AUTOMATIC CENTERING AND MATCHING OF CYCLOTRON BEAMS

S. Adam
SIN, Swiss Institute for Nuclear Research
CH-5234 Villigen, Switzerland

J. C. Collins
IUCF, Indiana University Cyclotron Facility
Bloomington, Indiana 47401, USA

Abstract

The task of automatic centering and matching comprises the following four steps:

It starts with taking a probe trace, followed by its interpretation yielding the turn structure. From this, one can find the error in centering and matching which forms the basis to calculate the parameter changes for its correction. Some problems arising from these steps are discussed and are illustrated with the practical example of the control-computer program that has been developed for the SIN 590 MeV Ringcyclotron.

Historical Review

In the early days of the commissioning of the SIN Ringcyclotron, centering at injection proved to be tedious and time consuming for two reasons: first, it is a problem with two tightly coupled parameters, the beam position and the beam direction at injection. Second, the diagnosis of the error is slow because probe tracing takes time and the interpretation of the trace is rather complex.

Therefore, the centering program became the first set-up procedure going the "numerical" way: measure - calculate - set, instead of the usual "try and look"-method (see Fig. 1 and Table I).

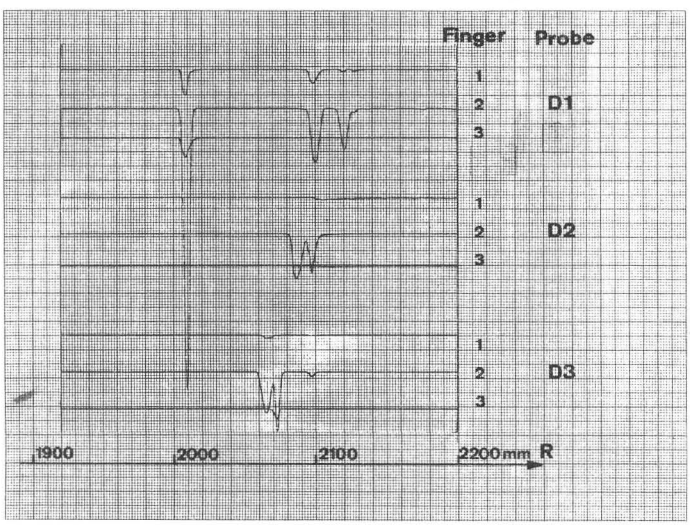

Fig. 1

A full set of traces from the three injection probes[1] plotted on Feb. 23, 1974. The few turns that are visible are sufficient to yield the centering error by the method shown in Table I. The first large peak on probe D1 at R=2010 mm is the incoming beam. It crosses the probe azimuth before passing the magnetic and electrostatic inflector channels.

PROBE	TURN	COS (ν_r · (θ-θ_{D2}))	SIN (ν_r · (θ-θ_{D2}))	TURNS	ΔCOS	ΔSIN	ΔRcoh.= ΔR-ΔRacc MM
	1	1.00	0.00				
D 2	2	.54	.84	2 - 1	-.46	.84	- 1
	3	.43	.90	3 - 2	-.97	.06	?
	1	-.92	.40				
D 3	2	-.83	-.56	2 - 1	.09	-.96	- 4
	3	.03	-.99	3 - 2	.86	-.43	12
	1	.69	-.73				
D 1	2	.98	.19	2 - 1	.29	.92	8
	3	.37	.93	3 - 2	-.61,	.74	- 4

Table I

The basic procedure to yield the centering error from a few turn spacings.

First, subtract the radial gain due to acceleration ΔRacc from the given turn spacings to get the reduced spacing ΔRcoh. (ΔRacc = 12 mm if only three of the four accelerating cavities are in operation).

Then try to find the coherent cosine- and sine- amplitudes A and B such that the reduced spacings can be defined as
ΔRcoh = A * Δcos + B * Δsin

In our example from Fig. 1 we get A=11.5 mm and B=5 mm, i.e. at probe D2 right after the injection septum, the beam is at too high a radius by 11.5 mm and tilted outwards by an equivalent of 5 mm. Normally, with more than two spacings the method is over-determined.

Since the mathematical method is overdetermined, the best way to find the result is fitting. First, this fit was done graphically with the help of the control computer (see Fig. 2). The human eye can easily filter out unreasonable lines coming from a misinterpretation of the turn structure caused by hidden turns. For a long time the computer least squares fit was used in parallel with the graphic method.

Once the centering error is known, its correction can be obtained from the inverted influence matrix of the injection elements. First, a recommendation to the operator and later an actual setting of the needed parameter changes were implemented in the program.

An extensive analysis on a larger computer determined the betatron oscillation frequency, ν_r as a function of radius to high precision. This enabled the program to start the probe pattern analysis at turn 10 instead of turn 1. This way it avoided the first few turns which are shifted by bumps in the magnetic field coming from the injection magnets.

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The essential step towards automatic centering was achieved with the computerization of probe tracing and turn pattern interpretation.

As a fringe benefit the program could also calculate the widths of the turns. Those were then fed to a new fitting program yielding information on the matching in the radial phase space.

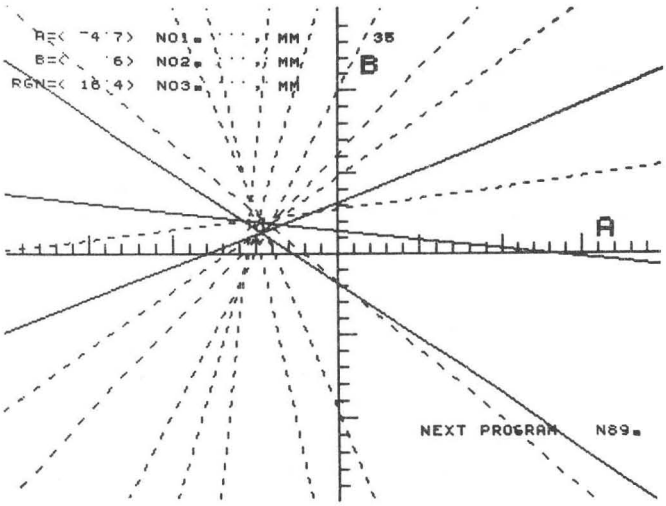

Fig. 2

Computer aided graphical method to find the coherent amplitudes A and B. In this diagram each straight line corresponds to one turn spacing. Full lines are from spacings between turns 2 and 1 while dashed ones are from higher turns.

Computed least-square fit values for A and B are shown in the upper left corner.

Probe Tracing

To make a beam probe work reliably, problems of inertia, vibrations, positioning accuracy, driving speed, vacuum feed-throughs and electronic pick-up all have to be solved simultaneously.

On the other hand, the program should also fulfill some tough conditions: - the measurement has to be quick and of high radial resolution, consisting of several thousand data points. It is also desirable to have the measured points at equal intervals and without any gaps in the trace. There is also an additional constraint: the multiprogramming system in most control computers rarely allows one to dedicate the computer to the task for the time needed to take a trace. It is obvious, therefore, that many compromises have to be made.

For the program at SIN we have come up with the following solutions: the extensive preparation work is done at low priority. This involves the reservation of the probe, moving the probe to the starting point of the trace, checking that no other probe can stop the beam, selection of addresses and ranges of the multiplexed nanoampere-meters and the preparation of the diskfiles.

During the actual measurement, the probe moves at constant speed except for the regions near the start and the stop. For this time, the probe-trace program is made to run at a very high priority. Here, it only needs to gather the data at equally spaced radial locations and put them on the disk using a double-buffer method. In addition it has to do some checks on the probe movement and on the disk status.

For the future, a small dedicated satellite-processor having access to a memory of sufficient size might be a satisfactory solution for probe tracing.

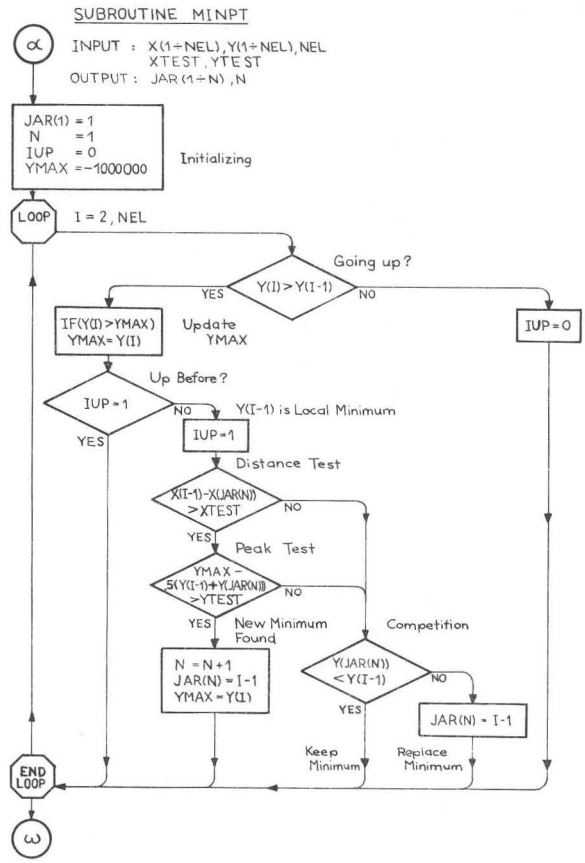

Fig. 3

Flow chart of the routine to find the one and only minimum in each gap between two "legal" peaks. The relevant variables are:

- X and Y, the NEL probe-trace data-points consisting of the radial position and the sum of the currents on the three vertical fingers,
- XTEST and YTEST, the minimum width and the height of a "legal" peak, respectively, and
- JAR, the array of indices where the N valid minima have been found.

Note that the last minimum found will be replaced if it loses the competition against a future local minimum with no "legal" peak in between. This way the routine is prevented from finding many useless local minima in a noisy signal.

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Interpretation of the Probe Trace

The strategy used in the program at SIN is very simple: cut the probe traces in slices such that each slice contains one peak. The locations of all those cuts are found by the subroutine MINPT described in Fig. 3. Before going through MINPT, the currents of the three vertical fingers of the probe are added and the sum current is digitally filtered[2].

Each turn is analyzed individually within the region restricted by the two adjacent minimum-point locations (see Fig. 4). The total area F of the peak, its center of gravity R_{cg} and its width $w = 2 \cdot \sigma$ are calculated according to the well-known method of statistical moments[3].

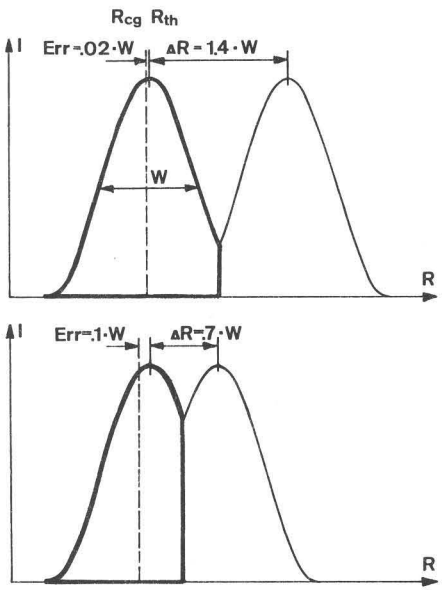

Fig. 4

Two cases of partially overlapping turns. The difference between the theoretical peak location R_{th} and the center-of-gravity R_{cg} determined by our method comes from the cut at the minimum-point between the two turns. This error is too small to foresee a correction for it.

After this procedure, turns which have an area F of less than 10 percent of the average area are cancelled. A picture of the result (see Fig. 5) is then presented to the operator.

The method used at SIN is just one out of several possible solutions. In cases where the turns are not so clearly separated, new methods should be developed where the interpretation of the probe trace and the calculations of the centering error are done in one common procedure.

In any case, to develop a program for probe trace interpretation one stores a series of probe-traces from extreme beam conditions for testing purposes.

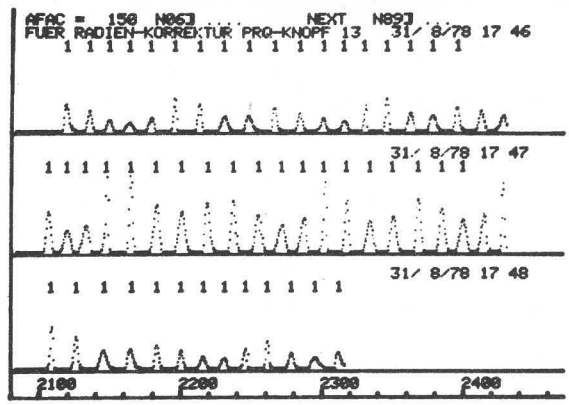

Fig. 5

The traces of the three injection probes plotted by the control computer. The marks show the turn-locations resulting from the probe trace-analysis. By looking carefully at this picture, the operator can check whether the computer has identified the turns reasonably.

Find the Error in Centering and Matching

The centering error is found by making a least squares fit to find the values A, B and ΔRacc (see Table I) according to the following model

$$R(\theta) = A \cdot \cos\nu_r\theta + B \cdot \sin\nu_r\theta + \frac{\theta}{360}\Delta Racc + Ro.$$

In this formula θ is the angle accumulated from turn 1 on probe D2 up to the turn in consideration. Ro is the radius of turn 1. Our fitting applies the above model to five successive turns on each of the three injection probes. The average residual error[4] of the fit is used as a quality figure. Usual values are around .3 mm. Above 1 mm a warning is given to the operator and above 2 mm the program exists.

A very similar least squares fit is done to find the five matching-parameters A2, B2, A1, B1, and A0 according to the model

$$w(\theta) = A2 \cos 2\nu_r\theta + B2 \sin 2\nu_r\theta + A1 \cos \nu_r\theta + B1 \sin \nu_r\theta + A0$$

The coefficient A0 is proportional to the beam emittance. The values A1 and B1 are the amplitudes of a first harmonic, A2 and B1 of a second harmonic modulation of the beam width w.r.t. the betatron phase advance angle $\nu_r\theta$. Fig. 6 shows how these values depend on the properties of the injected beam.

Similar procedures are possible for many other cyclotrons. For cases where the value ν_r is closer to 1.0 or the probes are located less favourably, the fit has to cover a larger radial range. Clearly separated turns are essential in order to obtain information about matching. On the other hand, with overlapping turns, the centering error can be found with a fit considering only the modulation amplitude of a probe-trace w.r.t. the radius.

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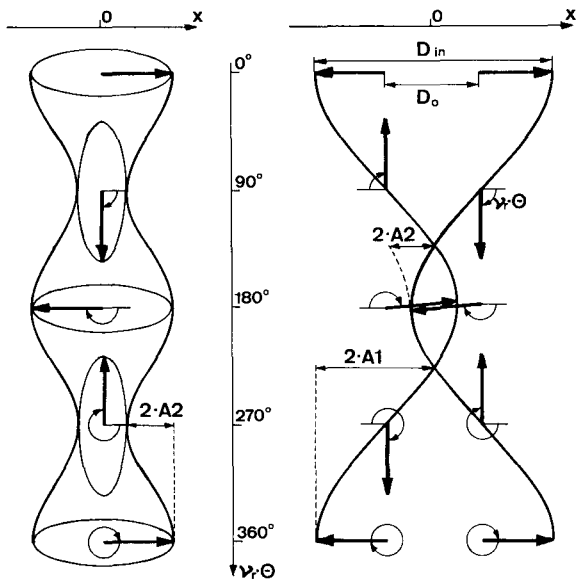

Fig. 6

Simplified view of the mechanisms which produce a variation of the radial turn width.

On the left hand side a mismatched beam ellipse is rotated over a betatron phase advance angle $\nu_r\,\Theta$ of 360 degrees. Its width projected into the x-direction forms the two identical modulation cycles. Hence, a beam mismatch produces a second harmonic modulation of the beam width with respect to the betatron phase advance angle $\nu_r\,\Theta$. On the right hand side is a hypothetical beam consisting of only two particles with different energies. The dispersion Din of this "beam" is not matched; it does not agree with the matched dispersion D_o. Each particle rotates around its own equilibrium point with a betatron phase advance angle $\nu_r\,\Theta$. The projected width of this two-particle beam is also plotted here against $\nu_r\,\Theta$. This shows that a dispersion mismatch produces mainly a first harmonic modulation of the beam width. The cross-over of the two cosine curves near the middle of the figure leads to an additional second harmonic beam modulation. Such a second harmonic modulation occurs only if the dispersion mismatch is very large as has been assumed here.

Matching and Centering

Usually a centering error in a cyclotron is corrected with bumps in the magnetic field produced by inner trimcoils. For ringcyclotrons it is simpler to use the injection elements. For all types of parameters a program for automatic centering can itself be used to determine the influence-matrix needed to calculate the corrections from a given error.

For matching it is much more difficult to find suitable parameters. We have tried the two quadrupoles in the injection beamline which have the least effect of the y-plane (see Fig. 7). Their effects on the beam-matching are almost identical. In order to have a nicely orthogonal set of paramaters, we will probably need a coupled variation of two or three quadrupoles. It would be too cumbersome to do this search for useful parameter combinations with the beam. We will have to do it on the computer. Therefore, it is encouraging for us that the measured points agree so well with the computed values.

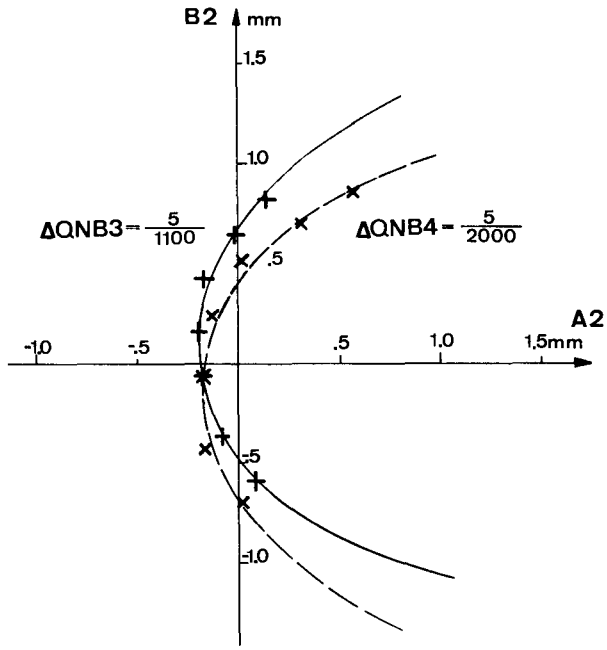

Fig. 7

Effect of two injection beamline quadrupoles upon the beam matching in the Ringcyclotron. The cosine-and sine-amplitudes A2 and B2 of the second harmonic beam width modulation are plotted for seven different settings of each quadrupole. The points obtained by probe tracing and turn analysis are in good agreement with their corresponding theoretical curves obtained from beam transport calculations.

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