PLOTTING OF BEAM VARIATION WITH Q VALUE ON THE 5 GeV ELECTRON SYNCHROTRON NINA

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This paper describes the development of a diagnostic technique that explores the variation of beam with injection Q value. The automation of the method is described, and some preliminary results are presented and discussed.

The Diagnostic Technique

The Reasons for Development

Until fairly recently, part of the optimisation procedure of NINA, the 5 GeV electron synchrotron at Daresbury, U.K., has been the independent adjustment of the quadrupole correction fields at injection, the criteria being to maximise the high energy beam. Direct currents in pole face windings are separately controlled on the F and D magnets, and are therefore called F_Q and D_Q. These two parameters completely control the radial and vertical betatron Q values (Q_R and Q_V) at injection, and hence the optimisation described should invariably lead to the synchrotron being set to the best low energy working point.

However, despite repeated attempts, this optimisation never led to a single working point that gave consistently good beams, and the optimum injection Q values varied considerably from month to month.

It was also difficult to understand why the current working point was usually considerably removed from the high energy working point, thus producing a large Q variation during acceleration. The high energy Q values in NINA are not adjustable and are approximately

$$Q_R = 5.22$$
$$Q_V = 5.28$$

The optimum low energy Q values were usually between 5.35 and 5.5, and the $Q_V = Q_R$ resonance was frequently crossed during acceleration.

It was decided to systematically explore radial/vertical Q space at injection, and the technique described below was developed.

'Resonance Plotting'

The F_Q and D_Q correction currents were varied in a systematic way to cover the interesting region of Q_V and Q_R space with a matrix of approximately equidistant points. At each point the beam current at 50 μs after injection and at high energy was recorded.

This information was presented by plotting contours of constant current on a map with the injection value of Q_R as abscissa and injection Q_V as ordinate. The resulting 'resonance plot' was intended to show the optimum working point and the resonances that were causing appreciable beam loss.

It will be appreciated that it was only possible to vary the injection working point, the Q values at high energy being relatively unaffected by the low direct currents in the pole face windings. Thus, the maps showing contours of equal high energy current represented the current remaining after the working point had moved from the variable injection value, against which it had been plotted, to the fixed high energy value. The plots of current at 50 μs however display the processes that are occurring at, or just after, injection. It was found that the general details, such as the major resonances, were very similar on both plots, showing that the injection conditions were dominant. Because of this it is now usual to use the high energy current, which is more easily monitored, to produce the plots. However, the low energy current plots show valuable details, and are part of the consistent diagnostic process.

This technique was initially carried out manually, and it was found to be very time consuming. A typical matrix of 12 x 15 points could take hours of accelerator time for beam measurement and recording, and contour plotting was also a lengthy process. Two examples of manually produced plots are shown in figs. 1 and 2.

It soon became clear that there was no standard resonance plot and that variations of machine parameters could considerably influence the results. Exploration of Q space became a standard diagnostic facility, and hence it was necessary to develop automatic data acquisition and processing techniques that would produce the diagrams quickly and easily.

Automated Resonance Plotting

Computer Facilities

The computer system available to perform the experiment is shown in fig. 3. The primary computer is an IBM 1801 process controller with 32K words of core. The 1801 is dedicated to NINA operations and is continuously performing a multiplicity of tasks to do with process control on the synchrotron. It has bulk storage in the form of two IBM 1810 disks most of which is taken up by stored programmes and the operating system.

Peripheral to the 1801 is a Honeywell 316 with 8K of core which supports data display terminals and the NINA CAMAC control system. Two of the controllable paramters are the F_Q and D_Q quadrupole currents.

The 1801 is connected by a two-way data link to an IBM 370/165 computer with two megabytes of core. 70K bytes of 370 core are dedicated to the NINALINK supervisor programme. Input and output via the 1801 is handled by NINALINK. An IBM 2314 disk capable of storing 29 megabytes of data is also dedicated to NINALINK and is taken up by various files devoted to NINA status and histroy and some temporary experimental data storage. The 370 also has two IBM 2250 visual displays and a 'Calcomp' graph plotter which can be used for output of contour maps. Neither of these facilities is available to NINALINK or its sub-tasks, but NINALINK can initiate ordinary batch jobs in the 370. Such batch jobs can produce output both for the 1801 and the 370.

Data Acquisition Procedure

The 1801, through the 316, causes F_Q and D_Q to go through the matrix of desired settings pausing whilst the beam current is read at each setting. The process is initiated by an experimenter typing a request to the 1801 giving the limits of the F_Q and D_Q matrix. The request is in free format and the programme prints the input data back as a check, and then waits for a GO or ABORT command. When the 1801 receives GO signals from both the experimenter and the 370 it takes one scan of data by varying F_Q. At each setting of F_Q the average of the circulating high energy beam over ten NINA cycles is read and recorded. The data is then assembled into a package which is sent to the 370 where a sub-task is attached to store the data in a temporary file. Meanwhile the 1801 sets D_Q to the next setting in sequence, resets F_Q to its initial setting and takes another scan of data. At the completion of this scan it checks for an operation complete message from the 370 before sending the next package off for storage. The scans are sent separately since the storage capacity of the 1801 does not cater for the quantity of data involved. In the event of 370 failure, only one experiment of 20 x 20 points can be stored for later processing without massive re-arrangement of 1801 files.

When the whole matrix has been examined, the 1801 asks the experimenter for a title for the experiment and a calibration point to relate F_Q and D_Q to Q_V and Q_R, this being the result of a separate measurement. This data is then sent to the 370 together with a command to attach a sub-task which sets up and starts a batch job to process the data.

Plotting the Contour Map

The 370 programme which produces the contour maps had to be written at Daresbury because of the non-orthogonal relationship between F_Q, D_Q space and Q_V, Q_R space. It can handle up to a 100 x 100 array of non-equispaced data points providing that the data is in the form of scans in monotonically increasing values of F_Q taken at monotonically increasing values of D_Q. It first transforms the data to a 100 x 100 equispaced matrix by interpolation and then scans this matrix for possible contour lines using a grid technique. Any contour found in an F_Q, D_Q grid square is then plotted in Q_V, Q_R co-ordinates. When every grid square has been examined and all the pieces of contour have been plotted, the result is a map with continuous closed contour lines. The technique has worked very well; practically all the rare irregularities in the maps have been traced back to fluctuations in the input data. An example of a computer plotted map is given in fig. 4.

The reduction in the time required for taking and processing of data has been quite dramatic. For instance a 25 x 25 point experiment takes about 13½ minutes for data taking and about 15 seconds for data processing. The resultant map is instantaneously available on a visual display or hard copy can be produced by the graph plotter in about 25 minutes. The primary data is also punched out on cards for future re-processing should this be necessary. Printed output, listing input data and giving processing information, is available via the 1801 fast printer as soon as the data processing is complete.

Preliminary Results

Resonances Exhibited in NINA

A glance at the resonance plots, figs. 1, 2 and 4, shows that the integral resonances

$$Q_R = 5 \quad \text{and} \quad Q_V = 5$$

are very broad, and it is usually found that beam cannot be accelerated if either of the injection Q values is less than 5.2. As the integral resonances are excited by dipole field errors, it would be expected that this situation could be improved by adjusting the dipole injection corrections. The map shown in fig. 1 was obtained after two optimisations of the radial correction fields. It can be seen that whilst there is some beam down to $Q_R = 5.1$, the beam obtained in this region is poor, and is crossed by some vertical troughs.

The reason for this critical situation is not understood, but it is suspected that synchrotron side bands and other forms of betatron synchrotron coupling are responsible.

The half integral resonances normally, but not always, cause beam loss. As these resonances are usually fairly narrow (see figs. 1 and 2) with steep sides, they are not a major problem. Occasionally, wide half integral resonances are found (fig. 4). It is believed that these are also caused by synchrotron oscillation effects.

Losses associated with higher order resonances are seen where a number of resonance lines cross. A 'bay' of little or no beam is often found at

$$4\,Q_R = 4\,Q_V = 21$$

(see fig. 4) and there is usually a minimum associated with

$$3\,Q_R = 3\,Q_V = 16$$

(see figs. 1 and 4).

The very detailed structure of the maps can probably be explained by third and fourth order summed resonances. However, the rapid variation in Q which occurs during acceleration appears to limit the loss, and clear cut resonance troughs cannot be distinguished. The only difference resonance which strongly effects the beam is

$$Q_R - Q_V = 0.$$

This is not a recent discovery, as beam loss was frequently seen during acceleration when this resonance was encountered.

It is now quite clear that the high energy working point is very poorly situated, and almost total beam loss is encountered if this point is chosen for injection. This is not surprising as it is close to

$$4\,Q_R = 4\,Q_V = 21$$

where six sum or difference resonances up to the fourth order cross. Because of this, and of the desire to control the Q values during acceleration, it is planned to insert quadrupole magnets, with fully programmed current waveforms, into the NINA lattice.

Critical Nature of Injection Conditions

It has become apparent that considerable changes can be produced in the strengths of resonances, and in the position of the optimum low energy working point by modification of the injection field corrections. It is surprising to find however that the modifications required to produce such changes are quite small. This critical behaviour is also demonstrated by the tolerance of the machine to working point change, particularly when moderate or high currents are injected. The fig. 2 plot corresponds to an injected current of 90 mA, and it can be seen that at the major peak, a change of 0.01 in Q_R results in a reduction of high energy beam current of greater than 20%.

It is believed that this evidence points to stray and/or remanent magnetic fields having a considerable influence at injection. If the resonances were only a function of magnet pole errors, the situation would be more reproducible, and the changes with magnetic correction would be less critical. Because of this, and other considerations, the possibility of increasing the NINA injection energy is being studied.

Conclusion

The described technique, when fully computerised, can become a useful standard diagnostic facility of a synchrotron, which can be easily and quickly used. The method is valuable not only for routine optimisation, but also for the investigation of the fundamental magnetic characteristics of a given accelerator.

Acknowledgements

We are indebted to the staff of DNPL who were involved in data taking for manual resonance plots, or who helped in producing the automated system, and we would like to thank Prof. A. Ashmore for permission to publish this paper.

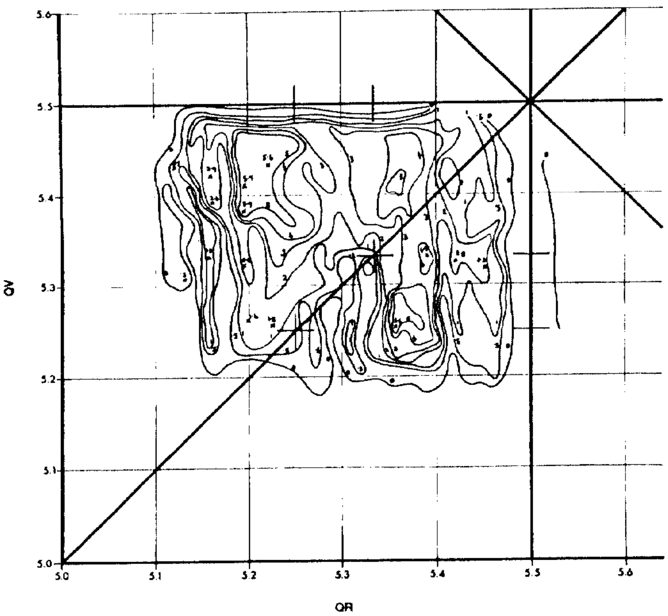

Fig. 1 Contours of constant high energy beam on map of radial and vertical Q value (Q_R and Q_V) at injection. Data taken after twice optimising the injection dipole corrections.

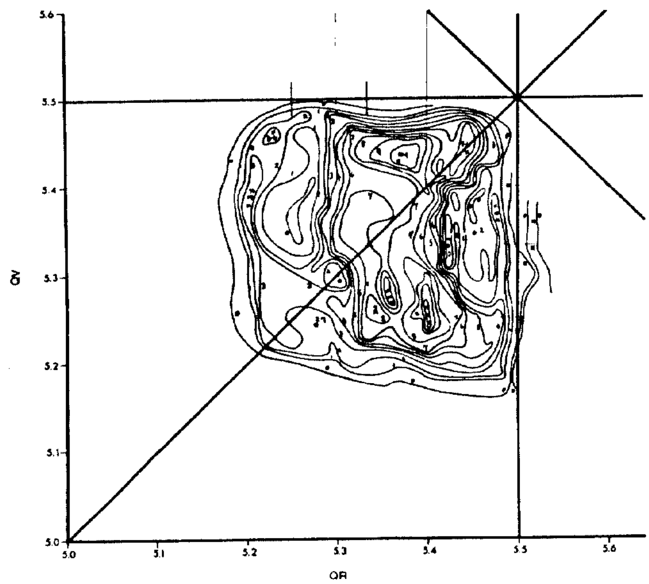

Fig. 2 Contours of constant high energy beam on map of Q_R and Q_V. Data taken with high injected current.

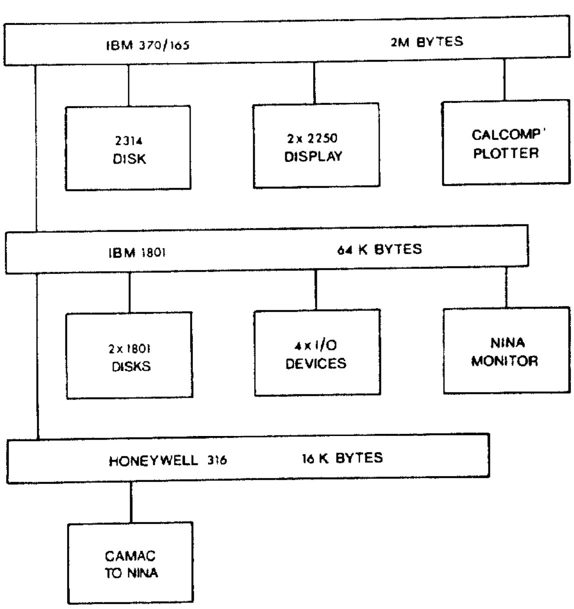

Fig. 3 Computer system relevant to automated resonance plotting.

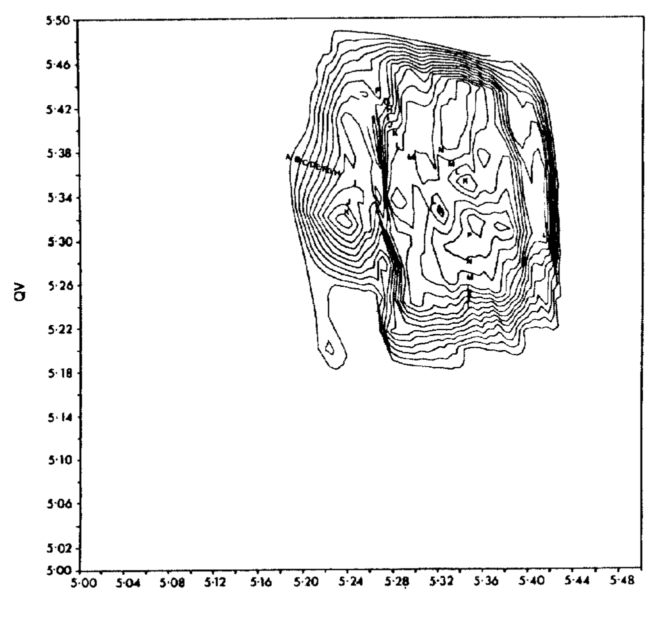

Fig. 4 An example of an automated resonance plot. Contours A to P (low to high current) in steps of 0.5 mA.