Indian Journal of Pure & Applied Physics
Vol. 57, July 2019, pp. 492-497

Design of electron beam bending magnet system for electron and photon therapy: A simulation approach

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Received 29 May 2017; accepted 29 April 2019

The doubly achromatic electron beam bending magnet system using two sector magnets has been designed for the medical applications to treat the cancer. The aim of electron beam bending magnet system is to focus an electron beam having a spot size less than 3 mm × 3 mm, energy spread within 3% and divergence angle ≤ 3mrad at the target position. To achieve these parameters, the simulation has been carried out using Lorentz-3EM software. The beam spot, divergence angle and energy spread have been observed with respect to the variation in angles of sector magnets and drift distance. Based on the simulated results, it has been optimized that the first and second magnet has an angle 206° and 35° and the drift distance 80 mm. It is also observed that at the 1125, 1762, 2570, 3265 and 4155 Amp-turn, the optimized design produces 3369, 4972, 6384, 7584 and 9568 Gauss of magnetic field at median plane which require to bend 6, 9, 12, 15 and 18 MeV energy of electron, respectively, for the electron therapy application. The output beam parameters of the optimized design are energy spread ±3%, divergence angle ~3 mrad and spot size 2.6 mm. Moreover, for 6 MV and 15 MV photon therapy applications, an electron beam of energy 6.5 MeV and 15.5 MeV extracted from magnet system and focused on the bremsstrahlung target. Various materials have been studied for photon generation using Monte Carlo based Fluka code and Tungsten material has been optimized as bremsstrahlung target which produces continuous energy bremsstrahlung spectrum. For the photon therapy, the 1233 and 3327 amp-turn, in an optimized design produces 3616 and 7785 Gauss of magnetic field at median plane require to bend 6.5 and 15.5 MeV energy of electron, respectively, which further produces bremsstrahlung radiation from Tungsten target.

Keywords: Beam bending magnet, Medical linear accelerator, Lorentz-3EM, Radiotherapy

1 Introduction

For the last several years, electron accelerators are extensively being used in the medical field with special applications of photon beam for cancer treatment and electron beam for treating various skin diseases. The absorbed dose by the human tissues is directly correlated with the energy and fluence of the electron beam and photon beam. The process leads to damage of DNA strands and diminishes the cell's ability to replicate indefinitely. Initially, the low energy linac tube was mounted vertically and the electron beam is straight way fall on the patient plane passing through the accelerator head assembly. But, to treat the deep seated tumors, high energy electron linacs are required which increase the length of the linac tube[1-4]. The longer length linac cannot mount vertically due to fully rotational gantry and to maintain 100 cm distance between the X-ray target and rotational center of gantry[5-7]. To overcome this difficulty, the linacs are mounted horizontally and beam bending magnet system is used to bend the electron beam. The emergent electron beam from the accelerating tube is to be deflected magnetically through 90° or 270° into a vertical plane to hit an X-ray target or electron scatterer. Due to beam energy variations, it is likely true that the angle of incidence and lateral displacement of the electron beam on the X-ray target may vary with the electron beam energy. Therefore, a small, stable, and axially symmetric beam spot on the target is needed. In addition, it is a basic requirement that the bending magnet is doubly achromatic, i.e., the position and angle of the output beam through the magnet are independent of beam energy. Therefore, the main objective of the beam bending system is to focus the electron beam on the X-ray target with desired parameters.

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A doubly achromatic magnet configuration with 270° deflection can be made by choosing any one of the three configurations (i) single dipole magnet with double focusing quadrupole, (ii) two dipole magnets separated from each other and one quadrupole magnet and (iii) three dipole magnets separated from each other. A single 90° sector magnet deflection system is capable of providing adequate focusing over only a restricted range of energies of the electron beam. Also, the radial displacement and angular divergence of the entrant beam result in spread of exit beam. Moreover, the magnet system which can deflect an electron beam by 270° can meet the requirements of the electron beam such as circular spot size, distance between the magnet exit port and X-ray target, uniformity of the electron beam on the X-ray target, beam divergence and energy dispersion. This system is doubly achromatic and can be made using one, two or three sector magnets. While using single magnet system, the system fails to take into account of the beam spot size and angular divergence of the beam spot at the target in the transverse plane. In addition, the pattern of X-rays produced at the target is not circularly symmetric and it is very difficult to manufacture and achieve very accurate magnetic field for bending an electron with 270°. To avoid lack of circular symmetry in the lobe of X-rays, elliptical beam spot and larger divergence of the beam at the target, it is desired to have two magnet doubly achromatic beam bending magnet system[8-13]. In this case, the electron beam must be bent towards the patient, while both minimizing the physical height of the machine and maintaining 100 cm distance between the X-ray target and the rotational center. For this purpose an achromatic magnet bending system is necessary, so that the electron beam angle and position on the X-ray target or scattering foil can be well defined, irrespective of variation in the electron beam energy. This system is used for the therapy applications particularly when linear accelerators are used.

Based on the orbit dimension and size, two dipole bending magnet system is advantageous. Therefore, an objective of the present paper is to provide a 270° beam bending using two dipole magnet system and to minimize the height of the orbit above the accelerator beam line. In the present paper, a simulation approach is presented to design a doubly achromatic two magnet beam bending system for both electron and photon radiation therapies. The proposed system may be used for the 6, 9, 12, 15 and 18 MeV energy of electron beam and 6.5 MV and 15.5 MV energy of photon beam for radiation therapy application.

2 Materials and Method

2.1 Electron accelerator, lorentz-3EM and FLUKA software

The linear electron accelerator available at Society of Applied Microwave Electronics and Engineering Research (SAMEER), Mumbai having energies 6, 9, 12, 15 and 18 MeV, average current ~80 µA, pulsed current 130 mA, pulsed width 4.5 µs, repetition rate 150 PPS was used for the present study. The linear accelerator can produce beam of 6 to 20 MeV with energy spread of ±7%.

The Lorentz-3EM software is used for studying the trajectory of charged particles through electric and/or magnetic fields in the three dimensional geometry. The calculations of the magnetic field between the poles and trajectory calculations for various electron energies have been done with the help of Lorentz-3EM software for better accuracy. Lorentz-3EM goes to work in just three easy steps: (i) create a physical model, (ii) obtain a field solution and (iii) analyze charged particle trajectory[14-16]. Also, a general purpose Monte Carlo based FLUKA code has been used for the study of bremsstrahlung spectra using 6 to 18 MeV electron beam from different high Z materials[17-19].

2.2 Magnet design

In order to take an advantage of the low height of an elementary single dipole and at the same time take advantage of achromatic system, a double focusing doubly achromatic magnet system was designed. It consists of two dipole magnets which are used to bend the 6 to 20 MeV energy electron beam by 270° onto the target within the acceptable geometry. The main requirements of the design of magnet system is to focus the electron beam at the target area with the spot size of less than 3 mm × 3 mm, beam energy spread at the output within ±3 % and divergence angle ≤3mrad[20-24].

The magnet system consists of two magnets, out of which one magnet deflects the electron beam by an angle greater than 180° and other magnet by less than 90°. If a finite energy spread beam is injected into a magnet with more than 180° deflection (first magnet), the output beam is convergent. The same beam is injected vertically upwards into a less than 90° deflection magnet (second magnet), the output beam would be diverging beam. The amount of convergence and divergence of beam is depending upon the bending angle of each magnet and the pole face angle at the exit edge of first magnet and entrant of the second magnet. Therefore, simulation has been carried out using Lorentz-3EM software for compensating the convergence angle with divergence angle and choosing the appropriate drift distance between both the magnets.

2.3 Simulation

Initially, a beam bending magnet system was designed using the two sector magnets of angle 195° and 45° having radius of curvature 65 mm and the drift space between both the magnets was taken 80 mm. The schematic of the simulation is shown in Fig.1. An electron beam of diameter 3 mm, energy spread of ±7%, Gaussian profile in intensity was incident on the pole face of first magnet. The incident electron beam parameters were adjusted such that it should match the actual electron beam from linac tube.

The output beam coming out from the second magnet was detected at the bremsstrahlung target position which was kept at 70 mm from the exit pole face of second magnet. The energy spread, beam divergence, and spot size of the beam were observed at bremsstrahlung target. For both the magnets, a common yoke of H-shape has been designed. Steel 1010 and Steel 12L14 material were used for yoke and magnets, respectively. Both these magnets have common magnetizing coils which has internal water cooling system. The pole gap between dipole magnet was kept of 10 mm.

The requirements of the design are (a) the central electron beam should remain perpendicular to the target surface at the distance of 70 mm from the exit edge of the second magnet (b) target beam spot should be less than 3 mm diameter. To achieve these requirements, the magnet angle and drift distance were varied in Lorentz-3EM. From the variations, it has been observed that as the magnet angle increases, the beam angle with respect to target also increases. Moreover, as the drift distance increases, the beam spot size decreases up to ~2.62 mm at a drift distance of 80 mm and further with increase in the drift distance the spot size increases. From these results, the first magnet of an angle ~206°, second magnet of an angle ~35° and the drift distance 80 mm were optimized. The variation in current passing through the coil gives different values of magnetic field. To compensate and to bend the desired energy of electron beam, a coil current was accordingly adjusted for the measurement of output parameters. A cross sectional view of the optimized two magnet system is shown in Fig. 2 for 270° beam bending.

The width and height of the optimized magnet pole pieces are 40 mm and 70 mm respectively, taking into the consideration of the fringing field effect on the electron beam. The contour of magnetic field distribution in the magnet at median plane is shown in Fig. 3. Contour shows the uniform contribution of magnetic field over the pole pieces.

2.4 e-γ target and bremsstrahlung radiation

After bending an electron beam through 270° magnet system, electron beam hits the surface of e–γ target perpendicularly. The bremsstrahlung yield depends on the electron energy and the atomic number of the target element. Therefore, high atomic number elements are used as e–γ target. The thickness of the e–γ targets was optimized such that the entire

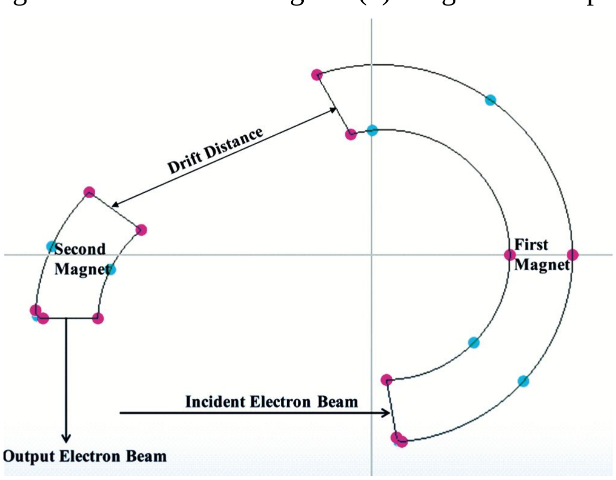

Fig. 1 – Schematic of simulation setup for two magnet system.

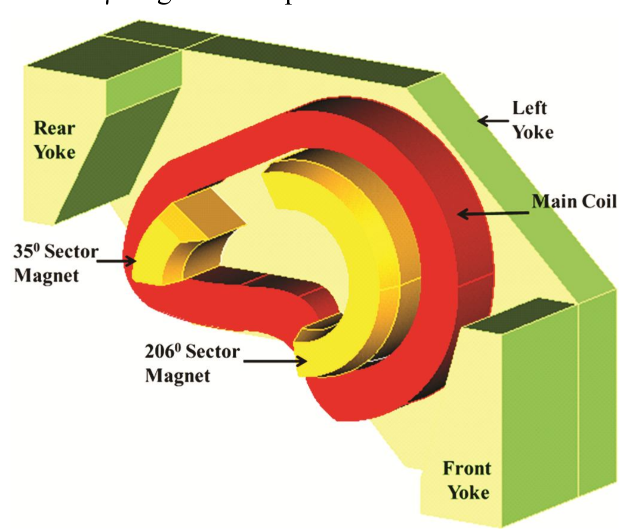

Fig. 2 – A view of proposed two magnet system for beam bending.

electron beam incident on the target gets absorbed in the target itself. The target thicknesses were optimized for 6 to 18 MeV energy of an electron beam. Various materials were simulated in Monte Carlo based Fluka code for the optimization of target material as bremsstrahlung targets.

3 Results and Discussion

The variation of magnetic field with respect to ampere turns has been observed at the median plane. The result shows that the magnetic field at the second magnet saturates at higher ampere turns as compared to the first magnet. Therefore, a triangular shim was introduced at the base of second magnet. The variation of magnetic field due to incorporation of triangular shim and trim coil in the magnet system has been studied and output parameters were observed. The designed triangular shim and trim coil is shown in Fig. 4. The variation in magnetic field with respect to amp-turns at the median plane of the second magnet with and without triangular shim is shown in Fig. 5. It is observed from the figure that with an introduction of triangular shim the magnetic field increases with increase in the total amp-turns.

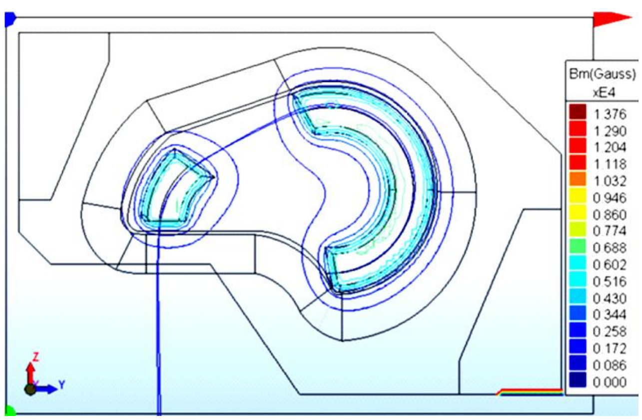

Fig. 3 – Contour of magnetic field distribution in the median plane of the first and second magnet.

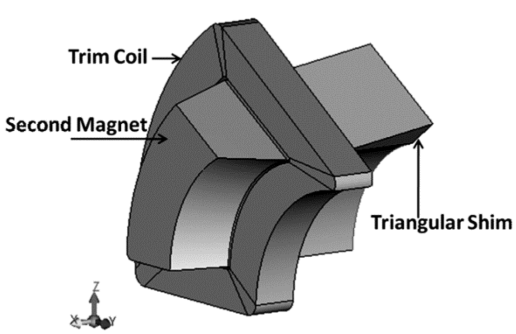

Fig. 4 – Schematic of triangular shim and trim coil on small pole piece.

To make slight corrections in the angle and /or the position of the beam on the target, a set of trim coils have been added to the second magnet. Very small amount of current require to be passed through these trim coils. The magnetic field change produced due to trim coil has been estimated for a case of 18 MeV electron beam energy and it is shown in Table 1. From the table it is observed that 3.41 % field change is obtained with 180 Amp-turns/coil of trim coil.

Moreover, to reduce the energy spread at the target, an energy defining slit was introduced in the vacuum chamber of magnet system as shown in Fig. 6. Therefore, an aluminum slit was introduced at the exit pole face of the first magnet, where large dispersion of beam was observed. The aluminum slit was specifically used to minimize the bremsstrahlung production due to the striking of the energetic electron beam at the magnet edge.

Overall, the variation in magnetic field as a function of distance along the radius of curvature in the median plane for the optimized system is shown in Fig. 7. It is observed that at the 1125, 1762, 2570,

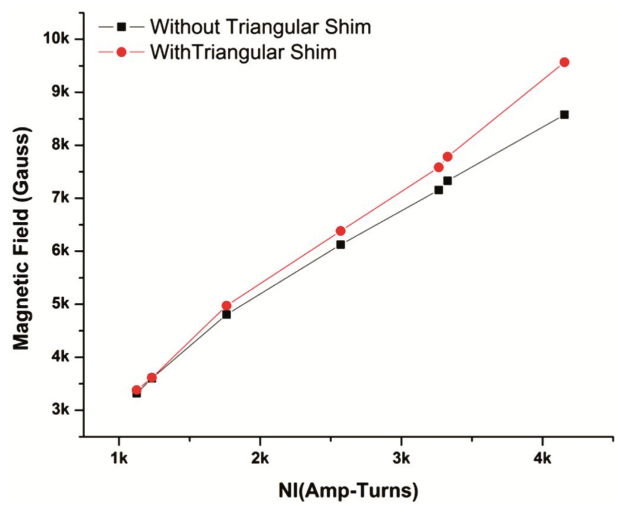

Fig. 5 – Variation in magnetic field with and without triangular shim at the second magnet.

Table 1 – Effect of Trim coil on second magnet.

I (A/coil)	NI/coil	B(G)	ΔB(G)	% change	Shift in beam spot position (mm)
0	0	9568	0	0	0
0.75	30	9621	53	0.55	0.28
1.5	60	9675	107	1.10	0.64
2.25	90	9735	167	1.71	1.24
3	120	9798	230	2.34	1.80
3.75	150	9859	291	2.95	2.96
4.5	180	9906	338	3.41	3.28

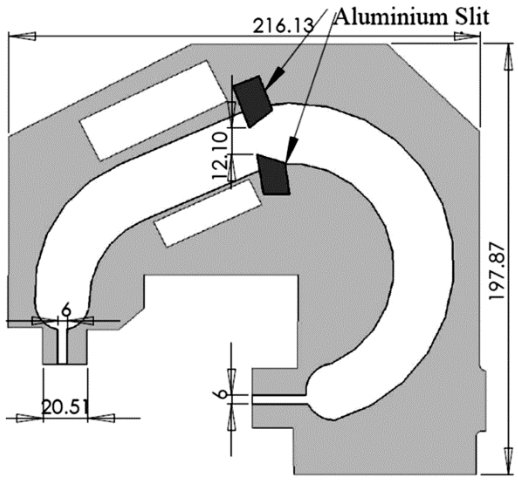

Fig. 6 – Cross sectional view of vacuum chamber with aluminum slit.

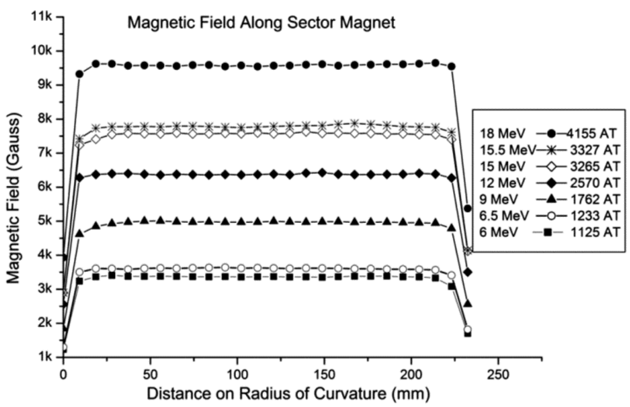

Fig. 7 – Magnetic field versus distance along the radius of curvature on the median-plane.

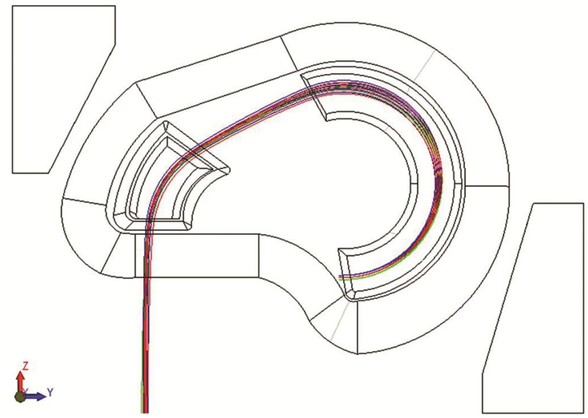

Fig. 8 – Trajectory of 6 to18 MeV electron beam in two magnet system.

Table 2 – Optimized parameter of the two magnet system.

Beam Particles	Electrons
Operating Beam Energy	6 to 18 MeV
Beam Current (Average)	~80 μ Amp
Input Beam Diameter	~3 mm
Input Energy Variation	± 7%
Output beam spot size	~2.62 mm
Output beam divergence	~3mrad
Output energy variation	± 3 %
Main Chamber	30×42.5 × 28cm^3
Magnet Type	Two Pole (C-shaped)
Yoke Material	Steel 1010
Magnet Material	Steel 12L14
Number of turns (Each coil)	40 turns
Pole Gap	10 mm
Radius of curvature	65 mm

3265 and 4155 Amp-turns, the optimized design produces 3369, 4972, 6384, 7584 and 9568 Gauss of magnetic field to bend the electron beam of energy 6, 9, 12, 15 and 18 MeV, respectively. Moreover, for 6 MV and 15 MV photon therapy applications, an electron beam of energy 6.5 MeV and 15.5 MeV extracted from magnet system and focused on the bremsstrahlung target. For the photon therapy, the 1233, and 3327 amp-turn, an optimized design produces 3616 and 7785 Gauss of magnetic field at median plane require to bend 6.5 and 15.5 MeV energy of electron, respectively, which further produces bremsstrahlung in Tungsten target.

An electron beam having energies 6, 9, 12, 15 and 18 MeV with beam diameter 3 mm and energy spread of ±7 % are passed through the optimized design of the two magnet system. The trajectory of an electron beam is shown in Fig. 8. It is observed that the convergence angle due to first magnet has been compensated by the divergence angle produced due to the second magnet.

Therefore, the output parameters of the optimized design of the two magnet beam bending system for medical linac are energy spread ± 3 %, divergence angle ~2.83 mrad and spot size ~2.6 mm. The optimized parameter for two magnet system is given in Table 2.

For the photon therapy application, an electron beam extracted from the magnet system was focused on the X-ray target placed at 70 mm from the exit port of the second magnet. Various materials have been simulated by using Monte Carlo based Fluka software for the optimization of X-ray target. Integrated Bremsstrahlung fluence versus e-γ target thickness for 6 MeV energy of electron incident on different materials is shown in Fig. 9. From figure it is observed that as the e-γ target thickness increases, the bremsstrahlung fluence also increases up to certain

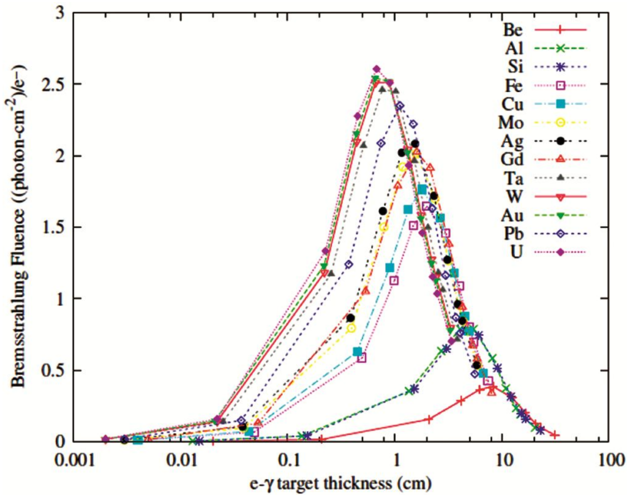

Fig. 9 – Integrated bremsstrahlung fluence versus e-γ target thickness for 6 MeV energy electron incidents on different materials.

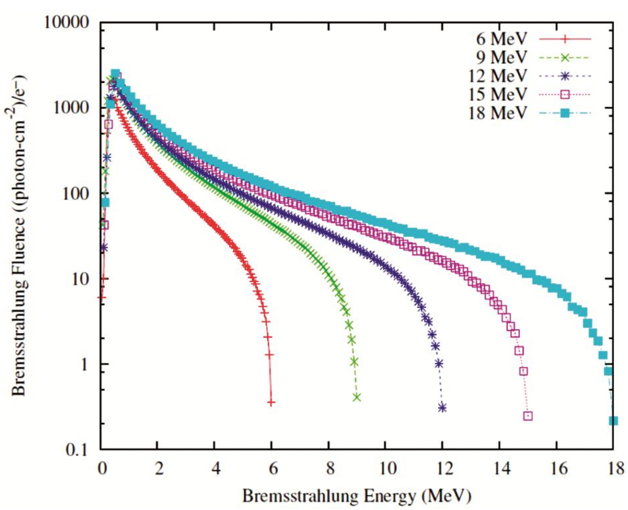

Fig. 10 – Bremsstrahlung spectra at e-γ target for 6 to 18 MeV electron energy.

thickness of e–γ target and decreases with increase in the thickness. Further, the bremsstrahlung fluence peak is shifted towards the lower thickness of the target with increase in the Z of the target. For higher density material the peak is found at lower thickness which is shown in Fig. 9. The same trend is observed for 9, 12, 15 and 18 MeV electron energies.

Amongst the materials studied, Tungsten is found to be the best suitable as e-γ target because of its physical properties like melting point, heat conductivity and high bremsstrahlung yield. The bremsstrahlung spectrum estimated on the target surface is shown in Fig. 10. It is observed from figure that the bremsstrahlung spectrum has peak at ~0.5 MeV for 6 to 18 MeV energies, respectively, and continuous spectrum up to the end point incident electron energy.

4 Conclusions

The optimized design of two magnet system gives uniform distribution of magnetic field and extracts 6 to 18 MeV electron beam having energy spread ± 3 %, divergence angle ~2.83 mrad and spot size 2.6 mm ± 0.1 mm. This system can be useful for the radiation therapy very effectively. Moreover, the Tungsten material has been optimized as e–γ target which produces more photon yield.

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