DESIGN, CONSTRUCTION AND COMMISSIONING OF A SIMPLE, LOW COST PERMANENT MAGNET QUADRUPOLE DOUBLET.

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In the framework of new beam line developments at the Australian National Medical Cyclotron, a permanent magnet quadrupole doublet was designed and built entirely in house. The design proceeded from the classical work by Halbach et al. but emphasised the "low cost" aspect by using simple rectangular NdFeB blocks and simple assembly techniques. Numerical simulations using the (2-D) Gemini code were performed to check the field strength and homogeneity predictions of analytical calculations. This paper gives the reasons for the selection of a permanent magnet, the design and construction details of the quadrupole doublet and its field measurement results.

1. Introduction

A new beam line has recently been developed at the National Medical Cyclotron, Sydney Australia, for radionuclide production [1]. After the initial development of this beam line it was realised a second quadrupole doublet was required, with similar specifications to the original variable quadrupole doublet, to focus the beam to the correct spot size at the target. The original quadrupole doublet is a standard 4 pole variable field strength unit (6.7 T/m in a 100 mm bore), requiring two dc power supplies (35 amps, 70 volts). Although two quadrupole doublets were required, only one needs to be variable for fine tuning of the proton beam on the target, since the range of energies to be transported through this line is restricted to 26-30 MeV. The addition of a second variable quadrupole doublet would also be a costly modification to the beam line.

Therefore, as a low cost alternative, a permanent quadrupole design was implemented using small NdFeB magnet blocks to generate the required field patterns. The permanent quadrupole doublet developed here was less than 20% the cost of a variable quadrupole doublet, with the component design and manufacture performed completely in house within an 8 week period. Having one of the quadrupole doublets permanently set to the correct field strength simplifies the beam set up considerably.

2 Permanent Magnet Quadrupole Field Generation

The theoretical considerations underlying the design of permanent magnet multipoles were developed in the early 80's, after the development of rare earth magnetic materials made it possible to build extremely compact devices with high field strength [2],[3]. The emphasis in this work is more the "low cost" aspect rather than the high performance, therefore we chose to use "off the shelf" NdBFe rectangular blocks and to arrange them in a simple mechanical fixture. The use of rectangular blocks induces some higher harmonic components in the field, the intensity of the n^{th} decreasing with the $(n-1)^{th}$ power of the radius [4]. Therefore, a good approximation of a "true" quadrupole can be obtained over a given radius by locating the magnet blocks at a radius larger than the physical size required: this is how a lower limit was set on the device's physical radius.

Besides those theoretical calculations, some numerical simulations were performed using a 2-D finite element software package [5] to confirm the field homogeneity and to calculate the forces in order to design the support structure.

The final layout of the doublet comprises 8 magnet bars with a cross section of $20x30mm^2$ and made up of NdFeB blocks, each $20x20x30\ mm^3$. A total of 168 blocks are used in the final doublet.

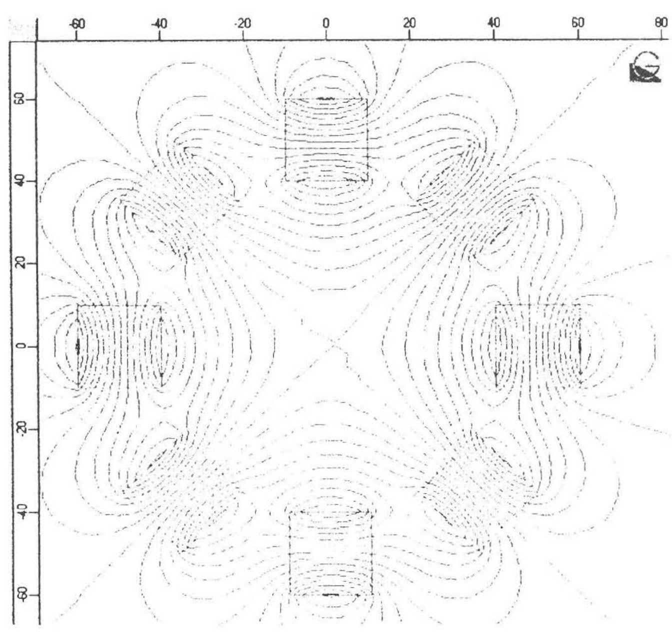

Figure 1: 2-D simulation showing flux lines of one of the tested configurations

3 Design and Construction of the PMQ Assembly

The design of the assembly to hold the permanent magnets for the quadrupole doublet needed to meet the following requirements

1. Arrange magnets in the correct orientation over the required doublet length
2. Constructed of non magnetic materials
3. Low cost
4. Physically compact
5. Easy to assemble and modify
6. Quick installation / removal on the beam line pipe
7. Provide some degree of alignment with respect to beam pipe.

The quadrupole assembly design that meets the above requirements is shown in figure 2. The small permanent magnet blocks are enclosed in rectangular aluminium tubes held in the required orientation by a series of aluminium flanges and stainless steel threaded rods. With the magnet blocks held closely together in the aluminium tubes the required quadrupole field pattern is created. A spacer block is used to separate the magnets in each of the rectangular tubes into two sections. The magnets in the first section are orientated to focus in the horizontal plane, while the magnets in the second section are orientated to focus in the vertical, thus creating the doublet in the same housing. The length of each quadrupole is adjusted by simply varying the number of magnets in that section.

Each rectangular tube is closed at one end by a flange with set screws that enter each tube. The other ends are closed off with end blocks that are removed to load the permanent magnets. Once the magnets for both sections, with the spacer block in between, are loaded into a particular rectangular tube, the end block is secured. The bolt in the flange at the opposite end of the rectangular tube is then used to compress the magnets together.

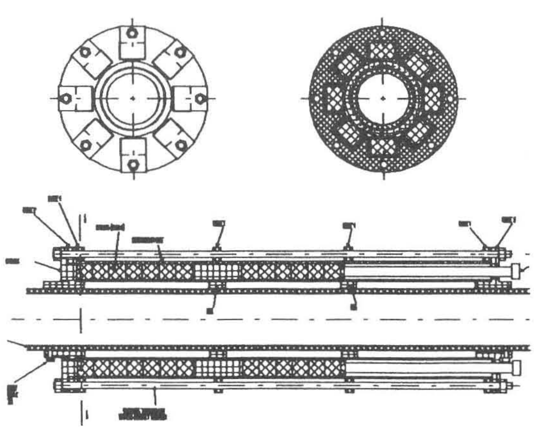

Figure 2: PMQ general assembly drawing

Once all the required magnets are loaded into the rectangular tubes and compressed together, the permanent quadrupole assembly is complete and ready to install onto the beam line, (Fig.3). The permanent quadrupole assembly is easily slid onto the beam line pipe and secured using the 3 locking screws at each end, these are also used to align the quadrupole to the beam path centre. The beam pipe is then inserted in the beam line with the permanent quadrupole assembly attached.

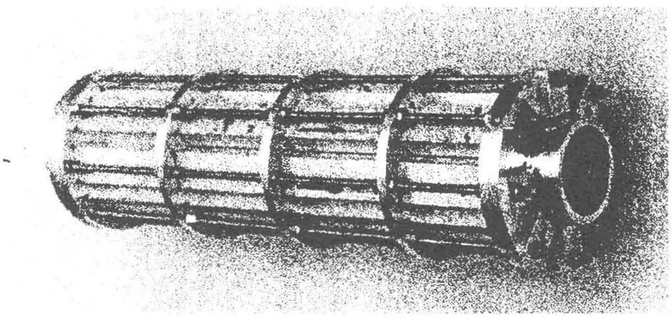

Figure 3: The completed permanent magnet quadrupole doublet

The permanent quadrupole assembly was thus installed on the new SPECT beam line, (fig.4). The size of the permanent quadrupole assembly is approximately 1/4 the size of a conventional doublet of the same maximum strength.

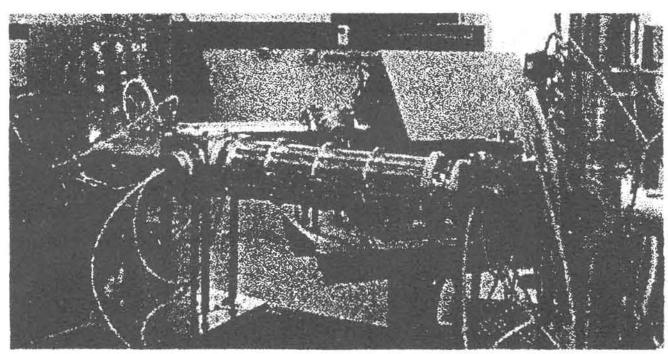

Figure 4: PMQ installed in new beam line

4. Field Measurements

The NdFeB magnets used here have a remnant field strength of 1.1 Tesla, which was calculated to give a quadrupole field gradient of 7.5 T/m. With the quadrupole doublet fully assembled, the first element, had a length of 200mm and the second 180mm. Some coarse magnetic field measurements were performed to confirm the field gradient and its departure from a constant value over the radius (higher order harmonics). The field measurements were performed using a lathe with digital readouts: the PMQ assembly was set up on the lathe bed with one end in the chuck and a Hall effect probe with a transverse sensing

direction was attached in the tool holder. This set up allowed us to map quickly the field's radial and tangential components along the radius and parallel to the z axis.
The above measurements confirmed the permanent magnet assembly generates a good approximation of a quadrupole, with a constant gradient of 7.3 T/m over 70% of the magnet radius. The edge measurements show a typical "S" shaped curve with the 50% value located exactly over the physical magnet edge.

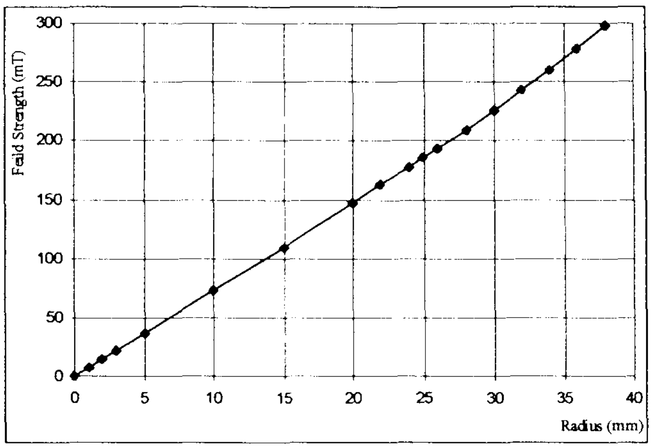

Figure 5: B vs radius inside magnet structure

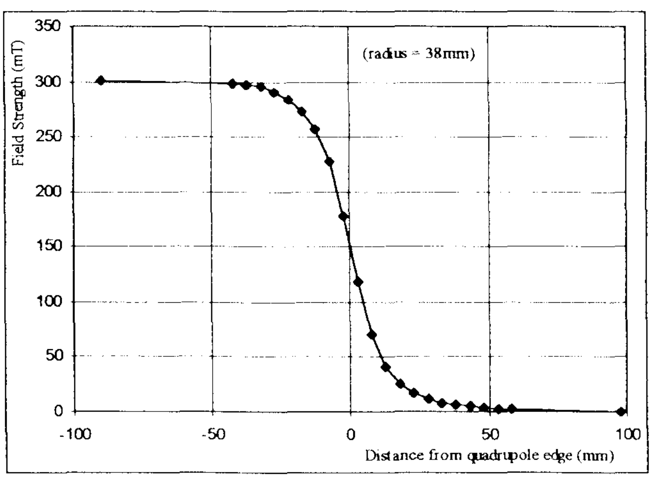

Figure 6: B vs z at 38mm radius

5. Commissioning

Initial beam tests performed on the new SPECT beam line without the use of either quadrupole doublet resulted in 10% of the beam incident upon the target which is located 6 metres away from the cyclotron exit. Beam tests with the PMQ in place and the active doublet in the beam room set at the predicted value allowed us to meet the goal of 90% of the beam on target.

6. Conclusions

The permanent magnet quadrupole developed here gave an alternative to a conventional variable quadrupole doublet with the advantage of being low cost (about 20% of an equivalent active doublet), of compact size with a simple assembly that allows in house manufacture.

References

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