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Low-level RF fine Tuning for two-bunch Operation at SwissFEL

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Outline

- Two-bunch Operation at SwissFEL
- LLRF Knobs for two-bunch Tuning
- RF Setup for second Bunch Transmission
- Regulation of the second Bunch

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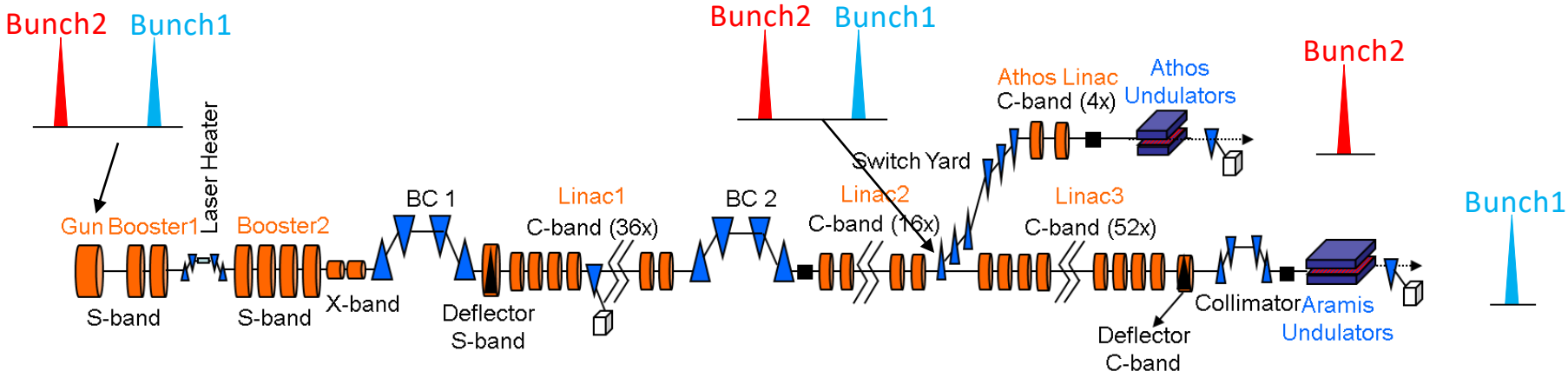
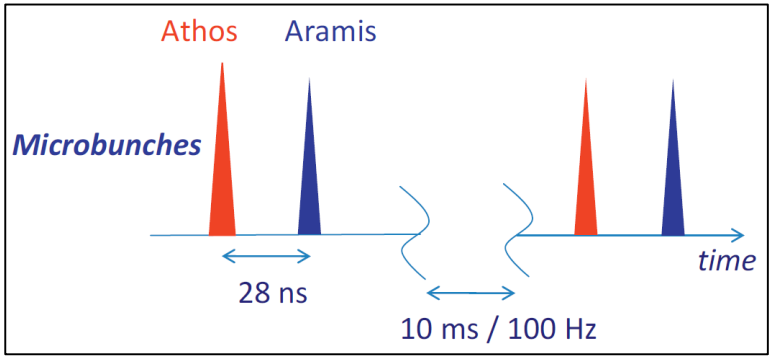
Two-bunch Operation at SwissFEL

Two Bunch Operation at SwissFEL

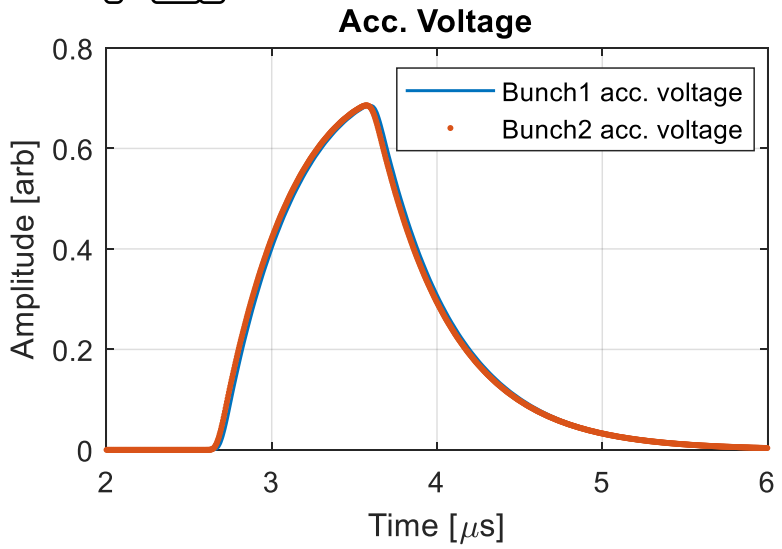


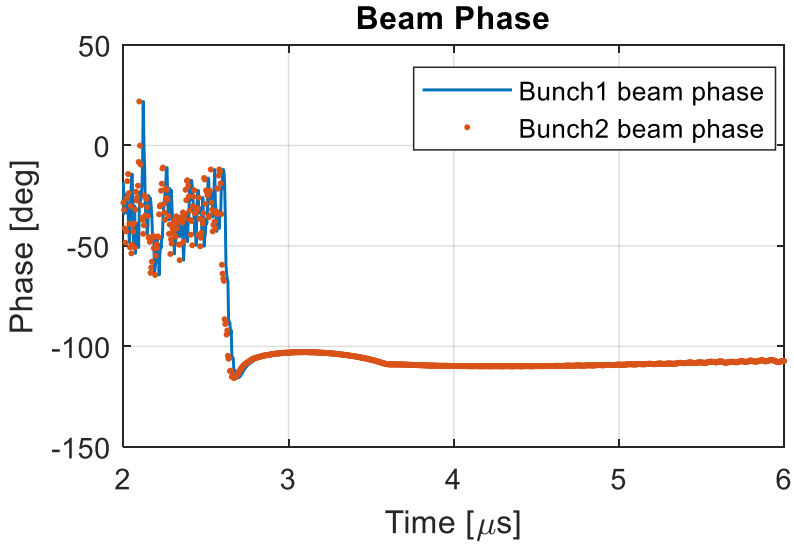


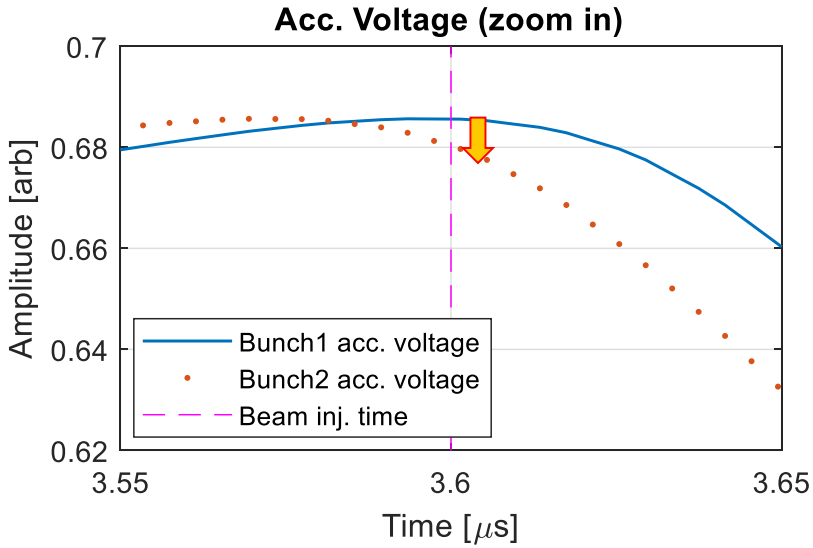
User Expectations:

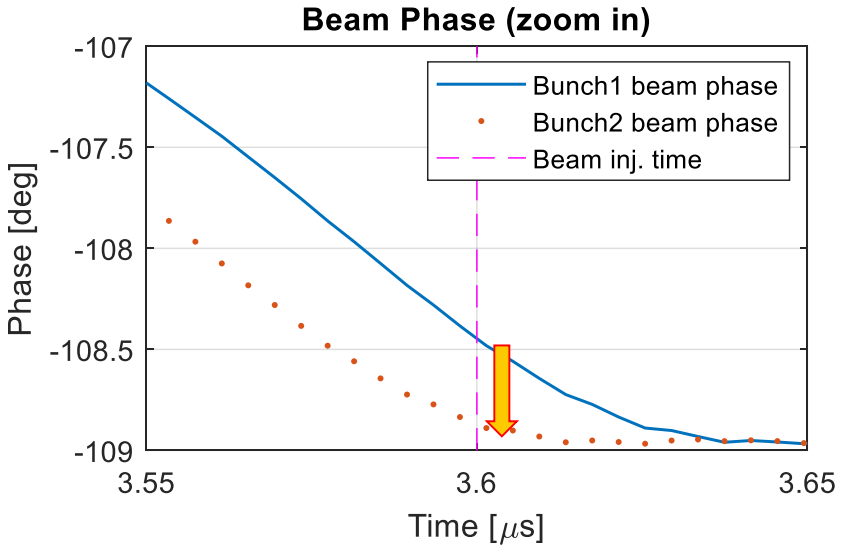
- Athos beam development and test will be performed in parallel with the Aramis user operation.
- We should be able to adjust the RF amplitude and phase for the second bunch without affecting the first one.
  - *Scenario 1*: Setup the second bunch for transmission – equalize the RF fields for both bunches.
  - *Scenario 2*: Fine tune the second bunch to satisfy the bunch parameter requirements.

RF Field Difference for two Bunches: Gun



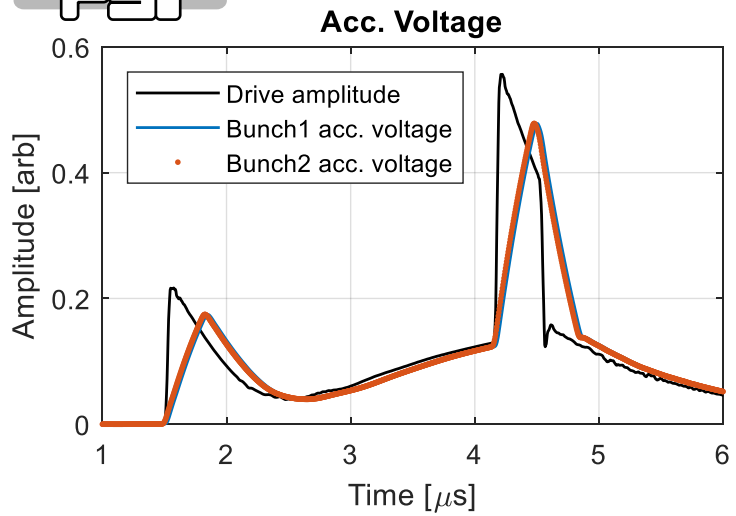


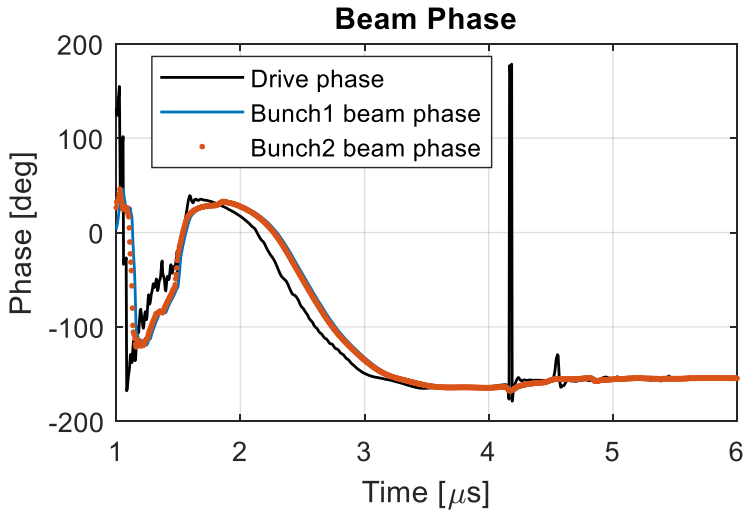


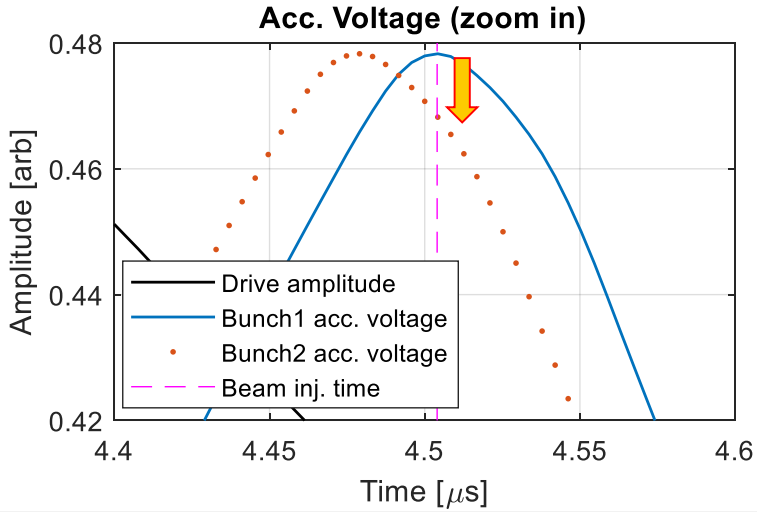


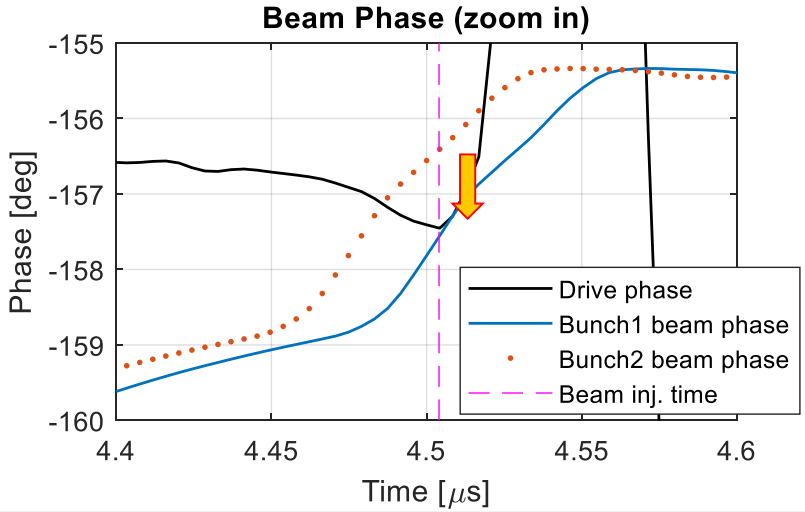
- Around current working point of the Gun, the amplitude and phase differences for the two bunches are about **0.8 %** and **0.4 degree**, respectively.

RF Field Difference for two Bunches: C-band









- Around current working point of the C-band stations, the amplitude and phase differences for the two bunches are about **2 %** and **1.2 degree**, respectively.
- Delay the RF pulse by 3~4 DAC clock cycles (12~16 ns), the two bunches will see the same accelerating voltage.

Requirements to two-bunch LLRF Tools

Functions of LLRF tools:

- With existing interfaces (RSYS:SET-ACC-VOLT and RSYS:SET-BEAM-PHASE), the amplitude and phase changes will be applied to the entire RF pulse and affect both bunches.
- A knob will be provided to tune the amplitude and phase seen by the second bunch without affecting the first one. But it is not possible to tell how much amplitude and phase for the second bunch has been tuned from the RF measurements.
  - **Consequence**: The beam diagnostics for the second bunch should be always referred when tuning the RF knob for the second bunch!

Procedures for two-bunch setup and regulation:

- Setup Gun RF field for two bunches with the same (or with specified offset) bunch energy and arrival time at Gun exit (and/or minimum energy spread).
- Setup injector/Linac1 RF station fields for two bunches with the same (or with specified offset) bunch energy, arrival time and compression at BC1/BC2 exit.

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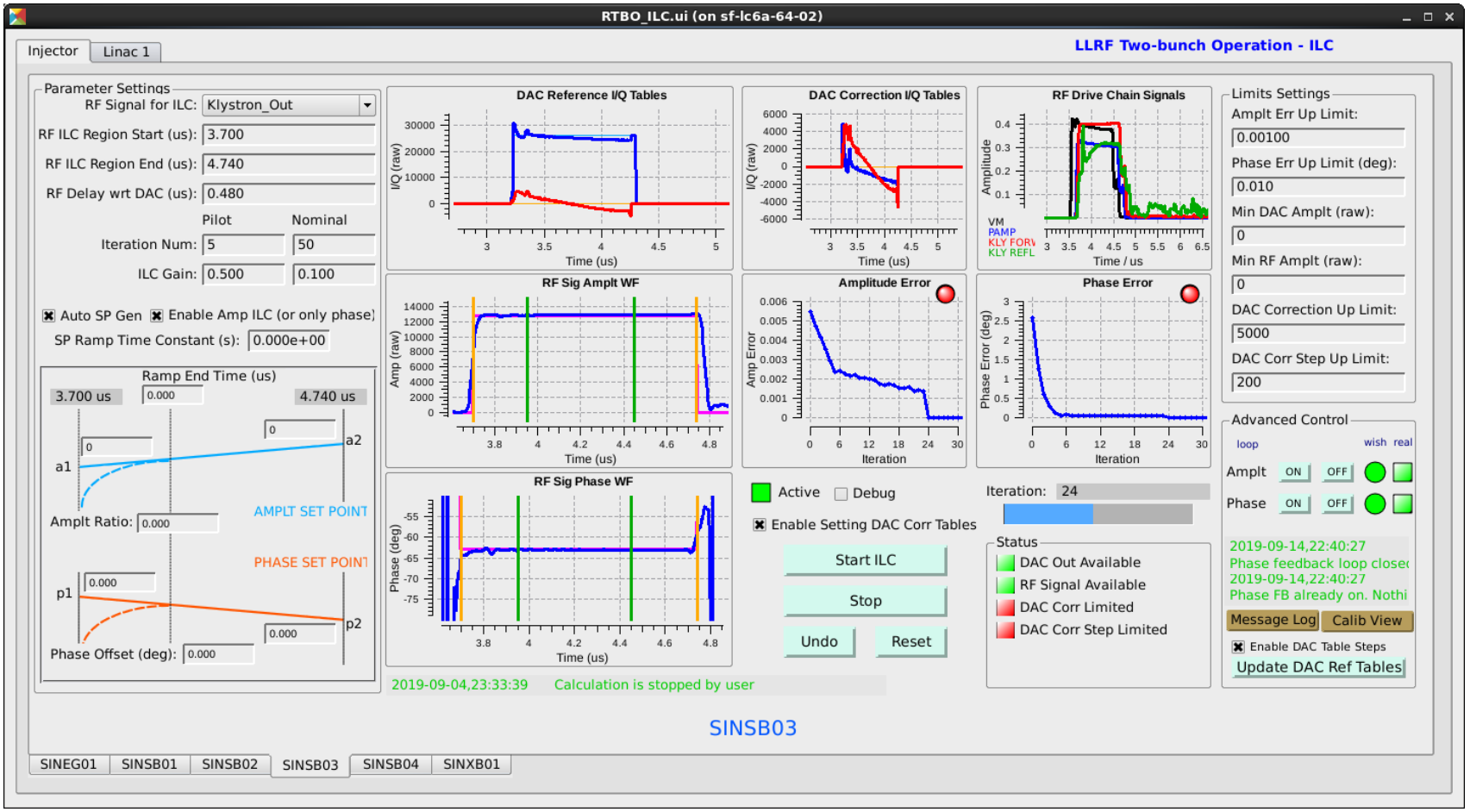
LLRF Knobs for two-bunch Tuning

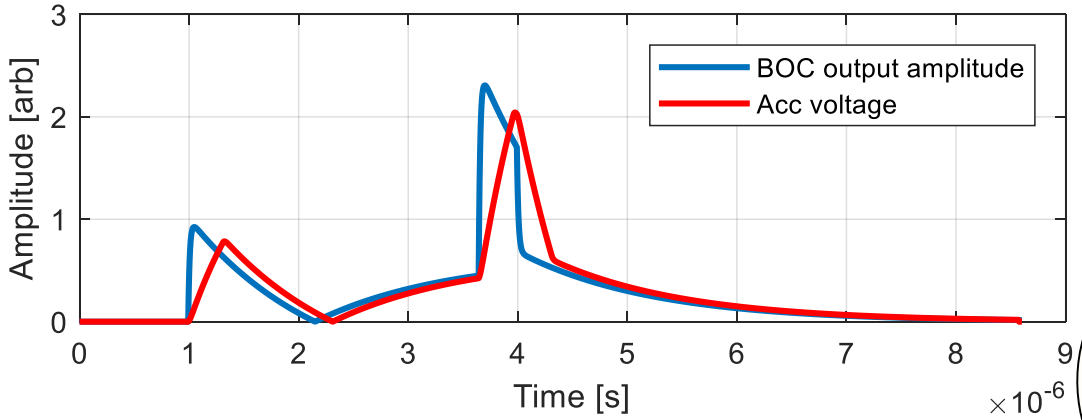
Knobs affecting both Bunches

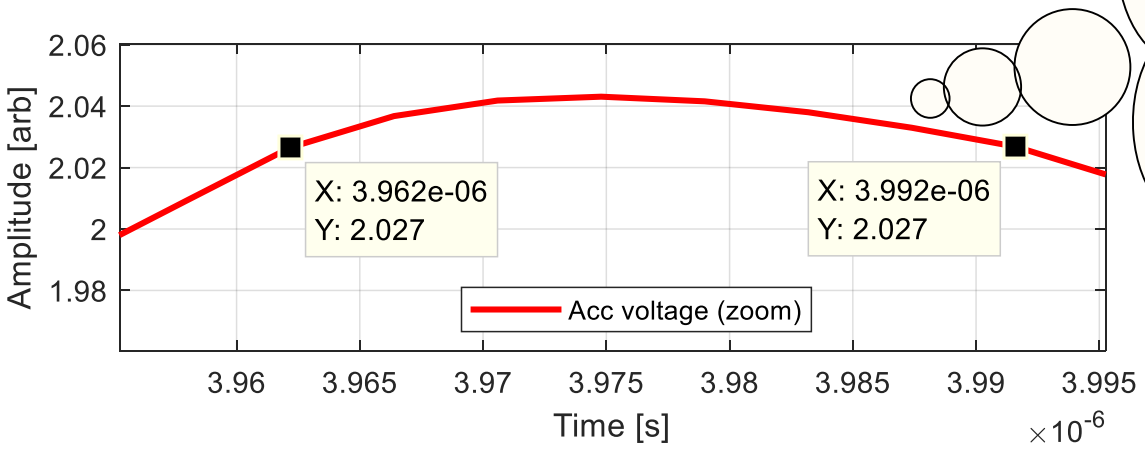
- **Iterative learning control**. Flatten the amplitude and phase within the RF pulse. Due to the limited tuning range for the second bunch, flattening the pulse is necessary to roughly equalize the amplitude and phase for both bunches.
  - Injector stations (S-band and X-band): flatten both amplitude and phase;
  - C-band stations in Linac1: flatten the phase (optional).



Knobs affecting both Bunches (cont.)

- **Delay adjustment for C-band**. After flattening the phase of C-band pulse, the delay of the pulse should be adjusted to roughly equalize the energy gain of both bunches.



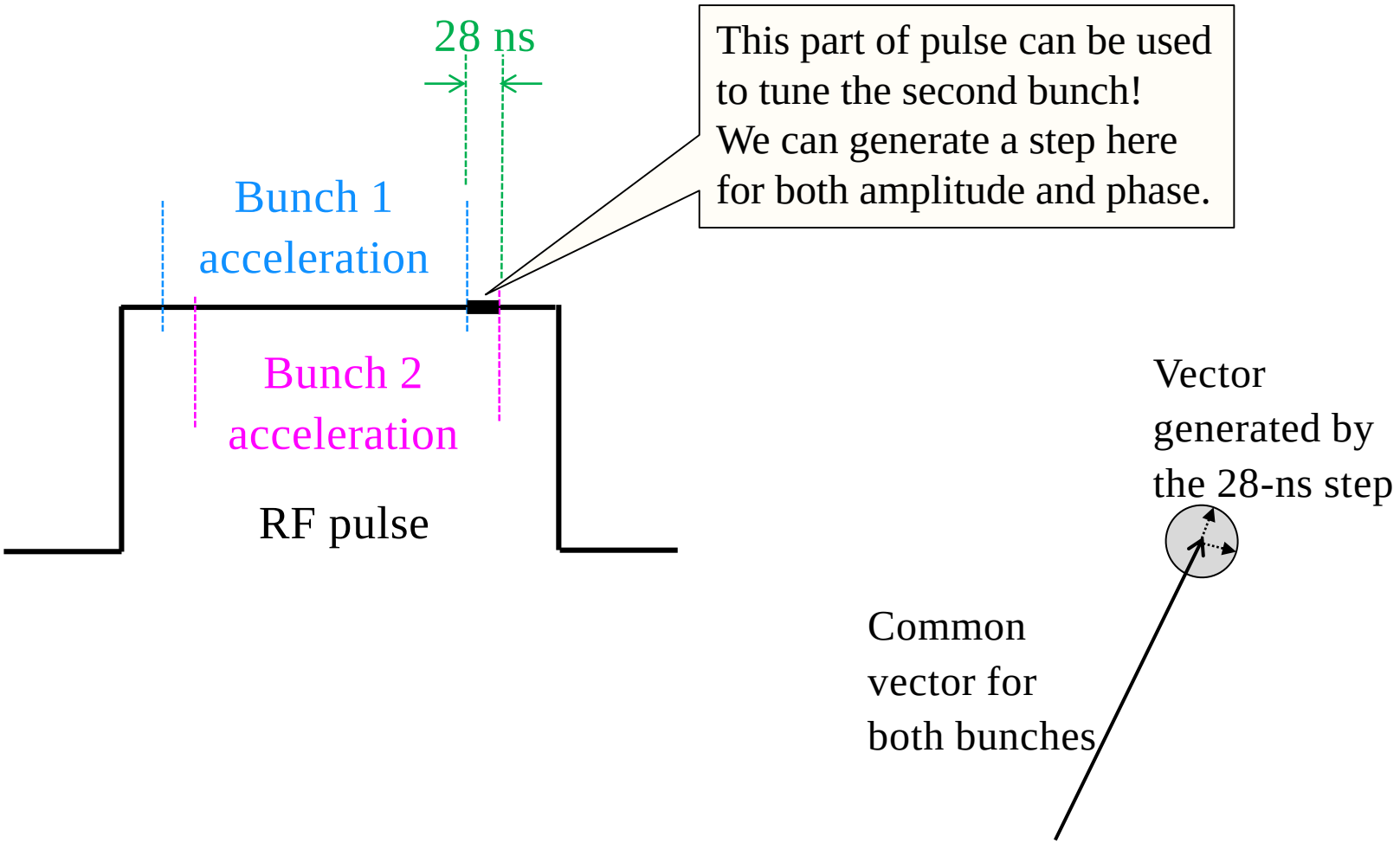


- Currently the single bunch is placed at the time with maximum acc. voltage.
- With two bunches, we lose slightly the energy gain!

Knobs tuning the second Bunch

The knobs to fine tune the second bunch after the first bunch is optimized:

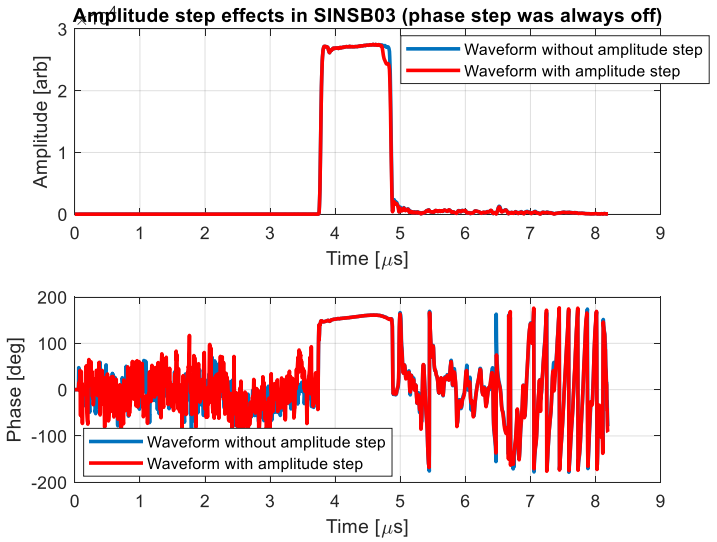
- **Amplitude and phase step in RF pulse**. The schematic.

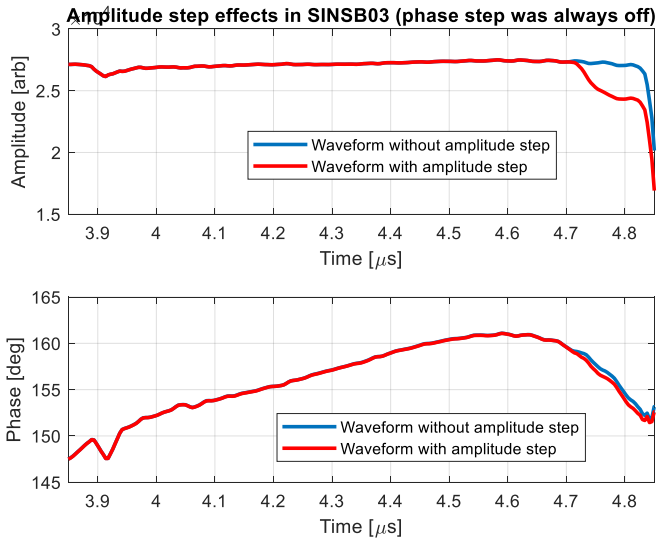


Knobs tuning the second Bunch (cont.)

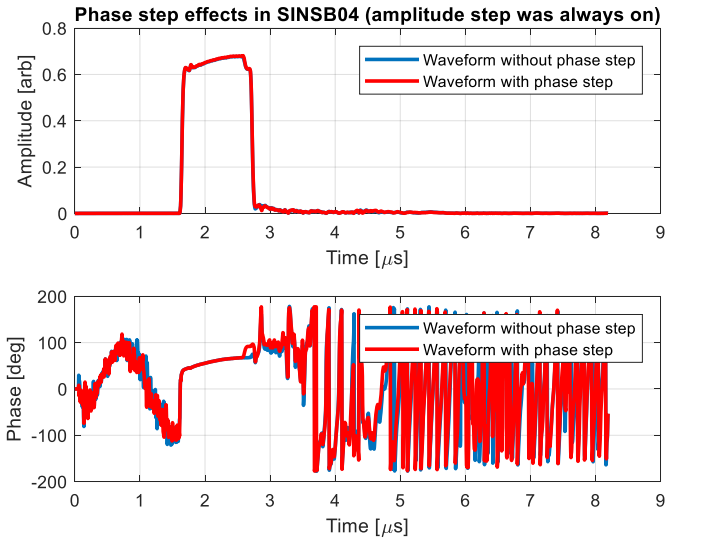
- **Amplitude and phase step in RF pulse.** Amplitude and phase step example.

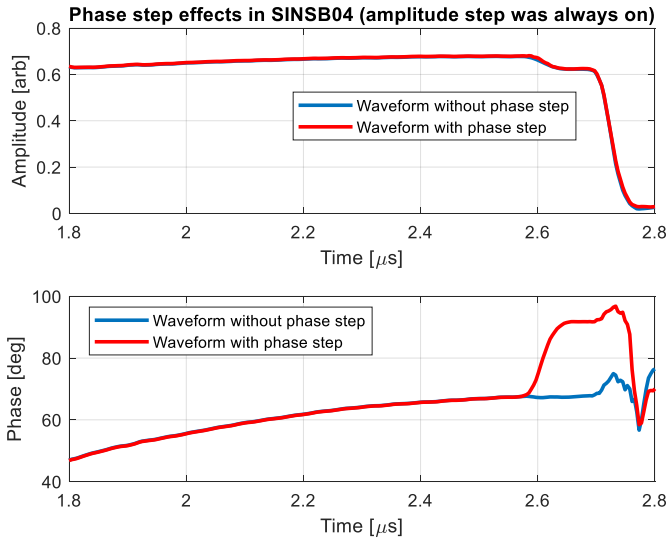
Only amplitude step





Only phase step





Knobs tuning the second Bunch (cont.)

- **Amplitude and phase step in RF pulse**. Tuning range.

Tuning range for step ratio 0 ~ 1.2 and step phase -30 ~ 30 degree:

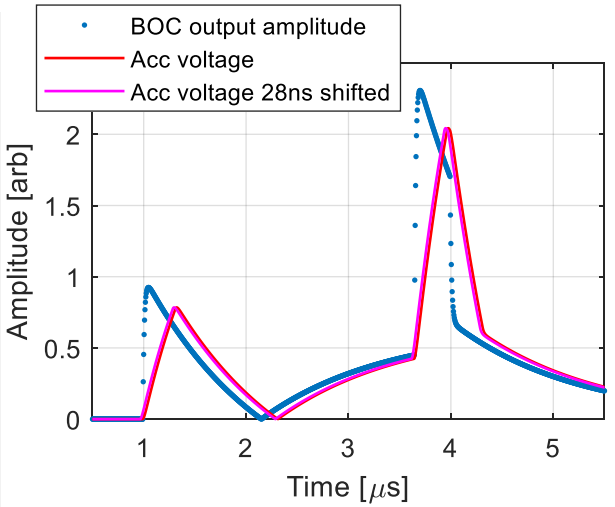
- Gun: **-2.5% ~ 1.5%** **±0.9 degree**
- S-band: **-1.0% ~ 0.5%** **±0.4 degree**
- C-band: **-10% ~ -5%** **±0.6 degree**
- X-band: **-25% ~ 5%** **±7.6 degree**

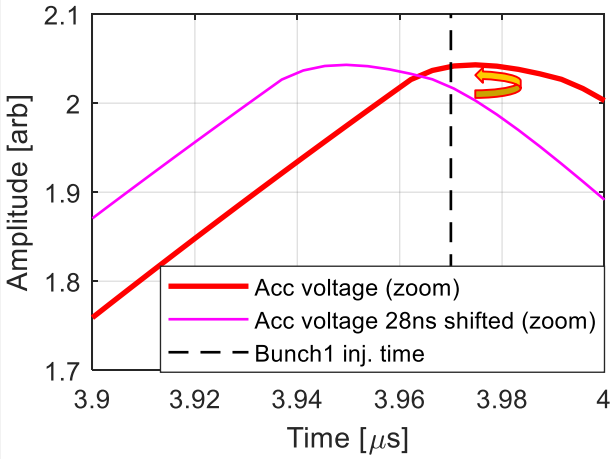
Numbers from simulation with cavity model.

RF Setup for second Bunch Transmission

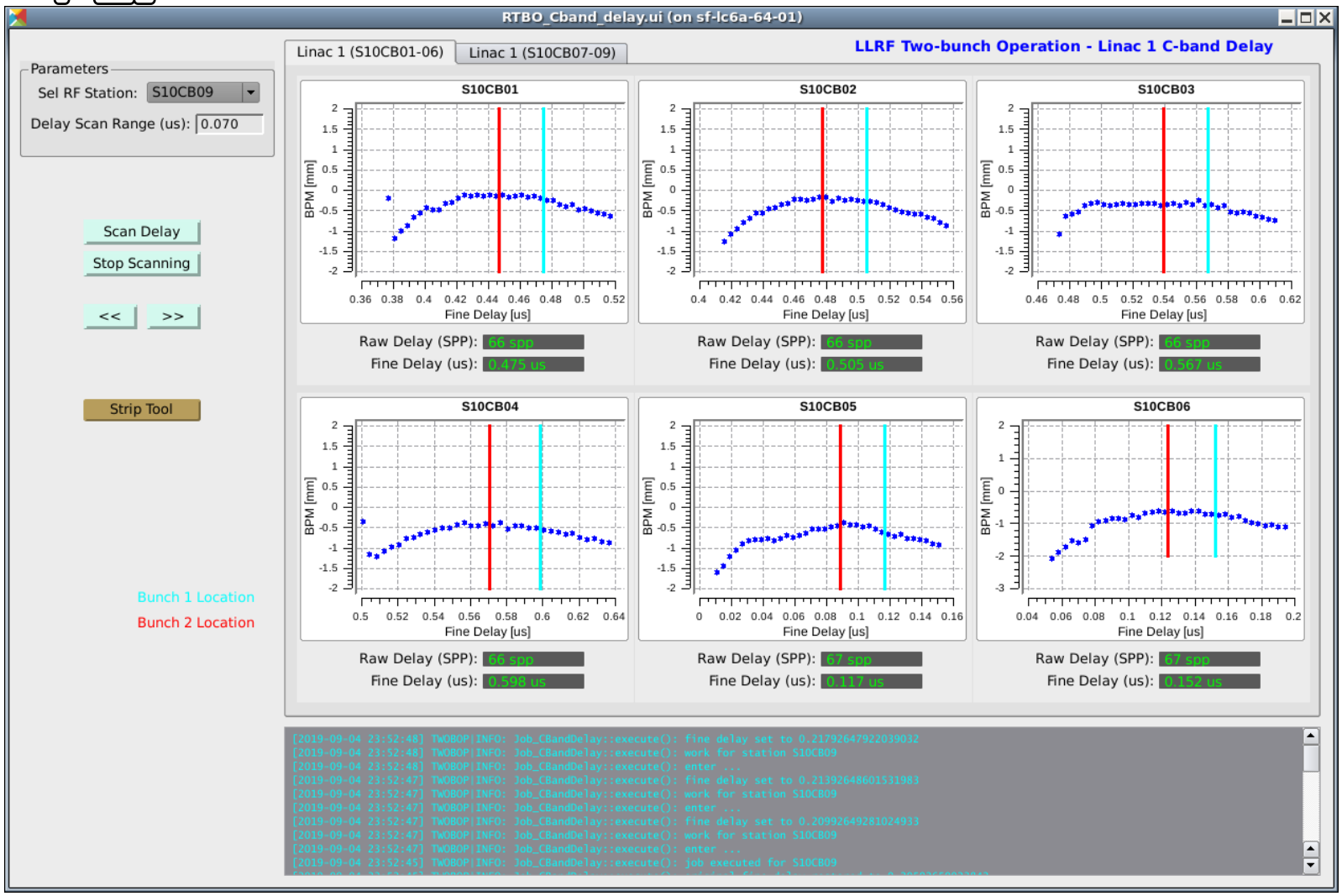
Overview of RF Setup for Bunch2 Transmission

- Before optimizing the bunch1 to lase in Aramis, the following settings should be performed in advance affecting both bunches:
  1. Flatten the RF pulse (S-band and X-band) with ILC;
  2. Optimize the delay of C-band stations to equalize the energy gain of both bunches;
  3. Identify the DAC step time so that the RF pulse step affects only bunch2.
- When initially switching on bunch2, it should be transmitted without loss with all settings optimized for bunch1 including the bunch compressors:
  4. The RF pulse steps should be predetermined before the bunch2 is available, so that bunch2 sees roughly the same RF field as bunch1.
     - Use bunch1 to do the initial setup by shifting the RF pulse timing.
- Procedure to predetermine the RF pulse steps without bunch2:
  - 4.1 Remember the beam diagnostic results of bunch1 (e.g. bunch arrival time at laser heater, beam energy/compression at BC1/BC2).
  - 4.2 Shift the RF pulse timing earlier by 28 ns (**with ±4 ns error**), so that bunch1 feels the RF field supposed for bunch2 acceleration.
  - 4.3 Tune the RF pulse steps to restore the bunch1 diagnostic results. This tunes the RF field supposed for bunch2 the same as for bunch1.
  - 4.4 Restore the RF pulse timing. Switch on bunch2 and tune the bunch2 gun laser delay to achieve best transmission.



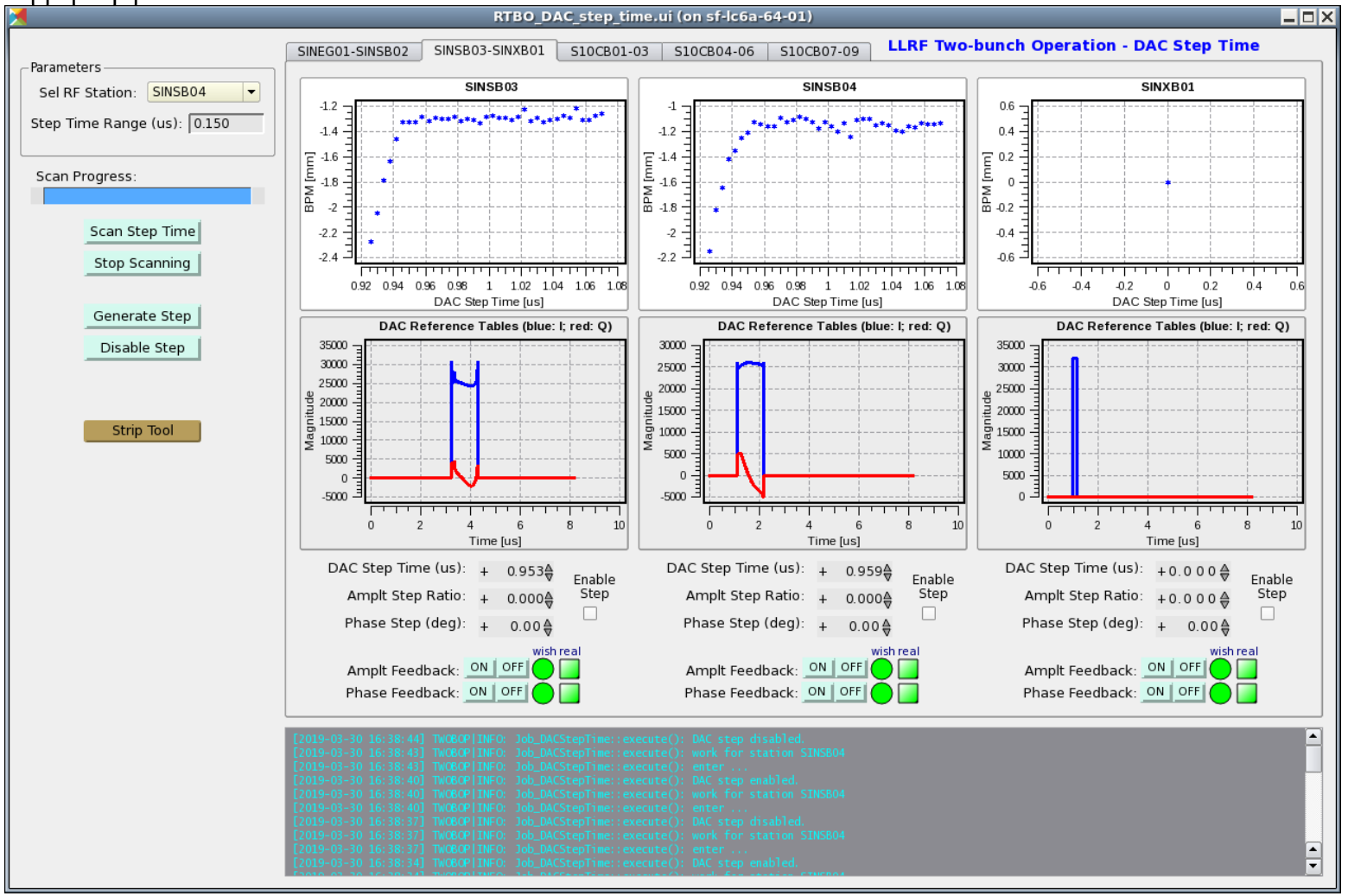


2. C-band Delay Adjustment



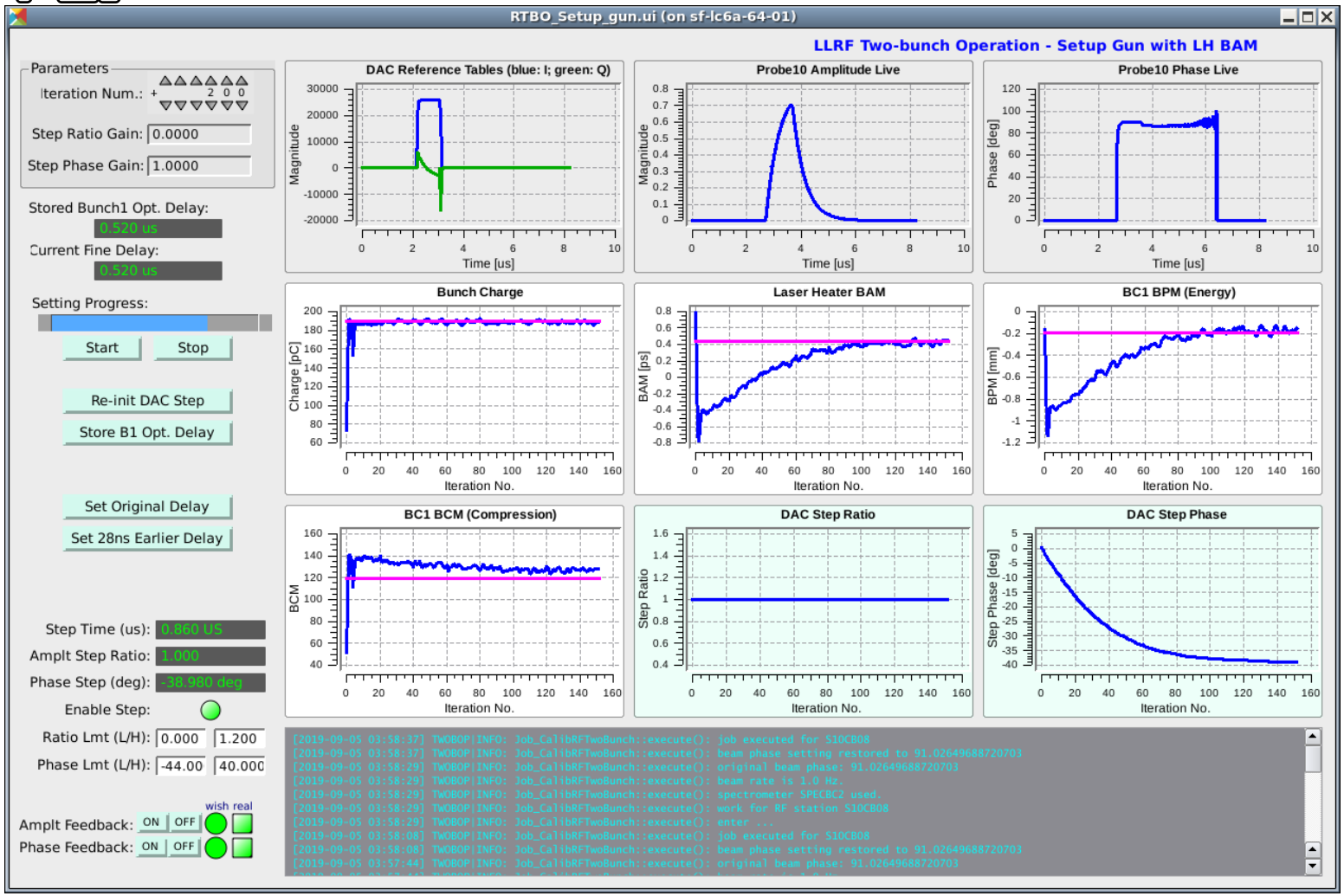
- Scan the delay (resolution 4 ns) of Linac1 C-band stations and correlate with the beam energy;
- Determine the delay of each RF station so that both bunches get the same energy gain (better slightly larger for bunch2 to provide headroom for step tuning).

3. DAC Step Time Calibration



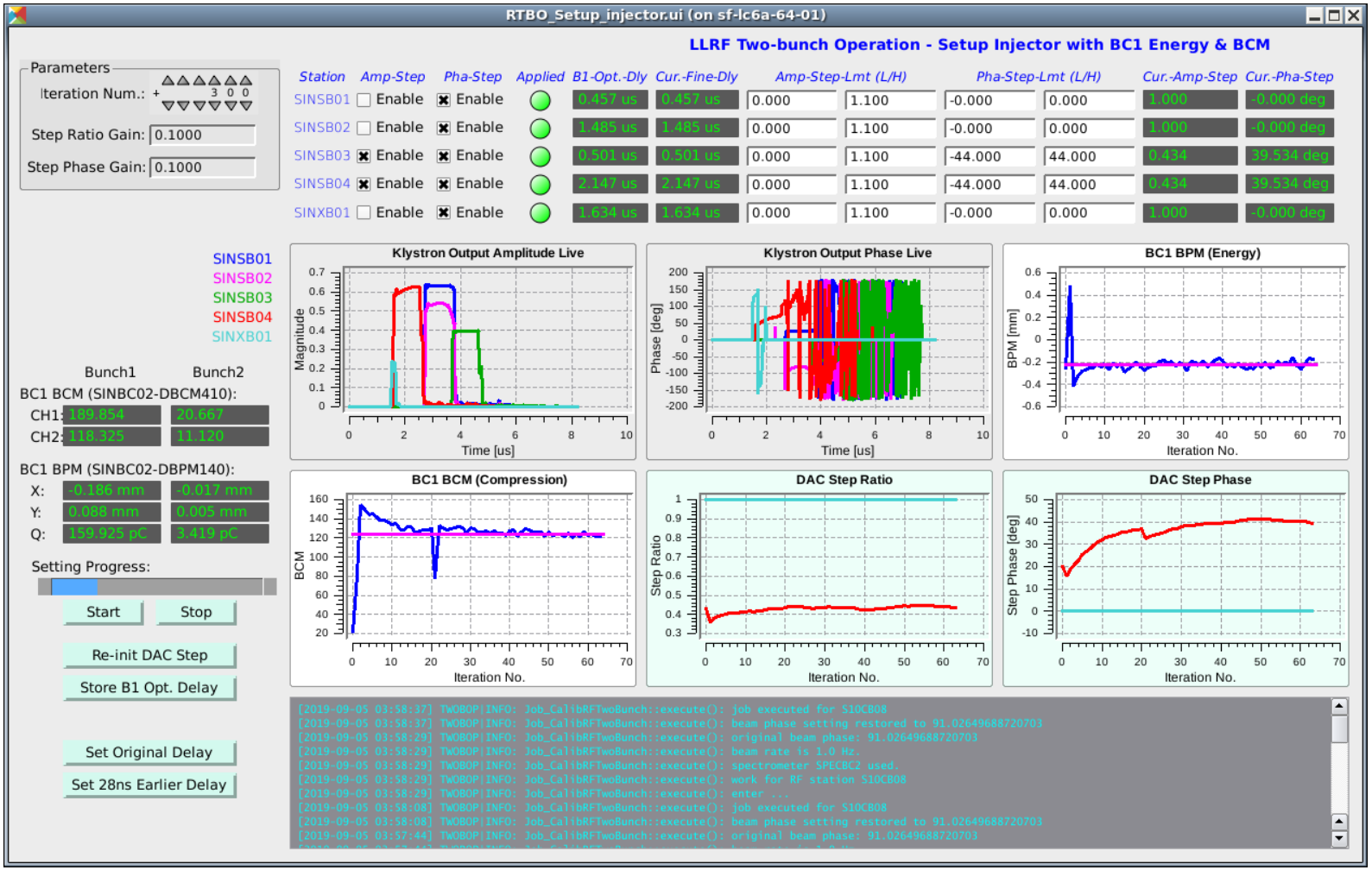
- Shorten the RF pulse in steps with a resolution of DAC clock cycle (4 ns) and correlate with the beam energy of the first bunch.
- This helps to find the DAC step boundary not affecting bunch1 but with maximum influence to bunch2. Usually needs a manual fine tuning to be sure the first bunch is not disturbed by the step.

4.3 Gun Setup with Bunch1 by shifting RF Delay



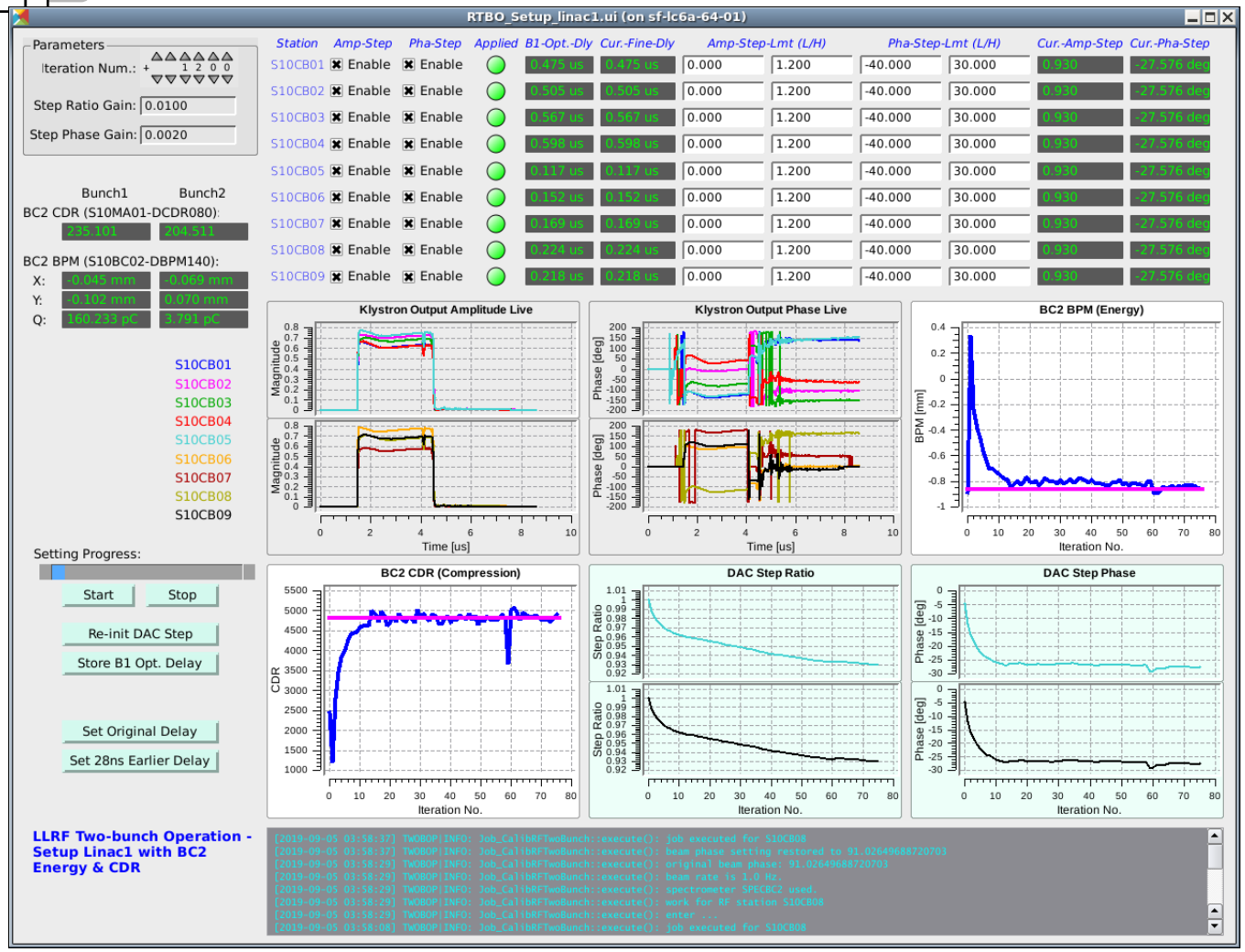
- After shifting the RF delay earlier by 28 ns, the **step phase** is optimized iteratively to restore the laser heater bunch1 arrival time. This equalizes the gun RF phase felt by both bunches.
- The step ratio is not changed – the two bunches may get slightly different acceleration voltages! Need improvement!

4.3 Injector Setup with Bunch1 by shifting RF Delay



- After shifting the RF delay earlier by 28 ns, the **step ratio and phase** are optimized iteratively to restore the bunch1 energy and compression at BC1. This equalizes the injector acceleration voltage and phase felt by both bunches.
- Tuning with two independent integral feedback loops: step ratio => energy; step phase => compression.

4.3 Linac1 Setup with Bunch1 by shifting RF Delay

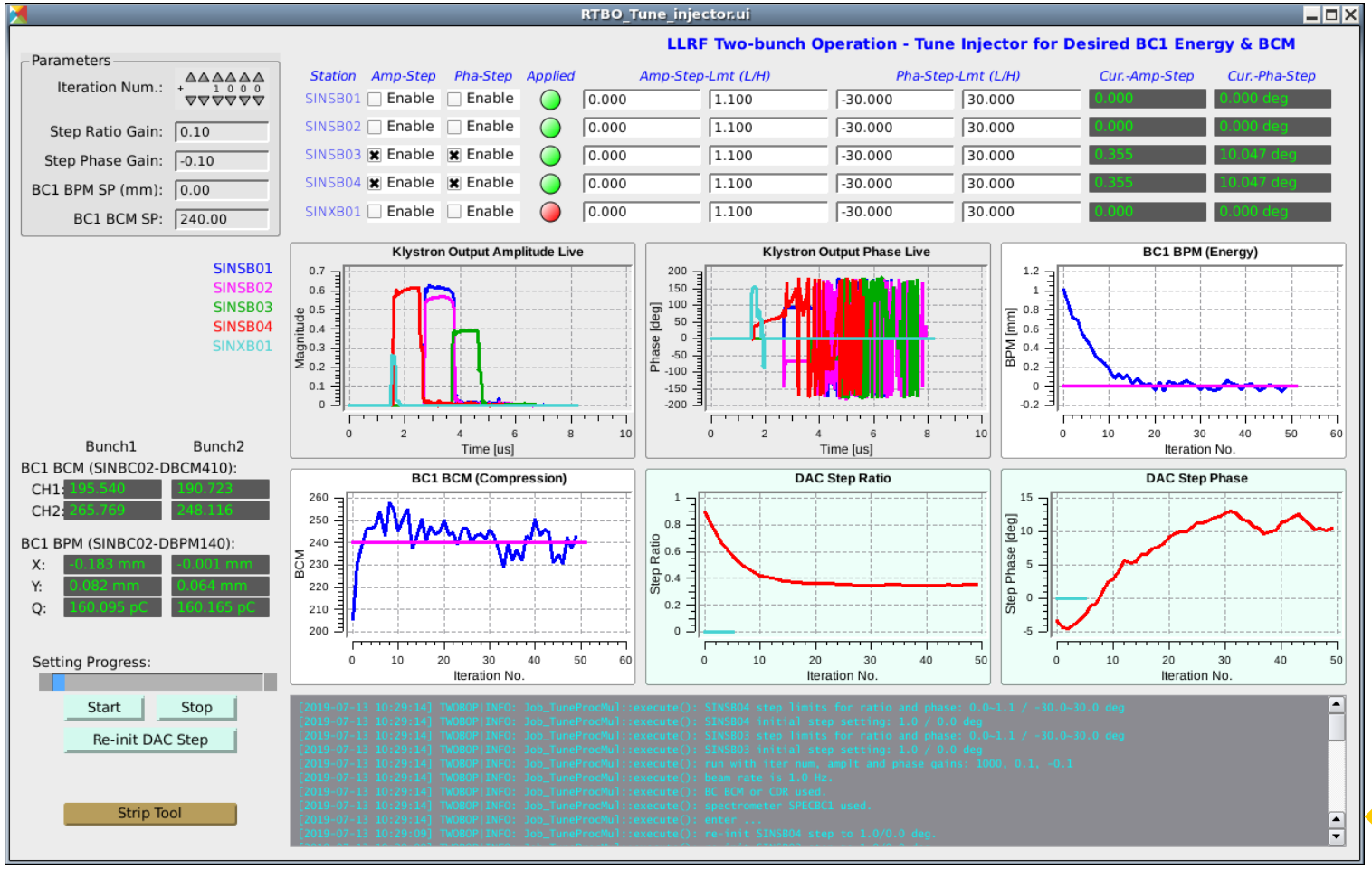


- After shifting the RF delay earlier by 28 ns, the **step ratio and phase** are optimized iteratively to restore the bunch1 energy and compression at BC2. This equalizes the Linac1 acceleration voltage and phase felt by both bunches.
- Tuning with two independent integral feedback loops: step ratio => energy; step phase => compression.

Regulation of the second Bunch

Overview of Bunch2 Regulation

- After successfully transmitted, the fine tuning of bunch2 can refer to its diagnostics.
- The algorithm is similar as the one used for the initial setup described before: implement independent or coupled (MIMO) feedback loops to regulate the beam parameters by acting on the RF pulse step ratio and phase.



Achieve desired BC1 bunch2 energy and compression by actuating on the RF pulse steps of the S-band stations.

Summary and Outlook

- Intensive study and test have been carried out to reach a solution for two-bunch operation for the RF system:
  - Initial RF setup for a successful transmission of bunch2;
    Run since April 2019 with two-bunch RF waveforms.
  - Fine tuning tool of bunch2 with the bunch2 diagnostics.

- The RF gun initial setup procedure together with the laser timing optimization of **two** laser systems is still not optimal and requires more iterations to define a robust procedure.
- More experience will be collected when optimizing the second bunch in the future and the LLRF tools will be improved continuously.
  - Establish permanent two-bunch operation as soon the Athos beamline installation is ready.


Thank you for your attention!
SINQ

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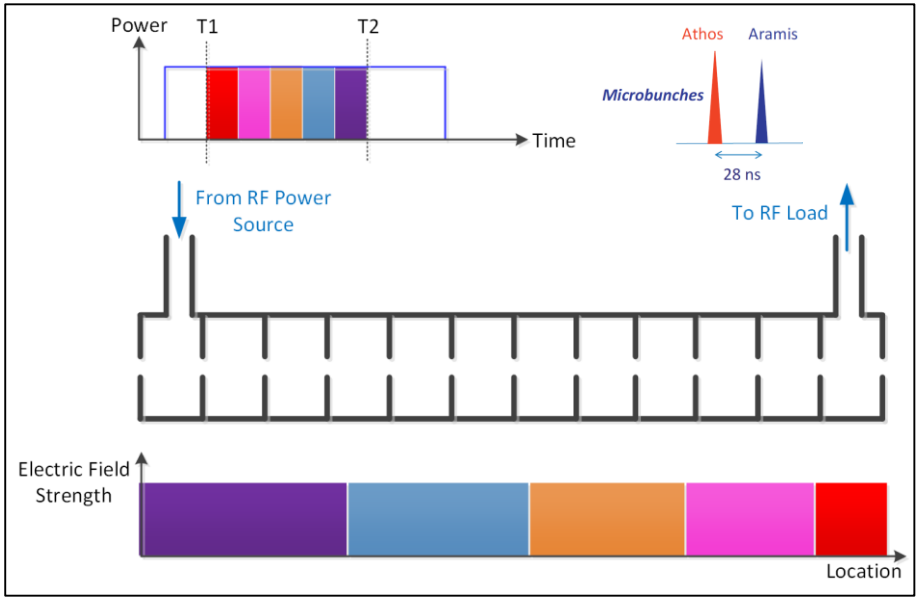
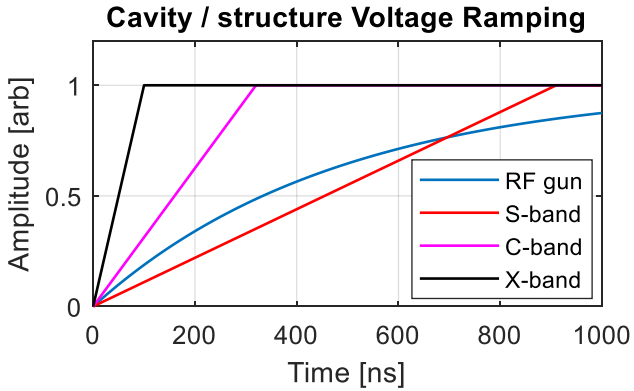
Backup Slides

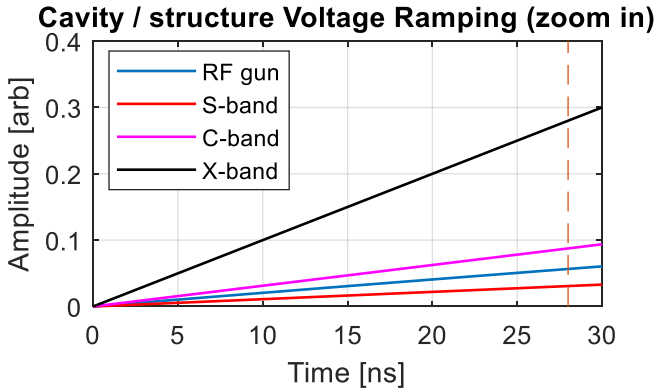
Accelerate two Bunches in a RF Pulse

SwissFEL RF system parameters:

Cavity / Structure	Frequency (MHz)	Time Constant or Filling Time (ns)
RF Gun Cavity	2998.8	480
S-band Structure	2998.8	910
C-band Structure	5712	320
X-band Structure	11995.2	100





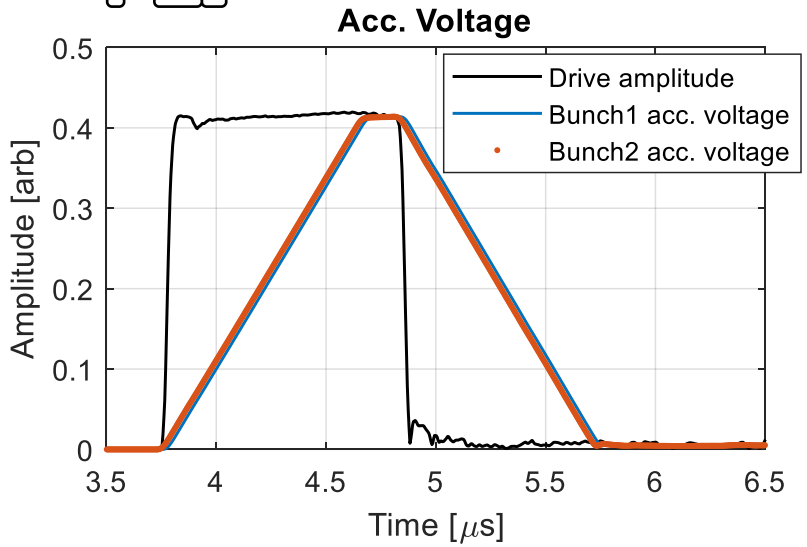


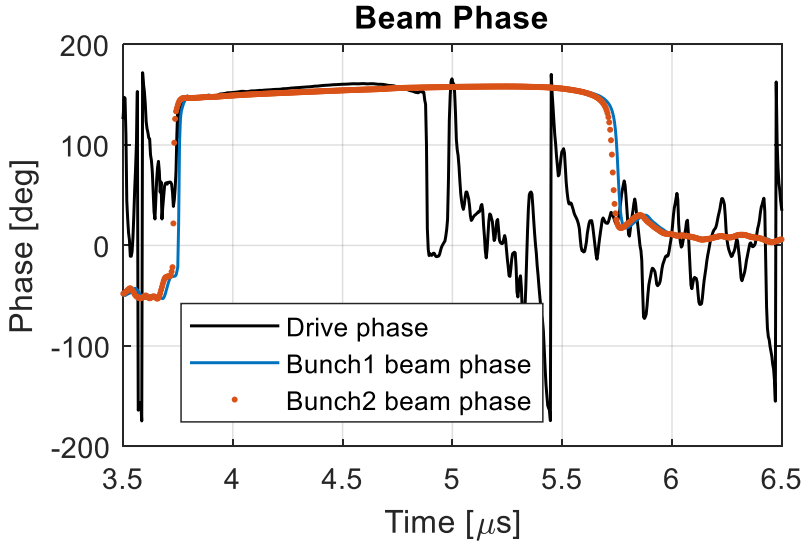
Amplitude and phase changes in 28 ns:

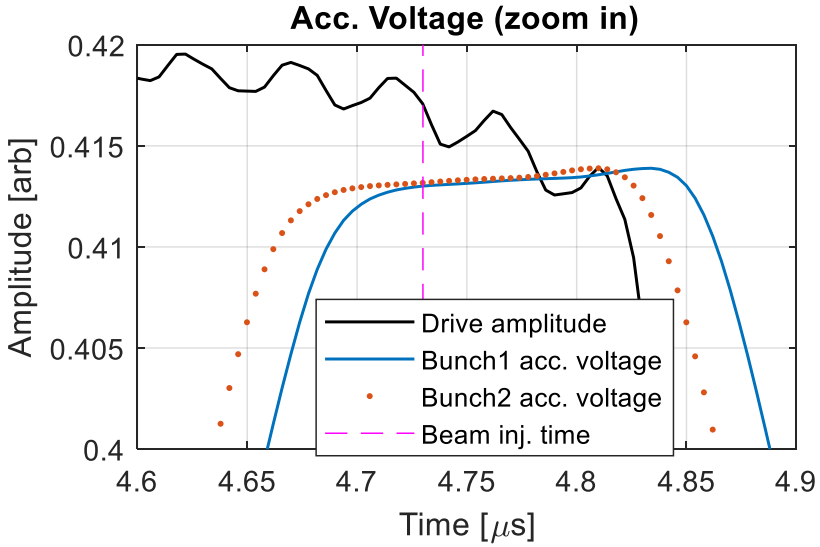
- Gun: 5.6 %, 3.2 degS
- S-band: 3.1 %, 1.8 degS
- C-band: 8.7 %, 5.0 degC
- X-band: 28 %, 16 degX

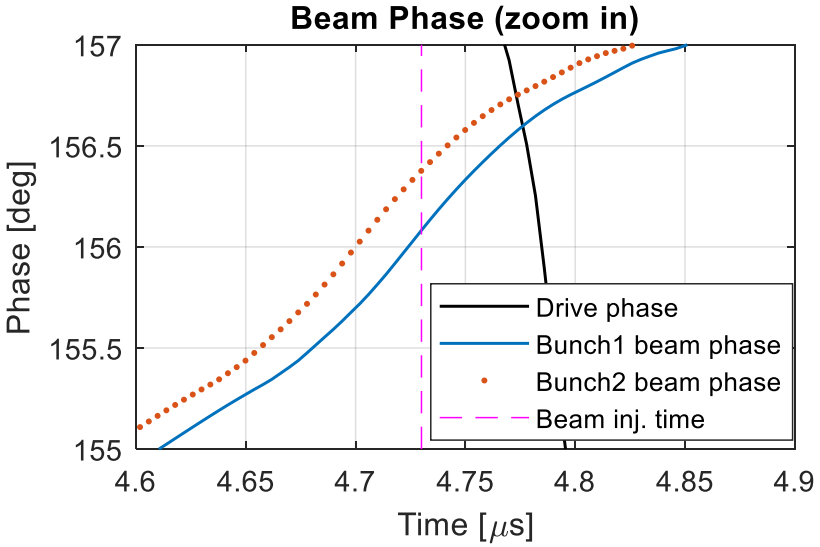
- Tune the second bunch with the 28 ns RF pulse after bunch1 is possible.
- Practically, the tuning range is much smaller!

RF Field Difference for two Bunches: S-band



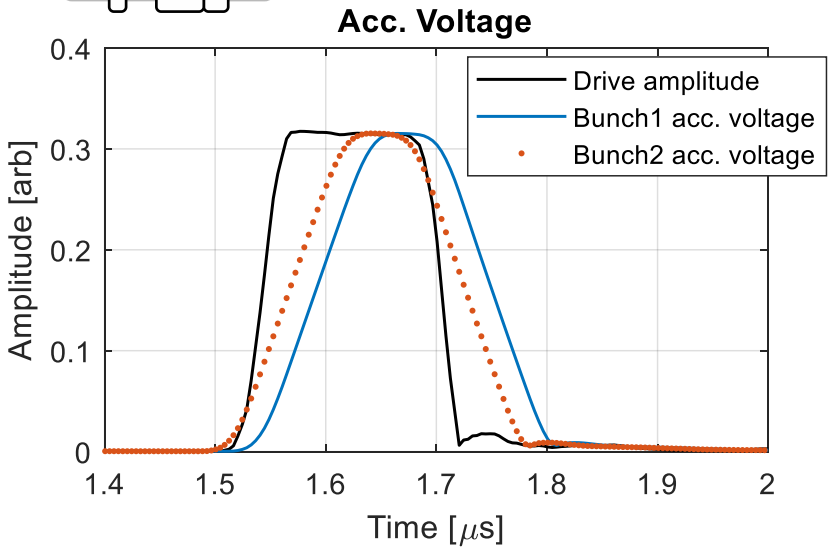


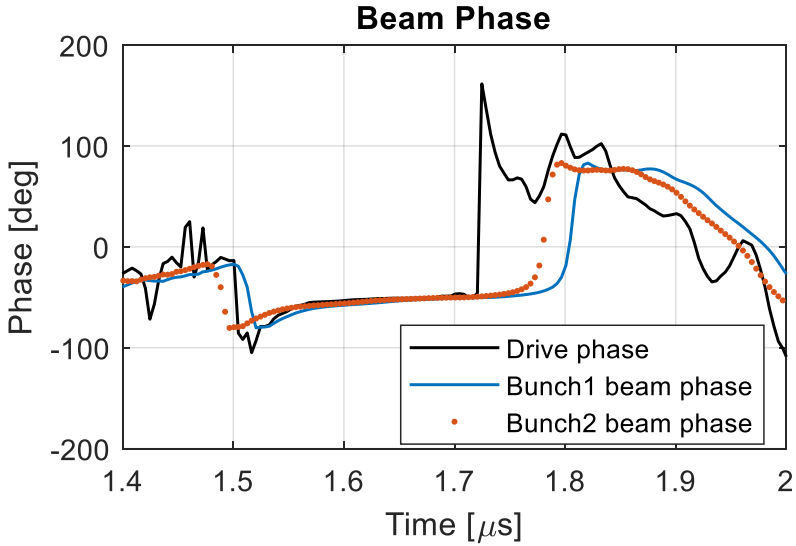


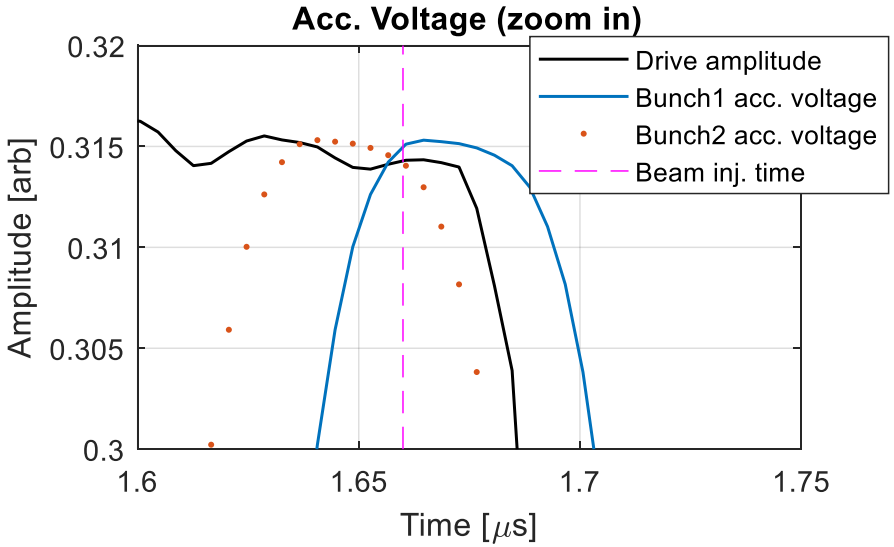


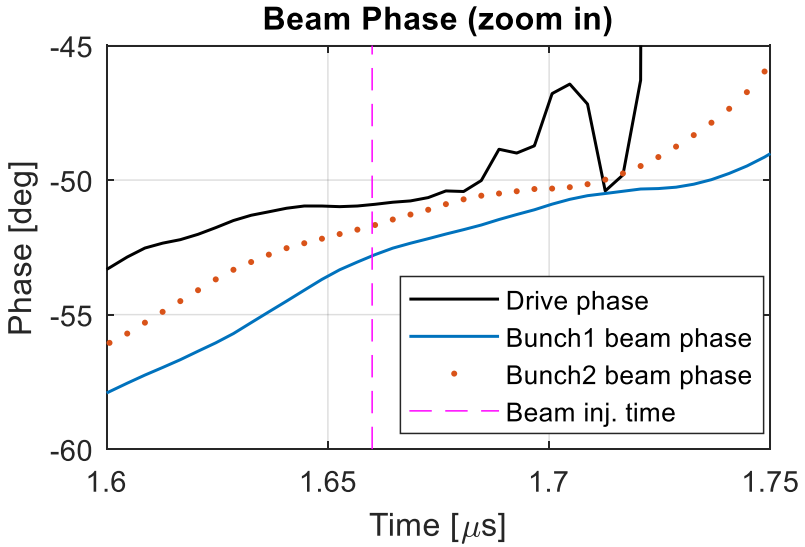
- Around current working point of injector S-band stations, the amplitude and phase differences for the two bunches are about **0.03 %** and **0.3 degree**.

RF Field Difference for two Bunches: X-band



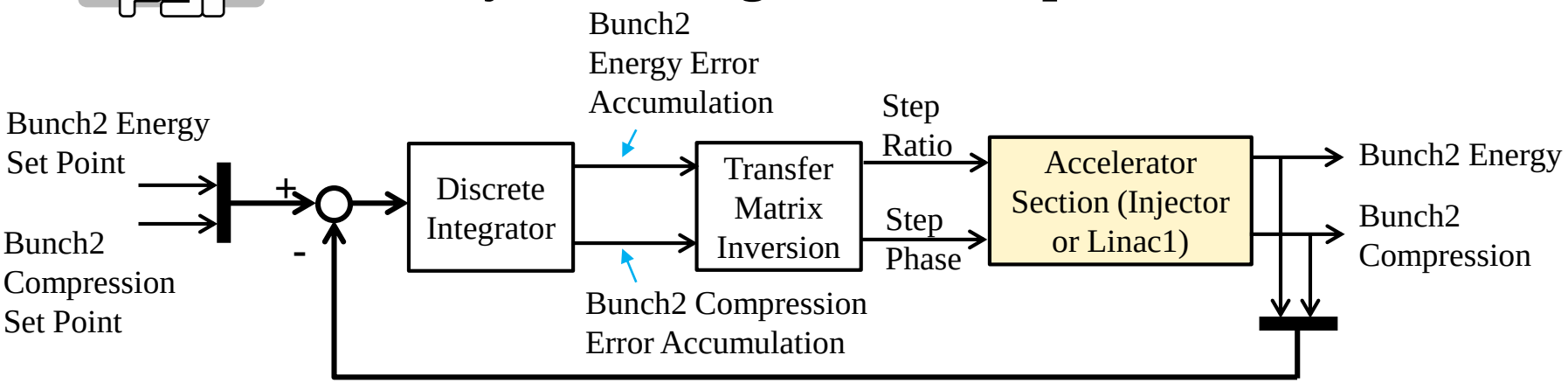




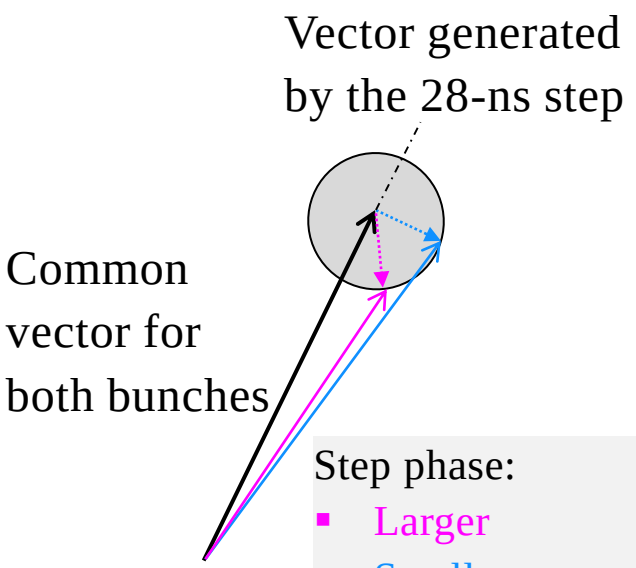


- Around current working point of SINXB01, the amplitude and phase differences between the two bunches are about **0.4 %** and **1.1 degree**.

Stability of the Regulation Loop



- In the current implementation, the "Transfer Matrix Inversion" was assigned to 1. We have assumed the step ratio dominates the bunch2 energy while the step phase dominates the bunch2 compression. **Not always true!** A real transfer matrix will be measured.
- The RF pulse step phase should not be larger than 90 degree, or the transfer relation between step phase to beam parameter flips its sign – the loop becomes unstable.
- Practically, the step phase should not be over around 40 degree. A large phase jump results in a high frequency transient that may trigger reflection interlocks.



Step phase:
- Larger
- Smaller

Overall phase change:
- Larger
- Smaller