Science and Technology Facilities Council

Beam experiments in January 2023

Shinji Machida
UKRI/STFC Rutherford Appleton Laboratory

13 January 2023
KURNS beam stacking

Publication

Science and Technology Facilities Council

Outline of the publication, my proposal

- Title?: Experimental verification of beam stacking in a FFA

- Introduction
  - FFA has wide momentum acceptance. Beam stacking of many acceleration cycle in momentum space is possible.
  - Only FFA can handle both acceleration and beam stacking in one ring.
  - Demonstration if it is feasible in practice, that is, **momentum spread is under control** (without beam loss).

- Momentum spread measurement
  - Schottky scan
  - Other methods
  - …

Science and Technology Facilities Council

Outline of the publication, my proposal

- Main part
  - Part 1: Optimisation of debunching and rebunching process for an accelerated beam.
    - Optimised rebunching is not necessarily the reverse process of debunching.
    - What is the key parameter we must control?
    - Why optimised process is the best, in what sense?

  - Part 2: Influence of an accelerating bucket to a coasting beam circulating at the top energy.
    - This is another source of deterioration of momentum spread.
    - When it becomes significant? Acceleration frequency become a harmonic of revolution frequency?

  - Part 3: How we combine a coasting beam and an accelerated beam together. How we can minimise the momentum spread of beams after stacking.
    - One sequence of optimised step1 and step2. See if it works.
    - Two beam stacking is enough for demonstration purpose.
    - Case of more than two is one of discussion items.

January experiment

- (horizontal) tune measurement with different initial amplitude [1~2 days]
- Preparation of March experiment
    - First try of step 1 experiment [~3 days]
    - Test of step 2 and 3 experiments [~1 days]

- Total ~ a week if allowed

Science and Technology Facilities Council

(horizontal) tune measurement

Science and Technology Facilities Council

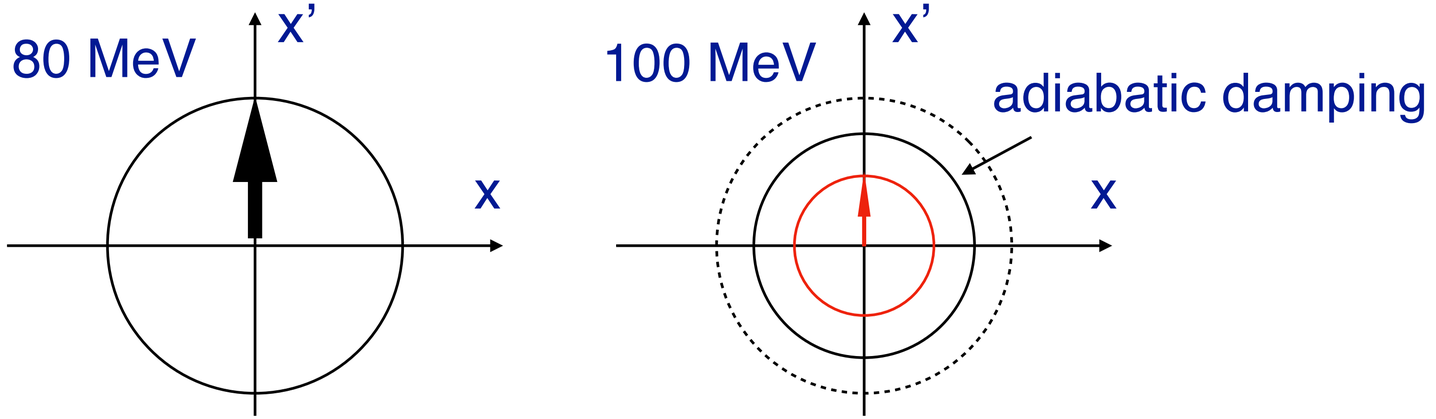
(horizontal) tune measurement
idea

- Measure amplitude dependent tune shift.
- Tune measurement by turn-by-turn BPM.
- Difficult part is to control initial betatron amplitude.
  - Small amplitude tune should be measured by small oscillations excited with a shaker.
  - Can the extraction kicker be excited with different strength?
  - Kick angle is inversely proportional to the beam momentum with the same kicker strength.
- Combined of two (at different beam momentum with different kicker strength) should give us results which can be scaled.

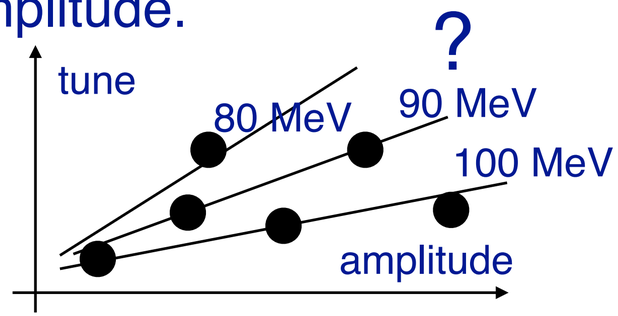
(horizontal) tune measurement

methods

- Accelerate the beams up to 2 or 3 different energy, e.g. 80 MeV, 90 MeV and 100 MeV.
- Using the extraction kicker, excite a coherent oscillations.
  - Measure horizontal tune with several different kicker strength at each energy.
  - Obtain amplitude dependent tune shift results.
  - For example, the same strength of the kicker magnet gives 90% of coherent oscillations at 100 MeV compared with 80 MeV (black and red arrows below).



- How the gradient of amplitude dependent tune shift scales with oscillation amplitude.
  - If the geometrical dynamic aperture is independent of momentum, …



Science and Technology Facilities Council

(horizontal) tune measurement

methods, more details

- Accelerate the beam up to 80 MeV and keep it.
- Apply the minimum kick possible by the extraction kicker.
- Record horizontal beam position for at least 1 ms or until signal disappear.
- Accelerate the beam up to 90 and/or 100 MeV and keep it.
- Apply the same minimum kick above.
- Recode horizontal beam position for at least 1 ms or until signal disappear.
    - Is the horizontal oscillation amplitude inversely proportional to the beam momentum?

- See the range of the kicker strength which gives horizontal oscillations within the aperture.
- Repeat the above with a few (~5) of the extraction kicker strength between min and max.
- FFT or NAFF of the horizontal beam position data gives horizontal tune.
    - It is not always true that the longer data give the accurate tune. Oscillation damps. Tune may change later time.
    - Try different window (the number of samples) and see if any reasonable results come out.

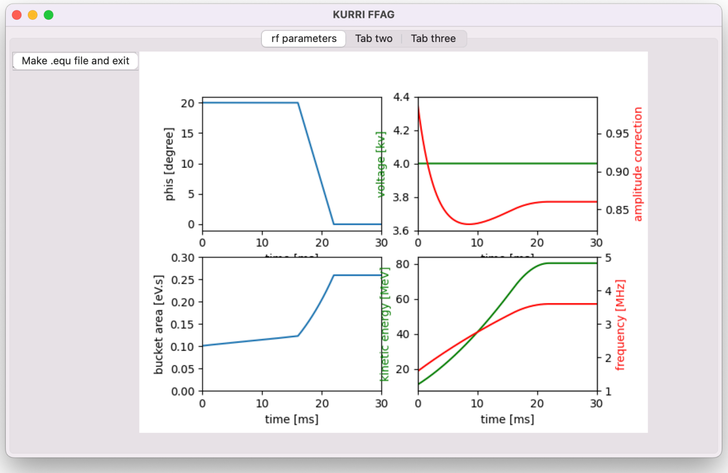
- If possible, measure oscillations in the vertical direction. Ideally no vertical oscillations are excited.

(horizontal) tune measurement

Preparation

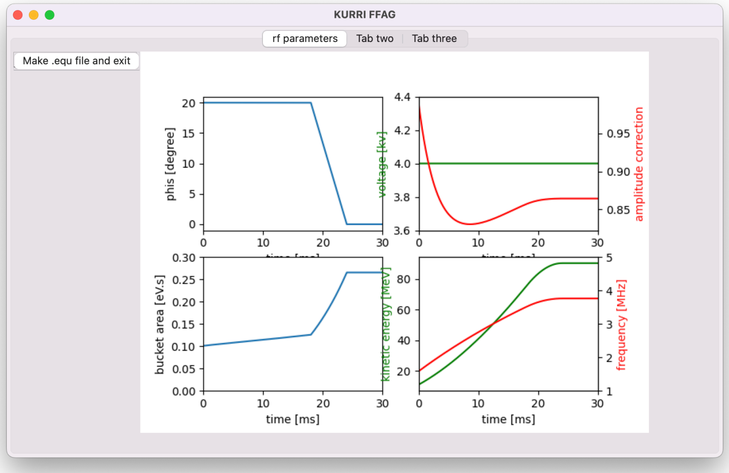
- AWG script for 80, 90 and 100 MeV acceleration.
  - You might want to try at different energy. Run wxPython to generate a new script.
- Script for frequency analysis: FFT and/or NAFF by Max.
  - Choose window (the number of samples) to get optimum and clean results.

80 MeV



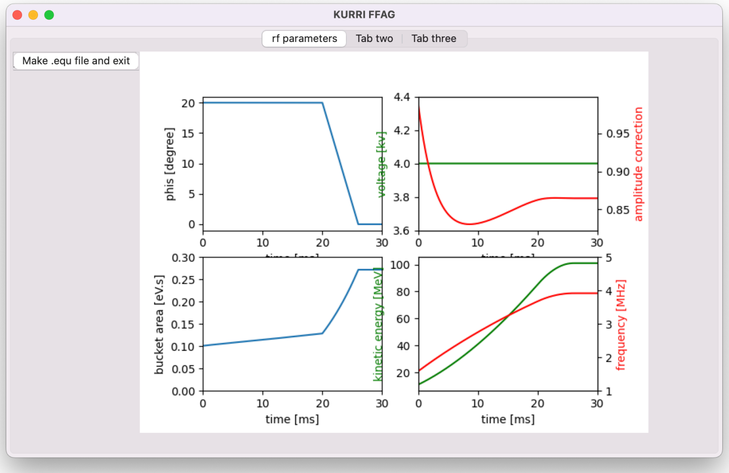
tmp_16_6_8_0.080424.equ

90 MeV



tmp_18_6_6_0.090493.equ

100 MeV



tmp_20_6_4_0.101002.equ

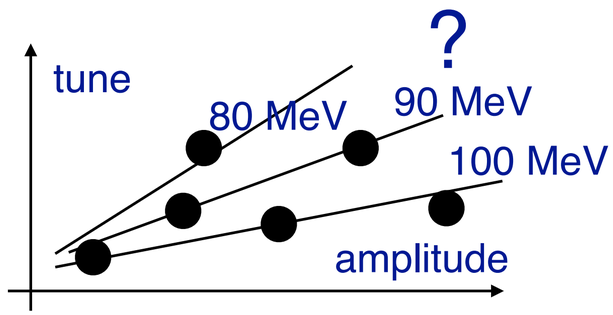
There are scripts with different transition time from acceleration to top energy.

Science and Technology Facilities Council

(horizontal) tune measurement

we are looking for

- Tune change with amplitude
  - Decrease or increase?
  - Inversely scale with momentum or not?
  - Tune change linearly or more complicated function.
  - Does the result agree with model?



Science and Technology Facilities Council

(horizontal) tune measurement

days necessary for data taking

- Is there any installation of equipment necessary?
  - BPM, extraction kicker, power supply, etc.
  - Vacuum breaking is involved?

- Measurement takes a day or two.
  - Do data taking in the early stage of two weeks period.
  - Offline analysis takes a few days.
  - If the results do not look convincing, do data taking again in the second week.

- Total 1~2 days (excluding offline analysis) depending on hardware preparation.

Science and Technology Facilities Council

First try of step 1 measurement

Science and Technology Facilities Council

First try of step 1 measurement

summary

- Basically, measurement of momentum spread after debunching ~~(and rebunching)~~ process with different RF patterns. Whether we can see the difference.

- Test several RF patterns for debunching after (or including) acceleration up to a certain energy (~58 MeV).
- Test dp/p measurement methods, one or some of below.
    - **Schottky measurement**
    - **Tomography**
    - Transverse beam size
    - **Phase displacement**
    - **Perturbation by an empty bucket**

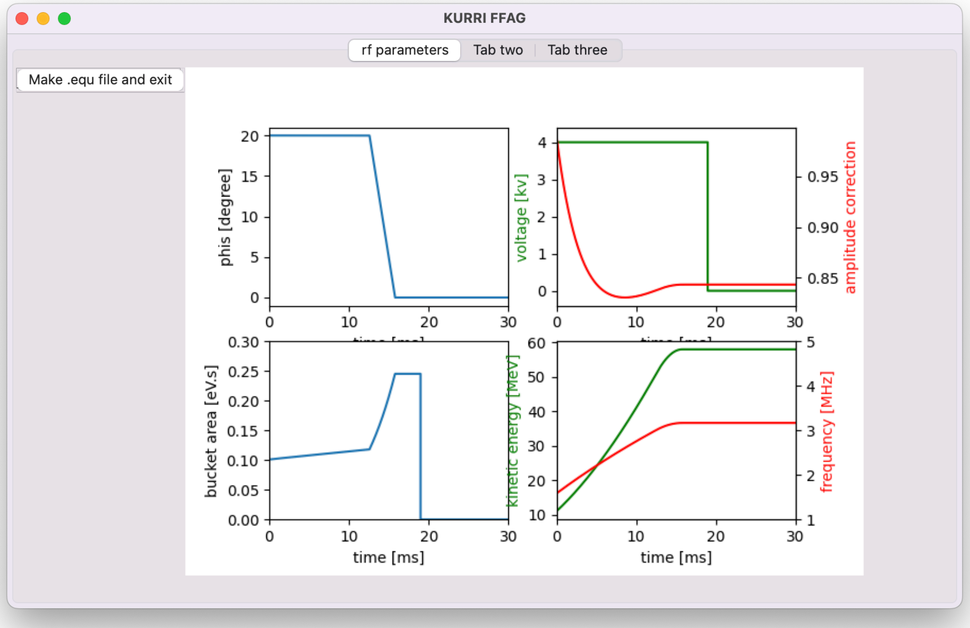
- Roughly ~3 days (excluding offline analysis)?

Science and Technology Facilities Council

First try of step 1 measurement

two extreme case of dp/p

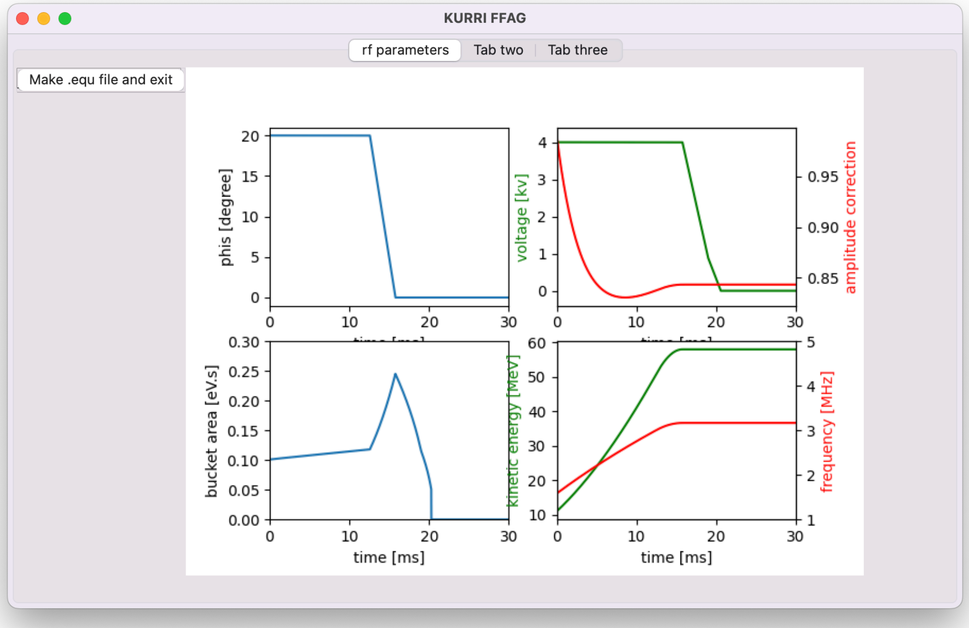
- Accelerate to 57.98 MeV and abruptly switch off RF.



tmp_13_3_3_11_0.057980_4kV.equ

- Accelerate to 57.98 MeV and adiabatically debunch.

  Similar to David's profile except phi_s and voltage decrease at different timing.



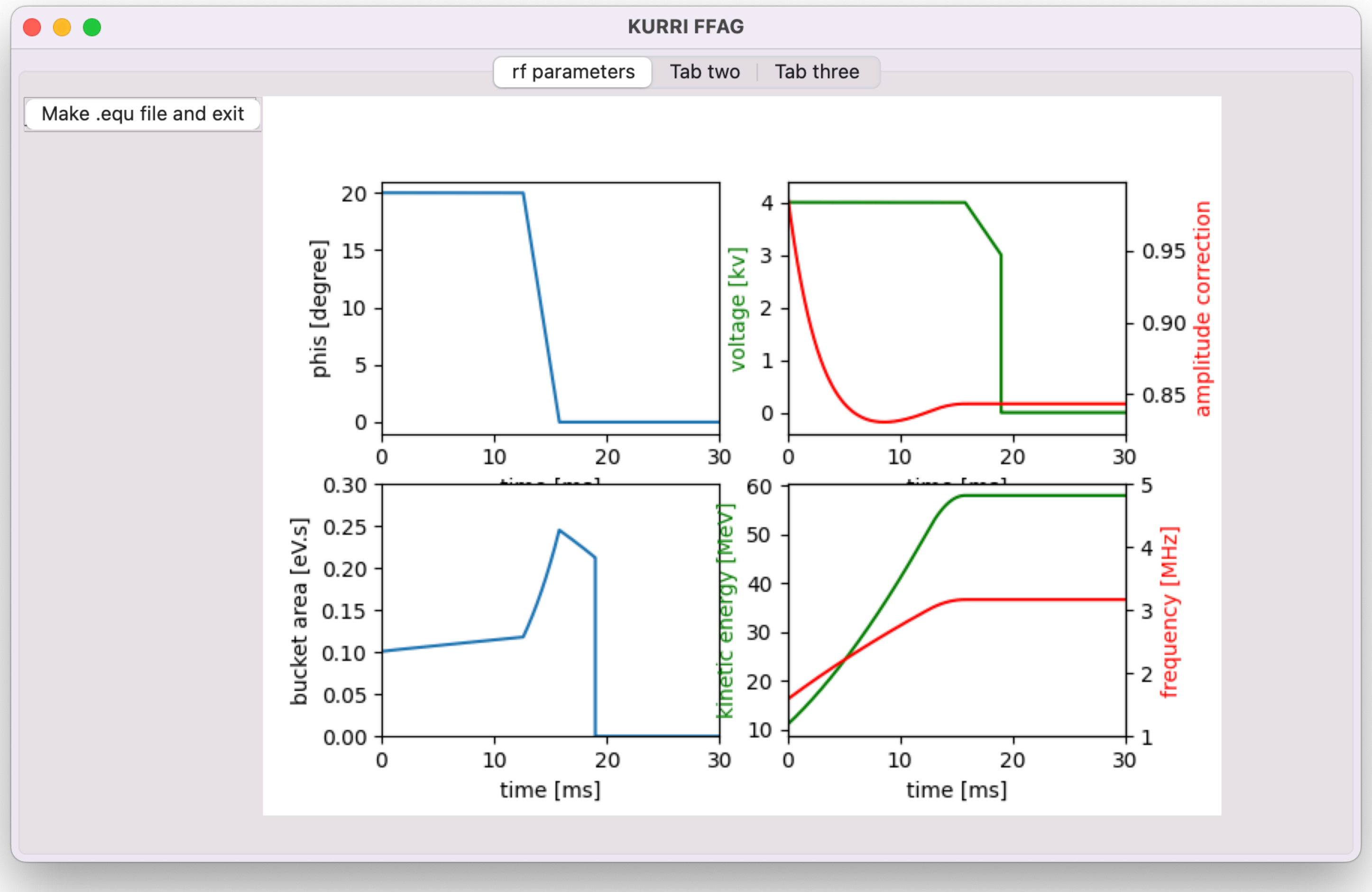
tmp_13_3_3_2_9_0.057980.equ

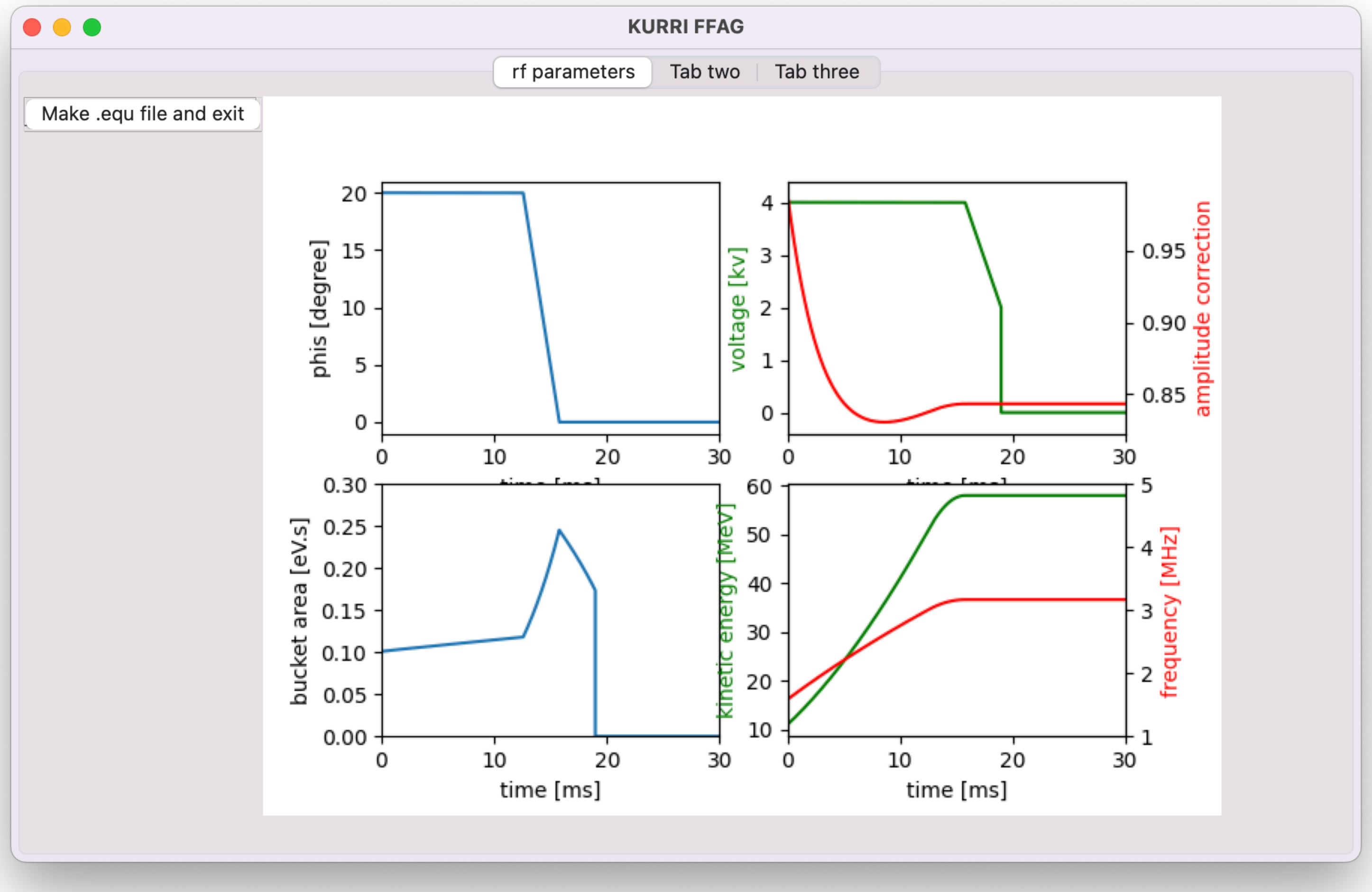
Science and Technology Facilities Council

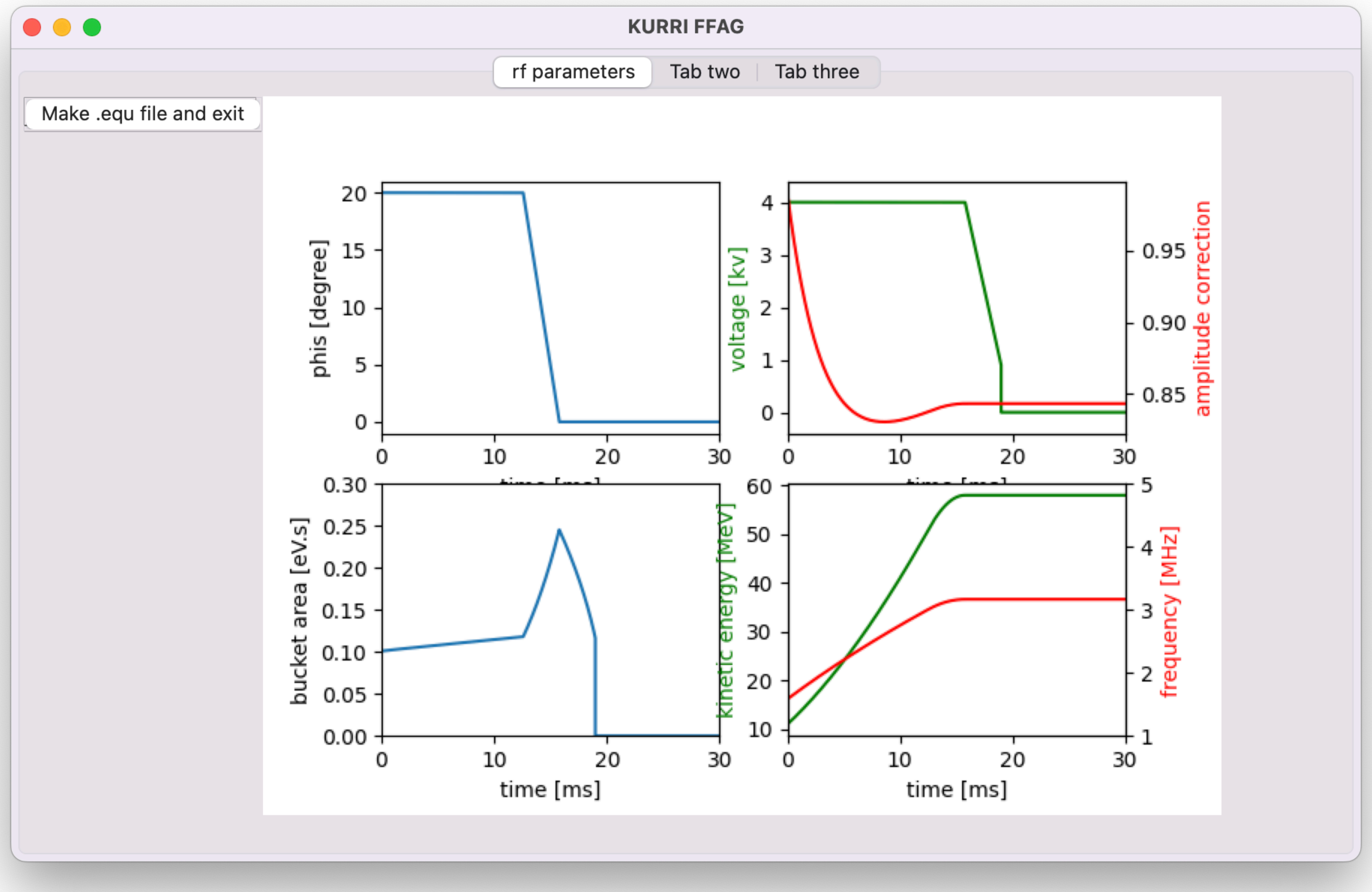
First try of step 1 measurement

between two extreme cases

- Accelerate to 57.98 MeV and abruptly switch off RF from stationary bucket with different voltage.







tmp_13_3_3_11_0.057980_3kV.equ tmp_13_3_3_11_0.057980_2kV.equ tmp_13_3_3_11_0.057980_0.9kV.equ

dp/p depends on (voltage)^0.25 so that the difference should be small.

Science and Technology Facilities Council

First try of step 1 measurement

Schottky scan

- Start taking FAB signal after (or slightly before) RF voltage becomes zero.
- Set windows 1 ms, 5 ms, 10 ms and analyse frequency spectrum.
- Repeat the same analysis for data starting from 1 ms, 5 ms, 10 ms later since RF is off.
    - Search which part of data gives clear signals.
        - The number of sampling.
        - Timing to start sampling.

- FAB signal comes an array of beam current sampled every X ns.
    - Prepare analysis code to see frequency spectrum.

- Width of frequency spectrum is proportional to momentum spread.
- See any difference of Schottky signal for different RF script (first, comparison of two extreme cases).

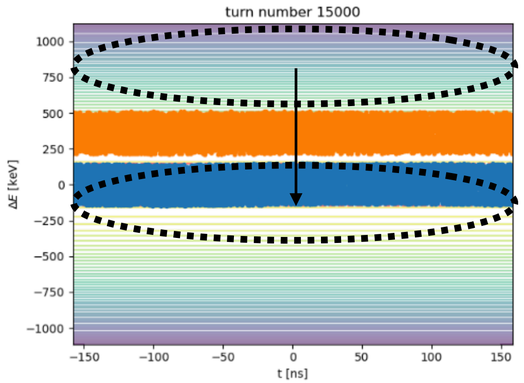
Science and Technology Facilities Council

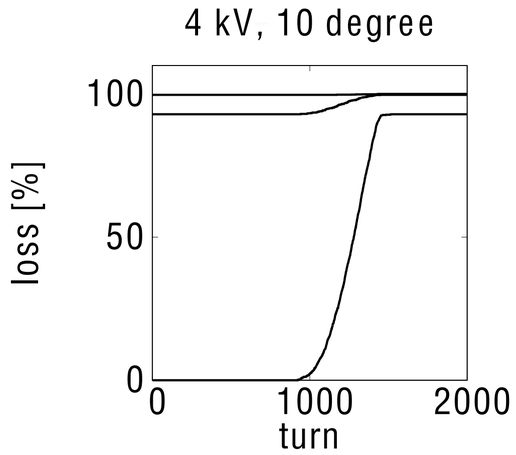
First try of step 1 measurement

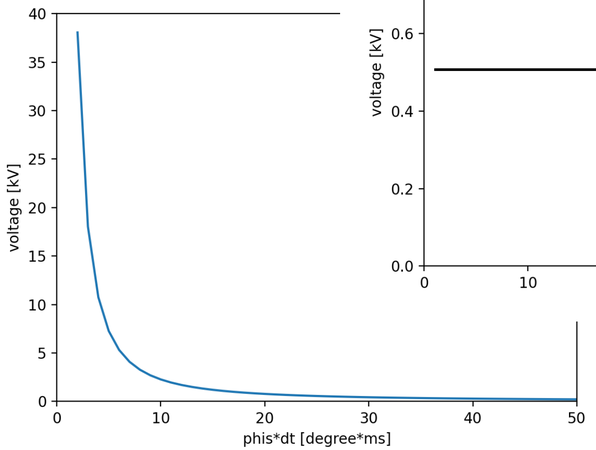
phase displacement

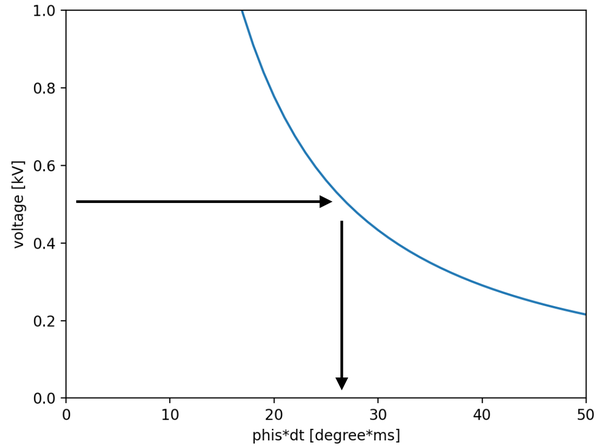
$$300 + 2\sqrt{\frac{V}{4}}630 = 3.167 \times 10^6 V \sin\phi_s \cdot dt$$

- Phase displacement script is added to Script 3 and 4.









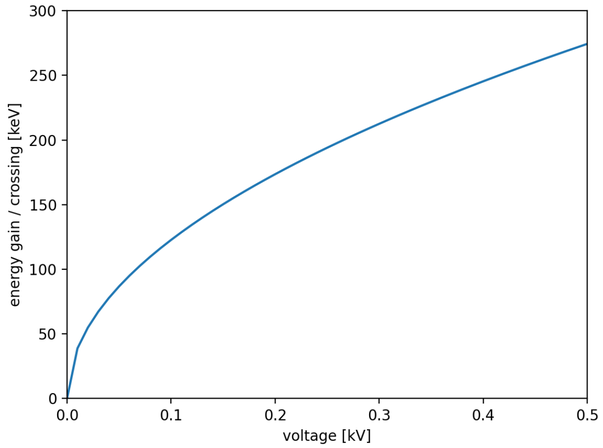
Minimum required shift of empty bucket

dp/p of the coasting beam (full) ~ 300 keV

bucket height (half) with 4 kV ~ 630 keV

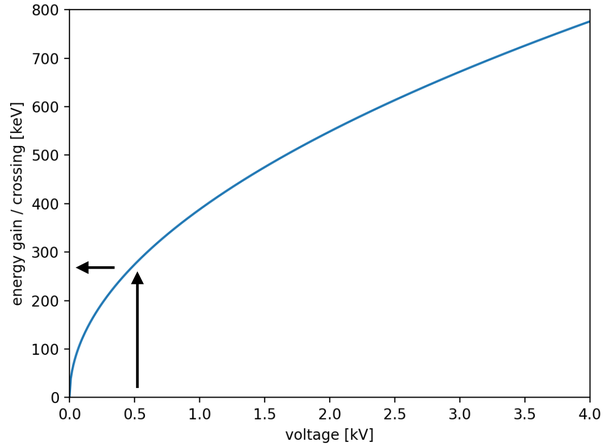
Shift of empty bucket with phis and dt

dE = f_rev V sin(phis) dt



Energy gain per crossing

$$\Delta E = 776\sqrt{V/4} \quad \text{[keV]}$$

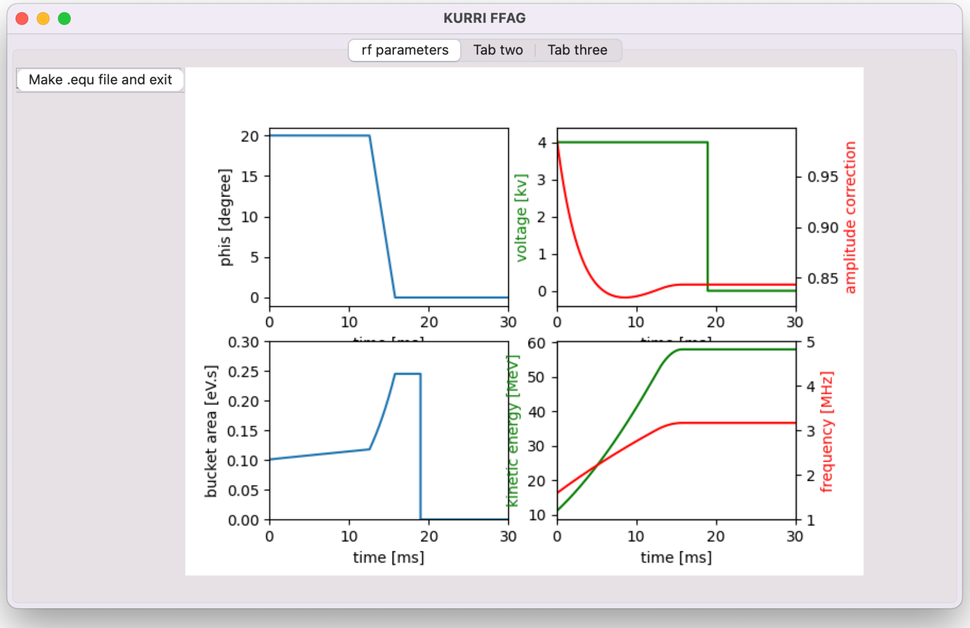


V = 0.5 kV, phis = 5 deg, dt = 6 ms

First try of step 1 measurement (to be ready by next week)

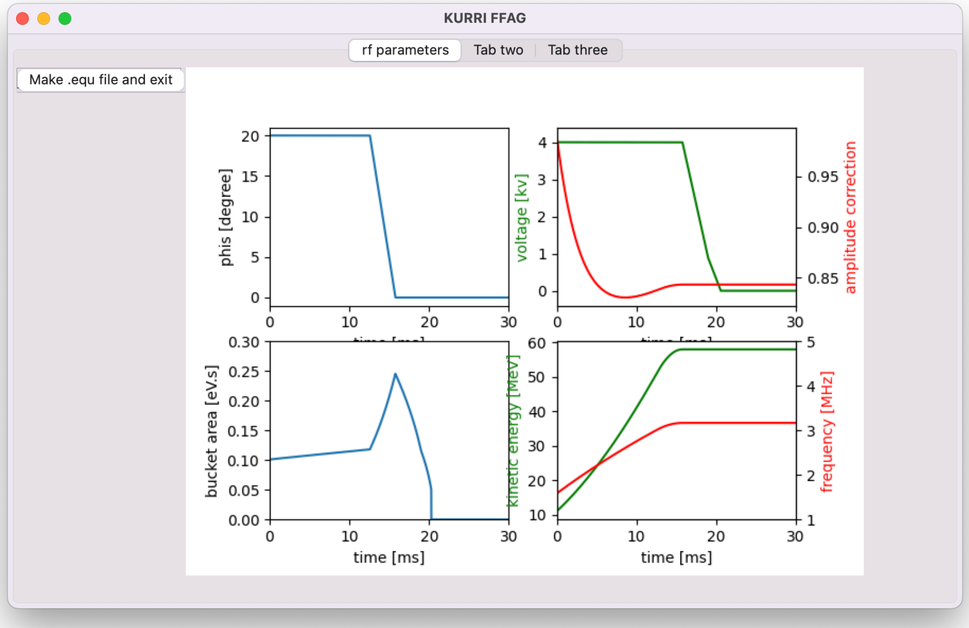
two extreme case of dp/p + phase displacement

- Accelerate to 57.98 MeV and abruptly switch off RF.



tmp_13_3_3_11_0.057980_4kV.equ

- Accelerate to 57.98 MeV and adiabatically debunch.



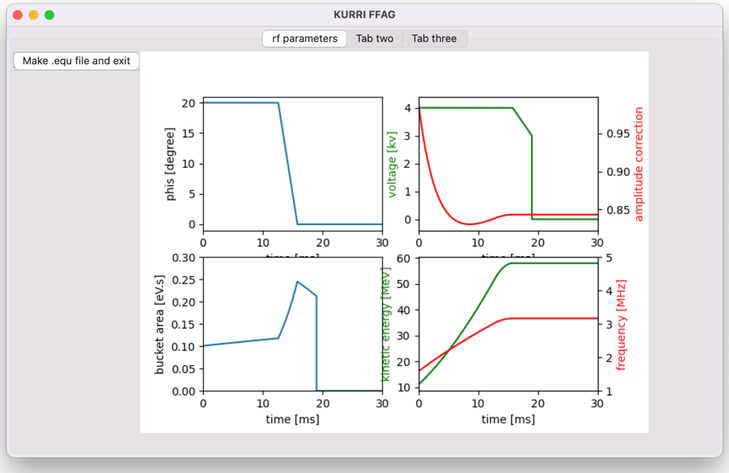
tmp_13_3_3_2_9_0.057980.equ

Science and Technology Facilities Council

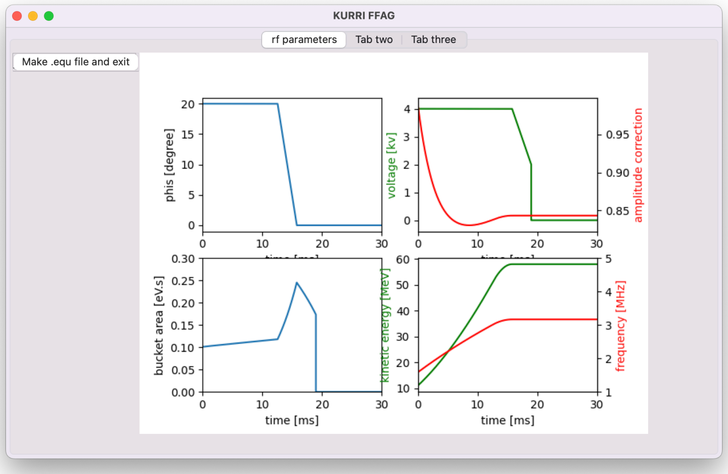
First try of step 1 measurement (to be ready by next week)

between two extreme cases + phase displacement

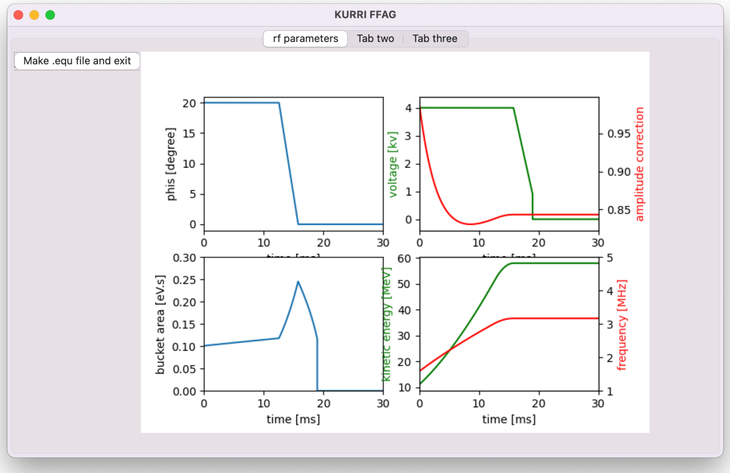
- Accelerate to 57.98 MeV and abruptly switch off RF with stationary bucket with different voltage.



tmp_13_3_3_11_0.057980_3kV.equ



tmp_13_3_3_11_0.057980_2kV.equ



tmp_13_3_3_11_0.057980_0.9kV.equ

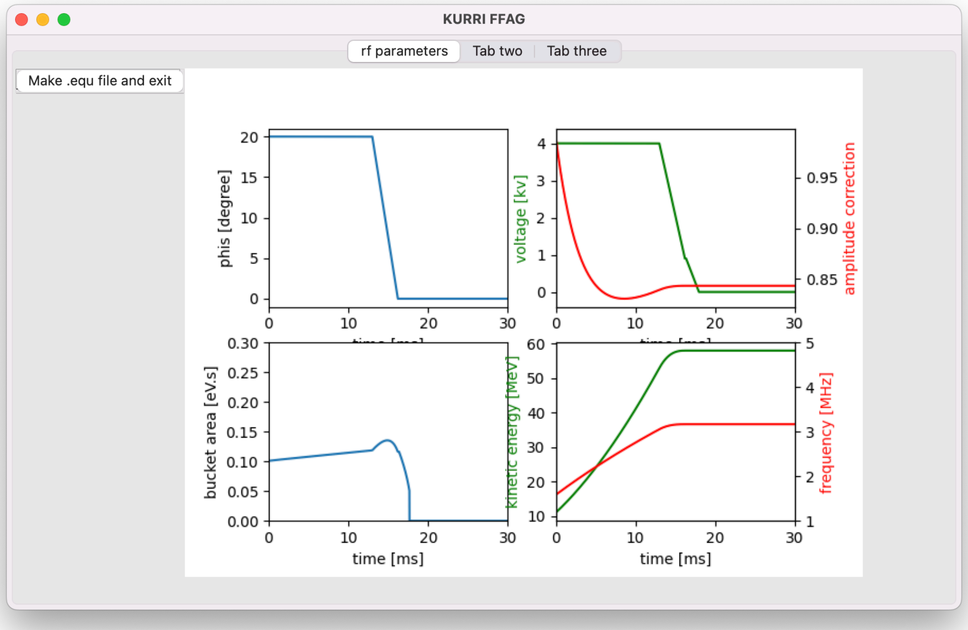
dp/p depends on (voltage)^0.25 so that the difference should be small.

Science and Technology Facilities Council

First try of step 1 measurement

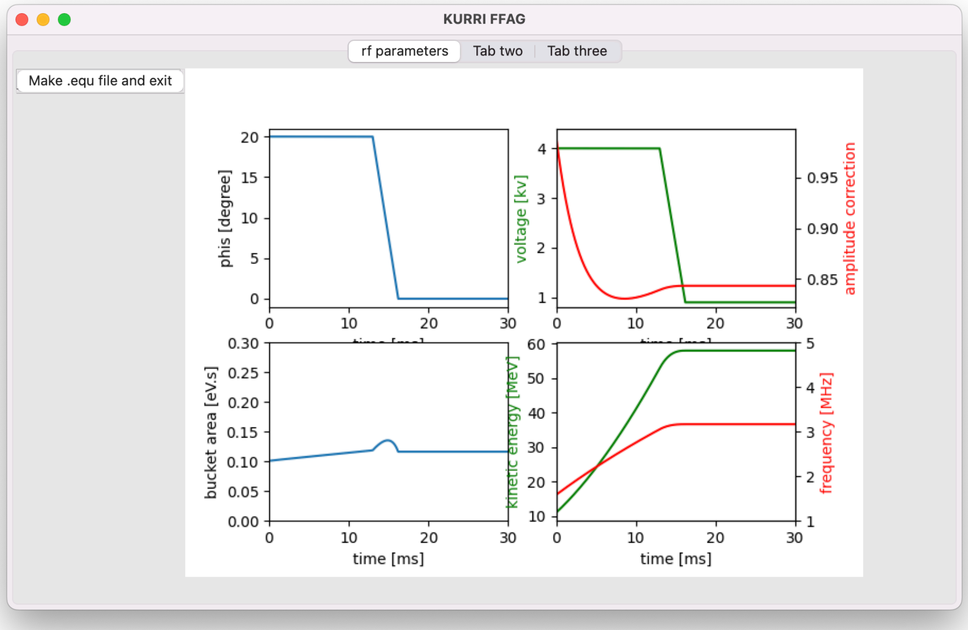
tomography before debunching

- David made this.



tmp_13_3_0_2_12_0.057983.equ

- Maybe no need to reduce voltage after tomography measurement.



tmp_13_3_14_0.057983.equ

Science and Technology Facilities Council

Step 1: One bunch only

Subject	Preparation	Measurements
Debunch adiabatically the 1st bunch	• Determine RF profile (frequency and voltage) to minimise dp/p after debunch • Fix energy for debunching (two or three).	• dp/p measurement • Feasibility and accuracy
Rebunch the coasting beam	• Determine RF profile (frequency and voltage) to minimise longitudinal emittance	• Beam intensity measurement • Longitudinal tomography measurement
Repeat debunch and rebunch process	• Same above	• **Beam intensity**, **dp/p** increase at debunch, **longitudinal emittance** increase at rebunch vs. the number of process

Science and Technology Facilities Council

What would be the AWG requirements?

Test of step 2 and 3 measurements

Science and Technology Facilities Council

Test of step 2 and 3 measurements

- Acceleration of h=2 RF frequency.
  - How high energy h=2 RF can be used for acceleration.

  - Accelerate the beams up to ~ 50 MeV and debunch to see if feasible.
  - Acceleration of h=2 empty buckets.

- Test trigger
  - If the second trigger can add another acceleration cycle without disturbing the first beam.

- Roughly ~1 days (excluding offline analysis)?

Science and Technology Facilities Council

Test of step 2 and 3 measurements (to be ready by next week)

h=2 acceleration

- Acceleration with h=1 RF up to ~50 MeV.
  - By integrating bunch signal, measure beam current (AC component) as a function of time.

- Acceleration with h=2 RF up to ~50 MeV.
  - Do the same above.

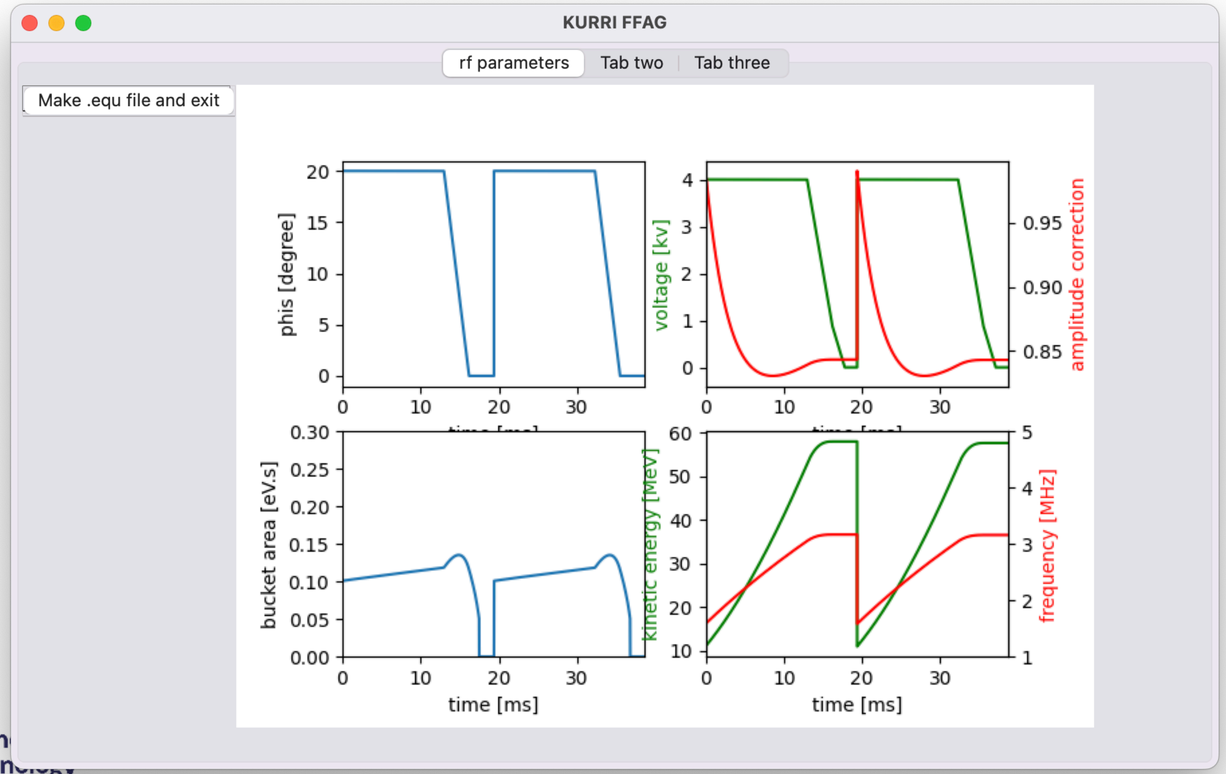
- Compare beam current vs time for h=1 and 2. Acceleration with h=2 may have significant beam current reduction at some timing (momentum).

- Repeat with different phis.
  - Assume that ordinary operation uses phis=20 degree. Try 10, 30, … degree and compare h=1 and 2.

Test of step 2 and 3 measurements

trigger test

- Test trigger
  - If the second trigger can add another acceleration cycle without disturbing the first beam.
  - AWG script composed of acceleration of 1st beam, debunching of 1st beam and acceleration of 2nd beam.
  - Synchronise the injection of 1st beam and 2nd beam. How?



Two beam stack with h=1.

1st beam injection at t=0

2nd beam injection at t=19.39 ms

How accurately the energy difference should be specified.

57.98 MeV and 57.62 MeV

tmp_13_3_2_2_13_3_2_2_0.057637.equ

Step 2: One coasting beam and an empty bucket

Subject	Preparation	Measurements
After debunching at E1, increase RF voltage with frequency at several points between injection and E1.	• Simulation to see how the coasting beam is affected. • When E1 is increased and RF frequency ratio approach 2, how quickly interference grows?	• dp/p measurement vs time (time scale should be determined by simulation)
Increase the energy of an empty bucket and adiabatically decrease voltage as if the beam is accelerated and debunched.	• Simulation to see how the coasting beam is affected.	• dp/p measurement
(optionally) rebunch the coasting beam	• Same with one bunch	• Beam intensity measurement • Longitudinal tomography measurement

Science and Technology Facilities Council

Step 3: One coasting beam and another accelerating beam

Subject	Preparation	Measurements
Increase the energy of the 2nd beam and adiabatically decrease voltage.	• Simulation to see how the coasting beam is affected and the 2nd beam is added.	• dp/p measurement
Rebunch the coasting beam from two acceleration.	• Determine RF profile (frequency and voltage) to minimise longitudinal emittance	• Beam intensity measurement • Longitudinal tomography measurement
Repeat debunch and rebunch process (similar to measurement with one bunch but different dp/p)		• **Beam intensity**, **dp/p** increase at debunch, **longitudinal emittance** increase at rebunch vs. the number of process

Science and Technology Facilities Council

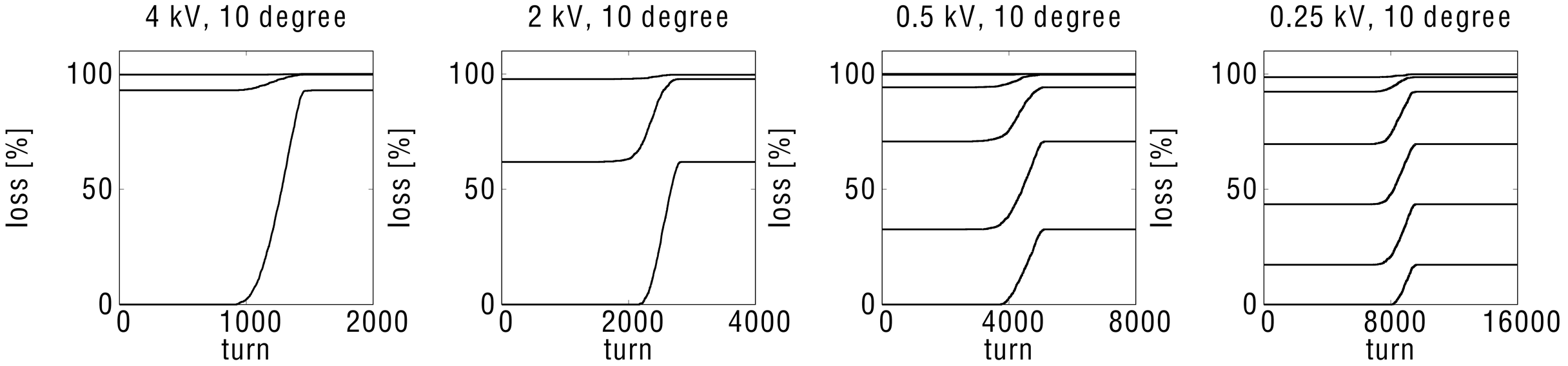
Backups

Science and Technology Facilities Council

First try of step 1 measurement

phase displacement and CR's proposal

- Repeat phase displacement acceleration with as low voltage as reasonable (0.25 kV?).
- Measure beam loss at scraper.
  - With larger dp/p, the beam loss signal lasts longer.



- Record bunch monitor signal in the process of empty bucket crossing.
  - Set the scraper position so that the first crossing does not cause beam loss, only appearance of bunch monitor signal.
  - Whether timing of bunch monitor signal is different for small and large dp/p beams.

Science and Technology Facilities Council