SUPERCONDUCTING CYCLOTRONS FOR NEUTRON THERAPY*

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Abstract

This paper describes a sequence of numerical studies of possible magnets for superconducting neutron therapy cyclotrons along with a comparison room temperature case. The cases studied represent a collection of likely combinations of magnetic, radiofrequency and therapeutic characteristics and provide a quantitative basis for assessing the pros and cons of various options (at least as regards the characteristics of the cyclotron magnet).

Text

The choice of projectile type, projectile energy and magnetic field level for a superconducting neutron therapy cyclotron involves rather intricate tradeoffs in which design advantages of compact magnets must be weighed against advantages of using standard RF frequencies and against possible theraputic advantages of different neutron spectra from various projectiles and different levels of residual radioactivity. Quantitative aspects of the magnet design component of this tradeoff can now be accurately computed using a combination of two dimensional relaxation calculations, and three dimensional full saturation calculations, following procedures developed and tested in the design of large superconducting cyclotrons for nuclear research.1) This paper presents results of such computations for six cyclotron configurations considered to be likely systems for use in neutron therapy. For comparison a study of a similarly optimized room temperature cyclotron is also included.

The six cases include three combinations of projectile and energy, namely, 50 MeV protons, 50 MeV deuterons, and 75 MeV ^{3}He's. For each of these cases relaxation calculations were made using the programs2) Trim or Poisson to determine a required magnet configuration. (Calculations of this type have been found to be highly accurate giving results which agree with measured field values to within one of two percent1).)

A typical relaxation grid for one of the seven configurations is shown in Fig. 1. The symmetry of the magnet about the r=0 axis and the z=0 plane, is accounted for by imposing appropriate boundary conditions at these edges of the grid. The region outlined in bold black is occupied by conventional 1020 low carbon steel with dimensions of significant points, in inches, indicated by bold numerals. The magnet coil is the rectangle with a bold lined X and the pole tip region and dee stem regions are assumed to be partially occupied by iron to the fractional degree indicated by the multiplier beside the label "M".

For all of the configurations the magnet is taken to be a three-sector dee-in-valley structure with spiral to enhance the focussing. The computations included evaluation of equilibrium orbit characteristics for each configuration to check isochronism and focussing.

The seven configurations studied are listed in Table I. Four of the configurations are for protons, the first listed, named "K50C", being the conventional field compariosn case using an isochonous central field "B_0" of 13.1 kilogauss and, inadvertantly, a significantly lower final energy (31 MeV). The next proton case named "K50" is the fifth entry in the table and is based on an "easy" or "natural" magnet design for particles of this energy, namely, a 31 kilogauss central field. This natural proton magnet unfortunately involves an awkward rf frequency (143 Mhz). A high field alternate (K50H) corresponding to a "standard" 200 MHz linear accelerator radio frequency system, and a low field alternate (K50L) corresponding to an FM band transmitter operating at 110 MHz were therefore also computed. The high field case is not fully realistic since focussing is inadequate even with a severe spiral;3) a reduced magnet gap would need to be employed to provide adequate forcussing for this configuration (details of such a configuration have not been persued).

For deuterons only one configuration was calculated (designated D50 in the table) since for deuterons the natural magnet design corresponds to a frequency in the standard FM band, namely 105 MHz. Two ^{3}He systems were computed designated K76 and K75. The differences between the two are small, namely, tailoring of the field edge to allow the internal beam to go closer to the physical edge of the magnet in one case than in the other. For the ^{3}He the RF Frequency was picked to be in the standard FM range for both cases since the resulting magnetic field is reasonably close to the natural optimum value for this projectile. Primary geometrical features for all of the structures studied are shown in Figs. 2-8.

Table II gives the computed average magnetic field as a function of radius for the seven magnet configurations illustrated in Figs. 2-8. Equilibrium orbit properties, which are not presented, indicated good focussing for all the structures studied with the exception of the K50H, where a smaller magnet gap would be necessary to obtain adequate vertical focussing.

Turning again to Table I, we see from the last column, which gives the magnet weight, that conventional rules for cyclotron size are strongly modified in the high field situation. Thus, from the

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usual scaling rules for low field cyclotrons we expect a 50 MeV deuteron cyclotron to involve a magnet which is twice as heavy as that for a 50 MeV proton cyclotron and we expect a 75 MeV ^{3}He cyclotron to have a magnet which is the same weight as that of a 50 MeV proton cyclotron. If high field cyclotrons of comparable magnetic field are compared in the table we see that these rules are approximately obeyed, namely the D50 case involves a magnet of approximately twice the weight of the K50H, and the K76/K75 involve magnets of approximately the same weight as the K50. The K50H however is not adequately focused and when the magnetic field is lowered to provide adequate focusing the weight of the magnet increases and if it is lowered still further to the K50L case to bring the RF into an easy range the magnet weight increases still furtherand becoming comparable to the D50 weight. If the room temperature (K50C) case is scaled to an energy of 50 MeV a magnet weight of approximately 45 tons is inferred. This is substantially less than the typical 100 ton weight of a 50 MeV room temperature cyclotron and reflects the efficiency of the cylindrical, close-in yoke, dee-in-valley magnet design. The magnet is of course much more massive than the high field magnets--scaling to 50 MeV deuterons a room temperature magnet of 90 tons is inferred.

For most of the configurations preliminary RF design studies have been carried out using the segmented transmission line approximation. These studies establish that a conventional half wave resonantor structure of the type used in superconducting cyclotrons designed for research$^{4)}$ would comfortably provide for the acceleration requirements in all the configurations studied.

Conclusions

Many combinations of magnetic field, projectile type, and projectile energy lead to realistic designs for superconducting neutron therapy cyclotrons. The weight difference between deuteron and proton cyclotrons of equal energy is considerably less than the difference which would hold for room temperature cyclotrons and is particularly reduced if both cases are constrained to run at RF frequencies in the standard RM range.

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References

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TABLE I. Important characteristics of the magnet configurations included in the study.

Case Label	Projectile	Energy (MeV)	RF Freq (MHz)	Isochronous magnetic field B_0(kilogauss)	Target radius (inches)	Magnet Stored Energy (Megajoules)	Magnet Weight (U.S. Tons)
K50C	proton	31	60.4	13.1	24.0		28.2
K76	^{3}He	75	109.7	35.899	11.64	0.77	13.1
D50	deuteron	50	105.1	45.923	12.17	1.87	20.1
K75	^{3}He	75	108.7	35.574	11.80	0.92	12.4
K50	proton	50	143.1	31.287	12.36	0.60	13.4
K50H	proton	50	200.0	43.413	8.8	1.10	10.4
K50L	proton	50	111.5	24.379	15.8	0.52	16.0

TABLE II. Computed median plane average magnetic field in kilogauss vs. radius in inches for the seven cases studied. Magnets have geometry as shown in Figs. 2-8.

RADIUS	K50C	K76	D50	K75	K50	K50H	K50L
0.00	13.575	34.263	44.622	34.314	30.109	43.78	24.054
0.25		34.389	44.729	34.431	30.212	43.78	24.185
0.50	13.535	34.748	45.058	34.789	30.527	43.76	24.508
0.75		35.303	45.581	35.344	31.011	43.70	24.823
1.00	13.499	35.889	46.173	35.928	31.508	43.64	24.881
1.25		36.163	46.418	36.193	31.704	43.62	24.695
1.50	13.483	36.108	46.329	36.117	31.597	43.61	24.478
1.75		35.965	46.156	35.941	31.420	43.60	24.356
2.00	13.479	35.858	46.021	35.794	31.290	43.62	24.337
2.25		35.803	45.936	35.692	31.215	43.63	24.310
2.50	13.478	35.782	45.890	35.623	31.175	43.64	24.297
2.75		35.780	45.869	35.578	31.157	43.65	24.286
3.00	13.477	35.790	45.865	35.550	31.153	43.66	24.278
3.25		35.810	45.873	35.536	31.159	43.67	24.271
3.50	13.477	35.831	45.890	35.533	31.172	43.68	24.266
3.75		35.851	45.912	35.538	31.192	43.72	24.264
4.00	13.476	35.872	45.934	35.547	31.217	43.77	24.264
4.25		35.893	45.957	35.558	31.246	43.83	26.266
4.50	13.476	35.925	45.979	35.570	31.277	43.89	24.271
4.75		35.925	45.999	35.582	31.310	43.95	24.276
5.00	13.475	35.939	46.018	35.593	31.346	44.01	24.293
5.25		35.951	46.036	35.605	31.381	44.10	24.322
5.50	13.474	35.963	46.054	35.618	31.416	44.17	24.375
5.75		35.977	46.073	35.633	31.452	44.25	24.376
6.00	13.474	35.996	46.094	35.652	31.487	44.33	24.352
6.25		35.016	46.118	35.671	31.520	44.44	24.335
6.50	13.473	35.037	46.143	35.691	31.553	44.53	24.325
6.75		36.059	46.170	35.718	31.588	44.66	24.321
7.00	13.473	36.084	46.200	35.748	31.621	44.76	24.324
7.25		36.112	46.231	35.776	31.655	44.88	24.333
7.50	13.472	26.140	46.265	35.807	31.695	45.00	24.347
7.75		36.169	46.302	35.843	31.734	45.13	24.366
8.00	13.472	36.204	46.340	35.882	31.775	45.28	24.388
8.25		36.238	46.380	35.923	31.823	45.40	24.415
8.50	13.471	36.274	46.422	35.963	31.871	45.56	24.445
8.75		36.313	46.466	36.007	31.928	45.70	24.478
9.00	13.471	36.360	46.513	36.057	31.988	45.77	24.513
9.25		36.407	46.561	36.108	32.052	45.79	24.550
9.50	13.471	36.464	46.613	36.160	32.122	45.76	24.589
9.75		36.523	46.669	36.215	32.196		24.631
10.00	13.470	36.591	46.726	36.275	32.274		24.673
10.25		36.667	46.784	36.340	32.355		24.717
10.50	13.471	36.750	46.845	36.416	32.441		24.763
10.75		36.837	46.906	36.505	32.530		24.810
11.00	13.471	36.929	46.966	36.605	32.619		24.859
11.25		37.030	47.027	36.732	32.710		24.911
11.50	13.470	37.147	47.092	36.852	32.803		24.963
11.75		37.252	47.172	36.733	32.906		25.018
12.00	13.470	37.152	47.264	35.918	33.019		25.075
12.25		36.392	47.290	34.251	33.134		25.134
12.50	13.470	34.771	47.104	32.264	33.249		25.196
12.75		32.809	46.224	30.403	33.314		25.259
13.00	13.470	30.964	44.304	28.702	33.087		25.323
13.25			40.587	27.092	32.180		25.389
13.50	13.469	27.714		23.340	30.487		25.455
13.75				19.273	28.474		25.519
14.00	13.469	20.621		15.087	26.567		25.579
14.25				10.976	24.822		25.633
14.50	13.468	13.067		7.159	23.163		25.678
14.75				3.968	20.205		25.711
15.00	13.467	6.126		1.628	17.093		25.731
15.50	13.466						25.779
16.00	13.466						26.098
16.50	13.467						26.430
17.00	13.466						26.098
17.50	13.465						23.850
18.00	13.464						20.521
18.50	13.462						17.979
19.00	13.457						15.823
19.50	13.451						
20.00	13.443						
20.50	13.436						
21.00	13.425						
21.50	13.410						
22.00	13.388						
22.50	13.358						
23.00	13.314						
23.50	13.248						
24.00	13.168						
24.50	13.053						
25.00	12.885						
25.50	12.646						
26.00	12.295						
26.50	11.757						
27.00	10.843						
27.50	9.269						

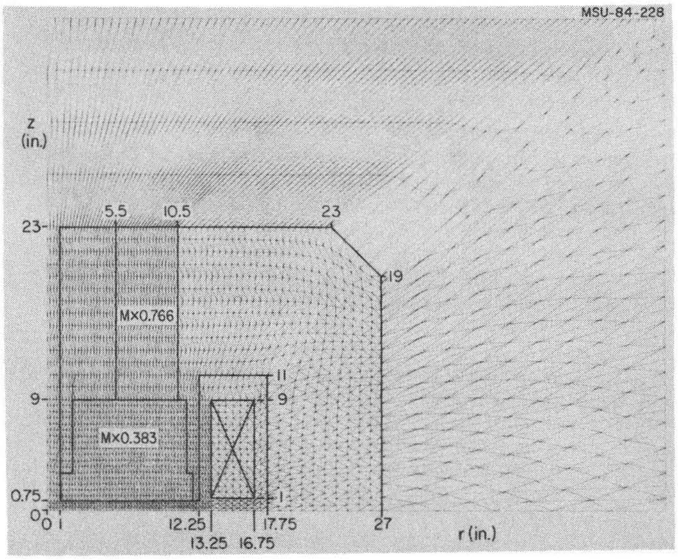

Fig. 1. Typical relaxation grid used in calculating the cyclotron average magnetic field.

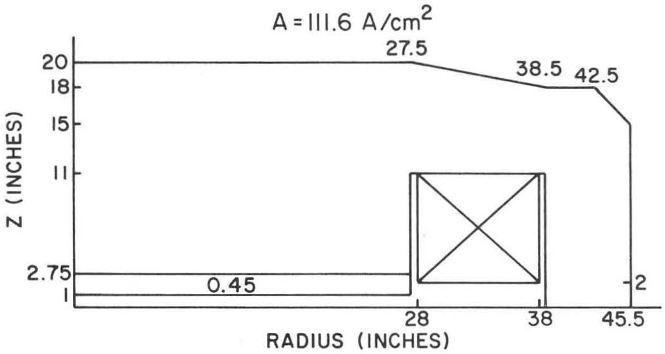

Fig. 2. Magnet geometry for the low field comparison configuration (label K50C). The quantity A in this and following figures is the current density in the coil in amperes per square centimeter.

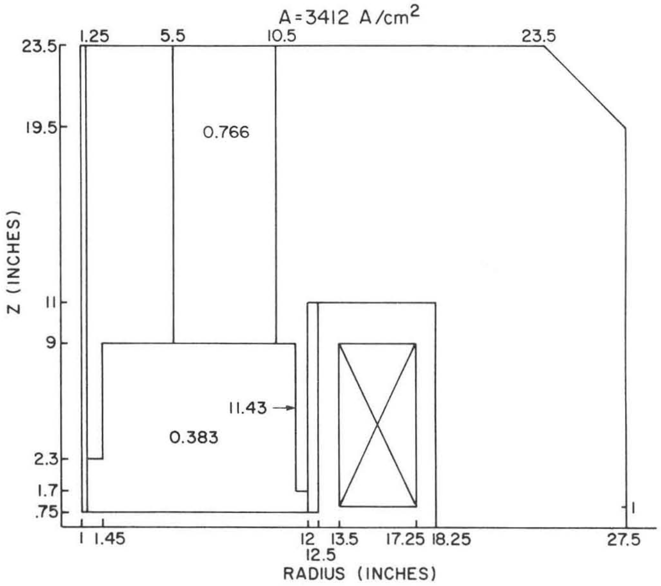

Fig. 3. Magnet configuration for a ^{3}He configuration (label K76).

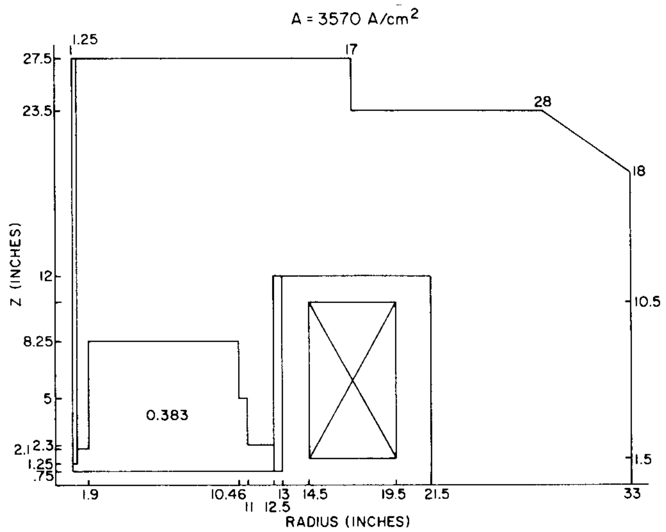

Fig. 4. Magnet configuration for a deuteron cyclotron (label D50).

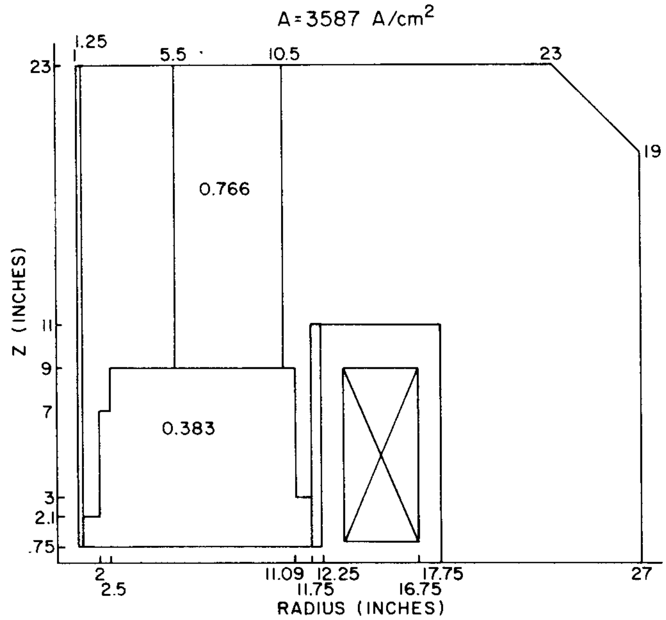

Fig. 5. Magnet configuration for an alternate ^{3}He configuration with tightened magnet edge (label K75).

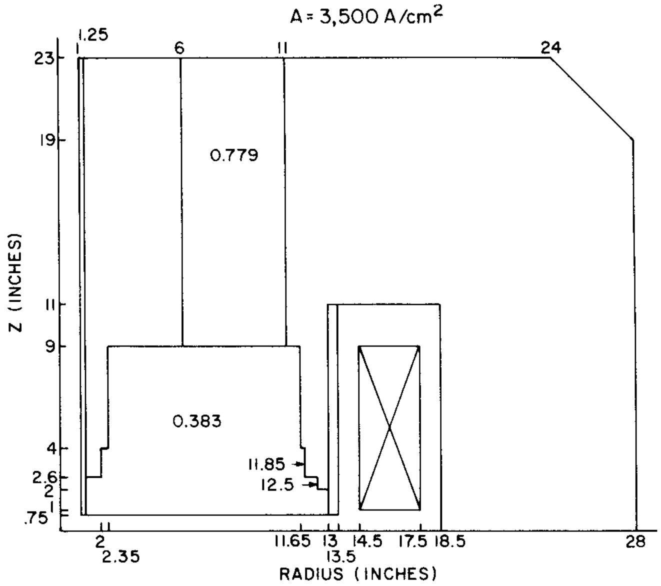

Fig. 6. Magnet configuration for an easy proton magnetic field (label K50).

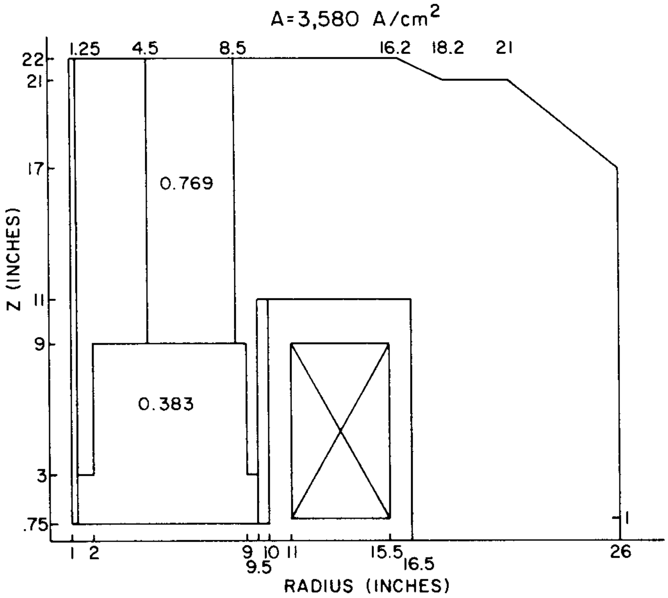

Fig. 7. Magnet configuration for a high field proton cyclotron (label K50H).

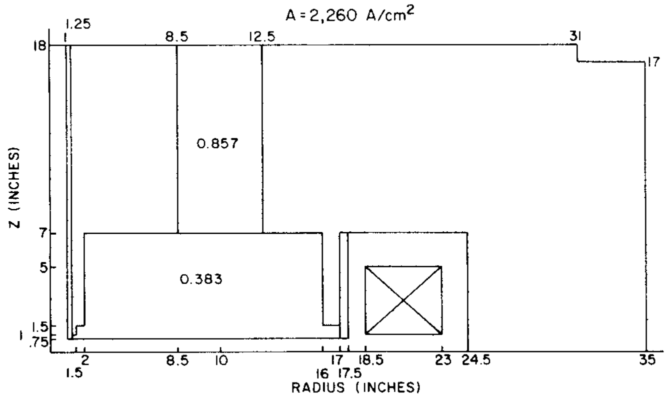

Fig. 8. Magnet configuration for a proton cyclotron with magnetic field selected to give an RF frequency in a standard FM band (label K50L).