

# DIPOLE MAGNETS FOR THE TECHNOLOGICAL ELECTRON ACCELERATORS

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## Abstract

For a 10-MeV technological accelerator, a dipole magnet with a permanent magnetic field was created using the SmCo alloy. The maximum magnetic field in the magnet was 0.3 T. The magnet is designed to measure the energy of the beam and to adjust the accelerator for a given energy.

For a linear accelerator with an energy of 23 MeV, a dipole magnet based on the Nd-Fe-B alloy was developed and fabricated. It was designed to rotate the electron beam at 90 degrees. The magnetic field in the dipole magnet along the path of the beam was 0.5 T. The effective length of the magnet was 242 mm.

## INTRODUCTION

There is a considerable interest in the magnetic systems on the base rare-earth permanent magnet for use in accelerators such as medical and technological accelerators, microtrons, liner colliders etc. [1-5]. Despite the well-known basic principals of magnetic system layout, every magnetic system is made almost adhoc due to the particular parameters of the accelerator and operation conditions. In this paper, we present magnetic systems (dipole magnets) on the base of Nd-Fe-B and Sm-Co magnets. Dipole magnets on the base of Nd-Fe-B and Sm-Co permanent magnets are used in two upgraded electron accelerators in NSC KIPT.

## DIPOLE MAGNET FOR THE LU-10 ELECTRON ACCELERATOR WITH THE ENERGY OF 10 MEV

LU-10 is an electron accelerator used for the radiation treatment of materials and devices in the energy range of 10 MeV [6]. An upgrade of the LU-10 accelerator will raise the beam power to 20 kW. Additionally, a beam power measurement at peak output is still a challenge.

It is known that high performance permanent magnets can be used for the designing compact devices detecting electron beam parameters [2, 5]. Thus, simple, cost-effective and free of power source device on the base of powerful permanent magnets can be created. This device is suitable for analyzing beam parameters at the energies up to 10 MeV.

In order to choose appropriate magnetic material for detecting device, the radiation resistance of Sm-Co and Nd-Fe-B magnets was studied [7, 8]. Magnetic samples underwent direct electron beam treatment with the energy of 10 MeV and bremsstrahlung. Absorbed dose for electrons was 16 Grad and 160 Grad. The temperature of

magnets under irradiation was about 38 °C. Whereas magnetic flux of Nd-Fe-B magnets decreased in 0.92 and 0.717 times for 16 Grad and 160 Grad accordingly, magnetic performance of Sm-Co magnets remained unchanged under the same radiation doses. Radiation activity of both Nd-Fe-B and Sm-Co magnets after irradiation was not increased keeping critical levels. It makes the Nd-Fe-B and Sm-Co permanent magnets more appropriate for accelerator's applications. The additional advantage of Sm-Co magnets is low temperature coefficient of remanence 0.035 (%/°C).

To assess the parameters of dipole magnet, the simulation of beam travel at the output of the accelerator was carried out. The parameters of the beam and magnetic field inside dipole magnet were fixed. The typical size of Sm-Co magnets for the design of dipole magnets was 30x24x12 mm. The distance between Sm-Co magnets was 25 mm. The typical magnetic field in the mid-plane of the dipole magnet was about 0.3 T. This peak magnetic field of 0.3 T was used for the simulation of beam travel. Hence, the simulation allowed building the construction of dipole magnet (Fig. 1).

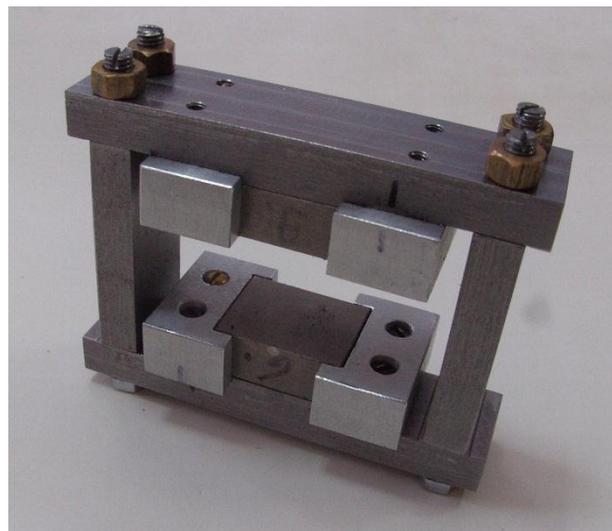


Figure 1: Dipole magnet for the LU-10 electron accelerator with the energy of 10 MeV.

Outside dimensions of the magnetic circuit were 90x73x24 mm. The magnetic circuit was made of soft magnetic steel. The tolerance and machining of parts were 5 microns. The upper bar was designed portable to facilitate the dismantling of the dipole magnet and the flange of accelerator during the measuring mode or adjustment accelerator energy procedure.

The mid-plane scans in the gap of dipole magnet are shown in Fig. 2. The measurements details can be found elsewhere [7]. It was found that peak magnetic field in the gap of dipole magnet was 0.331103 T. The effective length along the central line of beam track was  $-33.533$  mm. The rotation angle of electron beam with the energy of 10 MeV was 0.31 rad. The estimation of the rotation angle was done according to the simulation of electron beam motion.

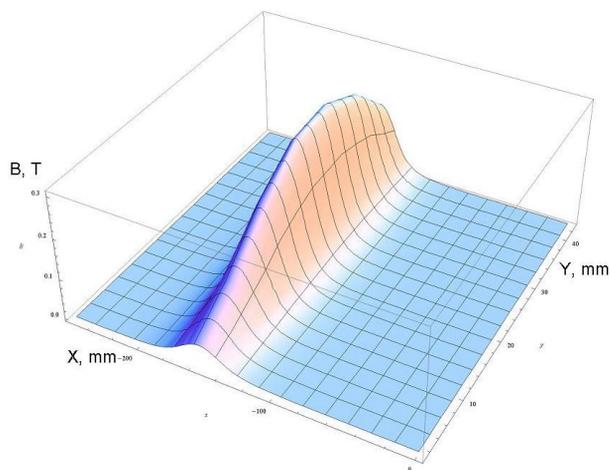


Figure 2: Magnetic field distribution in the mid-plane of gap of dipole magnet for the LU-10 electron accelerator with the energy of 10 MeV.

The deviation of magnetic field in the gap of dipole magnet was investigated under various regimes as opening and closing circuit, and the reconfiguration of the upper bar. Fig. 3 shows the measurements of seven Hall probes in the gap of dipole magnet during 10 cycles of opening and closing circuit for 1000 seconds [7]. Points of the one color depict the change of magnetic field at the point of each Hall probe after each cycle.

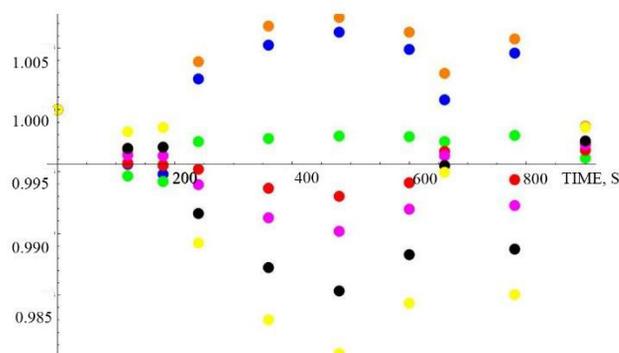


Figure 3: The change of magnetic field (Hall probe data) after each cycle.

The variation of data of Hall probe located in the centre of the gap (green, red and pink points) was not more than 0.5 % after closing circuit.

## DIPOLE MAGNET FOR “EPOS” TECHNOLOGICAL ACCELERATOR

“EPOS” linear electron accelerator is used for the radiation treatment of materials and products [6]. The upgrade of the “EPOS” resulted in the redesign of output unit with the addition of the second channel. Dipole magnet was provided for the rotation of the electron beam with the energy of 23 MeV at a 90 degree. In order to locate the rotary part of beam channel on the accelerator frame, a maximum magnetic field of 0.516 T in the magnet gap of 25 mm was required. Given the existing energy fluctuation of electron beam, the dipole magnet yoke should be 50 mm in length including shims and 1 mm in height at the edges to guarantee the radius uniformity.

Unfortunately, the existing electron beam forming and transporting system of the “EPOS” accelerator is not able to eliminate the loss of electrons at the walls of the vacuum chamber of dipole magnet. It was shown that direct irradiation of Nd-Fe-B magnets by the 23 MeV electrons with absorbed doses of 16 and 160 Grad let to the decrease of magnetic properties. However, the bremsstrahlung of the 23 MeV electron’s beam was not affected the magnetic performance of Nd-Fe-B magnets. Thus, the location of dipole magnet was designed as far away as possible from the electron beam to discard the direct interaction of Nd-Fe-B magnets with electrons. The general view of the dipole magnet is shown in Fig. 4.



Figure 4: Dipole magnet for “EPOS” linear electron accelerator.

The magnetic yoke formed the magnetic field in the gap and pole pieces made of low-carbon steel. The upper and lower parts of the dipole magnet were composed of two pieces. Special Cu-tube was installed in the beam channel and attached to the accelerator thermoregulation system. Fasting small segments with the cross-section similar to pole tips can alter the effective length of the dipole magnet. The titanium insert provided the stability of the gap size, behind which there was a box for Nd-Fe-B magnets assembly. The tolerance of the dipole magnet components was about 5 microns. Nd-Fe-B magnets of rectangular shape with the size of 50x50x10 mm were

used. Overall dimensions of the dipole magnet are 233x170x435 mm.

The distribution of magnetic field of the dipole magnet along and normal to the beam path are depicted in Fig. 5 and Fig. 6 accordingly. Measurements details can be seen in elsewhere [5].

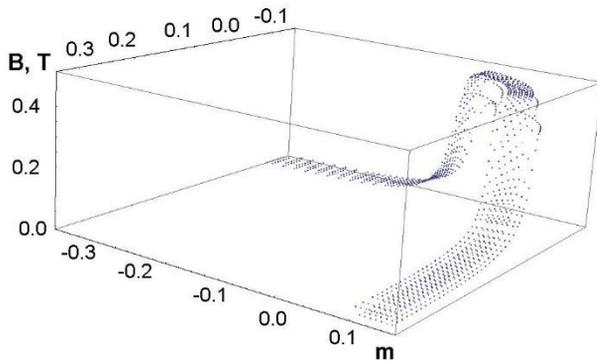


Figure 5: Magnetic field of the dipole magnet along the beam path “EPOS” linear electron accelerator.

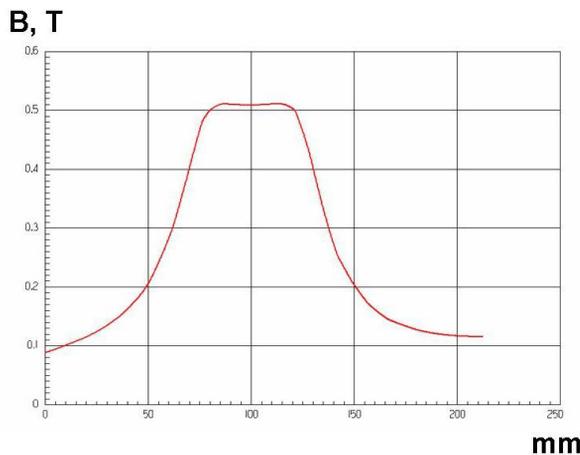


Figure 6: Central-pole magnetic field distribution transverse to the beam path.

The effective length of the dipole magnet was  $242 \pm 1.1$  mm. It was calculated using the trace of the particle with the energy of 23 MeV.

Beam tracing using experimental magnetic field measurements was carried out. The beam trajectory with experimental parameters passed through dipole magnet within specified limits.

Fig. 7 presents magnetic flux measured in the centre of the gap as a function of the temperature of the whole system. It was shown that reversible magnetic flux losses were about  $0.09 \text{ }^\circ\text{C}^{-1}$ .

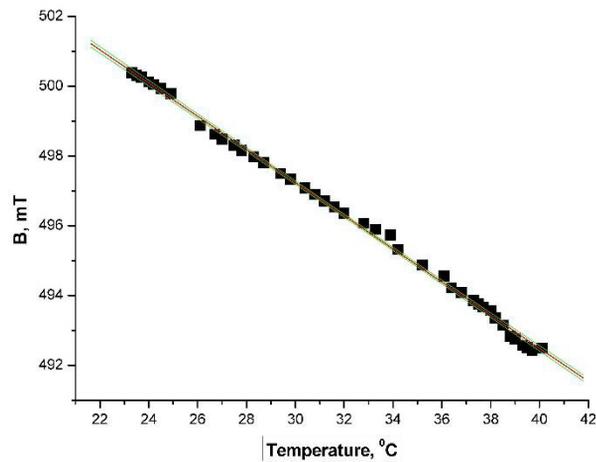


Figure 7: Temperature dependence of the magnetic field in the dipole magnet “EPOS” linear electron accelerator.

## SUMMARY

In summary, two types of dipole magnets were designed and produced for the technological electron accelerators. The key component of dipole magnets is rare-earth permanent magnets with high magnetic properties. Proposed and verified design of the dipole magnets enables their use under high radiation conditions.

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