Longitudinal instability studies for Landau cavities in the PS

MSWG #15
19/10/2018

A. Lasheen, H. Damerau
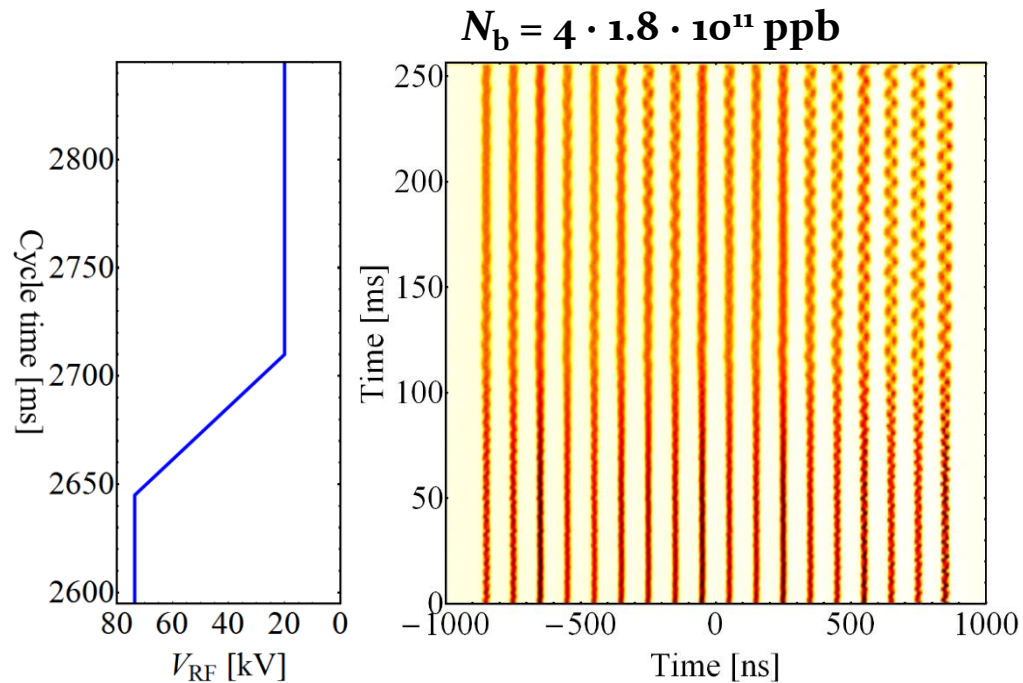
Outline

- Introduction

- Measurements of quadrupolar coupled bunch instability

- Landau damping with higher harmonic cavity

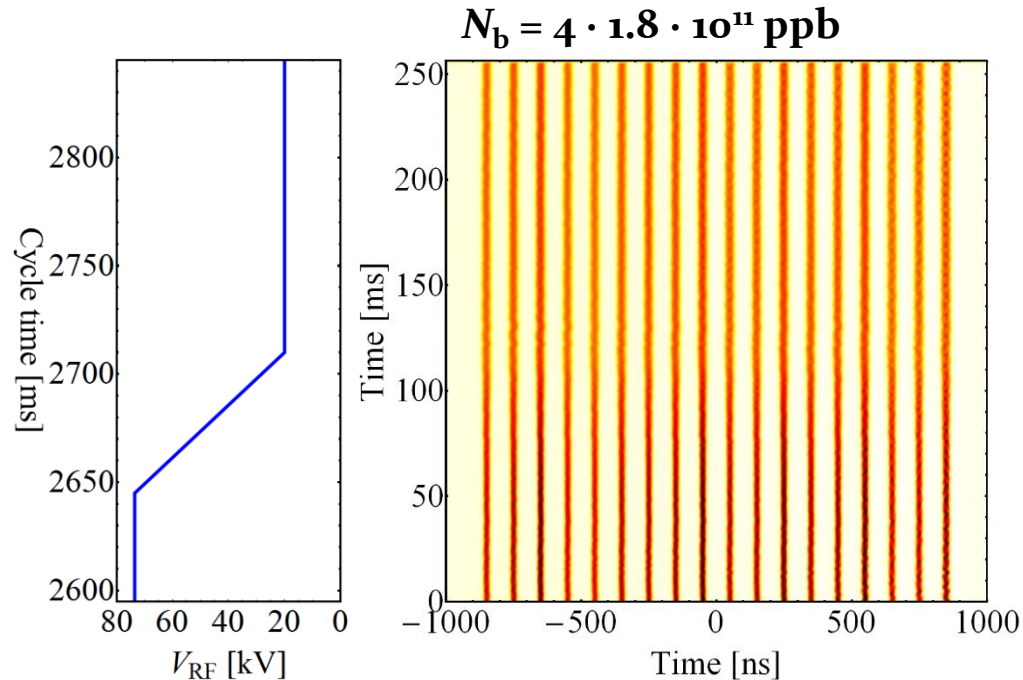- Particle simulations with Landau cavity

- Conclusions

Introduction

- **Stop RF manipulations at flat-top to observe evolution of stability**

$$N_b = 4 \cdot 1.8 \cdot 10^{11} \text{ ppb}$$

Introduction

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- **Coupled-bunch feedback enabled → significant improvement**

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- **Dipole coupled-bunch oscillations well damped**

Introduction

- **Stop RF manipulations at flat-top to observe evolution of stability**

- **Coupled-bunch feedback enabled → significant improvement**

$N_b = 4 \cdot 1.8 \cdot 10^{11}$ ppb $\qquad\qquad N_b = 4 \cdot 2.0 \cdot 10^{11}$ ppb
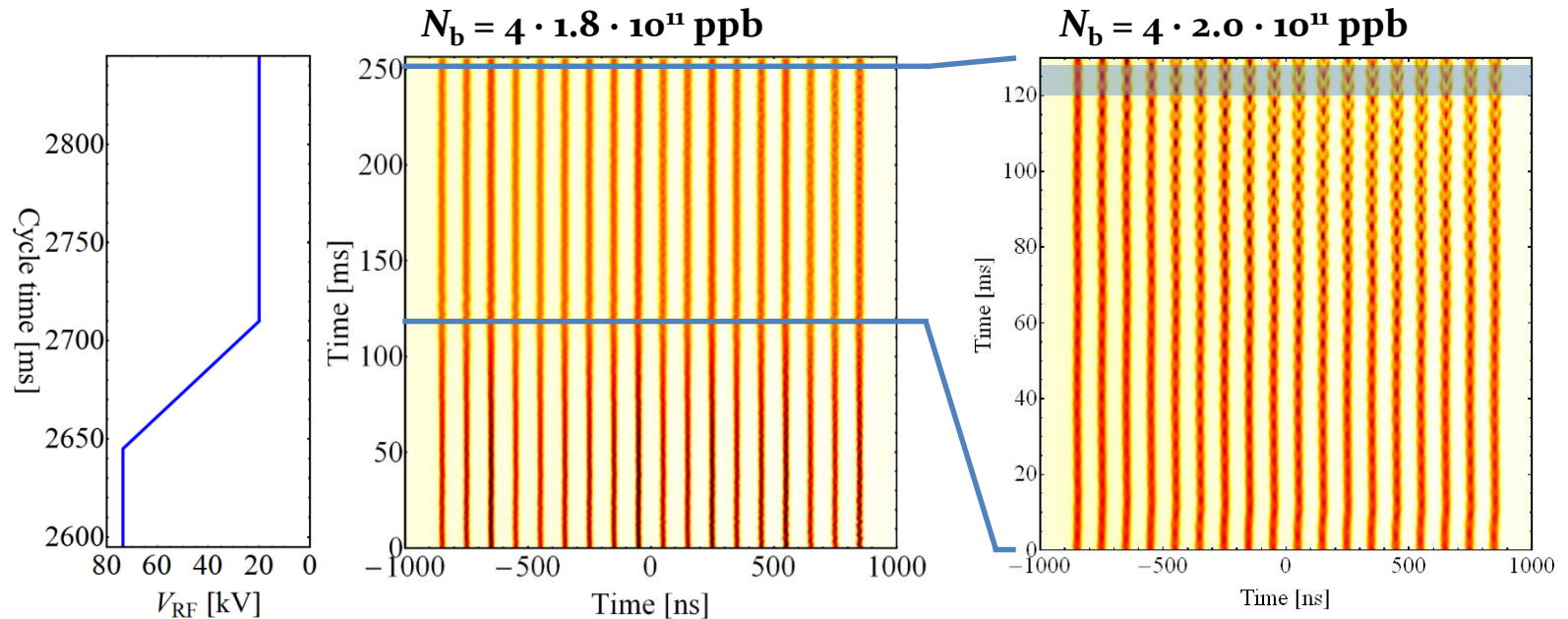
- **Dipole coupled-bunch oscillations well damped**

- **Quadrupolar oscillations at ~4 · 2 · 10^{11} ppb with small emittance**

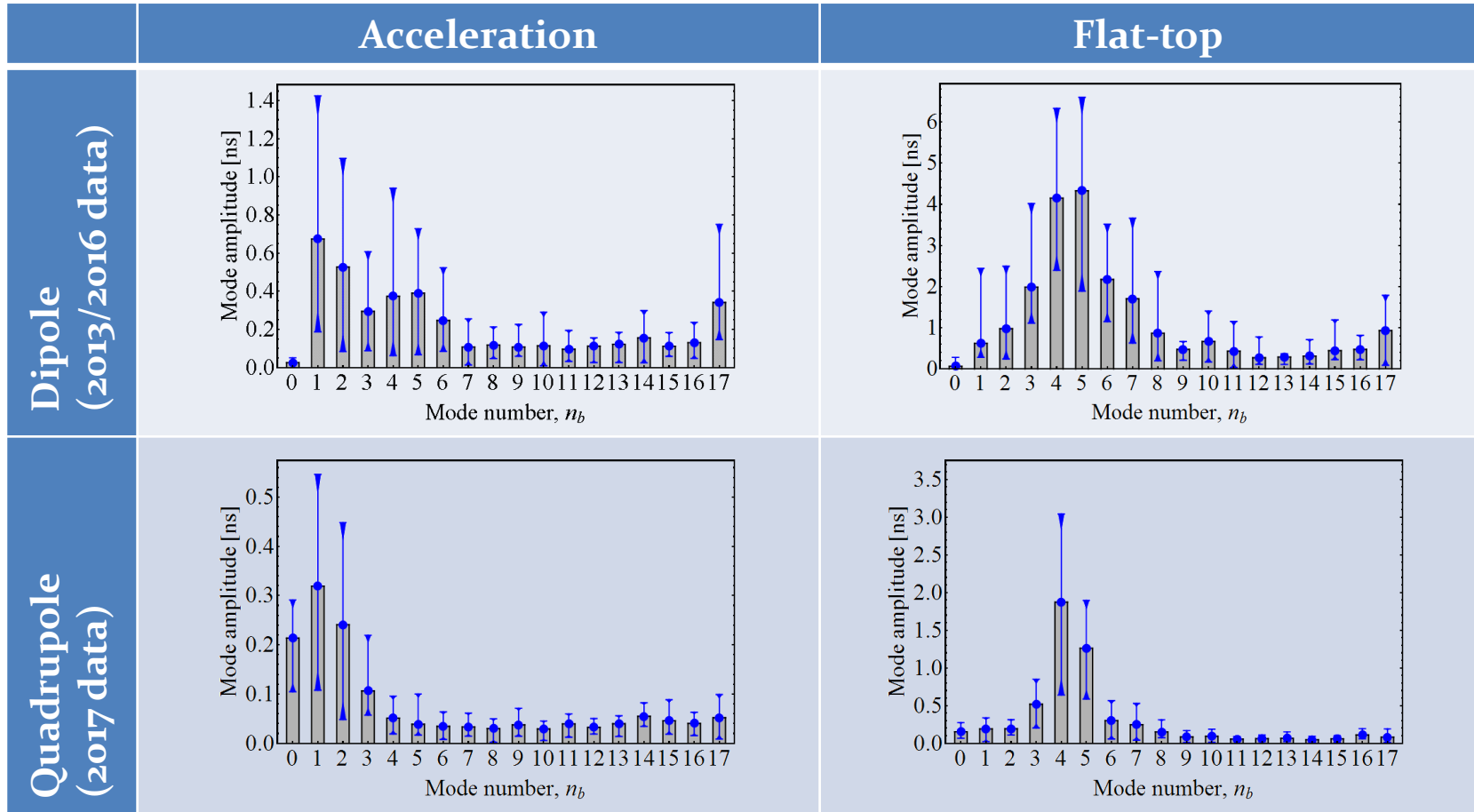- **Quadrupolar coupled-bunch instability appeared as a possible show-stopper for the LIU project**

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Bunch rotation, tails, and losses in the SPS

Losses: 0.619 percent - Fill factor 0.9: 5.819 percent

Losses: 3.96 percent
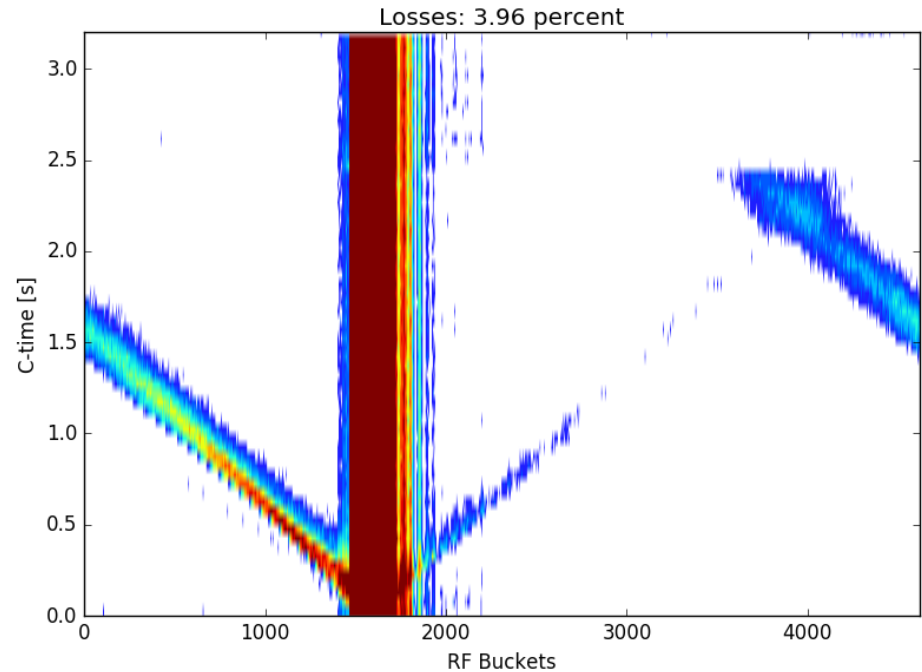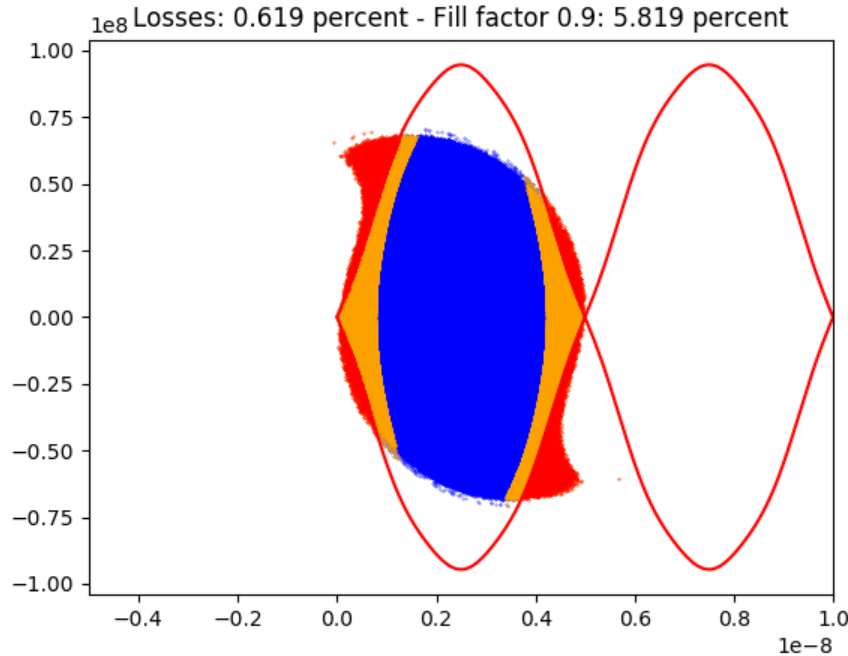
- Another potential show-stopper for the LIU project are the losses in the SPS, which exceed the baseline budget of 10%

- One of the main contribution to the losses in the SPS are particles with large amplitude, that don't fit in the SPS rf bucket after bunch rotation

- Longitudinal emittance control is key in the PS to avoid excessive losses in the SPS
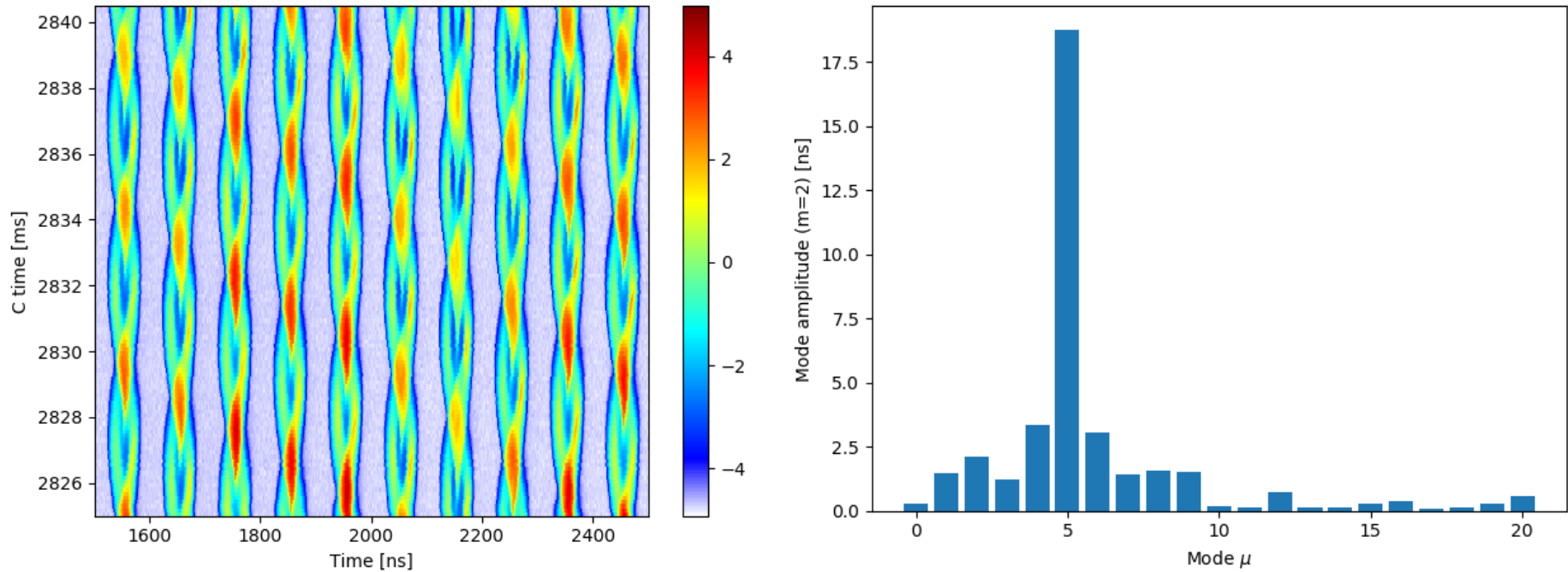
Mode pattern over the years

- **Mode pattern changes at flat-top, as observed for dipole oscillations**

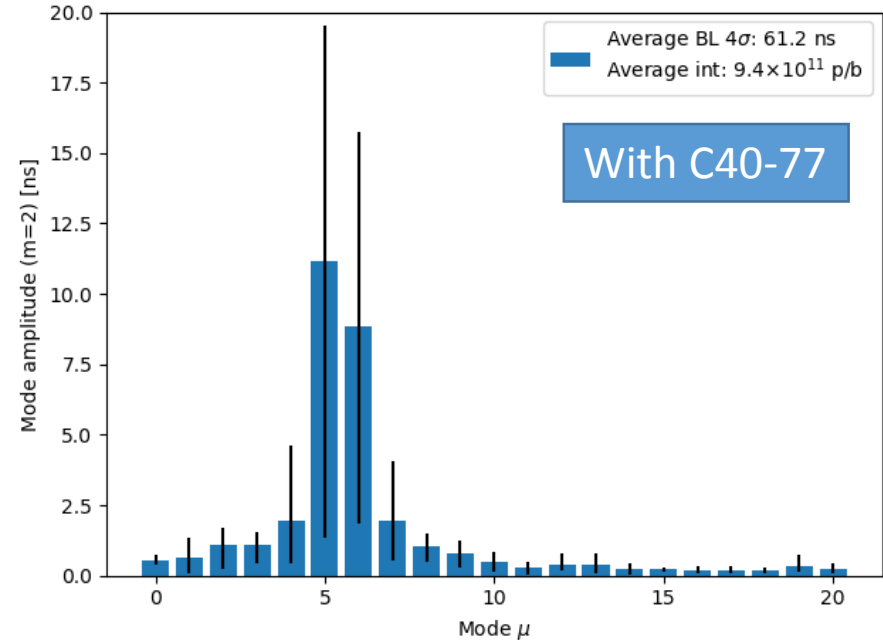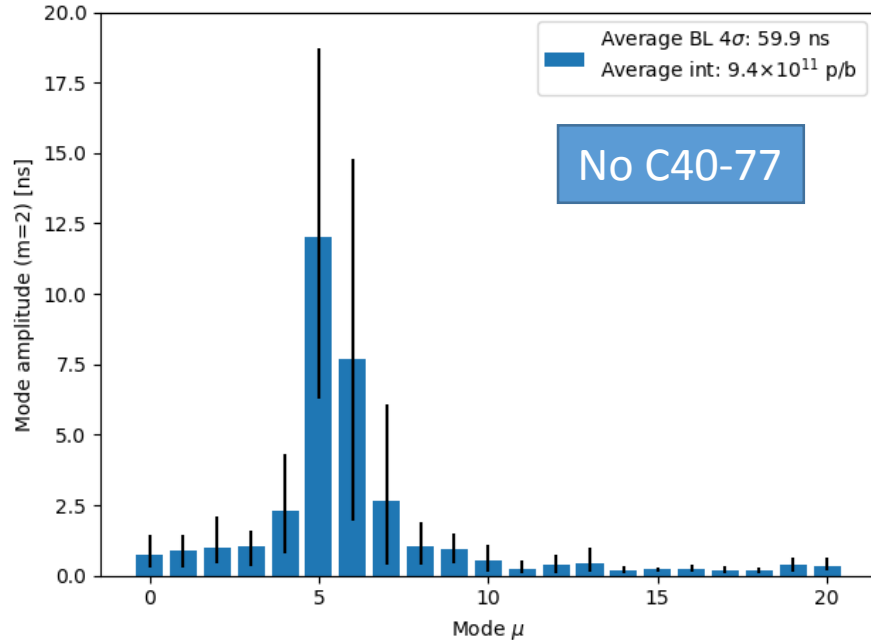→ **Measurements of coupled-mode spectra reproducible over years**

Quadrupolar coupled bunch instability with 21b

- Measured performed in 2018 with $4 \times 2.3 \times 10^{11}$ p/b with 21 bunches for clear mode analysis

$$A_n \sin(\omega_s t + \phi_n) = \frac{1}{N_b} \sum_{b=0}^{N_b-1} A_b \sin\left(\omega_s t + \phi_b - \frac{2\pi \, n \, b}{N_b}\right)$$

# Quad. instability, small emittance, no C80

- Some impedance sources can be reduced to attempt identify the source of instability

- Measurements done with the 80 MHz cavities gaps closed, with the gap of the 40 MHz cavity C40-77 closed/open

- The 40 MHz cavity does not seem to influence the quadrupolar instability

Measurements small emittance – with C80

BU4 : 3 × 3.5 kV / cav., < 3 × 80 MHz cavity gaps open, all 3 gaps open

With C40-77
All C80
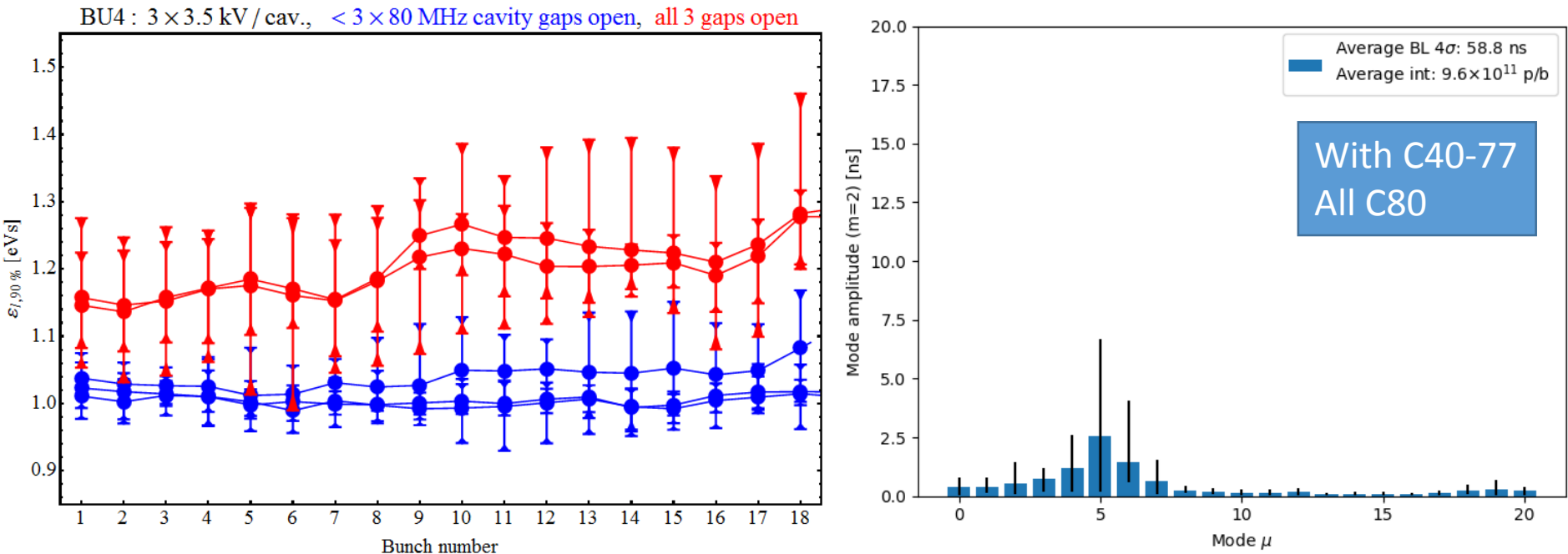
- The beam appears more stable with 3x80MHz gaps opened that with 0-2x80MHz gaps opened.

- This can be explained by the larger longitudinal emittance. The uncontrolled emittance blow-up along the batch is even since the ring is full.

- The 80 MHz cavities does not seem to contribute to the quadrupolar instability.

Landau damping
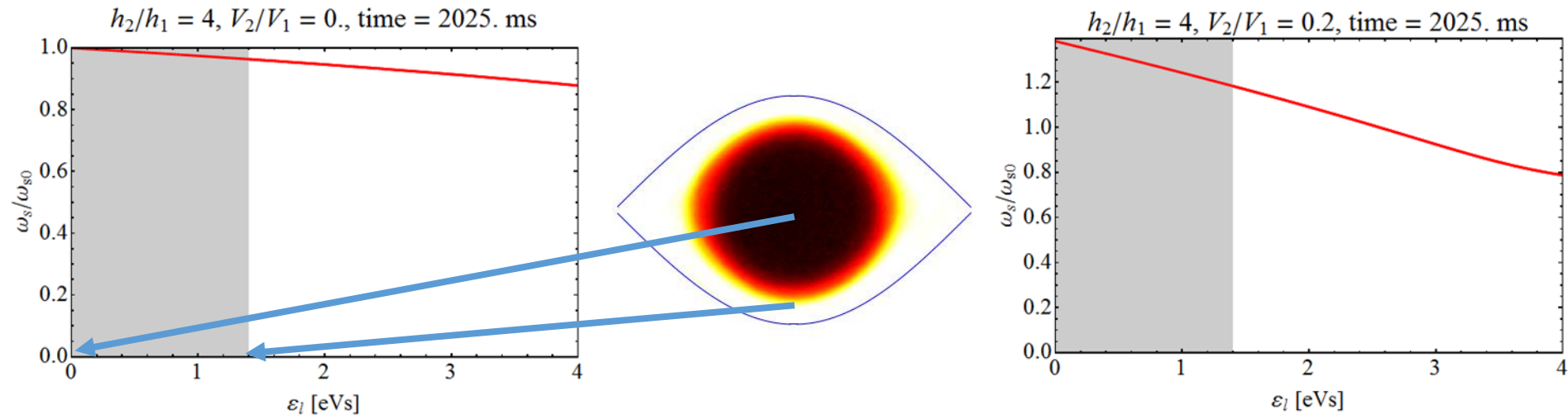
$h_2/h_1 = 4$, $V_2/V_1 = 0.$, time = 2025. ms

$h_2/h_1 = 4$, $V_2/V_1 = 0.2$, time = 2025. ms

- A bunch oscillates with the synchrotron frequency f_s in the bucket.

- Due to the non-linearities of the rf
  - all particles in the bucket oscillate with a different frequency
  - the spread provides with natural stabilization of the beam, which increases with longitudinal emittance.

- Extra non-linearities can be provided using a higher harmonic rf cavity, and can be used to stabilize the beam (e.g. the 800 MHz cavity in the SPS allows to increase beam intensity by factor ~4-5).

Landau damping
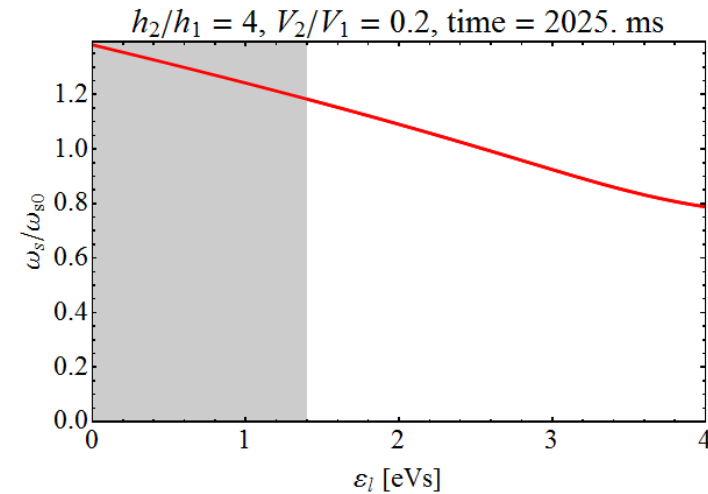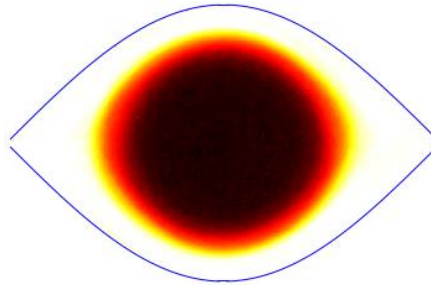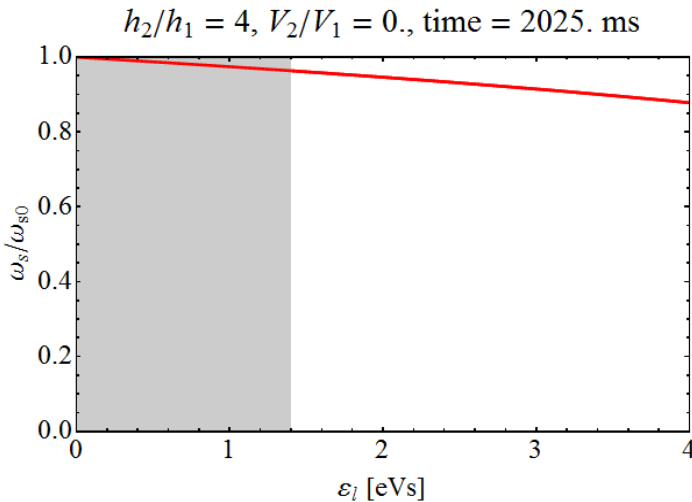
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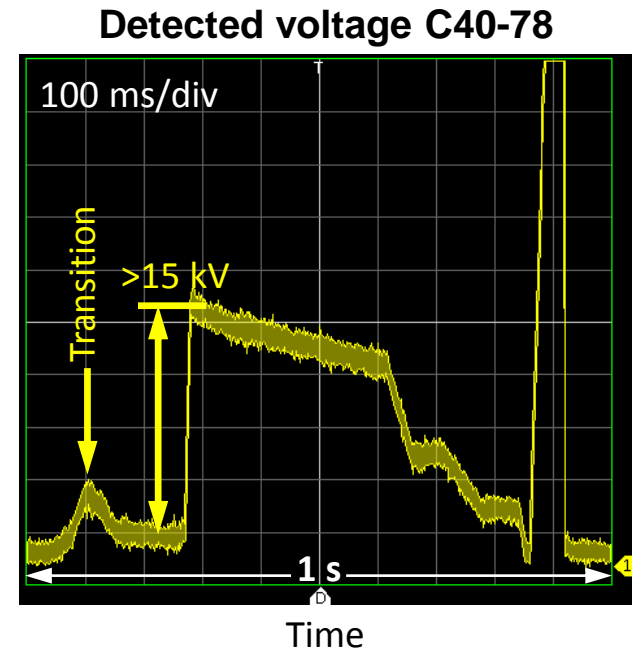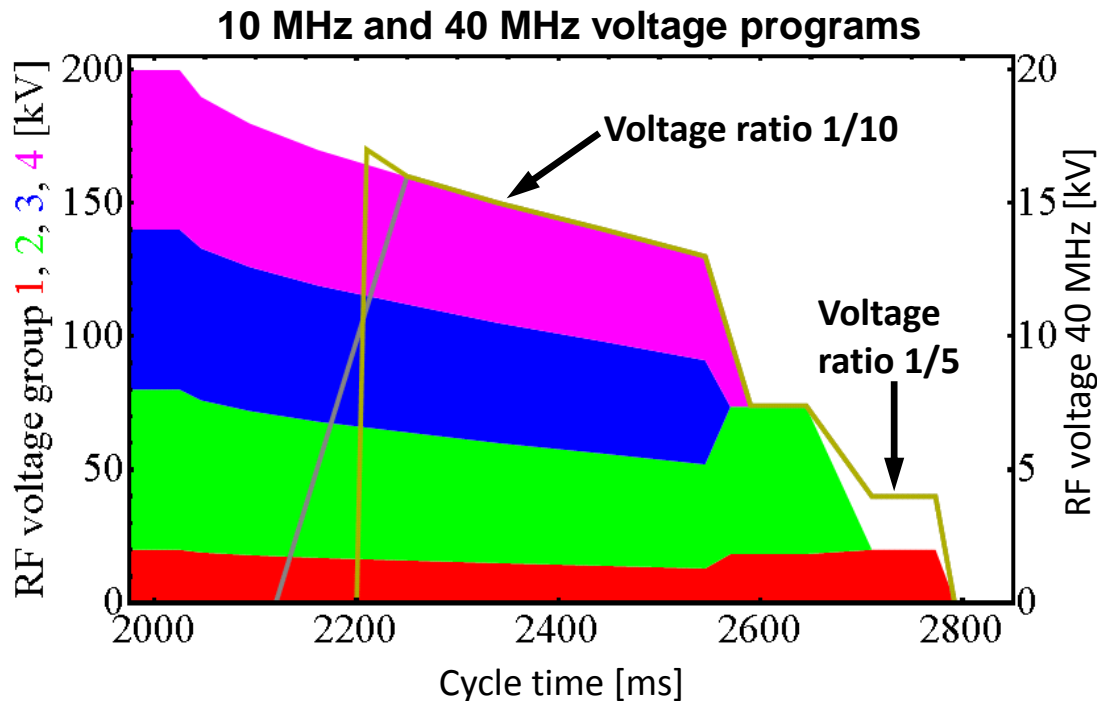# Existing 40 MHz cavity as Landau RF system

- Drive cavities off resonance during acceleration
 - → **Significant improvement** with new anode power converter

10 MHz and 40 MHz voltage programs

Voltage ratio 1/10

Voltage ratio 1/5

Detected voltage C40-78

100 ms/div

Transition

>15 kV

1 s

Time

→ **A. Jibar, M. Morvillo**

→ Gap of ~170 ms between transition and start of 40 MHz voltage

→ **Evidence of stabilizing effect during acceleration**

Existing 40 MHz cavity as Landau RF system

- Evaluate benefit of on longitudinal stability during acceleration
  - → **Disable coupled-bunch feedback ~225 ms after transition**

**10 MHz only**   **10 and 40 MHz, V_{h84}/V_{h21} ~0.1**
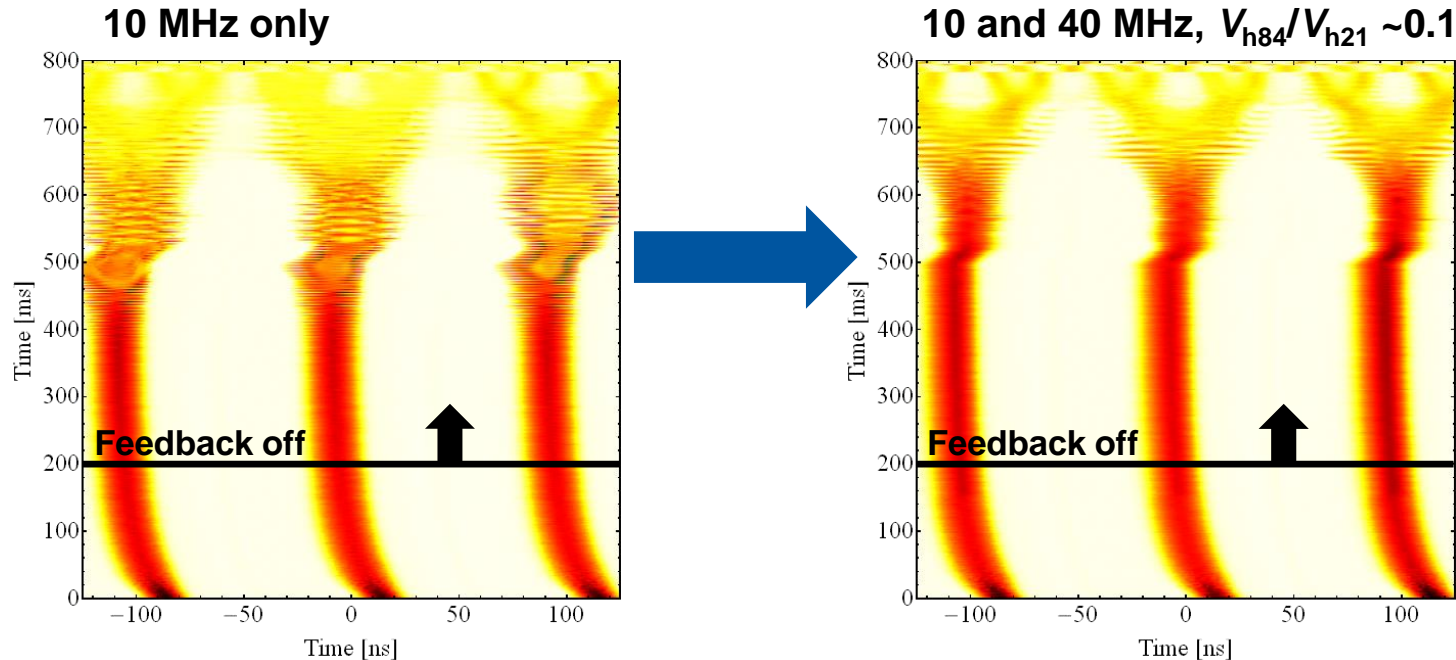

→ **Significant stabilization due to higher-harmonic RF**

→ **Stability margin beyond LIU baseline**

→ **Further optimization (relative phase and voltage) to be completed**

BLonD simulation set-up
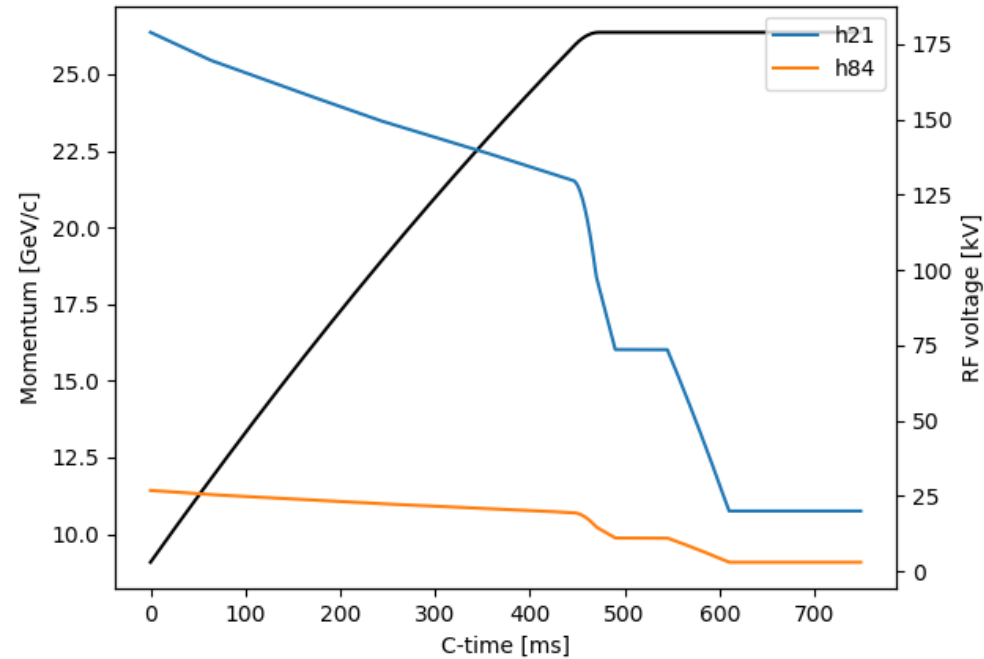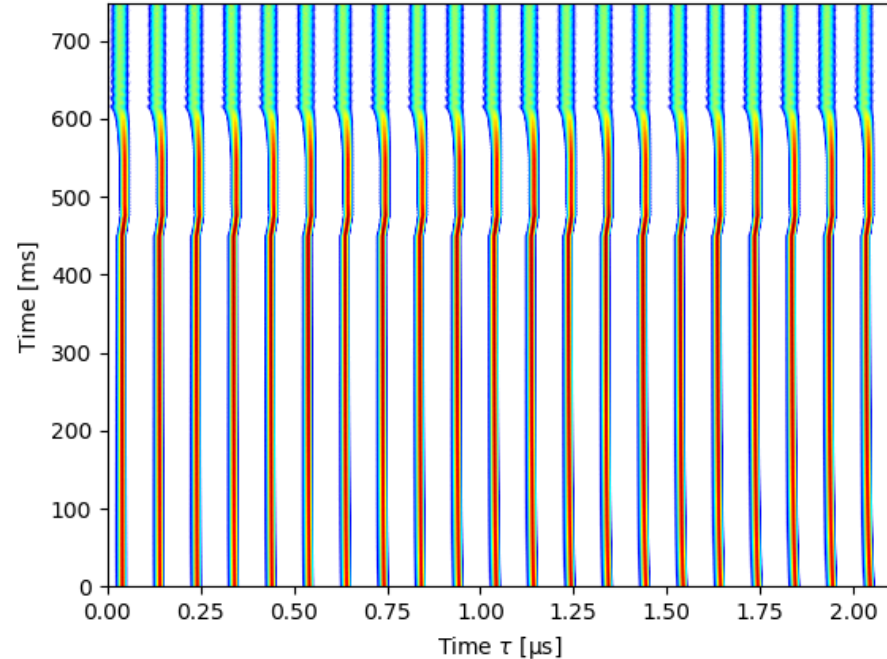
- Operational RF program from C-time=2100 ms (after transition and last controlled emittance blow-up)

- Splittings at flat top disabled

- 21 bunches generated matched with intensity effects

Present impedance model
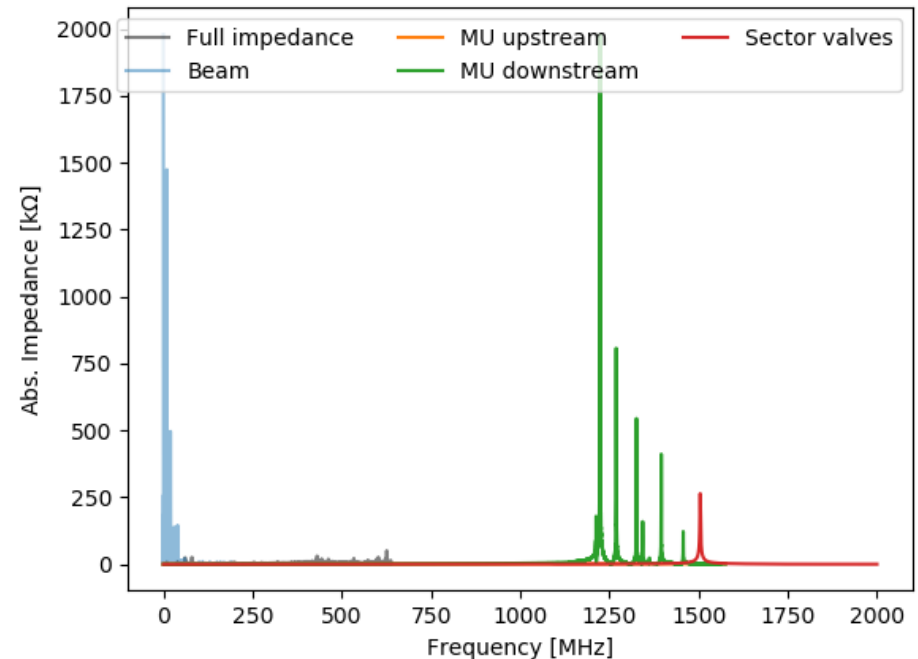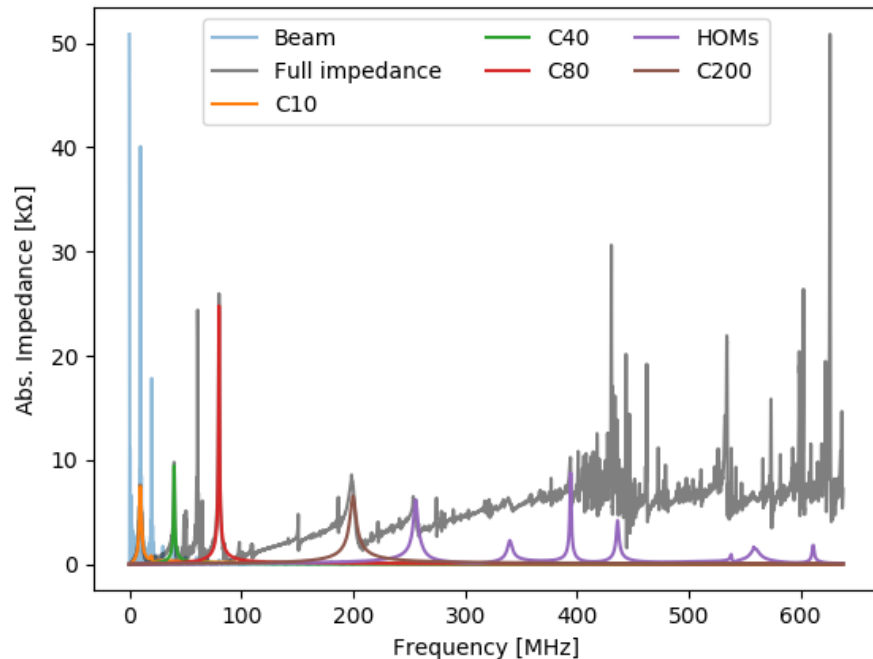
- Status of the impedance model:
 - → *RF cavities (C10, C20, C40, C80, HOMs…)*
  - → *Kickers (KFAs, BFAs)*
  - → *Vacuum equipment (Magnet Units)*
  - → *Beam dumps*
  - → *Space charge & resistive wall*
  - → *Ongoing (remaining kickers and beam instrumentation)*

Scan of beam parameters, present case
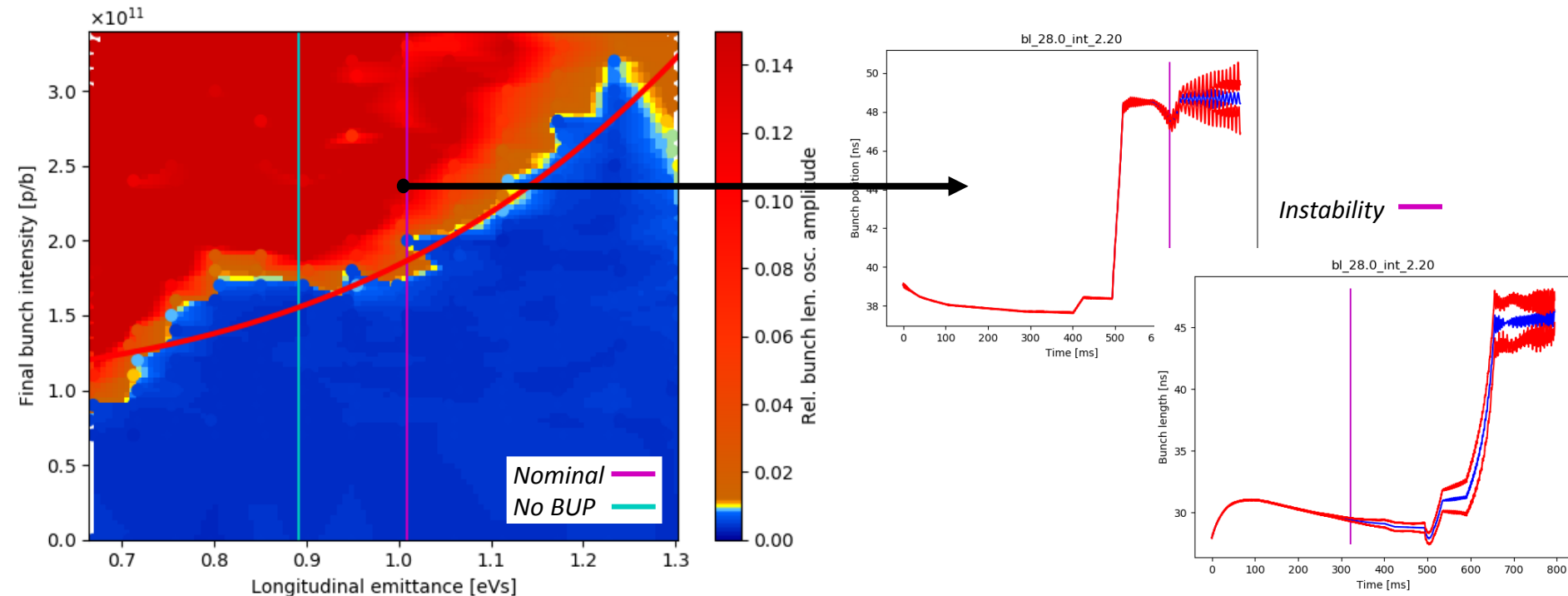
- **The beam parameters (longitudinal emittance and bunch intensity) are scanned assuming a parabolic amplitude distribution**

- **Each simulation is analyzed to determine whether the beam is unstable. The criterion for instability is the same for all simulations and is set manually (1% of relative oscillations)**

Simulations with Landau cavity
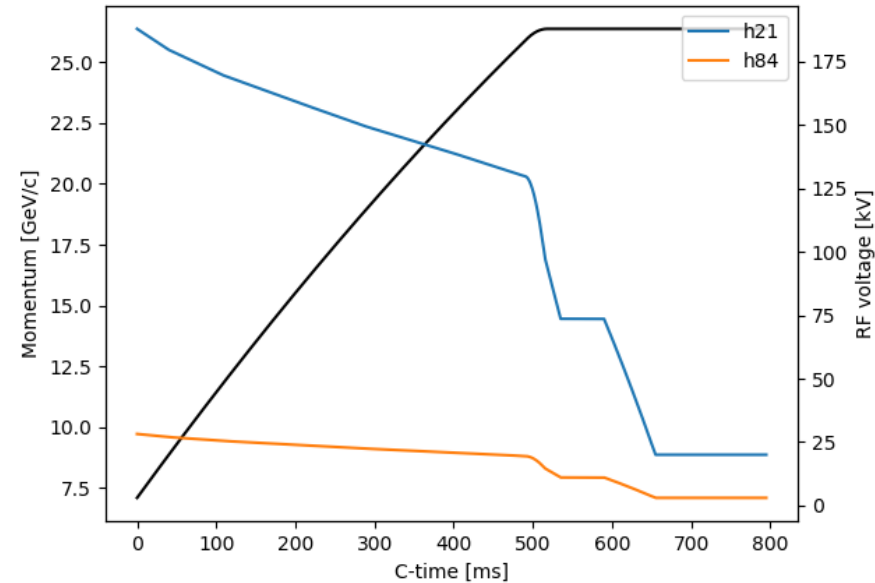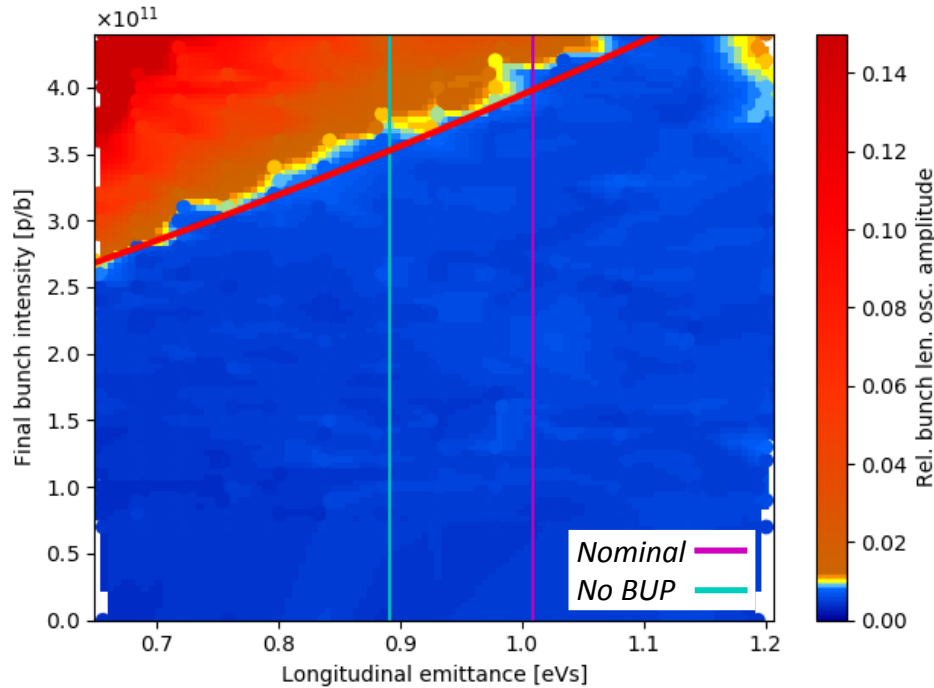
- An example of scan with Landau rf voltage set to a harmonic ratio of 4, an rf voltage set to 15% of the main harmonic (max voltage: 30 kV), in bunch shortening mode

- For the nominal emittance, the instability threshold is increased by a factor 2 according to simulations

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Choice of rf harmonic and voltage
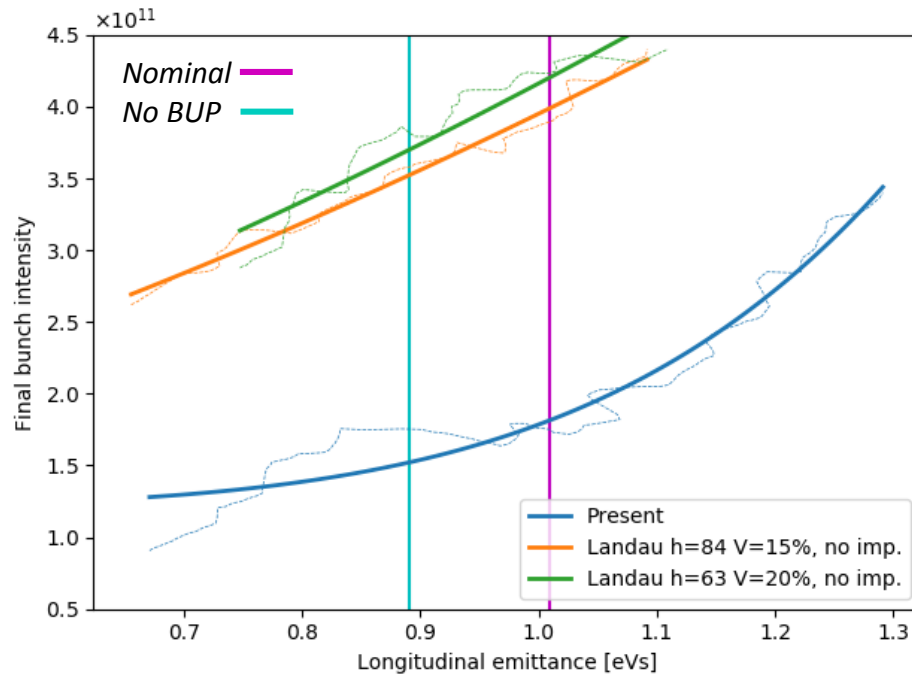
Cavity (x2)	Optimal ratio	Total rf voltage
h=63	15-20%	30-50 kV
h=84	10-15%	20-30 kV

- Comparing the cases with harmonic ratios of 4 (h=84) and 3 (h=63) (different voltage ratios, in bunch shortening mode). Both give more than x2 improvement of stability in intensity for nominal emittance.

- The two cases provide with comparable stabilization for nominal emittance.

- The choice can be based on what is the easiest to achieve from RF engineering point of view and applicability to other beams (for beams with main harmonic h=16 -> Landau at h=84)

Conclusions

- The quadrupolar instability was studied and the mode analysis can be used to identify the responsible impedance source (first hints towards the 10 MHz cavities).

- The 40 MHz and 80 MHz cavities impedance were shown to have minor impact on the quadrupolar coupled bunch instability. Nevertheless these impedance sources contribute to uncontrolled emittance blow-up.

- The PS impedance model is continuously updated to find guilty impedance sources and are used in particle simulations. Present simulations give fair agreement with measurements and are used to give early projections.

- The usage of a Landau cavity with harmonic ratio 4 and voltage ratio of 10-15% was demonstrated to stabilize the instabilities. The 40 MHz cavity C40-78 could be used almost all along the ramp after transition and provides with stability margin beyond LIU baseline.

- Another important intensity limitation are the losses in the SPS. The Landau cavity could be the necessary margin to reach lower longitudinal emittance, in order to lower the injection losses in the SPS.

Investigating the guilty impedance source
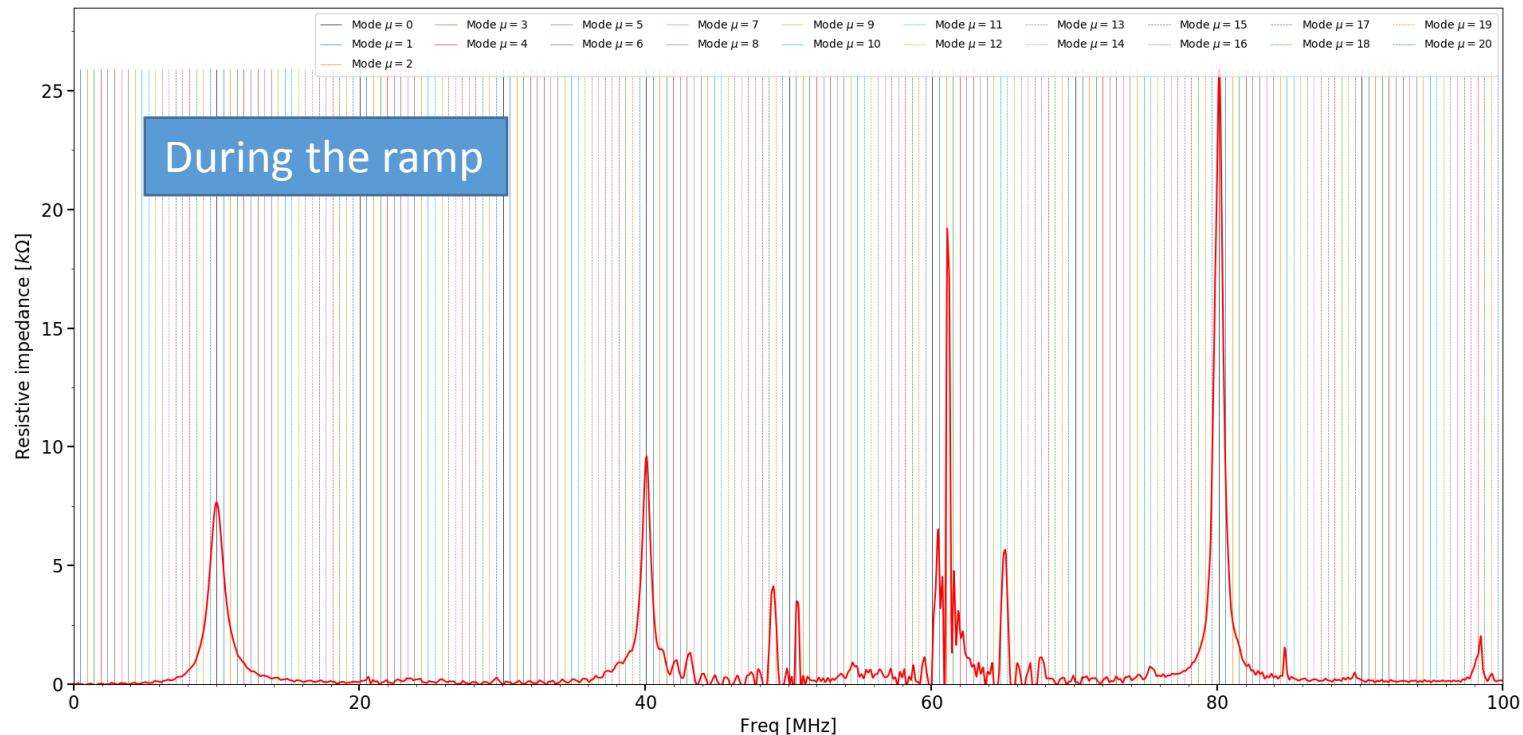
- The impedance source(s) responsible of the instability can be identified by checking the peak of resistive impedance vs. the frequency for each mode, located at

$$f_{p,\mu} = (p \, N_{\text{bunches}} + \mu) \, f_{\text{rev}} + m \, f_s \quad (m = 2 \text{ for quad. instability})$$

- We focus in the frequency region 0-100 MHz, since impedance sources at higher frequencies are in the regime $f_r \tau \gg 1$ which is more likely to drive microwave instability than coupled bunch instabilities.

- The biggest impedance sources are the cavities, tuned at revolution harmonics. The 10 MHz cavities are known to drive dipolar coupled bunch instabilities with modes $\mu = 19, 20, 1, 2$

Investigating the guilty impedance source
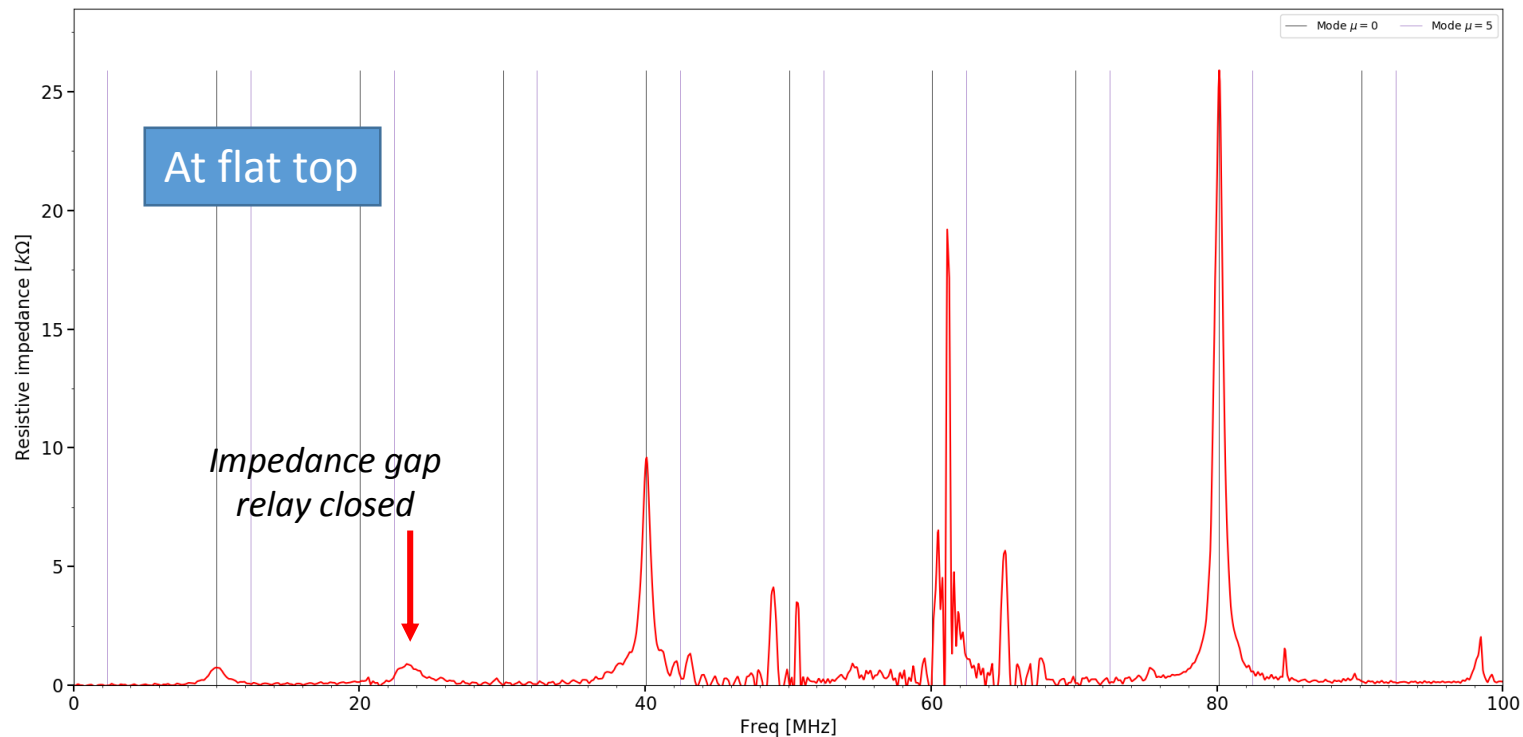
- From the impedance model and based on the mode $\mu = 5$ corresponds to $\approx n \times 10\ \text{MHz} + 2.4\ \text{MHz}$

- The only impedance source close to that criterion is the impedance of the 10 MHz cavities with closed gap relay. Although small, this impedance increases along the ramp when cavities are closed and is maximum at flat top, where the mode shifts to $\mu = 5$.

➤ Measurements with parking of the cavities after gap closure will be performed (further reduction of the impedance)

Investigating the guilty impedance source
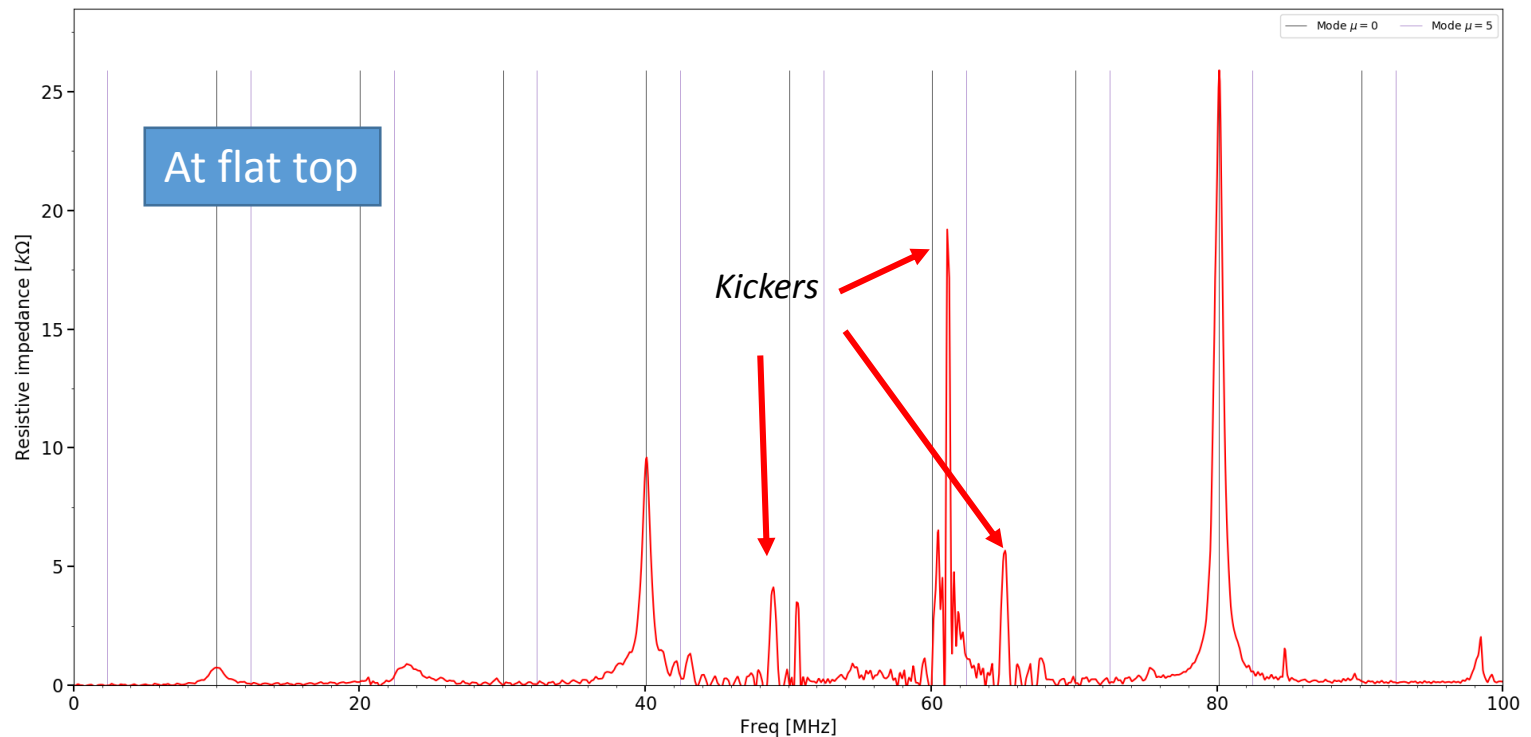
- Kickers have unexpected resonances at intermediate frequencies

- Need to further investigate on the origin of those modes in simulations, their presence in the actual kickers and refine the evaluation of their characteristics (frequency and amplitude)

Varying impedance sources along the ramp
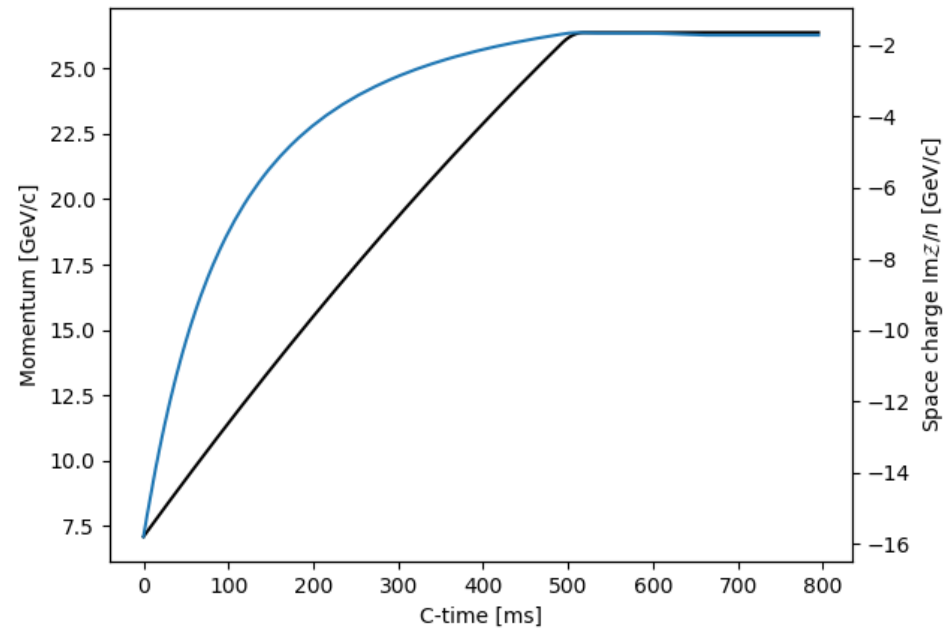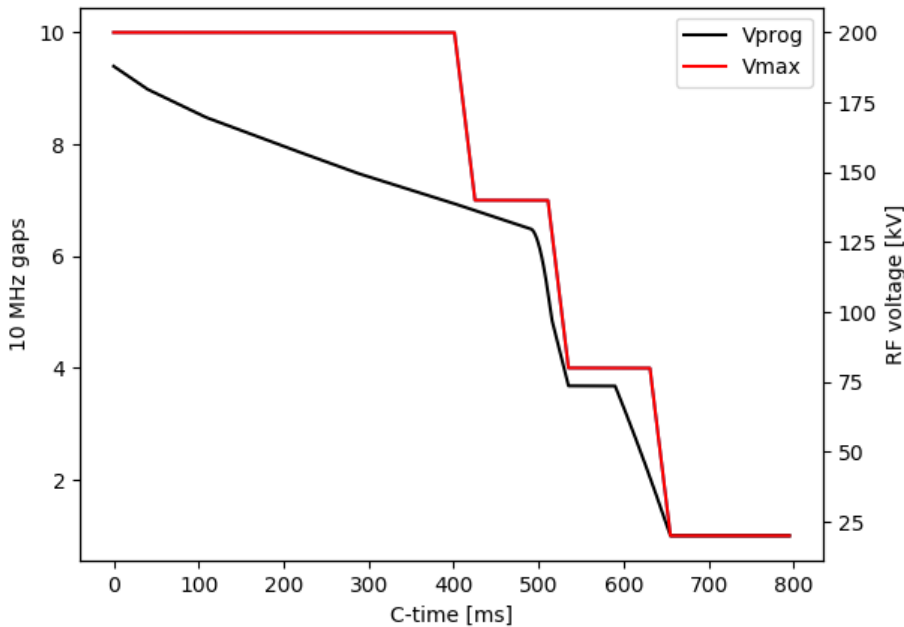
- Taking into account the closure of the 10 MHz gap relays based on real timings. The closure is assumed to take ~25 ms.

- Space charge along the ramp is accounting for evolution of $\beta\gamma^2$ and dp/p along the ramp

Mode analysis in simulations
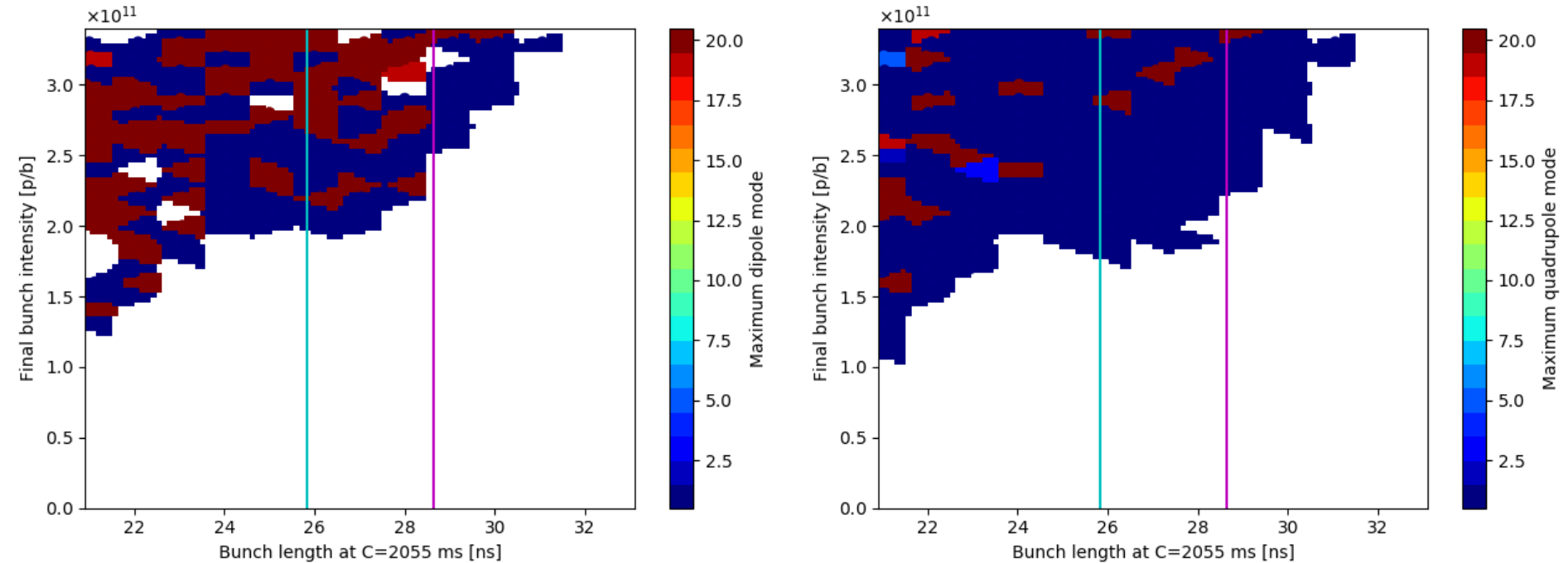
- Mode analysis along the ramp shows that it is mostly modes 1 and 20 which are excited along the ramp, as expected in measurements

- The observations in measurements are however not fully completed (missing impedance sources?):
    - Quadrupolar oscillations are observed at fairly low intensity
    - Mode of oscillations changes at flat top in measurements

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