CALIBRATION OF THE EMMA BEAM POSITION MONITORS: POSITION, CHARGE AND ACCURACY

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Abstract

The accurate determination of transverse beam position is essential to understanding the performance of an accelerator system, and this is particularly the case with non-scaling FFAG machines such as EMMA, where, due to fundamental principles of design, the beam may deviate widely from the central beampipe axis. This paper describes the various modelling approaches taken for the three different button pickup assemblies used in EMMA, and the subsequent methods of calibration ('mappings') which allow beam position and charge to be deduced from the processed BPM signals. The use and validity of the modelling and mapping approach adopted is described, and the contributions to positional and bunch charge uncertainty arising from these procedures is discussed.

INTRODUCTION

EMMA is the World's first operational proof-of-principle example of a non-scaling fixed field alternating gradient (FFAG) accelerator. Details of its design and construction are reported elsewhere [1]. The physical aperture requirements of the machine, along with its relatively compact nature, necessitated the use of three different mechanical constructions of BPM assembly. Fig. 1a shows the typical double BPM section used around most of the 48mm ID ring (rendered in the CST modelling package).

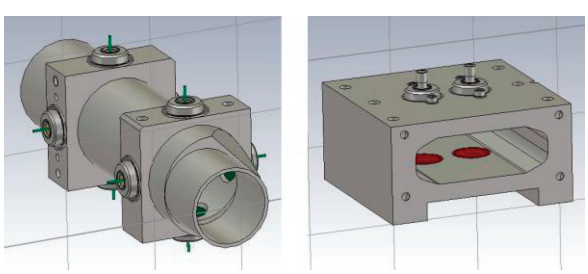

Figure 1: CST renderings, a) cylindrical beampipe section; b) rectangular beampipe section.

Each of the two square BPM blocks holds an identical arrangement of four pickups, two vertically positioned and two horizontally. For the block to the left in Fig. 1a the adjacent beampipe is longitudinally symmetric, whilst for the block to the right the beampipe is tapered on the inside of the ring just prior to the bunch entry point. In the part of the ring immediately after the injection septum, a different geometry again is used, see Fig. 1b, which allows for greater horizontal beam deviation (up to about ±35mm) during this injection stage. Naturally, it has been necessary to separately model and measure the response of each of the three types of BPM assembly.

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MODELLING THE BPM RESPONSE

The principle approach to modelling the response of the BPMs has been using CST's EM Studio [2]. The design specifications of all three types of BPM were input to CST directly from CAD SAT formatted files, and appropriate material properties (such as electrical permittivity, E, magnetic permeability, μ etc) for each sub-component then specified. A 3D hexagonal grid was used, with a total of about 4.5 10^6 individual cells. The cell parameters (dimension, location etc) were optimised automatically by CST, with appropriate boundary conditions being defined. A straight on-axis potential-carrying wire was modelled, and simulations were run both with a DC driving signal and also at a range of frequencies up to several 10s of MHz. No qualitative differences were found from the DC state, as expected.

In addition to CST, and for the purposes of comparison and validation, modelling was also carried out using the 2D electrostatic code 'Quickfield', and also using a modified 2D theory based on [3]. 'Stretched wire' bench measurements were also made with a NA and a section of beampipe, as shown in Fig. 1a, fixed onto a precision custom-made mounting block. The accuracy and repeatability in positioning the wire was estimated to be around ±50μm. More details will be reported separately.

These various approaches were used to validate the CST model for a number of sample beam positions, with the model then being used for characterisation across the full transverse plane for each of the three BPM configurations.

A number of beam positions were modelled (initially 437 for the cylindrical BPM configuration), each point lying on a 2mm rectangular grid set up across the transverse aperture. For each beam position CST modelled the electrostatic potential field in the whole 3D volume of the section. Example equipotential plots are shown in Figs. 2a and 2b.

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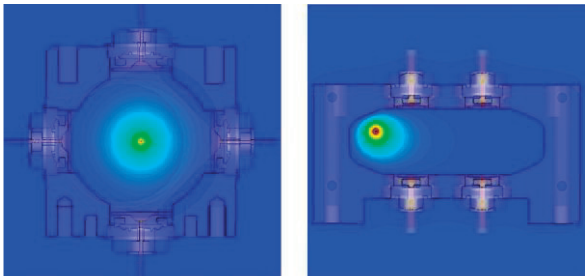

Figure 2: Potentials in the transverse plane: a) cylindrical pickup arrangement, b) rectangular pickup arrangement.

In Fig. 2a the change in longitudinal beampipe cross-section, and how this delicately affects the symmetry of the potentials, is clearly seen. In Fig. 2b the beam has been positioned well away from the centre, at $x \approx 28$mm and $y \approx 4$mm.

POSITION MAPPING

As is described elsewhere in these proceedings [4], the signal from an individual BPM pickup is processed and digitised to eventually yield a voltage signifying its response to a passing electron bunch.

We consider a normalised Cartesian coordinate frame in the transverse plane and centred on the beampipe axis, with +x pointing outwards along the central horizontal axis, and +y pointing upwards along the central vertical axis. The middle points on the surfaces of each of the four button pickups of the cylindrical assemblies are located as follows: L (-1,0), R (1,0), U (0,1), D (0,-1). Adopting the notation introduced in [4], pickups L, R, U, D are read as voltages V11, V12, V21, V22.

If we consider a pencil-thin beam which moves only in the horizontal plane (y=0) or the vertical plane (x=0), the measured beam position is deduced simply as:

$$Xu = (V_{11} - V_{12}) / (V_{11} + V_{12}) \quad (1a)$$

$$Yu = (V_{21} - V_{22}) / (V_{21} + V_{22}) \quad (1b)$$

where the suffix 'u' stands for 'uncalibrated' or 'unmapped'. The pickup voltages relate to a real presumed beam position (Xr,Yr). Using modelling results, we can plot the actual position of a beam, Xr, against this unmapped position to get the curve shown in Fig. 3.

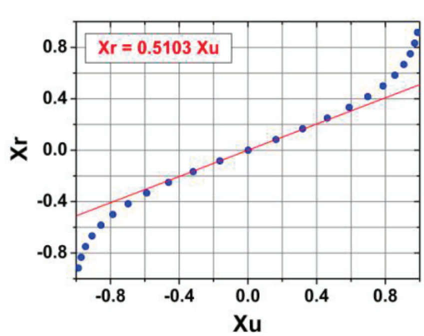

Figure 3: A typical calibration curve for x.

The region of linearity, in this case out to $Xr \approx \pm 0.2$ (corresponding to around ±5mm for the EMMA 48mm ID beampipe), means that for reasonably centred beams a scale factor of ≈ 12.247mm can be multiplied to Xu, to correct back to the real horizontal beam location. However, for an FFAG, beam deviations beyond ±5mm are highly likely. We also wish to have a mapping for cases where both x and y are non-zero..

To do this, we calculate (Xu,Yu) at each beam location from the modelled pickup responses, and construct a 3D surface plot, where (Xu,Yu) are Cartesian plane axes, and the z axis corresponds to the actual value that the beam was modelled at, Xr. An example is shown in Fig. 4.

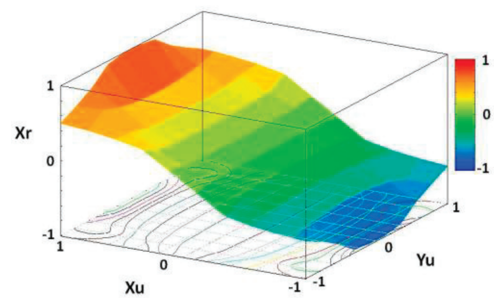

Figure 4: Mapping surface for horizontal position.

(Note that the real horizontal position depends upon both the uncorrected horizontal and vertical positions.)

The mapping process for horizontal beam position thus consists of interpolating to this surface at a point (Xu,Yu) derived from real experimental data. A similar but separate surface needs to be constructed for the vertical (y) locations, and also for bunch charge. Two approaches to fitting these surfaces have been examined: using a 7th order 2D polynomial in (Xu,Yu) to fit the entire surface with a single equation; identifying a small number of modelled points in the (Xu,Yu) plane lying closest to the experimental datapoint, and performing a local fit to these points only (knowing already their Xr values).

CHARGE MAPPING

It is evident, and has been demonstrated experimentally [5], that the sum of the four pickup signals in a single BPM is linearly proportional to the charge of a passing bunch located near the central axis, provided the bunch has not suffered significantly from bunch lengthening. However, the response of a single pickup itself is not linear with beam distance; as the beam approaches closely, the pickup's response rises more than linearly. As a result, the relation between the total 4-pickup signal and the bunch charge is beam position dependent, at least well away from the centre. Charge mapping is carried out in a similar fashion to that used for position, and a charge correction factor, Qf, is defined for a particular (Xu,Yu), which must be divided into the 4-pickup sum to normalise it to what it would be if the beam was at the centre. This is shown in Fig. 5, where the sum is normalised to unity at (0,0).

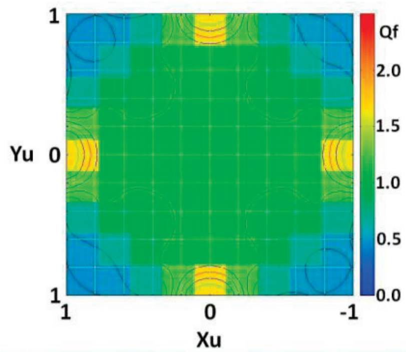

Figure 5: Contour plot of Qf in the (Xu,Yu) plane.

In this case, to fit a single polynomial to the whole aperture would lead to inaccuracies, and a local-fit mapping is used.

MAPPING ACCURACY

We take a grid of 'n' points (Xr_i,Yr_i), i=1,n, representing real beam positions, and from the modelled BPM pickup responses create an equivalent set of uncalibrated positions (Xu_i,Yu_i), as outlined in equations 1a and 1b. These pairs of values are then put through the mapping procedure to produce points (Xm_i,Ym_i), which, if the mapping procedure was perfect, would be identical to the initial starting values. For each beam position we calculate the difference values (Xr_i - Xm_i), (Yr_i - Ym_i) and (Qr_i - Qm_i).

RMS values of these differences, Σx , Σy, and Σq, are calculated across i=1,n for three groups of beam positions lying within annuli at different radial distances from the centre. The results are given in table 1 for both the 7th order 2D polynomial and the local-fit mappings.

Table 1: RMS errors from horizontal (x), vertical (y) and charge (q) mappings, inside three radial annuli

	7th Order Poly			Local Fit		
Range (mm)	Σx (μm)	Σy (μm)	Σq	Σx (μm)	Σy (μm)	Σq
0–8	106	109	.069	8	7	.001
8–16	100	100	.067	65	64	.014
16–24	286	286	.176	106	105	.034

While both approaches show increasing errors as the beam moves away from the linear central region, the local-fit method shows consistently superior results.

Recent measurements taken in the EMMA injection line and reported in these proceedings [4] show a total BPM resolution of ≈35μm at a bunch charge of 20pC. This figure, which is independent of beam movement during the measurements, is based upon mapped (local-fit) beam positions and thus includes any errors introduced by the mapping process itself. The real horizontal beam offset was around -4mm. At 40pC the overall BPM resolution is around 20μm, and reference to the numbers in table 1 shows that at this higher bunch charge the accuracy of the mapping procedure starts to become comparable to thermal and other noise introduced in the BPM circuitry.

SUMMARY AND FUTURE WORK

The way in which the EMMA BPM responses are linearised using a 3D EM modelling and mapping approach have been reviewed and discussed. The concept of charge mapping – correcting the summed BPM 4-pickup signal to what it would have been for a particular bunch if the bunch had passed through the centre of the beampipe – has been described. Overall figures for the contributions to position and charge uncertainty have been provided.

Future planned efforts will include investigation of bunch position determination for non-symmetric beams and those suffering significant transverse blow-up. The significance and accuracy of the charge mapping technique would benefit from further studies. Finally, a recently developed "quadrupole" approach to positional mapping, which has the potential to measure BPM noise independently of real beam jitter, will be tested using future data taken on ALICE.

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