BEAM CENTERING WITH A HARP AND PROBES IN THE NAC SSC

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ABSTRACT

Beam centering in the separated-sector cyclotron of the NAC is described, with special emphasis on the new beam centering probe (BCP) which has been installed in the extraction valley chamber of the SSC. The purpose of this harp is to display the horizontal beam pattern of the first few orbits in the SSC and to aid in setting up the injection elements and resonator phase. The harp consists of 170 vertically mounted 0.1 mm diameter tungsten wires supported in a frame. It is inserted pneumatically into the median plane of the accelerator. The resolution is either 1.2 or 2.4 mm, depending on mode of use.

The current-measurement electronics, multiplexer and interface units for the new harp are described briefly. Software has been developed for a personal computer to do the graphics display, control multiplexer selection and harp movement, read current values and communicate with the minicomputer of the NAC control system.

Software, based on a microprocessor system, has been developed to analyse beam data obtained with the multi-head probes and the beam centering harp. It consists of an orbit code to compute the beam position and properties of betatron oscillations, software to identify beam peaks and to find the precession amplitude and oscillation phase of off-centre beams, and an interactive program to simulate beam motion through the injection elements and to predict current settings for these elements.

1. INTRODUCTION

The NAC separated-sector cyclotron (SSC) is a variable-energy light-ion and heavy-ion accelerator, used for physics research, isotope production and radiotherapy. Its proton energy range is 25 - 200 MeV at resonator frequencies between 6 and 26 MHz, operating on harmonic numbers h=4 and h=12. Heavier ions have also been accelerated in the machine. A report on the present status of the machine is given elsewhere in these proceedings.[1)]

The layout of injection and extraction components in the SSC is given in figure 1. Diagnostic equipment used to measure the beam position in the machine is also shown in this figure, and consists of two harps and a scanner in the central region injection path, two diametrically opposed multi-head probes, each covering the full radial range, and two movable

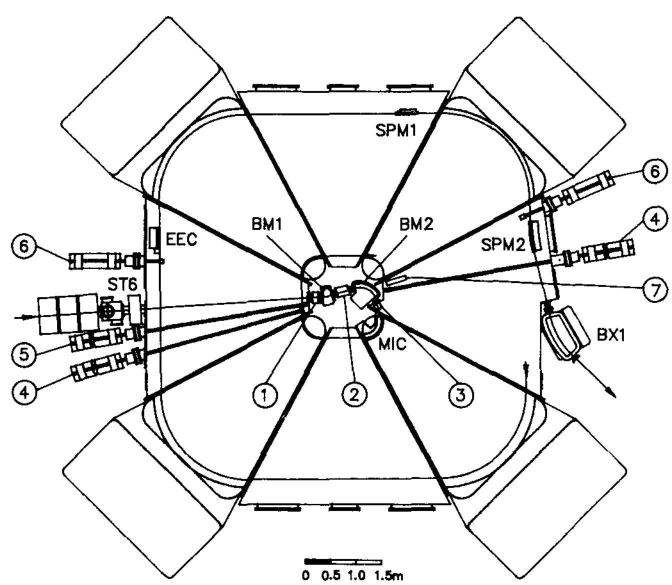

Fig. 1. Layout of injection and extraction components and diagnostic equipment measuring the beam position. Numbers refer to: 1. Harp, 2. Beam profile scanner, 3. Harp, 4. Multi-head probes, 5. Beam stop, 6. Extraction harps and 7. Beam centering probe.

harps covering the radial range near extraction. The two extraction harps are especially useful for fine tuning of the resonator phase in order to obtain optimum beam quality, and for adjusting the position of the extraction orbit. Each of the multi-head probes is fitted with a capacitive phase probe, a differential beam current probe, a vertical four-finger probe and a three-wire tomography probe, any one of which can be individually positioned in the beam path to make measurements over the full radial range of the machine. The diagnostic equipment is described in detail in reference 2.

Measurements obtained with the vertical wire of a tomography probe provide complete information about the beam position and width throughout the machine. Although the measurements do not provide an instantaneous beam pattern, good results are obtained owing to the excellent degree of beam stability. These measurements can be performed at low resolution (16 mm/s) or at high resolution (1.6 mm/s), but they are time-consuming, as it takes at least 7 minutes just to run a probe in from its parking chamber and back again at high speed. This time is required even if only a short radial range near injection must be measured to centre the injected beam.

It is for this reason that a new beam centering probe (BCP) has been designed, built and installed in the extraction valley chamber of the SSC. Its purpose is to display an instantaneous beam pattern of the first few orbits in the SSC and to aid in setting up the injection elements and resonator phase.

2. THE BEAM CENTERING PROBE

The beam centering probe system consists of a harp, pneumatic actuating components, control and current-measurement electronics and a minicomputer interface. The harp basically consists of 170 vertically mounted 0.1 mm diameter tungsten wires supported in a frame, which can be pneumatically inserted into the median plane of the accelerator. The vertical wires are spaced horizontally at intervals of 2.4 mm. The complete assembly is installed in the extraction valley vacuum chamber of the SSC.

The current-measurement electronics for this harp make use of a front-end multiplexer attached to the NAC standard current-measurement system. This system consists of an IBM-compatible personal computer with a BITBUS interface, a CAMAC interface and a 16-bit IGOR (Input-Gate Output-Register) interface. The BITBUS interface controls three 32-channel current-measurement cardframes. The CAMAC interface accepts commands from the control system minicomputer and returns status information. The IGOR interface controls the multiplexer. The output of this system (i.e. the orbit pattern) is displayed on a remote monitor in the control room. It may also be written to floppy disk for record purposes or for later analysis. A typical display is shown in figure 3.

Software has been developed for a personal computer to do the graphics display, to control the multiplexer selection and harp movement, to read the current values and to communicate with the minicomputer. In addition, software had to be written for the minicomputer to control the electronics from the control panel.

The BCP can operate in two modes. In the normal or low-resolution mode the beam current on the 170 wires (2.4 mm apart) is continuously monitored and the display is also continuously updated. The resolution is thus 2.4 mm. In the high-resolution mode, the 170 wires are scanned once, after which the harp is moved by 1.2 mm radially and then scanned again. The resulting 340 data points are then used to give a static display with an effective resolution of 1.2 mm. This display is only updated when a further scan is called for, when the whole process is repeated.

The complete system has been tested and successfully used from the control panel. Improvements have been made to the hardware and to the software at a later stage to increase the speed of the system.

A few harp wires have been broken as a result of too intense a beam. Beam currents on the harp should be less than 1.5 microamperes and therefore the harp insertion procedure has been subjected to certain safety conditions. A complete spare harp has been assembled to replace a possibly damaged one during scheduled maintenance shutdowns, the damaged harp is repaired later and stored as a new spare.

3. DATA ANALYSIS

3.1 Probe Data

The probe data provide information about the beam position and also about its width. For the purpose of beam centering, only the position is required, therefore the analysis of the probe data reduces to identification of peaks and a determination of peak positions in the recorded beam traces. A general automated peak searching and fitting routine is difficult to develop, but the task is simplified considerably if peaks do not overlap, if noise levels are low, and if the individual peaks are fairly smooth. These conditions are satisfied by traces of reasonably centered beams recorded

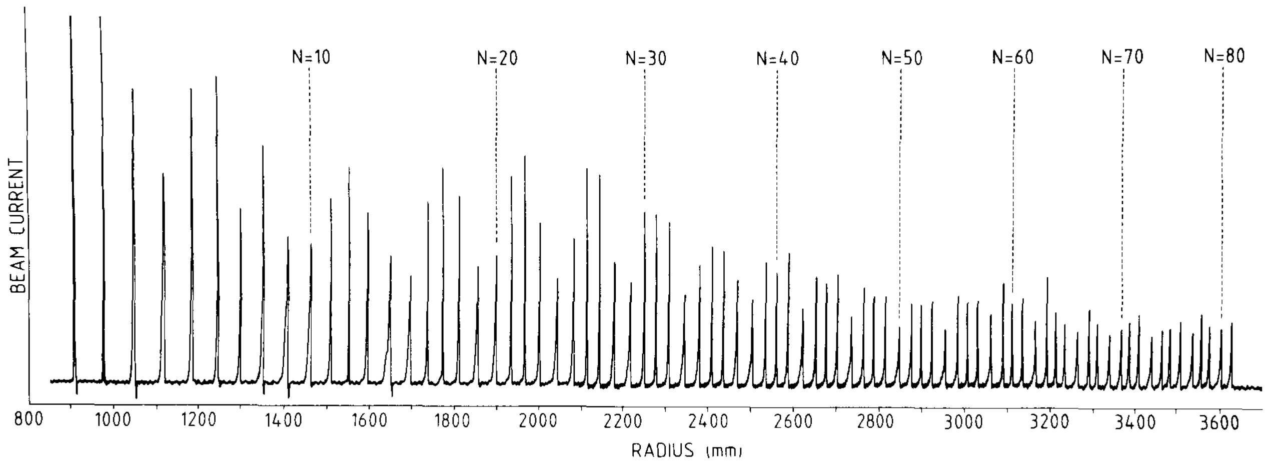

Fig. 2. Multi-head probe beam trace for 66 MeV protons

at high or low resolution with the multi-head probes (see figure 2). The conditions are also satisfied by traces obtained with the beam centering harp, although the resolution is lower (1.2 mm or 2.4 mm) and the recorded data also contain more noise, as seen in figure 3.

The effect of noise is removed by smoothing the data before it is analysed. We use a least-squares smoothing algorithm for points equally spaced along the abscissa, which reduces to a simple moving average using a set of weighted integers and a normalizing factor.[3] The method has the advantage that peak positions are not affected and peak heights are not significantly degraded. A cubic polynomial is fitted, averaged over 9 points, for a typical trace such as in figure 3.

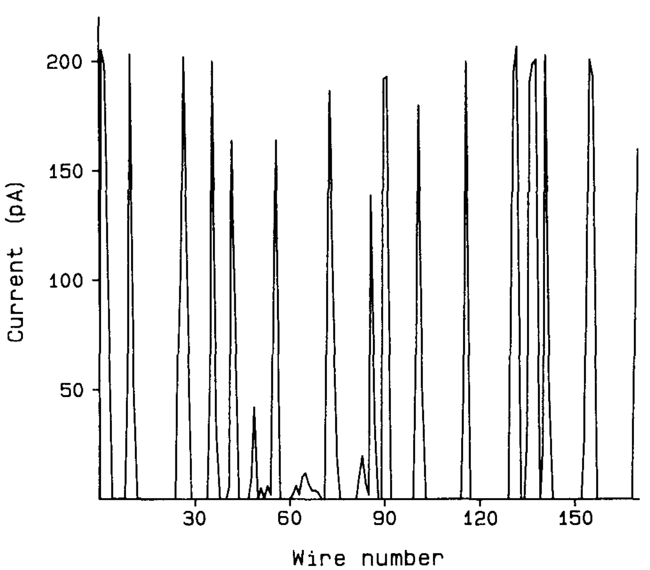

Fig. 3 Beam centering probe trace for off-centre 200 MeV proton beam

Peak identification is performed using second derivatives, i.e. a minimum (negative) second derivative value identifies a peak. To avoid false peaks caused by noise or statistical variations, a smoothed second derivative is calculated, using the above mentioned least-squares method. Only second derivative values exceeding a preset threshold value are accepted, to reject unwanted low count peaks and peaks caused by noise and statistics.

Software has been developed for a personal computer to read the beam centering probe trace data and to analyse the trace data. To keep the program simple, a high degree of interaction with the user is provided through a graphical interface – the program proceeds through stages, stopping after each stage to refer high level decisions to the user. The user sets the peak threshold level and accepts, rejects or inserts peaks into the beam trace. One iteration is usually sufficient to analyse a trace.

3.2 Centering Error

The error in beam centering is found from the formula giving the orbit separation Δr_n at probe angle θ_p between turn n-1 and turn n,

$$\Delta r_n(\theta_p) = \Delta r_{an}(\theta_p) + C\cos 2\pi n(\nu_r - 1) + S\sin 2\pi n(\nu_r - 1)\ ,$$

where C and S are constants determined by the amplitude, frequency and phase of the beam oscillations. The orbit separation Δr_{an} of the centered accelerated orbit is not known, but is an approximately linear function of turn number over a few turns. The peak positions found by the beam trace peak analysis routine are reduced to orbit separations and then fitted by the formula to obtain the energy gain per turn and constants C and S (see figure 4). The amplitude and phase of the beam oscillations are calculated from expressions in terms of C and S. Evaluation of these expressions require betatron functions which are calculated with an orbit code in an isochronous magnetic field for the particle and energy in question.

Using this method, it is possible to obtain the beam oscillation amplitude and phase at any point in the machine over the first few turns. The centering error is usually calculated at the exit of the magnetic inflection channel, just after injection is completed and just before acceleration begins.

4. Beam Centering

Once the centering error is known, it may be corrected with the magnetic field produced by the first few trim-coils. In a separated-sector cyclotron, however, it is simpler to use the injection elements. Referring to figure 1, we see that there are four injection elements, i.e. the last horizontal steering magnet ST6 in the transfer beamline, two bending magnets BM1 and BM2 in the central region, and the magnetic inflection channel MIC. The problem is over-determined, as there are four currents available to set only two parameters, i.e. the beam position and direction at injection. Only two parameters may be used at a time, or else the centering must proceed in two stages, firstly setting the beam position and direction (with ST6 and BM1) at an intermediate point between BM1 and BM2 and then centering the beam (with BM2 and the MIC) at injection in the SSC.

Unfortunately diagnostic equipment is not available to measure the beam direction directly along the injection path. Furthermore, the beam transfer matrices through the injection elements are not well known, because

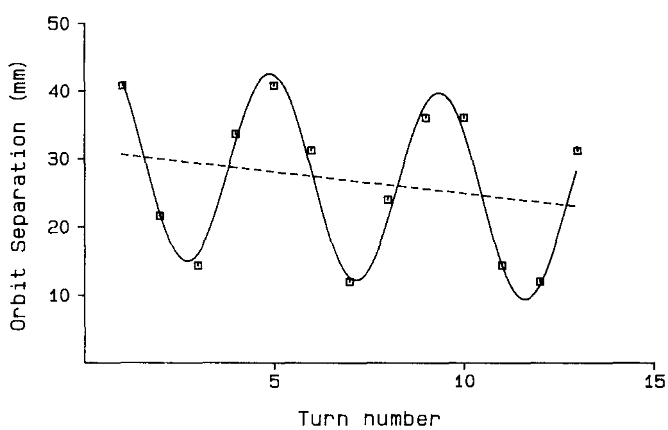

Fig. 4 Fit of formula (see text) to beam precession pattern of off-centre 200 MeV proton beam. Dashed line gives centered accelerated orbit.

the central region field has never been mapped with all components in position - but here the centering program itself can be used to determine the transfer matrix needed to calculate the corrections for a given centering error.

An investigation has been conducted to determine the influence of the four injection elements on the beam centering parameters, as a function of coil current in the respective magnets.[4)] We have also developed an interactive beam transport program based on a microprocessor system, to improve our understanding of the injection process. A unique solution to the inverse problem is not easily found, as the four injection element currents are closely coupled, making it difficult to isolate the effect of a single injection element. The method used at present is to optimize the injection elements separately or in pairs and to invert the system of equations to obtain a solution having a minimum centering error. Satisfactory results are obtained (see figure 2), but the centering process is slow, as it is mostly based on a heuristic approach, whereas an algorithmic solution would be preferred. However, once a given beam has been centered, its injection path and injection parameters are recorded for later use.

In future we plan to speed up the centering process by improving the data collection process and the data processing programs. Further studies will be conducted to improve our data base of injection parameters and to develop better centering algorithms.

5. Acknowledgements

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