THE OXFORD MDM-2 MAGNETIC SPECTROMETER


University of Oxford, Nuclear Physics Laboratory, Keble Road, Oxford, England

J.H. COUPLAND

Rutherford Appleton Laboratory, Chilton, Didcot, England

Received 10 December 1985

A new high resolution magnetic spectrometer – the Oxford MDM-2 spectrometer – has been designed, installed and tested. The layout of the magnetic elements is in the order: entrance sextupole and multipole, gradient-field dipole and exit multipole. The device has a “normal” focal plane, and the 1.6 m radius dipole magnet has a maximum mass-energy product of 315 MeV amu. At the maximum solid angle of 8 msr, the ratio of energies that can be accepted by the spectrometer ($E_{max}/E_{min}$) is 1.31.

Precise measurements have been performed on the magnetic elements. The dipole magnet has very low hysteresis and field integral errors that amount to less than 1 part in $10^4$. After some in situ modifications the field distributions of the magnets closely approximated the original design specifications.

On-line tests with various ion-beams have revealed the optimum setting for each element. These are close to theoretical predictions from the program RAYTRACE, incorporating the parameterised results of the magnetic measurements. An aberration limited resolution ($E/AE$) of greater than 3000 has been observed at 8 msr solid angle.

1. Introduction

A new design of magnetic spectrometer with emphasis on compactness, low cost and ease of operation, which nevertheless achieves high momentum resolution at large solid angle, has been built to meet the requirements of the Nuclear Physics Laboratory, Oxford. The MDM-2 spectrometer was designed to be used initially with heavy-ion beams from the 10 MV folded tandem accelerator and to be compatible with upgraded accelerator facilities.

The goals of the design were to obtain a device with a moderately high energy resolution ($E/\Delta E > 2000$) at large solid angle ($\approx 8$ msr) and with a mass–energy product ($ME/q^2$) greater than 120 MeV amu. A “normal” focal plane, where the particles are incident perpendicularly, was considered essential if simple position sensitive proportional counters were to be incorporated into a “live” detector and routinely achieve submillimetre resolution. To ensure that the chosen energy resolution was not limited by the position resolution of the focal plane detector ($\approx 0.5$ mm), the dispersion had to be greater than 2 cm/%. A detector length of about 0.5 m was consistent with the requirement of simplicity and led to a reasonable spread of energies transmitted by the spectrometer. Lastly, to comply with the experimental programme planned for the spectrometer, kinematic compensation up to $k = 0.3$ had to be accommodated, where $k = -(dp/d\theta)/p$ as in table 1.

A detailed study, performed with the aid of the computer code RAYTRACE [1], was undertaken to optimise a spectrometer system based around the above design goals. The final design, a single gradient-field dipole with three subsidiary higher-order correcting elements, is an extension of the uniform-field Berkeley heavy-ion spectrometer [2]. The inclusion of a gradient-field magnet is a notable departure from current practice in the design of high resolution spectrometers. The layout, shown in figs. 1 and 2, is in the order: input multipoles, dipole, exit multipole; hence the name MDM. The chosen dispersion of $\approx 4$ cm/% leads to a ratio of acceptance energies of 1.31 at the largest solid angle of 8 msr. A mass–energy product of 225 MeV amu is obtained at the maximum field of 1.35 T on the central radius of 1.6 m. The important parameters of the spectrometer are listed in table 1.

1 A. Progress report on aspects of the design has already been published [3].
Fig. 1. The layout of the MDM-2 spectrometer system showing all of the magnetic elements.
Table 1
Major parameters of the Oxford Spectrometer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum mass-energy product ($ME/q^2$)</td>
<td>315 MeV amu</td>
</tr>
<tr>
<td>Vertical acceptance</td>
<td>± 50 mrad</td>
</tr>
<tr>
<td>Horizontal acceptance</td>
<td>± 40 mrad</td>
</tr>
<tr>
<td>Solid angle (max.)</td>
<td>8 msr</td>
</tr>
<tr>
<td>Energy bite $E_{\text{max}}/E_{\text{min}}$ ($\Omega = 1$ msr)</td>
<td>1.52</td>
</tr>
<tr>
<td>Energy bite $E_{\text{max}}/E_{\text{min}}$ ($\Omega = 8$ msr)</td>
<td>1.31</td>
</tr>
<tr>
<td>Length of focal plane</td>
<td>0.69 m</td>
</tr>
<tr>
<td>Angle of focal plane normal to incident ions</td>
<td>normal to incident ions</td>
</tr>
<tr>
<td>Dispersion $k = 0.0$</td>
<td>3.8 cm/%</td>
</tr>
<tr>
<td>$k = 0.3$</td>
<td>3.3 cm/%</td>
</tr>
<tr>
<td>Horizontal angular magnification ($k = 0$)</td>
<td>-2.5</td>
</tr>
<tr>
<td>Horizontal linear magnification ($k = 0$)</td>
<td>-0.4</td>
</tr>
<tr>
<td>Vertical linear magnification ($k = 0$)</td>
<td>5.0</td>
</tr>
<tr>
<td>First order resolving power ($E/dE$) (calculated)</td>
<td>4500</td>
</tr>
<tr>
<td>Range of kinematic compensation</td>
<td>$k = -0.1$ min. $k = 0.3$ max.</td>
</tr>
<tr>
<td>Dipole field gradient, $\alpha$</td>
<td>-0.191</td>
</tr>
<tr>
<td>Maximum dipole field level</td>
<td>1.35 T</td>
</tr>
<tr>
<td>Angle of deflection</td>
<td>100°</td>
</tr>
<tr>
<td>Central radius, $R$</td>
<td>1.6 m</td>
</tr>
</tbody>
</table>

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$a)$ $k$ is defined as $-(1/p)(d p/d \theta)$, the fractional kinematic variation of momentum with scattering angle. Note that the sign of $k$ changes on either side of the beam direction.

$b)$ As is conventional, the gradient field parameterisation is $B(r) = B_0 [1 + \alpha(x/R_0) + \beta(x/R_0)^2 + \cdots ]$ where $x = r - R_0$ and $B_0$ is the field at the central radius $R_0$.

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Fig. 2. A photograph of the fully installed spectrometer system. The beam enters from the left of the photograph.
2. Spectrometer design

2.1. Choice of configuration

It is relatively straightforward to design a spectrometer based on a single dipole magnet so that large dispersion, low magnification and a high mass–energy product are simultaneously achieved. A 100°, 1.6 m central radius dipole magnet, with a maximum field strength in excess of 1 T, meets our design goals for the above three criteria and was chosen as the dispersive element of the spectrometer. The advantage of a single dipole magnet is the simplicity and reliability of operation it provides under experimental conditions. Care must be taken in the design and construction phases, when the small number of variable parameters makes the reduction of aberrations a complex task, and the accurate realisation of the design parameters important. The aberrations need to be reduced so that, even when using a large acceptance solid angle, the desired momentum resolution is achieved across the entire focal plane and over the full range of kinematic factors, while maintaining a normal focal plane. The solution to the design problem is described below. The coordinate system to be used in the following discussions is standard [4], and is shown in fig. 3.

The most convenient method of achieving a normal focal plane with a single dipole spectrometer is to machine a concave boundary at the exit of the dipole magnet as in the Berkeley design [2]. Such a boundary provides a positive sextupole field component [4] and directly influences the second-order aberrations. As a result the focal plane angle can be made normal to the incident particles, by suitable choice of the exit boundary curvature, for one particular value of the kinematic factor. A variable sextupole magnet beyond the exit of the dipole may then be used to correct the angle of the focal plane over the full range of kinematic factors. However, the sextupole field strongly affects all of the second order aberrations. In the Berkeley design these aberrations were left uncompensated and severely restricted the usable input solid angle. This was acceptable, however, since the spectrometer was designed to study reactions using a small median plane acceptance angle. The Oxford design has overcome this limitation by providing higher-order horizontal and vertical aberration compensation. This additional correction is aided by introducing a linear gradient into the field of the main analysing magnet. This not only serves to increase the dispersion of the system, but also provides a positive contribution to the \((x/\theta^2)\) aberration term [5]. This term is also corrected by the convex curvature of the entrance window of the analysing magnet and by incorporating extra multipole elements before the dipole. These features result in a final design which achieves complete second-order aberration correction across the focal plane.

2.2. Design procedure

A basic spectrometer configuration, incorporating quadrupole and dipole magnetic elements, was determined from first-order theory according to the dispersion, magnification and mass–energy product defined by the design criteria. These specifications were transferred as input to the RAYTRACE computer code, and higher multipolarity magnetic components were then introduced. This allowed the optimisation and correction of higher-order aberrations of the image. (RAYTRACE was modified to incorporate a minimisation routine and to allow for interactive operation.) The theoretical properties of a particular configuration were investigated by tracking the paths of a standard ray set of fourteen input rays and evaluating the aberration coefficients as the focal plane. The fourteen rays were placed on and above the median plane so that the performance at an entrance solid angle of 8 msr could be evaluated. Using three sets of momenta 450, 480 and 510 MeV/c in order to span the length of the focal plane, the design procedure was as follows:

1. The sextupole and octupole components of the exit dipole boundary were adjusted in order to straighten and linearise the focal plane for \(k = 0.1\);
2. Next, the sextupole (octupole) field components of the entrance multipole and the dipole entrance boundary were adjusted so as to minimise the image aberrations \((x/\theta^2)\) and \((x/\phi^2)\) [(\(x/\theta^2\)) and \(x/\theta\phi^2\)]:
3. Thirdly, all magnetic parameters were adjusted to reduce the magnitude of all second-order image aberration terms dependent on \(x\) to below 0.04 and all third order terms to below 1.0, so that no individual term contributed more than 0.1 mm to the image width;
4. Finally, higher-order magnetic components were varied so as to minimise the image width across the focal plane over the full range of kinematic factors.

![Fig. 3. Curvilinear coordinate system used in describing a particle trajectory through a magnetic spectrometer, from the origin O. The projected distance along the central trajectory is given by \(z\). The median, or zx, plane lies parallel to the plane of magnetic analysis. Angles in the \(zx\)-plane are denoted by \(\theta\), while angles in the \(yz\)-plane are denoted by \(\phi\).](image)
Table 2
MDM-2 spectrometer RAYTRACE input with central ray momentum 480 MeV/c and k = 0.1

<table>
<thead>
<tr>
<th>Multipole magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A = 77.0 )</td>
</tr>
<tr>
<td>( B = 113.2 )</td>
</tr>
<tr>
<td>( L = 26.0 )</td>
</tr>
<tr>
<td>( \text{RAD} = 6.50 )</td>
</tr>
<tr>
<td>( B_{\text{OCT}} = 0.027 )</td>
</tr>
<tr>
<td>( B_{\text{DEC}} = -0.019 )</td>
</tr>
<tr>
<td>( B_{\text{DDEC}} = -0.009 )</td>
</tr>
<tr>
<td>( B_{\text{DDEC}} = -0.009 )</td>
</tr>
</tbody>
</table>

Dipole magnet

\( A = 26.0 \)
\( B = 145.0 \)
\( D = 11.5 \)
\( R = 160.0 \)
\( B_{F} = 1.001 \)

\( S_{02} = 1.271 \)
\( S_{03} = -2.68 \)
\( S_{04} = 1.587 \)
\( S_{05} = -4.20 \)

\( S_{02} = 1.271 \)
\( S_{03} = -2.68 \)
\( S_{04} = 1.587 \)
\( S_{05} = -4.20 \)

\( a) \) Notation as in [1], except that the field boundary curvature is given by \( Z/R_o = x \tan \beta + S_{02}(x/R_o)^2 + S_{03}(x/R_o)^3 + \cdots \) using the notation of fig. 1 of ref. [1].

Table 3
RAYTRACE output: Predicted aberration coefficients for input set of table 2. Solid angle 8 msr, k = 0.1 and 27 tracked rays.

<table>
<thead>
<tr>
<th>( P_0 )</th>
<th>455 MeV/c</th>
<th>480 MeV/c</th>
<th>505 MeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>( (x/x) )</td>
<td>-0.45</td>
<td>-0.40</td>
<td>-0.36</td>
</tr>
<tr>
<td>( (x/z) )</td>
<td>2.63</td>
<td>2.28</td>
<td>2.04</td>
</tr>
<tr>
<td>( (x/\phi) )</td>
<td>0.86</td>
<td>-0.005</td>
<td>-0.21</td>
</tr>
<tr>
<td>( (x/\theta) )</td>
<td>0.07</td>
<td>-0.008</td>
<td>-0.07</td>
</tr>
<tr>
<td>( (x/\theta^2) )</td>
<td>-18.90</td>
<td>1.01</td>
<td>6.92</td>
</tr>
<tr>
<td>( (x/\theta^3) )</td>
<td>4.40</td>
<td>0.40</td>
<td>-1.25</td>
</tr>
<tr>
<td>( (x/\theta^4) )</td>
<td>224</td>
<td>187</td>
<td>86</td>
</tr>
<tr>
<td>( (x/\phi^2) )</td>
<td>6</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>( (y/\phi) )</td>
<td>-0.28</td>
<td>0.001</td>
<td>0.33</td>
</tr>
<tr>
<td>( (y/\theta/\phi) )</td>
<td>-3.9</td>
<td>5.1</td>
<td>6.5</td>
</tr>
<tr>
<td>( (y/\phi^2) )</td>
<td>43</td>
<td>56</td>
<td>64</td>
</tr>
</tbody>
</table>

The final, optimised RAYTRACE parameters for a kinematic factor of 0.1 are shown in table 2, and the resulting aberration coefficients are shown in table 3.

2.3. Description of individual elements

The entrance multipole magnet is dominated by a vertically focussing quadrupole field component. This reduces the required dipole magnet gap for a given vertical object acceptance angle and facilitates aberration compensation because of the change in beam profile. Higher-order multipolarities are present in fixed ratios up to duodecapole and are essential for aberration reduction at full solid angle. Immediately preceding the multipole is a smaller aperture sextupole magnet which is intended as an adjustable fine-tuning device. It is designed to reduce the image width under normal conditions, or zero the \( (x/\phi^2) \) aberration if an off-line raytracing analysis is performed to improve the resolution at the focal plane.

The dipole magnet has a field gradient

\[
\left( \frac{r}{B} \right) \frac{dB}{dr} = \alpha = -0.19.
\]

It has been designed to generate a maximum mean field \( B_0 \) of 1.35 T, which leads to a mass-energy product of 315 MeV amu on the largest bending radius of 1.9 m. The exit boundary has a concave radius of 0.5 m, with higher-order curvature terms up to fifth-order superimposed. The resulting octupole and sextupole field components are designed to linearise the focal plane and rotate it to be normal to the central ray at a kinematic factor of 0.1. The entrance boundary of the dipole also has a fifth-order profile with a convex radius of 0.63 m designed to compensate some of the aberrations resulting from the exit curvature.

No attempt has been made to restrict the movement of the focal plane with variation of the kinematic factor. Since, to first order, the focal plane merely undergoes a translation due to the kinematic effect, the focal plane detector may simply be repositioned as required. Because the translation is proportional to the product of the dispersion and the horizontal magnification, the required displacement over the full range of kinematic factors is 0.59 m, which is quite acceptable. However, the focal plane shape would change quite significantly with kinematic factor were it not further adjusted. Hence a wide aperture multipole magnet, with individually variable sextupole and octupole field components, is positioned between the dipole exit and the focal plane. These field components can tilt and straighten the focal plane to recover a perpendicular and flat configuration at any given value of the kinematic factor between -0.1 and 0.3.

The spectrometer design is well suited for use with a gas-filled focal plane detector. The horizontal magnification is in the range -0.40 to -0.50, which corresponds to an angular magnification between 2.5 and 2.0. An angle signal derived at the focal plane is therefore very sensitive to the acceptance angle of the spectrometer. Such a signal has proved invaluable as a diagnostic, for track reconstruction and for providing extra kinematic information. The spectrometer has a large vertical magnification of five. Although the image is stigmatic at the centre of the focal plane \((y/\phi) = 0 \) at the horizontal focus, most higher order vertical aberrations are left uncompensated. The result is a vertical image height which varies between 30 and 50 mm from the low to the high momentum end of the focal plane. (This variation results from the requirement of a normal focal plane.) The focal plane detector is therefore required to have a large vertical acceptance of 60 mm.
3. Construction details

The ultimate performance of any high resolution magnetic spectrometer depends on the desired field distributions being realised as accurately as possible. This is especially true in the case of this design where there are few degrees of freedom for aberration correction. It is also important to ensure a high stability of the field distribution over a wide range of field levels. Consequently careful attention was paid to the details of design and construction of all the magnetic elements of the MDM-2 spectrometer.

3.1. Dipole magnet

The dipole magnet was designed to generate a large area (0.6 m x 2.9 m) of uniform gradient field, with low hysteresis and low differential hysteresis. The latter effect can be time consuming to minimise and may limit the ultimate performance of high resolution magnetic spectrometers. A relatively low maximum field level of 1.35 T allowed the construction of a "picture frame" dipole magnet. This compact type of magnet, with the excitation coils inside the magnet gap, makes for low remanence and low hysteresis in the gap field. The magnetic circuit consists of upper and lower sector plates, or "pole pieces", which are joined by side checks of height 110 and 120 mm at the inner and outer aperture radii respectively to give an efficient return yoke (and a low remanence field). The high purity iron [6] (carbon content 0.021%) was cast as a pair from the same melt; care was taken to ensure that similar orientations were taken from each cast before forging. Both sectors were ultrasonically scanned for defects, especially in the region of the magnet gap. An area of slight inhomogeneity was observed and positioned near the dipole exit where it would have least effect. In the interests of simplicity the ideal hyperbolic pole face profile, introducing the linear gradient, was approximated by a series of three flats. Allowance was made for reluctance in the return yoke by a slight increase of the magnet gap near the excitation coils. The coils [7] take the form of a symmetric saddle-shaped pair, each containing 48 turns of hollow copper conductor which were vacuum potted in epoxy resin. Care was taken with the positioning of each conductor to ensure uniform placement, with a larger inter-conductor separation at larger radius in accordance with the increase of the magnet gap. Current is supplied by a 0–1500 A 200 kW Brentford stabilised power supply [8].

Detachable "bay windows" are used to shape the entrance and exit field boundaries of the dipole magnet. These are steel sections from the same melt as the main body of the magnet, tightly bolted to the entrance and exit faces above and below the magnet gap. A series of vertical flats machined on the bay windows approximate the required fifth-order curvature of the edge boundaries to an accuracy of 0.1 mm. A 45° bevel was machined on the corners of the windows nearest the magnet gap in order to reduce magnetic saturation effects. Previous work [9] has shown this procedure to be as effective as the more costly machining of "Rogowski" profiles [10].

There was initial concern that the tight curvatures of the field boundaries (especially the 0.5 m radius exit boundary) would be difficult to maintain at high field levels. However, computations using a three-dimensional scalar-potential method [11], suggested that if the boundaries were fitted with "field clamps"—in effect, magnetic short circuiting rings—the desired curvature could be achieved over the required range of dipole fields. Each field clamp consisted originally of two steel plates, following the bay window curvature, situated above and below the magnet aperture. A magnetic flux return path between the ends of the plates is provided by vertical sections of steel that complete the rectangular profile. The field clamp influences the fringing field profile by diverting magnetic flux from the magnetic aperture into the clamp itself. In the original design, the large amounts of magnetic flux absorbed by the field clamps resulted in more saturation of the iron in the vertical return paths than expected. The final design is a "hybrid" field clamp that extends the initial configuration by creating a supplementary cancelling flux in the manner of Halbach [12]. Sections of high quality Sheffield Plate connect the original field clamps with the top and bottom of the magnet yoke. By altering the width of an air gap between the field clamp and the magnet it is possible to tune the reluctance of this second return path. The field clamps and detachable bay windows together provide a flexible post-manufacture means of altering the boundary curvatures, to optimise the spectrometer performance.

3.2. Entrance multipole magnet

The larger of the two magnets at the spectrometer entrance is predominantly quadrupole and has four poles arranged around a circular aperture with a bore diameter of 130 mm. The pole faces are distorted from perfect hyperbolic profiles in order to generate substantial components of order up to duodecapole. At an excitation current of 450 A the quadrupole field gradient is designed to be 11 T m⁻¹. The detachable pole pieces, which overhang the coils, are bolted to base plates on the rectangular yoke. Both are fabricated from mild steel plate. The excitation coils are copper conductors wound in a stepped double pancake configuration between the pole pieces and the yoke.
3.3. Entrance sextupole magnet

The sextupole magnet has a 45 mm bore and is the magnetic element nearest to the target, at a distance of 900 mm. The required sextupole symmetry is achieved by six flat pole shoes within a thin cylindrical steel yoke. Higher-order multipolarities, particularly 18-pole, are introduced by the pole shoes, although reduced to some extent by judicious choice of the height of the windings.

3.4. Exit multipole magnet

The exit magnet is a 600 mm wide multipole element which provides independently variable sextupole and octupole field components. The fields are generated by two independent sets of current-carrying conductors wound into a series of 30 toothcomb slots placed above and below the 90 mm magnet gap. The conductors are thin strips of copper insulated by a Kapton coating, potted in araldite and tightly wound to achieve a high current density. One set of windings has the number of turns increasing linearly with respect to the distance from the centre, while the other increases quadratically. These windings generate, respectively, sextupole and octupole fields as described, for example, in ref. [13]. A return yoke connects the centre of the upper and lower toothcombs and there is room for a small compensating winding to zero any associated dipole field, but it has not proved necessary.

3.5. Auxiliary apparatus

As well as the magnetic elements, the complete spectrometer system also includes specially designed vacuum components, a support assembly and the focal plane detector.

The vacuum vessel was made from the nonmagnetic N8 aluminium alloy. The section extending through the magnet gap was fabricated without any intermediate seals. The focal plane detector is accommodated inside a large stainless steel vacuum vessel at the exit of the spectrometer. It is located on a movable table so that it may be translated along the direction of the central ray over the full range of kinematic displacement of the focal plane. The present detector is 300 mm wide and therefore spans only 50% of the length of the focal plane. It is a design similar to the “hybrid” detectors described in ref. [14] and uses position sensitive proportional counters as the position and angle measuring devices. A typical position resolution of 0.5 mm is achieved using the charge division method. The design and performance of the detector itself is described in ref. [15]. At the spectrometer entrance, the connection to the target chamber is made through an aperture in a sliding seal, shown in fig. 4, which was designed in the laboratory. The sliding seal comprises a thin strip of sprung steel which slides across an O-ring in the cylindrical wall of the target chamber, following the movement of the spectrometer system as it is rotated. The seal is wound across the O-ring by a pair of rotating...
drums geared directly to the motion of the spectrometer. The sliding seal permits a range of 80° in reaction angle to be accessed without disturbing the vacuum. Used in conjunction with a series of beam entry ports on the target chamber, a full reaction angle of +150° to −50° can be spanned.

The whole spectrometer assembly is mounted on a support platform that is designed to be rotated about a vertical axis through the target position. Before rotation, the platform is lifted a few millimetres above the specially levelled floor using a system of compressed air pads. It is then moved to the new position by means of a pneumatically sprung friction drive. All power cables, cooling water pipes, pneumatics and other services enter and leave the spectrometer via a vertical tower above the pivot axis.

4. Field measurements

The median plane magnetic field distributions in the dipole and entrance and exit multipoles were investigated at a variety of excitation currents. In order to meet the design criteria, it was important that the magnetic field profiles of the assembled equipment agreed closely with the optimised values of the computer code RAYTRACE. Magnetic field profiles were measured on the median plane, since the RAYTRACE code uses parameterised median plane values to evaluate the complete field distribution. Details of the measurement technique are given in the appendix.

4.1. Dipole magnet: inner field region

The magnetic survey of the dipole magnet was split into an investigation of the inner field and boundary field regions. The gradient field and field nonuniformities of the inner field region were investigated by surveying in a cylindrical coordinate system. The radial field profile, shown in fig. 5, has a clear quadratic component. This sextupole term arises from an over-machining of the poles, performed to allow for reluctance in the return yoke (the reluctance was less than expected due to the exceptionally high purity of the iron). The radial profile was investigated at three different field levels between 0.5 and 1.3 T and no appreciable variation of field gradient was observed. The sextupole discrepancy was compensated by small alterations to the entrance and exit field boundaries of the dipole magnet.

The field uniformity of the dipole magnet was examined, as described in the appendix, by generating contours of the variations of the difference between the central ray field and the field at other radii – essentially error plots from the previously measured radial field profile. Fig. 6 shows such plots for 0.52, 0.98 and 1.24 T at the central ray. The deviations from uniformity at small radii were initially greater than shown in the figure. The improved uniformity was achieved after repositioning the dipole field coils in the magnet gap. The remaining effect is probably due to a residual gap between the upper and lower conductors. The negative deviation at the end of the magnet is in the region of some inhomogeneous iron noted during ultrasonic scanning. The effects of opposing regions of excess and deficient field at large radii tend to cancel out when integrated over actual ray paths. Variations of field integral over particle trajectories amount to less than 1 part in $10^4$ at all field levels, and are not expected to cause degradation of the performance of the spectrometer.

The surveys described above were performed without special regard to excitation procedure and hence reveal that the extent of differential hysteresis is small and acceptable. The high quality of the iron, the thickness of the side cheeks and the picture frame design all lead to a magnet with a hysteresis in absolute field level of less than 0.2%. As a result, no special excitation procedures have been found to be necessary for experimental work with the spectrometer. The field is monitored by a gradient-compensated NMR probe [16], located in a pocket at one corner of the vacuum vessel. At an excitation current of 1000 A the mean dipole field was...
measured to be 1.18 T. Fig. 7a shows the current versus magnetic field relationship at the centre of the magnet. The time constants for damping of the field level after change of excitation of the magnet were investigated, as shown in fig. 7b. These time constants depend on the rate of diffusion of the eddy currents through the magnet. In spite of the thickness of the side limbs, the field was always noted to settle within 1 part in $10^4$ of its final value 15 min after the initial change of excitation.

4.2. Dipole magnet: entrance and exit boundaries

Measurements of both the variation of the vertical magnetic field component parallel with the central ray (the falloff profile) and the curvature of the effective field boundary (EFB) in the dispersive direction (the boundary curvature) enabled a comparison with the design RAYTRACE parameters *. The measurement of

* The effective field boundary is formally defined [4] as the point along a line parallel with the central ray to which the interior field would need to be extended to give a field integral equal to that of the actual fringing field.
Fig. 8. The measured entrance boundary curvature of the dipole, with the field clamp assembled, plotted as the difference from the design curvature. Three different magnet excitations are shown. The straight line at $x = 17.0$ cm represents the desired curvature. The dotted region at $x = +16$ cm to $+24$ cm was adjusted by reshaping the field clamp. The variations with field strength of the distance of the central ray effective field boundary from the entrance poleface is shown as an insert. The conventional clamp begins to saturate at point A. At point B the amount of flux travelling by the alternative return path results in saturation at the ends of the main magnet.

Fig. 9. The concave exit boundary curvature of the dipole at three different excitation currents, plotted in the manner of fig. 8. The desired curvature would be represented as a straight line at $z = 7.5$ cm.

Fig. 10. Integrals of the harmonic components of the entrance multipole magnet at a variety of excitation currents. The field integral at a fixed radius of 55.4 mm was measured as a function of angle around the axis of symmetry, followed by a Fourier analysis fitting terms up to 20-pole. The $2\pi$-pole components appear as the terms $(n\theta)$.

With the original field clamps attached, preliminary investigations of the boundary field profiles showed a rather field dependent curvature. After including the modifications described in sect. 3.1, the field dependent variations of the EFB at both entrance and exit were reduced from centimetres to millimetres.

The front bay window was remachined slightly to a new optimum curvature as a result of the initial survey of its boundary curvature and the magnetic measurements of the dipole field. The final EFB values at three different field levels are shown in fig. 8. Over the working aperture of $\pm 24$ cm the measured curvature is clearly quite satisfactory.

At high field levels, the tight boundary curvature due to the concave exit bay window deteriorated rapidly at the edges of the aperture. The variations were reduced considerably by increasing the local separation of the
field clamp and the bay window edges. The final error curvature plot is shown in fig. 9.

4.3. Entrance multipole magnet

The variation of the major magnetic components of the entrance multipole as a function of excitation is shown in fig. 10. All of the components behave linearly up to 300 A. The ratios of the integrated multipole components were very close to the design values, apart from the small duodecapole term, which was of the opposite sign. This was clearly influenced by the end geometry of the magnet, but has little effect on the ion-optical properties of the spectrometer.

A small and almost linear dipole field component was observed, as expected. This results from the pole face distortions and asymmetries required to provide higher-order field components from a basically quadrupole structure. This unwanted term was compensated simply by situating the multiple 0.6 mm off its central axis, at a point where the dipole field was cancelled by the quadrupole term.

The effective length of the quadrupole component was determined to be 26.0 cm. Although the effective-lengths of the higher-order multipoles were slightly less, this value was adopted for each multipolarity in the RAYTRACE input.

4.4. Exit multipole magnet

The sextupole windings produce a high-quality square-law field – see fig. 11a – which at wide aperture deteriorates slightly at the highest excitations. A sextupole field integral of $95x^2$ G cm (where $x$ is measured from the central ray) is achieved at the maximum current of 28 A. There is a small, negative dipole offset to the sextupole field which increases linearly with excitation current. This results from the reluctance of the return yoke and could be corrected by a suitable set of dipole windings.

The octupole windings show a field integral distribution with little unwanted multipole contamination. A small, positive and constant dipole term is present in the field distributions, which are shown in fig. 11b.

5. On-line tests

The measured magnetic distributions of the individual elements of the MDM-2 spectrometer were parameterised and entered as input to the RAYTRACE code. Subsequently the optimised operating conditions over the full range of kinematic factors could be predicted. The required excitation of each magnet was then simply parameterised in terms of kinematic factor and
could be scaled in proportion to the central ray rigidity for other momenta. The aim of the on-line tests was to determine empirically the performance of the spectrometer and the optimum settings for each magnetic element, using the RAYTRACE predictions as a starting point.

5.1. Experimental raytracing technique

Due to beam and target effects it is difficult in practice to generate experimental conditions under which the image width is wholly determined by the ion-optical properties of the spectrometer. The quickest and most effective method we have found for optimising the ion-optics is similar in concept to the tracing of rays through the system in the programme RAYTRACE and follows a method close to that used in ref. [17]. For the tests, the entrance aperture to the spectrometer comprised five narrow vertical slits, separated in the median plane by 1°. The rays defined by these five slits converged to a waist at a point in the detector box. The focussing properties of the spectrometer as a whole, and each magnetic component individually, could then be extensively investigated by examining the behaviour of the rays in the region of this waist. A range of operating conditions was provided by alpha particle beams (generated by the Folded Tandem and EN Tandem accelerators) elastically scattered from gold and carbon targets at a variety of angles and energies. Typically, for each setting of the magnets, the raytracing was performed with five different beam energies so that image quality across the focal plane could be studied.

For each measurement, the hybrid detector was placed successively 15 cm upstream and 15 cm downstream from the nominal focus so that the image of the individual entrance slits were well resolved. The centroid of each peak was determined and hence the “ray” paths interpolated in the region of the focus. The resulting ray diagram was then a very sensitive indication of the focussing properties of the spectrometer. The minimum waist also provided a measure of the aberration limited resolving power.

The use of particle beams from an accelerator was desirable for a systematic investigation of the spectrometer optics. The dipole is designed to provide kinematic compensation for particles from reactions with a kinematic factor, \( k \), of 0.1. Therefore, it was appropriate to begin by observing the focussing of particles produced in such reactions. It was assumed initially that the dipole component of the bending magnet behaved according to the design. The dipole strength for each set of measurements was adjusted so that the central ray arrived at the centre of the focal plane. (From these results it was deduced that the bending radius was within 0.5 mm of the design value.) The focussing at different distances along the focal plane was studied by varying the beam energy and keeping the dipole field fixed. Once this focussing was established, the behaviour for \( k \)-values different from 0.1, as well as the efficiency of the auxiliary kinematic compensation could be studied and evaluated. The experimental ray tracing technique was employed to study each focussing element and was shown to be reliable and reproducible.

5.2. Entrance multipoles: focal plane for \( k = 0.1 \)

At a kinematic factor of \( k = 0.1 \) it was expected that only the entrance sextupole and multipole magnets would be required to optimise the focussing across the

![Fig. 12. The image region of the spectrometer surveyed by experimental raytracing. Changes of the entrance multipole current from the predicted optimum setting \( I_0 \) result in clear changes to the image quality. The dashed line is the expected first-order focus position. A negative \( (x/\theta^2) \) aberration term is evident.](image-url)
focal plane. The effect, at the middle of the focal plane, of varying the multipole field about the predicted value may be seen in fig. 12. The optimum multipole field setting is \( \pm 8\% \) below that predicted by the RAYTRACE code. This value also resulted in optimum focussing across the focal plane. Over a wide range of input particle energies the optimum multipole field scaled with that of the dipole magnet.

The shape of the focal plane over the 300 mm width of the hybrid detector was determined by varying the input beam energy and locating the locus of the waists of the raytracing diagrams. This confirmed that at \( k = 0.1 \) no exit multipole fields were required for a straight and normal focal plane (see fig. 13). In the \( z \)-direction, the best resolution occurs 50 mm in front of the expected first order focus.

In all of the tests performed it has been found that the median plane focussing properties of the spectrometer are quite insensitive to the field setting of the entrance sextupole. This point will be discussed further in sect. 5.6.

5.3. Exit multipole: focal plane for \( k \neq 0.1 \)

The effect on the spectrometer focussing of energising the exit multipole was investigated with the raytracing technique. The results for some extreme values of currents through the sextupole and octupole windings, shown in fig. 14, demonstrated the capability of these components for rotating and linearising the focal plane respectively. The kinematic factor was then systematically varied between \( k = 0.01 \) and 0.3, by varying targets and reaction angles. For \( k = 0.01 \) the focal plane was surveyed out to \( \pm 200 \) mm by using a position sensitive silicon detector. The amount of exit sextupole and octupole field correction required to straighten and normalise the focal plane was found to scale with the dipole field and vary with kinematic factor in the manner expected. The position of the focal

![Fig. 13](image-url)  
Fig. 13. Plan of the focal plane at four different \( k \)-values. The experimental points are derived from raytracing. The focal plane shape in each case has been optimised with the exit multipole magnet at the noted currents. The full lines are normal to the central ray trajectory.

![Fig. 14](image-url)  
Fig. 14. The measured focal plane shape at \( k = 0.01 \) with different excitation currents in the octupole windings (IMO varied in A) and sextupole windings (IMS varied in B). A straight line parallel with the \( x \)-axis would be a “normal” focal plane. The exit poleface lies in the negative direction on the vertical scale.
plane did, however, display a tendency to move closer than predicted to the exit boundary (by some 20 mm as the kinematic factor was increased from 0 to 0.3). The results of the measurements are summarised in fig. 13.

5.4. Dipole: energy resolution and dispersion

The measured half-width of the waist of the raytracing diagrams determined an upper limit of the spectrometer's resolving power. A value of \( E/\Delta E = 4000 \) was obtained at the centre of the focal plane for \( k = 0.01 \). This deteriorated slightly (by \( \approx 30\% \)) at the edges of the focal plane and at higher kinematic factors. This raytracing procedure did not, however, sample the full solid angle of the spectrometer. The resolution at the maximum entrance solid angle of 8 msr was investigated directly with a 27 MeV alpha particle beam from the Folded Tandem accelerator, scattered from a very thin layer of gold (\( \approx 2 \mu g/cm^2 \)) deposited on a thin carbon backing. The optimum resolution occurred at the same magnet settings that resulted in the minimum raytracing waists. A reproducible full-width-at-half-maximum value of \( E/\Delta E = 3000 \pm 200 \) was seen at the centre of the focal plane (see fig. 15). This corresponds to a position resolution of 0.6 mm. The observed energy resolution of 9 keV was similar to the expected contribution of detector effects, target effects and that from the beam spot size on the target. This may therefore be considered a lower limit on the aberration limited resolving power of the spectrometer. The absence of large higher-order aberrations is demonstrated by the narrow base width of the image. At higher kinematic factors the observed energy resolution has been noted to decrease, but that is mainly accounted for by effects due to the angular divergence of the beam at the target. For the range of targets studied, no dependence of the image position at the focal plane with incident vertical or horizontal angle was noted. In other words, kinematic compensation and vertical aberration correction were achieved simultaneously across

Fig. 15. Focal plane position spectra of 27 MeV alpha particles scattered from a thin gold target and detected using an 8 msr acceptance. An energy resolution of \( \approx 1 \) part in 3000 was obtained. The upper plot (a) shows a superposition of two spectra taken with beam energies differing by 50 keV. Note the narrow base width of the left hand peak (b), which indicates small higher-order aberrations. The focal plane for scattering from the carbon in the target lies 100 mm in front of the focus for scattering from gold, and hence there is a defocussed peak.

Fig. 16. The measured position of particle groups across the focal plane versus momentum difference from the central ray, for two different values of \( k \). The solid lines are the momentum calibrations predicted by RAYTRACE. The data points were obtained from known levels populated in \(^{39}\text{K}(^3\text{He, d})^{40}\text{Ca} \) \( (k = 0.01, \text{circles}) \) and \(^{12}\text{C}(^{16}\text{O, a})^{24}\text{Mg} \) \( (k = 0.21, \text{crosses}) \).
the whole focal plane. However, for those reactions where the kinematic factor varies significantly over the entrance aperture (as when the target and projectile masses are similar), allowance must be made by a retuning of the input multipole field.

The degree of reproducibility of the raytracing diagrams could be used to estimate the differential hysteresis of the dipole. The five rays take quite different paths around the magnet, sampling between them a large fraction of the field distribution. The relative movements of the rays in the region of the waist was studied for a number of different approaches to the same excitation. The effect indicated a variation of less than one part in ten thousand in the total field integral encountered by each ray. This confirmed the conclusion from the magnetic field measurements that no special excitation procedure was necessary for achieving the highest resolution.

Accurate measurements of the dispersion of the spectrometer have been made over the central 300 mm of the focal plane that is spanned by the present detector. Examples for two different kinematic factors are shown in fig. 16. The agreement of the measured dispersion with the predictions of RAYTRACE is excellent. The calibration of position spectra using the predicted dispersion curve, together with one point of known rigidity, has always proved accurate to the equivalent of, typically, 25 keV in nuclear excitation. For more accurate calibrations in individual experiments, an empirical third-order polynomial fit of position to excitation energy using several peaks is usually sufficient and results in 5–10 keV accuracy. A typical position spectrum over the 30 cm width of the present focal plane detector is shown in fig. 17.

5.5. Vertical extent of the image

The presence in the design of significant higher-order vertical aberrations leads to an expected vertical image height of approximately 40 mm at the centre of the focal plane for a 3 mm high beam spot. The image height varies across the focal plane due to the sextupole correction required to keep the focal plane normal.

The vertical extent of the image was investigated using a signal derived from the electron drift time in the focal plane detector, in the manner of Sann et al. [18]. As predicted, the vertical image height differed substantially between the high and low rigidity ends of the magnet, but the variation – from 55 to 35 mm for a 3 mm high source at the target – was greater than expected and limited the acceptable vertical extent of the entrance collimation to ±1.5 mm at full solid angle.

RAYTRACE calculations indicated that the image at the centre of the focal plane should be inverted and

![Fig. 17. Composite focal plane position spectrum, for two field settings, of analysed deuterons in the $^{39}\text{K}(^{3}\text{He}, \text{d})^{40}\text{Ca}$ reaction. Peaks corresponding to $^{40}\text{Ca}$ states are labelled by excitation energy (MeV). The observed resolution is 25 keV, limited by target thickness effects.](image-url)
at a vertical waist. For particles following the central
\((\theta = 0)\) trajectory around the spectrometer, the first-
order image should also be stigmatic \([i.e., (y/\phi) = (x/\theta) = 0]\). In contrast, the ‘image’ actually observed using the
empirically optimised settings was not inverted. Further, it was determined that the vertical waist on the
central trajectory lay at least 1 m behind the horizontal
waist, with accounts for the increased vertical height.
Energising the entrance sextupole had the effect of only
slightly reducing the vertical image size, although the
effect on the vertical motion of individual rays above
and below the median plane was quite marked.

5.6. Discrepancies with computer predictions

In general, the spectrometer is found to operate in
quite good agreement with the predictions of RAY-
TRACE. The two outstanding discrepancies are that the
entrance multipole must be run at nearly 10% lower
excitation than expected and that the small “tuning”
sextupole in front of it fails to have the large effect on
the resolving power which is predicted.

At the optimum multipole current \((I_q)\) predicted by
RAYTRACE, the experimentally observed horizontal
waist is 20 mm in front of the predicted first order focus
(i.e. closer to the dipole) and the image is focussed
vertically some distance behind the focal plane. By
increasing the current to \(1.1I_q\), the horizontal waist can
be pushed back to the predicted position and the vertical
waist brought forward. Either of these two currents
and associated focusing conditions would probably be
acceptable if it were not for large negative \((x/\theta^2)\)
aberrations, also evident in the ray diagrams. These
have the effect of making the aberration limited resolv-
ing power about three times worse than the design goal.
There is, however, a strong coupling of the entrance
multipoles to the \((x/\theta^2)\) aberration term, which is
minimised at a current of 0.92 \(I_q\). With this setting the
horizontal waist is moved to 50 mm in front of the
predicted first order focus for \(I_q\) and, most important,
the design resolution is recovered. The vertical waist
now occurs even further behind the focal plane. This
does not appear to cause any problems with the attaina-
ble resolution, but does mean that the beam collimation
must be limited when using the full 8 msr solid angle of
acceptance.

The entrance sextupole is found to be quite insensi-
tive as a fine tuning device for the resolution of the
spectrometer. Its only observed effect has been to verti-
cally displace large angle input rays in the region of the
image. Although the qualitative influence on the vertical
motion is as predicted by RAYTRACE, it has not been
possible to fully understand the lack of coupling to the
horizontal motion.

The 10% adjustments in multipole strength discussed
above are outside the uncertainty in the field strength
calibration. There is only a small uncertainty in strength,
since the search coil was calibrated in the main magnet.
Hence it is concluded that RAYTRACE fails to con-
sistently predict both the horizontal and vertical focus-
sing behaviour of the entrance magnets. The entrance
multipoles and the gradient field dipole each contribute
to the \((x/\theta)\) and \((x/\theta^2)\) aberrations and to the vertical
focussing. Obviously, their contributions are not inde-
pendent. Hence, it is not possible to identify unambigu-
ously the source of the discrepancies with the RAY-
TRACE treatment of a single element. It appears most
likely that these are due to inaccuracies in the computer
treatment of the entrance multipole magnets. The prob-
lem may lie in the description of the fringing fields,
which were not measured and may be more dependent
on the overhanging coil geometry than assumed by the
program in its estimate of a “typical” falloff. All the
discrepancies, it should be noted again, are quite small
and can be compensated empirically.

6. Conclusion

The Oxford MDM-2 spectrometer has been fully
operational since early 1983, and a number of experi-
mental programmes have been successfully initiated and
completed using the device. The spectrometer has proved
to be a reliable and powerful instrument which is simple
to use. Its performance compares very favourably with
the highest resolution spectrometers currently available.
The normal focal plane has proved advantageous both
in lending simplicity to the focal plane detector design
and for processing the data. Angle dependent correc-
tions to energy loss and other parameters required for
particle identification are small, due to the normal
incidence, and this greatly simplifies both on-line and
off-line analyses are compared to systems with signifi-
cantly angled focal planes. The simplified analysis ex-
tends to coincidence experiments, since the spectrome-
ter is also reasonably isochronous \((\Delta t/t < 0.1)\).

Extensive measurements of the field distributions
have been valuable in enabling post-manufacture cor-
rections to the system through field clamps and de-
tachable bay windows. Our experience with field clamps
on such a wide aperture magnet has shown the difficul-
ties encountered if the amount of magnetic flux ab-
sorbed by the clamps in underestimated. This can result
in excitation-dependent boundary curvatures. Clearly,
the safest procedure is to ensure that the clamps are well
separated from the magnet. Although not essential for
maintaining the boundary curvature, the field clamps
are beneficial by reducing the stray field outside the
dipole magnet and by affording a useful way of fine
tuning the EFB. The design specifications have now
been accurately realised. The field measurements have
also allowed an accurate parameterisation of the actual
magnetic configuration for the RAYTRACE computer code. This code has been successful in predicting the properties of the spectrometer except for the discrepancy concerning the entrance multipoles, which has been discussed.

A notable feature of the design is the gradient in the field of the dipole. We have shown that it is possible to build a high resolution, large solid angle spectrometer around a gradient field dipole magnet. This has proved sufficiently successful that one might consider going a step further and incorporating a small positive sextupole term in the main dipole field. The effect would be to allow a more relaxed curvature to the concave exit boundary.

Acknowledgments

We wish to warmly acknowledge the encouragement of L.K. Fifield, D. Sinclair and J.B.A. England, the support of A.R. Holmes, W. Linford and the technical staff of the Nuclear Physics Laboratory, Oxford, the work done by T.C. Randle and M.J. Watson of the Rutherford Appleton Laboratory, and the assistance of S.K.B. Hesmondhalgh and E.F. Garman during on-line testing.

Thanks also to N. Sanderson of the Daresbury Laboratory, who first suggested the use of the experimental raytracing technique and H.A. Enge who kindly supplied a version of the RAYTRACE computer code.

Financial support from the SERC is gratefully acknowledged, as is the award of a fellowship by the Carnegie Trust to DMP.

Appendix

The field profiles of the magnets were determined by measuring the voltage induced in search coils by motion in the field. This method was ideal in the present case where high relative accuracy of field measurement was required rather than high absolute accuracy. Such accuracy was ensured by judicious use of methods aimed at reducing inaccuracies (e.g. by connecting two coils in opposition) and by employing a highly stable current integrating system. Since field integrals are an important ion-optical parameter, the ability to use long integrating coils, particularly in regions of fringing field, represented a considerable advantage over other techniques.

The gradient field of the dipole magnet was measured by connecting two opposing point coils and locating them on a rigid aluminium bar placed in a radial direction. One coil was stepped along the bar and the integrated induced voltage for each step recorded.

The field pattern in the dipole magnet was investigated by connecting the search coils in opposition, with one fixed on the central ray and the other positioned successively at a variety of radii. For each radial position the bar was stepped through the 100° sector.

The falloff profile of the dipole magnet was examined by stepping a point coil along a rigid bar, which was placed parallel with the central ray outside the magnet, and recording the integrated induced voltages. The profile could then be fitted to the RAYTRACE parameterisation [19]:

\[ B_s(z) = B_0 \left( \frac{1}{1 + e^s} \right), \]

where \( s \) is a polynomial in terms of distance, \( z \), from the effective field boundary (EFB) in units of the gap width and \( B_0 \) is the interior field value.

A more direct measurement of the effective field boundaries was achieved by flipping a long coil which extended from the interior field region to the extremities of the fringing field. In this case only two measurements were required to evaluate the position of the EFB along each line parallel with the central ray.

Let the coil be flipped twice, where its end is at depths \((Z + Z_1)\) and \((Z - Z_1)\) relative to the bay window boundary, resulting in induced voltages \(V_1\) and \(V_2\) respectively. Then, by definition, the EFB is situated at the position

\[ Z_{\text{EFB}} = Z - \frac{(V_1 + V_2)}{(V_1 - V_2)} Z_1, \]

where \( Z \) increases in the direction towards the magnet. The actual survey, performed with a 0.72 m long integral coil, ignored the extreme tail of the fringing field. However, this introduced an inaccuracy of less than 1 part in 2000, or 0.1 mm.

The field components of the entrance multipole were investigated with a long integral coil extending through the magnet and a small point coil placed at the centre of the magnet. These coils could be rotated about the central axis of the multipole and were aligned so that they were sensitive only to the radial field components.

The RAYTRACE description of the multipole defined a value of the effective length of the magnet and the pole tip field strength of each multipole component. Since the integral radial field components in a finite magnet can be expressed as a Fourier series, a harmonic analysis of the induced voltage from the integral coil when rotated about the central axis gave the value of the integral multipole field components. Such an examination was performed at a series of excitation currents up to 500 A.

Field integrals parallel to the central ray across the wide aperture exit magnet were measured with an integral coil at a series of excitations.
References