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

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 energized partly from Nimrod fringe flux and partly from powered windings. The applied current has to be programmed with the magnet pulse to minimize 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 targeting 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 in use at Nimrod employs a plunged quadrupole XW9 of 1.6 cm septum and a plunged extractor magnet XM with a 6 cm septum. These magnets are 3/4 and 6/8 octants away from the target, (0.28 and 0.52 radial betatron wavelengths), and the beam leaves the machine through an exit port 1 3/4 octants beyond XM, diverging in the horizontal and vertical directions with a radial emittance of about 50 cm mrad. Quadrupoles focusing then turn 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 transport systems 1,2,3. In L-system the beam is being shared between internal transport systems 1,2,3. In L-system the beam of LIMP, solving sections of the configuration at various azimuths as two-dimensional problems. The lip and targeting 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.

Hall 3 at Nimrod will be served by the beam $X_3$. 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.

Bean 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 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:
Thermal the following table:

<table>
<thead>
<tr>
<th>Cause of loss</th>
<th>Reduction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old</td>
<td>New</td>
</tr>
<tr>
<td>Nuclear interactions</td>
<td>0.85</td>
</tr>
<tr>
<td>Targeting action</td>
<td>0.84</td>
</tr>
<tr>
<td>XQ</td>
<td>0.92</td>
</tr>
<tr>
<td>XM</td>
<td>0.93</td>
</tr>
<tr>
<td>XKQ2,3</td>
<td>-</td>
</tr>
<tr>
<td>External optics</td>
<td>0.75</td>
</tr>
<tr>
<td>Overall efficiency</td>
<td>0.74</td>
</tr>
</tbody>
</table>

**Table 1:** Extraction efficiency, old vs. new.

**Table 2:** Table showing the reduction in loss factors.

**Table 3:** Table showing the impact of different loss factors.

**Table 4:** Table showing the overall efficiency.

The design of XKQ2: A conductive sheet analogue gave 'infinite permeability' solutions for the end and mid cross-sections, treated as two-dimensional problems. By this means, an approximate profile, amperes-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 (4,000 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 'G' 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 3300 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 mm 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, 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

\[ e = 8.6 \times 10^{-3} \int_{B} \Delta B \, d\ell \]  

where \( \int_{B} \Delta B \, d\ell \) is the line-integral of percentage field error, and e and \( \Delta B \) are in cm. From figures 12 and 13, with XHQ2 excitations of 7200 and 1600 At respectively, \( \Delta B \) -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 \( \int_{B} \Delta B \, d\ell \) are also small. From Figures 12 and 13, \( \Delta B \) = 0.5 and 0.2 at 14,000 and 300 G respectively, at B = 40 cm. These errors result in Q, changes of -0.003 and 0.001 respectively, at the above quoted excitations of XHQ2. The amper-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 0.5 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 100-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 'G' 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 'G' 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. Dosall for significant improvements to LIMP and NIMZYN; and D.R. Moore and his staff for engineering design.

References

Figure 9. Cross Section of XHQ.

Figure 10. Plan and Section of XHQ2.

Figure 11. Namrod high-field model.

Figure 12. Namrod low-field model.

Figure 13. Plan and Section of XHQ2.