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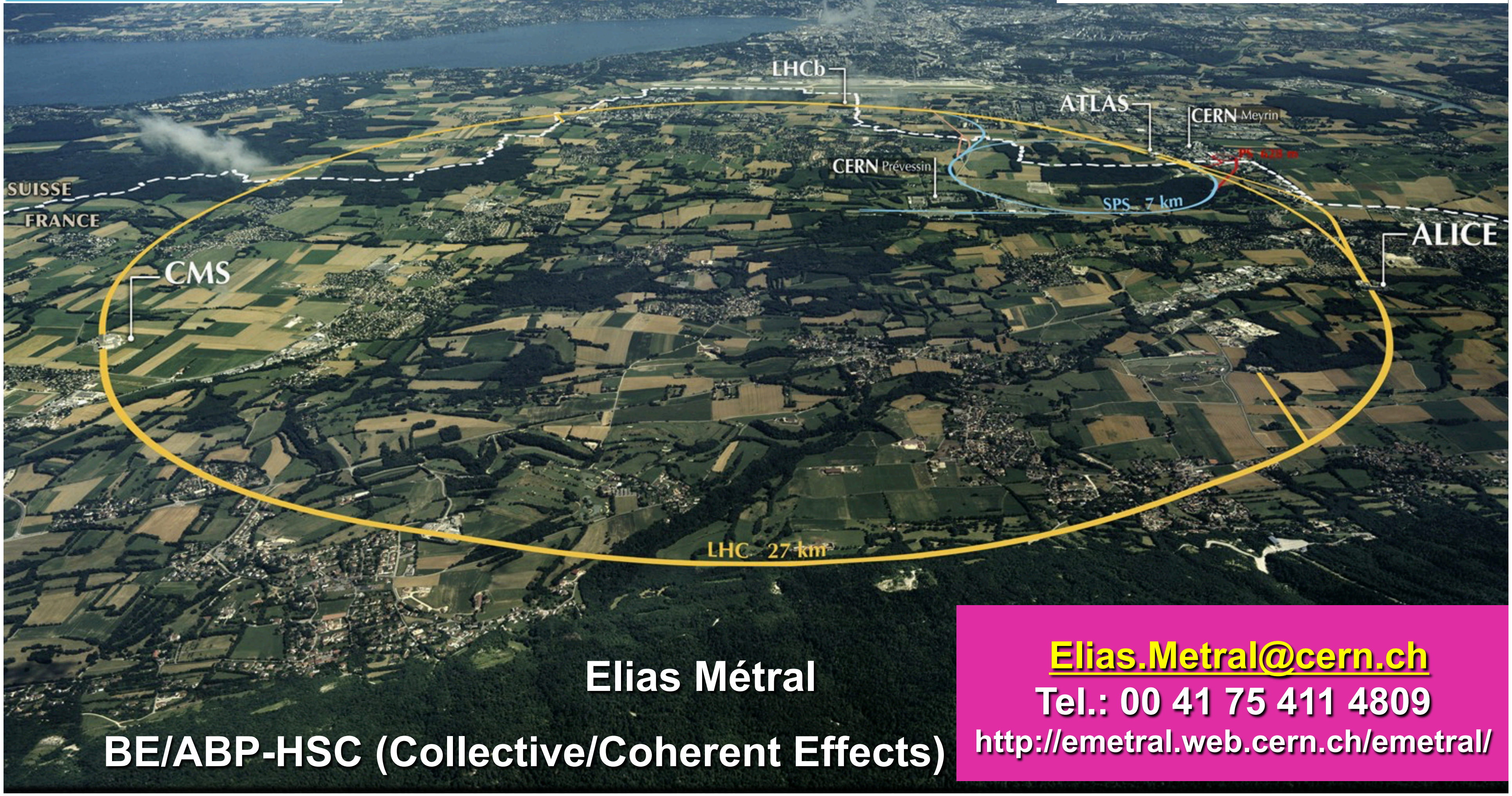

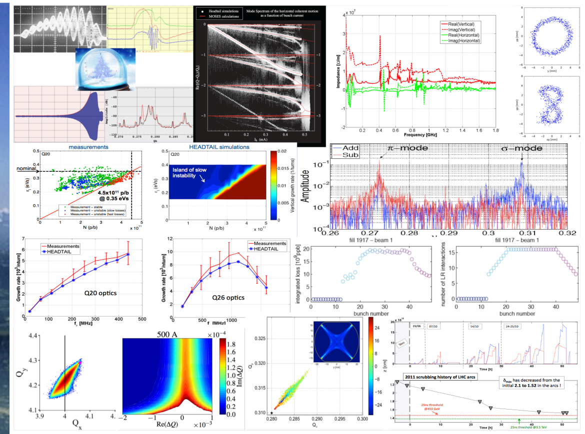

Elias Métral

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Tel.: 00 41 75 411 4809
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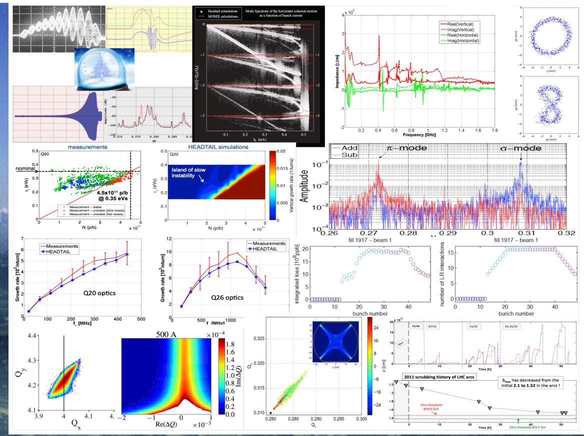

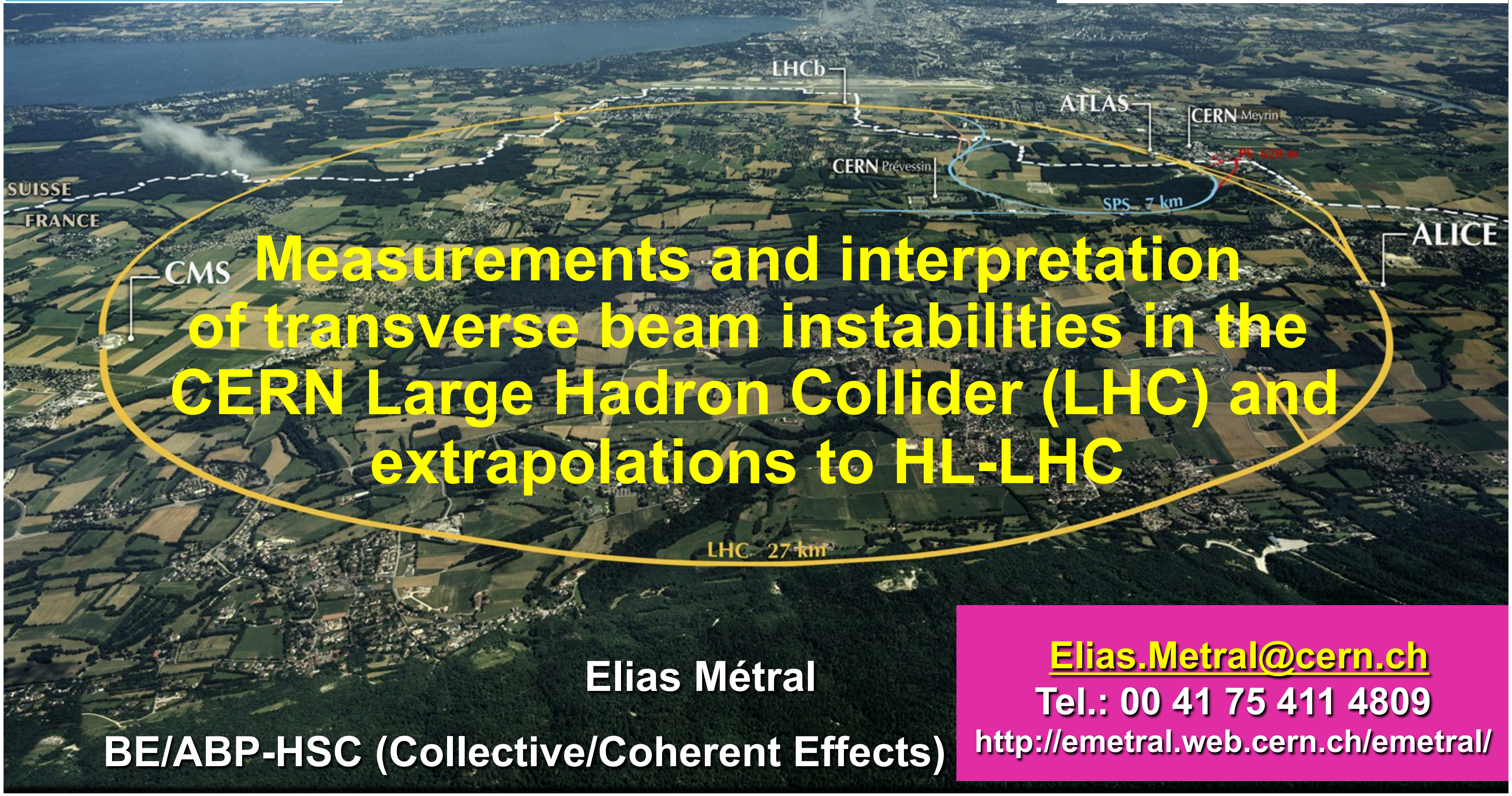

Measurements and interpretation of transverse beam instabilities in the CERN Large Hadron Collider (LHC) and extrapolations to HL-LHC

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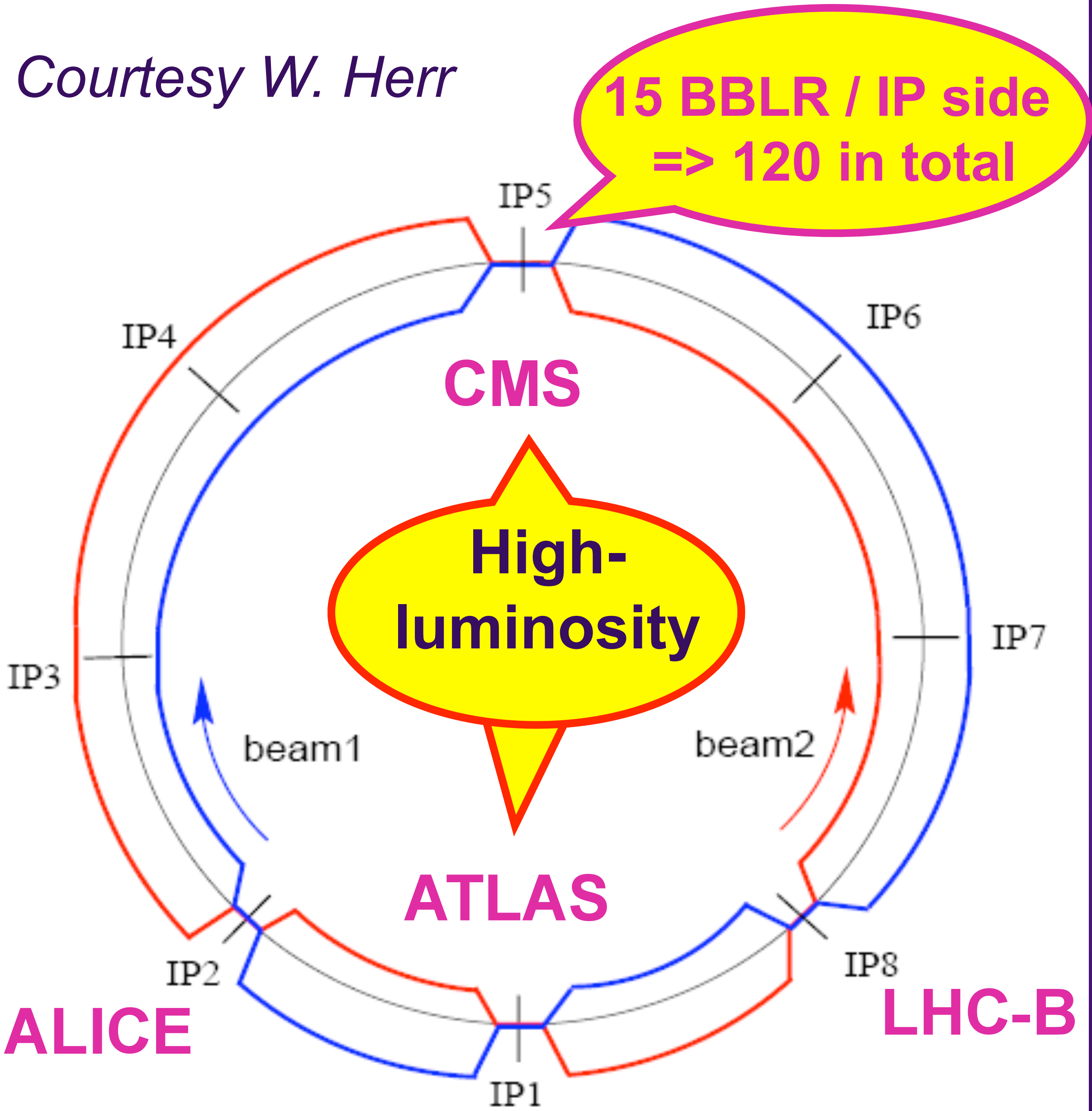
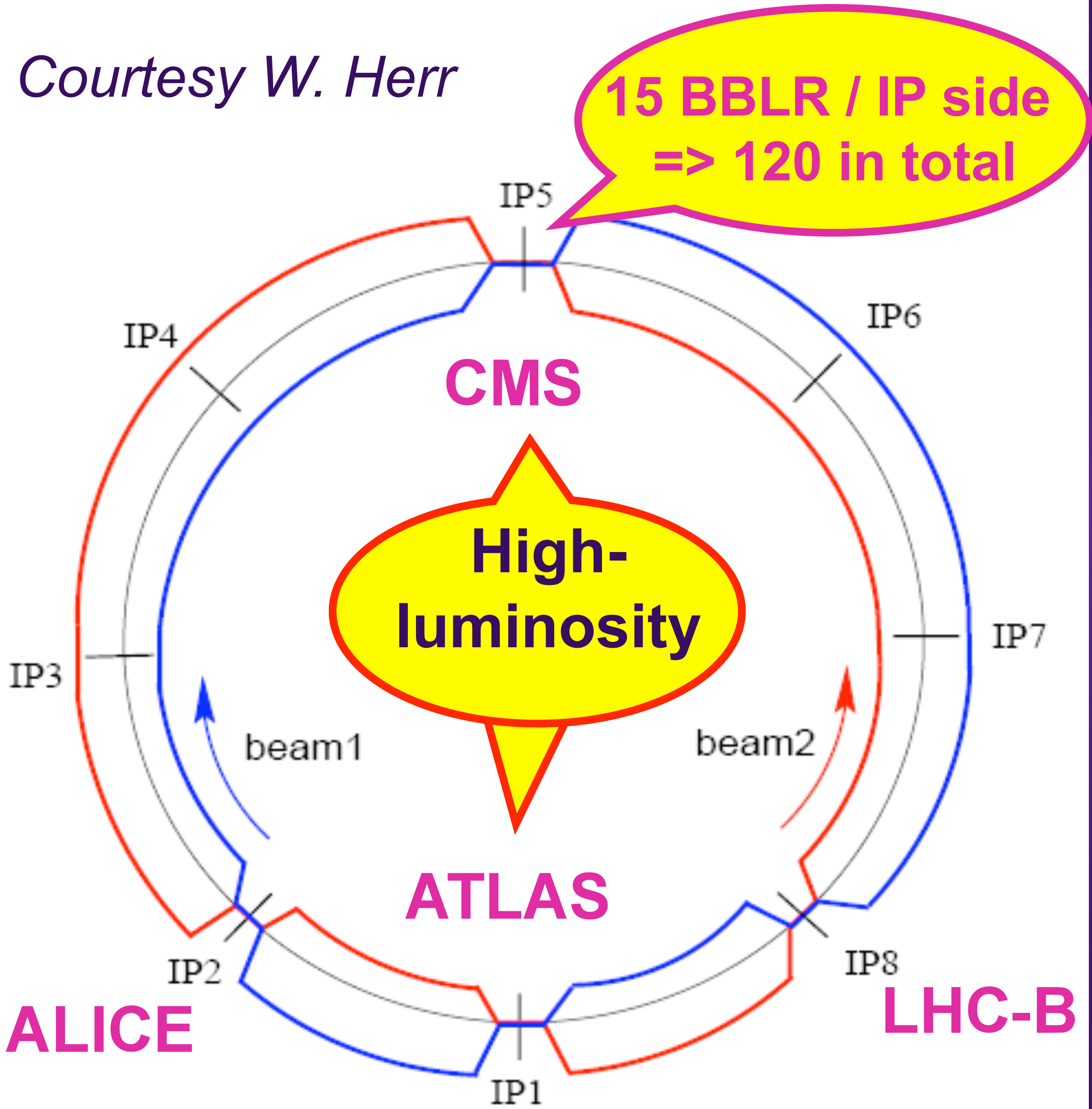
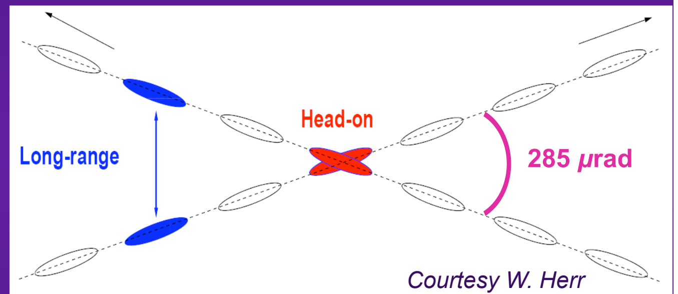
LHC

Courtesy W. Herr



LHC


Courtesy W. Herr
15 BBLR / IP side
=> 120 in total
IP5
IP4
IP6
CMS
High-
luminosity
IP3
IP7
beam1
beam2
ATLAS
IP2
IP8
ALICE
LHC-B
IP1


Head-on
Long-range
285 μrad
Courtesy W. Herr

CONTENTS

CONTENTS

- **Introduction**

CONTENTS

- Introduction
- Observations, actions taken and lessons learned

CONTENTS

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- Observations, actions taken and lessons learned
  - Run 1 (2010-2012)

CONTENTS

- Introduction
- Observations, actions taken and lessons learned
  - Run 1 (2010-2012)
  - 2015

CONTENTS

- Introduction
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  - Run 1 (2010-2012)
  - 2015
  - 2016

CONTENTS

- Introduction
- Observations, actions taken and lessons learned
  - Run 1 (2010-2012)
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- Future: LHC and HL-LHC

CONTENTS

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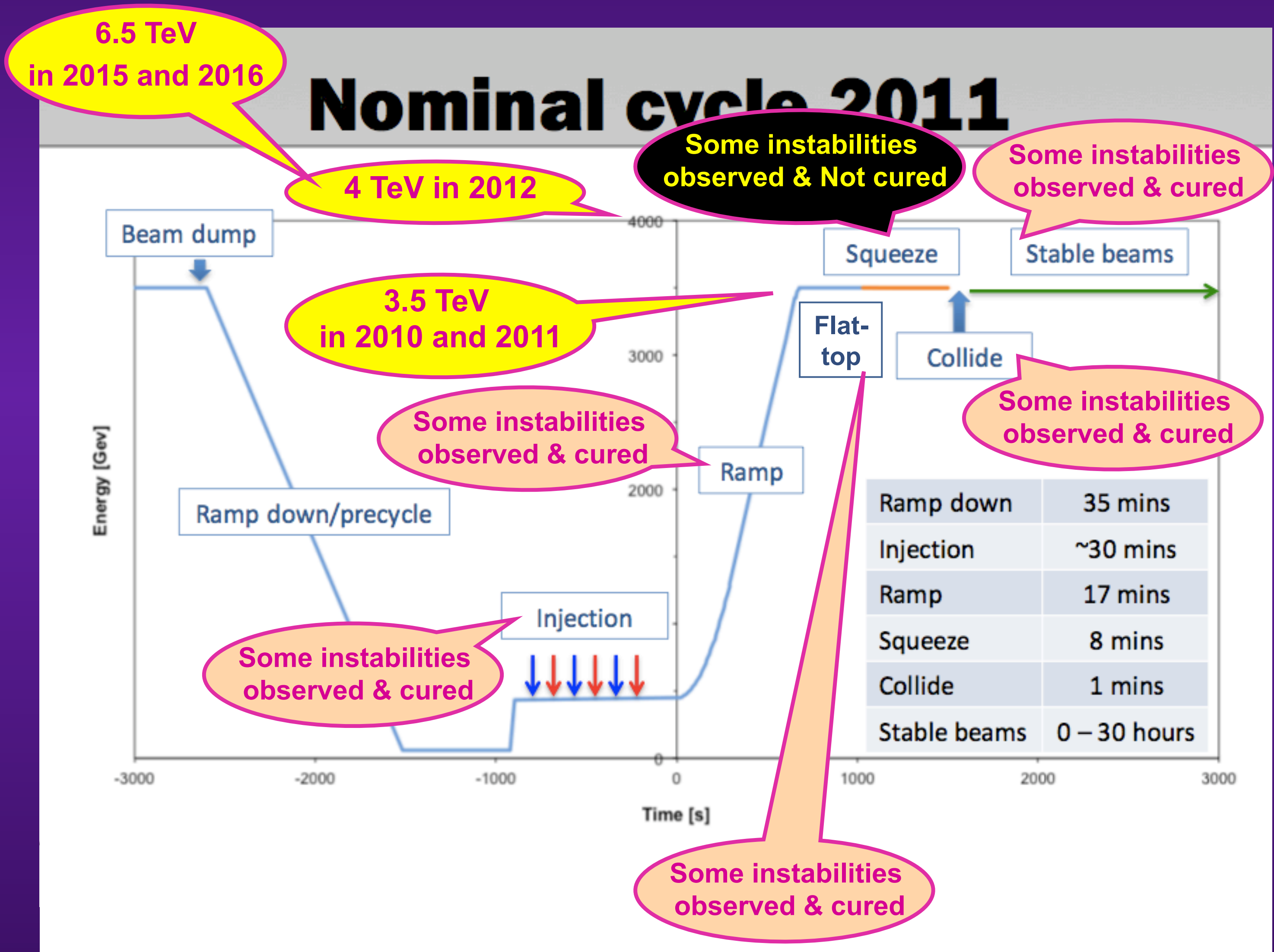

RUN 1 (2010-2012)

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  - **Instability at ~ 2 TeV for both beams**
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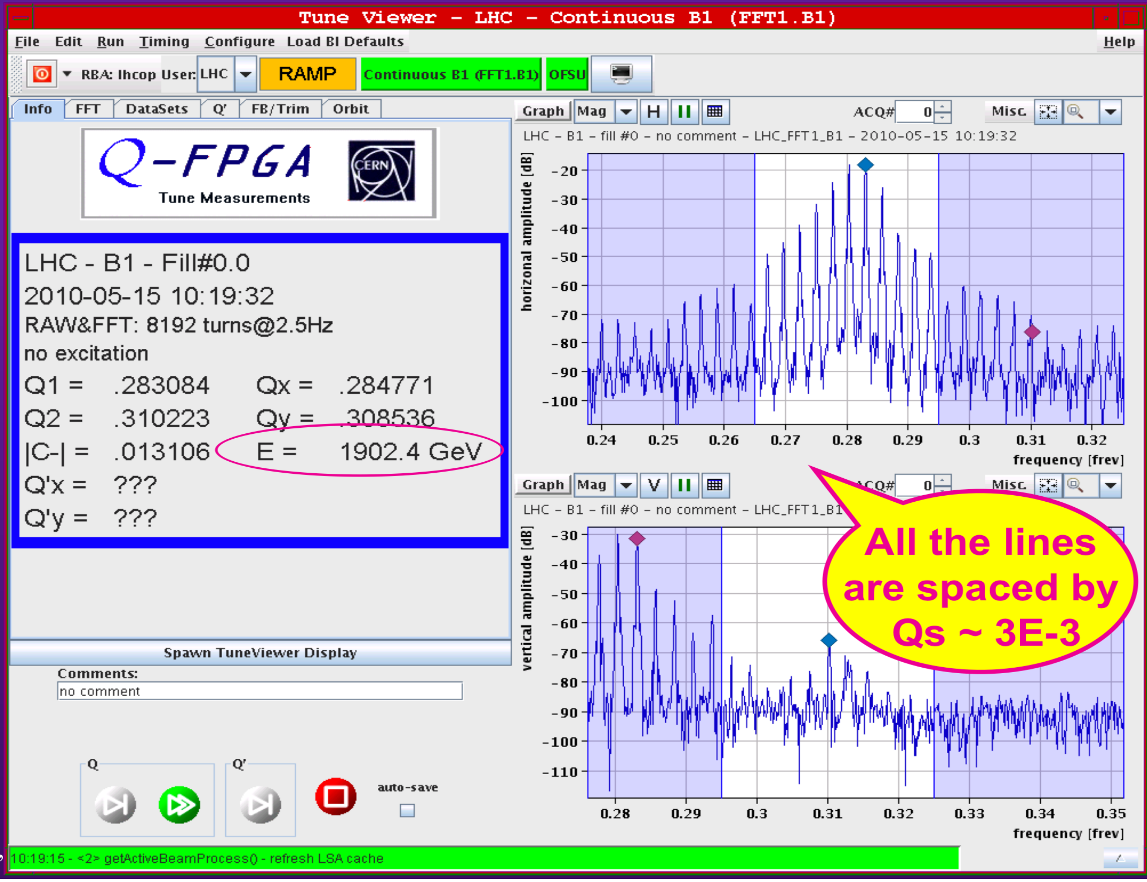

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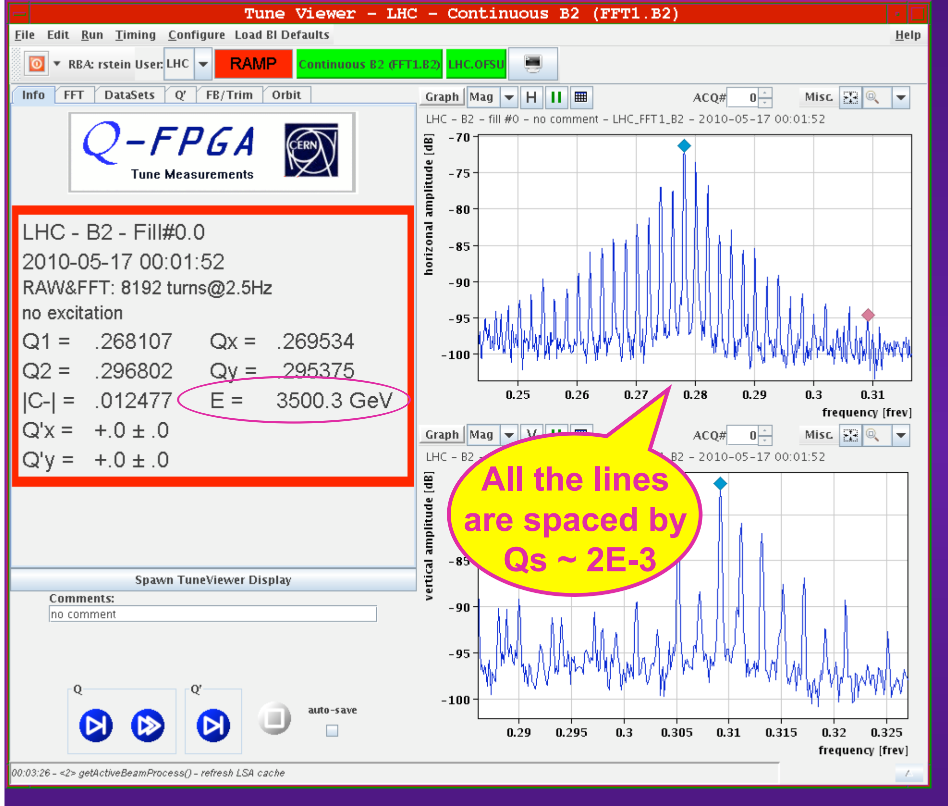

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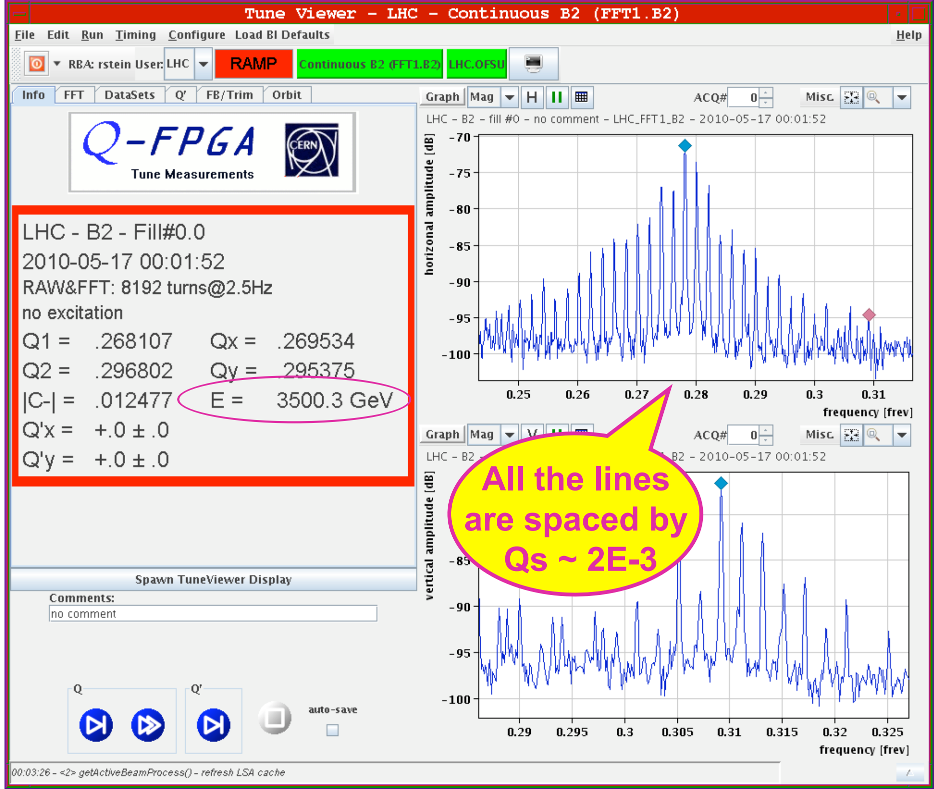

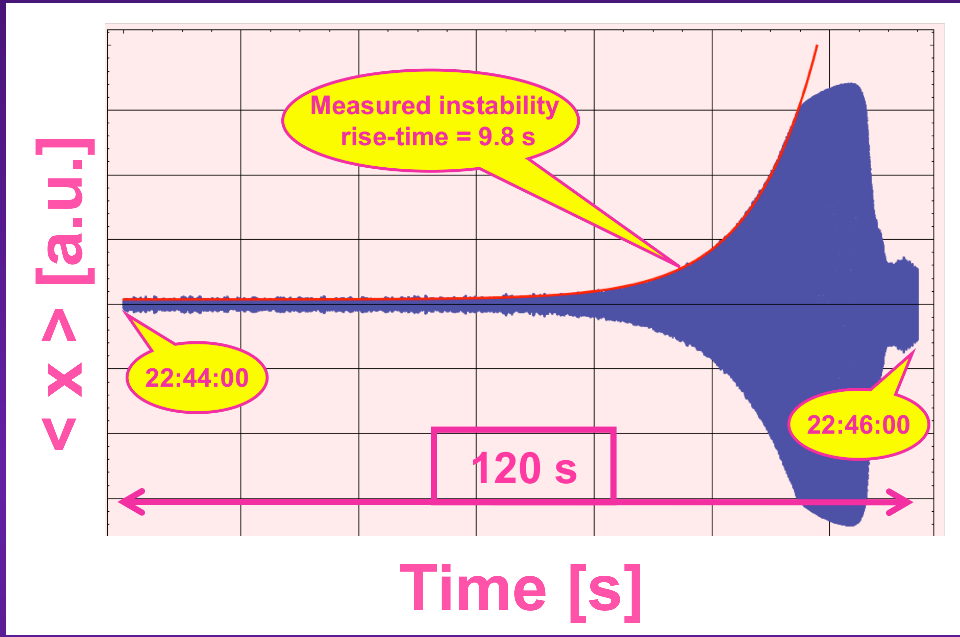

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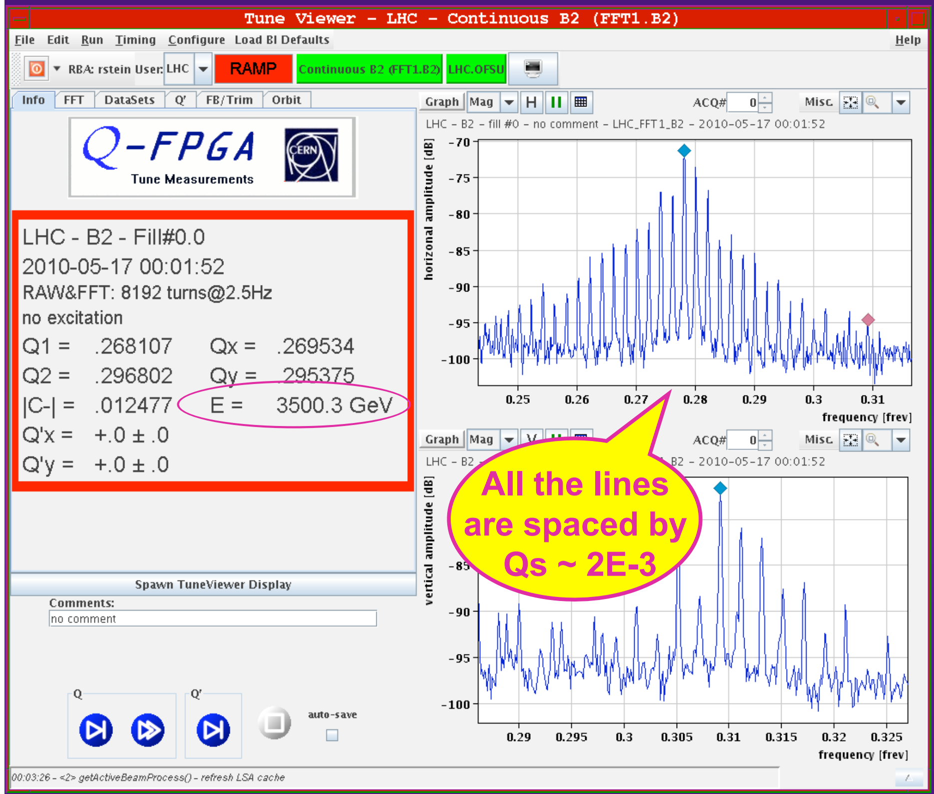

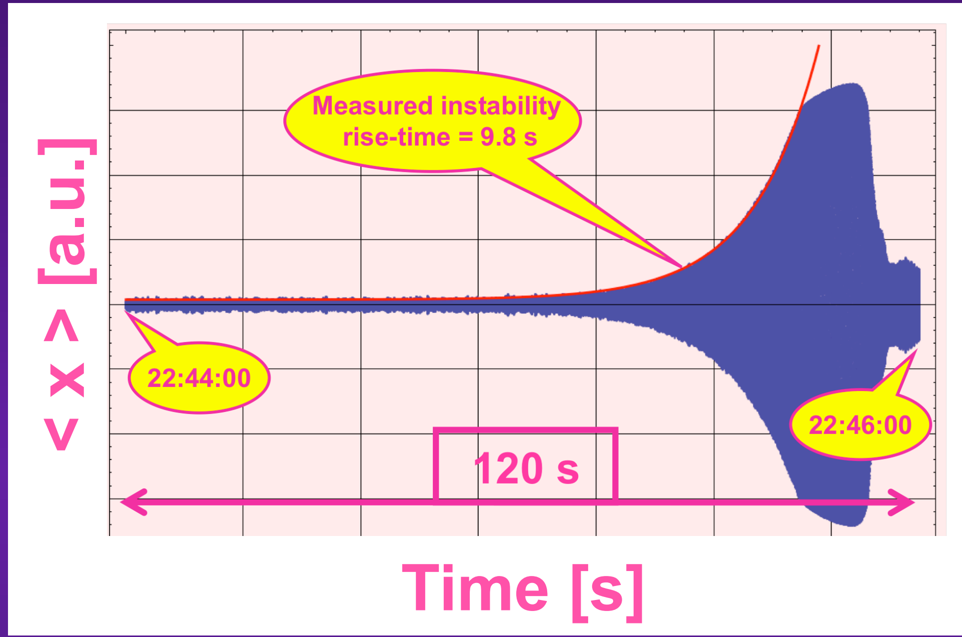

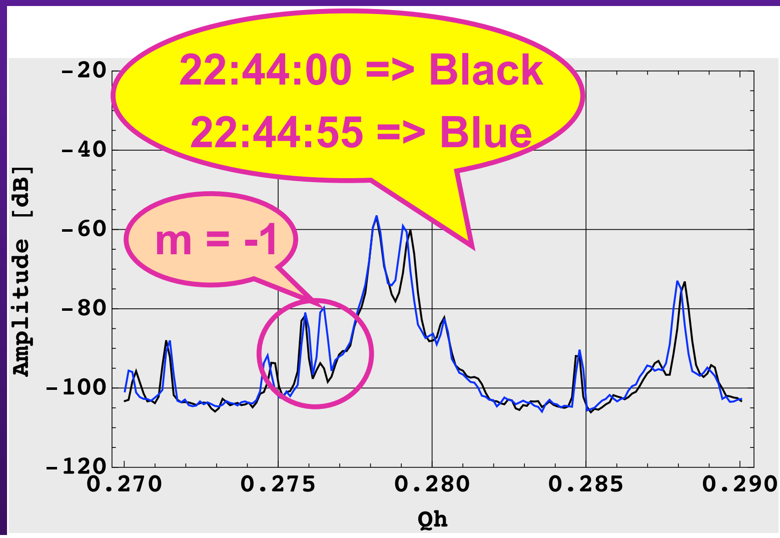

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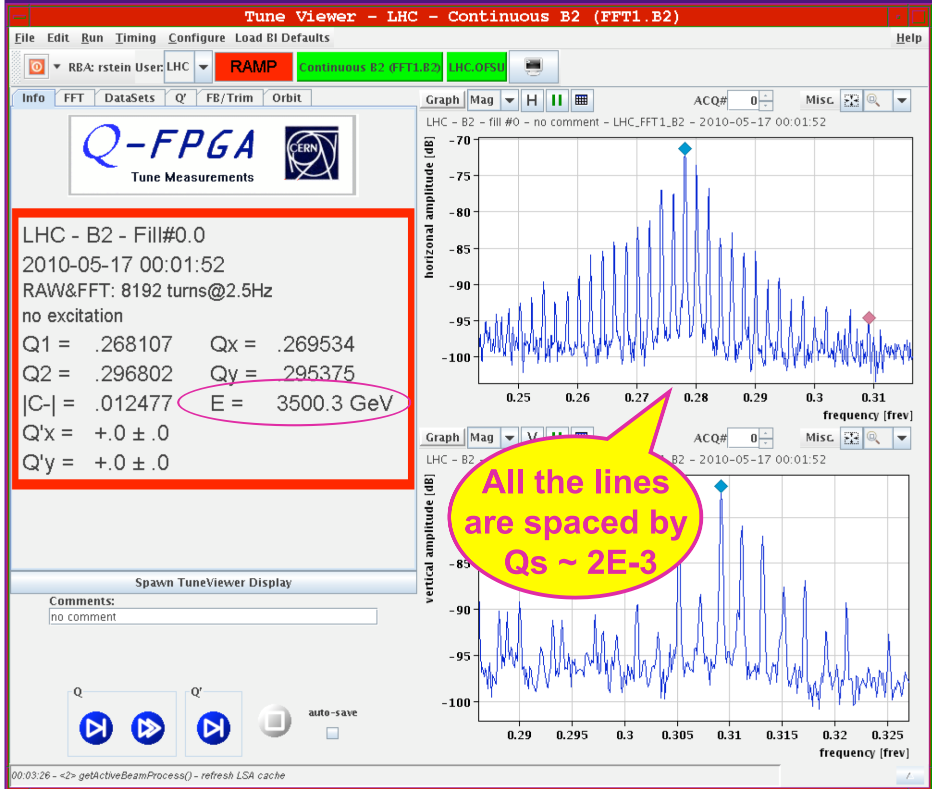
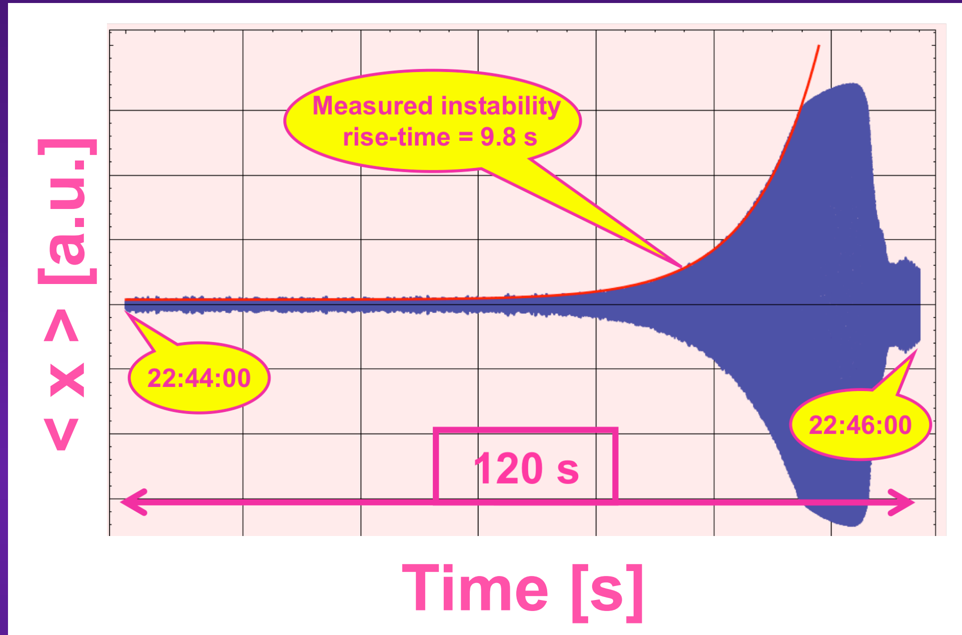
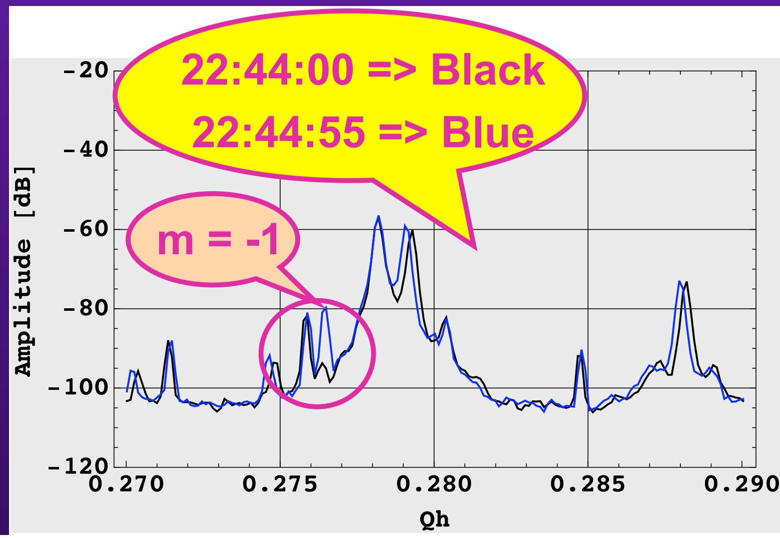




- Rise-time and Landau octupole current for stability (between -20 and -10 A) within factor ~ 2 with predictions



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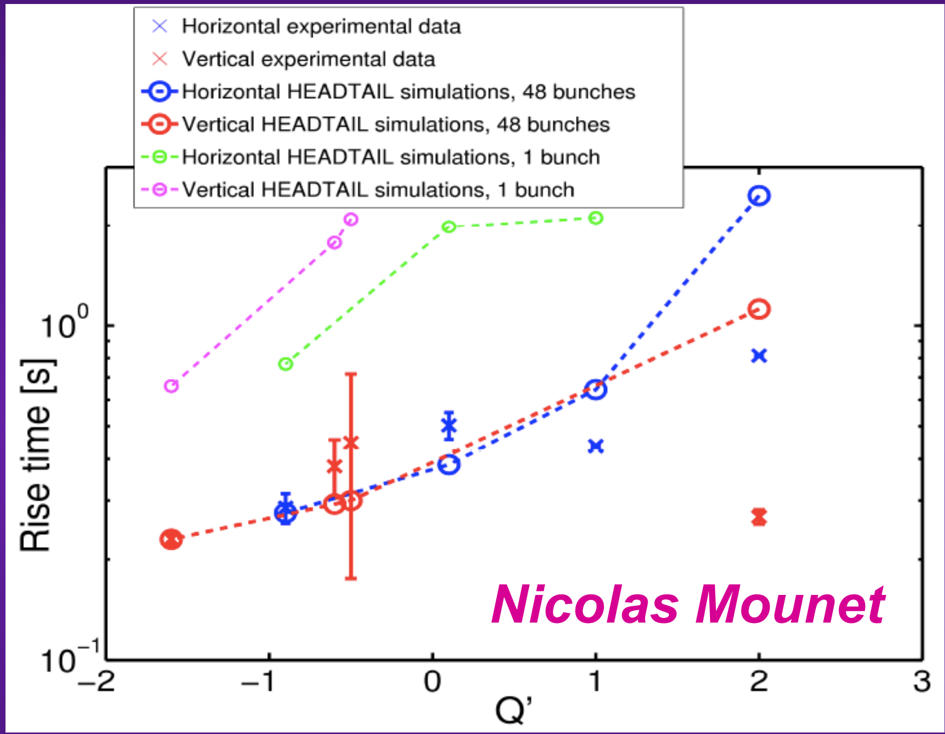

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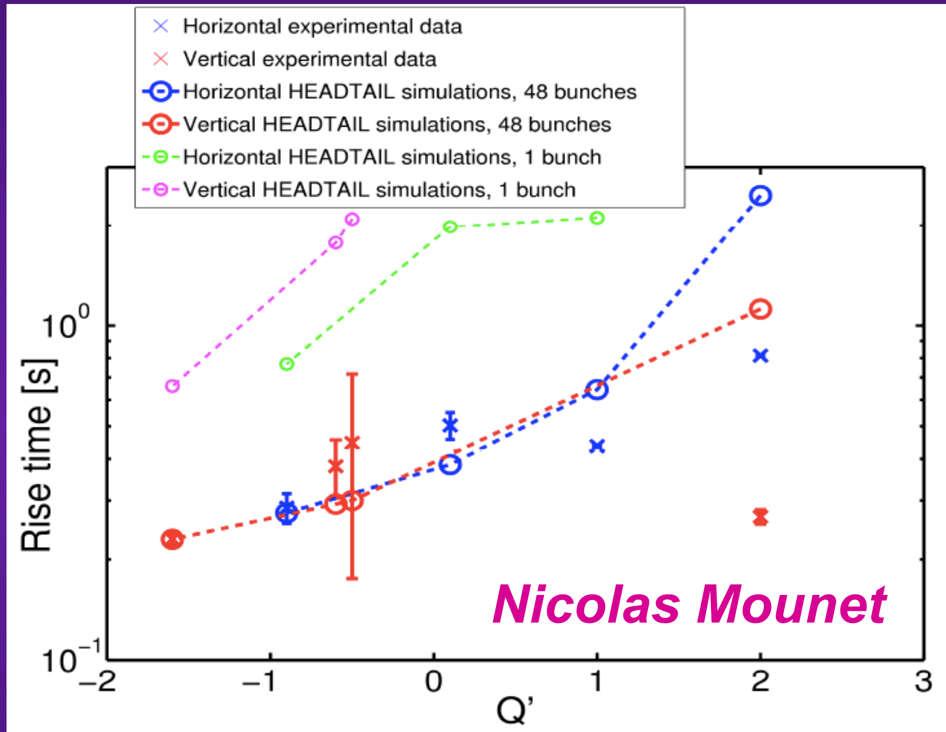

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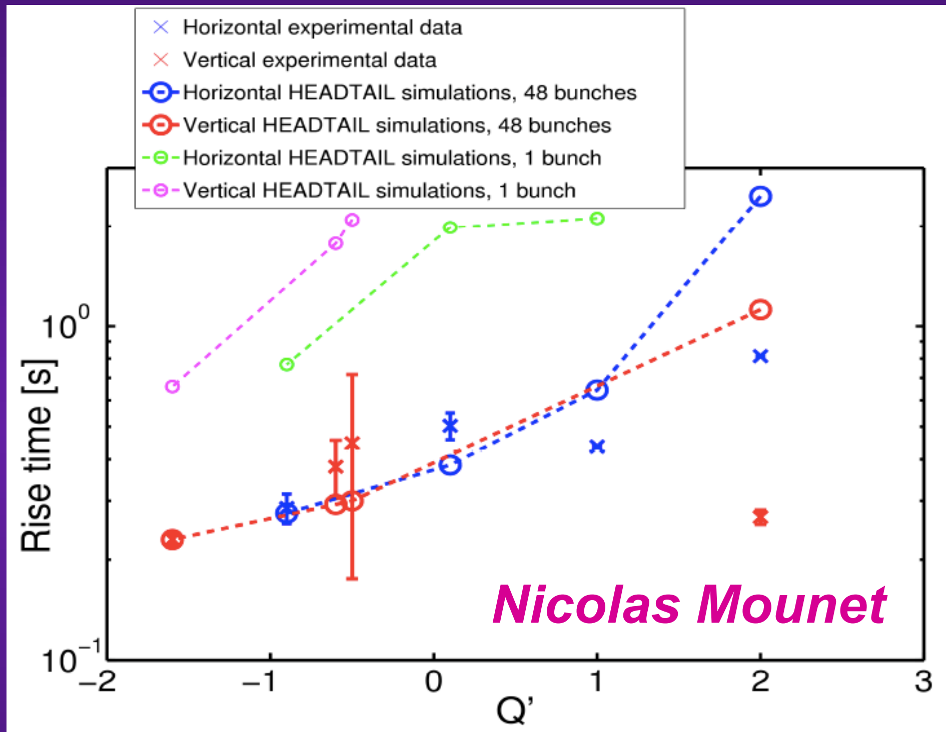

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  - **Landau octupole current for stability at 3.5 TeV within factor ~ 2 with predictions (even less than predicted)**

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=> Everything started very well (~ as predicted)!

- …Things started to become more involved when we tried to push the performance of the LHC in 2011, and in particular in 2012 (year of discovery of the "Higgs-like" boson)…

RUN 1 (2010-2012)

Beam energy	E	7 TeV (4 in 2012)
Number of particles per bunch	N_b	1.15 10^{11} (~ 1.6 in 2012)
Number of bunches per beam	M	2808 (1380 in 2012)
Bunch spacing	Δt	25 ns (50 in 2012)
Norm. rms. trans. emittance	ε	3.75 μm (~ 2.2 in 2012)
Revolution frequency	f_0	11245 Hz
Rms bunch length	σ_z	7.5 cm (~ 10 in 2012)
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Total beam current	I_b	0.58 A (~ 0.4 in 2012)

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=> Record peak luminosity: 0.77 × 10^{34} cm^{-2}s^{-1}

RUN 1 (2010-2012)

=> 3 types (in fact 2 after careful analysis) of instabilities were observed

RUN 1 (2010-2012)

- 1) In collision: “snowflakes”

RUN 1 (2010-2012)

Courtesy of X. Buffat

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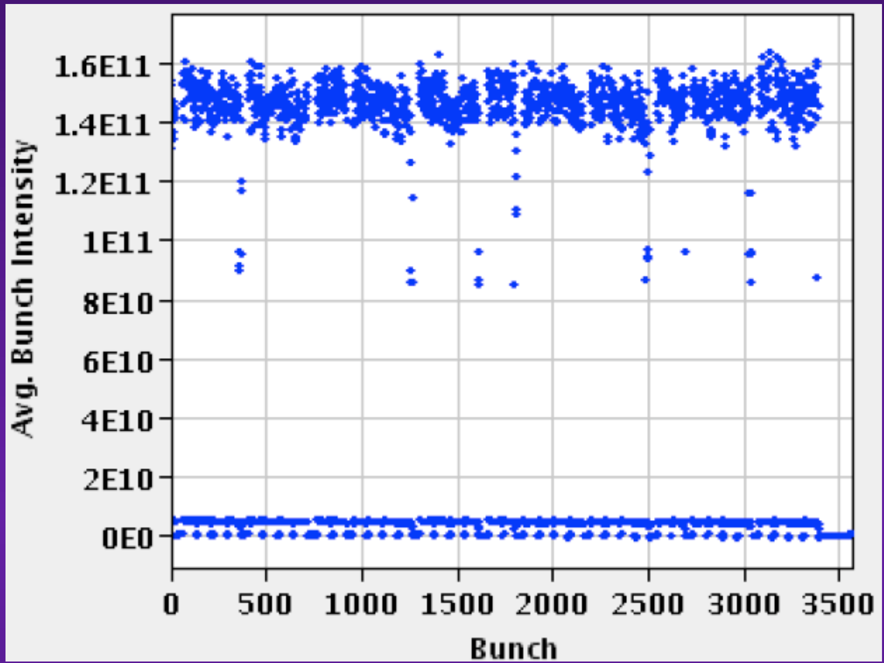

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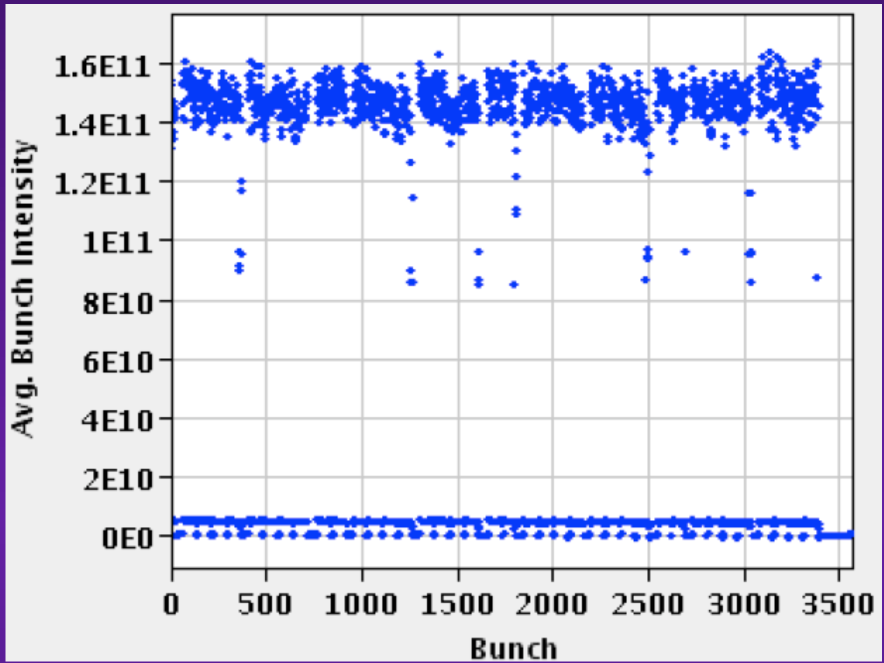

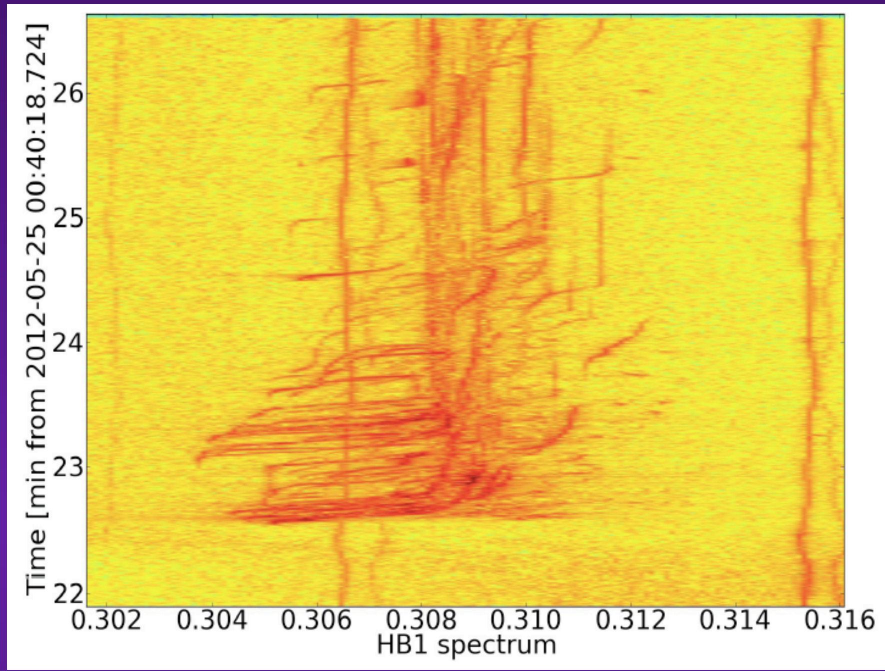

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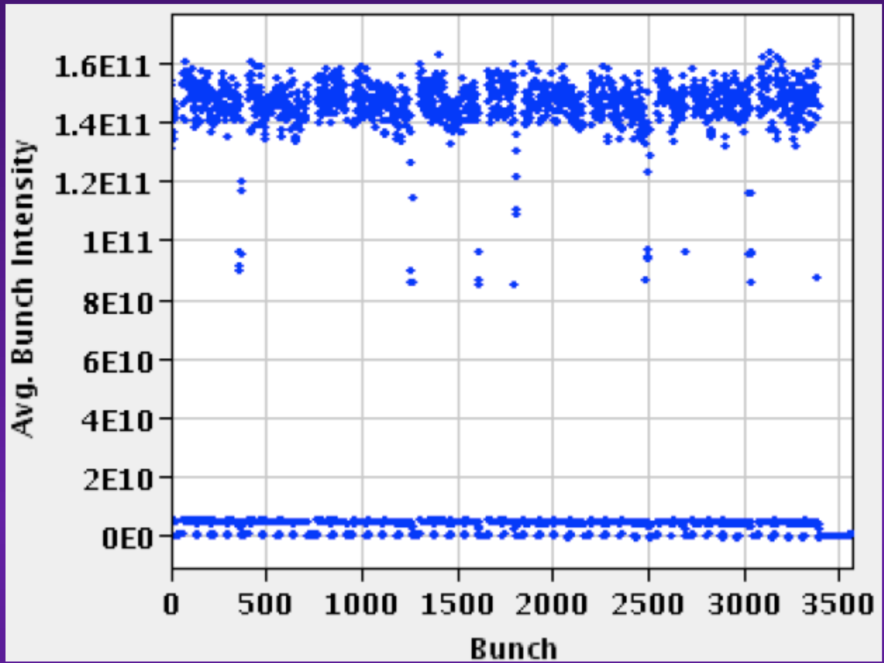

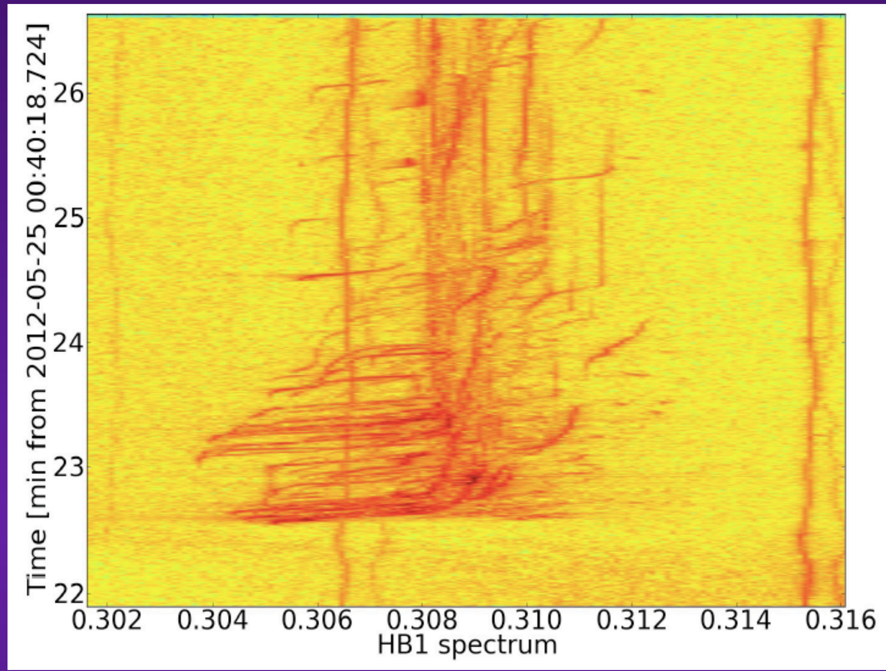

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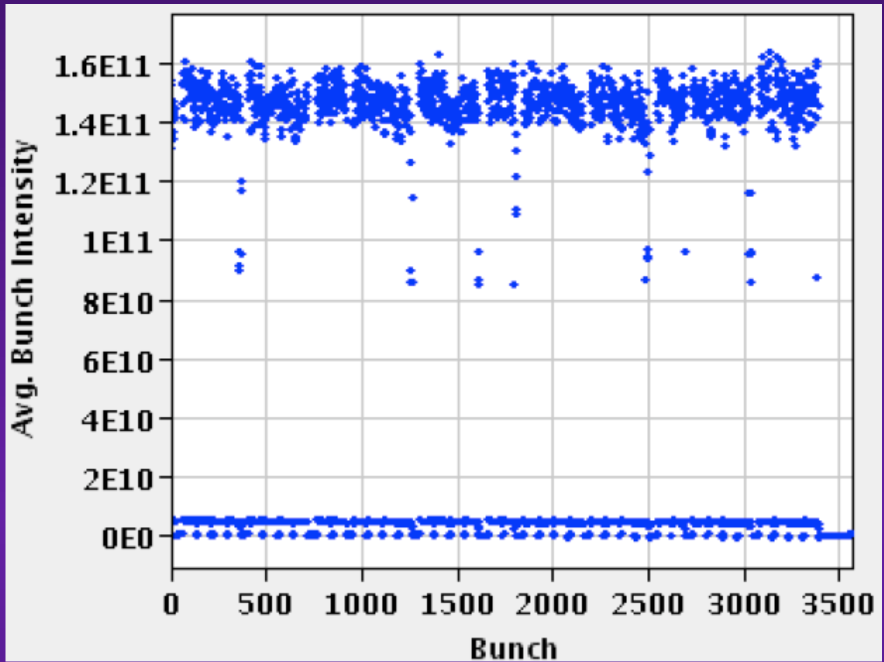

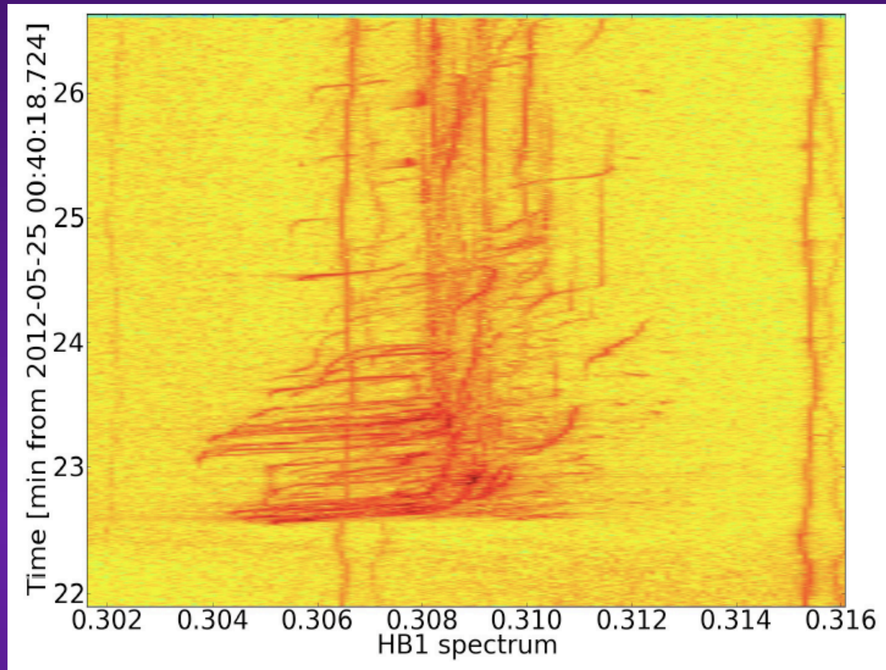

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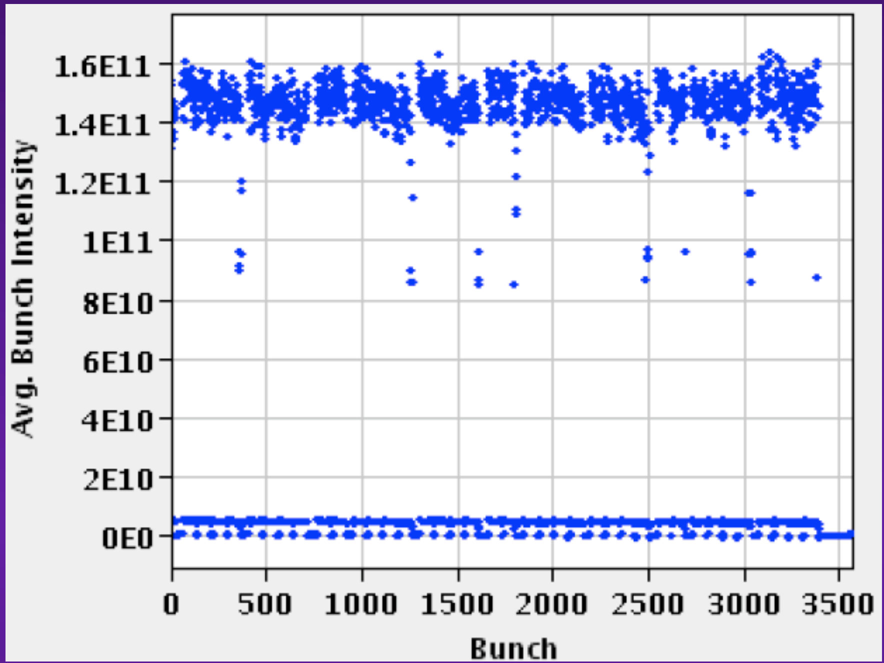

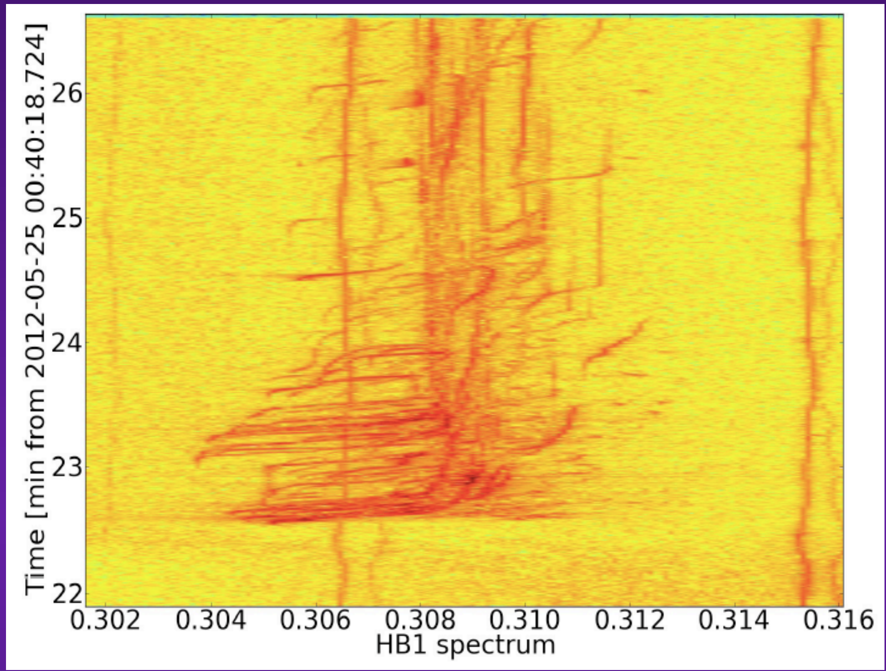

- **Always in H only (both beams)**
- **Concerned initially only IP8 private bunches => Disappeared when filling scheme was changed**
- **Happens on selected bunches with insufficient tune spread (and thus Landau damping) due to no BBHO collisions (or offsets)**

RUN 1 (2010-2012)

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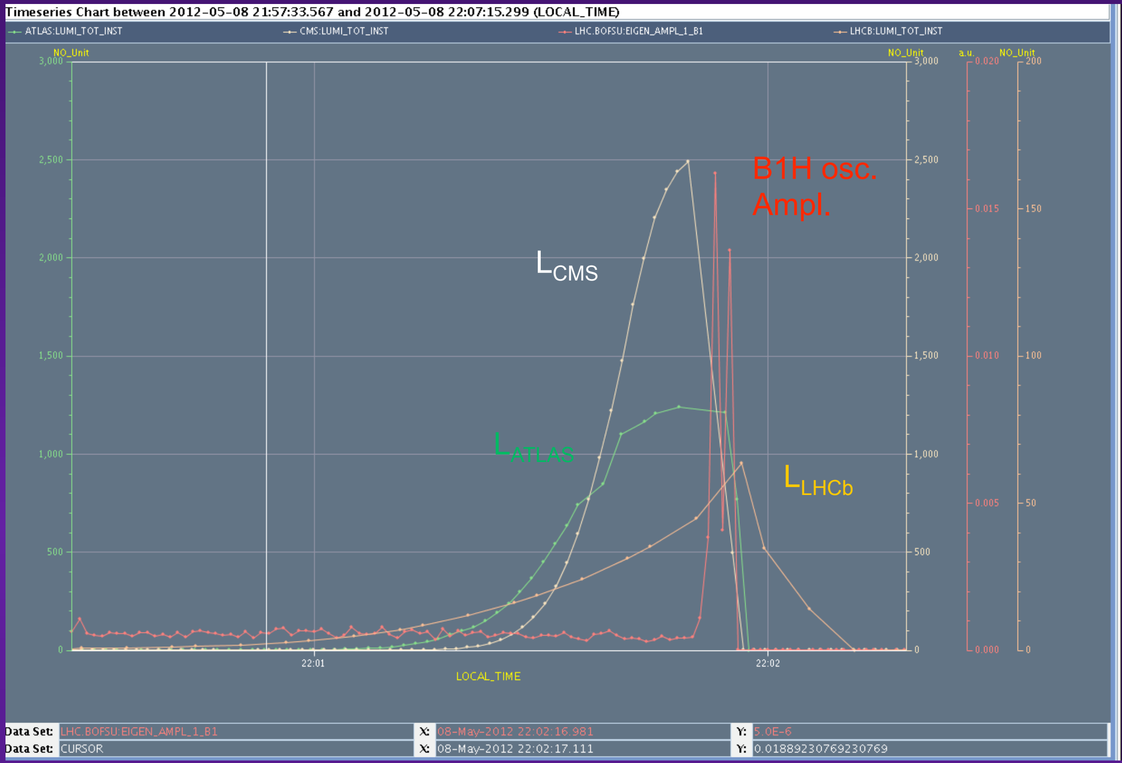

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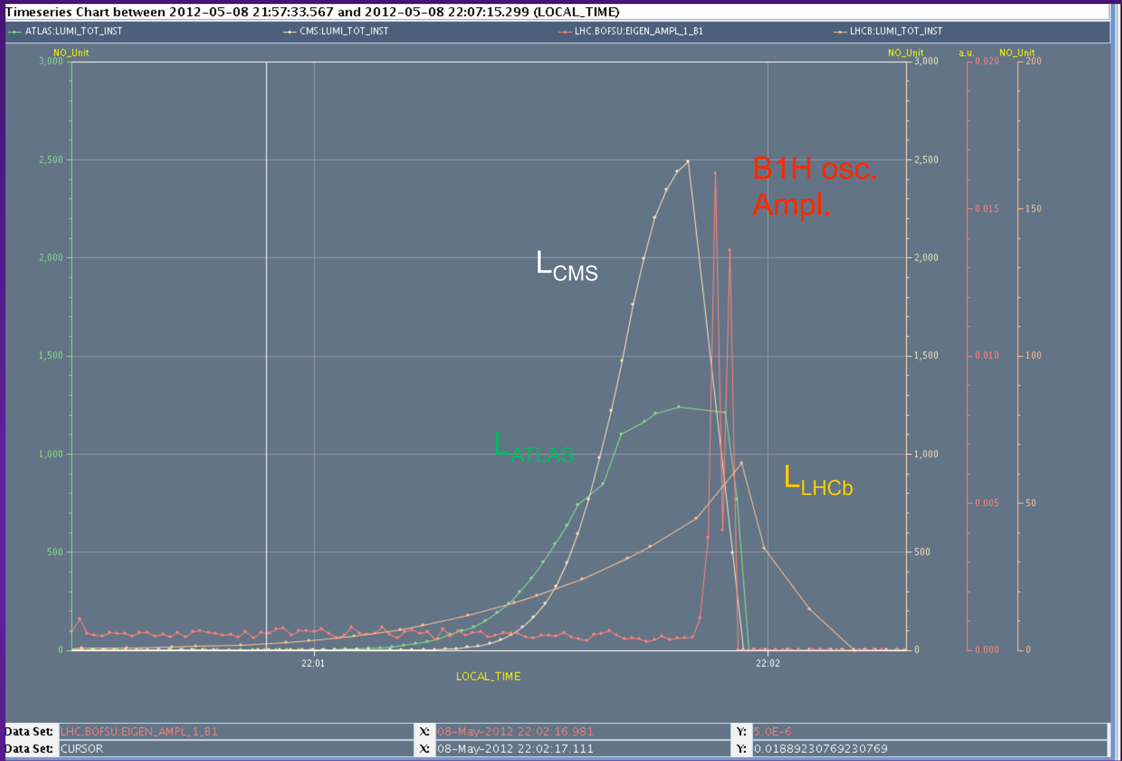

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- Example of instability at ~ 2.1 σ in IP1 and ~ 1.2 σ in IP5 (estimated from luminosities at the moment of the dump)

RUN 1 (2010-2012)

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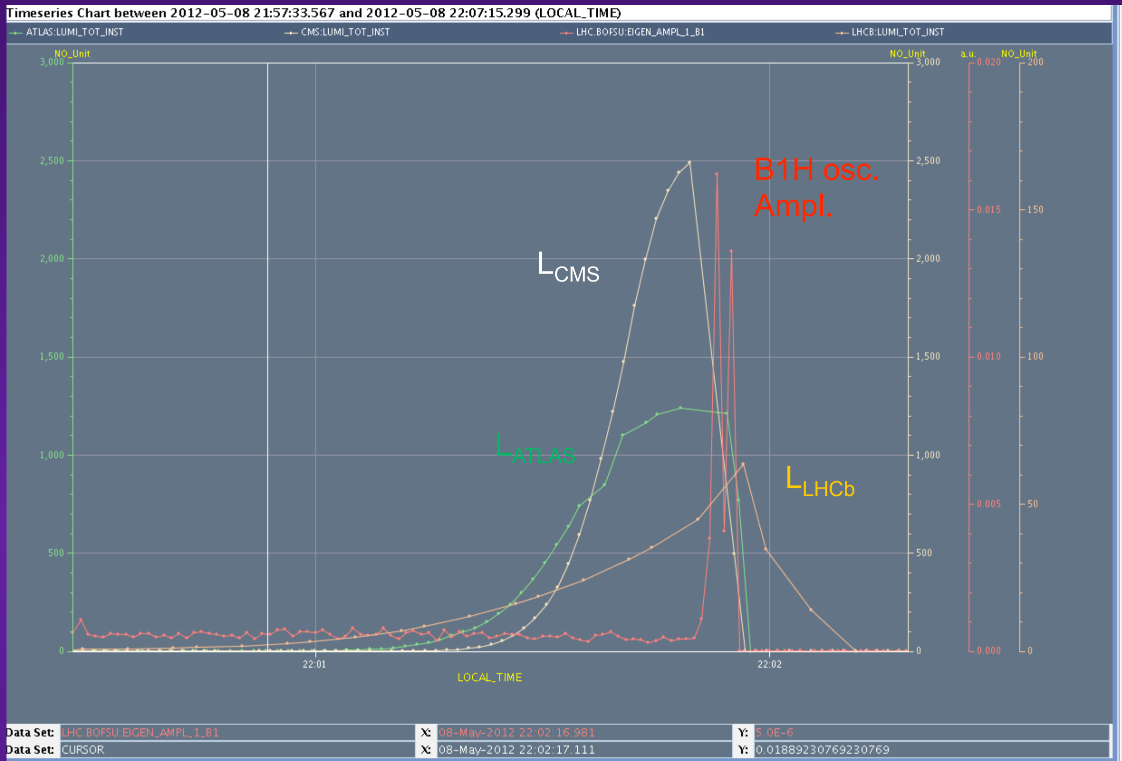

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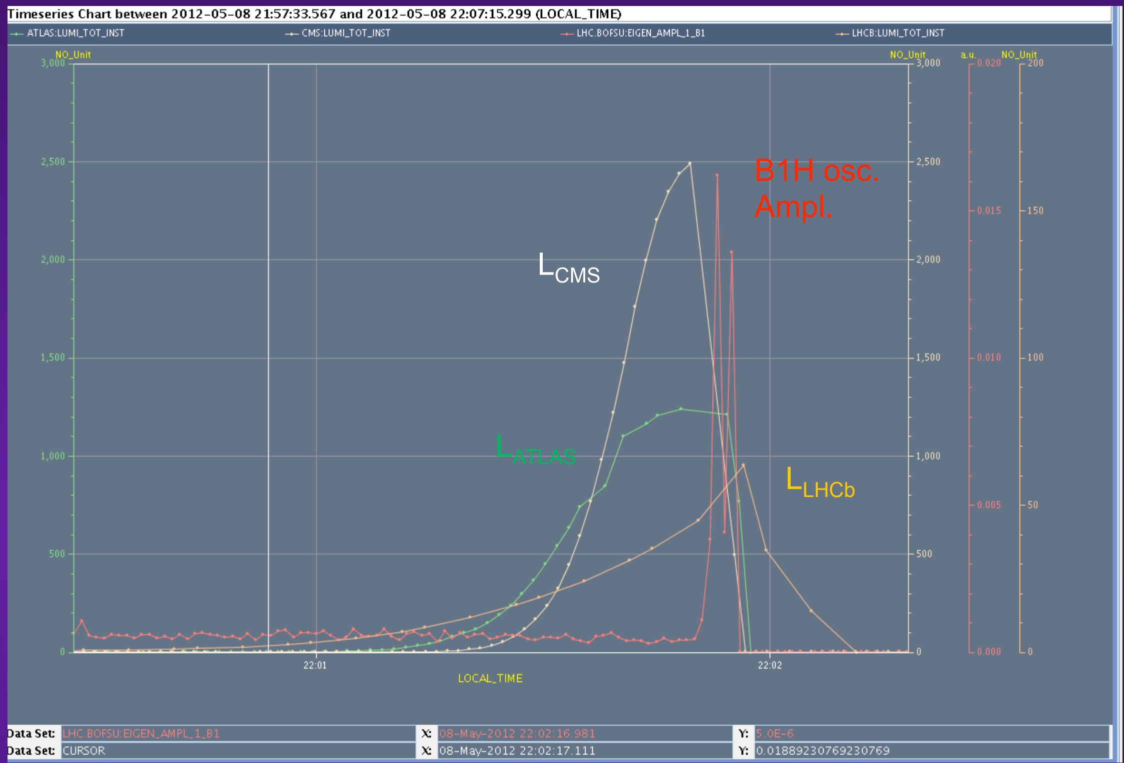

Courtesy of G. Arduini

- **Example of instability at ~ 2.1 σ in IP1 and ~ 1.2 σ in IP5 (estimated from luminosities at the moment of the dump)**
- **Also in H**
- **Happened only once or twice during the intensity ramp-up => Was never observed later in operational conditions**

RUN 1 (2010-2012)

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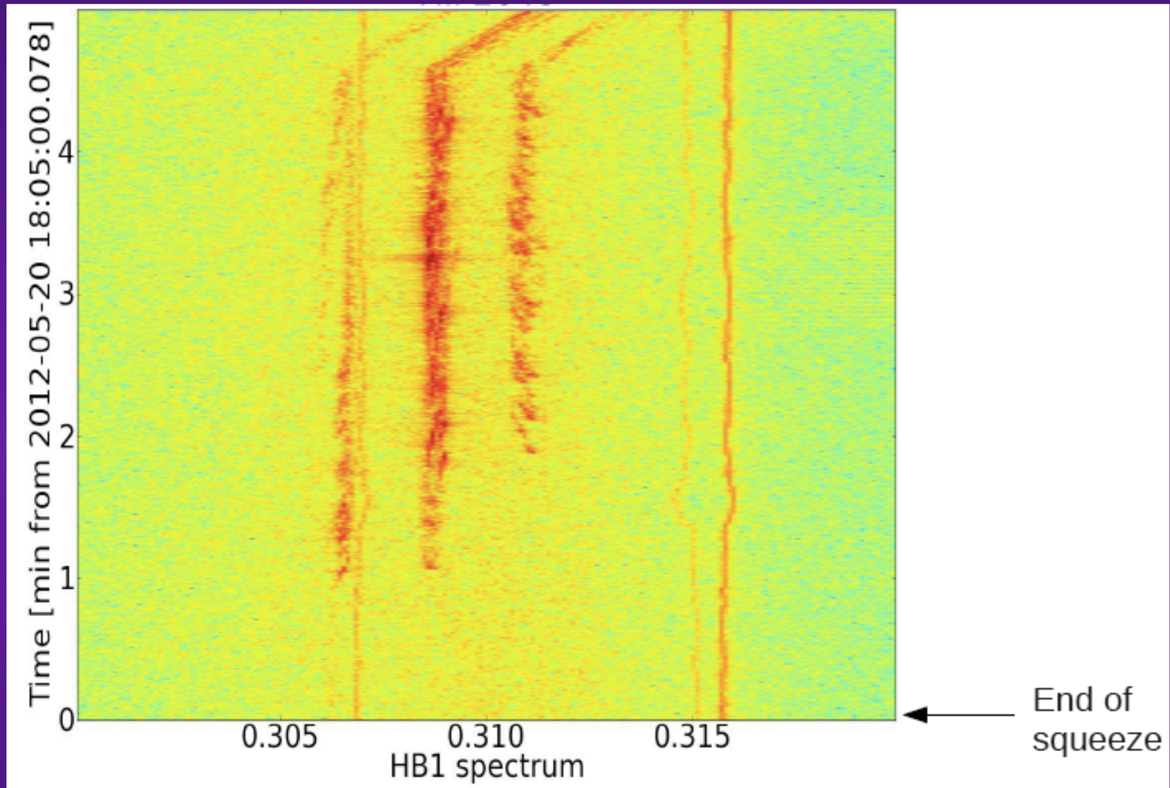

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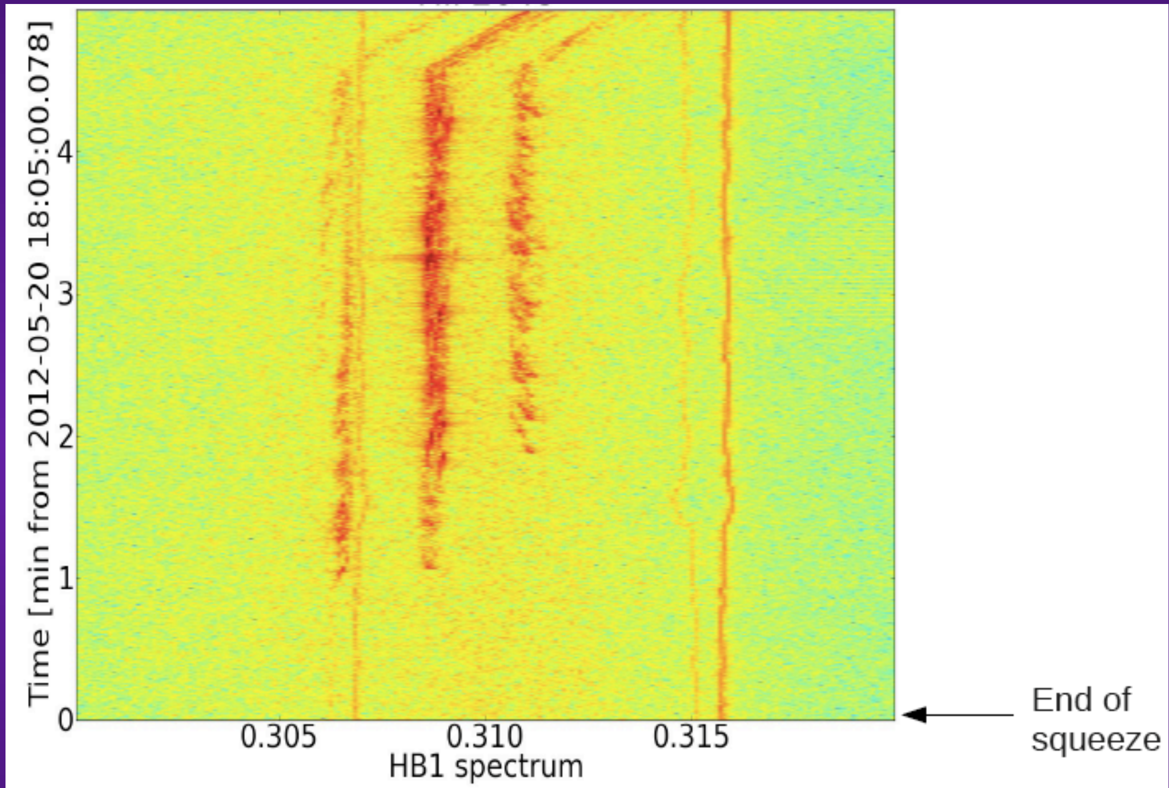

Courtesy of X. Buffat

- **Also in H**

RUN 1 (2010-2012)

- **Actions taken**

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Focusing octupoles

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  => Finally used high chromaticities (~ 15) + ~ maximum octupole current (max = + 550 A) + ~ maximum damper gain (50-turn damping)…

RUN 1 (2010-2012)

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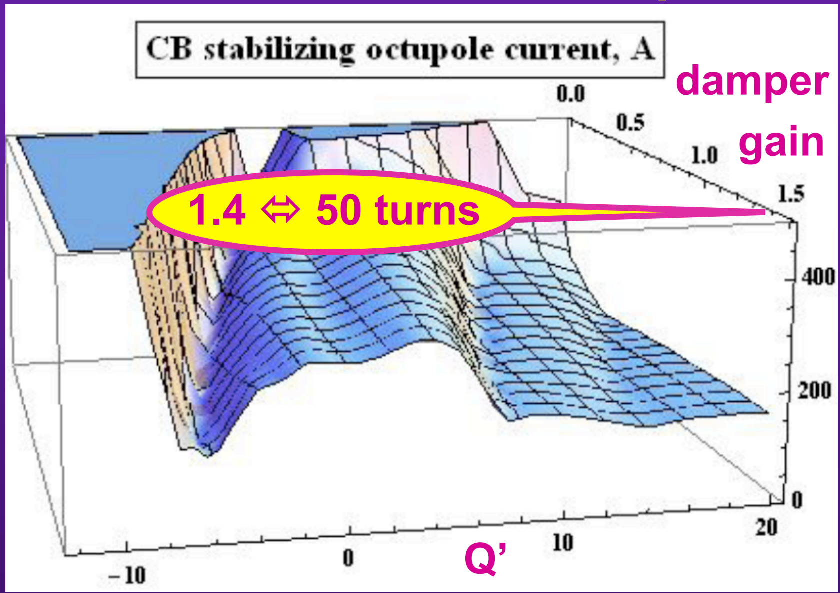
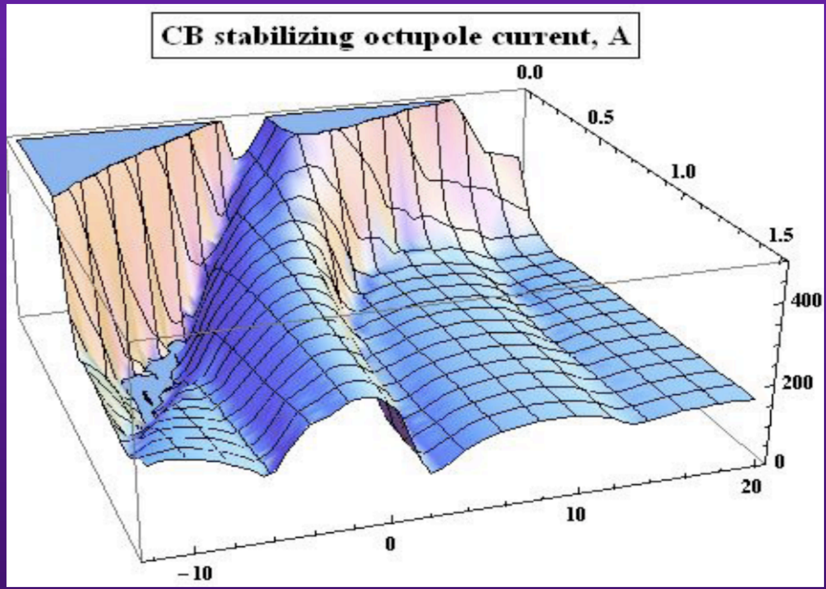
Initial transverse damper



Fully bunch-by-bunch (flat gain)



Courtesy of A. Burov

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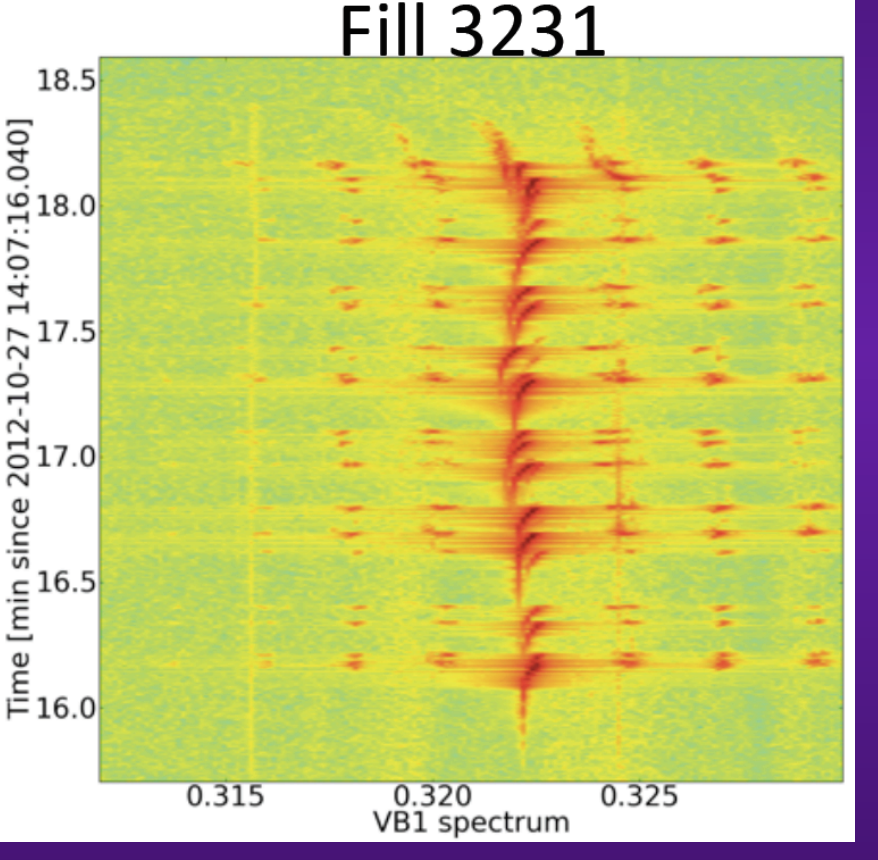

Courtesy of T. Pieloni

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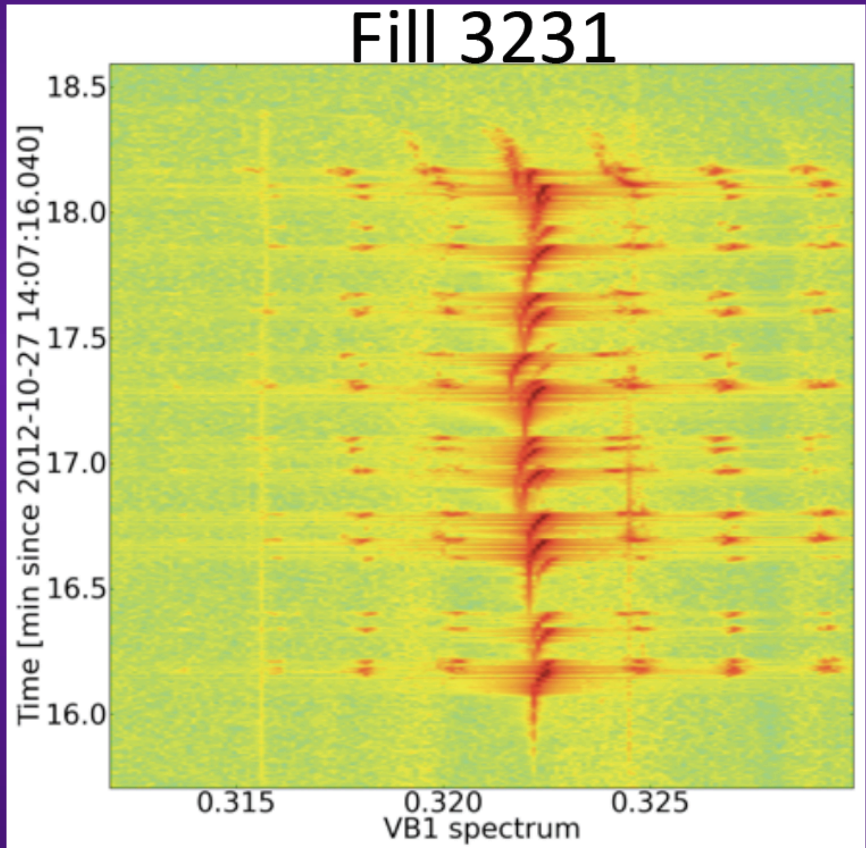

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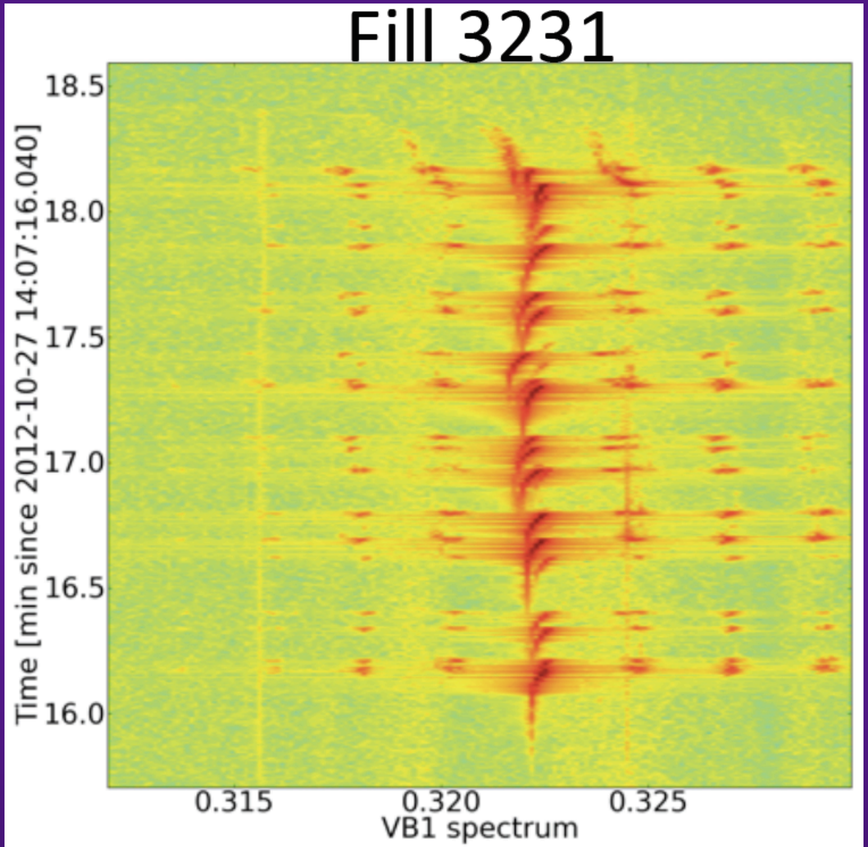

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=> Still potential worry for the future

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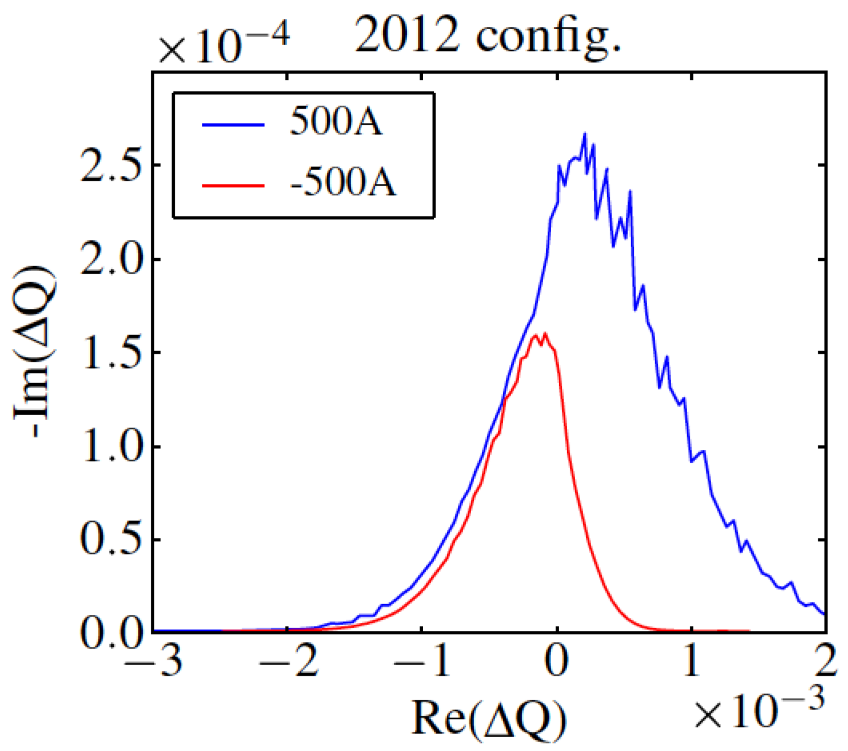

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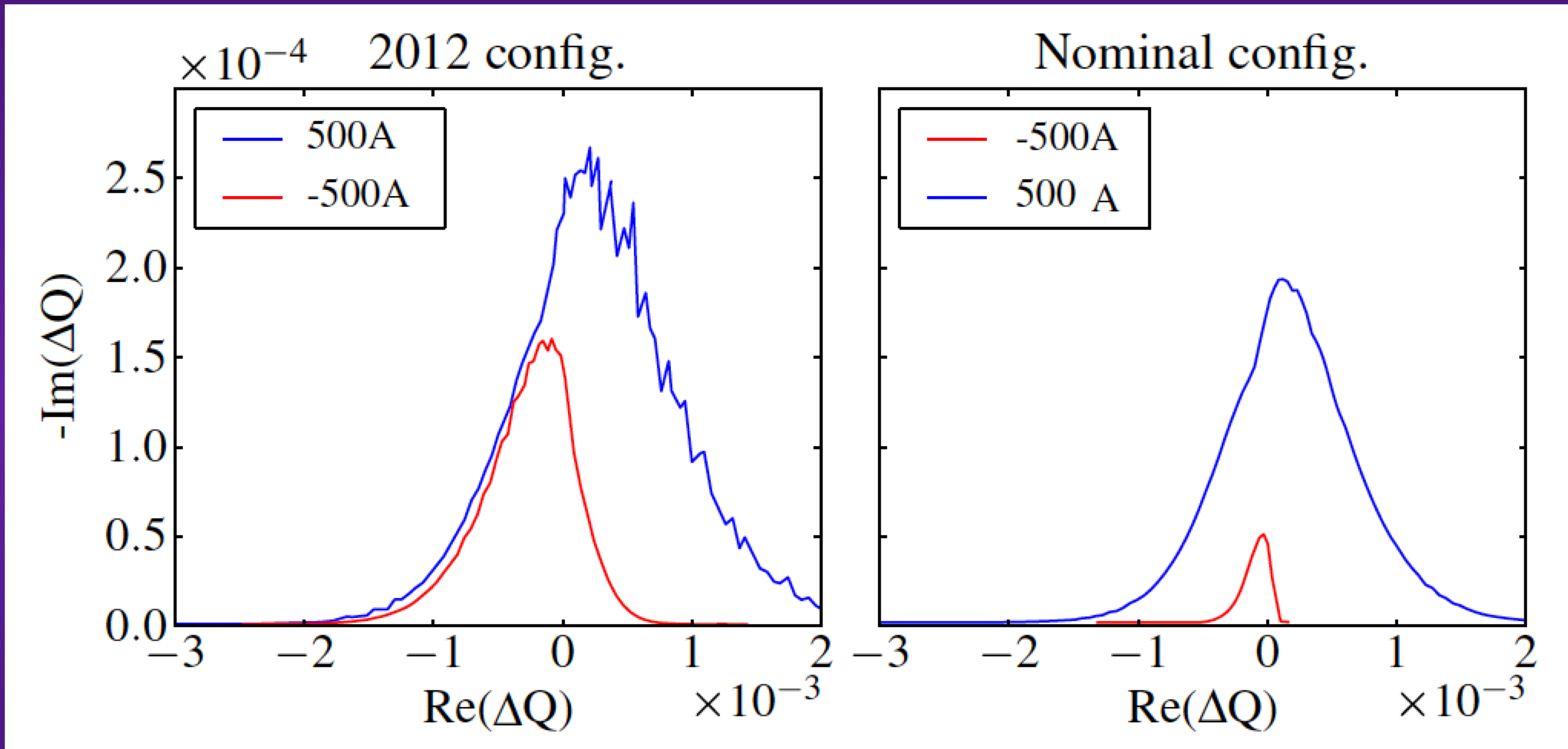

  - However, a positive sign is predicted to be much better for the case of the Nominal configurations => This is why the positive sign of the octupoles is used during Run 2

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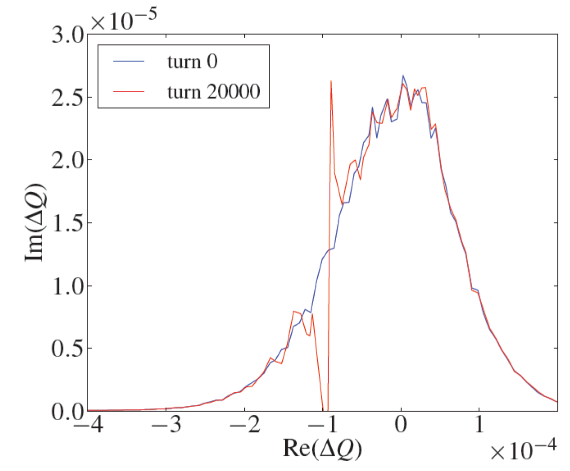

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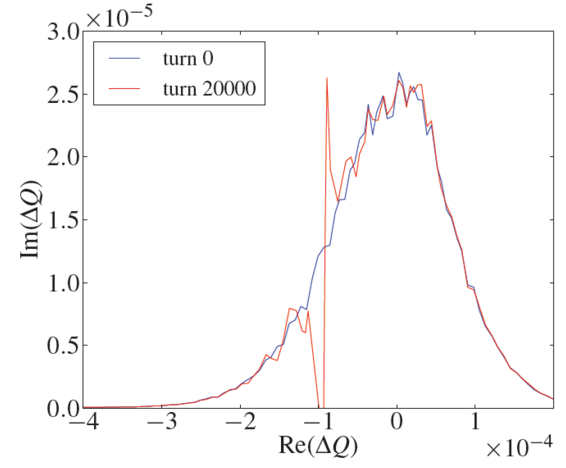
Courtesy of X. Buffat



2015

2015

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2015

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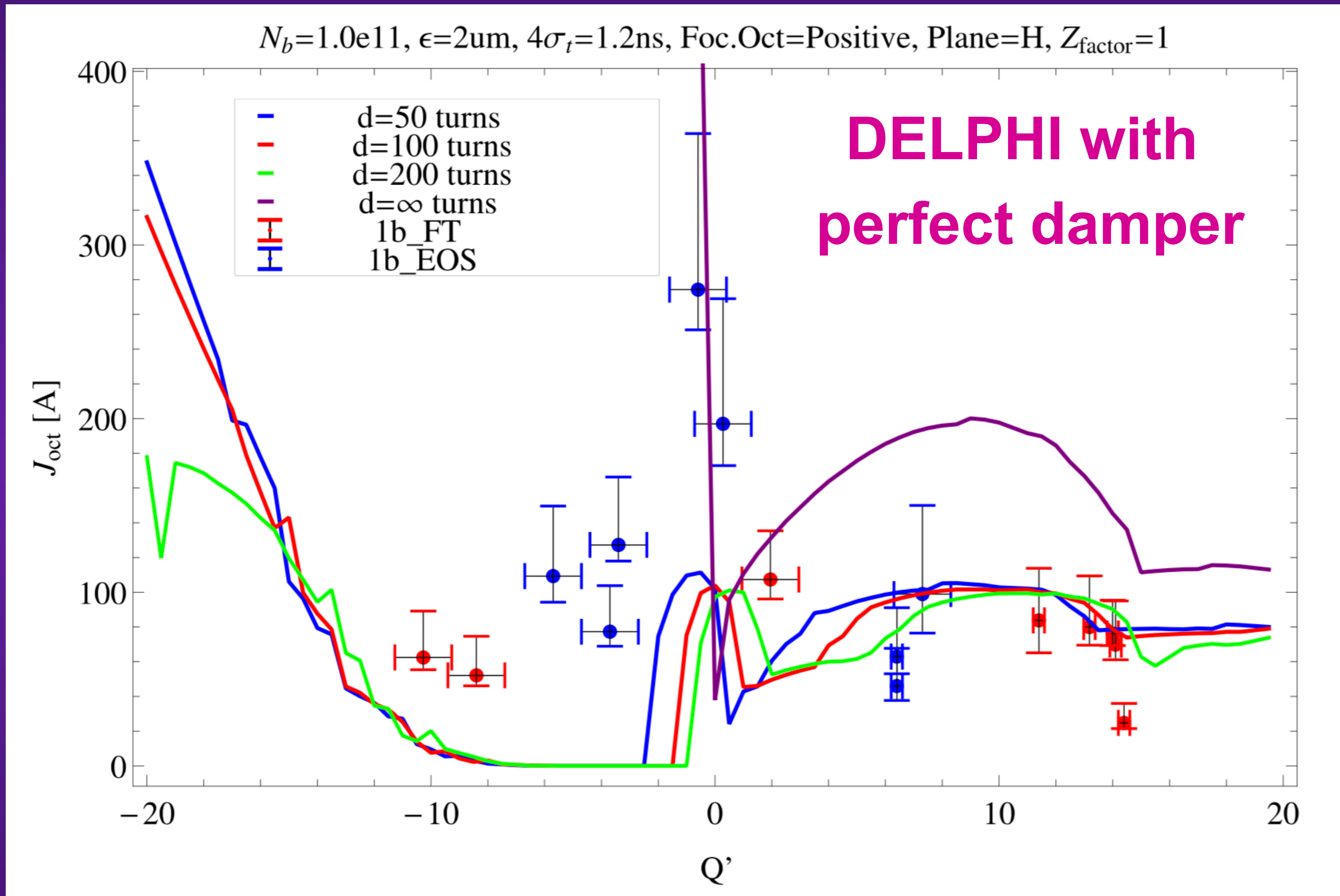

Courtesy of L.R. Carver

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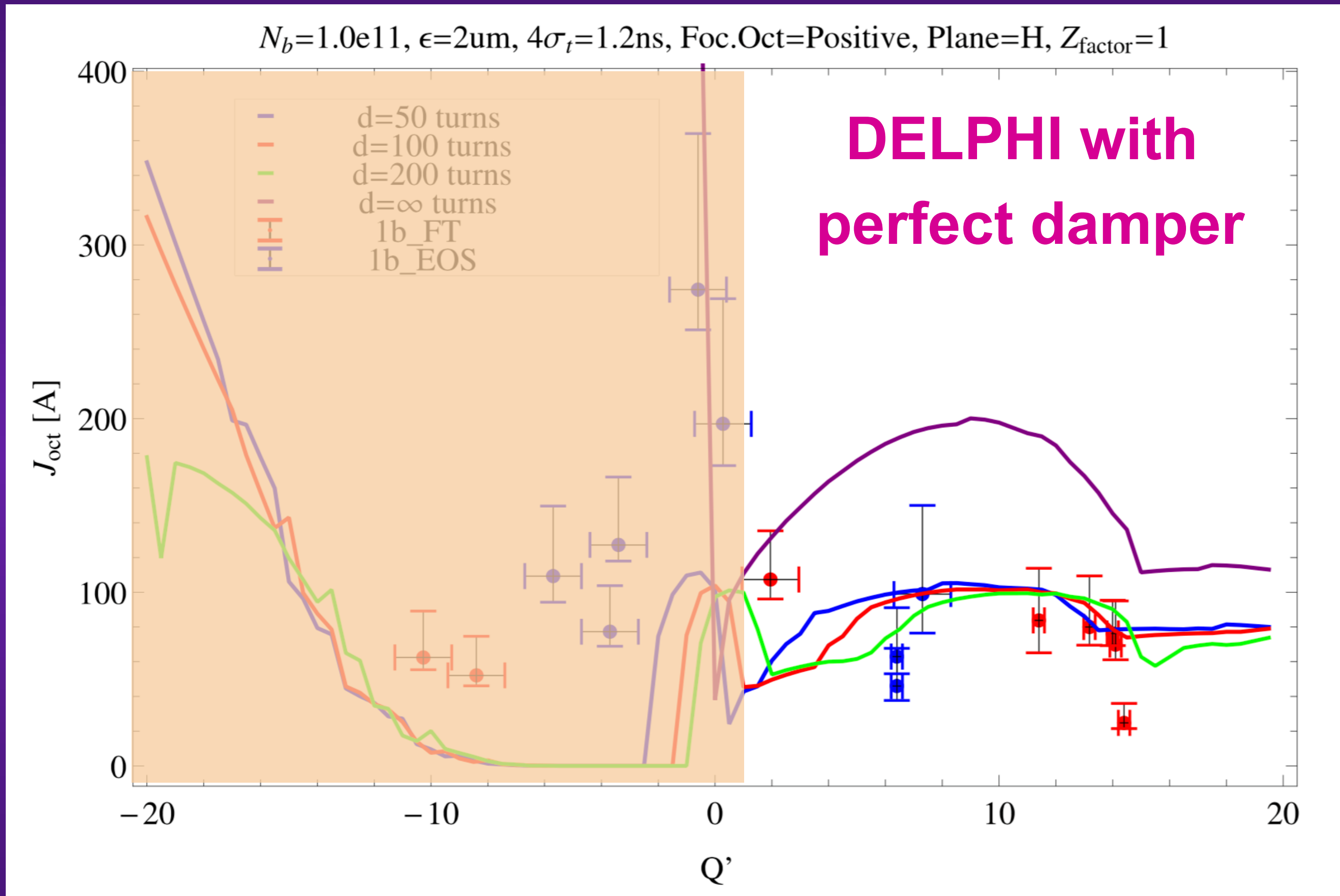

Courtesy of L.R. Carver

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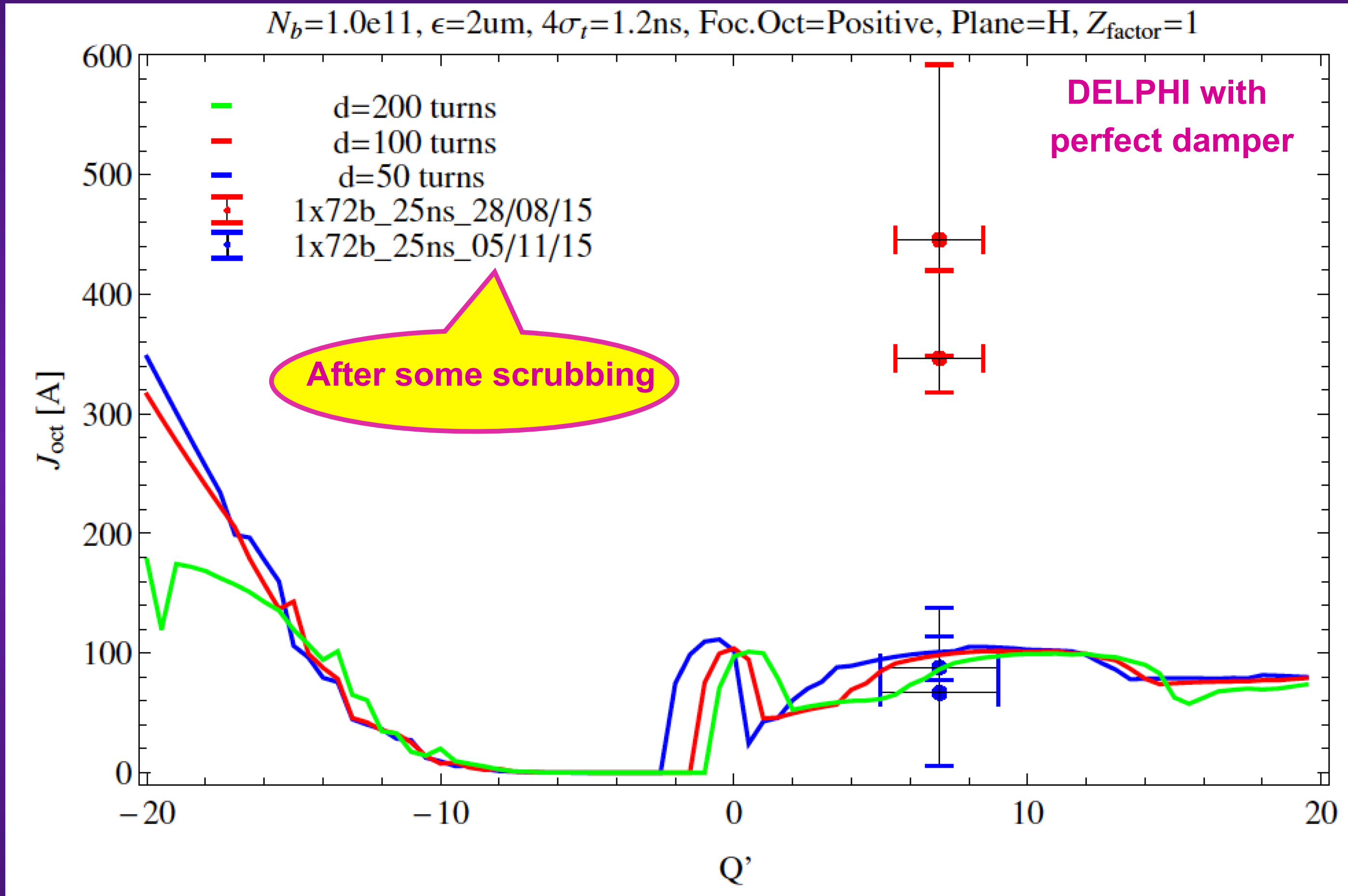

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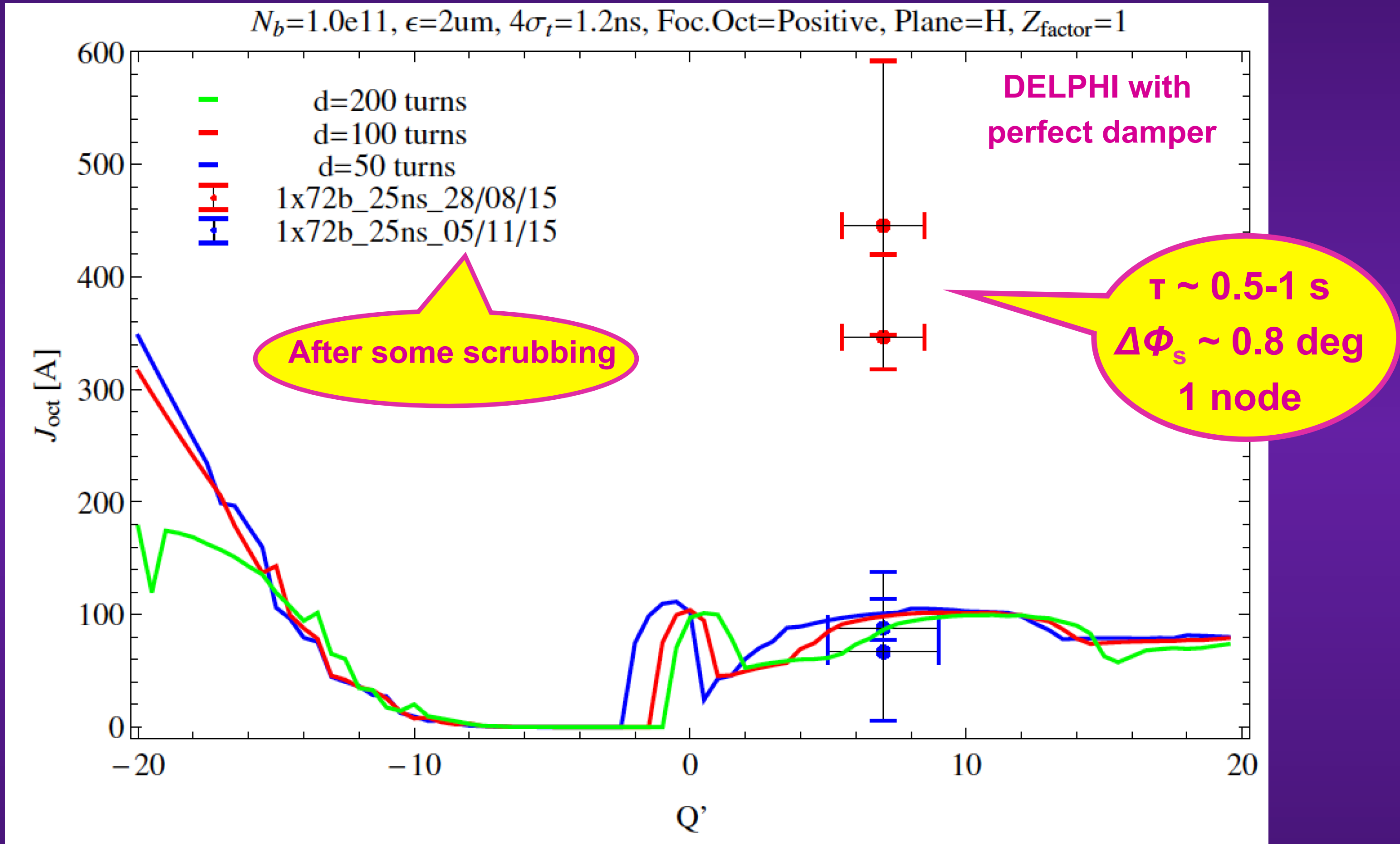

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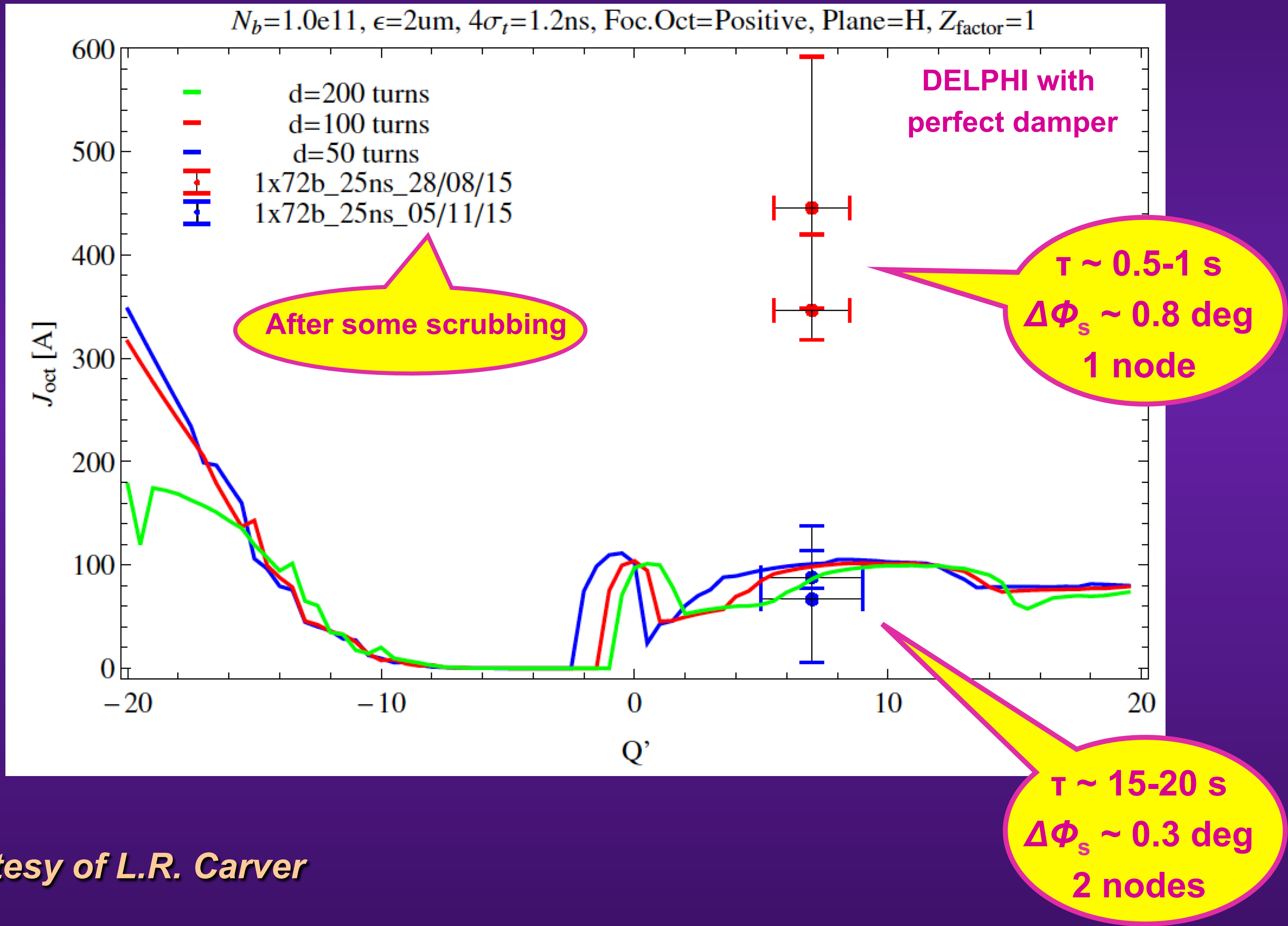

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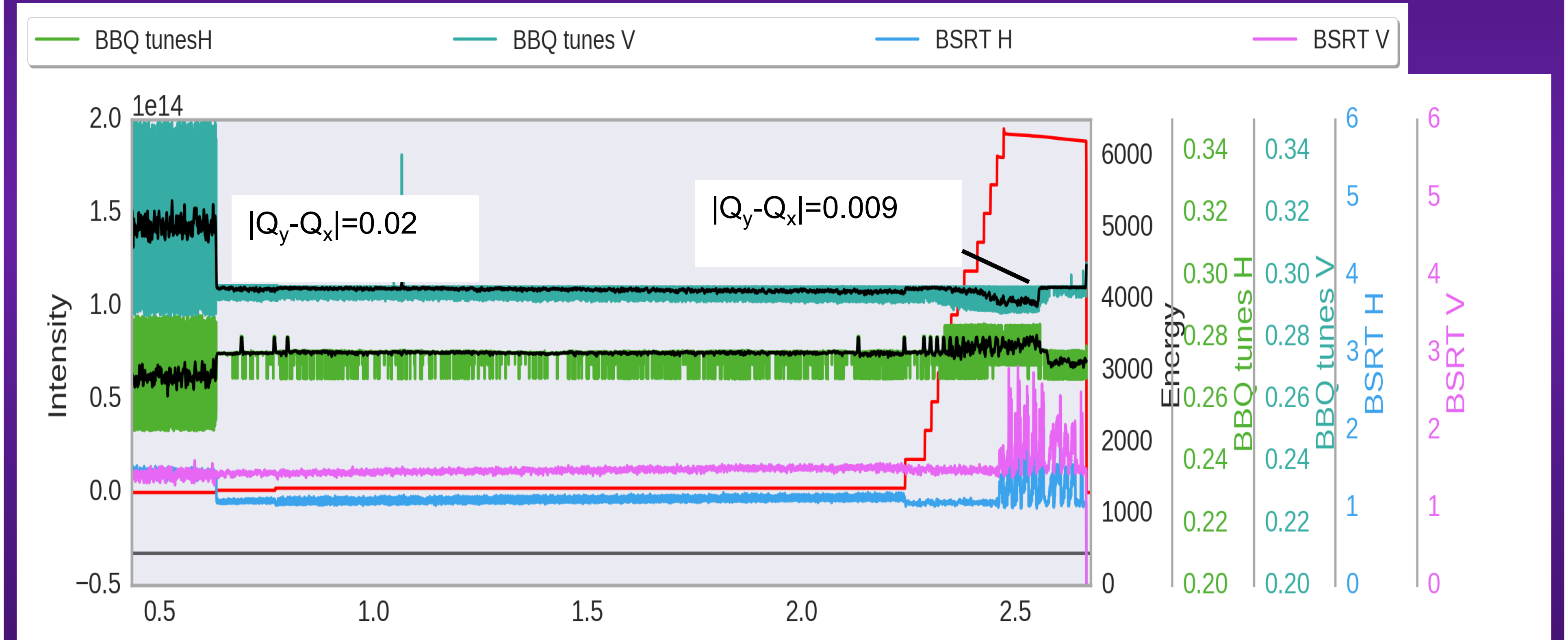

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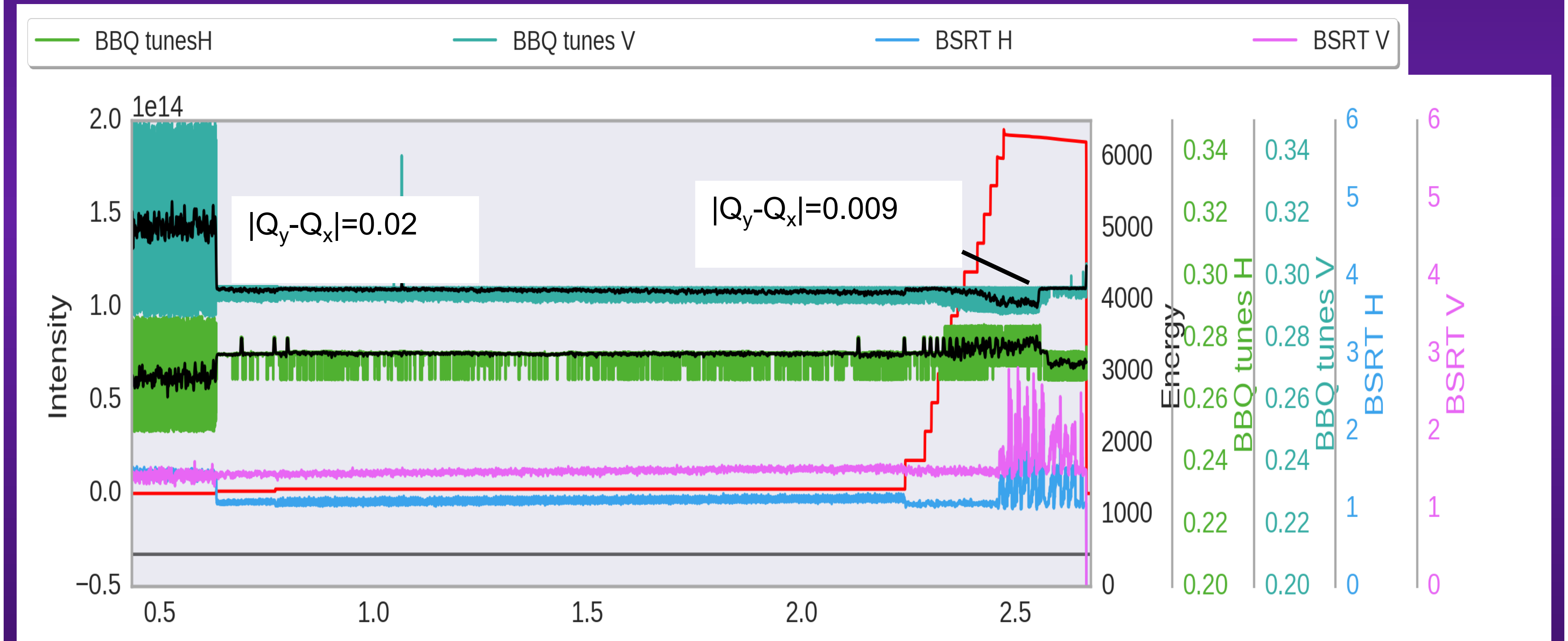

Courtesy of L.R. Carver

=> Believed to be due to linear coupling (see later)

2015

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2015

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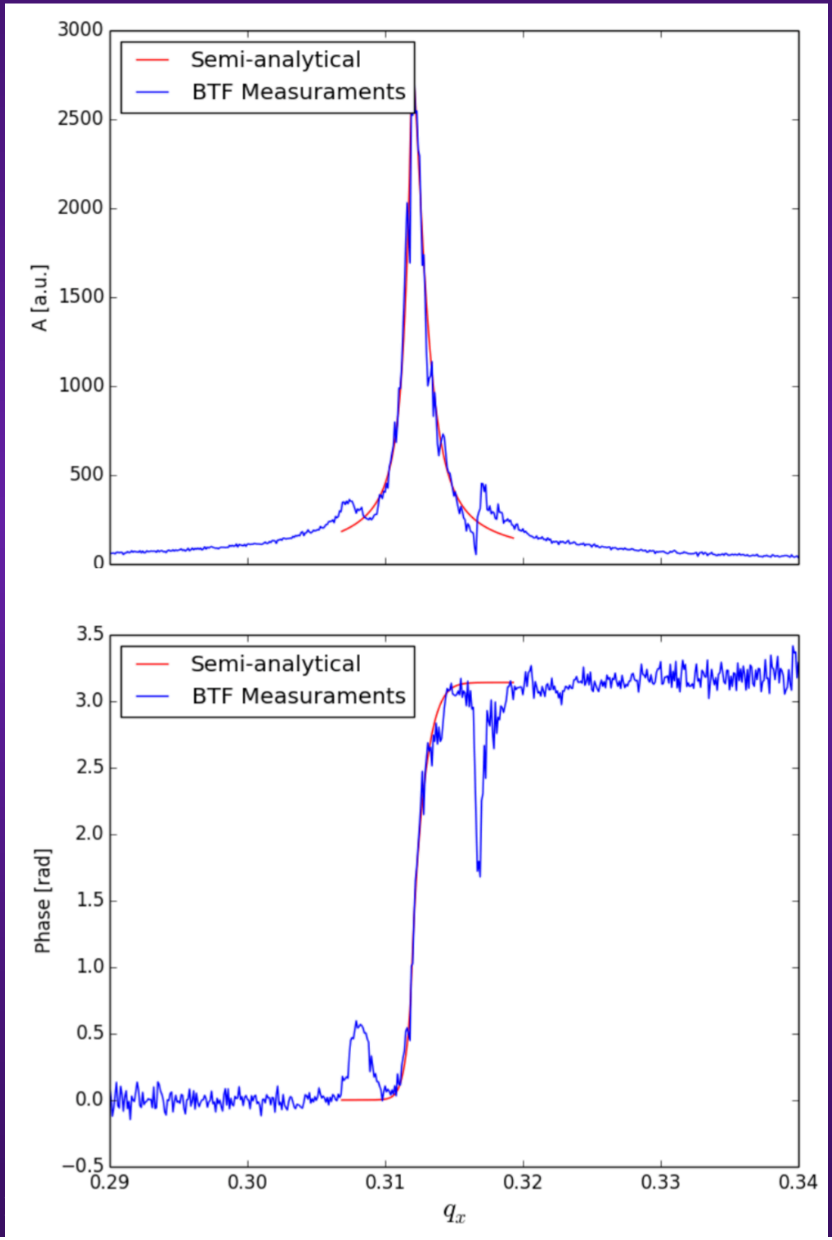

Courtesy of C. Tambasco

2015

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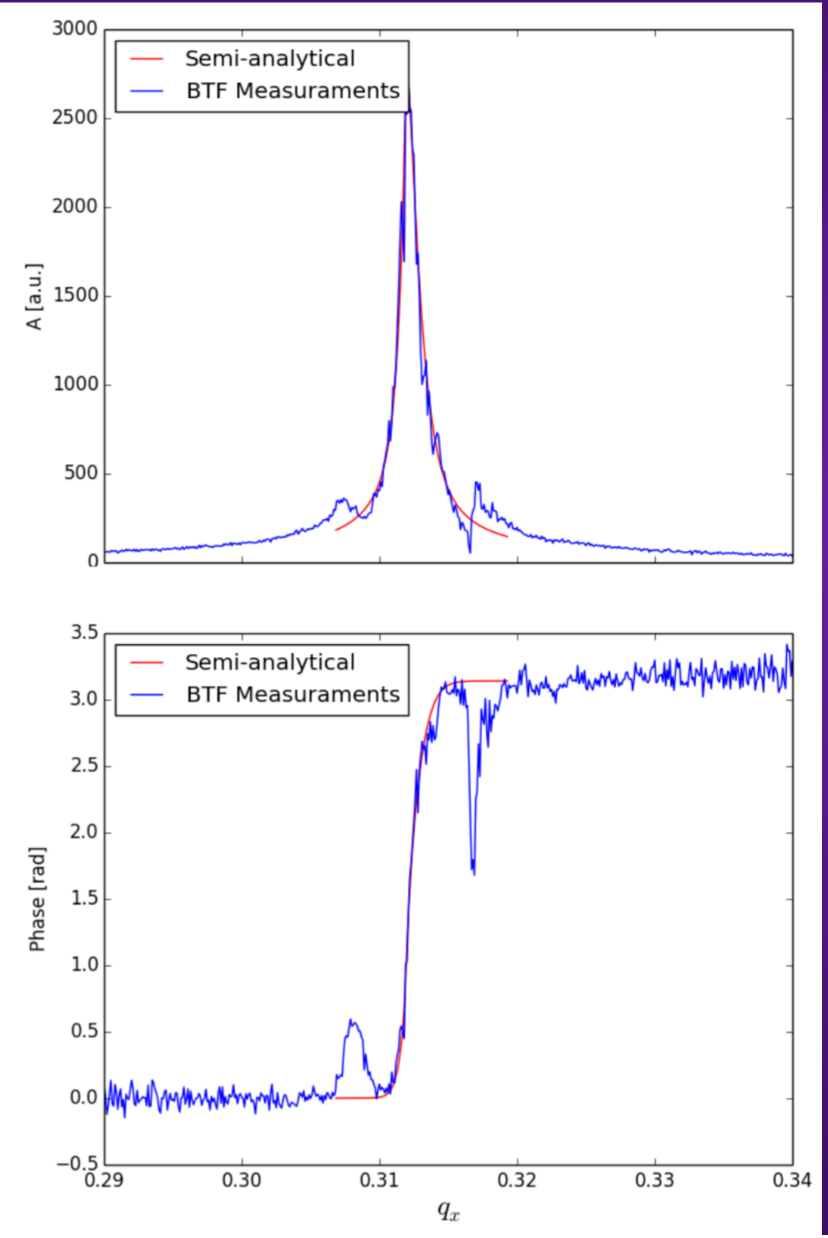
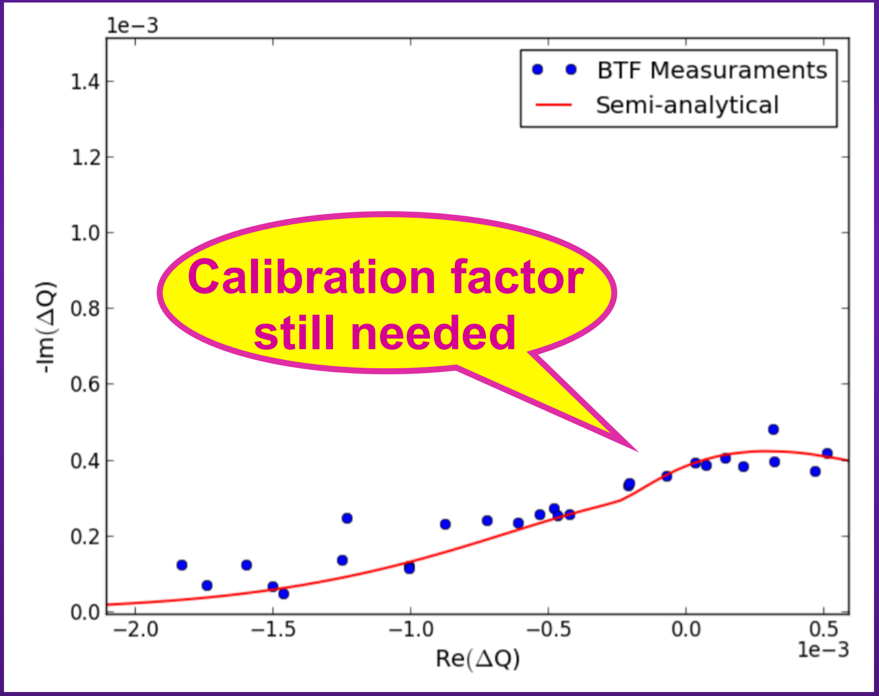


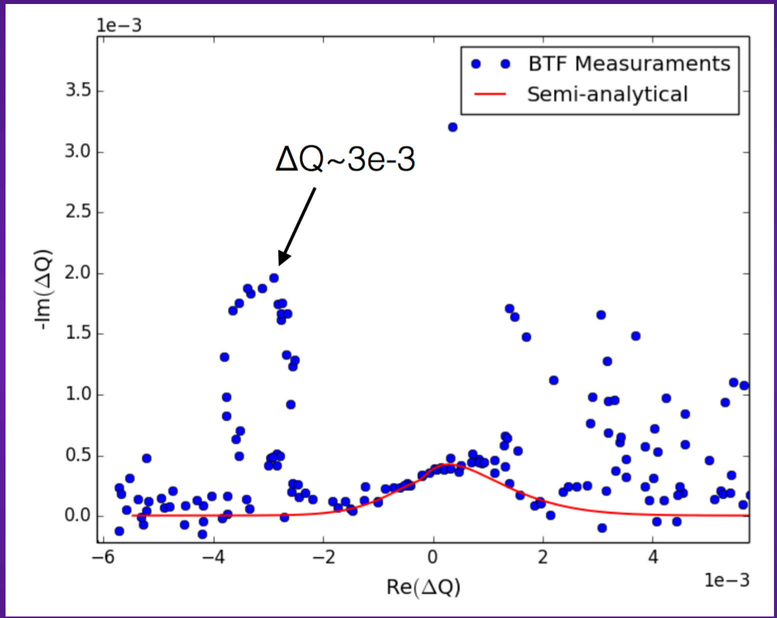


Courtesy of C. Tambasco

Elias

2015

- **Closer look recently: why do we see a loop in the BTF and what are its characteristics?**



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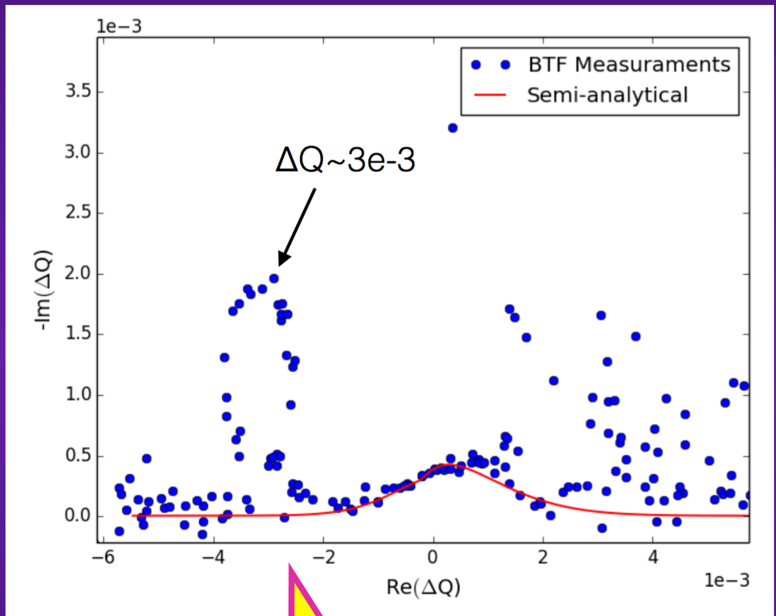

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Loop also revealed in simulation (COMBI)

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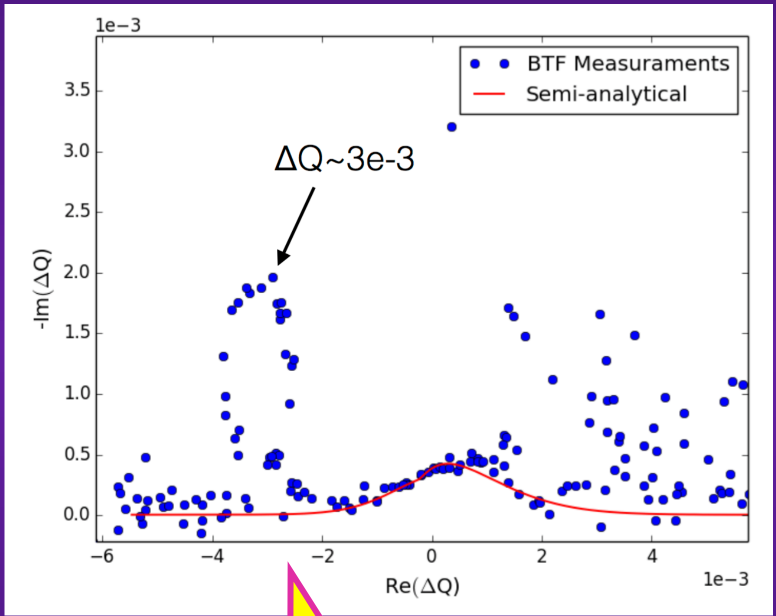

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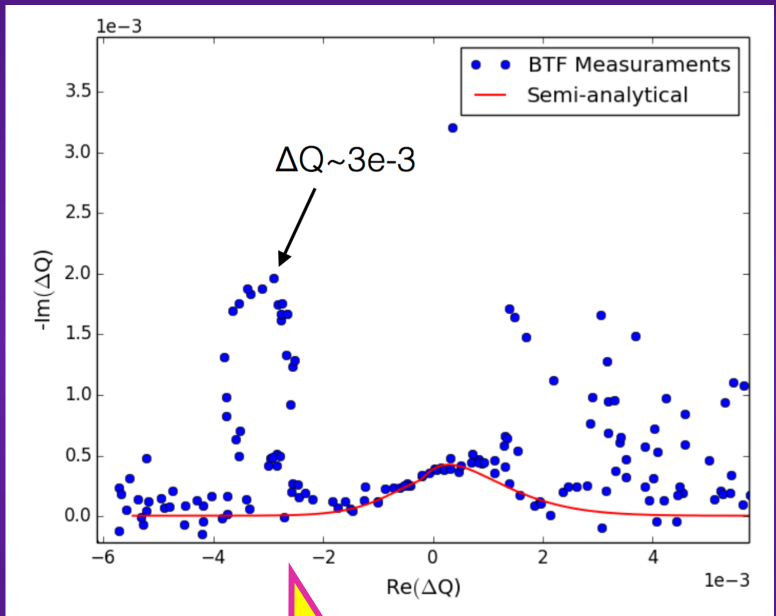

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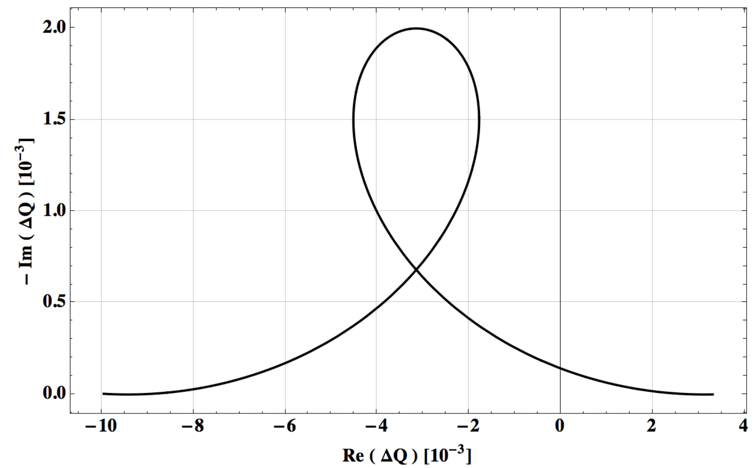
```
Clear[q];
F1 = 0.4;
F2 = 1 / 5;
F3 = -0.01;
F4 = 0.001;
F5 = F4;
qmin = -1.6;
qmax = 4.8;
deltaQRe[q_] := (F1 * Cos[q] + F2 * q) * F3;
deltaQIm[q_] := F4 * Sin[q] + F5;
ParametricPlot[{deltaQRe[q] * 1000, deltaQIm[q] * 1000}, {q, qmin, qmax}, Frame → True,
 FrameLabel → {"Re ( ΔQ ) [10^-3]", "- Im ( ΔQ ) [10^-3]"}, GridLines → Automatic,
 ImageSize → imsize, PlotRange → All, PlotStyle → {Black, Thick}, AspectRatio → 0.6,
 LabelStyle → Directive[Black, 16, Bold]]
```



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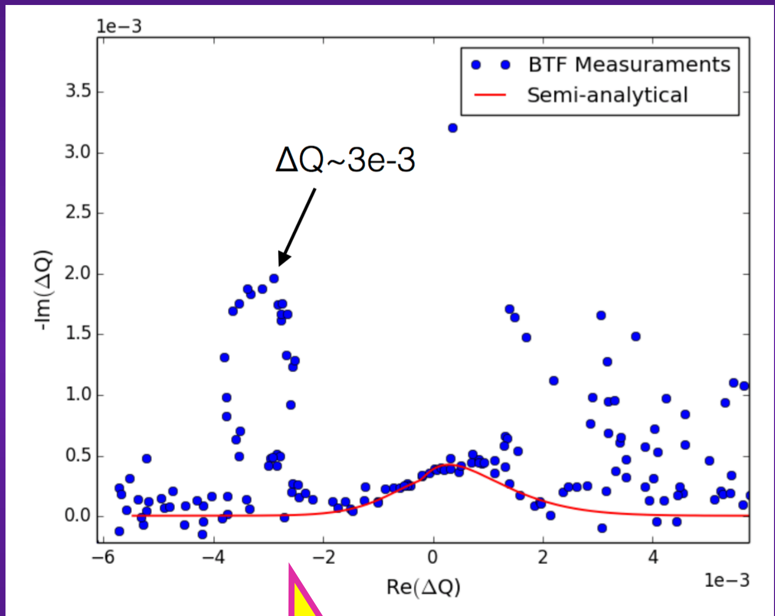

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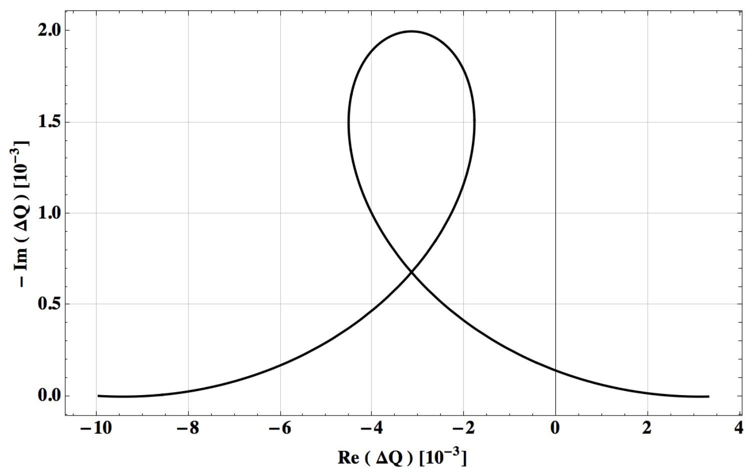

- Next: what is the physics?

2015

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  - Detailed analysis of effect of linear coupling on transverse beam instabilities also started with a single bunch at high energy
  - BTF measurements started to be benchmarked

2015

- **Lessons learned**

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  - **While it is still not completely clear why such high values were needed in 2012, it was clear in 2015 that an important e-cloud was still present at high energy and that it could drive the beam unstable**
  - **Furthermore, linear coupling should be studied in more detail during all the LHC cycle**

2016

2016

- **Destabilising effect of linear coupling at 6.5 TeV => Linear coupling can be beneficial or detrimental**

2016

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2016

- Destabilising effect of linear coupling at 6.5 TeV => Linear coupling can be beneficial or detrimental

  - Why could linear coupling be a problem for beam stability?

  - => Because the coherent tunes are shifted by linear coupling differently compared to the incoherent tunes (providing the Landau damping) due to the nonlinear fields (from octupoles to create the tune spread). Therefore in some cases a too strong coupling can be detrimental, leading to instabilities due to a loss of transverse Landau damping

2016

Proceedings of EPAC 2002, Paris, France

DESTABILISING EFFECT OF LINEAR COUPLING IN THE HERA PROTON RING

E. Métral, CERN, Geneva, Switzerland
G. Hoffstaetter, F. Willeke, DESY, Hamburg, Germany

Abstract

Since the first start-up of HERA in 1992, a transverse coherent instability has appeared from time to time at the beginning of the acceleration ramp. In this process, the emittance is blown up and the beam is partially or completely lost. Although the instability was found to be of the head-tail type, and the chromaticity and linear coupling between the transverse planes was recognized as essential for the instability to occur, the driving mechanism was never clarified. An explanation of the phenomenon is presented in this paper using the coupled Landau damping theory. It is predicted that a too strong coupling can be detrimental since it may shift the coherent tune outside the incoherent spectrum and thus prevent Landau damping. Due to these features, the name "coupled head-tail instability" is suggested for this instability in the HERA proton ring.

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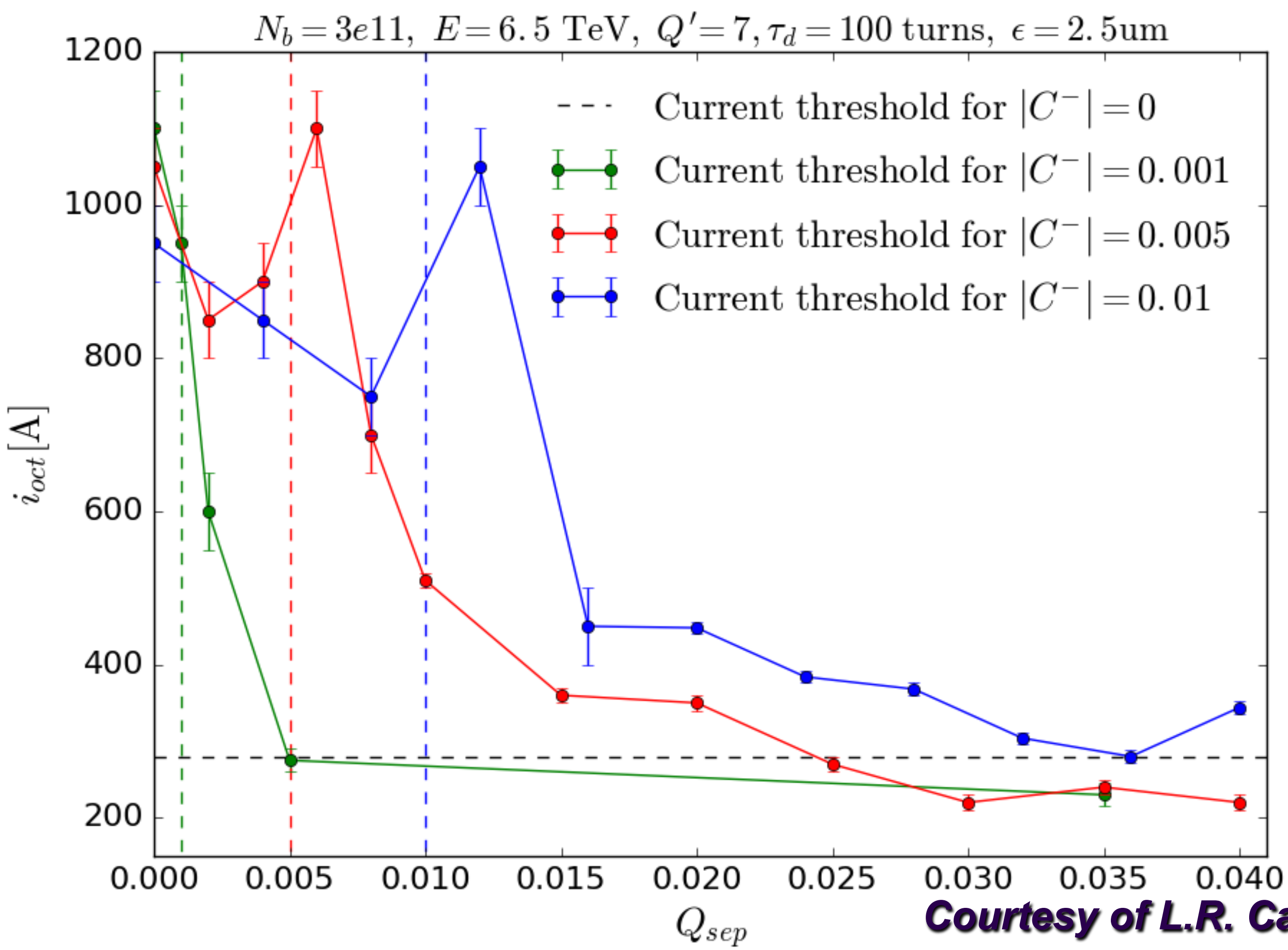
Simple model used (externally given elliptical spectrum…) => Detailed simulation study currently being performed for the LHC by L.R. Carver (see after)

2016

- **pyHEADTAIL simulations with an octupole as detuner**



Courtesy of L.R. Carver

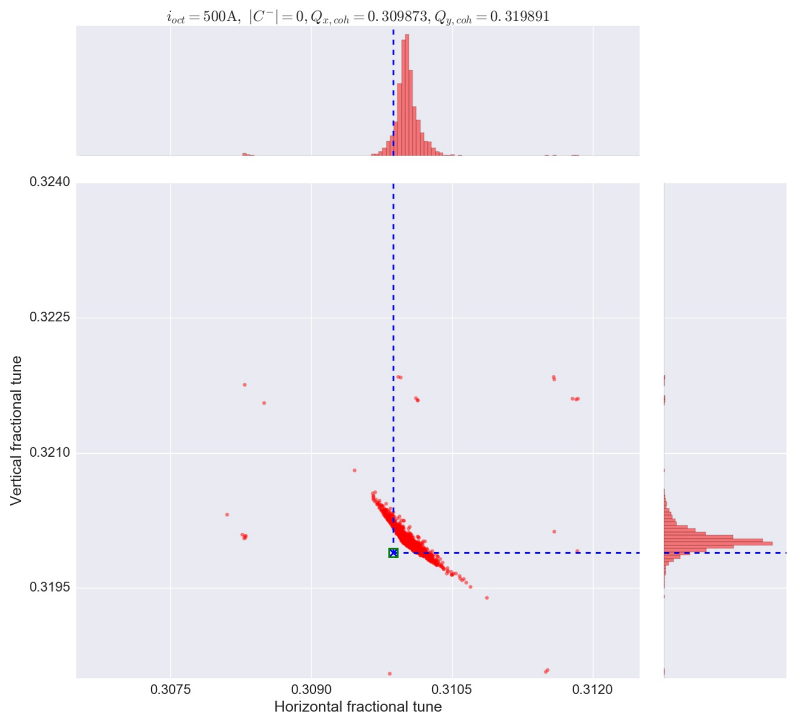
2016

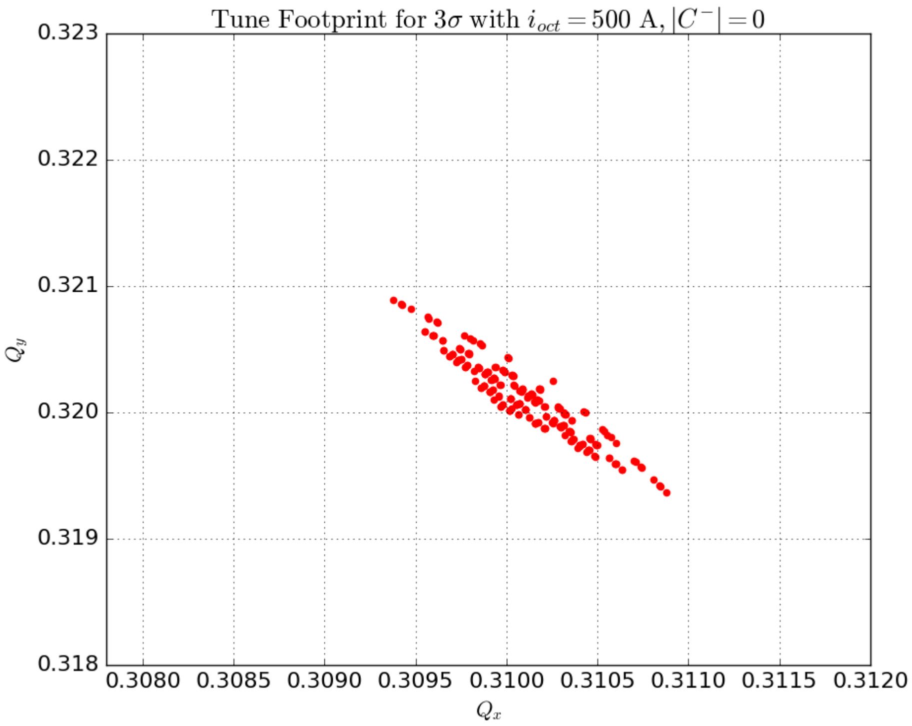
- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

LOF > 0

$$\left|C^{-}\right| = 0$$

Courtesy of L.R. Carver





2016

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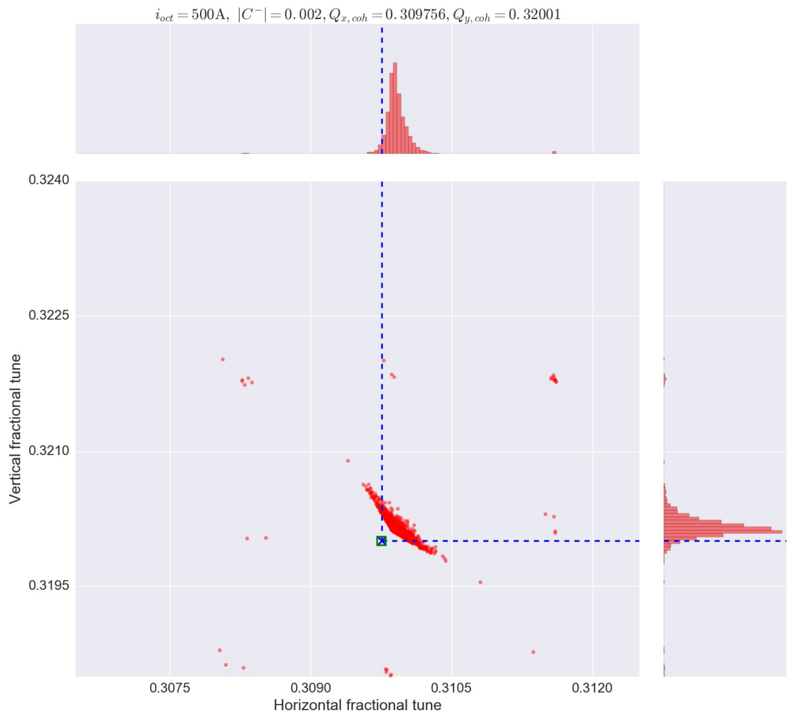
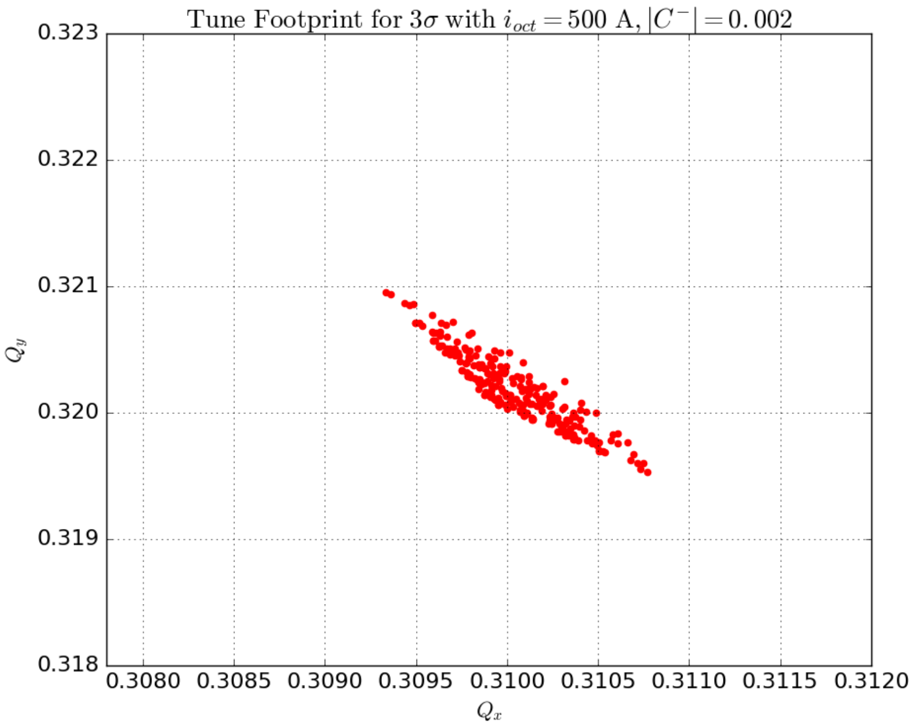
LOF > 0

$$\left|C^-\right| = 0.002$$

Courtesy of L.R. Carver





2016

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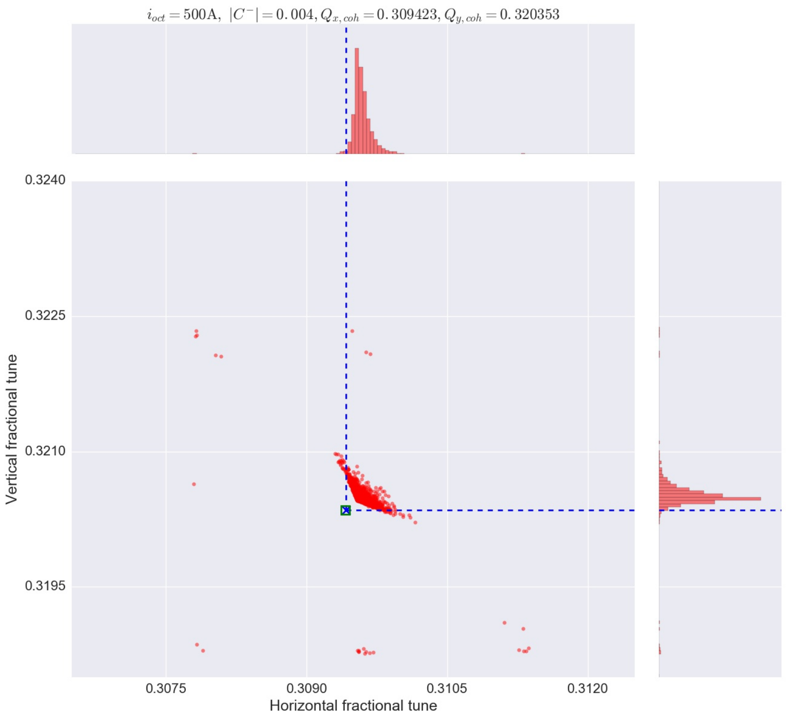
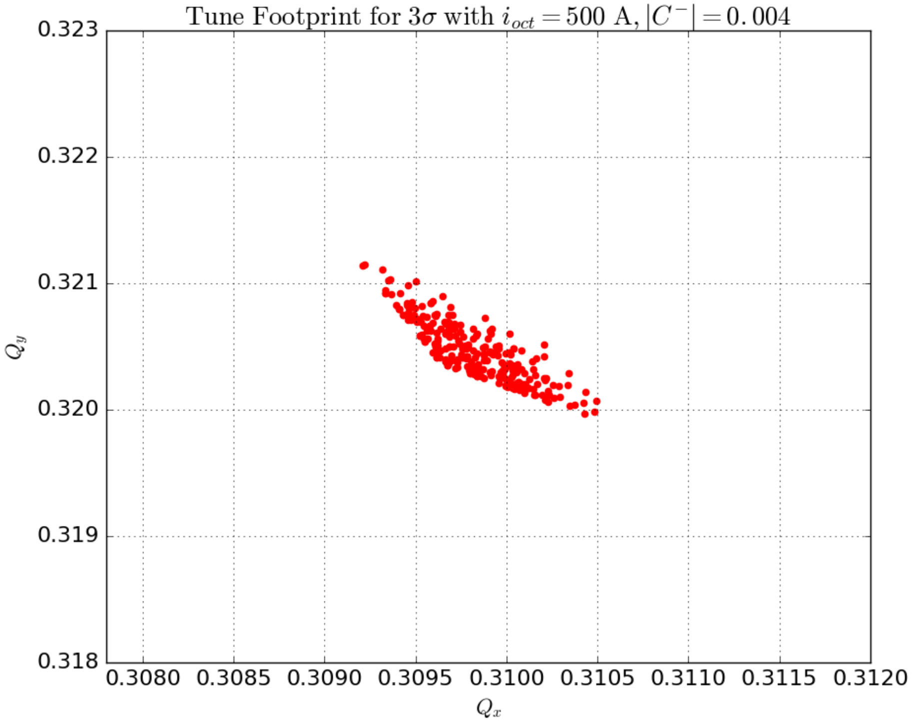
LOF > 0

$$\left|C^{-}\right| = 0.004$$

Courtesy of L.R. Carver





2016

- pyHEADTAIL simulations with an octupole as detuner
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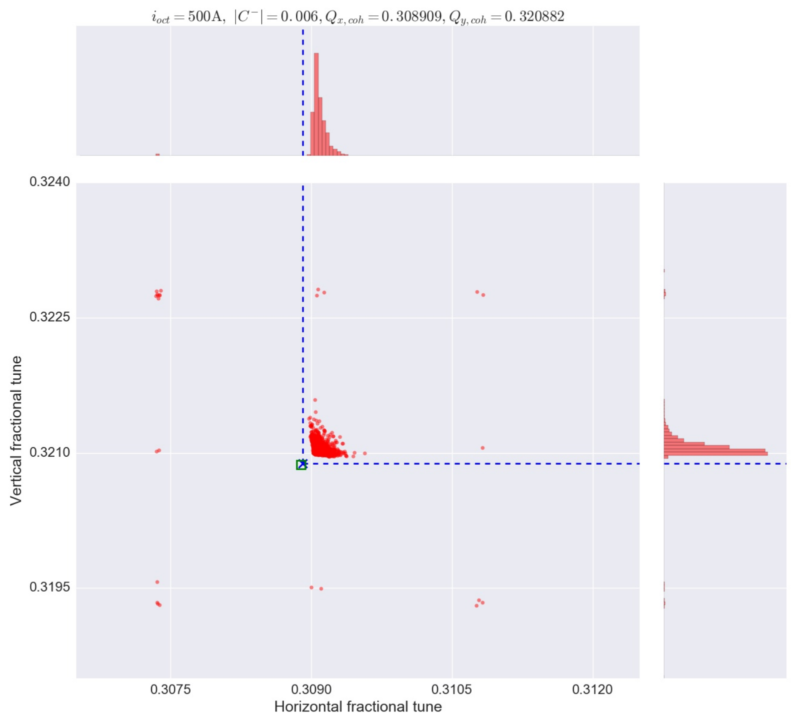
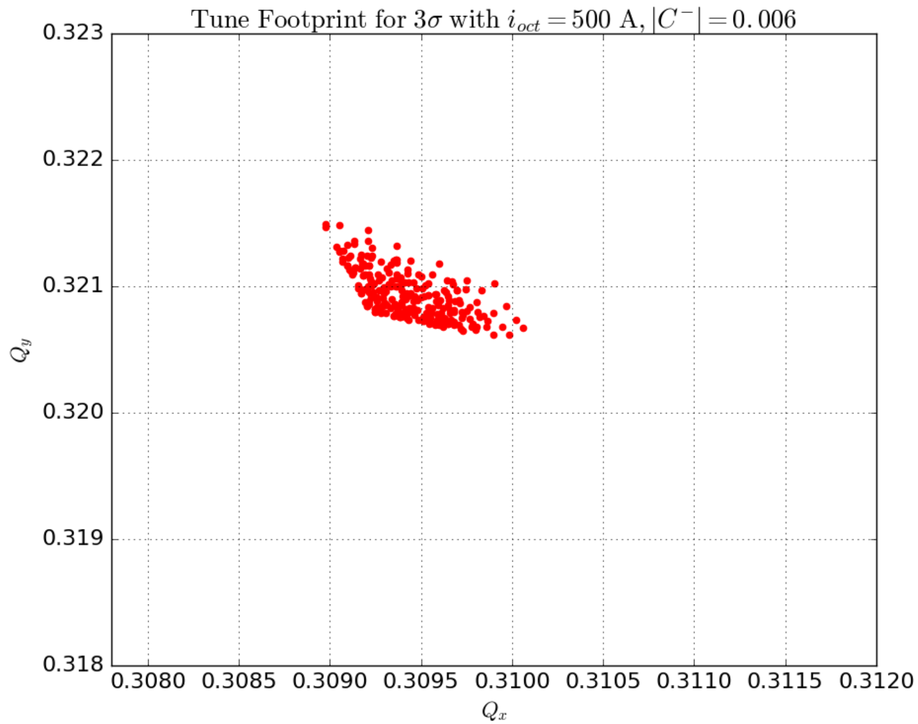
LOF > 0

$$\left|C^-\right| = 0.006$$

Courtesy of L.R. Carver





2016

- pyHEADTAIL simulations with an octupole as detuner
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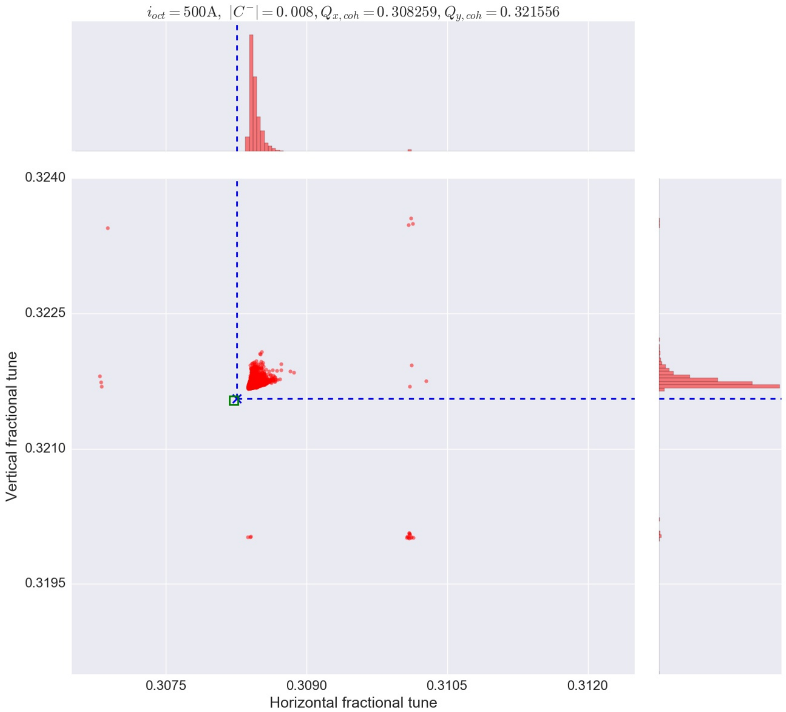
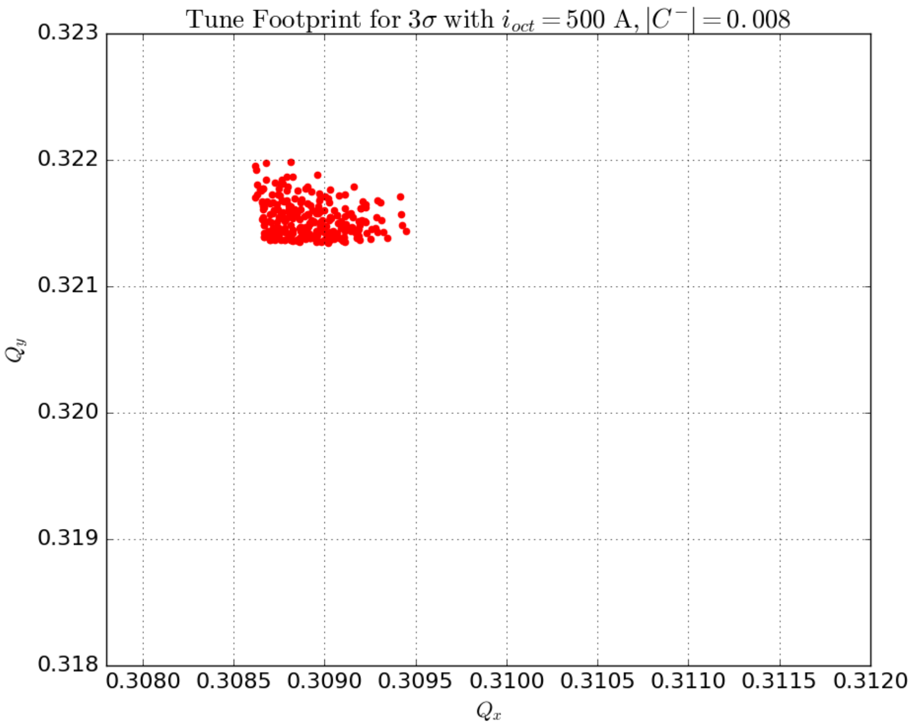
LOF > 0

$$\boxed{\left|C^-\right| = 0.008}$$

Courtesy of L.R. Carver





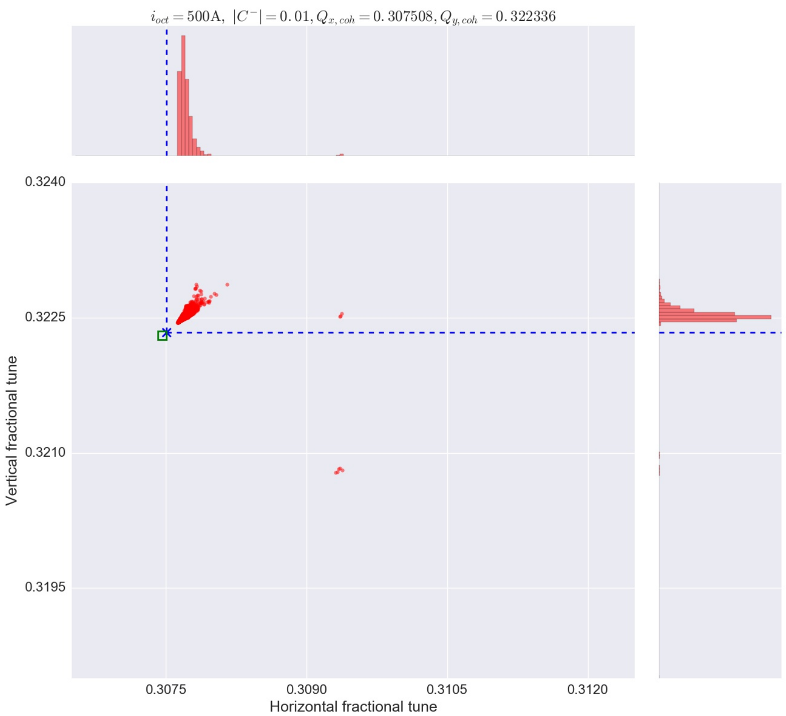
2016

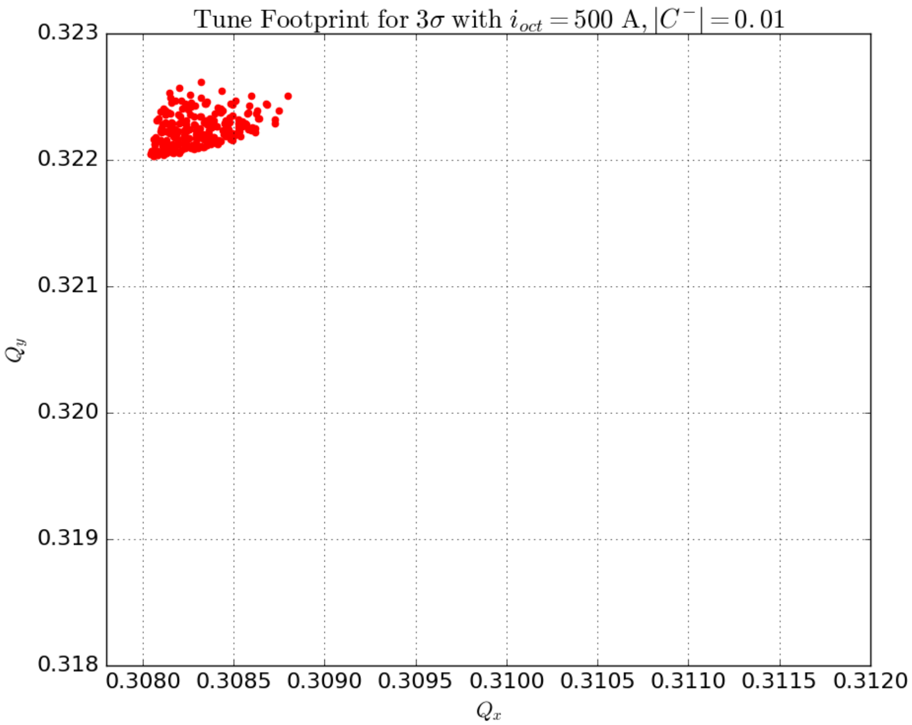
- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

LOF > 0

$$\left|C^-\right| = 0.01$$

Courtesy of L.R. Carver



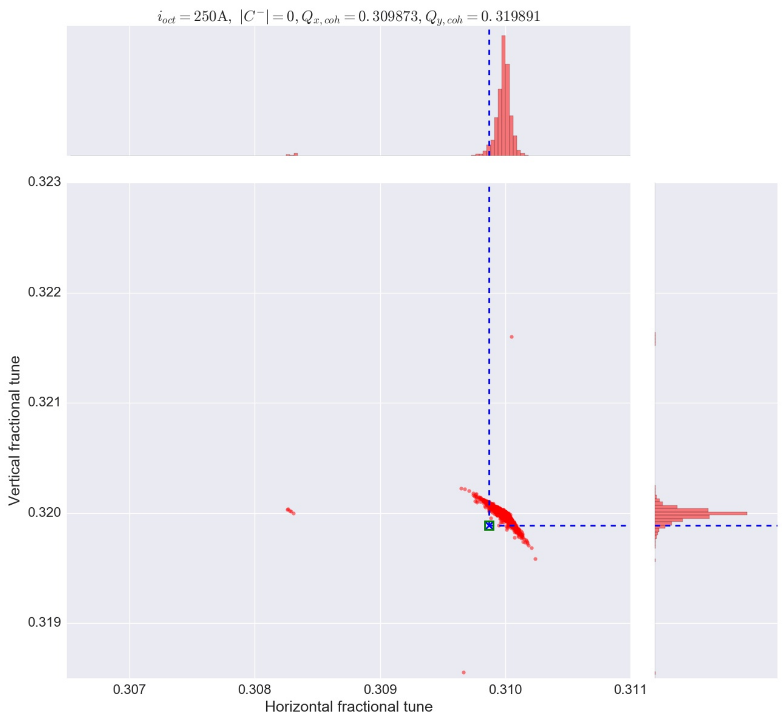


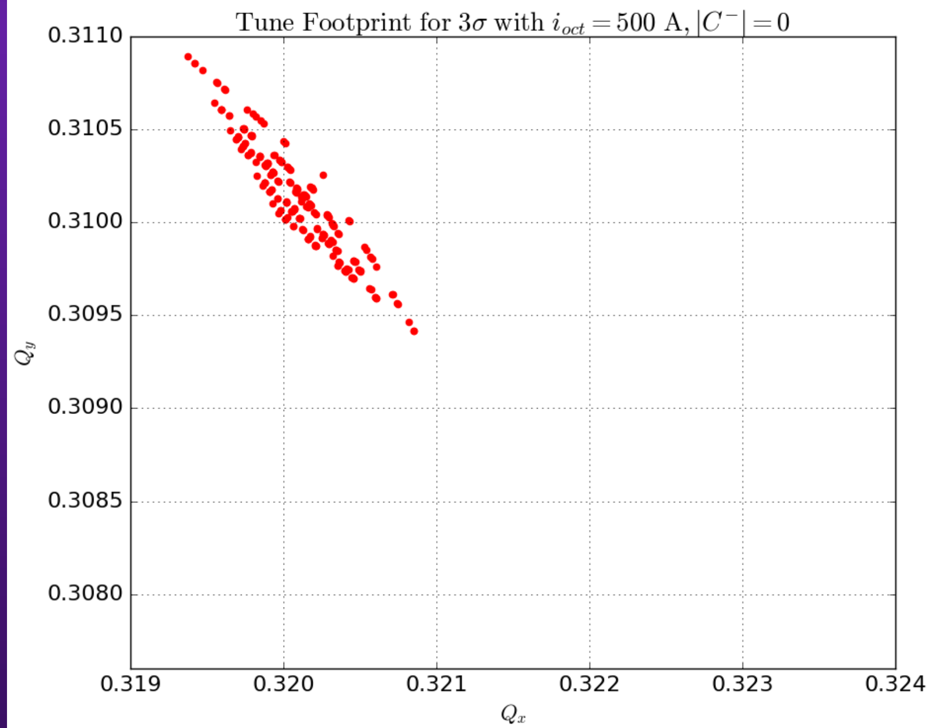
2016

- **pyHEADTAIL simulations with an octupole as detuner (LOF < 0)**
- **MADX with the real octupoles (LOF > 0, swapped tunes)**

$$\left| C^{-} \right| = 0$$

Courtesy of L.R. Carver



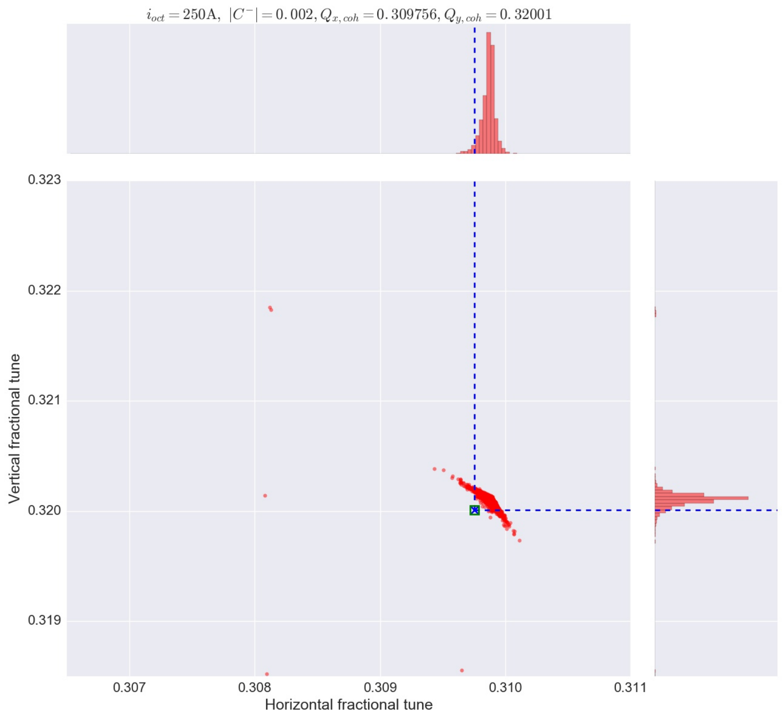


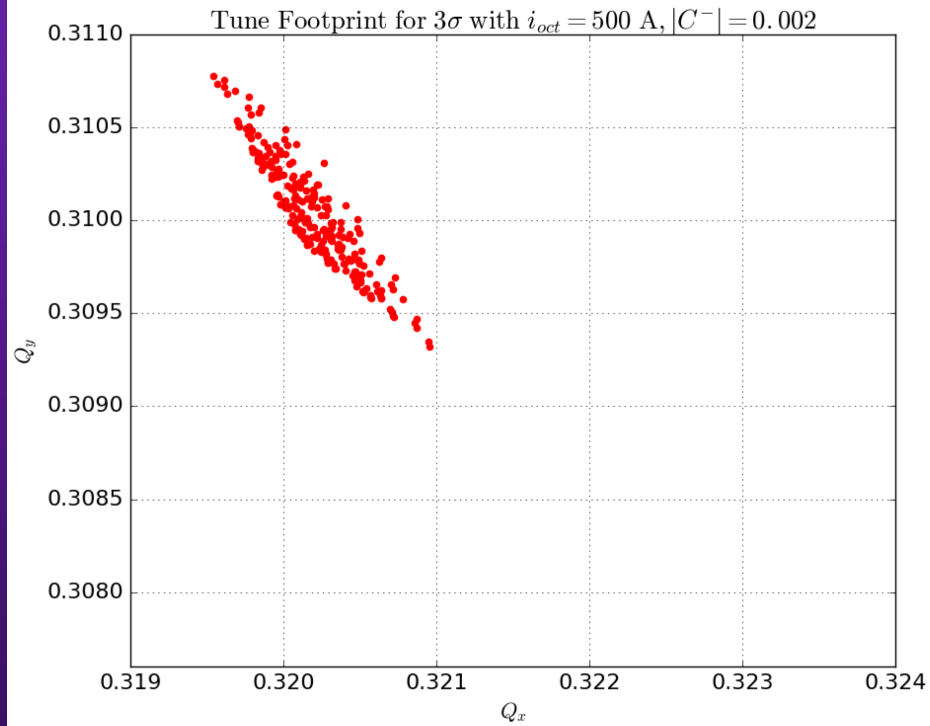
2016

- **pyHEADTAIL simulations with an octupole as detuner (LOF < 0)**
- **MADX with the real octupoles (LOF > 0, swapped tunes)**

$$\left|C^{-}\right| = 0.002$$

Courtesy of L.R. Carver



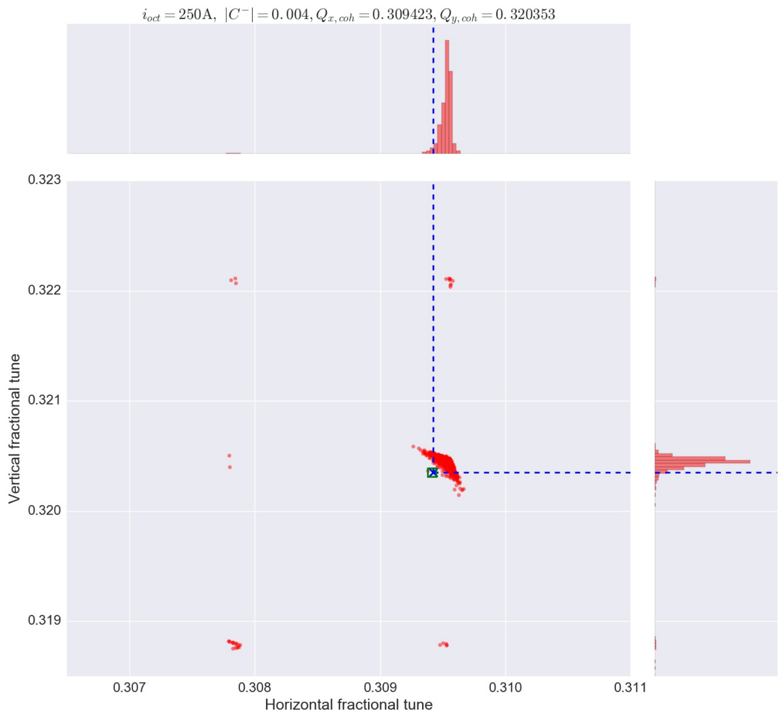


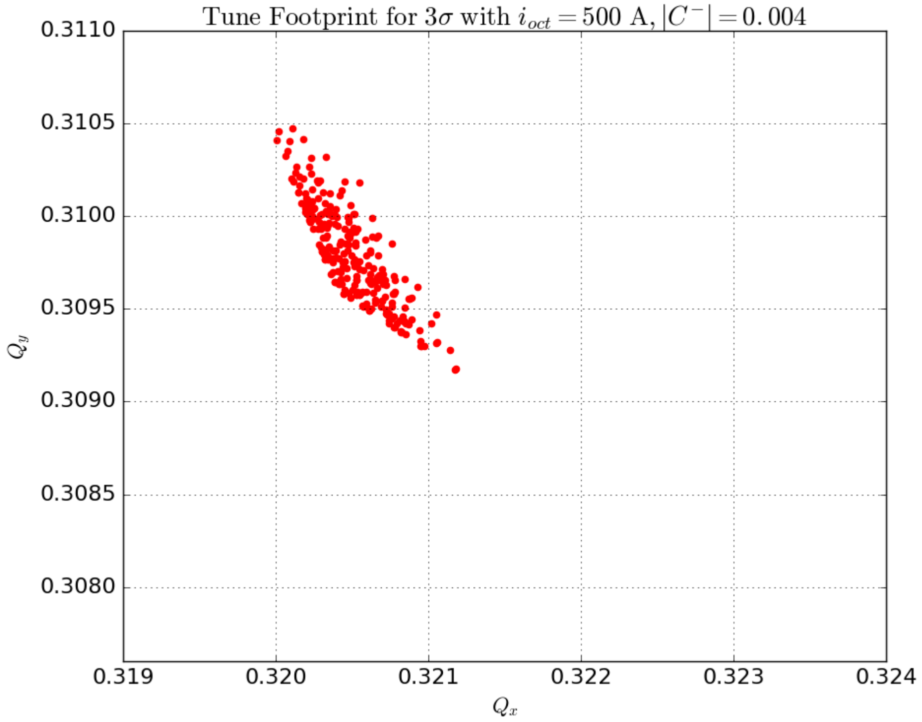
2016

- **pyHEADTAIL simulations with an octupole as detuner (LOF < 0)**
- **MADX with the real octupoles (LOF > 0, swapped tunes)**

$$\left|C^-\right| = 0.004$$

Courtesy of L.R. Carver



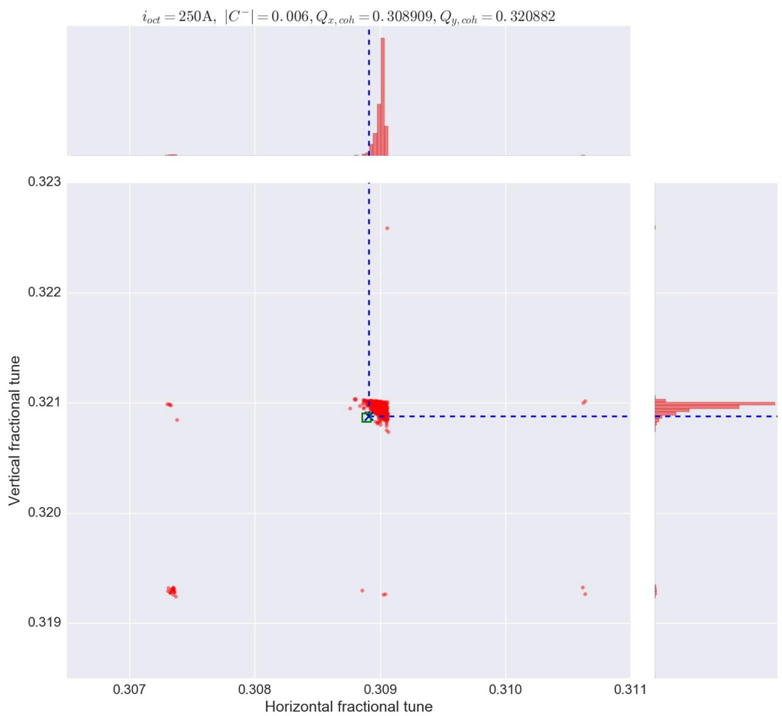


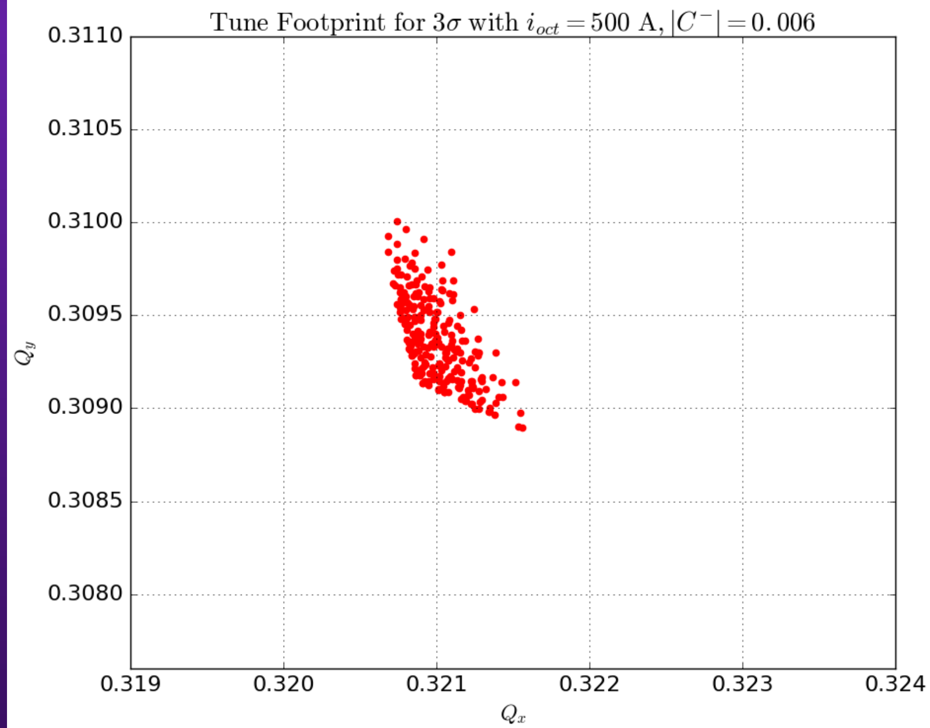
2016

- pyHEADTAIL simulations with an octupole as detuner (LOF < 0)
- MADX with the real octupoles (LOF > 0, swapped tunes)

$$\left|C^-\right| = 0.006$$

Courtesy of L.R. Carver





2016

- **pyHEADTAIL simulations with an octupole as detuner (LOF < 0)**
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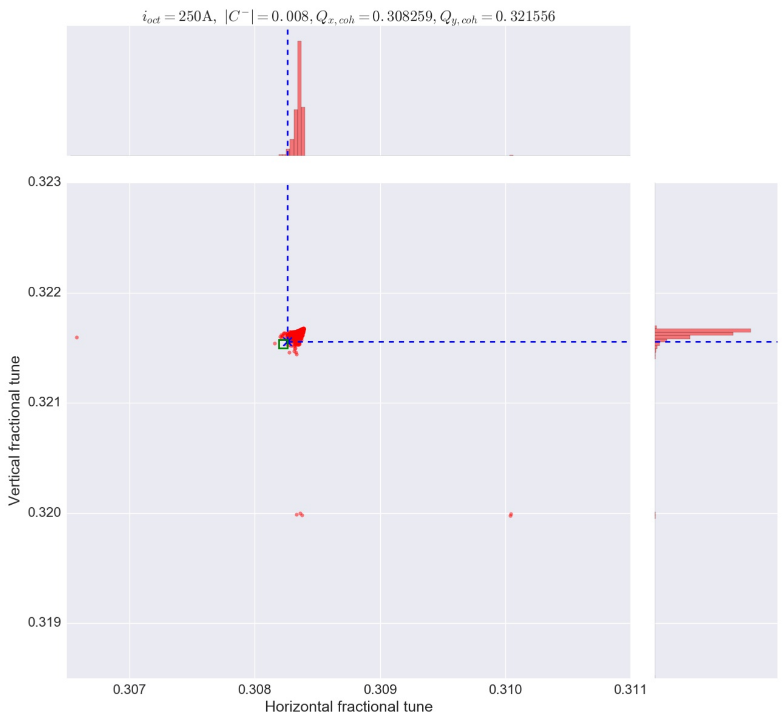
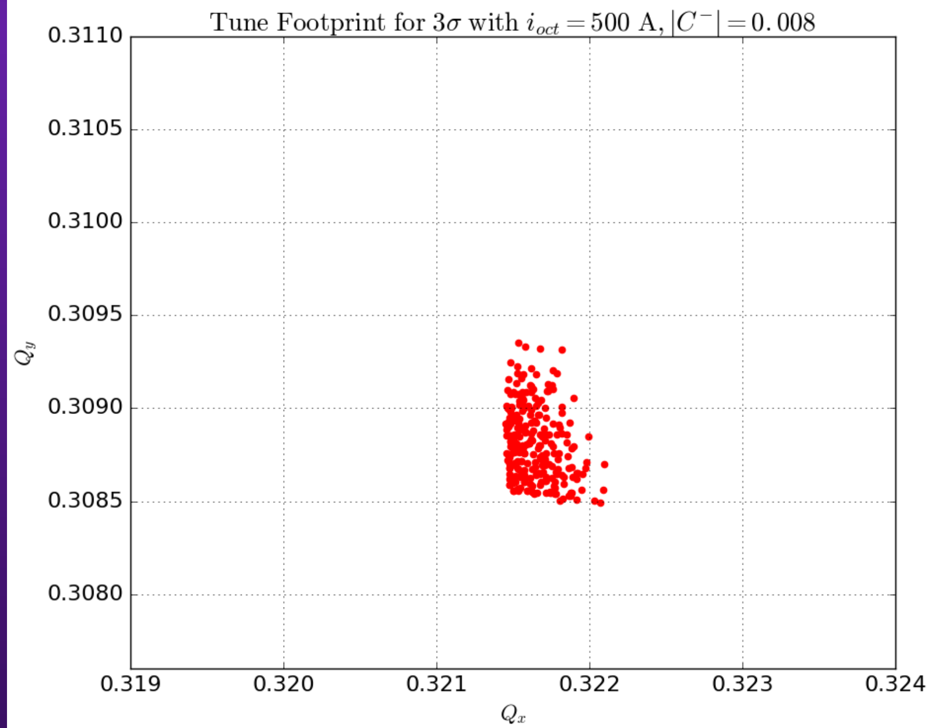
$$\left|C^{-}\right| = 0.008$$

Courtesy of L.R. Carver



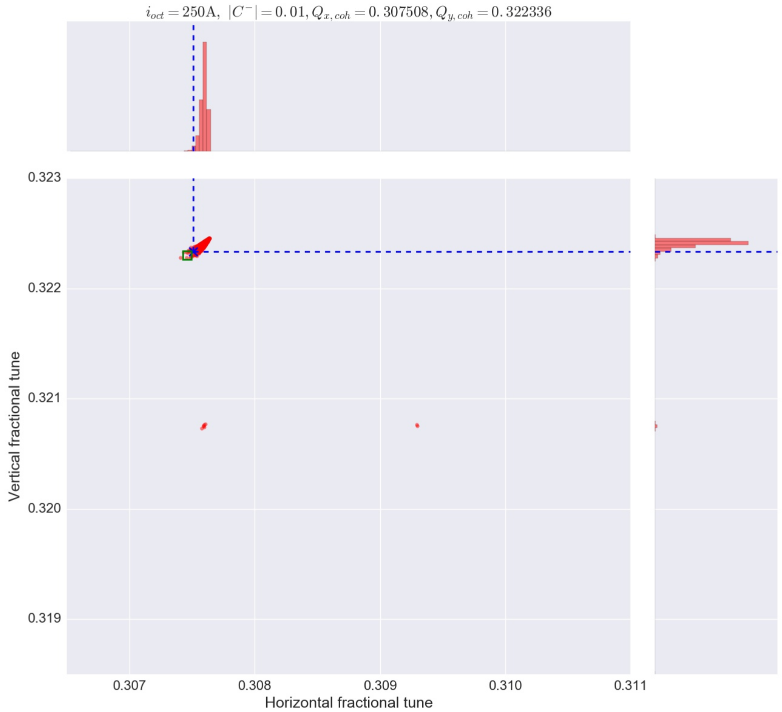


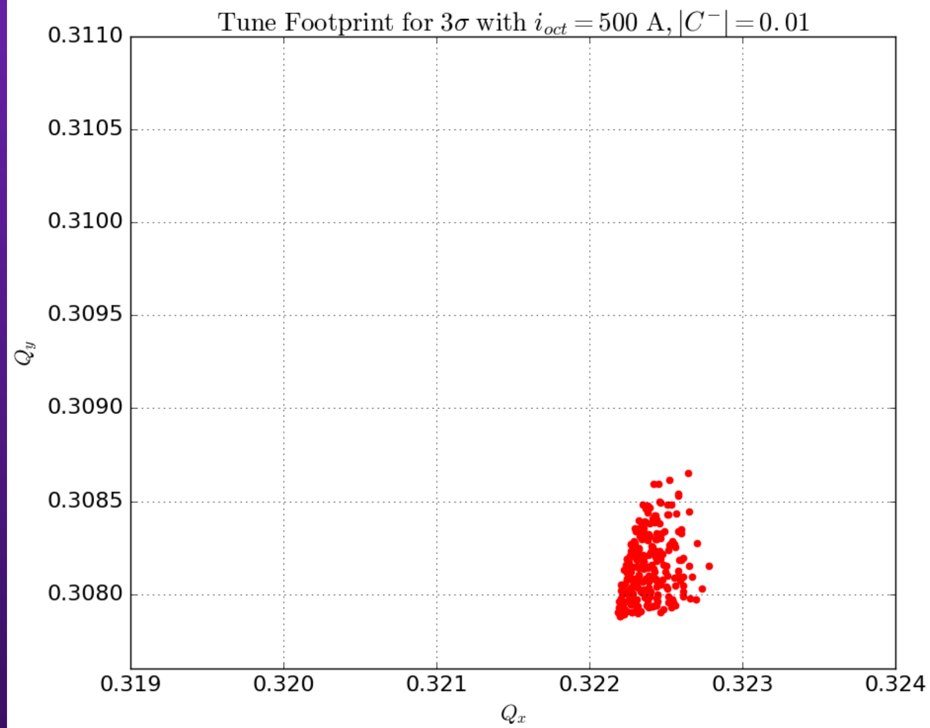
2016

- **pyHEADTAIL simulations with an octupole as detuner (LOF < 0)**
- **MADX with the real octupoles (LOF > 0, swapped tunes)**

$$\left| C^{-} \right| = 0.01$$

Courtesy of L.R. Carver





2016

- **Physical mechanism => Simple model?**

2016

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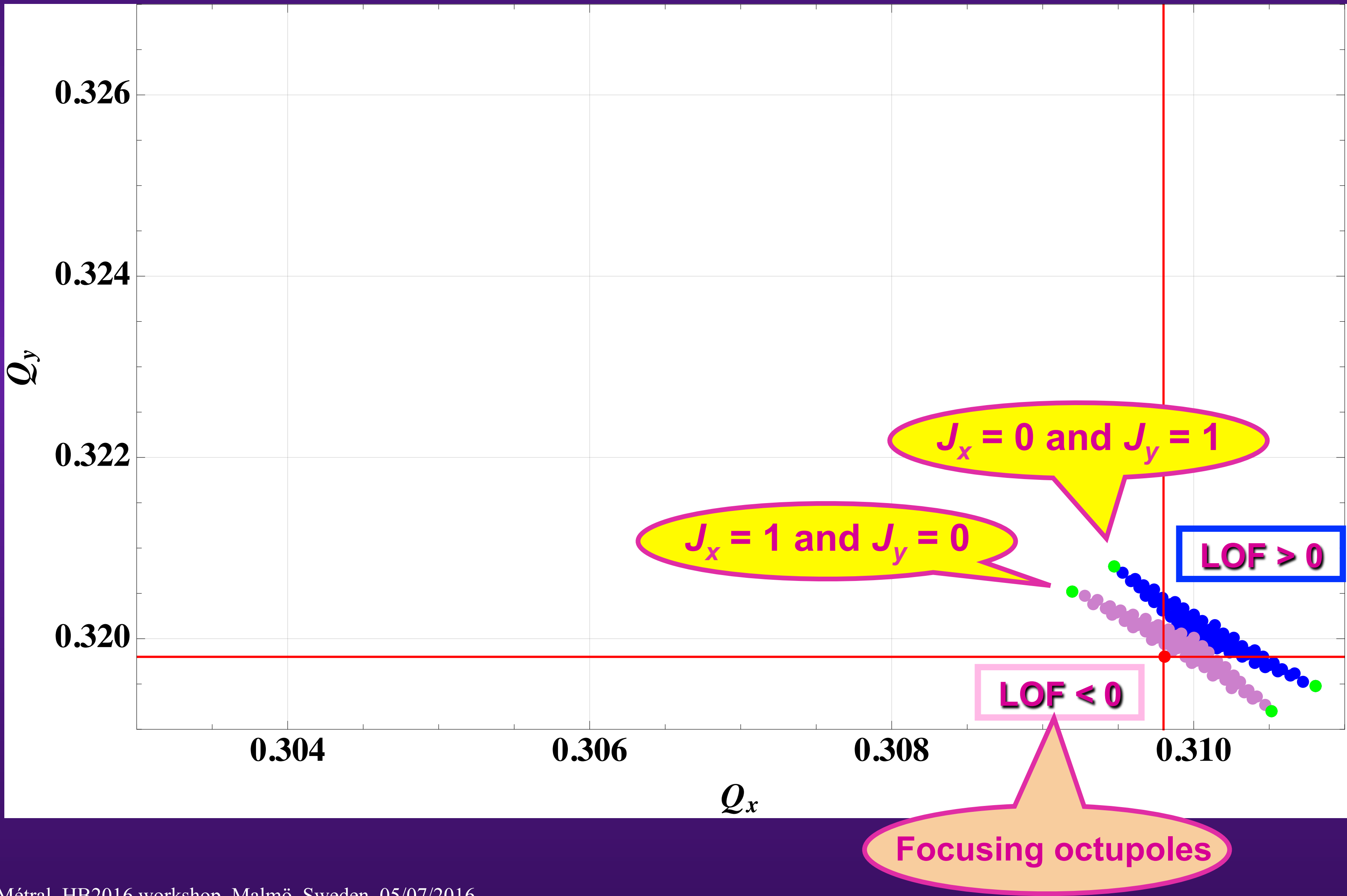
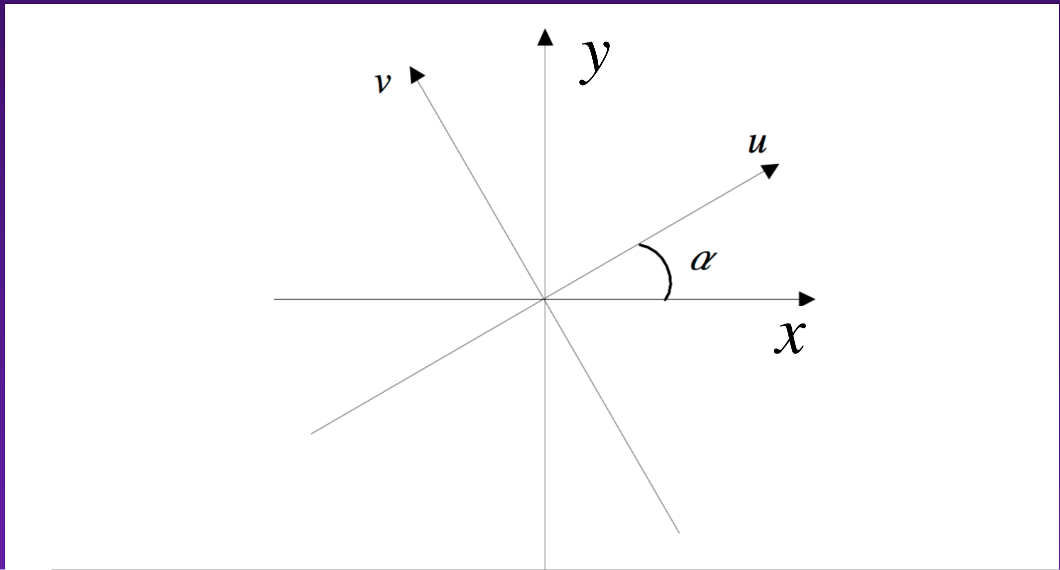
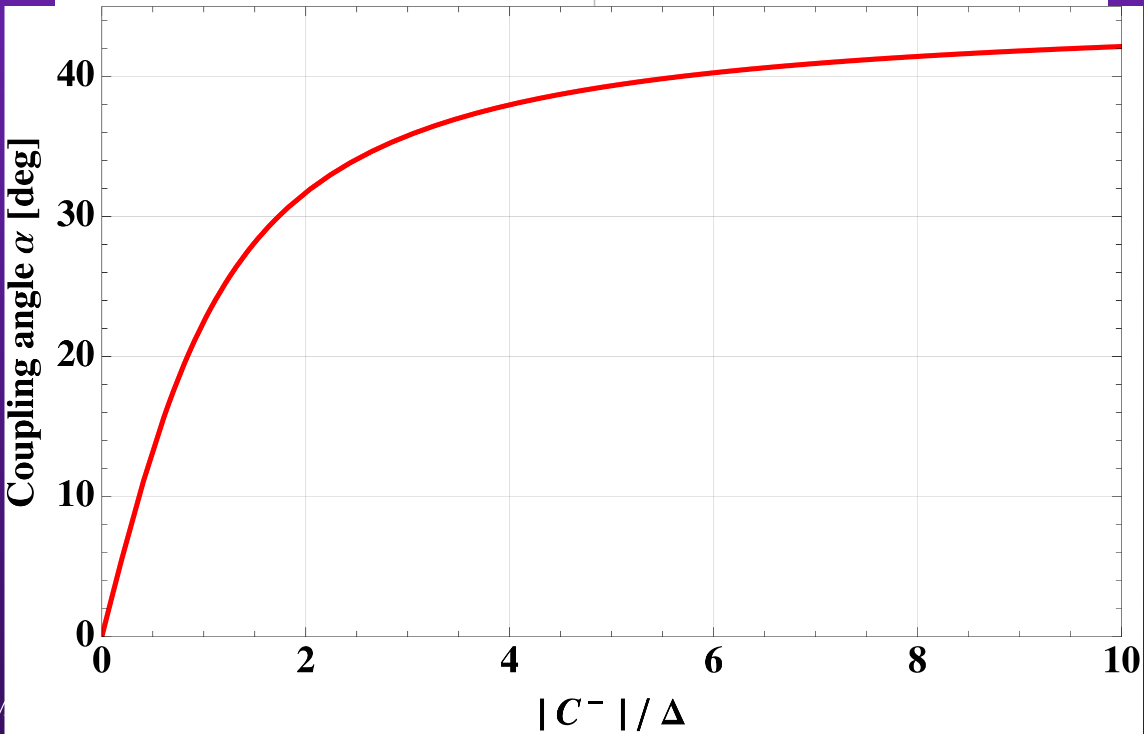


2016





$$Q_u = Q_x - \frac{|C^-|}{2}\tan\alpha$$

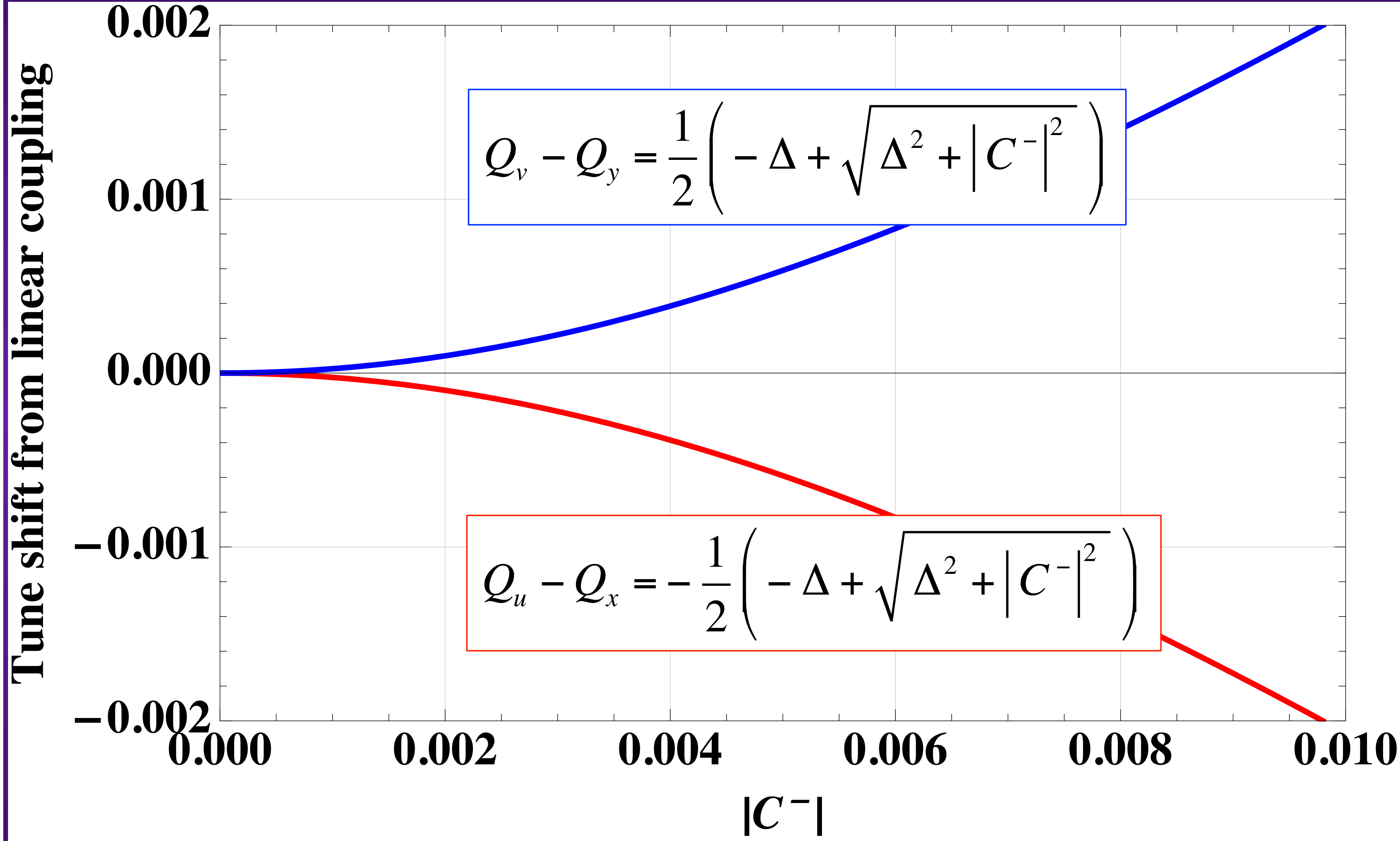
$$Q_v = Q_y + \frac{|C^-|}{2}\tan\alpha$$

$$\Delta = Q_y + l - Q_x = q_y - q_x$$
$$= Q_{sep}$$

$$\tan(2\alpha) = \frac{|C^-|}{\Delta}$$

Elias M

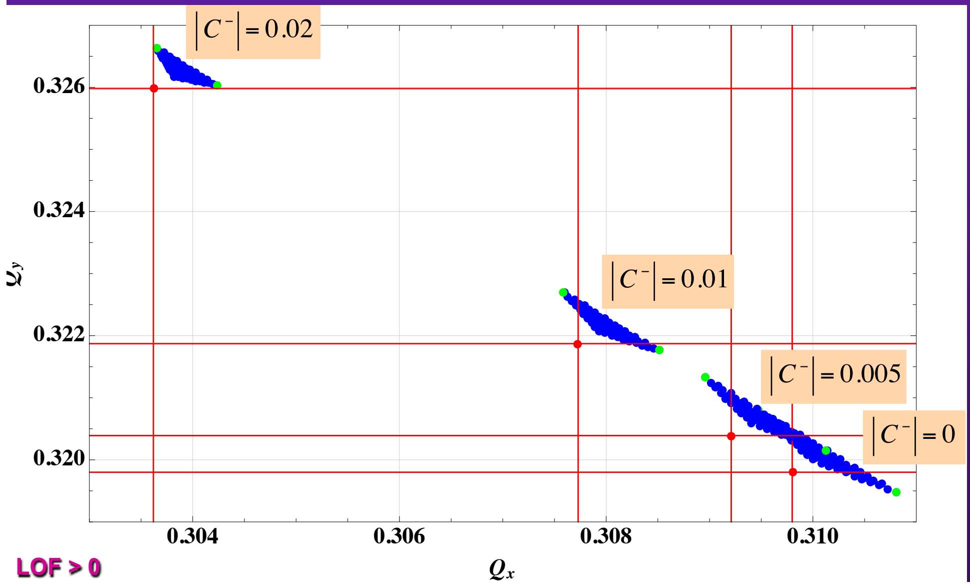
2016



0.002
0.001
0.000
−0.001
−0.002
0.000
0.002
0.004
0.006
0.008
0.010
Tune shift from linear coupling
$|C^-|$
$Q_v - Q_y = \frac{1}{2}\left(-\Delta + \sqrt{\Delta^2 + \left|C^-\right|^2}\right)$
$Q_u - Q_x = -\frac{1}{2}\left(-\Delta + \sqrt{\Delta^2 + \left|C^-\right|^2}\right)$

2016

- Similar (but much smaller) behaviour seen



LOF > 0

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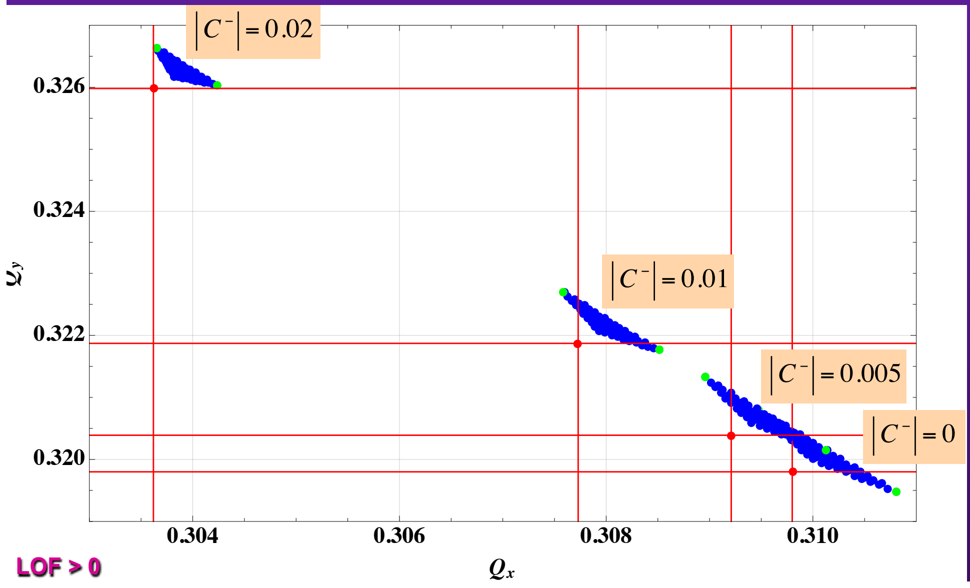
- Another ingredient is needed => Amplitude-dependent C^-



LOF > 0

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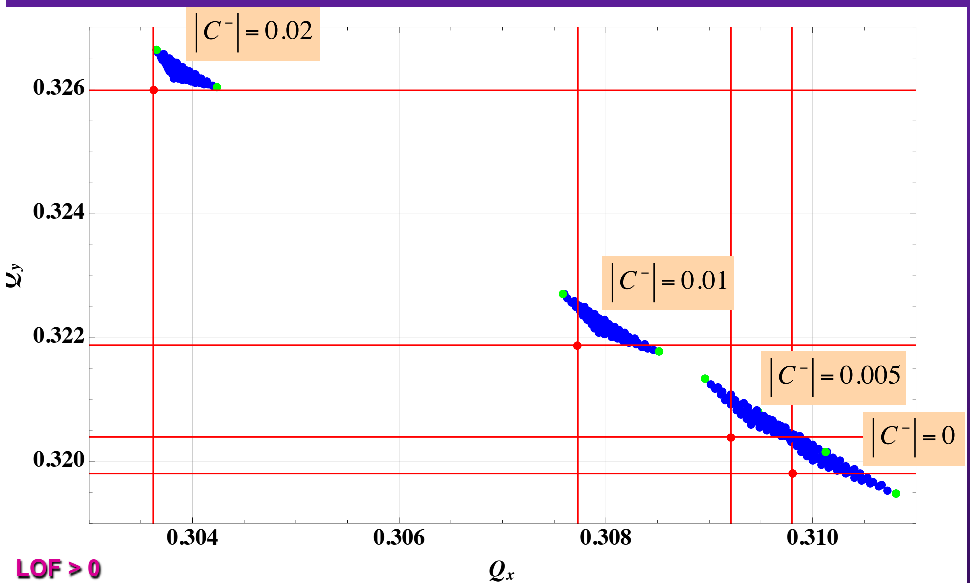
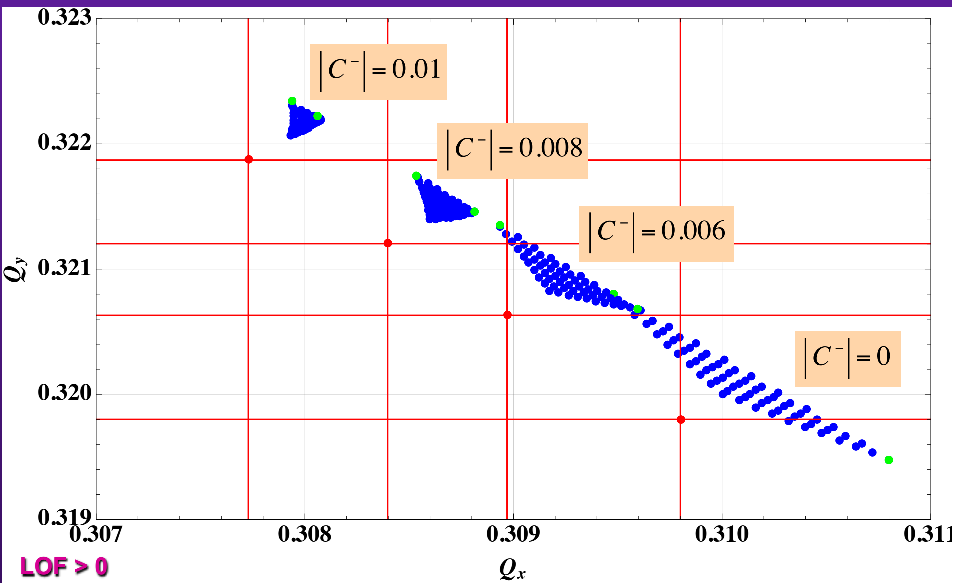
- Another ingredient is needed => Amplitude-dependent C-
  - Example found empirically:

$$\left|C^-\right| \times \left[1 + 0.15\left(J_x - J_y\right)\right]$$





2016

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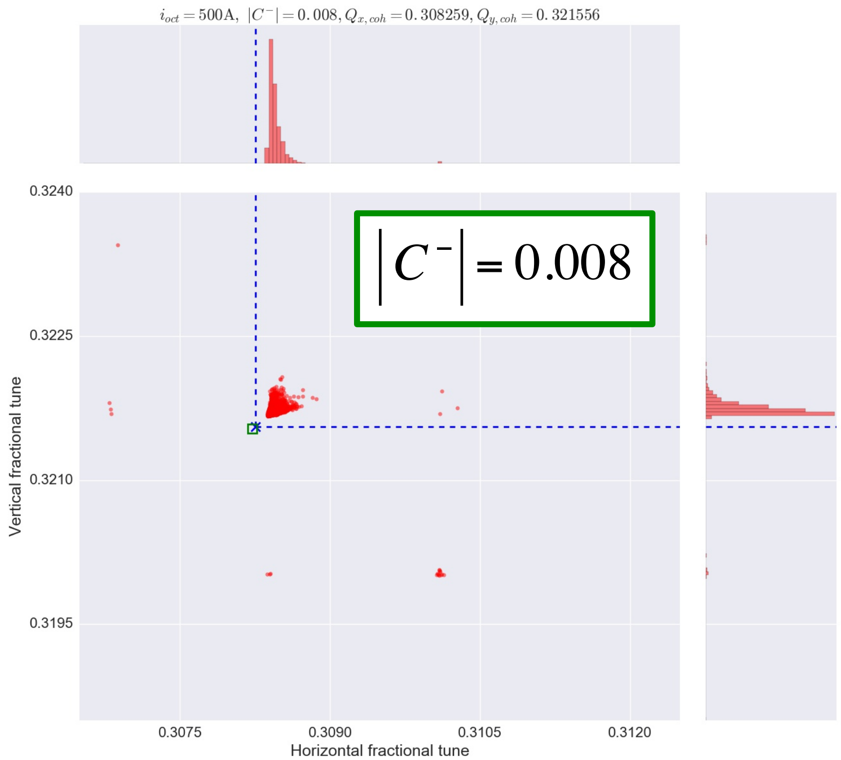
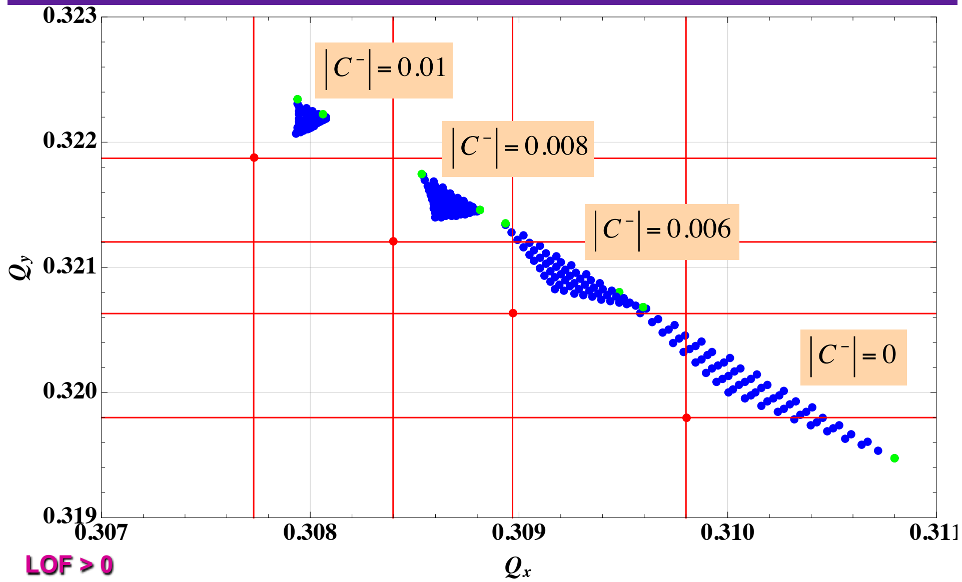
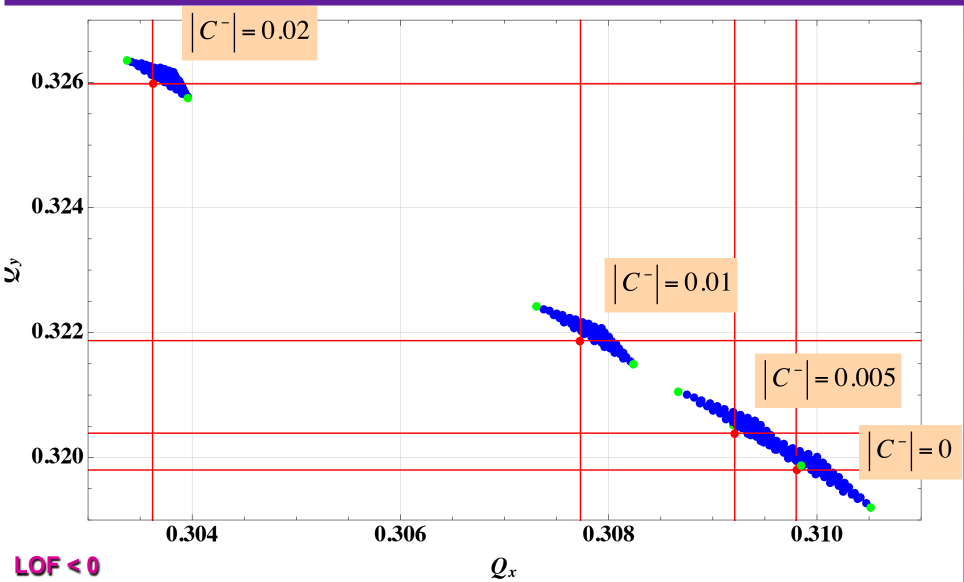


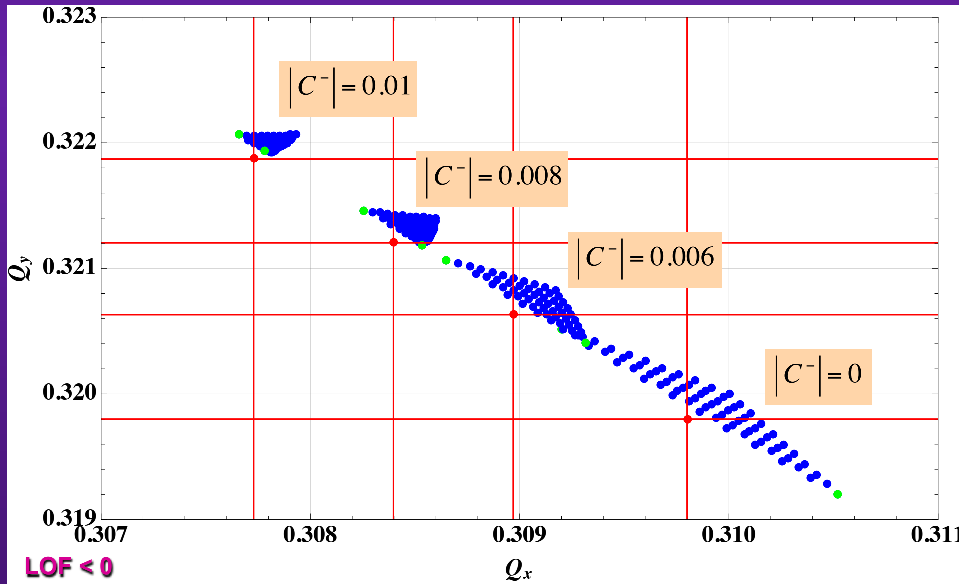


2016

LOF < 0

$$\left|C^-\right| \times \left[1 - 0.15\left(J_x - J_y \right) \right]$$





2016

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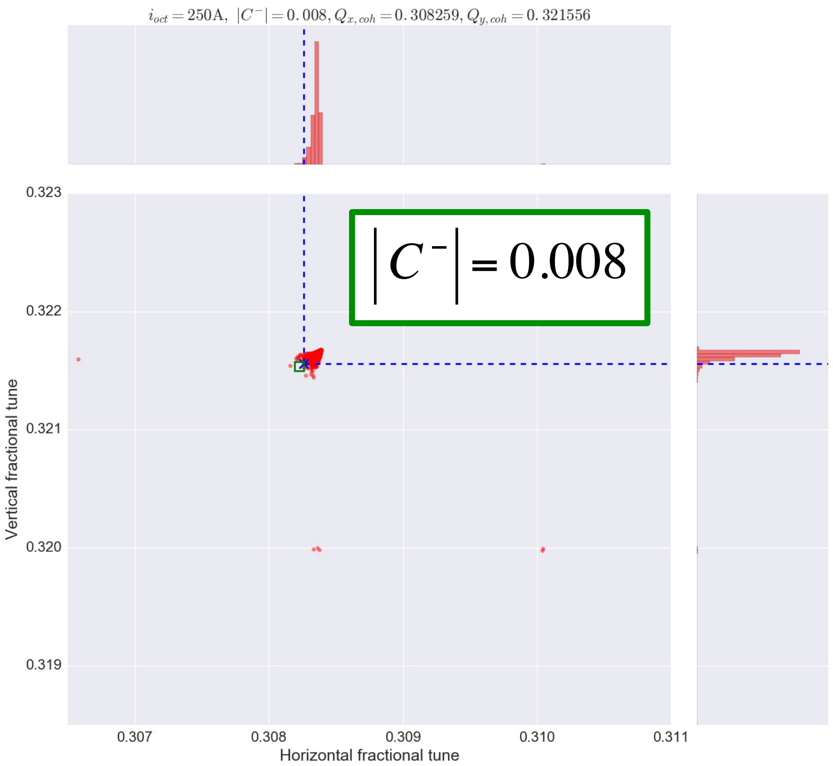

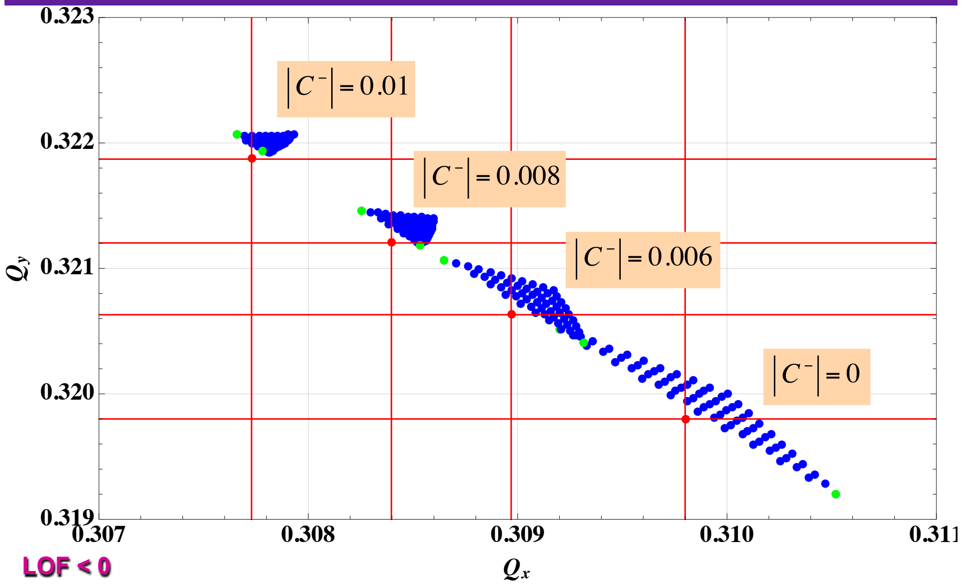

2016

- See also R. Tomas et al., "Amplitude dependent closest tune approach" (submitted to PRAB) => However, the amplitude-dependent C^- discussed before is not the same as the one in the paper and has been deduced empirically => To be continued…

2016

- **Dedicated instability measurements in the LHC on 16/04/2016**

2016

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  - **1) During the betatron squeeze**

2016

- **Dedicated instability measurements in the LHC on 16/04/2016**
  - **1) During the betatron squeeze**
  - **2) At top energy (before the betatron squeeze)**

2016

Transverse damper

- 1) During the betatron squeeze: ADT on, Q’ ~ 9 and LOF = + 285 A

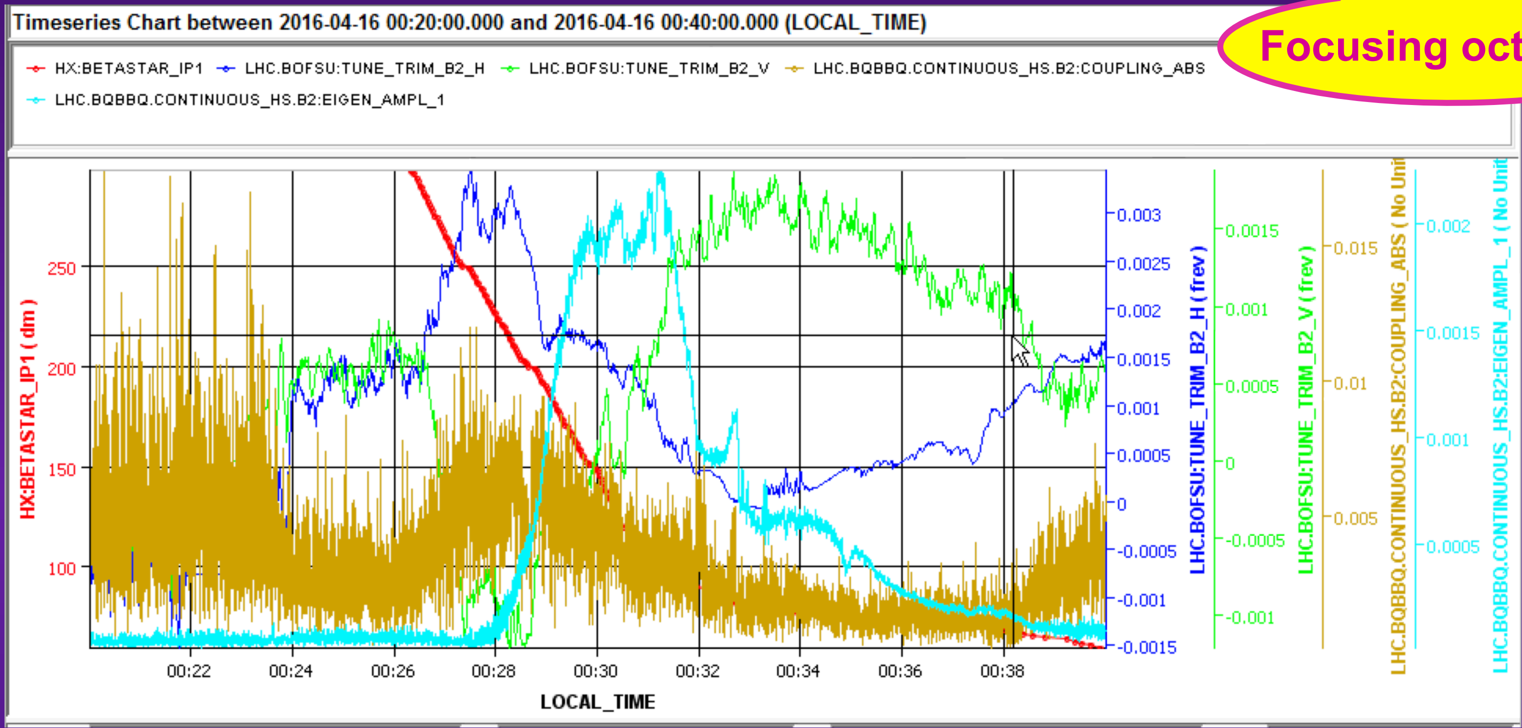
Focusing octupoles

2016

Transverse damper

- 1) During the betatron squeeze: **ADT on, Q' ~ 9 and LOF = + 285 A**

Focusing octupoles



2016

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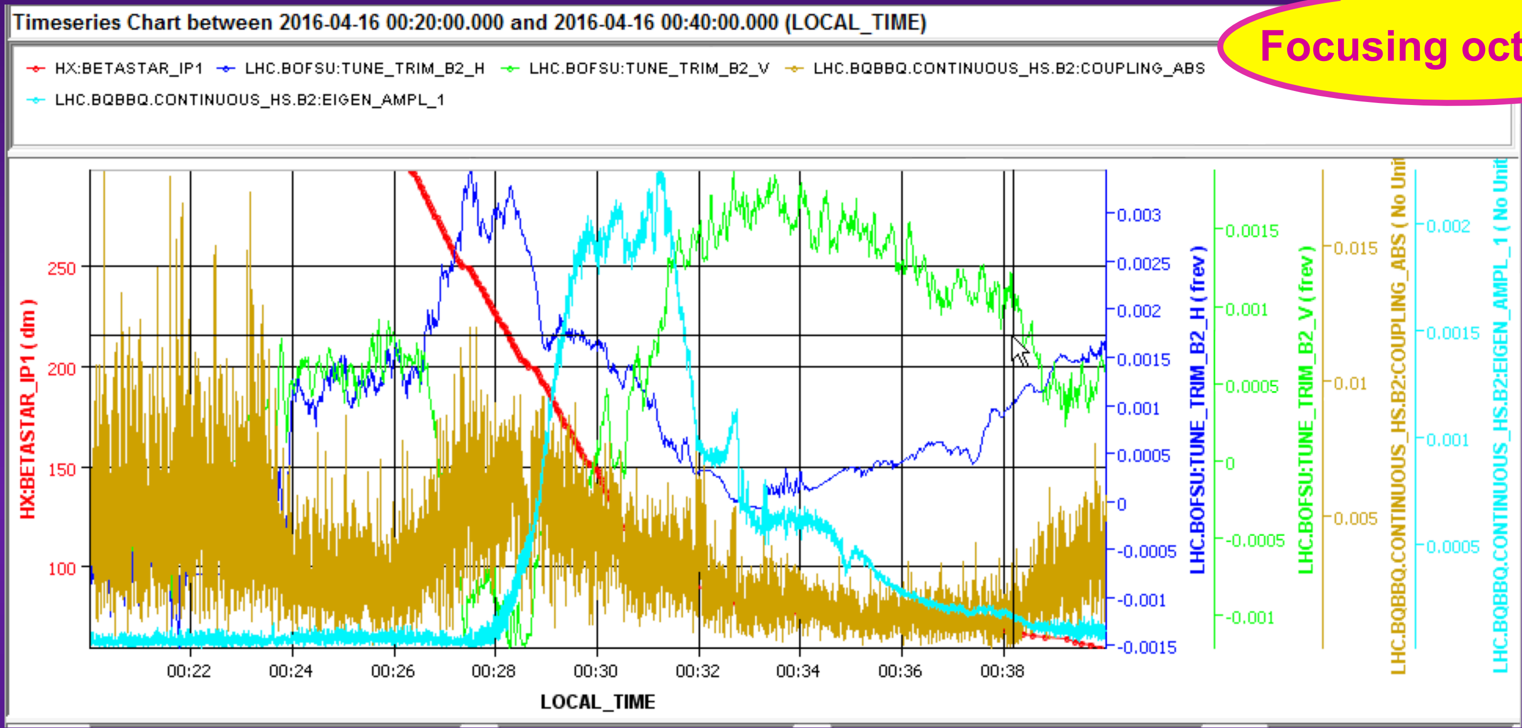

- ✧ Bump of $|C^-|$ ~ 0.008

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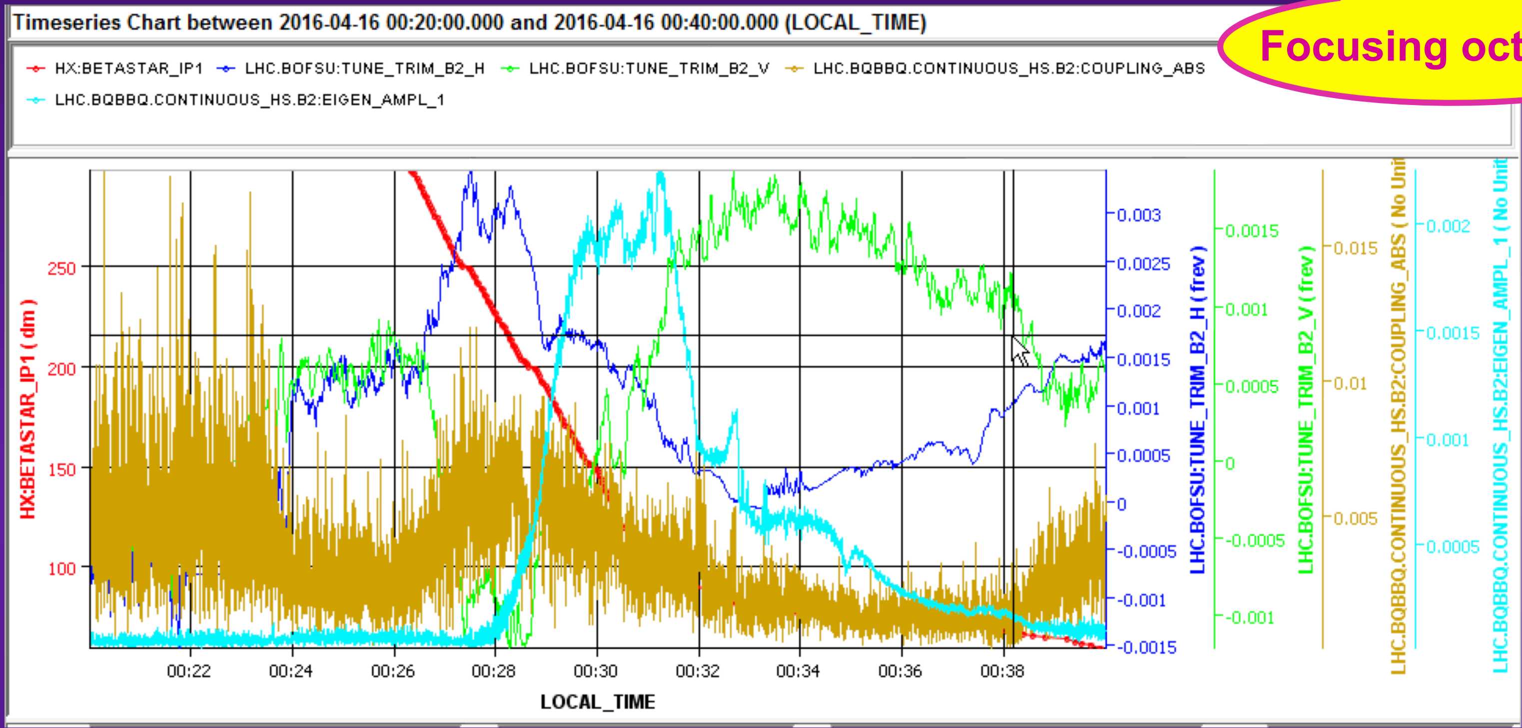

- ✧ Bump of $|C^-|$ ~ 0.008
- ✧ Q_1/Q_2 kept at 0.31/0.32 (tune feedback) => Q_x ~ 0.312 and Q_y ~ 0.318 => $Q_y - Q_x$ ~ 0.006 (i.e. tune feedback is amplifying the coupling effect!)

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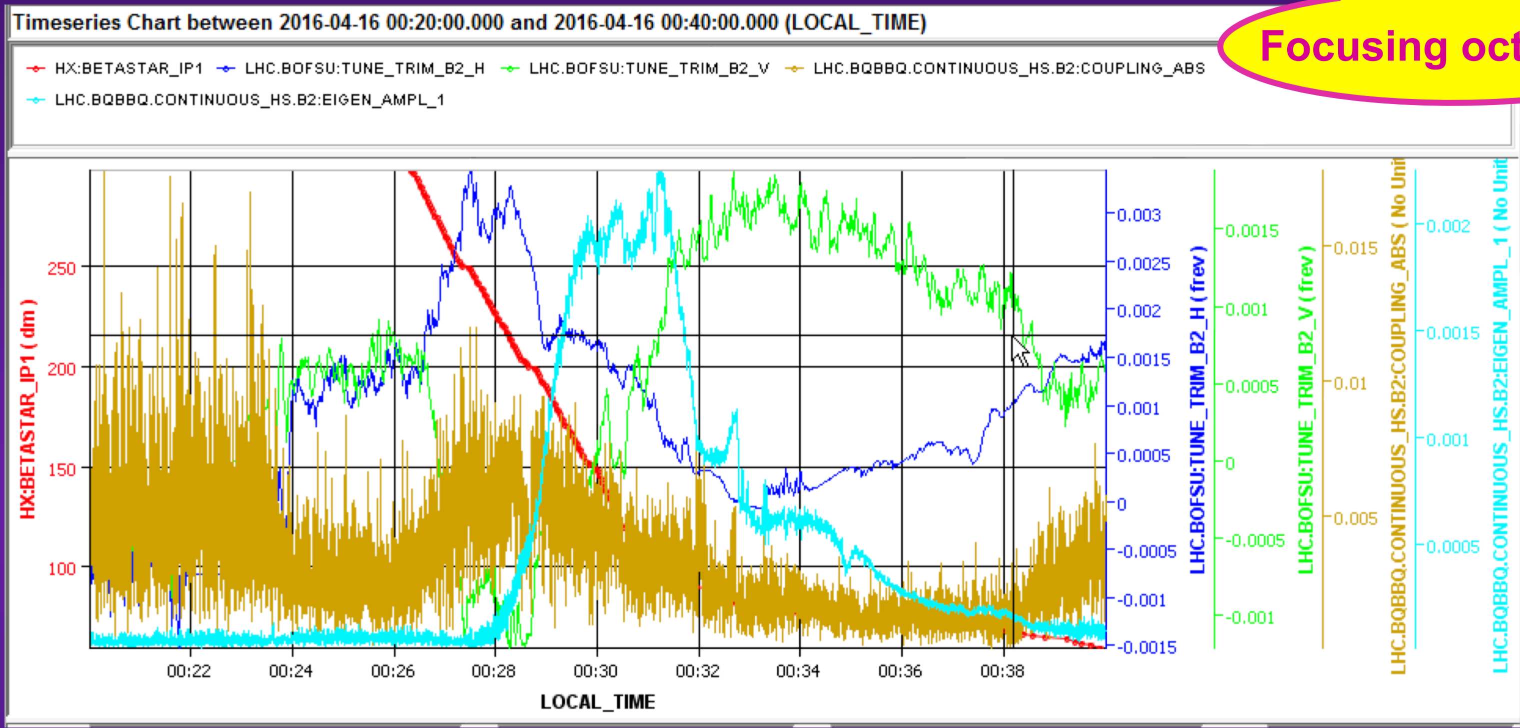

- Bump of $|C^-| \sim 0.008$
- Q_1/Q_2 kept at 0.31/0.32 (tune feedback) => $Q_x \sim 0.312$ and $Q_y \sim 0.318$ => $Q_y - Q_x \sim 0.006$ (i.e. tune feedback is amplifying the coupling effect!)
- Instability observed with LOF = + 285 A, i.e. ~ 4 times higher octupole current than uncoupled threshold

2016

- 2) At top energy (before the betatron squeeze)

2016

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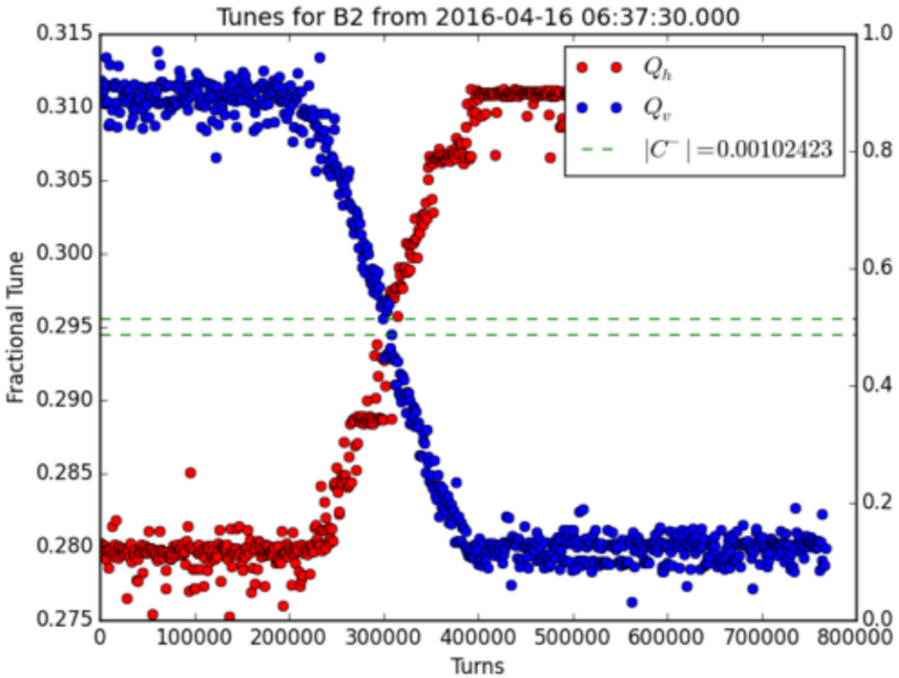
✧ |C-| ~ 0.001 and Q_{sep} = 0.03:

=> Stability for LOF = + 71 A

Courtesy of L.R. Carver



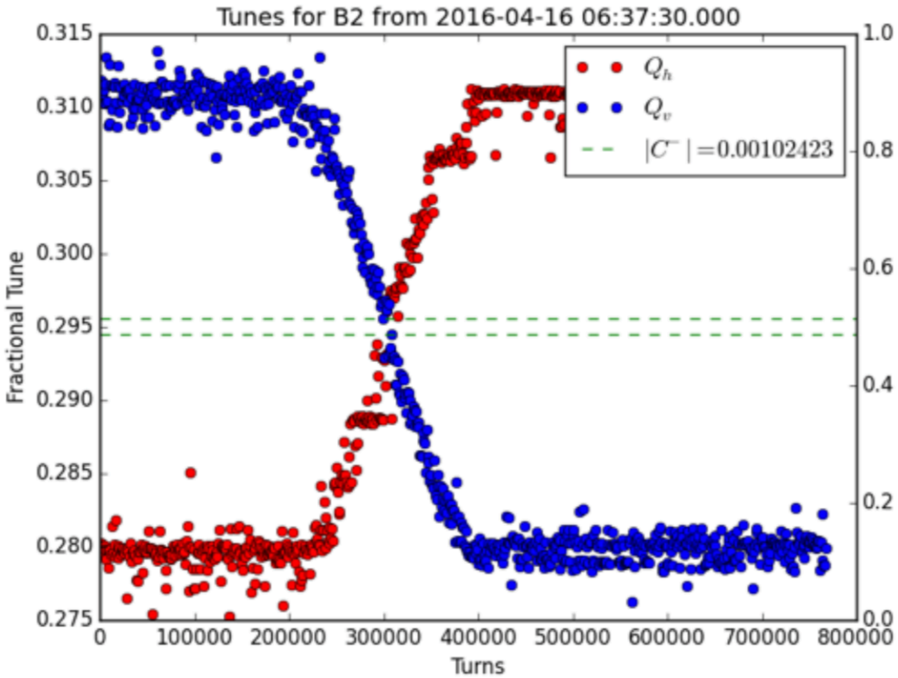
2016

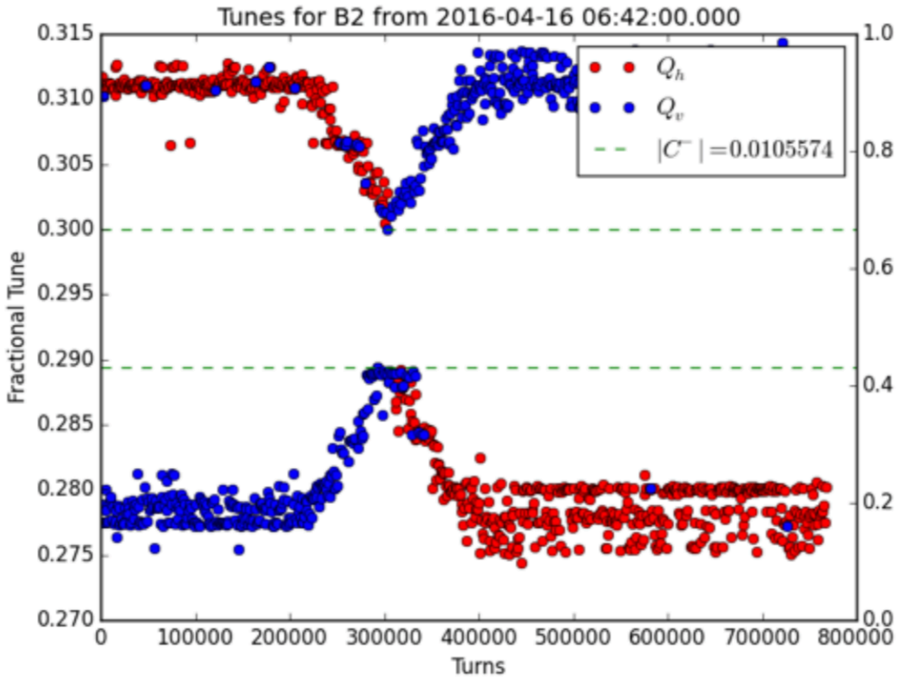
- 2) At top energy (before the betatron squeeze)

✧ |C-| ~ 0.001 and Q_{sep} = 0.03:
=> Stability for LOF = + 71 A

✧ |C-| ~ 0.01 and LOF = + 310 A
=> Instability for Q_{sep} ~ 0.018

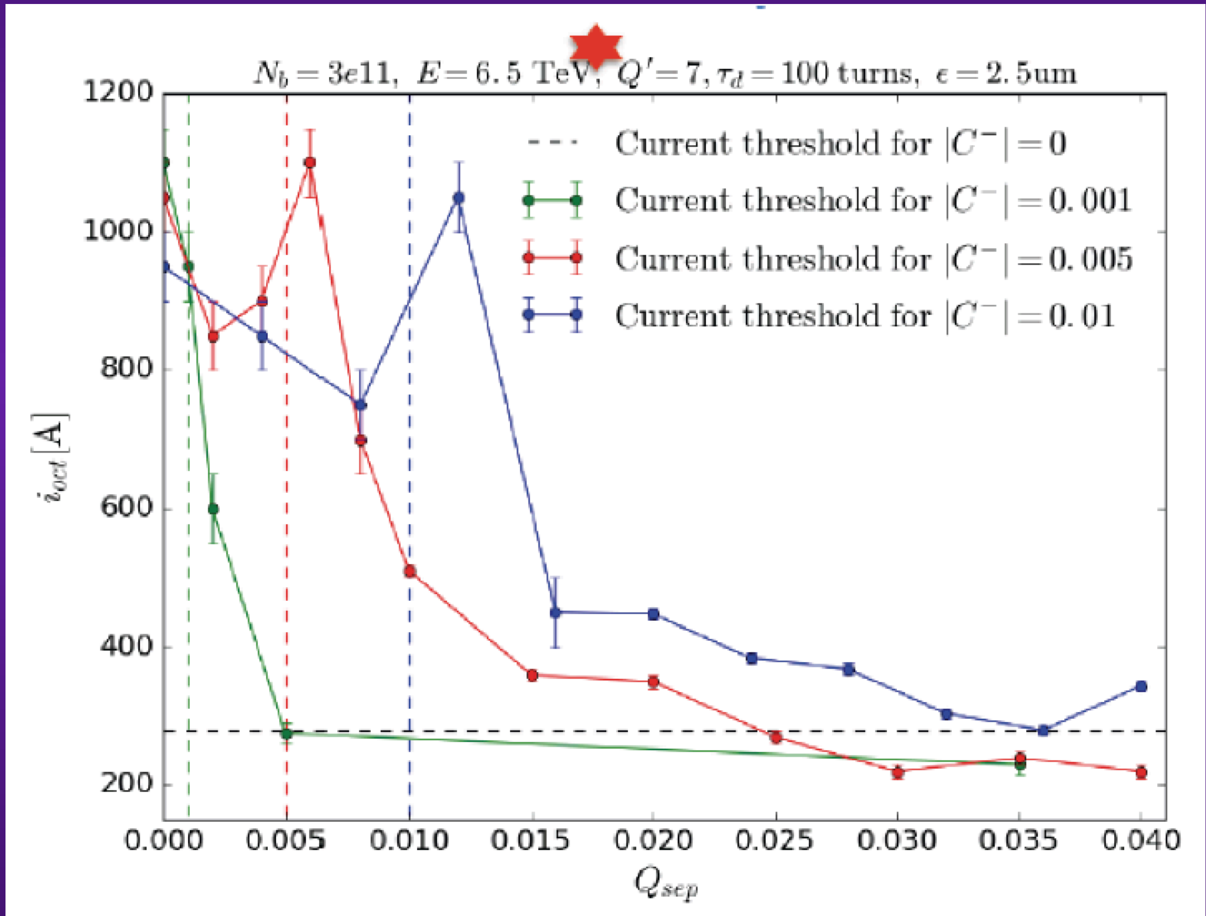
Courtesy of L.R. Carver





2016

- This gives a **factor 310 / 71 = 4.4 increase in Landau octupole current** compared to the uncoupled case



Courtesy of L.R. Carver

2016

- Signs of e-cloud (?) instability in stable beam with batches of 72 bunches for Q' ~ 15

2016

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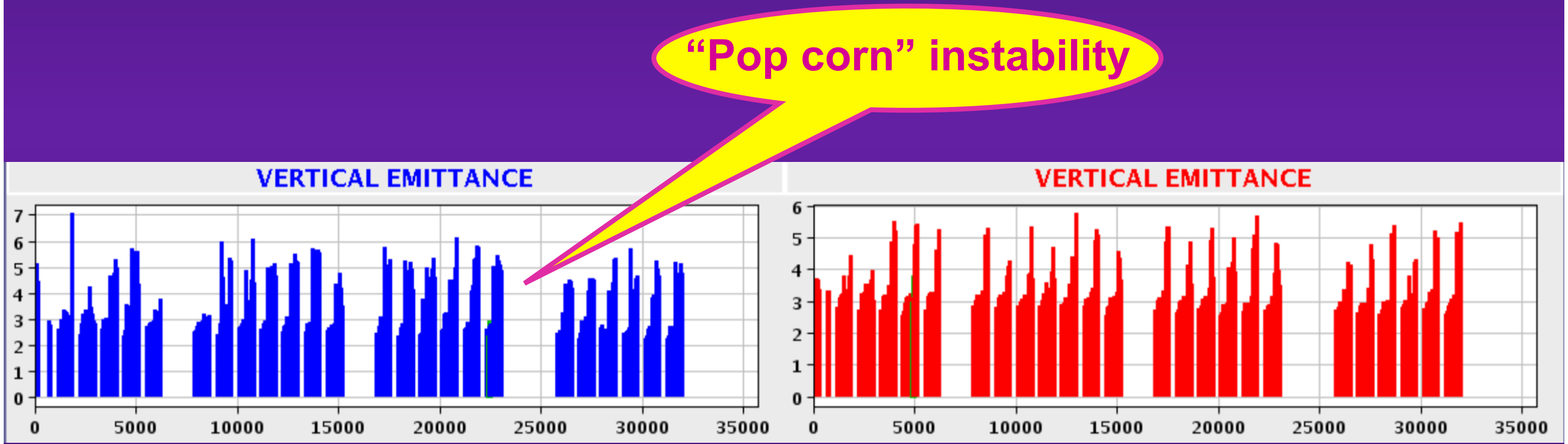
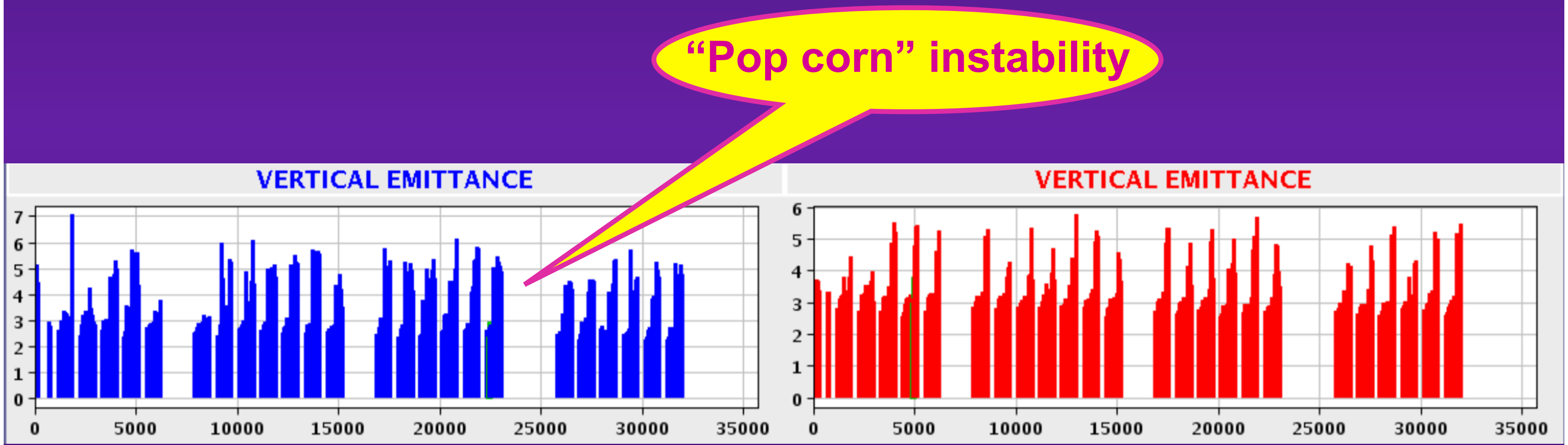


2016

- **Signs of e-cloud (?) instability in stable beam with batches of 72 bunches for Q' ~ 15**
  - **Only vertical (B1&B2)**



2016

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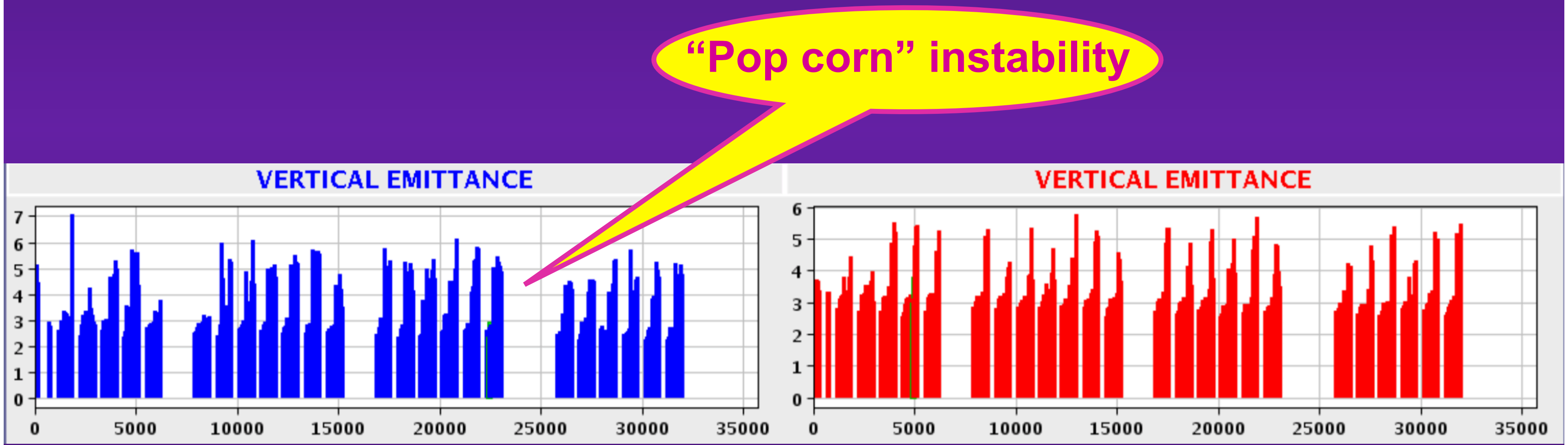

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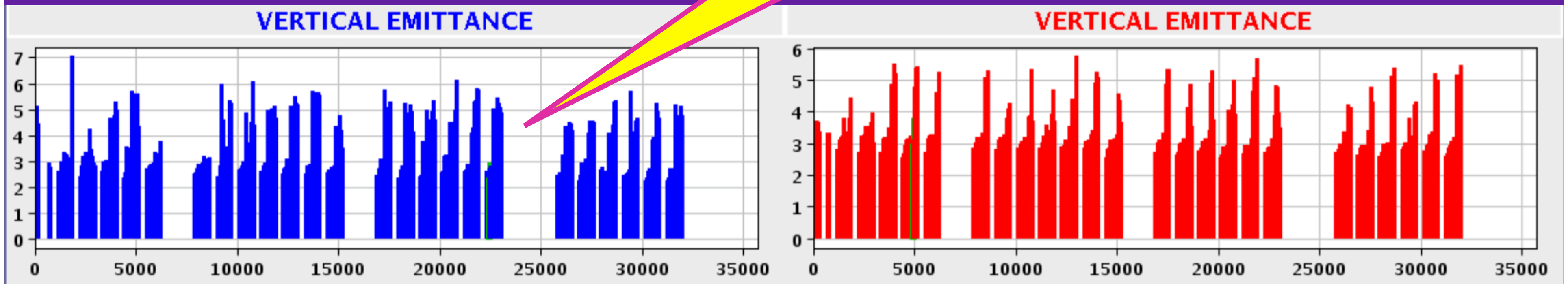
  - **Emittance BU by a factor ~ 2**

"Pop corn" instability



2016

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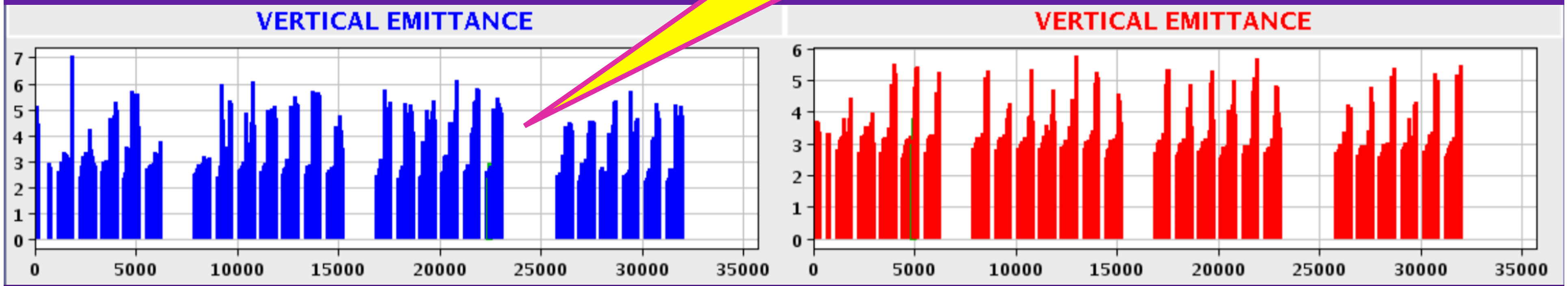

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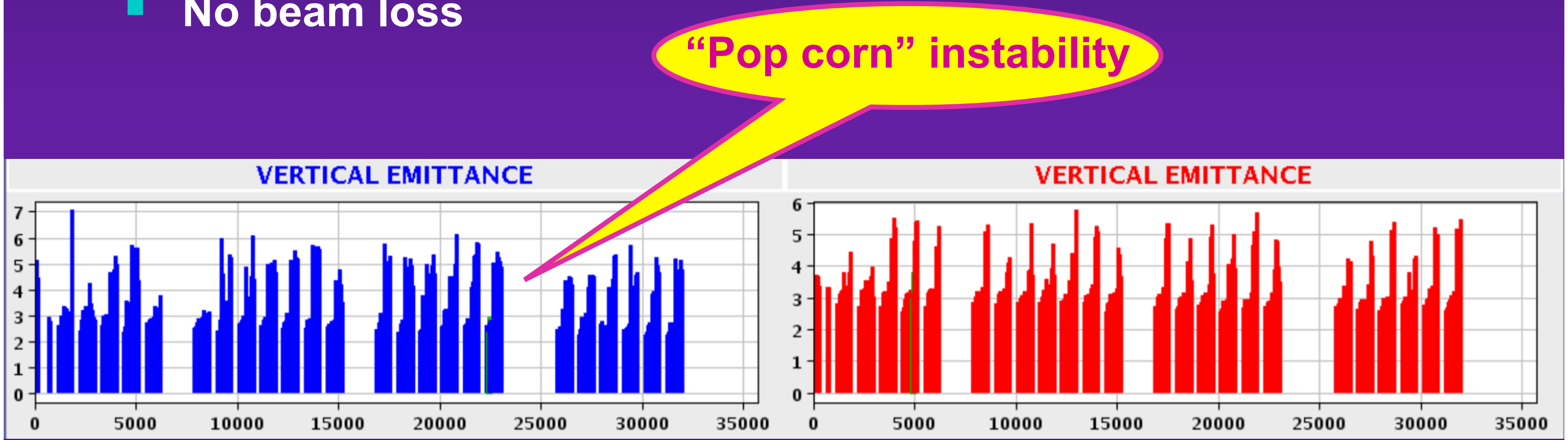
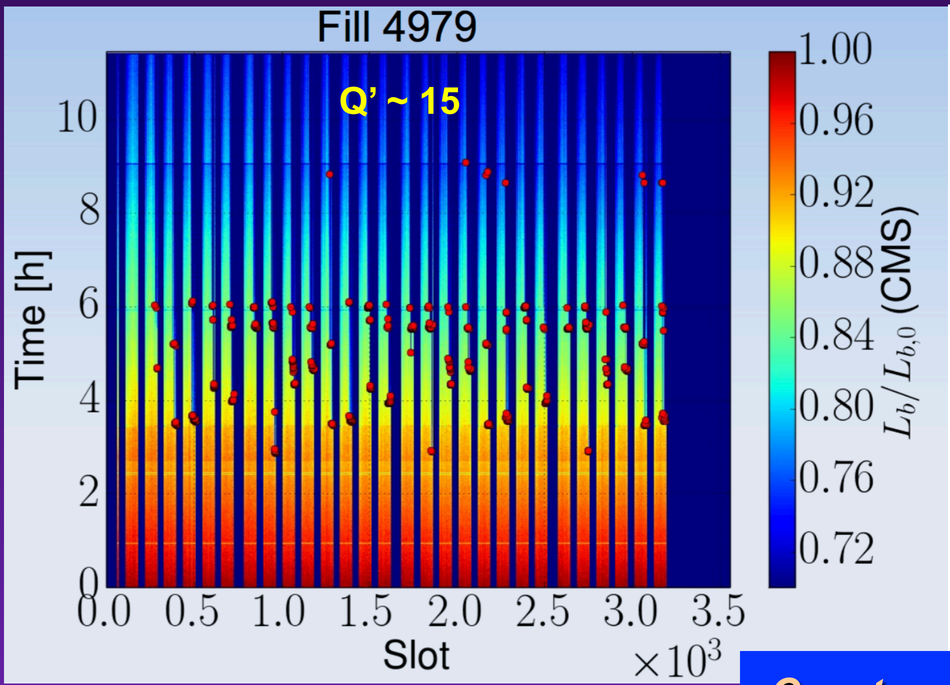
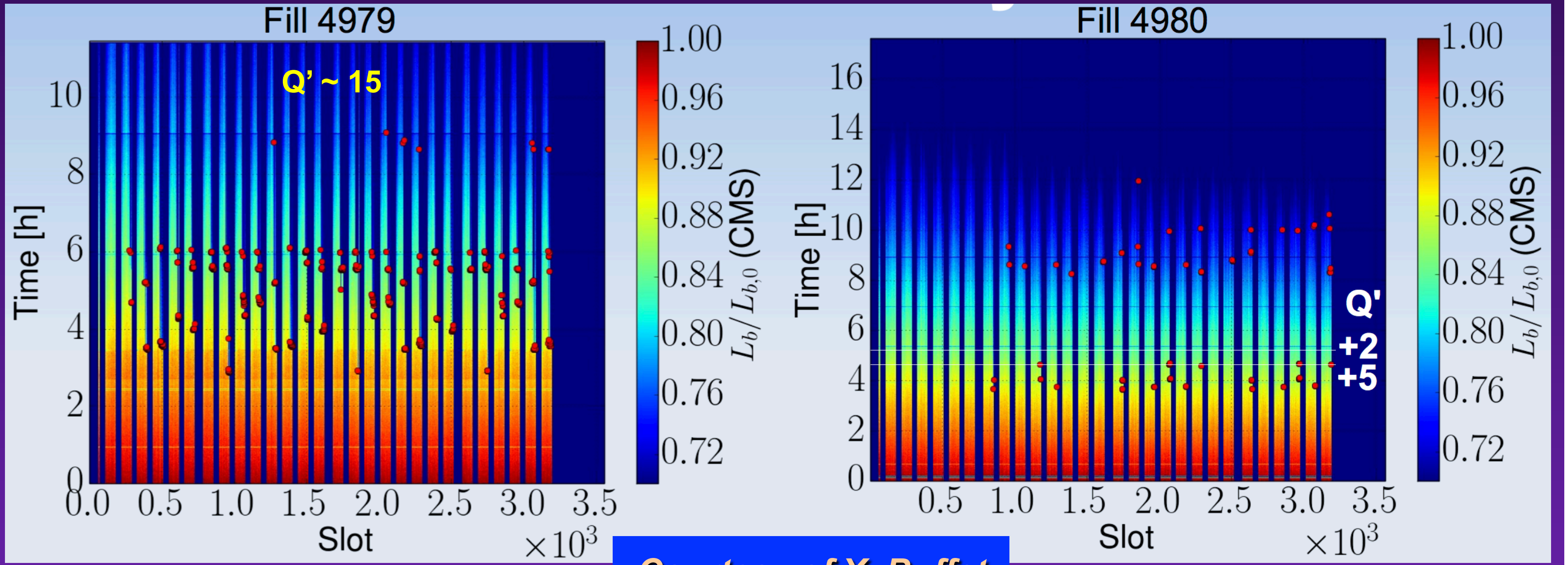


=> Was cured by increasing the vertical chromaticity (+7) in stable beam (to ~ 22)!



Courtesy of X. Buffat



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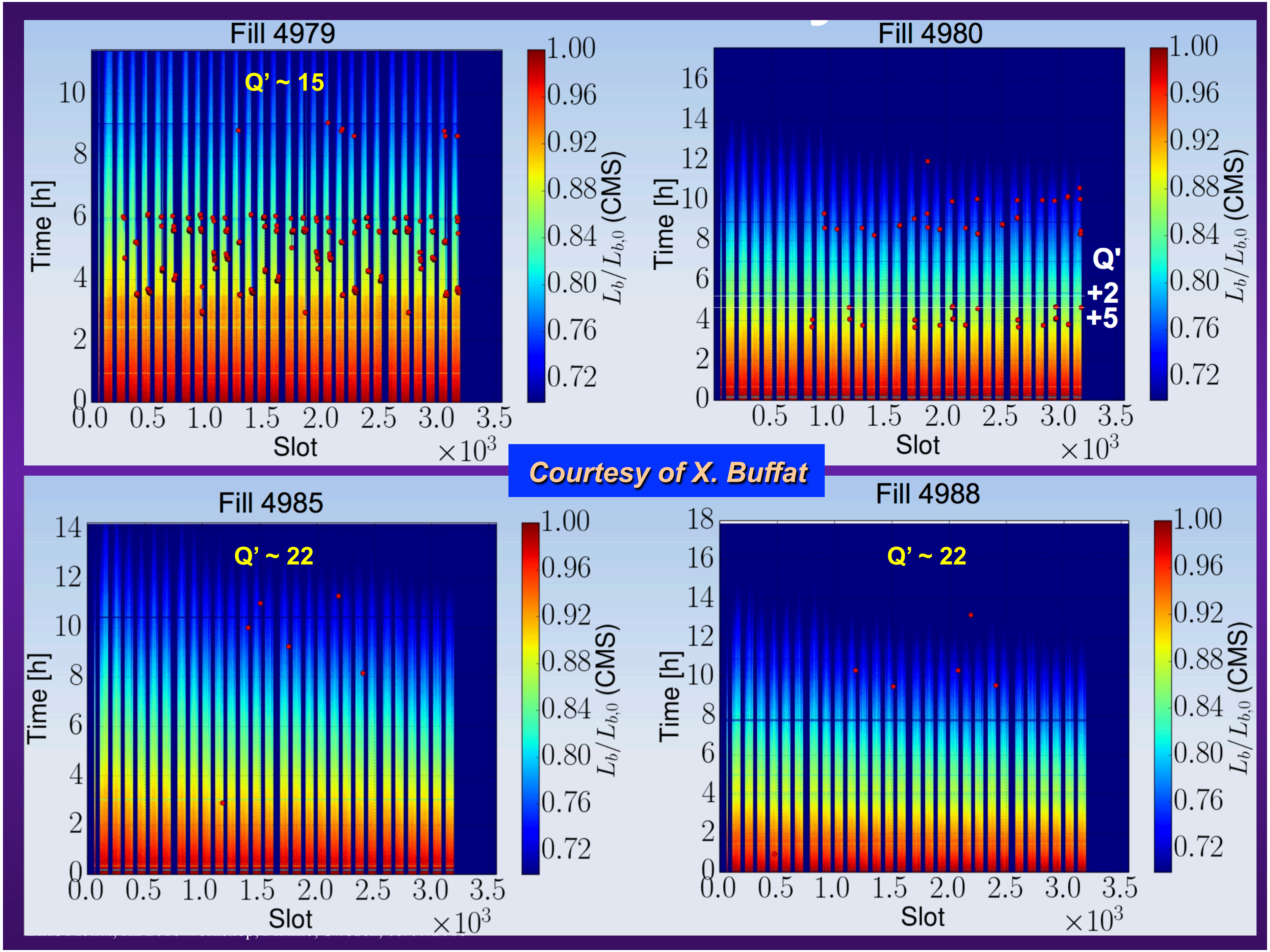
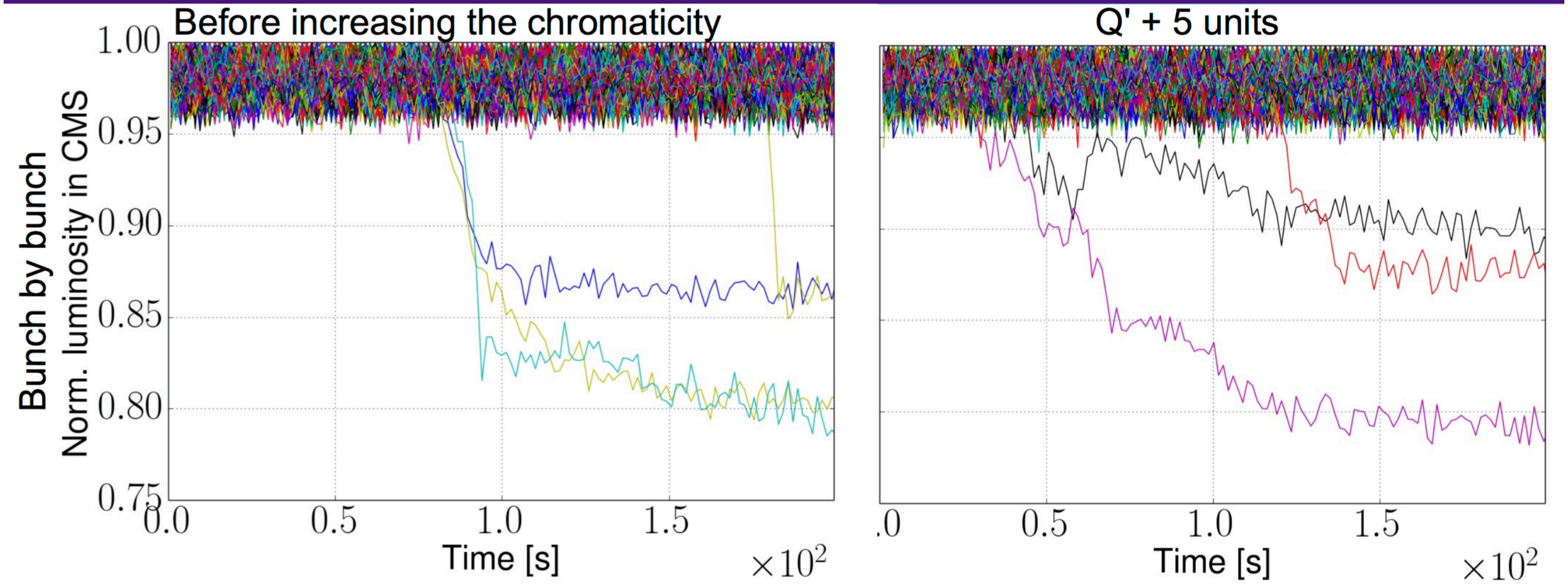

Fill 4979
Q' ~ 15
Time [h]
Slot
$\times 10^3$
$L_b/L_{b,0}$ (CMS)
Fill 4980
Q'
+2
+5
Courtesy of X. Buffat
Fill 4985
Q' ~ 22
Fill 4988
Q' ~ 22

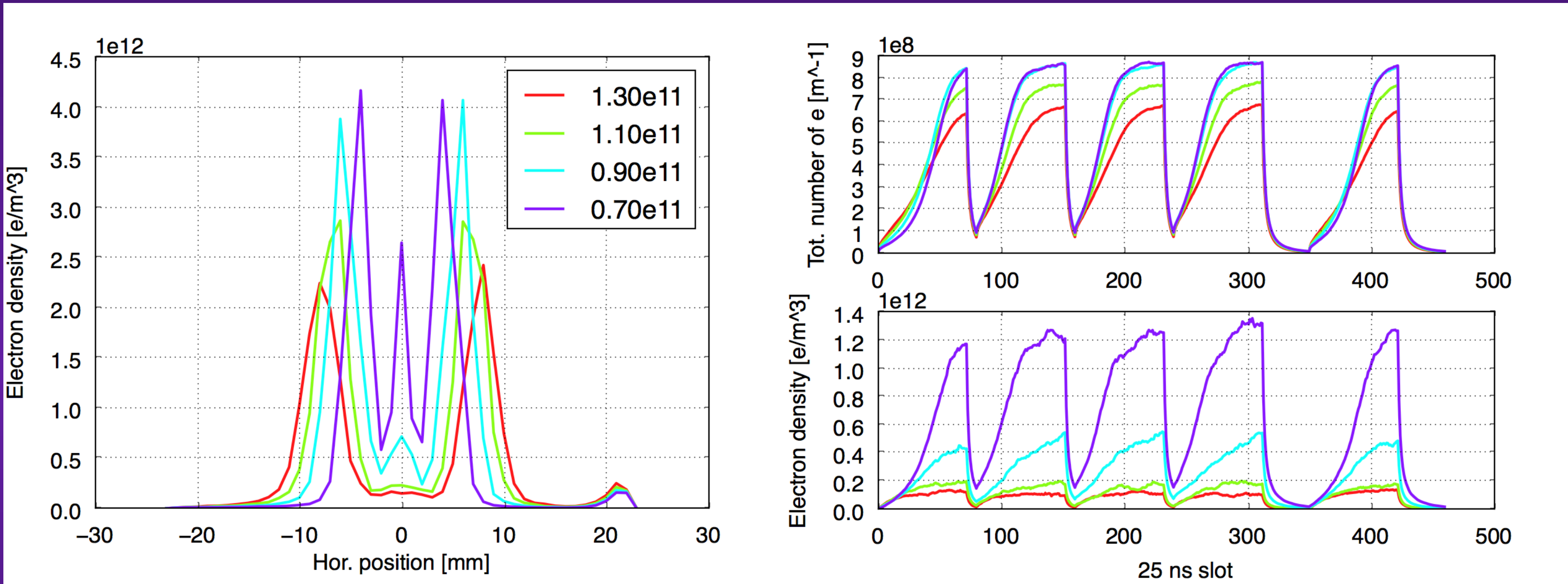
2016

Courtesy of X. Buffat



2016

- **Possible mechanism? (G. Iadarola and G. Rumolo)**



2016

- **Since few days we have been injecting batches of 2 × 48 bunches from the SPS instead of 1 batch of 72 bunches**

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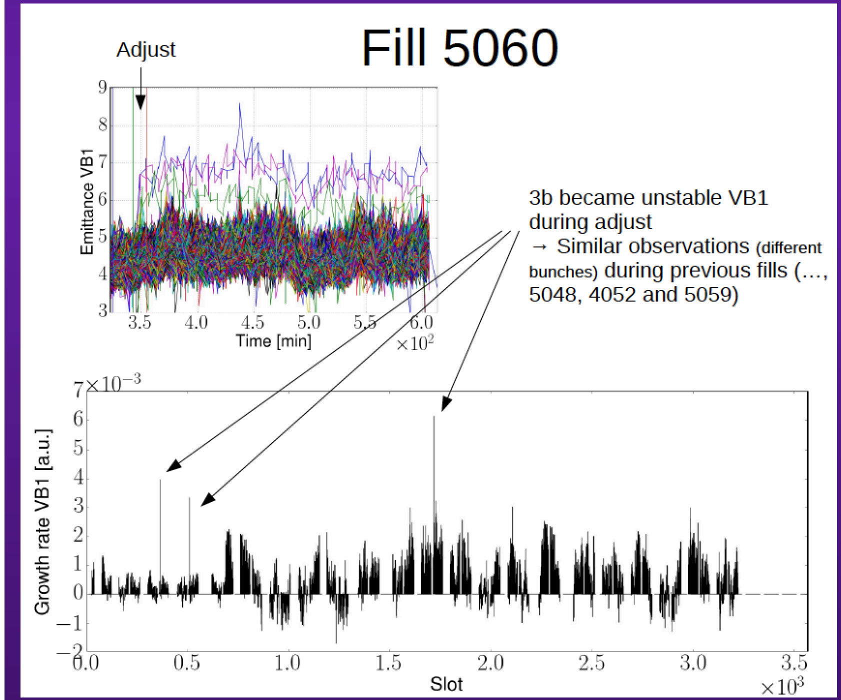

Courtesy of X. Buffat

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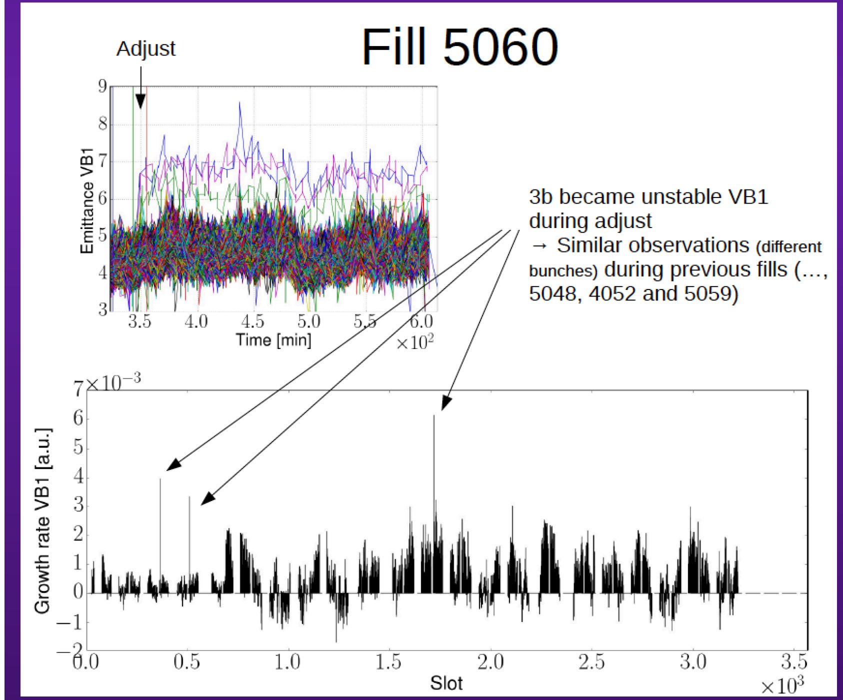

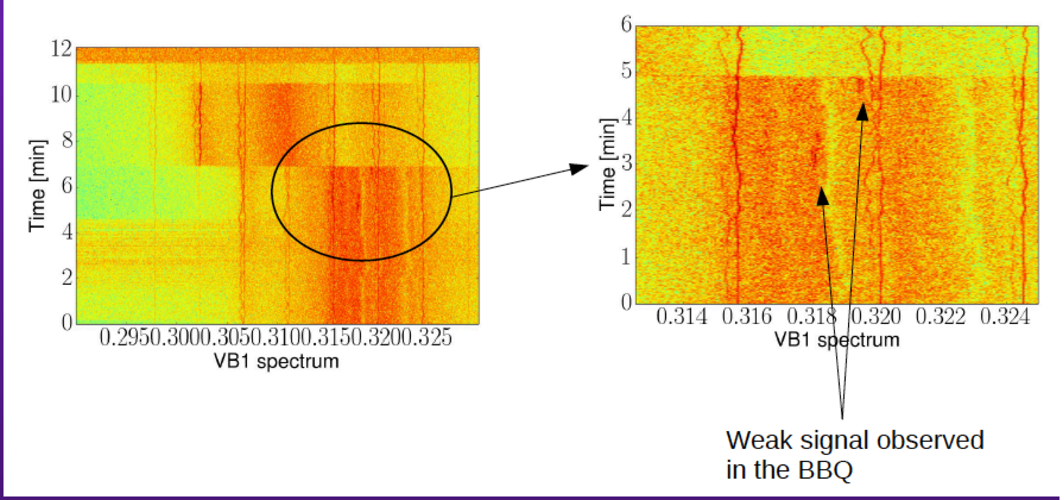

Courtesy of X. Buffat

2016

- **Actions taken**

2016

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  - **Linear coupling corrected all along the cycle and in particular during betatron squeeze**

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2016

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  - **Laslett tune shifts now corrected automatically at injection**
  - **Vertical chromaticities increased by 7 units in stable beam (to reach values of ~ 20-25) => Almost completely suppressed vertical emittance blow-up**
  - **Next: try and measure vertical tune shift along a batch during stable beam to try and confirm the proposed mechanism for beam instabilities in stable beam => Expected tune shift of the order of 10^{-4}…**

2016

- **Lessons learned**

2016

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  - **Linear coupling has to be well corrected all along the LHC cycle to avoid using too much octupole current**

2016

- **Lessons learned**
  - **Linear coupling has to be well corrected all along the LHC cycle to avoid using too much octupole current**
  - **Even in the presence of a large tune spread in stable beam (due to BBHO) the beam can become unstable**

2016

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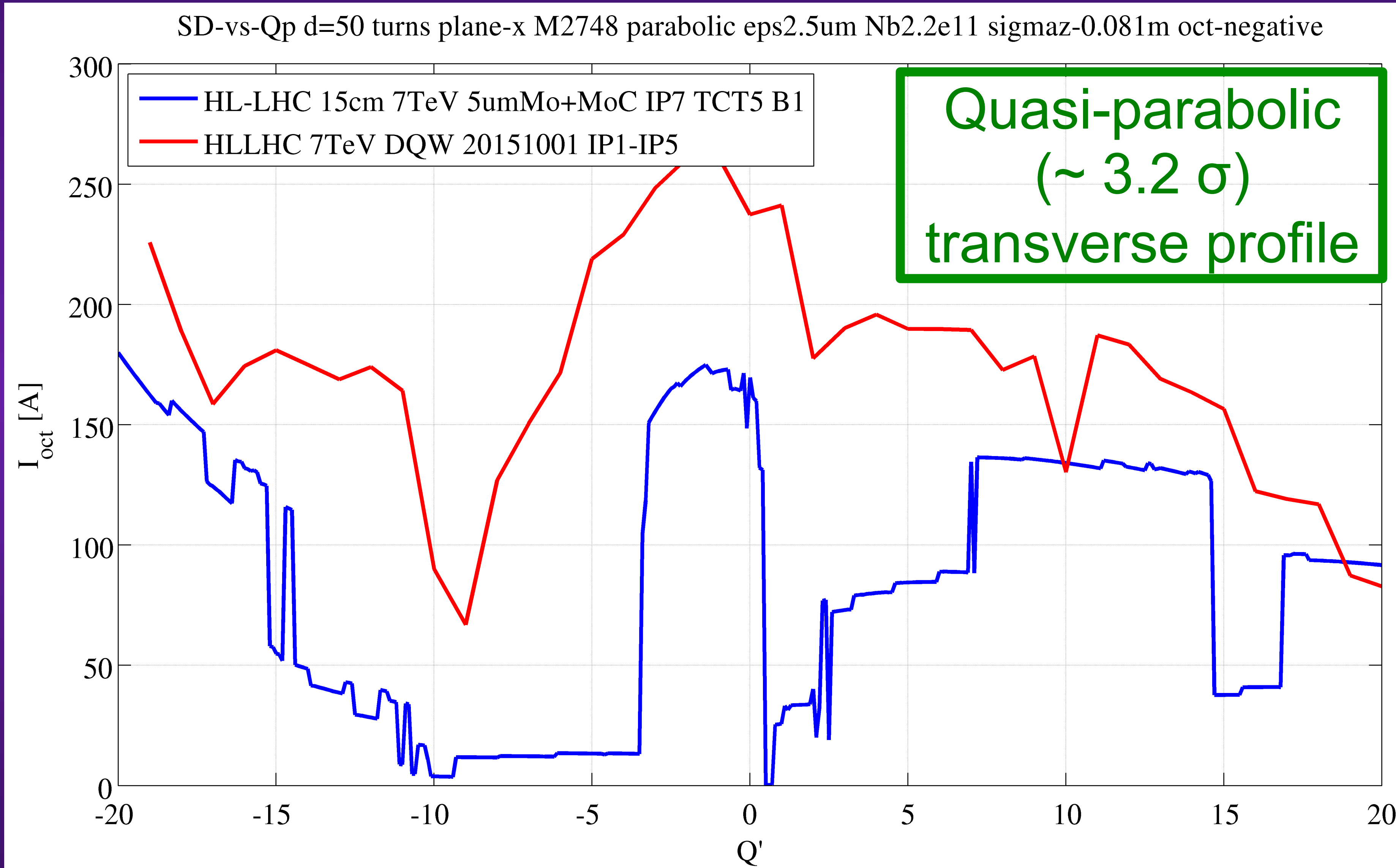

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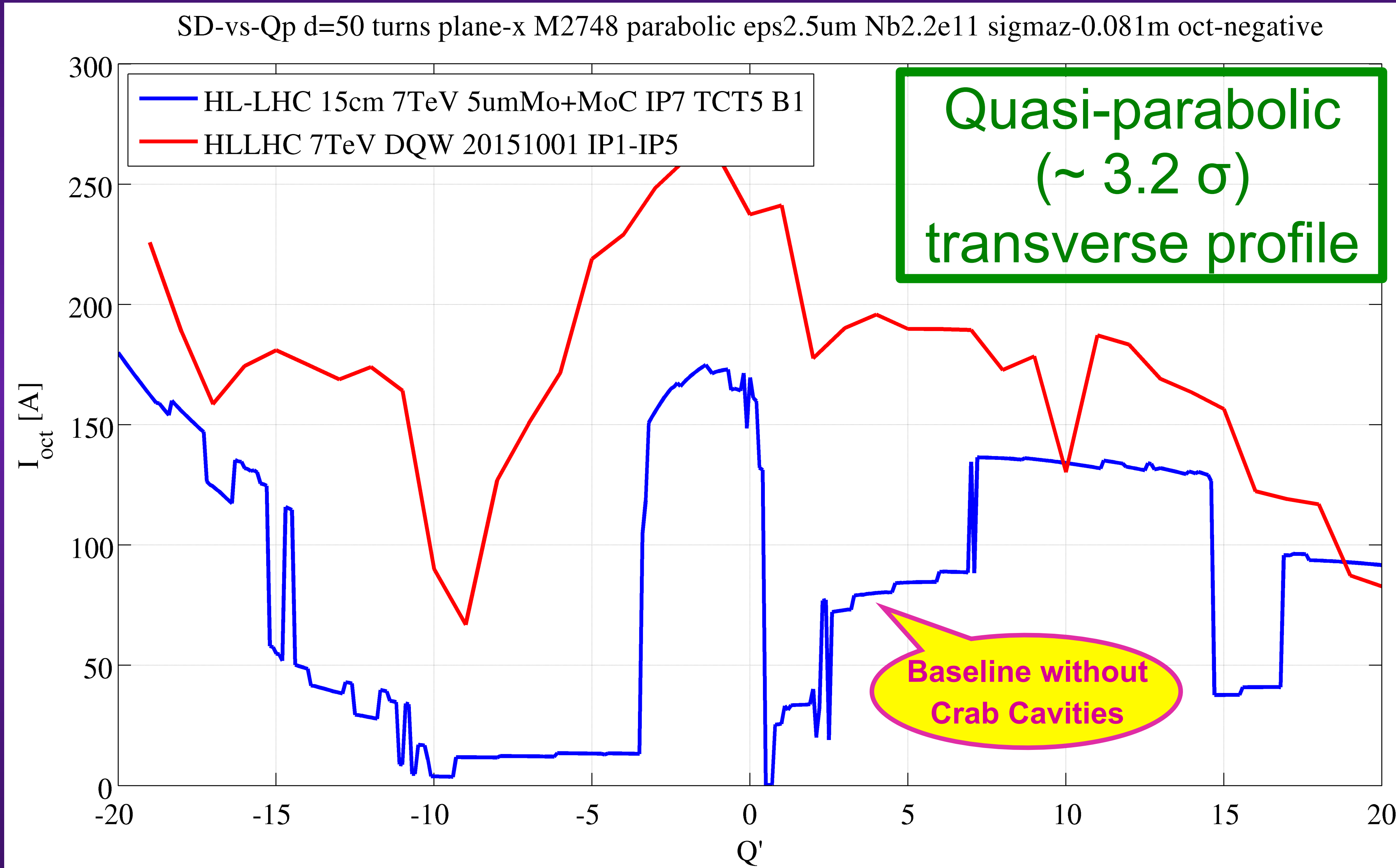

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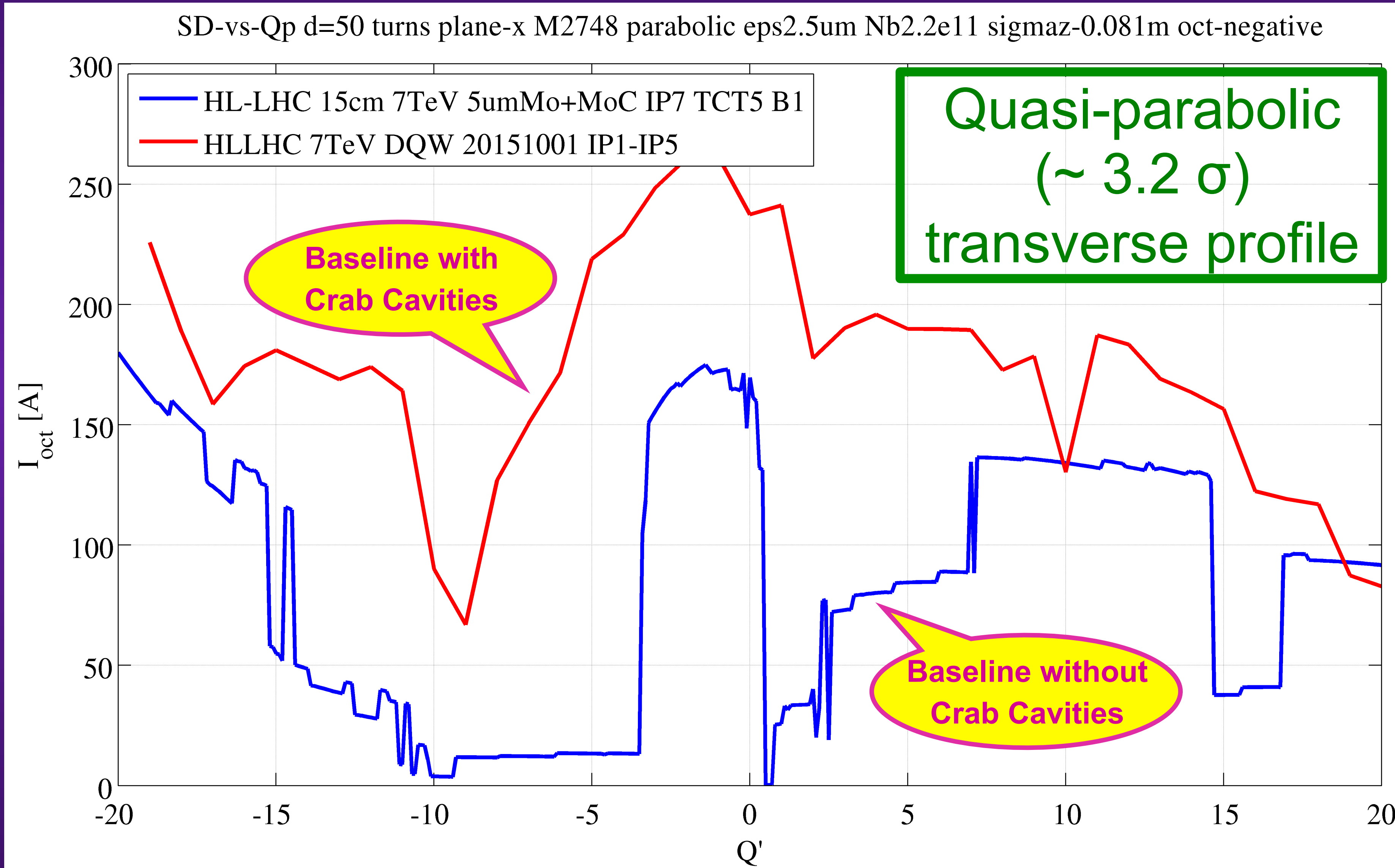

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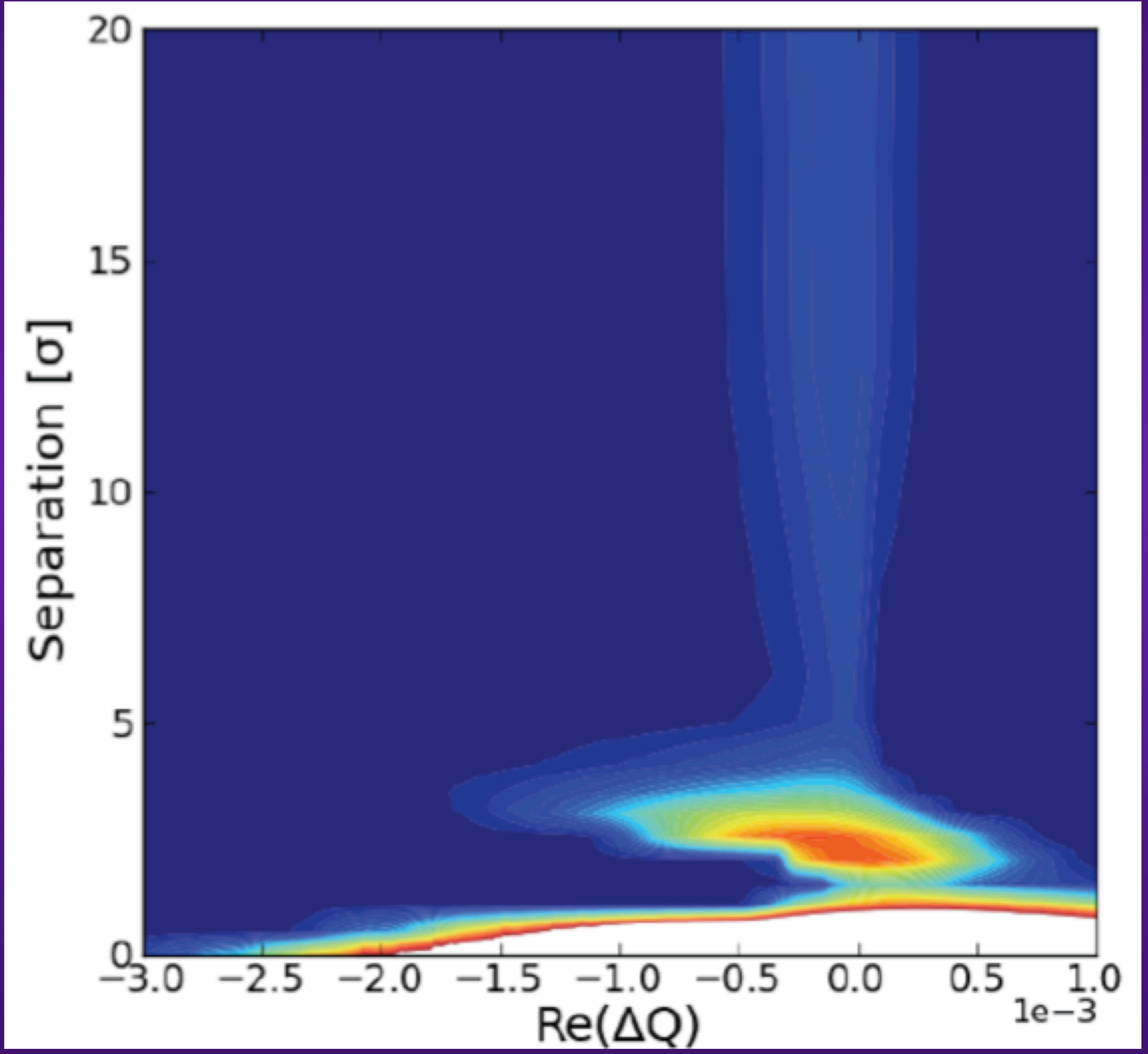

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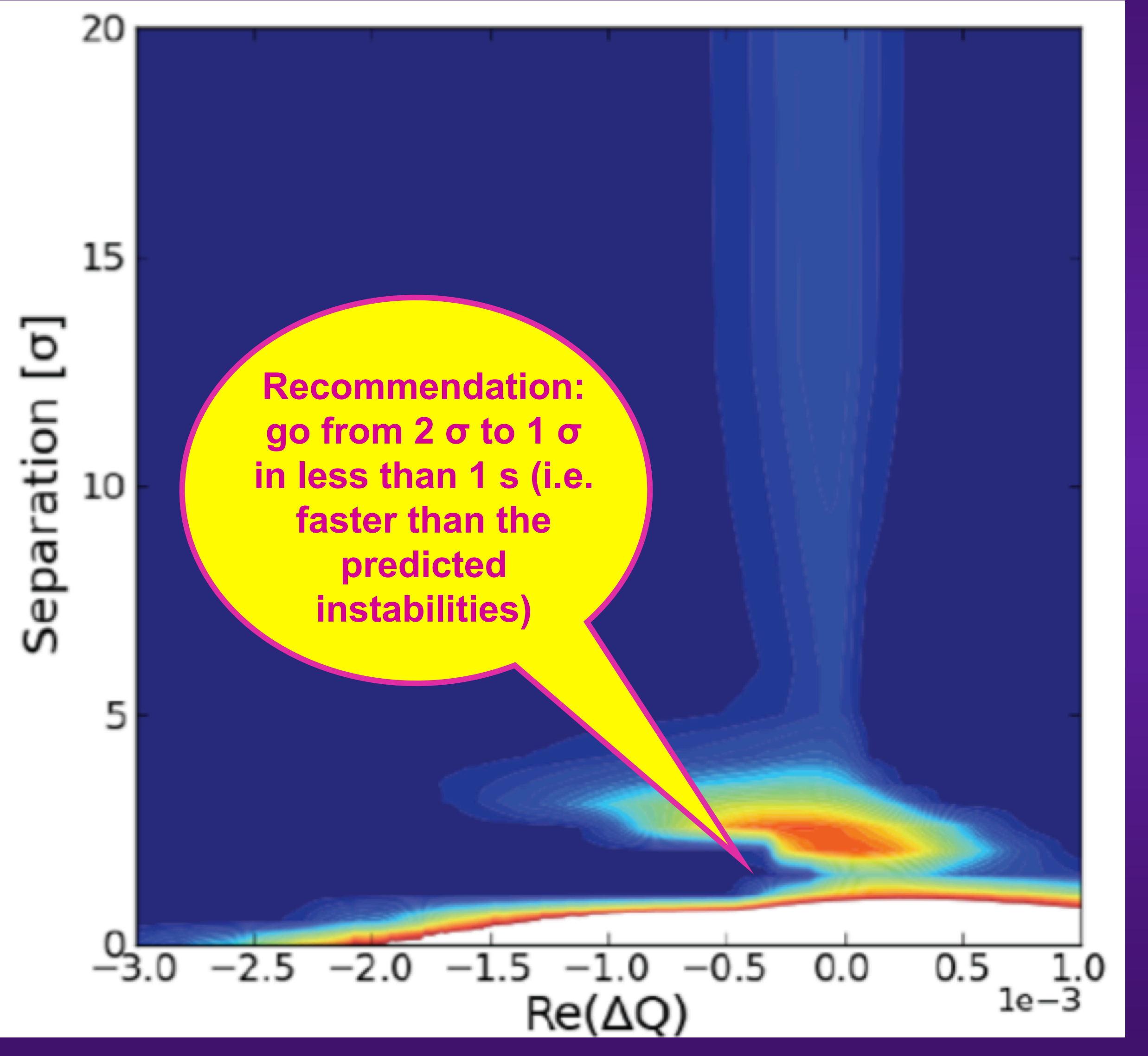

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