I.FAST Workshop 2024 Bunch-by-bunch feedback systems and related beam dynamics

Transverse collective effects simulation with bunch-by-bunch feedback system

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SOLEIL and SOLEIL II operation

SOLEIL (measurements)		SOLEIL II (simulations)	
Operation mode	Current threshold (w/o FB)	Operation mode	Current threshold (w/o FB)
Uniform, 500 mA	350 mA (TCBI*)	Uniform, 500 mA	~ 30 mA (TCBI/BII)
Hybrid, 450 mA	350 mA (TCBI*)	32-bunch, 200 mA	~ 90 mA (head-tail)
8-bunch, 100 mA	7 mA / bunch (head-tail)	Uniform+HC, 500 mA	>500 mA
Single-bunch, 20 mA	7 mA / bunch (head-tail)	32-bunch+HC, 200 mA	~ 90 mA (head-tail)

In the past combination of TCBI and BII was limiting the current
TCBI – Transverse coupled-bunch instability (due to resistive wall impedance)
BII – Beam-ion instability (due to residual gas ionisation)

- Design beam currents only reached with FB
- FB should be able to deal with all instabilities (TCBI, BII, head-tail)
- Another way would be to increase chromaticity
- Additionally, for uniform mode, BII can limit the current
- For other FB application at SOLEIL see talk by A. Gamelin

- Large parameter space to scan!
  - Chromaticities
  - Impedance models
  - Feedback parameters
  - Beam current
  - ID open/close
  - And many more

Feedback: simulation point of view

Semianalytical

- Many approximations
- Understanding of underlying processes
- Very fast
- Large parameter scans
- **Transverse feedback models:**
  - Ideal damper
  - Karliner-Popov model

Particle tracking

- Complex models
- Resource-demanding
- Time-demanding (hours-weeks)
- Large parameter scans difficult or impossible
- **Transverse feedback models:**
  - Ideal/exponential damper
  - FIR filter

Experiment

- Actual reality
- Sometimes very difficult to relate to physics...

Faster models

More complex models

Some theory

One tries to solve Sacherer's integral equation

$$(\Omega - Q_{y0}\omega_0 - l\omega_s)R_l(\tau) = -\kappa g_0(\tau) \sum_{l'=-\infty}^{+\infty} j^{l'-l}$$
$$\cdot \int_0^{+\infty} \tau' R_{l'}(\tau') \left[\mu J_l\left(-\omega_\xi \tau\right) J_{l'}\left(-\omega_\xi \tau'\right) \mathrm{d}\tau'\right.$$
$$\left. + \sum_{p=-\infty}^{+\infty} Z_y(\omega_p) J_l\left((\omega_\xi - \omega_p)\tau\right) J_{l'}\left((\omega_\xi - \omega_p)\tau'\right)\right],$$

Reduces to a "simple" eigenvalue problem

$$M_{ln,l'n'} = \frac{-j^{l'-l} n! \kappa \tau_b^{|l|-|l'|}}{2^{|l|}(n+|l|)!} \left[\mu G_{ln}(-\omega_\xi, a) I_{l'n'}(-\omega_\xi, a)\right.$$
$$\left. + \sum_{p=-\infty}^{+\infty} Z_y(\omega_p) G_{ln}\left(\omega_p - \omega_\xi\right) I_{l'n'}\left(\omega_p - \omega_\xi, a\right)\right], \quad (21)$$

https://e-publishing.cern.ch/index.php/CYRCP/article/view/757/563

Here typically an ideal damper is assumed

- Improvement on ideal damper is Karliner-Popov formalism
- Feedback is represented by an "impedance"
- Another improvement would be inclusion of rad. effects

$$Z_F(s - jm\omega_0)$$
$$= \frac{Z_0 \cdot V'(0)}{a} \cdot K(s - jm\omega_0) \cdot e^{-j\frac{mL_0}{R}} \cdot e^{-(s-jm\omega_0)\tau}$$
$$\cdot \frac{(1 - \exp[-(\gamma_m - j\frac{m}{R})L_1]) \cdot (1 - \exp[-(\gamma_m - j\frac{m}{R})L_2])}{\gamma_m - jm/R}.$$

10.1016/j.nima.2004.08.068

The dream: the equations actually work and we don't need to simulate every possible parameter

Reality:
- Initial scans with these simplified models
- Tracking
- Confirmed with the new machine operation
- Understand why results differ

Benchmark with theory (DELPHI) for single-bunch

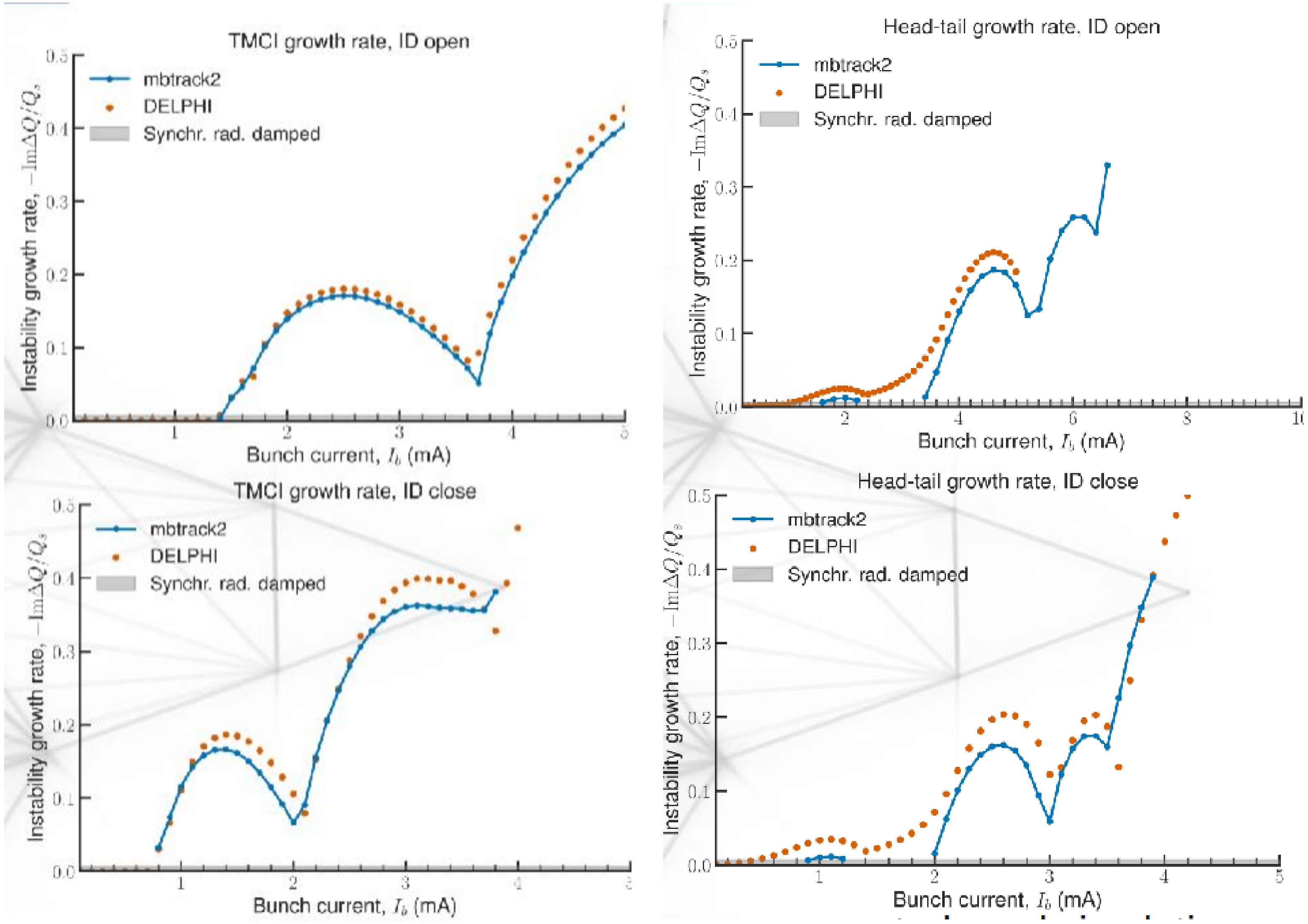
TMCI Q'=0

Head-tail Q'=1.6

- Uniform mode with 1.2 mA per bunch is below all the threshold with bunch lengthening from long. Impedance

- 32b mode with 6.25 mA per bunch is not saved by bunch lengthening

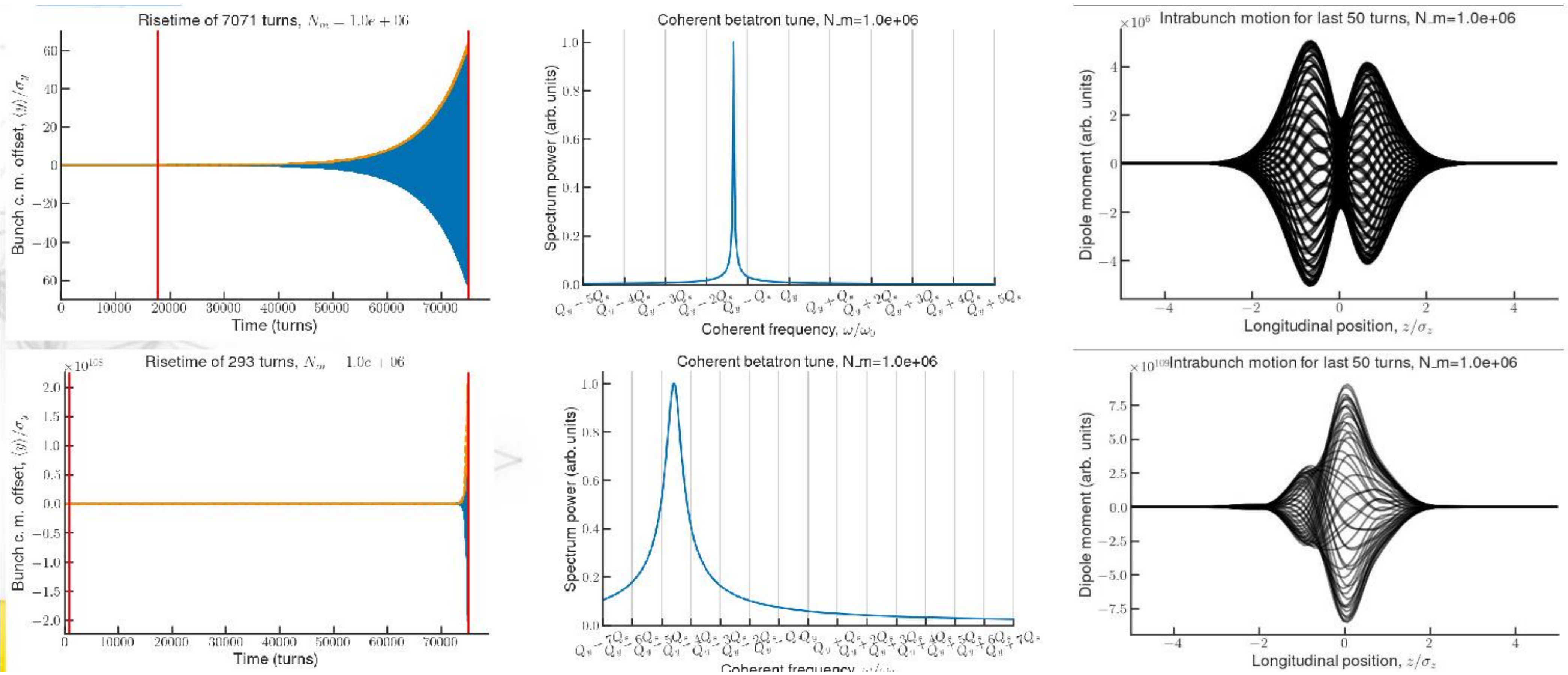
- 32b mode head-tail instability is very similar to TMCI - > head-tail modes are not independent from each other



! No bunch lengthening in these benchmark plots !

Single-bunch instabilities

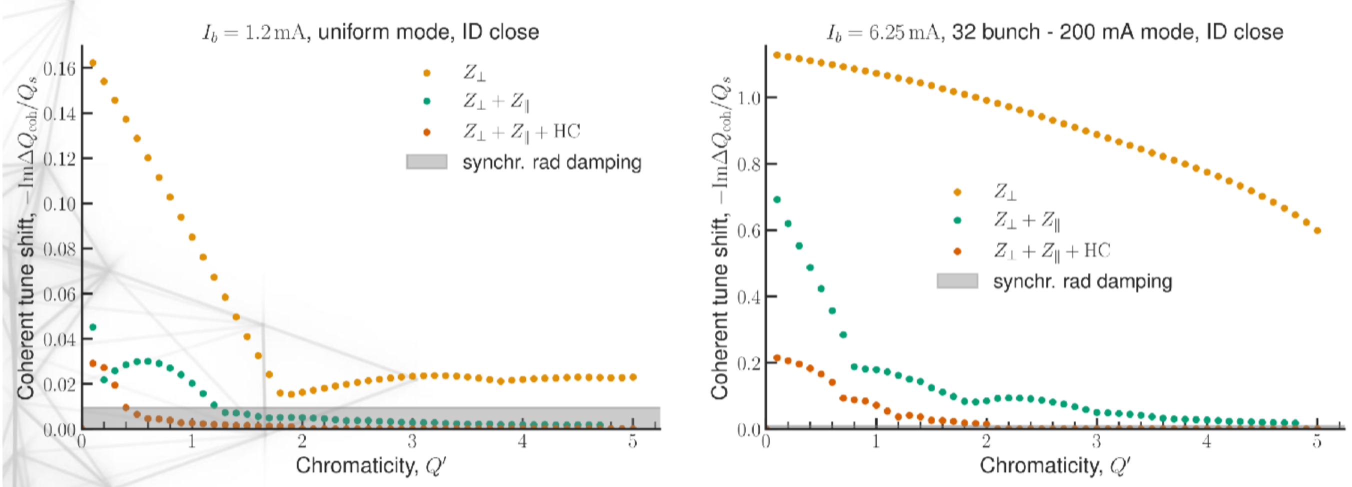
Instability in uniform and 32b@6.25 mA per bunch at nominal chromaticity



- Feedback can still be required for single-bunch instabilities
- Required damping time is ~300-500 turns
- Intrabunch motions is a mix of different head-tail modes

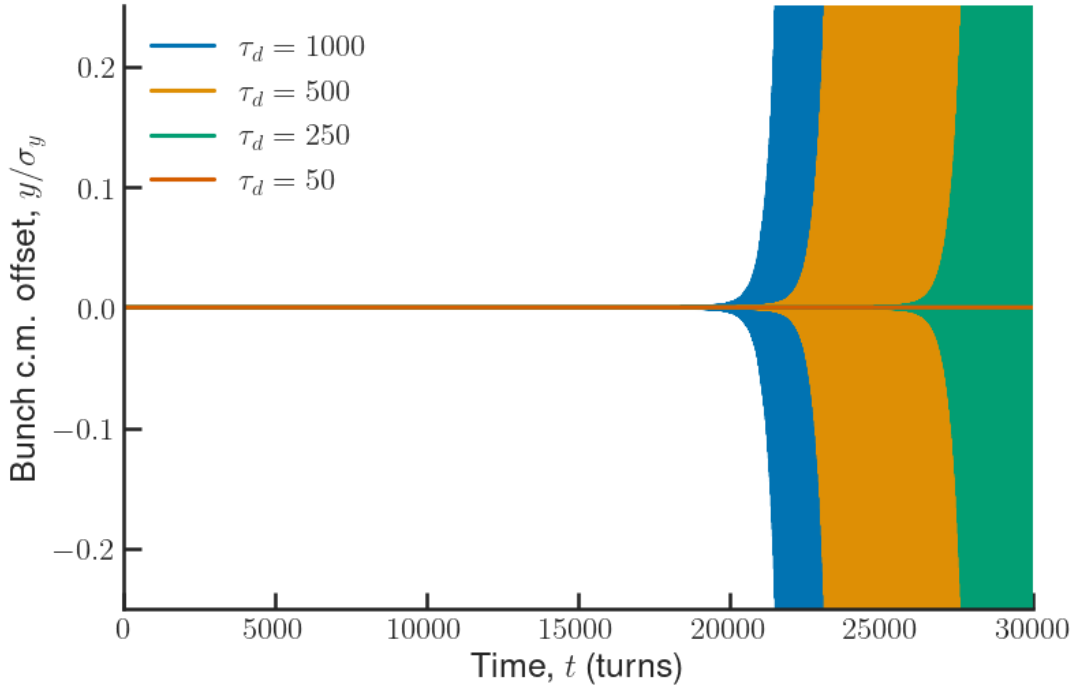
Preliminary feedback performance: single-bunch

- Increasing chromaticity to suppress instability as 6.25 mA is not efficient



! Results are from DELPHI only. After Q'=2 the benefits are negligible

- No harmonic cavity included to get worst case scenario
- This single-bunch instability will require a strong feedback < 100 turns damping time
- Damping time here is the one at Q'=0

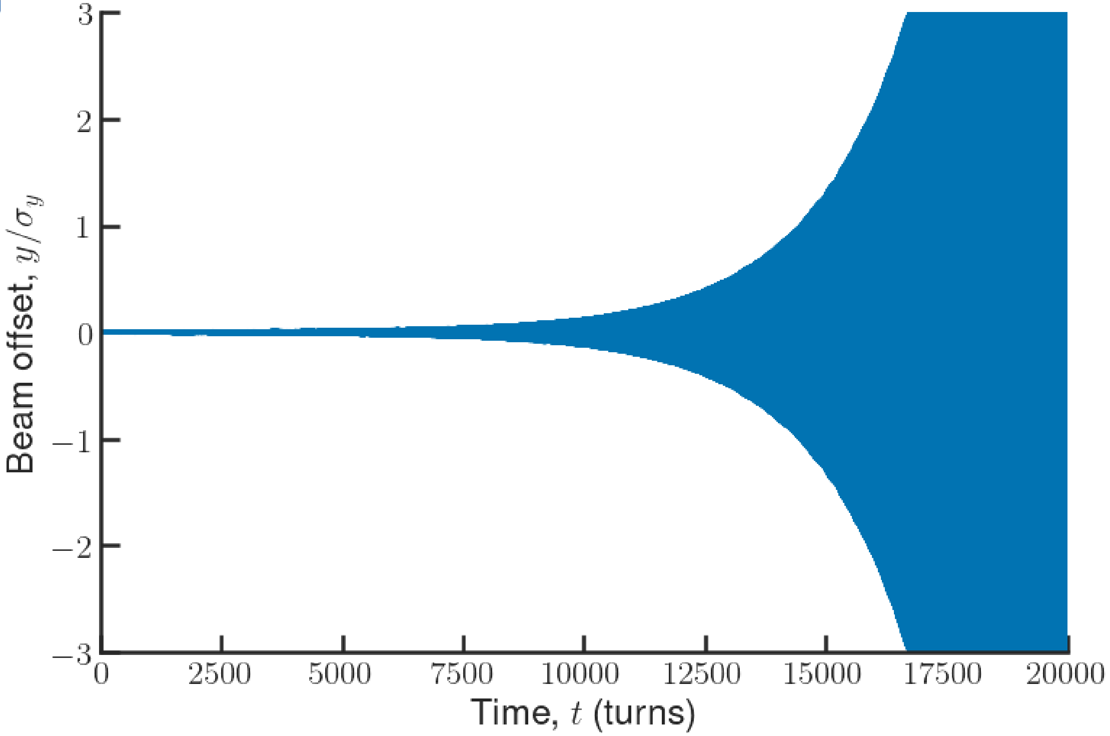


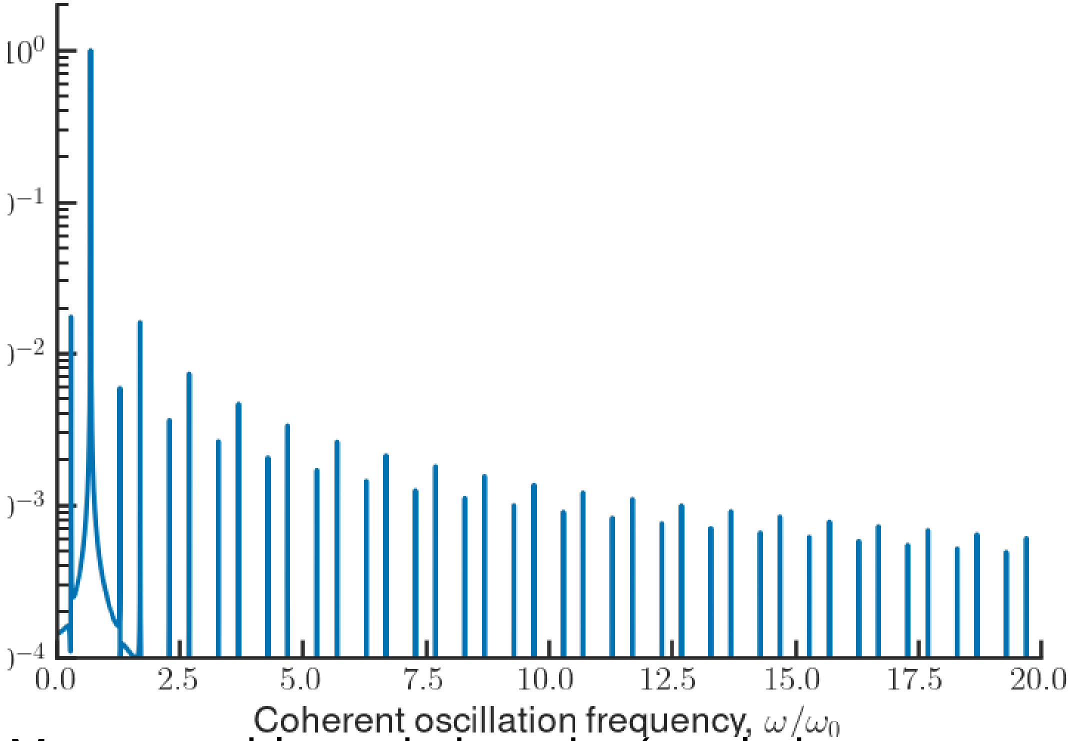
"Ideal" damper

Possible measures to alleviate feedback requirements:

- Increasing chromaticity
- Getting lower current

Transverse coupled-bunch instability



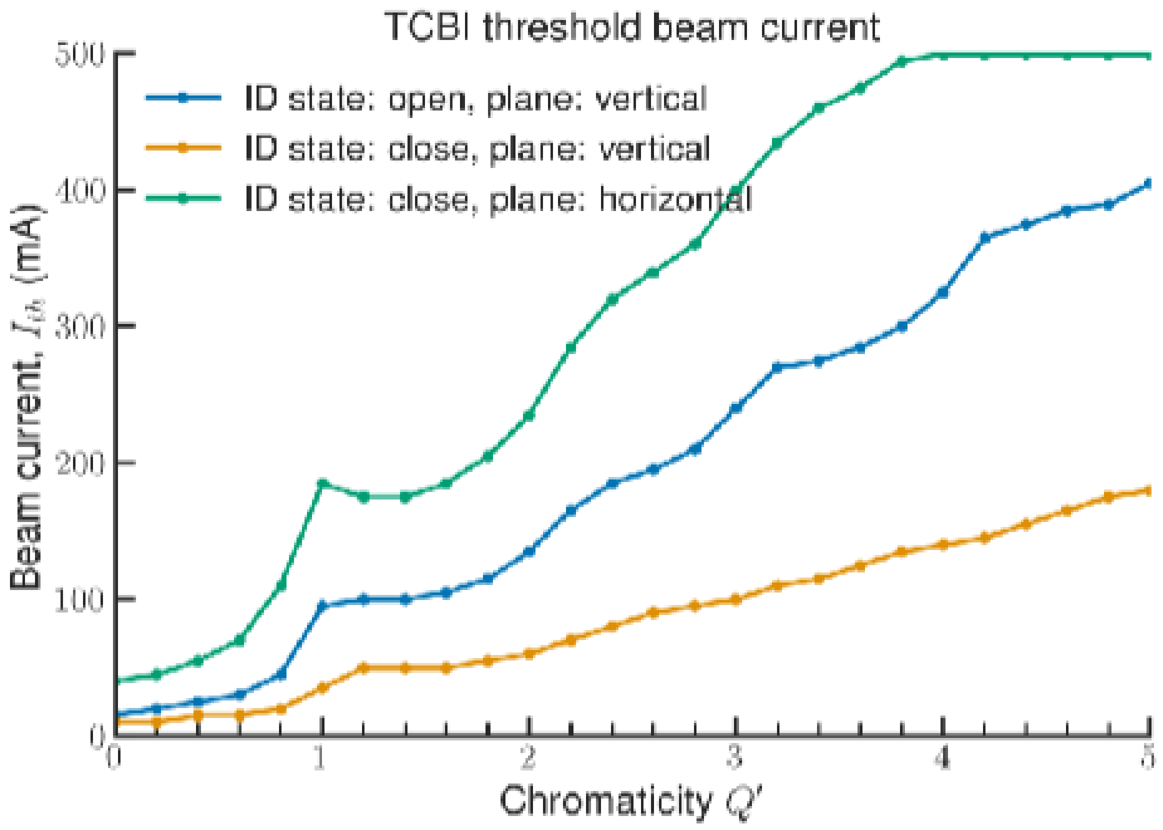


- Exponential growth rate
- Impedance-driven
- Linear with beam current
- Can be suppressed by chromaticity
- Both long-range and short-range wakes have to be included in the simulations

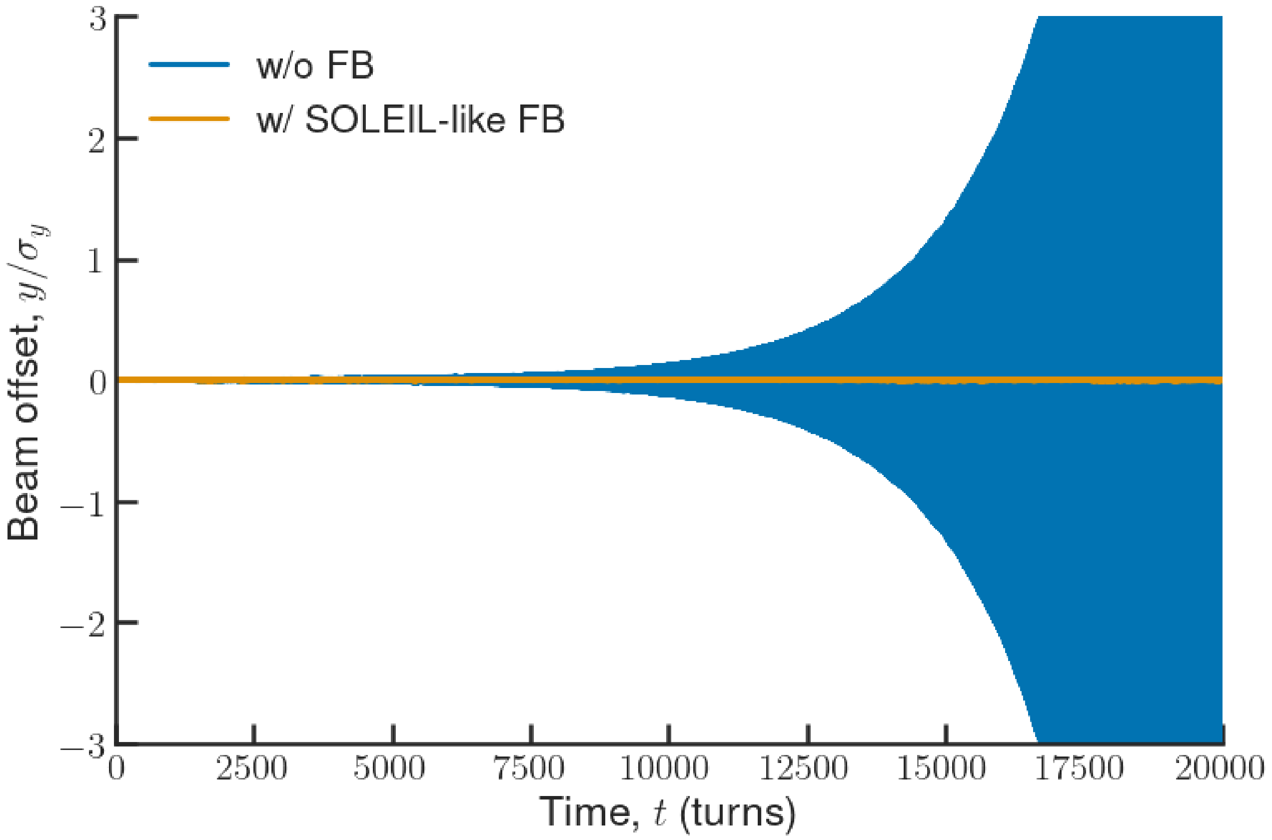
- Most unstable mode is at the (revolution harmonic – tune)
- Other modes unstable too but strength decays fast

Preliminary feedback performance: TCBI

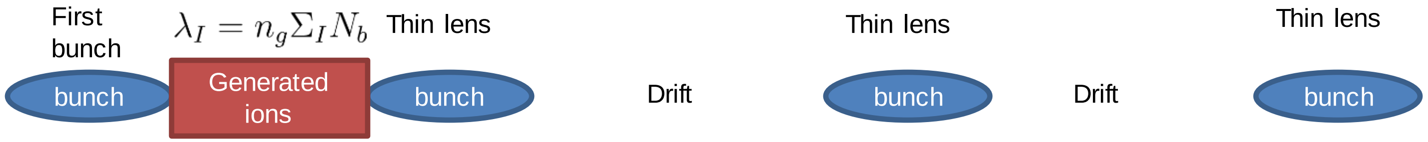
- To fully suppress the instability with chromaticity we would need to go really high (Q' ~ 10)

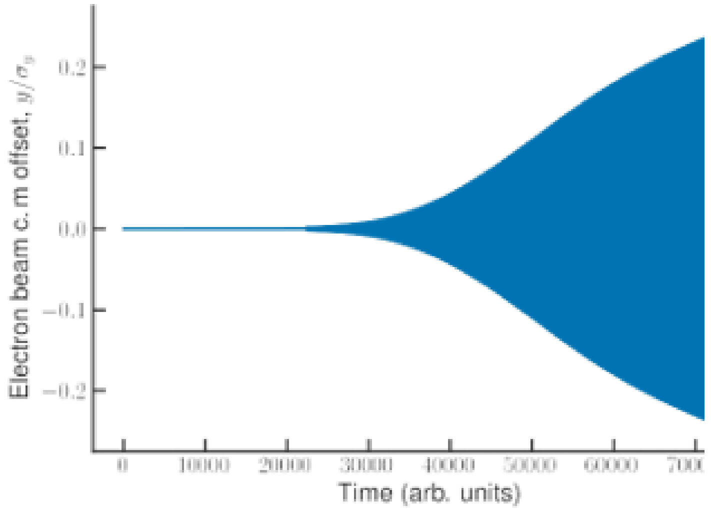


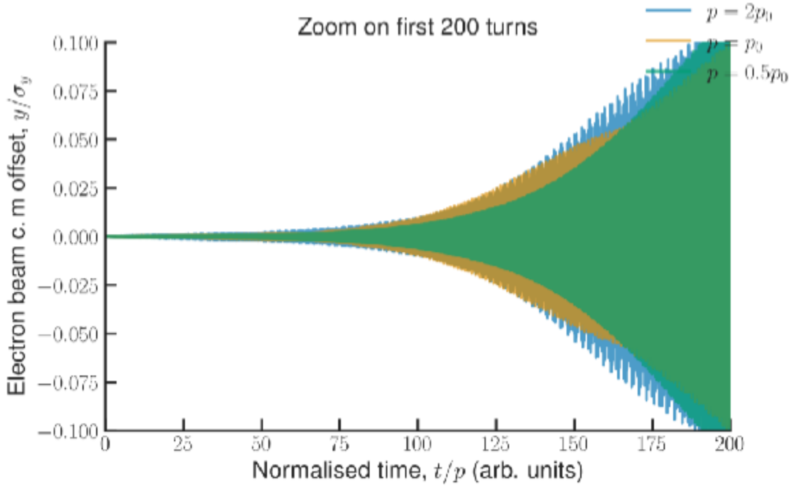
- Feedback with SOLEIL-like parameters suppresses the instability

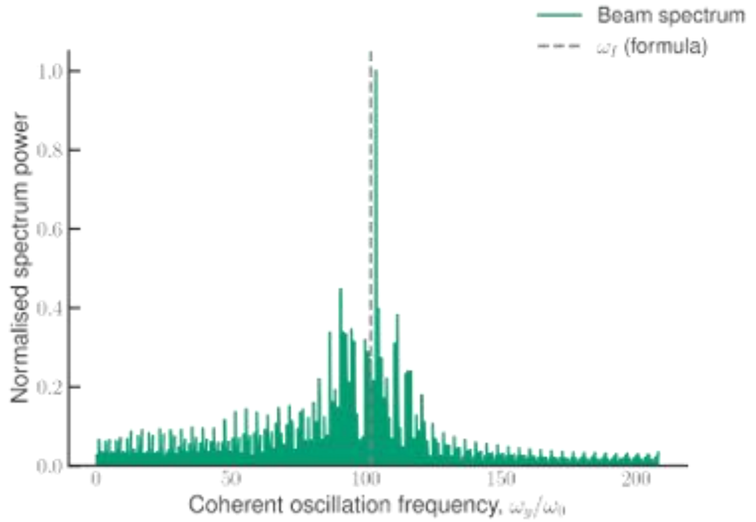


Beam-ion instability









- Instability risetime
  - linear with vacuum pressure
  - Linear with number of gaps for a given gap length
  - Gap effectiveness is nonlinear with beam current
  - Instability risetime is nonlinear with beam current

- Instability spectrum:
  - Centered at large rev. frequency harmonics
  - Large spread of frequencies in the spectrum
  - Frequency depends on beam current

Preliminary feedback performance: BII

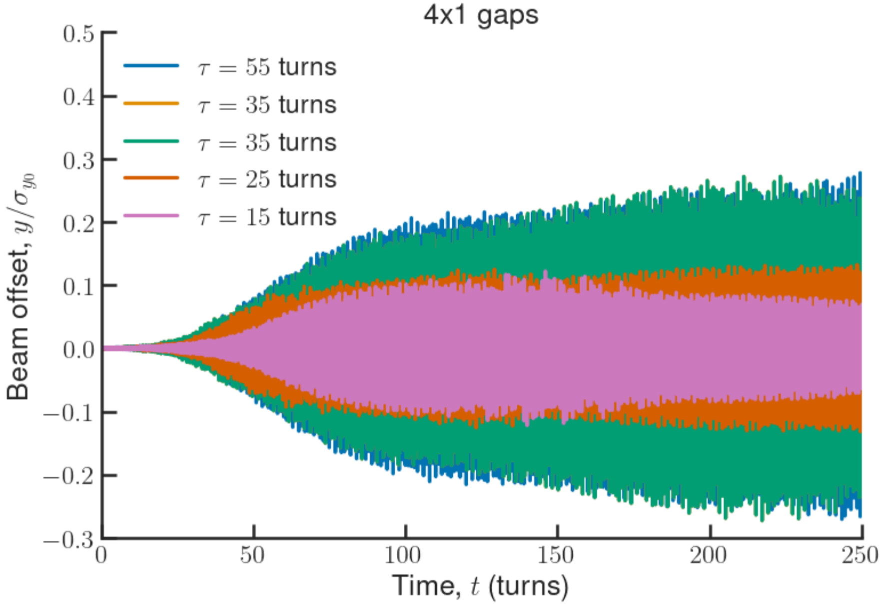
Uniform@500 mA with 100 A.h vacuum conditions

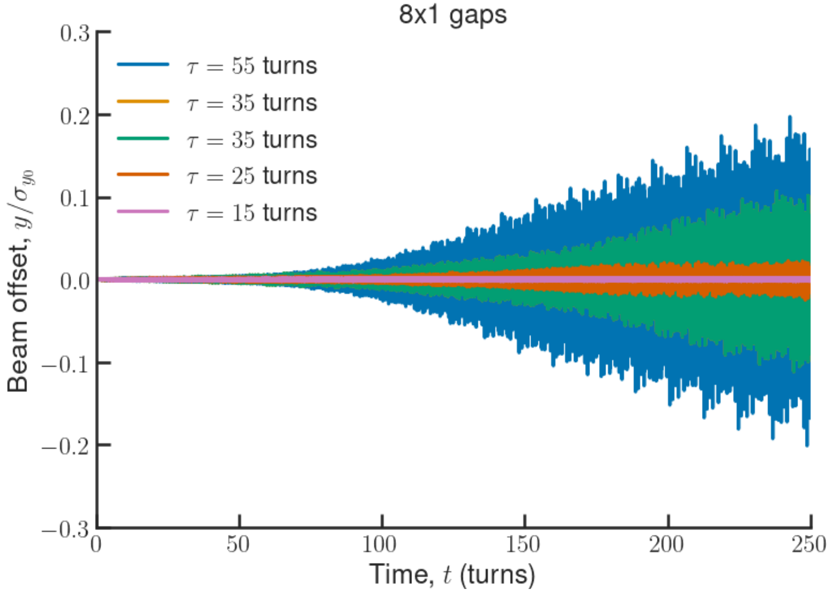
- Feedback quickly stabilises first bunches in a train

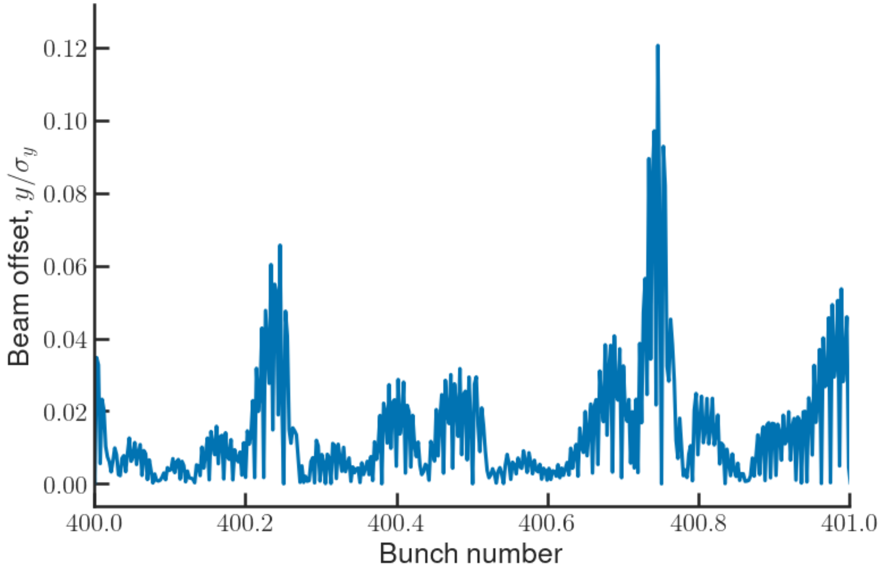
- A few most unstable bunches dictate the residual oscillation amplitude

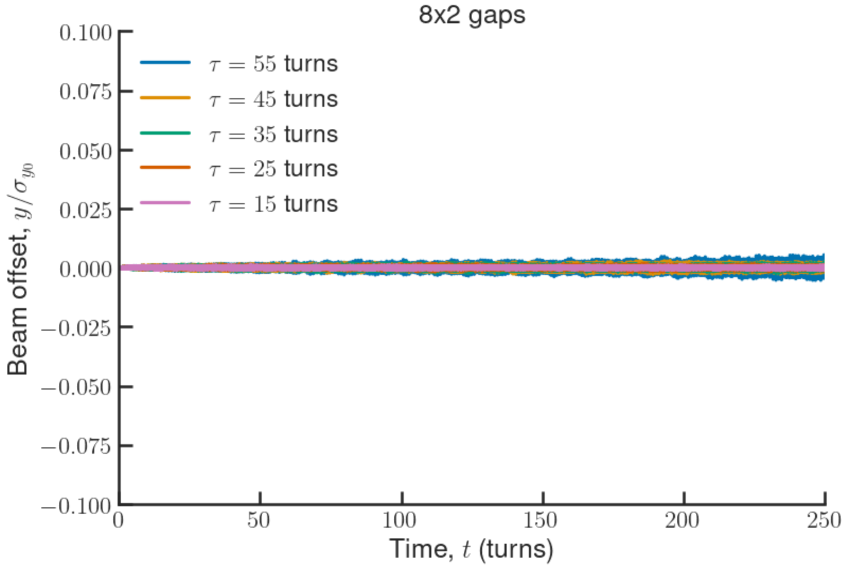
- A solution with low enough feedback strength can be found by increasing the number of gaps

- "Ideal" damper is used









Conclusions

- Starting with simple models and increasing complexity

- One of the goals for instability modelling is to get estimations in two ways: semianalytical and tracking

- Feedback is essential: coupled-bunch instabilities and single-bunch instabilities
  - Single-bunch instability in timing mode
  - Coupled-bunch and beam-ion in uniform mode

- Single-bunch instability in 32b@200mA is more concerning than TCBI

- (impedance) Challenges are similar to those of 3rd-generation (with closed ID gaps)

- Beam-ion instability appears to be the strongest one in simulations

  - A combination of optimal gap configuration and bunch-by-bunch feedback is necessary
  - All beam-ion simulations assume pessimistic parameters
  - Information on vaccum pressure vs dose is crucial for correct estimations of the instability

Thank you!