ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA11

MAGNET SYSTEM FOR A COMPACT MICROTRON SOURCE*

S. A. Kahn†, R. J. Abrams, M. A. C. Cummings, R. P. Johnson, G. M. Kazakevich
Muons, Inc., Batavia, IL, USA

Abstract

A microtron can be an effective intense electron source. It can use less RF power than a linac to produce a similar energy because the beam will pass through the RF cavity several times. To produce a high-quality low emittance beam with a microtron requires a magnetic system with a field uniformity ΔB/B < 0.001. Field quality for a compact microtron with fewer turns is more difficult to achieve. In this study we describe the magnet for a compact S-band microtron that will achieve the necessary field requirements. The shaping of the magnet poles and shimming of the magnet iron at the outer extent of the poles will be employed to provide field uniformity. The extraction of the beam will be discussed.

INTRODUCTION

Microtrons provide a medium energy electron beam with low emittance and a repetition rate consistent with RF frequencies. A microtron is an accelerator based on a resonant kick given to the beam as it passes through an RF cavity multiple times. For a relativistic beam, the energy boost with each circulation through the RF cavity is the same and the trajectory length increases as a multiple of the initial turn. An illustration of the classic microtron is shown in Fig. 1. A description of microtron physics is described in Refs. [1-3].

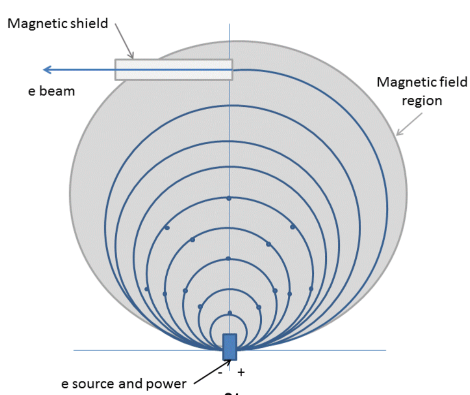

Figure 1: Illustration of microtron concept. Electrons are injected at a source inside the cavity. Electrons receive a boost at each passage through the cavity. Electrons are extracted by a magnetic shield after n turns.

A compact microtron can have industrial, security, and medical applications. To make a microtron more compact, one would reduce the number of turns and increase the magnetic field. This paper describes our approach to do this and the adjustments to the magnet and extraction systems.

MAGNET SYSTEM

The uniformity of the magnetic 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. Generally with larger coil and pole radii the field is more uniform. However, we would like to reduce the microtron radius to make it more compact. Steel shims will be inserted to correct the field non uniformity associated with the smaller radius. Table 1 shows the parameters for an S-band II which is the subject of this study. Also shown are the parameters of an S-band I microtron previously studied [4] which is shown for comparison. Figure 2 shows a not-to-scale sketch of a concept for the microtron magnet. This will be described in a following section. By reducing the size of the microtron fewer turns with larger energy gain per turn will be needed to reach the final energy of the electrons.

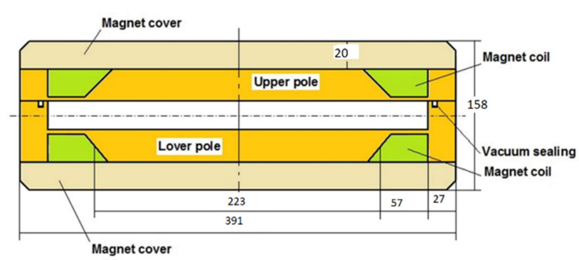

Figure 2: Sketch of microtron S-band II magnet.

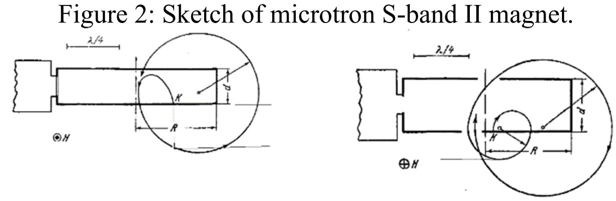

Figure 3: Type I (left) and type II (right) injection schemes as described in Ref.[1].

The parameter Ω shown in Table 1 is the ratio of the increase in energy per turn to its rest energy m_0c^2. Also $\Omega = \frac{H}{H_0}$, in the fundamental mode, where H is the magnetic field and H_0 is the cyclotron field. Figure 3 shows two schemes for injection of electrons into the cavity from a source at the cavity wall. The Type I injection is most effective in the range 1.0 < Ω <1.25 [1]. The Type II injection is most effective in the range 1.8 < Ω < 2.2.

* Work supported by U.S. D.O.E. SBIR grant DE-SC0013795.
† kahn@muonsinc.com

ISBN: 978-3-95450-232-5   ISSN: 2673-7000   doi:10.18429/JACoW-NAPAC2022-TUPA11

Table 1: The parameters describing the microtron used in this study (S-band II) are shown along with parameters used for an S-band I model [4] previously studied.

Parameter	Units	S band II	S band I
Frequency	GHz	2.998	2.801
Final Energy	MeV	6	7
Wavelength	cm	10	10.7
Cyclotron H_0	T	0.107	0.107
Magnet Field	T	0.1926	0.107
Ω		1.8	1.0
N /turns		6	12
N-turn Diam.	cm	22.28	44.32
Pole Diameter	cm	32.28	55.08
Gap	cm	10	10.7

FIELD CALCULATIONS

Figure 4 shows a contour plot of |B| in the R-Z plane of the upper half of the magnet. The dark red regions have fields large enough to satureate the iron. The saturating field in the region above the coil will allow a small amout of field to punch through. The 5 mm thick steel web below the coil also is saturated, but does not seem to have a significant effect on the field in the gap which would be corrected by the shimming process.

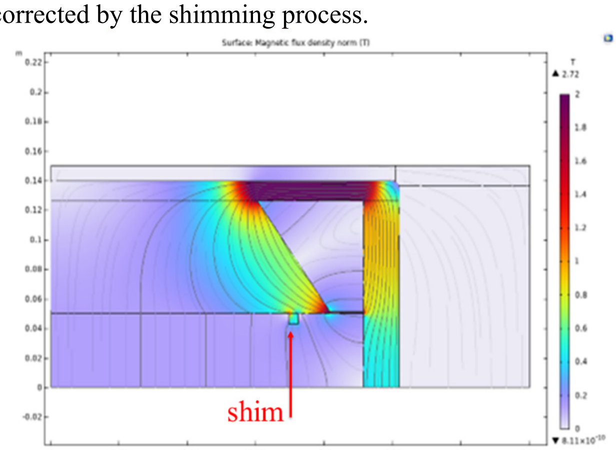

Figure 4: Contour plot of |B|.

Correcting the Field with Shims

A low-carbon steel shim is placed in the gap just below the start of the coil as shown in Fig. 4. The radial position of the shim is located at 1.4 times the radial position of the sixth turn where the beam would be extracted. Figure 5 shows |B| as a function of radial position for different shim sizes. To choose the optimum shim size we looked at the deviation in field in the region between the center and the extraction radius. Figure 6 shows the field deviation as a function of shim cross section area. The field deviation has a minimum at 47 mm^2. This is the size of the shim in Fig. 4.

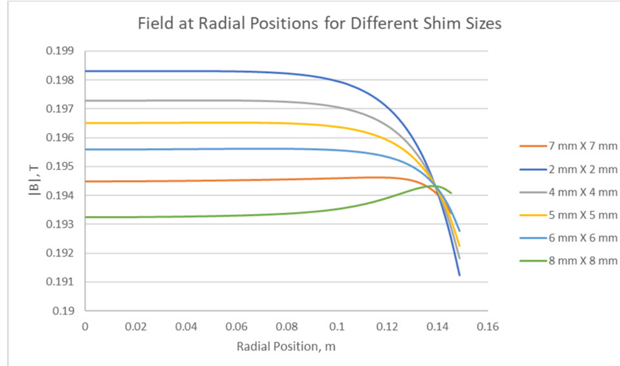

Figure 5: |B| vs. r for different size shims.

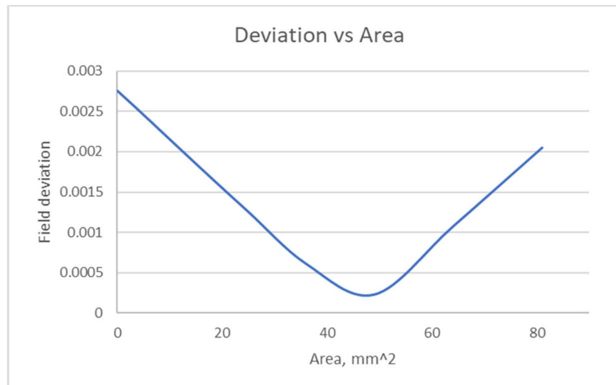

Figure 6: Deviation in Field as a function of shim area.

Other Magnet Issues

The magnet will need to openned periodically to perform maintenance such as replacing the LaB_6 cathode source. To perform the maintenance the upper half of the magnet must be lifted off. The inner magnet gap region must be in vacuum to avoid unwanted interactions. An indium seal is placed between the magnet halves to seal the vacuum.

The copper coils will need to be water cooled. Either copper conductor with an open channel in the conductor center will be used or water tubes will be placed adjacent to the conductors.

BEAM EXTACTION

The electron beam can be passively extracted by placing a low carbon steel tube at the last orbit tangent to the path of the beam. This tube will shield the beam from the magnetic field that keeps the electrons on a circular orbit. This will effectively allow the beam to exit the microtron along a straight path. The shielding steel will perturb the field in its vicinity. To control the field non-uniformity introduced by the extraction channel tube, low-carbon steel compensating rods are introduced. A sketch of the extraction conical tube with the compensating rods is shown in Fig. 7. By adjusting the diameter d of the compensating rods and the extension distance δ the beam extraction the beam extraction efficiency of another microtron had achieved 90-95% [5]. This extraction system can be easily combined with an external target and deflecting magnet for applications such as scanning objects with a gamma beam.

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA11

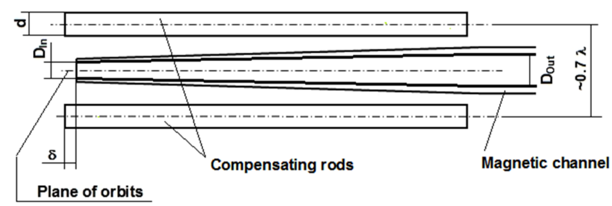

Figure 7: The extracting system for the microtron.

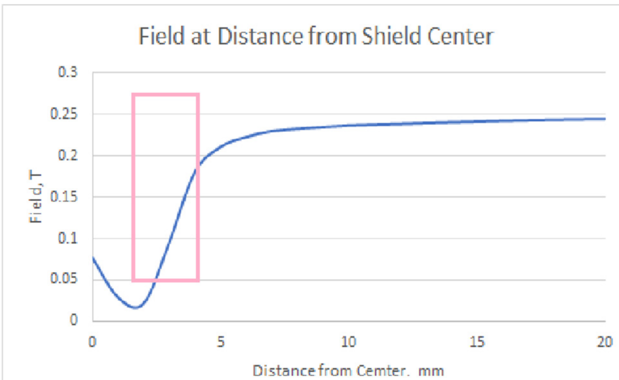

Figure 8: Field at a distance from the center of the shielding cylinder. The red box represents the location of the shield steel.

Magnetic Shield Analysis

A study of the magnetic shielding of the extraction system was performed using a finite element program. The analysis was performed for a C-band microtron with type I injection. The extraction shield and compensating rod were included with the existing microtron magnet in a 3D analysis. The shielding and rods were made with 10-10 low carbon steel. The field along the axis of the shield approximates a tanh shape with a 1.9 mm fall off. The field effectively vanishes inside the shield. Outside the shield the flux is pulled toward the steel which perturbs the field uniformity. Figure 8 shows the field as the distance from the center of the shield. The red box illustrates the position of the steel in the shield. The flux perturbation has its largest effect on the next-to-last turn orbit. The local field variation at the next-to-last orbit is ~1%, however the deviation averaged on the entire orbit is ~0.1% This deviation is large enough that some correction may be necessary by varying the compensation rods or small positioning and orientation of the shield intself. A field map is generated to use with a particle tracking simulation.

Tracking Simulation Studies

The G4beamline particle tracking program [6] was used to study the effects of field errors on the beam. C-band microtron parameters were used for this study. A similar study using an S-band Type II microton is in progress. Figure 9 (left) shows the microtron geometry with electron beam trajectory shown in red. The figure shows the RF cavity on the left and the extraction shielding tube on the right. There is a magnetic field perpendicular to the plane of the figure to constrain the beam to circular orbits. The beam is initialized on the wall of the cavity with negligible energy and is accelerated by the RF gradient. The cavity walls have slits in them at the appropriate positions to select the right initial exit energy and to allow the re-entrance of the beam after completing its revolution. Only approximately 2% of the RF period will be successfully captured by the RF. Figure 9 (right) shows a blow-up of the trajectory of an electron emitted from the source on the cavity wall and is captured by the RF and subsequently exits the cavity with the resonant energy.

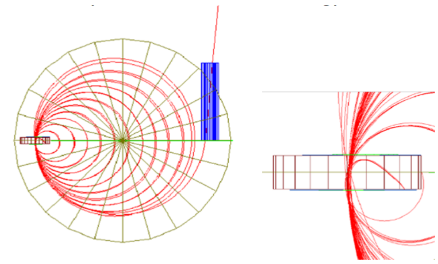

Figure 9: (left) Graphic of the microtron with an electron beam trajectory. (right) Blow-up of the RF cavity to show the electron injected from the source on the RF wall.

A separate study [7] using a microtron as an injector of electrons to an FEL. That study included a 2D tracking simulation of that microtron to determine extraction efficiency and current as a function of turn number, which are shown in Fig. 10.

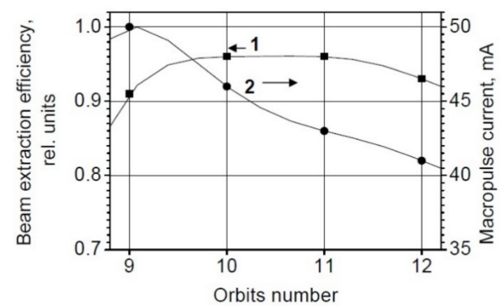

Figure 10: Beam extraction efficiency (left) and current (right).

REFERENCES

[1] S. P. Kapitza, V.P. Bykov and V.N. Melekhin, "An efficient high-current microtron," *JETP,* vol. 14, no.2, p. 266, 1962.

[2] A. P. Grinberg, "The microtron," *Soviet Physics Uspekhi*, vol. 4, p. 857, 1962.

[3] P. Lidbjörk, *Microtrons*. Scanditronix AB, Uppsala, Sweden, 1994.

[4] R. Abrams *et al.*, "S-Band microtron as an intense source of neutrons and gamma rays," Muons, inc. Internal Report, 2016.

[5] H. Reich and K. Löns, "Zur Vollständingen Herausführung des Elektronestrahles aus einem Mikrotron, Kompensation Magnetischer Störfelder," *Nucl. Instrum. Methods*, vol. 31, pp. 221-225, 1964. doi:10.1016/0029-554X(64)90162-4

[6] T. J. Roberts, *G4beamline User's Guide,* http://g4beamline.muonsinc.com

[7] G. M. Kazakevich *et al.*, "Magnetron-driven Microtron Injector of a Terahertz Free Electron Laser," *Phys. Rev. STAB* vol. 12, p. 040701, 2009. doi:10.1103/PhysRevSTAB.12.040701