AN EXPERIMENTAL METHOD OF ABERRATION CORRECTION FOR HIGH RESOLUTION MASS SPECTROMETERS

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Abstract

The PIAFE project needs high resolution mass spectrometer. A new experimental method of aberration correction has been designed and demontrated. A small emittance beam is sent in the system with different angles. The different trajectories are reconstructed and permit the drawing of the aberration figure. Then an appropriate shimming can be done on the poles.

1 INTRODUCTION

The PIAFE [1] (Projet d'Ionisation et d'Accélération de Faisceaux Exotiques) objectives are to produce exotic ion beams, with masses from 80 to 150 amu and intensities between 10^5 and 10^{12} particles per second and produced by the fission of an uranium target put in the high neutron flux of the ILL reactor.

In the low energy part of the facility, between 10 and 30 keV, a high resolution mass spectrometer is required (resolution $m/\Delta m \approx 10^4$). Such a resolution can be obtained only by an appropriate correction of the optical aberrations. In some scenarios, this has been done by putting sextupoles and octupoles in the system. Another way for correction is the "shadow method" [2]. In this case, a large beam is sent inside a dipole magnet. At the entrance of the magnet, a grid made of several wires is put. At the exit of the system, the grid makes "holes" or "shadows" inside the beam profile, corresponding to some perticular trajectories. Two beam profile monitors are then used to contruct each trajectory. Due to aberrations, the trajectories do not converge towards the same point. Then, the correction is done by putting an appropriate iron piece on the pole (shimming).

We propose here a new method, which has been tested successfully on the 105 degrees spectrometer of ISN and described figure 1. A low emittance source is used. A magnetic steerer put at the object point sends the beam anywhere in the region used by the real beam (±9 degrees in our case), inside the magnetic dipole. Due to aberrations, the beams do not converge towards the same point (fig. 2). At the exit of the spectrometer, a calibrated magnetic quadrupole is set, followed by a very accurate beam profiler. For a given beam at the entrance of the dipole, the beam position is measured by the profiler for different excitations of the quadrupole. This permits the reconstruction of the trajectory at the exit of the dipole (fig 3) by using different excitations of the entrance steerer, corresponding to different microbeams. A calculation of an appropriate shimming is done and iterated until a perfect correction.

The advantages of this method are its easiness, its accuraccy and its simplicity, corresponding to the correction of the real abberrations, without using additionnal non-linear lenses and/or too sophisticated calculations.

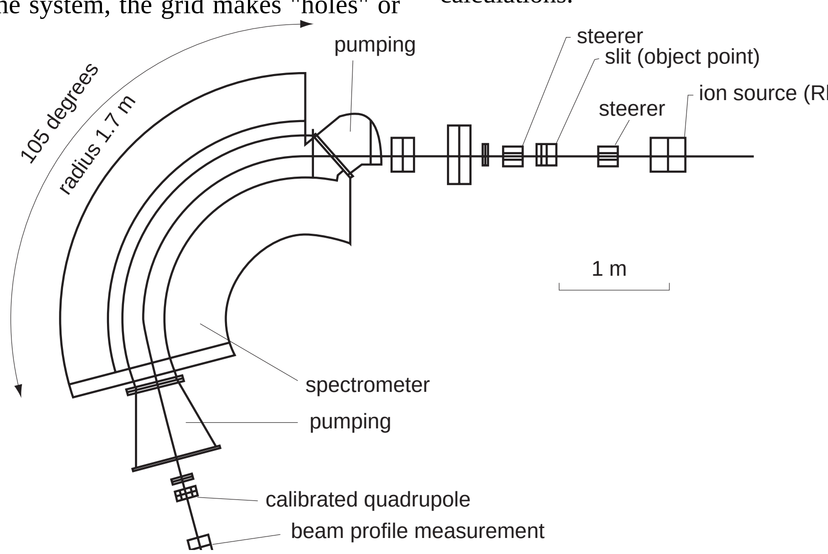

Figure 1: experimental setup

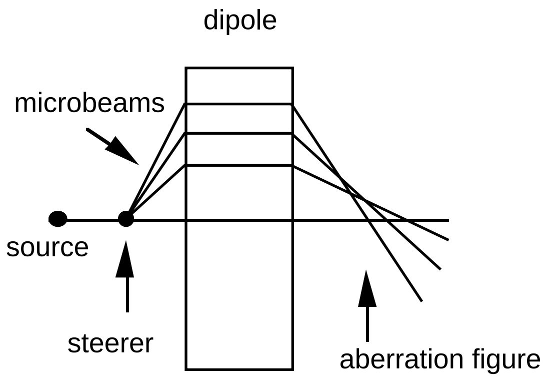

Figure 2: A steerer put at the object point sends the beam along different paths. Due to aberrations, these trajectories do not converge towards the same point.

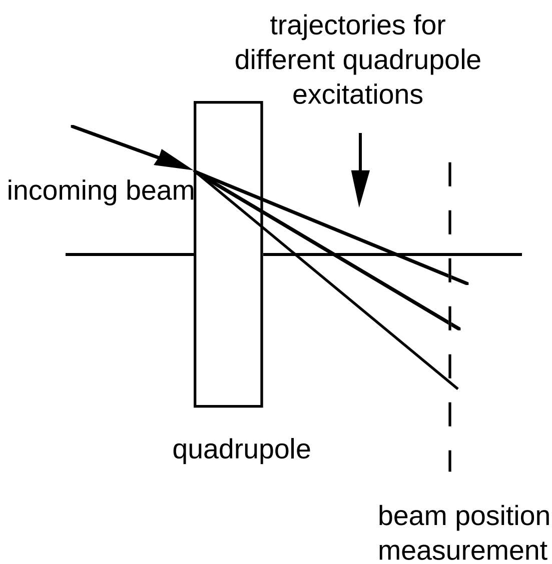

Figure 3: A three gradient method gives the trajectories at exit of the system (3 or more quadrupole excitations and the corresponding beam mass center measurement)

2 THEORY

2.1 Non-linear transport of a micro-beam

Let $X = \begin{bmatrix} x \\ x' \end{bmatrix}$ (or Y) the vectors in the transverse phase space. If the sign ~ denotes transposition, if (X_i) are a set of points describing the beam, supposed to be centered, then the beam matrix is:

$$\Sigma = \langle X_i \tilde{X}_i \rangle = \begin{bmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{bmatrix}$$

We also describe the beam at higher order with, for illustration at order 2:

$$X_i^{(2)} = \begin{bmatrix} x_i^2 \\ x_i x_i' \\ x_i'^2 \end{bmatrix}$$

We study now the effect of non-linearities on a micro beam, which is never centered around origin of (x,x'). Let X_0 be its center of mass. If T is the mapping describing the transport, it can be written, with $Y_0 = T(X_0)$:

$$T(X_0 + X_i) = Y_0 + MX_i + HX_i^{(2)} = Y_0 + Y_i$$

M being the linear part of the transport and H describing the second order part. The new beam matrix:

$$\Sigma_1 = \langle Y_i \tilde{Y}_i \rangle = M \Sigma_0 \tilde{M} + H \langle X_i^{(2)} \tilde{X}_i^{(2)} \rangle \tilde{H}$$

The first term is the classical transport of emittance, the second is the variation of RMS emittance due to non-linarities. It is of second order. The non-linearities are mainly included in Y_0 (measured) and not elsewhere (for example in the emittance). This result can be generalized to a describtion of the beam and transport at any order.

2.2 Calculation of trajectoriues by a multigradient method

Let s_1 be the distance between the intersection microbeam/optical axis and the entry of the mesasurement system (quadrupole), let θ_1 be the beam angle. At the entry of the measurement system, the microbeam is centered around:

$$X_1 = \begin{bmatrix} s_1\theta_1 \\ \theta_1 \end{bmatrix}$$

To know s_1 and θ_1, N excitations of the quadrupole and N beam positions measurements are made, to build a vector Y made of N lines. This vector can also be written

$$Y_1 = M X_1$$

where M is a Nx2 matrix containing the transport M_{11} et M_{12} terms of the measurement system. More precisely, the line i of Y_1 is$Y_{1i} = M_{11i} s_1\theta_1 + M_{12i} x'_1\theta_1$. M is unknown and can be written $M = M_0 + \varepsilon$ with M_0 the theoretical value of M and ε an error term due to the various uncertainties. Y_1 being known, one looks for the RMS best value of X_1, writen X_1^* which minimizes the error function $E = \| M_0 X_1^* - Y_1 \|$. One obtains:

$$\mathrm{grad}E^2 = 2 \tilde{M}_0 M_0 X_1 - 2 \tilde{M}_0 Y_1$$

Making this gradient zero and writing $R = \tilde{M}_0 M_0$ leads to:

$$X_1^* = R^{-1} \tilde{M}_0 Y_1$$

This provides the way to calculate X_1^* from Y_1
In addition, one obtain the uncertainty by writing:

$$X_1^* = X_1 + R^{-1} \tilde{M}_0 \varepsilon X_1$$

Then, if we consider a second vector X_2, the error is:

$$X_2^* - X_1^* = X_2 - X_1 + R^{-1} \tilde{M}_0 \varepsilon \left[X_2 - X_1 \right]$$

This shows that this method introduces a relative error (and not absolute). This is fundamental. For example, an error on the distance between the quadrupole and the position monitor is 5 mm over 500 mm is totally acceptable (1%), even if 0.2 mm has to be measured.

3 EXPERIMENT

3.1 Devices

A rubidium beam, 1^+, 35 keV, $2.5\pi\ 10^{-6}$ m emittance, 500 nA is sent trough a 0.3 mm slit to get a 20 nA microbeam at the object point. The magnetic steering does not affect the position of the object point. A calibrated quadrupole has been used (2.725 cm radius, 98mm magnetic length). The beam position monitor was made of a Faraday cup. In front of it was a slit (0.2 mm large, 8 mm high). This cup was set on a translator driven by a personnal computer, and the precision on the position was 0.1 mm. This experiment was done only to validate the method. A precision of 0.05 mm on the position and the use of a 0.1mm large slit would lead to better results. An estimation of the magnitude of the aberrations has been done by using the code TRANSPORT. It has been seen that, in that case, the accuracy needed for aberration correction was 0.1 mm in position, which is our case. For future applications, it will be easy to get a significant gain of accurarcy.

3.2 Experimental results

Figure 4 shows the slope versus the position of each microbeam at the image plane of the spectrometer.The non linearity of the curve shows the aberrations.

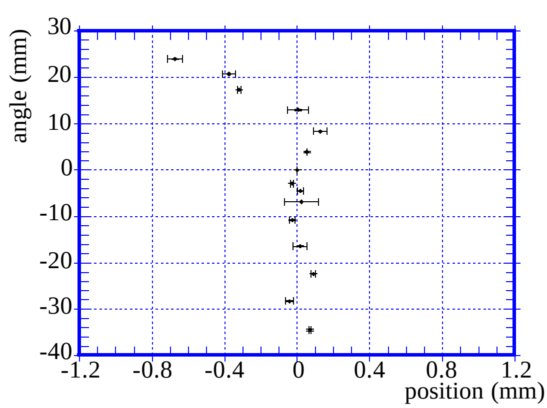

Figure 4: position of the microbeams at the image plane.

3.3 Calculation of the shims

An additionnal local magnetic length of the dipole (shim) gives an angular variation of the trajectory:

$$\zeta = \Delta x' = \int_{\text{shim}} (B.dl)\ /\ (B\rho)$$

where B is the local value of the field and ρ the local value of the magnetic radius.

Let L be the distance from the exit of the dipole to the image plane, x and x' the position of the microbeam at exit of the dipole, M the transfer matrix of the dipole. At first order, neglecting the effect of aberrations on the correction at entrance, if ζ_0 is the correction at entrance and ζ_1 the correction at exit, the beam will cross the axis on the image plane if:

$$\begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x+M_{12}\zeta_0 \\ x'+M_{22}\zeta_0 + \zeta_1 \end{bmatrix} = \begin{bmatrix} 0 \\ x'_s \end{bmatrix}$$

leading to $\zeta_1 = \frac{1}{L_0}(x+M_{12}\zeta_0 + L_0 x' + L_0 M_{22}\zeta_0)$

This gives a choice to get positive values of corrections at entrance/exit, in an iterative way.

Figure 5 gives the theoretical value of the shim magnetic length at entrance. A few mm are needed. We have shown that he sensitivity of the system is high enough to detect a 0.03 mm long iron foil at about 100 mm of the pole.

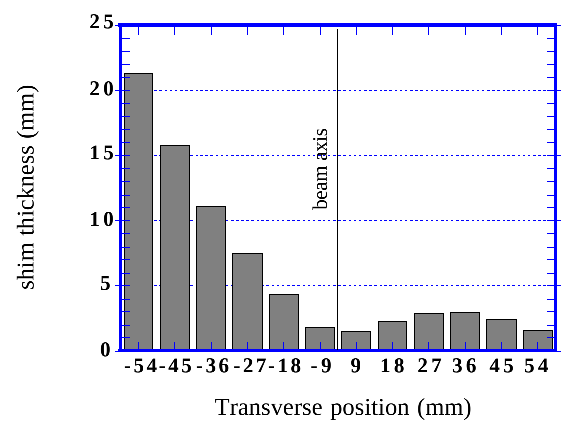

Figure 5: Shim magnetic length required at the entry of the spectrometer for aberration correction.

CONCLUSION

A new method has been demonstrated to correct totally the aberration of a high resolution mass spectrometer. It is on line, easy to operate and avoids non linear elements lenses and sophisticated calculations. The demonstration has been done with a very simple system abble to detect a 0.03mm iron magnetic length. Further and simple improvements of this system can be done easily.

REFERENCES

[1] Proc. Int. Workshop on the Physics and Techniques of Secondary Nuclear Beams. Dourdan, France, 23-25 March 1992. Edited by J.F. Bruandet, B. Fernandez and M. Bex.

[2] J. Camplan, R. Meunier: Experimental study of the magnetic prism of an electrostatic Isotope separator - Nuc. Instr. and Meth. 57 (1967) 252.