs or intensity ramp up
  - Unexpectedly bright beams
  - Lack of preparation / oversight
  - Unclear recommendation

  → Take the time to consult the instability team for your MD

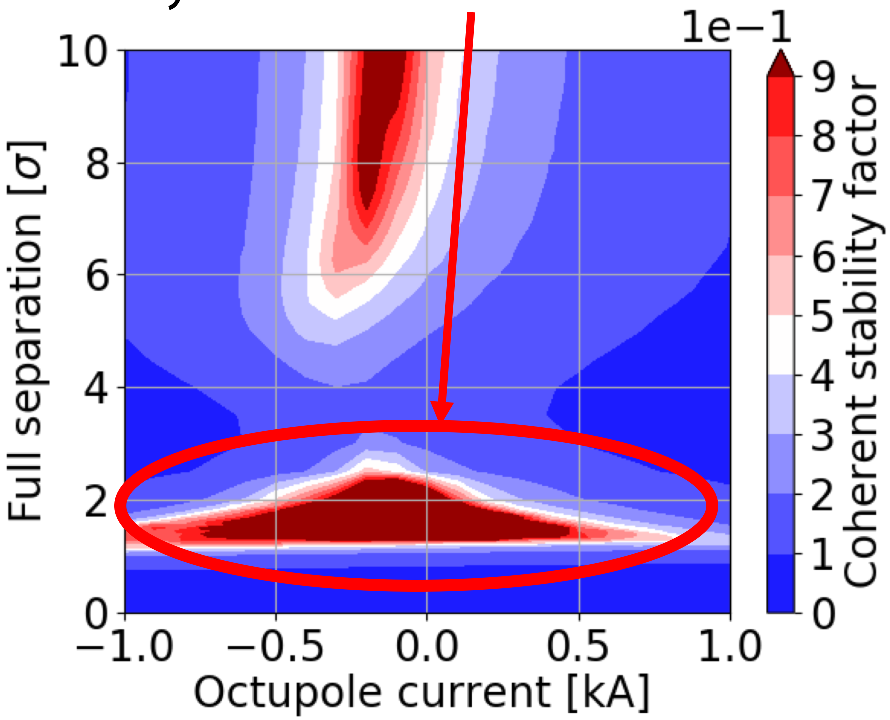
- Reproducibility issue:
  - Several fills reached brightnesses above the recommended margins, yet were stable (e.g. BSRT calib.)

Screenshot

The two options: answers for stability

- **Option 1: large Piwinsky angle**
  Question: "Is it OK for impedance for the beam brightness limits of above (1.6E11 within 1.8 micron – i.e. brightness=0.89e11 p+/μm, 1.8E11 within 2.2 micron – i.e. brightness=0.82e11/μm)?"
  - ✓ Single-beam: limit with 20% margin = 0.88e11 p+/μm ⇒ ~OK
  - ✗ Two beams: **NOT OK** ⇒ instability with offset beams

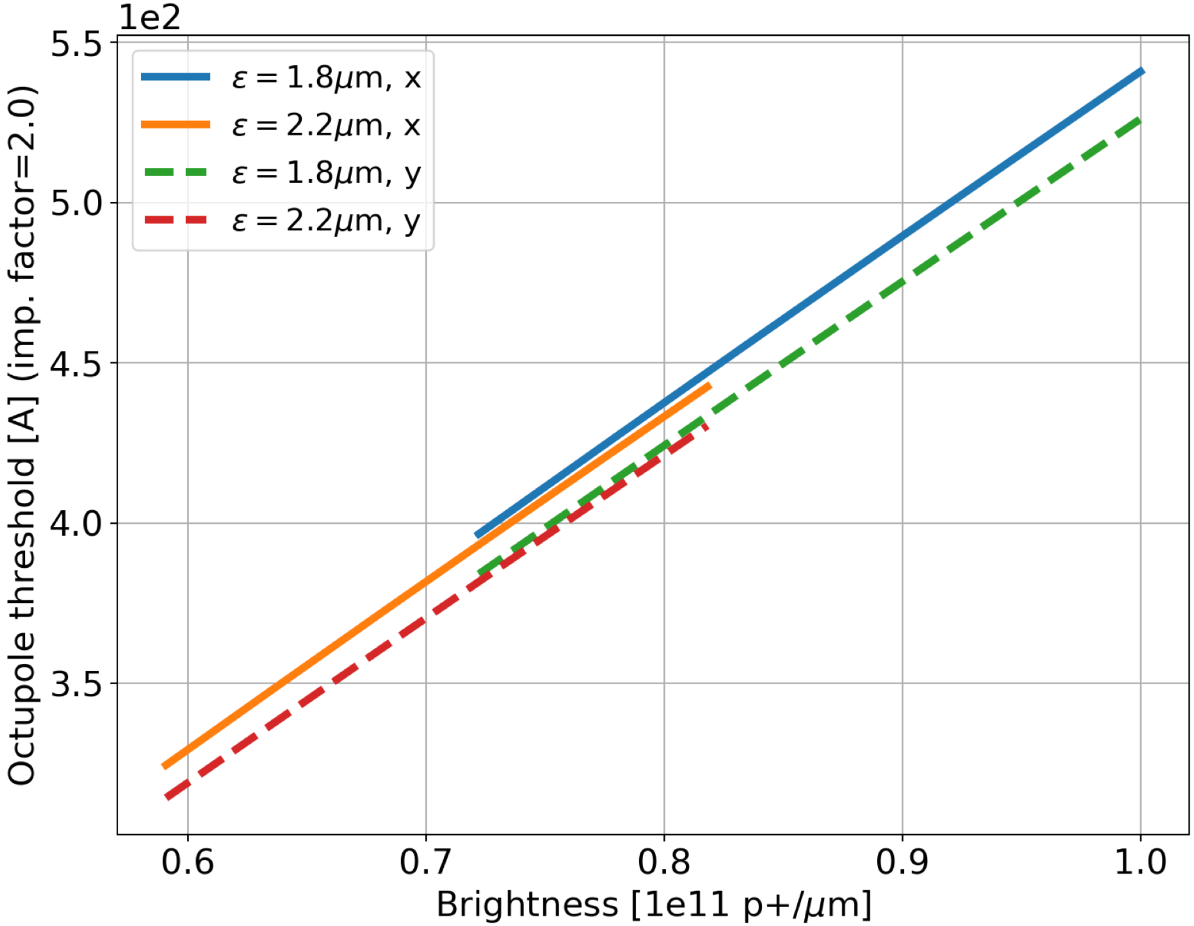
Stability parameter (should be >0.5) vs. separation and octupole current with slightly lower emittance (half crossing angle 220μrad, β^*=0.65m, 7TeV, N_b=1.6e11 p+/b, ε=1.6 μm):



Xavier Buffat

Checking the brightness dependency

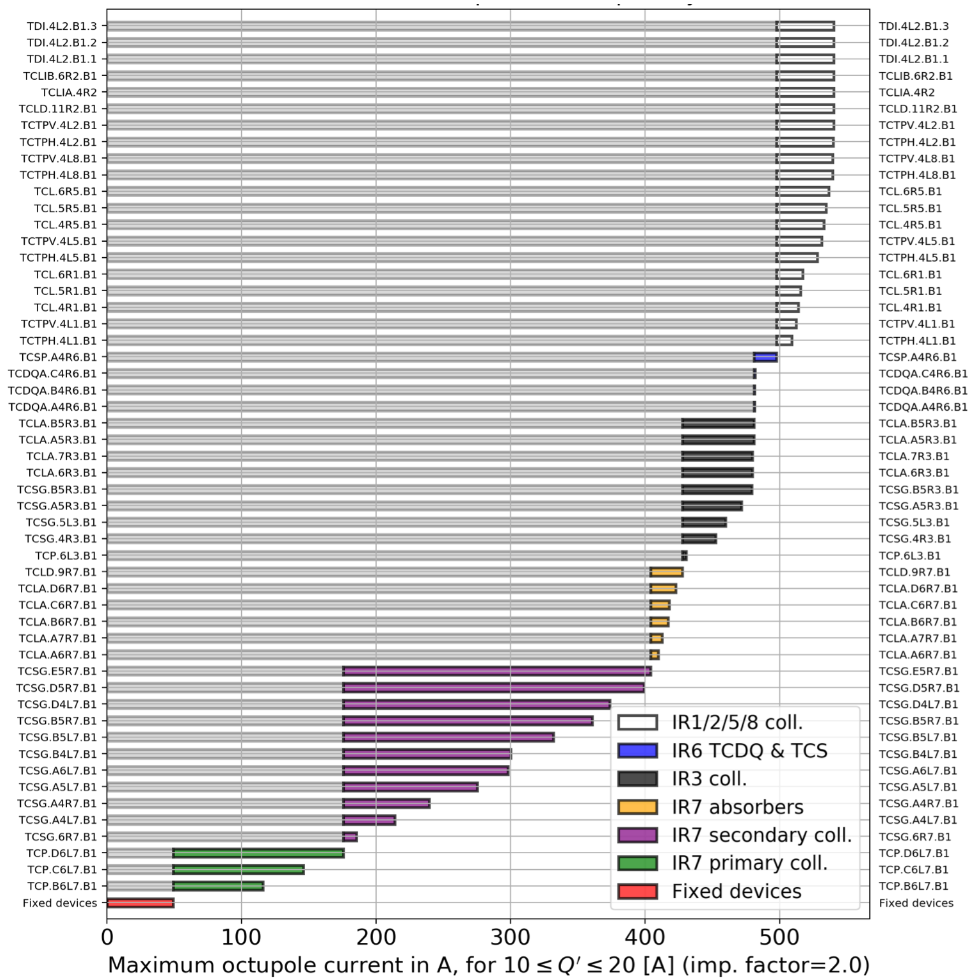
We plot the octupole threshold (max. for 10≤Q'≤20) vs. brightness (N_b/ε) for two different emittances ($4\sigma_{RMS}$ = 1.2ns, positive polarity, TeleIndex=1, with factor 2, ADT gain 0.02).



Very linear dependency, independent on emittance

Impedance contributions in Run III

Single-bunch octupole threshold (max. for 10≤Q'≤20), N_b=1.8x10^{11} p+/bunch, bunch length 4σ_{RMS}=1.2 ns, ε=1.8 μm, d=0.02, **with factor 2**:



LHC Run III & HL-LHC collimator settings

- At top energy:

Collimators	LHC half-gaps [#σ (3.5μm)] β*=1.5m	HL-LHC half-gaps [#σ (3.5μm)] β*=40cm	HL-LHC half-gaps [#σ (2.5μm)] β*=40cm
TCP/TCS/TCLA(D) IR7	5 / 6.5 / 10 (10)	5.7 / 7.7 / 10.7 (14)	6.7 / 9.1 / 12.7 (16.6)
TCP/TCS/TCLA IR3	15 / 18 / 20	15 / 18 / 20	17.7 / 21.3 / 23.7
TCDQ/TCS IR6	7.3	8.5	10.1
TCT IR1/5	7.8	13.9	16.4
TCL (IR1/5) Q4/Q5/Q6	15 / 15 / parking	18.9	22.4
TCT IR2/8	37 / 15	30 / 15	35.5 / 17.7

Note: injection protection collimators and TCLD in IR2 are always in parking position at top energy.

LHC Run III & HL-LHC parameters

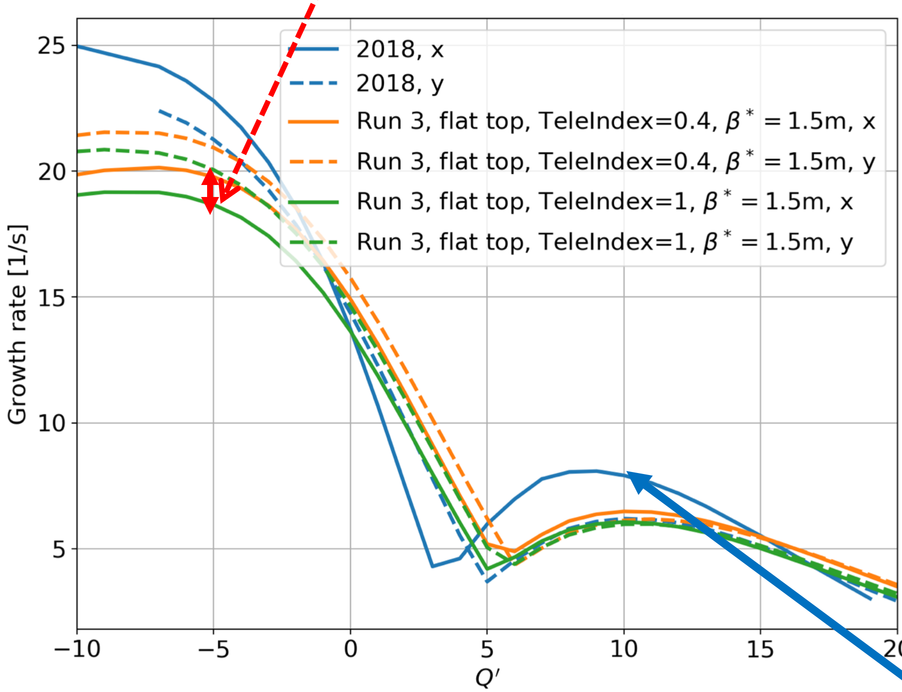
- At top energy, and unless specified differently, the main parameters used in DELPHI simulations are:

	LHC (B1)	HL-LHC (B1)
Intensity	1.8 10^{11}	2.3 10^{11}
Energy	7 TeV	
Bunch length (4*rms)	1.2 ns	
Revolution frequency	11.2455kHz	
Q_x / Q_y	62.31 / 60.32	
Slippage factor $\eta = \alpha_p - 1/\gamma^2$	3.48 10^{-4}	
RF voltage	16 MV	
Q_s	2.12 10^{-3}	

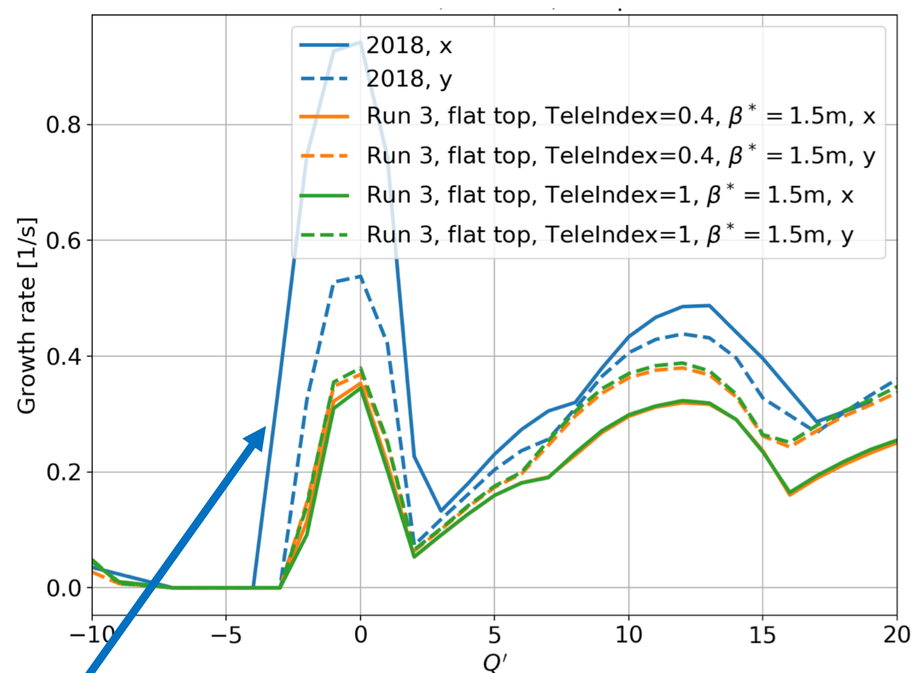
Growth rates vs. chromaticity – checks

- Do growth rates depend on the **optics** (here **LHC Run 3**, 25ns beam)?

YES (slightly) **without damper**



NO, **with damper** (here 100 turns)

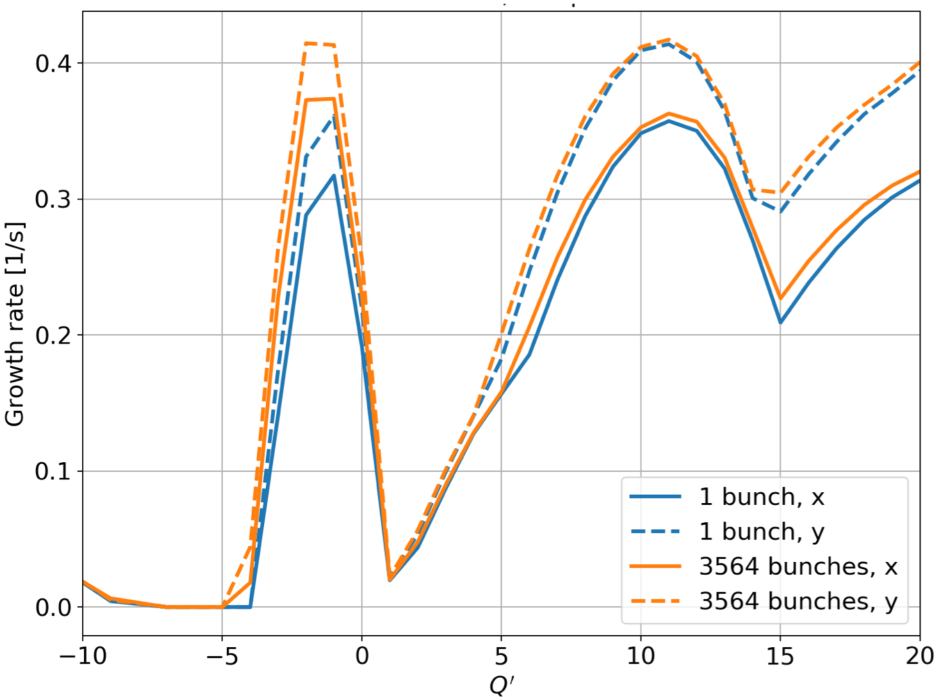


Pre LS2 (2018), for comparison

Growth rates vs. chromaticity – checks

- Do growth rates with **damper on** (here 50 turns), depend on **number of bunches**?

~NO for LHC

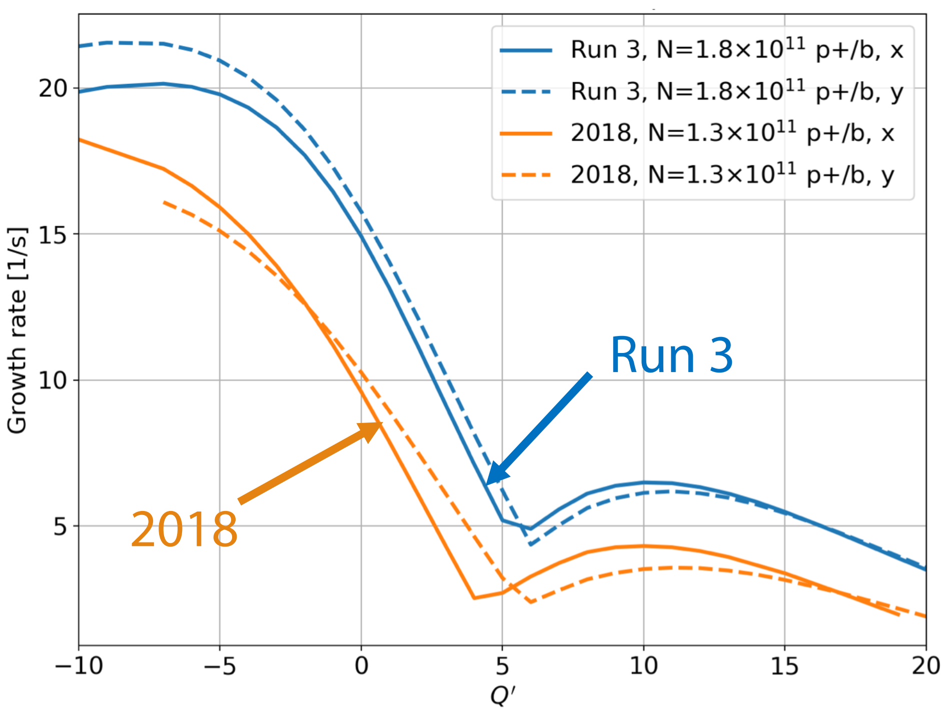


LHC Run 3, flat top with 2022 ramp 2022 ($\beta^* = 1.5$m , TeleIndex=0.4)

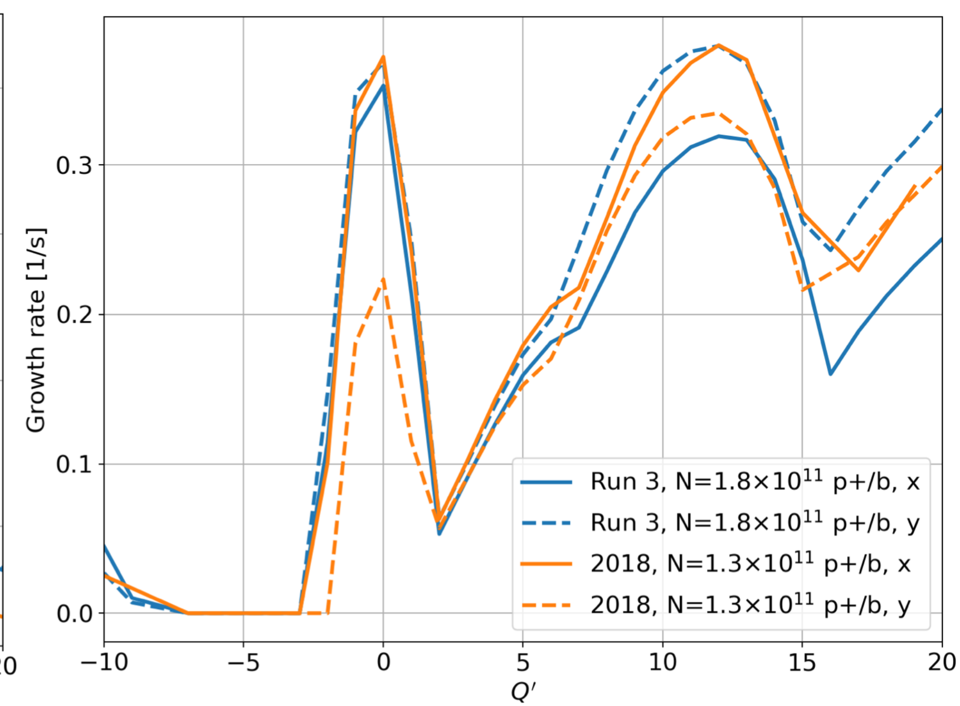
Final growth rates vs. chromaticity: LHC

➢ **LHC Run 3** (end of 2022 ramp, $\beta^* = 1.5$m, TeleIndex=0.4) , 25ns beam, compared to pre LS2 (2018, with corresponding intensity)

No damper



Damper 100 turns

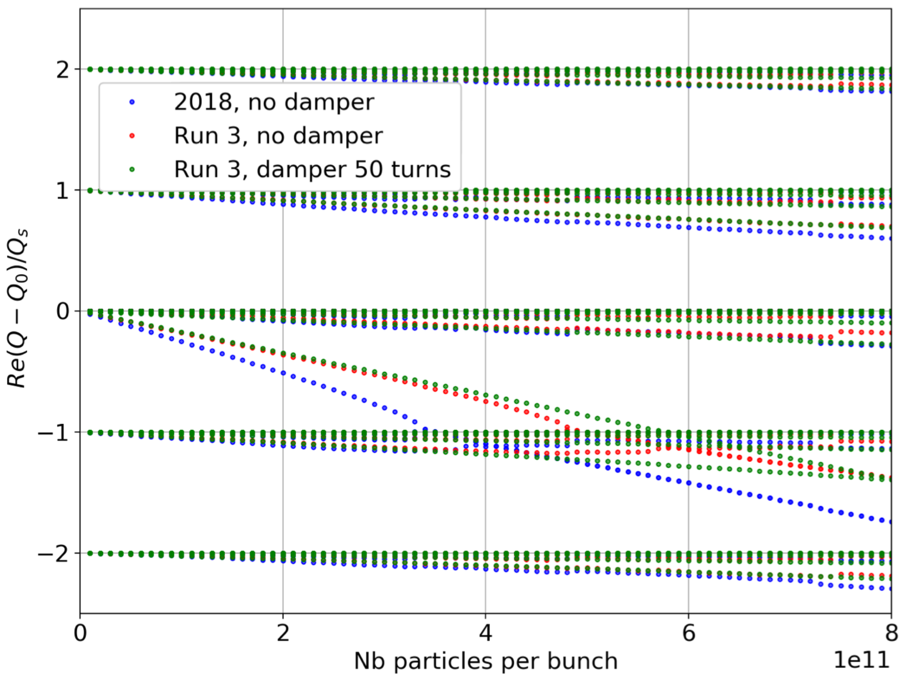


- **Higher coupled-bunch growth rates** without damper for Run 3 vs 2018, despite the impedance upgrade (from beam screens impedance & higher intensity).

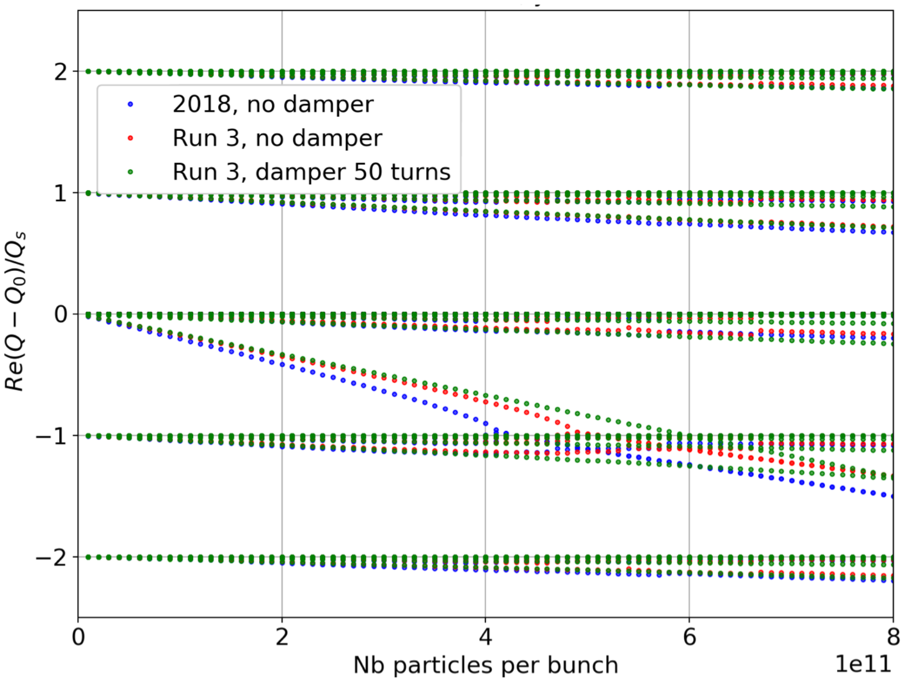
Transverse Mode-Coupling Instability: LHC Run 3

- In single-bunch: TMCI threshold ~4.9 10^{11} p+/bunch (vs. 3.4 10^{11} in 2018)

Horizontal



Vertical

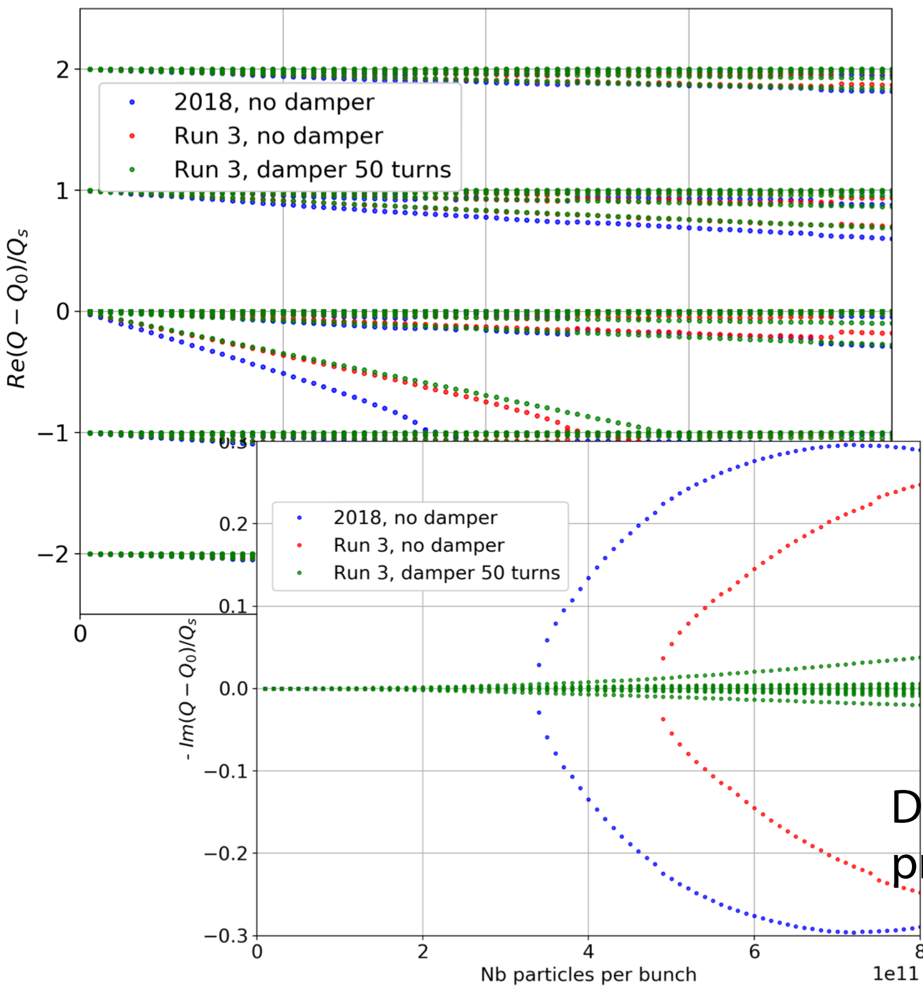


- Independent on optics choice for Run 3.
- ***David Amorim*** found **5.7 10^{11}** in 2018, for HL-LHC with LS2.2 configuration (HSC meeting, 20/08/2018).

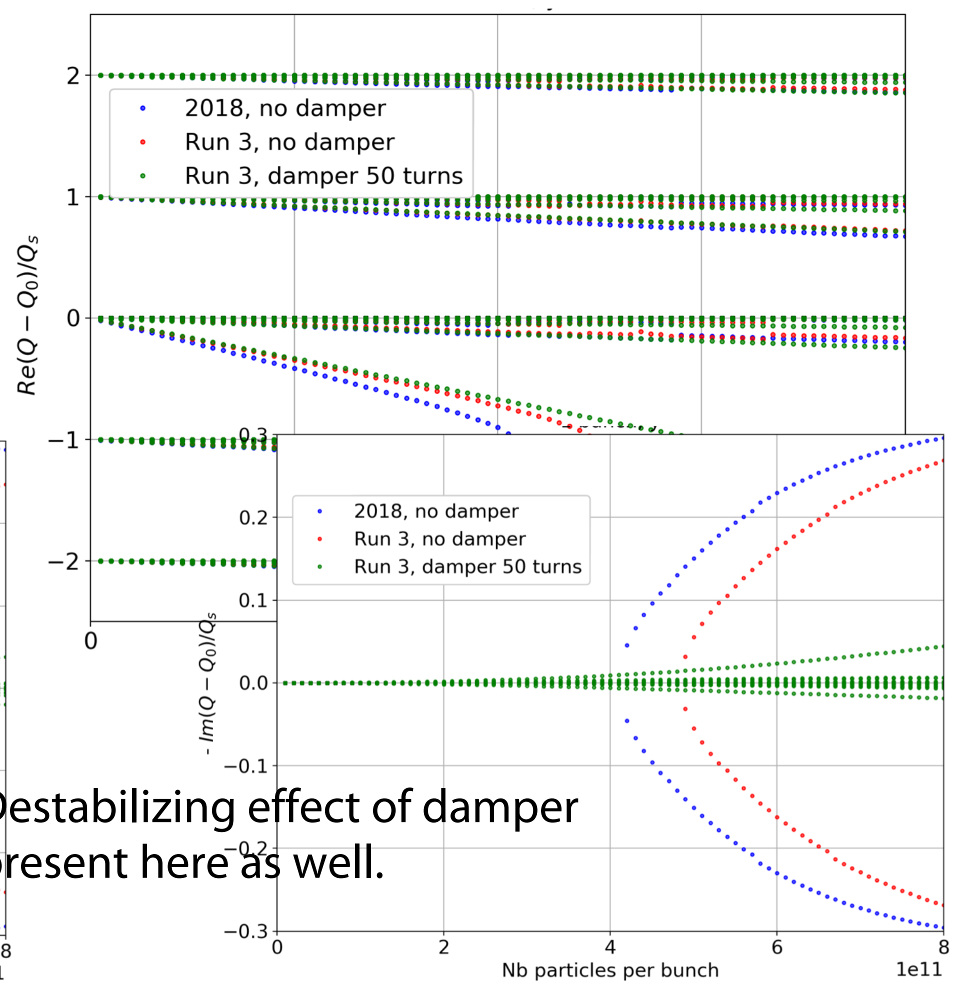
Transverse Mode-Coupling Instability: LHC Run 3

- In single-bunch: TMCI threshold ~4.9 10^{11} p+/bunch (vs. 3.4 10^{11} in 2018)

Horizontal



Vertical



Destabilizing effect of damper present here as well.

LHC impedance model – Run III

- The main LS2 planned modifications that can affect impedance at top energy, are in the model:
  - ✓ Low-impedance collimator upgrade (jaws of 2 TCPs and 4 TCSs in IR7 replaced by Mo-graphite ones, Mo-coated for the TCSs),
  - ✓ Updated tapers of collimators (thanks to **E. Carideo** & **S. Antipov**),
  - ✓ Addition of TCLD absorber (tungsten) in IR7,
  - ✓ Addition of TCLD in IR2 (will stay in parking for the proton run),
  - ✓ Beta functions in the arcs and triplets (new optics from **S. Fartoukh**),
  - ✓ fully updated TDIS – geometric and resistive-wall (thanks to **N. Biancacci** & **B. Salvant**),
  - ✓ New MKI cool (implemented by **D. Amorim**).

LHC Run 3 impedance model – what's not there

- Planned modifications that are not yet in the model (thanks to **B. Salvant**):

  - ✗ experimental chamber upgrades (CMS, ALICE, LHCb),
  - ✗ VELO and SMOG2 (LHCb),
  - ✗ in-situ aC-coating in Q5 and Q6 (beam screens of stand-alones),
  - ✗ new BGC (negligible) and potential new beam instrumentation.