ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT004

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DESIGN OF A COMPACT 180-DEGREE SINGLE-SHOT ENERGY SPECTROMETER BASED ON A HALBACH DIPOLE MAGNET

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Abstract

In the AXSIS project at DESY, we develop compact THz accelerating structures for a table-top x-ray source. Acceleration is achieved by passing the electron beam through a dielectric-loaded waveguide powered by multi-cycle THz radiation. The final electron energy strongly depends on THz-power injected into the LINAC and timing. Thus in first experiments we expect large energy fluctuations and a large range of energies to cover. Therefore, We designed an electron energy spectrometer for a wide range of final energies covering 5 to 20 MeV in a single-shot. Here, we present the design of an energy spectrometer which uses a compact dipole magnet based on the Halbach array concept to deflect the electron beam through a 180° path intercepted by a Fiber Optic Scintillator (FOS) mounted inside the vacuum perpendicular to the beam. The 180-degree bending geometry provides the possibility of having the focus point of all energies at the same distance from the magnet edge which makes the design simpler and more compact. It also removes the necessity of installing a safety dipole at the end of the accelerator. A slit system at the spectrometer entrance increases resolution to better than 0.2%.

INTRODUCTION

Particle energy analysis lies at the heart of numerous diagnostic and spectroscopic techniques in areas such as particle acceleration, electron diffraction and high-energy physics. Surface science alone relies on a host of methods that use electrons to probe matter and gain information regarding physical structure, composition and chemistry. In the AXSIS project, we develop a compact accelerator that leads to a highly optimized and compact THz-driven table-top x-ray source. A key aspect of the design principle is the use of single-cycle/multi-cycle to power an electron gun and multi-cycle terahertz pulses to power a dielectric-loaded metallic waveguide as a linear accelerator (LINAC. Since THz -pulse energy required has not been yet achieved, the design accounts for a wide range of final energies from 5 to 20 MeV which is then delivered through quadrupoles to a magnetic spectrometer in order to measure the energy of the accelerated electrons. THz-driven accelerators have shown significant progress over the past years, and have attracted considerable interest as the next generation linear accelerators. For the present LINAC, requirements placed on the electron spectrometer are somewhat different from those for conventional accelerators. A broad momentum acceptance with high resolution is critical. Most spectrometer implementations use a dipole magnet as a dispersive element and a collimator to control the instrumental resolution. Due to the expected varability in initial performance, the capability of single-shot measurement over the full range is desirable.

SPECTROMETER DESIGN

A novel 180° magnetic electron spectrometer having the distinct features of ultra-low fringe field, fully enclosed magnetic environment, compact design and wide energy range (5–20 MeV) is used as an energy analyser for the AXSIS project (Fig. 1). In order to realize a high energy resolution, a small slit width at the entrance of the spectrometer is necessary. The spectrometer uses a compact dipole magnet with a Halbach array concept to deflect the electron beam through 180°. The dispersion created by the magnet leads to an energy-dependent position then intercepted by a Fiber Optic Scintillating (FOS) screen mounted inside the vacuum perpendicular position to the beam to increase the resolution.

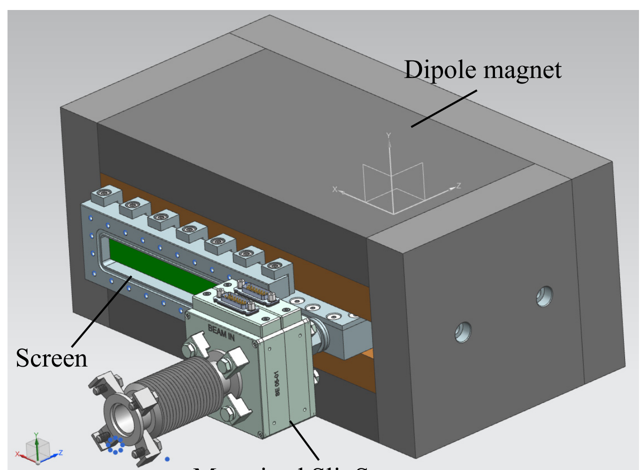

Figure 1: 180-degree bending spectrometer design.

Four synchronously triggered CCD cameras image a 16 cm screen, allowing simultaneous single-shot measurement of electrons from 5 to 20 MeV with a peak magnetic field of 0.6 T. To avoid damage from electrons hitting the CCD cameras directly, first-surface mirrors were used at 45° following the exit flanges, which separated fluorescent light from the electrons. The detector used in this system may be either a phosphor or any electron sensitive film. For our purposes a Fiber Optic Scintillating (FOS) screen proved most convenient since the image can be transferred from one end of the fiber to the other without any distortion. This layout generates excellent resolution, smaller than the thickness of the scintillating crystal [1].

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The 180-degree bending geometry has multiple benefits including: 1) Spectral focusing occurs on a straight line which is the front surface of the magnet, then the electrons for the full energy range collide the scintillator in perpendicular position. 2) The focusing is independent of energy for an ideal magnet with small fringe fields. This effect may allow development of a permanent magnet-based spectrometer, simplifying the design and avoiding the necessity of subsequent deflector magnets to dump the beam making the accelerator layout more compact. 3) Use of a permanent magnet also allows a very compact design because electromagnetic coils would not be required and because stronger fields could be achieved. Ray tracing simulations using detailed field maps are used to determine electron energy based on the measured magnetic field.

The vacuum chamber is made of aluminium, and static simulation using ANSYS software [2] showed that with a 4 mm thick lid, the maximum deformation would be 0.3 mm, which is quite acceptable (Fig. 2).

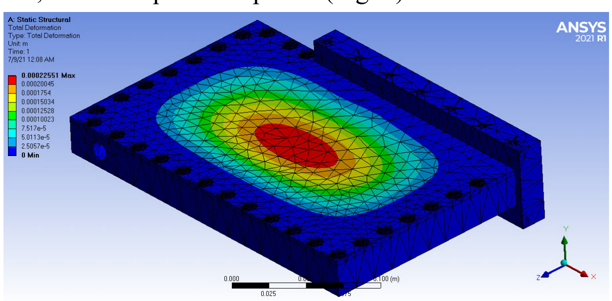

Figure 1: Static simulation of vacuum chamber

MAGNETOSTATICS SIMULATION

The dipole magnet of the spectrometer is based on a Halbach Box Magnet (HBM) concept which reduce the size, weight and fringe fields of the dipole. The idea is to surround the pole on five sides with magnet material and then surround that with a flux return yoke. The direction of magnetization of magnets is specified in Fig 3.

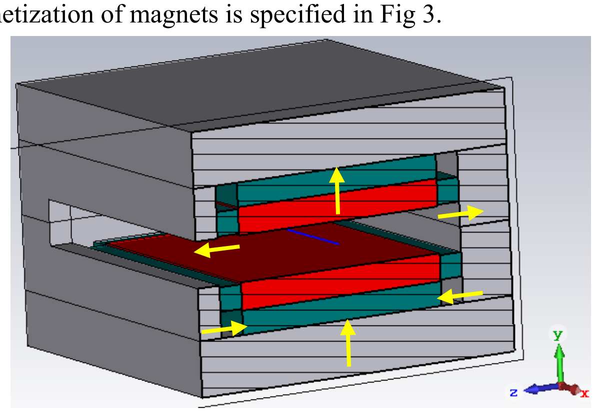

Figure 2: Halbach dipole magnet, green, red and Grey parts shows magnet, pole, and yoke, respectively

Along with the Halbach array concept, a H-Type dipole magnet could be an appropriate choice having strong enough magnetic field, an as small size as possible, and the same direction of the fringe field with the central field. The Halbach design turned out to be more efficient than the H-type, using only 9 kg of magnet material, the H-type design requires 44 kg. The Halbach box design does not have the reverse field problem due to the iron pole and flux return. There will be a very small reverse field (Fig. 4) outside the magnet due to the finite coercivity of the iron. We propose to use N48M magnet material instead of N52. N48M has better resistance to demagnetization than N52, although it has a slightly lower remanence. Other components of the dipole magnet are made of low-carbon steel.

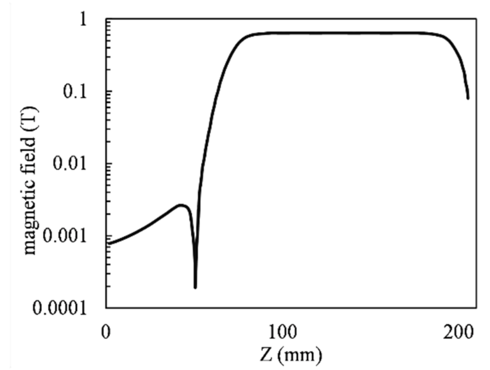

Figure 3: magnetic field profile in Halbach magnet.

BEAM TRAJECTORY AND RESOLUTION

Electron bunches leaving the linear accelerator with energies between 5 and 20 MeV are focused by magnetic quadrupoles and then pass through the slit and enter the Halbach dipole magnet energy detection. Figure 5 shows the particles tracking with CST software [3]. All the electrons are focused again on a straight line after 180° of deflection from the entrance direction. As shown in the figure, the dispersion function is quite linear and proportional to the electrons' energy, which greatly simplifies the calibration of this energy detector. Since the electrons are focused on the scintillator plane and their collision is perpendicular, it will result in the highest light yield and resolution.

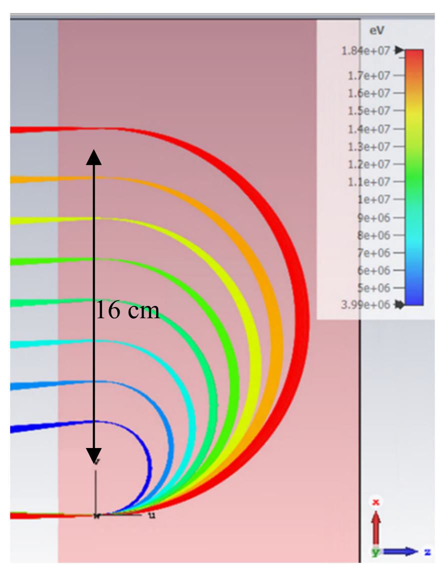

Figure 4: Electron tracking through the dipole magnet.

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The slit system controls how much charge enters the spectrometer. The width of the slit affects the resolution; the narrower the slit, the higher the resolution. However, narrower slits also decrease signal strength. These two factors must be balanced when selecting a slit size. For a 180 spectrometer, a slit system would help us to measure the beam with a higher resolution. The double slit collimation system limits the acceptance angle and width of the electron beam. The thickness of the material used for the slits in the collimator should be greater than the range of the most energetic electrons. The maximum penetration depth of electrons into the matter for highest energy electrons 20 MeV is 5 mm using Tungsten for the slit blades [4].

Resolution is an important consideration in the design of an energy analyzer. For convenience we define the relative energy resolution as the uncertainty in the energy measurement at some energy as a fraction of that energy ($R = \Delta E/E$). nonideal collimation has the largest effect on resolution in this energy spectrometer. Figure 6 shows three different particle trajectories with different energies that travel along a circular trajectory to the detector, while all trajectories are still hitting the detector in the same position are shown. So θ_{max} is given by

$$\theta_{max} = \tan^{-1}\frac{d}{L} \tag{1}$$

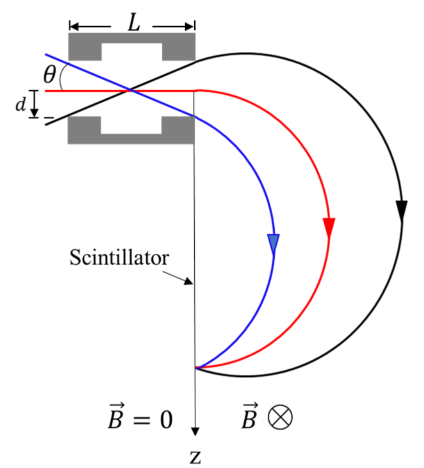

Figure 6: Three electron beam with different angular deviation, magnetic field region and the slit system.

When following the circular trajectories upon entering the B field, we find the distance from the center of the entrance slit to the point of impact on the detector as

$$z = 2\rho(T)\cos\theta + d \tag{2}$$

Where $\rho(T)$ is Larmor radius corresponding to the kinetic energy T

$$\rho(T) = \frac{(T^2+2Tmc^2)^{1/2}}{ecB} \tag{3}$$

Where B is the magnetic field, and e is the electronic charge c is the velocity of light and m is the electron's rest mass. Using equations (1) to (3), the maximum uncertainty introduced into the kinetic energy (ΔT_{max}) can be obtained and then the energy resolution can be calculated for different slit sizes (d), L = 30 mm, and B = 0.6 T (Fig. 7) [5].

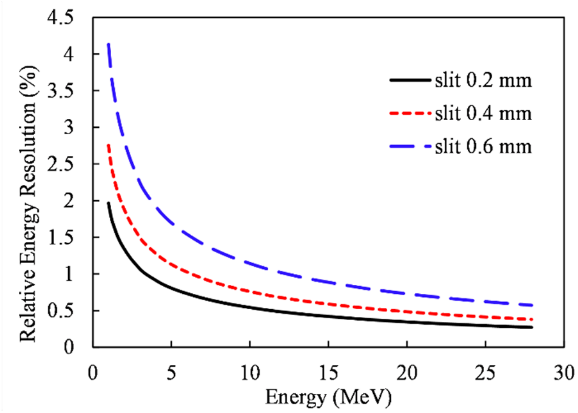

Figure 7: Three electron beam with different angular deviation, magnetic field region and the slit system.

CONCLUSION

The energy analyser design discussed is extremely versatile. A broadband single-shot electron spectrometer for MeV-class THz driven electron beam measurements has been developed for AXSIS. We presented the design of an energy spectrometer covering 5 to 20 MeV in a single-shot which uses a compact dipole magnet based on the Halbach Box concept to deflect the electron beam through a 180° path intercepted by a Fiber Optic Scintillator (FOS) mounted inside the vacuum perpendicular to the beam to increase the resolution. The 180-degree bending geometry using permanent magnets provides the possibility of having the focus point of all energies on a straight line which makes the design and the calibration simpler, and also removes the necessity of installing a safety dipole at the end of the accelerator. Since the dipole magnet is external to the vacuum system, operation of the spectrometer is amenable to ultra-high vacuum systems and corrosive environments. This spectrometer design provides a powerful diagnostic tool for research and development of next generation compact THz accelerating structures.

ACKNOWLEDGEMENTS

The authors are very grateful for Many helpful discussions and support from Dr. Hossein Delsim-Hashemi, Dr. Markus Tischer, and Dr. Pavel Vagin.

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