Design and development of Beam Diagnostics for an FETS-FFA ring for ISIS-II upgrade studies

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Abstract

The ISIS-II project aims to deliver a new spallation neutron source by 2034, driven by a 1.2 GeV proton accelerator capable of delivering a beam power of 1.25 MW with a repetition rate of 50 Hz or higher. One of the options for this future accelerator is a Fixed Field alternating gradient Accelerator (FFA). To demonstrate the suitability of an FFA for use in a user facility such as ISIS, there is a plan to construct a smaller scale FETS-FFA. Developing beam diagnostics for this FETS-FFA ring presents a challenge due to a large orbit excursion and the aperture (~60 mm x 700 mm). Diagnostics must cover the full size of beam chamber whilst still providing measurement sensitivity and resolution comparable to that seen in the ISIS synchrotron. This paper presents the current design and development of beam diagnostics for the FETS-FFA ring, including finite element studies of Beam Position Monitors (BPMs) and Ionisation Profile Monitors (IPMs).

Introduction

The feasibility study for intensity upgrade of ISIS, toward 1.25 MW proton driver for neutron provision in Europe, was started in 2016 [1] One of the options being considered is a Fixed Field Alternating gradient (FFA) ring [2,3]. FFA's utilise static magnetic fields to accelerate a particle beam with a high repetition rate (~100 Hz), achieving high beam intensities. In order to demonstrate the viability of an FFA for a high intensity user facility, a small-scale FETS-FFA ring will be built first, before the final decision is made on which type of accelerating ring will be used in for ISIS-II. The preliminary parameters of this FETS-FFA ring are summarised in Table 1.

Table 1: Preliminary parameters of FETS-FFA ring

Beam energy range	3 - 30 MeV
Central radius	4 m
Orbit excursion	0.58 m
Bunch intensity N_p	10^{10} ppb
Harmonic number	2
RF bandwidth	4 - 7 MHz
Bunch length at 3, 30 MeV ($4\sigma_L$)	31, 54 ns

Development for Beam Position Monitor

BPM development for the FETS-FFA ring has focused on a rectangular, electrostatic shoe-box type monitor (also known as a split-plate BPM) [4], with two pairs of electrodes to allow measurement in both the horizontal and vertical planes. The preliminary design of each straight section of the ring is 0.75 m long, with internal aperture of 778 mm x 138 mm, meaning any installed BPMs must have very large widths. Figure 1 shows the preliminary design of the BPM, rendered in CST electromagnetic finite element software [7], which have an aperture of 710 x 70 mm with 4 mm electrode thickness.

Maximum detected pick-up signal ($V(t)$) [4] is given by:

$$V(t) = \frac{1}{c\beta C}\frac{A}{2\pi(a+b)/4}I_{beam}(t)$$

Position sensitivity (S) :

$$\frac{U_2 - U_1}{U_1 + U_2} = S\cdot x + \delta.$$

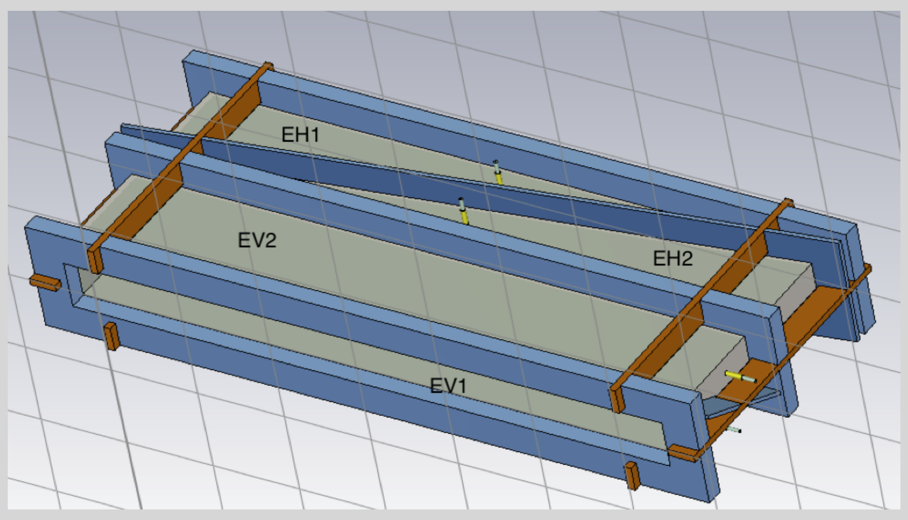

Figure 1: 3D CST model of the preliminary BPM design. The electrode pairs are named EH1,2 and EV1,2 for the measurement of horizontal and vertical position respectively.

Table 2: Simulated capacitances between each electrode and ground.

EH1	EH2	EV1	EV2
120 pF	119 pF	96.9 pF	96.9 pF

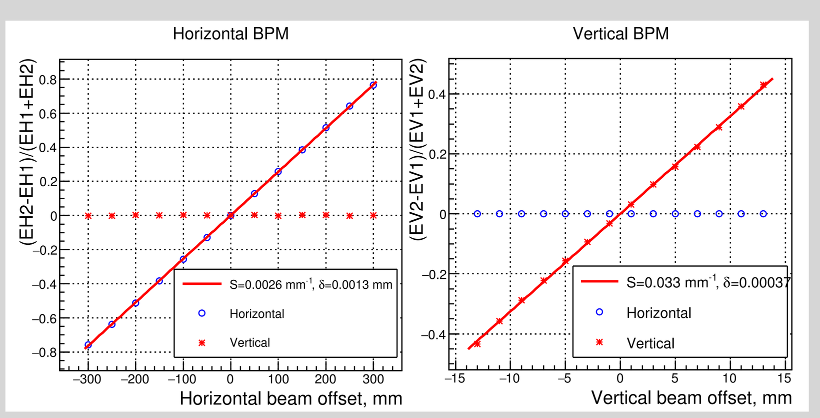

Figure 2: Difference over sum plots for the horizontal and vertical sections of the BPM, along with their associated sensitivity values. Linear fitting function presented by Eq.(2). was applied to estimate sensitivity and offset error.

The ideal sensitivity (~2/W) of BPM is 0.0028 mm−1 in the horizontal plane and 0.033 mm−1 in the vertical plane. Inter-electrode coupling in both the horizontal and vertical sections of the monitor is well mitigated, and the position sensitivity is very close to the ideal values.

The impact of varying the angle of the cut between the horizontal electrodes on both capacitance and position sensitivity was analysed. To maximise the output signal, a balance between capacitance and sensitivity must be found, and these plots confirm that for the preliminary design, a cut angle of 7.96 degrees is optimal.

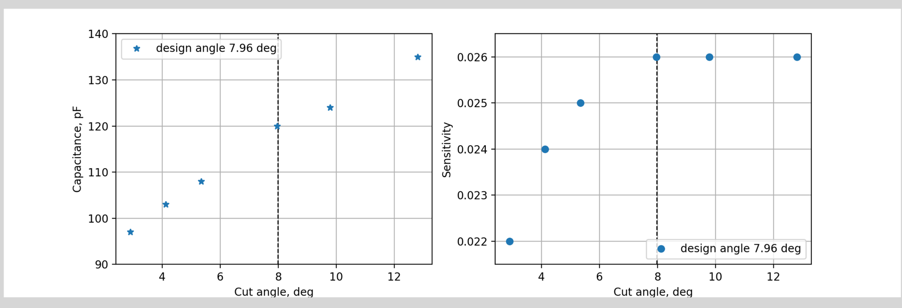

Figure 3: Variation of the horizontal BPM electrode capacitances to earth (left) and beam position sensitivity (right) with the cut angle between the electrode pair.

Ionization Profile Monitor Development

IPM is under development to provide non-destructive beam profile monitoring for taking turn-by-turn measurements during operation. The preliminary horizontal and vertical IPM designs (Fig. 4) consists of (I) Guiding and detecting residual gas ions, to avoid needing to install huge magnets around the beam pipe, (II) 'Shaping-field' electrodes: to ensure the drift field has a uniform transverse shape within the monitor[9], (III) Particle detectors: placed on ceramic housing, attached to the grounded plate, (IIII) anode plates: 10 kV (H) and 1 MV (V) are required to guide the ions to the detectors within the revolution time of the ring (~200 ns). From this, a turn-by-turn vertical IPM measurement is not realistic for the FETS-FFA.

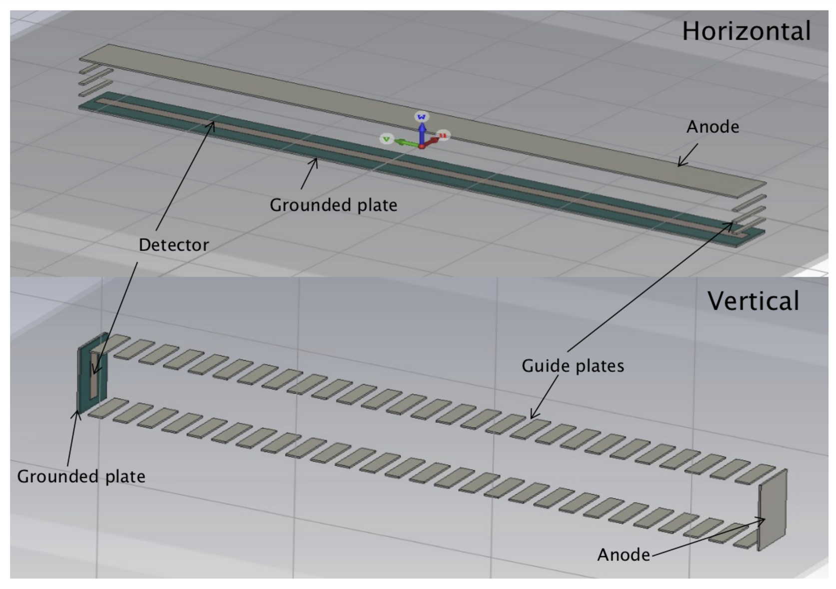

Figure 4: Simplified CST models of the horizontal (top) and vertical (bottom) IPMs for the FETS-FFA ring. Anode and grounded plate of horizontal IPM has 710 mm×5 mm with 2 mm thickness, separated by 60 mm. For vertical IPM, anode and grounded plate has 80 mm×5 mm with 2 mm thickness, separated by 710 mm. Detectors are 700 mm×14 mm with 0.3 mm thickness in horizontal and 60 mm×14 mm with 0.3 mm thickness in vertical.

Assuming that hydrogen gas is the main particle present, the number of ion-electron pairs generated, *N*, by a proton beam of energy *E*, within a monitor of length *dZ*, can be estimated by [11]:

$$N = N_p \rho P \frac{dE}{dx}\frac{1}{W}dZ,$$

P: vacuum pressure (10^{-5} Pa)
dE/dx: stopping power
W: mean energy
ρ: density of hydrogen

13,000 ion-electron pairs are expected to be generated at 3 MeV (injection energy), and 2,000 pairs at 30 MeV (extraction energy).

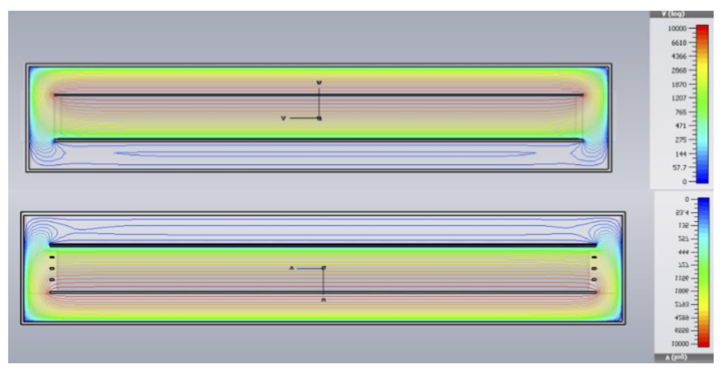

Figure 6: Transverse cross sections showing electric potential contours in the horizontal IPM without (top) and with (bottom) the shaping field. Potentials near the monitor edges are distorted unless the shaping fields are present. In both plots, the beam space charge field is not taken into account.

CST particle simulations:

1. The initial velocity of the beam generated ions was set to zero.
2. Approximate beam space charge field in the, a cylindrical pipe made of vacuum was created, consisting of 4 layers of increasing radii: σ, 2σ, 3σ and 4σ, where σ = 4 mm.
3. Each layer had a proportion of the bunch charge distributed uniformly across its surface, with the charge applied to each layer calculated as:

$$Q(x) = N_p q_e \frac{A_x}{A_t}\frac{L_x}{L_t},$$

q_e : Elementary charge
A_x: cross section of each layer
A_t : cross section of the 4σ beam layer
L_x: beam length in CST
L_t : bunch length for $4\sigma_L$

30 MeV

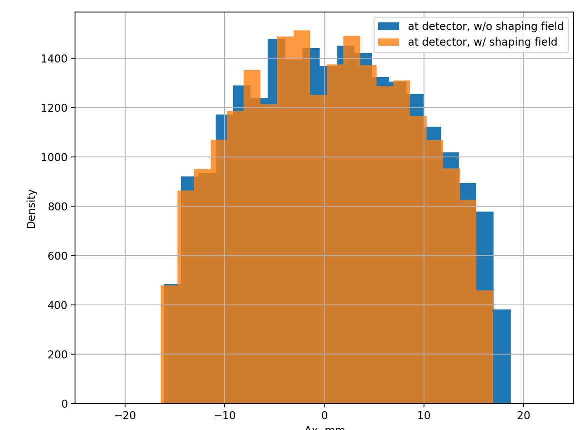

Figure 5: Histogram plots of detected profiles with and without shaping fields at 30 MeV proton beam energy. Δx is the displacement from the beam centre.

When the beam is close to the edge of the anode, the measured ion profile becomes asymmetric with respect to the beam centre if the shaping field is not active, (Fig. 5) as the drift field guides ions towards the earthed beam pipe walls in addition to guiding them towards the detectors (Fig. 6).

Two additional pairs of electrodes have also been added to the preliminary design to ensure there is no net kick applied to the beam. Further simulation studies will be performed in the future.

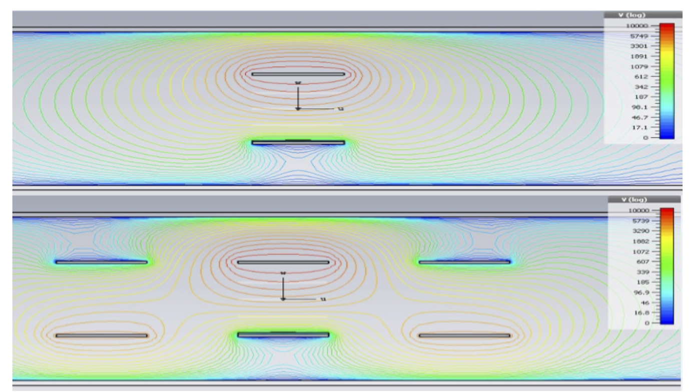

Figure 7: Cross sections of the monitor, showing the electric potential along beam direction without (top) and with (bottom) compensating field. The bias potential on the anode is 10 kV, while the bias on each compensating electrodes is 5 kV.

Summary

Preliminary designs for a BPM and IPM have been produced for the ISIS FETS-FFA ring. In both cases, the extremely large beam pipe aperture poses the main challenge when designing these monitors. BPM design parameters have been optimised by CST simulations. The monitor's beam position sensitivity has been maximised while signal coupling between adjacent electrodes has been well-suppressed, using earthed guard rings placed between each electrode. At the time of writing, a prototype 4-electrode BPM which has been scaled down to half the width of preliminary design is being manufactured, to enable bench measurements to be carried out and to verify the design simulations presented in this paper. It has been determined that a vertical IPM is not a feasible option for the ISIS FETS-FFA ring, as the large aperture requires approximately 1 MV to be applied to the drift field anode, which is not realistic. On the other hand, a horizontal IPM only requires an anode potential of 10 kV to guide the residual gas ions sufficiently. Potential distortion of the measured profile by a non-uniform drift field has been mitigated with the use of additional shaping field electrodes. The use of additional compensating fields has been considered, to prevent the IPM applying a kick to the beam as it passes through the monitor. Further simulation work will be performed to study effect in more detail, using more realistic beam charge distributions and including the affect of magnetic fringing fields of main magnets located near to the monitor.

References

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