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AUTOMATIC BEAM TUNING AT GANIL

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The GANIL facility consists of three successive cyclotrons. The tuning of these cyclotrons and of the transfer beam lines is achieved in about 24 hours. Reducing this setting time would enable to increase the time allocated to physics experiments. New tools are realized for automatic beam tuning. These tools are expected to make the tuning easier, shorter and more reproducible.

1 Introduction

The GANIL facility consists of 3 successive cyclotrons : C01 or C02, CSS1, CSS2. A fourth one : CIME, is to be added this year. The tuning of these cyclotrons, including the transfer beam lines, may be achieved in approximately 24 hours.

Efforts must be made to reduce the time necessary to set up the machine, in order to get more beam time for experiments. In addition, the requirements for the beam intensity and quality become more stringent (THI project).

However, two years ago, only one program was in use for automatic beam tuning. This program concerns isochronism in the cyclotrons. The measurement of the beam central phase at several radii is used to calculate the values of the trim coils needed to get a perfect isochronism. A new version of this program has been written for CIME[1].

In addition, the optimization of the beam transmission in the cyclotrons was also automatic. The method is purely empiric : it consists in finding the best set of values to maximize the intensity at the output of the cyclotrons. This is not a tuning program, but an optimization program.

As regards the beam lines, the tuning remained « manual » : the operator visualized the beam size and position on a beam profile monitor and changed a quadrupole intensity, or a steerer intensity. The effect of each equipment was seen directly by the operator.

Of course, the effect of quadrupole settings or of steerers may be calculated on line and a program may set globally all these values.

Automatic transverse matching is now operational. Beam centering is being checked. Both are presented here, along with other future developments.

2 Transverse betatron matching

2.1 Matching sections

The GANIL beam lines[2] are composed of sections with separated functions. The first section following each cyclotron is matched to decorrelate the radial position and angle from the energy (fully achromatic beam). Then, another section is used to realize transverse betatron matching and to measure and to limit the transverse emittance.

This section include :

- 4 magnetic quadrupoles to get transverse matching in both radial and vertical planes
- 3 beam profile monitors to get the beam size in both planes.
- 3 sets of horizontal and vertical slits, to reduce the transverse emittances to the acceptance of the following cyclotron, or to the value needed for the experiment.

By construction, the beam is matched if the beam presents a cross-over on the central slit, and this implies that the beam sizes on the profile monitors verify :

$H1 = H3 = R_H\,H2$
$V1 = V3 = R_V\,V2$

where :
H1, H2, H3 are the horizontal beam sizes on the monitors (numeroted as encountered by the beam)
V1, V2, V3 the vertical beam sizes
R_H and R_V are predefined factors (generally $R_H = R_V = 2$).

This disposition makes the matching easy to check visually.

The quadrupoles are initially set to values defined according to theoretical conditions at the output of the preceding cyclotron. The manual tuning consisted in varying one quadrupole, visualizing the effect on H1, H2, H3, V1..., then trying another quadrupole, so that the best set of values may be found.

2.2 Automatic matching

The program uses an on-line beam optics calculation.

The first step is to translate the beam sizes on the 3 profile monitors in terms of emittance and betatron functions (β_μ, α_μ and γ_μ, in both horizontal and vertical planes) at the middle monitor. The beam sizes are calculated as R.M.S. values. As an example, the horizontal emittance ε_H is a function of σ_{x1}, σ_{x2}, σ_{x3} , R.M.S. widths at the location of the first, second and third monitor, and of the distances L_1 and L_2 between these profile monitors. The emittance and betatron functions at the middle monitor are calculated using the following formulae :

$$\beta_m \varepsilon_H = \sigma_{x2}^2$$

$$\alpha_m \varepsilon_H = \frac{L_2^2(\sigma_{x1}^2 - \sigma_{x2}^2) - L_1^2(\sigma_{x3}^2 - \sigma_{x2}^2)}{2L_1L_2(L_1+L_2)}$$

$$\gamma_m \varepsilon_H = \frac{L_1(\sigma_{x3}^2 - \sigma_{x2}^2) + L_2(\sigma_{x1}^2 - \sigma_{x2}^2)}{L_1L_2(L_1+L_2)}$$

$$\beta_m \gamma_m - \alpha_m^2 = 1$$

The second step is to calculate these betatron functions at the entrance of the first quadrupole. Using the quadrupole gradients, deduced from the quadrupole intensities, the transfer matrix (M) from the entrance of the first quadrupole to the middle monitor is calculated. The betatron functions are deduced this way :

$$P = M^{-1} = \begin{pmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{pmatrix}$$

$$\begin{pmatrix} \beta_e \\ \alpha_e \\ \gamma_e \end{pmatrix} = \begin{pmatrix} P_{11}^2 & -2P_{11}P_{12} & P_{12}^2 \\ -P_{11}P_{21} & P_{12}P_{21} & -P_{12}P_{22} \\ P_{21}^2 & -2P_{21}P_{22} & P_{22}^2 \end{pmatrix} \begin{pmatrix} \beta_m \\ \alpha_m \\ \gamma_m \end{pmatrix}$$

where β_e, α_e, γ_e are the betatron functions at the entrance of the first quadrupole, β_m, α_m, γ_m are the betatron functions at the middle profile monitor.

The third step is to optimize the matrix M, so that :

$$\begin{pmatrix} \beta_m \\ \alpha_m \\ \gamma_m \end{pmatrix} = \begin{pmatrix} \beta_{theo} \\ \alpha_{theo} \\ \gamma_{theo} \end{pmatrix}$$

(betatron functions corresponding to a matched beam).

This optimization consists in minimizing the function :

$$\chi^2 = (\beta_m - \beta_{theo})^2 + (\alpha_m - \alpha_{theo})^2 + (\gamma_m - \gamma_{theo})^2$$

This is made very simply : let G_1, G_2, G_3, G_4 be the gradients of each quadrupole. The best set of values is found in (11*11*11*11) possible sets, with G_1 varying from :

G_{10} - 5*H_0 to G_{10} + 5*H_0 (and so on for G_2, G_3, G_4)

where G_{10} is the initial value and H_0 a step value, predetermined for each beam line case and that the operator may modify. When the best set is found, H_0 is divided by 5 and the whole operation is repeated, 2 times.

This simple optimization is very quick, because it is purely mathematical (no modification of the quadrupole gradients and no beam profiles measurement during the optimization). It is, also, very sure (no way of mathematical divergence).

2.3 Results

An example of the results is presented bellow. The beam profiles in the horizontal plane, and in the beam line at the output of CSS2, are represented. The profile monitors are multiwire chambers. The central monitor has 0.5 mm spaced wires, instead of 1 mm for the 1st and 3rd ones. Before matching, the waist is located on the third monitor. After matching, the first and third beam sizes are equal (≈ ±4 mm), and the central one is half of this value, as desired.

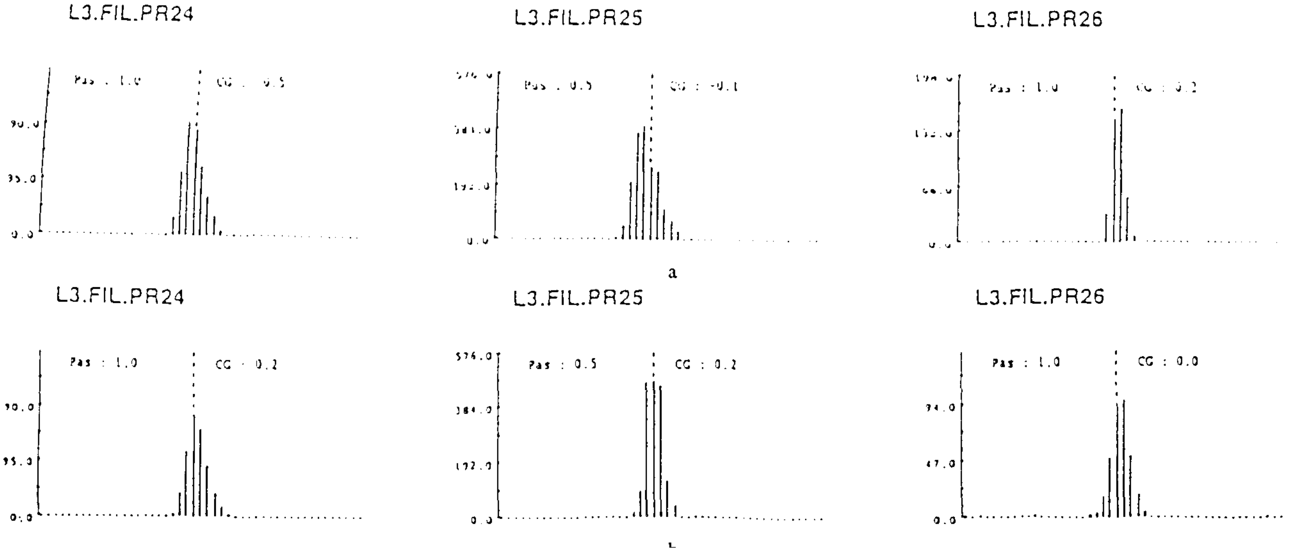

Figure 1 : beam profiles before (a) and after (b) matching

Similar results may be given for vertical plane (matching must be realized simultaneously in both planes). Automatic matching is operationnal since the beginning of 1997, and the results are convenient. When matching is difficult, the manual method can be achieved in 10 to 20 minutes, with, sometimes, a mediocrious result. In the same case, the automatic method may need several iterations. Nevertheless, it lasts only a few minutes, and the matching is realized.

3 Beam centering

3.1 Description

A beam misalignment is systematically observed on the profile monitors. Indeed, the angle and position of the beam centroid are not zero at the output of the cyclotrons. Furthermore, misaligned quadrupoles deviate the beam from the reference trajectory.

The beam centering in the beam lines is, up to now, realized manually : the operator modifies a steerer intensity, and looks at the beam position on the profile monitors. If the result is convenient (for example, the beam center of gravity tends to zero on the two first monitors), he keeps the value and try another steerer. The result of the second steerer may, for example, be convenient for the third monitor, but may degrade the alignment on the second one.

Of course, an automatic beam centering will be useful, and two different methods were already tested at GANIL in 1990[3].

A new program has been written, and the first tests are realized.

The first step of the method is to measure the beam center of gravity as seen by the wire profile monitors.

The second is to calculate the effect of each steerer on each monitor. An on-line calculation of the transfer matrices is, again, needed. Let P_i be the beam center of gravity on the beam profile monitor number i and S_j be the intensity of the steerer j. It is desired that :

$$P = \begin{pmatrix} P_1 \\ P_2 \\ . \\ . \\ . \\ P_p \end{pmatrix} = -M \begin{pmatrix} S_1 \\ S_2 \\ . \\ . \\ . \\ S_n \end{pmatrix} = -MS$$

with the coefficients M_{ij} of the matrix M approximately proportionnal to the term T_{12} of the transfer matrix from the steerer j to the monitor i.

If the number p of profile monitors is equal to the number n of steerers, the solution is determined as :

$$S = -M^{-1}P$$

If those numbers are not equal, the solution may be determined as :

$$S = -(M^T M)^{-1} M^T P$$

with M^T the transposition of the matrix M.

It may be shown that this formula corresponds to a least-squares fit to minimize the beam misalignments on each monitors. In fact, the following quantity is minimized :

$$\chi^2 = \sum_{i=1}^{p}\left[\sum_{j=1}^{n} M_{ij}S_j + P_i\right]^2 + \left(\frac{W_s}{W_p}\right)^2 \sum_{j=1}^{n}(S_j)^2$$

where W_s and W_p are the weights for the steerer intensity values and for the beam misalignements on the monitors.

The second term corresponds to a minimization of the corrector values. This term improves the stability of the resolution. As an example, solutions may sometimes be found where the effects of two steerers equilibrate on several monitors (depending on the transfer matrices). Then, without this second term, the intensity values calculated for this steerers may be very high, and any imprecision on the calculation may have a great importance.

In addition, the weights may be different for each profile monitor.

3.2 Results

In writing this program, the main difficulty was that all the data needed in the beam optics calculation were to be added in the data base used for operation. This addition has required some modification of the structure of this data base, and is not yet achieved.

Nevertheless, some preliminary results have been obtained. In the following table, beam centers of gravity in both planes are given, before and after automatic beam centering. These figures concern the beam line at the injection of C01. The number of steerers is 4 in the horizontal, 3 in the vertical plane, for 6 profile monitors.

Profile monitor	Center of gravity (mm)	
	before	after beam centering
1 (HOR)	- 1.4	- 0.2
1 (VER)	0.1	0.1
2 (HOR)	3.7	- 0.3
2 (VER)	- 1.6	- 0.3
3 (HOR)	3.9	0.1
3 (VER)	- 2.4	0.4
4 (HOR)	4.6	0.4
4 (VER)	- 3.4	0.2
5 (HOR)	0.1	- 0.4
5 (VER)	- 1.2	- 0.6
6 (HOR)	4.5	0.1
6 (VER)	9.2	0.3

4 Future developments

4.1 Automatic CSS injection-ejection tuning

The aim of automatic injection-ejection tuning is mainly to reduce cyclotron tuning time on one hand, and to obtain reproducible tuning on the other hand, this last point being of great importance.

The principle is based on beam tuning and centering using interceptive beam current diagnostics as well as beam loss diagnostics placed at the entrance of each electrostatic and magnetostatic channel. Beam losses must be reduced to zero, except for heavier ion beams, which have energy spread and radial width too large (from A~ 150).In these cases, beam losses will be minimized, in any case to values acceptable by the THI safety system[4].

In the ejection automatic tuning, the beam vertical centering is also tuned.

The software program will be written and hopefully tested by the end of this year.

4.2 Achromaticity

In the matching sections, no correlation exists in theory between transverse planes and energy. But this correlation exists at the output of the cyclotrons. The goal of the first section of the beam lines is to decorrelate the transverse and longitudinal planes, so that the beam is fully achromatic (in angle and position) in the following section.

It is easy to check, using again the profile monitors : a slight variation of the voltage of the HF cavity (which does not perturb the transmission of the cyclotron) must not imply a variation of the beam position.

If it is not the case, a variation of the setting of the quadrupoles of this first section is required. This may be made manually, or automatically.

Because of the coupling between the transverse and longitudinal planes, an on-line calculation is in general difficult (optimization of the 6-dimensionnal transfer matrix of the section). However, it is hoped that, when the theoretical and real beam matrix at the output of the cyclotrons are not too different, an optimization of the quadrupoles settings may be found.

5 CONCLUSION

The different steps in tuning the GANIL cyclotrons and transfer beam lines are progressively made automatic. The first results are encouraging.

Automatic tuning programs are expected to make tuning faster, easier and more reproducible.

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