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NINA PROGRAMMED QUADRUPOLES

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Introduction

In order to improve the high energy focussing and to provide for separated function extraction, four pairs of quadrupole magnets have recently been added to the lattice of the 5 GeV fast cycling electron synchrotron NINA. Because of the complexity of the system, computer control of the pulsed waveform is required, and the programmed power supplies can track widely varying waveform shapes.

The system is now commissioned and operating.

Tune Variation in NINA

An experimental technique has been developed[1] that gives a rapid and clear indication of the strengths and relative importance of the resonances encountered in a circular accelerator. The data is presented as contours of constant beam intensity at the end of acceleration, on the plane of radial and vertical tunes (Q_R and Q_V). In fig. 1, the plot shows the beam obtained when the NINA injection tunes are varied by means of pole face windings, and it can be seen that large areas are unsuitable for beam acceptance. At the time that this data was obtained, the high energy Q values were constant, the focussing provided by the combined function magnets giving $Q_R = 5.218$, $Q_V = 5.265$. It can be seen that this point is far from optimum at low energy, and hence it was necessary to allow large variations of tune during acceleration. The consequent crossing of multiple resonances is clearly undesirable, and hence the possibility of controlling the high energy Q values was investigated.

Further advantages of variable, controlled Q excursions appeared when separated function extraction was considered, as the extraction efficiency, and the

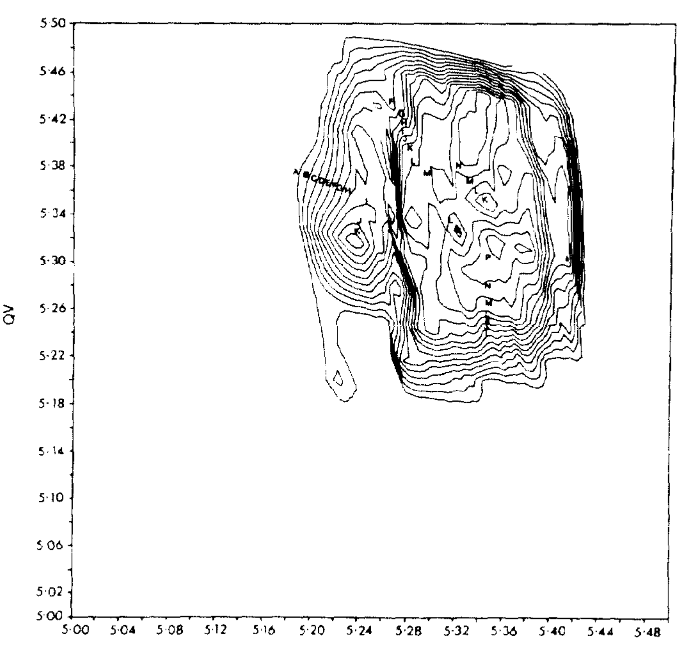

Fig. 1 Contours of beam accelerated in NINA against radial and vertical tunes (Q_R and Q_V).

quality of the external electron beams, could be improved by engaging the $3Q_R = 16$ resonance and using a pure sextupole magnet to enlarge the beam. It was therefore decided to insert four pairs of quadrupole magnets into the NINA lattice, this number being chosen to minimise super-periodic effects. The magnets, together with power supplies and control system, were installed in late 1973 and are now commissioned and operating.

The Programmed Quadrupole System

Each pair of quadrupoles contains a radially focussing, and a radially defocussing magnet, and as these magnets have separately defined waveforms, control of the radial and vertical tune is achieved throughout the acceleration cycle. However, each magnet influences both Q values to a different extent, and to obtain independent control this interaction must be taken into account. Further complications are introduced by the natural Q variation present in the machine and by the rapid, non-linear energy variation during acceleration. It was obvious, at an early stage of design, that computer calculation of the quadrupole waveforms would be necessary, and this has been provided. In the present system, the NINA operator specifies the variable Q values as a function of time, and the correct magnet waveforms are calculated and transmitted to the programmed power supplies.

These power supplies are designed to follow any waveform that is within the maximum voltage and slew rate limits. As NINA is a fast cycling synchrotron with an acceleration time of 9 ms, this ability calls for a novel design, and the power supplies use transistor banks operating in class C to generate the magnet waveforms. Because of the limited ratings of power transistors, it has been necessary to provide a separate power supply for each magnet, with waveforms common to the four magnets of each type.

The problem of designing a servo system to control Q variation to 1% over an energy variation of up to 125 was overcome by using voltage control of the pulsed waveform. The Q shift is then the integral of the controlling waveform, and this largely compensates for the two orders of magnitude energy variation.

The Quadrupole Magnets[2]

The magnets have a length of 0.5 m. This results in a magnet that is not dominated by end effects, and which is the longest that can be easily accommodated in a NINA straight. A maximum gradient of 4 T/m can be obtained, allowing a Q variation of ± 0.2 in both planes at the peak NINA energy of 5 GeV.

It was decided for reasons of production economy to make all the quadrupoles identical, and the electrcal connection alone determines whether they are radially focussing or defocussing. However, differing ceramic vacuum chambers are required from the two types, and an inscribed radius of 55 mm encompasses both sets of dimensions. Because of the beam width being greater than its height, an aysemtric magnet was built, and this results in a saving in magnet inductance of 25%, with a corresponding reduction in power supply voltage.

The magnets are each composed of two blocks, which are constructed from 0.35 mm silicon steel bonded by a system of 0.05 mm glass cloth preimpregnated with eopoxy resin. Shear strength and electrical resistance of the resulting blocks greatly exceed those of blocks bonded by more conventional techniques, and control of block length is also more readily obtained.

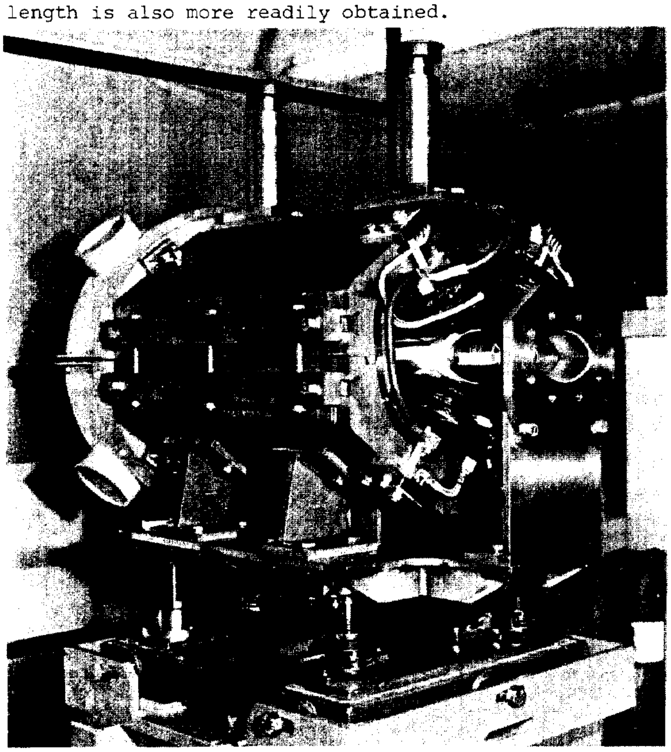

Fig. 2 A NINA programmed quadrupole magnet.

The coils are constructed from stranded conductor and have a maximum current density of 3 A/mm^2. Forced air cooling is used, as it is believed that this is of great advantage in a small, a.c. magnet where the inclusion of water ducts into a coil is both technically difficult, and expensive. A single 3 h.p. fan cools a pair of magnets, giving a temperature rise of about 50°C under conditions of maximum excitation. Coil bonding is achieved with a high temperature resin system that will withstand temperatures up to 150°C.

A photograph of an assembled quadrupole is shown in fig. 2.

Power Supplies[3]

The power supplies each use an inductor as the main energy store, but intermediate capacitative storage is necessary to control the energy transfer.

A simplified schematic diagram of the power supply for one quadrupole magnet is shown in fig. 3. During each synchrotron cycle, energy is transferred from the energy storage inductor to the magnet and returned to the inductor. The energy lost during the cycle is replaced at the beginning of the following cycle from a power supply not shown in fig. 3. The transistors are operated as switches to keep their dissipation minimal.

Initially current is assumed to be circulating through T2, D1 and the enrgy storage inductor L1, and the magnet current and capacitor voltage are zero. Assume also that T3 and T4 are non-conducting. When T2 is switched off, the inductor current will be diverted through D2 and the capacitor C, causing the capacitor voltage to increase. When T2 is switched on again the current will again circulate through T2, D1 and the inductor, and the capacitor voltage will remain constant. By switching T2 on and off at the correct times, the mean rate of increase of capacitor voltage can be controlled. In a similar way the mean rate of decrease of capacitor

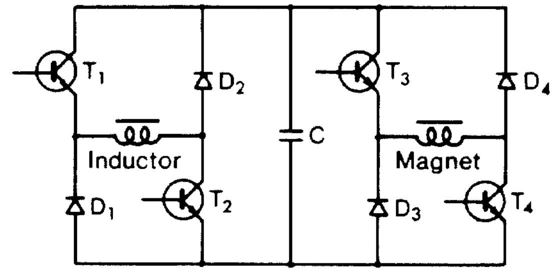

Fig. 3 Programmed quadrupole power supply circuit (simplified).

voltage can be controlled by switching T1 on and off at the correct times while T2 is conducting. Within certain limits any positive capacitor voltage waveform can be obtained by suitable switching of T1 and T2.

This voltage waveform is applied to the quadrupole magnet by switching on transistors T3 and T4. The magnet current will then be proportional to the integral of the voltage. To recover the energy from the magnet, T3 and T4 are switched off, forcing the current to flow through D3, D4 and the capacitor. At the same time T1 and T2 are switched on and off to control the capacitor voltage so as to obtain as short a recovery time as possible.

Each transistor shown is, in fact, a bank of 15 transistors. One transistor is used as a drive for the remaining 14 devices, which have emitter resistors to help share the current more equally between them. The storage time in the main transistors is low because overdrive of their bases is prevented by the fact that the gain of the drive transistor drops as its collector voltage is pulled down by the main transistors. The combination is rated as 300 V, 100 A with switching times of less than a microsecond.

Control System

The NINA operator uses an interactive graphics terminal to define the required curves of Q versus time. After smoothing to remove discontinuities of gradient,

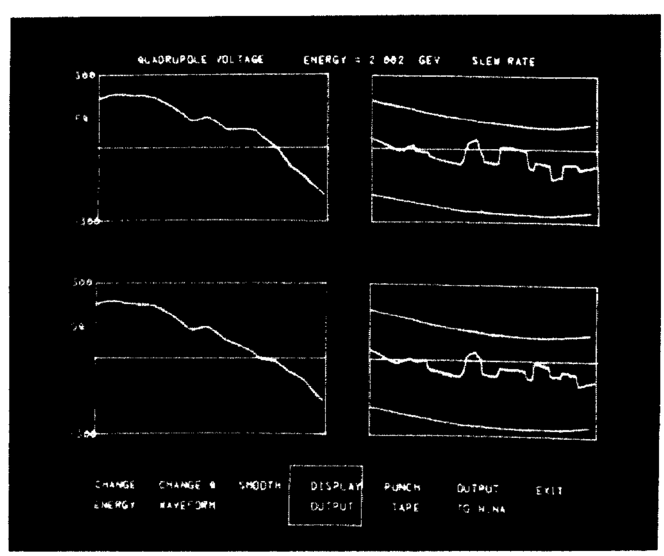

Fig. 4 Visual display of voltage and voltage slew rates applied to F and D type programmed quadrupole magnets.

the voltage waveforms are calculated in the central IBM 370 computer, and providing these waveforms do not exceed the power supply ratings, the variation of voltage and slew rate (dV/dt) with time, together with variable slew rate limits, are displayed to the operator. Such a display is shown in fig. 4. The two voltage waveforms are then transmitted through the NINA IBM 1801 computer complex, to a dedicated PDP 11/05, where each waveform is stored as 550 points of ten bit length. This minicomputer cycles in phase with NINA, retrieving each point of the waveforms at the correct instant and transmitting the data, via a CAMAC interface, to two digital to analogue convertors. The resulting waveforms are fed to the appropriate power supplies where they are used as the reference signal in a fast servo system. A backleg winding on the magnet provides a reset signal of purely inductive voltage (i.e. rate of change of magnetic flux) and the servo system switches the transistor banks to maintain a 1% similarity between these signals. An essential feature of such a system is that the magnet current should become zero at the end of each cycle.

Conclusion

The Programmed Quadrupole system is now used in routine operation of NINA. Separated function extraction has been achieved, and improved beam quality has been observed. A detailed survey of resonance behaviour with constant Q value will now be made, and it is anticipated that optimum tunes will be obtained from this study.

Acknowledgements

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References

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