# MAGNET SYSTEM FOR A COMPACT MICROTRON*

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*Abstract*

A compact microtron can be an effective gamma source that can be transported to locations outside the laboratory. As part of a Phase I study we have studied a portable microtron that can accelerate electrons with energies of 6 MeV and above as a source for gamma and neutron production. The mass of the magnet is a significant contribution to the overall mass of the system. This paper will discuss conceptual designs for both permanent magnet and electromagnet systems. The choice of microtron RF frequency range is determined by the application requirements. The RF frequency band influences the size of the microtron magnet and consequently its weight. We have looked at how the design would vary with the different frequency configurations.

## INTRODUCTION

There is a growing need for compact accelerators for security and medical applications. These applications may involve the ability to transport the accelerator to outside locations where operating resources may be limited. A microtron can accelerate electrons to 6 MeV and above with intensities 10 to 100 times greater than with a betatron. The electron beam can be extracted to targets for gamma ray production. With a microtron designed to produce electrons with energies greater than 9 MeV, the microtron can with an external target be an intense neutron source. This paper describes the magnet system for a compact microtron. The dimensions of the magnet vary with the RF frequency. Higher frequency microtrons have smaller dimensions and consequently weigh less. The frequency choice does depend on the application. In this study we have looked at magnet designs for X-band, C-band and S-band microtrons. Table 1 summarizes the parameters used to describe a microtrons in each of these frequency bands. Similar parameters are shown for the 6.5 MeV and 9.5 MeV microtrons with the difference being the number of orbits before extraction.

Although the X-band microtron would be smaller and lighter which would be beneficial for portability the lifetime of the emitter cathode is too short to be practical and replacement of the emitter would require breaking the vacuum seal and opening the RF cavity making this less desirable.

Table 1: Microtron Parameters

| Parameter | Unit | X-band | C-band | S-band |
|---|---|---|---|---|
| Frequency | GHz | 9.3 | 5.85 | 2.8 |
| Wavelength | mm | 32 | 51 | 107.1 |
| Cyclotron Field | Oe | 3319 | 2088 | 1000 |
| Magnet Field | Oe | 2655 | 2506 | 1800 |
| ΔE per turn | $mc^2$ | 0.8 | 1.2 | 1.8 |
| 6½ MeV Turns | | 15 | 12 | 7 |
| 9½ MeV Turns | | | 15 | 10 |
| Cathode Lifetime | hrs | 10 | 500 | 1000 |

We have examined three candidate magnet designs. These included (1) a permanent magnet without coils, (2) a hybrid magnet where the dominant part of the field comes from the permanent magnet material, but with trim coils to provide some variation of the magnetic field for tuning and (3) a conventional magnet with copper coils and iron poles.

The uniformity of the magnet field is an important consideration. The field must be uniform over the region where the beam traverses with a field non-uniformity error $\Delta B/B<1/n^2$ where n is the number of orbital turns in the microtron.

## PERMANENT MAGNET OPTION

The advantage of using a permanent magnet is that no power supply would be necessary. This could be very important for operation away from a location where electricity and cooling water may not be readily available. Permanent magnet materials that have been used for magnets include Alnico, ferrite, neodymium ($Nd_2Fe_{14}B$) and samarium cobalt ($SmCo_5$ and $Sm_2Co_{17}$). Although Alnico has a large remnant field ($B_R$), it has a strong demagnetization curve because of its small coercivity which makes it undesirable. Ferrites have been previously used for accelerator applications, but it does not have a large enough $B_R$. The cobalt in the SmCo material can become strongly radioactive from the beam and this material tends to be more expensive. Neodymium is the best choice for permanent magnets and it is used for many industrial applications. The large variation in $B_R$ with temperature is a concern. This is particularly true for operation outside of a temperature controlled environment. A temperature compensation scheme would be necessary for using the permanent magnet option. This will be discussed.

Figure 1 shows an R-Z sketch of a template to define the geometry using a permanent magnet. The geometry parameters shown in the figure depend on the cavity frequency and the output beam energy. Table 2 shows the parameters found for the S-, C-, and X-band configurations.

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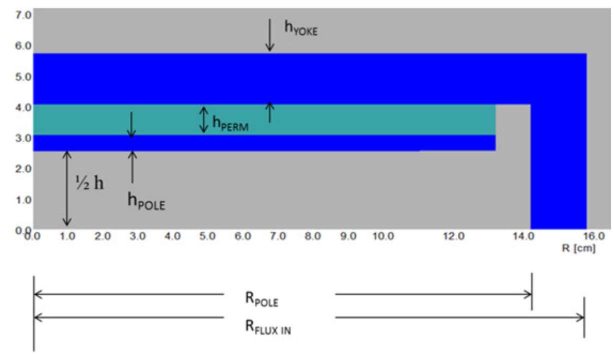


Figure 1: Sketch of the geometry template for a permanent magnet microtron. The figure defines the parameters.

Table 2: Geometry Parameters of a Permanent Magnet Microtron for Different Frequency Bands

| Symbol | Description | X-band | C-band | S-band |
|---|---|---|---|---|
| H | Gap Height | 32 | 51 | 107 |
| N | Number of Turns | 15 | 12 | 12 |
| $D_N$ | N-turn Diameter | 196 | 212 | 443 |
| $R_{POLE}$ | Pole Radius | 98 | 131 | 275 |
| $h_{POLE}$ | Height of Iron Pole | 10 | 10 | 10 |
| $h_{Nd}$ | Height of Neo | 10 | 10 | 15 |
| $h_{YOKE}$ | Height of Yoke Top | 13 | 16 | 20 |
| $R_{FLUX\ IN}$ | Inner Radius Flux Rtn | 108 | 141 | 285 |
| $R_{FLUX\ OUT}$ | Outer Radius Flux Rtn | 121 | 156 | 310 |
| W | Magnet Mass | 24 Kg | 46 Kg | 247 Kg |

There must be enough iron not only to achieve the maximum field from the permanent magnet, but also to minimize the stray fields outside the magnet. As we also want to minimize the weight of the magnet, the thickness of the flux return was chosen to keep the permeability greater than 100 (the minimum at a local spot at the end of the pole). The magnet mass for the different configurations considered is shown in Table 2.

An important issue for permanent magnet material is its dependence on temperature. For most magnetic materials the change in magnetization $\frac{d\log(B_R)}{dT}$ is approximately constant over a large temperature range. The rate of variation is largest for those materials close to their Curie temperature. There is a correlation between $B_R$ and the temperature dependence parameter d log($B_R$)/dT where the neodymium material with larger $B_R$ also has a larger temperature variation. We have chosen to use the material with the smaller temperature dependence which has $B_R$=1.1 T and d log($B_R$)/dT=–0.08%/°C. The approach to temperature compensation is to provide in addition to the permanent magnet material a magnetic shunt whose flux falls faster with temperature than the permanent magnet material. Ni-Fe and Ni-Cu alloys have been used as shunts for temperature compensation. Ni-Fe with 30% Ni appears to be an optimal choice. The ratio of the Ni-Fe shunt to $Nb_2Fe_{14}B$ material is 19%. $Nb_2Fe_{14}B$ is commercially available in a number of sizes. Figure 2 shows an array of 1”×1”×3/8” blocks with Ni-Fe strips between the blocks for temperature compensation.

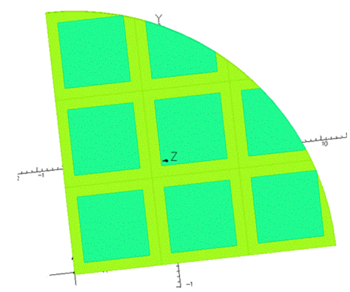

Figure 2: A quarter of the magnetic pole comprised of $Nb_2Fe_{14}B$ blocks arranged in an array with Ni-Fe strips interleaved for temperature compensation.

There are certain issues associated with using the neo-dymium material. Each block is attracted to the adjacent iron with a force of 30 to 55 lbs (depending on the $B_R$ chosen). Disassembling the blocks from the pole steel would be very difficult. Specification sheets of the per-manent magnet material indicate that the material can have a ±3% variation of $B_R$. There is also a large varia-tion of the polarization direction. The variation can be reduced by rejecting samples with large deviations which can increase the cost. We have performed a study where the magnet was composed of material with a $B_R$ variation of ±3%. The ΔB/B non-uniformity in the aperture was examined as a function of the iron pole thickness. With $h_{POLE}$=10 mm ΔB/B would be 0.2%. The permanent magnet would need a separate vacuum-sealed chamber, which would increase the complexity and weight of the microtron. Disassembly and reassembly of the permanent magnet microtron may introduce positioning errors of the vacuum chamber relative to the magnet. A permanent magnet precludes varying the field or changing the microtron energy. Because of the short lifetime of the cathode for the X-band microtron the use of a permanent magnet may not be feasible.

As an additional alternative we have examined using the permanent magnet option but adding trim coils to provide some ability to tune the magnetic field so that the beam will arrive at the cavity with the proper phase. Since the demagnetization curve for $Nb_2Fe_{17}B$ is linear over a large range, the magnetization will return to its original value when the current is turned off, one can add coils to the permanent magnet so long as the field from the coils does not exceed the linear range of the demagnetization curve. The current carried in the trim would be much smaller than that necessary to provide the entire field. The simu-lations showed that this would be a viable alternative, however to change the energy of the microtron in a notable range would need an electromagnet with significant current. The problems of disassembly of the hybrid magnet would be the same as the permanent magnets.




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## ELECTROMAGNET OPTION

Magnets with coils have been typically used for microtron applications. These magnets need ample power for their operation and could require cooling for the power generated in the coils. Using coils allows greater flexibility. The magnet field could be varied to allow tuning to keep the beam on resonance in the microtron. It could also be used change the output energy by varying the magnetic field.

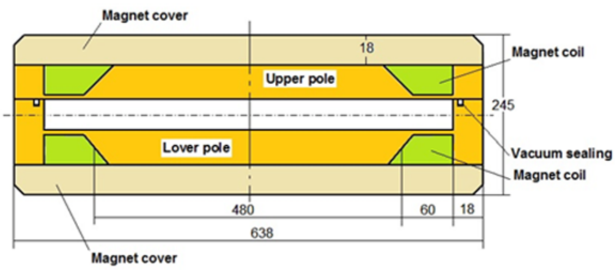


Figure 3: Template of electro-magnet geometry.

Figure 3 shows a sketch of an electro-magnet that was used as a template for the microtron magnet. In this figure the iron pole and flux return serve as the vacuum containment with an indium seal between the upper and lower poles. The coils have a trapezoidal shape to provide a better shaping of the field at larger radius. Table 3 shows the parameters for the electromagnet geometry for different microtron configurations. The design criteria were to minimize the magnet weight, to keep the iron permeability greater than 100 and to keep the current density to approximately 3 A/mm$^2$.

The table also shows the total mass of the magnet system for the different frequency bands for the Fig. 3 design. Much of the central part of the flux return top hat is not saturated and can be removed to reduce the magnet weight. The reduced mass is shown in the last line of the table. The mass of the electromagnet is significantly larger than the corresponding permanent magnet system. One can still imagine that microtron with the electromagnet could be put on a truck for mobility. The magnet pole can be shaped to provide the high field uniformity necessary for the microtron magnet. Figure 4 shows the field profile for the S-band magnet after the optimization of the pole shape. The figure shows that the largest deviation in field over the region where beam is present can be held to $\Delta B/B = 0.00024$.

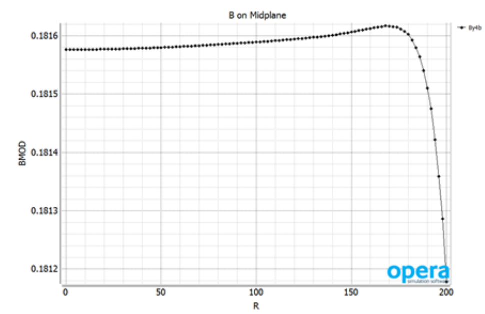


Figure 4: Optimization of the field profile for the S-band magnet.

## CONCLUSIONS

We have investigated the design of a magnet for a transportable microtron to be used as a gamma and neutron source. We have examined the use of a permanent magnet system, but we favour a system where tuning would be possible. We have examined systems with different RF frequency ranges. The smaller and lighter X-band system was ruled out because the lifetime of the emitter system was too short to be commercially practical. The S-band system was chosen for our future R&D studies.

Table 3: Parameters Describing Electromagnet Geometry

| Symbol | Parameter Description | Units | S-Band I | S-Band II | C-Band | X-Band |
|---|---|---|---|---|---|---|
| **U** | Final Beam Energy | MeV | 6.5 | 9.5 | 6.5 | 6.5 |
| **H** | Magnetic Field | T | 0.12 | 0.18 | 0.2088 | 0.2655 |
| **$R_{pole}$** | Mean Inner Coil Radius | mm | 326 | 241 | 132 | 102 |
| **$h_r$** | Flux Return Width | mm | 28 | 26 | 18 | 18 |
| **$h_y$** | Upper Yoke Height | mm | 25 | 26 | 24 | 22.5 |
| **$h_{pole}$** | Height of Pole and Coil | mm | 35 | 59 | 35 | 29 |
| **$R_{yoke}$** | Outer Yoke Radius | mm | 408 | 326 | 201 | 170 |
| **I** | Current in Each Coil | A turns | 5513 | 9234 | 4585 | 3492 |
| **J** | Current Density | A/mm$^2$ | 3 | 2.85 | 2.77 | 3 |
| **$h_{coil}$** | Coil Height | mm | 35 | 54 | 28 | 24 |
| **$b_{coil}$** | Coil Width | mm | 107.5 | 60 | 56 | 48.5 |
| **W** | Total Magnet Mass | Kg | 439 | 339 | 96 | 61 |



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