Longitudinal dynamics in the FETS FFA

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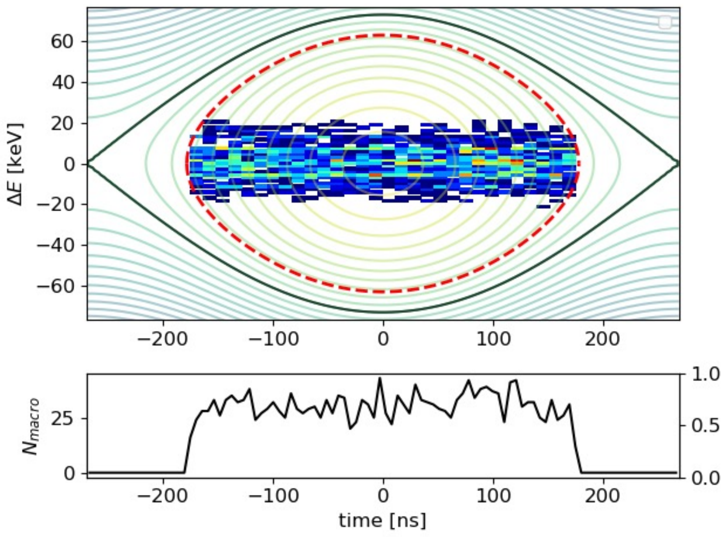
Introduction

- The fixed field of a FFA allows a flexible RF program including:
  - **Adiabatic capture at injection** – allows injection of long pulse and can reduce RF voltage needed.
  - **Rapid sweep of synchronous phase ϕ_s** – no need to follow a ramping bending field (B-dot).
  - **Beam stacking at extraction** – allows flexibility of repetition rate seen by target.
  - **Bunch rotation** – can be used to minimise bunch length.

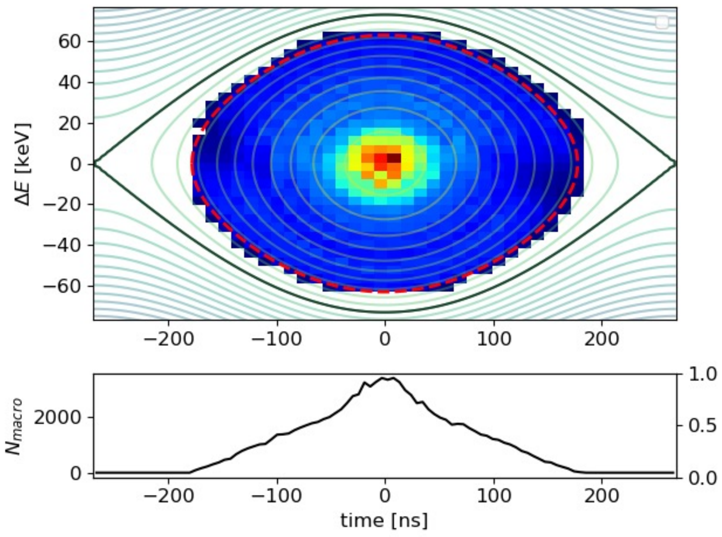
- Main Goals:
  - **Lossless acceleration in 100Hz-equivalent cycle**– In practice we aim to accelerate within 8ms
  - **Demonstrate beam stacking at extraction –** Stack, rebunch and extract 4 bunches.

Bunched beam capture at injection

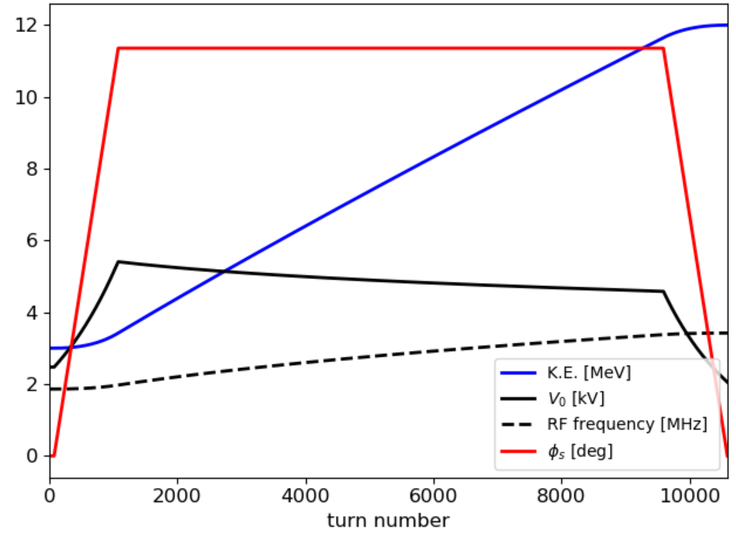
- Synchrotron oscillations causes the beam to fill a Hamiltonian contour leading to an increase in emittance.
- Here a beam with duration 350ns with momentum spread +/- 0.004 is injected for 50 turns. Synchrotron period ~100 turns.



Injection turn 1



Injection turn 50

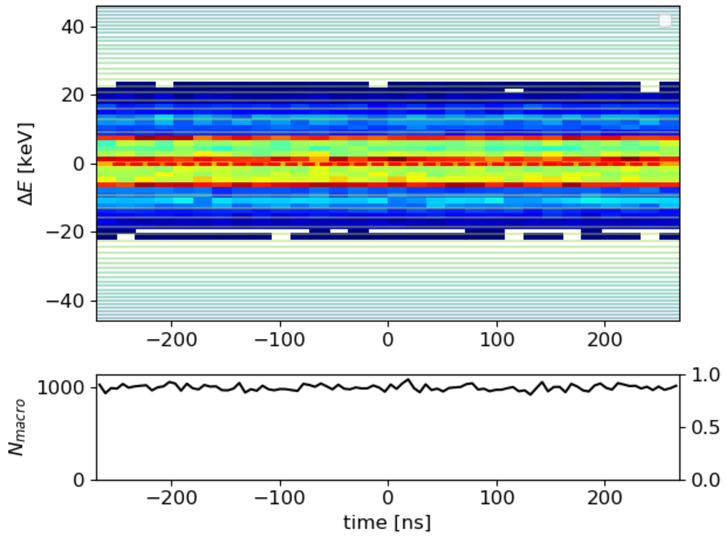


RF program

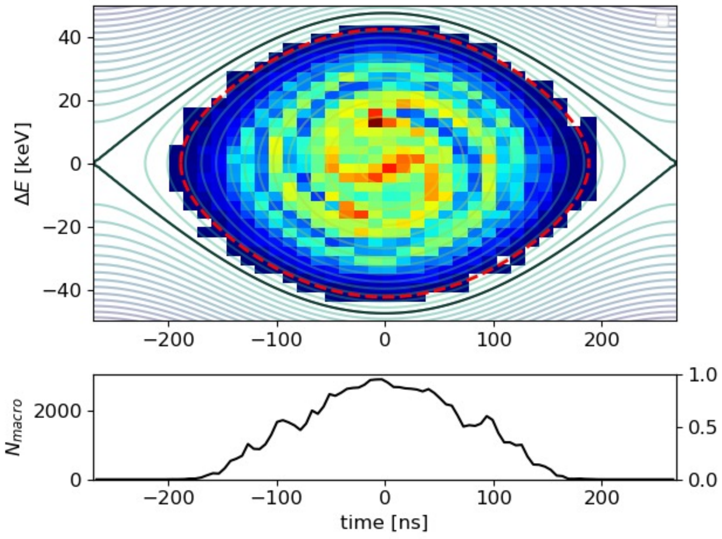
- Low intensity case (space charge is neglected).
- Effect of foil crossing neglected.
- Bucket area: 0.1 Vs, RF voltage at injection: 2.5 kV

Adiabatic capture at Injection

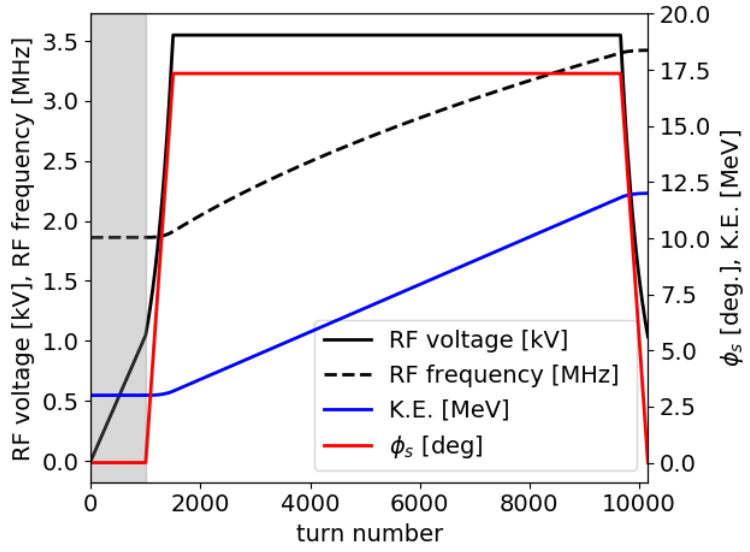
- Adiabatic capture, in the ideal case, avoids an increase in longitudinal emittance. This leads to a lower RF voltage requirement as the bucket area can be reduced.
- This must be balanced against the longer time required for capture.



Injection complete



Turn 1000



RF program

- Low intensity case (space charge can be neglected).
- Effect of foil crossing neglected.
- Emittance is conserved.
- Bucket area: 0.065 Vs, RF voltage: 1.0 kV

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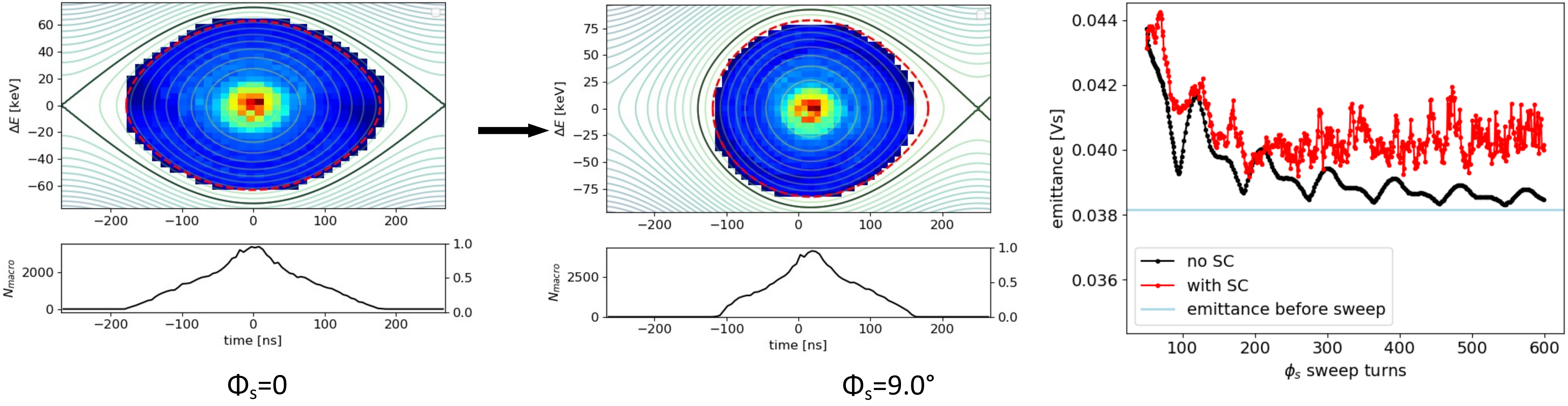
Synchronous phase sweep



- In a synchrotron ϕ_s follows time derivative of dipole field (”B-dot”). No such constraint in FFA.
- Changing ϕ_s is analogous to moving the pivot of a pendulum. For minimal emittance increase, sweep should be done in an integer multiple of synchrotron periods.

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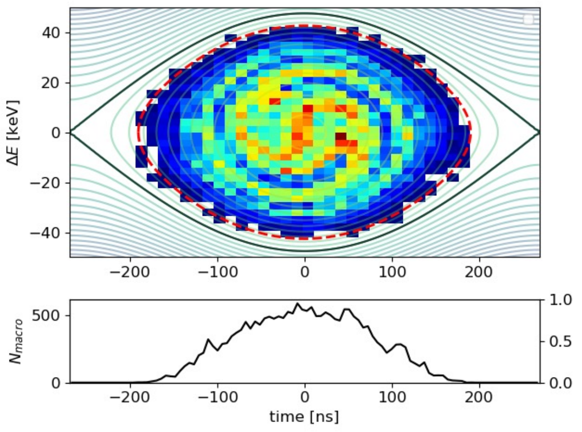
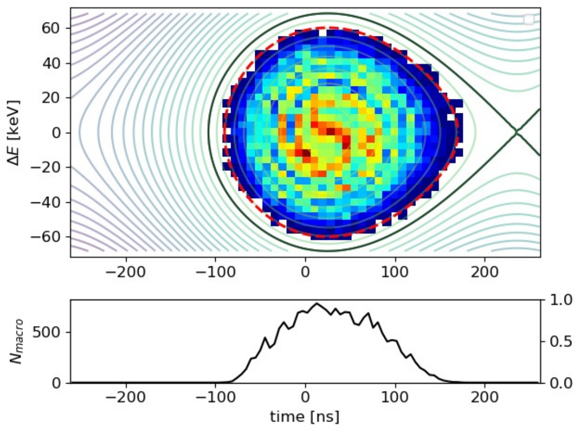
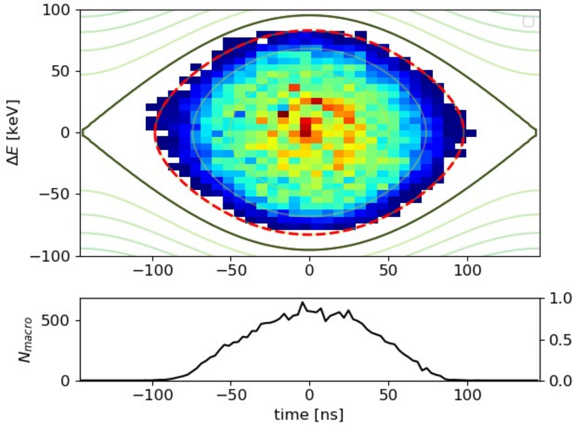
Tracking results without space charge (adiabatic capture case)



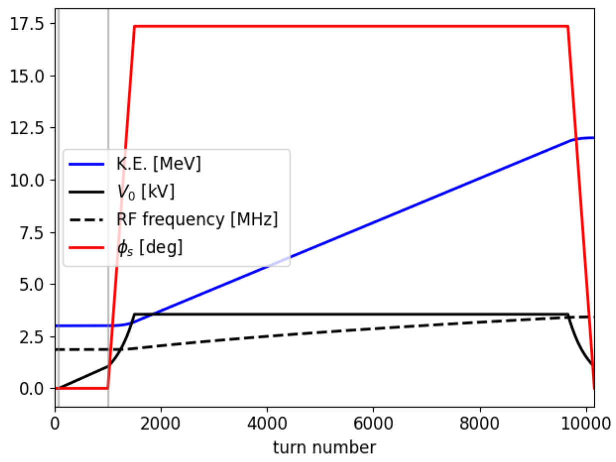
Turn 1000 (after capture)



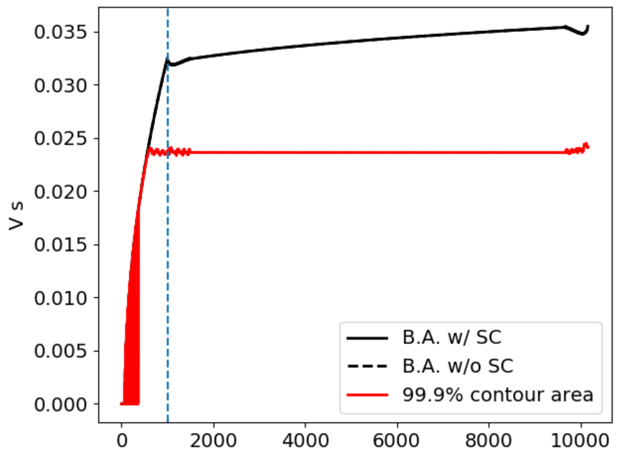
Turn 1500 (after ϕ_s sweep)



Final turn (12 MeV)

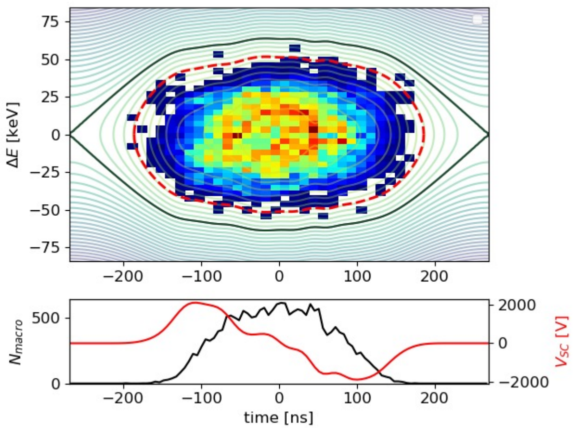


RF program

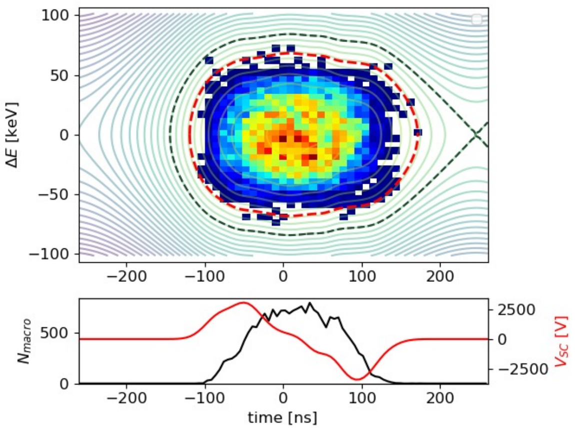


Emittance and bucket area

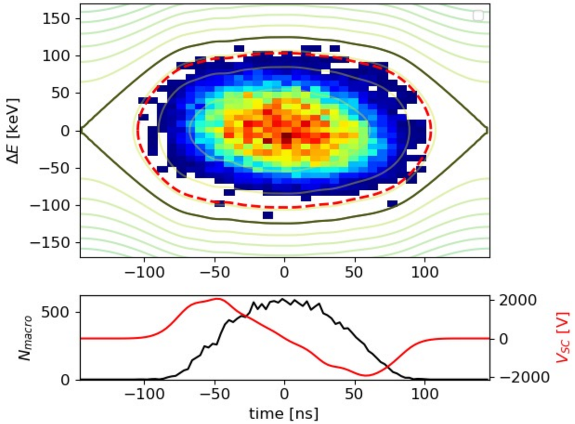
Tracking results with space charge (adiabatic capture case)



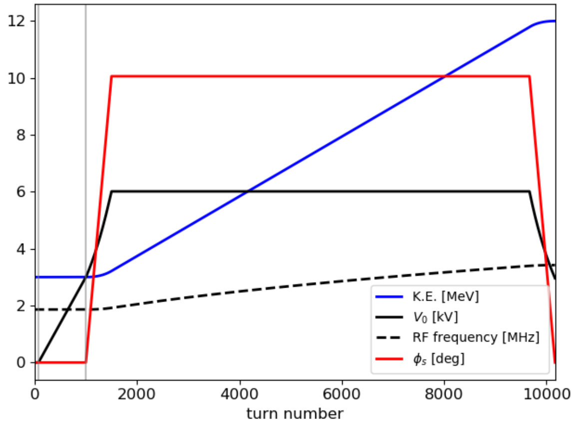
Turn 1000 (after capture)



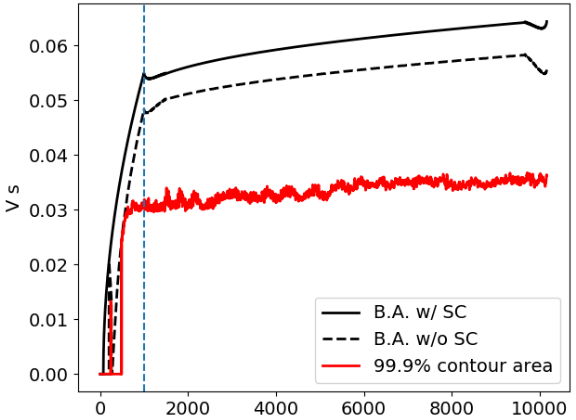
Turn 1500 (after ϕ_s sweep)



Final turn (12 MeV)



RF program



Emittance and bucket area

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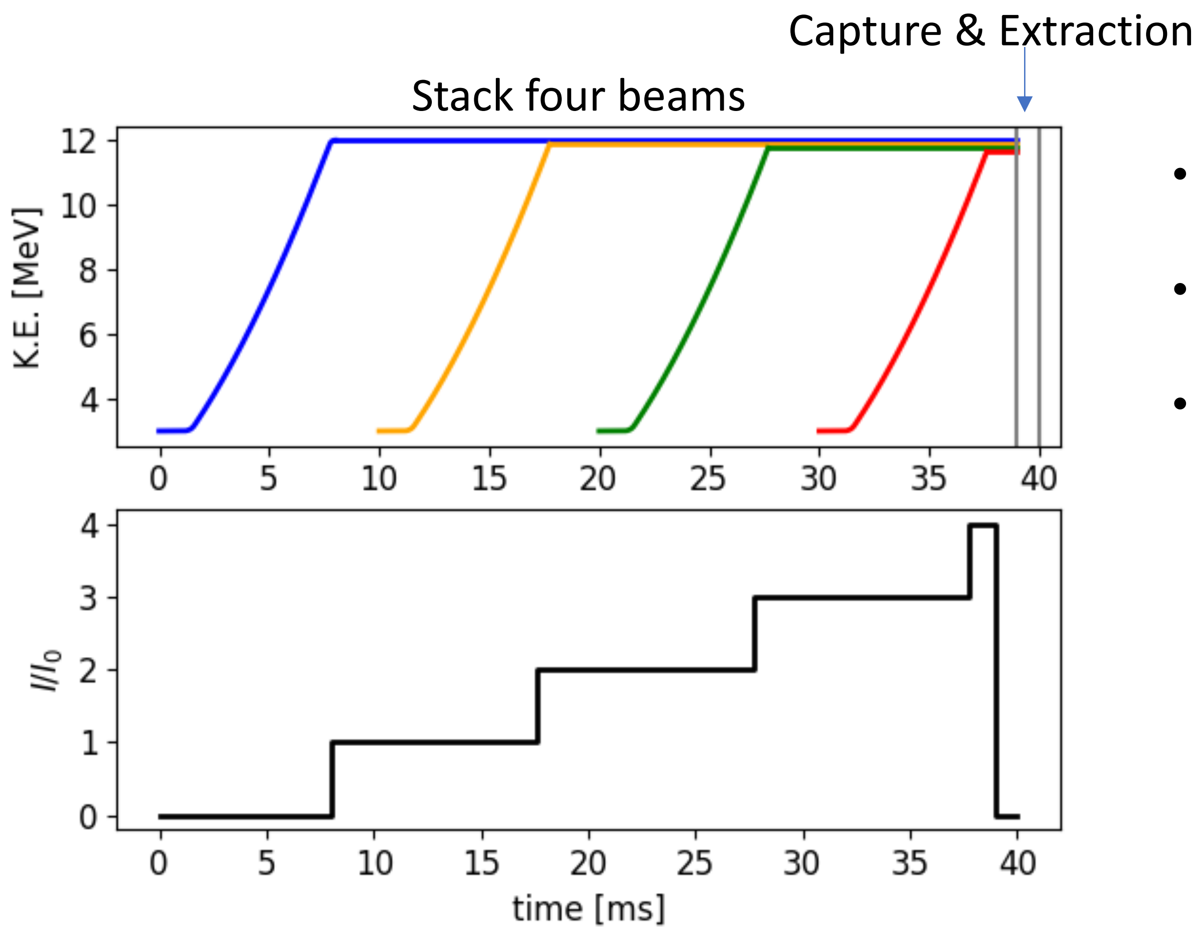
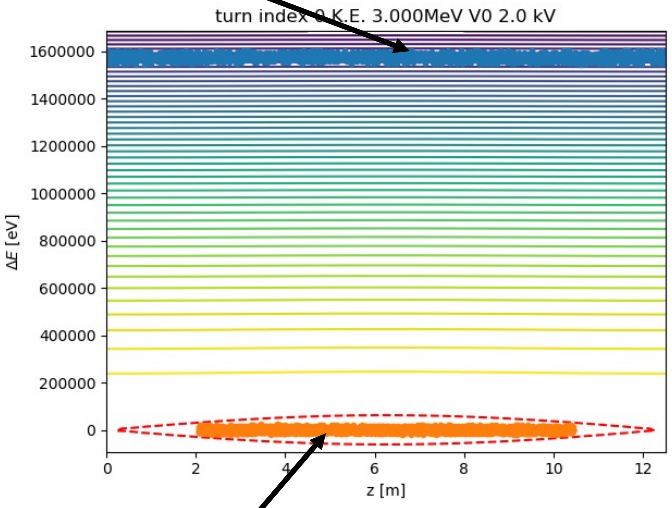
Beam Stacking



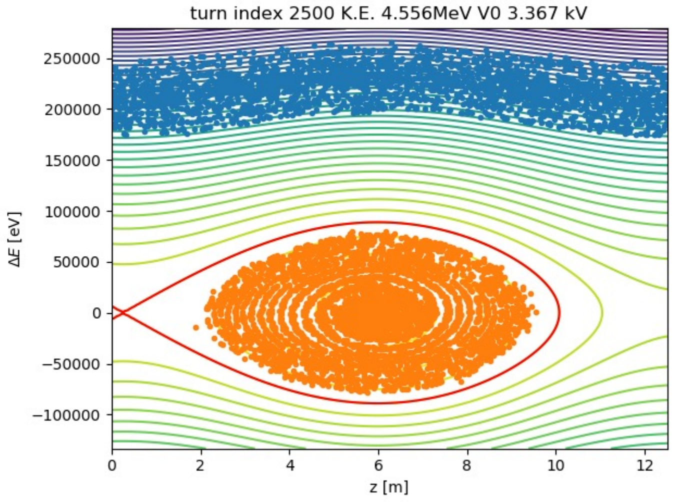
- Stack N beams to reduce the repetition rate seen by target by a factor N.
- Stack successive beams at slightly lower energies to avoid phase displacement.
- Capture to ensure enough beam-free time for the kicker rise time.

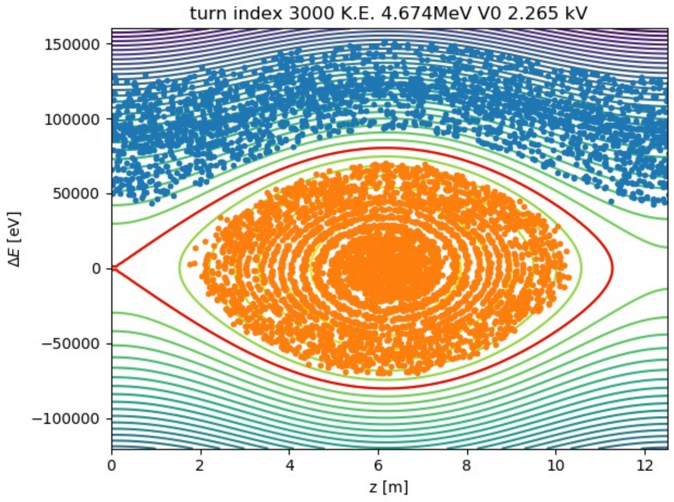
Stack two beams

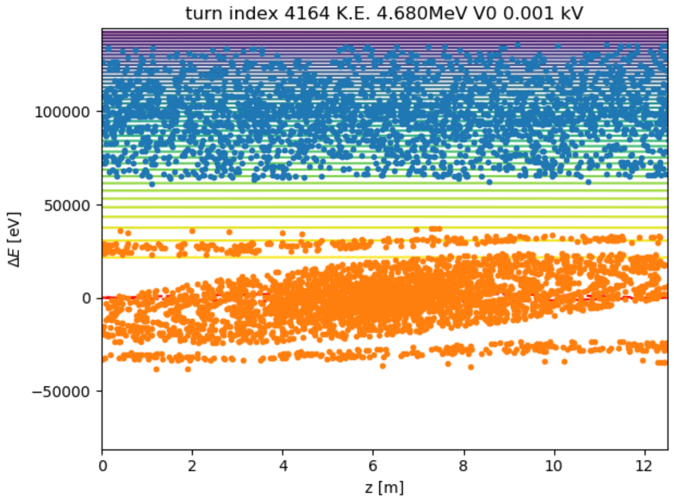
Coasting beam at higher momentum

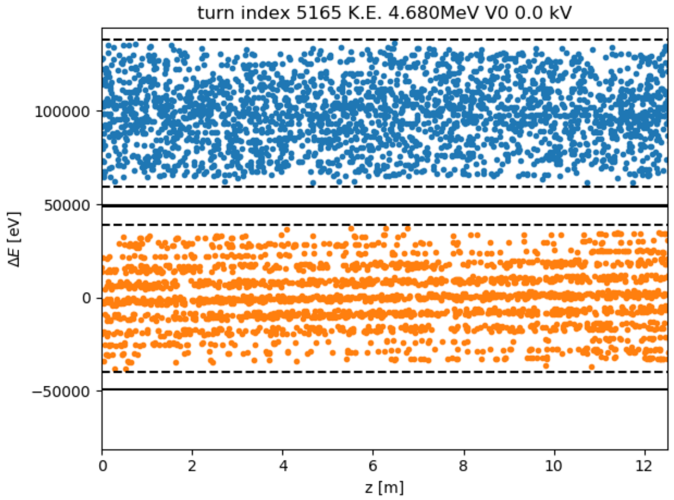


Injected bunch



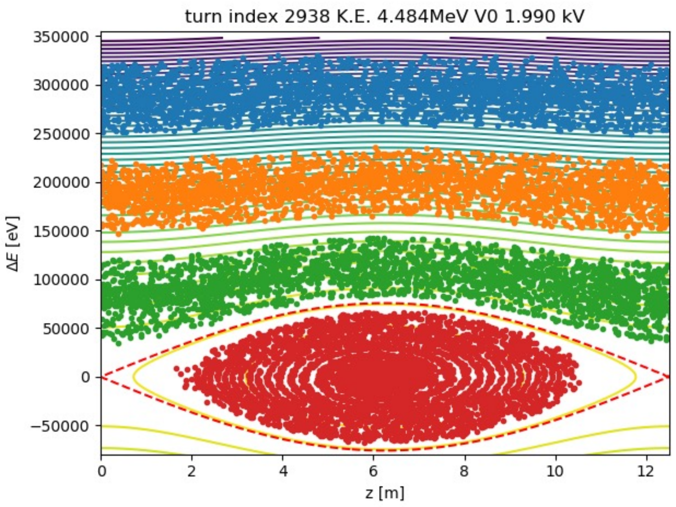




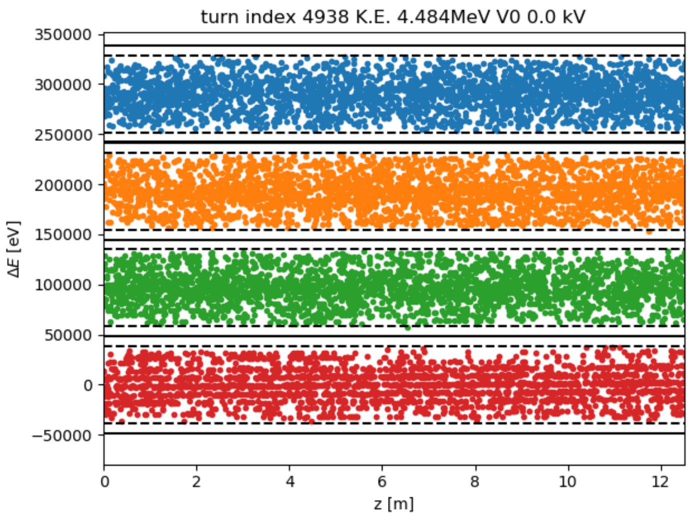


Beam Stacking method

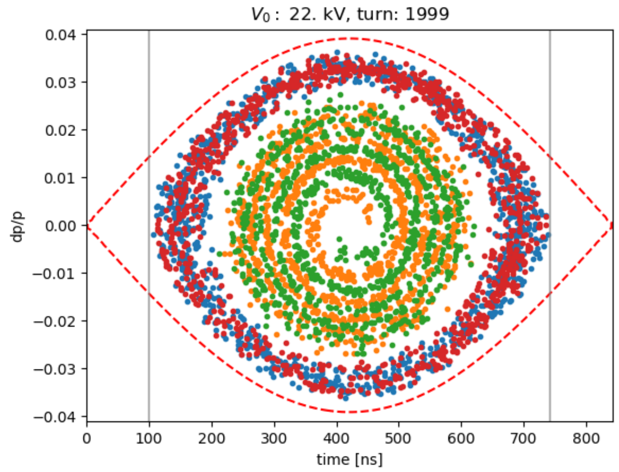
1. Adiabatically reduce the synchronous phase to zero.
2. Adiabatically debunch by reducing the voltage linearly over ~1000 turns. Repeat for N injection cycles stacking the beams, one below the other to avoid phase displacement and scattering.
3. Capture adiabatically by increasing the voltage over ~1000 turns in a harmonic 1, stationary bucket.



1. End of Acceleration



2. Adiabatically Debunched



3. Adiabatically Captured (200ns beam free)

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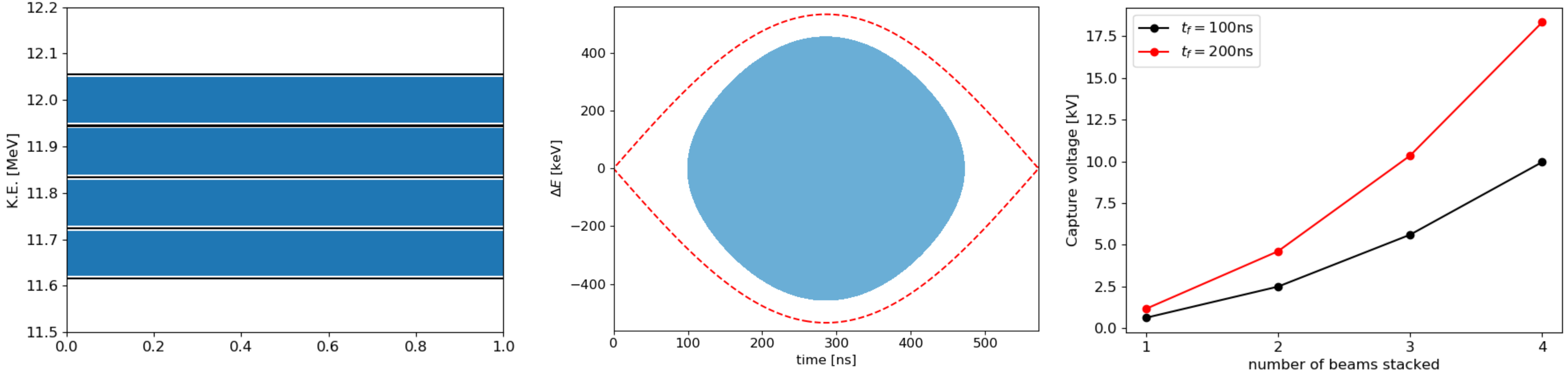
Capture requirements for hFFA



- Left: Ideal stack of four beams assuming 90% bucket fill and emittance 0.062 Vs.
- Right: Capture voltage assumes a beam free time of 100ns or 200ns is required. This is to accommodate the extraction kicker rise time.
- The bunched beam after capture has a momentum spread dp/p = +/- 0.02.

RF Cavity specification

Parameter	Value
Cavity for Acceleration	
RF frequency range (h=2, broadband)	1.8 – 3.42 MHz
RF peak voltage	6 kV
Acceleration time	8ms
Physical aperture	TBC
Cavity for Stacking	
RF frequency range (h=1, fixed)	1.7 MHz
RF peak voltage	20 kV (stack 4 beams)
Physical Aperture	TBC

- Ferrite and MA options are currently being investigated

Ferrite-loaded cavity

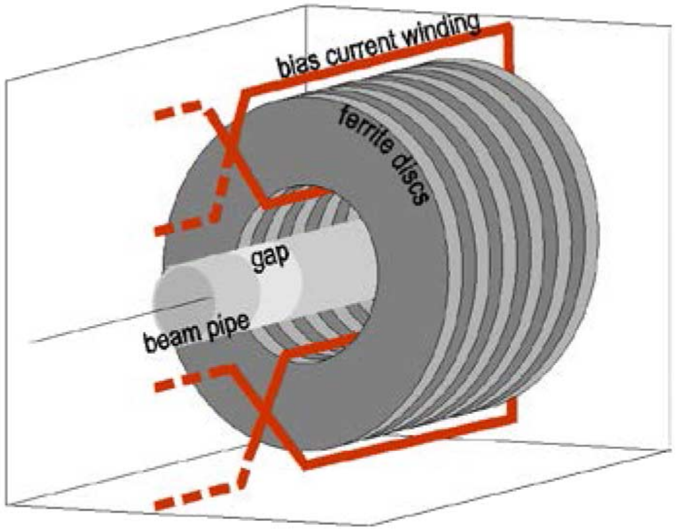
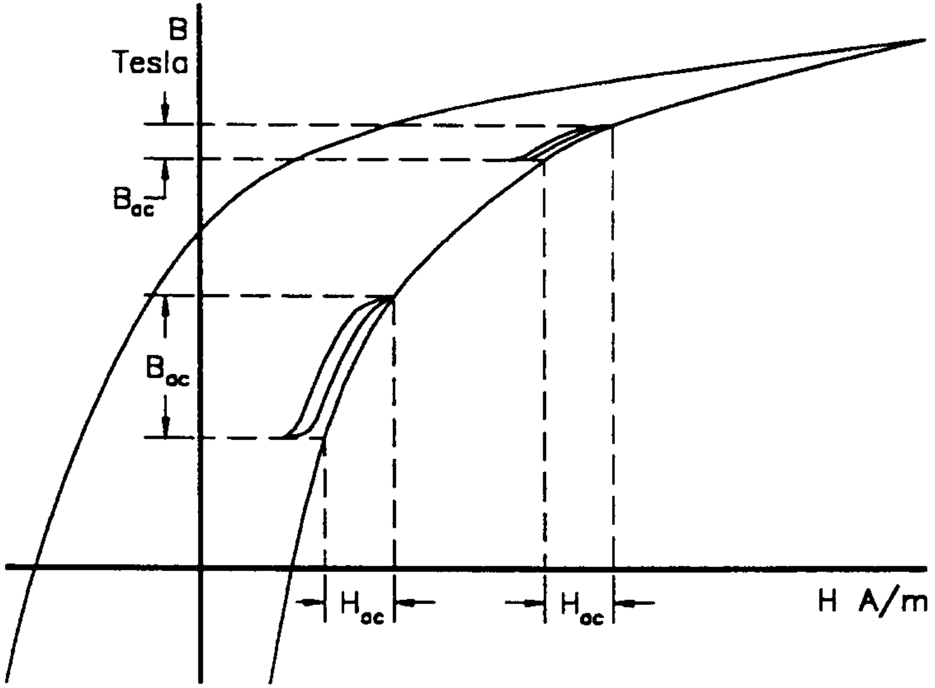


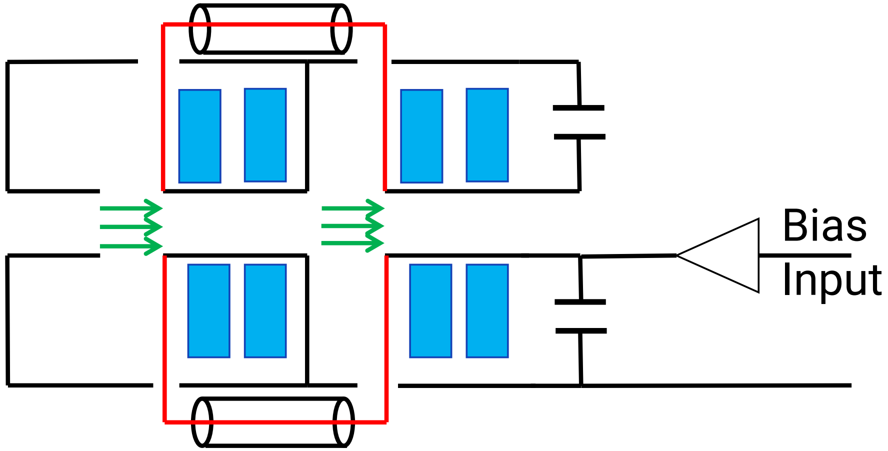
Fig. 11. Schematic of a ferrite loaded cavity; the bias current allows changing the magnetization of the ferrites, which in turn changes the effective permeability and thus the resonance frequency.

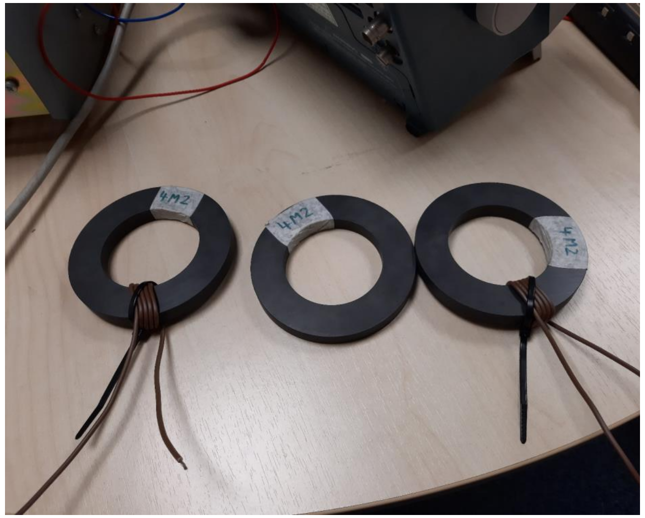


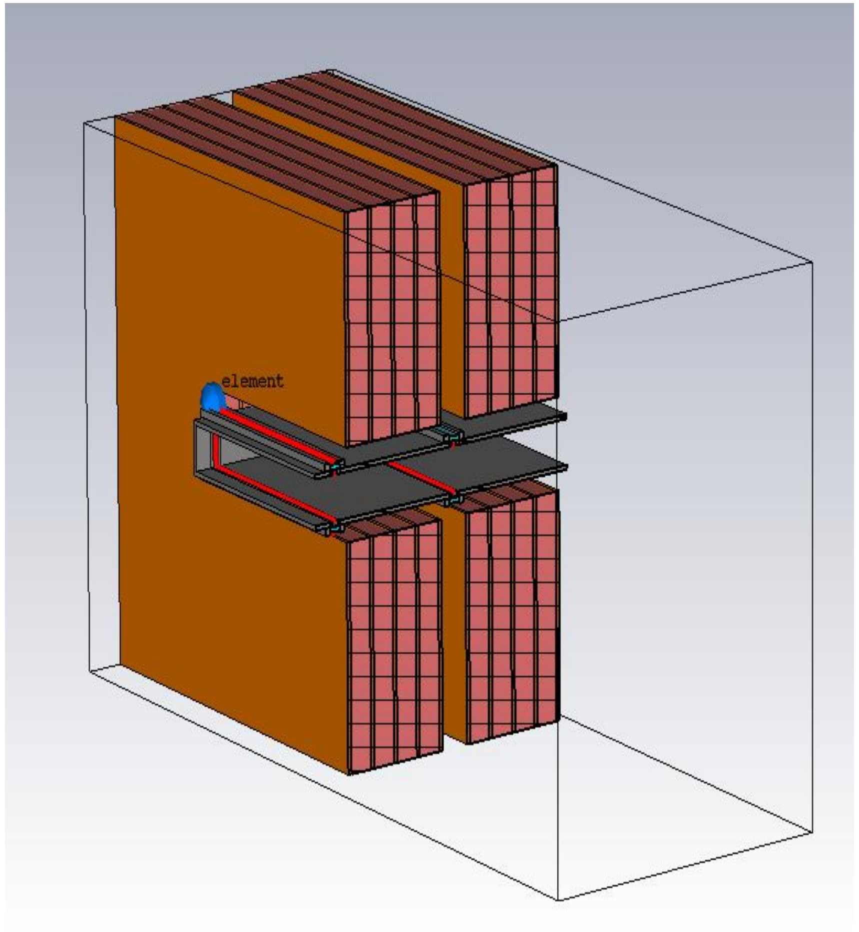
At resonance, $Z = Q\omega L = Q\omega\mu' L_o = (\mu' Q f) 2\pi L_o$

The factor ($\mu' Q f$) is often used as a figure of merit for ferrite materials

Two Gap Ferrite Cavity







- Azimuthal length < 1 m
- Three ferrites tested GF5, 8C15 & 4M2 - 4M2 selected
- Estimated RF power with 4M2 Ferrite ~ 6 kW + tuner power
- Recovery time a concern for 100Hz operation (2ms)

2 – 5 MHz
3kV / Gap
3kW / Gap

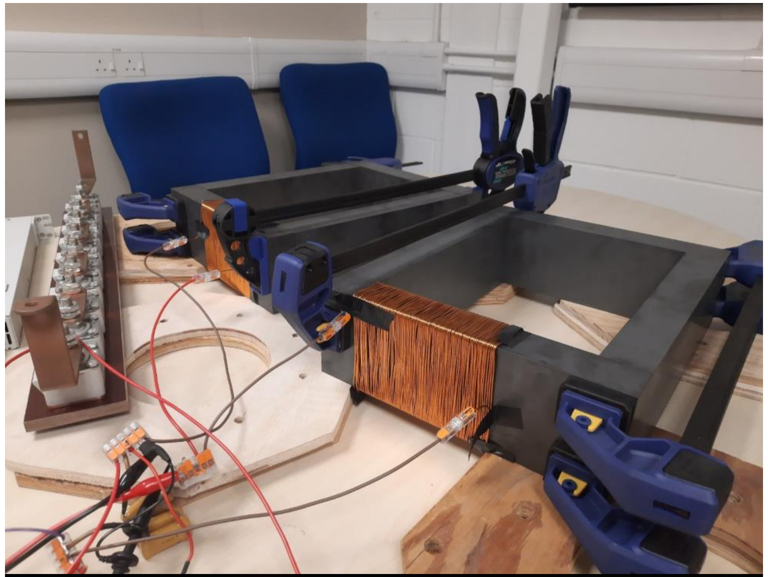
R. Mathieson (7/2/2023)

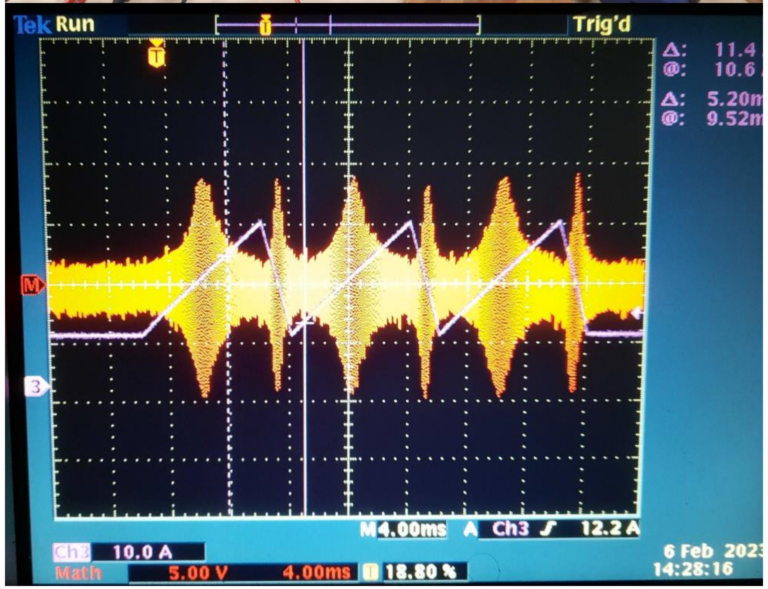
Ferrite tests

- 4M2 Sample Ferrite Frames
  - Tender Exercise November 2021
  - First 8 blocks arrived December 2022
  - Further blocks short lead time pending approval

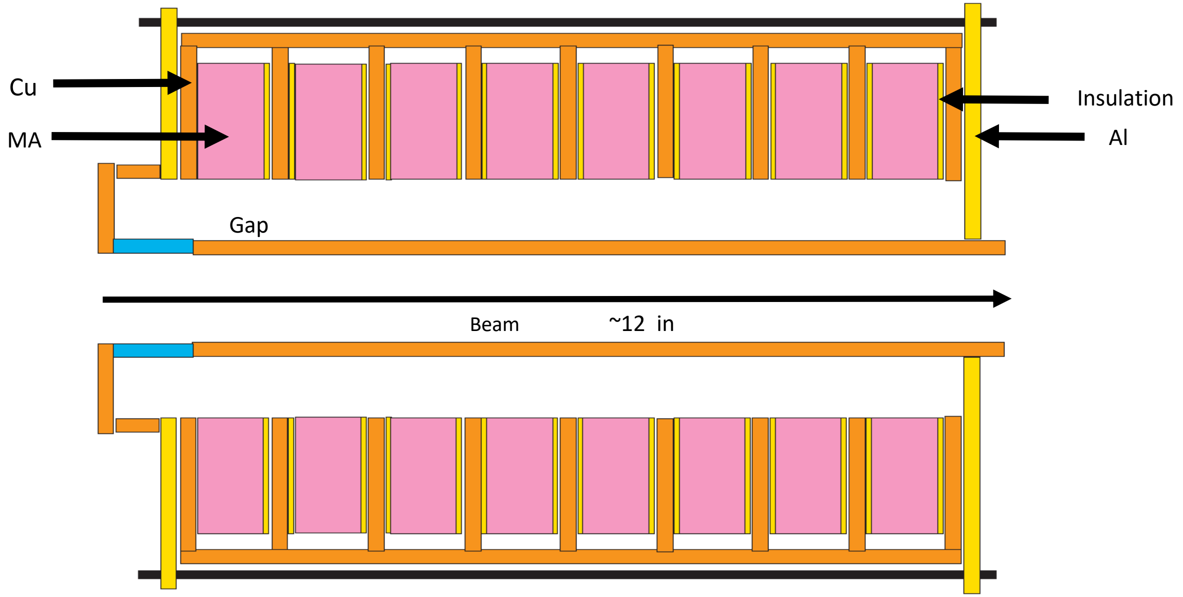
- Initial tests confirm material performance
  - Q ≈ 100 at RF frequencies
  - Some evidence of magnetisation

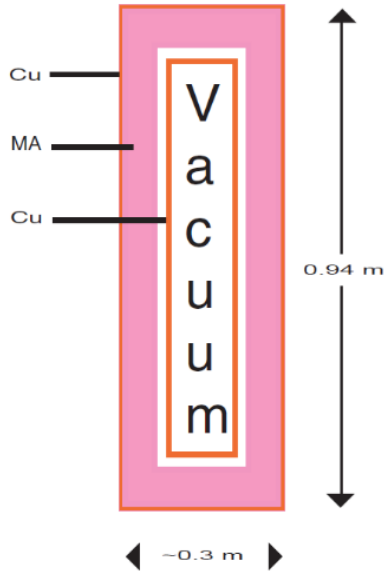
- Bias winding requires peak of 2800 Amp turns for $\Delta f/f_0$
  - Implies 5600 Amp turns for full cavity
  - Multiple bias turns required





FETS 8 Core MA Cavity with Water Cooling Plates (initial design)





- 6 kV peak gap voltage over 1-6 MHz
- Brf limited to 0.1 T in MA

- Much higher saturation field, higher B_{rf}, shorter cavities
- Low Q so broadband with no tuning loop, more power needed
- Broadband allows addition of more harmonics

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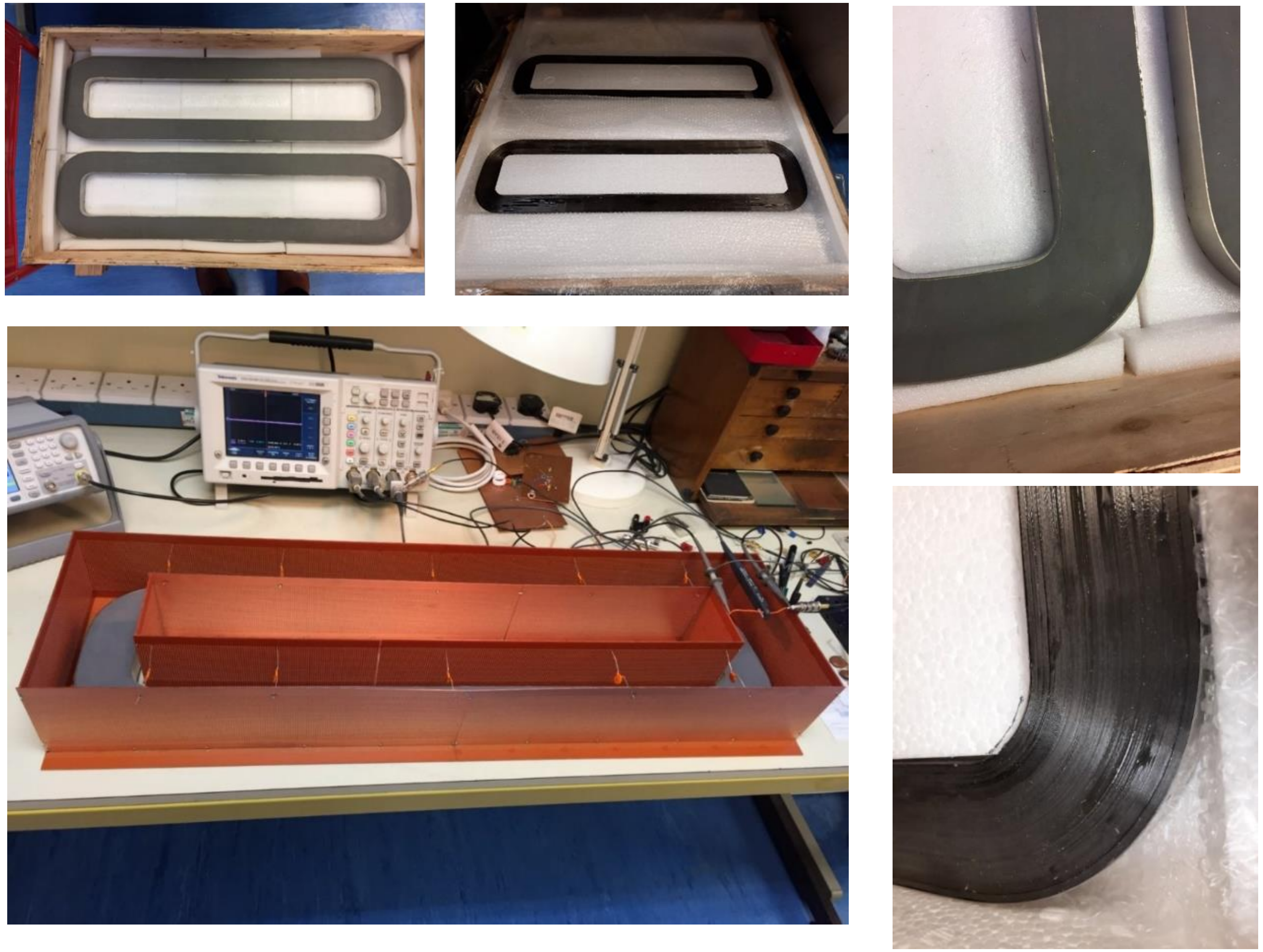

FETS Test MA cores

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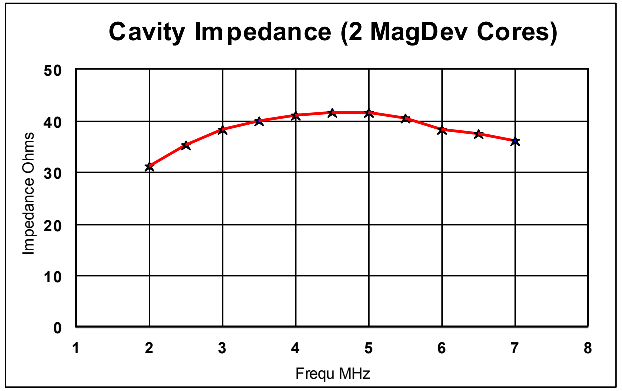
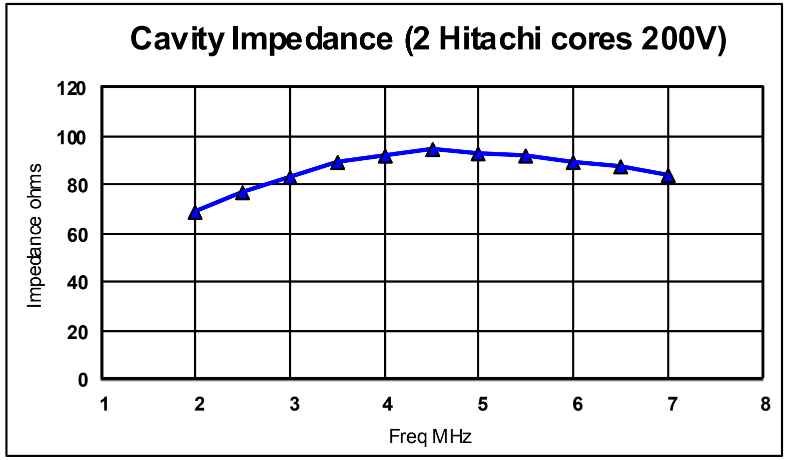
Initial tests of MA cores

MagDev 1K107 Core Measurements



- Measured with 75 V peak per core (Design voltage 750 V per core).
- Power for 8 core cavity at 6 kV peak 110 - 150 kW
- Consider using 2 cavities at ½ voltage ~38 kW each, meaning no Tuning system and wideband for fast modulations

Hitachi FT3L Core Measurements



- Measured with 100 V peak per core
- Power for 8 core cavity at 6 kV peak 50 - 65 kW
- Consider using 2 cavities at ½ voltage ~16 kW each, meaning no Tuning system and wideband for fast modulations

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Ferrite vs MA

	Ferrite	MA
RF Power req. for 6kV	6kW	35kW
Amplifier	Solid State Class B (or A)	Large SS/ Small Vacuum Tube Class A or AB Push-pull
Bias Required	Yes Likely ~35kW	No
Est. Wallplug Power (ignoring plant)	45kW (Class B) 60kW (Class A)	140kW (A)
Proximity to Magnetic Fields	$\mu \approx 140$, absorbed into bias	Problematic $\mu \approx 4000$
Rep Rate 100Hz+	Possible	No recovery
Bunch Stacking	Supplied by separate cavity ~20kV	Possible 10kV burst on two cavities
LLRF	Simple	Simple (little beam loading)

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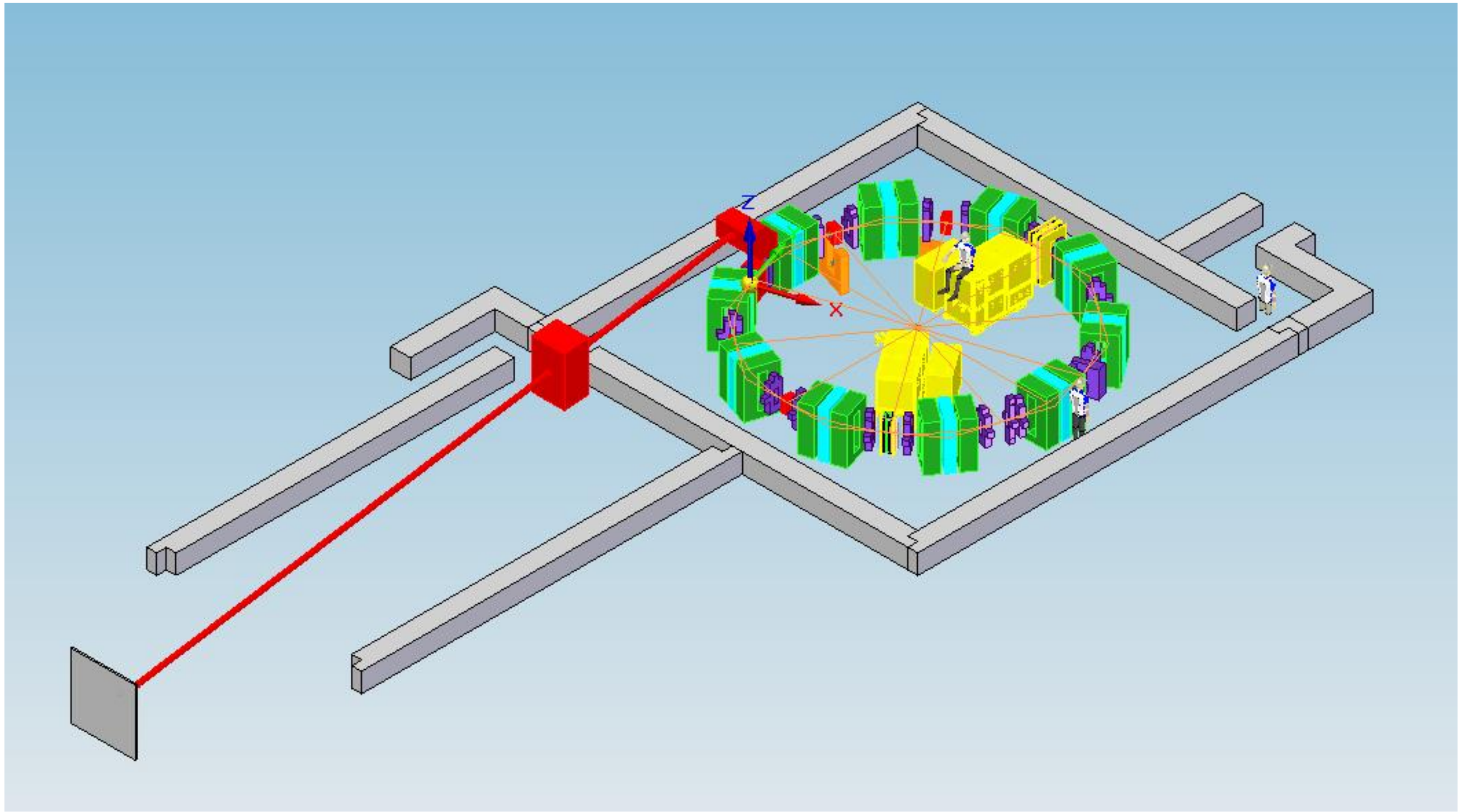
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