Demonstration of stacking in a scaling FFA

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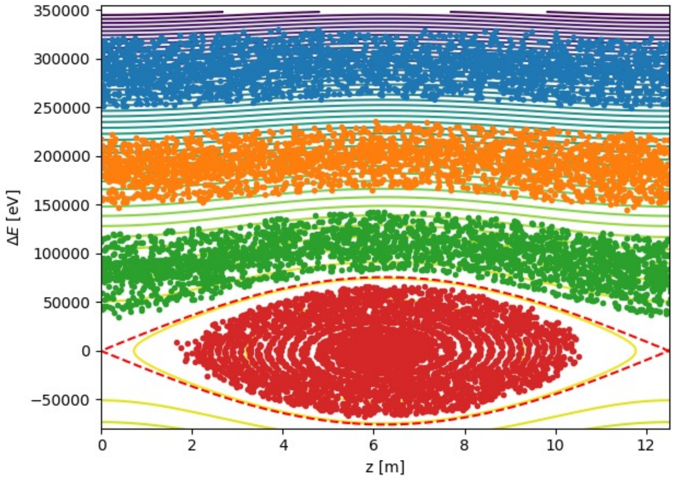
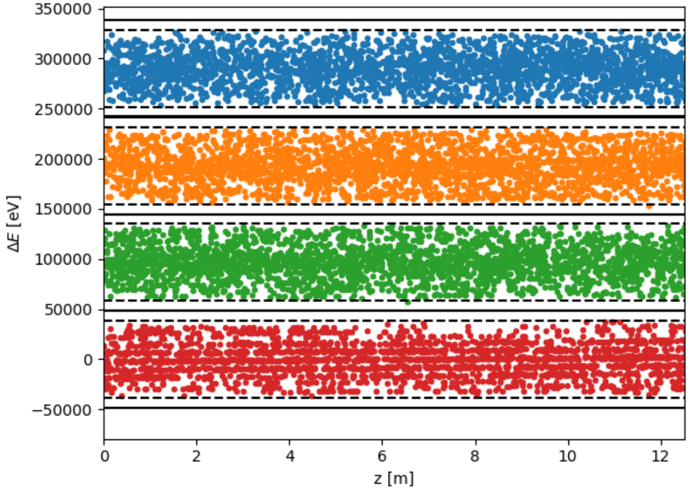
Beam stacking

- Beams can be stacked by placing multiple coasting beams alongside one another in longitudinal phase space.
- FFAs naturally accommodate stacking because of their large momentum acceptance, DC magnets and flexible RF.
- Beam stacking allows a low rep rate beam to be extracted with high brightness, circumventing the space charge limit at injection.

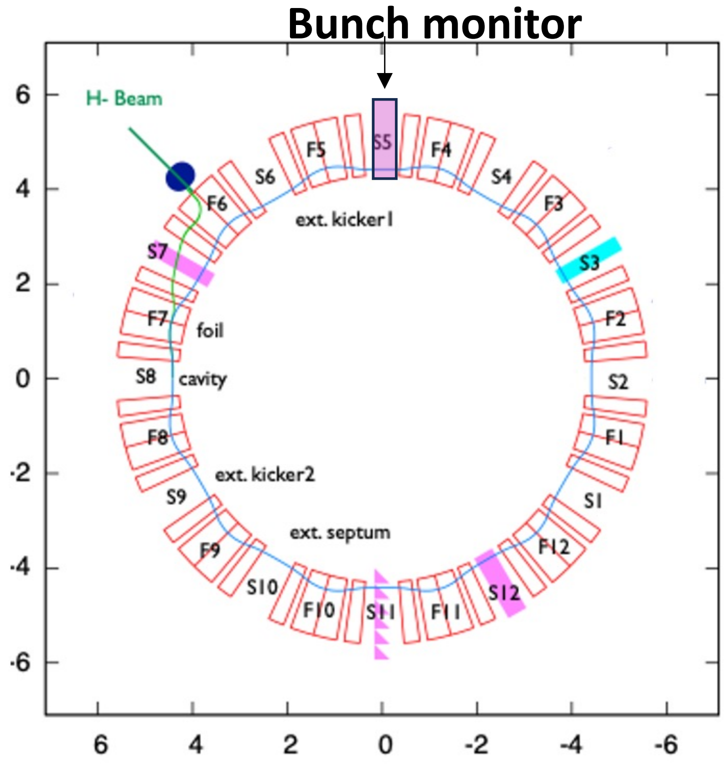




KURNS demonstration

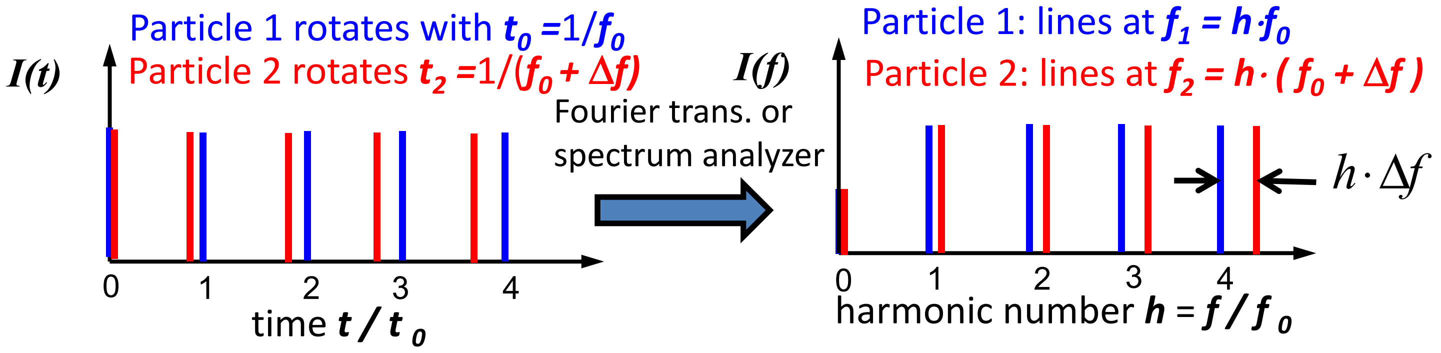
- Aim - first systematic demonstration of beam stacking in FFAs.
- Two beams brought to stacking energy (35 MeV) and allowed to coast.
- Acquire Schottky signal while beam is coasting.

KURNS FFA parameters	
Energy range	11 – 150 MeV
Radius	4.6m – 5.3m
RF Cavity Type	Magnetic Alloy
RF voltage	4 kV
RF frequency range (h=1)	1.6 – 5.2 MHz



Schottky signal of a coasting beam

- A single particle circulating with period T_i produces an infinite train of delta function in both the time and frequency domain.

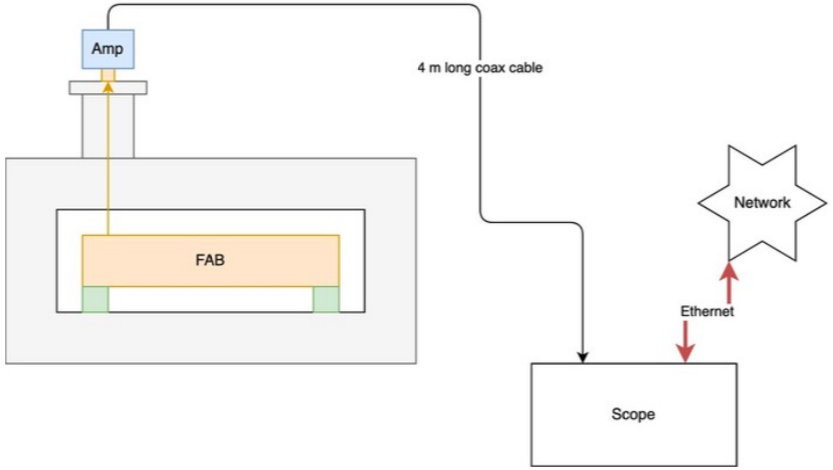


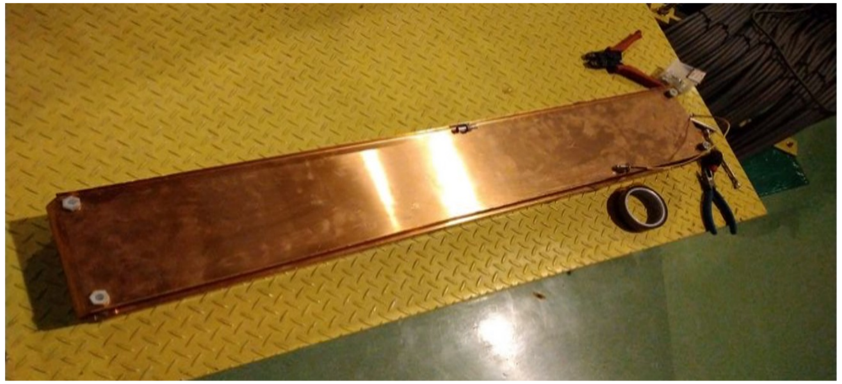
- For N randomly distributed particles, each line is replaced by a band with finite width.
- The Schottky signal provides a measure of momentum spread and intensity N (via the power spectrum density).

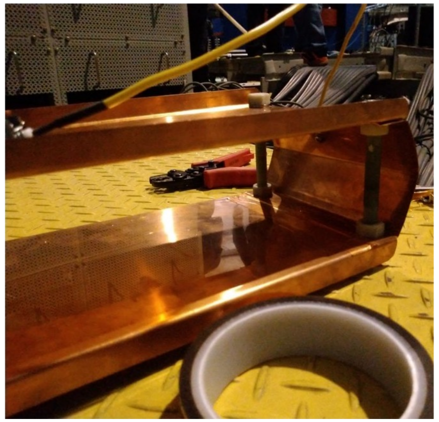
$$df = h\eta h_0 \frac{dp}{p_0} \qquad \int \frac{dP_h}{df} df = 2Z_t e^2 f_0^2 \int \frac{dN}{df} df$$

Bunch monitor

- Full Aperture Bunch monitor (FAB) is a capacitive pickup that measures the bunch sum signal.
- The signal amplifier (46 dB, bandwidth 80 MHz) is mounted directly above the monitor.
- In order to reduce noise, a LeCroy scope was placed next to the monitor and controlled remotely. Low pass filter before amplifier to eliminate aliasing from higher frequencies. Scope sample rate set of maximum.

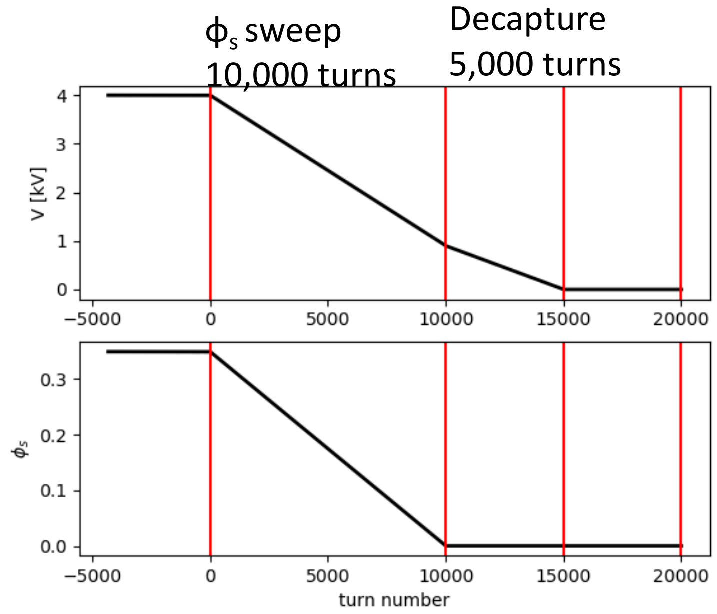


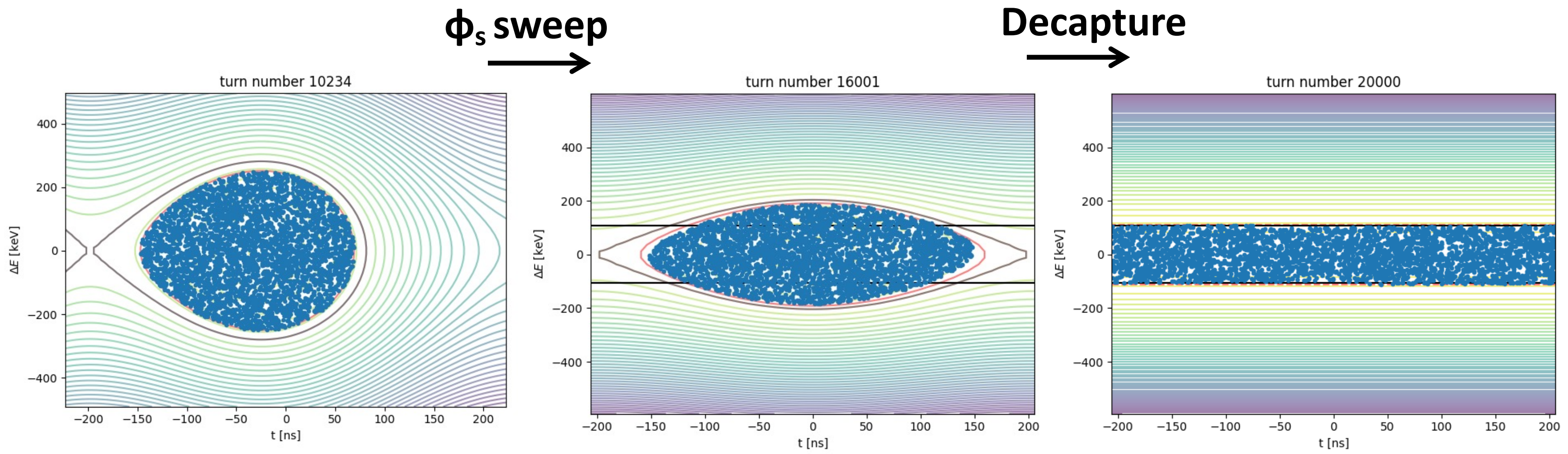




RF program to stack one beam

- Stacking each beam involves two steps
  - **ϕ_s sweep**: Reduce synchronous phase so that it reaches zero at required energy.
  - **Decapture**: Reduce RF voltage to zero to allow debunching (abrupt or adiabatic).
- Simulations carried out in PyHEADTAIL to establish RF parameters.





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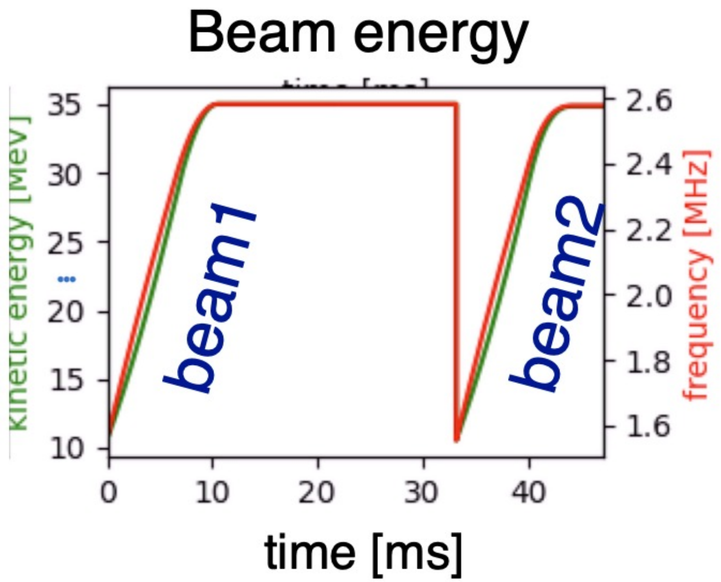
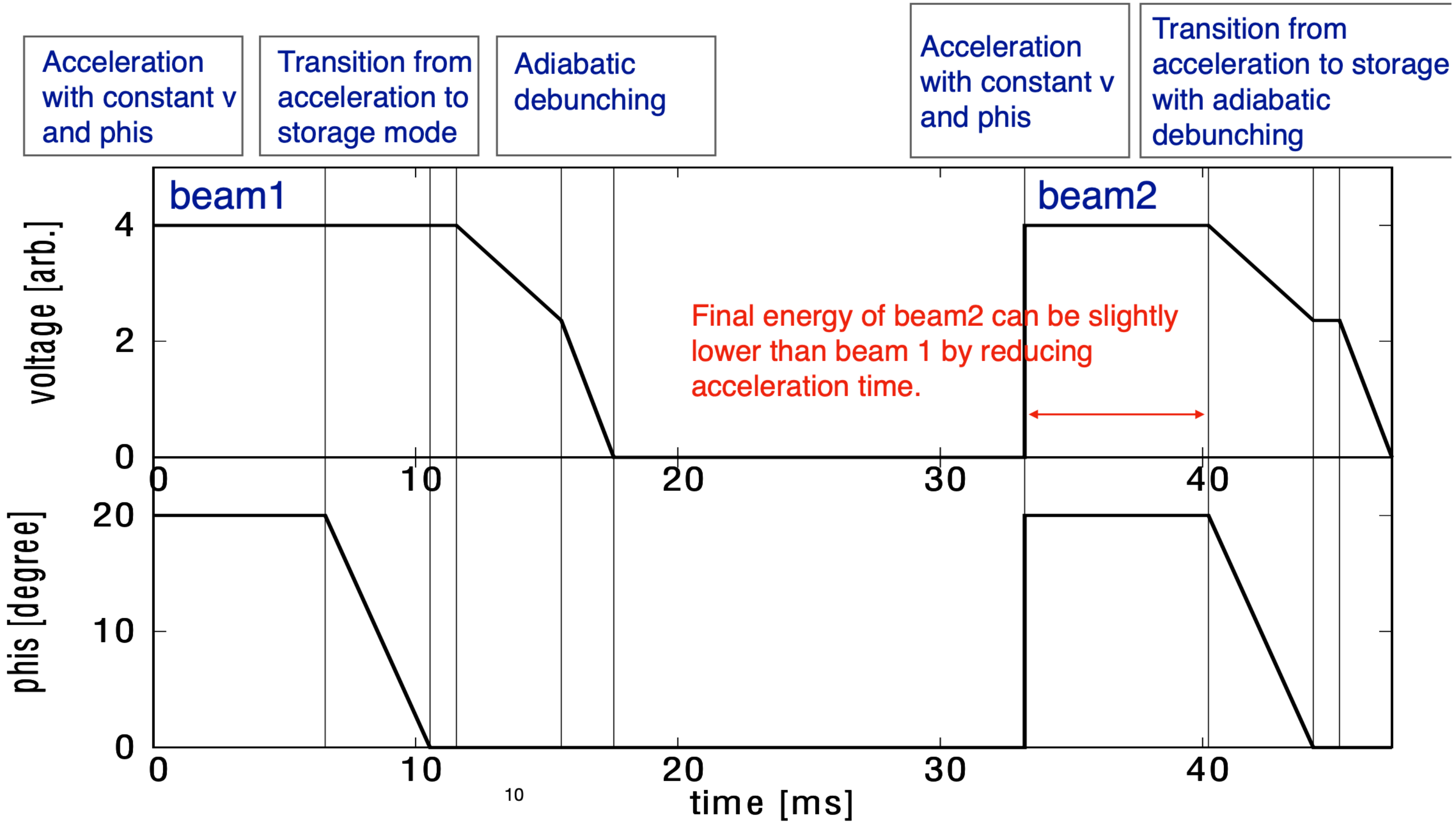
RF program to stack two beams





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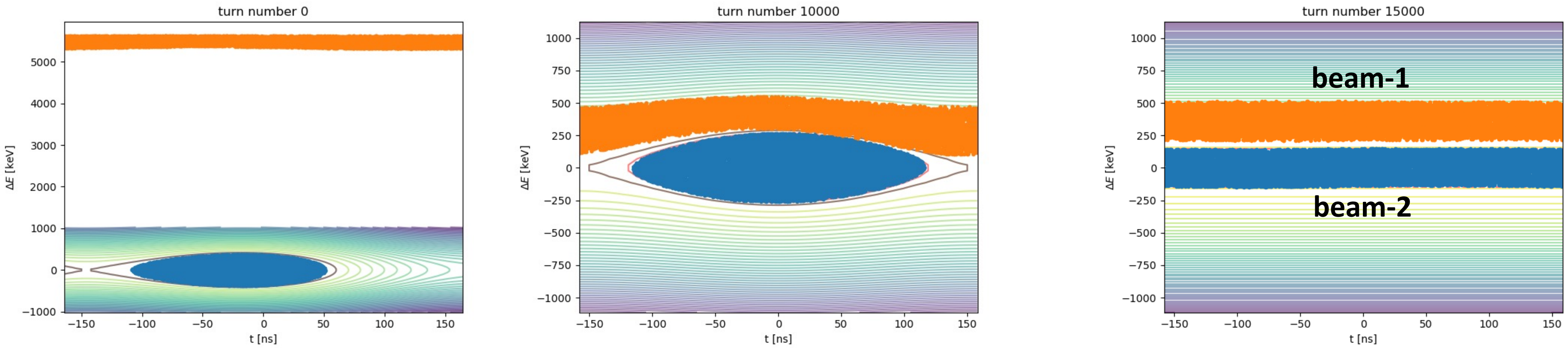
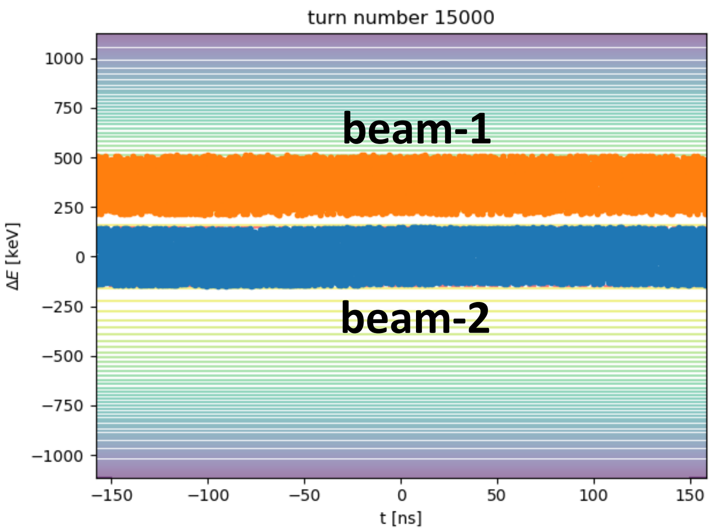
S. Machida

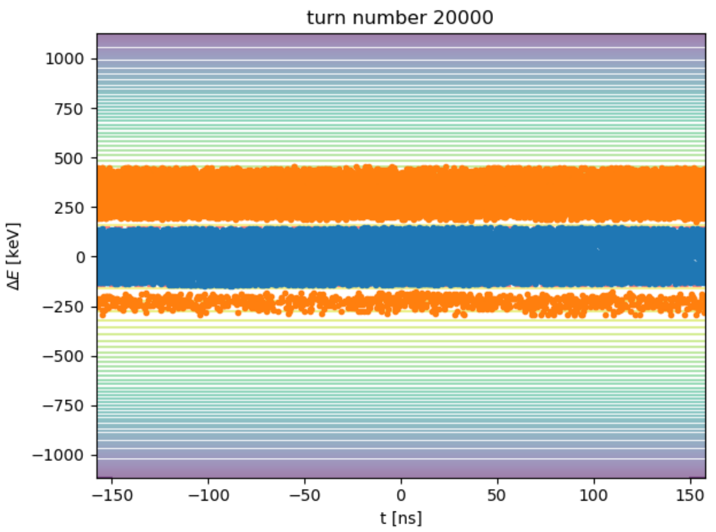
Simulate two beam stacking

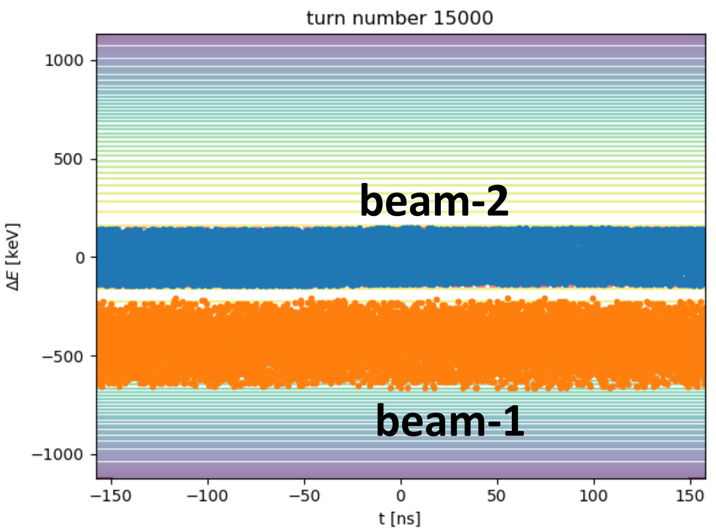


- RF program for beam-2 adjusted so it coasts just below beam-1 in longitudinal phase space.
- Gap due to unfilled bucket. Phase displacement will occur if beam-2 is stacked any closer.

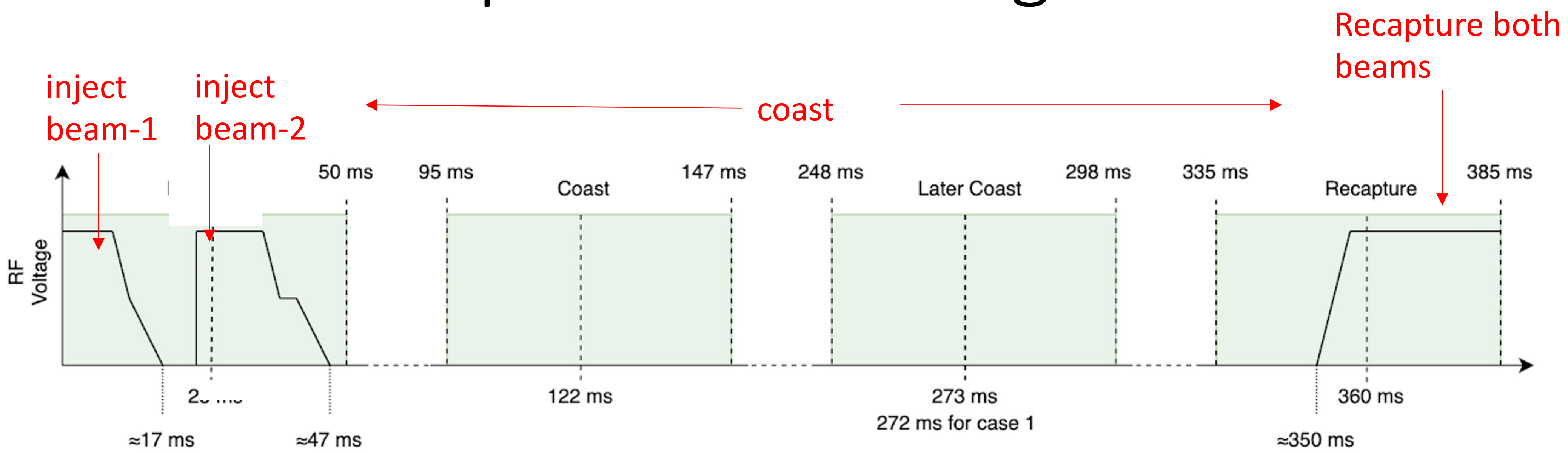
Varying final energy separation







Experiment timings

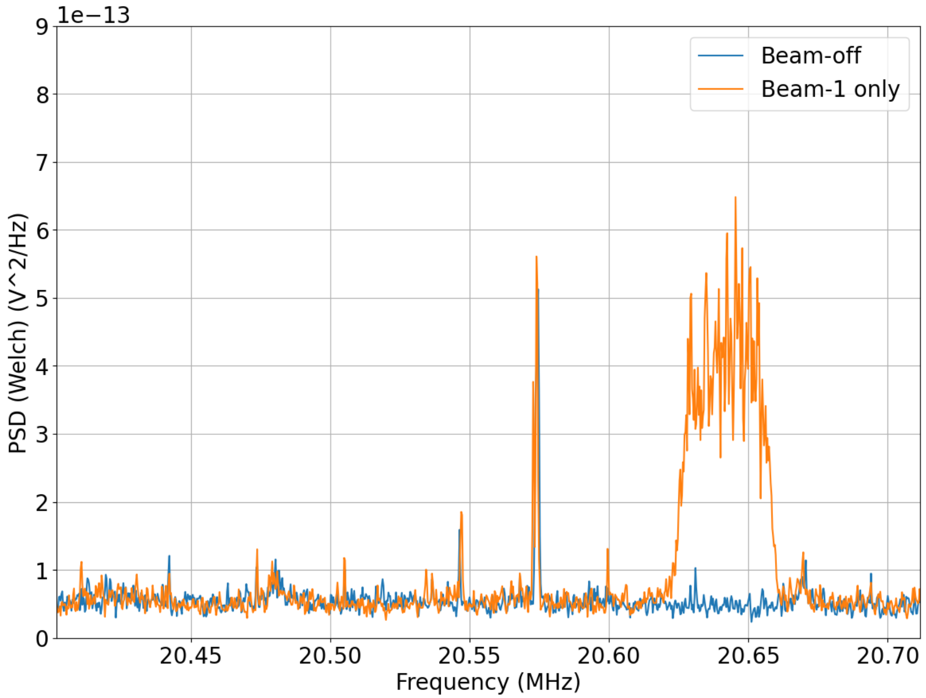


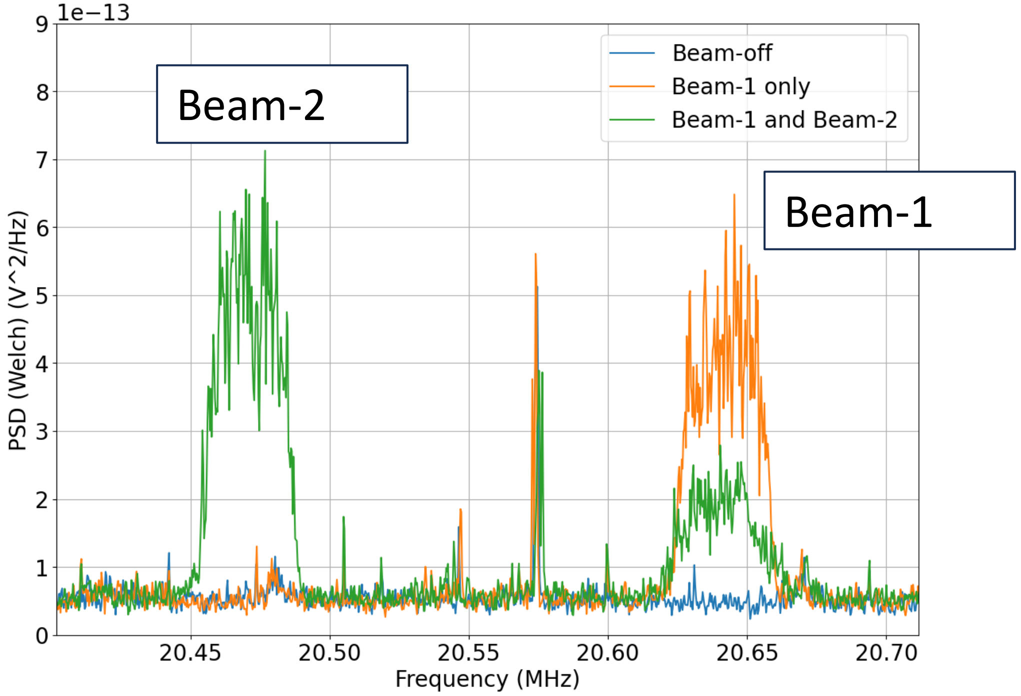
- Aim was to stack two bunches:
  - accelerate then debunch beam-1
  - accelerate then debunch beam-2
  - All both stacked beams to coast
  - recapture both bunches
- Scope data acquisition window set to capture various stages of acceleration, debunching, coasting and recapture.

Beam Stacking

- With a single injected beam, Schottky revolution harmonics were visible after debunching.
    - Plots shows power spectral density (PSD) of 8th harmonic, estimated with Welch method [12, 13].

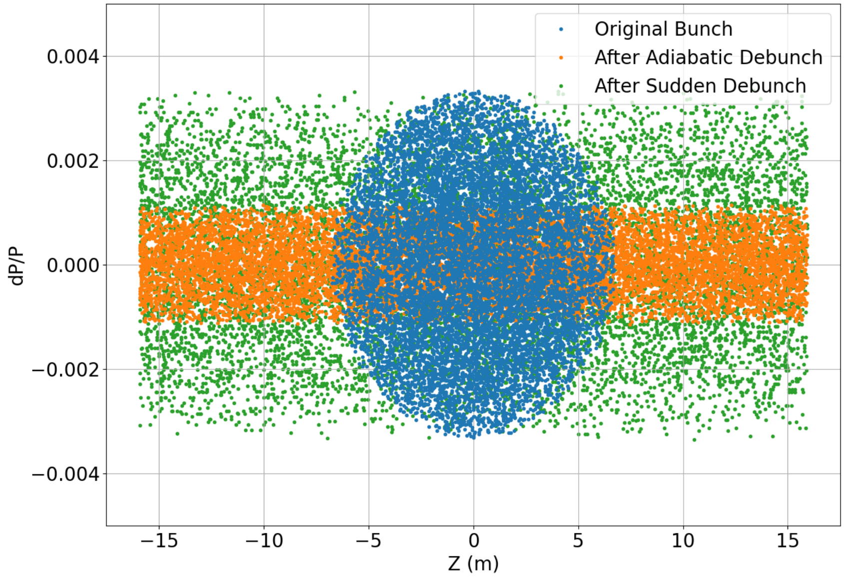
- With two injected beams, two revolution harmonics were visible.
    - Beam-1-losses were observed and are currently being investigated.

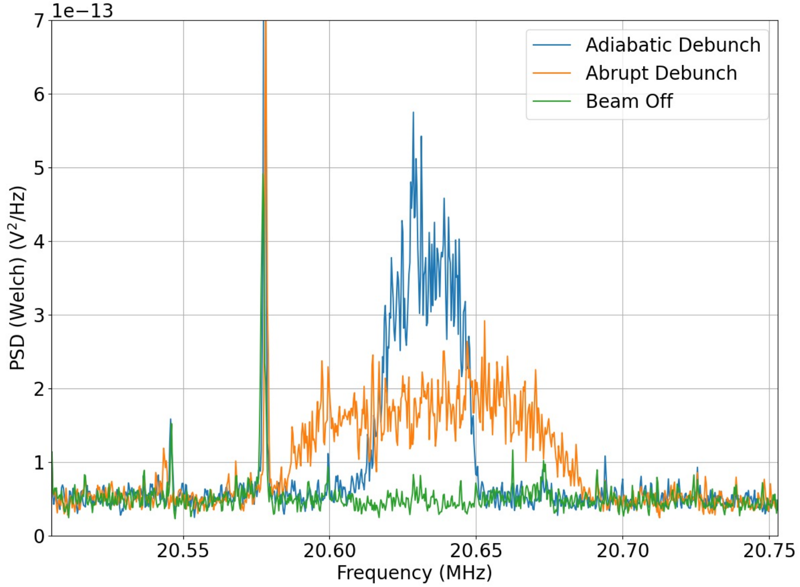




Abrupt vs Adiabatic debunch

- Verified that peak in PSD was a Schottky signal from two measurements with a single injected beam (no stacking).
- In first case, RF amplitude was reduced slowly. Ideally, this should conserve phase space area (adiabatic debunching).
- In second case, RF amplitude suddenly reduced, causing abrupt debunch. Phase space area is not conserved; frequency spread is increased.
- Observed increased peak width when RF amplitude was suddenly reduced.





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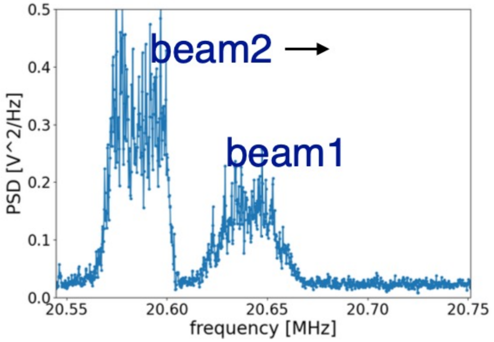
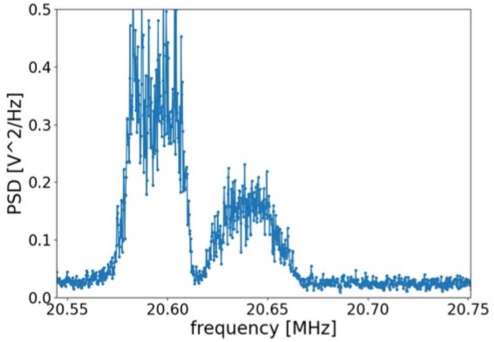
David Posthuma de Boer

Schottky signal as a function of the final energy of beam 2.

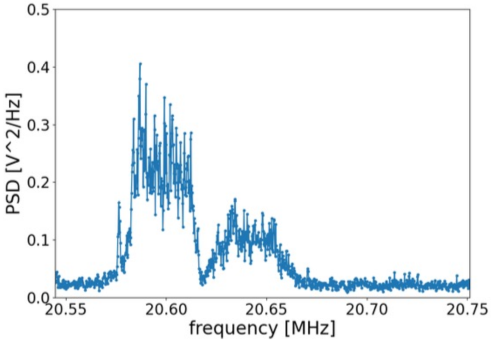
Fitting 2 separated beams.



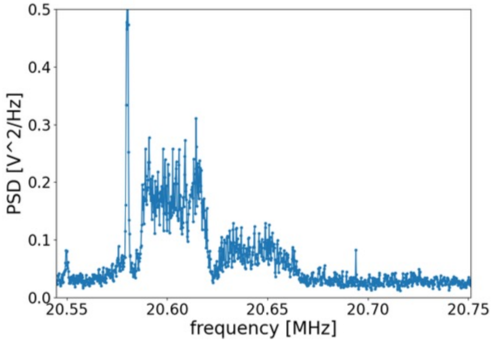
6.96 ms, -235.4 keV



6.97 ms, -200.6 keV

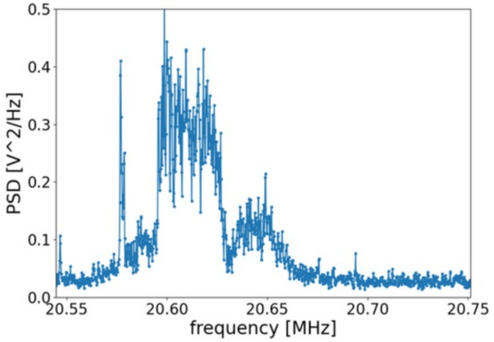


6.975 ms, -182.5 keV

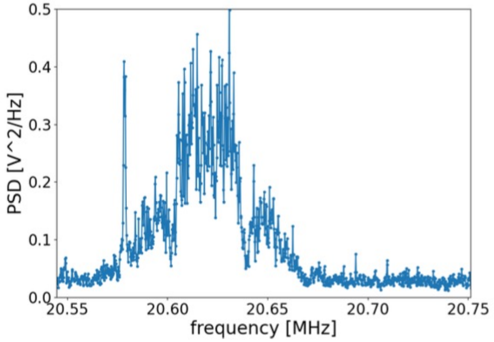


6.98 ms, -165.0 keV

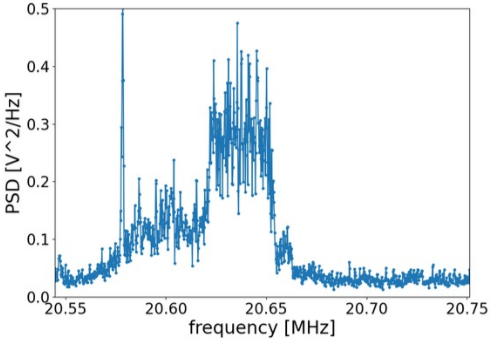
Fitting 3 separated beams, beam2 in the middle with split beam1.



6.99 ms, -129.7 keV



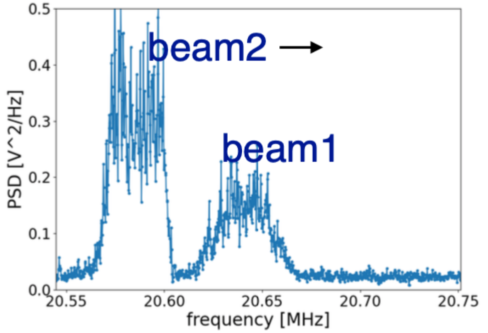
7.00 ms, -94.4 keV



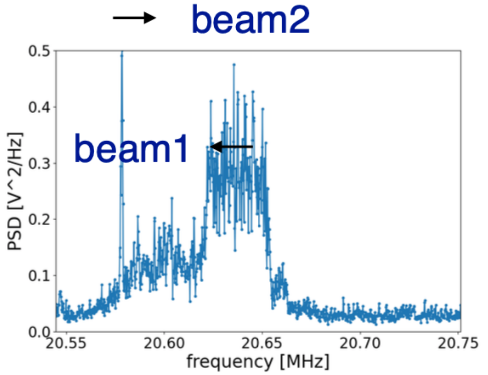
7.02 ms, -23.8 keV

Acceleration time of beam2 — Energy separation (beam2-beam1)

“Phase displacement”



6.96 ms, -235.4 keV



7.02 ms, -23.8 keV

When the RF bucket with or without beams approaches the coasting beam, “phase displacement” occurs.

Theory of cyclic accelerators
A.A. Kolomensky and A. N. Lebedev

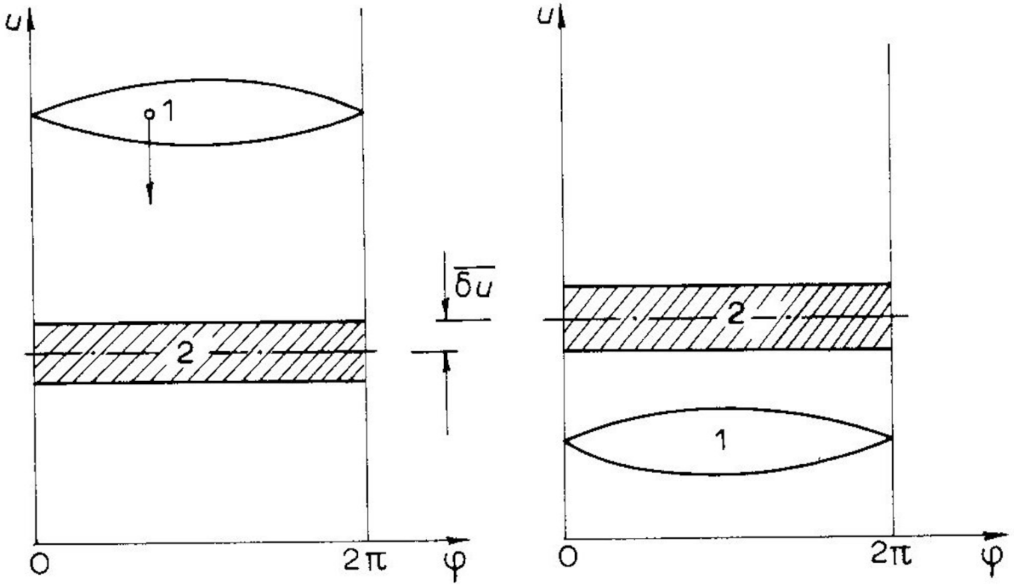


Fig. 81. Illustration of the phase displacement mechanism. 1, region occupied by the bucket; 2, region occupied by the beam; δu, mean displacement along co-ordinate u caused by the motion of the bucket.

$$2\pi\delta u = \text{bucket area}$$

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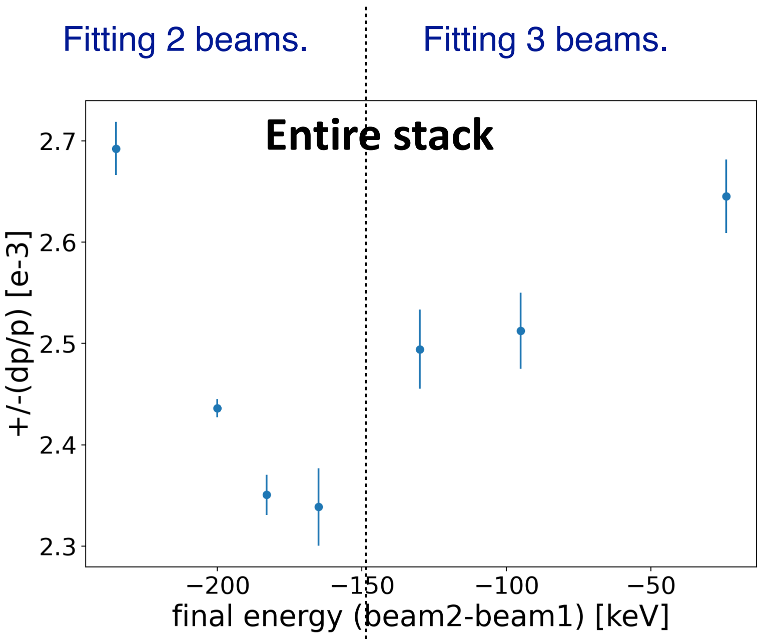
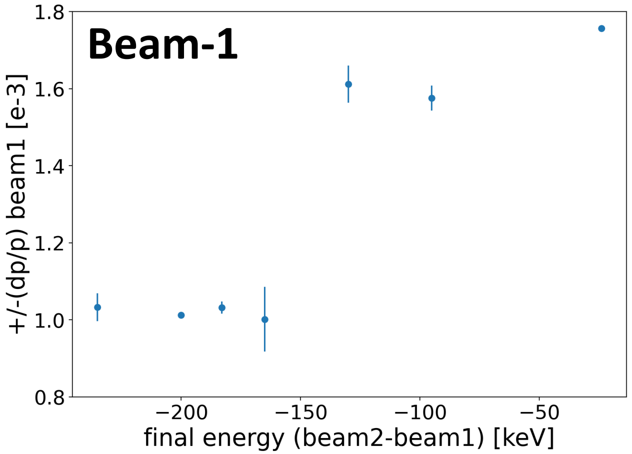
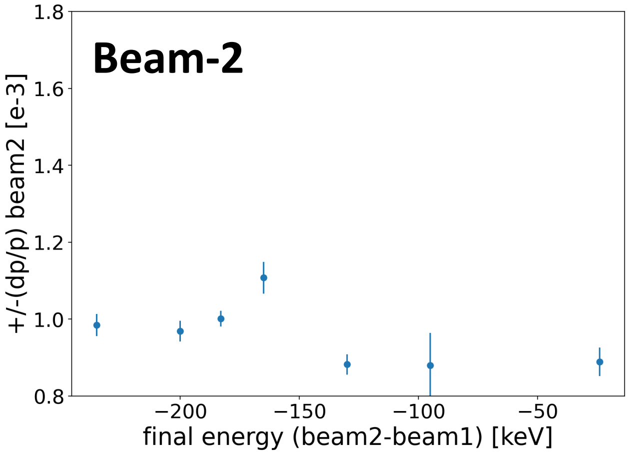
Momentum spread of stack



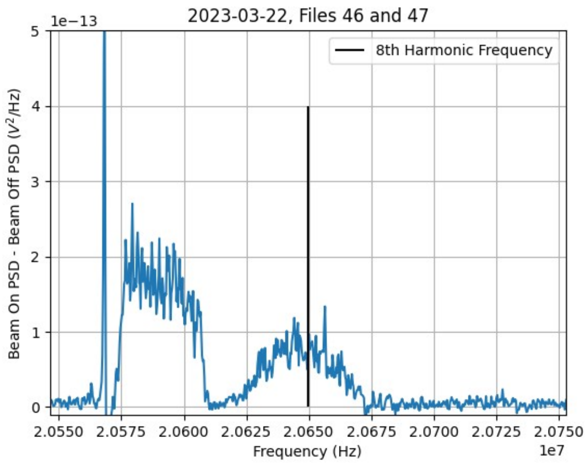


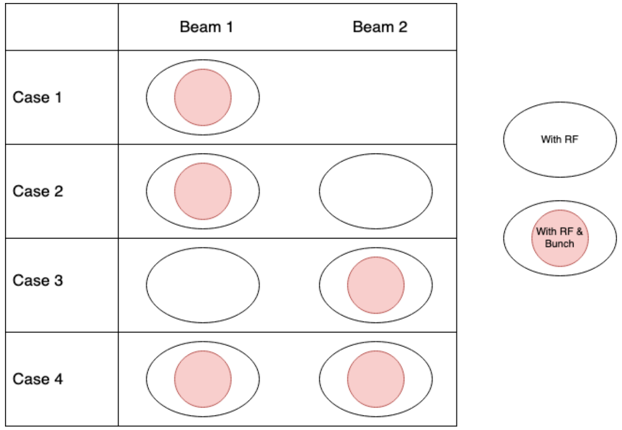


- dp/p unchanged until energy separation falls to ~150 keV.
- Beam-1 momentum spread increases when energy separation <150 keV due to proximity of beam-2 rf bucket.

Beam intensity loss

- beam-1 intensity substantially lower than beam-2 for all cases (by a factor 40% - 60%).
- It is not caused by the extra time beam-1 spends coasting as that is much less than the beam lifetime (~400ms measured in bunched beam storage mode).
- It was found that the loss was similar whether beam-2 was injected or not. It is also observed that the frequency spread of beam-1 is similar to beam-2.
- This implies that the loss is in the transverse plane and is caused by beam-2 RF, i.e. RF knockout.

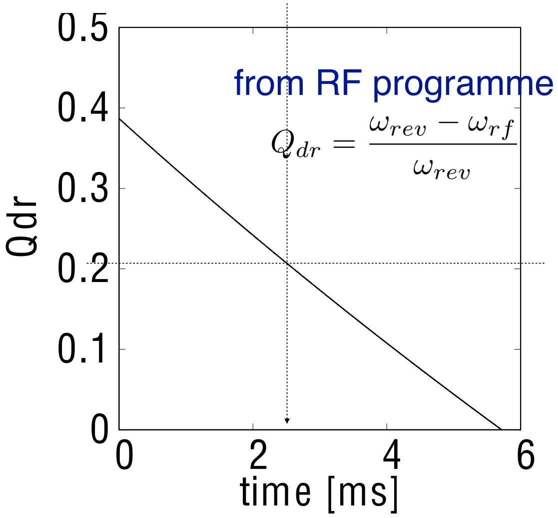


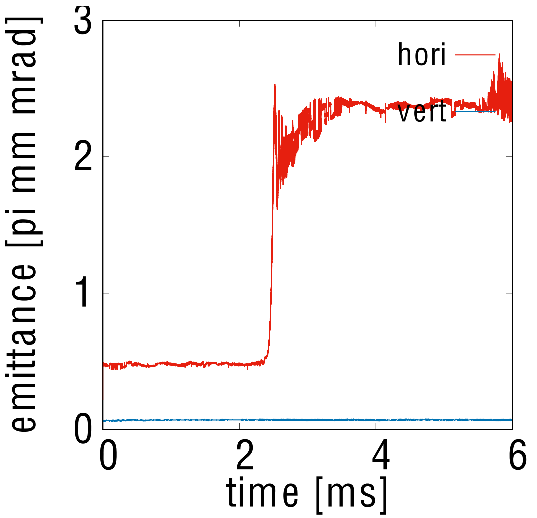


RF Knockout

- Finite dispersion at the RF cavity results in an effective dipole kick.
- When the RF frequency and the betatron frequency satisfy a rational relationship, a resonance can occur.
- The effects was studied during the MURA years!

$$Q_x + mQ_{dr} = n \quad \text{where} \quad Q_{dr} = \frac{\omega_{rev} - \omega_{rf}}{\omega_{rev}}$$





Simulation by S. Machida

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Conclusion

- Controlled stacking of two beams has been demonstrated in the KURNS FFA.
- RF Knockout is a candidate for the loss of intensity in the first beam.
- Solving this issue is critical to establish the feasibility of beam stacking in FFAs.