14. September 2022, FFA workshop 22.

FETS-FFA beam diagnostics development plan

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Required Diagnostics in **FETS-FFA**

Commissioning Phase1: Diagnostics for characterisation of the beams (emittance, momentum spread, bunch structure)		
Comissioning Goal	**1. Acceleration to the top energy and extract in low current beam without painting.**	
FETS-FFA Ring Diagnostics		
	Qty	***Property***
Motorised Wire Scanner (H&V)	1	1. After Foil, beam position, beam size and bump orbit measurements. 2. Intermediate energy beam profile and beam position measurement.
Motorised Faraday Cup + Scintillating Screen	1	1. After Foil: injected beam current, transmission efficiency to design orbit. 2. Intermediate energy: accelerrated beam current measurement. 3. Faraday Cup can be replaced with screen to measure beam size at extraction orbit.
Ring BPM	1 or 2 per cell	1. Beam position, tune and lifetime measurement from injection to extraction orbit. 2. Bunch structure measurement when multi turn injection without painting. 3. Beam position and gradient to reconstruct Poincare map and orbit correction.
Beam Loss Monitor	1 or more per cell	1. Monitor beam losses to identify beam loss locations. 2. Develop into machine and personnel protection systems.
Commissioning Phase2: Diagnostics for injection painting and matching in longitudinal and transverse directions to mitigate beam loss		
Comissioning Goal	**1. Ideal matching in longitudinal and transverse directions** **2. Achive injection painting to mitigate intensity effects.** **3. Accurate beam current and size measurements.**	
	Qty	***Property***
Wall Current Monitor (WCM)	1	1. Measurement of bunch structure and current during acceleration
DC Current Transformer (DCCT)	1	1. Measurement of casting and stacked beam current
Motorised Beam Scraper	1	1. Beam size measurement (if possible, read-out from scraper can be used to calibrate DCCT).
Additional uses of phase 1 monitors	N/A	1. Intermediate: Beam size, position and profile measurement using motorised wire (H only). 2. BPM tomography. 3. Possible beam halo measurements with wire monitors or scraper.
Commissioning Phase3: Diagnostics for advanced beam commissioning		
	Qty	***Property***
Ionisation Profile Monitor	1	1. Turn-by-turn, non-destructive horizontal beam profile measurement.
Additional uses of phase 1 monitors	N/A	1. DCCT measures 1% beam loss if any due to halo development.

Diagnostics Required for FETS-FFA Commissioning Phase 1

(Highest Priority)

Phase 1. FETS-FFA BPM

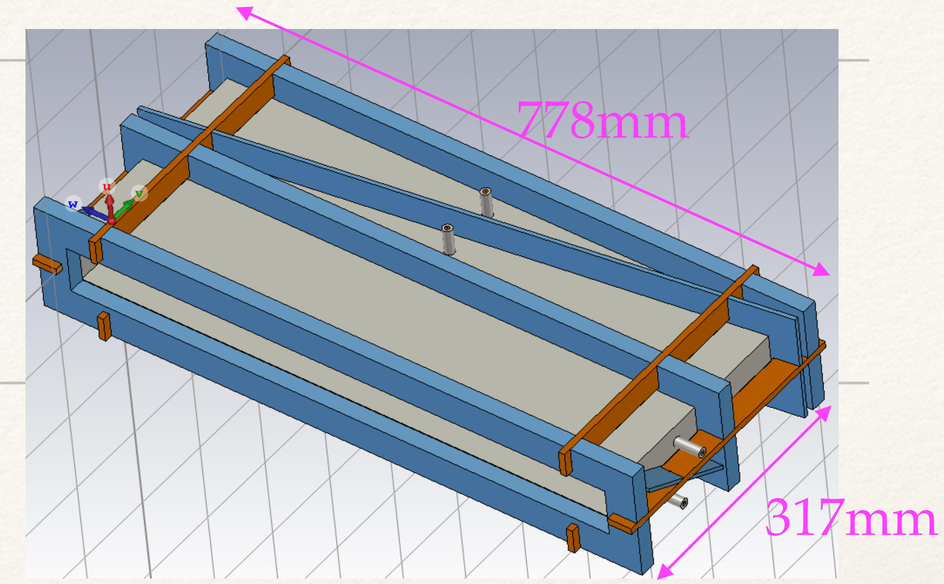


Fig.1. Preliminary design of FETS-FFA BPM.

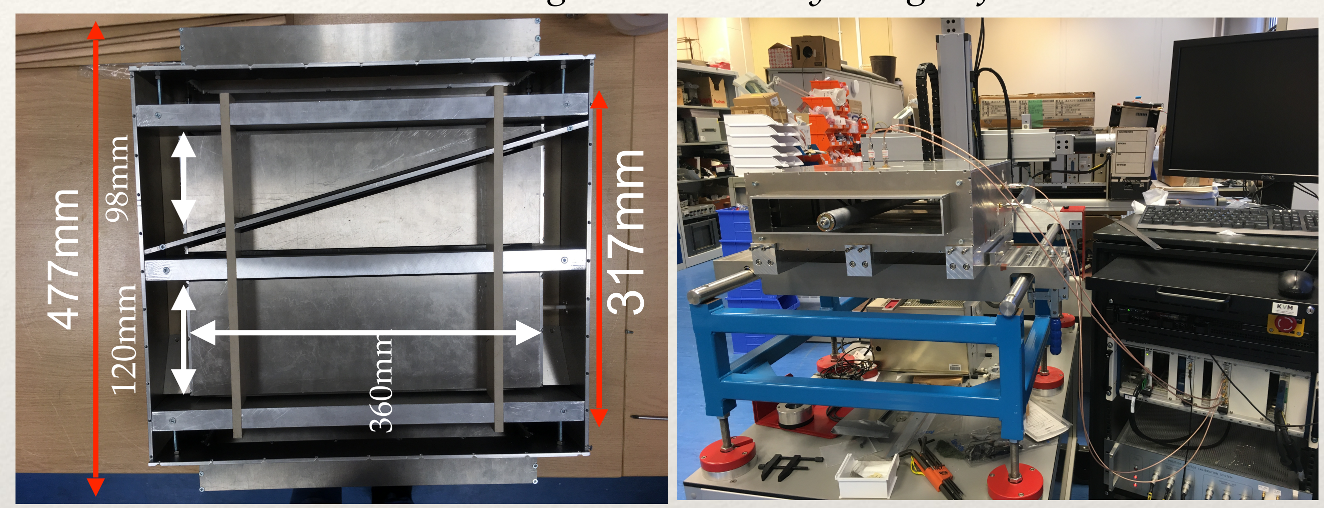


Fig.2. Half size prototype FETS-FFA BPM.

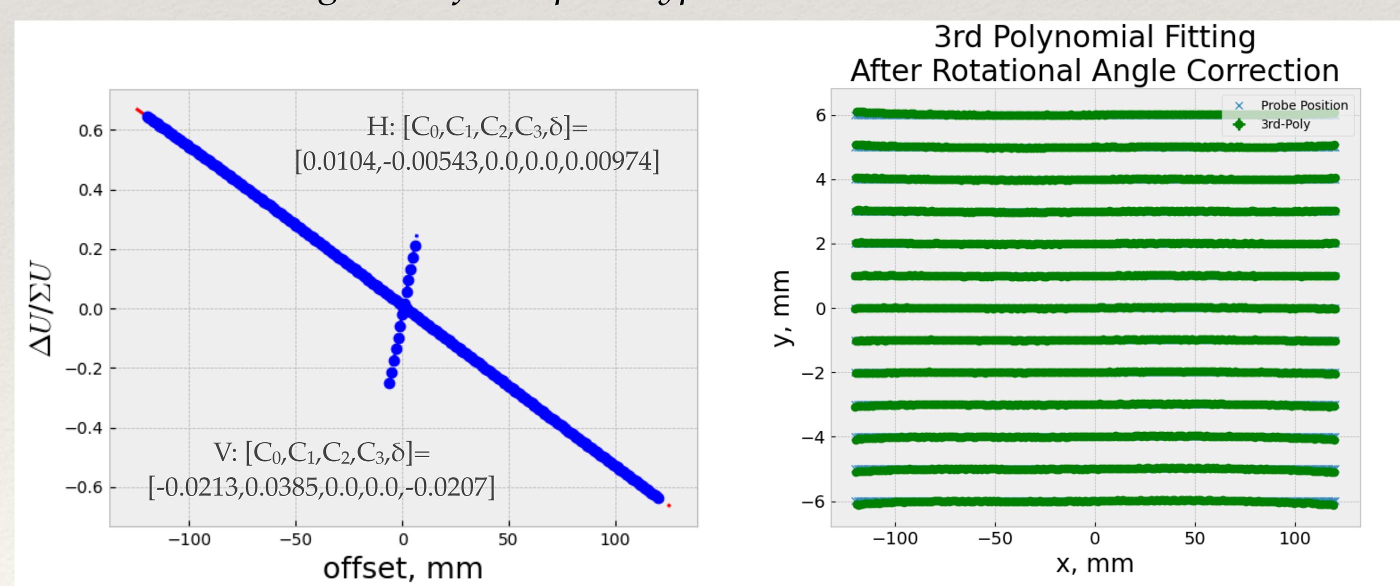


Fig.3. Left:Difference over Sum as a function of displacements of probe in horizontal and vertical. Right: x,y probe positions compared with computed probe positions. In these plots, a drive amplitude was 500mV on the probe.

How it works

- A pair of electrodes (grey components in Fig.1), separated with a diagonal cut are placed along the beam direction.
- Earthed rings (blue components in Fig.1) are placed between adjacent electrodes to prevent electrical coupling between electrodes, improving position sensitivity.

Work Done So Far

- To demonstrate feasibility of the design, a half size prototype FETS-FFA BPM (Fig.2) was manufactured and tested at ISIS.
- Position calibration (3rd Polynomial fitting function):

$$\frac{dU}{\Sigma U} - \delta = C_3 x^3 + C_2 x^2 + C_1 x + C_0$$

was measured by scanning the test probe in the BPM with sinusoidal drive signal at 2 MHz.

Phase1. FETS-FFA BPM

Work Done So Far

- BPM was tested at KURNS in May 2022.
- A beam Position was computed by BPM with averaged position calibration factors (Fig.1).
- A beam position and angle were measured by the scraper to estimate the beam position at the location of horizontal BPM (Fig.2).
    - Beam acceleration was stopped at certain energy (FT energy).
    - Push the scraper inward to interrupt the beam at FT energy.

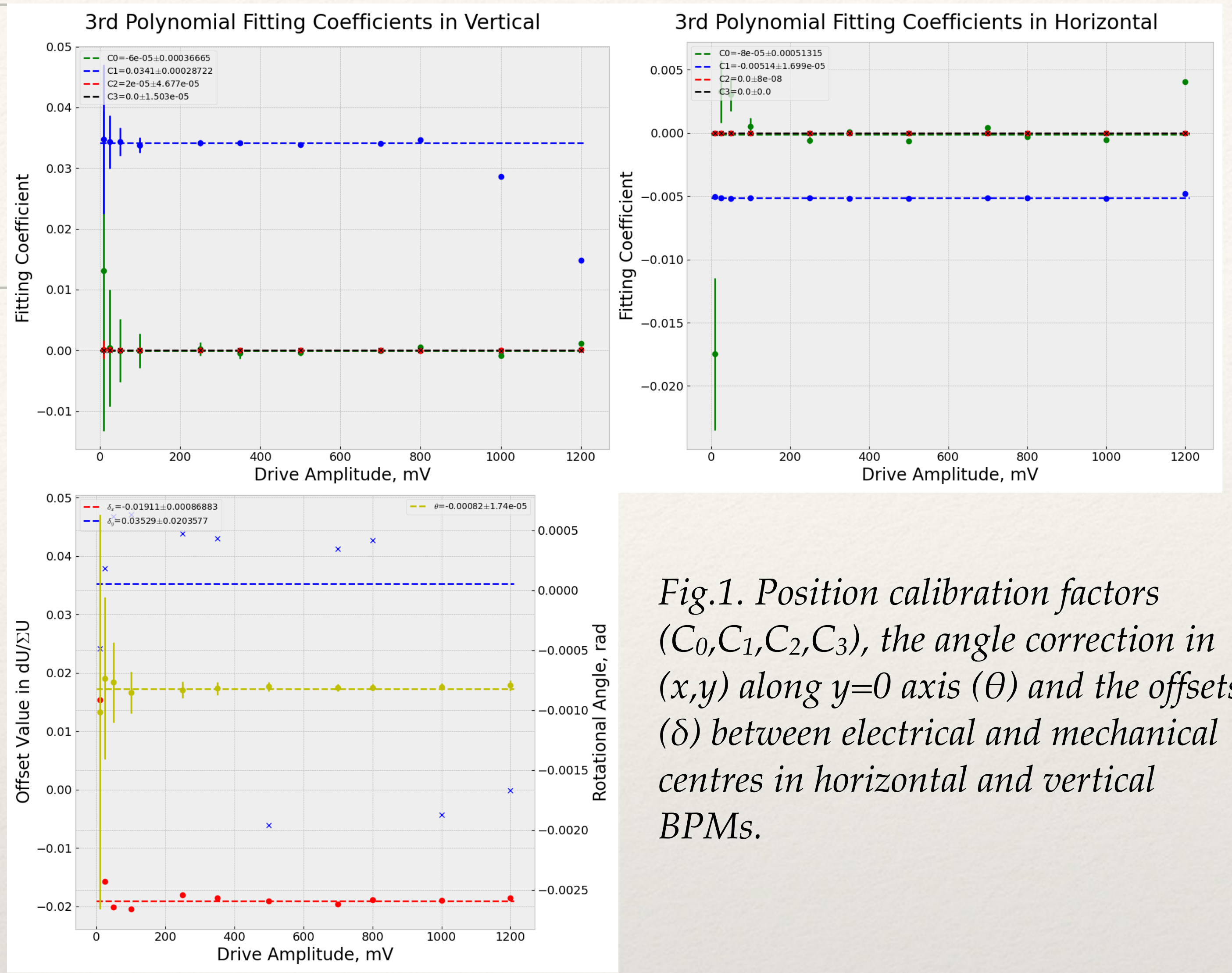


Fig.1. Position calibration factors (C_0,C_1,C_2,C_3), the angle correction in (x,y) along y=0 axis (θ) and the offsets (δ) between electrical and mechanical centres in horizontal and vertical BPMs.

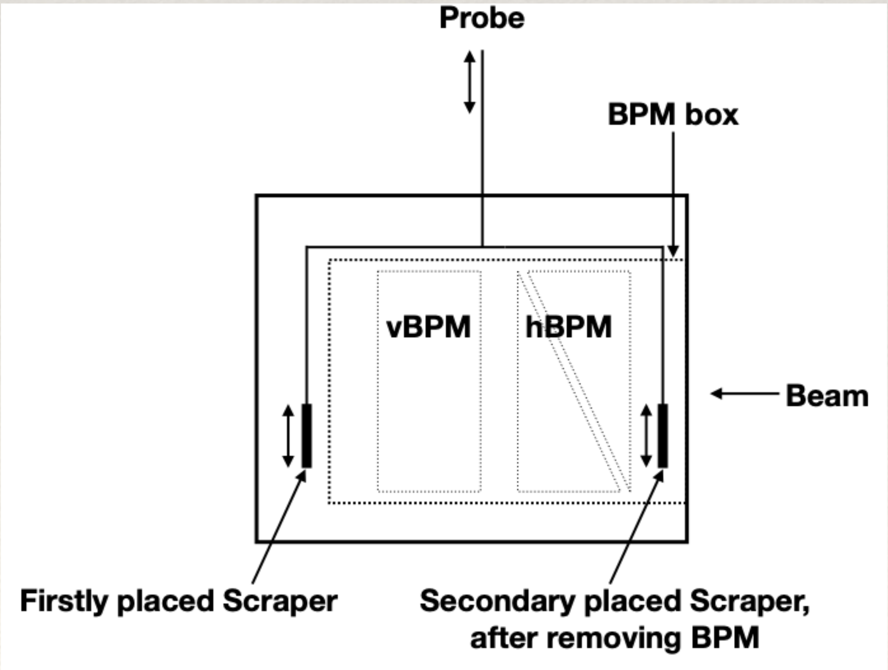
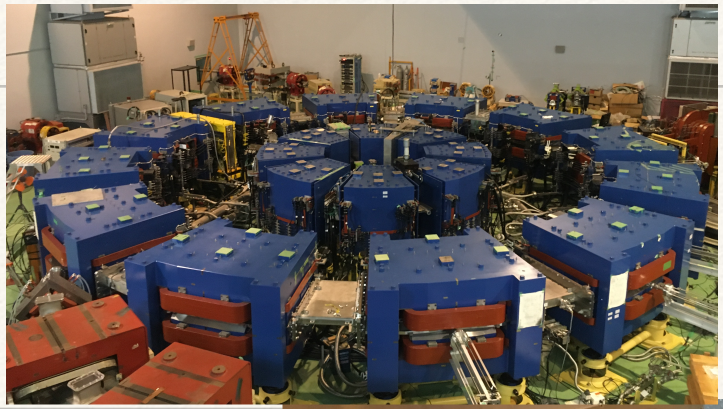
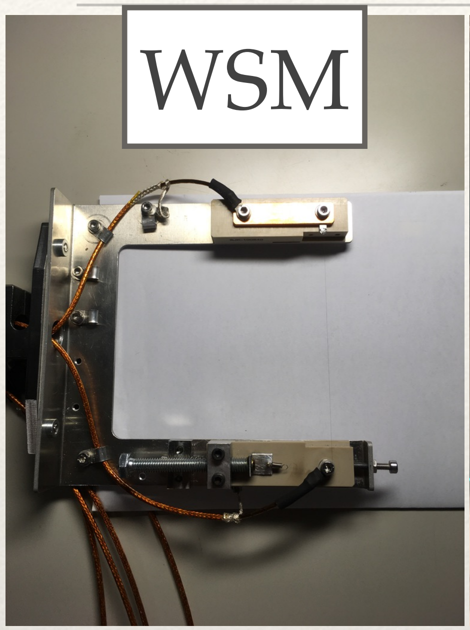


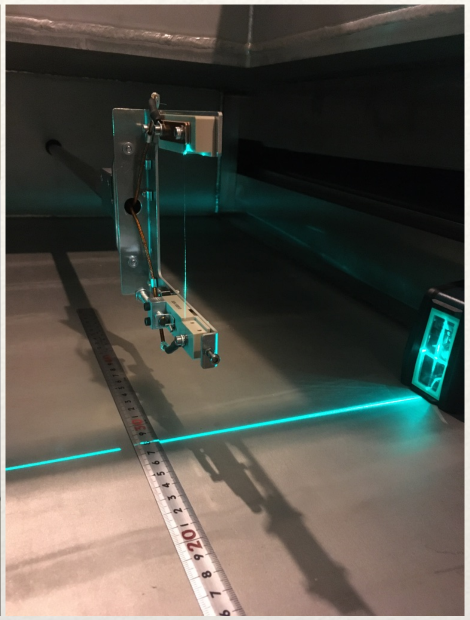
Fig.2. Destructive beam position and angle measurements by scraper at KURNS.

Layout at KURNS



WSM





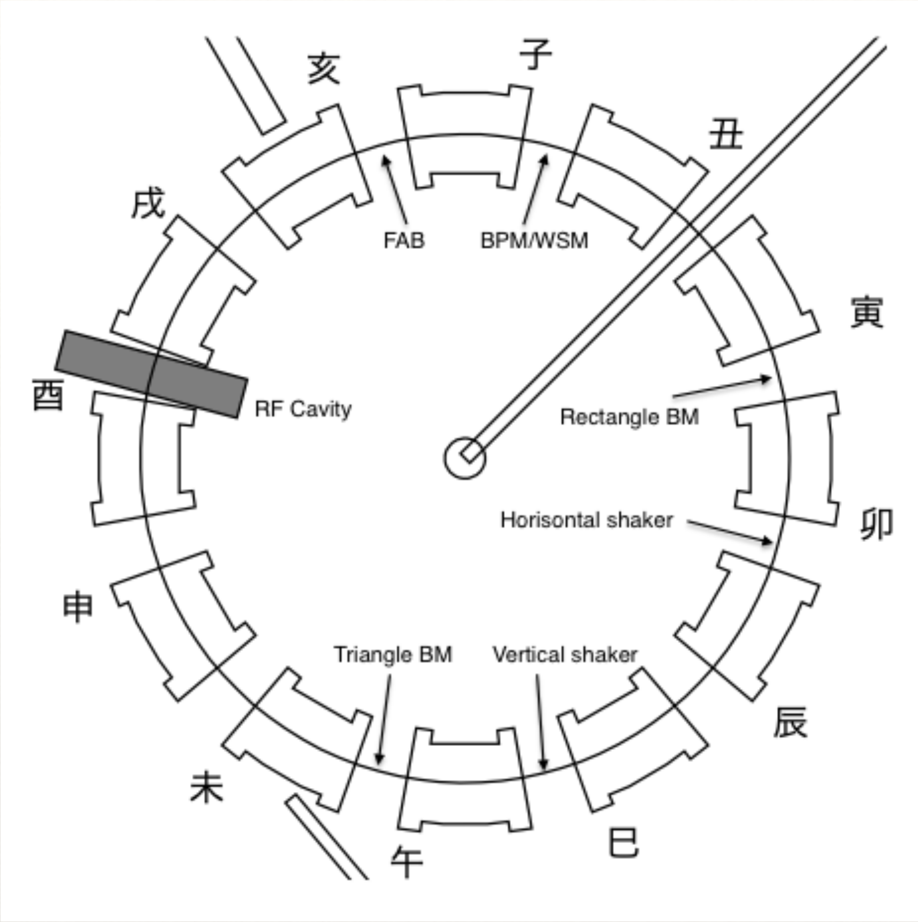
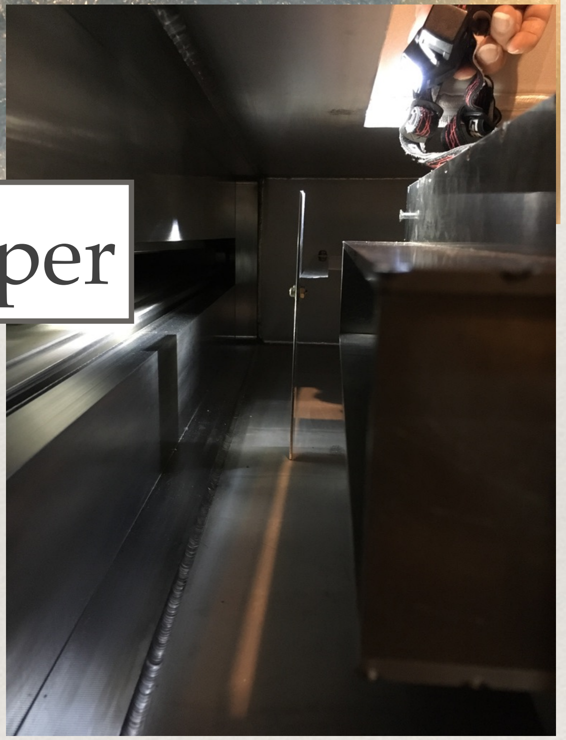
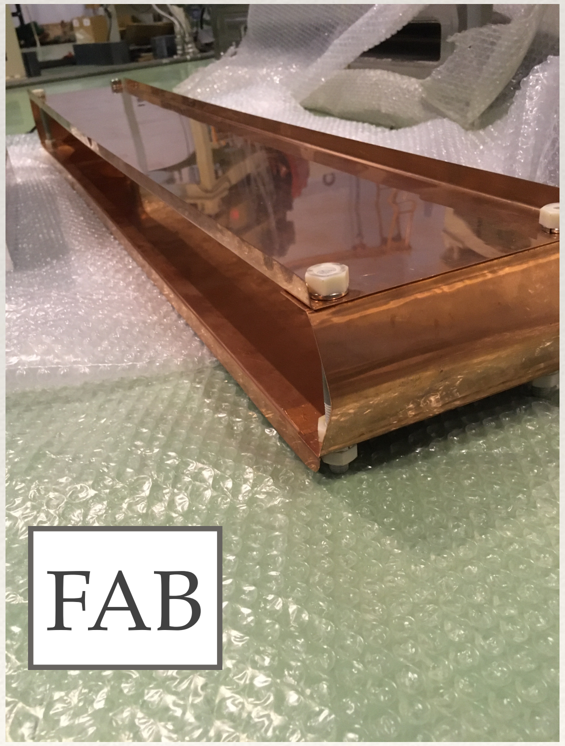


Figure 4: The illustration of beam monitors installed in the KURNS main ring.

BPM

Scraper





FAB

Beam exciter

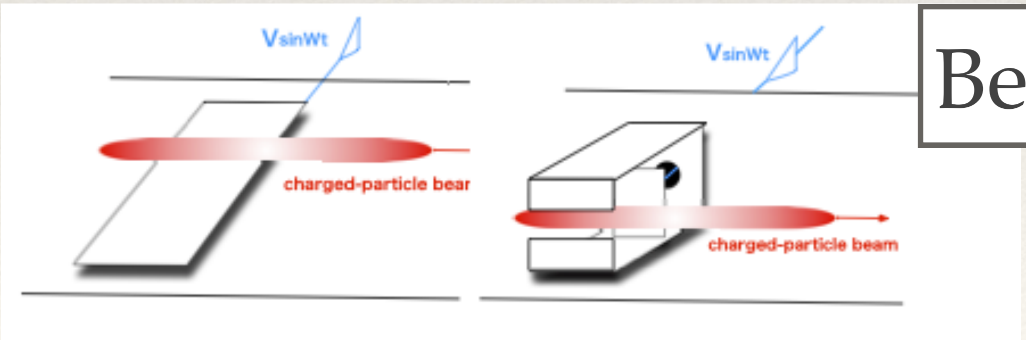


Figure 12: Left: the shaker to excite the vertical betatron oscillation. Right: the shaker to excite the horizontal betatron oscillation.

Phase1. FETS-FFA BPM

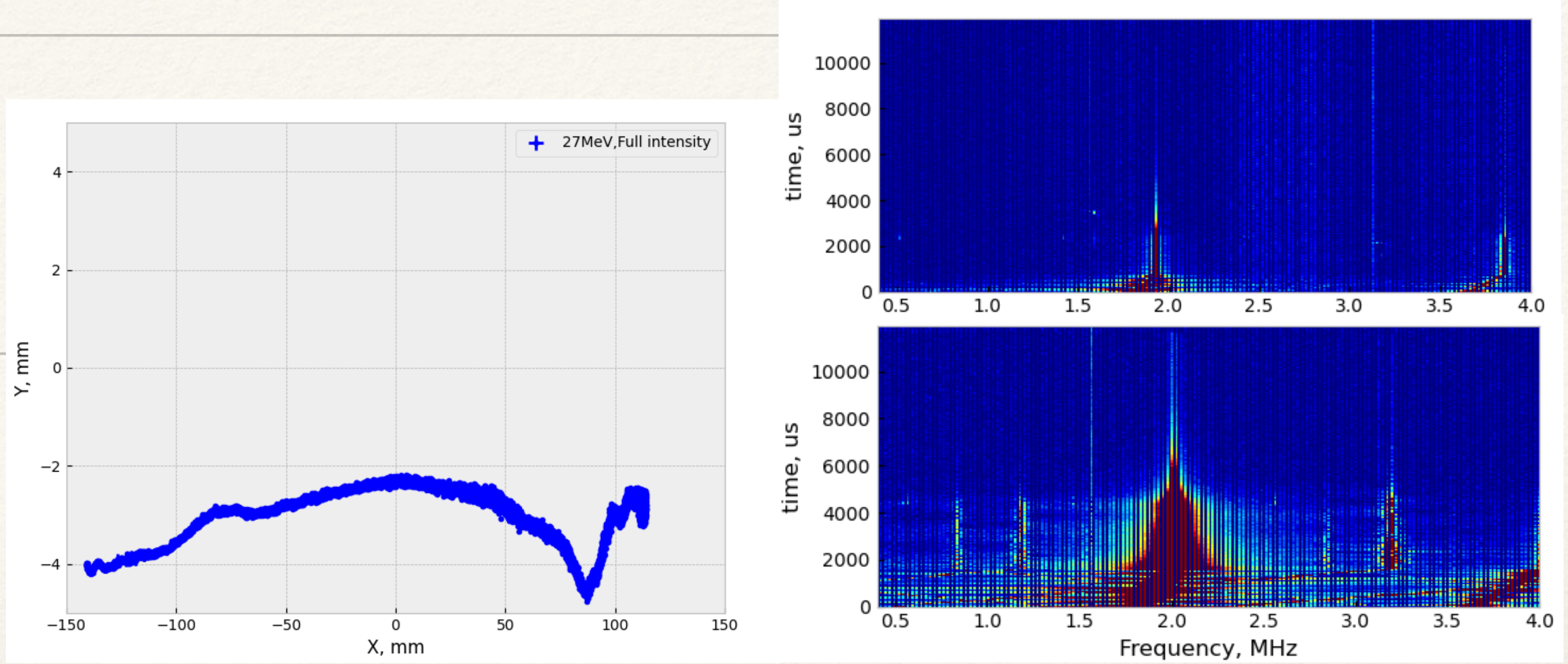


Fig.1. Measured 2D beam positions over beam acceleration from 11 to 27 MeV at KURNS FFA and Tune measurements.

Work Done So Far

- Horizontal beam displacements as well as transverse tunes were successfully measured by prototype BPM.
- Position accuracy of the prototype is within 4.98 mm, but the accuracy of position displacements is within 1.96 mm.
- Position accuracy (absolute position) will be improved in the final design due to **better manufacturing tolerances and improve geometry of electrodes as well as software and electronics treatments.**
- **Beam-based offset calibration can be used to improve position accuracy.**

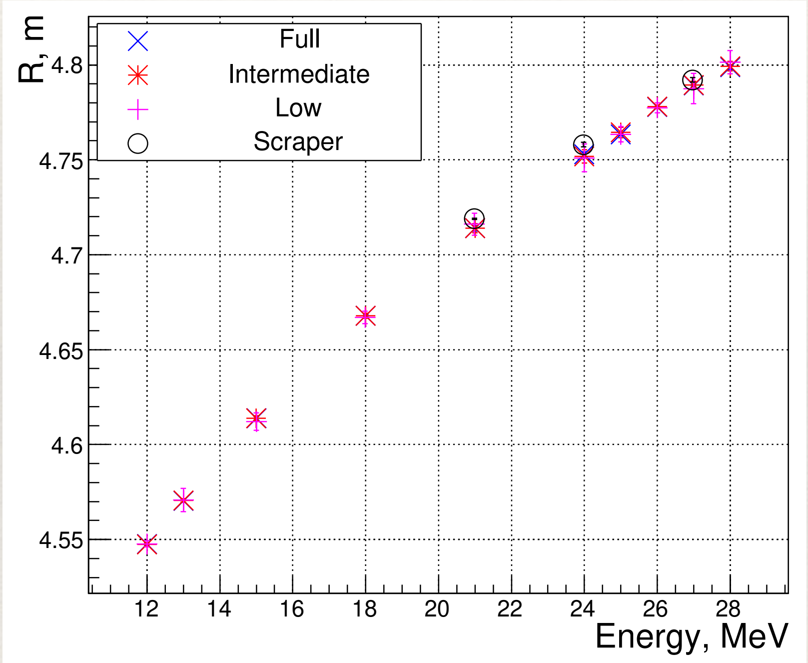


Fig.2. Measured horizontal beam position with beam flat top energies.

Beam Flat Top Energy, MeV	21	24	27
Position accuracy (R_{BPM}-$R_{scraper}$), mm	4.96	4.98	2.96
Relative position accuracy, (dR_{BPM}-$dR_{scraper}$) mm	—	0.022	1.96

Work Plan

- The practical design of FETS-FFA BPM will be performed in 2022-2023.
  - Study on mechanical tolerances to achieve **a position accuracy within 1mm.**

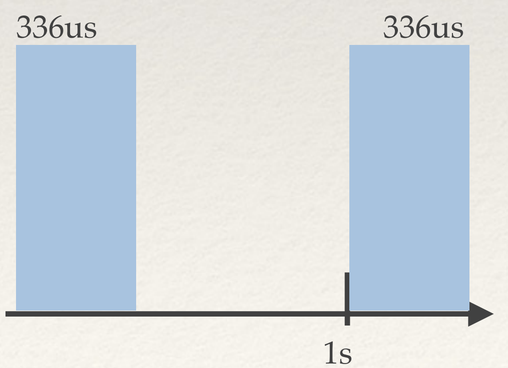
Phase1. Wire Scanner Monitor (WSM)

How It Works

- **After the foil, the injection orbit, beam profile, beam size are required to be measured in horizontal and vertical.**
- **Profile measurements (H only) can be also performed at fixed position of WSM in hFFAs, as the beam moves across the wire during acceleration.**
- Requirements for the measurement during acceleration:
    - To enable turn by turn profile measurements, the wire must be thinner than 1 turn separation. This means less than ϕ10um wire for FETS-FFA injection energy.
    - A negative bias voltage should be applied to the signal wire to prevent interference from emitted secondary electrons returning to the wire.
- Thermal damage on CNT wires are concerned due to an interaction with low energy beam.

Fig.1. Modified ISIS-WSM setups to betested in FETS test area.

Fig.2. KURNS motorised radial probe. The probe can move over 900 mm in horizontal direction.



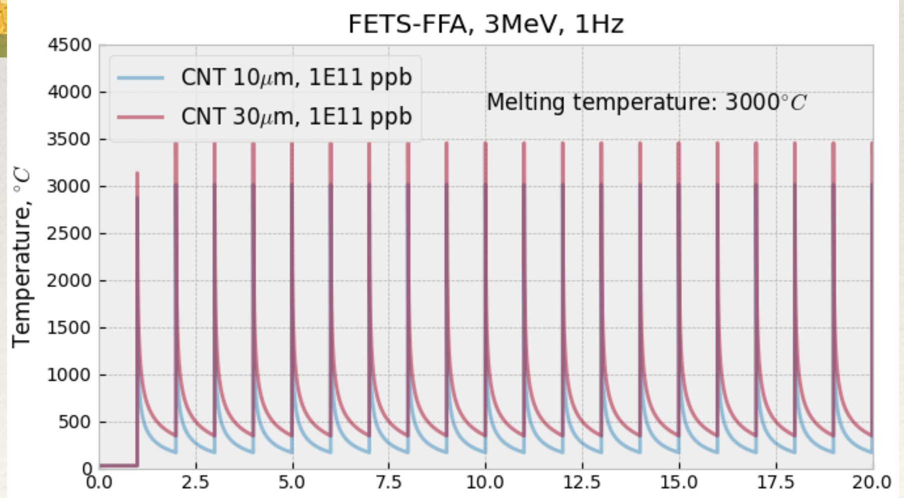


*Fig.3. Thermal simulation of 46 mA peak bunch current (1E11*1.6E-19/348ns) for 336us pulse duration, to move the beam core by 8mm, at 3 MeV injection.*

Phase 1. WSM

Work Done So Far

- To demonstrate WSM at FFA, prototype FETS-FFA WSM has been designed and tested at KURNS in 2022.
    - Frame was grounded to vacuum chamber.
    - Wire signal was amplified by the 1MΩ inversive RF amplifier with shunt impedance.
    - The beam signal was measured by ϕ30um CNT wire without bias voltages on the wire.
- Successfully a beam signal was measured by the thin CNT wire.

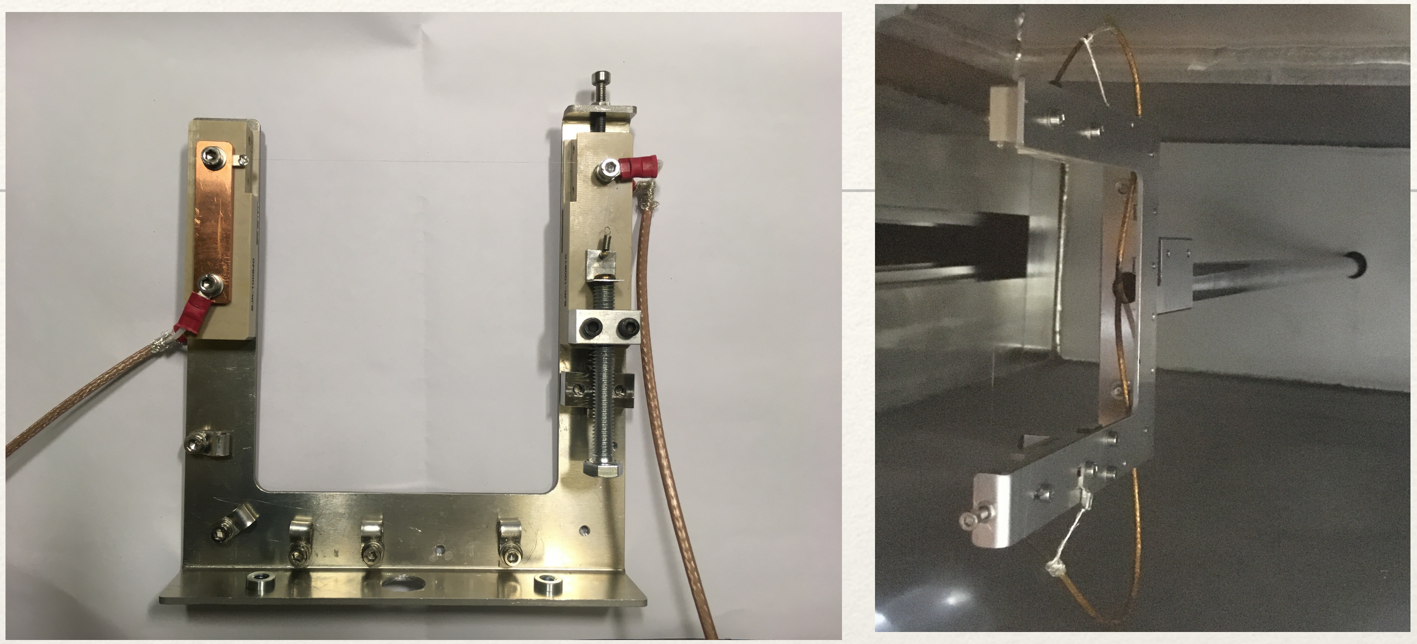


Fig.1. Prototype FETS-FFA WSM with ϕ30um CNT wire.

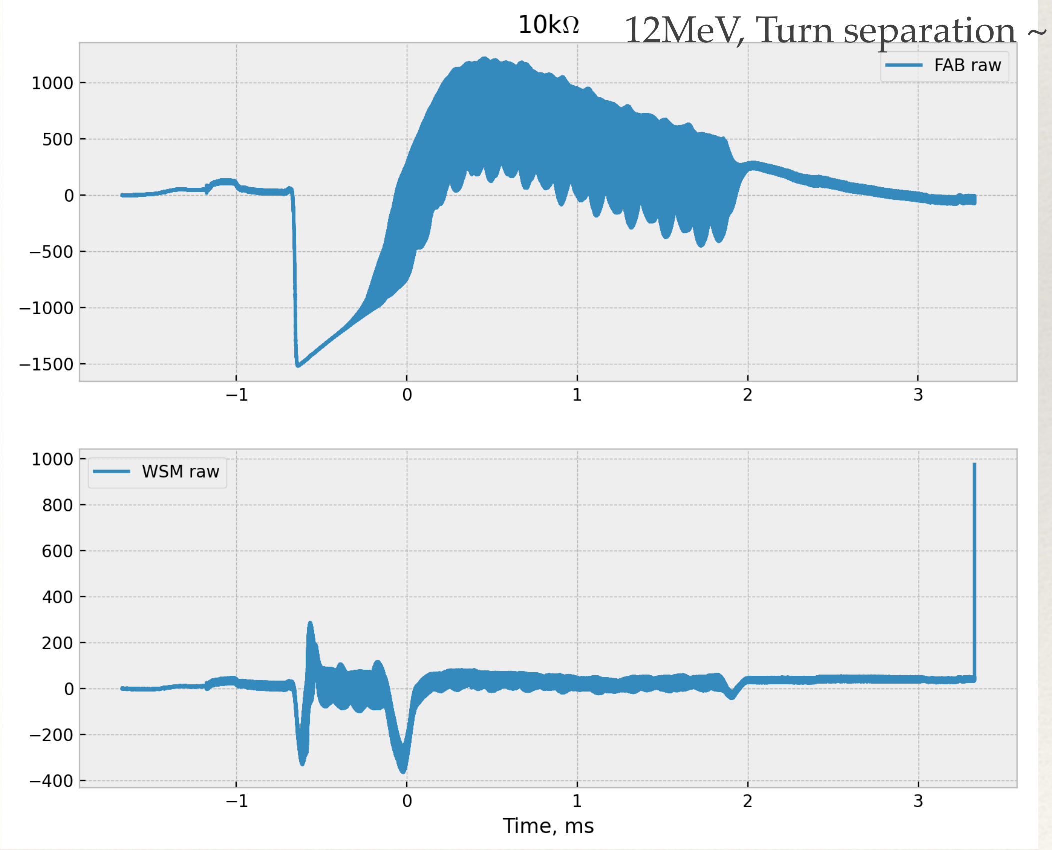


Fig.2. Raw signals from FAB (top), and WSM (bottom). The wire was at around 12 MeV without bias voltages. Vertical axis indicates a signal amplitude in mV.

Phase 1. WSM

Work Done So Far

- RMS beam size was estimated as 6.5 mm at 12 MeV, which is close to the beam size measured by the scraper (~5 mm).
- In simulation, a single particle tracking was performed by transfer matrix, assuming initial horizontal beam size of 5 mm (σ_{rms}). The scattering angles and energy losses at wire, adiabatic dumping, longitudinal dynamics and dispersions were included.
- Asymmetry was seen in measured profile and simulation when the wire position was shifted to higher beam energy orbit.
- After 4 days beam operation, the wire was elastic and stretched. But, any critical damages on the wire were not observed by a Microscope (Fig.2).

Work Plan

- Beam test with ϕ10um CNT at KURNS.
- Test another CNTs (IMDEA) at Diag. Lab. to find a suitable wire for our demand (e.g. low electrical resistance, high tensile strength etc).

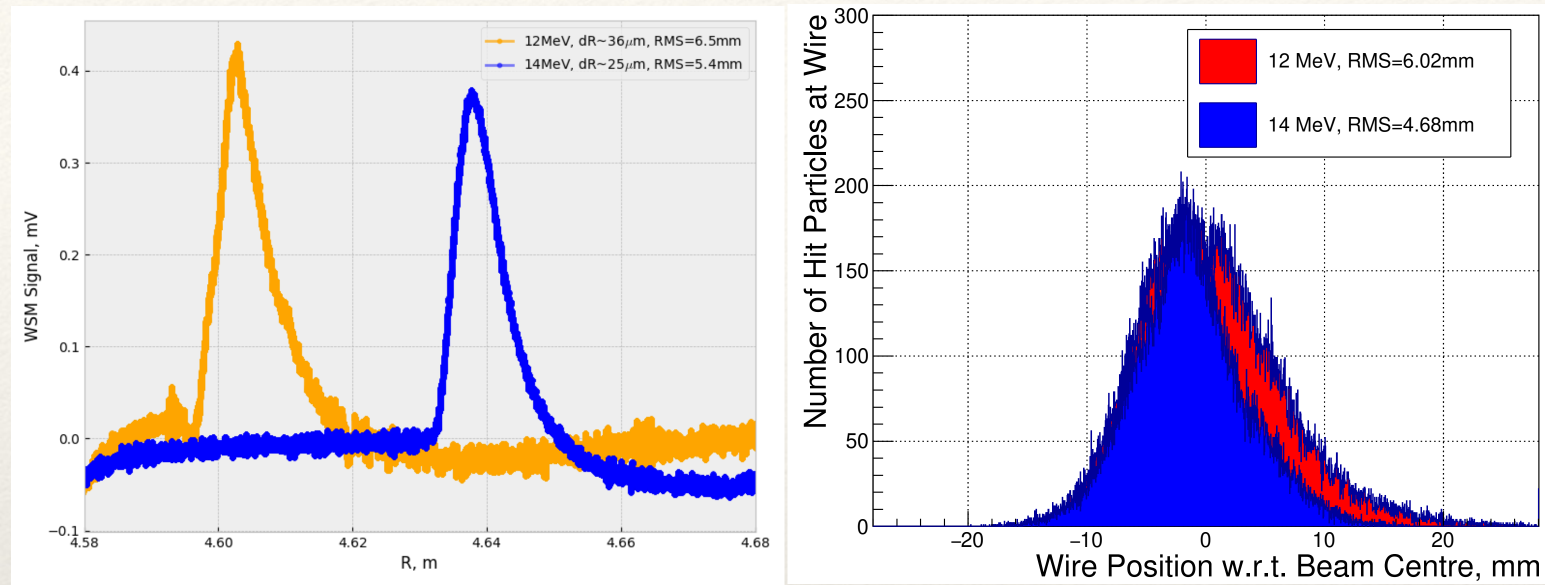


Fig.1. WSM signal after decay constant correction and filtering (left) and simulation results (right).

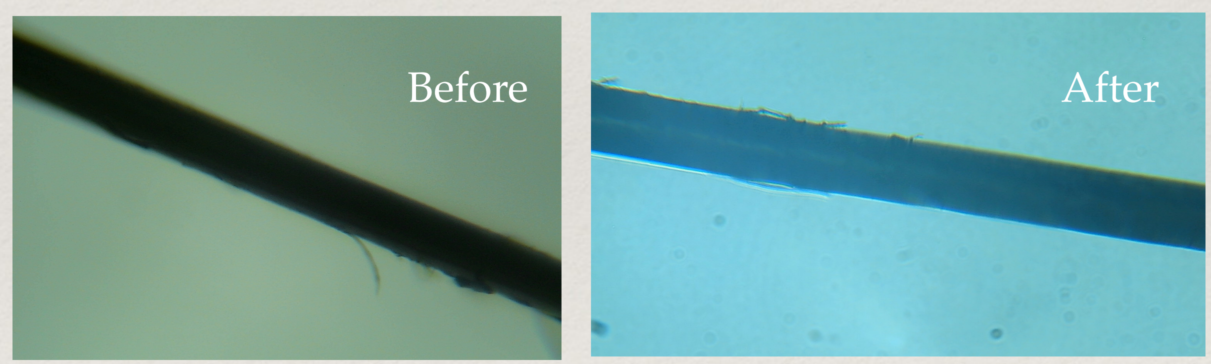


Fig.2. Microscope pictures of ϕ30um CNT before and after beam test.

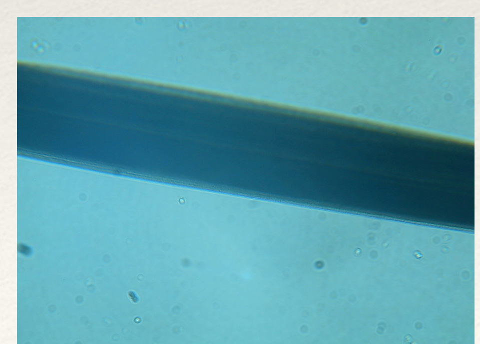


Fig.3. Microscope pictures of ribbon-shape CNT, 40~60um width over 100mm length.

Phase1. Beam Loss Monitor

Beam power of FETS-FFA ring is 50W maximum. The BLM must detect 1% beam losses of 1E11 ppp.

How They Work

- **Ionisation chamber**: slow time response, low-cost
  - Commercial **ionisation chamber** (Fig.1) and Short length **ISIS ionisation chamber** (Fig.2) will be used for a beam commissioning/machine protection system in long time periods (~1ms).
- **Scintillation plates**: expensive, fast time response. Small size scintillators are used for a beam commissioning in short time periods (< 1ms).
  - The large structure of Iron (York) magnets can be a natural shielding.
  - Can we detect photon emissions by a scintillator which is placed outside of vacuum chamber?

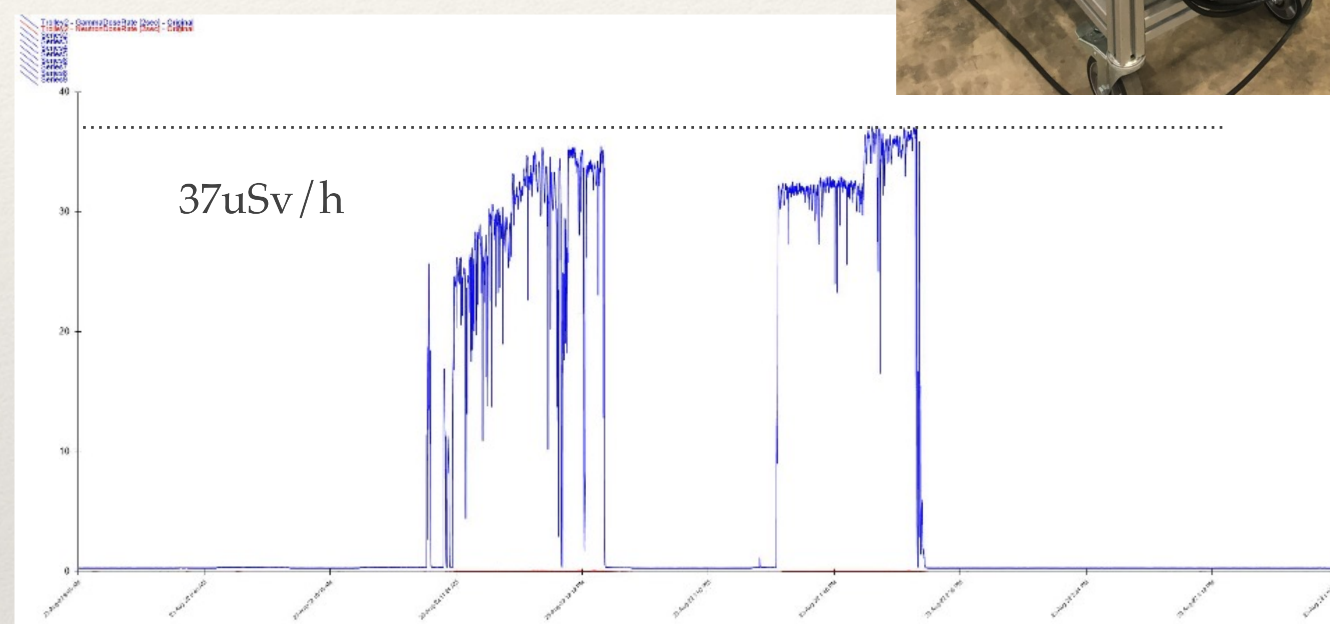


Fig.1.FHT-192 ionisation chamber and Gamma does-rate for 8hours in every 2sec. in FETS beam dump area.

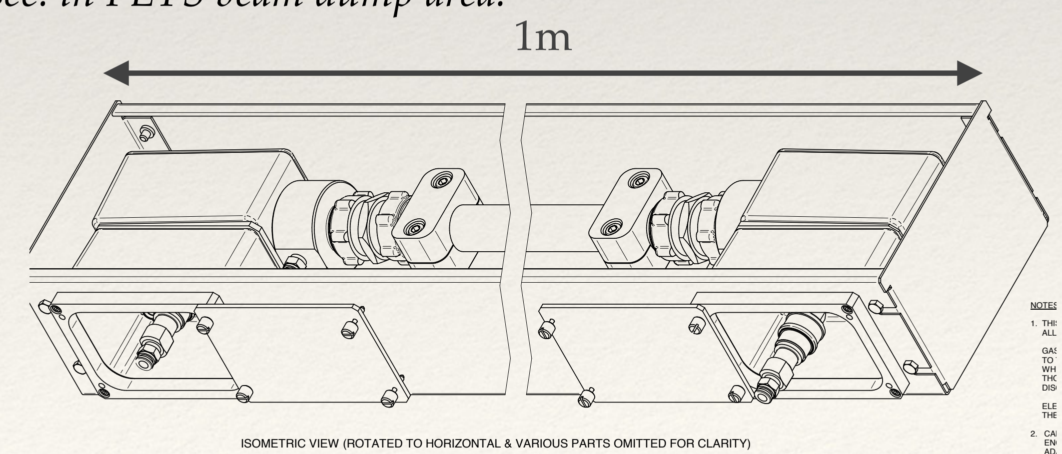


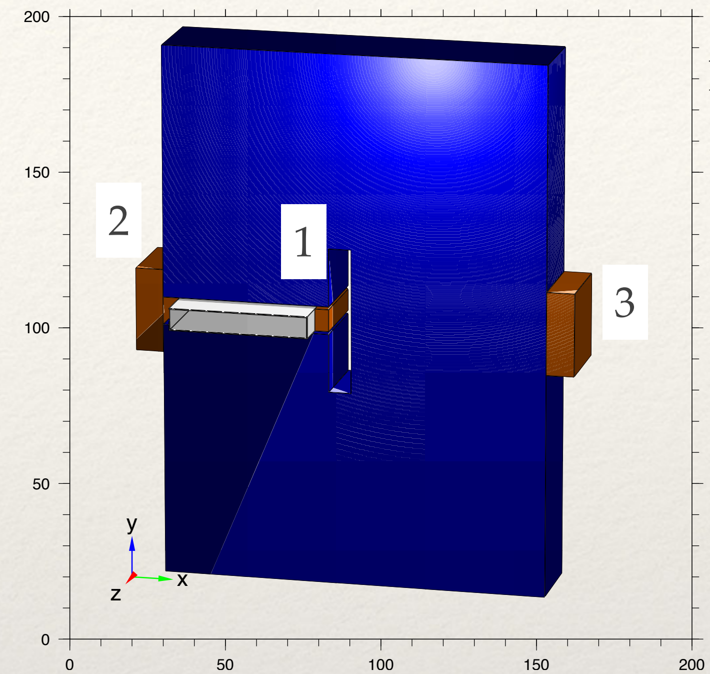
Fig.2. Design of shorter ISIS Ionisation chamber.

Phase1. Beam Loss Monitor

- **Scintillation plates**:
  - PHITS simulation is applied on a simple magnet model (Fig.1):
    - A tilted proton (pencil beam: 3MeV) beam hit the vacuum chamber.
    - SUS vacuum chamber was 3mm thick.
    - Counted secondary particles in the Scintillators (BLM: void box) which were placed next to the chamber and York.
  - Depending on a beam loss location, if scintillation plates can be placed on the chamber (top, bottom, sides), it will detect secondary photons (Fig.2). Not necessary to be installed inside vacuum chamber.

Work Plan

- Tests will be performed using short ionisation chamber with existing electronics at FETS to evaluate monitor sensitivity.



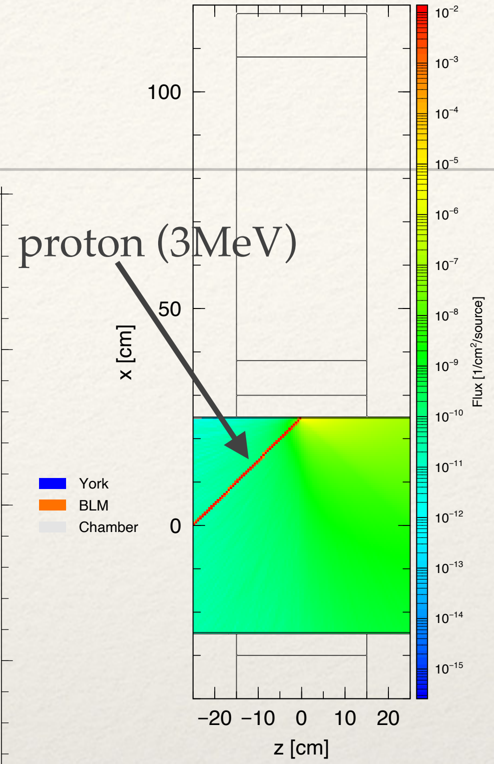


Fig.1. Structure made in PHITS (left) and trajectory of 3 MeV protons (right).

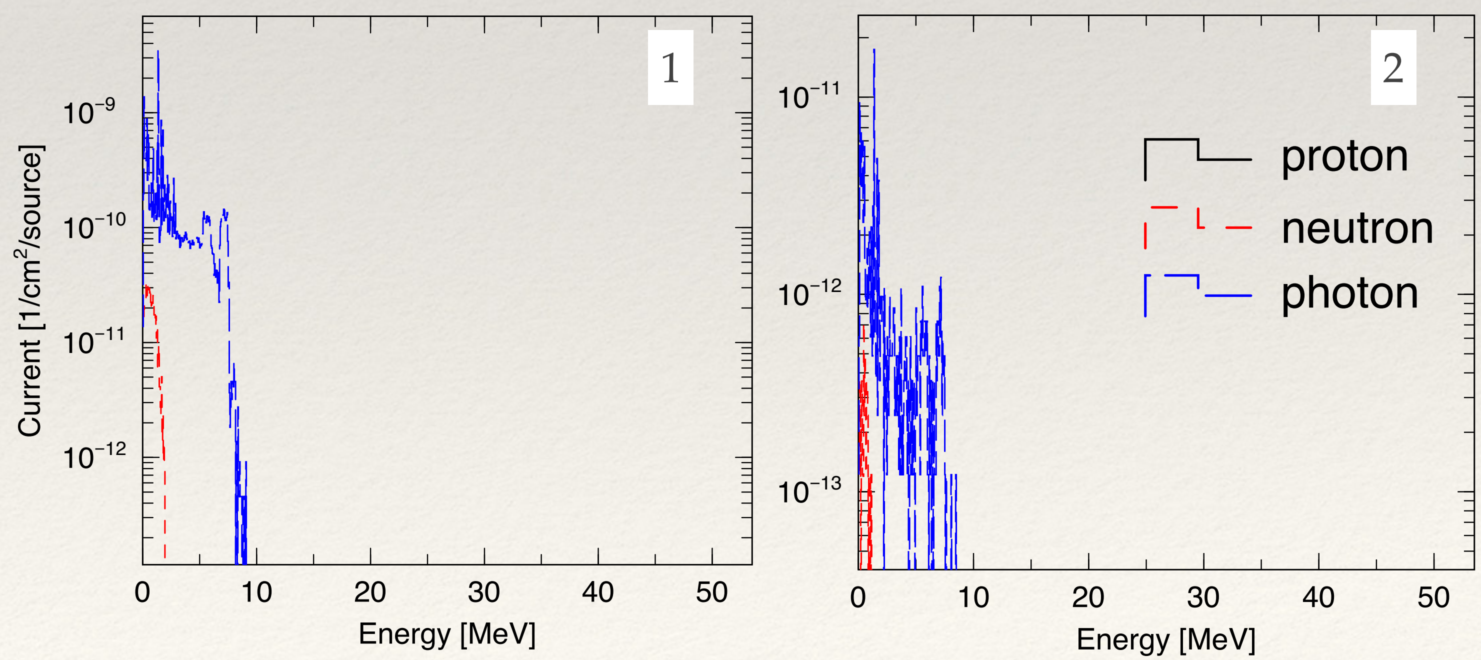


Fig.2. Photon emissions detected by BLMs.

Phase 1. Several Tests in FETS

- The low energy beam of the FETS-FFA will cause significantly more damage to materials when it interacts with than the ISIS beam.
- Therefor, several beam diagnostics tests are planned using the FETS beam line in 2022-2023.
    - **A Prototype WSM** *(Installed. Waiting for the drive control units.)*
    - ***Scintillation screen materials*** (YAG crystal, P46 and ceramic) will be tested to identify suitable materials with reasonable lifetimes while interacting with a 3 MeV beam. *(screens are already purchased)*
    - ***The performance test of a Faraday Cup*** will be also performed in the beam line to verify its cooling system to prevent from thermal damage of 3 MeV beam. *(design work has not been started.)*
    - ***Beam Loss Monitors*** are planed to be tested to evaluate monitor sensitivities. A scintillation fibre will be tested in vacuum chamber. *(preparing monitors has been started.)*

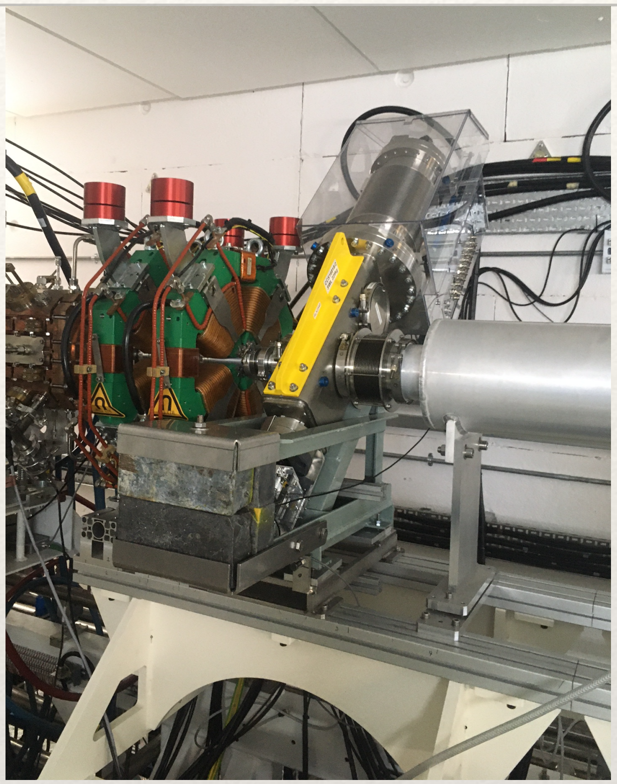


Fig.1 Test chamber on the FETS beam line.

Fig.2 Screen mount folder to be installed on WSM head.

FETS-FFA Ring Diagnostics Summary

Priority: High → Low

Commissioning phase	Required diagnostics	Progress and future plan
phase1	• Faraday Cup (FC) • Wire Scanner Monitor (WSM) • Phosphor Screen (PS) • Beam Loss Monitor (BLM) • Beam Position Monitor (BPM)	• Preliminary design study of WSM and BPM were done and beam test was done. Practical design and has been started. • BLM, PS are planned to be tested on FETS in 2022-2023.
phase2	• DC Current Transformer (DCCT) • Wall Current Monitor (WCM) • Beam Size Monitor (Scraper)	• Design study and manufacture a small-scale prototype of DCCT and WCM in 2022-2023.
phase3	• Ionisation residual gas Profile Monitor (IPM)	• Fundamental design study was done.

Good progress, but still many exciting challenges to be addressed.

Thank you

BPM Calibration on Test Bench