Zheqiao Geng :: LLRF Group :: RF Section

LLRF Tools for Two-bunch Operation

Athos workshop, Windisch, 01.02.2019

Outline

- User Requirements
- LLRF Knobs for Two-bunch Tuning
- Beam based Setting Procedures for Two-bunch Operation
- R&D and Test Plans

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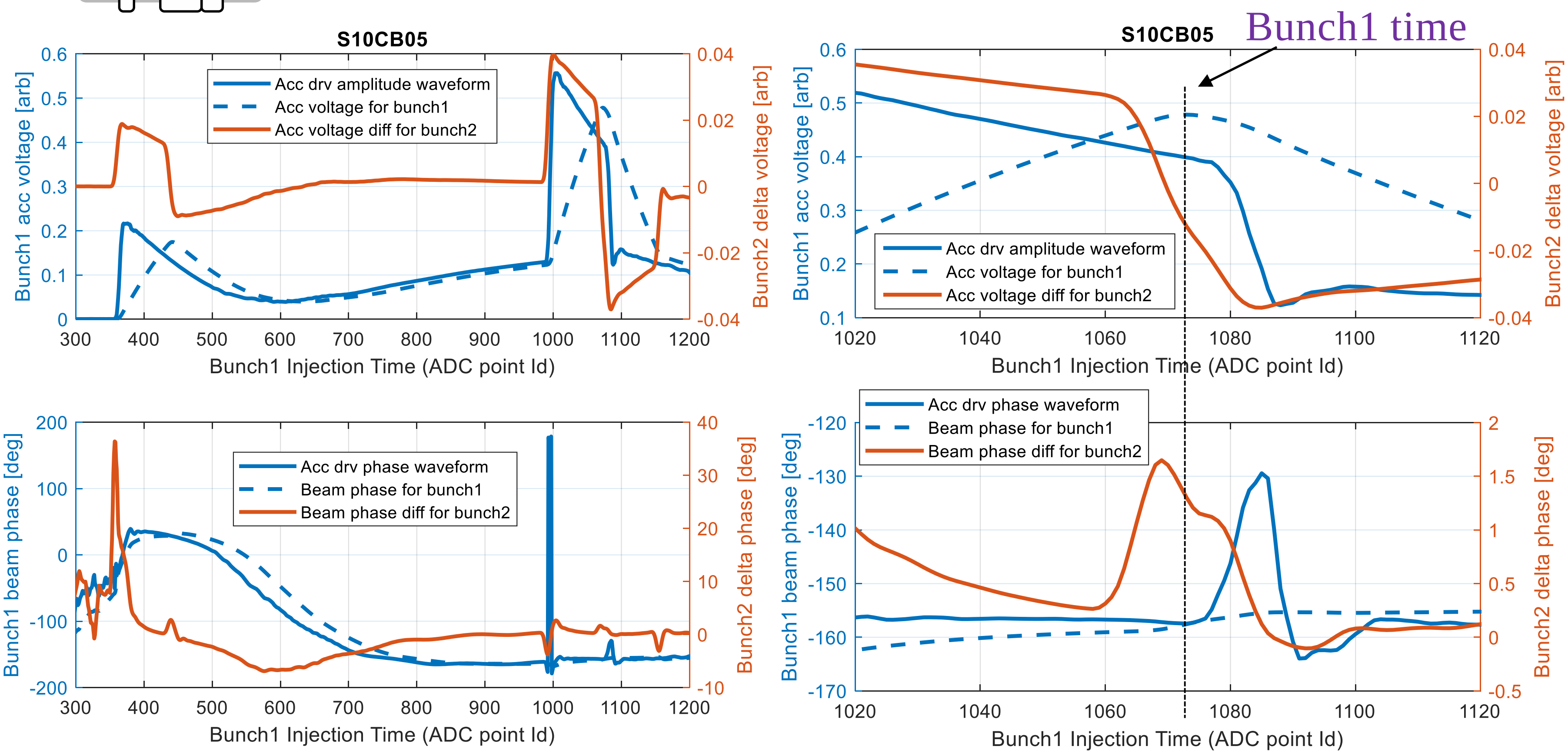
User Requirements

Amplitude and Phase Diff. for two Bunches



- If delaying the RF pulse by 3~4 clock cycles (12~16 ns) with respect to the beam, the two bunches will see the same accelerating voltage but with larger phase difference.
- Around the current working points, the amplitude and phase differences between bunch 1 and bunch 2 are

Gun:	**1.0 %**	**0.4 degree**
S-band:	**0.3 %**	**0.7 degree**
C-band:	**2.7 %**	**1.3 degree**
X-band:	**1.6 %**	**1.6 degree**

User Requirements

Requirements to LLRF interfaces:

- ❑ Adjust the RF amplitude and phase for the second bunch without affecting the first bunch. Furthermore, set the exact amplitude and phase (or delta values compared to the first bunch) for the second bunch without affecting the first bunch.
  - *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 or by beam-based feedback specifically for the second bunch*
- ❑ Adjust the RF amplitude and phase for the first bunch without affecting the second bunch.
  - *Scenario 1: Calibrate beam diagnostics for the second bunch*
- ❑ Measure the RF amplitudes and phases seen by both bunches.
  - *Scenario 1: Calibrate beam diagnostics for the second bunch*
  - *Scenario 2: Study RF-beam jitter correlations*

Legend of text colors:

Achievable; Achievable but not exact; Almost not possible

Proposed interfaces:

Bunch 1 RF Set Points		Bunch 2 RF Set Points	
Acc. Voltage (MV):		Delta Voltage (MV):	
Beam Phase (deg):		Delta Phase (deg):	

- Bunch 1 RF amplitude and phase changes will be applied to the entire RF pulse and affect both bunches (e.g. BBFB corrects the drifts common for both bunches).
- The bunch 2 is fine tuned by adjusting the RF field difference with respect to bunch 1.

User Requirements (cont.)

Procedures for two-bunch setup and regulation:

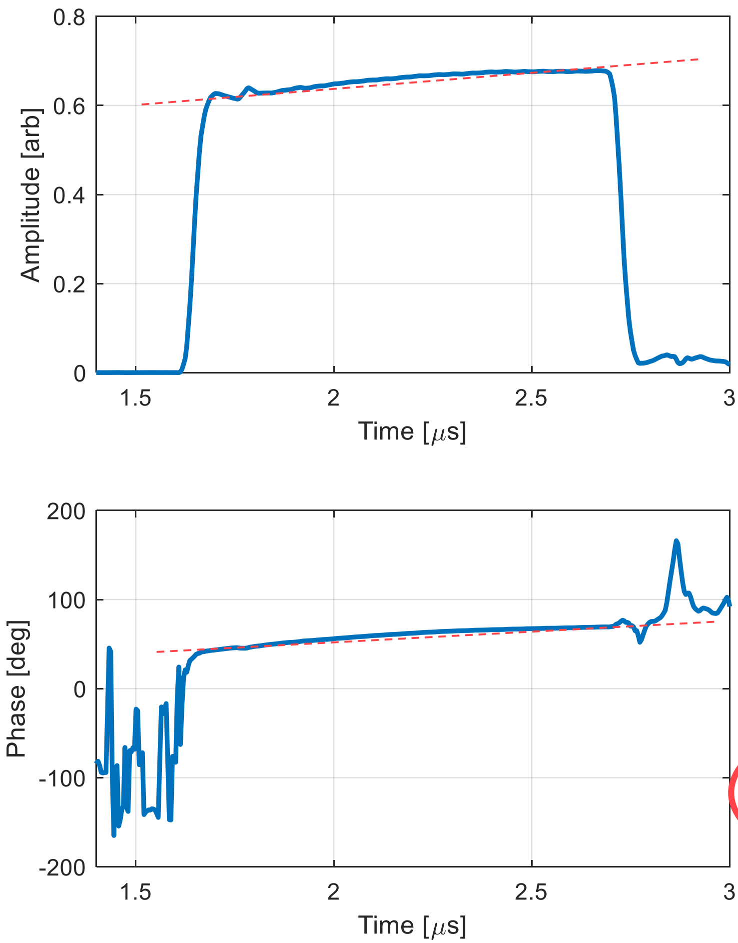
- Setup Gun RF fields for two bunches with the same (or with specified offset) bunch energy and arrival time at Gun exit.
- Setup injector RF station fields for two bunches with the same (or with specified offset) bunch energy, arrival time and compression at BC1 exit.
- Setup Linac1 RF station fields for two bunches with the same (or with specified offset) bunch energy, arrival time and compression at BC2 exit.
- *Calibrate the accelerating voltage and beam phase for both bunches – two-bunch phasing.*
- *Beam based feedback for the second bunch.*

LLRF Knobs for Two-bunch Tuning

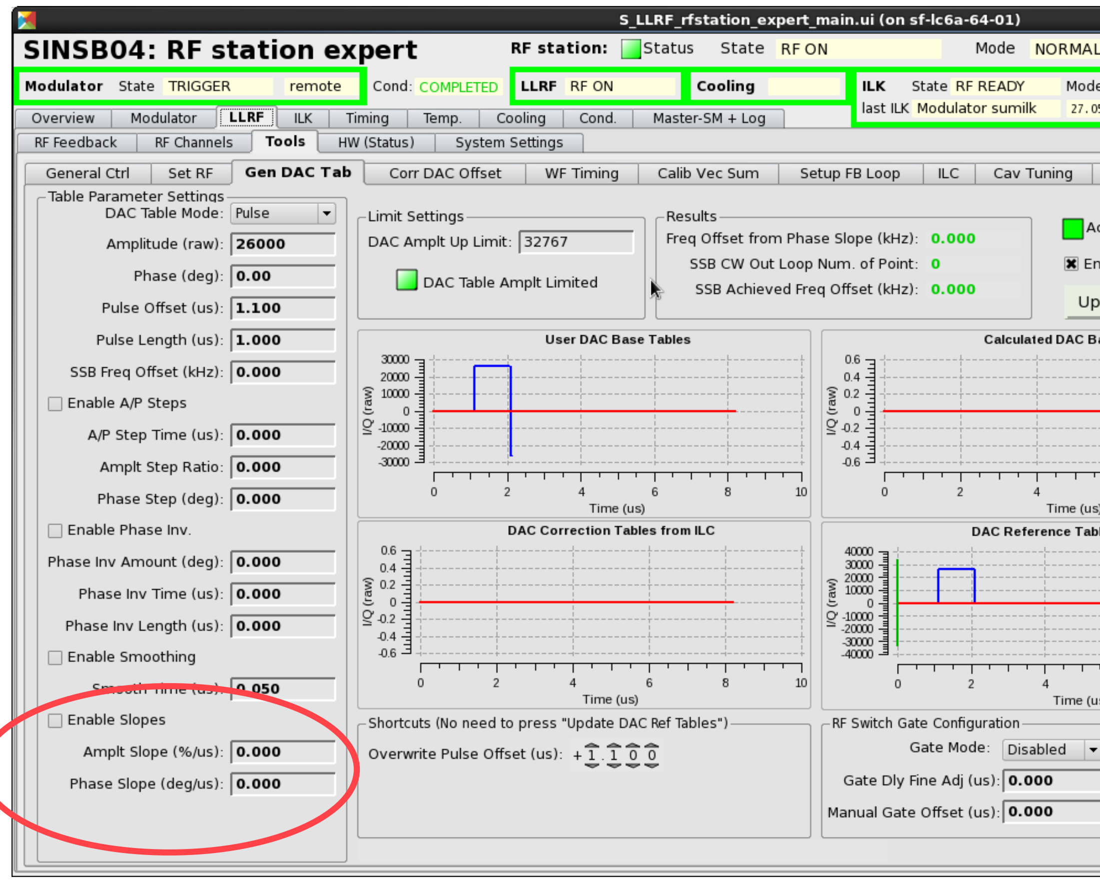
Knobs Affecting both Bunches

The knobs to shape the RF pulse before optimizing the first bunch:

- ❑ **RF pulse slopes in amplitude and phase**. Used when there is a clear slope in the amplitude or phase waveform of the RF pulse.



Waveforms of SINSB04

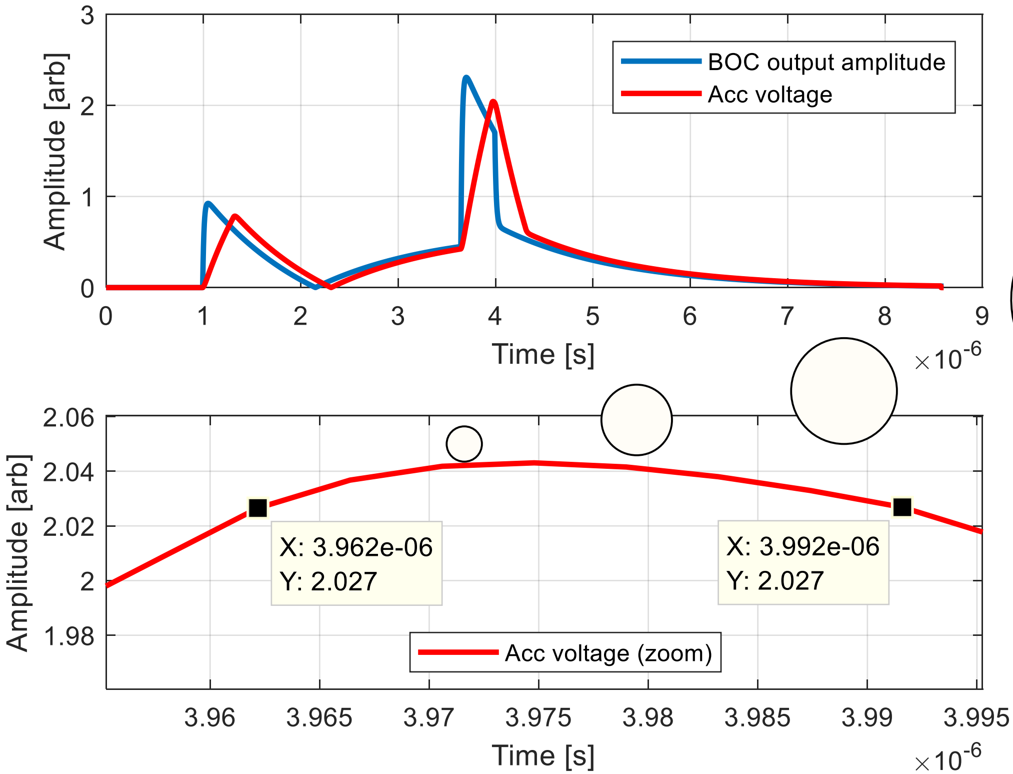


Knobs Affecting both Bunches (cont.)

- **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 (SINSB01-04 and SINXB01): flatten both amplitude and phase
  - C-band stations (S10CB01-09): flatten the phase

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.

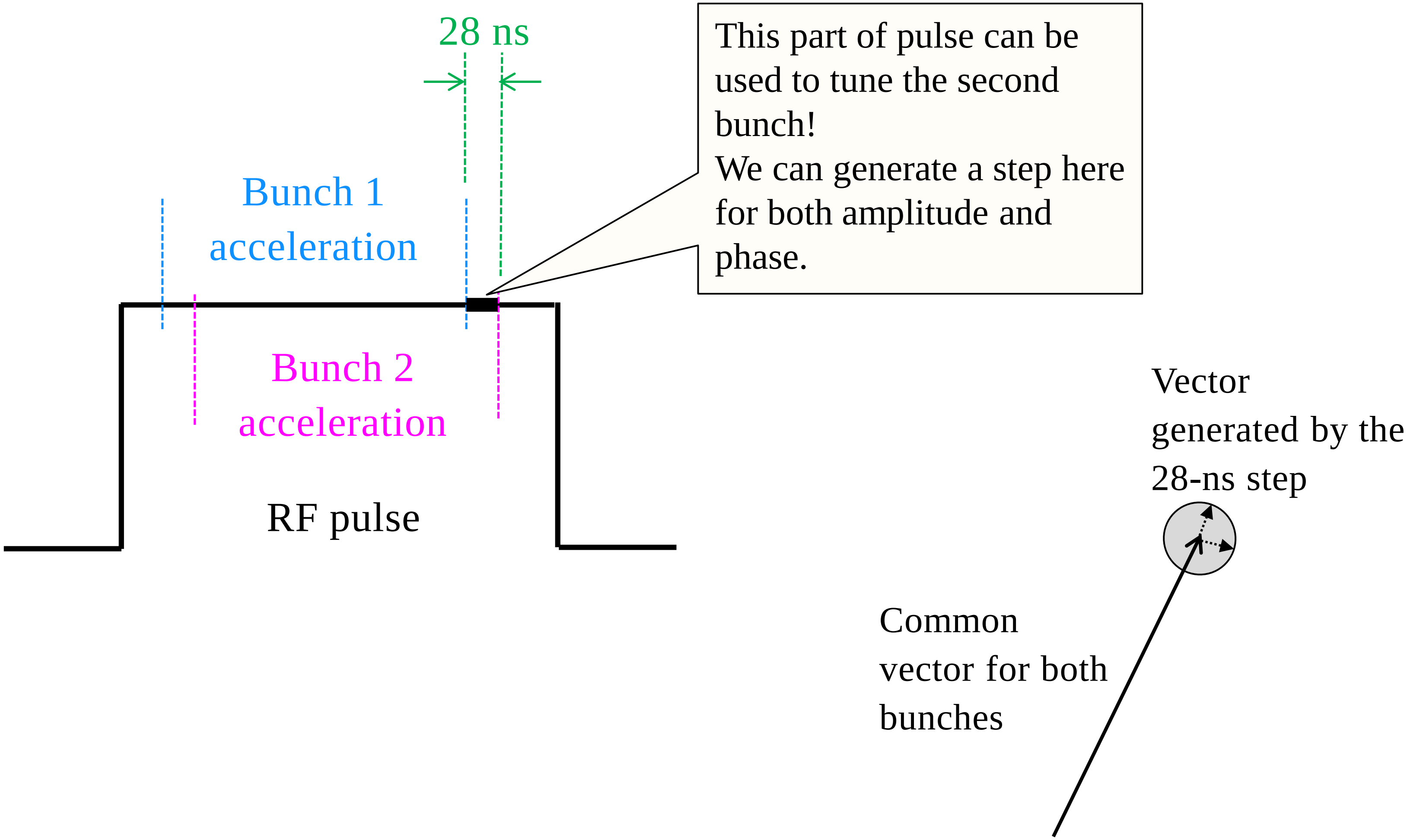


- Currently the single bunch is placed at the time with maximum acc. voltage.
- With two bunches, we lose slightly the energy gain!

Knobs Tuning the Second Bunch

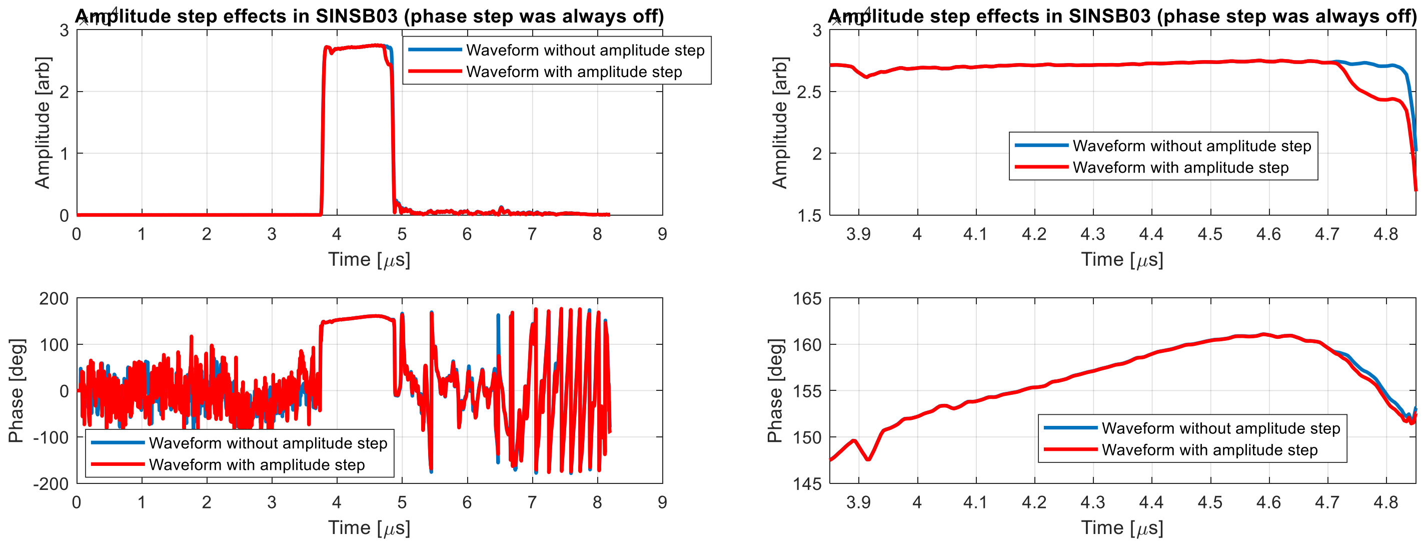
The knobs to fine tune the second bunch after the first bunch is optimized:

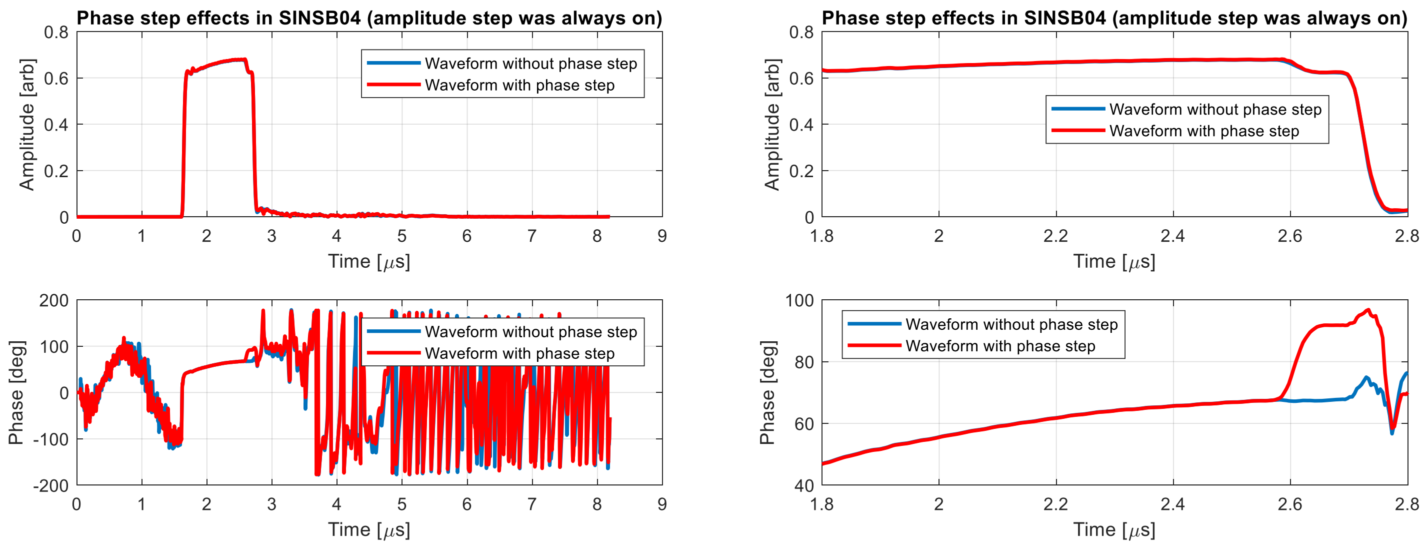
- ❑ **Amplitude and phase step in RF pulse**. The schematic.



Knobs Tuning the Second Bunch (cont.)

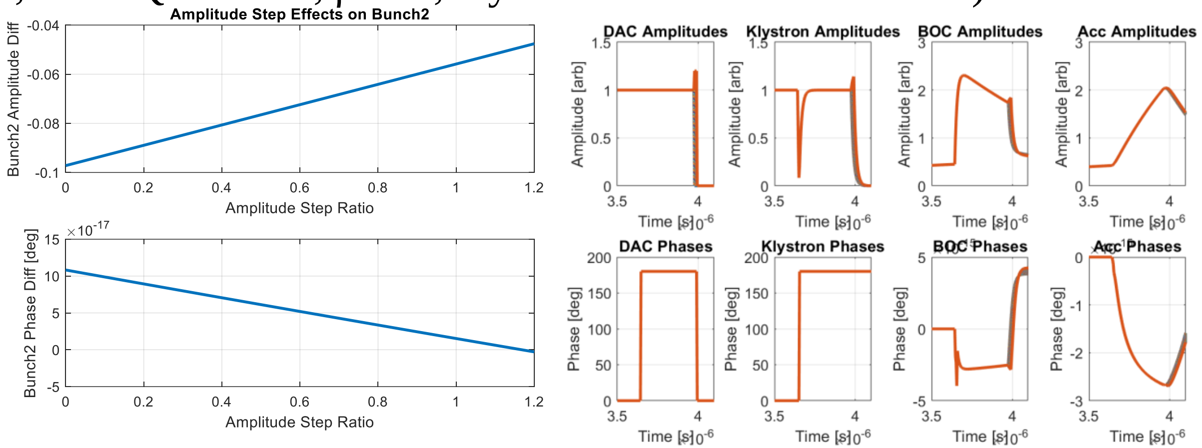
- **Amplitude and phase step in RF pulse**. <u>Amplitude and phase step example</u> in SINSB03/04.

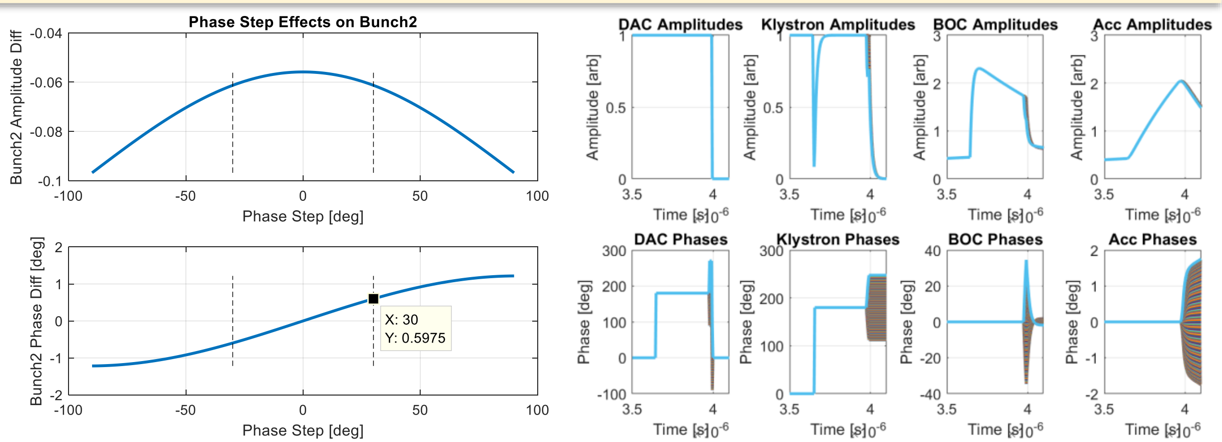




Knobs Tuning the Second Bunch (cont.)

- **Amplitude and phase step in RF pulse.** C-band tuning range study with simulation (filling time = 320 ns, BOC Q_L=21800, β=4.5, klystron bandwidth = 10 MHz)





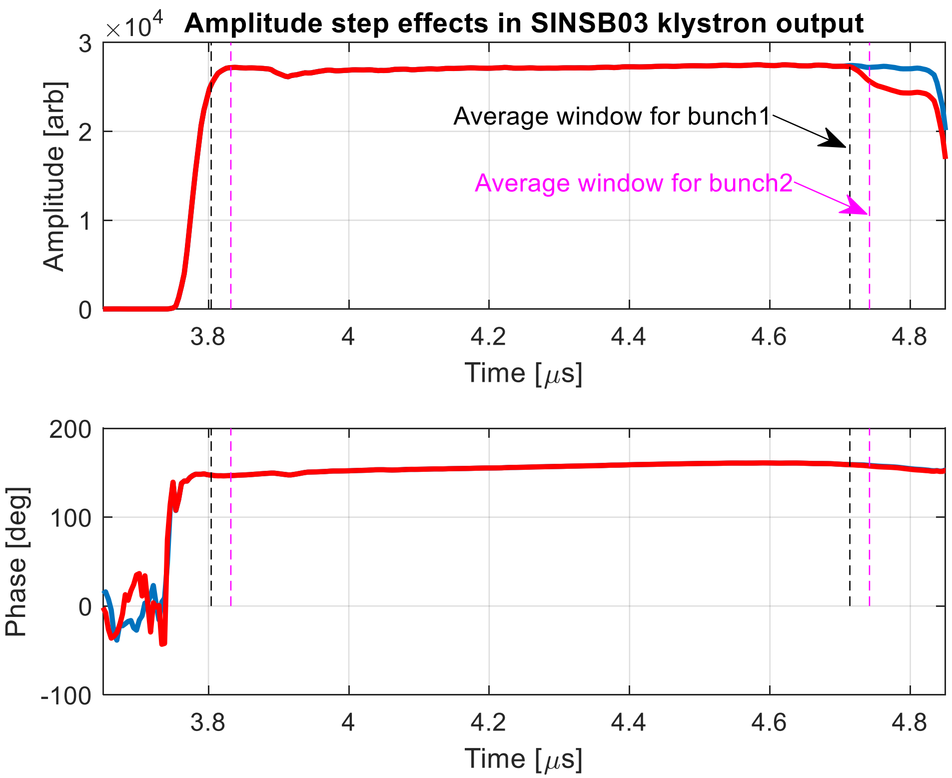
For C-band stations, it is necessary to firstly equalize the energy gains for both bunches by shifting the pulse timing!

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**

RF Measurements for both Bunches

Average windows for the two bunches:



In the plot above, the step ratio is 0.2 and step phase is 0. The bunch2 RF amplitude and phase difference relative to bunch1 is:

- Without step: 0.17 %, 0.42 deg
- With step: 0.10 %, 0.41 deg

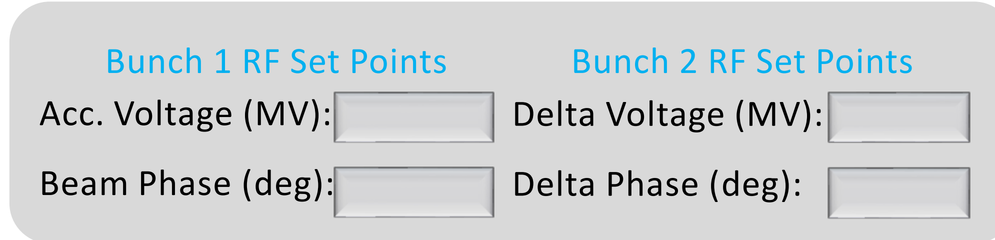
Errors in RF measurement for bunch2:

- ❑ Uncertainty of the structure filling time – errors in the length of the average window.
- ❑ Uncertainty of the identification of the step time on the measured RF pulse.
- ❑ RF measurement model errors: currently the pulse is averaged without considering the group velocity variations in the structure.
- ❑ Bandwidth and transient response in the RF detectors.

► *When the pulse shape is changed, the RF measurement will be not accurate for the RF field felt by the beam even the accelerating voltage and beam phase are previously calibrated like via phasing.*

Measurement and setting of the second bunch RF amplitude and phase are not accurate!

Tasks to Implement the LLRF Interfaces



Short-term:

- LLRF high level software tasks:
  - Update the step generation function in DAC table
- Implement the LLRF interface functions in Python soft IOC:
  - Implement the interface PVs
  - Update the tool to identify the step time in DAC table
  - Implement the RF amplitude and phase measurement for the second bunch (*temporary solution*)
  - Implement the regulation loops for delta voltage and phase settings (*temporary solution*)

Long-term:

- LLRF firmware tasks:
  - Implement the accumulation of RF pulse points in the average window of the second bunch
- LLRF real-time software tasks:
  - Implement the RF amplitude and phase measurement for the second bunch
  - Implement the regulation loops for delta voltage and phase settings

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Beam based Setting Procedures for Two-bunch Operation

Setup Procedure for Gun

1. The first bunch should be optimized by the nominal Gun setup procedure.
2. Still only with the first bunch, remember the bunch charge, BC1 energy the LH BAM reading.
3. Move the Gun RF timing earlier by 28 ns and now the first bunch experiences the RF field for the second bunch.
4. Tune the Gun RF pulse step amplitude and phase to recover the bunch charge, BC1 energy and LH BAM reading of the first bunch as saved in step 2. This can be done with the following considerations:
   a. In this case, the LH BAM reading difference from the one in step 2 is only caused by Gun phase. If we tune the RF pulse step to recover the LH BAM, the phase that the beam feels is recovered, which means, the second bunch will see the same phase as the first one.
   b. In principle, we can implement the following two loops:
      i. Bunch2 delta voltage (or directly RF pulse step ratio) => BC1 energy (?)
      ii. Bunch2 delta phase (or directly RF pulse step phase) => LH BAM

   After setting this step, the second bunch will experience the same RF amplitude and phase with the first bunch.
5. Restore the Gun RF station timing as original values.
6. Enable the second bunch, observe the two-bunch arrival times at LH and tune the timing of second laser to equalize the two-bunch arrival times at LH.

Setting procedures for injector and Linac1 are similar.

R&D and Test Plans

What have been implemented?

1. DAC table: amplitude and slope generation;
2. DAC table: amplitude and phase step generation (*need upgrade*);
3. Iterative learning control;
4. DAC step time calibration (*need upgrade*);
5. Two-bunch phasing (*need upgrade*);
6. Gun setup procedure (*partly*);
7. Injector setup procedure (*partly*);
8. Linac1 setup procedure (*partly*)

What are needed if after April permanent two-bunch setting?

1. Implement the LLRF interfaces (short-term):
   - ❑ LLRF high level software tasks:
     - Update the step generation function in DAC table
   - ❑ Implement the LLRF interface functions in Python soft IOC:
     - Implement the interface PVs
     - Update the tool to identify the step time in DAC table
     - Implement the RF amplitude and phase measurement for the second bunch (*temporary solution*)
     - Implement the regulation loops for delta voltage and phase settings (*temporary solution*)
2. Implement the beam based setup procedures in Python soft IOC
   - ❑ Update the step time calibration tool;
   - ❑ Update the two-bunch phasing tool;
   - ❑ Fully implement the Gun setup procedure
   - ❑ Fully implement the injector setup procedure
   - ❑ Fully implement the Linac1 setup procedure

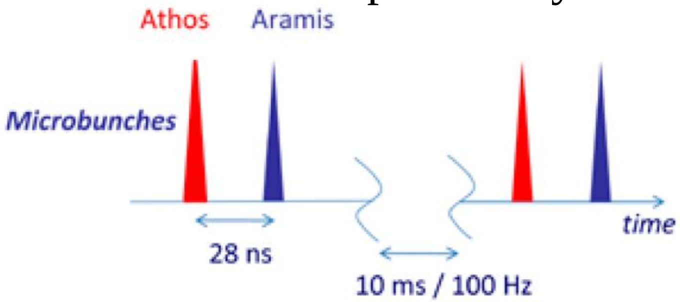
- (at least) 3 or 4 shifts are needed to test all these tools!
- Initial test does not need both bunches because we can move the RF timing.
- The test time should be distributed not so early to allow time for implementation of the tools.

Thank you for your attention!

Backup

Two Bunches in the same RF Pulse

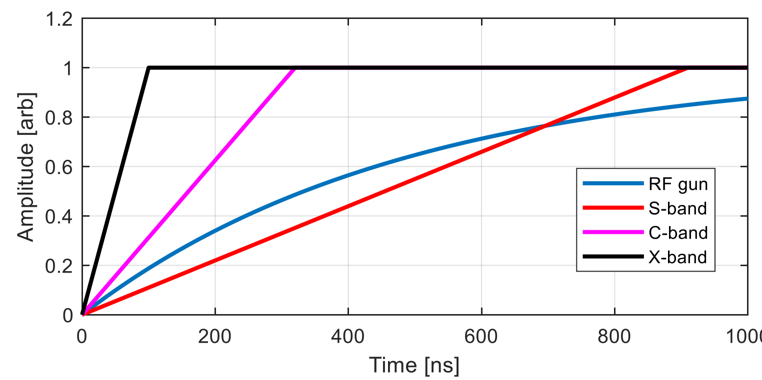
Two bunches are separated by 28 ns!

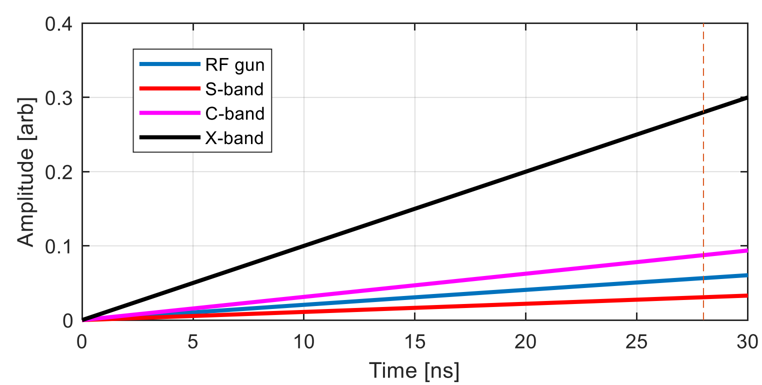


Cavity / Structure	Frequency (MHz)	Time Constant or Filling Time (ns)
RF Gun Cavity	2998.8	480
S-band Structure	2998.8	910
C-band Structure	5712	320
X-band Structure	11995.2	100

How much can cavity field change within this 28 ns in ideal case?

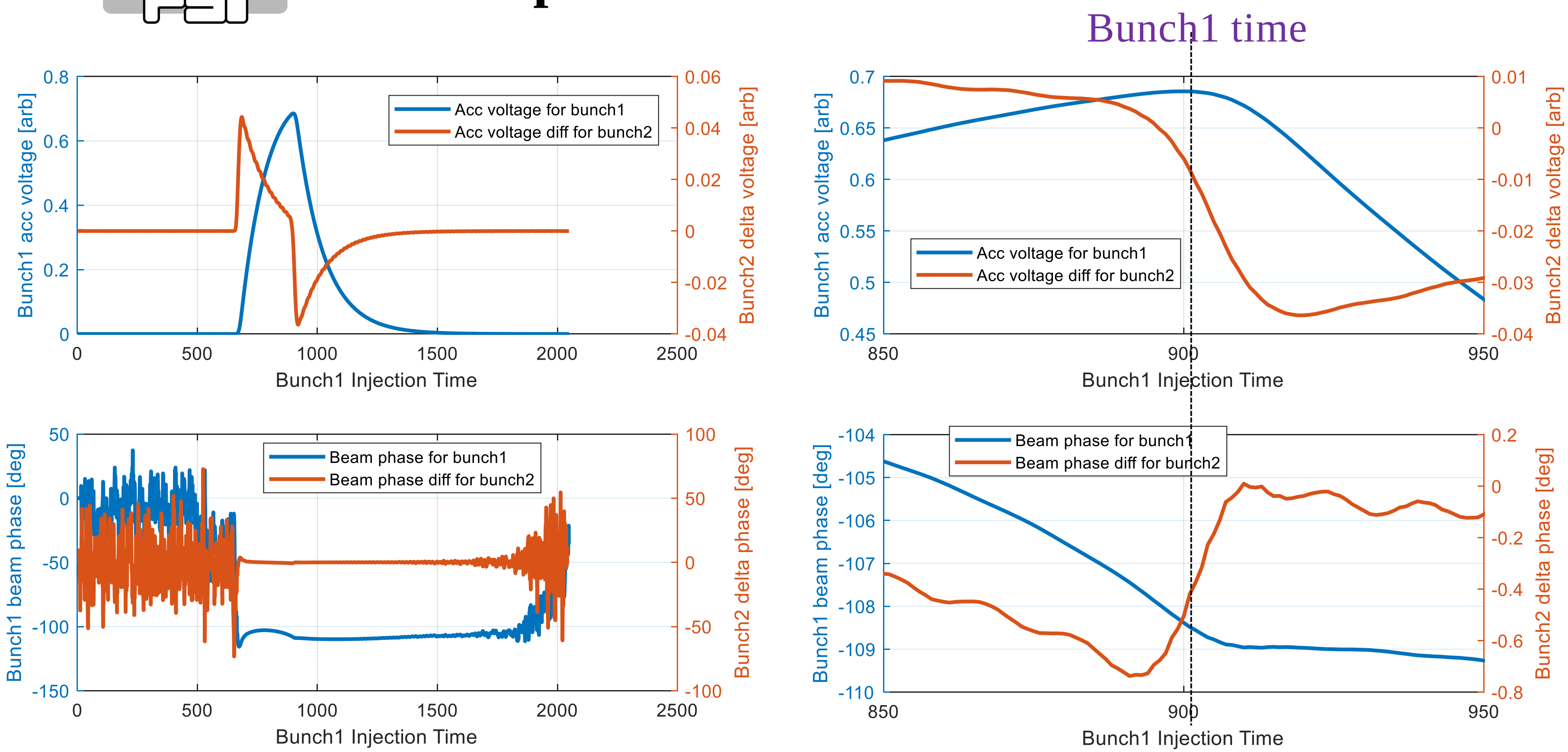
Gun:	5.6 %,	3.2 degS
S-band:	3.1 %,	1.8 degS
C-band:	8.7 %,	5.0 degC
X-band:	28 %,	16 degX





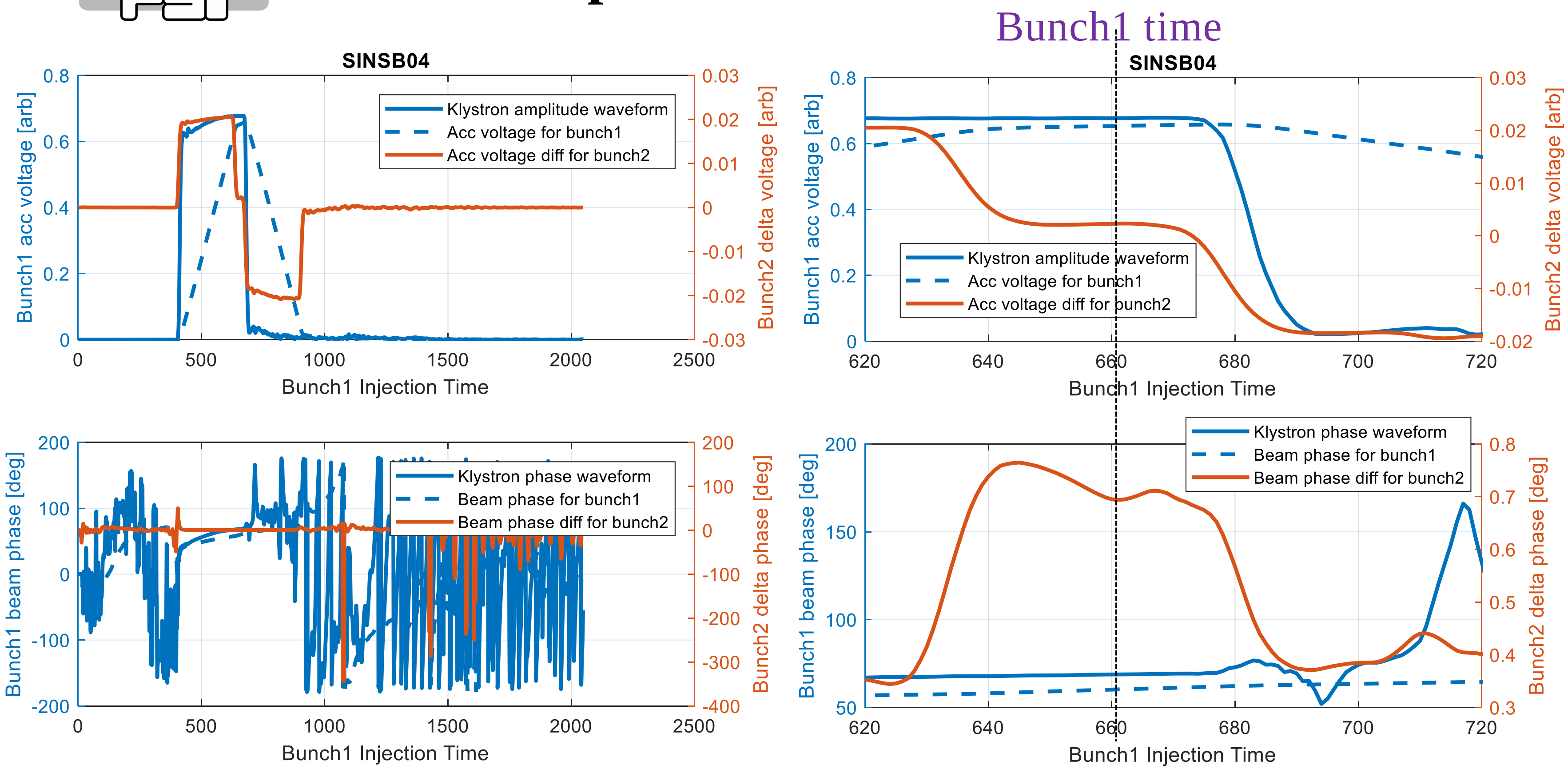
- Tune the second bunch with the 28-ns RF pulse after bunch1 is possible.
- Practically, the tuning range is much smaller!

Gun Amplitude and Phase Diff. for two Bunches



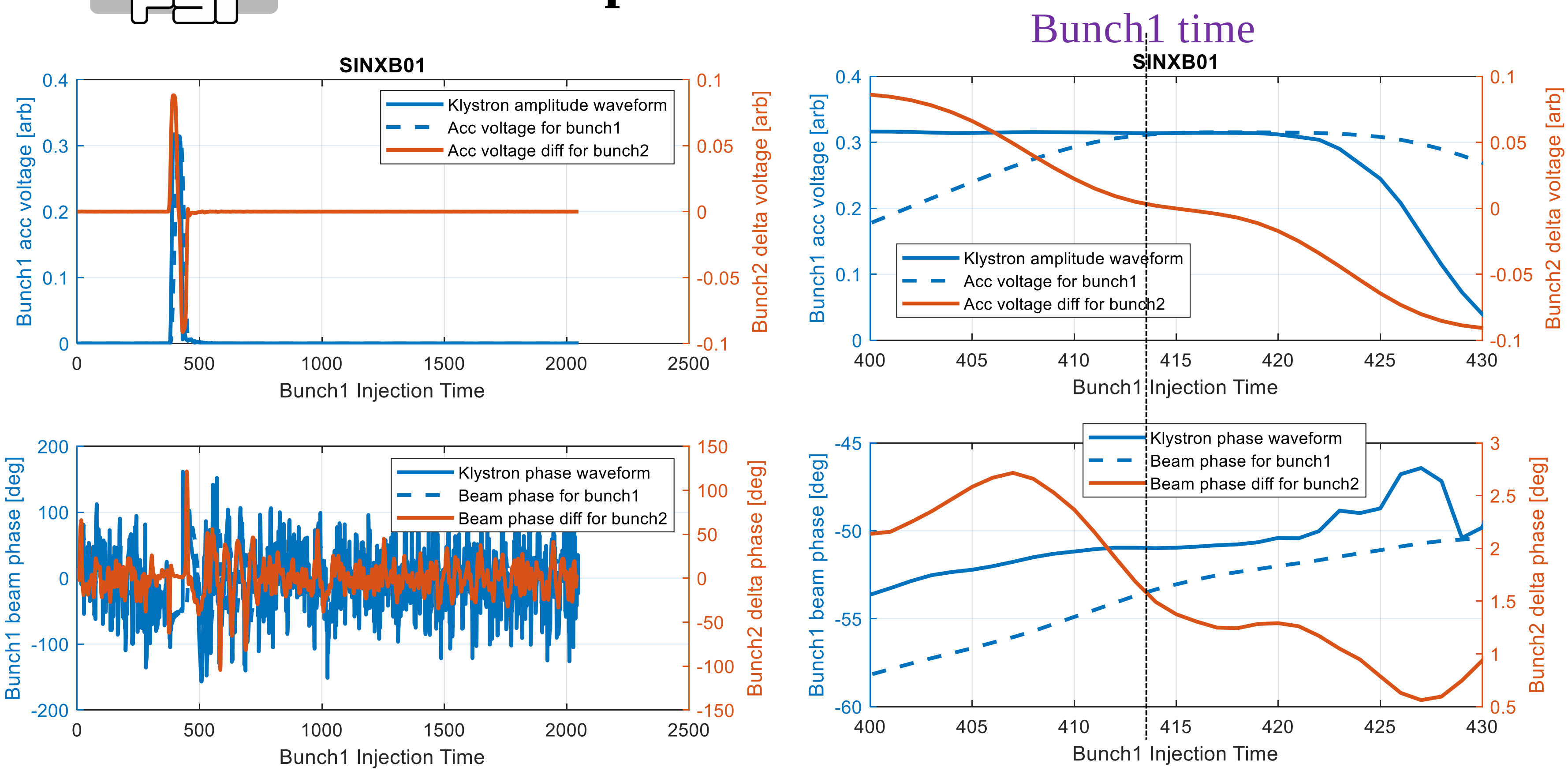
- Around current working point of the Gun, amplitude and phase differences between bunch 1 and bunch 2 is about **1 %** and **0.4 degree**.

S-band Amplitude and Phase Diff. for two Bunches



- Around current working point of SINSB04, amplitude and phase differences between bunch 1 and bunch 2 is about **0.34 %** and **0.7 degree**.

X-band Amplitude and Phase Diff. for two Bunches



- Around current working point of SINXB01, amplitude and phase differences between bunch 1 and bunch 2 is about **1.56 %** and **1.6 degree**.

Knobs Tuning the Second Bunch (cont.)

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

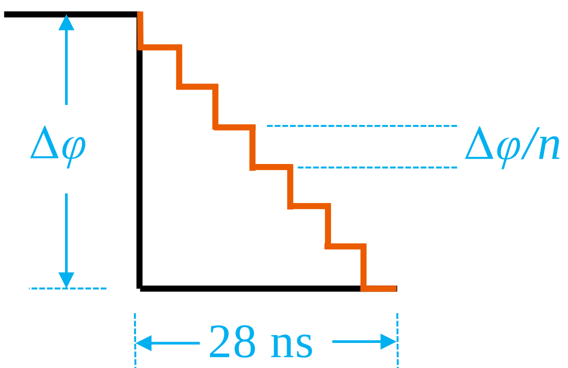
- **Amplitude and phase step in RF pulse**. Issues with phase step.

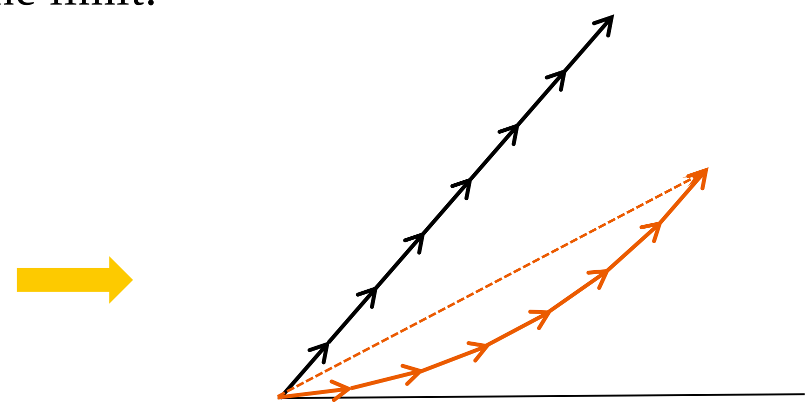
A phase step $\Delta\varphi$ is generated by a single DAC clock cycle and the DAC establish time is δt, this will generate a frequency change in the transient

$$\Delta\omega = \frac{\Delta\varphi}{\delta t}$$

and further generate reflections in the RF system causing reflection interlock trips.

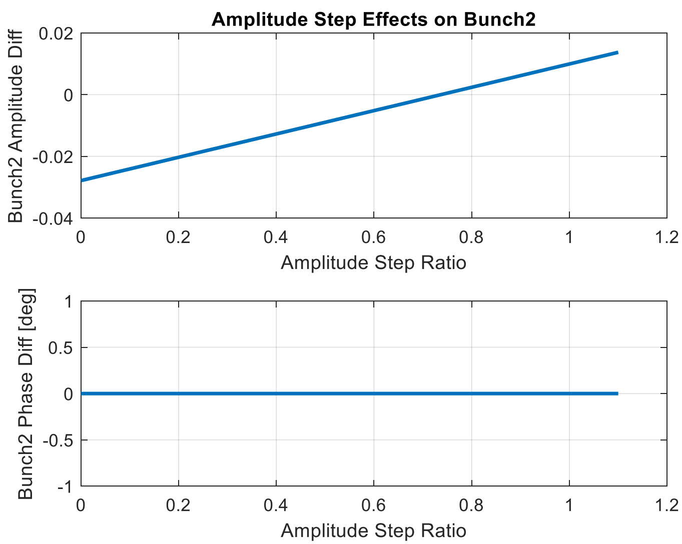
Normally the phase step $\Delta\varphi$ should be limited (e.g. < 30 degree) to avoid reflections. The alternative is to smooth the phase step to be sure the phase change in each clock cycle is smaller than the limit.

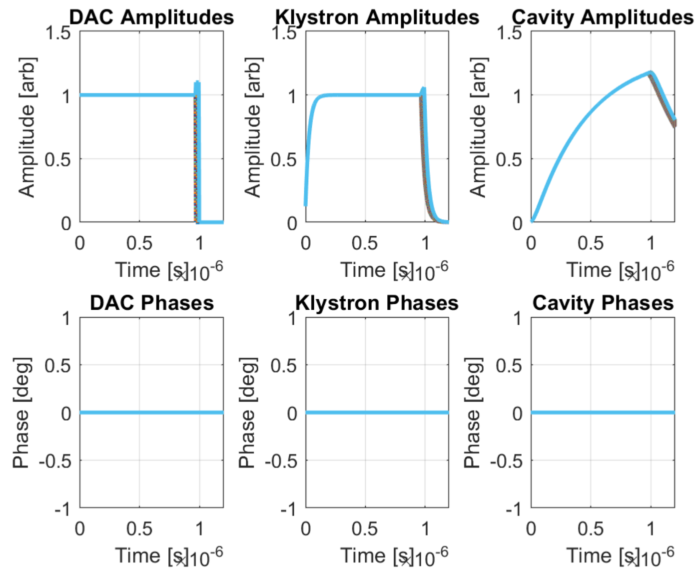




Knobs Tuning the Second Bunch (cont.)

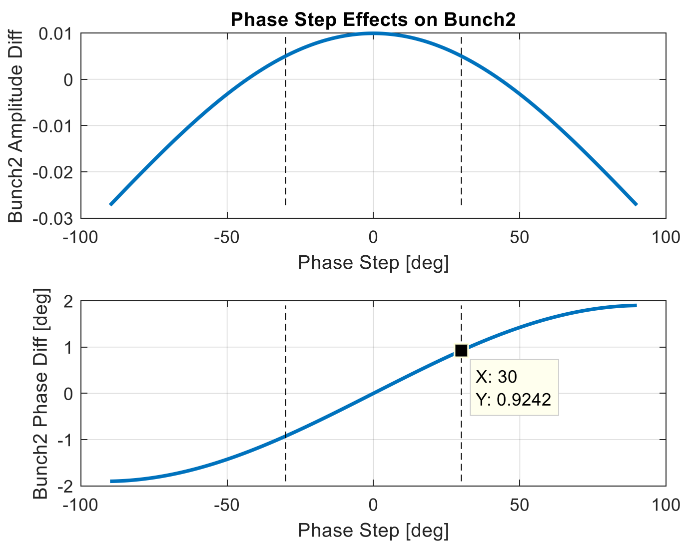
- **Amplitude and phase step in RF pulse**. <u>Gun tuning range study with simulation </u>(Gun cavity Q_L=4280, β=2, klystron bandwidth = 10 MHz)

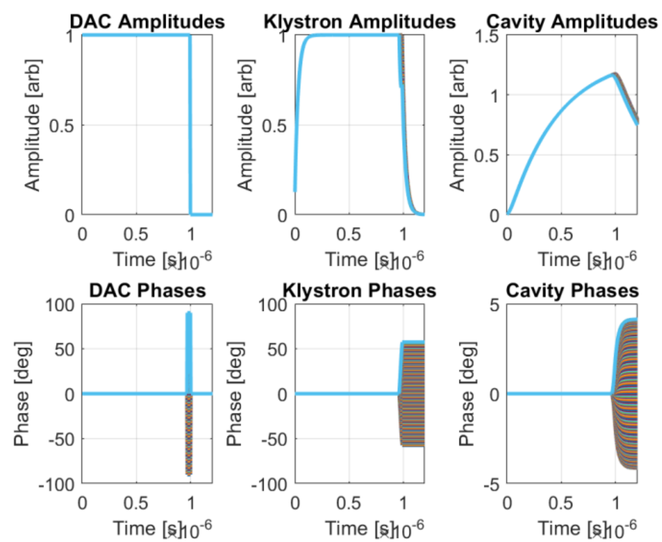




Tuning range for step ratio 0 ~ 1.2 and step phase -30 ~ 30 degree:

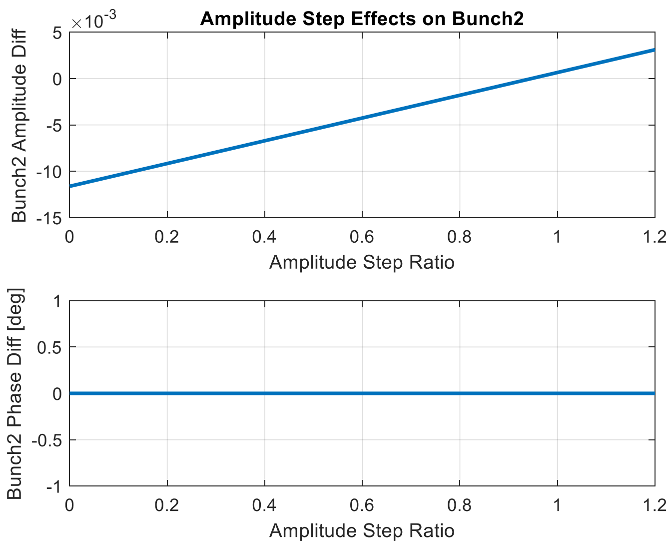
- **-2.5 % ~ 1.5 %**
- **±0.92 degree**

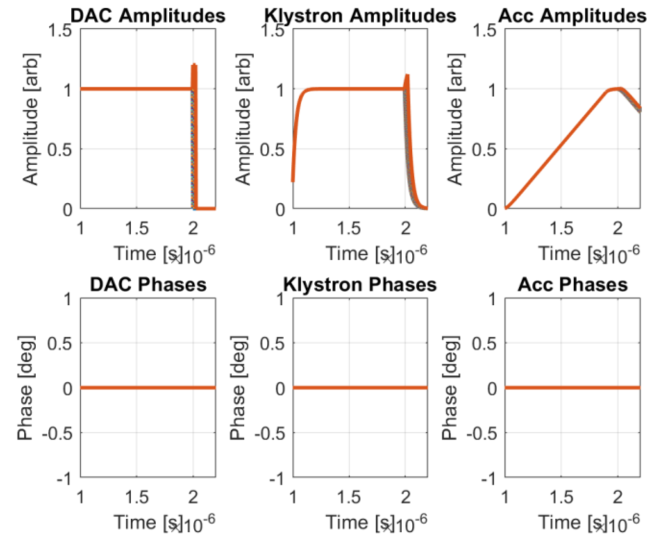


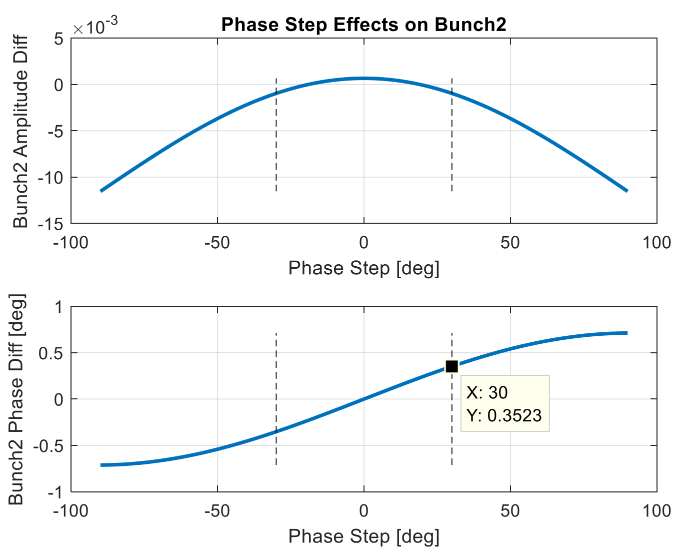


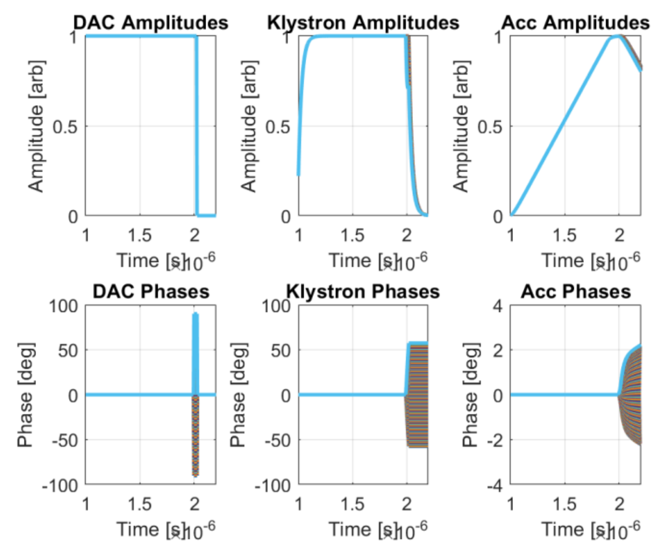
Knobs Tuning the Second Bunch (cont.)

- **Amplitude and phase step in RF pulse**. S-band tuning range study with simulation (filling time = 910 ns, klystron bandwidth = 10 MHz)







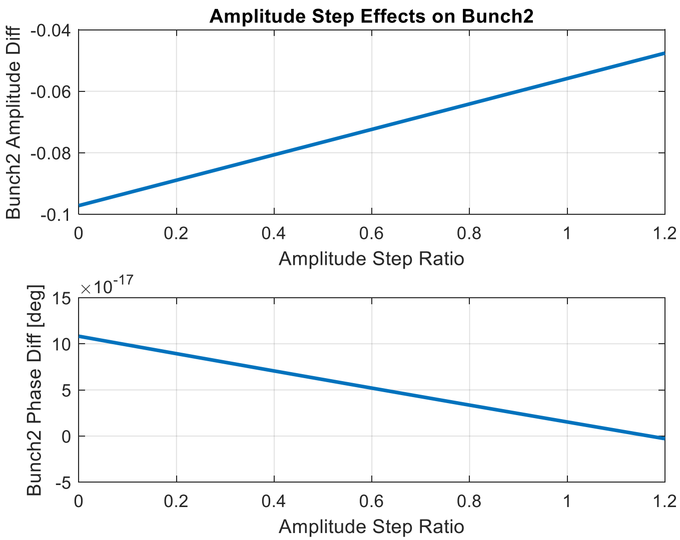


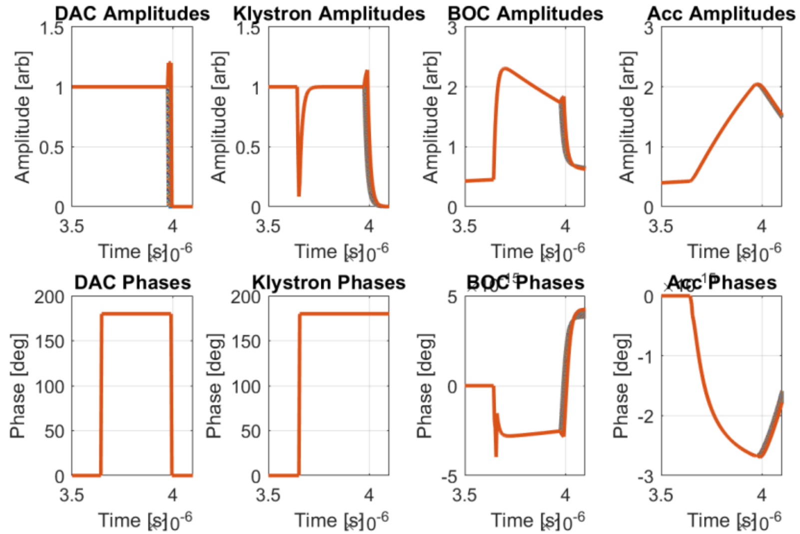
Tuning range for step ratio 0 ~ 1.2 and step phase -30 ~ 30 degree:

- **-1 % ~ 0.5 %**
- **±0.35 degree**

Knobs Tuning the Second Bunch (cont.)

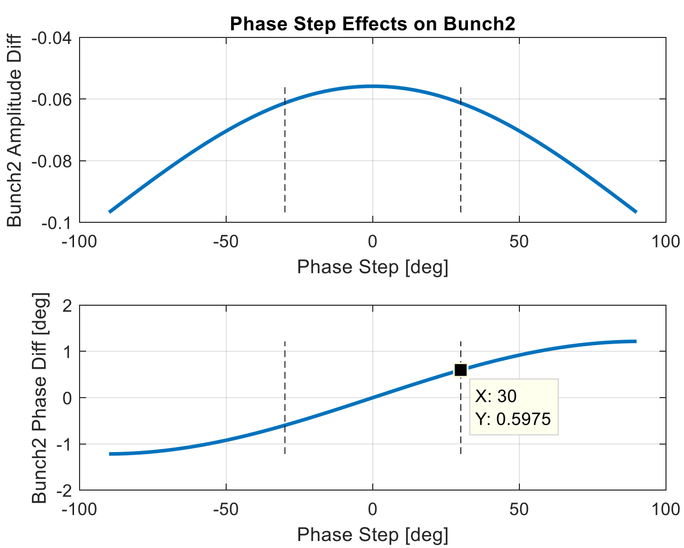
- **Amplitude and phase step in RF pulse**. C-band tuning range study with simulation (filling time = 320 ns, BOC Q_L=21800, β=4.5, klystron bandwidth = 10 MHz)

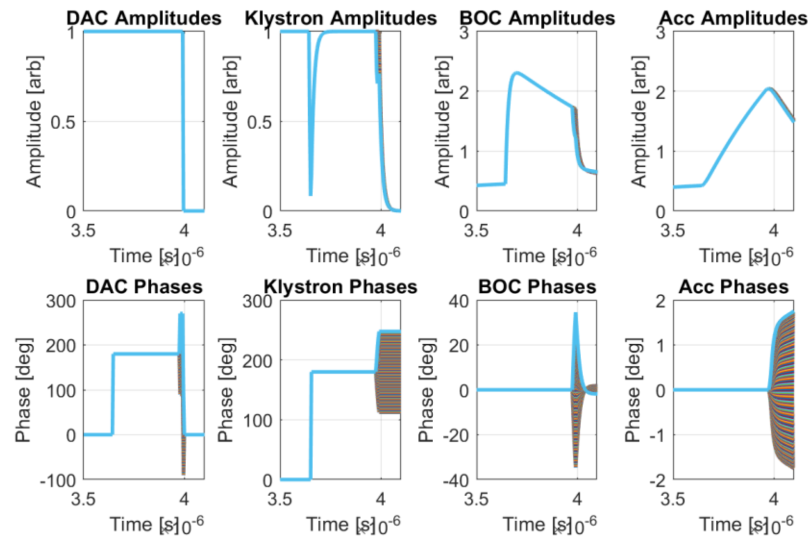




Tuning range for step ratio 0 ~ 1.2 and step phase -30 ~ 30 degree:

- **-10 % ~ -5 %**
- **±0.59 degree**

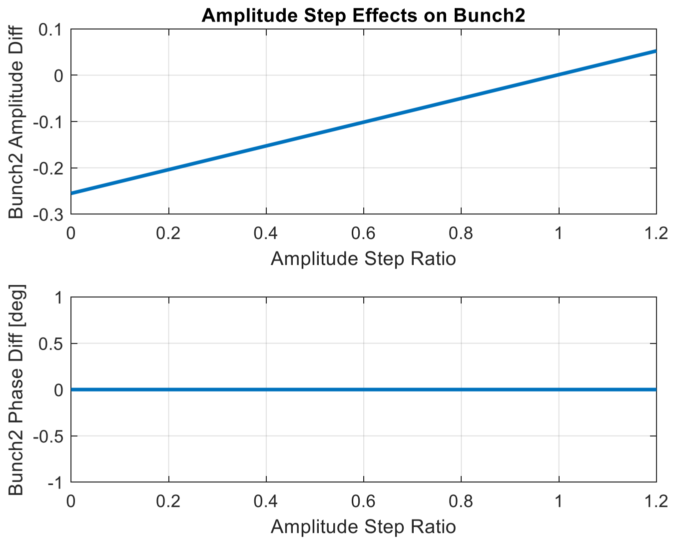


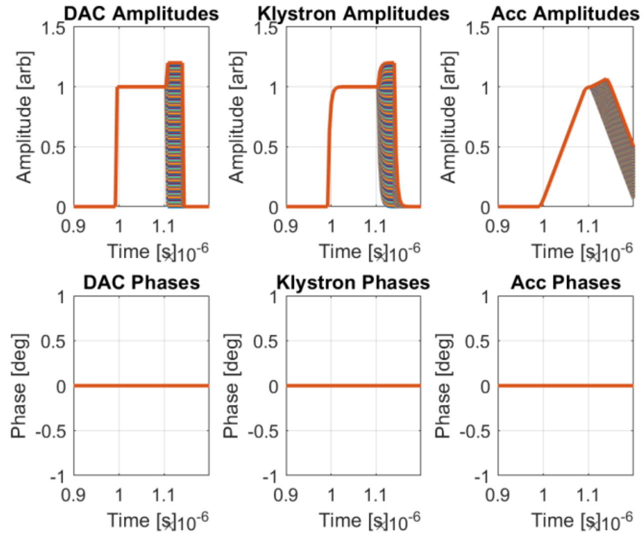


It is necessary to firstly equalize the energy gains for both bunches by shifting the pulse timing!

Knobs Tuning the Second Bunch (cont.)

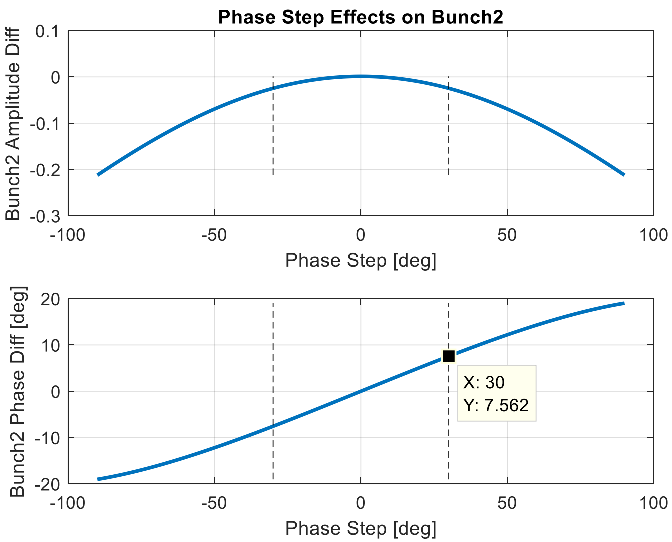
- **Amplitude and phase step in RF pulse**. X-band tuning range study with simulation (filling time = 100 ns, klystron bandwidth = 50 MHz)

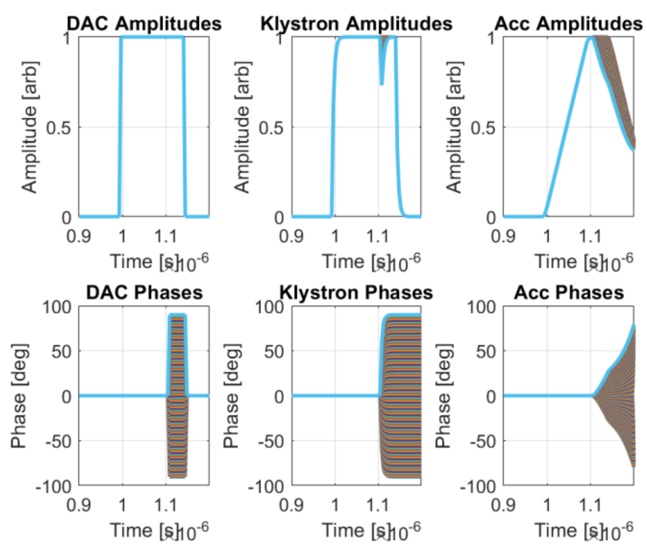




Tuning range for step ratio 0 ~ 1.2 and step phase -30 ~ 30 degree:

- **-25 % ~ 5 %**
- **±7.56 degree**





Difficulties in LLRF Side

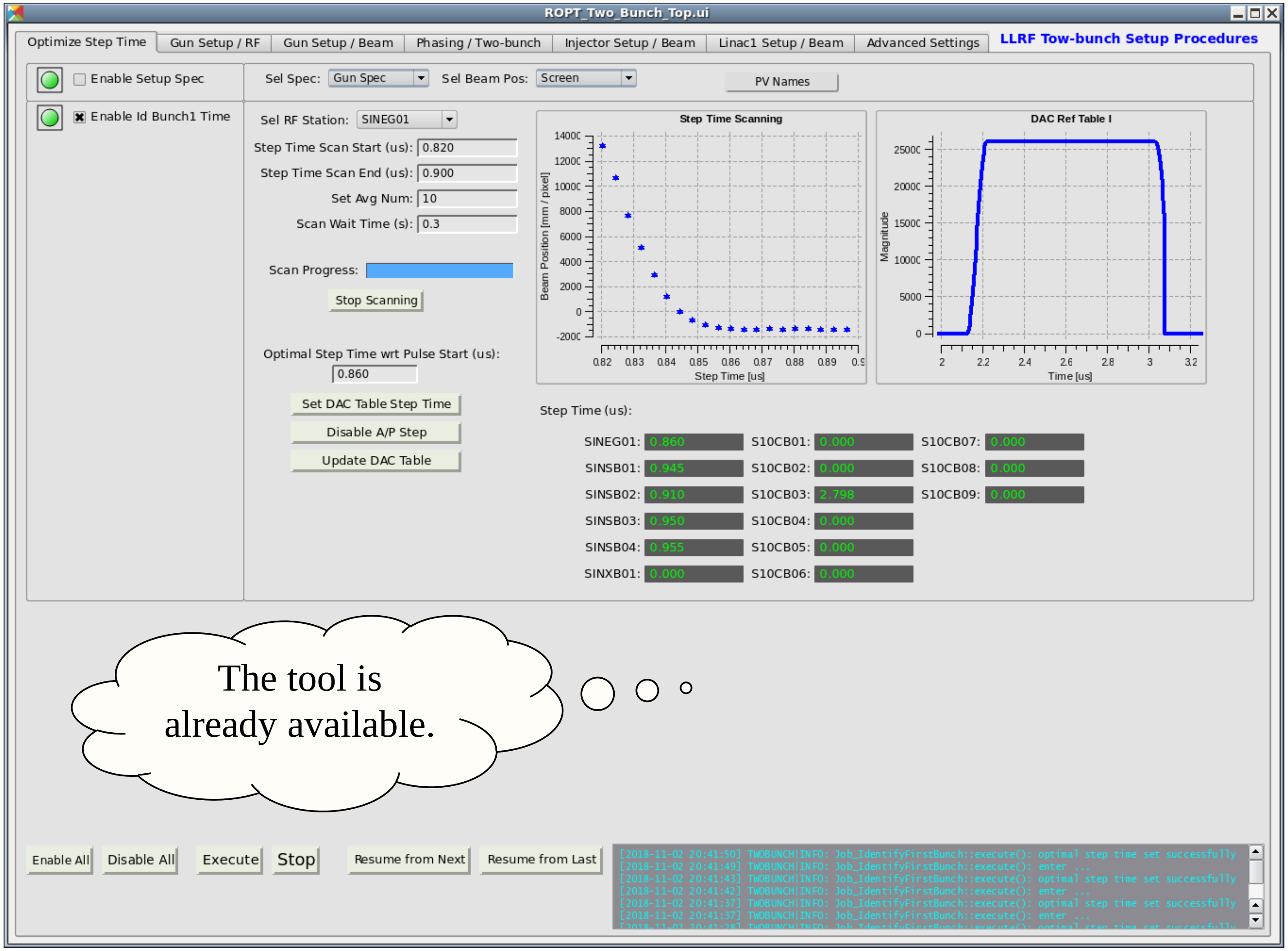
Proposed interfaces:

Bunch 1 RF Set Points		Bunch 2 RF Set Points	
Acc. Voltage (MV):		Delta Voltage (MV):	
Beam Phase (deg):		Delta Phase (deg):	

- The step (ratio and phase) in the RF pulse will be adjusted to achieve the delta voltage and delta phase for the second bunch. How? Changing the step phase will affect both the delta voltage and delta phase!
- Possible solution: Implement two integral loops:
  - *Actuate on the step ratio to achieve the desired delta voltage;*
  - *Actuate on the step phase to achieve the desired delta phase.*

  The cross-talk between these two loops will be viewed as disturbances to each other.
- Difficulties for implementing the integral loops:
  - *Identify the time in DAC tables to generate the step in RF pulse which only affects the second bunch;*
  - *Measure the RF amplitude and phase seen by the two bunches respectively;*
  - *Generate the amplitude and phase step in the RF pulse;*
  - *Implement the integral loops to achieve the desired delta voltage and delta phase.*

DAC Step Time Identification



- Cut the DAC pulse from end towards start and observe the beam energy. The last point that does not affect the beam energy should be the starting point of the step.

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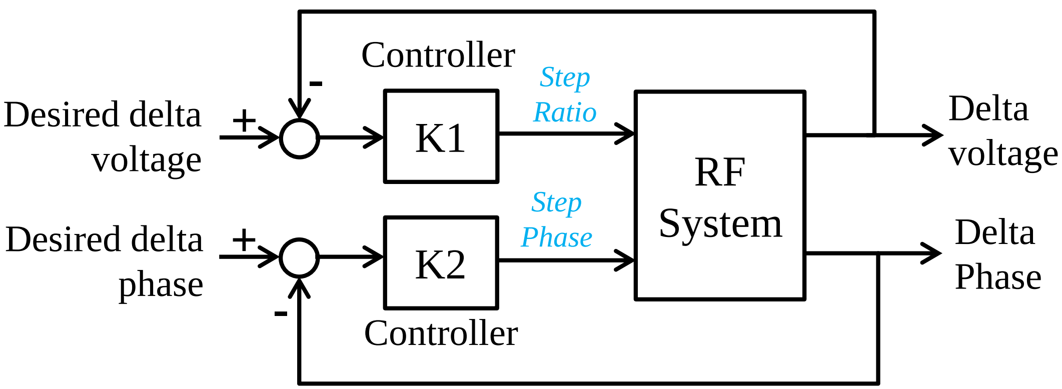
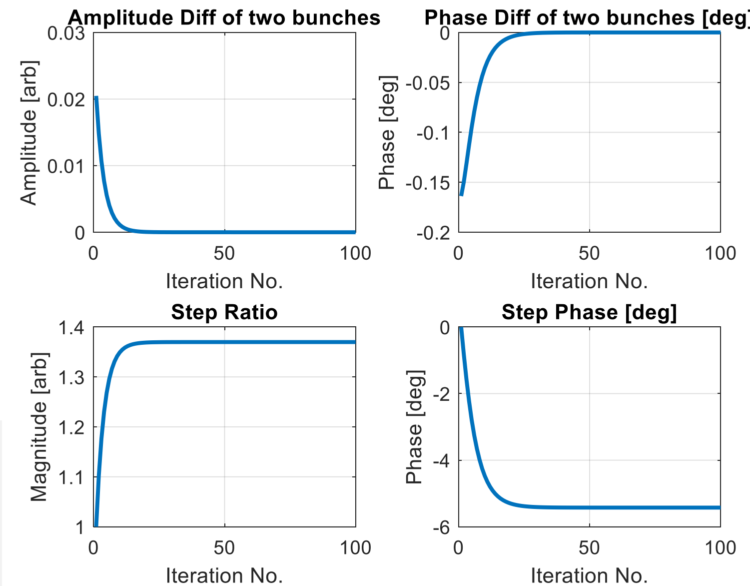
DAC Table Step Generation

Upgrade of the step generation tool:

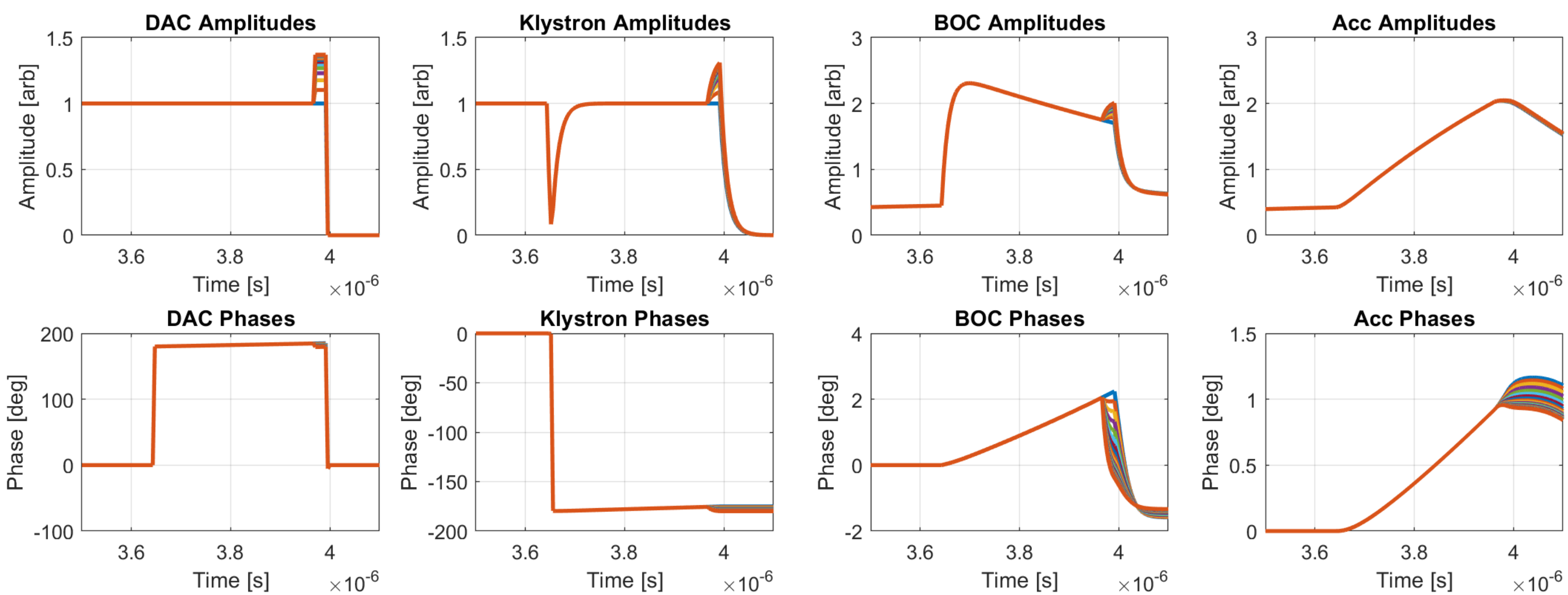
- ❑ Allow the step generation when RF feedbacks are on. The pulse-to-pulse feedbacks should use the RF measurement of the first bunch.
- ❑ Implement the phase linear ramping within the 28-ns period to avoid reflection interlocks.

Simulation of Integral Feedback Loops





- The two loops are coupled because any change in the step ratio or step phase will change both RF amplitude and phase for the second bunch.
- The cross-talk slows down the convergence of the loops.



Problems with RF Stations Working in Saturation

Problems:

- Increasing the step amplitude in DAC table does not result in more klystron output power within the step due to the saturation!
- Phase step still works, but will result in a reduction in klystron output power within the step.

Solution:

- C-band stations will work in saturation. When adjusting the delay of the RF pulse (before optimizing the first bunch), the energy gain for the second bunch can be set slightly higher than the energy gain for the first bunch. This will offer some headroom to tune the phase of the RF pulse step.

Setup Procedure for Injector

1. Flatten the RF pulses for SINSB01-04 and SINXB01 via amplitude/phase slopes or ILC.
2. The first bunch should be optimized by the nominal injector setup procedure.
3. Still only with the first bunch, remember the BC1 energy and BC1 compression.
4. Move the timing of all injector RF stations (SINSB01-04, SINXB01) earlier by 28 ns and now the first bunch experiences the RF fields for the second bunch.
5. Using the following two loops to restore the BC1 energy and compression (or with a desired offset):
   a. Bunch2 delta voltage (or directly step ratio) of SINSB01/02/03/04 => BC1 energy;
   b. Bunch2 delta phase (or directly step phase) of SINSB03/04 => BC1 compression.
6. Manually fine tune the X-band bunch2 delta voltage and delta phase (or directly RF step ratio and phase) to further optimize the second bunch, keep the loops in 5 running to compensate the small influence in compression. Is it possible to automate the X-band tuning? After setting this step, we can assume the second bunch will experience the same RF amplitude and phase with the first bunch.
7. Restore the injector RF timings as the original values.
8. Enable the second bunch, verify the two bunch BC1 energy, BC1 compression and BC2 BAM.

If the beam diagnostics for both bunches exist, the RF station timing does not need to be moved and the two loops in step 5 can directly refer to the beam diagnostics!

Setup Procedure for Linac1

1. Flatten the BOC phase of the RF pulse part after phase inversion via ILC for S10CB01-09.
2. With only the first bunch, scan the delay of each RF station and find the delay where the first bunch will gain slightly smaller energy than the second bunch. Set the delay to this value.
3. The first bunch should be optimized by the nominal Linac1 setup procedure.
4. Still only with the first bunch, remember the BC2 energy and BC2 compression.
5. Move the timing of all Linac1 RF stations (S10CB01-09) earlier by 28 ns and now the first bunch experiences the RF fields for the second bunch.
6. Using the following two loops to restore the BC2 energy and compression (or with a desired offset):
   a. Bunch2 delta voltage (or directly step ratio) of S10CB01-09 => BC2 energy;
   b. Bunch2 delta phase (or directly step phase) of S10CB01-09 => BC1 compression.
7. Restore the Linac1 RF timings as the original values.
8. Enable the second bunch, verify the two bunch BC2 energy, BC2 compression and BC2 BAM.

If the beam diagnostics for both bunches exist, the RF station timing does not need to be moved and the two loops in step 6 can directly refer to the beam diagnostics!