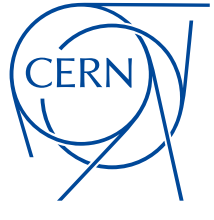
LONGITUDINAL BEAM DYNAMICS

JUAS 2023

COURSE 1: THE SCIENCE OF PARTICLE ACCELERATORS

A. Lasheen



LESSON 5: APPLICATION

MODULE 10: LONGITUDINAL BEAM DYNAMICS IN ACTION

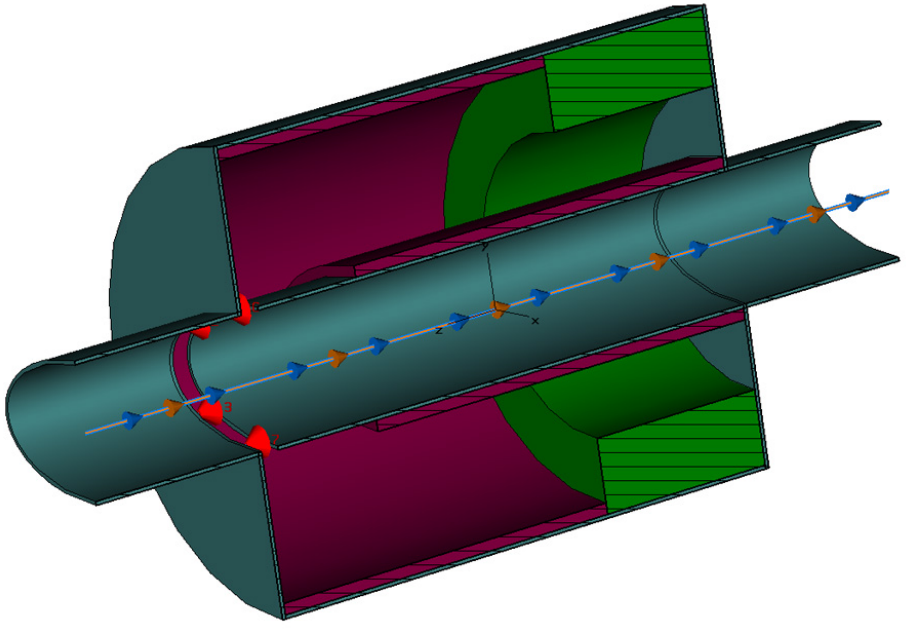
→ **Beam observation**

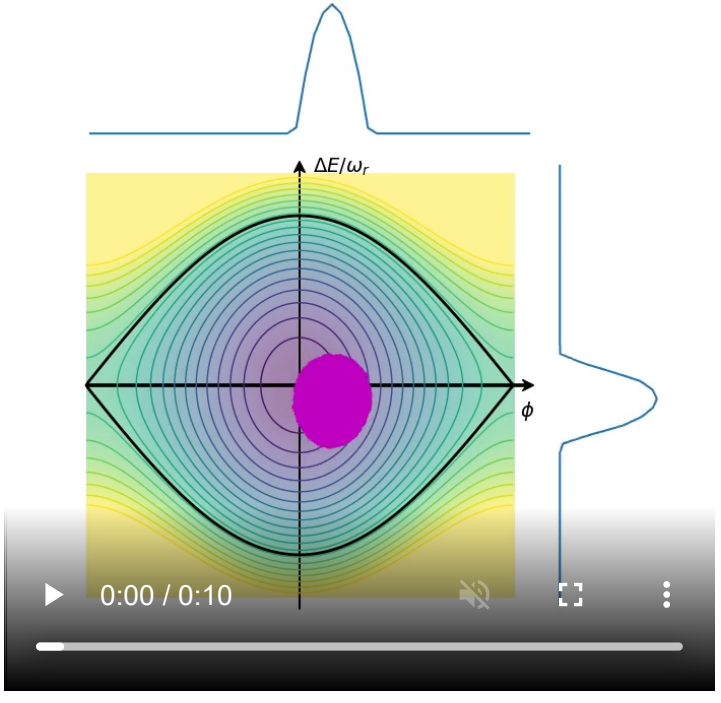
→ **Example RF operation (injection oscillations)**

→ **Introduction to RF manipulations**

→ **Beam instabilities**

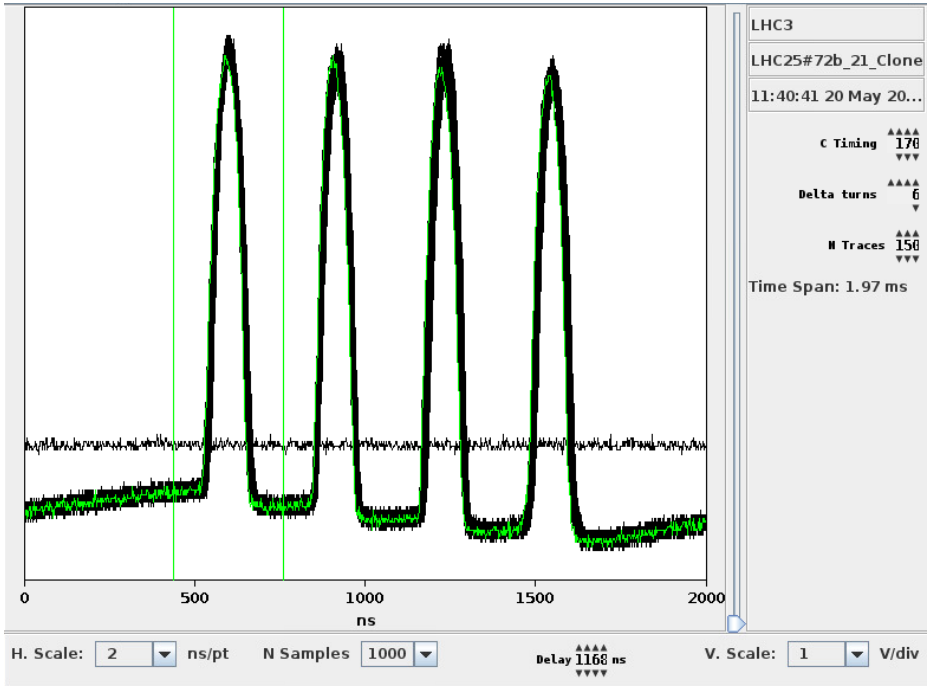
BEAM OBSERVATION

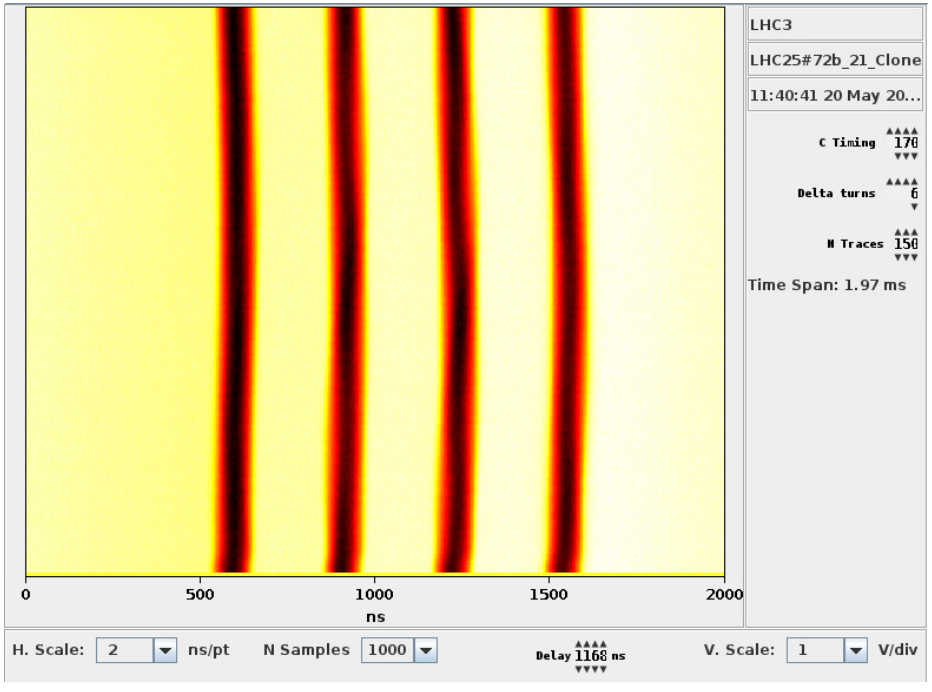




- The longitudinal bunch profile is measured using Wall Current Monitor (WCM, beam current converted in voltage).
- The WCM is connected to a digitizer or an oscilloscope, which is triggered before the bunch passage to acquire the bunch profile.

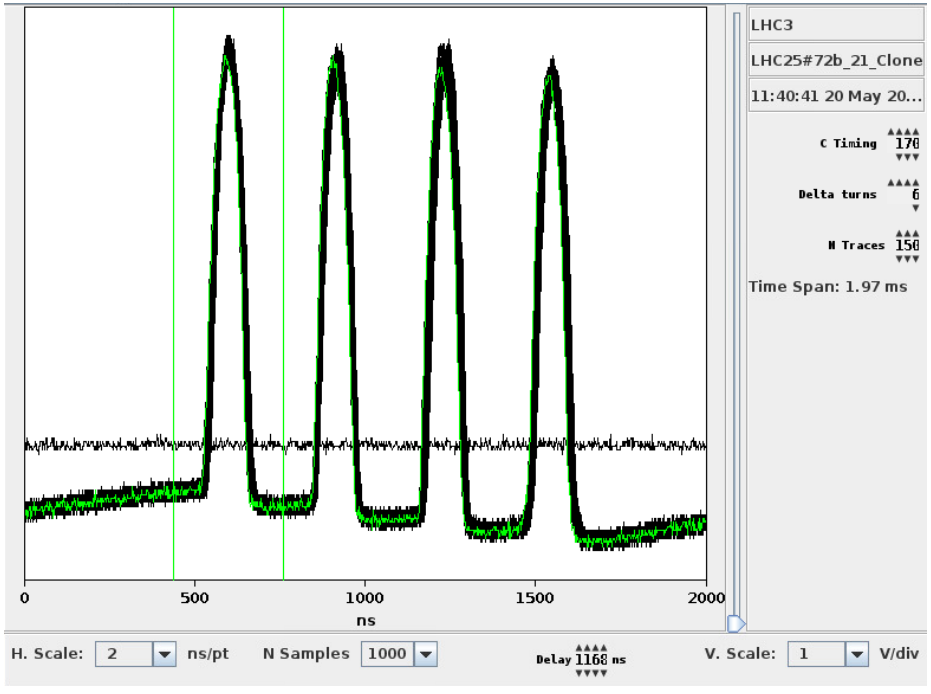
BEAM OBSERVATION

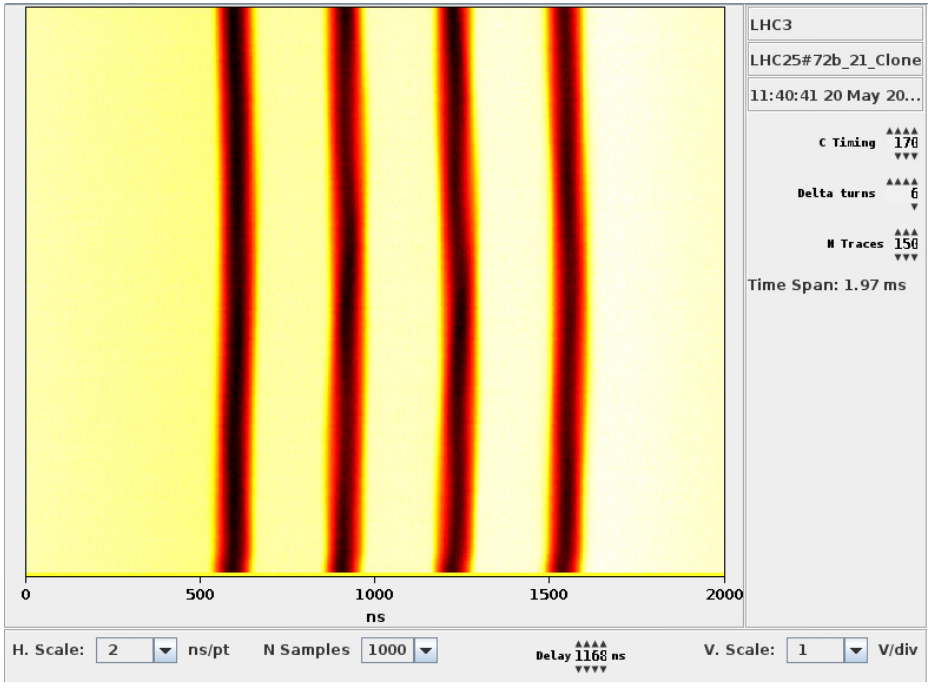




- Here is a real example of an acquisition software. The acquisition starts 170 ms after the beginning of the cycle (corresponding to injection).
- The acquisition lasts for 2000 ns, enough to measure the profiles of the 4 bunches in the machine.
- The acquisition is repeated 150 times, every 6 machine turns.

BEAM OBSERVATION

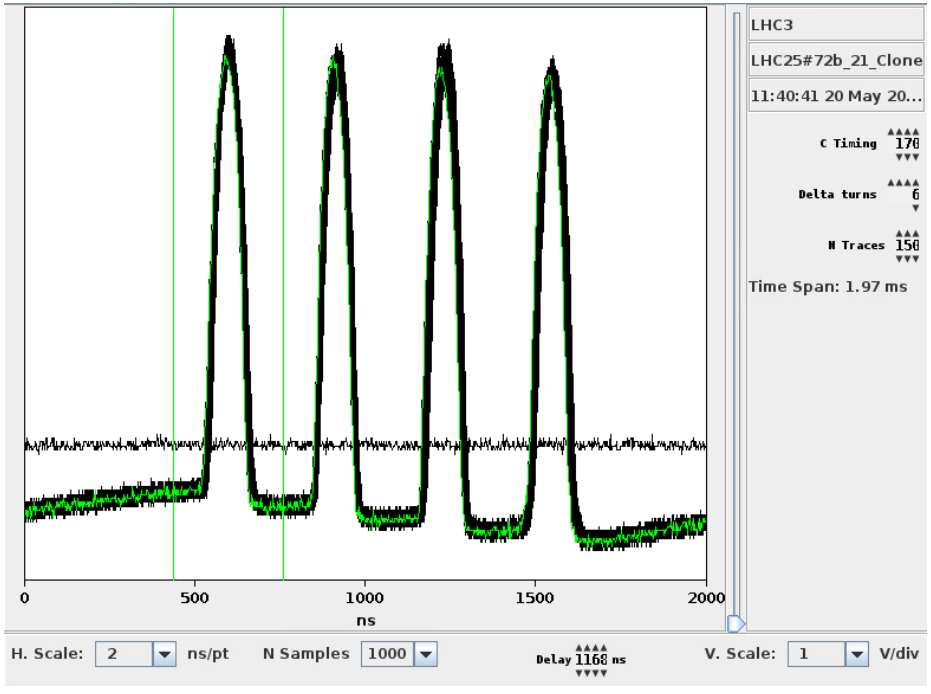


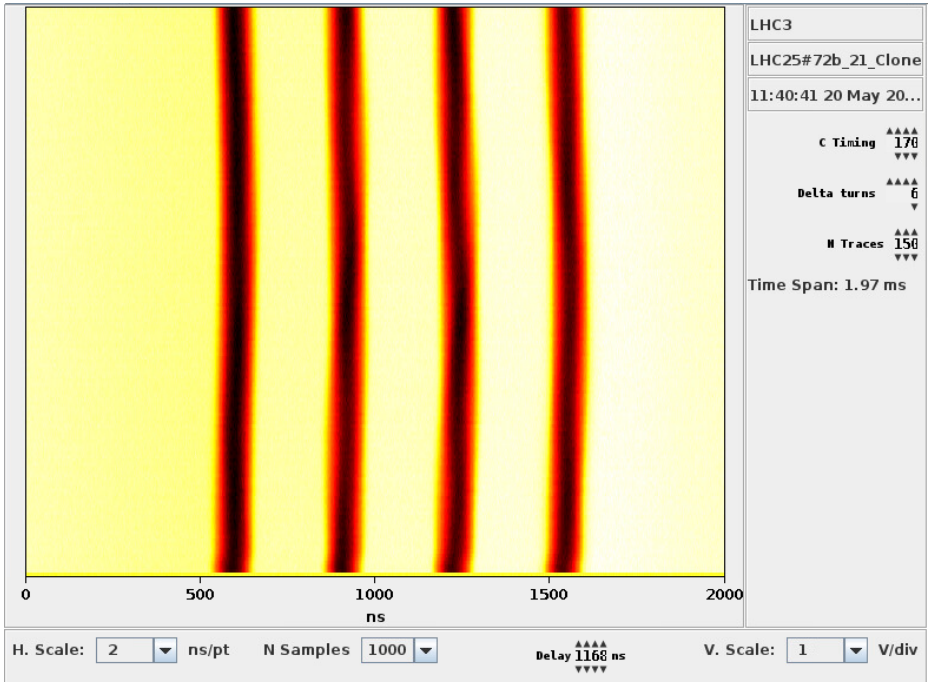


- In the left figure are all profiles are shown overlapped (the trigger is synchronous with the RF).

- The right figure shows the evolution of the profiles (horizontal, 1 trace is 2000 ns long) vs time in the cycle (vertical, 1 line = 1 trace every 6 turns).

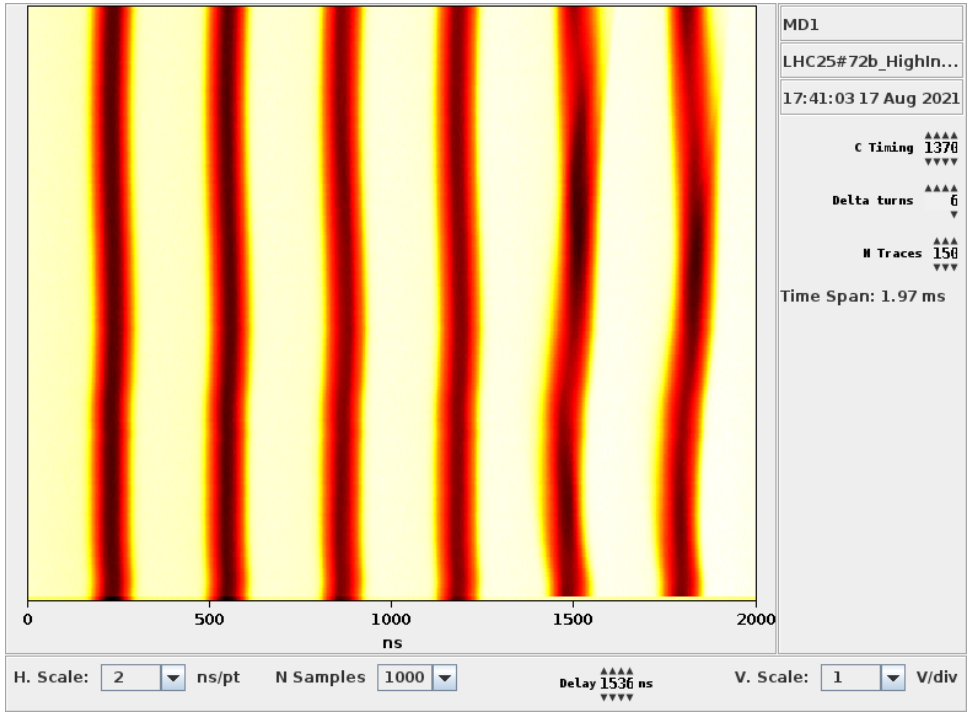
BEAM OBSERVATION





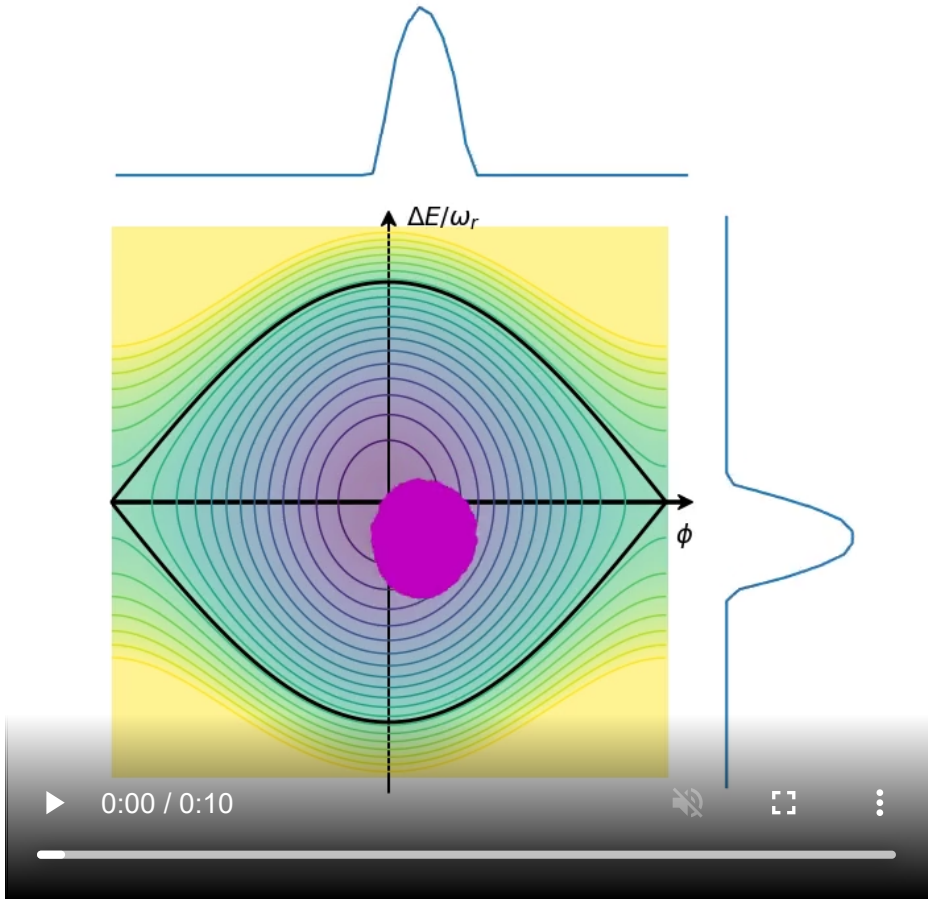
- The first trace is empty, before beam injection.
- The bunches are well matched, no signs of oscillations.

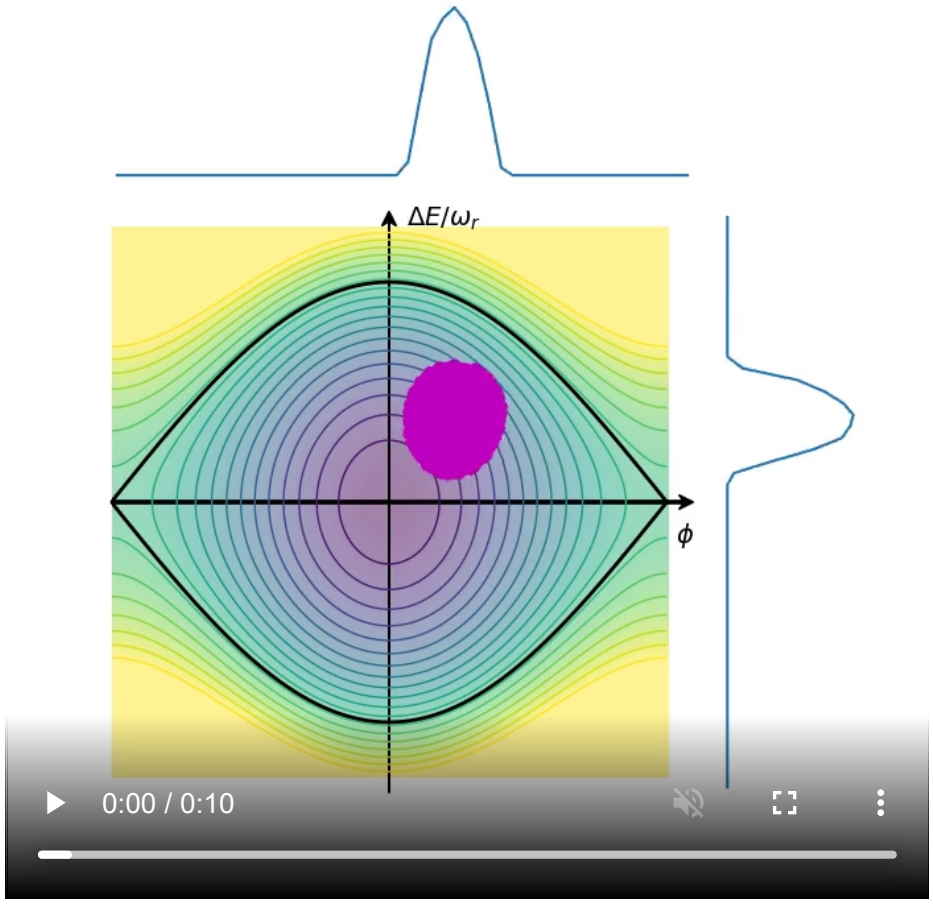
INJECTION OSCILLATIONS (PHASE)



- Two more bunches are injected, 1370 ms after the beginning of the cycle (low energy).
- The two extra bunches are not matched, they oscillate more that the 4 first bunches.
- What is wrong?

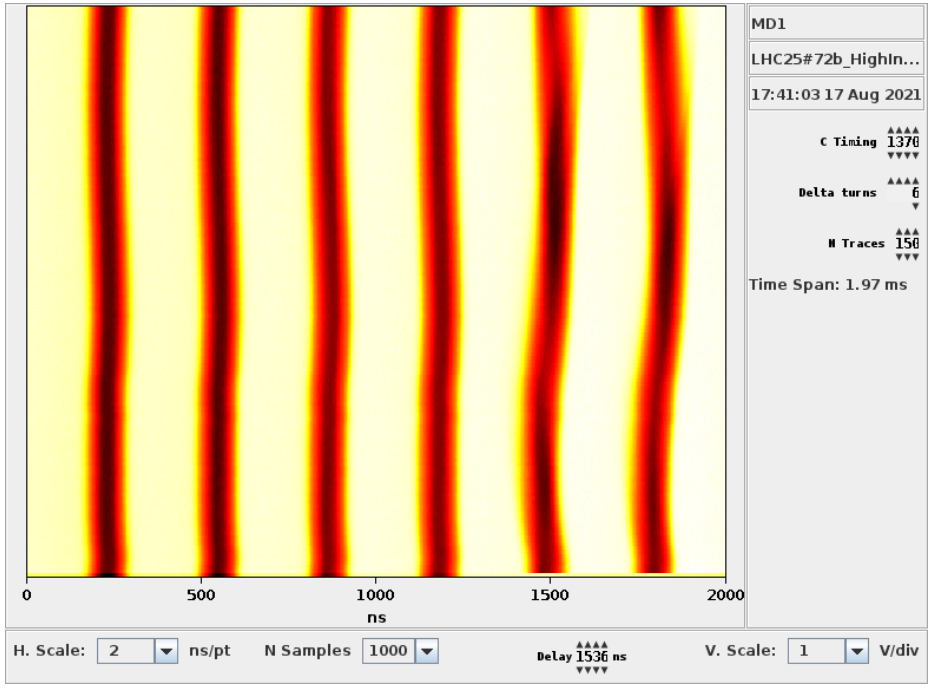
INJECTION OSCILLATIONS (PHASE)

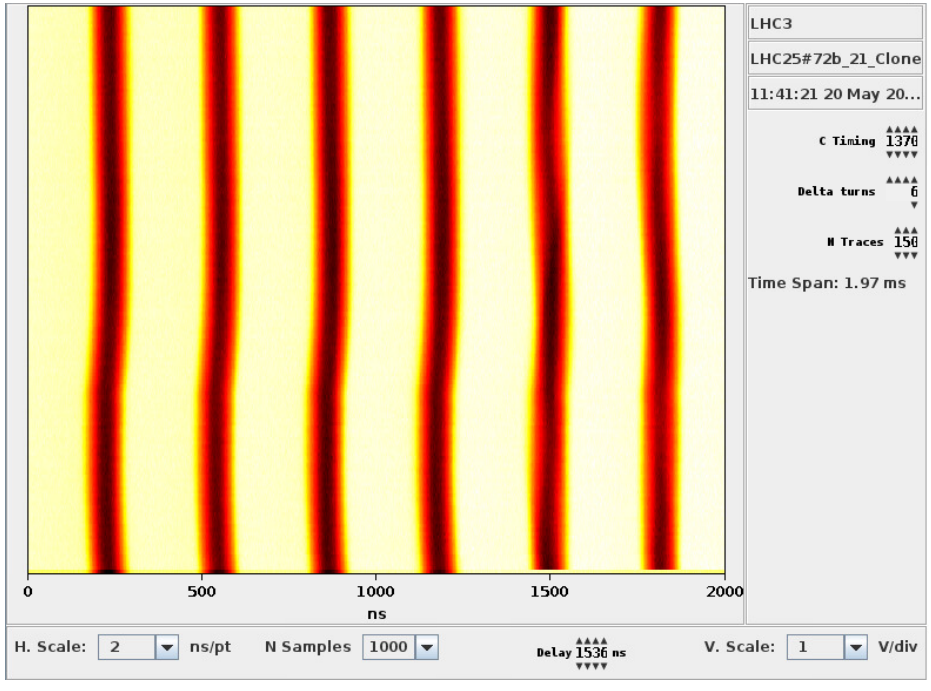




- A bunch can be mismatch because injected at wrong RF phase (left), or wrong energy (right). The bunch phase (and energy) oscillates after injection.

INJECTION OSCILLATIONS (PHASE)

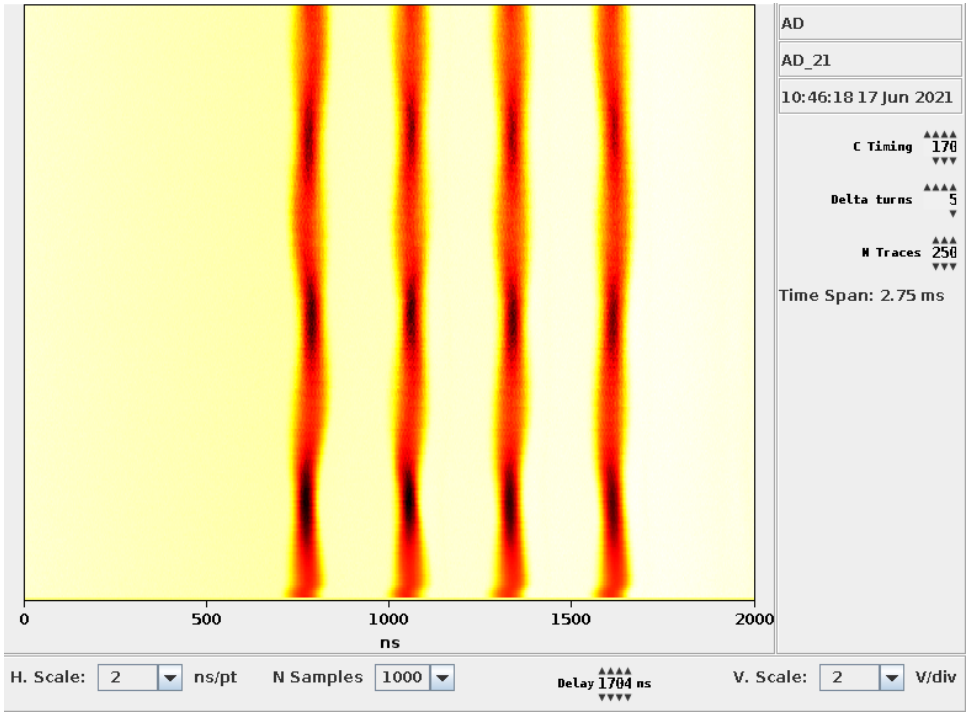




- The injection phase of the 2 extra bunches, or the energy of the circulating beam can be adjusted.

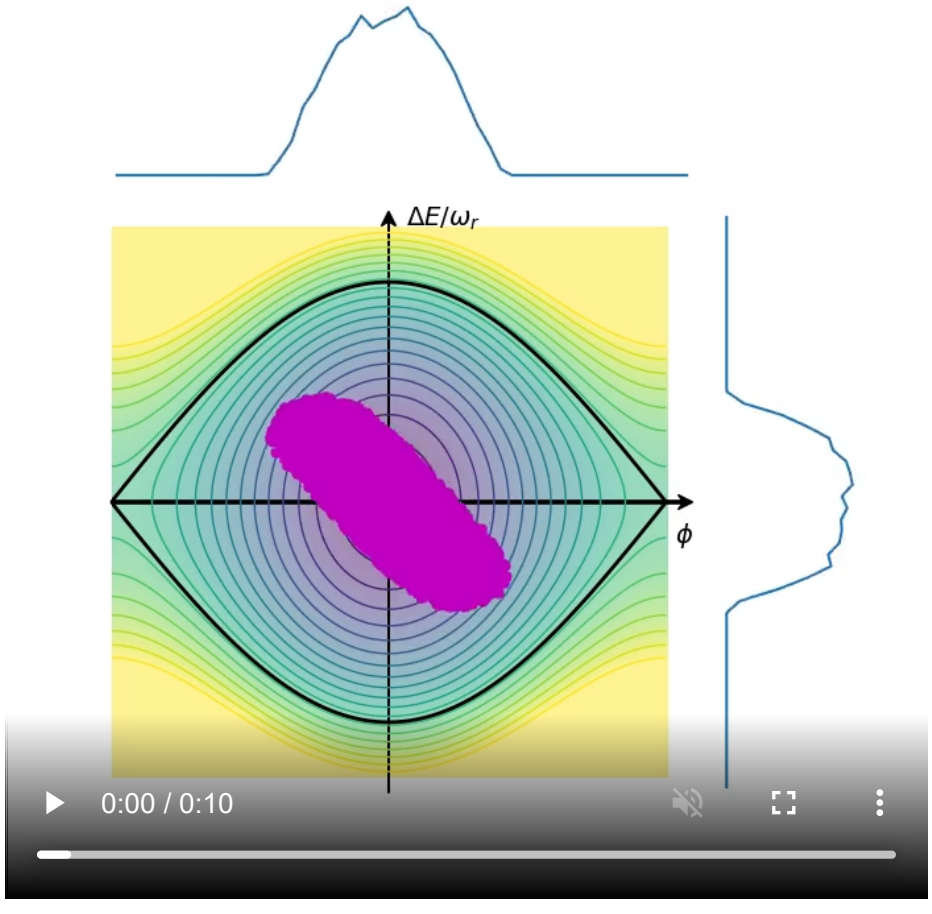
- In that case, the energy of the circulating beam was adjusted by changing the RF frequency at fixed magnetic field

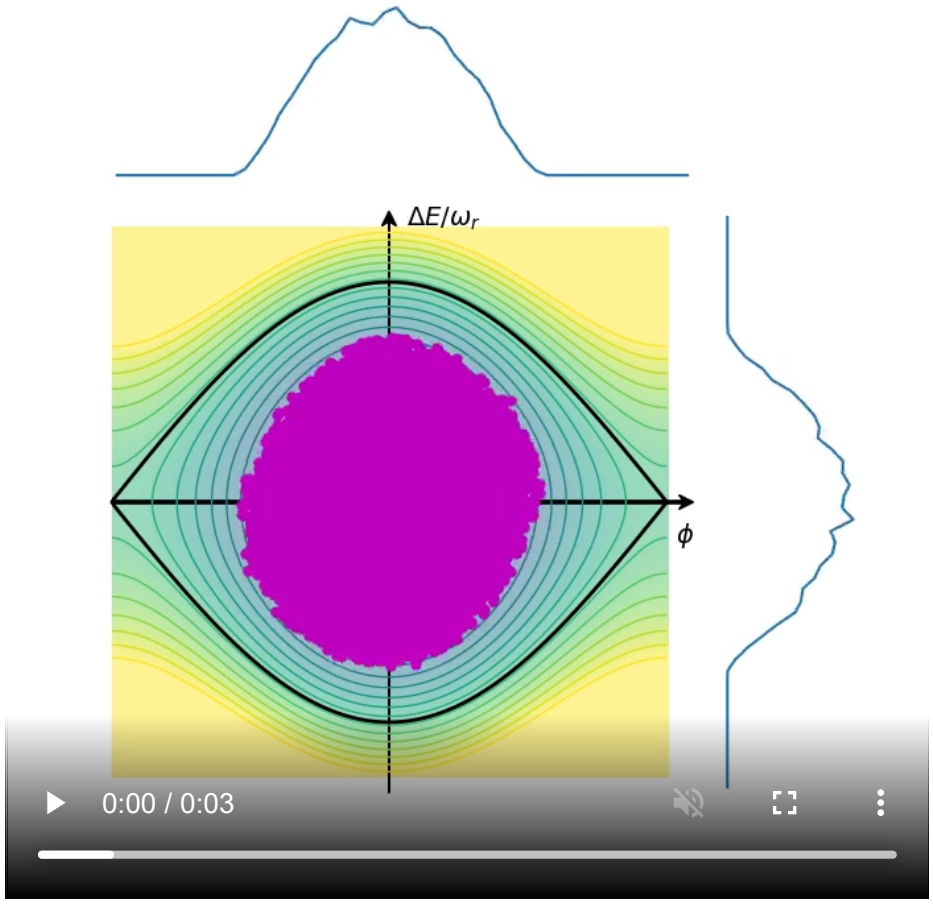
INJECTION OSCILLATIONS (AMPLITUDE)



- In another cycle, 4 new bunches are injected 170 ms after the beginning of the cycle.
- The peak amplitude of the bunches (and the bunch lengths) oscillate.
- What is wrong?

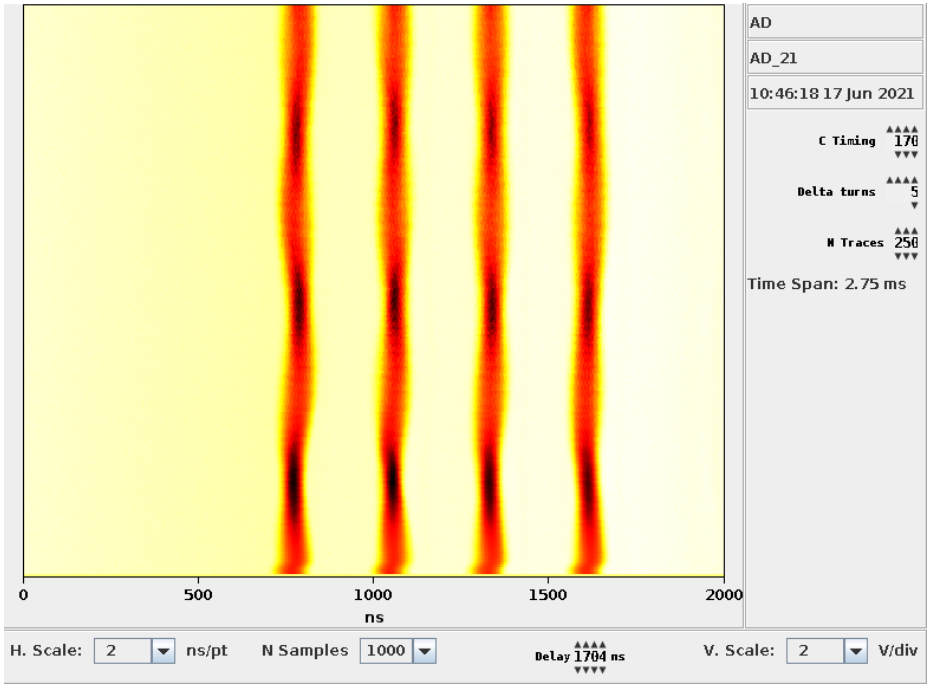
INJECTION OSCILLATIONS (AMPLITUDE)

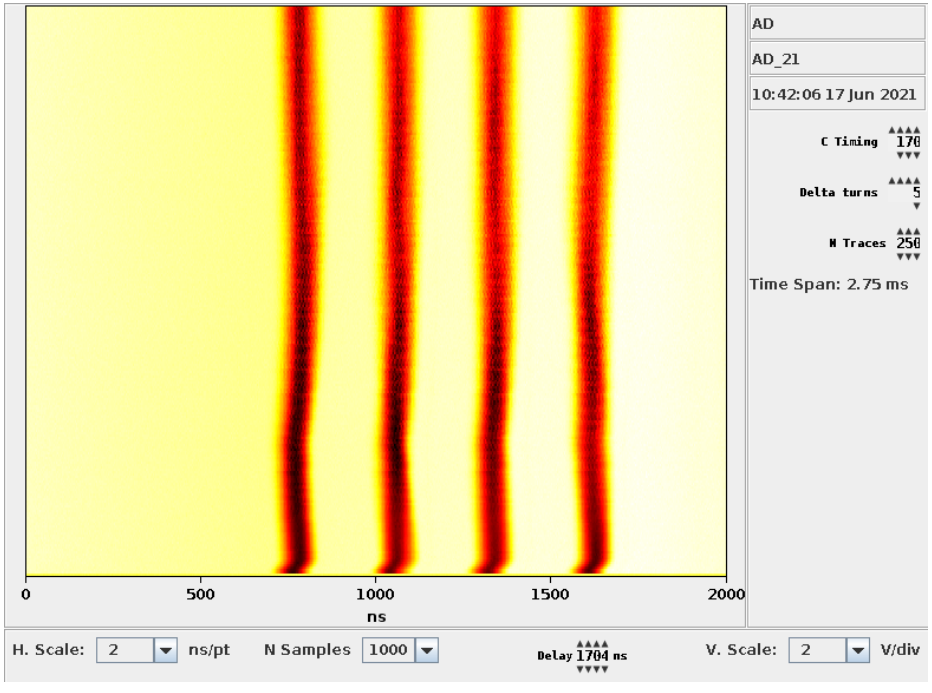




- The bucket is too high in amplitude, the bunch is mismatched (left). After reduction of the voltage, the bunch is matched (NB: different scale in energy!)

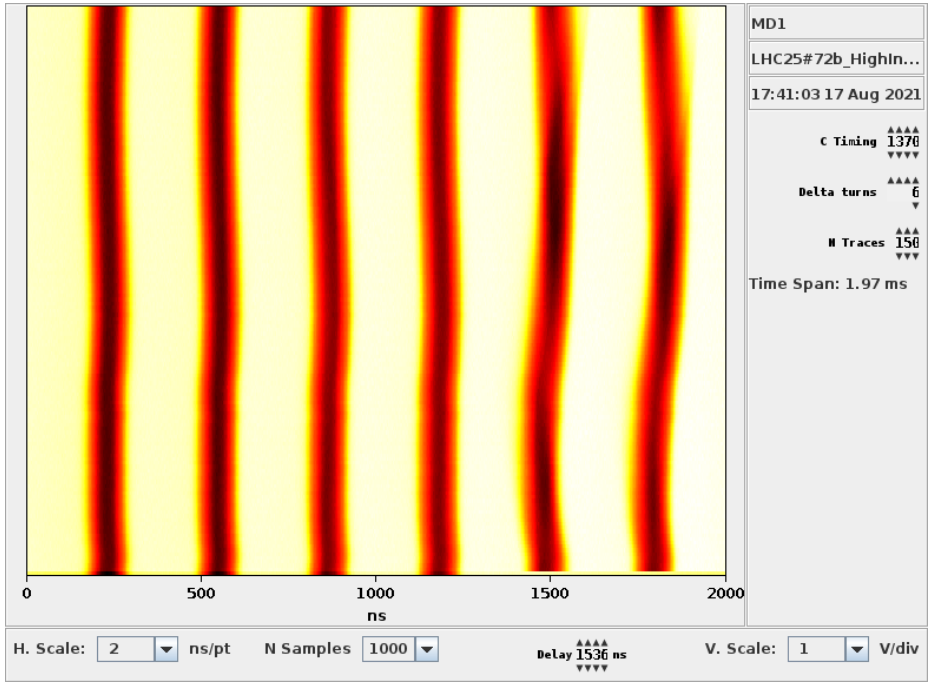
INJECTION OSCILLATIONS (AMPLITUDE)

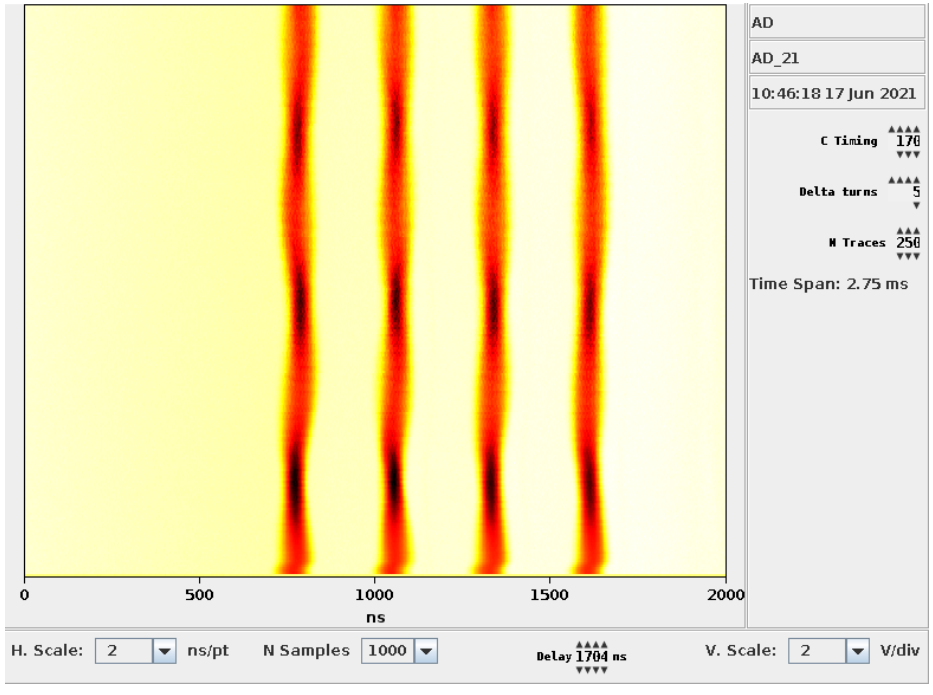




- The RF voltage can be adjusted to increase/reduce the amplitude of the bucket for matching.
- In that case, the RF voltage was reduced by a factor of 2 to improve the matching.

INJECTION OSCILLATIONS



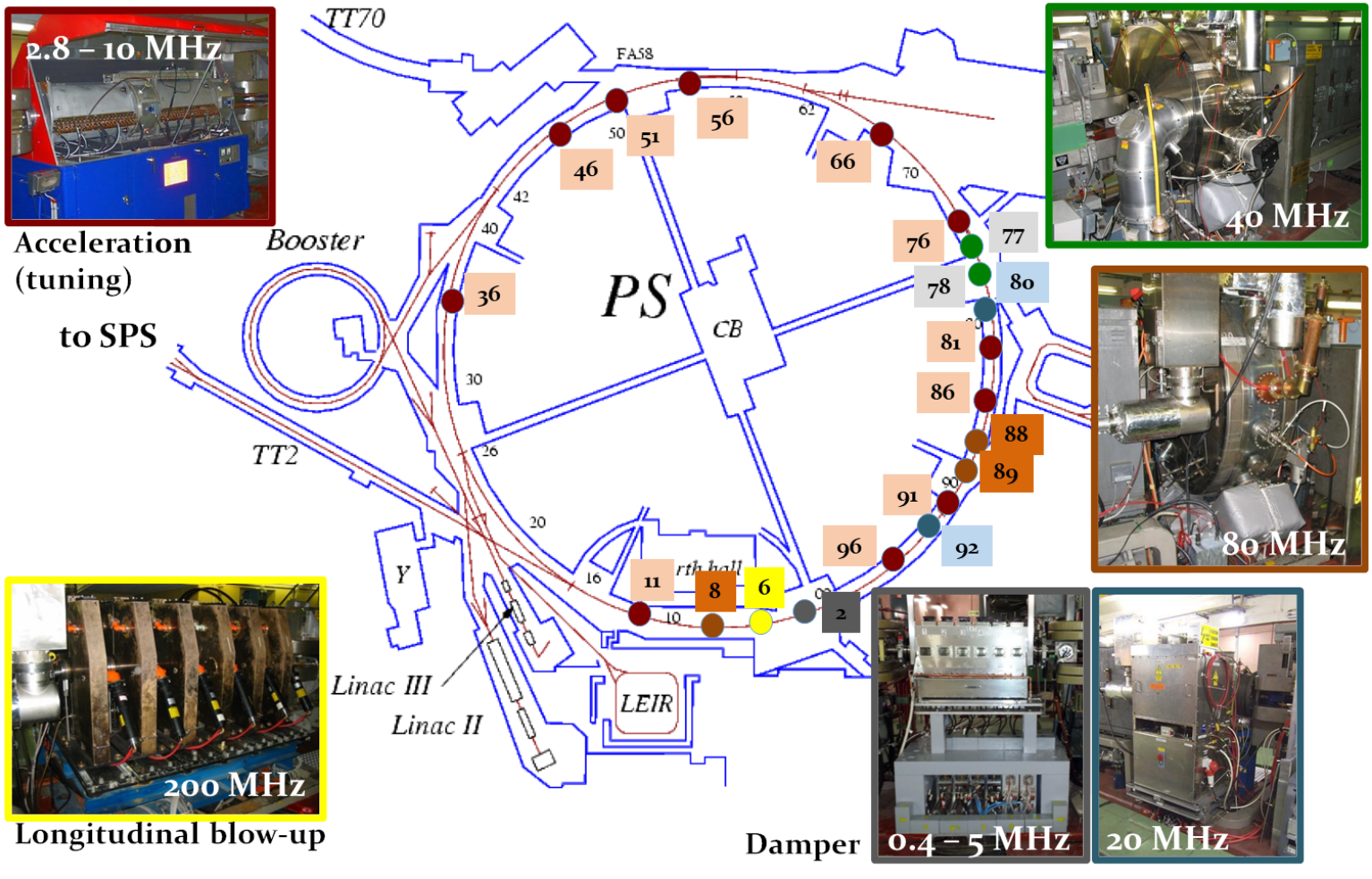


- Adjusting injection oscillations is a concrete example of routine operation to adjust machine parameters.

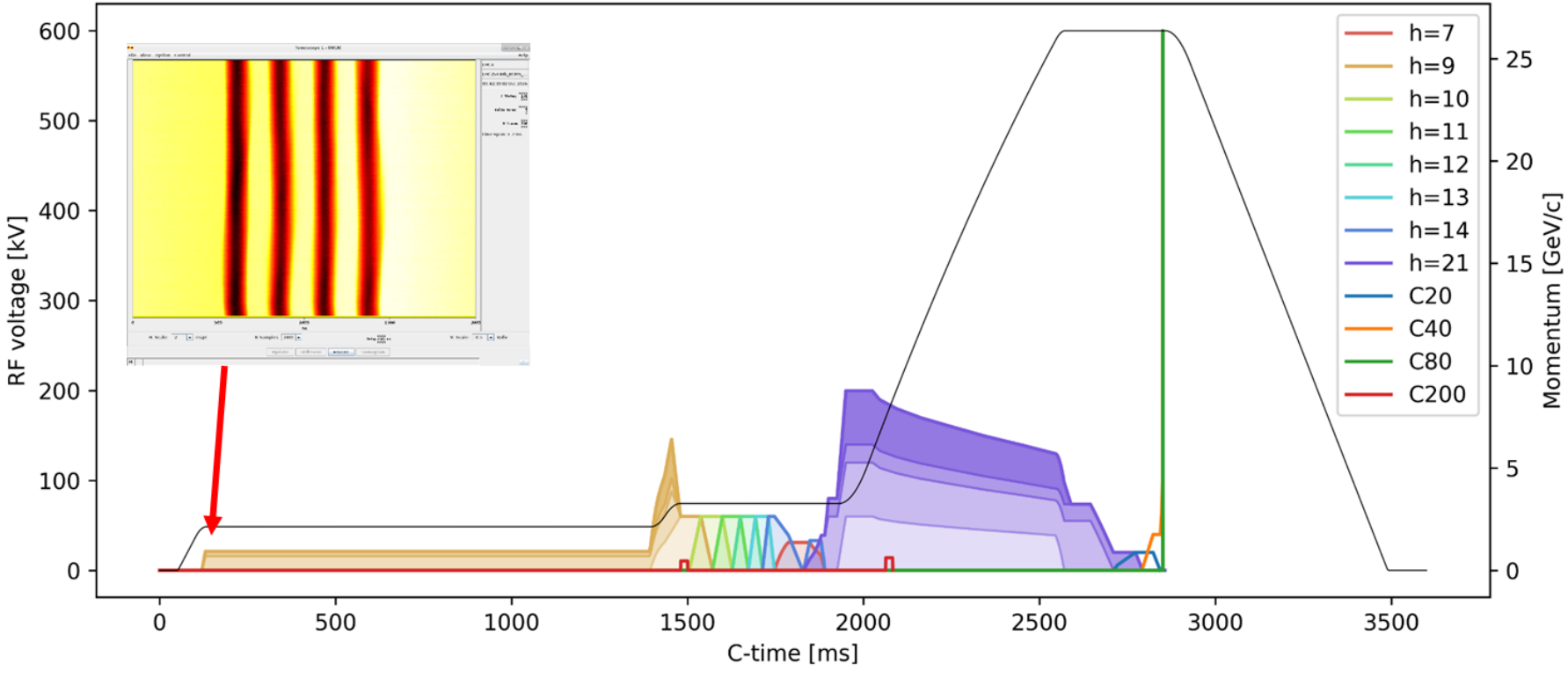
- The goal is to avoid filamentation and emittance blow-up, and fine tune the beam quality right from the start.

RF MANIPULATIONS

THE PS, ONE RING TO RULE THEM ALL

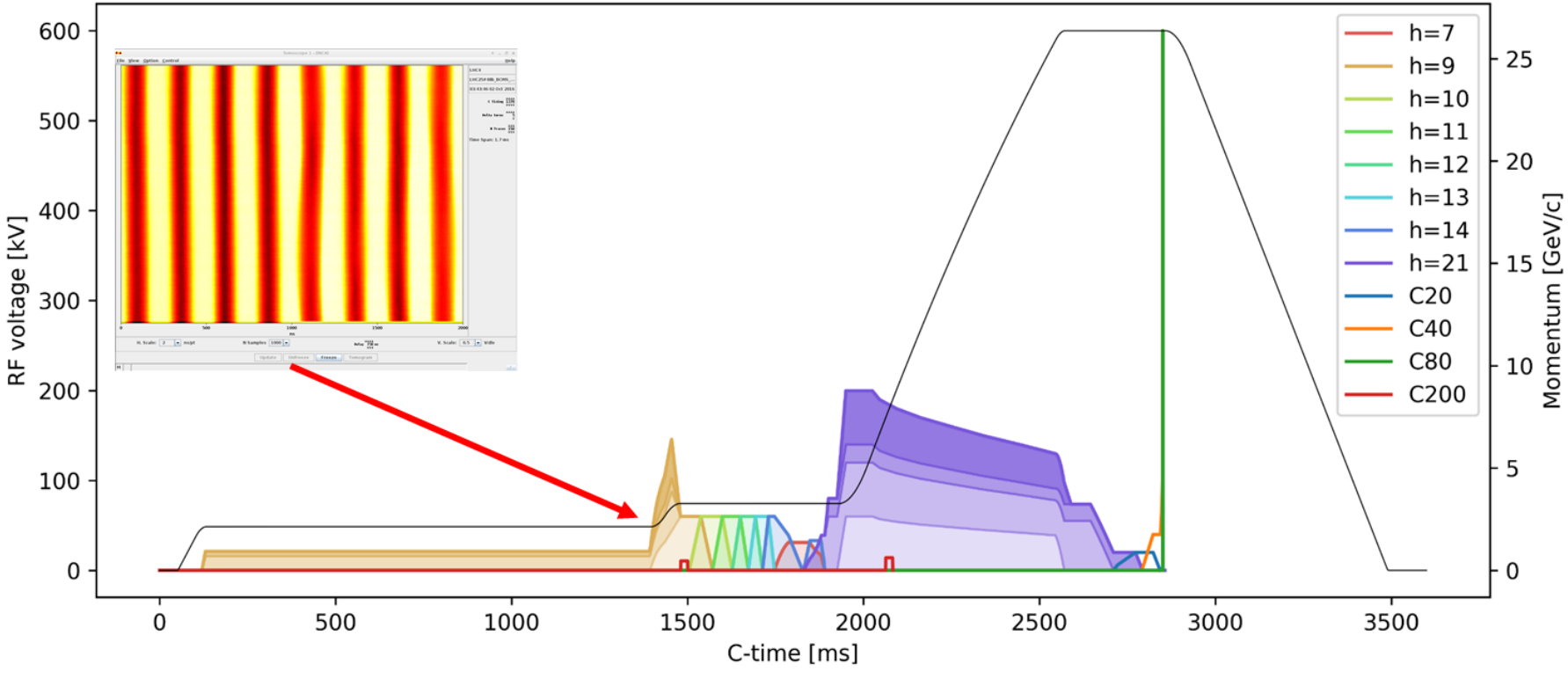


RF MANIPULATIONS OVERVIEW



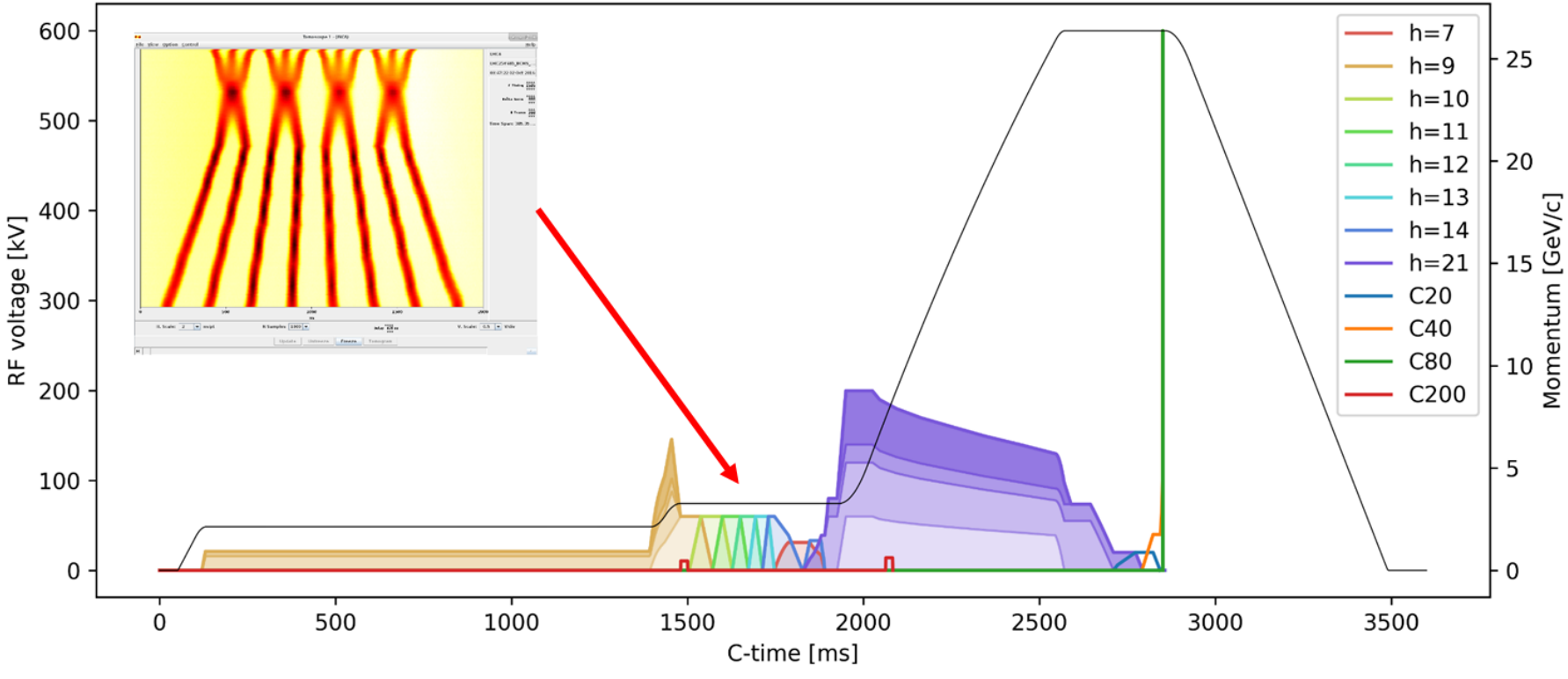
- Four bunches are injected from the pre-injector (PSB)

RF MANIPULATIONS OVERVIEW



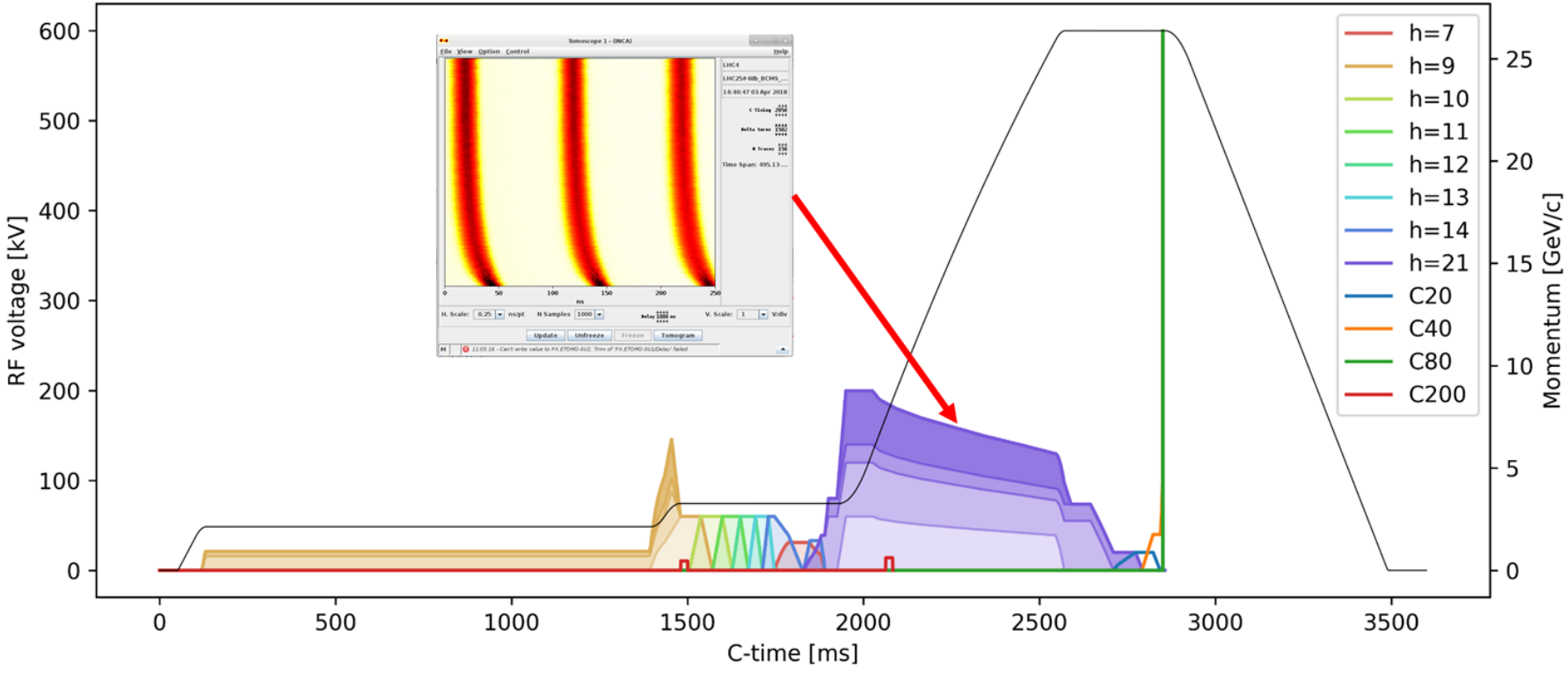
- Four more bunches are injected from the pre-injector (PSB)

RF MANIPULATIONS OVERVIEW



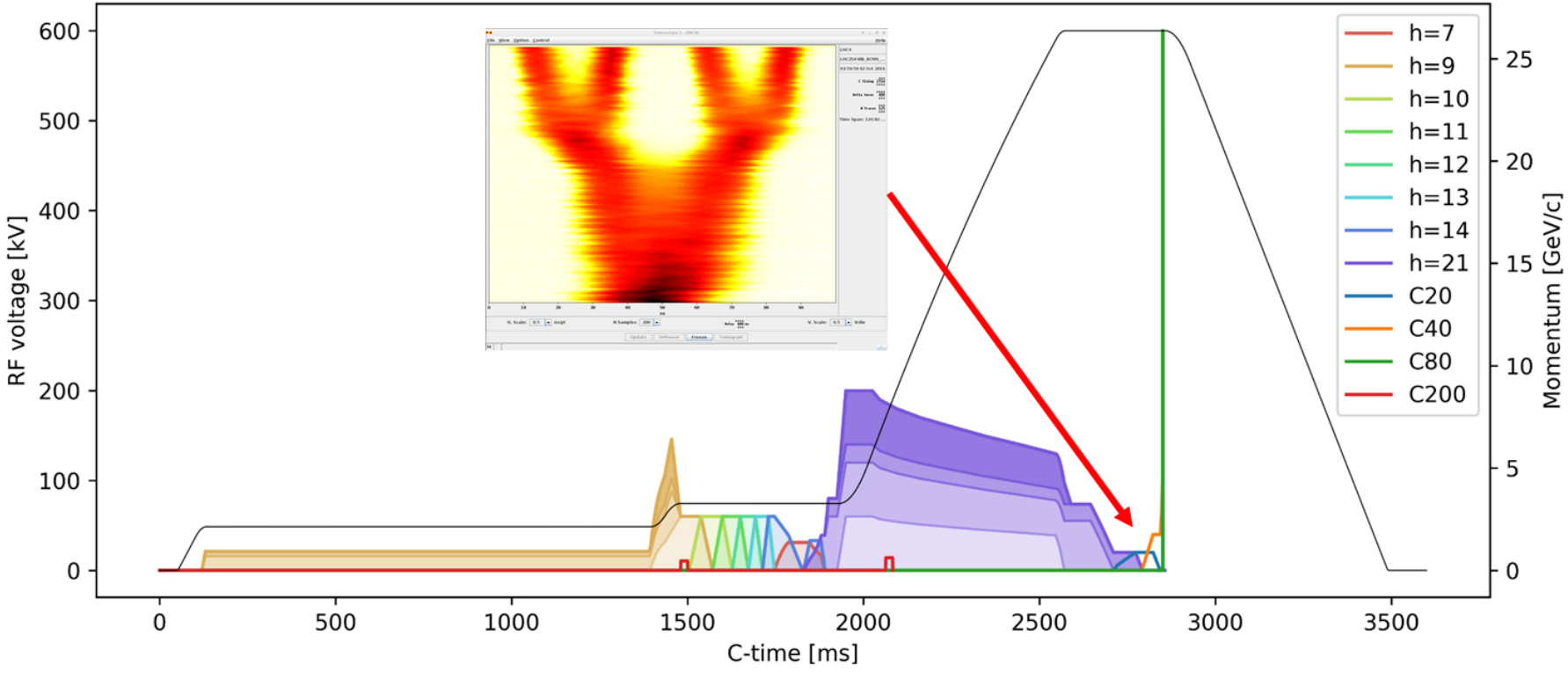
- The beam is accelerated to a plateau and undergoes many RF manipulations.
- The batch is compressed, bunches are merged, and split again

RF MANIPULATIONS OVERVIEW



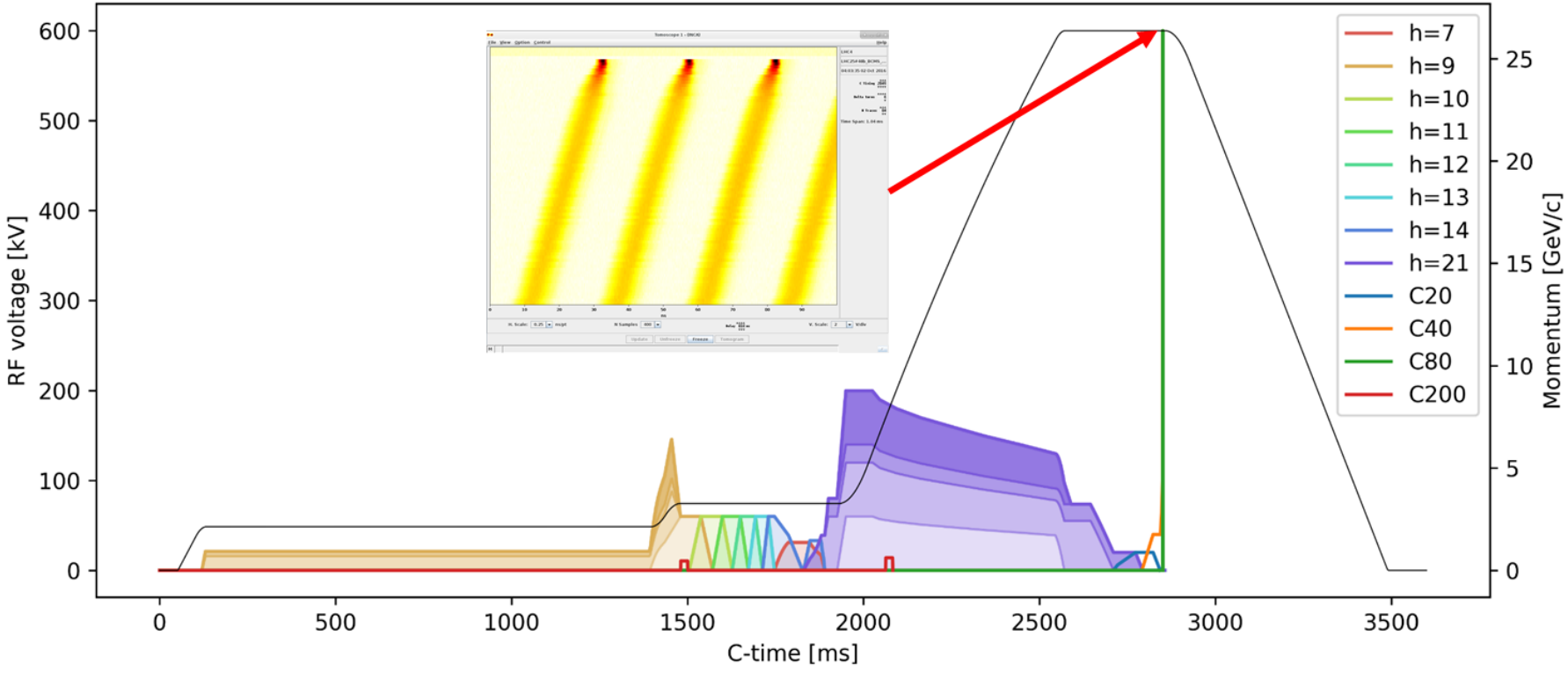
- The beam is accelerated, no (heavy) RF manipulation during the ramp.

RF MANIPULATIONS OVERVIEW



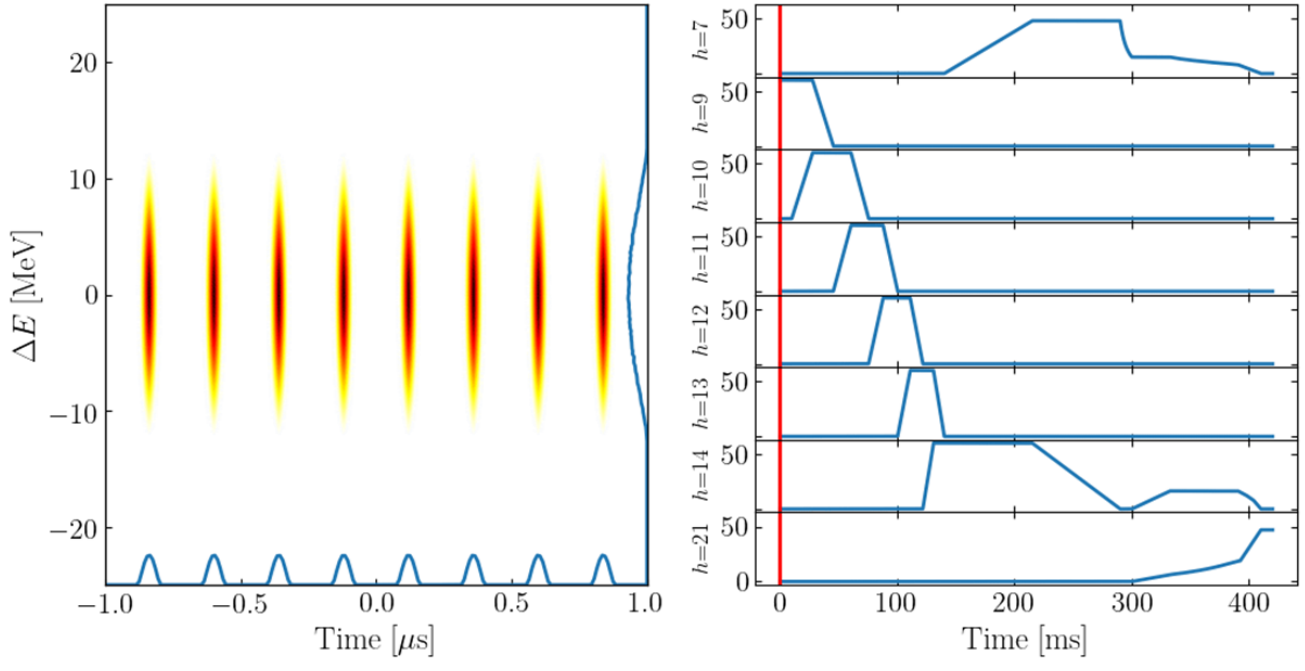
- The bunches are split again twice.

RF MANIPULATIONS OVERVIEW



- The bunches are compressed and extracted to the next machine, the SPS.
- The RF manipulations serve one purpose, define the 25 ns bunch spacing required by the final destination, the LHC!

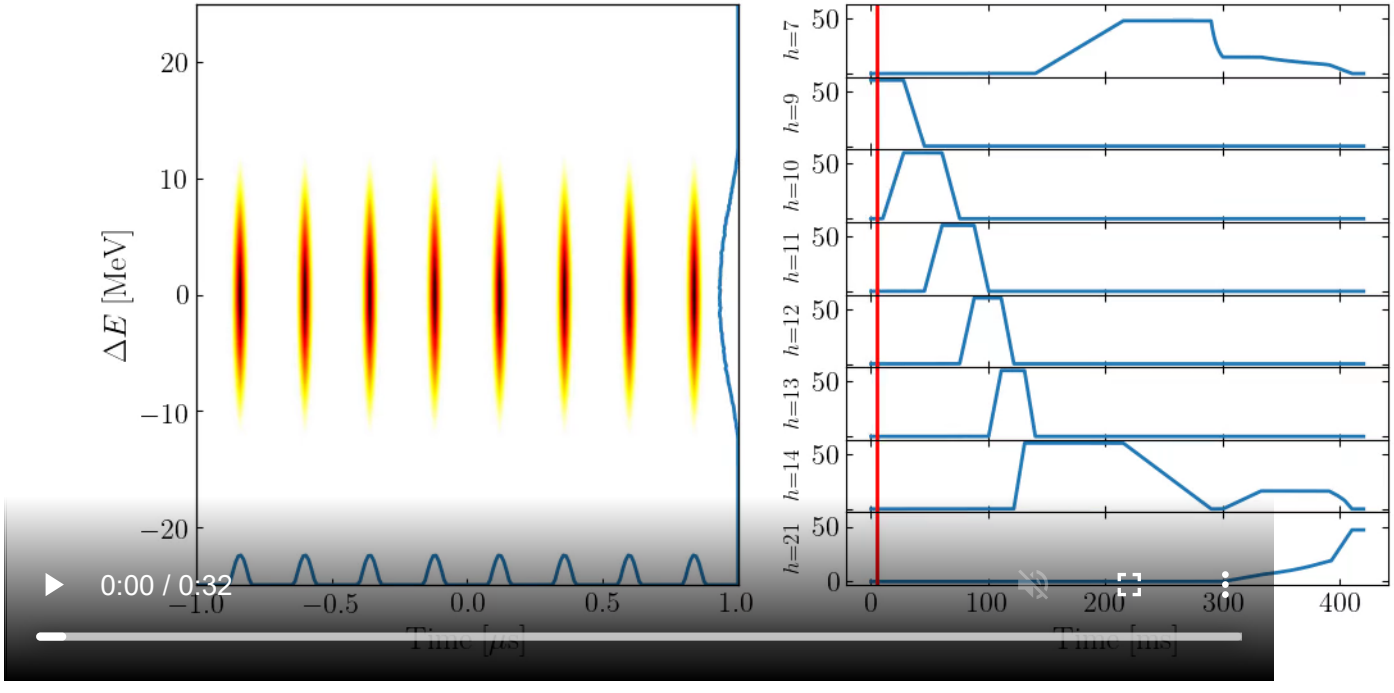
BATCH COMPRESSION, MERGING, SPLITTING



Batch compression h=9 to 14, Merging h=14to 7,

Triple Splitting h=7 to 21, with intermediate 14

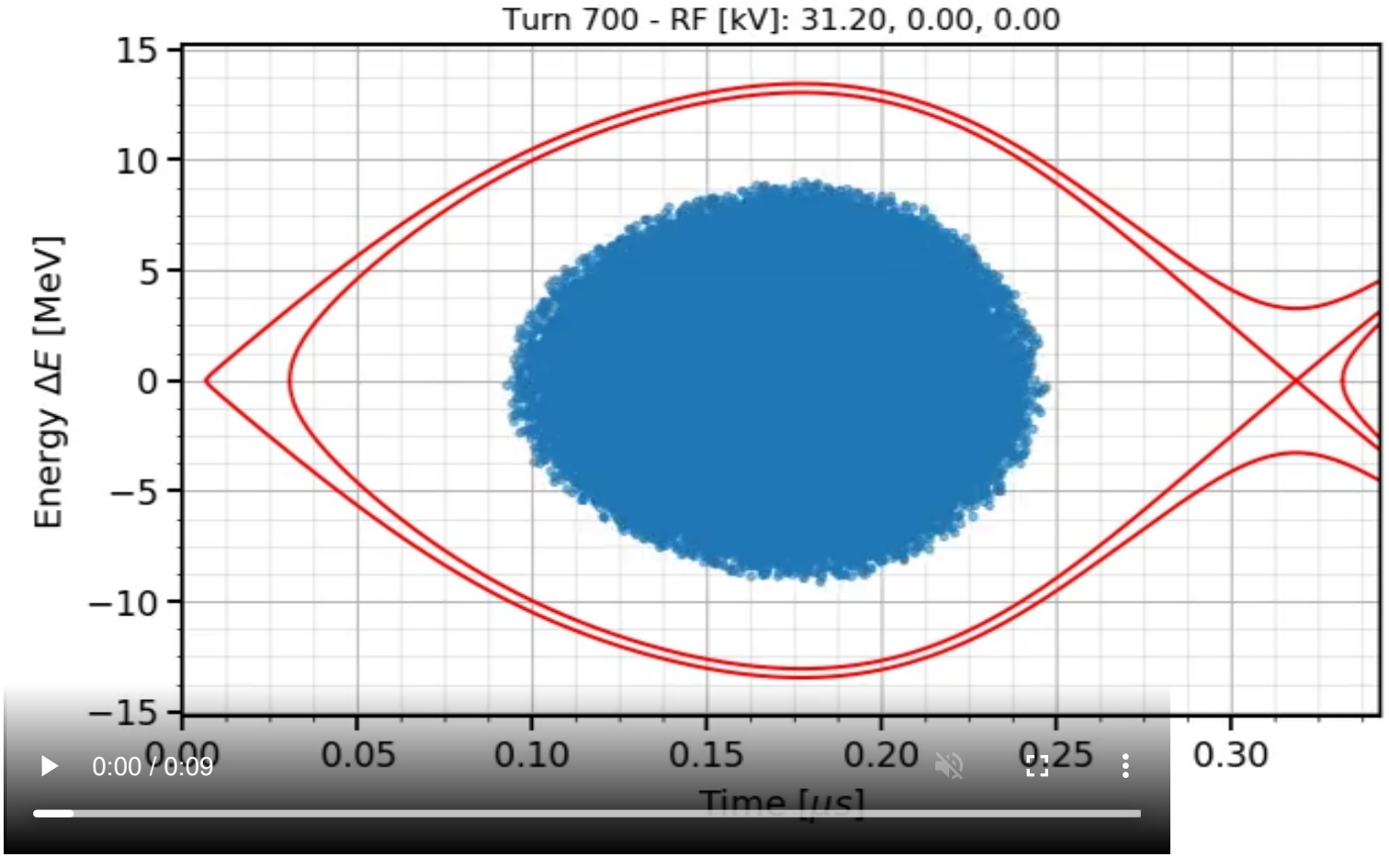
BATCH COMPRESSION, MERGING, SPLITTING



Eventually, 2 bunches merged and then split in 3. Emittance is preserved ideally (divided when split, multiplied when merged).

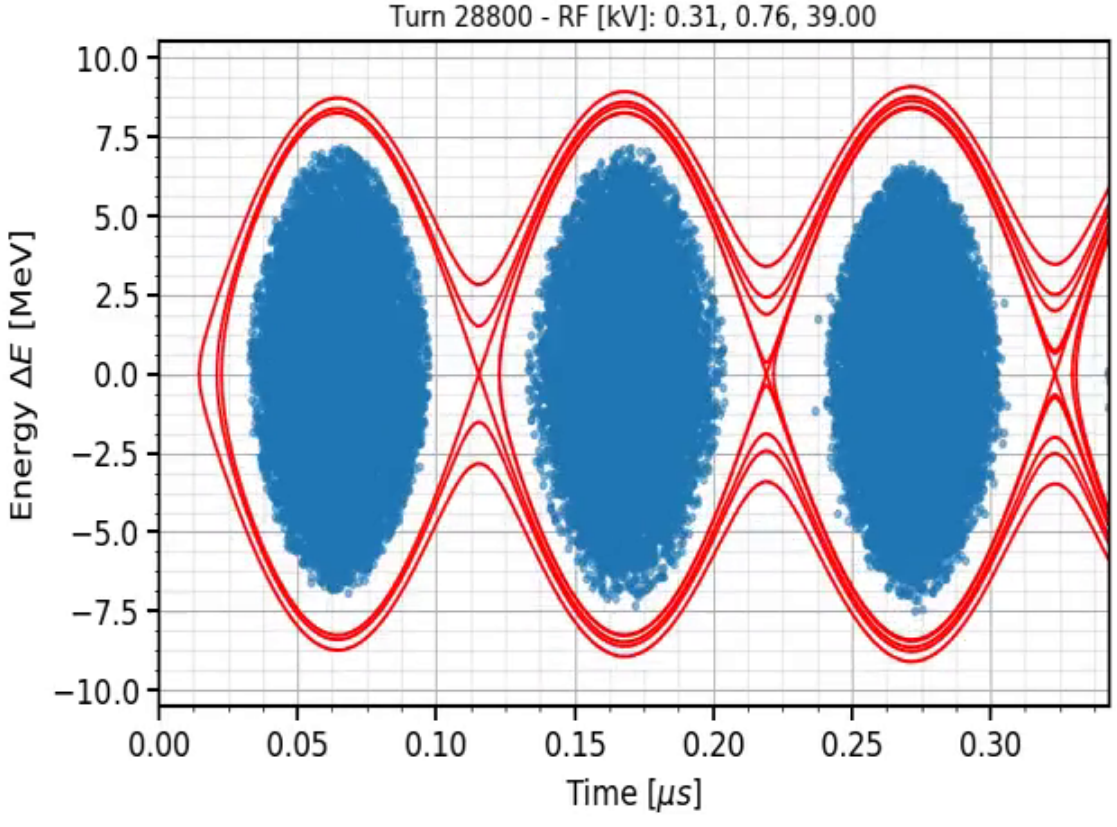
Animation: H. Damerau

ZOOM ON THE TRIPLE SPLITTING



The separatrices are reprensented in red (several inner/outer separatrices, including intensity effects).

ZOOM ON THE TRIPLE SPLITTING



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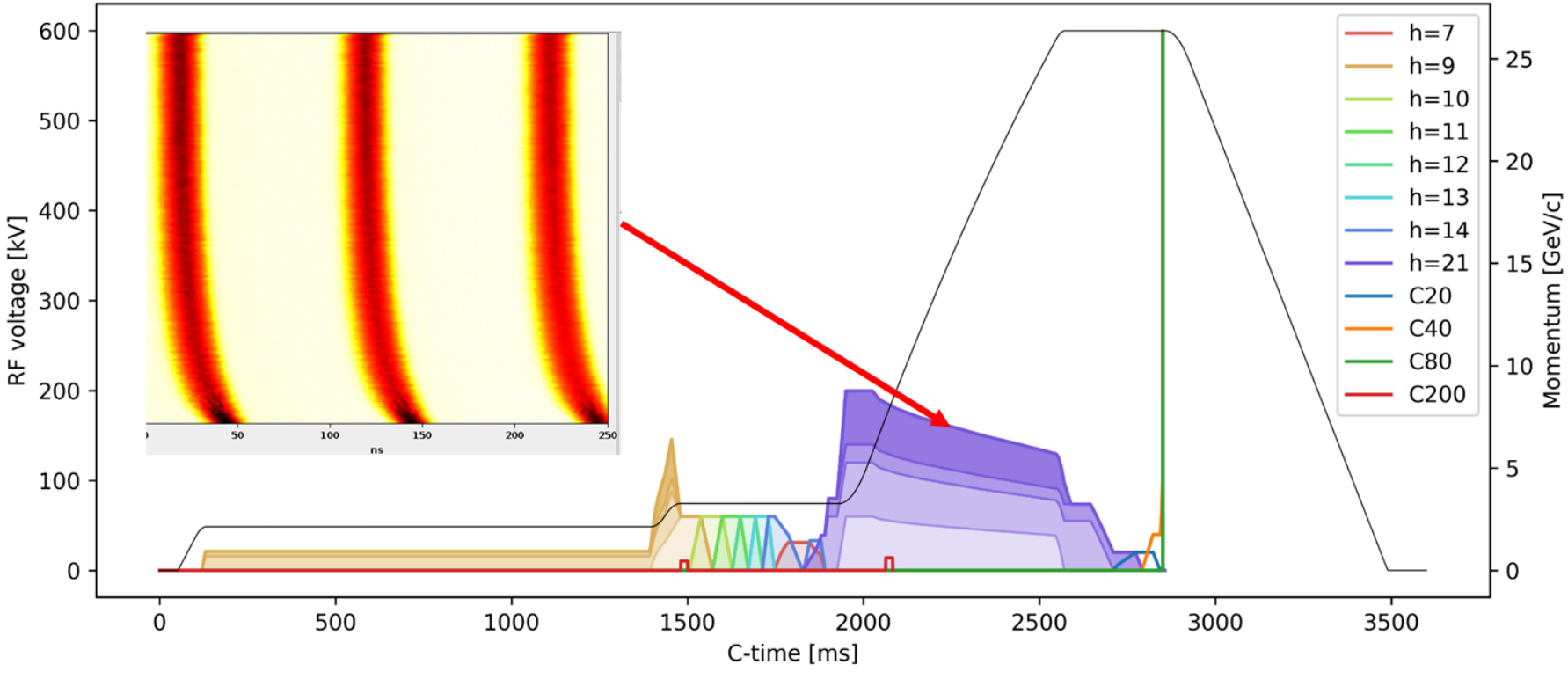
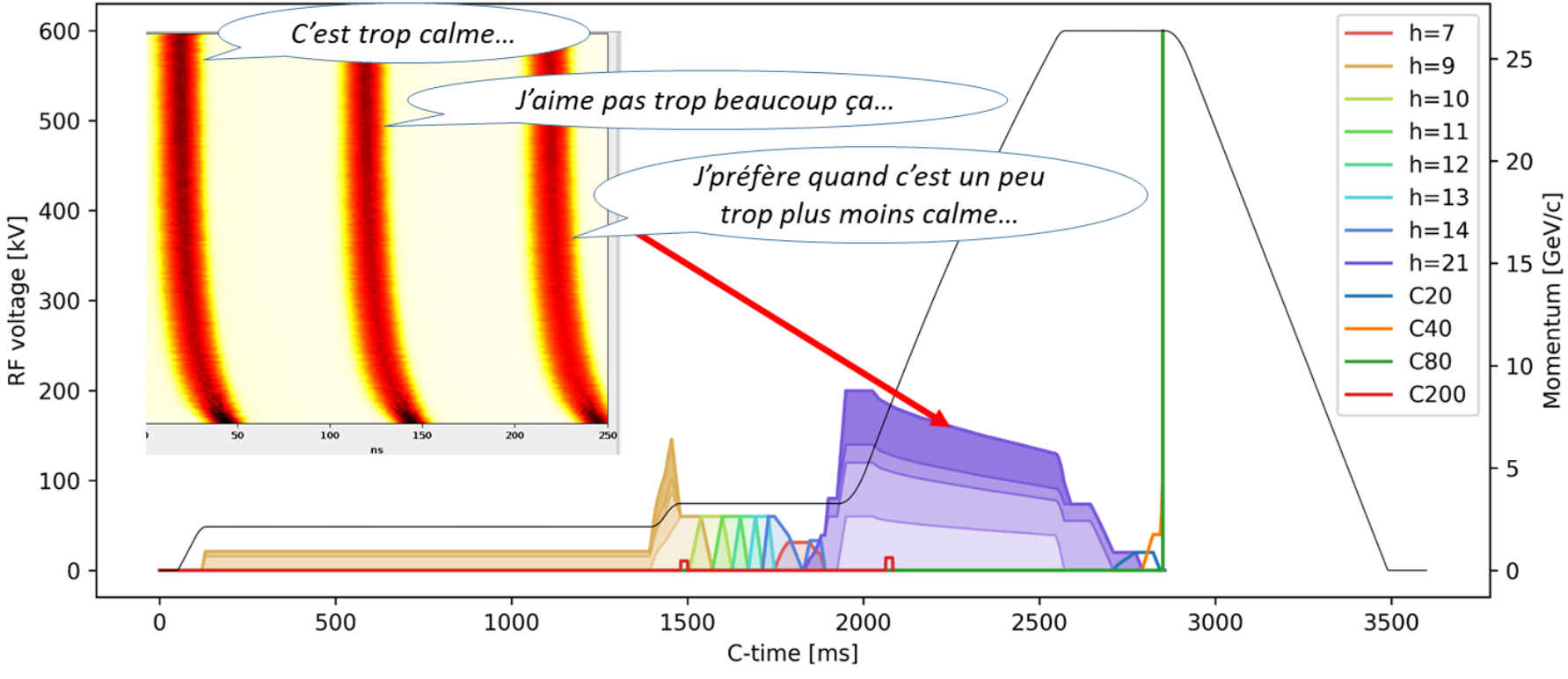
DURING THE ACCELERATION RAMP



The acceleration ramp is the moment when the bunch is manipulated the least, the bunches are accelerated smoothly till reaching top energy.

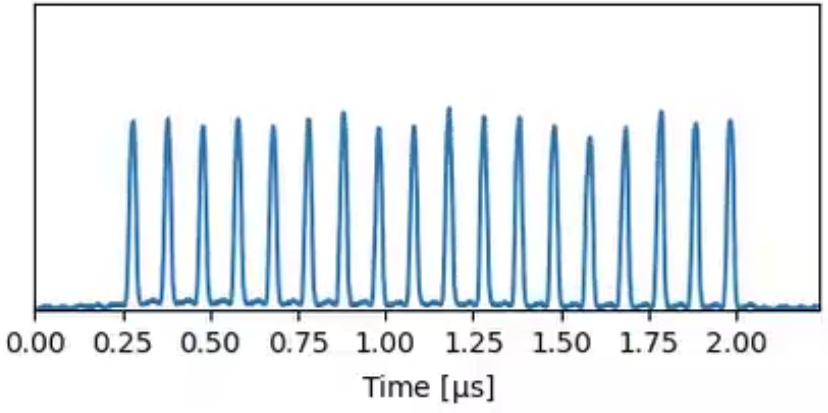
DURING THE ACCELERATION RAMP

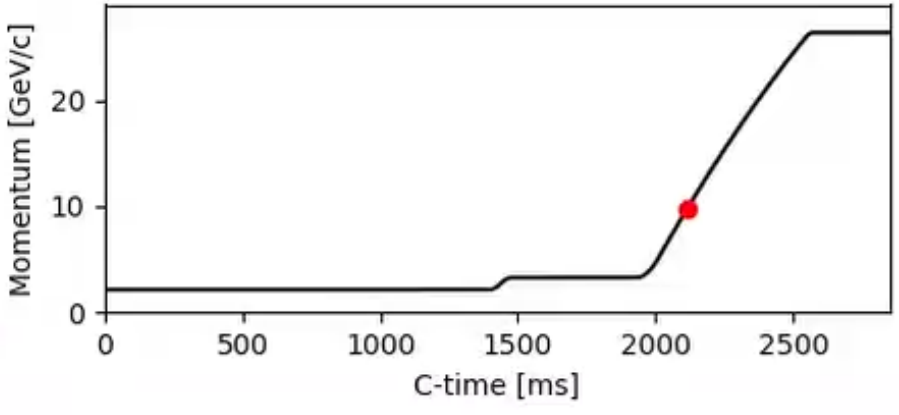


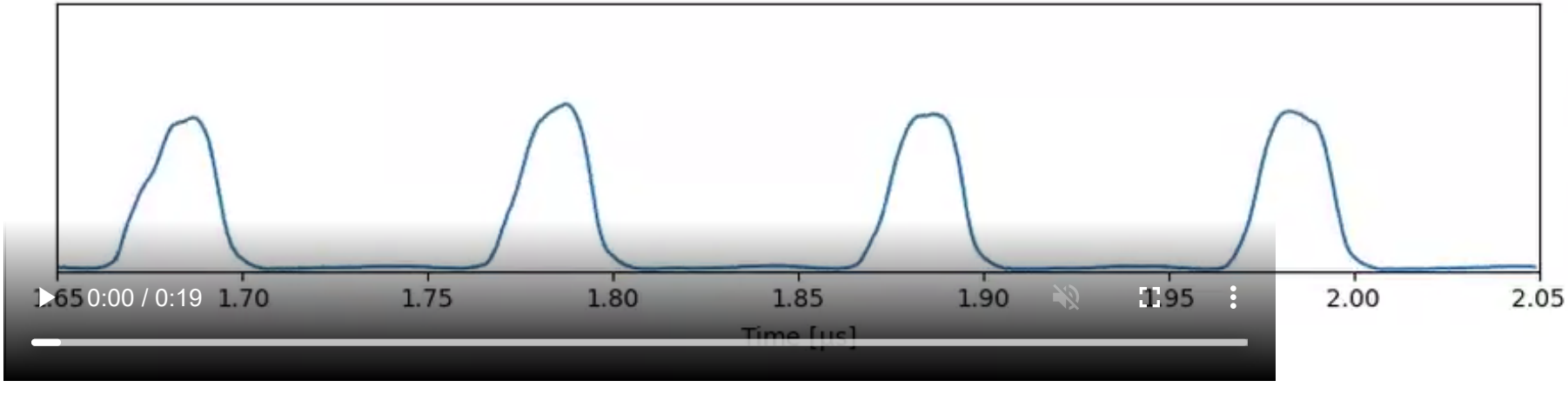
The acceleration ramp is the moment when the bunch is manipulated the least, the bunches are accelerated smoothly till reaching top energy.

Or so it seems...

COUPLED BUNCH INSTABILITIES

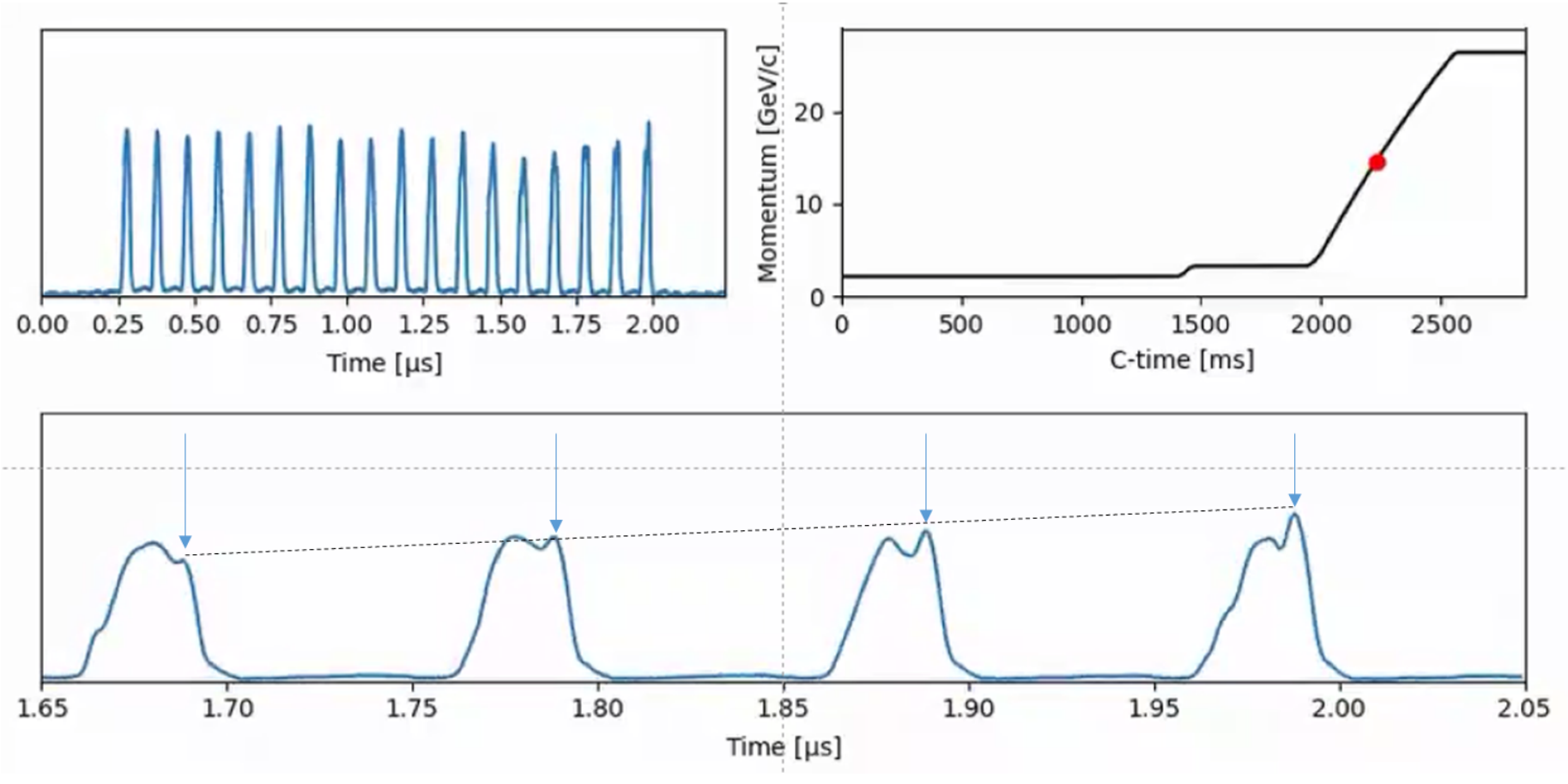






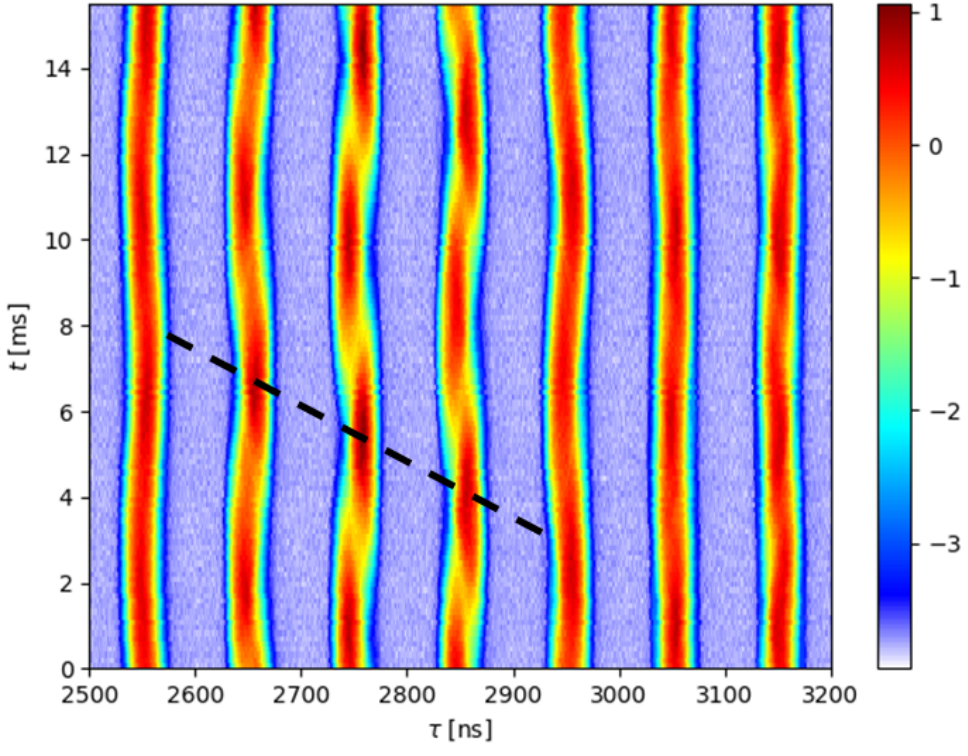
Bunches start to oscillate during the ramp at very high beam intensity (wakefields and instabilities!!)

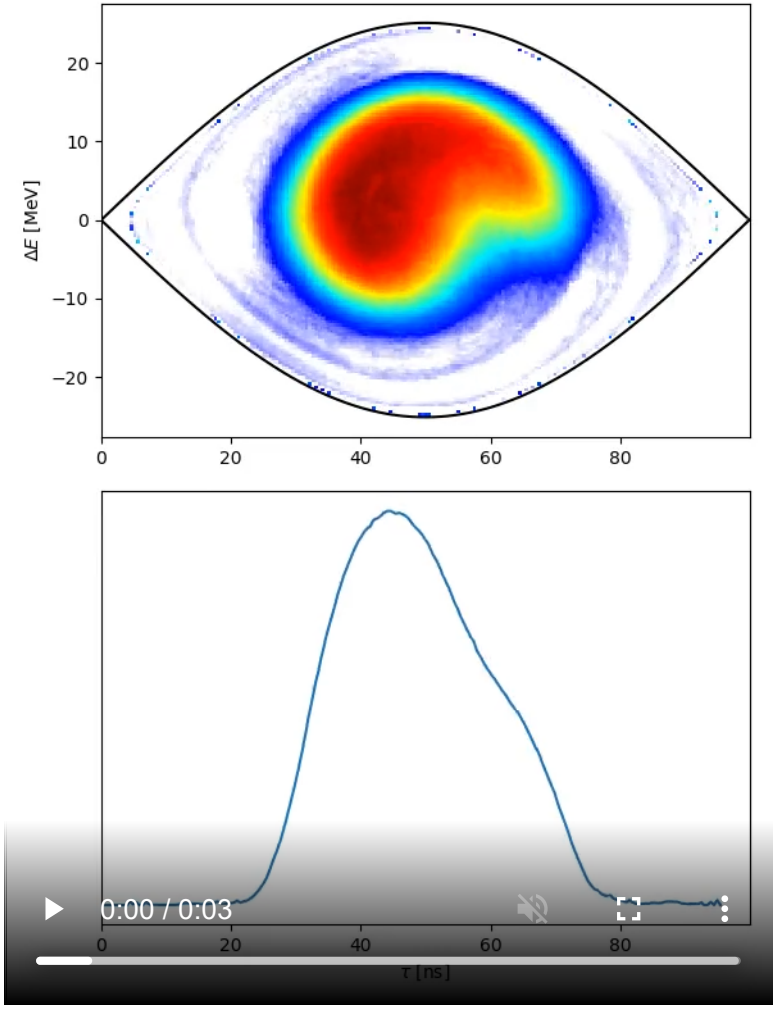
COUPLED BUNCH INSTABILITIES



Coupling between the bunches, phase advance from one bunch to the next in phase space.

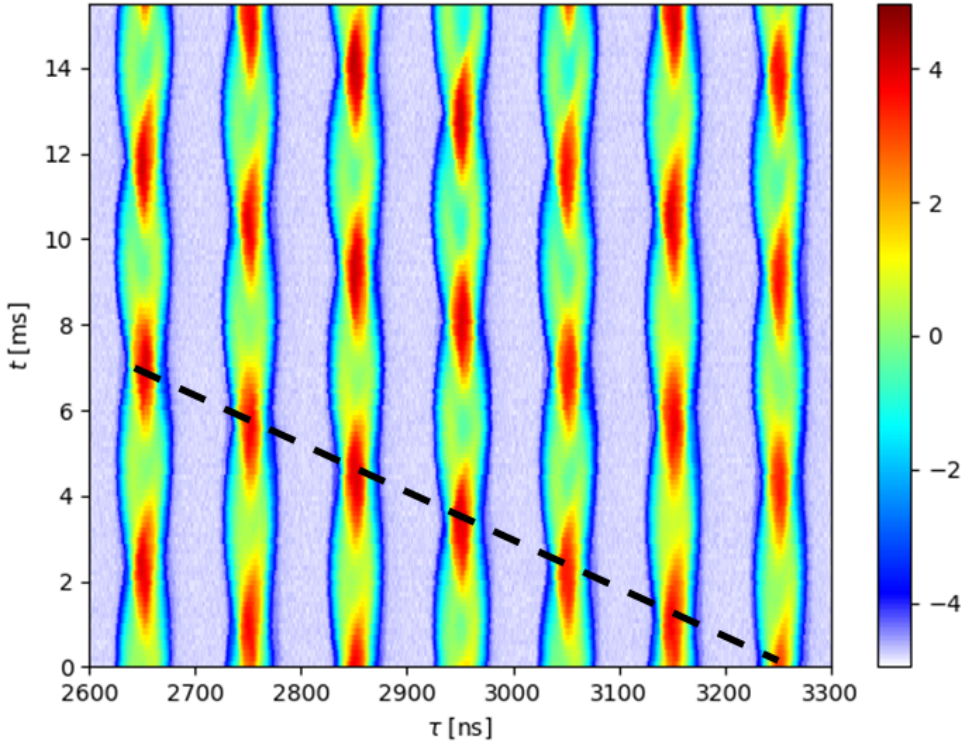
DIPOLE MODE OF OSCILLATIONS

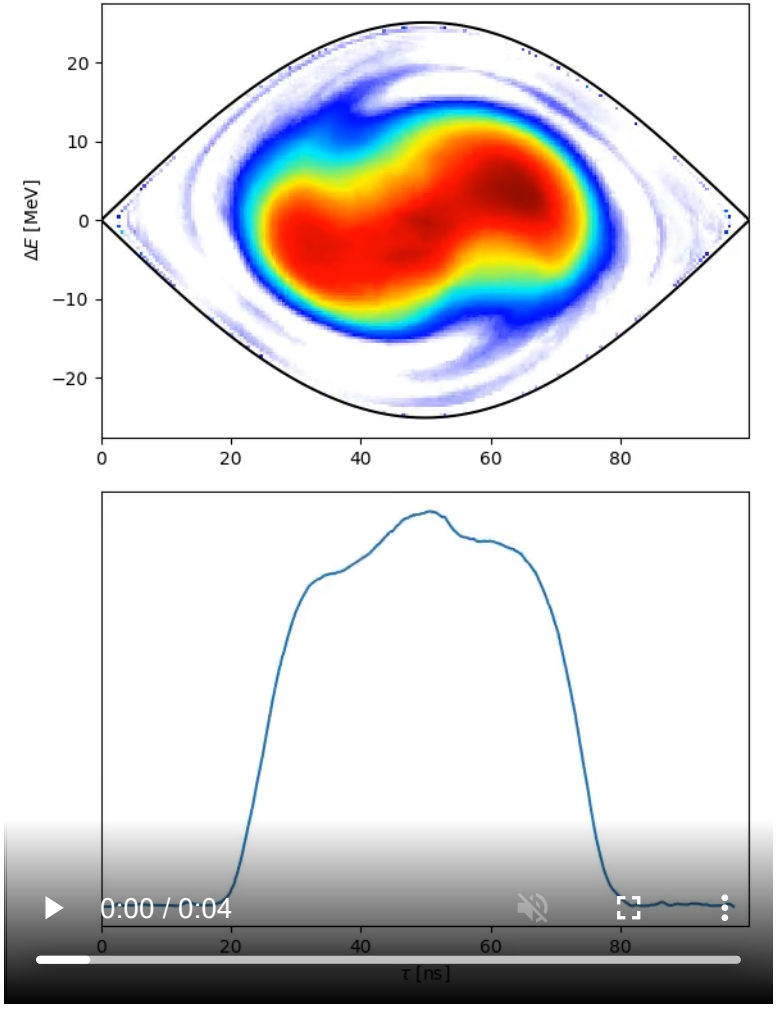




- Dipole mode of instability.
- Phase oscillations of the bunch, single node.
- Oscillates at 1 x fs0.

QUADRUPOLE MODE OF OSCILLATIONS





- Quadrupole mode of instability.
- Oscillations of the bunch length, two node.
- Oscillates at 2 x fs0.

THE END