A Diagnostic Suite for the FETS-FFA

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on behalf of FETS-FFA Diagnostics Development Team

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UKRI Science and Technology Facilities Council

ISIS Neutron and Muon Source

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Introduction

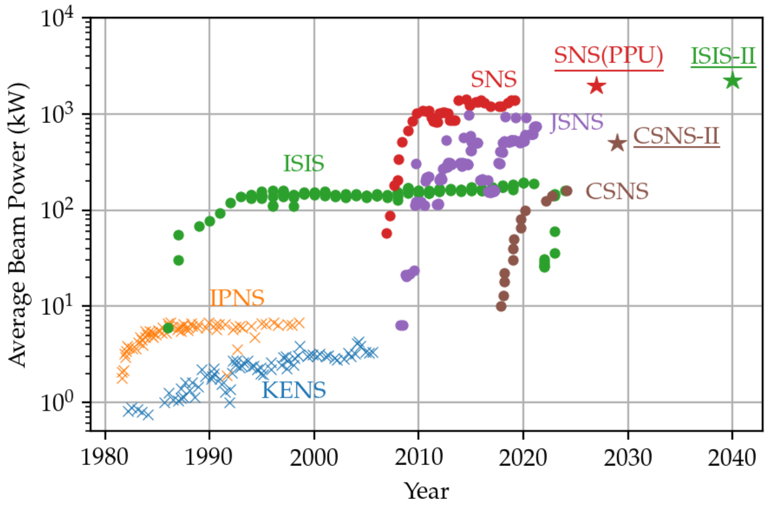
ISIS is a Spallation Neutron and Muon source at the Rutherford Appleton Laboratory in the UK.

With some reactor sources anticipated to close in 2030's, and continued demand for neutron science a recent report stated: *"The UK should therefore look to re-iterate its commitment to neutron science as a core strength of its scientific portfolio…"* [0]

ISIS-II is a proposed short-pulsed neutron source to partially address an anticipated gap in instrument capacity.

<u>ISIS-II Headline Specifications (subject to change)</u>

- 1.25-2.50 MW power on-target
- 1.2 GeV beam energy on-target
- 0.1% beam loss during operations
- Environmental impact is fundamental consideration



M. Kawai, S. Ikeda, and T. Ino, 'KENS-II, its History from Design to Removal'.
B. S. Brown and J. Carpenter, 'Status of IPNS', presented at the ICANS-XIV.
J. Galambos, 'Operations Experience of SNS at 1.4MW and Upgrade Plans for Doubling the Beam Power', IPAC2019.
H. Hotchi et al. "1 MW J-PARC RCS Beam Operation and Further Beyond", HB2021.
L. Huang. Private Correspondence.

FETS-FFA

FETS-FFA Headline Specs (subject to change)

3e11 protons per pulse
100 Hz repetition rate
(60 W equivalent average power)
3-12 MeV proton beam energy
3.6 – 4.2 mean orbit radius

Proton drivers being considered include:

- Rapid Cycling Synchrotron (RCS)
- Accumulator Ring (AR)
- Fixed Field Alternating Gradient Acc. (FFA)

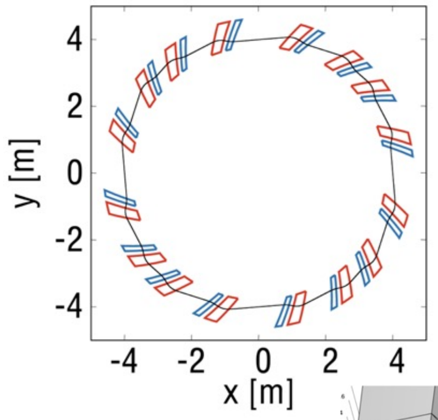
FFA has some potential strengths, but it would be the first high-intensity FFA, so requires a demonstrator (FETS-FFA).

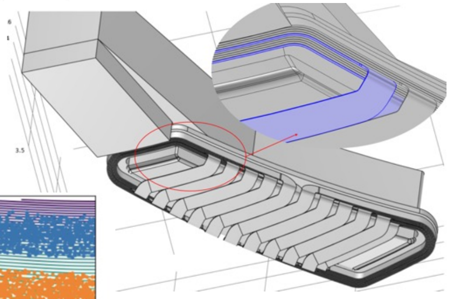
The 2025 FETS-FFA CDR [1] describes three high-level goals:

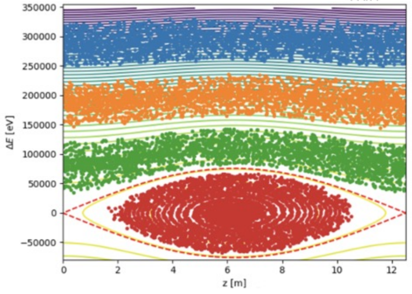
- **Control or Characterise Beam loss**
- **Identify Characteristics of Impedance and instability**
- **Optimise Power consumption**

Beam diagnostics are required for at least the first two goals.

- Won't describe the FFA here, please see other talks.







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FETS-FFA Commissioning

Phase 1

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

- 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

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.

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Diagnostics for FETS-FFA

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 to measure and locate losses.

(Nearly) DC Current transformer to identify loss and measure current of stacked beam.

Contents

Thin 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.

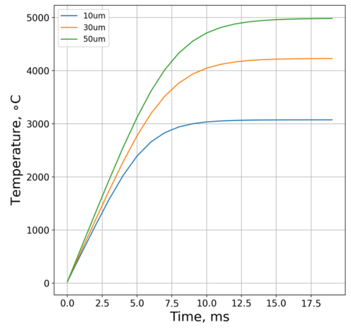
Thermal simulations for injected beam predicted thin CNT as the most promising material [2].

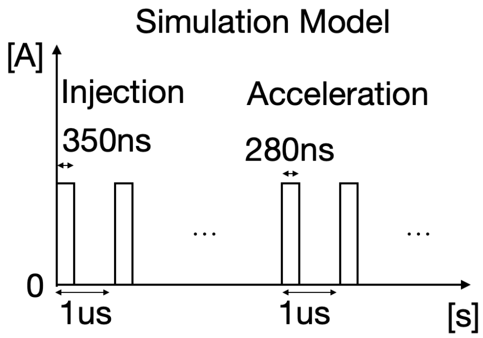
Motorised beam test on FETS. (20, 30, 40, 50 μm)

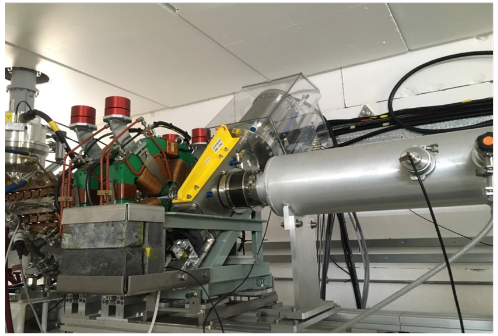
- Profiles measured and thermal tests carried out with 20um wire. Left exposed for 10 minutes. Simulations predict T > 1000 C. Wire unbroken.

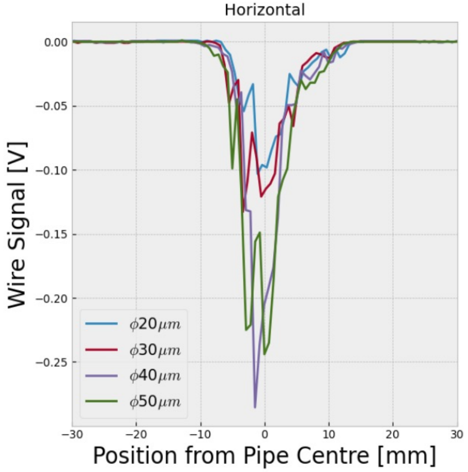
Stationary wire test on KURNS FFA.

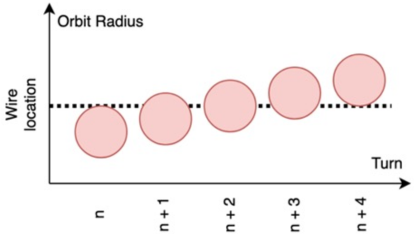
- Design RMS = 5mm, measured = 3.5 mm.

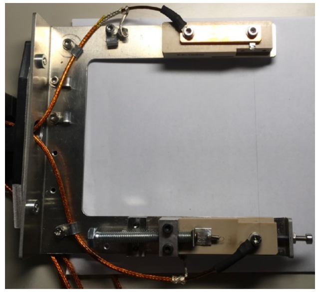


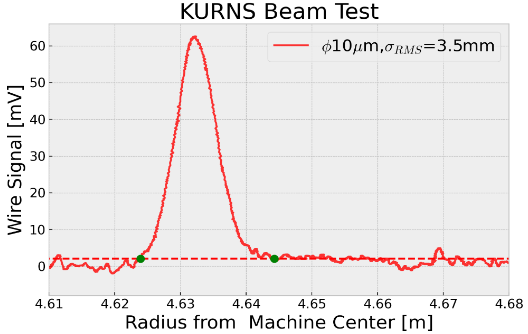












Beam Position Monitors

Combined H and V to save long. Space [3].

Uncertainty of ~1mm turn-by-turn required.

Neglecting systematics, largely determined by amp.

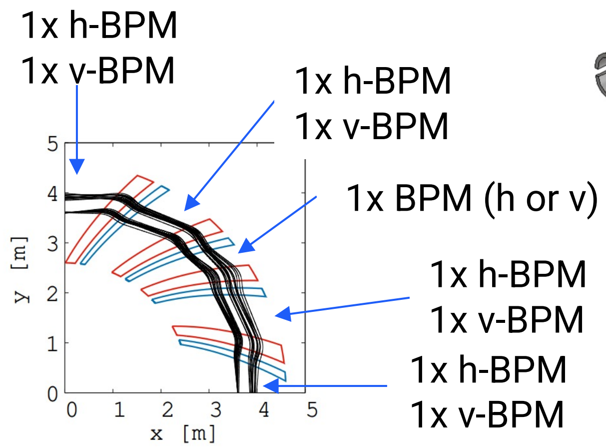
Sum computed as a function of electrode length.

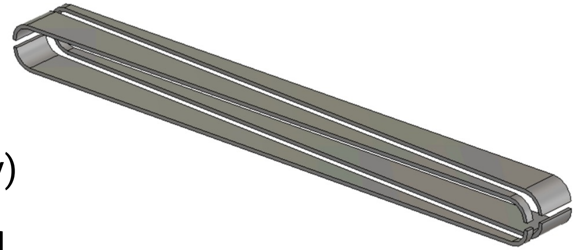
Amplitudes of ~0.5 V with < 10cm achievable, 6 cm practical. Low-noise amplifier required.

Nonlinearity close to electrode edges.

Near-perfect correction for a pencil beam.

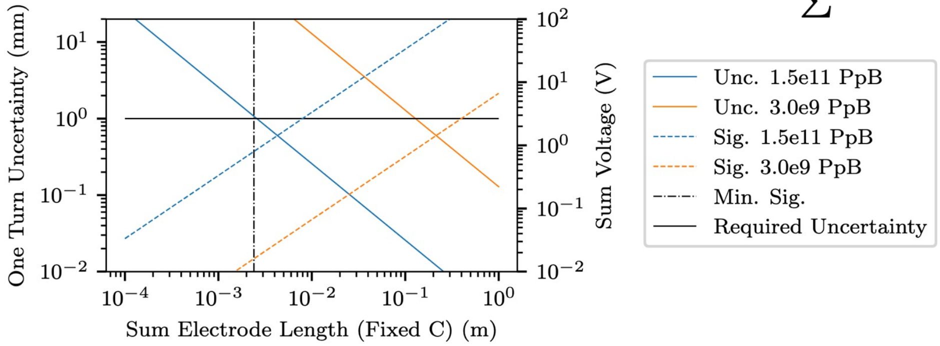
1mm accuracy achieved for vertical offsets <~ 8mm with Gaussian $(\sigma_x, \sigma_y) = (6.5, 8.1)$ mm.

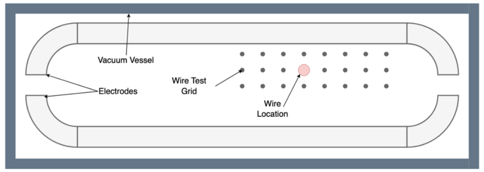


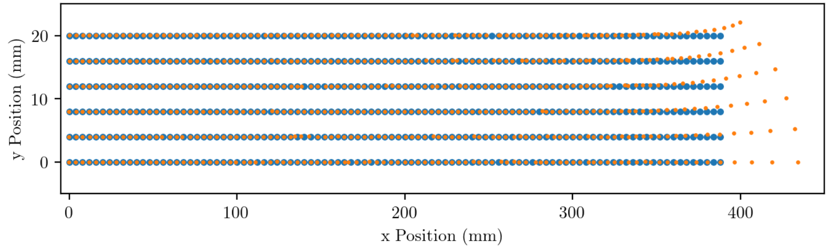


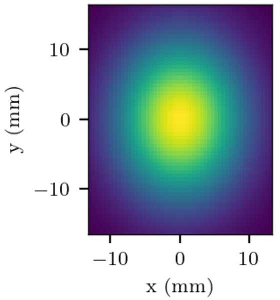
$$y = k_y \frac{V_1 - V_2}{V_1 + V_2} + \delta_y = k_y \frac{\Delta}{\Sigma} + \delta_y$$

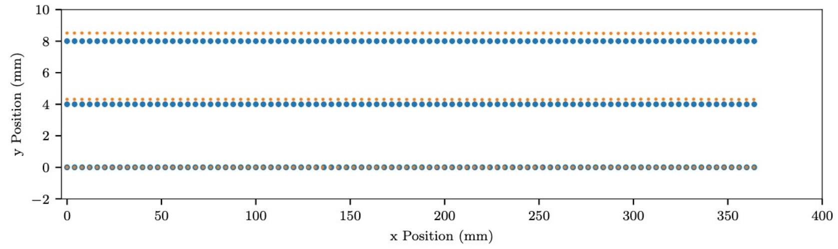
$$\sigma_y \approx k \frac{\sigma_\Delta}{\Sigma}$$











Wall Current Monitor

Wideband (>~ 200 MHz) longitudinal monitor for curre
longitudinal profile and Schottky.

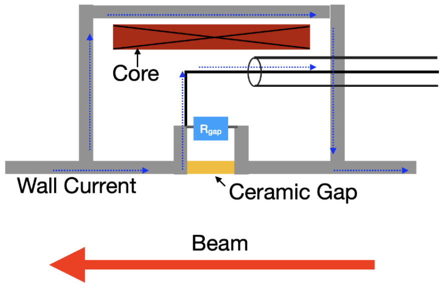
Prototype WCM constructed with alumina gap and resistors mounted on a flexible PCB [4].

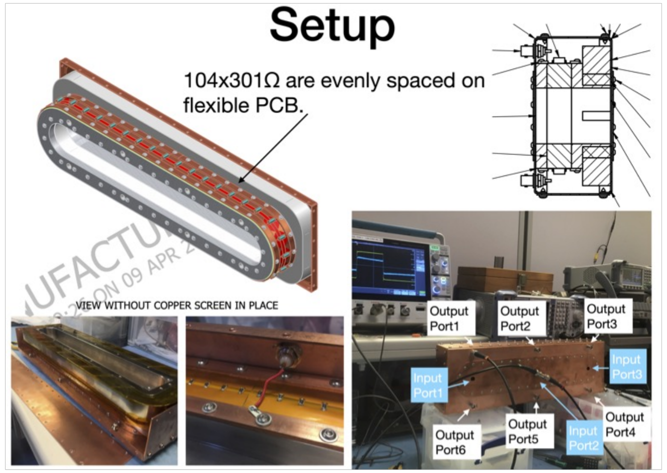
- Three wires through aperture to excite WCM.
- Alumina ceramic gap, based on KURNS RF Cavity.
- Ferrite increases impedance of conducting shield.
  - FT3M magnetic Al - *high permeability for low-f*
  - FR68 ferrite – *high permeability for high f*

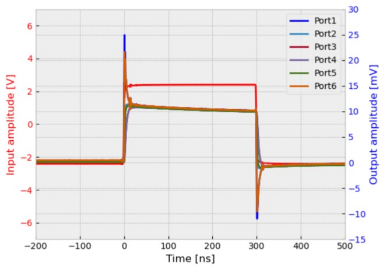
FR68 does not significantly improve bandwidth

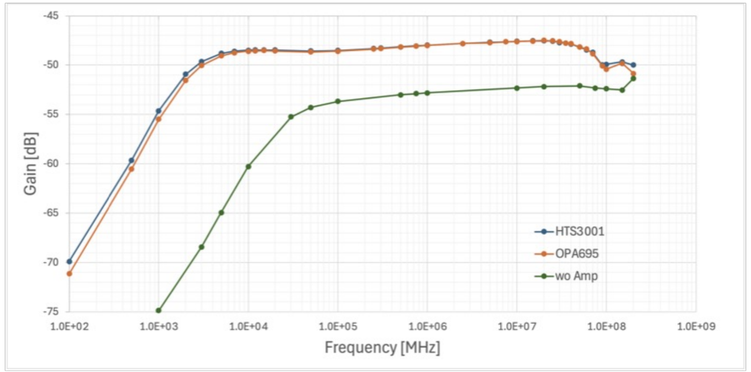
- Flat response until ~ 200 MHz

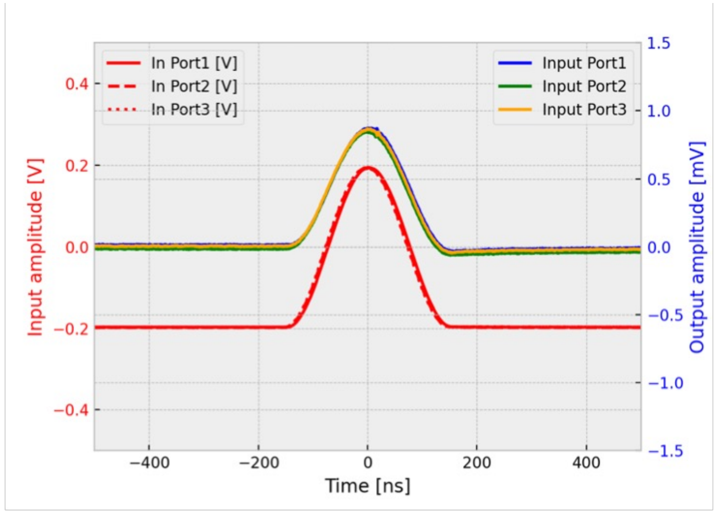
Input signal corresponds to one injected pulse (3e9 ppp) and were measureable (but small).











(Nearly) DC Current Transformer

WCM not suitable for coasting beam, or stacked beams coasting for long periods of time.

Investigated traditional DCCT, but requirement to have two similar cores challenging.

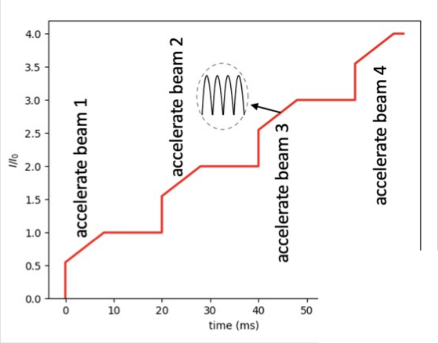
- Moved to looking at CTs with low frequency cutoff (a practical coasting beam isn't DC)

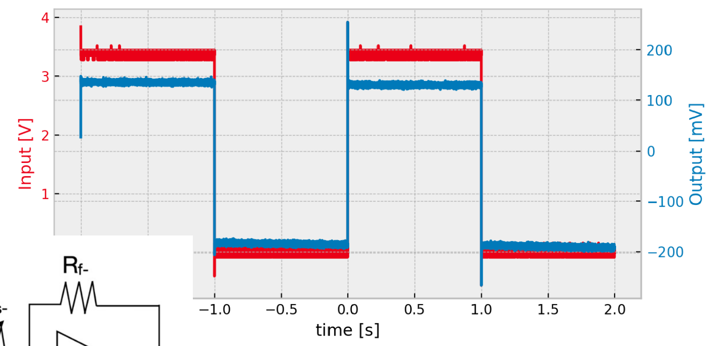
Identified Negative Impedance Converter circuit

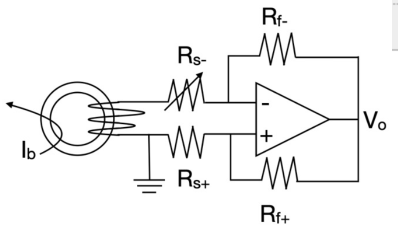
- Example shows no visible droop over ~1s.

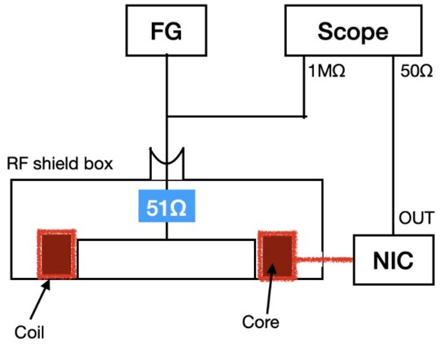
Measureable signals demonstrated for both full intensity and 1% beam current (left, right) [5].

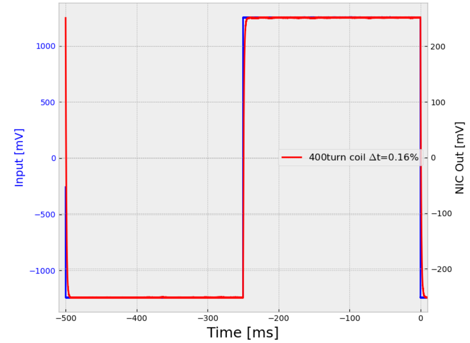
- Droop rate of ~0.2 % over 250 ms demonstrated.
- Even with 1% beam current, obtained SNR of 10.

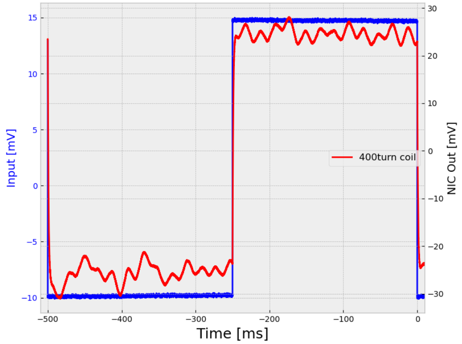












Scintillator BLMs

Beam losses could occur anywhere in the ring [1]. Secondary photons almost isotropically distributed.

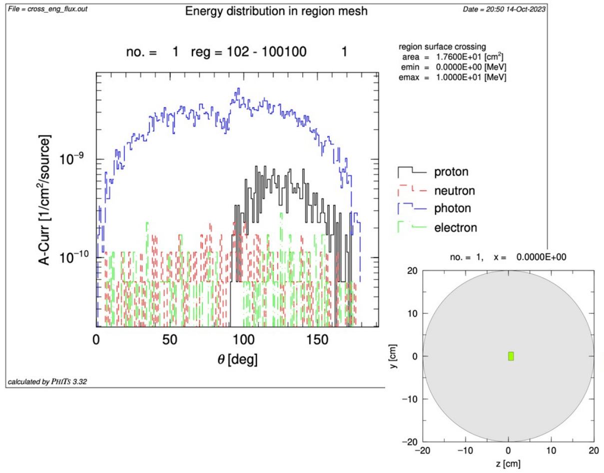
- Entire circumference should be sensitive, scintillators as close as possible to chambers.

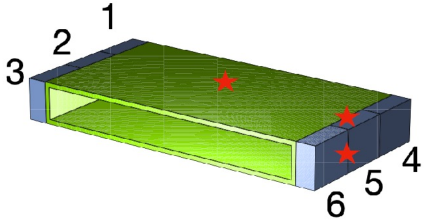
Secondaries from 3 MeV protons could be difficult to detect outside vacuum vessel.

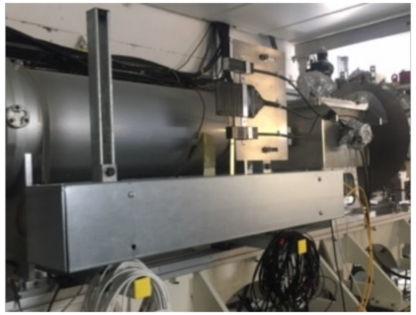
- PHITS simulations show photons penetrate chamber, not yokes. Scintillators must be inside yokes.

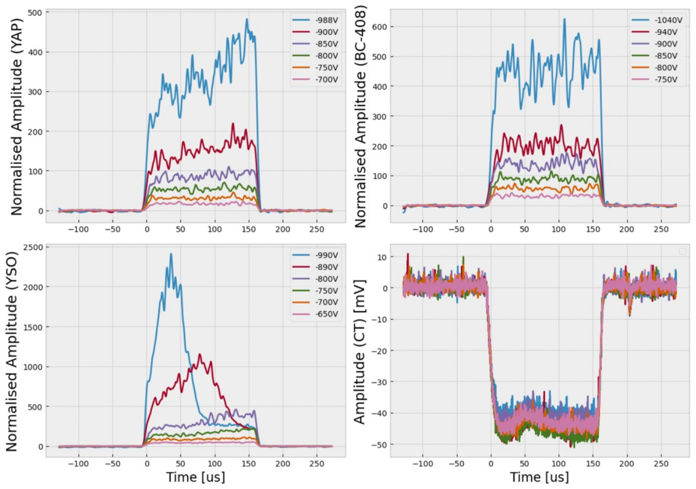
Three scintillators tested with FETS Beam.

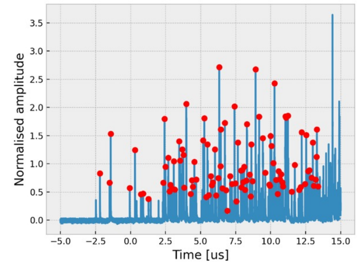
- 3 MeV, 20 mA, 200 μs. 1kV bias on scint. PMTs.
- Even plastic scintillator (BC-408) detected signals.
- Single events detectable from microbunches with populations of 10^7. **1% of FETS beam detectable.**



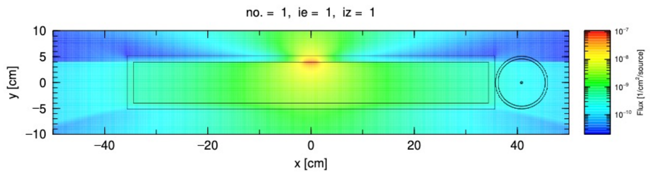


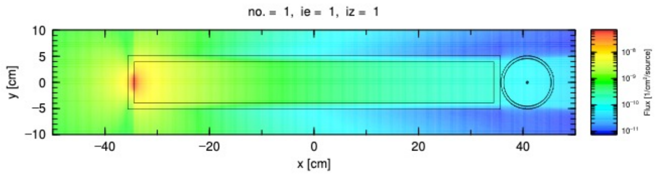






Ion Chamber (IC) BLMs





Experience on ISIS suggests scintillator performance can degrade with time (radiation damage etc).

- IC BLMs very robust.

IC requires very high gain transimpedance amplifier, which limits rise time. IC's not turn-by-turn.

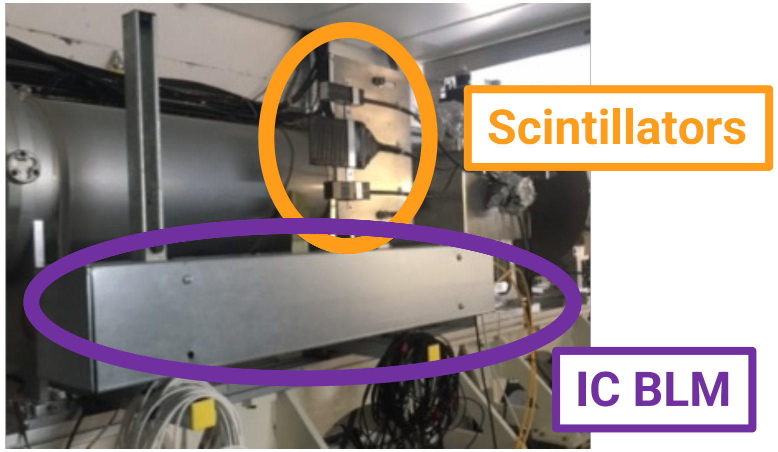
- Test had 10.3 MV/A, 100 kHz bandwidth
- Noise level ~3mV

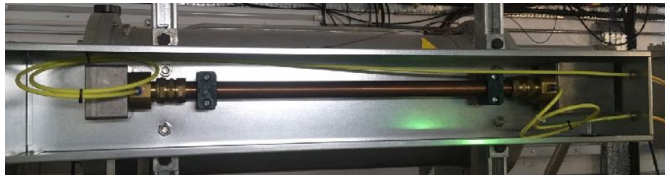
FETS beam tests demonstrated a single-shot signal amplitudes of ~ 10 mV with bias voltages >~ 50 V.

- Further optimisation of detector is possible.

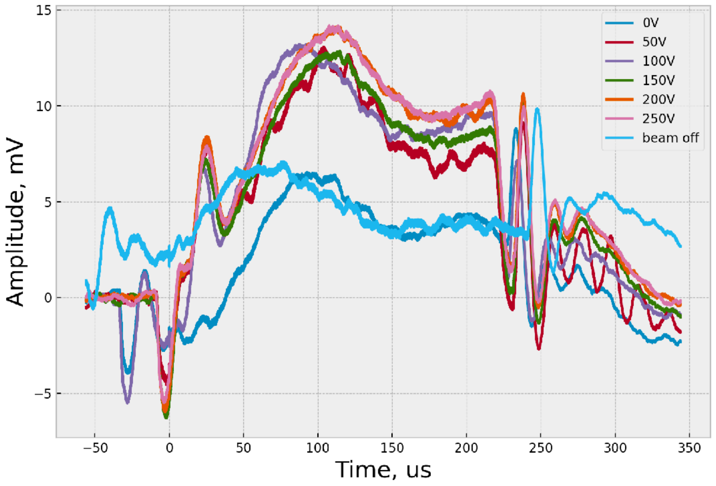
Conclude that IC's <u>can</u> detect signals outside chamber.

- Suggest that maybe that IC's can be used for machine protection (large loss) and scintillators for tuning.





BLM data after pedestal subtraction



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Conclusion

FETS-FFA is a prototype machine to demonstrate elements of high-intensity operations for an FFA, as a part of the ISIS-II project.

FETS-FFA will require that beam losses to be well characterised and controlled.

- A suite of diagnostics were chosen for setting up the machine and understanding beam losses.

Results from simulations, lab prototypes and beam tests have been presented:

- Aspects of diagnostic performance have been demonstrated for: Beam Position Monitors, Profile Monitors Beam Current Monitors, Beam Loss Monitors.
- Scintillating screens and scrapers not presented. Faraday cup presented separately.

All presented monitors seem feasible at this stage.

- See references. Several IBIC2025 publications. CDR contains a lot of instrumentation details.

References

[0] – “Neutron Review 2024 Panel Report”, https://www.isis.stfc.ac.uk/SiteAssets/STFC%20Neutron%20Review%202024.pdf

[1] – S. Machida et. al., “Fixed Field Alternating Gradient Accelerator (FFA) Task Report” 2025.

[2] – E. Yamakawa et. al., “Study of Single Wire Scanner Monitors for FETS-FFA Test Ring”, IBIC 2023.

[3] – D. W. Posthuma de Boer, “Optimisation of a Beam Position Monitor for the FETS-FFA”, FFA Workshop 2024.

[4] – E. Yamakawa et. al., “Development of Wall Current Monitor on FETS-FFA Test Ring”, IBIC 2025.

[5] – E. Yamakawa et. al., “Development of Current Monitor for Stacking Beam in FETS-FFA Test Ring”, IBIC 2025