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LHC Injectors Upgrade

LIU beam performance ramping up: SPS ions

T. Argyropoulos, Montreux, 20-22 January 2020

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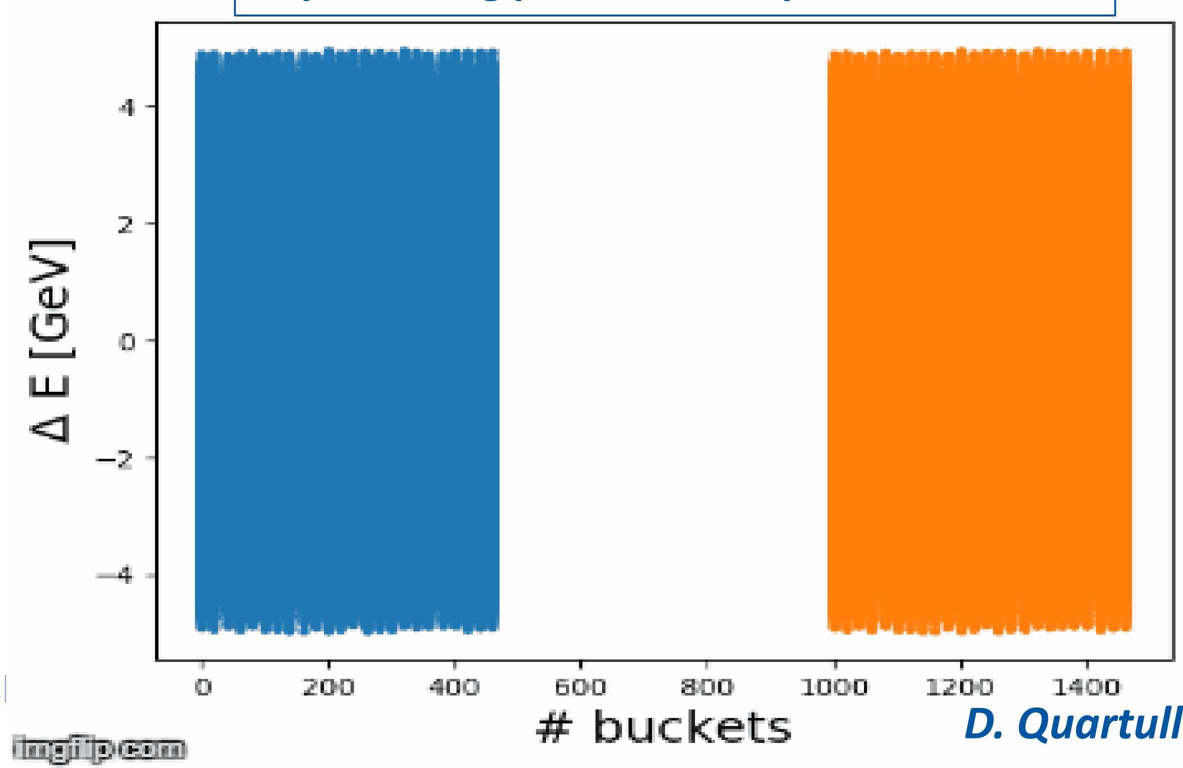
Introduction

- **HL-LHC requirement to double the peak luminosity at the Pb-ion run after LS2**
  - Increase the number of bunches in the LHC
- **LIU baseline to achieve that is by performing slip-stacking (slip-interleaving) in the SPS**
  - Two beams of different momenta slip azimuthally, relative to each other, in the same beam pipe.
  - The beams can be then interleaved reducing the bunch spacing by half and thus doubling the number of bunches

Slip-stacking procedure as planned for SPS



D. Quartullo

Slip-stacking procedure in SPS

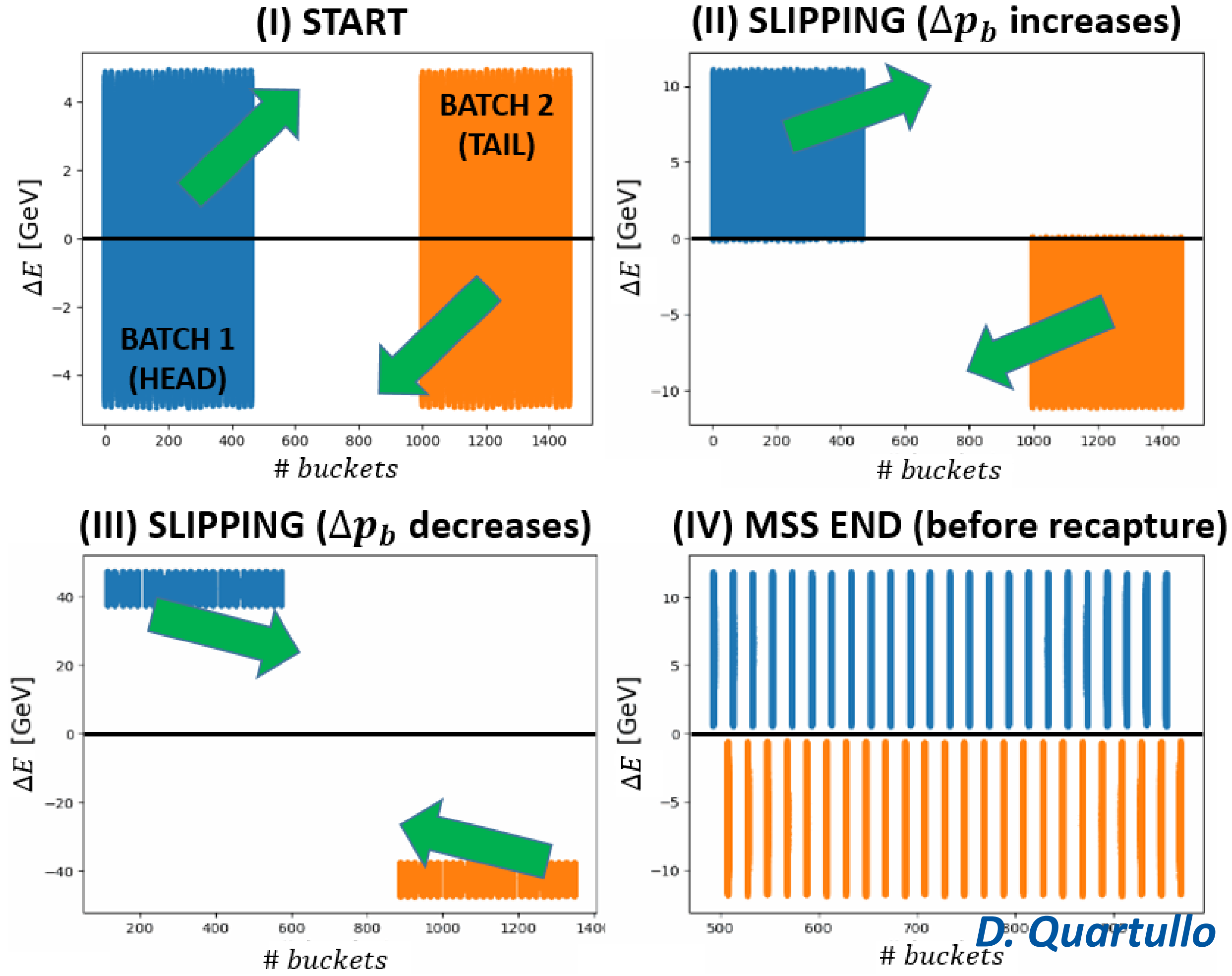
- **Two SPS batches of 24 bunches spaced by 100 ns are going to be interleaved at a constant energy plateau**
  - Resulting to a **single batch of 48 bunches with 50 ns bunch spacing**

I. The two batches are **controlled by two independent RF systems** with small frequency difference between them (within the bandwidth of the main 200 MHz RF system)

II.-III. The batches slip towards each other, following the designed RF programs (frequency, voltage).

IV. When the two beams are in correct position the full beam is recaptured with a much higher RF voltage at the average RF frequency.

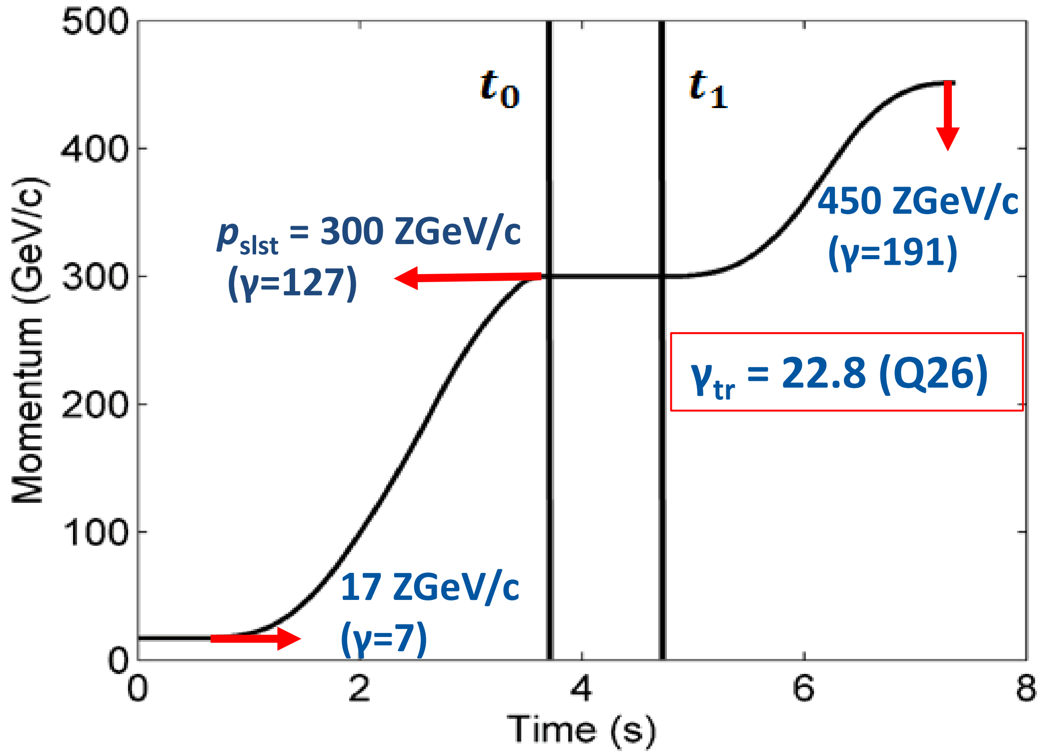
Schematics of the slip-stacking procedure



Slip-stacking implementation

- **Energy plateau selection**
  - **Flat bottom:** relatively strong transverse space charge and intra-beam scattering effects, simplified scaling laws show that all the relevant to slip-stacking parameters favour higher energies.
  - **Flat top:** bunches more prone to longitudinal instabilities, un-captured beam generated during the process, would be transferred to the LHC
  - **Slip-stacking at intermediate energy plateau at 300 ZGeV/c** → around 1 s needs to be added to the cycle.

✓ Well above γ_{tr} → favourable for slip-stacking.
✓ No intra-beam scattering and space-charge issues as in the long (~40 s) injection plateau.
✓ Better longitudinal beam stability compared to flat-top.
✓ Uncaptured beam will not be transferred to the LHC.



Slip-stacking implementation

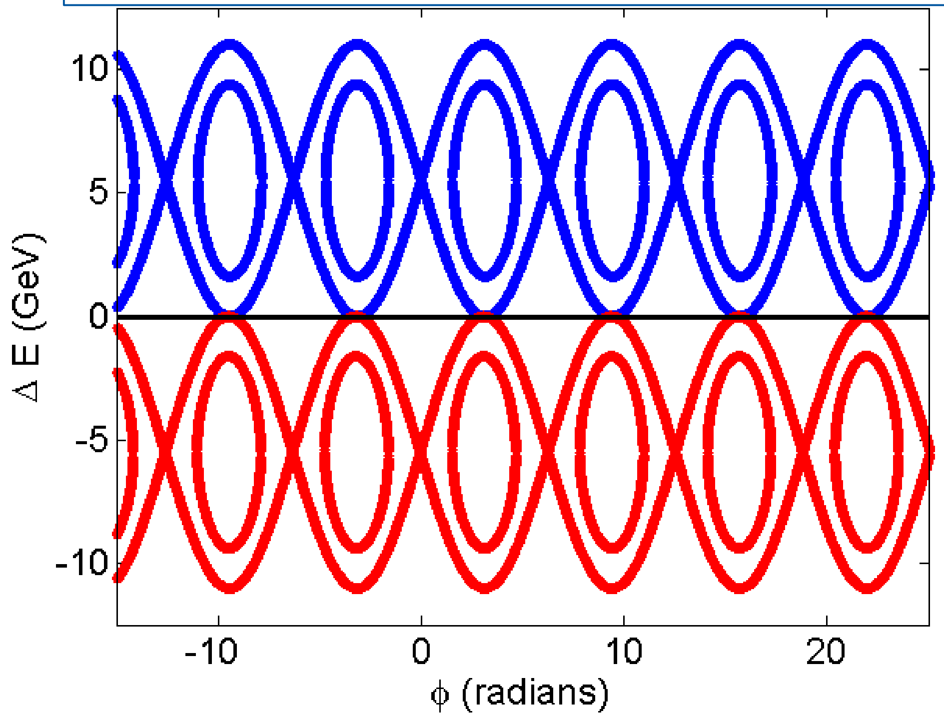
- **RF perturbation**
  - The group of cavities that is not synchronised with the batch will perturb its motion.
  - The perturbation is described by the slip-stacking parameter

$$\alpha \overset{\text{def}}{=} \frac{\Delta f_{RF}}{f_{s0}} = 2\frac{\Delta E}{H_B}$$

Δf_{RF}: difference in RF frequency
f_{s0}: zero amplitude synchrotron frequency
ΔE: Energy difference
H_B: half bucket height

α =4 lowest stability limit → for **$\alpha \leq 4$ motion becomes chaotic!!**

Particle motion in the longitudinal phase-space with α = 4 (no intensity effects)

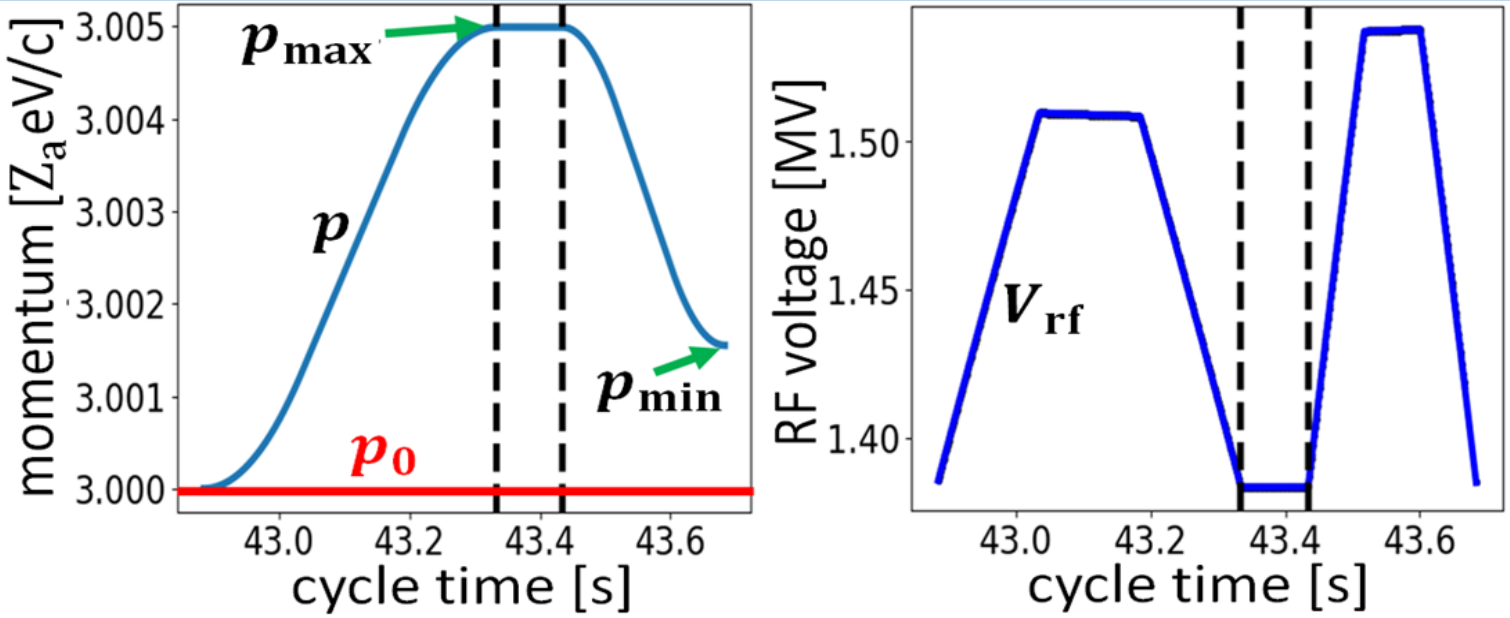


- **Two implications during slip-stacking**
  - **Start: α =0 → RF amplitude modulation** necessary to separate the batches (one group should be active when the corresponding batch passes by) → minimum acceptable initial distance between the batches based on the cavities filling time.
  - **End: beams should remain separated in energy** at the moment of recapture → **high RF voltage is needed** at the end to capture all the particles of the separated beams → **large emittance blow-up.**

Slip-stacking implementation

- **RF program calculations**
  - At the start of slip-stacking the RF cavities will split into two groups and each group will be synchronized with one of the two batches
  - Each group should follow different RF frequency (momentum) and voltage and programs

Examples of momentum (RF frequency) and RF voltage programs for one group of cavities



Slip-stacking implementation

- **RF program calculations**
  - At the start of slip-stacking the RF cavities will split into two groups and each group will be synchronized with one of the two batches
  - Each group should follow different RF frequency (momentum) and voltage and programs.
  - These programs are calculated assuming constant longitudinal emittance ε_l and filling factor in energy q_E and also treating independently the two RF systems
  - In the future they will be calculated through a high level application and will be given as an input to the hardware.

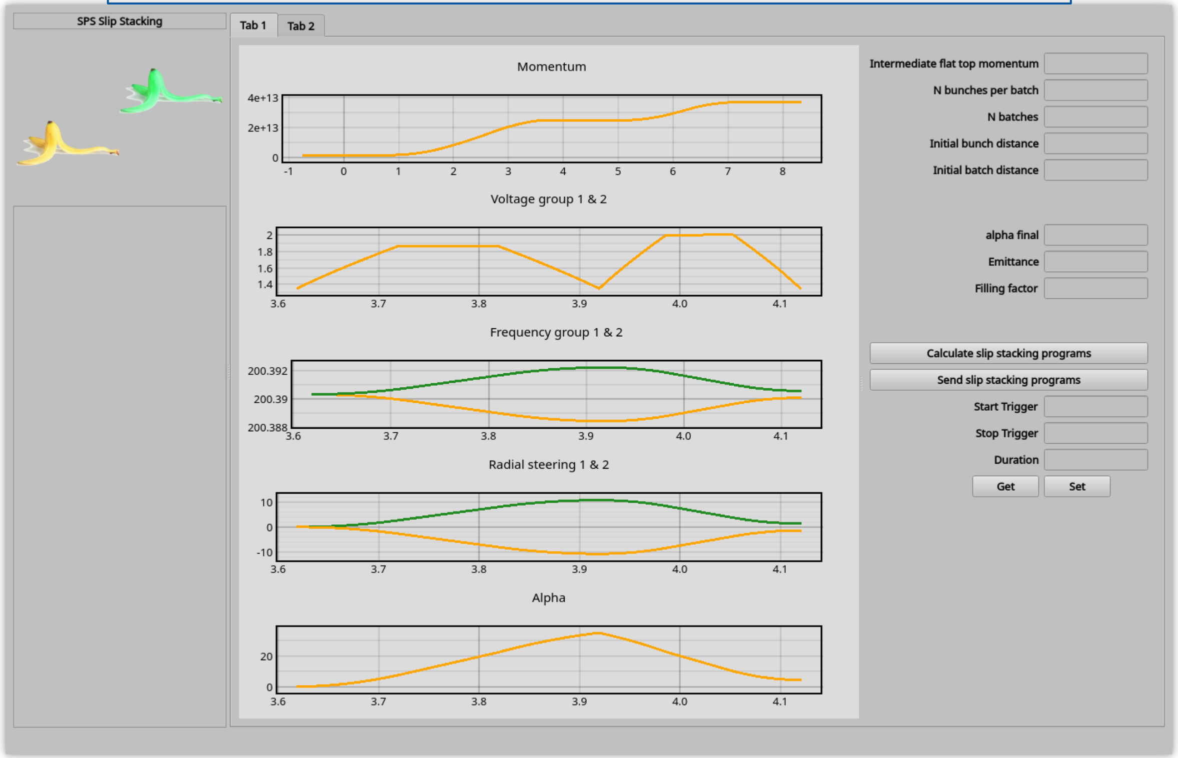
✓ Calculation of programs using required machine and beam parameters

✓ Send values to the hardware

✓ Very fast to run (less than a minute)

✓ Easy to change parameters and recalculate during the beam set-up

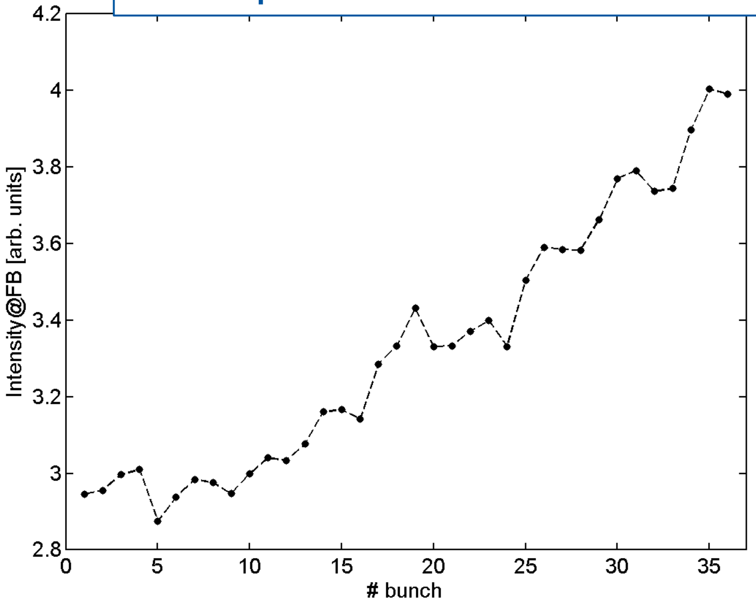
Very preliminary GUI for Slip-stacking, (by K. Li)

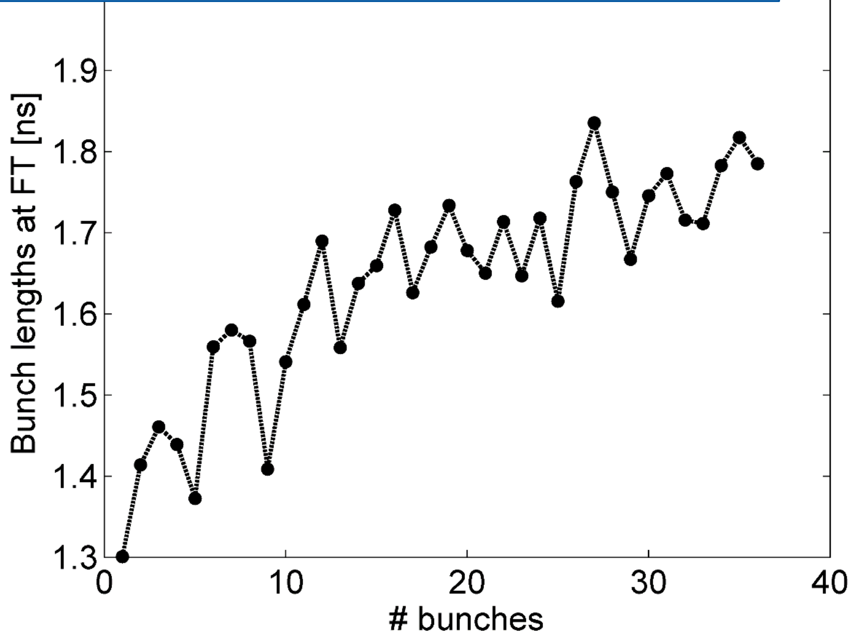


Slip-stacking implementation

- **Beam parameters**
  - Significant bunch to bunch variation in intensity and emittance along the batch generated during the long injection plateau (~40 s).
  - Voltage programs calculated for the largest bunch to avoid losses during slip-stacking.
  - **The RF noise reduction is expected with the new LLRF which will decrease the blow-up of the beam and thus will reduce the spread**

Example of the nominal LHC ion beam measured in the SPS in 2018

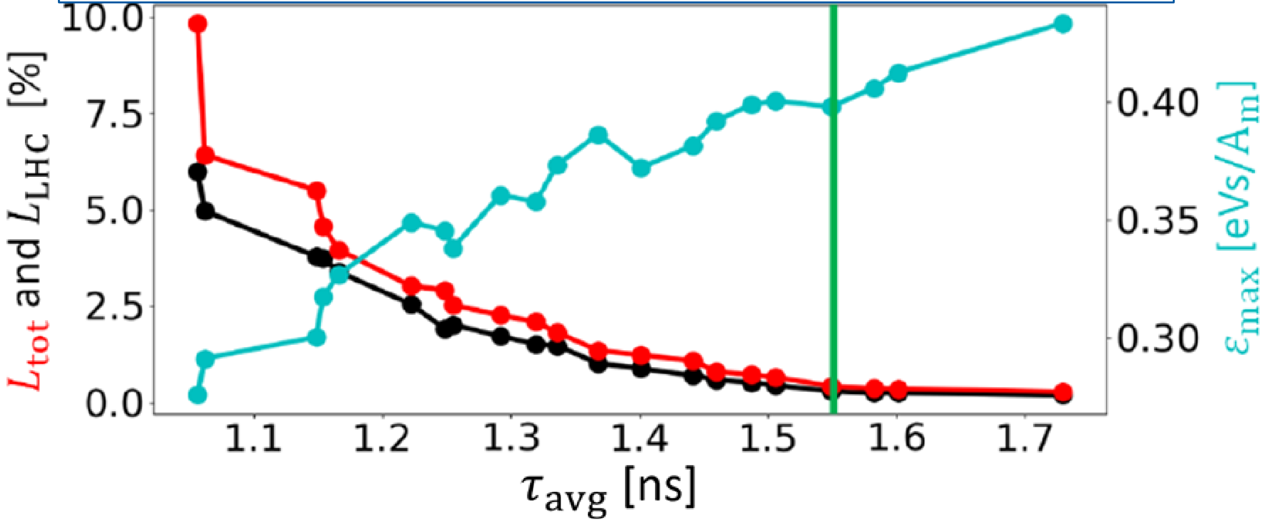




Slip-stacking macro-particle simulation

- **Independent LLRF controls for each group of RF cavities after LS2**
  - Design of the **slip-stacking process was based on realistic macro-particle simulations** using the **BLonD** code, including
    - Measured beam parameters (longitudinal bunch distribution, emittance, intensity).
    - The detailed longitudinal impedance model.
- **Large number of simulations to optimize the process**
  - Both for Q20 and Q26 optics.
  - Simulations of the full beam started at 300 ZGeV/c taking into account the measured beam parameters at this moment of the cycle.
  - Scanning parameters: $\boldsymbol{\alpha}, \boldsymbol{q_e}, \boldsymbol{V_{rf}}$
  - Minimization of:
    - Total losses $\boldsymbol{L_{tot}}$
    - Long. emittance $\boldsymbol{\varepsilon_l}$ (fit the LHC 400 MHz RF bucket)
  - At flat top ($V_{rf} = 15MV$):
    - Adiabatic bunch compression
    - Bunch rotation

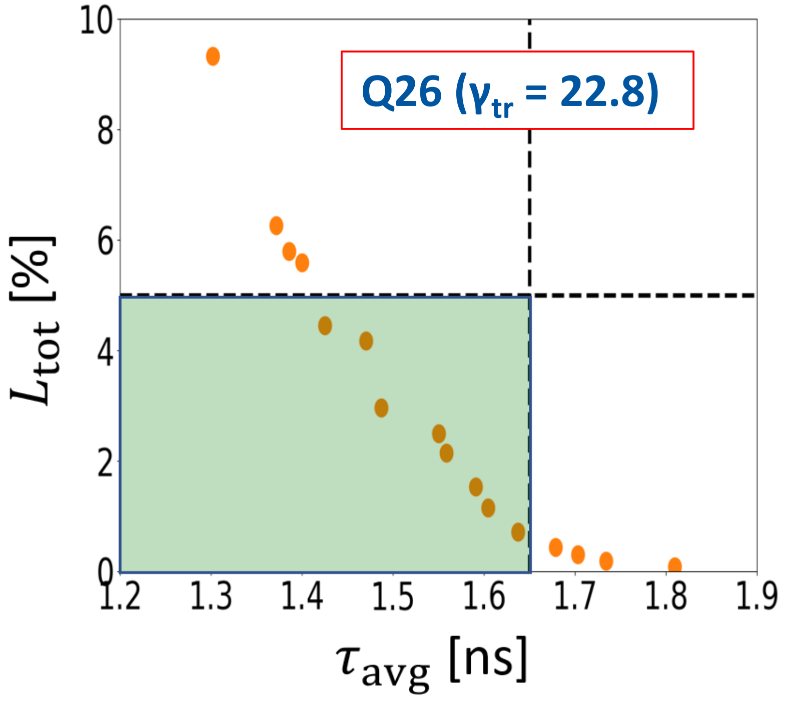
Full scan of beam parameters during slip-stacking

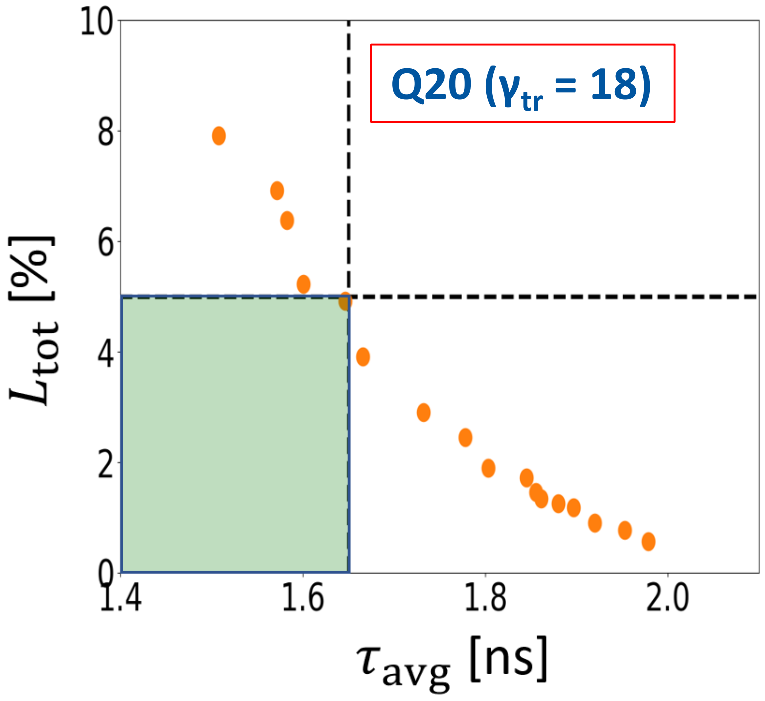


Slip-stacking macro-particle simulation

- **No acceptable solution (in bunch length) for Q20 optics with adiabatic bunch rotation**
  - bunch rotation is needed in order to achieve sufficiently short bunches at extraction
- **Q26 optics was selected for slip-stacking**
  - provides more margin to the final beam parameters.

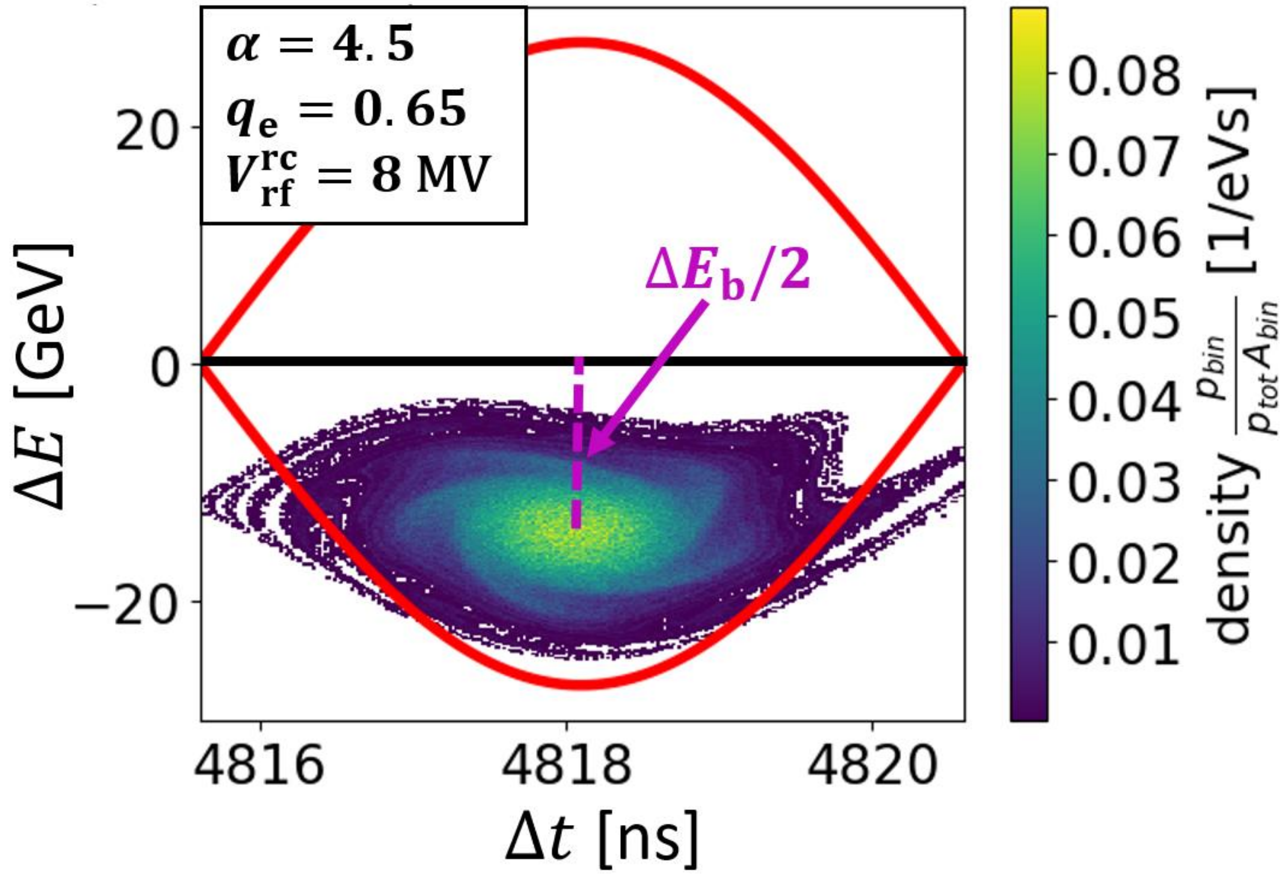
Possible solution found from simulations





Slip-stacking macro-particle simulation

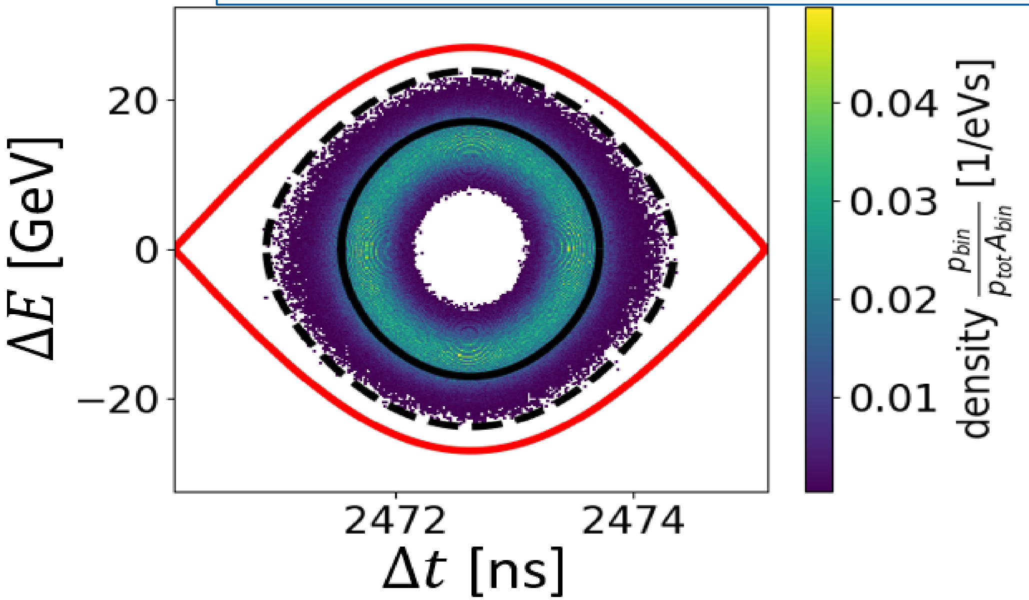
- **Hollow bunch generation after momentum slip-stacking**
  - At the end of slip-stacking manipulation α >4 to avoid losses.
  - Bunches strongly un matched to the RF bucket at the moment of recapture.

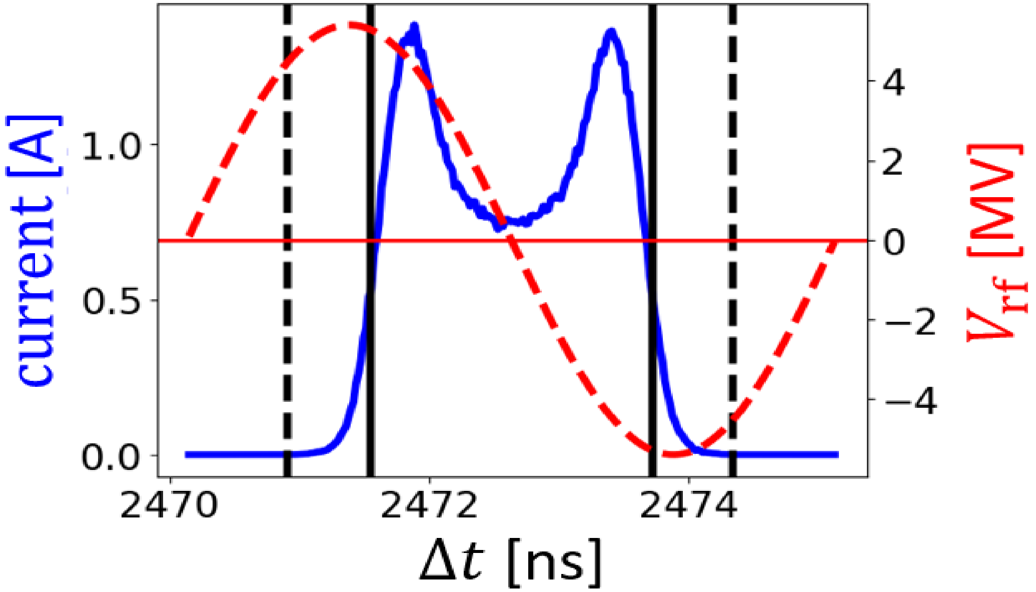


Slip-stacking macro-particle simulation

- **Hollow bunch generation after momentum slip-stacking**
  - At the end of slip-stacking manipulation α >4 to avoid losses.
  - Bunches strongly un matched to the RF bucket at the moment of recapture.
  - After filamentation a hollow bunch will be generated in the longitudinal phase space
  - This distribution is preserved until the end of the cycle

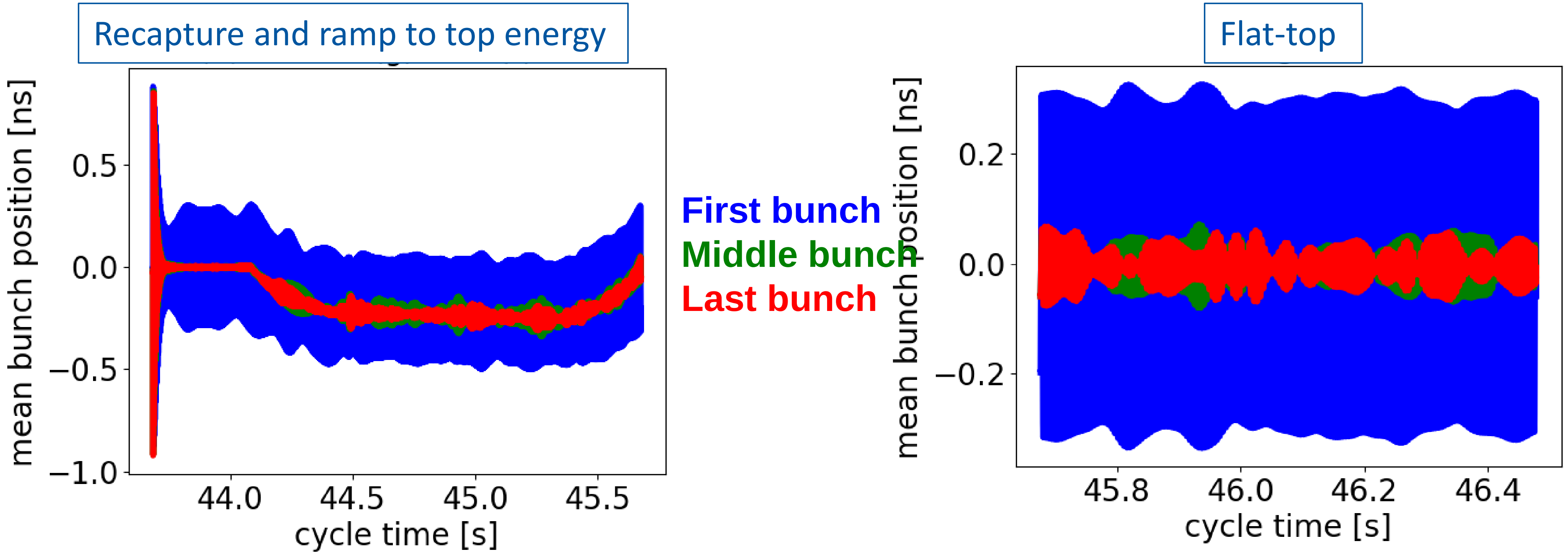
Example of the bunch distribution at the end of flat top without intensity effects





Slip-stacking macro-particle simulation

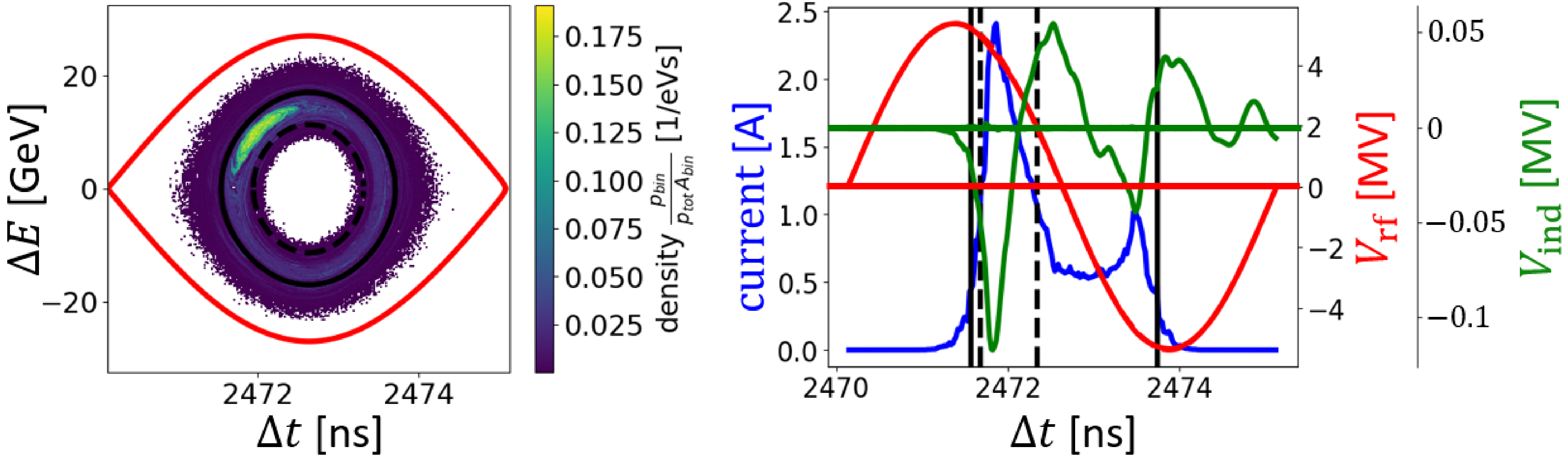
- **Loss of Landau damping is observed for the shortest bunches in the batch when intensity effects are included in simulations**
  - Dipole oscillations are not damped until the end of the cycle



Slip-stacking macro-particle simulation

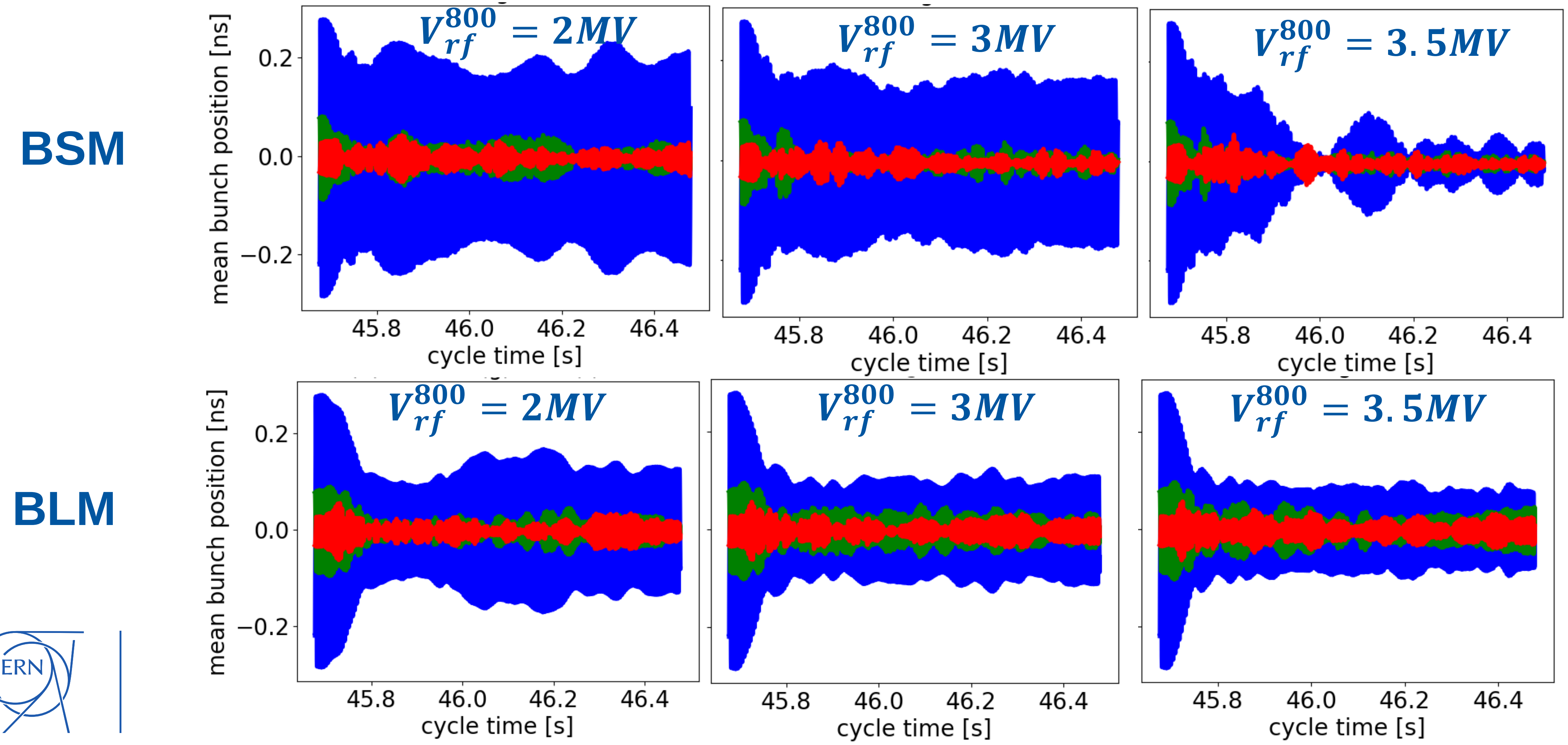
- **Loss of Landau damping is observed for the shortest bunches in the batch when intensity effects are included in simulations**
  - Dipole oscillations are not damped until the end of the cycle
  - High density island in phase-space that keeps oscillating around the bucket centre

Example of a simulation with intensity effects at the SPS flat-top



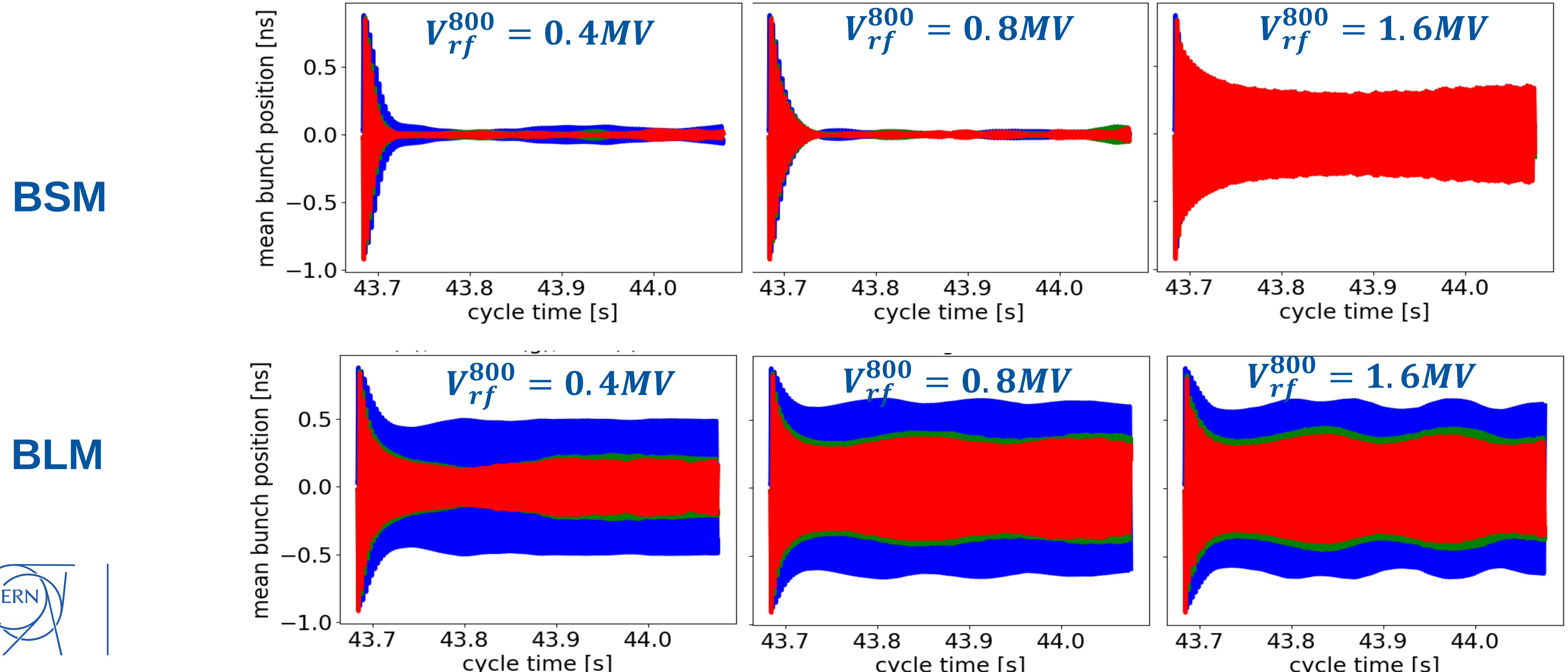
Slip-stacking macro-particle simulation

- **Obvious solution to increase the Loss of Landau damping threshold is to use the 800 MHz RF system**
  - Effectively no damping when 800 MHz is switched on only at flat top



Slip-stacking macro-particle simulation

- **Obvious solution to increase the Loss of Landau damping threshold is to use the 800 MHz RF system**
  - Effectively no damping when 800 MHz is switched on only at flat top
  - We need to use it immediately at recapture and keep it on for the rest of the cycle

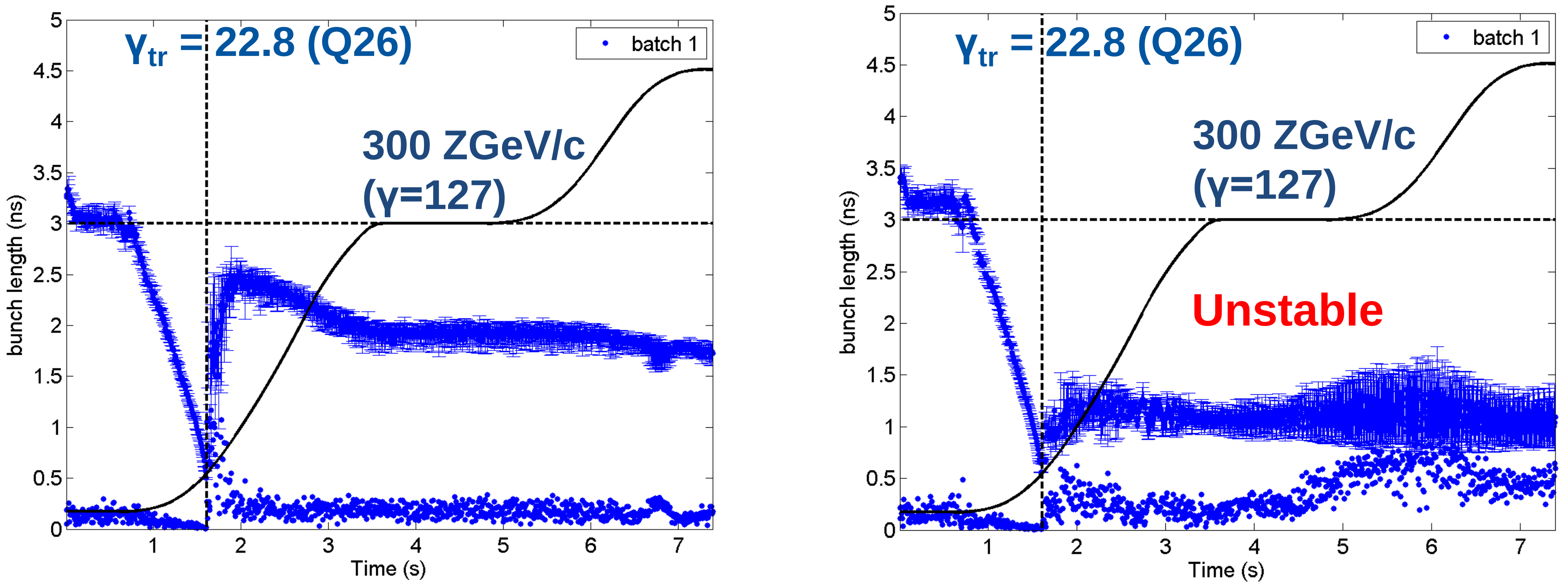


Longitudinal beam stability of ion beams

- **Series of relevant to slip-stacking measurements was carried out in end of 2018**
  - Check longitudinal beam quality
- **A new slip-stacking short MD cycle with the addition of 1 s energy plateau at 300 ZGeV/c.**

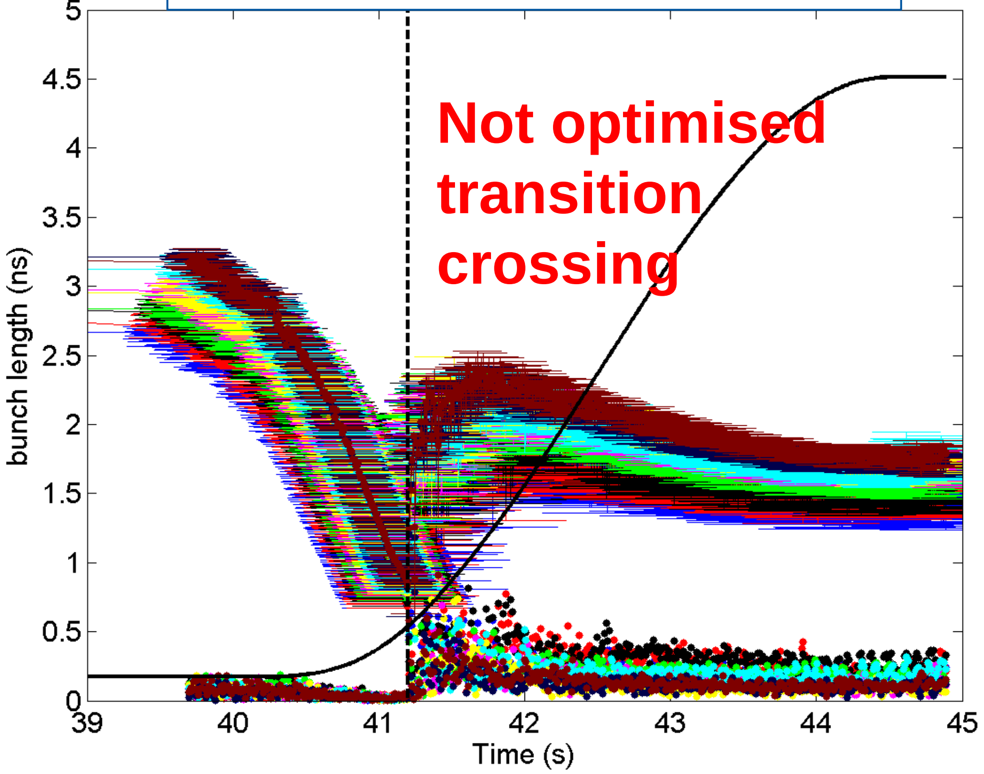
Beam measurements in 2018

- Beam stability and reproducibility key component for a successful implementation of slip-stacking.
- Beam instabilities after transition crossing observed in measurements
- Stabilised by a deliberate degradation transition crossing
  - **Strong longitudinal emittance blow-up**
- Optimisation of transition crossing shifted instabilities later in the cycle



Beam measurements in 2018

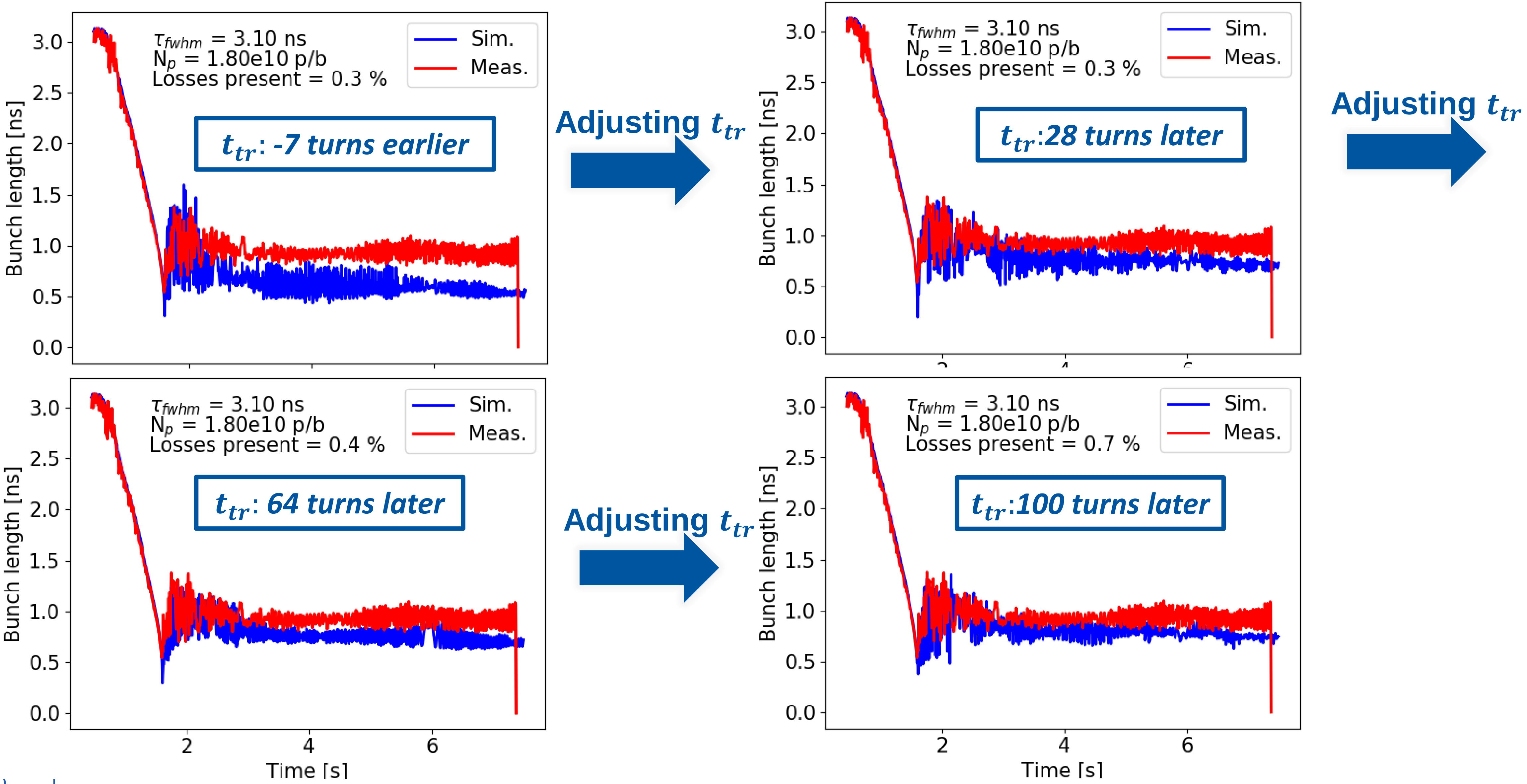
Nominal cycle during LHC filling



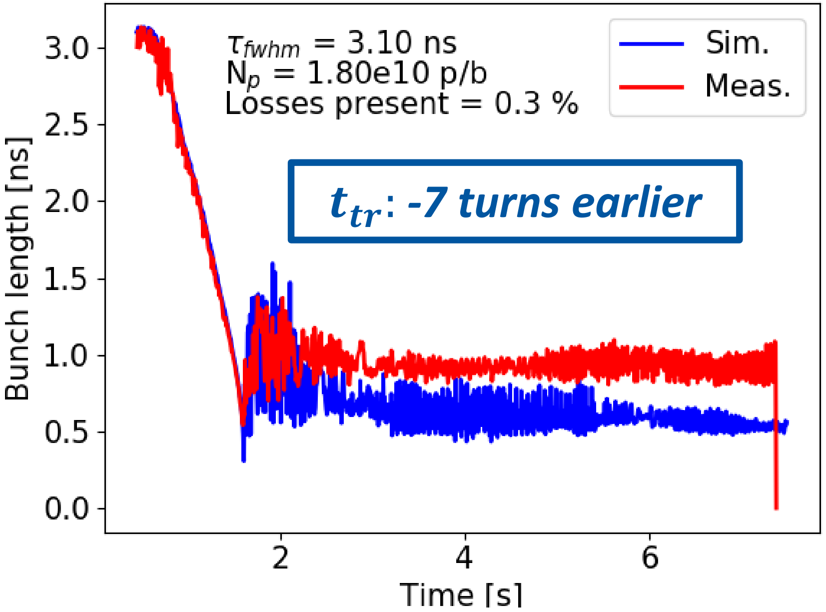
- ❑ Enhances bunch-by-bunch variation in the batch
- ❑ Uncontrolled blow-up → non reproducibility from cycle to cycle

Important to stabilise the beam before slip-stacking can be applied

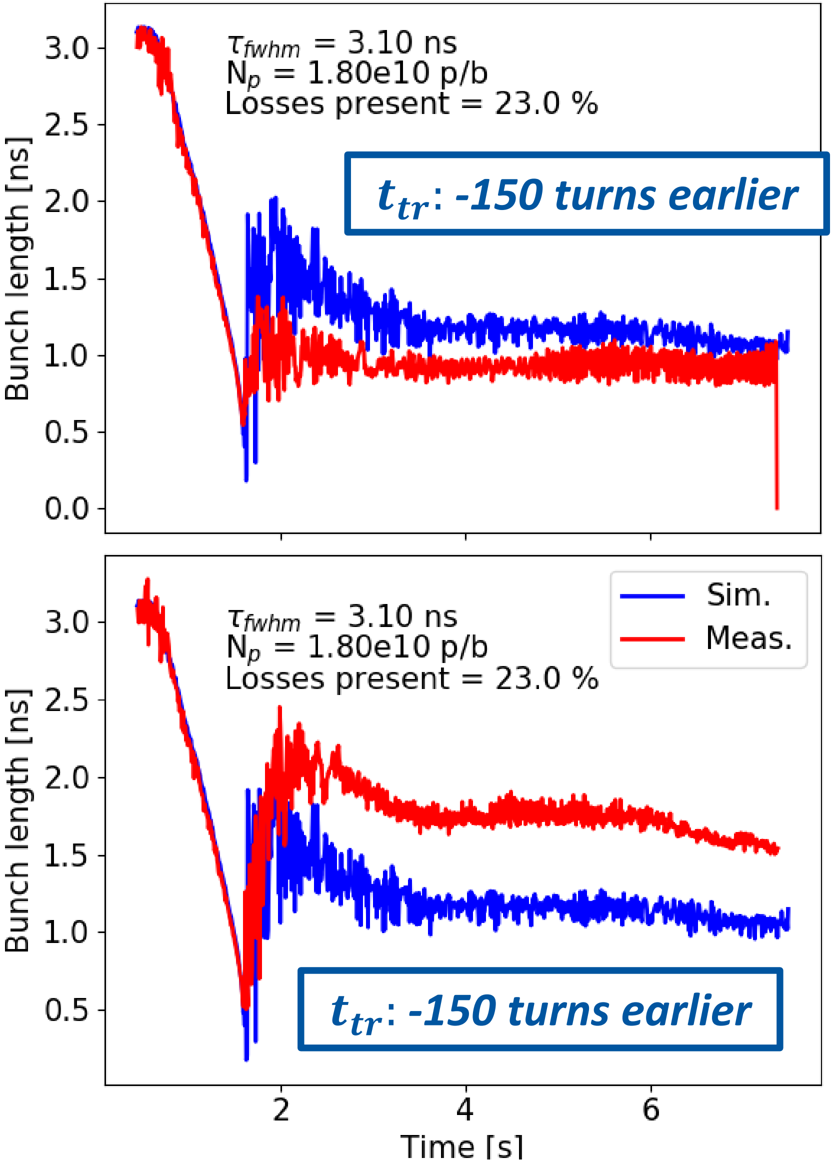
Macro-particle simulations



Macro-particle simulations

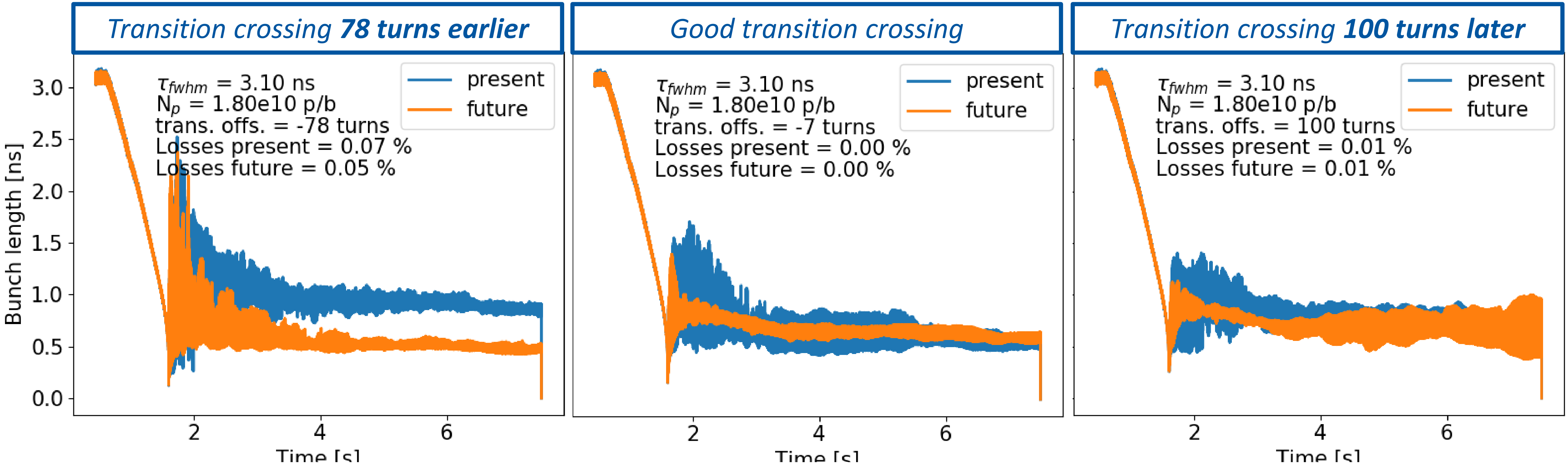


Adjusting t_{tr} in other direction



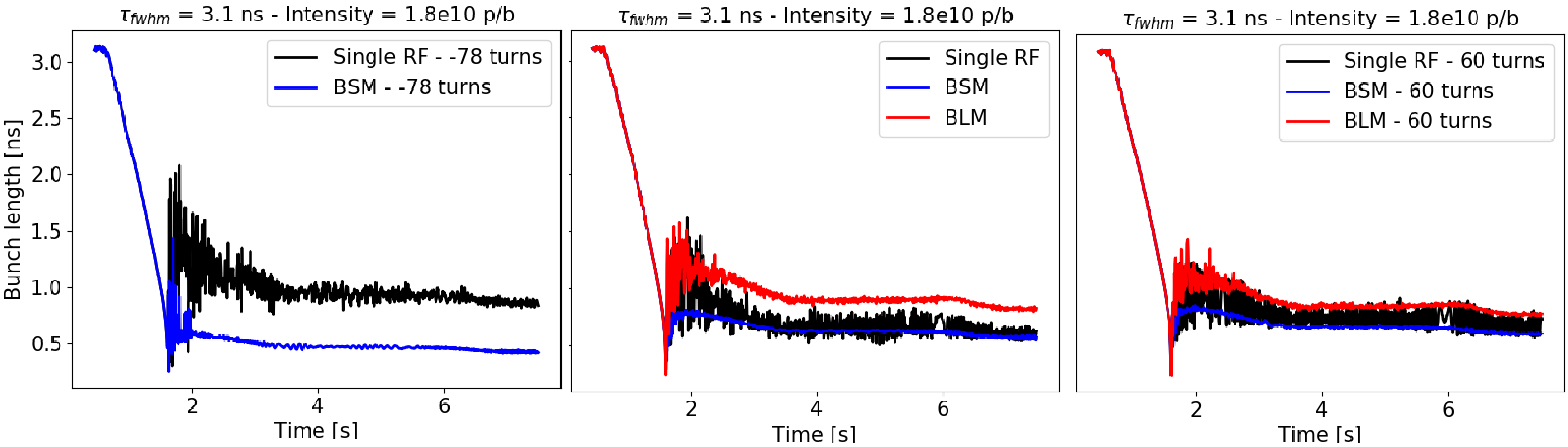
- Corresponds to the measurements when t_{tr} was not aligned

After LS2 impedance reduction



- Slightly smaller beam perturbation after transition crossing is expected from simulations in the future, after the SPS impedance reduction
- Bunch is still quite unstable even at low energy (1.8x10^{10} protons/b).
- Bunch parameters are still strongly depended on any jitter during the phase-jump at transition crossing → non reproducible beam parameters at extraction

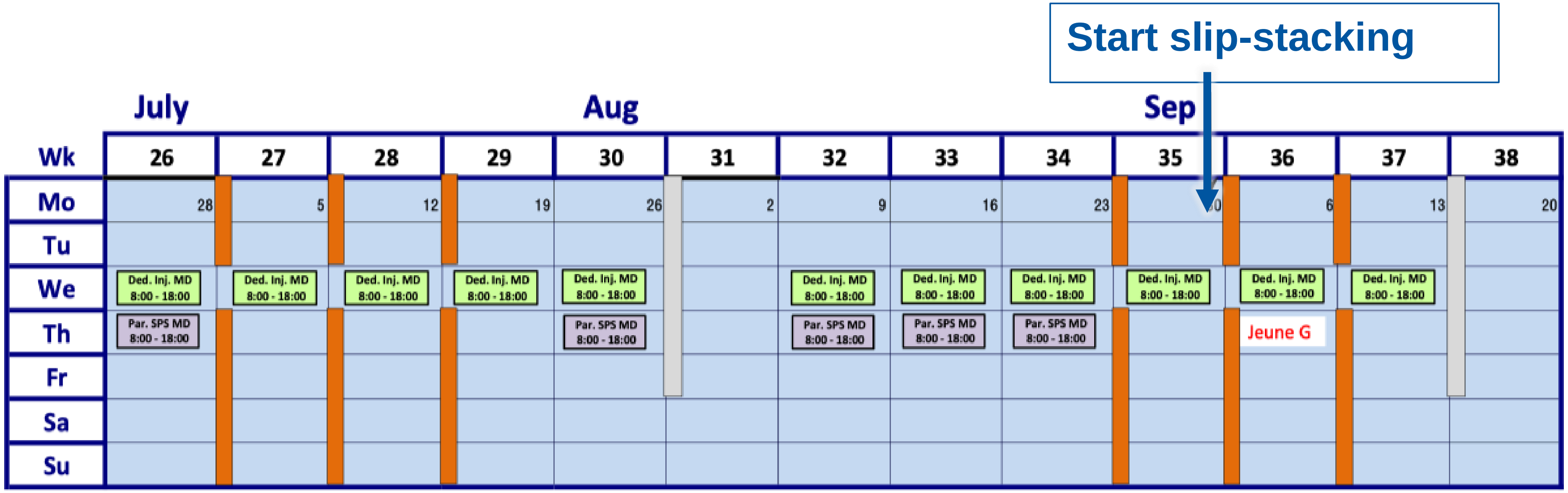
Double RF operation



Transverse instability?

Beam commissioning

- **One week is preliminary reserved in September 2021 for the slip-stacking commissioning**
  - SPS ions FFA will be commissioned at the beginning of the summer.
  - Possibility to check the slip-stacking hardware already in summer (RF programs generation, grouping and controlling independently the RF cavities, etc.), even without beam.
  - Possibility to check the slip-stacking manipulation with proton pilot bunches in MDs (requires generation of new MD cycle)
  - **Everything depends on the availability of the LLRF experts and how the setting up of the proton beams is evolving.**



R. Steerenberg, EATM, 23 Nov. 2019

Beam commissioning steps

- **Commissioning the high level tools for generating the frequency and voltage programs and sending them to hardware**
  - Could be checked earlier without beam
- **Commissioning with a short magnetic cycle**
  - Only up to two injections needed. Very similar to the one used in 2018 MDs
- **Start with one bunch to check and improve the longitudinal beam quality through the cycle**
  - Reproducible bunch parameters in terms of emittances at the slip-stacking plateau
  - Use of the 800 MHz RF system will be needed after FFA. Will be hopefully checked earlier in summer during the SPS ions cycle setting up.
- **One (or two) bunches to check the slip-stacking procedure and final beam parameters**
  - RF voltage amplitude modulation
  - Beam emittance and losses at extraction
  - Optimise the designed RF programs during slip-stacking and also later when ramping up to top energy (capture voltage, bucket filling factor etc.)
  - Need of quick macro-particle simulations at the same time
- **Increase the number of batches gradually**
  - Long, nominal cycle is needed → dedicated supercycle
  - Adapt the designed RF programs for the new beam parameters.

Summary and conclusions

- **Man power during the week of setting up slip-stacking**
  - It’s possible that we need to work also during nights
  - Simulations might be needed at the same time to understand and overcome potential difficalties

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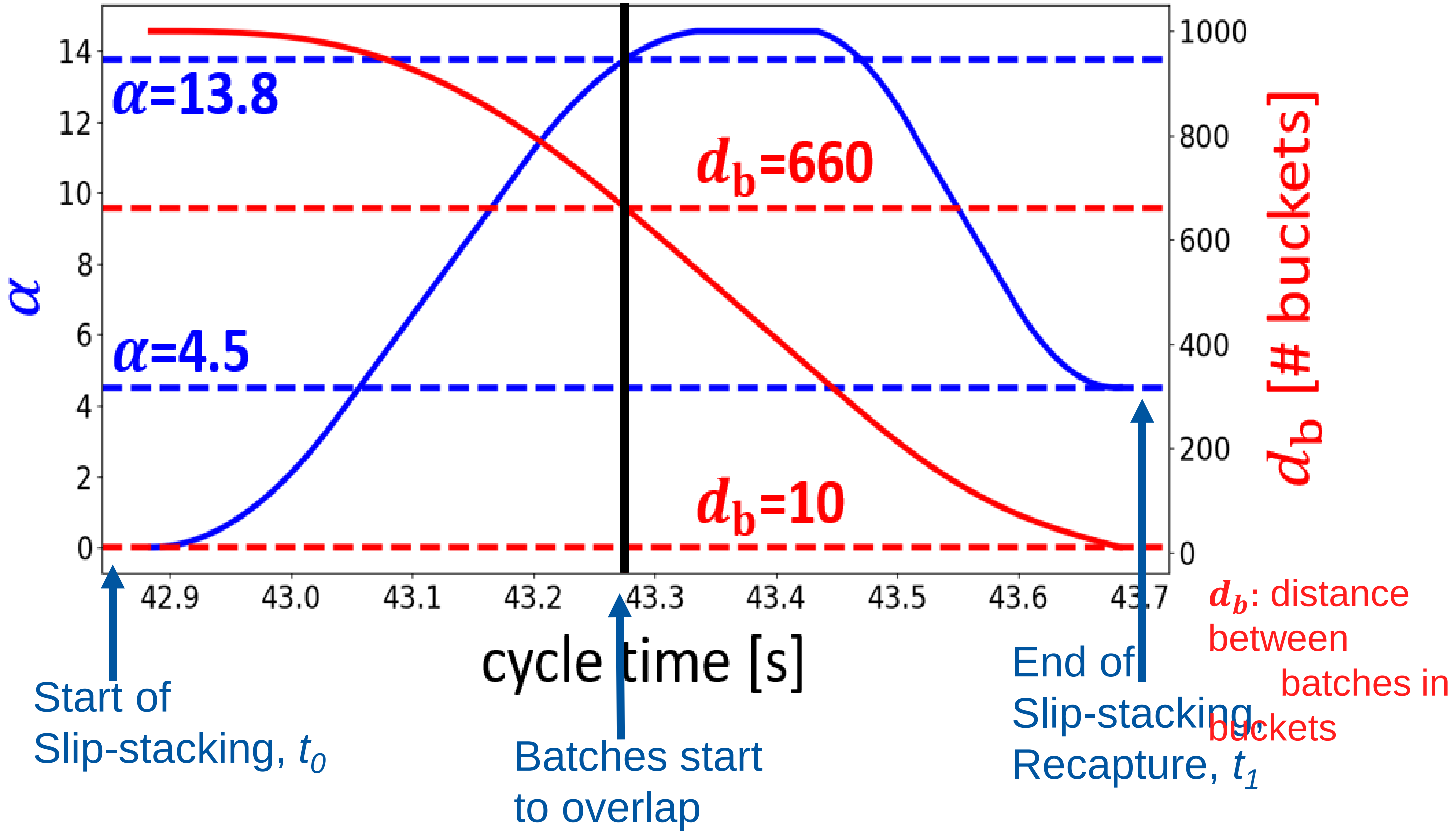
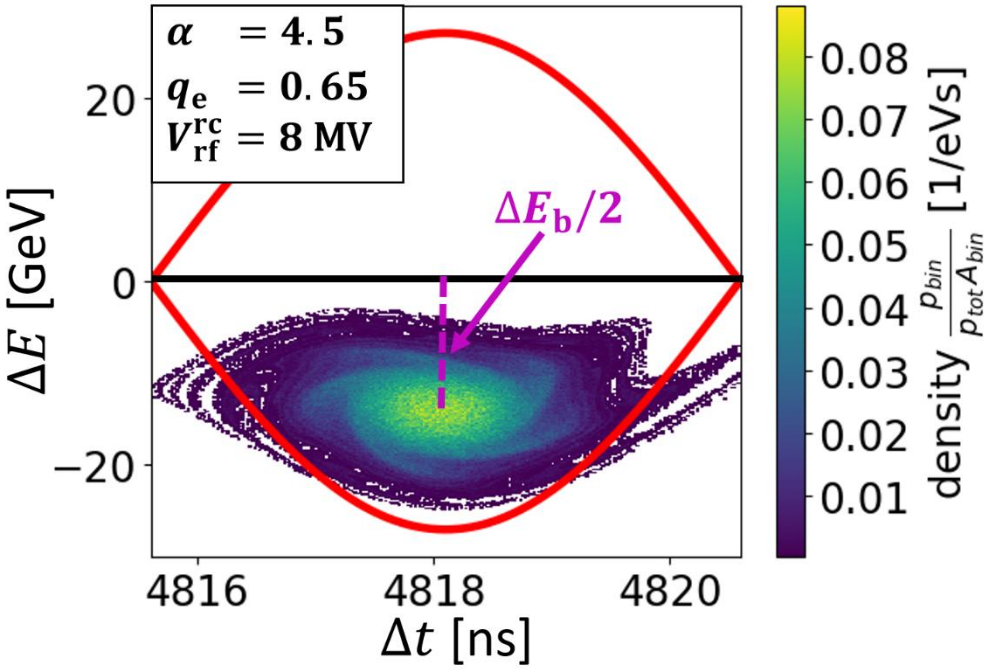
RF perturbation during slip-stacking

Example of the α-parameter evolution during slip-stacking



Phase-space distribution at the moment of recapture, t_1



- Very distorted particle trajectories, even though α > 4.

α = 0 in the beginning → RF amplitude modulation is necessary to separate the batches → minimum d_b (T_B in time) based on the filling time of the cavity

- High RF voltage is needed at recapture → **a large emittance blow-up.**

Macro-particle simulations → reproduce the data