FETS-FFA Commissioning Plan

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FETS-FFA Commissioning

Phase 1

Inject a low current beam without painting, accelerate it to top energy and extract it.

Phase 2

Match the injected beam in longitudinal and transverse planes, optimise injection painting and characterise beam properties.

Phase 3

Advanced optimisation. Investigate sources of emittance growth, optimise beam stacking etc.

Phase 1 - Overview

Goal of phase-1 is to inject, accelerate and extract a 12 MeV beam.

No transverse painting, or matching at injection.

- 1.1 **Injection**
- 1.2 **One Turn Circulation**
- 1.3 **Multi-Turn Circulation**
- 1.4 **RF Capture**
- 1.5 **Acceleration**
- 1.6 **Extraction**

1.1 - Injection

Inject pulse from FETS

- Find beam position at the foil location
  - **Scintillating screen, wire profile monitor etc**
- Move beam onto design bump trajectory
  - **Screen/ profile monitor must move**
- Measure and adjust beam trajectory in bump
  - **Second moving screen/ profile monitor**
- Measure transverse beam size in both locations, and adjust FETS focusing and local FFA focusing
- Measure injection efficiency
  - **Moving Faraday cup**

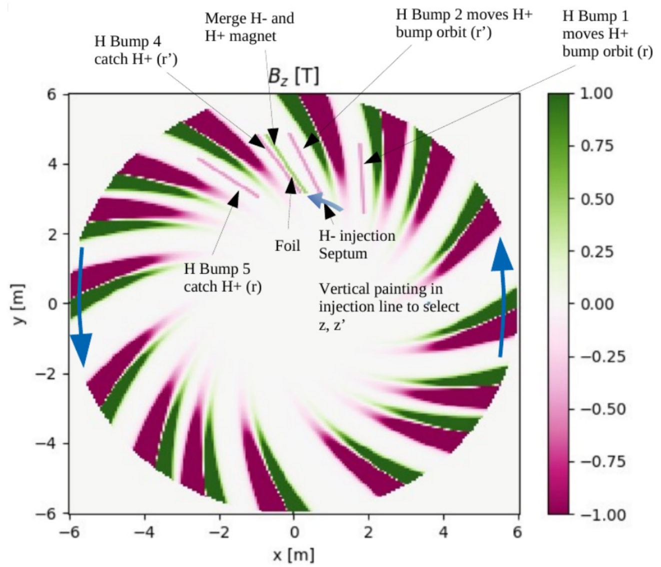

Figure 3.3: Basic field map of the injection system shown in cartesian coordinates showing vertical field strength. For clarity the field strength of injection magnets has been enhanced and the radial aperture exaggerated.

1.1 Injection

1.2 One Turn Circulation

1.3 Multi-Turn Circulation

1.4 RF Capture

1.5 Acceleration

1.6 Extraction

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1.2 – One Turn Circulation

Perform one revolution of the FFA with a short pulse from FETS

On the bump orbit.

Assumed that non-interceptive diagnostics not *fully* functional.

Beam will be lost as it progresses around ring because of imperfect trim-coil settings or aperture restrictions etc.

- Detect beam's azimuthal position with any diagnostic.
  - **Position monitors, beam loss monitors, wire monitors, scrapers**, **screens, Faraday cups etc.**
    Monitors must be distributed around ring.
- Measure transverse position and correct orbit with trim coils.
  - If BPMs don't work, use interceptive diagnostics (scrapers, wire monitors etc)
- Measure transverse profiles and correct focusing.
  - **Scrapers can intercept the beam to prevent recirculation.**

1.1 Injection

1.2 One Turn Circulation

1.3 Multi-Turn Circulation

1.4 RF Capture

1.5 Acceleration

1.6 Extraction

1.3 – Multi-Turn Circulation

Allow the beam to circulate for many turns

Not possible to use most interceptive diagnostics.

Without RF beam will decohere over several turns.

Beam intensity still expected to be low

- Measure transverse position as bump field reduces and correct trim coils.
  - **BPM if possible**
  - **Multi-turn interceptive diagnostic (thin wire)**
  - **Beam Loss Monitors**

- Measure and optimise transverse tunes.
  - BPM, deflection method

1.4 – RF Capture

Capture the injected beam with a stationary bucket

Dedicated commissioning time for RF cavities will be required

Several pulses from FETS will be accumulated (not full intensity)

- Measure current as beam is accumulated
- Measure lifetime of stored beam
  - **Wall current monitor**

- Verify that lifetime exceeds acceleration time and correct sources of uncontrolled beam-loss.
  - E.g. non-ideal trim coil currents, vacuum problems, aperture restrictions etc.

1.5 – Acceleration

Accelerate the beam to a larger orbit radius and set-up trim coils

As orbit radius increases, trajectory will be impacted by different trim coils.

RF programmes will be prepared to accelerate the beam by ~half a trim-coil width.

Scrapers will be inserted to prevent beam from moving much further than this.

- Measure closed-orbit position and transverse profile, tune
  - **BPMs**
  - **Thin single-wire profile monitor**

- Measure beam lifetime
  - **WCM**

1.6 – Extraction

Extract the beam at its top energy

Orbits corrected at intermediate energies.

Beam can be stored at its top energy.

- Commission timing system for extract kickers
  - Required synchronisation with beam, so WCM or BPM

- Measure trajectory after extraction kick
  - BPM, wire monitor, scrapers etc

- Measure extracted beam profile
  - **Wire profile monitor must be suitable for extraction energy.**

- Measure extraction efficiency
  - **Faraday cup must also work for extraction energy.**

Phase 1 – Summary

- In the early stages, interceptive diagnostics are key:
  - **Scintillation screen** – fast feedback of beam position and profile near injection
  - **Faraday cup** – robust measurement of injection efficiency
  - **Scraper** – transverse beam position
  - **Thin wires** – transverse profile, reliable position, maybe even tune
- After completing a single revolution, non-destructive diagnostics are key:
  - **Beam position monitors** – tune, azimuthal position, transverse position
  - **Wall current monitor** – beam current and longitudinal distribution
  - **Thin wires** – transverse profile, reliable position, maybe even tune
- **Beam loss monitors** will be needed throughout. They provide a coarse beam location and help to identify the cause of beam-loss.

1.1 Injection

1.2 One Turn Circulation

1.3 Multi-Turn Circulation

1.4 RF Capture

1.5 Acceleration

1.6 Extraction

Phase 2/ 3

Goal of phase-2 is to achieve near full beam intensity.

Match injected beam in both planes, start injection painting and optimise key equipment parameters.

- Beam-losses will be reduced and intensity increased.
- Non-interceptive diagnostics will play a major role
  - BPMs
  - WCMs
- Beam-loss monitors will be used to locate and diagnose the cause of beam-losses.
  - Very localised losses may be challenging to measure.
- Precise average current measurement is required to identify beam losses.
  - Would ideally work for beam stacking experiments too.
  - **High Precision (Nearly DC) Current transformer**

FETS-FFA Diagnostics

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Contents

- Faraday Cup
- Thin Wire Profile Monitor
- Scintillating Screen
- Scraper

- Beam Position Monitor
- Wall Current Monitor

- Long Pulse Current Transformer
- Beam Loss Monitor

Beam Current Monitor: Faraday cup

Faraday cup: Specification

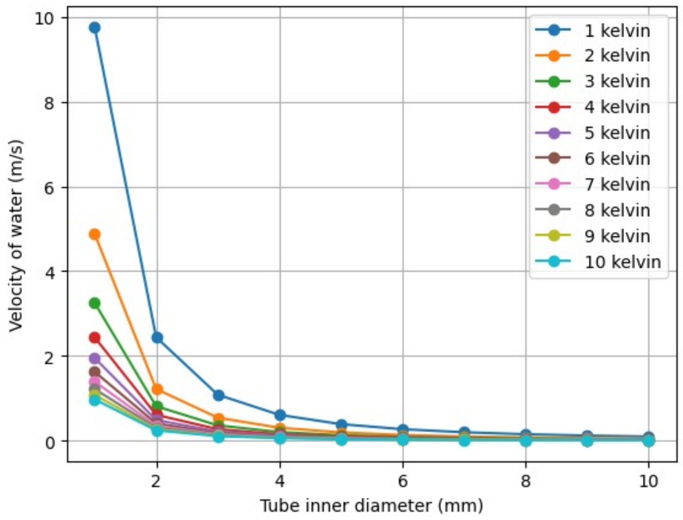
Target Specifications

- Current measurement better than 1% of injected beam
- Dynamic range suitable for 6e9 and 3e11 PPP at 3 and 12 MeV
- Time structure not required
- Moveable
- Located near injection and extraction line

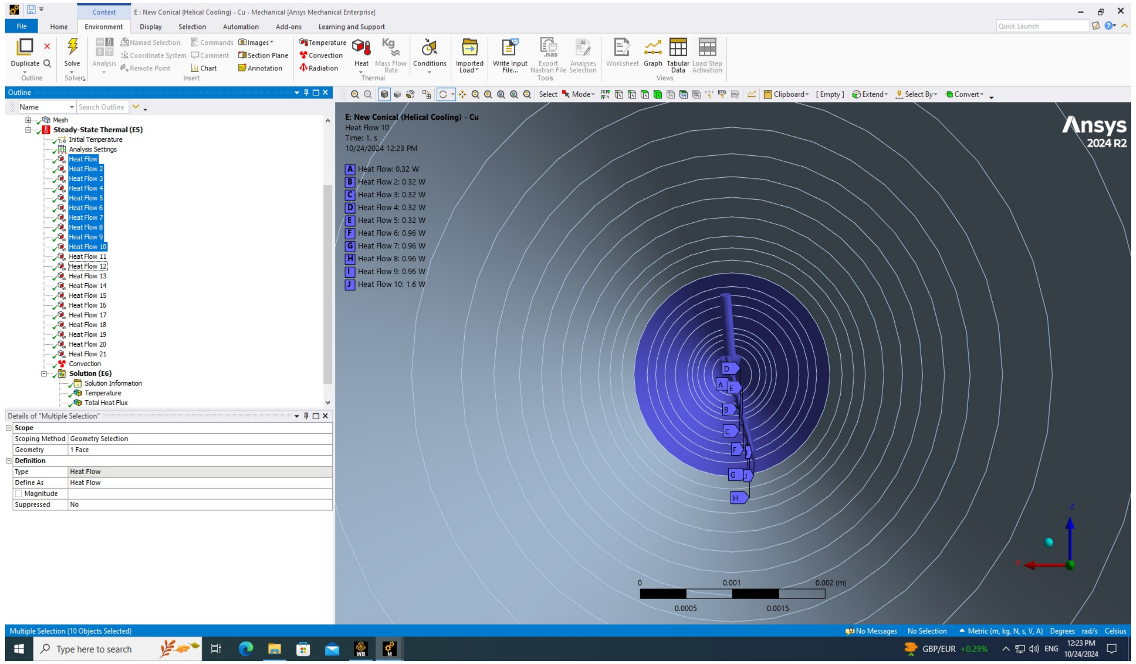
Thermal Analysis

Assessing the thermal load is vital part of the feasibility study.

- Using FETS transverse beam with SRIM stopping power data (on Copper) resulted in ~170 K rise at 3 MeV and ~96 K at 12 MeV.
- FETS-FFA average beam power (~32 W) was used for water flow rate calculation before the convection coefficients were evaluated.



- Gaussian heat flow was added into ANSYS Steady-State thermal simulation using analytical method.



- Thermal Simulations showed that helical water cooling maintained the steady-state temperature around 40℃, rising only ~5℃ from ambient temperature of water.

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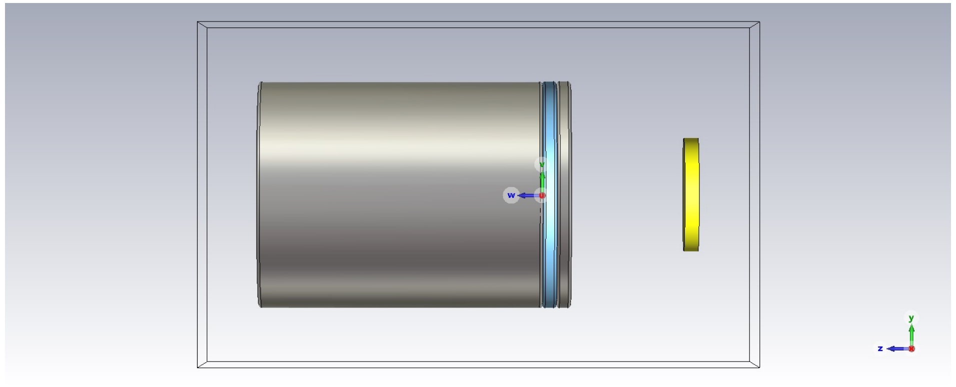
Secondary Electrons Suppression

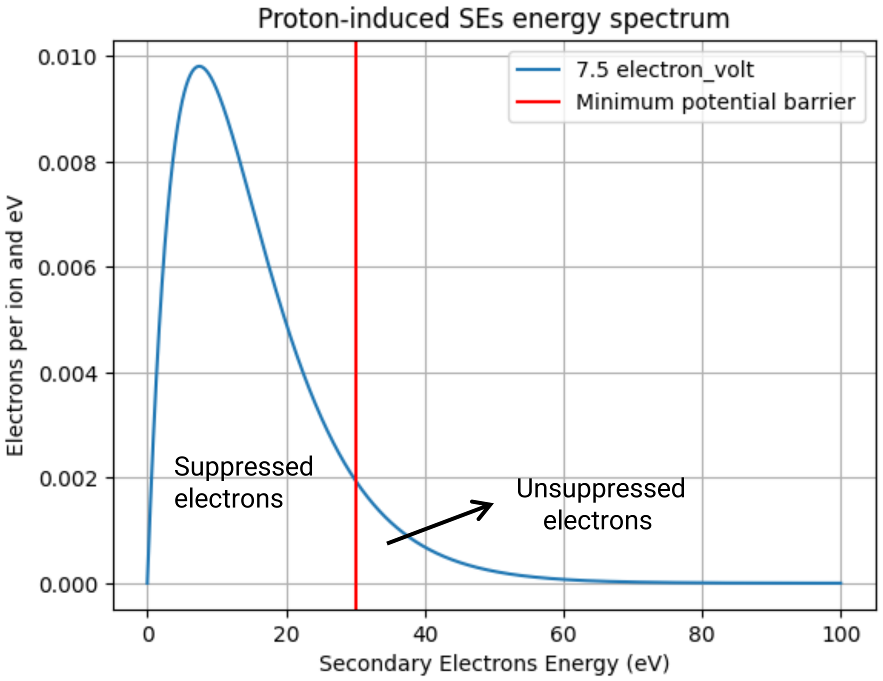
Significant source of error on beam current signal is secondary electrons' emission (SEE).

- Negative potential applied to the isolated circular ring was decided for electron suppression.
- Electrons escaping FC were probed while varying the electric potential of the suppressor on CST particle tracking solver.
- Alternative numerical method was used due to intrinsic error of the solver.
  - ➢ CST function was used to generate the SEs energy distribution, after comparing with experimental spectrum.
  - ➢ Ratio of unsuppressed electrons were estimated by integrating the energy spectrum.

$$f(E) = \delta(E_0, \theta_0)\,\frac{E}{T^2}\exp\left(-\frac{E}{T}\right)P^{-1}\left(2, \frac{E_0}{T}\right)$$

- Numerical analysis showed the number of unsuppressed electrons reduced to less than 1% when -1 KV potential was applied.





Beam Profile Monitors:

Wire Profile Monitor

Single Wire Profile Monitor: Specification

Target Specifications

- Better than 0.1 mm spatial resolution
- Better than 1 mm absolute positioning
- Dynamic range suitable for 6e9 and 3e11 PPP at 3 and 12 MeV
- Pulse-by-pulse readout
- Multi-turn capability
- Moveable
- Located near injection

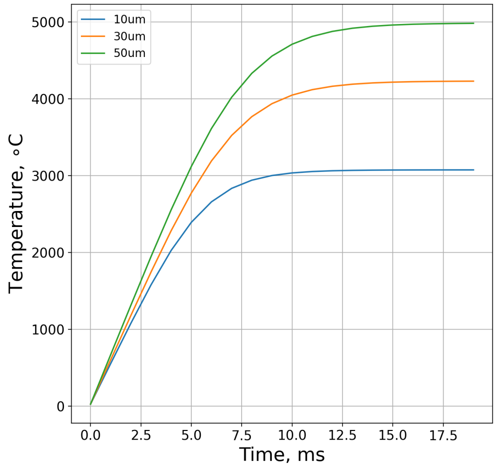
Feasibility Study

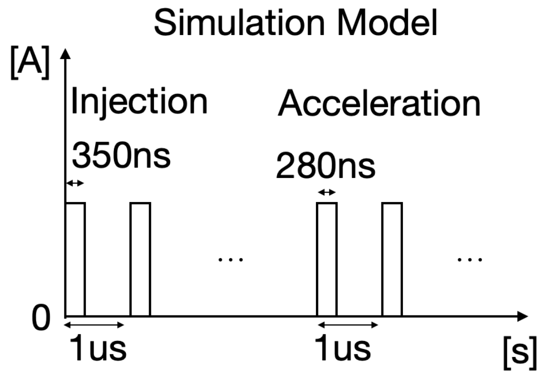
- Report on specifications recommends wire profile monitor.
- These can measure beam position and size independently and are robust. They also indicate relative current changes.
- Focus on material study to ensure wires are sufficiently robust and perform beam test to investigate signal in a practical scenario.

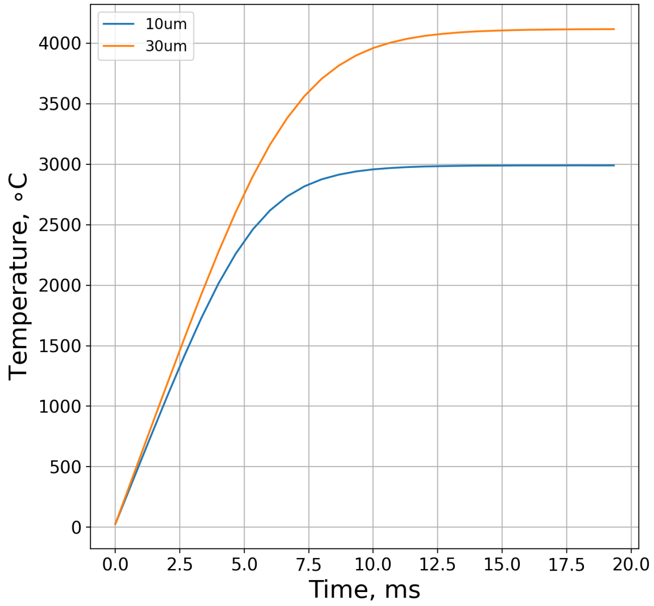
Single Wire Profile Monitor

A single wire will be stepped through the beam over several pulses to acquire a horizontal profile. The wire can also be held at a fixed position as the accelerating beam traverses it.

Thermal simulations carried out at injection (peak current of 137 mA) for Carbon Nano Tube (CNT), Tungsten (W) and Silicon Carbide (SiC) wires predicts CNT as the most promising material.







Similar simulation performed for profile measurements during beam accelerations at 3 MeV (peak current of 171 mA) demonstrates 10 μm CNT as the best material and size for the single WSM in the FETS-FFA.

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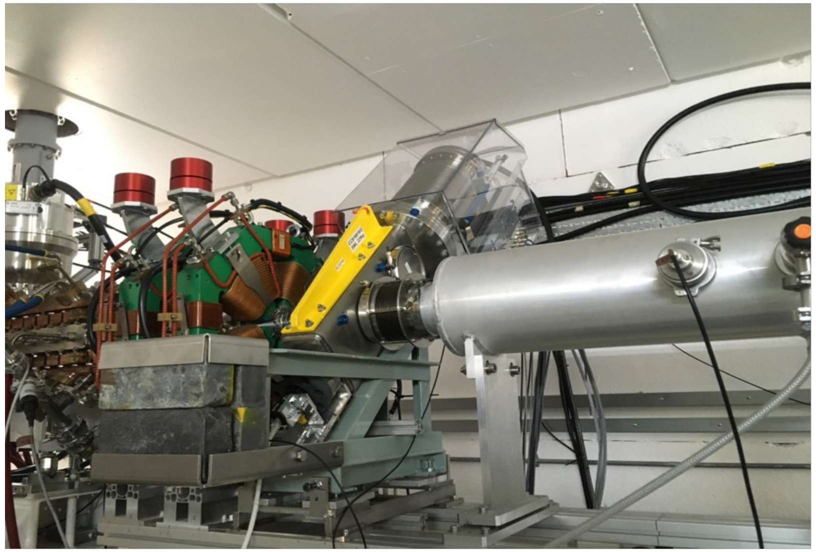
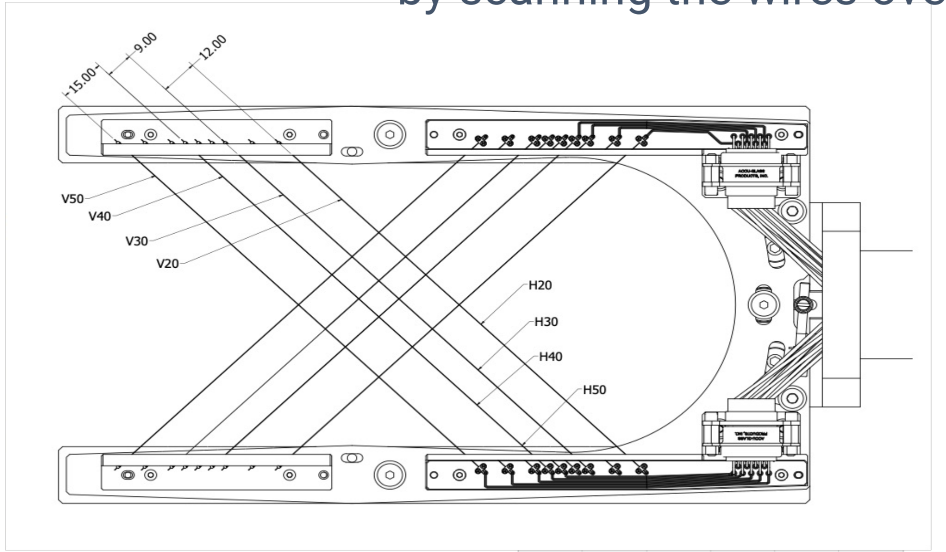
Test on FETS Linac

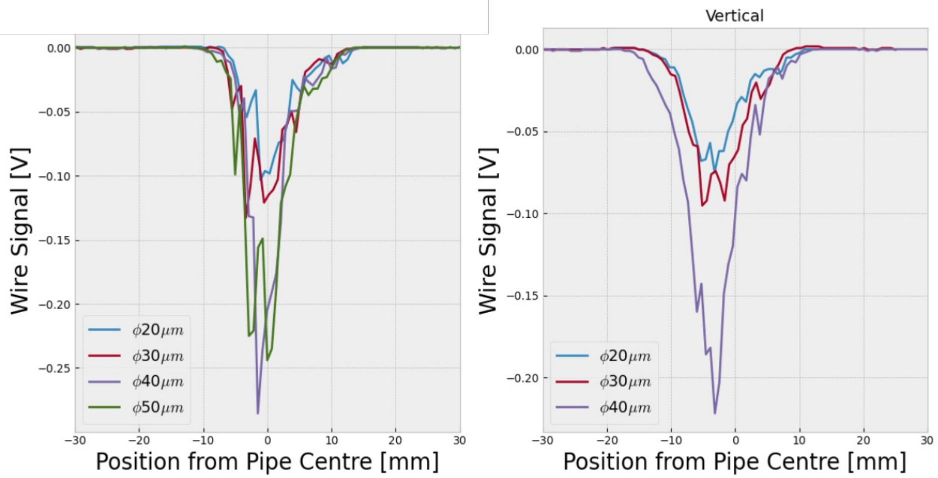
CNT wires with 20, 30, 40 and 50 µm diameters were installed in the FETS Linac on a motorised stage for thermal test.

Profile measurements were also performed by scanning the wires over the beam size.





The CNT wires did not get damaged instantaneously by the injection beam in the FETS-FFA ring while long exposure needs to be investigated.



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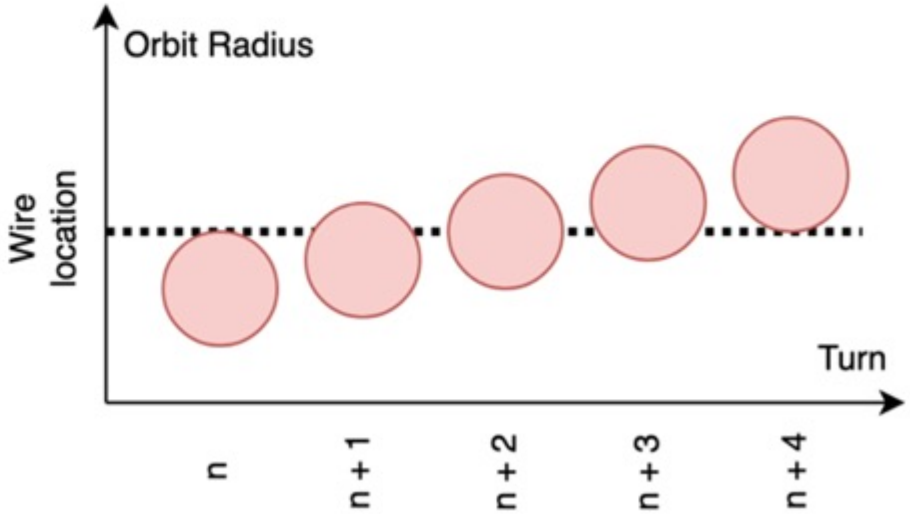
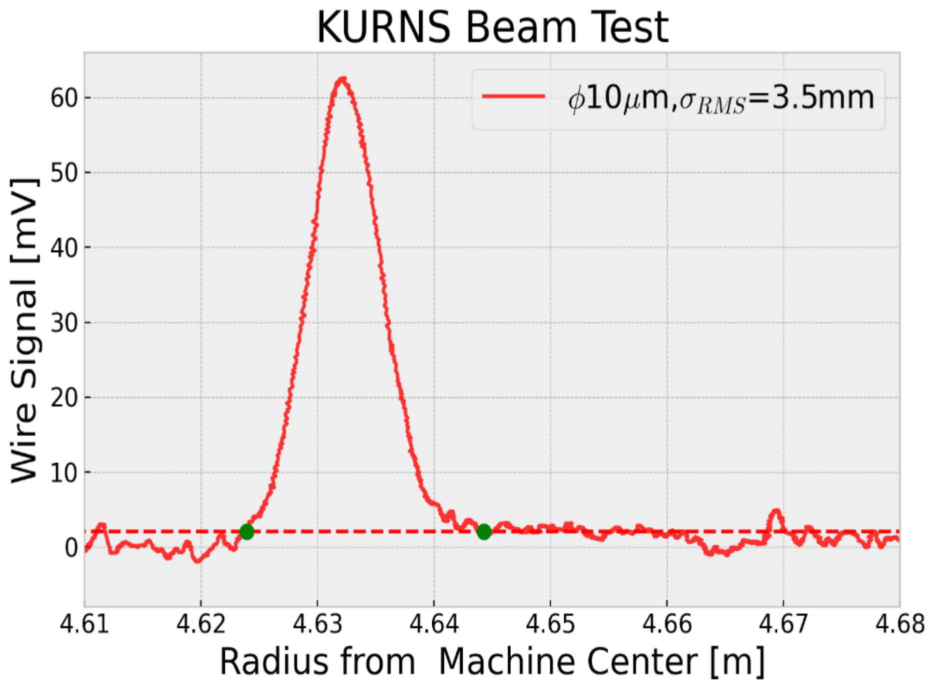
Test on KURNS

10 μm wire was mounted on the frame and placed in KURNS hFFA for transverse profile measurement.

Multi-turn accelerating beam profile was measured by 10 μm CNT wire.





Profile measurements with a positive bias voltage were planned but not performed due to time constraints.

Beam Position Monitor

Beam Position Monitors

Target Specifications

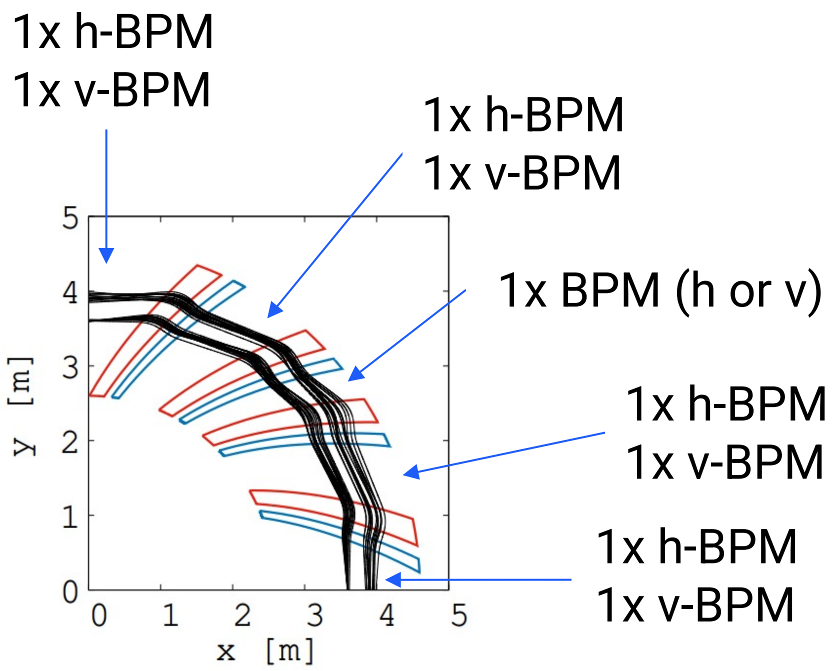
- 1 mm absolute position accuracy (average)
- 1 mm relative accuracy (turn-by-turn)
- Fit within vertical beam-stay-clear

Nice to have

- High bandwidth for longitudinal reconstruction
- Minimise longitudinal extent

Ideal Placement

- 18x horizontal BPMs
- 18x vertical BPMs



Beam Position Monitors

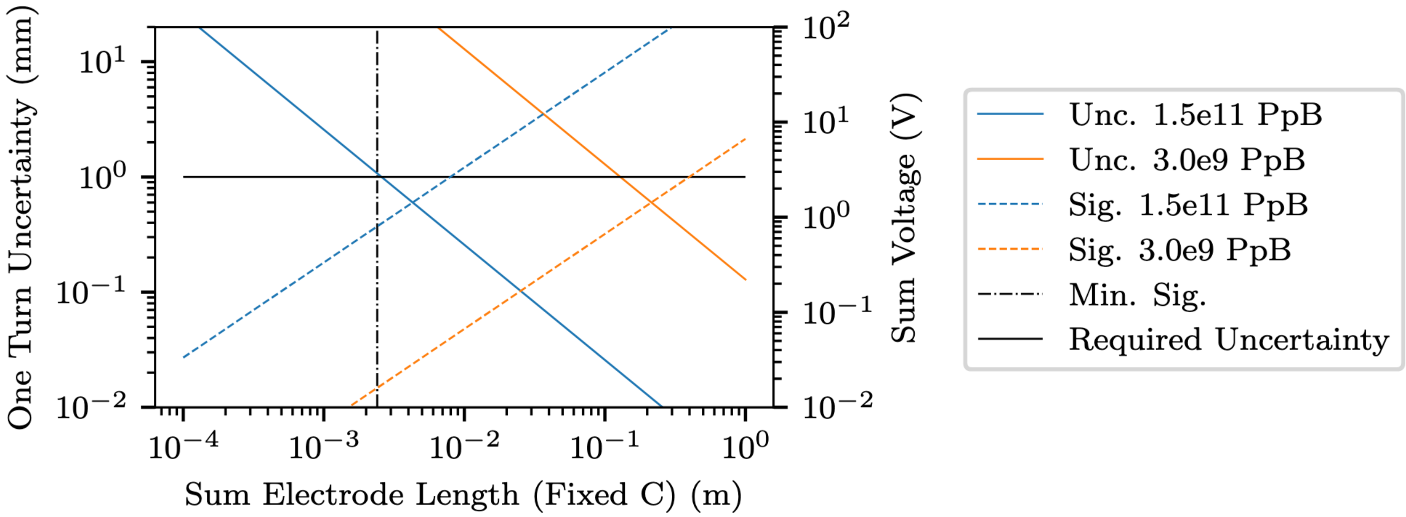
- To reduce space requirements I have investigated a combined horizontal and vertical BPM.
  - Effective horizontal electrodes by summing two signals on left and right
  - Effective vertical electrodes by summing two signals on top and bottom.

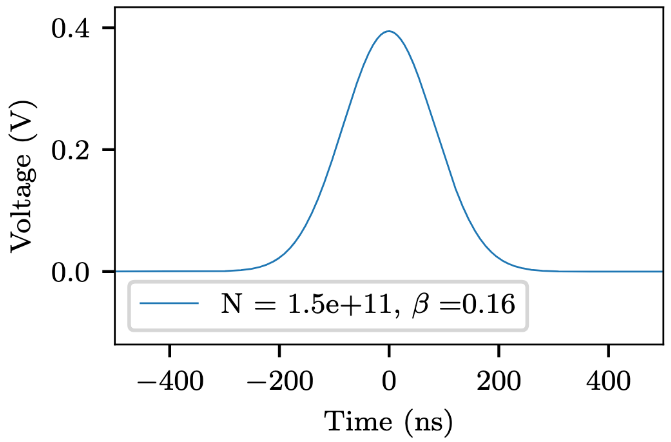
- Reducing electrode length reduces signal amplitude and therefore worsens position uncertainty.

Beam Position Monitor Sum Signals and Uncertainty

$$\sigma_y \approx k \frac{\sigma_\Delta}{\Sigma}$$

- Sum signal amplitude computed as a function of electrode length.
- Signal amplitudes compared against some high input impedance amplifiers.
- Amplitudes of ~0.5 V with < 10cm.
- Typical value of k used to estimate position uncertainty from noise figure of a low-noise amplifier (NF-Corp SA-240F5)
    - Better than 1mm with a full intensity.



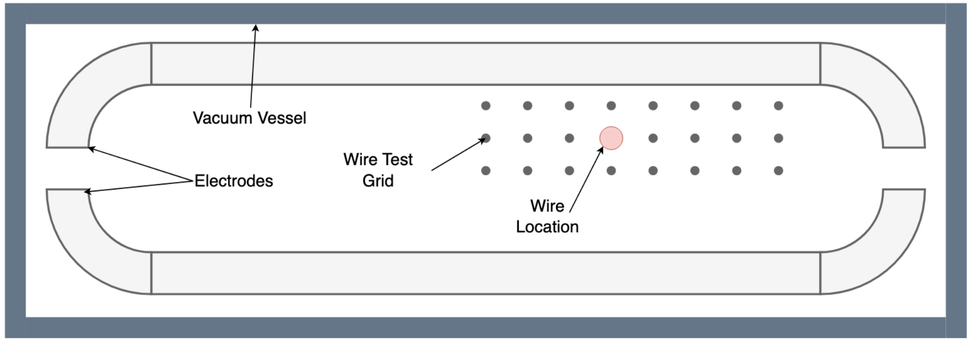


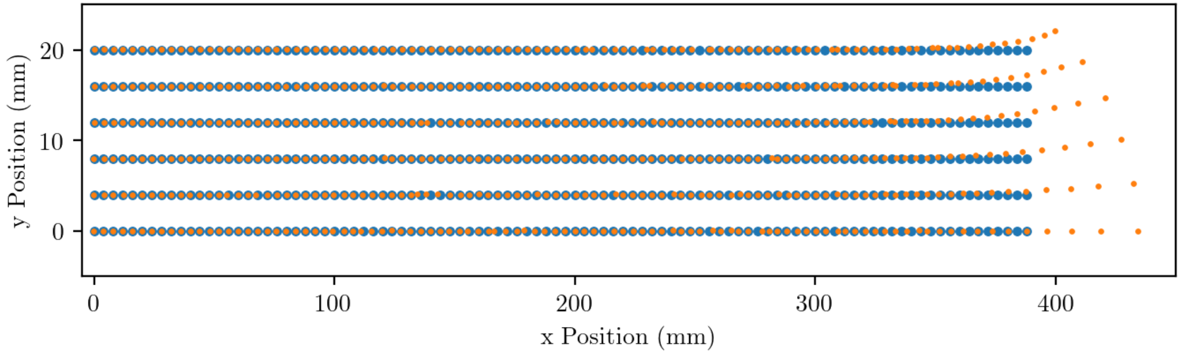
Beam Position Monitor Non-Linear Correction

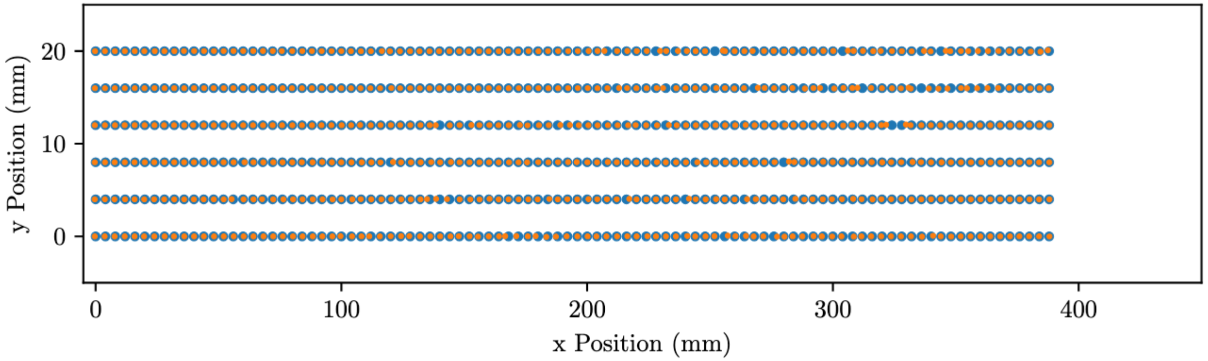
- Hadron machines often favour split-plate position monitors because DoS is linear with offset in a large fraction of the aperture.
  - Beam posititition and profile are decoupled.

- Expect significant non-linearity at ends. Simulate difference-over-sum vs. position.
  - Linear fit along axes produces significant position errors.

  - Represent DoS vs. position with a 2D Chebyshev approximation, then use a root finder. Small position errors throughout simulated range.
    - Some individual points have errors, probably because of meshing.







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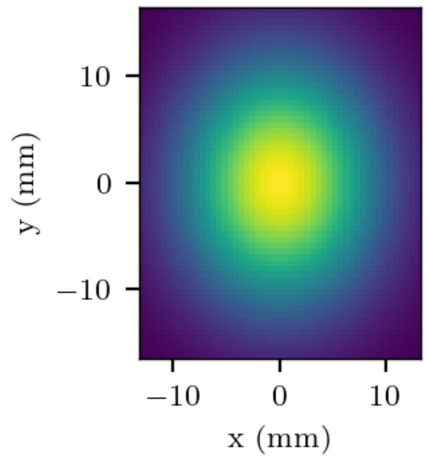
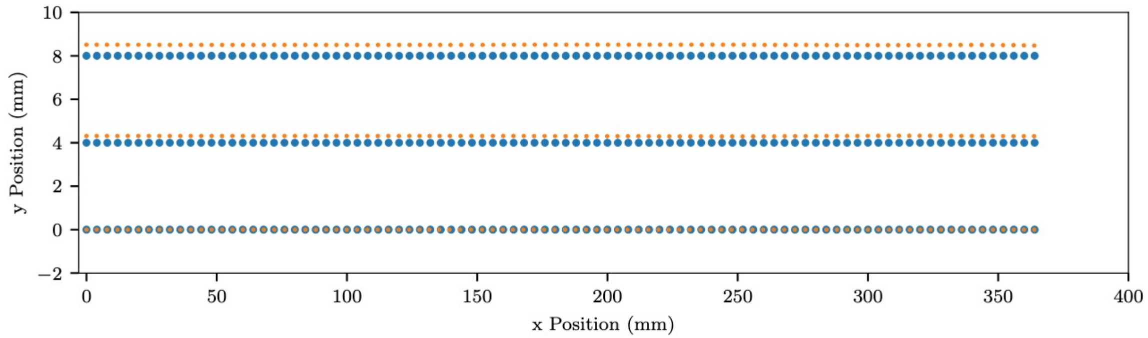
Beam Position Monitor Non-Linear Correction 2

- Previous results were for a pencil beam or thin wire. A beam with a finite transverse size will be more complex.
- Generate a beam 2D distribution and compute electrode signal as the sum of signals from discretised elements.
  - Repeat with the beam centre moved to different positions in the aperture.
- Use these signals as inputs to root finder.
  - Position errors still much less than 1mm, but usable aperture is now restricted.
- Useable aperture encompasses maximum expected horizontal excursion.





Wall Current Monitor

Beam Current - WCM

Target Specifications

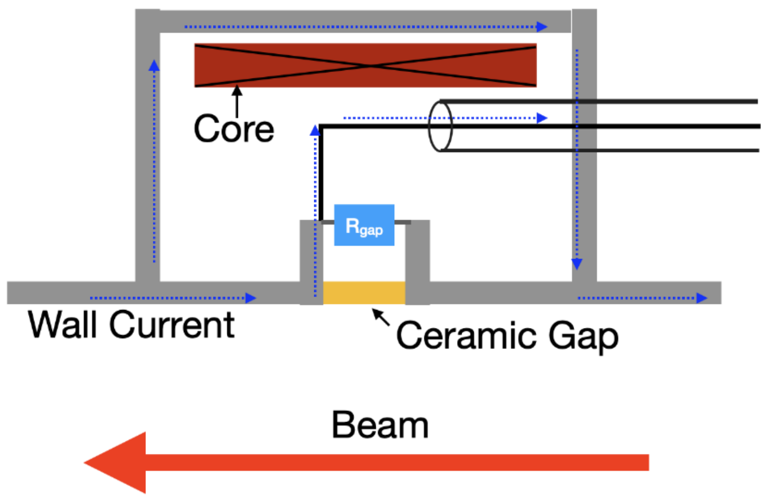
- Resolve ~100 harmonics of revolution frequency for longitudinal tomography (~374 MHz).
- Resolve up to ~ 200 MHz for Schottky.

Nice to Have

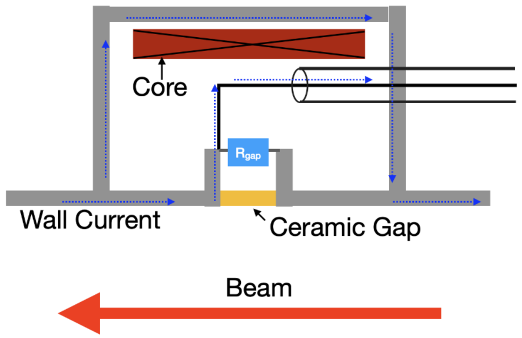
- Resolvable signal for a single injected pulse

Ideal Placement

- 1x WCM



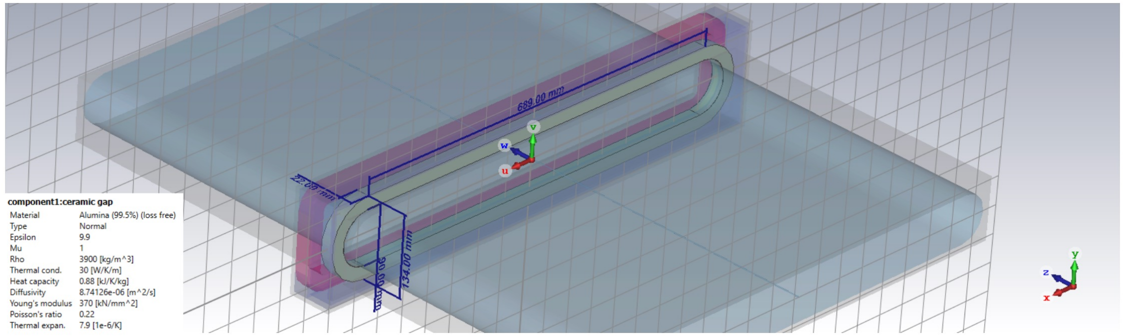
Beam Current – WCM - Materials



- WCM requires a ceramic gap.
  - RF cavities in KURNS FFA uses **Alumina** which is larger than the FETS-FFA aperture.

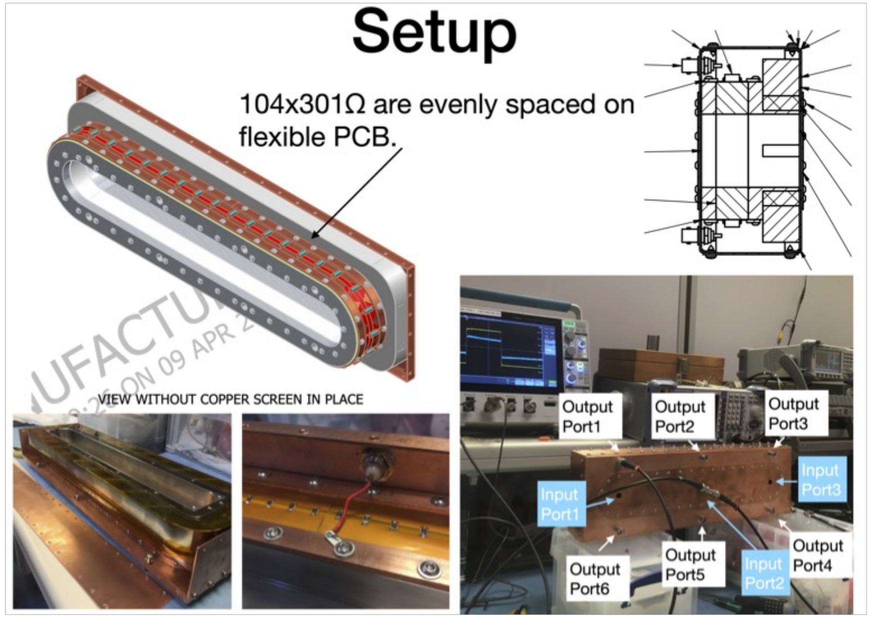
- Ferrite core increases impedance around the conducting shield for high-frequency signals, which travel through resistor.
  - Two materials tested:
    - FT3M magnetic Al - high permeability for low-f
    - FR68 ferrite – high permeability for high f

- Spec sheets available, but prototype constructed to verify experimentally.



Beam Current – WCM - Demo

- Prototype WCM has alumina gap and resistors mounted on a flexible PCB.
- Wire connected through aperture, at three different horizontal locations.
- With this test set-up FR68 does not significantly improve high-frequency performance.
  - Flat gain response until ~ 200 MHz
- Position dependence of signal identified.
  - Summing the voltage over several positions largely resolves this issue.



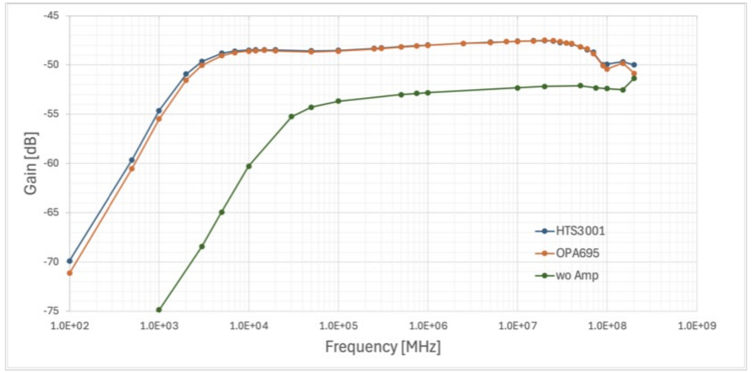
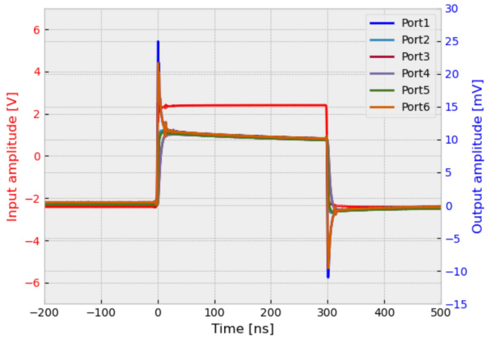


Figure 8.123: Gain plots with and without summing amplifiers: OPA695 and HTS3001.



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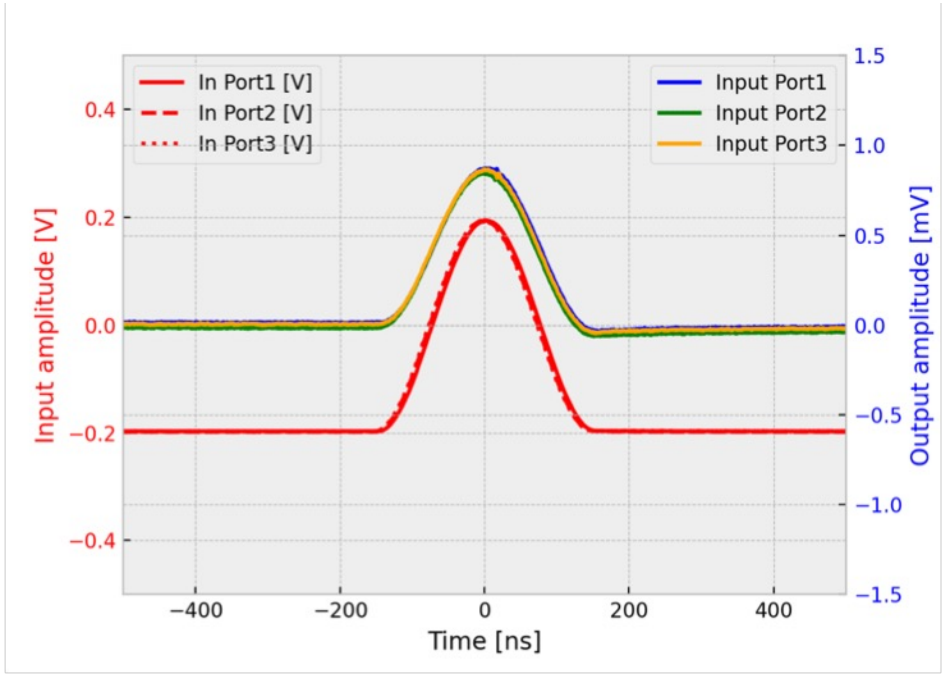
Beam Current – WCM - Signals

- WCM will be used during commissioning to observe the accumulation of injected beam.
  - WCM would ideally resolve this process.
- Input a current of ~0.4 mA to the demo, with a half-sine distribution. Signals were measureable with an oscilloscope.
  - Corresponds to < 3e9 ppp
- Demonstrates that this monitor can resolve a single injected pulse.



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Long Pulse Current Transformer

Beam Current – LCPT

Long Pulse Current Transformer

- Alternative to DCCT

Target Specifications

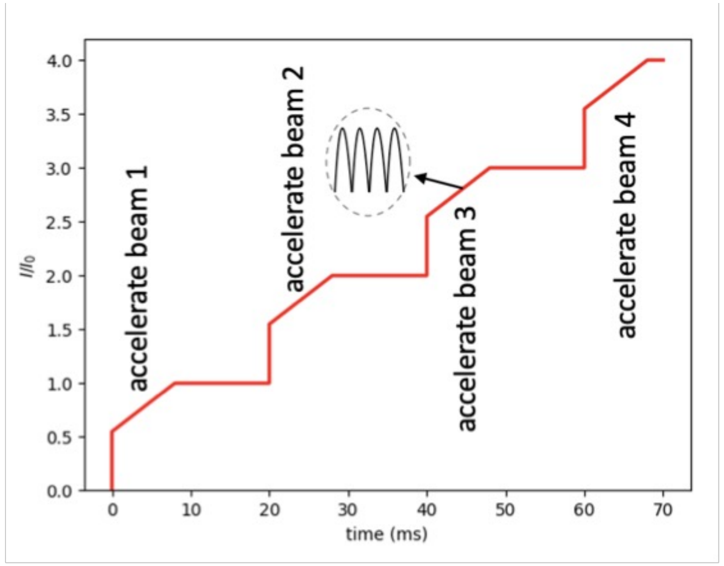
- Resolve 1% of injected beam current
- Suitable frequency response to measure stacked beams for several 10's of ms.

Nice to Have

- Best possible current resolution to assist with commissioning of phase 3.

Ideal Placement

- 1x LPCT, ideally in a long straight



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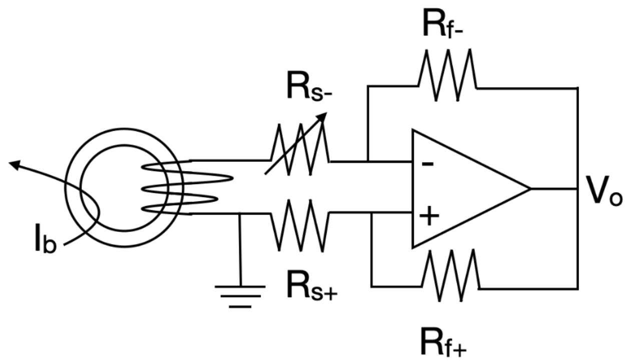
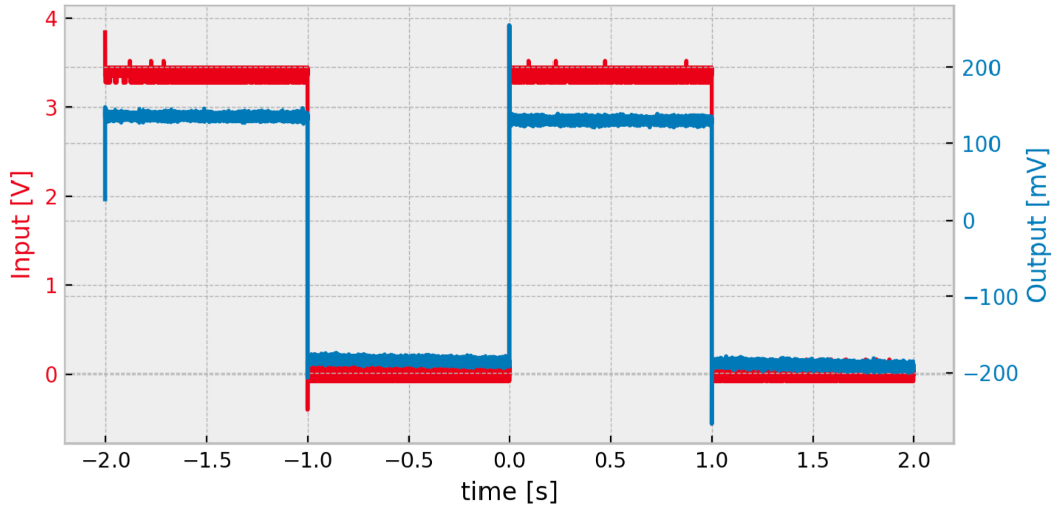
Beam Current – LCPT Electronics

- Originally investigated a DCCT to measure current of coasting (DC) beams during stacking.
    - Requires multiple high-permeability cores.
    - Difficult to obtain such large cores with near identical characteristics.
- Moved to looking at single-core designs, but with a bandwidth that was suitable for measuring **near** DC beams.
    - The coasting beam is not 100% DC
- Core is then a "standard" CT, but with special electronics to focus on low-frequency performance.
- Identified negative-impedance converter (NIC).
    - Example signal with a NIC shows no visible droop over time scales of seconds.





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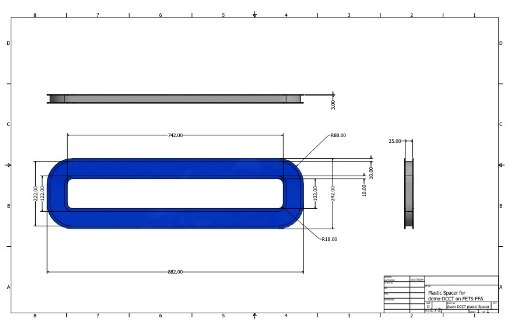
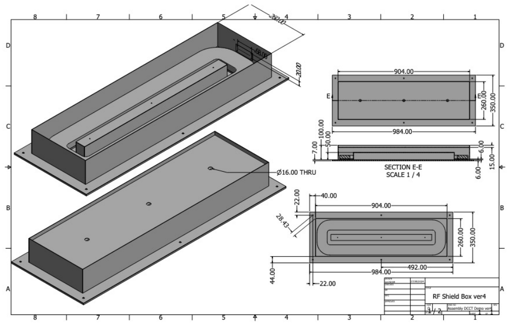
Beam Current – LCPT Demonstration

- Constructed a demonstration system
  - FT3M magnetic alloy core (high permeability at low frequencies)
  - Inside a conducting RF screen box.
  - Beam currents mimicked with an exposed wire.

- Photograph shows the FT3M core inside the RF shield box, with four sets of 100-turn windings.
  - Connected so that the number of windings could be adjusted.





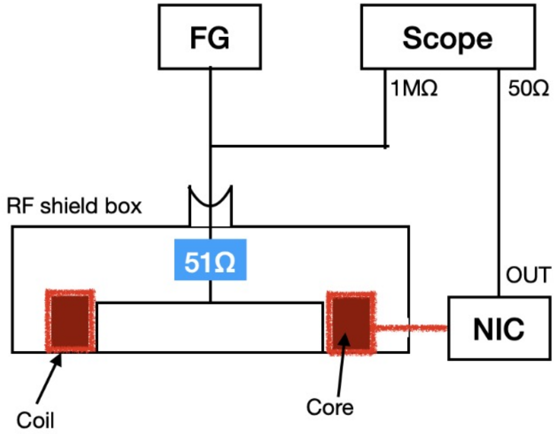
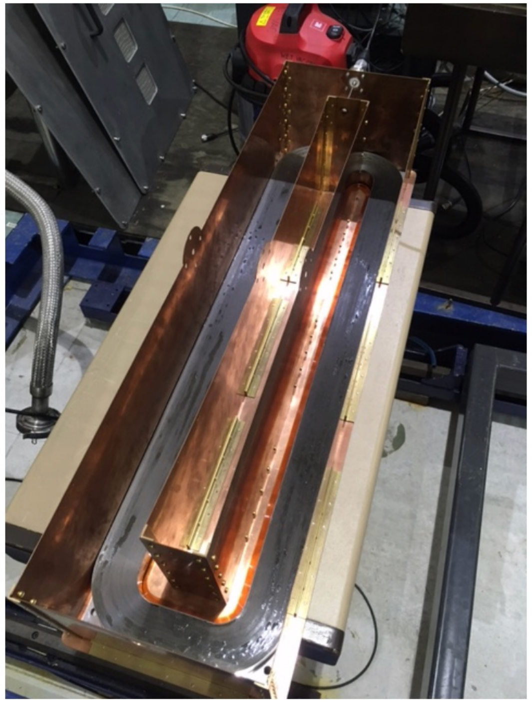


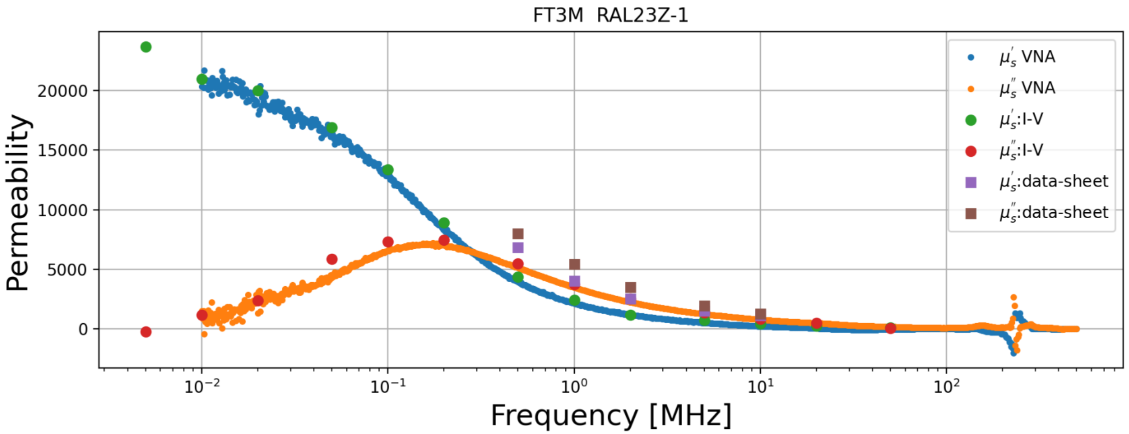
Figure 8.134: Picture of FT3M core in the RF shield box.

Beam Current – LCPT Material

- FT3M magnetic alloy core procured and its permeability characterised.
  - Measured both with a VNA and a signal-generator + scope.

- Properties largely consistent with expectation.





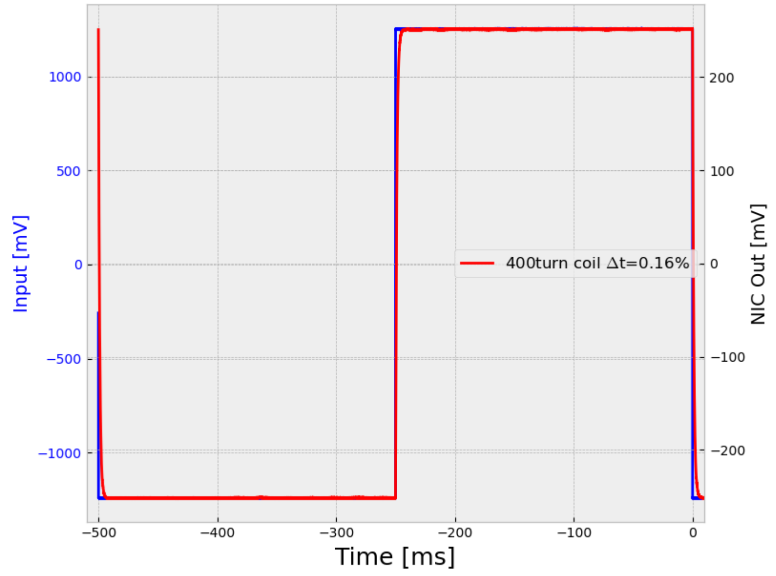
Beam Current – Demo Performance

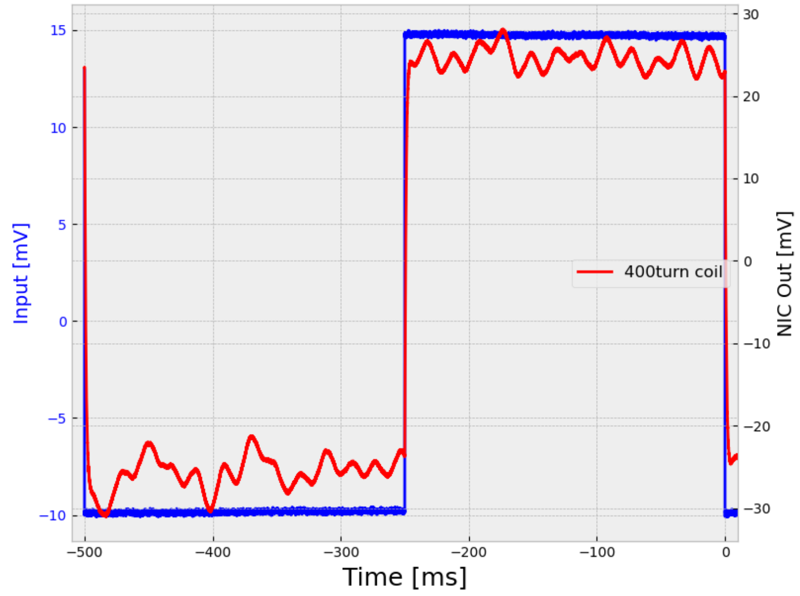
- Top plot shows signal corresponding to ~24mA of beam.
  - 24mA ~ 3e11ppp * 1.6e-19 * 1MHz / 2

- Bottom plot shows peak signal corresponding to ~0.25mA.
  - 0.25mA ~ 3e9ppp*1.6e-19*1MHz / 2

- Droop rate of ~0.2 % over 250 ms has been demonstrated.

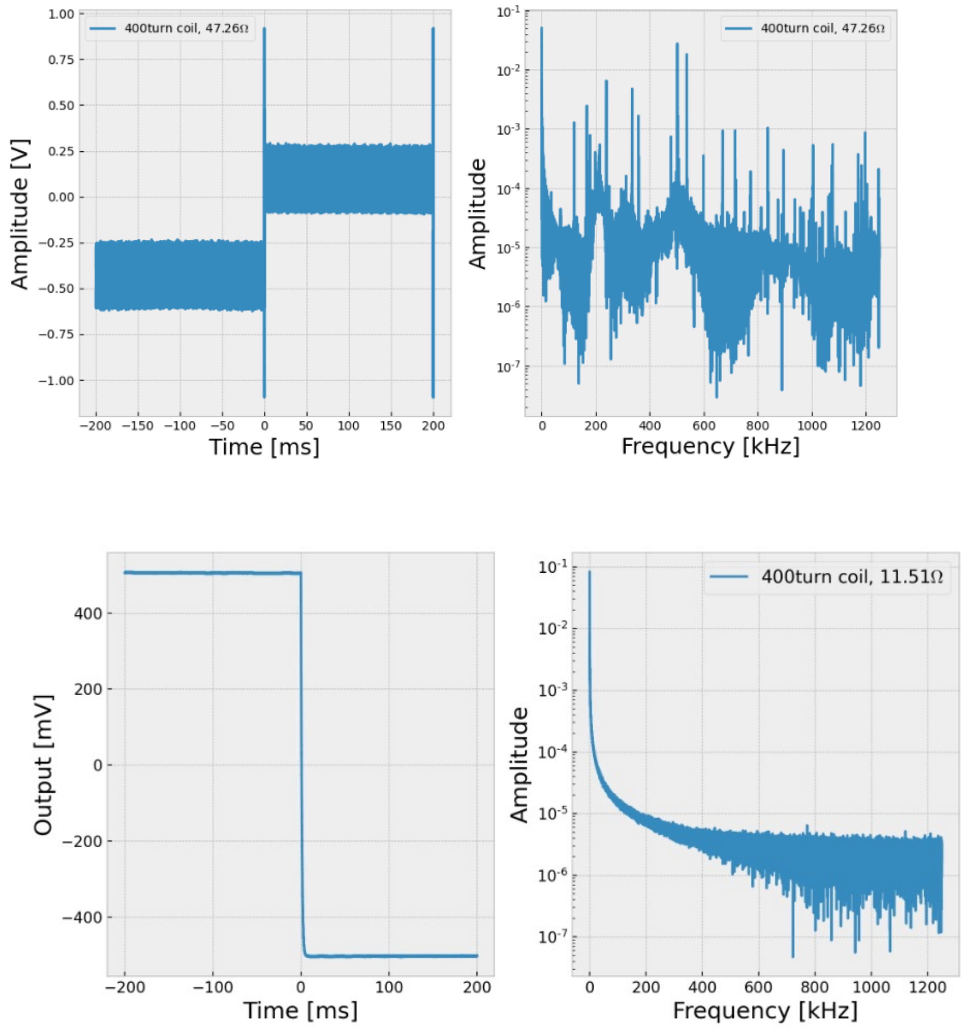
- 1% systemtic accuracy has been demonstrated.
  - Even with 0.25 mA, obtained SNR of 10. Could maybe do better than 1% with averaging.





Beam Current – LPCT - Noise

- Plots show example measurements with and without the RF shield box.
- This monitor is very sensitive to sources of noise.
  - 50 Hz noise
  - Slow thermal variations
- Optimisation of these factors are under development.



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Beam Loss Monitor

Beam Loss Monitors

Target Specifications

- Detect average loss of 1% of the full-intensity beam.
- 1 μs time response for commissioning
- 1 ms for machine protection

Nice to Have

- Radiation hard

Ideal Placement

- 100% coverage, including in magnets

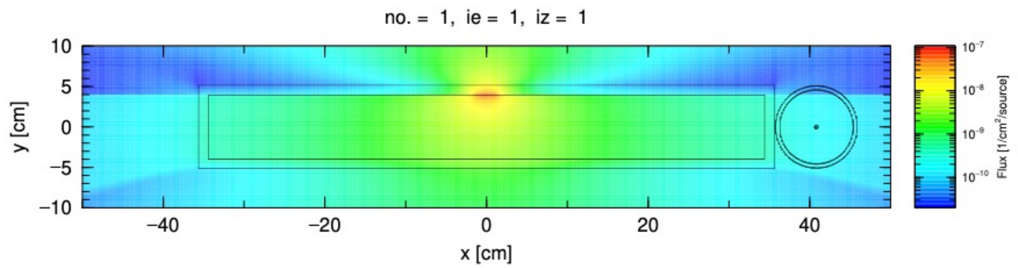
Investigate two types of BLM:

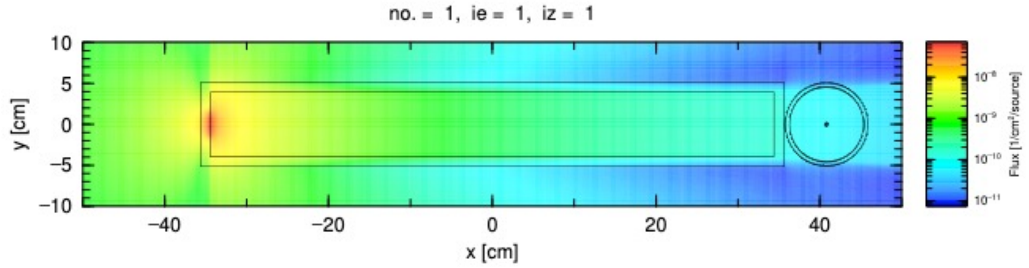
- Ion Chamber – rad-hard, slow response
- Scintillator – not rad-hard, fast response

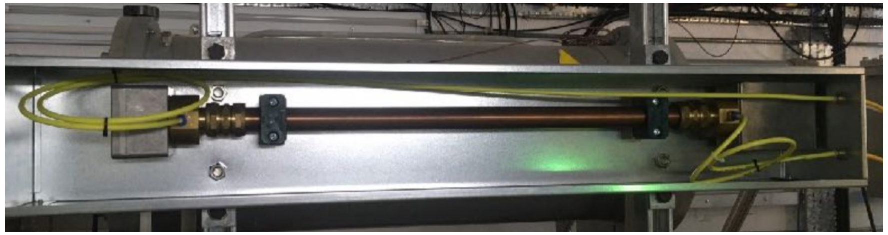
Beam Loss Monitors - IC

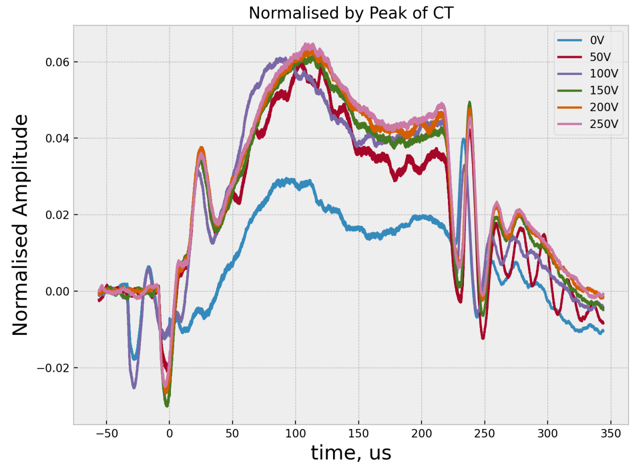
- Monte Carlo simulations of beam-losses in different locations have been performed.
  - Some particles will penetrate the vacuum vessel.

- A prototype BLM has been prepared and installed in the FETS linac.
  - Measurable signals have been produced with 100% beam loss of the FETS beam.
  - Confirms that secondaries can be detected outside the vacuum chamber walls.









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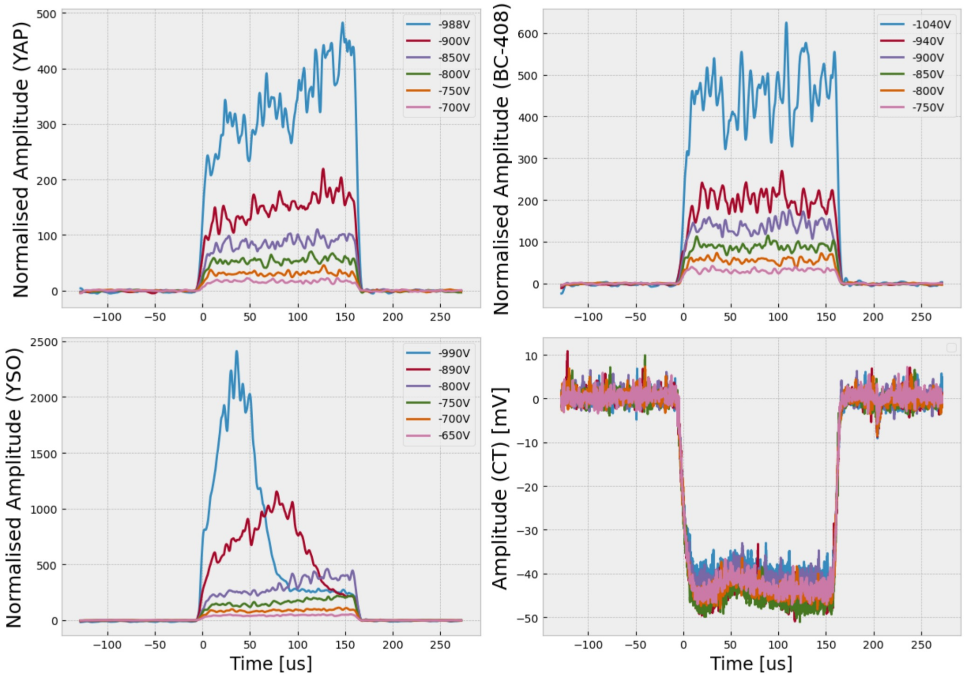
Beam Loss Monitors – Scintillator – FETS Tests

- Investigated several different materials.
  - YAP and YSO single crystals
  - BC-408 plastic scintillator

- All scintillators coupled to PMTs with fibreoptic cables.

- 3 MeV, 20 mA, 200 μs FETS beam directed onto beam dump.
  - High SnR signal measured on all scintillator materials with typical bias voltages (~ 1kV).



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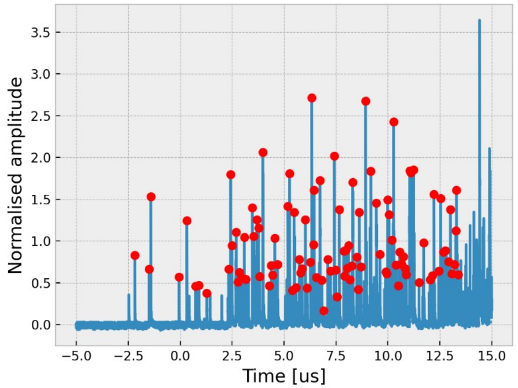
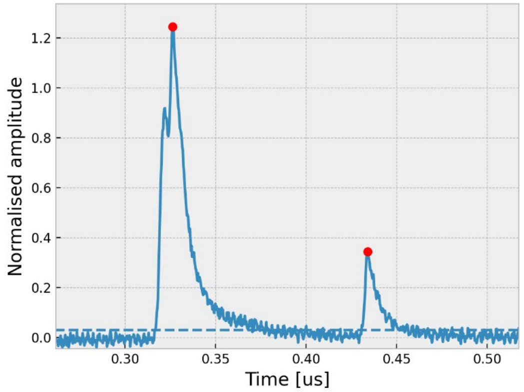
Beam Loss Monitors – Scintillator – Micro Bunches

- Signals shown previously were low-bandwidth, but looking at fast signals we can see beam-losses from micro-bunches in the FETS linac beam.
  - Don't need to lose a whole beam to detect a signal.
- Micro-bunch populations were on the order of 10^7. We have measured individual events from these.
- Suggests that scintillator BLMs can detect beam-loss levels at 1% or better, but these may be very localised.
  - Either need to average over several pulses or locate losses with a portable BLM.





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