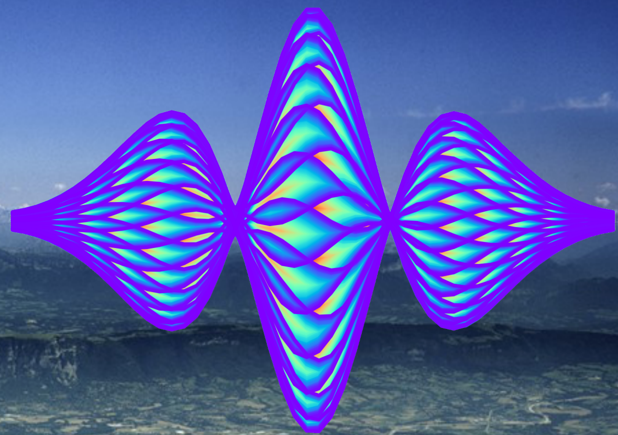
Many thanks to all instability team!



INSTABILITIES IN CERN MACHINES

Elias Métral

BE/ABP-HSC (Collective/Coherent Effects)

https://espace.cern.ch/be-dep-workspace/abp/HSC/SitePages/Home.aspx

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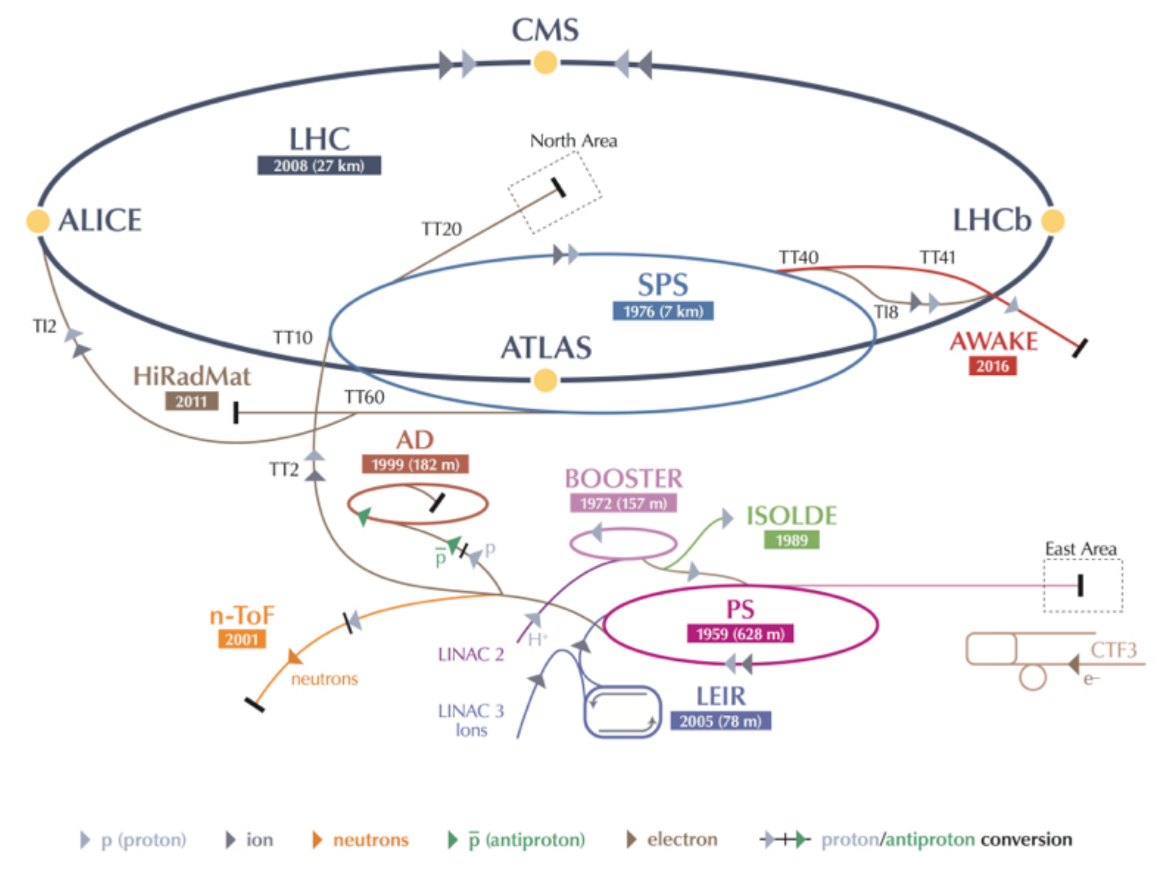
CONTENTS

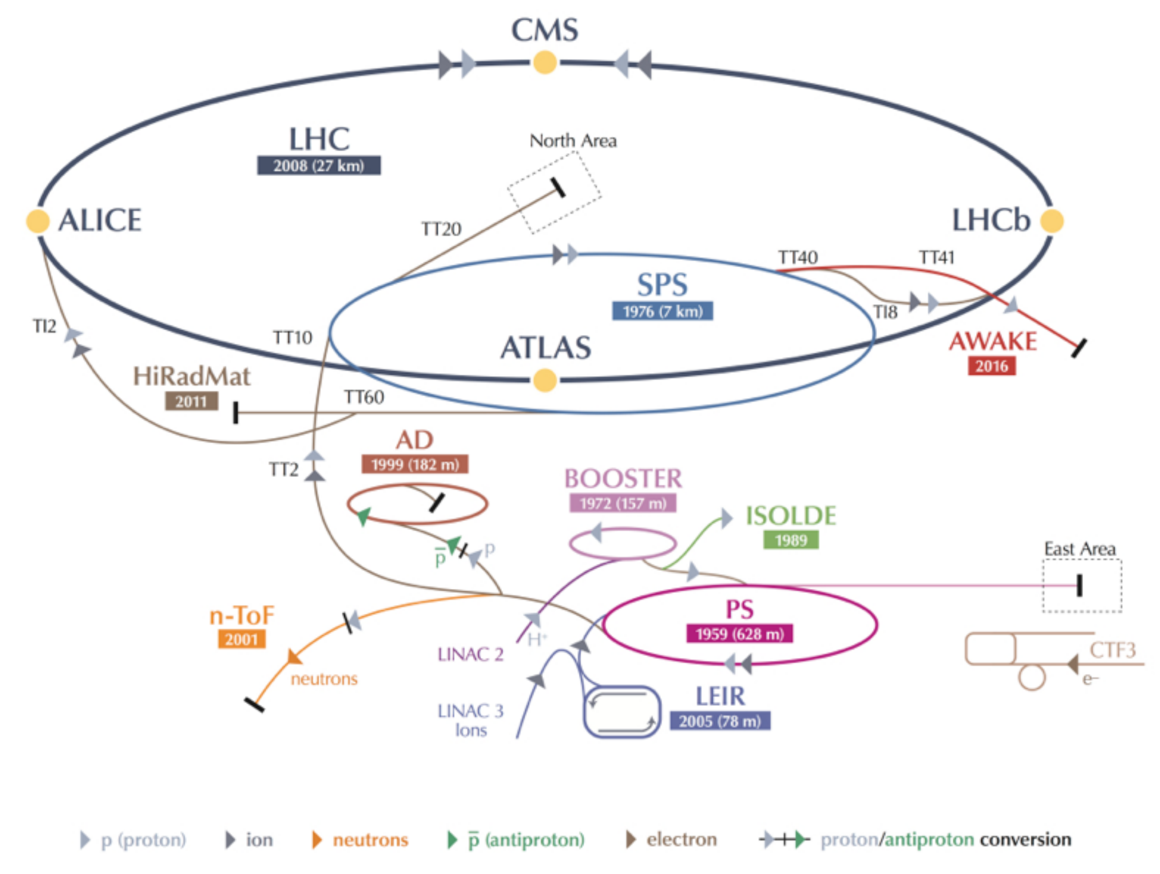
- Introduction
- Current challenges
- 4 questions raised and discussed here
- Conclusion and next steps

INTRODUCTION



PSB (with LINAC4)	50 (160) MeV => 1.4 (2) GeV
PS (with LINAC4)	1.4 (2) GeV => 25 GeV
SPS	25 GeV => 450 GeV
LHC	450 GeV => 7 (6.5) TeV

INTRODUCTION



LIU = LHC Injectors Upgrade

HL-LHC = High-Luminosity LHC

At SPS extraction:

	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)
LIU/HL-LHC	2.3	2.1

At SPS Injection:

	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)
Achieved	2.0	~2.0
LIU/HL-LHC	2.6	1.9

G. Rumolo (Chamonix2018)

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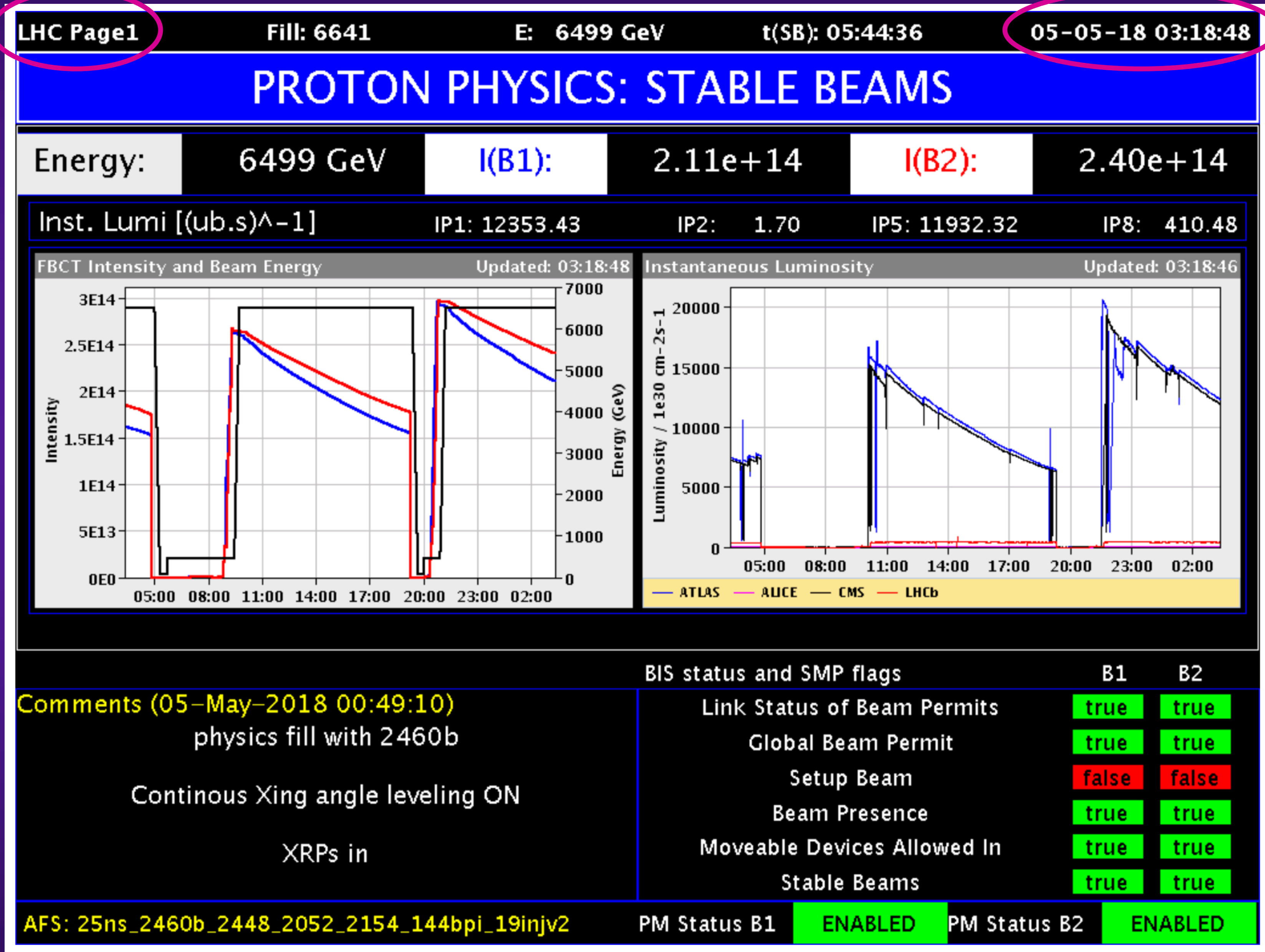

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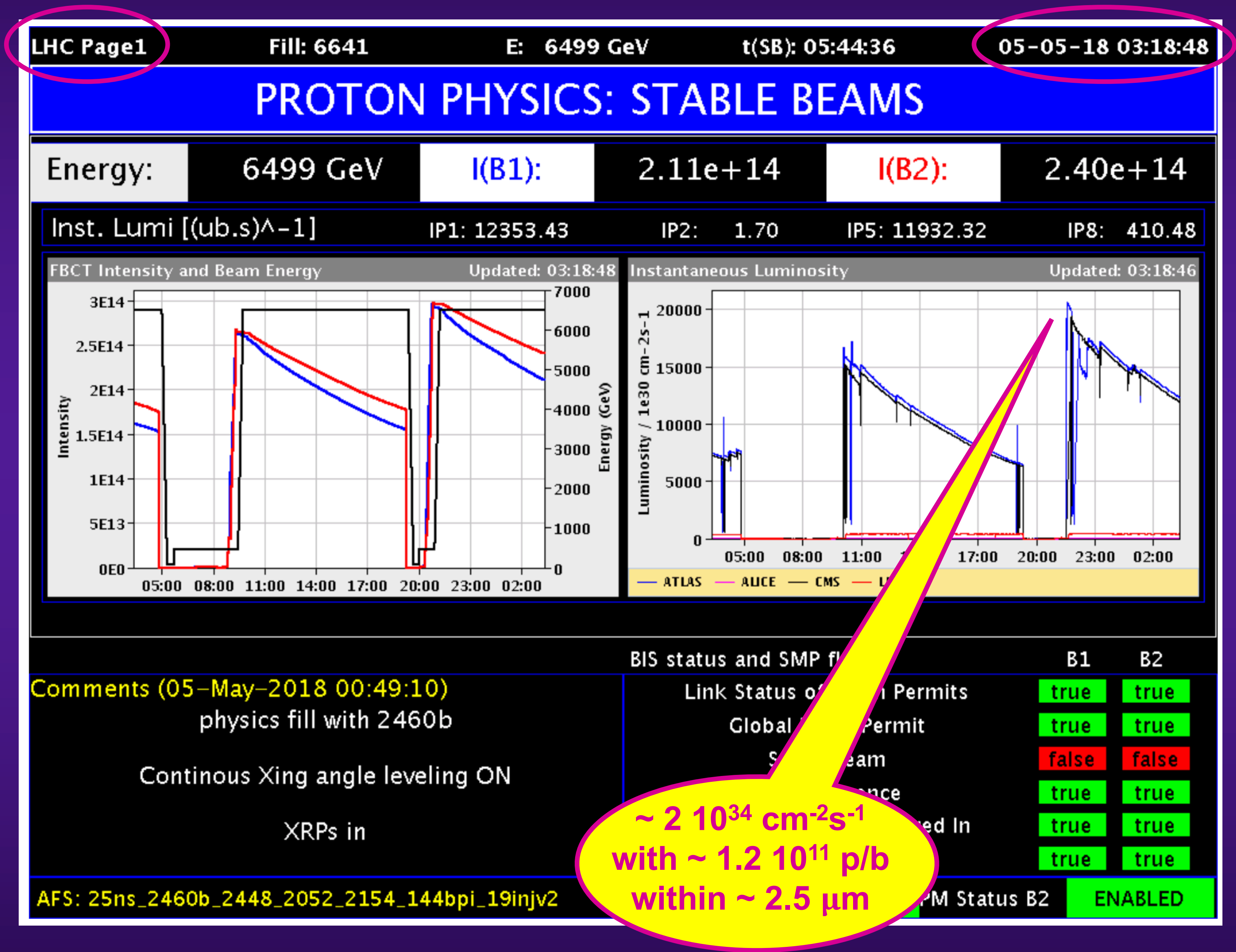

CURRENT CHALLENGES

- **For LIU**
  - **PSB instability during ramp (close to future injection energy) without damper => Could this be a problem in the future?**
  - **PS longitudinal instabilities => New Landau cavity under discussion**
  - **SPS longitudinal instabilities => RF power upgrade + longitudinal impedance reduction**
  - **New SPS horizontal instability observed with higher than nominal bunch intensity => Could this be a problem in the future?**

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- **For HL-LHC**
  - **At LHC injection, high chromaticities, high Landau octupoles current and high damper gain are needed => What will happen for HL-LHC?**
  - **Why do we need more Landau octupoles current than predicted at high energy in the LHC?**
  - **Will we have enough Landau damping for HL-LHC (with new equipment: Crab Cavities, low-impedance collimators, etc.)?**

4 QUESTIONS RAISED AND DISCUSSED HERE

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3) **What is the “16L2 instability” observed in the LHC in 2017 (and 2018)?**

4) **Why do we need more Landau octupoles current than predicted at high energy in the LHC (potential worry for HL-LHC)? => Subject I will mostly discuss, with 2 destabilising effects currently studied**

1) EFFECT OF DIRECT SPACE CHARGE ON CERN INSTABILITIES?

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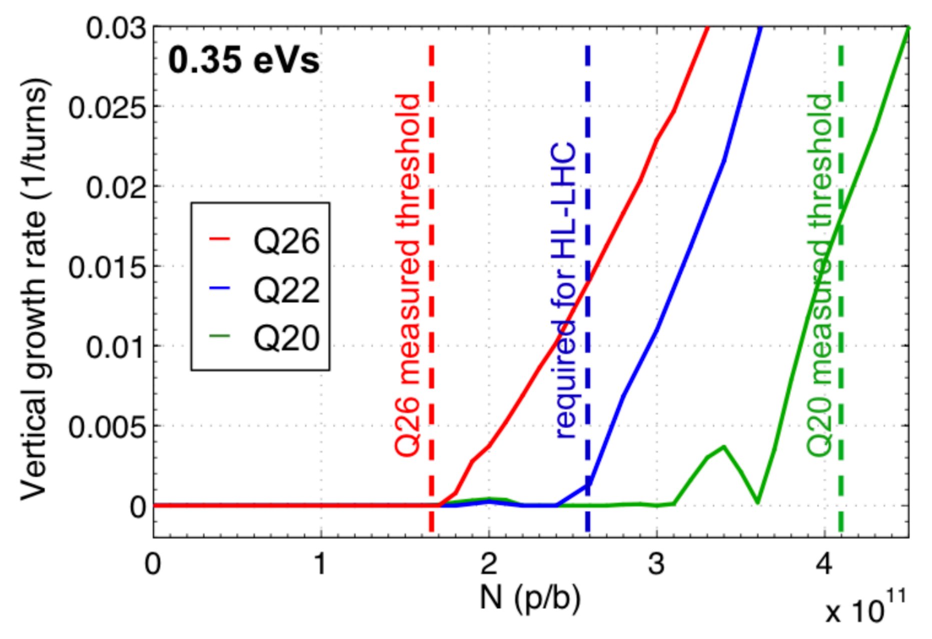
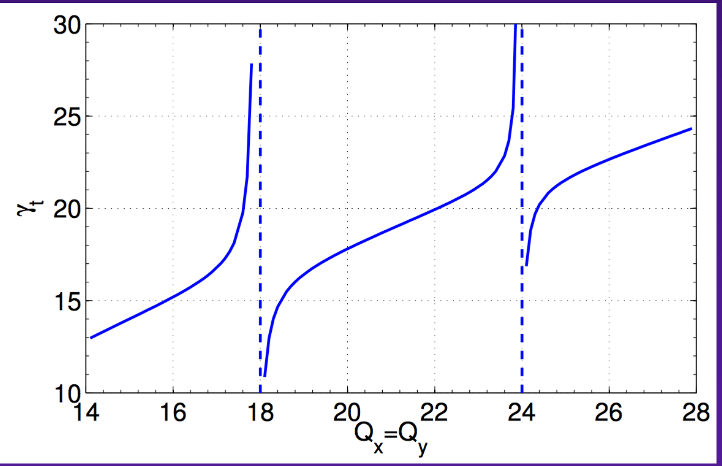
- **LHC (ΔQ_{sc} / Q_s ~ 1)**
  - **Head-Tail instability with 1 node (Q' ~ 5) => Stabilized by space charge below a certain energy**
  - **Predicted threshold for TMCI (modes - 1 and 0) at injection (Q' ~ 0) increased by space charge**

- **SPS case: HEADTAIL simulations from 2014 (H. Bartosik) for different optics WITHOUT space charge**





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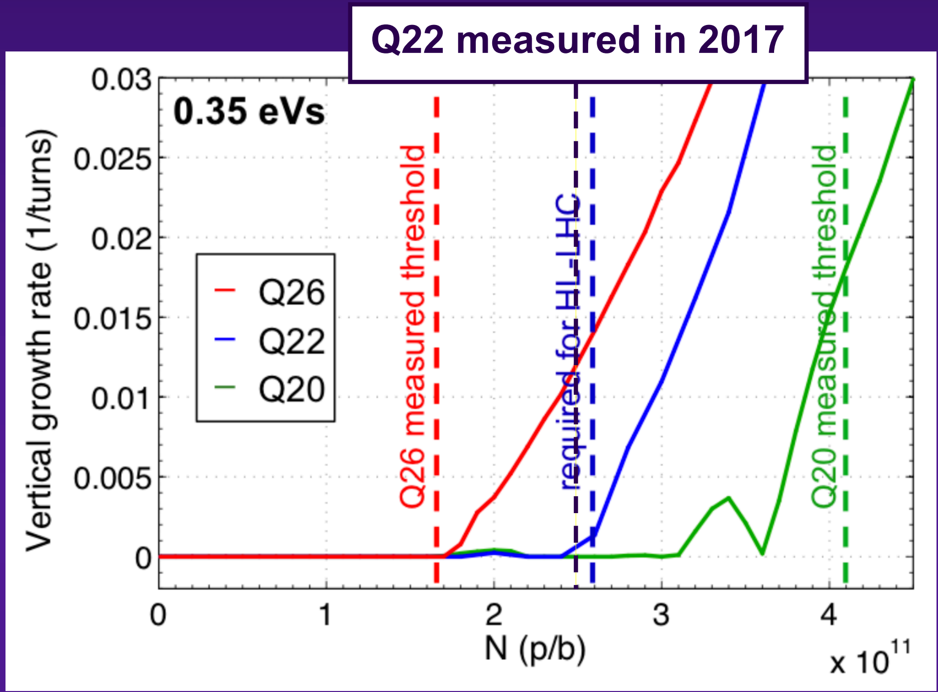

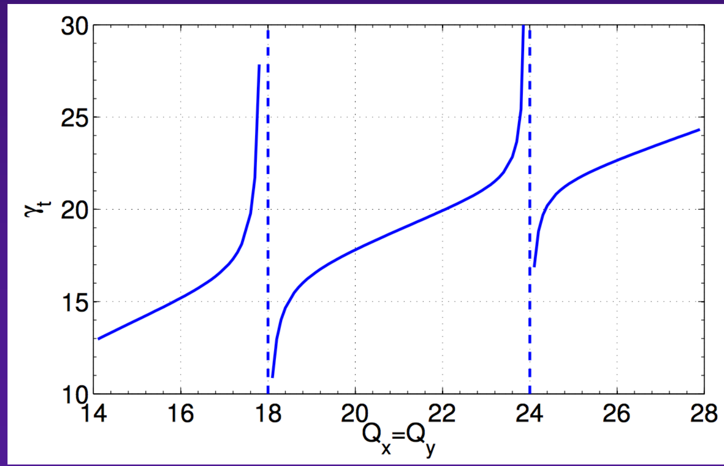

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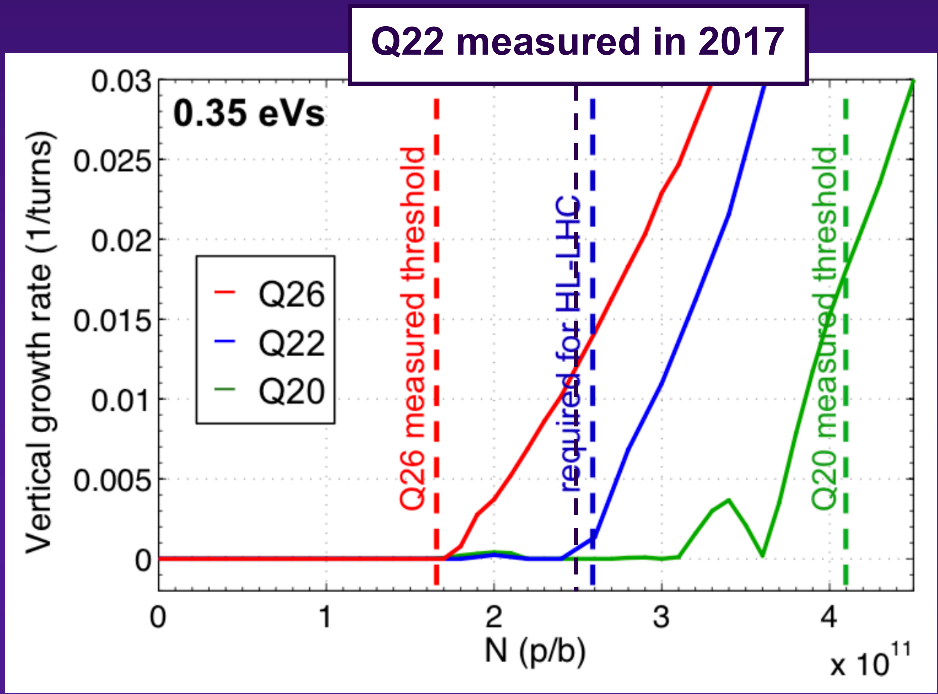

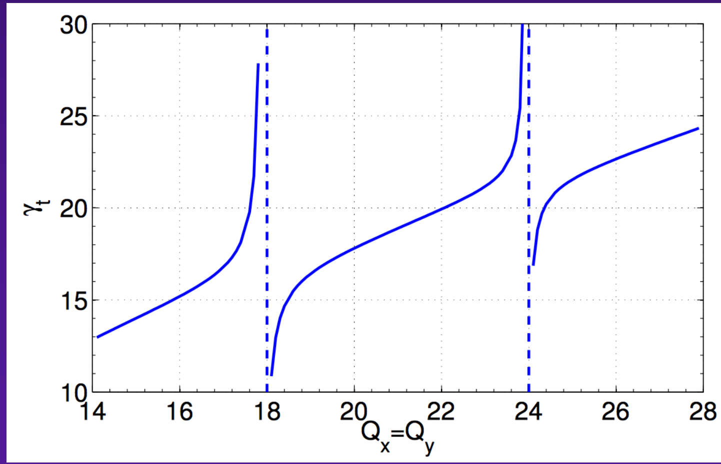

$$N_{b,th}^{y} \propto |\eta| \, Q_y \, \varepsilon_L$$

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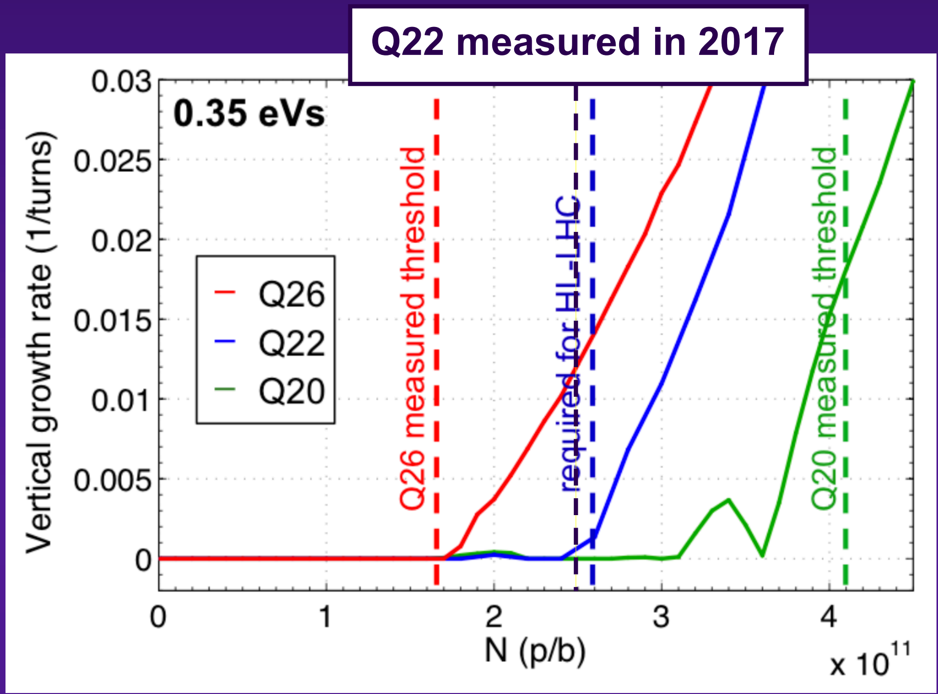

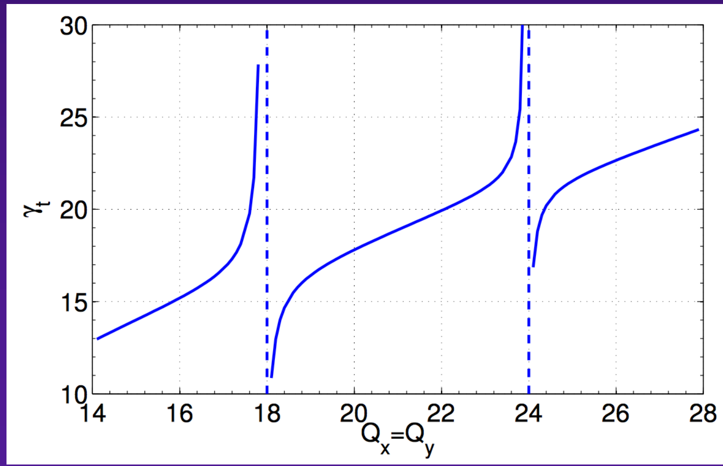

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- **Our simulations predict only little effect of space charge on threshold**

=> Question for theories with space charge: can they explain these 3 thresholds by changing the optics?

2) LHC INSTABILITIES AT INJECTION

- E-cloud in dipoles (~ 65% of the machine) is not expected to drive instabilities both at injection and top energy
  - Becomes better with higher intensity => No issue expected for HL-LHC
  - Becomes worse for lower intensity => Some observations already made

A. Romano (finalising PHD)

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  - **Becomes worse for lower intensity => Some observations already made**

- **E-cloud in quadrupoles (~ 7% of the machine) alone is a key driver of instabilities at LHC injection energy**
  - **Explains high chroma (~ 15-20 units) + high Landau octupoles current (~ 20-40 A) + high damper gain (~ 10-20 turns) in both transverse planes**

    => Favorable scaling with intensity expected
  - **Instability suppressed when increasing beam energy up to 6.5 TeV due to increased beam rigidity**

A. Romano (finalising PHD)

3) “16L2 INSTABILITY”

- **16L2: cryogenic beam vacuum at half-cell 16 left of LHC-IP2**

See 2 IPAC18 papers by B. Salvant et al.

- **16L2: cryogenic beam vacuum at half-cell 16 left of LHC-IP2**

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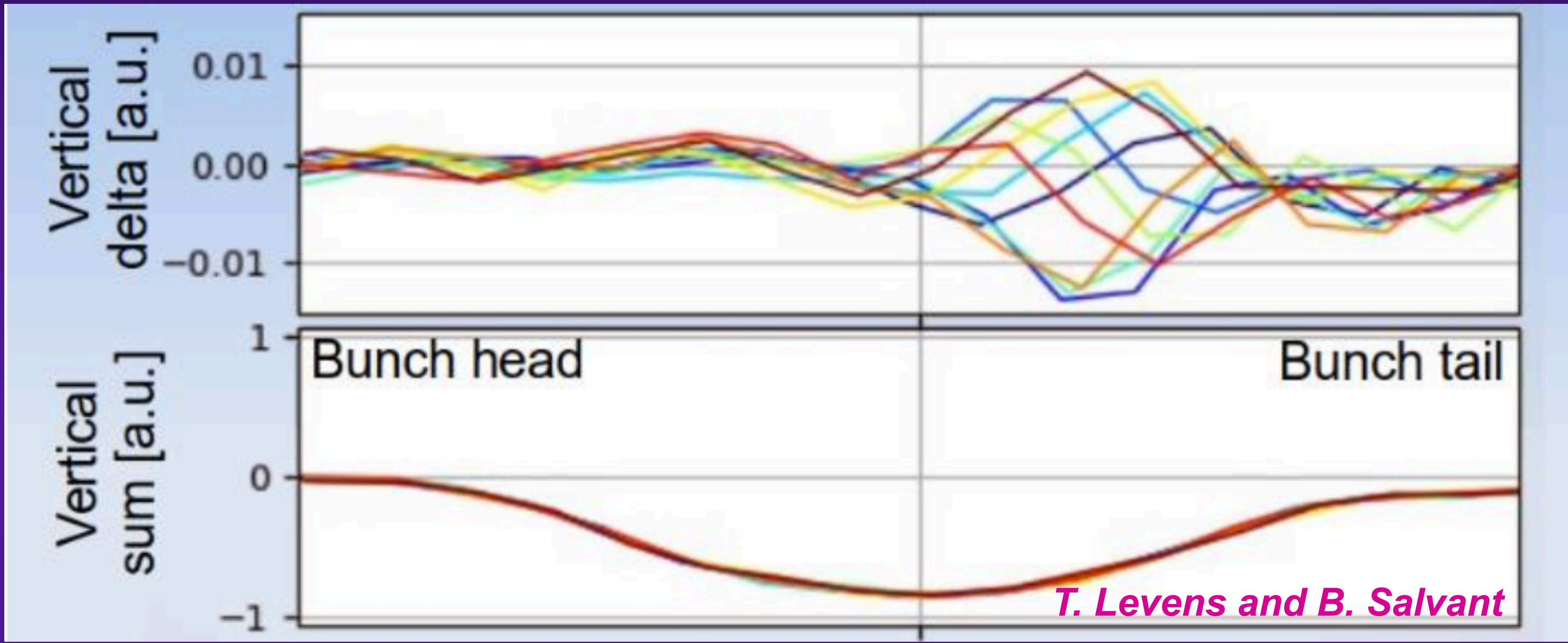
- Interaction of LHC proton beam with flakes of these frozen gases detaching from beam screen surface is assumed to be at the origin of the beam losses in 16L2 => Ionization: ions + e-

See 2 IPAC18 papers by B. Salvant et al.

- **Single-bunch and coupled-bunch instabilities observed**



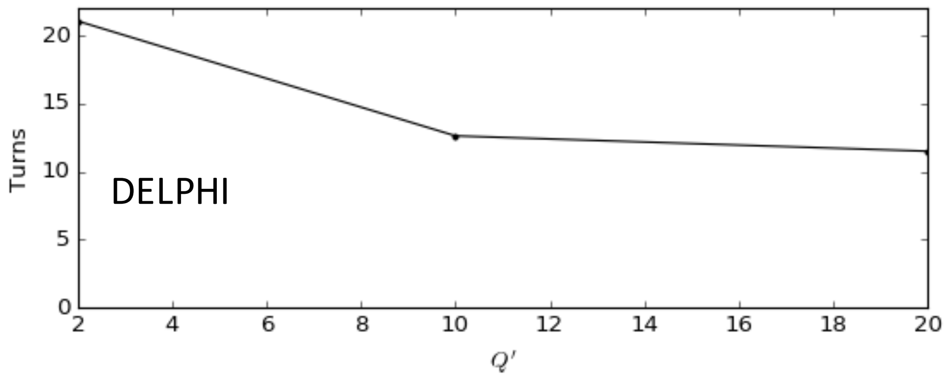
- **Important > 0 tune shift measured: + ~ 0.01-0.02**

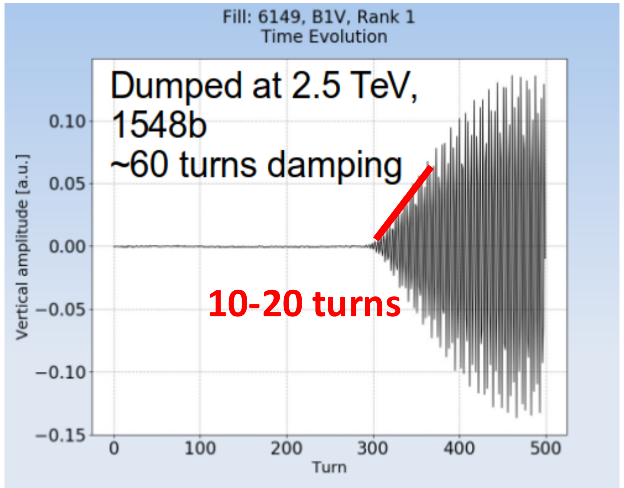
- **Approximated model (as only e- are expected to oscillate within bunch passage)**
  - **Equivalent impedance from an e-cloud (as F. Zimmermann et al.)**
    - **Measured (>0) tune shift => Deduce e- density => ~ 150 MΩ/m shunt impedance**
    - **e- frequency => ~ 2.6 GHz**
    - **Q = 1**
  - **Simulations with DELPHI Vlasov solver**
- **Note: Self-consistent simulations, taking into account both ions and e-, are on-going (L. Mether)**

Comparison with observations

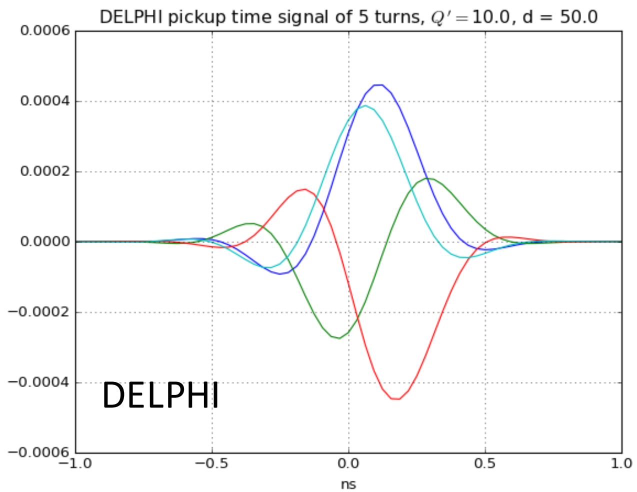
N. Biancacci and D. Amorim

Growth rate:

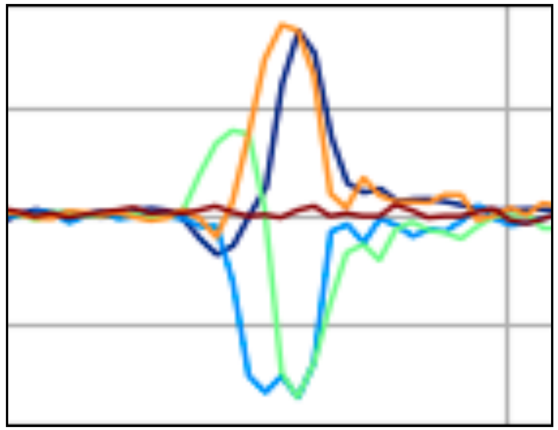




Radial pattern:



B1V HT pickup, 5 turns, 600 GeV



SIMULATIONS **MEASUREMENTS**

4) WHY DO WE NEED MORE LANDAU OCTUPOLES CURRENT THAN PREDICTED AT HIGH ENERGY IN THE LHC?

- **2 main issues => Already observed with 1 bunch**
  - **Factor ~ 2 higher Landau octupoles current in OP conditions (Q' ~ 15, ~ 50 turns damper) => ~ 400-450 A needed vs. ~ 200-250 A predicted**
  - **Even more critical for Q' ~ 0**

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  1) "Perfect" damper (for Q' ~ 0)
  2) External source of noise (e.g. damper)

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- 2 destabilising mechanisms under study
  1) "Perfect" damper (for Q' ~ 0)
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In addition to other 3 already discussed in the past:

1) Interplay octupoles & beam-beam

2) Linear coupling

3) Lattice non-linearities

PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 044401 (2018)

Transverse beam instabilities in the presence of linear coupling in the Large Hadron Collider

L. R. Carver,[1,*] X. Buffat,[1] K. Li,[1] E. Métral,[1] and M. Schenk[1,2]

CERN, CH-1211 Geneva, Switzerland

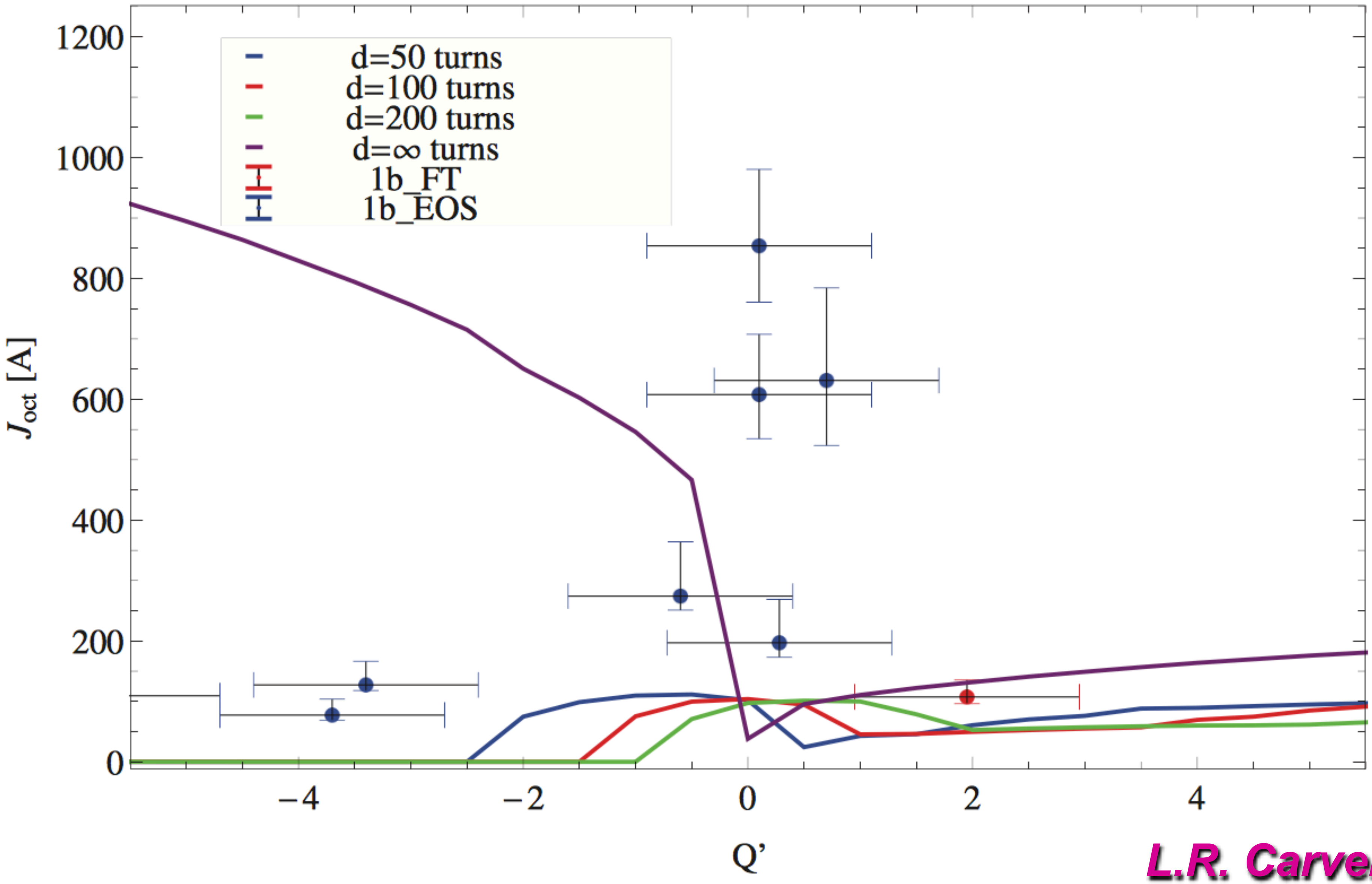
EPFL, CH-1015 Lausanne, Switzerland

4.1) DESTABILISING EFFECT OF “PERFECT” DAMPER

Needed for TCBI
(Transverse Coupled-Bunch Instabilities)

MOTIVATION

LHC single-bunch instabilities with Q’ ~ 0 (2015)



L.R. Carver et al.

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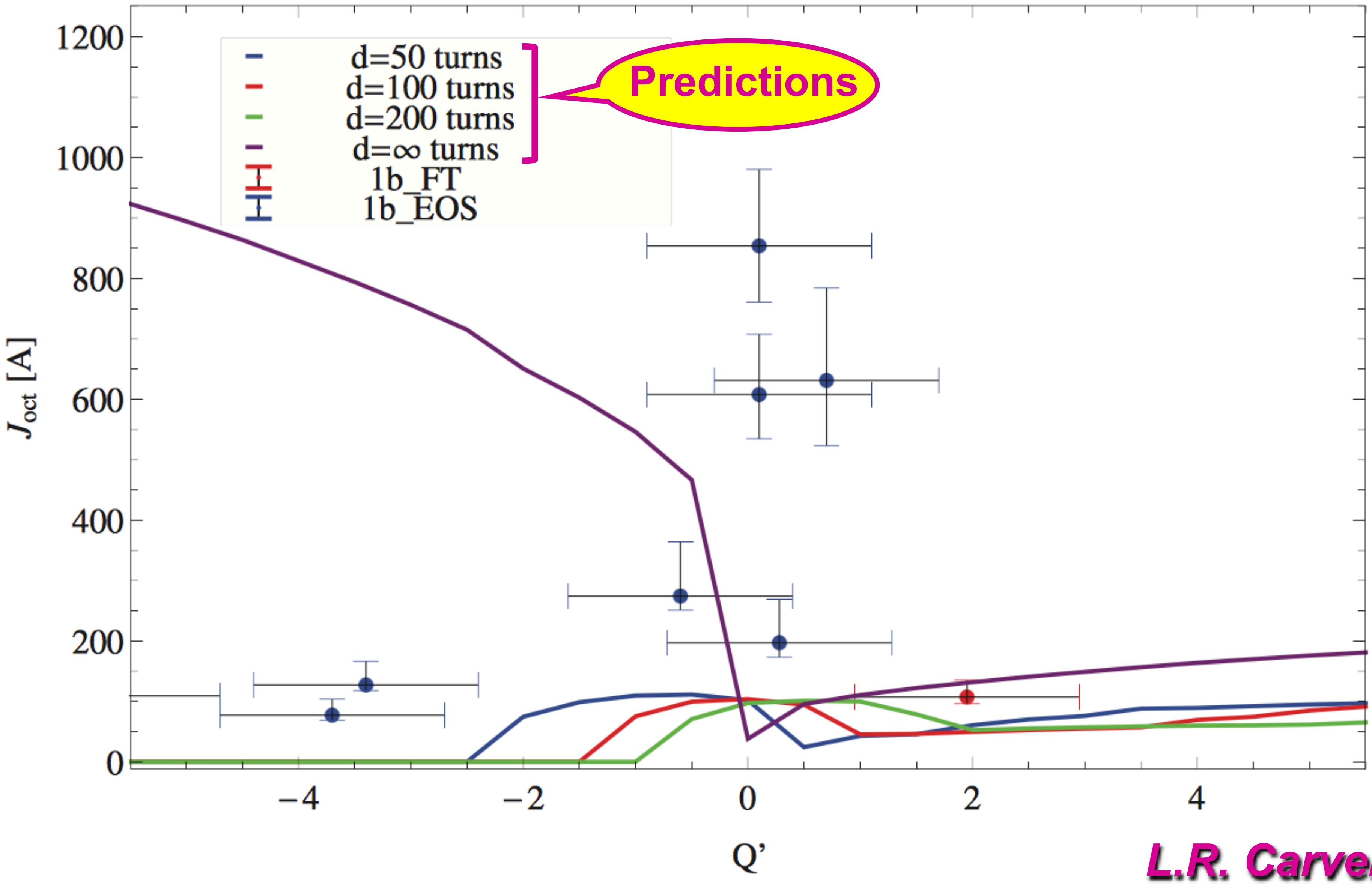

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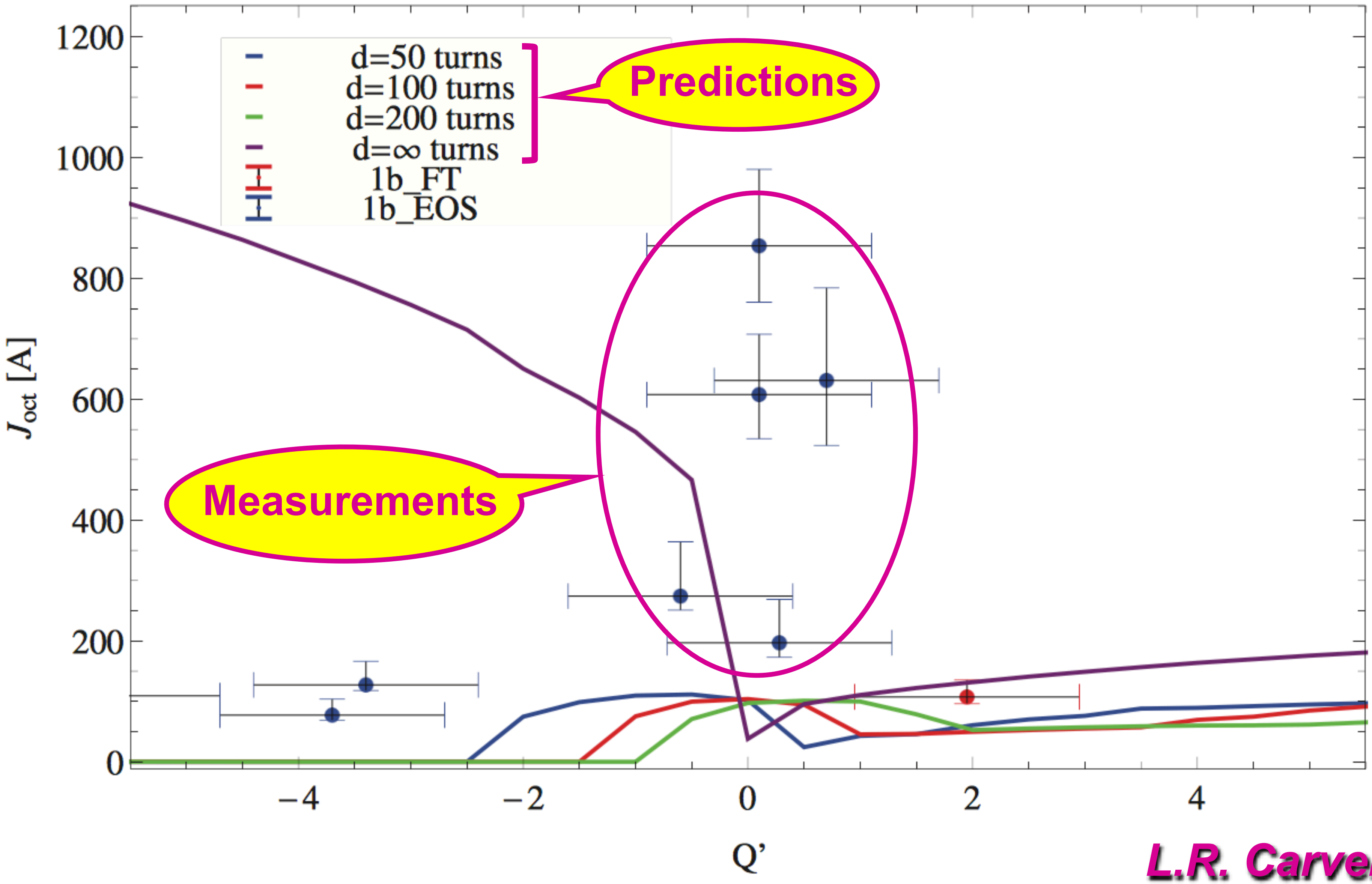

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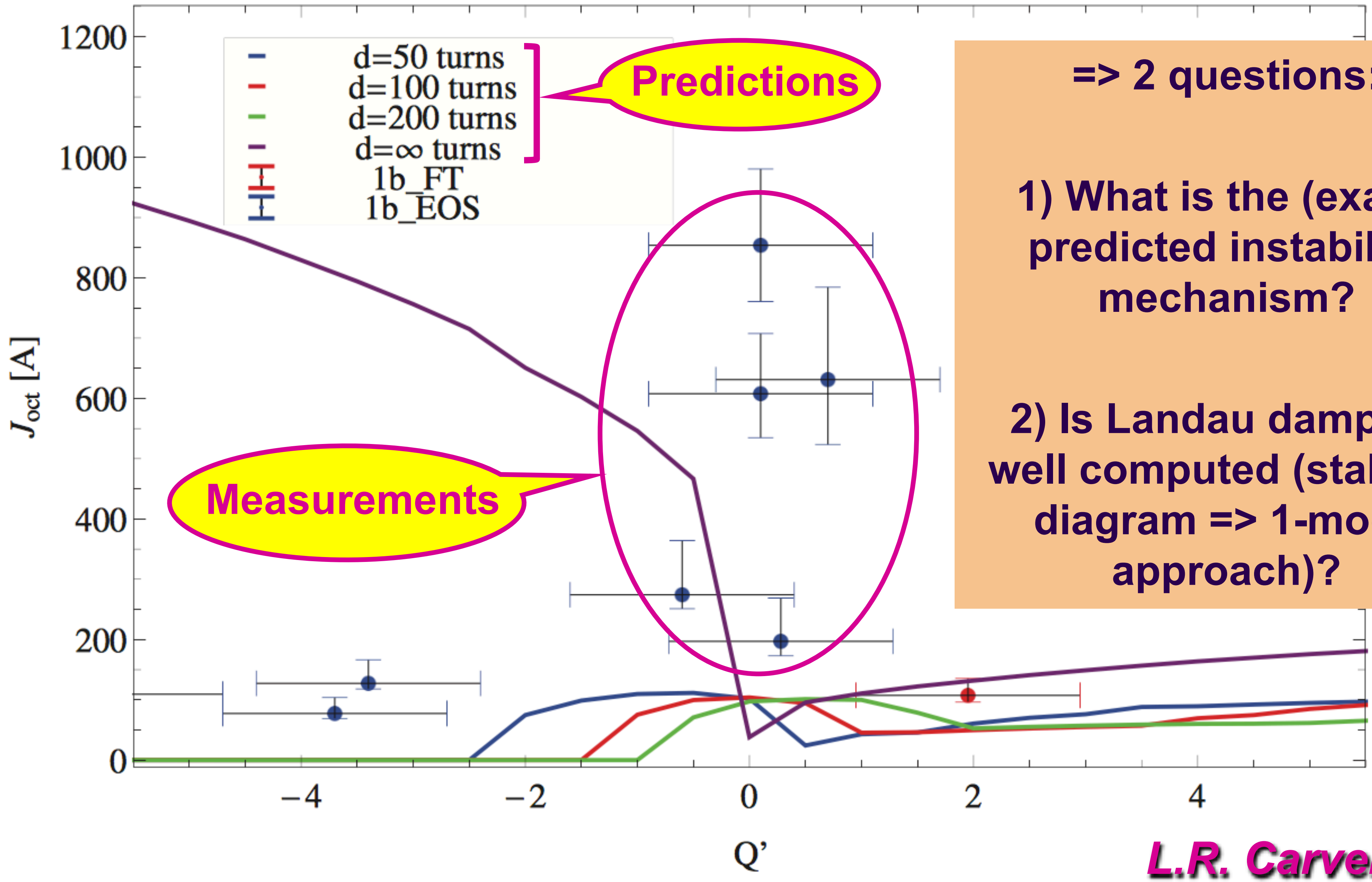

=> 2 questions:

1) What is the (exact) predicted instability mechanism?

2) Is Landau damping well computed (stability diagram => 1-mode approach)?

L.R. Carver et al.

NEW VLASOV SOLVER: GALACTIC
(GArnier-LAclare Coherent Transverse Instabilities Code)

See IPAC18 paper by E. Métral et al.

Note that the same approach can be used also for Longitudinal Instabilities: GALACLIC => Will be discussed at CERN at the next section meeting on 14/05/18
(https://indico.cern.ch/event/725645/)

NEW VLASOV SOLVER: GALACTIC (GArnier-LAclare Coherent Transverse Instabilities Code)

- **Approximated model with Q' = 0 (no damper, no Landau damping)**

$$\begin{pmatrix} -1 & -0.23\, j\, x \\ -0.55\, j\, x & -0.92\, x \end{pmatrix}$$

α bunch intensity

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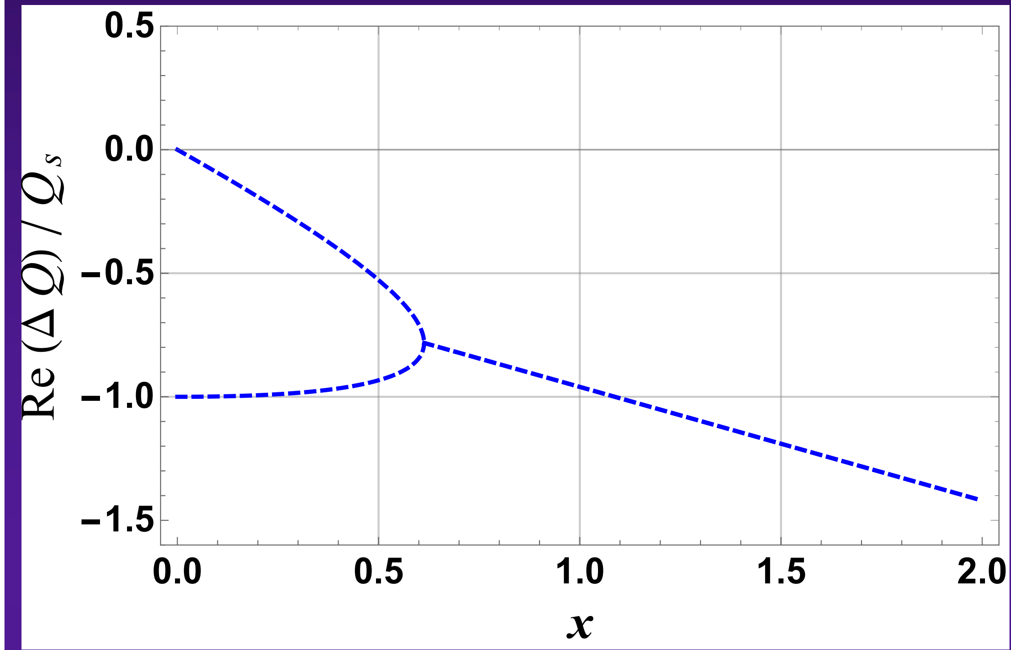

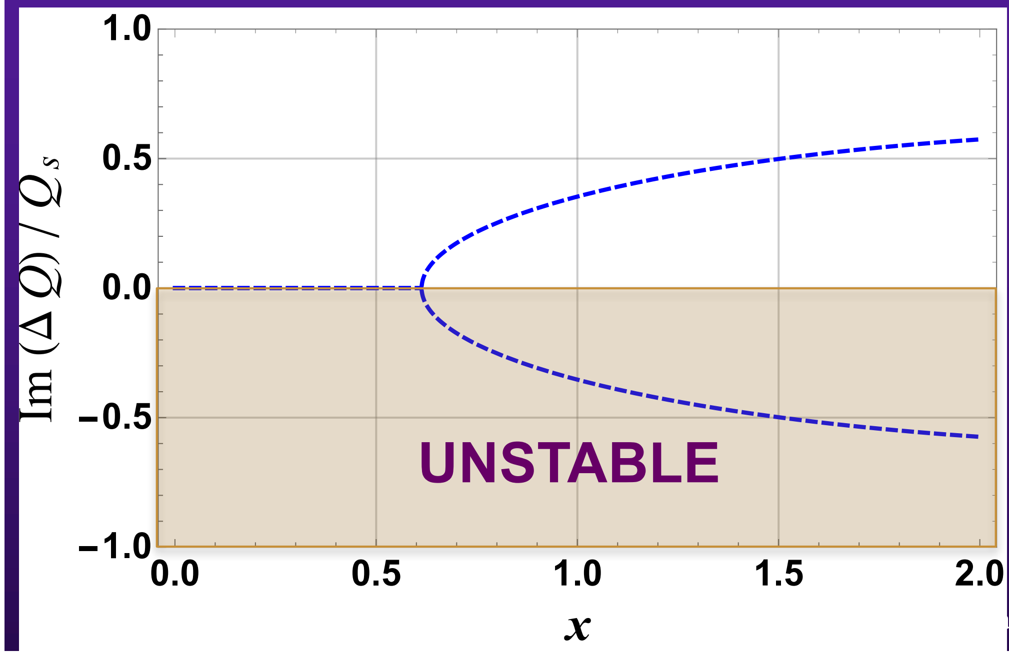

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TMCI

(Transverse Mode-Coupling Instability)

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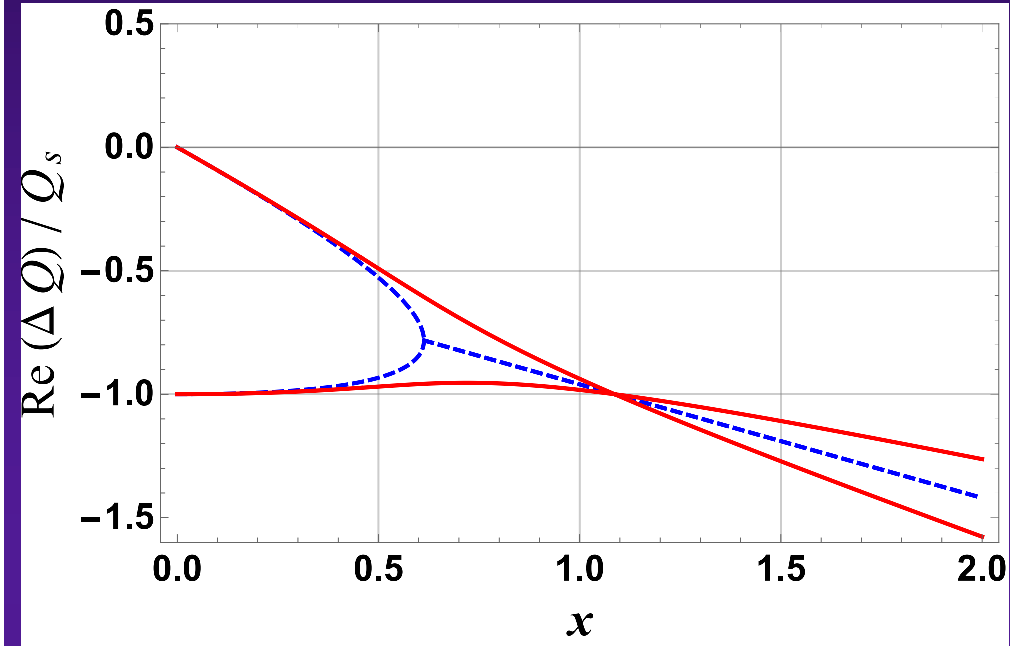

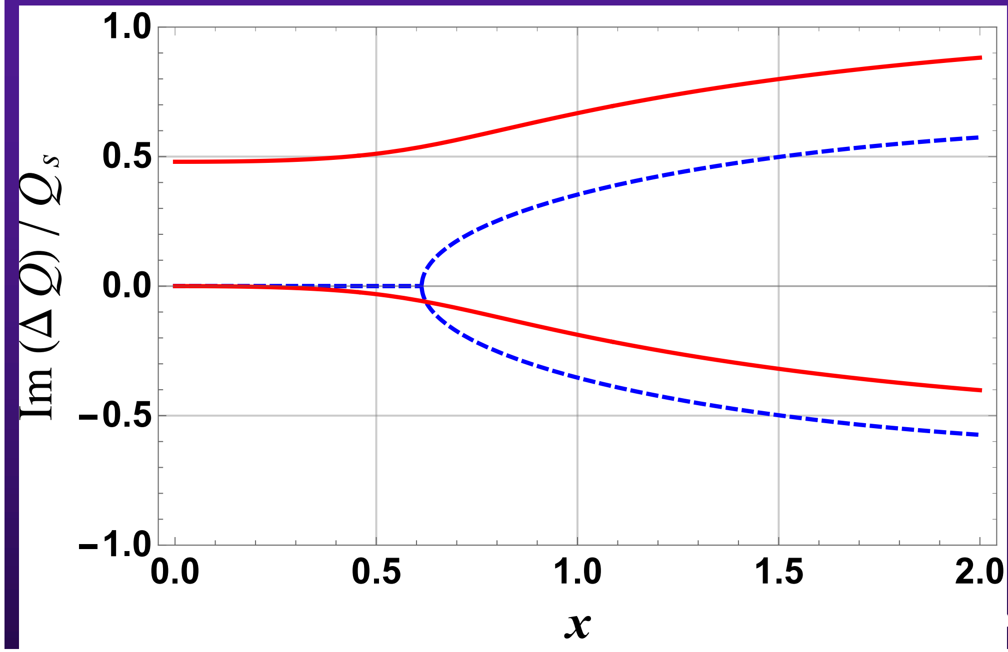

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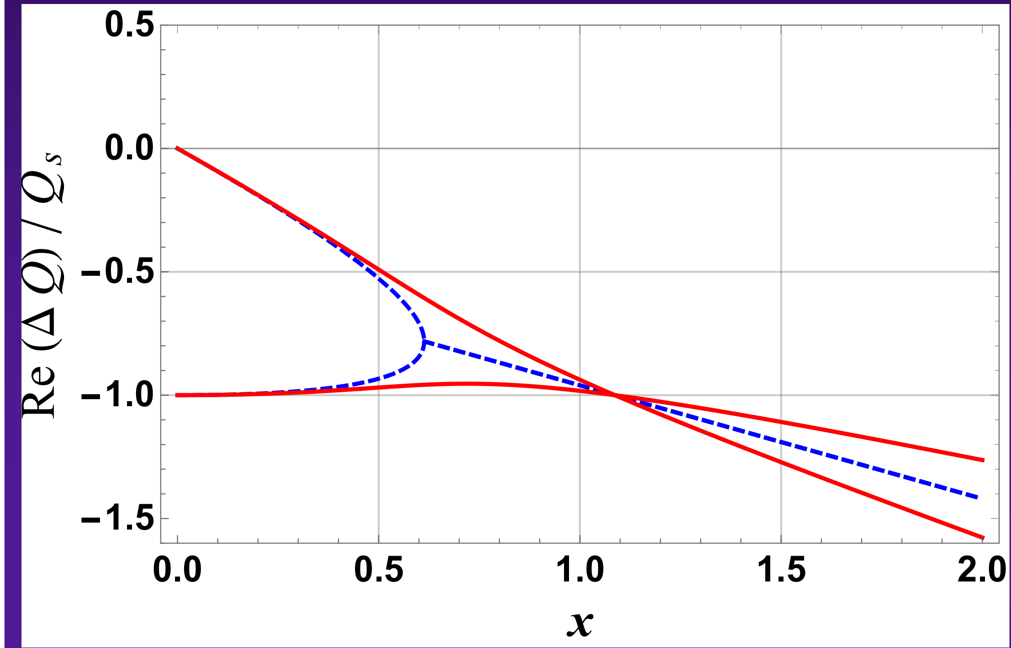

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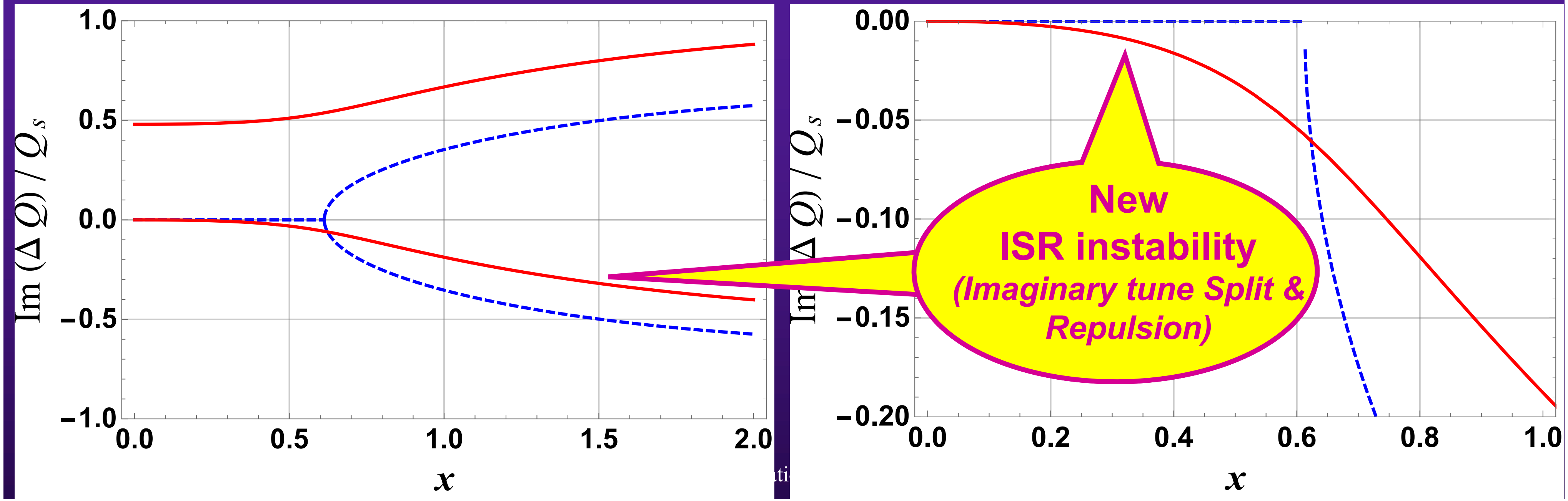
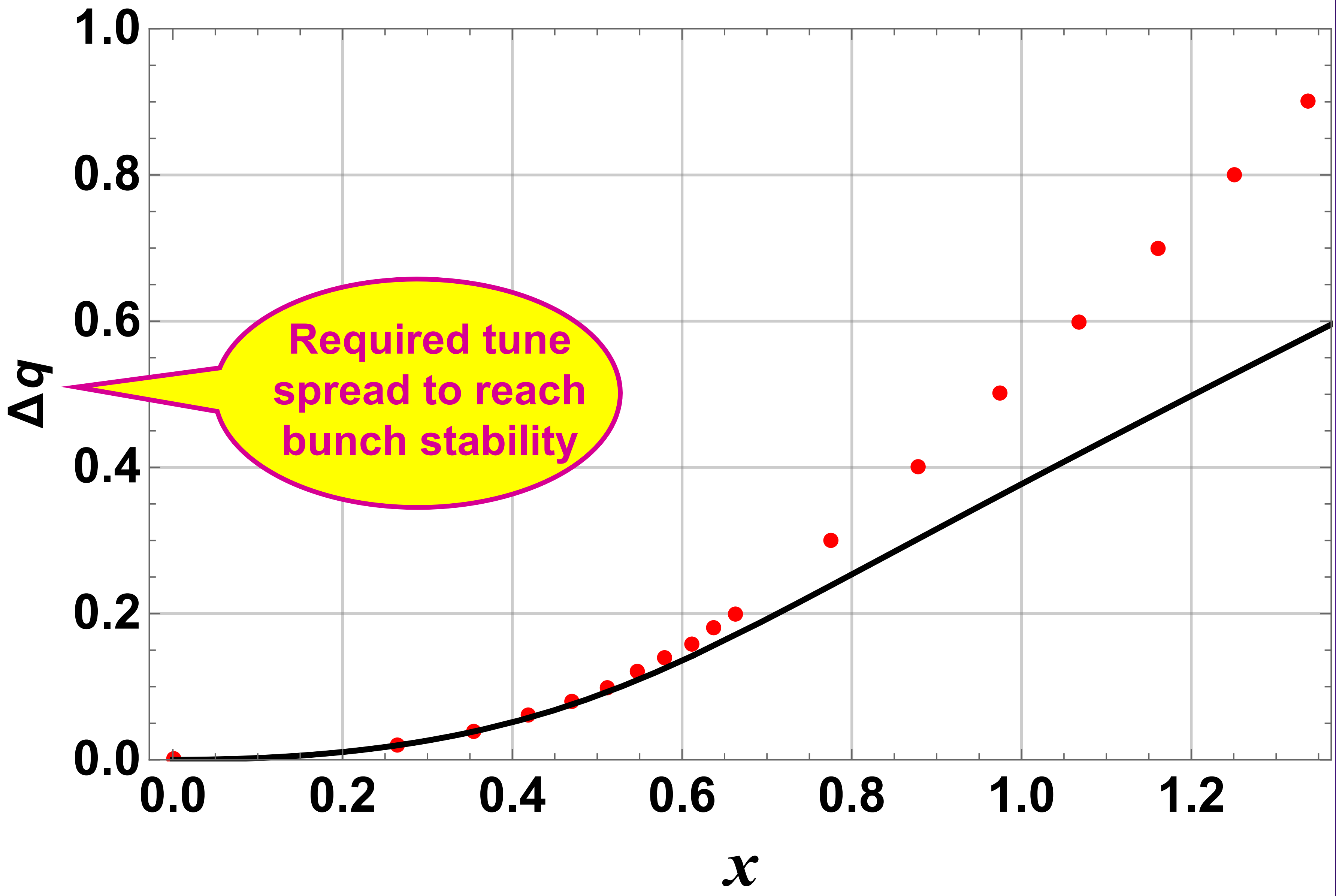


IMPACT ON LANDAU DAMPING



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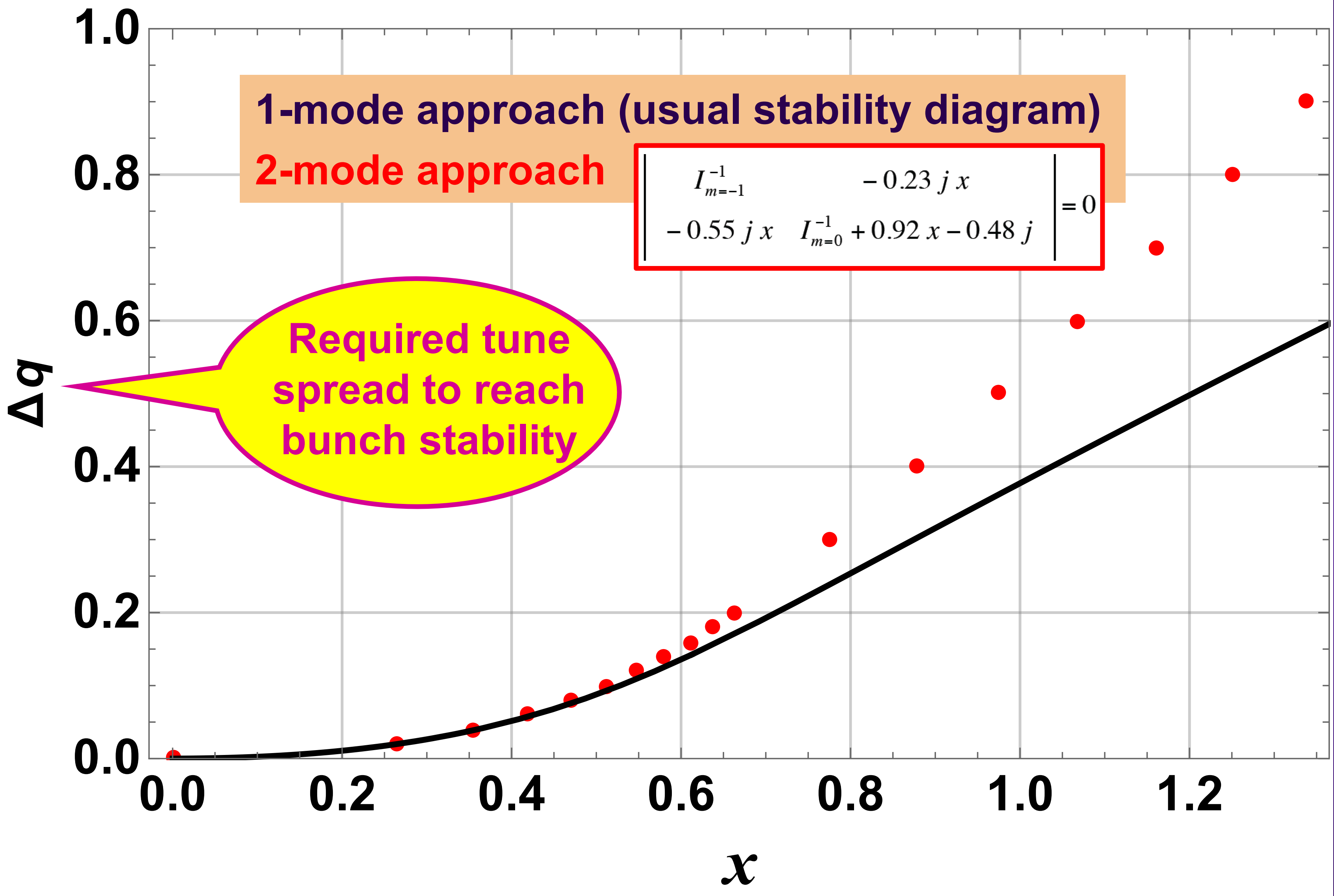

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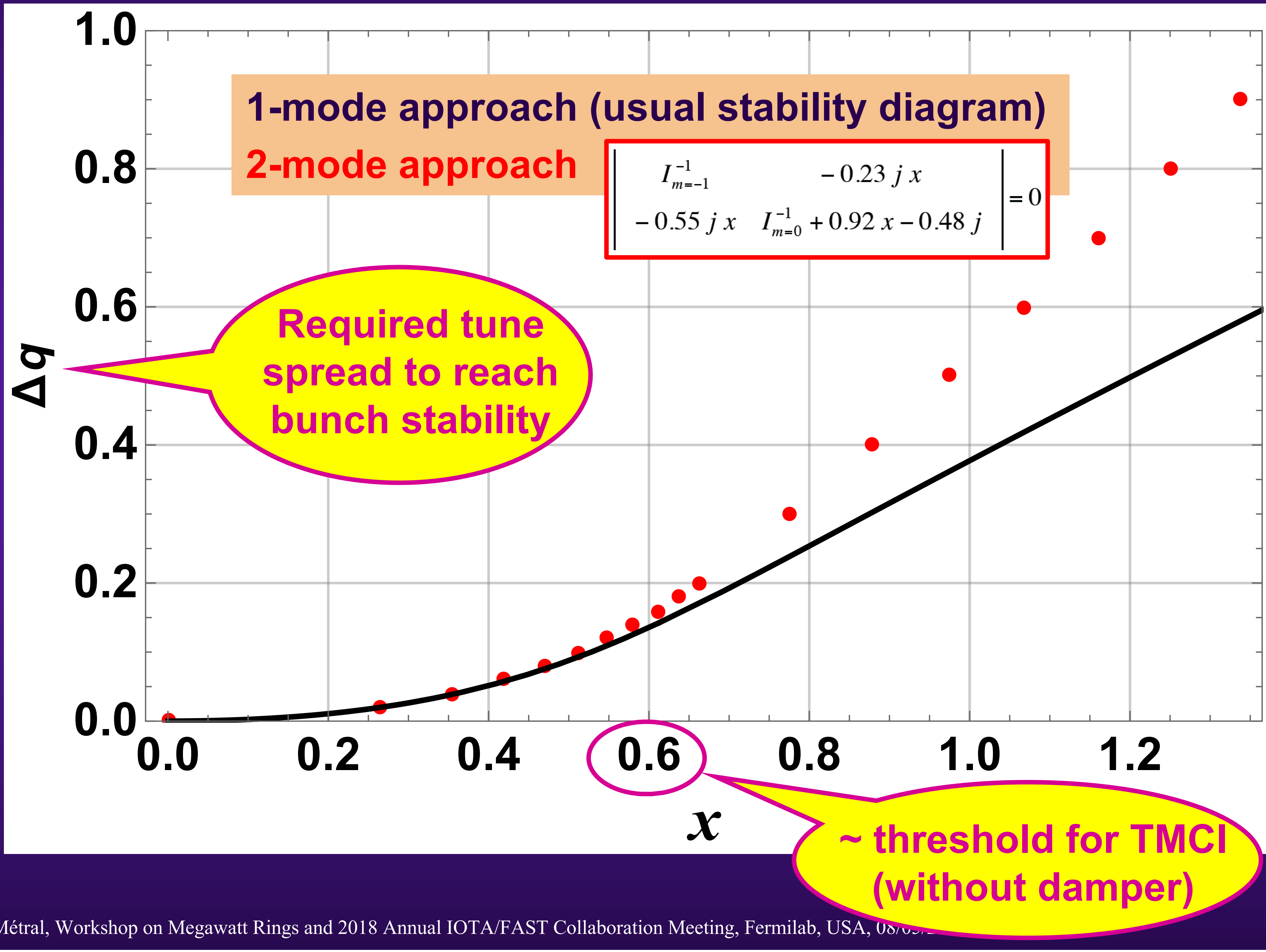

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- 1st step: new (single-bunch) instability mechanism => Confirmed and finalised (still to be confirmed by measurements)
- 2nd step: Landau damping => To be confirmed and finalised
    - Below ~ TMCI intensity threshold (without damper), 1-mode approach (usual stability diagram) seems fine

CONCLUSION for 4.1)

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- Seems that destabilising effect of LHC (resistive) transverse damper (alone) cannot explain LHC observations with Q' ~ 0

=> Another mechanism needs to be identified / added...

4.2) DESTABILISING EFFECT OF EXTERNAL SOURCE OF NOISE

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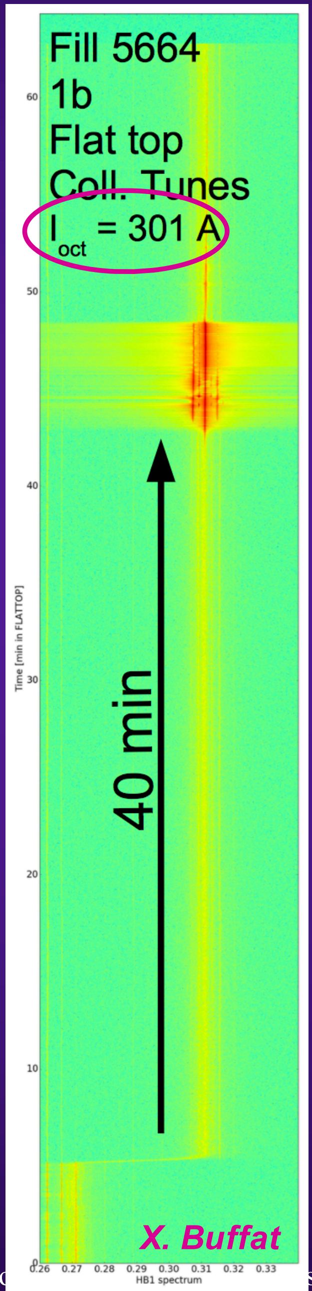
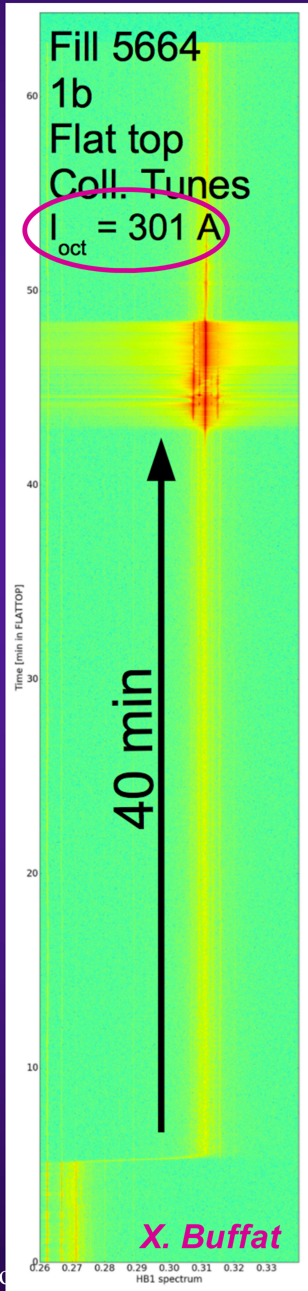
- **Observation in 2017 (and confirmation by simulations) of an instability triggered by a harmonic excitation during BTF (Beam Transfer Function) measurements without damper (C. Tambasco et al.)**

Observations



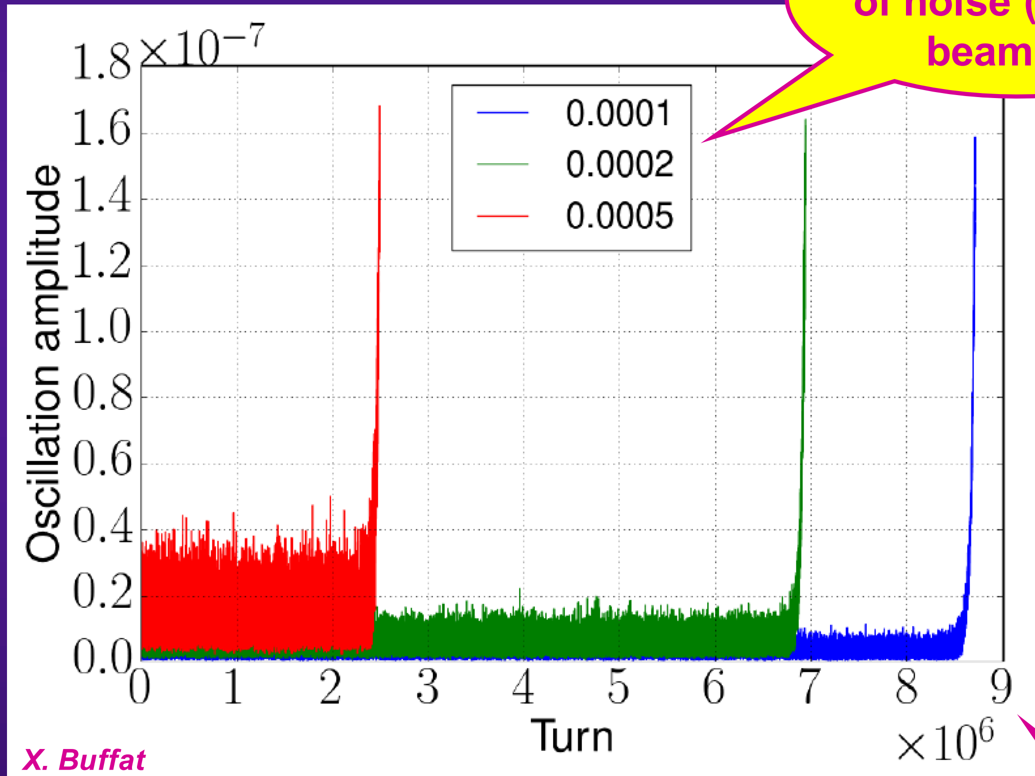
LONG LATENCY

Observations



Simulations (COMBI)

External source of noise (in unit of beam size)



~ 13 min

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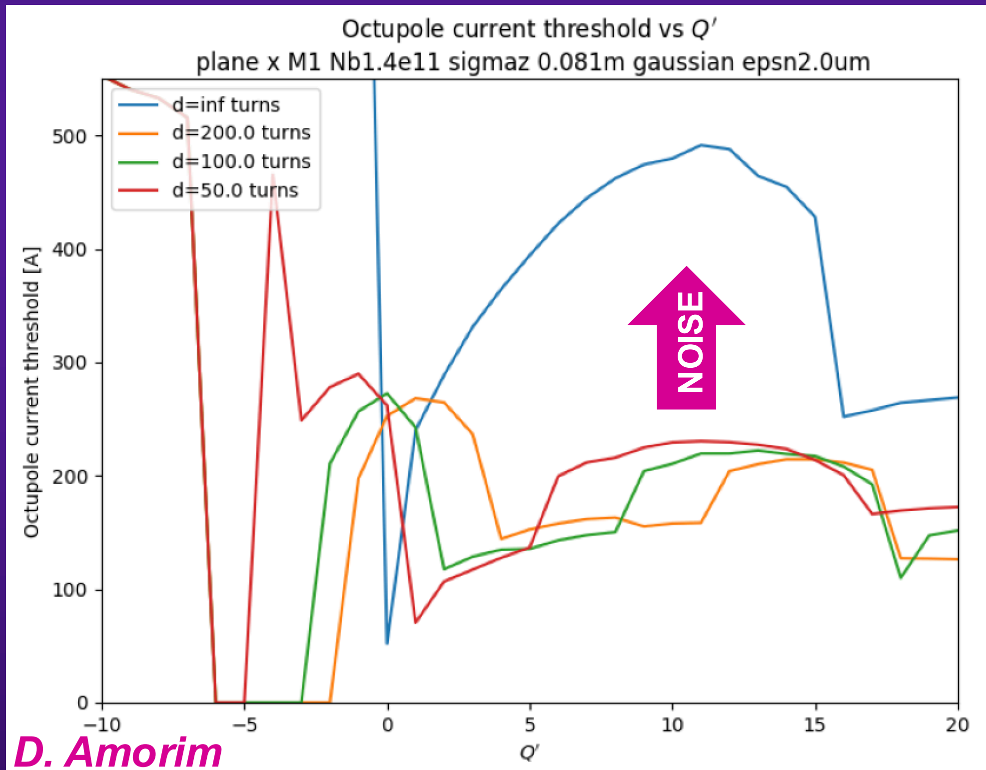

CONCLUSION AND NEXT STEPS

- **Answers to 4 questions raised**
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4) Why do we need more Landau octupoles current than predicted at high energy in the LHC?

   => Destabilising effect of damper (for Q' ~ 0): not enough

   => External source of noise (e.g. damper) could explain remaining missing factor ~ 2 and long latency time. Tbc…