Beam transport system optics studies for the University of Maryland cyclotron

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ABSTRACT

The University of Maryland cyclotron beam transport system is designed about two 90°, 60 in, double focusing analysing magnets.

Magnetic field measurements have now been completed for all optical elements. Initial optics studies indicate that high-quality performance of the analysing magnet system down to energy resolution of approximately 0·01% is achievable. The field is very uniform, allowing scaling of operation up to over 12·5 kG fields and absolute energy calibration to better than 0·04%. Results of calculations to optimise performance of the magnets in their dispersive mode are presented.

1. INTRODUCTION

The University of Maryland cyclotron, described in detail in a previous paper,[1] will deliver up to ~4 kW of external beams of up to 140 MeV protons, 185 MeV alphas, and other particles to corresponding energies.

The basic external beam optics design has been outlined in a previous paper,[2] in which the modes of operation of the system as a whole are summarised. Due to space limitations the ensuing presentation will be limited to a summary of field measurements for the magnetic elements and a brief discussion of their resulting optical properties.

All magnets were engineered and fabricated at Alpha Scientific Laboratories[3] after design consultation with the University of Maryland, and field data were taken at the Alpha plant.

2. QUADRUPOLE DOUBLETS

The University of Maryland system uses 4-in aperture, 10-in effective length quadrupoles with a doublet centre-to-centre spacing of 16 in and a maximum

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gradient of 4 kG per in. Alignment of the pole tips to 0·002 in (Total Indicator Readout) symmetry was required. The optic axis was compared to the axis of symmetry using a magnetic colloid, and no deviation of the magnetic axes from a straight line was observed.

Magnetic field linearity and gradient symmetry were measured with a rotating coil fluxmeter;[4] the results are summarised in Tables 1 and 2. Using a maximum aperture of about 2 in, the gradient non-linearity is less than 1%. No calculations have been made using a measured edge field.

Table 1. QUADRUPOLE FIELD LINEARITY vs EXCITATION CURRENT

I (amps)	B (gauss)	B/I (gauss/amp)
0	11	–
50	1455	29·1
100	2883	28·8
150	4328	28·8
200	5766	28·8
250	7041	28·2
300	8014	26·7

Table 2. QUADRUPOLE FIELD GRADIENT LINEARITY

$\pm x$, $\pm y$ (in)	B_{+x} (gauss)	B_{-x} (gauss)	B_{+y} (gauss)	B_{-y} (gauss)
0·25	686	684	690	690
0·50	1371	1370	1383	1383
0·75	2058	2059	2070	2070
1·00	2738	2740	2759	2758
1·50	4068	4117	4097	4091
2·00	5229	5287	5262	5256

3. SWITCHING MAGNETS

It was desired to keep the field of the switching magnets as low as possible to retain orbit symmetry for all fields and minimise resulting alignment problems. Choice of 42 in pole radius (with a 3 in gap) resulted in a maximum field of ~15·5 kG for the required bending strength.

Careful edge field measurements at several angles allowed check of cylindrical field symmetry. At the maximum required field strength, the cylindrical asymmetry of the field is negligible over the regions used in our system, and orbit scaling over the entire range should therefore result. Non-uniformity over the bulk of the pole region was less than 1 part in 2000.

Because of the symmetry and uniformity linear optics was used in switching magnet studies (see Ref. 2).

4. ANALYSING MAGNETS

Following initial linear optics studies to establish the general optical properties of the analysing magnets (90° bend, 60 in radius, 3 in gap, $N = 0$, double focusing using edge angles of 33·15° and 17·0° for focal distances of 160 in and 90 in), details in edge angles and focal properties were established using ray tracing.[5]

The edge shapes for the analysing magnets and switching magnets are very similar, and their gaps equal, so that it was possible to use the measured switching magnet edge fields to pre-compute focal lengths and detailed edge angles for the analysing magnets, as well as edge curvatures to cancel spherical aberration on the median plane. The analysing magnets were then fabricated according to these specifications. Comparison with calculations using the actual

Table 3. SATURATION DATA FOR ANALYSING MAGNETS

I (amps)	B (gauss)	B/I (gauss/amp)
50	927	18·5
100	1828	18·3
200	3645	18·2
300	5438	18·1
400	7240	18·1
500	9021	18·0
600	10 747	17·9
700	12 299	17·6
730	12 703	17·4
800	13 546	16·9

Table 4. ANALYSING MAGNET EDGE FIELD MEASUREMENTS

r (in)	3 kG	6 kG	9 kG	12 kG
		17° Edge		
143	1·0000	1·0000	1:0000	1·0000
145	0·9982	0·9982	0·9978	0·9981
147	0·9168	0·9163	0·9165	0·9152
149	0·5538	0·5530	0·5533	0·5529
151	0·3261	0·3258	0·3258	0·3258
153	0·1795	0·1792	0·1791	0·1781
155	0·0742	0·0741	0·0738	0·0716
157	0·0199	0·0198	0·0194	0·0166
159	0·0038	0·0036	0·0032	0·0008
		33·15° Edge		
143	1·0000	1·0000	1·0000	1·0000
145	0·9983	0·9979	0·9983	0·9981
147	0·9149	0·9147	0·9150	0·9136
149	0·5521	0·5523	0·5525	0·5525
151	0·3306	0·3304	0·3306	0·3310
153	0·1897	0·1899	0·1900	0·1896
155	0·0848	0·0850	0·0850	0·0833
157	0·0240	0·0246	0·0243	0·0219
159	0·0039	0·0041	0·0037	0·0015

measured analysing magnet edge fields showed agreement to within 0·05° for each of the edge angles and within 0·5 in. in overall focal length; curvature for spherical aberration correction was relatively insensitive and remained the same.

Table 3 indicates the saturation properties of the analysing magnets; maximisation of the radius of curvature yields excellent linearity up to our maximum field specification of 12·5 kG.

Table 4 shows edge field data for one of the analysing magnets at four excitation levels, covering lowest to highest fields, measured using the rotating coil fluxmeter, normalised to unity at the edge of the flat region.

By cycling of the current before reaching the final setting, a field uniformity of better than 1 part in 2000 over the flat region is obtained, with the edge fields as in Table 4. Clearly, extremely linear optical properties can be expected over the entire operating range. A reproducibility of better than 1 part in 10 000 in energy can be expected;[6] from the above data the absolute energy calibration should also approach this value, and reproducibility should exceed it.

A small difference exists between edge shapes at each end; this difference has been included in orbit calculations using the fields. The two analysing magnets were identical in field to within the accuracy of the measuring devices.

Results of orbit tracing in the measured analysing magnet fields indicate that the first order resolution of 0·012% per millimetre in energy can be achieved. Limits can also be placed on the aberration coefficients, the most important of which are (in the x, θ, z, Φ co-ordinate system):

$$(x, \theta_0^2) < 0{\cdot}0025 \text{ mm/mr}^2$$

$$(x, \Phi_0^2) < 0{\cdot}0001 \text{ mm/mr}^2$$

$$(z, \theta_0 \Phi_0) \sim 0{\cdot}05 \text{ mm/mr}^2.$$

The first two of these are negligible; the third leads to significant blow-up of axial phase space, and results in limits on the phase space acceptable in the magnet system, which can be avoided by appropriate shaping of the input beam phase space.[2]

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