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SYNCHROTRON MAGNETS FOR THE SNS

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Summary

The design and construction of the magnets for the 800MeV proton synchrotron which forms part of the Spallation Neutron Source[1] is described. Operating at 50Hz, the design intensity of 2.5×10^{13} protons per pulse imposes stringent conditions on design and hardware, and requires that maintenance philosophy should be determined well in advance. The parameters of the main ring dipoles and quadrupoles are largely dictated by the fact that they must form a suitable load for the resonant power supply, inherited from Daresbury Laboratory's NINA electron accelerator. Programmable correction quadrupoles and octupoles are required to provide ramped fields during the 480μsec-long injection period.

Introduction

The design of the lattice (see figure 1), and of the magnets themselves, has been dominated by two considerations: the fact that the NINA resonant power supply is available as an energising source, and the decision to have a ceramic vacuum chamber. The power supply consists of a make-up source, resonating capacitors and a choke having ten secondaries. The secondary windings are rated at 14kV, 722A rms, and it is found that in order to achieve the design goals the full capability of the power supply is required. The high voltage is significant in that it precludes the use of concrete-or mineral-insulated coils, which would be a desirable feature of such a high-intensity machine. A glass-mica-epoxy insulation is therefore being used; it is intended to minimise the irradiation of the coils by the collection of lost beam on scrapers placed at appropriate points around the ring. The windings themselves consist of four water-cooled conductors in parallel, insulated from one another and transposed at intervals in order to reduce eddy current losses in the copper.

The magnet cores comprise 0.35mm-thick transformer steel laminations bonded together with epoxy resin and strengthened by means of straps welded along the outside. Because the main quadrupoles are powered in series with the dipoles, tracking of the bending field by the focussing fields could be a problem at high fields. This is overcome by keeping the average flux in the steel down to 1.1T at peak fields and by the use of trim quadrupoles.

Care is being taken to ensure that magnets, together with their bases, can be readily removed from the ring, and a spare unit installed with the minimum of alignment being necessary. Where quick-disconnects are not practicable, local shielding will be deployed to minimise the exposure of personnel to radiation.

Further requirements of the magnets are that they should be divisible in order to allow the installation of vacuum chambers with flanges attached, and that they should have no mechanical oscillation modes at or near 50Hz or higher harmonics. Table 1 gives parameters of the major components.

Dipoles

The 36° sector dipoles are combined function magnets

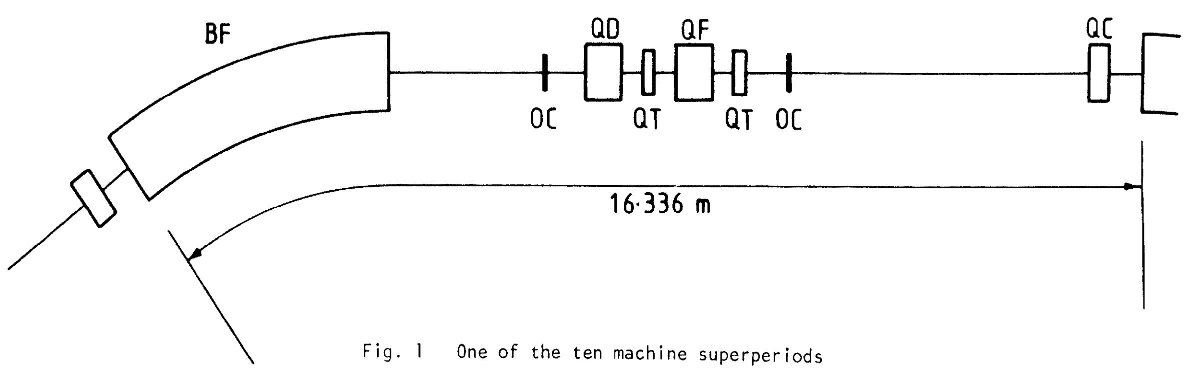

Fig. 1 One of the ten machine superperiods

TABLE 1 MAGNET PARAMETERS

Magnet Type	BF	QD	QF	QC	QT	OC
Number of magnets	10	10	10	10	10	12
Field on R_o: at injection (T)	0.176					
at extraction (T)	0.697					
Normalized strength $B'/B\rho$ (m^{-2})	-.06785	0.6377	-0.6377	0.7262	±0.103	
$B'''/B\rho$ (m^{-4})						±5
Aperture on R_o, inscribed diameter (mm)	160	274	274	212	274	280
Good field region HxV (mm)	190x140	252x186	252x186	104x148	252x186	220x176
Core length (mm)	4400	608	589	317	203	100
Magnetic length (mm)	4400	725	707	402	314	157
Turns/pole	42	22	22	15	15	8/5
Inductance/magnet (mH)	127	10	10	3	2	0.56/0.22
Peak current (A)	1057	1057	1057	1057	±250	63
RMS current (A)	718	718	718	718	-	-

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having a very low, but precisely controlled gradient. By fanning the H-section yoke laminations, the steel configuration is optimised for minimum eddy-current losses, the laminations being resin bonded and welded into upper and lower magnet halves to facilitate the fitting and replacing of vacuum vessel sections. The two energising coils, each of 6 pancakes, 7 turns/pancake, are wound from composite conductor fabricated from four water-cooled and mutually insulated cores. Glass tape and mica, vacuum impregnated with epoxy resin form the bulk of the coils' insulation: all epoxy resins used have proven radiation resistance to at least 10^9 rads. An extensive manifolding system supplies demineralised water to all pancakes in parallel, whilst the ±7kV power supply drives all turns in series electrically; the yoke is cooled by water flowing in tubes brazed to the outside of the lamination stacks.

To keep the geometric median plane flat to within ±0.05mm, the magnet is to be assembled as pre-fabricated modules on the concrete base, where it will be fitted with height-correction shims after an optical survey. At the ends, the ideal roll-off (to keep $\int Bdl$ constant with energisation) is approximated by reprofiled laminations in packets ranging from 5 to 10mm thick Figure 2 shows the magnet on its base in plan view and in vertical section.

Magnetic field computation was divided into an investigation of the shims required at the edges of a hyperbolic profile to give a field within the magnet, away from the ends, to within 1 part in 10^4 of the required distribution, followed by an analysis of the end roll-off. Three separate computer programmes GFUN(3D,non-linear iron)[2], BIM(2D,linear)[3] and TRIM(2D,linear)[4] were tried and results are compared in Figure 3. The design has been based on the GFUN results, and figure 4 shows the departure from the precision required off the median plane. For the two-step roll-off, the shims have been computed to suit the radial cuts and to carry the 2D field precision through to the integrated field. These shims will be built into the prototype magnet, and new shims prescribed as necessary for the production magnets after prototype measurement and evaluation.

Field measurement will consist of a thorough mapping of the prototype and one production unit, whilst the integrated field and gradient on R_0 will be compared for all other dipoles. Search-coils mounted on a remotely-controlled trolley running against a precision rail will enable the pulsed performance of the magnets to be assessed to a precision of the order of 0.01%.

Quadrupoles

Apart from the need to keep the inductance low, the major problem with the quadrupoles QD, QF and QC is to match them properly to the bending field: that is, to ensure that $\int gdl$ is as close to the theoretical value as possible as well as being uniform across the aperture. Hence, although the 3D magnet programmes used in their design are reasonably accurate, the determination of the exact core lengths must await the measurement of a prototype in each case. Since the lengths are short compared with the bore diameters, end effects are significant and have been accomodated in the pole-shimming. Despite the short lengths, however, it was found necessary when computing the lattice functions to represent the quadrupoles with soft- rather than hard-edges, and this resulted in slightly different lengths being required.

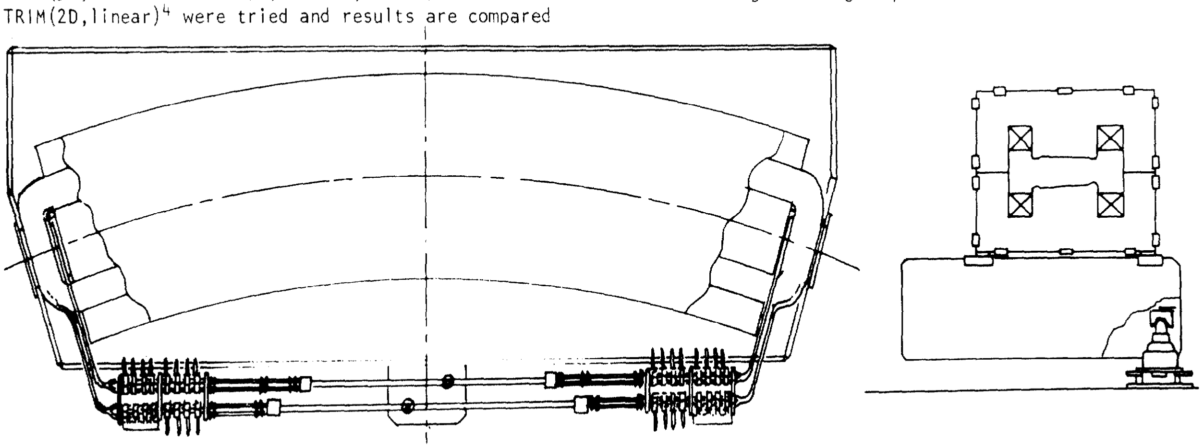

Fig. 2 Plan and section of dipole BF on concrete base.

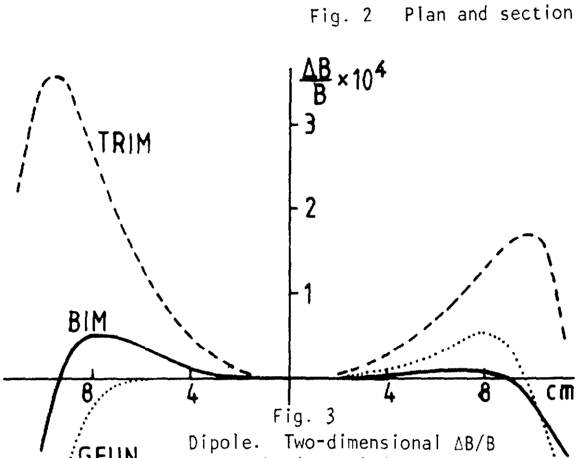

Fig. 3
Dipole. Two-dimensional ΔB/B versus horizontal displacement

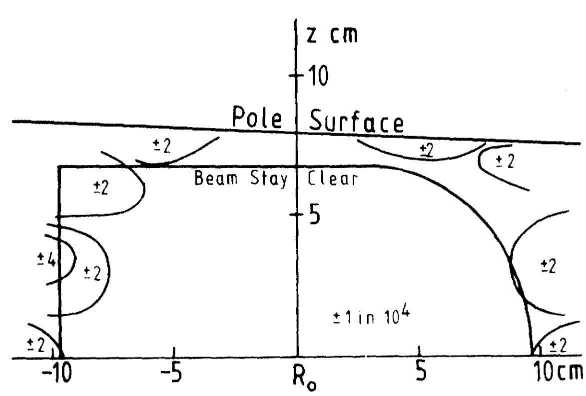

Fig. 4 Dipole. Two-dimensional ΔB/B contour - parts in 10^4

QD and QF are essentially the same, conventional, quadrupole differing only in core length. This difference of about 19mm has the effect of reducing to zero the nominal gradient required in the trim quadrupoles (see below) at the end of injection. QC, however, has to be of figure-of-eight configuration, since the extraction septum magnet would otherwise foul the flux return yoke. The two-fold symmetry introduces an octupole component which unfortunately is of the wrong polarity to assist in Landau damping. This octupole term will therefore be reversed in sign by pole-profiling, and have a value such as to produce a $\Delta Q_v = .001$, supplementing the effect of the 12 octupoles (see below).

The trim quadrupoles are each powered separately from a programmable supply. They will perform the triple function of keeping the Q-values constant throughout injection, making up for relative saturation effects in the main quadrupoles, and correcting for any harmonic errors in focussing strength around the ring. This is expected to be of importance in preventing beam envelope oscillations when the synchrotron approaches the space-charge limit in accelerated beam.

At the beginning of the 480μsec-long injection period the linac beam has a $\Delta p/p$ relative to the central bending field of -1.6%. The trim quadrupoles correct for the Q-shifts which would otherwise be introduced by the combination of this momentum error and the natural chromaticity of the machine. The correction will fall linearly to zero as the bending field reaches its minimum at the end of the injection interval. The corresponding rate of current change in the trim quadrupoles, whose inductance is 2mH, is 1.25×10^5 A/sec, and tests have shown that the gradient in the quadrupole follows this ramp to within about 1%.

Correction Magnets

Twelve octupoles will be distributed around the ring to provide Landau damping. They consist of two identical groups[5], each comprising four octupoles with 5 turns/pole and two with 8 turns/pole. Each group has a power supply for series energisation, and because these magnets need to be ramped during injection, care will have to be taken to ensure that the capacitance to ground of the current leads is not significant. Because of limited straight-section space the octupole cores, whose inscribed radius is 140mm, will be only 100mm long. A new version of BIM (3D, non-linear)[3] is being used to optimise the pole-shims. The remaining correction elements presently planned (four vertical and four horizontal dipoles) will be of the same length.

These dipoles will be used to align the beam during injection and the early part of acceleration so that the scrapersare effective in collecting lost protons. In addition, a vertical closed orbit bump will be introduced during the last 2msec of acceleration to move the beam close to the extraction septum. This reduces the demands on the fast kicker magnets. The dipoles will be independently programmable and possibly made from ferrite rather than from steel laminations. Space is being allocated in the ring for further correction dipoles and sextupoles, but there are no plans to manufacture these as yet.

Magnet Measurements

Apart from the combined function dipoles, field plots of all the magnets will be obtained by means of a computer-controlled harmonic coil apparatus. A master search coil will be used to compare the QD, QF and QC quadrupoles; comparing the dipole central field with the quadrupoles' gradient integrals is not so easy, and requires very careful calibration of the different coils involved.

Acknowledgements

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