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Original Article

Monte Carlo simulation of electron modes of a Siemens Primus linac (8, 12 and 14 MeV)

Mohammad Taghi Bahreyni Toossi[1], Mahdi Ghorbani[1], Fateme Akbari[2], Leila Sobhkhiz Sabet[1], Mohammad Mehrpouyan[3]

[1]*Medical Physics Research Center, Medical Physics Department, Faculty of Medicine, Mashhad University of Medical Sciences, Mashhad, Iran,* [2]*Medical Physics Department, Reza Radiation Oncology Center, Mashhad, Iran,* [3]*Nutrition and Biochemistry Department, Faculty of Medicine, Sabzevar University of Medical Sciences, Sabzevar, Iran*

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Abstract

Background: Electron mode is used for treatment of superficial tumours in linac-based radiotherapy.

Purpose: The aim of present study is simulation of 8, 12 and 14 MeV electrons from a Siemens Primus linac using MCNPX Monte Carlo (MC) code and verification of the results based on comparison of the results with the measured data.

Materials and methods: Electron mode for 8, 12 and 14 MeV electron energies of a Siemens Primus linac was simulated using MCNPX MC code. Percent depth dose (PDD) data for 10×10, 15×15 and $25 \times 25\,cm^2$ applicators obtained from MC simulations were compared with the corresponding measured data.

Results: Gamma index values were less than unity in most of points for all the above-mentioned energies and applicators. However, for $25 \times 25\,cm^2$ applicator in 8 MeV energy, $10 \times 10\,cm^2$ applicator and $15 \times 15\,cm^2$ applicator in 14 MeV energy, there were four data points with gamma indices higher than unity. However among these data points, there are a number of cases with relatively large value of gamma index, these cases are positioned on the bremsstrahlung tail of the PDD curve which is not normally used in treatment planning.

Conclusion: There was good agreement between the results of MC simulations developed in this study and the measured values. The obtained simulation programmes can be used in dosimetry of electron mode of Siemens Primus linac in the cases in which it is not easily feasible to perform experimental in-phantom measurements.

Keywords: electron mode; gamma function; MCNPX; Monte Carlo simulation; Siemens Primus linac

INTRODUCTION

There are several methods for treatment of cancer but linac-based radiotherapy is the most common technique worldwide. Deep-seated

Correspondence to: Dr Mahdi Ghorbani, Medical Physics Department, Faculty of Medicine, Mashhad University of Medical Sciences, Pardis-e-Daneshgah, Vakil Abad Blvd., Mashhad 9177948564, Iran. Tel: +98 511 8002316. Fax: +98 511 8002320. E-mail: mhdghorbani@gmail.com

tumours are treated by X-rays produced by bremsstrahlung interaction of electron beam with a target. However superficial tumours are treated by electron mode of a linac.[1] Electron beam in radiotherapy is used extensively for treatment of head and neck cancers to avoid irradiation of spinal cord, which is poisoned in the pathway of beam. It is also used for radiotherapy of chest wall cancers to avoid excessive irradiation of lungs. Dose distribution calculations for electron beams are complicated since electron beams will undergo multiple scattering specially when interact with heterogeneities.[2]

To apply Monte Carlo (MC) code for clinical application, it is essential to define all relevant characteristics of the electron beam such as: energy, angular and spatial distributions of electrons.[3] MC simulation has proved to be a fast and effective technique to acquire radiation dose distribution of a source. The calculated data by this technique can be used to verify the measured data.[4]

MC method is the most accurate approach for electron dose calculation.[5] There are various commercially available systems that utilise MC algorithms for dose calculations. Examples of such MC-based treatment planning softwares are MasterPlan, eMC and Eclipse.[6–8] However there are other systems for electron treatment planning which may suffer from large uncertainties, especially when they are applied to an inhomogeneous media. Such treatment planning systems use different algorithms such as pencil beam algorithm and they have limitations in predicting hot and cold spots in inhomogeneous regions.[5,9]

The accuracy of dose calculations in radiation therapy has improved with advances made in the calculation power of computers. MC methods that are highly dependent on the calculation power of computers are being as superseders of analytical methods that are currently used in dose calculations in treatment planning systems.[4]

Several researchers have applied MC techniques to simulate and define the electron beam characteristics. Nedaie et al. obtained dose distribution produced by an ELEKTA Precise electron linear accelerator at 8 and 15 MeV energies for $10 \times 10\,cm^2$ applicator by simulation of this linac. Dose profiles in depth of 2 cm were measured by a diode detector. The differences between the measured results and MC calculations for both energies were equal to 2%. The MC results agreed well with the measured data.[10] Darko et al. performed a MC study on electron beam central axis depth dose data in water media. They compared MC results with corresponding measured data. Central axis depth dose distributions were calculated for electron beams of 6, 9 and 12 MeV energies for Varian 2100C (Varian, Paolo Alto, USA) medical linear accelerator with FOTELP code. Agreement between the calculated and measured data was demonstrated for depths from the surface of water phantom to depth on which dose falls to about 50% of maximum dose on the beam's central axis. However differences between measured and calculated data were found at depths below depth of 50% of the maximum dose. Simplification in geometry of the accelerator's head was thought as the main reason for these discrepancies.[11]

Verhaegen et al. used MC technique to simulate an electron accelerator and calculated the output factors for circular, rectangular, and square fields in 6–20 MeV energy range. Output factors for circular, rectangular and square fields were measured using a parallel-plate ionisation chamber and were compared with the results obtained by the simulations. The comparison showed an agreement within 1–2% between calculated and measured values.[12]

Sempau et al. used PENELOPE MC code to simulate 6 and 12 MeV electron beams of a Siemens Primus linear accelerator (model KDS, Siemens Medical Systems, Concord, CA, USA). The results of the simulations have shown that dose distribution in water agrees well with the measured values obtained by a silicon detector and an ionisation chamber. Simulation results by PENELOPE code were compared with those from BEAM and DOSXYZ codes. Angular and energy distributions of electrons and photons from both codes were similar. However, significant differences were observed in some cases.

It was shown that the effect of these differences on the calculated dose distribution was negligible.[13] Jabbari et al. studied 6, 8 and 10 MeV electron beams of a NEPTUN 10 PC linear accelerator using BEAMnrc code. The central axis depth dose curves and dose profiles of the electron beams were measured using a diode detector. In order to validate the simulation model, the percentage depth dose (PDD) curves and dose profiles obtained from MC in a water phantom were compared with the measured data. The comparisons have shown that data obtained by simulations are consistent with the experimental measurements.[2]

The aim of this study was to simulate electron mode of a Siemens Primus linac at three electron energies: 8, 12 and 14 MeV, then verify the simulations by comparing the PDD values obtained by MC simulations with the corresponding data acquired by measurements.

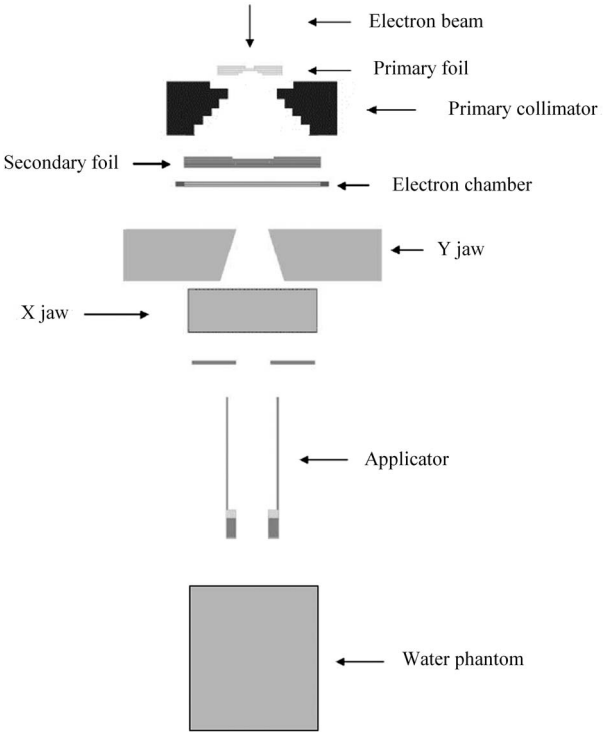

Figure 1. Geometry of head of Siemens Primus linac in electron mode as well as the water phantom.

MATERIALS AND METHODS

Geometry of Siemens Primus linac in electron mode

Siemens Primus medical linac (Siemens Medical Systems, Concord, CA, USA) has two treatment modes: photon and electron. The photon mode has normally two nominal energies: 6 MV and a high-energy option. The high-energy option may provide 15 MV or 18 MV X-rays depending on the therapeutic requirement. The electron mode has normally a number of energies. In the present study we have simulated a medical Siemens Primus linac installed at Reza Radiotherapy and Oncology Center (Mashhad, Iran). This machine is working with two nominal photon energies: 6 and 15 MV as well as six nominal electron energies: 5, 7, 8, 10, 12 and 14 MeV. We have selected three electron energies of 8, 12 and 14 MeV. Simulations were based on geometry of the head of the linac in electron mode provided by the manufacturer (Siemens Primus, Siemens Medical Systems, Concord, CA, USA). Based on the geometry, the primary foil consists of stainless steel in 8 MeV and gold in 12 and 14 MeV. The following head components were defined: primary foil, secondary foil, electron dose chamber, Y and X jaws, applicator. Furthermore the head components a water phantom was simulated as well. The electron dose chamber is made of Kapton and the jaws are made of stainless steel. The electron applicator of Siemens Primus linac consists of six parts: scraper, tray, body, shield, plate and a collimator. The water phantom was defined as a cylinder, which had 15 cm radius and 30 cm height. The geometry of the head is illustrated in Figure 1.

Simulation of electron mode

As it was mentioned before, three electron energies of Siemens Primus linac were incorporated in our simulations of the linac: 8, 12 and 14 MeV. The simulations were performed by utilising MCNPX (version 2.4.0) MC code[14] based on the energy spectrum of the primary electrons that was provided by Siemens manufacturer for three nominal energies of 8, 12 and 14 MeV.

An electron source with diameter of 2 mm was defined, electrons were exiting in downward direction towards the phantom surface. Source to surface distance was set as 100 cm.

Dose values in cylinders of 2 mm in height and 1 cm in radius were calculated. The cylinders were positioned on the central beam axis. Maximum doses deposited in the cylinders were then calculated and PDD values were obtained by normalising dose values to the maximum dose value. The energy deposited in the tally cells (cylinders) were calculated by *F8 tally for the water phantom.

A number of simulations were run for $10 \times 10\,cm^2$ applicator. In these simulations the manufacturer provided energy spectrum was changed for energies ranging from 0·5 MeV energy less than the spectrum to 0·5 MeV energy higher than the spectrum in a stepping manner with 0·1 stepping intervals. The optimum energy spectrum was then selected based on analysis of the outputs of the simulations. Our definition of the optimum energy was the energy having the best build up depth and gamma index when comparing the PDD data obtained by simulations with the corresponding in-phantom measured data. Based on gamma index calculations, the energy spectrum was selected as optimum energy in which fewer number of data points would have gamma index values higher than unity. For 8, 12 and 14 MeV nominal electron energies, the optimum spectrum were, respectively, 0·2, 0·5 and 0·4 MeV less than the energy spectrum which was certified by the Siemens manufacturer.

In the next step the optimum energy spectrums were used for simulations of the linac when 15×15 and $25 \times 25\,cm^2$ applicators are implemented. Each input file was run for 2×10^8 source particles. The MC statistical errors in the tally cells were $<2{\cdot}95\%$. This level of error is acceptable. This error and those close to this value are related to a limited number of data points and are correspond to farthest points on the tail part of the PDD curves. However the average error values for the three electron energies were considerably less than this value. Energy cut off was set as 0·5 MeV for both photons and electrons.

In-phantom measurements of PDD values were performed by an automated Scanditronix-Wellhofer system (model: RFA-300; Scanditronix Wellhofer, Uppsala, Sweden). Dose measurements were carried out in a water phantom by using a silicon diode.

PDD comparisons using gamma function

Comparisons of PDD values obtained by MC simulations and measurements were based on calculation of gamma function. This function is a useful tool for comparison of two dose distributions: one as calculated dose distribution that should be evaluated and the other as the reference (measured) dose distribution. Gamma function combines two criteria that previously have been used in comparisons of two dose distributions: percentage dose difference (in terms of %) and distance to agreement (DTA, in terms of mm). When only dose difference is used, it is sensitive in high-dose gradient regions; however DTA criteria is sensitive in low-dose gradient regions. So it is useful to combine both criteria to calculate a binary gamma function. Gamma index (function) has two values: 0 and 1. The gamma value of equal to unity is considered as 'pass' and will be obtained when both dose difference and DTA criteria are fulfilled. However gamma index of more than unity is considered as 'fail' or disagreement of two sets of dose distributions and is obtained when both or one of the criteria (dose difference and DTA) are not fulfilled. Gamma function was later modified to include continuous values between zero and unity. In the new form, gamma indices between zero and unity (inclusive) are considered as pass and gamma values higher than unity are considered as fail. Furthermore the magnitude of gamma value indicates the degree to which two dose distributions are in agreement or disagreement and thus provides a more quantitative criterion than the previous binary gamma index. In order to calculate gamma function, the PDD values from MC simulation as well as the corresponding depth data (in terms of mm) were incorporated in a text file. The PDD values acquired by measurement as well as the depth data were incorporated in another text file. The two text files then were processed by a gamma function software as input files to calculate gamma indices versus depth (mm) for the two relative dose (PDD) distributions. In the present study the gamma function software which was utilised was provided by DOSIsoft company and is able to calculate one-dimensional gamma indices. The software is

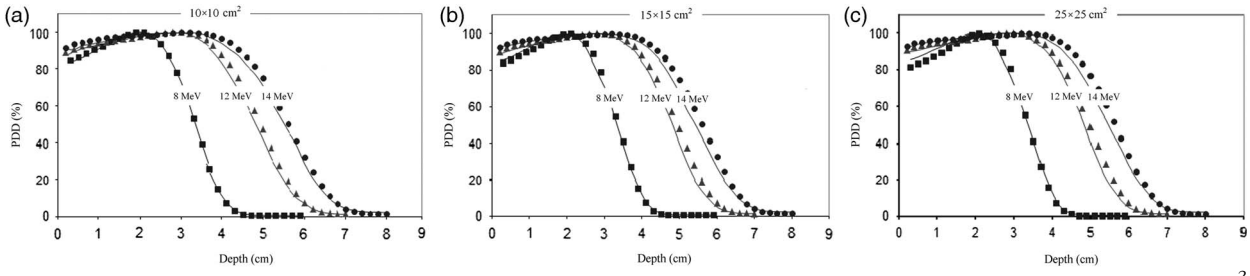

Figure 2. PDD values versus depth for 8, 12 and 14 MeV electron energies. (a): for 10 × 10; (b): for 15 × 15 and (c): for 25 × 25 cm² applicators. The lines are related to the measured data and the points are related to the data from Monte Carlo simulations. Abbreviation: PDD, percentage depth dose.

named gamma_index.exe and works in Gnuplot (version 4·4 patch level 3, Geeknet Inc., Fairfax, VA, USA) software environment. Dose difference and DTA criteria were, respectively, set as 3% and 2 mm in our gamma index calculations by the gamma_index software.

Following verification of the simulations, the average DTA for the MC and measurement data was also calculated for each electron energy. The averaging was performed on the DTA data of the three applicators in each energy. Furthermore, three depths that are commonly used for description of electron PDD curve were calculated from MC PDD data: z_{max}, R_{90} and R_{50}. The calculated depths then were compared with the corresponding data obtained from measured PDDs. z_{max} is the depth of maximum dose. The depths R_{90} and R_{50} (cm or g/cm^2) are defined as depths on the PDD curve at which the PDD value attain to values of 90% and 50%, respectively. These are those depths beyond z_{max}. These depths were calculated for the 10×10 cm^2 applicator in terms of mm.

RESULTS

PDD values obtained by MC simulations and measurements for 10×10, 15×15 and 25×25 cm^2 applicators for 8, 12 and 14 MeV electron energies are plotted in Figure 2.

Gamma index values for 10×10, 15×15 and 25×25 cm^2 applicators and 8, 12 and 14 MeV electron energies are plotted in Figure 3. The dose difference and DTA criteria used in calculation of gamma function was, respectively, set as 3% and 2 mm.

As it is evident from the nine parts presented in Figure 3, the number of points where the gamma function is higher than unity (namely disagreement between the PDDs from two methods) is ranging between 0 and 4 points.

The average DTA for the three energies of 8, 12 and 14 MeV were 1·6, 1·4 and 2·2 mm, respectively.

The z_{max}, R_{90} and R_{50} data required by MC simulations and measurements are listed in Table 1. When data presented in this table are compared, maximum difference between z_{max} by MC technique and measurement is 2 mm which is related to 12 MeV energy. The maximum difference between R_{90} obtained by the two methods was 2·1 mm, which is corresponding to 14 MeV energy. The maximum difference of R_{50} values is 1·3 mm. This value is related to 12 MeV electrons. As it was mentioned before, the z_{max}, R_{90} and R_{50} depths were obtained for 10×10 cm^2 applicator.

DISCUSSION

Maximum agreement between the two sets of data were obtained for 15×15 and 25×25 cm^2 applicators in 12 MeV energy in which no data points had gamma values more than unity (Figure 3). However the maximum discrepancy was related to 25×25 cm^2 applicator in 8 MeV energy, 10×10 and 15×15 cm^2 applicators in 14 MeV energy in which four data points had gamma values more than unity (Figure 3). Points with gamma index higher than 1 are failed. As it was mentioned in the 'Materials and methods'

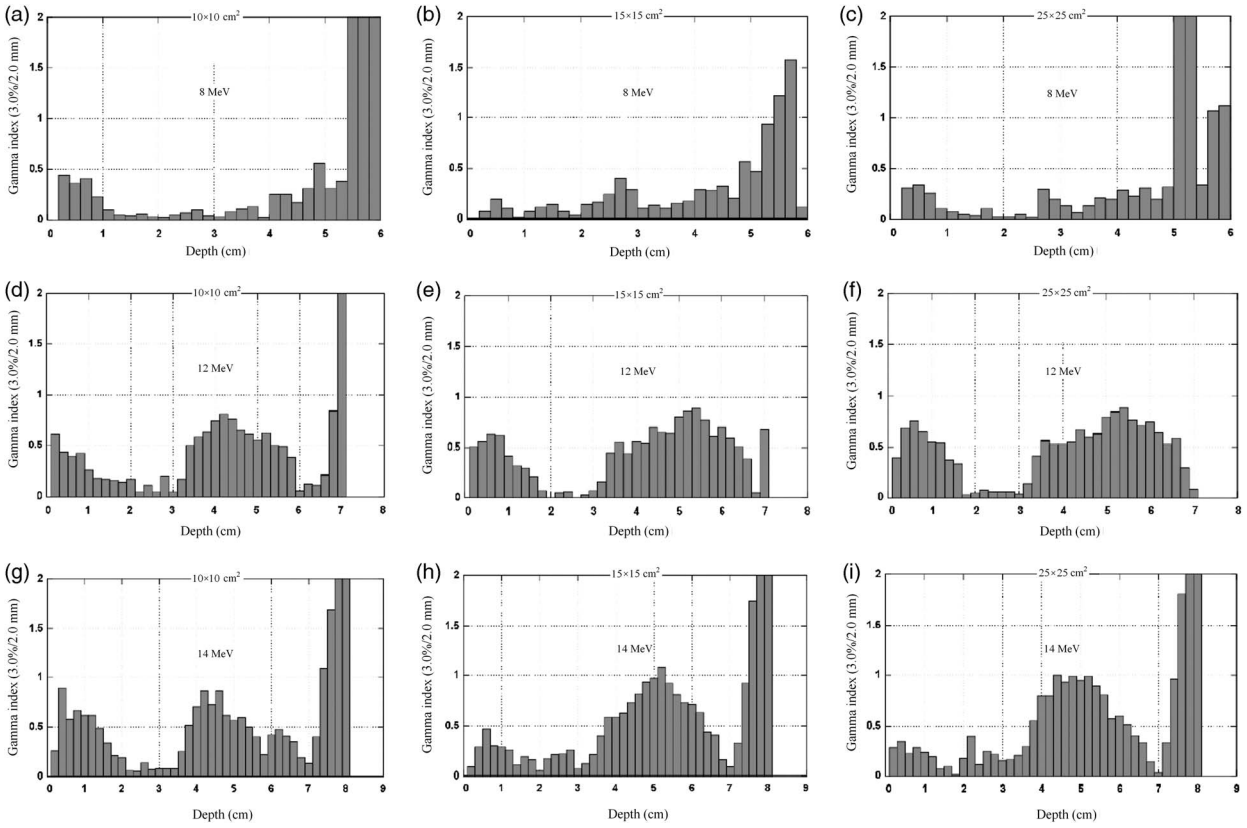

Figure 3. Gamma values versus depth in phantom (cm) for various applicators and electron energies. Parts (a), (b) and (c) in the figure are related to 8 MeV electron energy, respectively, for 10 × 10, 15 × 15 and 25 × 25 cm² applicators. Similarly parts (d)–(f) and (g)–(i) are related to 12 and 14 MeV electrons, respectively.

Table 1. *z_{max}, R_{90} and R_{50} depth values calculated from Monte Carlo simulation and measurement data*

Depth	Energy					
	8 MeV		12 MeV		14 MeV	
	Monte Carlo	Measurement	Monte Carlo	Measurement	Monte Carlo	Measurement
z_{max}	19 mm	19 mm	28 mm	30 mm	32 mm	32 mm
R_{90}	26·2 mm	26 mm	39·1 mm	37·6 mm	44·4 mm	42·3 mm
R_{50}	33·5 mm	33·4 mm	49·5 mm	48·2 mm	56·04 mm	55·2 mm

section, magnitude of gamma index is indicative of how much agreement does exist between experimental and simulated data. As it is shown in Figure 3, gamma indices were plotted for 8, 12, 14 MeV electron beams for depths up to 6, 7, 8 cm, respectively. These depths are much greater than the useful depth, which is normally used in treatment planning. According to Figure 3, few points have gamma index much higher than 2. Theses points are positioned on the tail of the PDD curves and they are not important in therapeutic applications. Generally speaking, our gamma function evaluations have indicated that there is a good agreement between the MC and measured PDD data. Based on the gamma function results, our MC models for electron mode of Siemens Primus linac at 8, 12 and 14 MeV electron energies are validated. We also aimed to compare our gamma function results with other similar studies but it was not found a similar study using gamma function in quantitative evaluation of electron beams.

Based on the average values of DTA for the three energies which were presented in the results section, these values are low (<2·2 mm) and are pointing out the close proximity of the MC data to the measured ones. However Verhaegen et al. compared R_{50} and R_p from simulations and measurements and observed a maximum difference of up to 1 mm between the two datasets.[12] When comparing the z_{max}, R_{90} and R_{50} depths calculated from MC and measured PDD data (Table 1), the values of z_{max}, R_{90} and R_{50} from MC technique are in agreement with the corresponding data obtained from in-phantom measurements.

Based on the values of gamma function, average DTA, and various characteristics depths, the points with low agreement of our MC data with the measured ones are located on the distal points of the tail part of the PDD curves. In clinical treatment planning with electron beams, the tumour normally is not located in the bremsstrahlung tail of the PDD curve. Thus the uncertainty in PDD values in this part does not affect the accuracy of dose delivered to the tumour. However normal tissues may be corresponded to the tail part of the PDD curve. In this situation since the dose value in these points is a low fraction of the maximum dose at build up depth (namely <4%), some uncertainty in dose in these points will not be correspond to a large absolute dose value and thus will not mainly affect the dose received by the normal tissues on this part.

CONCLUSION

In the present study electron modes of a Siemens Primus linac were simulated by MC code in three different energies: 8, 12 and 14 MeV and the results were verified through comparisons of the data with the corresponding measurement values. Using the developed simulation programmes here-in it will be possible to calculate dose distributions in complex clinical cases, for example in the case of inhomogenities, in which some treatment planning systems do not present dose distributions accordingly. The models presented in this study for 8, 12 and 14 MeV electron beams of Siemens Primus linac can be used in the future studies for evaluation of absolute or relative dose in a phantom in situations which performing experimental measurements may not be easily feasible. Using the developed MC models in the present study, it can be possible to study photon contamination, neutron contamination, effect of prosthesis and other inhomogeneities on dose distribution for the electron mode of Siemens Primus linac. Since there are only little differences in geometry of the Siemens Primus linac head in various electron energies, it will be possible to easily develop the MC models for other energies by simple modifications on the MC models for the 8, 12 and 14 MeV energies simulated. The main difference in the geometry of various energies is in the composition and thickness of primary foil. However in this case, energy optimisation will be also necessary for other energies other than the three energies studied in this work.

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