ENERGY-LOSS EXTRACTION SYSTEM WITH THIN-SEPTUM PLUNGED MAGNET AT NIMROD

A.G.A.M. Armstrong, M.J. O'Connell, V.W. Edwards, R.H.C. Morgan and M.J. Sheehan
Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England.

Summary

Details are given of a system involving an energy-loss target, a plunged 1 cm septum magnet and correction of the Nimrod field by radially focusing elements where the beam emerges. These elements are energised partly from Nimrod fringe flux and partly from powered windings. The applied current has to be programmed with the magnet pulse to minimise disturbance of the accelerator field. Design work has so far been done with the program TRIM, solving sections of the configuration at various azimuths as two-dimensional problems. The lip and targetting program LIMP has been used to generate "realistic" assemblies of, typically, 100 particles, which are then tracked through the extraction system using the program NIMDYN. A tagging facility enables particle identity to be retained through to the final statistics on assemblies of 100 particles or less.

Introduction

The chromatically corrected energy-loss system^{1,2} in use at Nimrod employs a plunged quadrupole XQ with 1.5 cm septum and a plunged extractor magnet XM with a 6 cm septum. These magnets are $3\frac{1}{2}$ and $6\frac{1}{2}$ octants away from the target, (0.28 and 0.52 radial betatron wavelengths), and the beam leaves the machine through an exit port $1\frac{1}{2}$ octants beyond XM, diverging in the horizontal and vertical directions with a radial emittance of about 30π mm-mrad. Quadrupole focusing then turns the beam parallel for transport purposes and later refocuses it at the external target. The extraction efficiency depends on the way in which the beam is being shared between internal targets. Typically, values are in the range 35-40%, with 4.4×10^{11} protons per pulse delivered to the external target. We will call this scheme the 'old' energy-loss system.

It now appears feasible to reduce the septum thickness of XM to 1.02 cm in XM9 and to place powered shims XHQ2 and XHQ3 in the header vessel near the exit port. A modest gradient (185 G/cm) in the field of XM9 reduces chromatic aberration in the exit region to a negligible amount and the radially focusing shims overcome the dispersive effects of Nimrod's fringe field. The beam converges in the horizontal plane and is diverging but physically small in the vertical plane as it enters the external transport system.

Calculations indicate that the efficiency of this 'septum' energy loss system should exceed 60%. The magnetic design of the shims and of the septum magnet XM9 has been based on the use of TRIM³, and the programs LIMP and NIMDYN have been used to study the lipping and targetting processes and the dynamics of the beam from target to exit port.

Hall 3 at Nimrod will be served by the beam X3. The 'old system' will be used at first, to be replaced in the spring of 1970 with the installation of XM9, XHQ2 and XHQ3; see Figure 1.

At that time, a resonant extraction scheme, using XM9, will also be tried.⁴

Beam Optics

The Programs LIMP and NIMDYN

The action of the lip and target reduces the mean amplitude of radial betatron oscillation and the mean equilibrium radius of the beam, at the cost of increasing the energy spread and the spread of beam divergence. LIMP simulates this action. The fictitious particles, usually in batches of 100, are given initial momentum and phase-space co-ordinates chosen at random from distributions representing the full-energy beam. Repeated applications of single-turn transfer matrices bring the particles within range of the lip. The number of turns used to bring the beam on to the target is consistent with the real Nimrod field and its ramp at "flat top". At each lip traversal the momentum and phase-space co-ordinates are changed by amounts governed by the appropriate Landau and gaussian distributions and the process is ended by a target traversal. Typical LIMP results are shown in Figures 2 to 5. The resulting information about phase-space co-ordinates, momentum loss and number of turns taken is made available on cards which are used as the input data for the tracking program NIMDYN. NIMDYN performs a step-by-step integration of the equations of motion, through magnetic fields described by tabulated values. The phase co-ordinates are available at all stages of the motion, in particular before and after XM and throughout the XHQ2, XHQ3 system. The behaviour of the samples of 100 particles can be displayed in the form of histograms or scatter plots. In the case of histograms the particle identity is retained by tagging the particles from 00 to 99 and entering these labels on the histogram; see Figure 6.

LIMP studies. The materials of the lip and target are chosen from elements having low atomic number so that the required energy loss is accompanied by small multiple scattering. In practice, beryllium targets are used with lips of either beryllium or aluminium. The LIMP studies show that, length for length, a beryllium lip gives a greater reduction in mean radial betatron amplitude and causes fewer particles to be lost behind the target. Multiple scattering causes the amplitude of vertical oscillations to grow as the lipping proceeds, and for this reason also a beryllium lip is better than one made from aluminium. The dimensions in mm chosen for the new scheme are:

Be lip 0.5 long, 50 high, 20 wide
and Be target 15.0 long, 10 high, 10-15 wide

NIMDYN studies. In an ideal synchrotron the separation between target and XM could be chosen as half a betatron wavelength, and the radial spread of the beam would then be a minimum at XM, leading to a high transmission of particles through it. In practice this separation leads to loss in the vertical direction of about 7% of the beam. This may be exchanged for a radial loss of 5% by moving the target azimuth from 189° to, say, 136°. Thus a slight overall improvement in transmission results. This change in target azimuth has two further advantages: the small amount of vertical defocusing caused by XM9 is reduced, and the radial divergence at the beginning of the magnetic channel is made smaller. See Figures 7 and 8 for comparisons of the motion.

The mean radial position of the beam changes by about 14 cm between the beginning of the lipping process and the entrance to XM9. If the target is too short much of the beam is lost on the upstream face or the inside of the septum, (since the particles drift 1 cm outwards while they are inside XM9). Similarly, if the target is too long, beam loss occurs on the back of XM9 or through particles leaving the good field region and striking the walls of the vacuum vessel. The best target length is 15 mm of Be for target azimuth 136° with XM9 in straight 4.

Under these conditions the beam passes through the 10 cm aperture of XM9, expands radially to 12 cm at the entrance to the 1 m header vessel quadrupole XHQ2 where it continues to grow to 15 cm while its divergence is being reduced from ± 17 mrad to ± 4 mrad. In the 0.5 m long XHQ3 the divergence is further reduced through zero, and the 16 cm beam, slightly convergent, travels on through the exit port to the quadrupoles of the external transport system. A radial aperture of 20 cm allows the beam to pass through XHQ2 and XHQ3 without detectable loss. The demands of vertical aperture are easily met since the fringe field causes the protons to converge in the vertical plane, producing a waist at 200°, midway between XHQ2 and XHQ3. Some loss of beam occurs in the external transport system due to the vertical source quality and the variation of $\int B d\ell$ at large radii in the quadrupoles. On this score the new scheme should be better than the old one because of the radial convergence of the beam leaving the machine.

The extraction efficiency in each scheme is estimated in the following table:

Cause of loss	Reduction factor	
	Old	New
Nuclear interactions	0.85	0.90
Targetting action	0.84	0.90
XQ	0.90	-
XM	0.90	0.95
XHQ2,3	-	0.99
External optics	0.75	0.80
Overall efficiency	0.44	0.62

Design of Extractor Magnet XM9

A cross-section of XM9 is shown in Figure 9. It has a central field of 9800 G, with a radially focusing gradient of 185 G/cm. The septum consists of four 2.5 mm copper sheets. Each sheet has eighteen 2 x 0.75 mm water channels and carries 1 gal/min of water at a pressure drop of 100 lb/in². The yoke consists of a stack of $\frac{1}{4}$ in plates, with the profile machined as a series of flats to a tolerance of 0.03 mm. At the design current of 14,000 A the current density in the septum is 8284 A/cm². The magnet is pulsed similarly to the Nimrod magnet. The outward deflection of the septum will affect the leakage field, and the possibility of precurving the septum will be investigated when the magnet is available. The leakage field may be controlled also by the anti-reluctance winding shown. The pole profile was settled using TRIM, and the predicted magnetic field will be compared with the measured field when the assembly of the magnet is complete.

The Header-Vessel Quadrupole System

The aim is to provide a radially focusing set of elements to replace part of the Nimrod fringe field: the beam should enter the first element at the earliest point possible. The presence of the magnetic elements should cause no significant decrease in Nimrod good field aperture, and the extracted beam is required to enter the external beam transport channel on the same line with or without the preceding elements. The desirable overall focusing strength of the system is typically 800 G/cm over 1 m. Figure 10 shows the path of the beam in the region where it leaves Nimrod, drawn from NIMDYN output. Also shown are beam cross-sections generated by 100 LIMP particles, in the regions proposed for the elements XHQ2 and XHQ3. Figure 11 shows, inter alia, how the Nimrod fringe flux falls with radius; in conjunction with Figure 10 this prescribes how the fields in the centres of the elements should vary. Successive elements of constant cross-section are proposed, each with approximately the same bending power as the replaced fringe field. The length of individual elements is limited by the local rate of radial variation of fringe field. Thus an early element known as XHQ1, 30 cm long, was originally proposed to begin at azimuth 195.6: (cf. Figure 10). This has been postponed pending experience with XHQ2, due to its extreme proximity to Nimrod. XHQ2 has a length of 1 m, and the following element, XHQ3 is limited to 56 cm by the pillar shown in Figure 10, which cannot easily be moved or modified.

Design of XHQ2. A conductive sheet analogue⁵ gave 'infinite permeability' solutions for the end and mid cross-sections, treated as two-dimensional problems. By this means, an approximate profile, ampere-turns, coil size and flux distribution were found. The design was then put into TRIM, in preparation for which two Nimrod models, for injection (300 G) and high field (14,000 G) had been developed. Little attempt was made to match the exact characteristics of the Nimrod poles or the exact field-index value. These models enabled

us to study the field and gradient perturbations caused by XHQ2, for example.

XHQ2 is a 'C' magnet with its open end facing radially inwards towards Nimrod, and having a winding around the vertical leg. Excitation is partly by means of this winding, and partly by the Nimrod fringe flux. The current is chosen to produce a balanced magnetic condition in which the Nimrod internal field disturbance is minimised; to this end a current ramp is applied, starting at 3200 At at injection and rising to 14,400 At at 14,000 G. The high field flux distribution is shown in Figure 11. It can be seen from Figure 11 that the field at the centre of the aperture of XHQ2 should be approximately 4000 G; this permits a gradient of 450 G/cm if a field zero exists at the inside edge of the aperture. Production of a field zero within the aperture, and consequent field reversal on the radially inward side, necessitates a more complex design, bearing in mind the required flux balance with Nimrod. It was decided to reserve these complications for XHQ3 where, for the required order of field gradient, a field zero within the aperture is unavoidable. In XHQ2, we have exploited the unidirectional field as far as possible. The main profile is hyperbolic, with origin consistent with the field zero position, where a neutral pole is located. When the excitation is such as to minimise disturbance to Nimrod, the line-integral of central field in XHQ2 is about 2 kG-m in excess of the fringe field it replaces. This results in a 7.6 mrad inward slope error which it is proposed to remove in XHQ3. In Figures 12 and 13 the effects of XHQ2 on the good field region at 14,000 and 300 G are shown.

We now consider the closed orbit distortion resulting from a localised field error, and the change in Q_r value due to the associated field index error. The maximum value of closed orbit distortion e occurs a half-turn away from the disturbance and is given neglecting straight sections, for Nimrod, by

$$e = 8.6 \cdot 10^{-3} \int \frac{\Delta B}{B} d\ell \quad (1)$$

where $\int \frac{\Delta B}{B} d\ell$ is the line-integral of percentage field error, and e and ℓ are in cm. From figures 12 and 13, with XHQ2 excitations of 7200 and 1600 At respectively, $\frac{\Delta B}{B}$ -values of -0.15% and -0.48% occur. Over 100 cm these cause orbit distortions of 0.13 cm and 0.41 cm at 14,000 and 300 G respectively.

The effects of $\int \Delta n \cdot d\ell$ are also small. From Figures 12 and 13, $\Delta n = 0.5$ and 0.2 at 14,000 and 300 G respectively, at $R_0 + 40$ cm. These errors result in Q_r changes of 0.003 and 0.001 respectively, at the above quoted excitations of XHQ2. The ampere-turns quoted in Figures 11, 12 and 13 refer to the half-section of XHQ2, and the required figures are twice these.

Constructional details of XHQ2. Figure 14 shows XHQ2. The main part of the yoke is made of $\frac{1}{4}$ in

low carbon steel laminations; and the neutral pole, which has a rather high flux density, of 38% Co steel. Six equally spaced non-magnetic plates are included in the stack of laminations for mechanical assembly purposes. The winding is a simple 120-turn rectangular coil. Also shown in Figure 15 is part of the Nimrod vacuum vessel (see also Figure 10). The aim has been to keep the magnets within the vertical limits of this vacuum vessel. It is proposed to mount the magnets on radially retractable shafts which also carry services and permit radial adjustment.

Design of XHQ3. The field in the centre of the XHQ3 aperture is such that, with the desired gradient, the field crosses zero intensity at a point within the aperture. The need to compensate for the inward bend of XHQ2 lowers the desired field level, and moves the zero point radially outwards. The maximum length of XHQ3 is 56 cm. It is obviously desirable that the amount of bending in XHQ3 should be adjustable.

First efforts were directed towards a version of XHQ2 in which the neutral pole was replaced by a second powered 'C' facing away from Nimrod. It soon became clear that a device of this nature could only with difficulty be prevented from interfering with the Nimrod field. At present, a 'C' core facing Nimrod is being investigated, with suitable profile and windings to produce the desired field with a gradient of about 500 G/cm. The range of adjustment this affords and the precise effect on the accelerator field are being evaluated at present.

Acknowledgments

We gratefully acknowledge the help of our colleagues in the Nimrod Division, especially D.A. Gray and N.M. King, for their support and encouragement; M.H.R. Donald for significant improvements to LIMP and NIMDYN; and D.R. Moore and his staff for engineering design.

References

1. R.G.T. Bennett and J.W. Burren, 'An achromatic system for extraction from proton synchrotrons'. J. Nucl. Energy, part C, 1961, vol. 3, p.14.
2. A.J. Egginton et al, 'The extracted proton beam from Nimrod'. Proc. 5th International Conf. on Accelerators, Frascati, 1965, p. 468.
3. A.M. Winslow, 'Magnetic field calculations in an irregular triangle mesh', UCRL-7784-T, Rev.1, 1965.
4. M.R. Harold, 'A resonant extraction system for Nimrod'. Rutherford Laboratory Report RHEL/R173, Nov. 1968.
5. A. Ašner et al, 'The orthogonal analogue model helps to solve magnetic field problems difficult to be treated by analytical methods'. Proc. International Symposium on Magnet Technology, 1965, p. 126.

Figure 1.

Figure 3.

Figure 5.

Figure 2.

Figure 4.

RADIAL PHASE SPACE AND HISTOGRAMS AT XHQ2 ENTRANCE

Figure 6.

COMPARISON OF RADIAL MOTION (RELATIVE TO A MEAN TRAJECTORY)

Figure 7.

COMPARISON OF VERTICAL MOTION

Figure 8.

Figure 9. Cross Section of XM9.

Figure 11.

Figure 13.

Figure 10.

Figure 12.

Figure 14. Plan and Section of XHQ2.