CAPACITIVE BEAM POSITION MONITORS AND AUTOMATIC BEAM CENTERING IN THE TRANSFER LINES OF GANIL

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Abstract

A non-interceptive beam position monitor, made of four capacitive electrodes, has been designed at GANIL in order to allow a permanent measurement of the ion beam position over a large intensity range (50 enA to 10 eμA). Signal processing is based on a 10 kHz heterodyne and on an amplitude to phase conversion in order to measure the beam position. The accelerator is equipped with ten of these probes, six of them on the first beam line. Seven other probes are planned. An immediate application of these monitors is the automatic beam centering. For this, two algorithms have been developed using the information on the center of gravity given by the beam position monitors which is then fed back to the steerers. The first is an iterative method based on an optimization algorithm (Pattern Search, Hooke and Jeeves). It consists in improving the criterion defined as the mean quadratic deviation of beam positions on the monitors. The second is a variational method which consists in determining for each steerers and each position monitor, the variation coefficient (mm/A) and solves a linear system. Both of these methods have been used on a section of beam line and have given similar and encouraging results. The next step is to center the beam on the completely equipped line.

I. INTRODUCTION

Up to now at GANIL, ion beam position in the beam lines was measured with profile monitors using wire grids. As they can not be used permanently to compute beam position in real time, a non interceptive beam position (BPM) has been designed. A first application of these probes was the development of software which should permit in a later stage the automatic centering of the beam in the different lines. The accelerator is equipped with ten probes, six of them on the first beam line. Seven other probes are planned.

II. TECHNICAL DESCRIPTION[3, 4]

1. *Expected technical specifications*

Technical specifications of this BPM were :
- beam intensity range : 10 enA to 10 eμA,
- beam structure frequency : 7 to 14 MHz,
- beam energy : 20 keV/u to 100 MeV/u,
- sensor aperture : 50 mm,
- accuracy of position measurement : < 10% ± 0.5 mm,
- resolution : < 0.2 mm,
- no tuning by the operators before measuring,
- automatic test procedure on request of the operators,
- mechanically compatible with profile sensors,
- linkable to the GANIL control system.

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2. *Sensor description*

a. Mechanical description

Probes are based on the electrostatic coupling, their geometry is a cylinder of 10 cm length cut into four equal parts. The ground electrode is machined in a copper block.

b. Sensitivity to beam position

The electrical charge Q_E deposited by the beam on an electrode is function of beam position P(x,y) and of beam current.

If Q is the total charge deposited on the four electrodes, the vertical position y is, for x = 0 :

$$y \approx R\ (Q_H - Q_B)/Q \qquad (1)$$

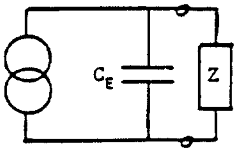
In practice, only the beam position at the center is important for us, so we detect

$$Py = (Q_H - Q_B)\ /\ (Q_H + Q_B) \qquad (2)$$

$$y = \frac{1}{2}\ R \times Py \qquad (3)$$

c. Sensitivity to beam current

The equivalent circuit of an electrode is :



Z is a 50Ω amplifier

$$V_E(t) = 50\frac{dQ_E(t)}{dt} \quad \text{if} \quad \frac{1}{C_E\,\omega} > 50\ \Omega$$

As the electrode signal is very low, the second harmonic signal is extracted to avoid the RF parasitic noise.

$V_{E,2} = 50 \times 2\pi \times F \times Q_{E,2}$

$V_{E,2}$: rms value of the second harmonic of $V_E(t)$

For a quarter of cylinder

$$V_{E,2} = \pi\ 10^{-5} \times L \times F\ \frac{I}{\sqrt{W}} \qquad (4)$$

L : electrode length
F : beam structure frequency
I : beam intensity
W : beam energy in MeV/u

example : F = 10 MHz and L = 0,1 m

$V_{E,2} = 30\ I/\sqrt{W}$

that is	30 nV/enA for	1 MeV/u beam
	3 nV/enA for	100 MeV/u beam

The theoritical resolution is limited by the electronic noise :

for a centered beam $y = \frac{V_{H,2}(t) - V_{B,2}(t)}{V_{H,2}(t) + V_{B,2}(t)}$

$V_{B,2}(t)$, $V_{H,2}(t)$ = 2nd harmonic electrode signals

with noise the measurement resolution is :

$$Ny \cong 3 \times 10^4 \times \frac{R \times N\sqrt{B}\sqrt{W}}{L \times F \times I} \qquad (5)$$

N : amplifier noise
B : measurement bandwidth

for $N = 1\ nV/\sqrt{Hz}$, $B = 10\ Hz$, $F = 10\ MHz$, $R = 30\ mm$ and $L = 0.1\ m$ we get :

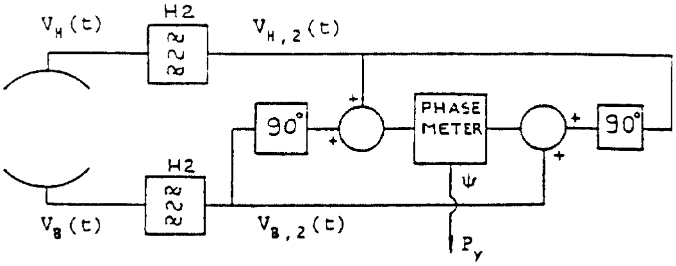
$$Ny \cong 3\sqrt{\frac{W}{I}} \text{ (in mm/enA)} \qquad (6)$$

the expected resolution of 0.2 mm should be obtained with 1 enA if the energy beam is 1 MeV/u and 150 enA if the energy beam is 100 MeV/u.

3. *Processor*

a. Processor principle[1]

$V_{H,2}(t) = V_H \cos(\omega t + \phi)$ = 2nd harmonic of $V_H(t)$
$V_{B,2}(t) = V_B \cos(\omega t)$ = 2nd harmonic of $V_B(t)$



$C(t) = C\cos(\omega t + \psi c)$
$D(t) = D\cos(\omega t + \psi d)$

if $\phi = 0$ ($V_{H,2}(t)$ and $V_{B,2}(t)$ are in phase)

$$C = D = \sqrt{V_H^2 + V_B^2}$$

$$\tan \psi/2 = \tan (\psi d - \psi c)/2 = \frac{VH - VB}{VH + VB} = Py \qquad (7)$$

if $Py \cong 0$ $\quad Py \cong \frac{\psi}{2}$

and $$y = \frac{R \times \psi}{4} \qquad (8)$$

with $R = 30$ mm, the sensitivity to beam position is
$\psi \cong 0.13$ rad/mm $\cong 7.5°$/mm

if $\phi \neq 0$

$y = 0 \rightarrow \psi = 0 \rightarrow Py = 0$
$y < 0.5\ R$

$$Py = \frac{\psi}{2} \cos \phi \qquad (9)$$

The error is kept smaller than 10% when ϕ is not too large ($< \pi/3$)

b. Real processor system

Only the preamplification is made at the RF frequency to take advantage of the very low noise RF amplifier.

Then the 2nd harmonic of the electrode signals is detected by a 10 KHz heterodyne in order to realize the amplitude-phase conversion and the phase detection at 10 kHz.

The amplitude-phase conversion provides a phase noise $N\psi = \frac{4Ny}{R}$ [see (8)].

An analog memory allows to keep the position value when beam goes off. The beam position and the status of the processor are read by the accelerator control computer via the CAMAC.

III. AUTOMATIC BEAM CENTERING

Several steps to prove the faisability of automatic beam centering, using the information on the center of gravity given by the beam position monitor, have been initiated during the last two years, on a limited part of the first beam line (between the injector cyclotron and SSC1) and with only four position probes.

With this aim of view, two methods have been tested, using quite different research algorithms. The first of them is called iterative method and the second one variational method.

1. *Iterative method*[2]

This method is based on an optimization algorithm called Pattern Search of Hookes and Jeeves which has been adopted because it allows an iterative search with a low informatic cost. It is not necessary to solve complex numerical systems nor to know the analytical function of the criterion to optimize.

The general principle is : from a finite set of parameters which work on the criterion, the program finds a direction which improves the criterion starting from a local search around an initial point X_o ($x_1, x_2, \ldots x_i$ with x_i value of the parameter i). In this direction, it arrives at the point x_1 for that the criterion is maximum, then it tries to find around X_1 another direction up to a point X_2 where the criterion is better, and so forth up to the optimUM. It may be possible to reduce the value of the optimization step of parameters such the field of variation.`

The adjustment of this algorithm to the automatic beam centering is based on the following data :

- Criterion definition

As the purpose is to center the beam at the locations where its position is measured, the criterion is a global one, i.e. it is the mean quadratic deviation (m.q.d) of the beam positions on the four probes and it must be minimized.

$$\text{m.q.d.} = \sum_{i=1}^{4} ei^2/4 \text{ ; ei = beam position on the probe i}$$

- Constraint

It is only the variation limits of the steering equipments (for example ± 10 Amp for the steerers).

- Variation step

steerer : 0.5 Amp dipole : 0.2 Amp

For these values one step for one equipment gives a visible effect on the beam displacement. Other values seem to have no effect on the results but a sensitivity study must be done.

- Limitation of the criterion

With this algorithm and the criterion as defined it is necessary to give a limit to stop the search, otherwise programs could take too much time. Here, the limitation is m.q.d. = 0.25, i.e. a beam deviation of ± 0.5 mm on each probe. When the program has finished one iteration, it is possible to stop it or to start another iteration with a smaller variation step.

2. *Variational method*

It is a numerical resolution method defined from experimental tuning considerations.

The principle is the following : the program searchs for each steering equipment and for each position probe the variation coefficient, in mm/Amp. From these coefficients, a linear equations system is deduced and it is solved as usually. The solution gives the current to apply to center the beam.

Initial hypothesises

- Linear effect of equipment on beam displacement.

It is assumed that the angle of deviation of the beam in a steerer is proportionnal with the current, inside the limits (± 10 Amp) and the angles are enough small to admit a linear displacement with the angle.

Then, with Y_i = beam position on the probe i,
X_i = current of the equipment j
$Y_i = a_{ij}.X_j + b_i$
with a_{ij} : variation coefficient of equipment on the probe i
b_j : beam position when $Xj = 0$

- The effect of an equipment is independent from another. In the field of deviation angles the effect of a steerer on the beam is independent of the initial angle. Then, there is a non correlation between the deviation angles.

That gives :

$$Y_i = A_{ij}.X_1 + a_{i2}.X_2 + \dots + a_{ij}.X_j + b_i = \sum_j a_{ij}.X_j + b_i$$

- The steering effects of other equipments are ignored. The perturbating steering effects of other equipment (essentially the quadrupoles) are too complex to be described easily and become more and more weak that the beam is centered. The centering is made by convergence, i.e. using several times the algorithm.

The numerical system

Initial stage :

$$Y_{io} = \sum_j a_{ij} \,.\, X_{jo} + b_i = B_i$$

For another set of currents :

$$X_i = X_{jo} + \Delta X_i$$

$$Y_i = \sum_j a_{ij} \,.\, \Delta X_j + B_i$$

That gives the following equations syïem :

$$[Y]_i = [A]_{ij}\,[X]_j + [B]_j$$

with [Y] : beam position vectors
[A] : matrix of coefficients
[X] : current vector
[B] : initial conditions

The beam centering is given by [Y] = 0 and it is obtained by solving the system [A] . [X] + [B] = 0

The program organization

a. Statement of the initial state = acquisition of B_i

b. Determination of the matrix of coefficients

For each steering equipment and in order to take account of perturbating effects of other equipments, the coefficient is computed for six values of current, if possible (±2 Amp, ±5 Amp, ±7 Amp) by measuring the displacement on each probe. Thus, the matrix is made of mean variation coefficients.

c. Choice of linear system

It is necessary to have a square matrix, i.e. the same number of probes and steering equipments. For example, for the vertical plane, there are four probes and only three steerers. So, the linear system is made with the three probes with the most significant coefficients.

d. Calculation of the solution

The solution of the system is computed with the Gauss method with partial pivot.

e. Application of currents

Finally, the program applies the computed currents on the steering equipments. And, after checking the beam centering, it is possible to start the program at the point 1 again.

3. *Results*

position (mm)	Example 1		Example 2		Example 3	
	before	after	before	after	before	after
Probe 1	-6.8	+1.7	-2.2	+1.1	+3.7	+1.2
Probe 2	+3.5	+2.7	+5.7	+0.8	+6.6	-1.5
Probe 3	-2.5	+0.7	+0.7	+0.5	+1.7	-0.7
Probe 4	+7.7	+1.4	+12.2	+0.4	-4.4	0
Criterion	30.9	3.3	46.7	0.6	19.8	1.0
Plane	Horizontal		Vertical		Vertical	
Method	Iterative		Iterative		Variational	

The both methods have given encouraging results from the first tests. There is no great difference in the final centering. But the iterative method seems to be more interesting because it converges more quickly to a very correct centering with a lower informatic cost (less time consumed). Nevertheless, these programs which have been developed rapidly for these tests have to be improved to confirm their first results.

IV. CONCLUSION

As the first results of automatic centering seem to be correct, and as the running of these monitors are relaible it has been decided to equip the L1 beam line on totality. It is planned to adapt the programs to this new configuration and to test it on a whole beam line before using one to center automatically the beam in routine.

V. REFERENCES

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