FETS-FFA Beam Diagnostics

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ISIS-II Project and FETS-FFA Test Ring

- ISIS-II project aims to be a stand alone spallation neutron source facility, driven by 1.2 GeV proton beam with beam power of 1.25 MW by 2034.
- FFA ring is one of the options as a proton driver.
- To demonstrate the suitability of FFA, there is a plan to construct a smaller scale proof of principal ring, called FETS-FFA test ring, by 2027.

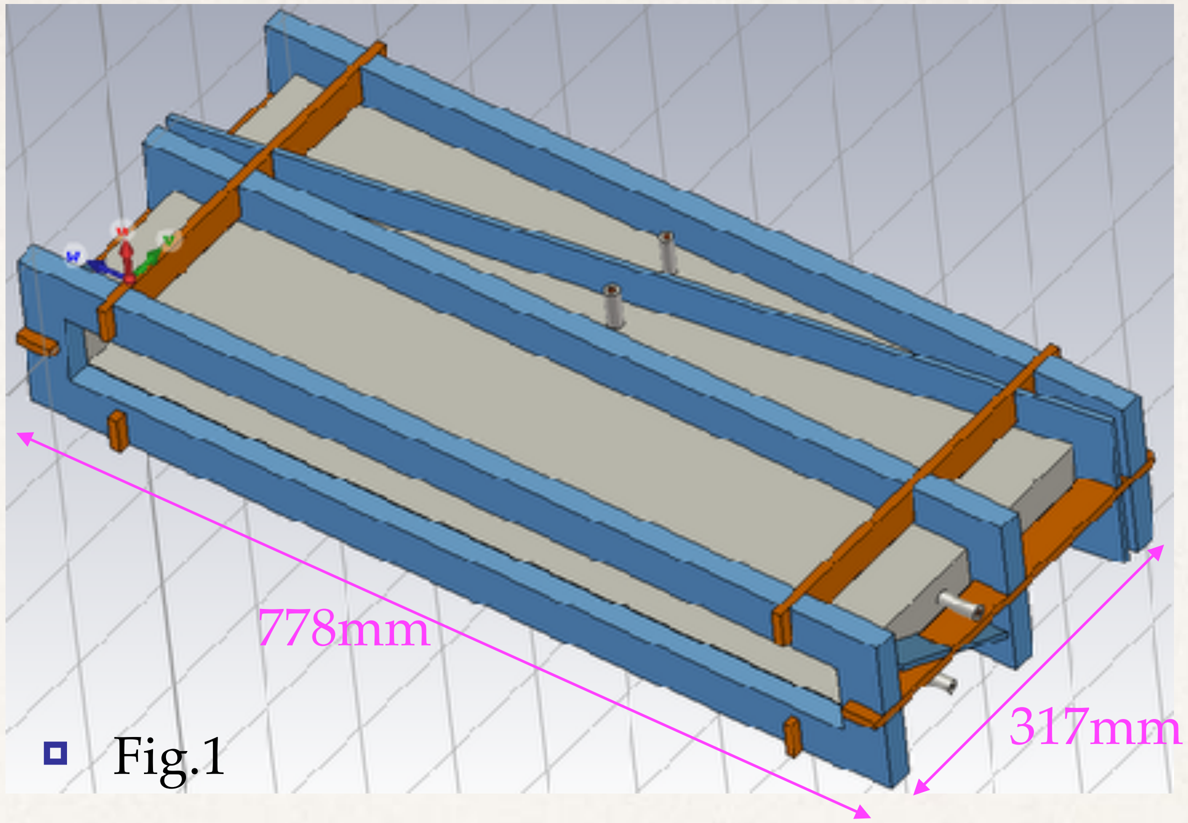
Parameters of FETS-FFA test ring	
Beam energy, MeV	3 – 12
Bunch intensity, ppb	10^{10}
Repetition rate, Hz	50 – 100 Hz
RF frequency bandwidth, MHz	1.91 – 3.8
Harmonic number	2
Straight section, m	1
Orbit excursion, m	0.69
Gap width of chamber, mm	60
Full beam size, mm	30

Beam Diagnostics in FETS-FFA Ring

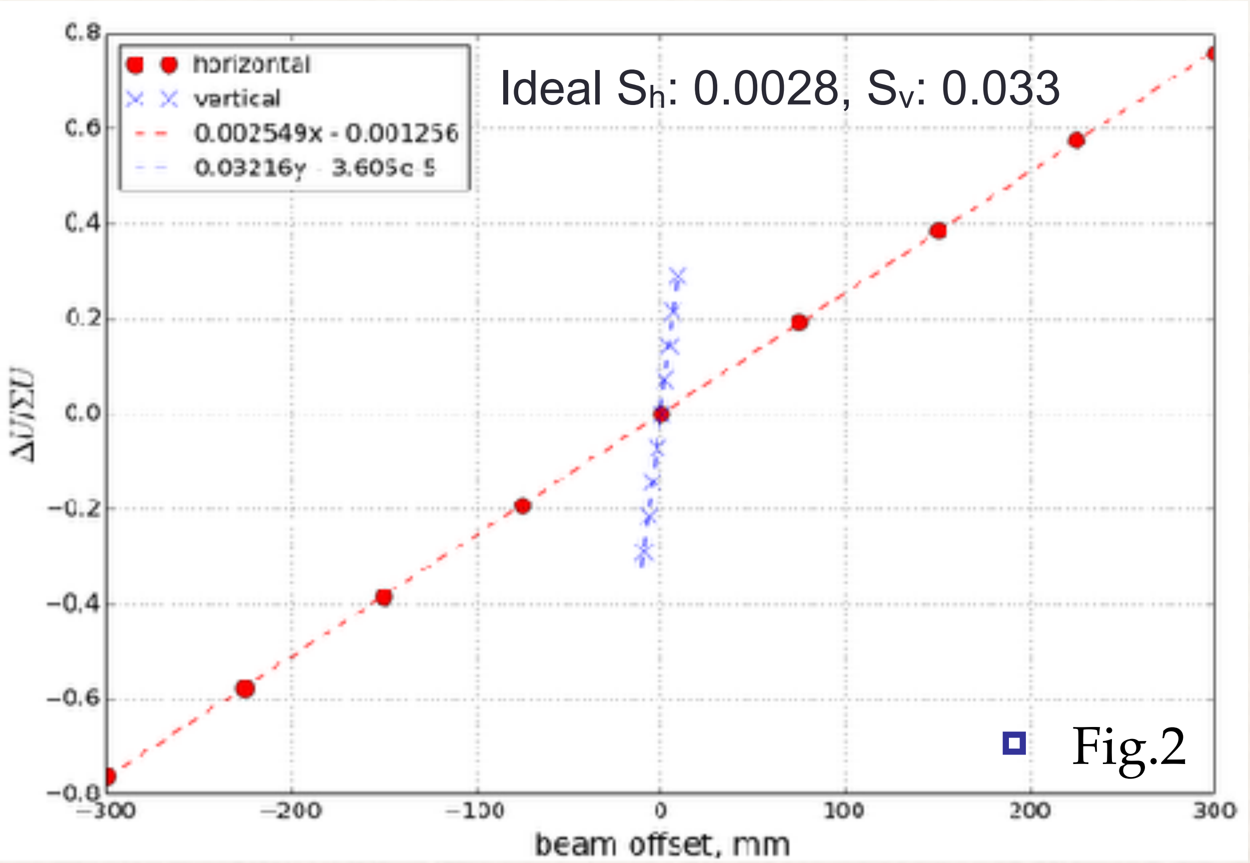
- Wide range of beam diagnostics for FETS-FFA test ring must be developed and delivered by 2027.
- Required beam diagnostics are:
    - Beam Position Monitors : capacitive pick-up BPM
    - Beam Current Monitors : movable Faraday Cup (FC), Wall Current Monitor (WCM) and DC Current Monitor (DCCT)
    - Beam Profile Monitors : movable Scintillation Screen, Wire Scanner Monitor (WSM) and Ionisation Profile Monitor (IPM)
    - Beam Loss Monitors
- Main challenge of FFA diagnostics is to provide a reasonable measurement sensitivity and resolution over the range of large beam excursion.
- Progress of feasibility and design study of beam diagnostics are presented in this talk.

FETS-FFA BPM Preliminary Design

- A pair of electrodes (grey components in Fig.1), separated with a diagonal cut are placed along the beam direction.
- If the beam is offset from the centre of the chamber, the electric potential induced by the beam is larger on one electrode than the other.
- Earthed rings (blue components in Fig.1) are placed between adjacent electrodes to prevent electrical coupling between electrodes, improving position sensitivity.
- Electrode capacitance, which affects bandwidth and pick-up signal, optimised with PEEK supports (orange components in Fig.1) and geometry changes.
- Beam displacement x is related to position sensitivity S and difference over sum of signal induced on electrodes ($\Delta U/\sum U$) as described by: $\dfrac{\Delta U}{\Sigma U} = S \cdot x + \delta$.
- From CST simulation (Fig. 2), linearity over the beam excursion is good. Estimated position sensitivities are close to the ideal ones.

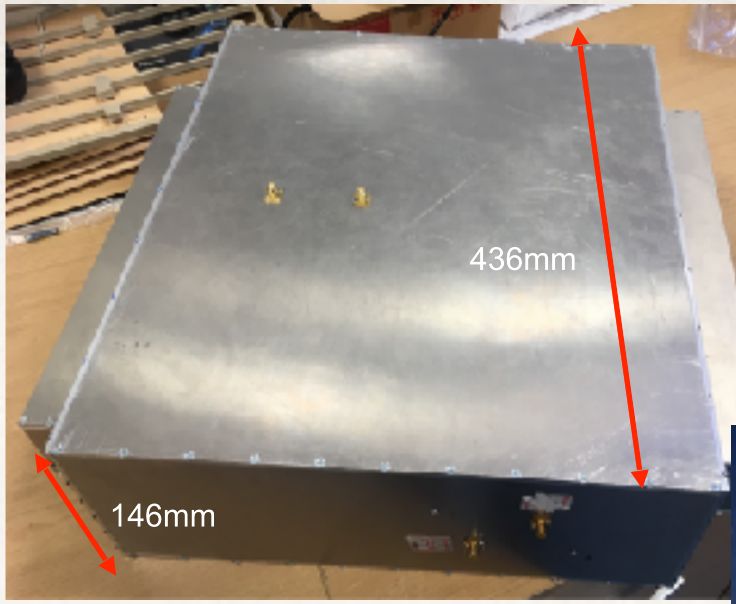


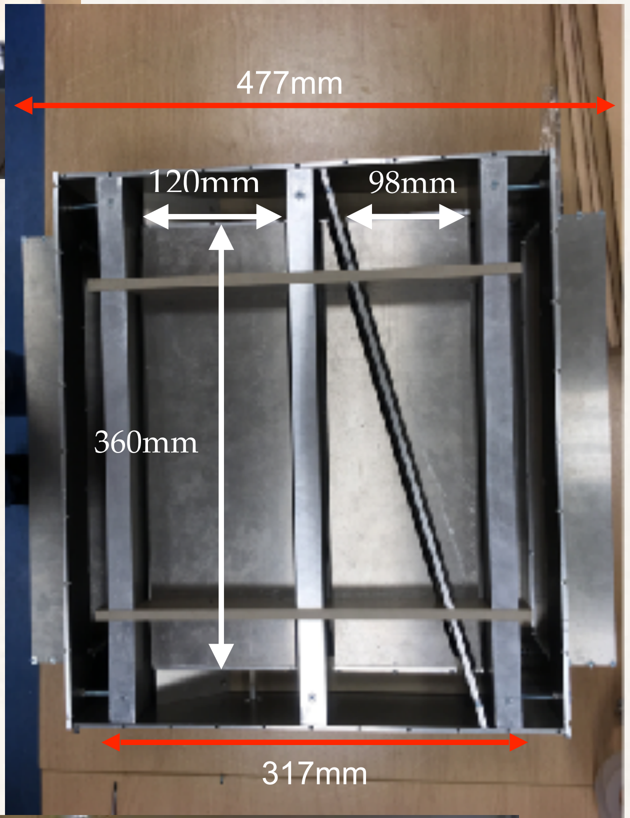
- Fig.1


Ideal S_h: 0.0028, S_v: 0.033

- Fig.2

Prototype BPM Design

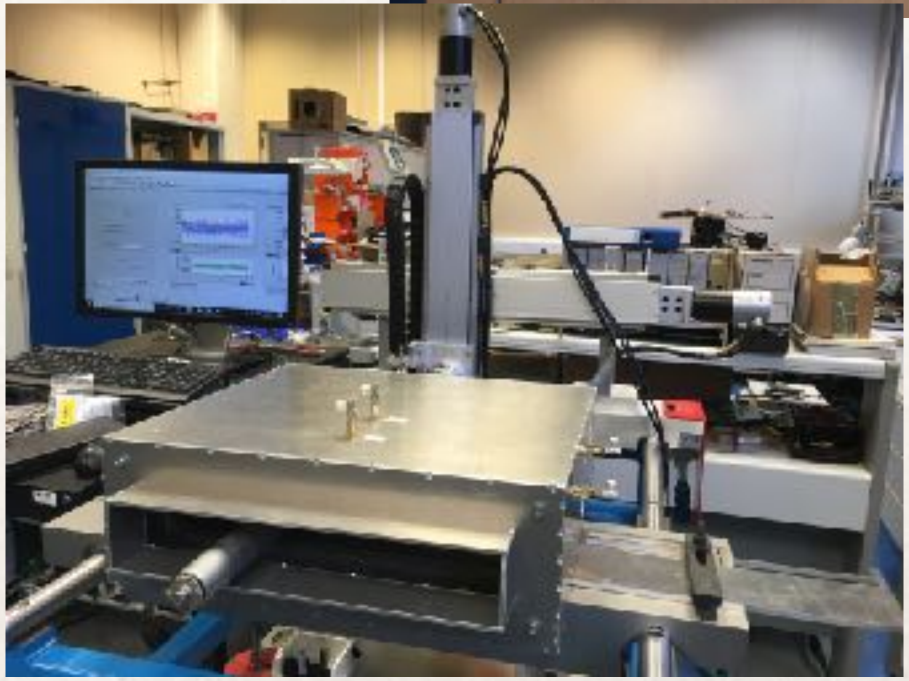




- Prototype BPM, half the width of preliminary design, has been manufactured and assembled to enable bench measurements and to verify the design simulations.
- Bench measurements used a movable pipe inside the BPM with an electric signal on it. The measured position sensitivity to changes in pipe position and capacitances had good agreement with CST simulations.
- The prototype BPM will be delivered at KURNS (Japan) for beam test next spring.

Capacitance	EH1	EH2	EV1	EV2
Meas. pF	69.5	67.7	62.1	61.5
CST model, pF	70.4	69.4	62.5	60.4

Sensitivity	Horizontal S	Vertical S
Theoretical	0.00556	0.0329
CST model	0.0051	0.035
Measured 2MHz *1mm steps	0.00503	0.0348



Tune Shift Due To Beam Coupling Impedance of Preliminary Design of BPM

- **Purpose**
    - To evaluate transverse and longitudinal beam coupling impedance of FETS-FFA BPM chamber, which induces tune shifts in a machine.
- **Impedance source** of FETS-FFA BPM chamber consists of:
    - Indirect Space Charge Impedance: Depends on geometry of the monitor, including each part of the BPM as well as the edge transitions between the monitor body and beam pipe. This is computed by CST wakefield solver.
    - Resistive Wall Impedance : Depends on material of the monitors (BPMs, guard-rings, etc) and chamber walls. In the FETS-FFA model, the resistive wall impedance of rectangular beam pipe, which made of stainless steel, is considered. This is computed analytically.
- **Tune shift**
    - Tune shift is computed analytically. Beam coupling impedance of preliminary design of FETS-FFA BPM is negligible (Figs. 1 & 2).

Analytical tune shift

$$\Delta Q_{\perp} = \frac{\beta e I_0 c^2}{4\sigma_z\sqrt{\pi}\omega_0^2\gamma Q_\beta m_0 c^2} i(Z_t)_{eff}$$

$$\Delta Q_s = \frac{I_0 e\eta\beta c^3}{8\sqrt{\pi}\sigma_z^3\gamma Q_s\omega_0^2(m_0c^2)} i\left(\frac{Z^{//}}{\omega}\right)_{eff}$$

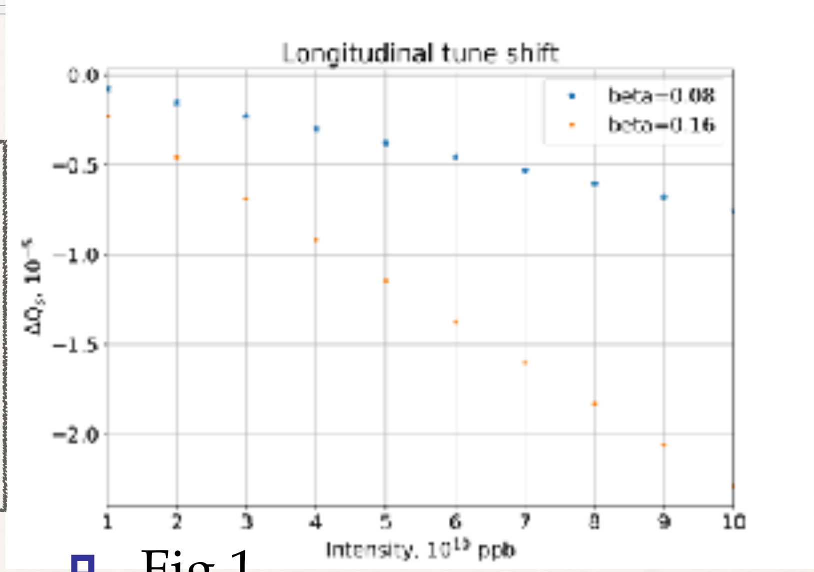


Fig.1

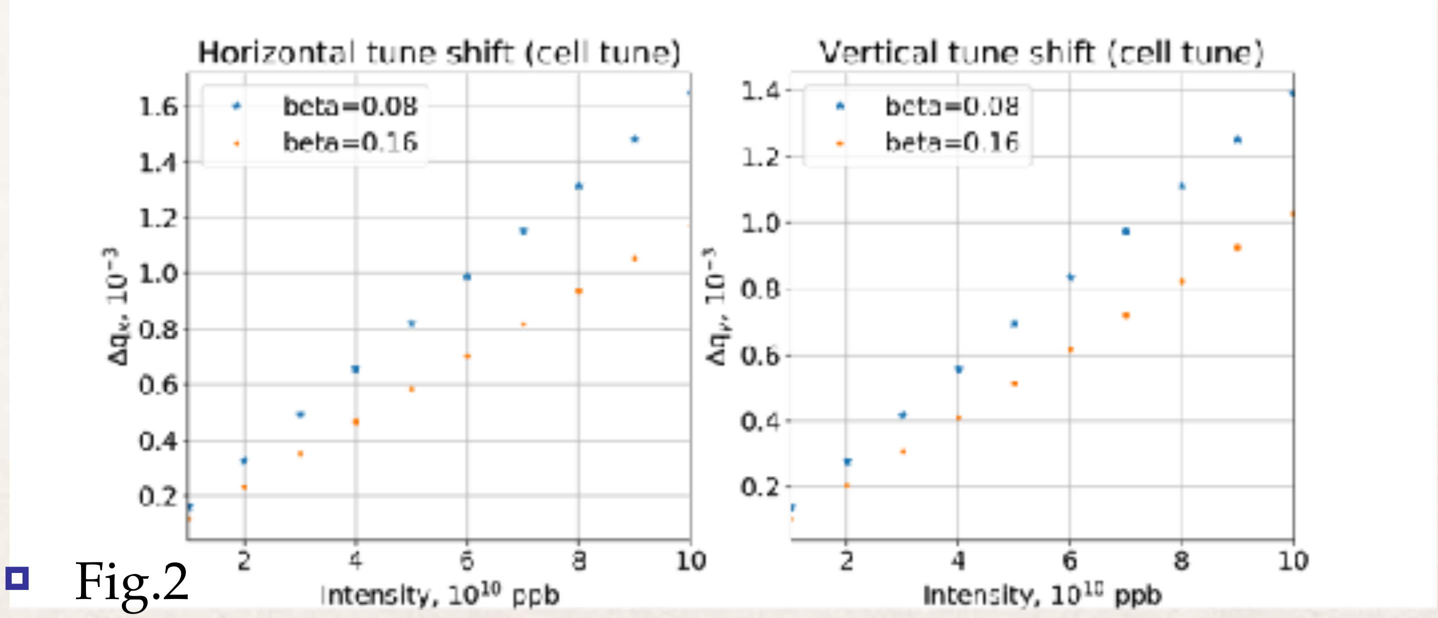
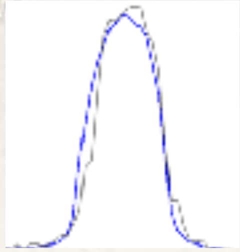


Fig.2

FETS-FFA IPM Design

- Residual gas particles in the vacuum chamber are ionised by the beam.
- A high voltage electrode is placed on one side of the beam aperture, and a plate of charged particle detectors is placed on the opposite side.
- The generated ions are guided along electric field lines into the detectors.
- The number of ions produced at each point is proportional to the beam density. Therefore the beam profile can be determined from this measurement.
- Horizontal and vertical IPMs have been designed for FETS-FFA test ring (Fig. 2&3).
- Required anode voltage to make a single-turn measurement is 10kV in vertical and 1.8MV(!) in horizontal. Horizontal IPM is not realistic in practice at FETS-FFA test ring.



Example Profile Measurement

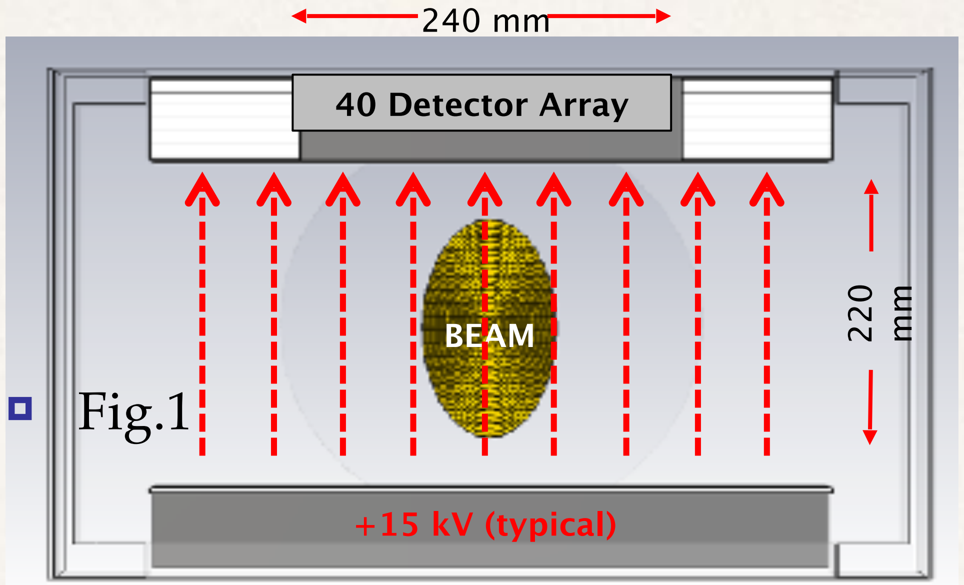


Fig.1

Transverse cross-section view of an ISIS IPM

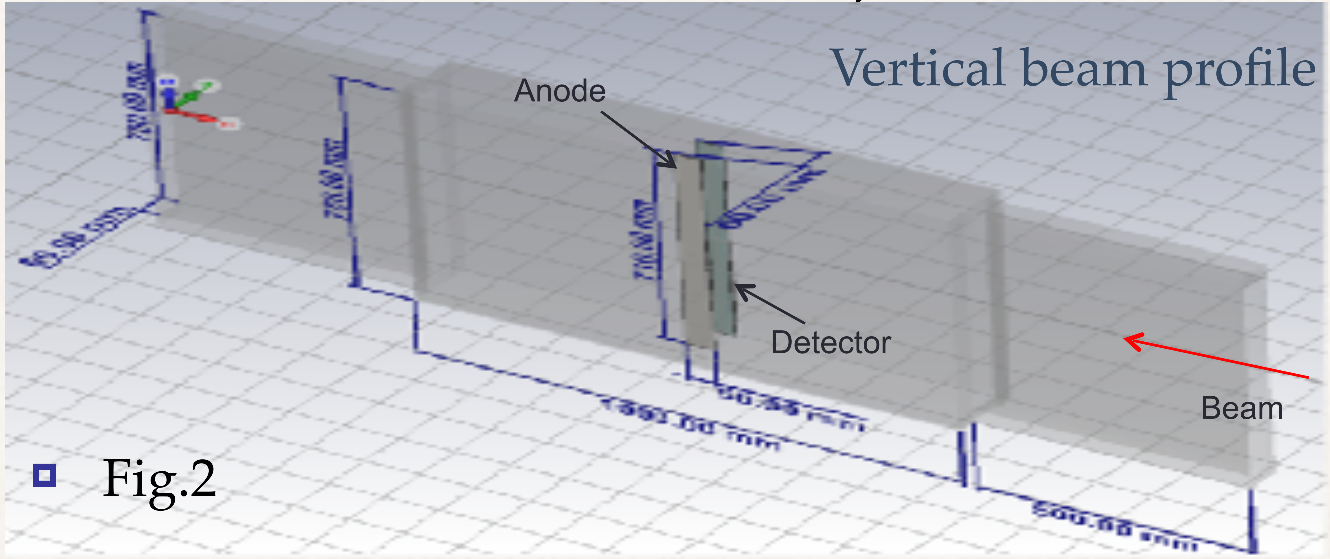


Fig.2

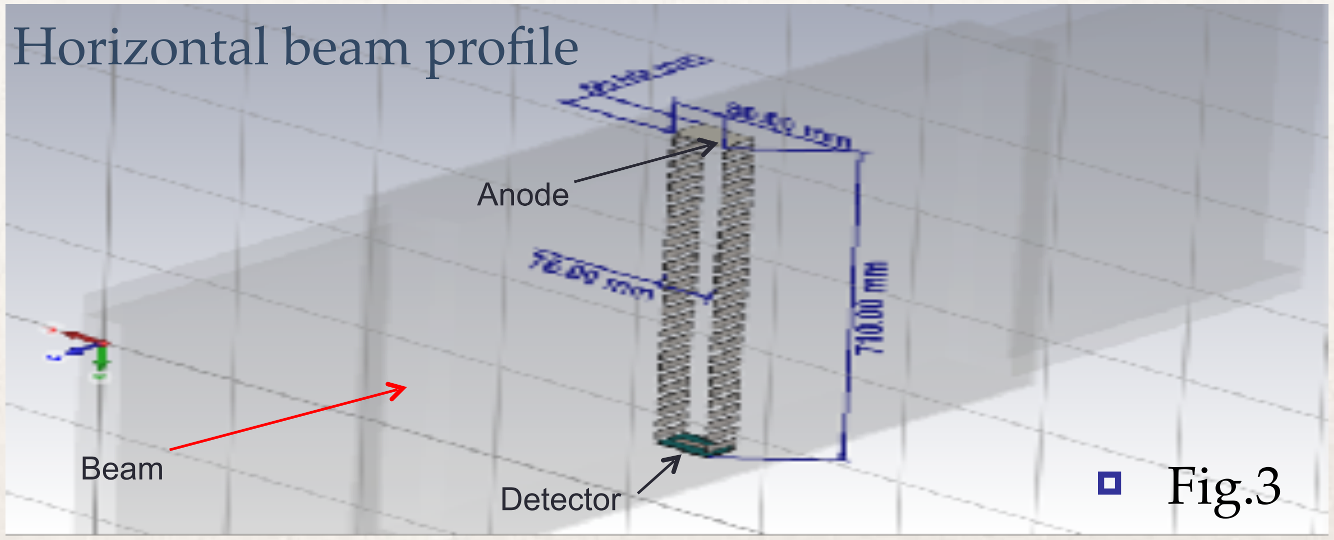


Fig.3

Particle Tracking with Compensating Field

To study the effect of compensating field on the measured profile, CST particle tracking Simulation has been applied.

- The beam is placed with 300 mm vertical displacement from the chamber centre (at the 12 MeV position).
- Assuming H^+ ions are the dominant ion generated by the proton beam (from water vapour). The ions are distributed on the area of 4σ (transverse beam size) uniformly (blue components in Fig.1).
- H^+ ions are counted at the detector.

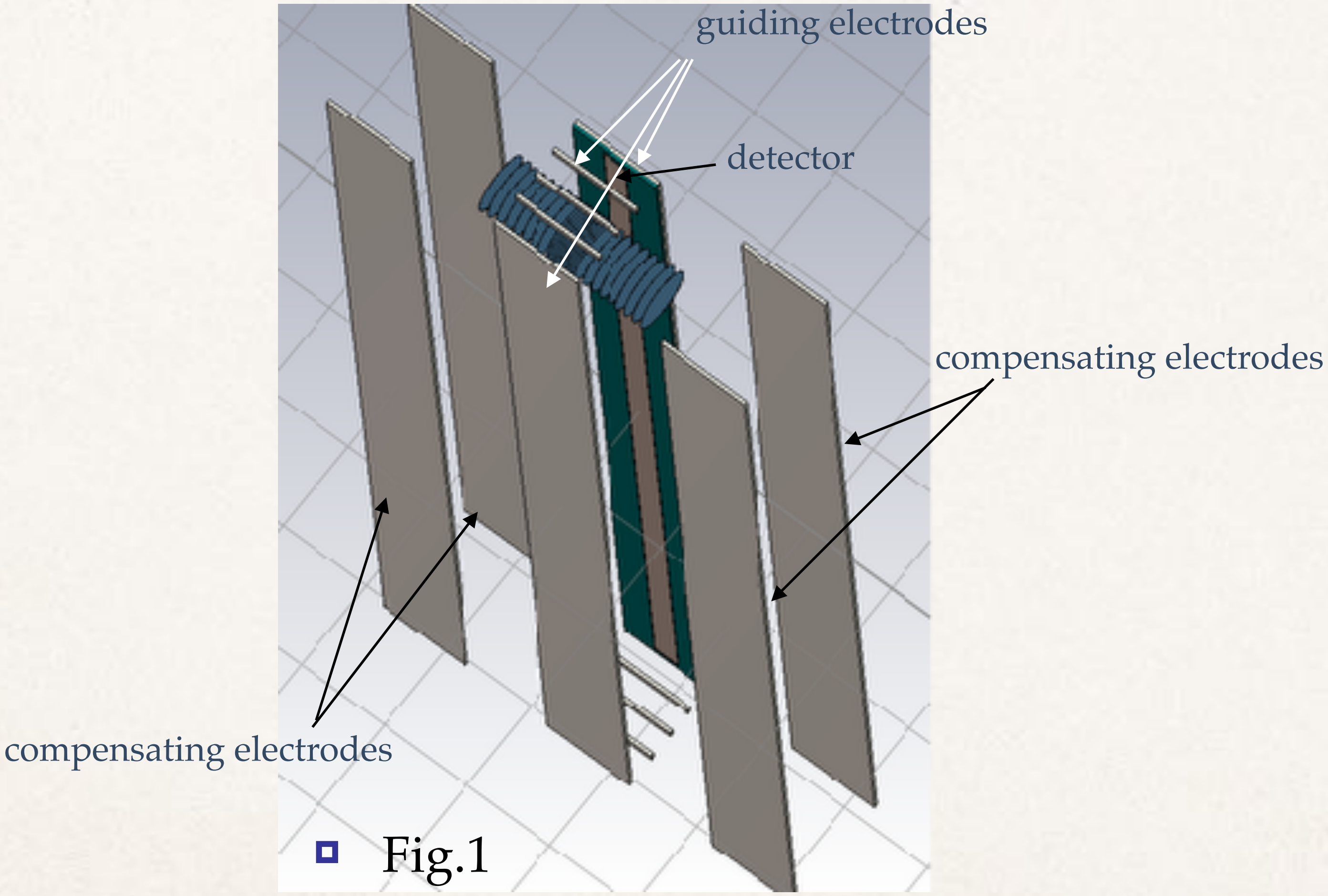
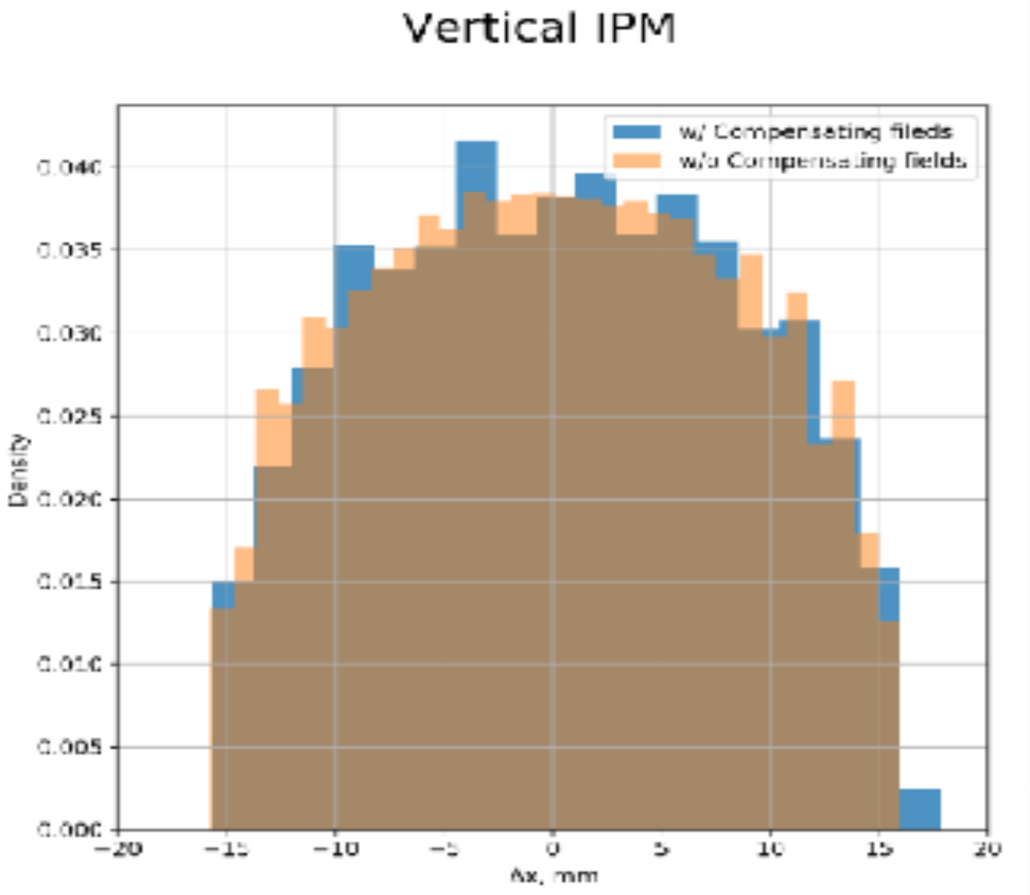
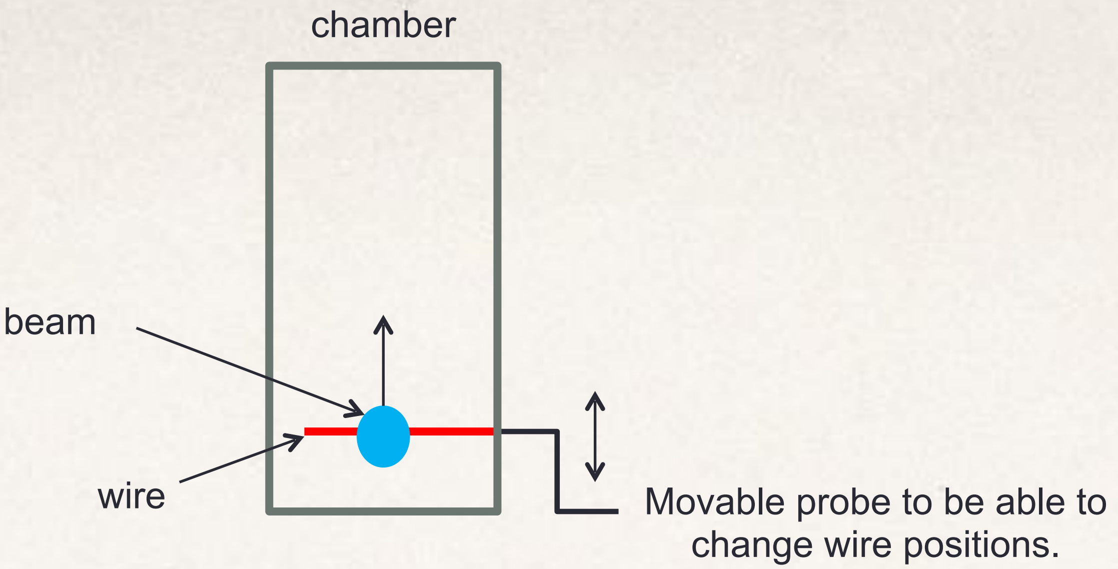


Fig.1

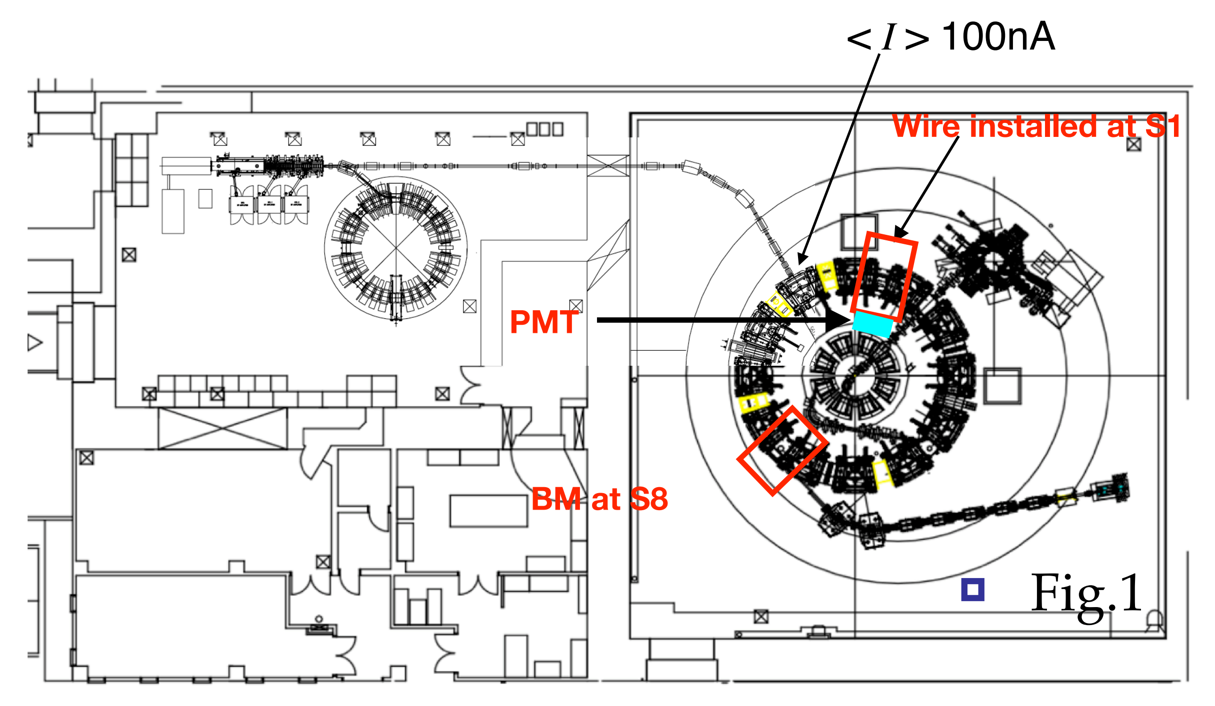


The compensating fields protect against kicking the beam, but do not have a big effect on the measured profile. Further realistic simulations (self developed scripts, created by C. Wilcox) to be done if details of beam profile are fixed in the future.

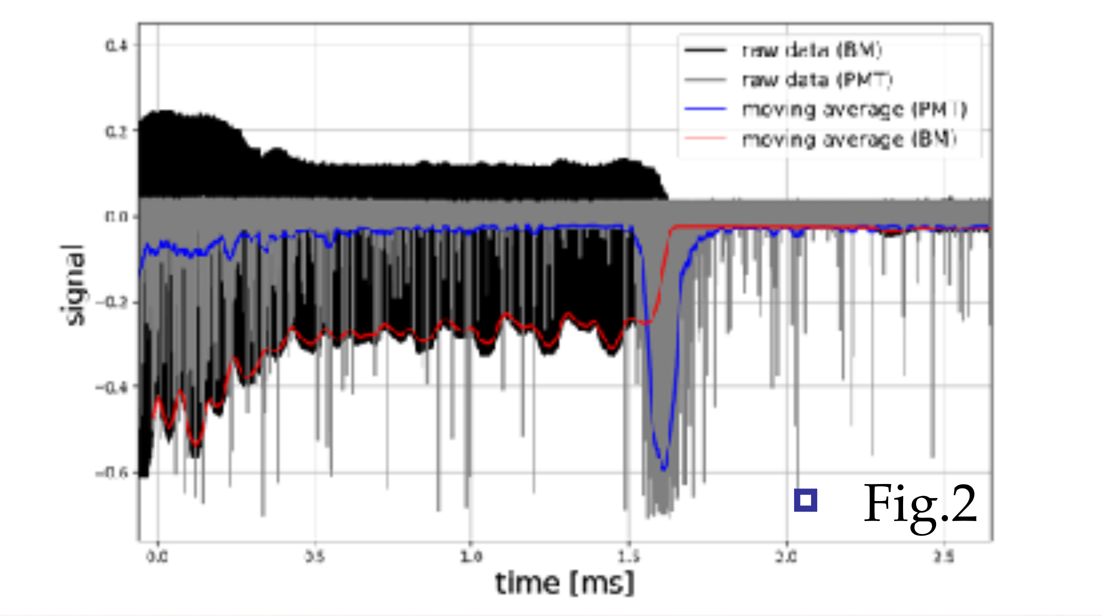
FETS-FFA WSM Study



- Conventional Wire Scanner Monitors (WSM) move the wire across the beam to measure its profile.
- To remove vibration effects from moving the wire, the wire position can be fixed in an FFA instead, as the beam will move across the wire.
- But, beam profile would be broad due to multi-scattering at the wire.
- Requirements for wire thickness:
  - Thinner than a turn separation to measure turn by turn profile measurements.
  - <u>Turn separation over the beam energy in FETS-FFA test ring is about 20um, so profile measurements could be done if a wire thickness is less than 10 um.</u>
- To demonstrate WSM at FFA, ϕ142um SiC wire was installed at KURNS and beam test was done in 2019.
- Beam signal was monitored by bunch monitor (Fig.1 BM). Secondaries generated at the wire were monitored by scintillation counter (Fig.1 PMT).
- <u>In this experiment, the wire scatters the beam significantly, resulting a beam spread and beam loss (Fig.2).</u>



▫ Fig.1



▫ Fig.2

Beam Test with CNT Wire and Foil

- We will install very thin CNT wire at KURNS next spring for beam profile measurements:
  - ϕ30um CNT wire and 3um thickness CNT foil.
- Fig.1 presents a simulation of profile measurement with ϕ30um wire. Beam profile is measurable by ϕ30um wire and its beam size is good agreement with the ideal one.
- We are currently working on frame design to prepare for the beam test at KURNS.

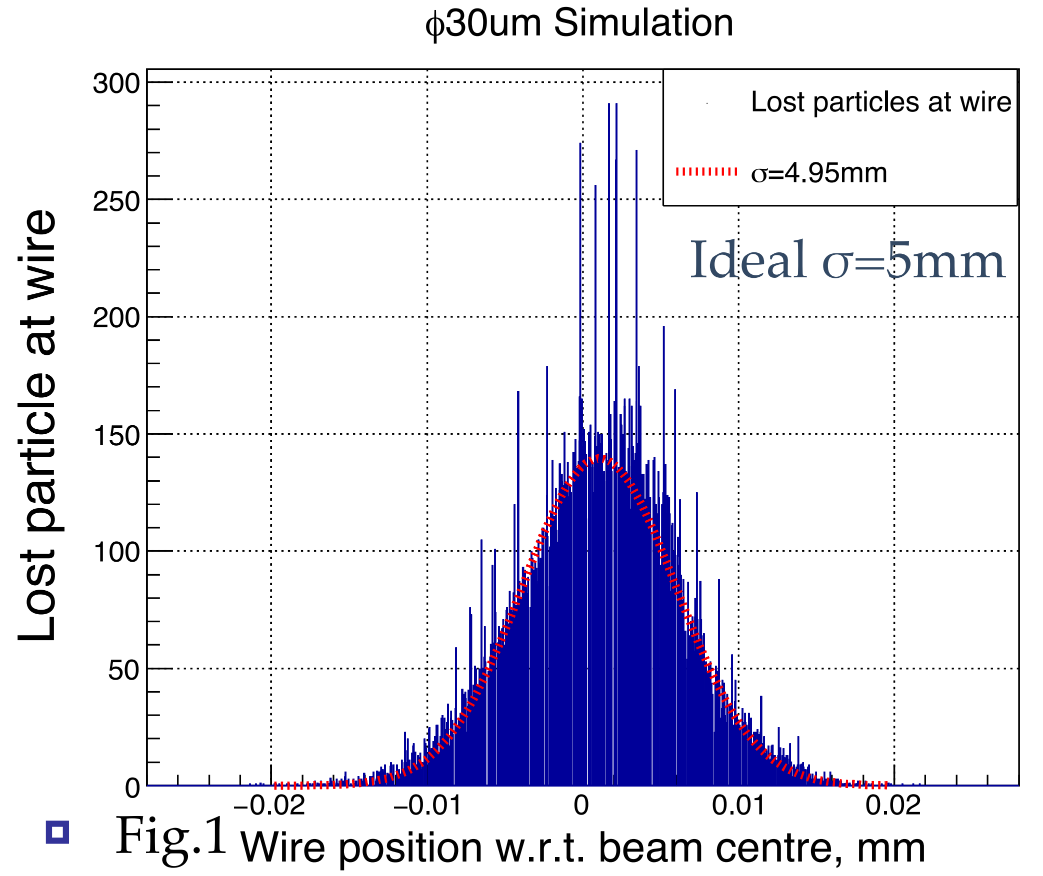
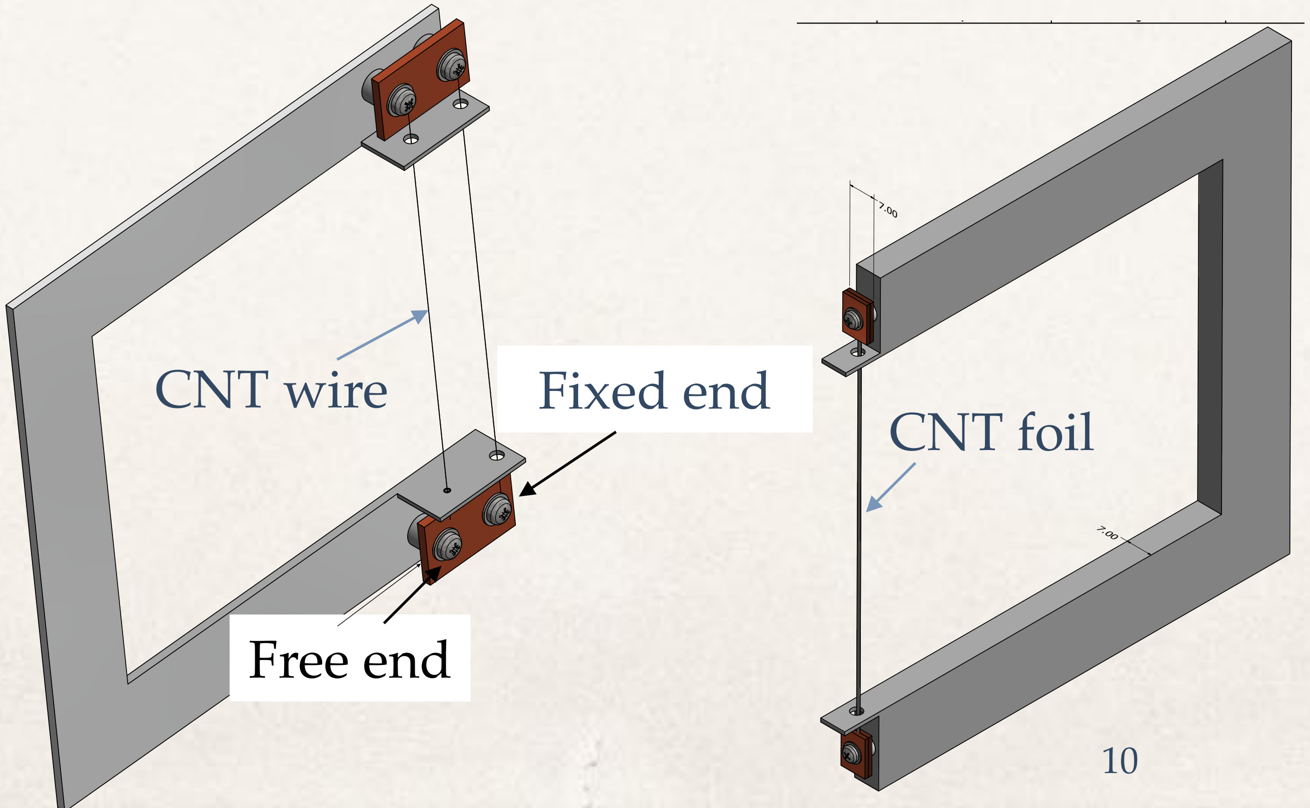


Fig.1



FETS-FFA WCM

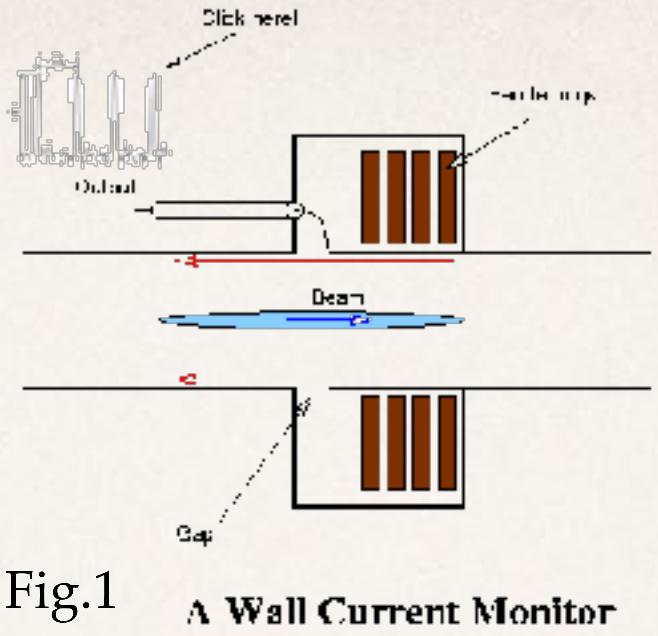
- Resistive wall current monitor (WCM) picks up an image current on the wall (Fig.1).
- Image current flows across the gap resistance.
- To get lower cut-off frequency, high permeability material (Ferrite) is placed around the gap.
- An Aluminium housing is put around the Ferrite core.
- Gap is filled with ceramic material to keep vacuum level in beam pipe.
- Sheet type of resistors are placed over the ceramic gap. Gap voltage is detected by monitor.
- Lower and higher cut-off frequencies are computed by

$$f_{low} = \frac{R}{2\pi L}$$

$$f_{high} = \frac{1}{2\pi RC}$$

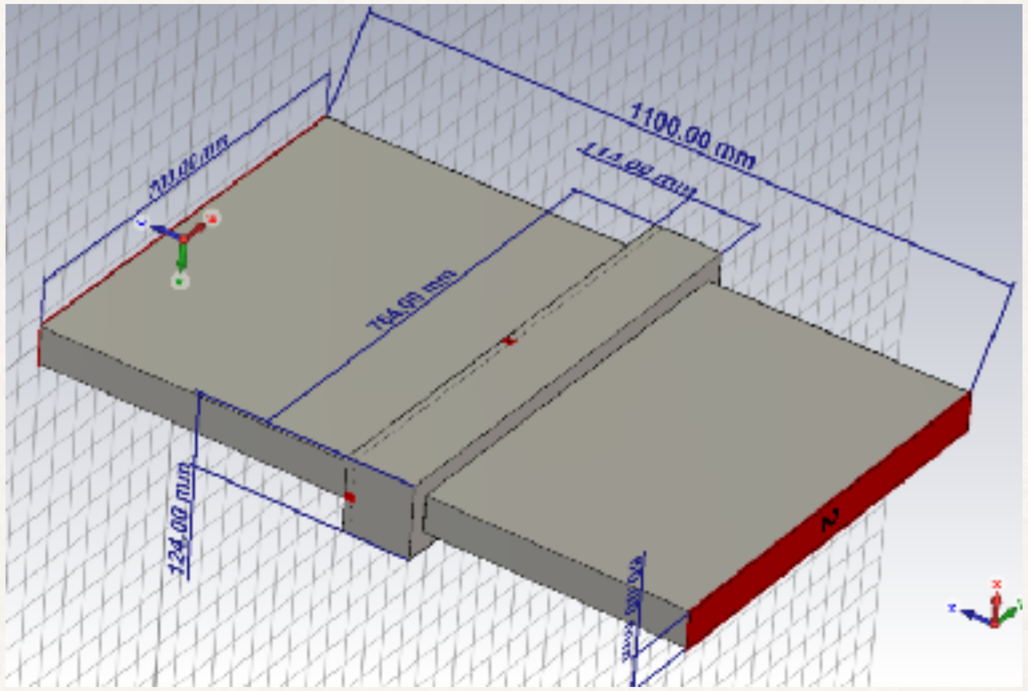
L: ferrite Inductance,
R: resistance,
C: capacitance of ceramic gap

- In the model, there are 80 resisters of 330Ω covering the ceramic gap. F_{low} is 643kHz and F_{high} is 285MHz.

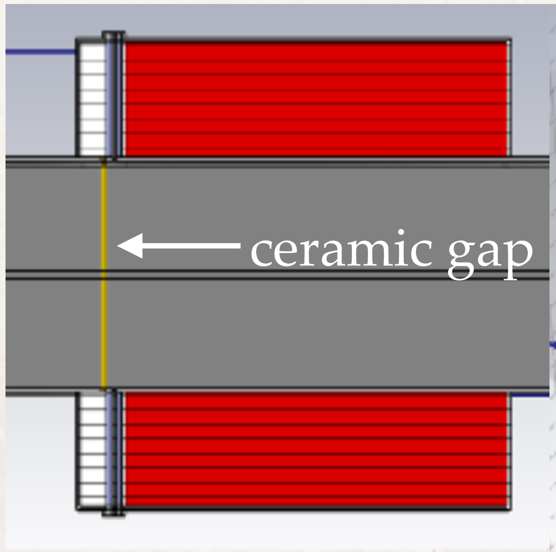


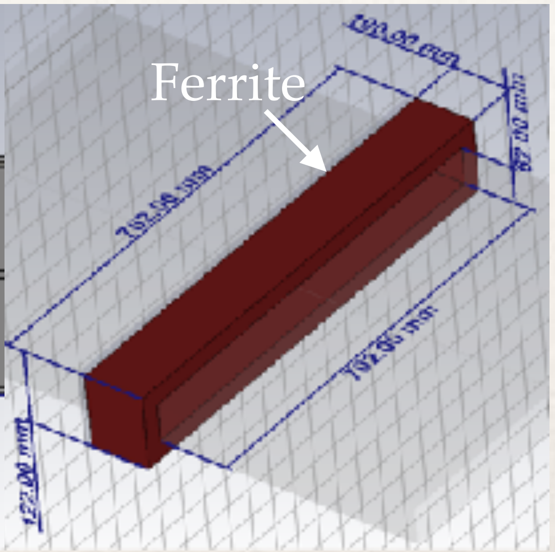
- Fig.1

Ref: http://psring.web.cern.ch/psring/psring/misc/wcm.html



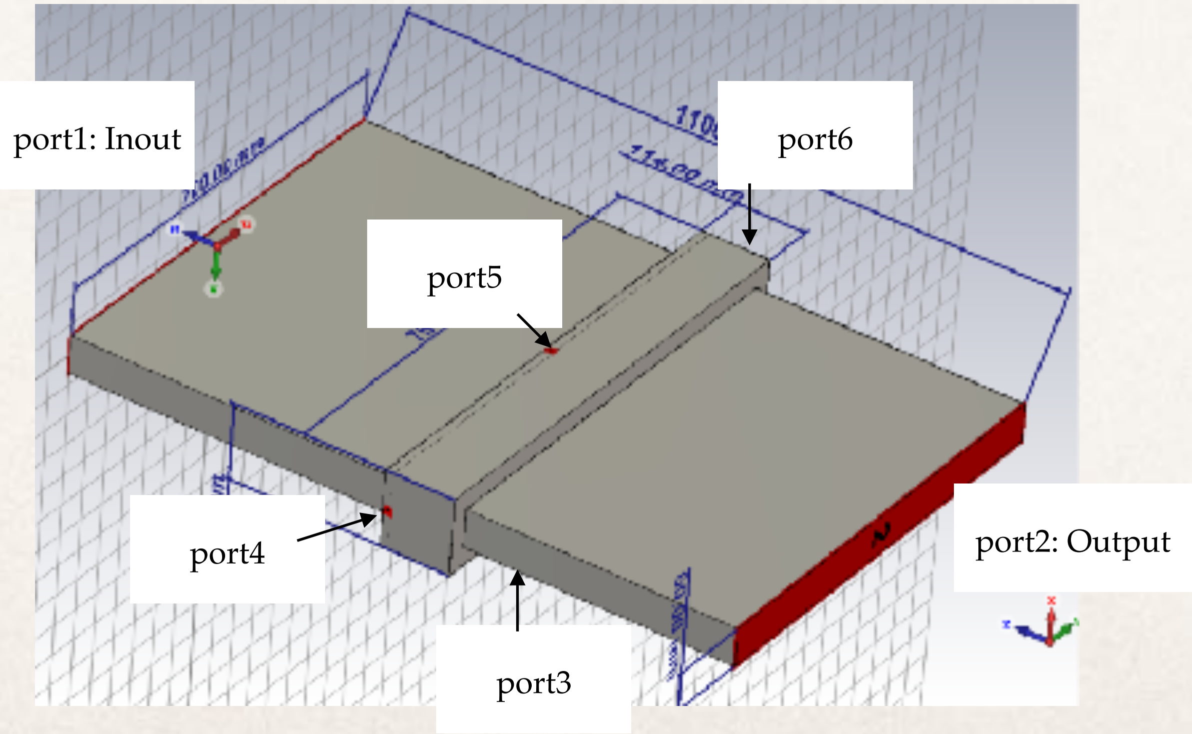
$f_{TE10} = 214\text{MHz}$

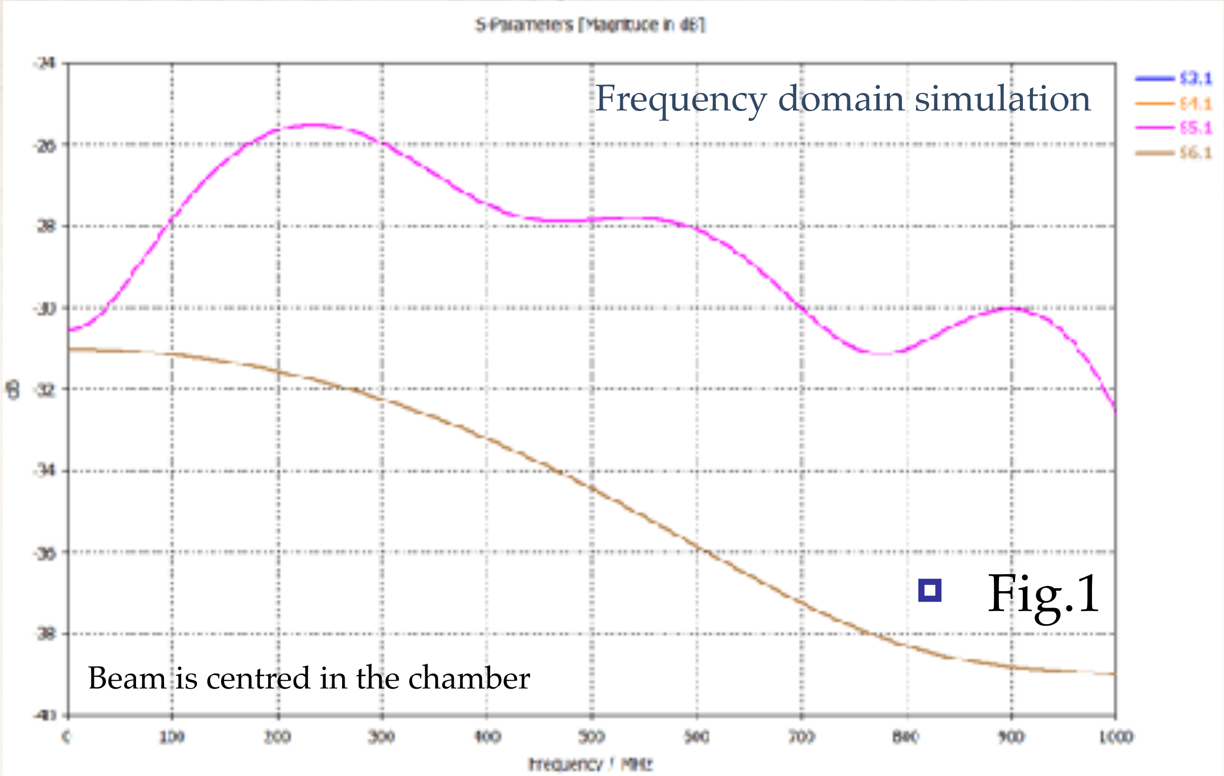




Frequency and Time Domain Simulation

- Frequency response in CST (Fig.1) shows that preliminary design has a reasonable bandwidth (a few MHz-200MHz).
- From time domain simulation (Fig.2), it is better to add several feedthroughs on every side of the vacuum chamber, to cancel out position dependency of voltage signal.





Frequency domain simulation

Beam is centred in the chamber

Fig.1

Time domain simulation

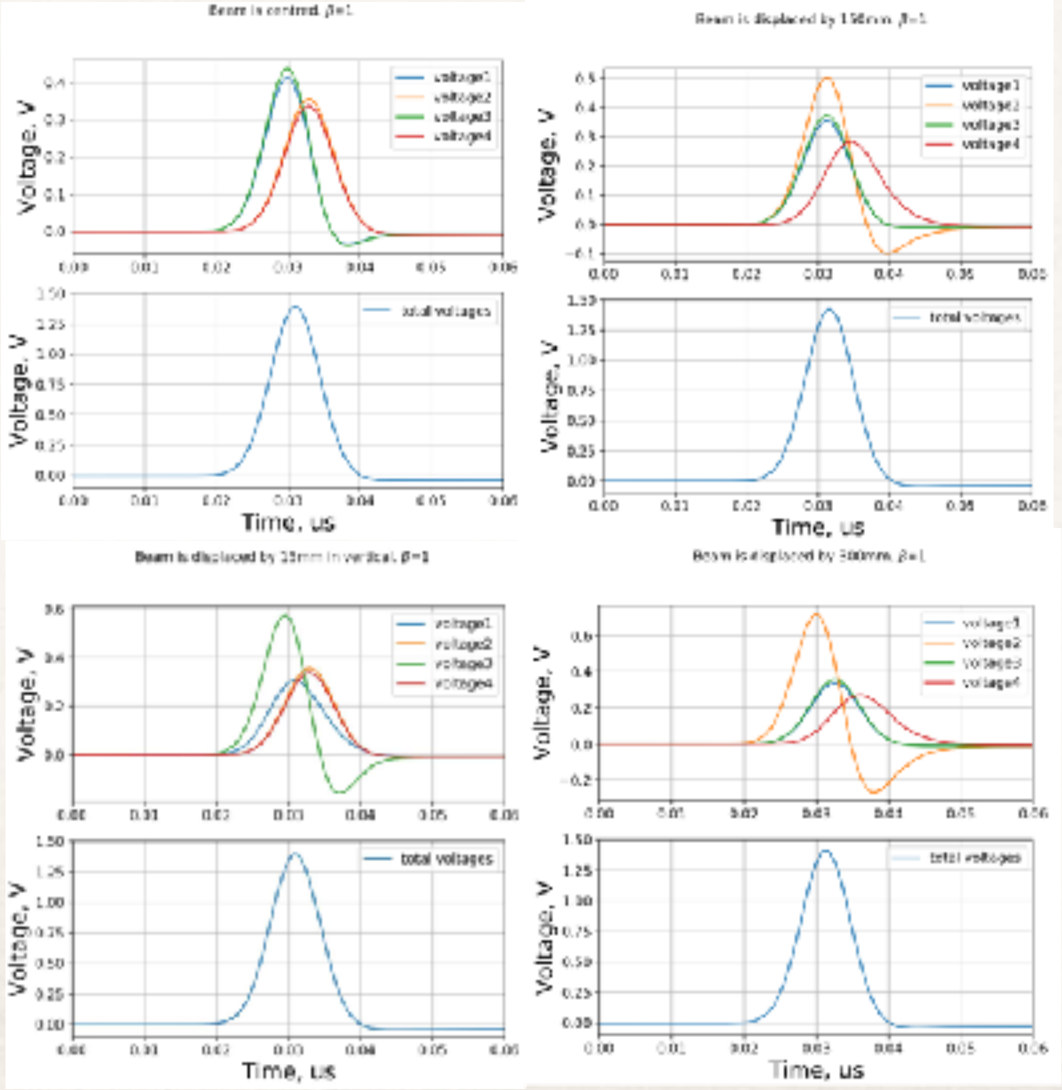


Fig.2

Summary and Future Study

- Design study of **FETS-FFA BPM** has progressed well. We will install prototype BPM at KURNS for beam test next year.
- Design study of **FETS-FFA IPM as well as WSM** have been also started. Feasibility study and developments of WSM is the main target in next year.
- Design study of **WCM** has been done last year. Prototype WCM will be manufactured to demonstrate its reliability for FETS-FFA in the future.
- Other monitors, Beam halo monitors, DCCT, Faraday cup, beam loss monitors and screen profile monitors, are planned to be developed successively in the future.