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A new method for designing dual foil electron beam forming systems. II. Feasibility of practical implementation of the method

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ABSTRACT

In Part I of this work a new method for designing dual foil electron beam forming systems was introduced. In this method, an optimal configuration of the dual foil system is found by means of a systematic, automatized scan of system performance in function of its parameters. At each point of the scan, Monte Carlo method is used to calculate the off-axis dose profile in water taking into account detailed and complete geometry of the system. The new method, while being computationally intensive, minimizes the involvement of the designer. In this Part II paper, feasibility of practical implementation of the new method is demonstrated. For this, a prototype software tools were developed and applied to solve a real life design problem. It is demonstrated that system optimization can be completed within few hours time using rather moderate computing resources. It is also demonstrated that, perhaps for the first time, the designer can gain deep insight into system behavior, such that the construction can be simultaneously optimized in respect to a number of functional characteristics besides the flatness of the off-axis dose profile. In the presented example, the system is optimized in respect to both, flatness of the off-axis dose profile and the beam transmission. A number of practical issues related to application of the new method as well as its possible extensions are discussed.

1. Introduction

In Part I of this work [1] a motivation for the development and a concept of a new method for designing dual foil electron beam forming systems was outlined. Here, we demonstrate feasibility of this new method on an example of a real life design problem. The reader is, however, strongly advised to read the Part I of this work first, as it includes useful background information as well as explanations and definitions of many quantities referred to here. As explained in Part I, the motivation behind development of the new design method is to eliminate the shortcomings of the existing design methods and improve overall efficiency of the dual foil design process. The existing methods are based on approximate analytical models applied in an unrealistically simplified geometry. Designing a dual foil system with these methods is a rather labor intensive task as corrections to account for the effects not included in the analytical models have to be calculated separately and accounted for in an iterative procedure. To eliminate these drawbacks, the new design method is based entirely on Monte Carlo modeling in a realistic geometry and using physics models that include all relevant processes. In our approach, an optimal configuration of the dual foil system is found by means of a systematic, automatized scan of the system performance in function of parameters of the foils. These parameters are thickness of the scattering foil, the separation distance d between the scattering and the flattening foil, and parameters H and R describing the height and width of a Gaussian radial thickness profile of the flattening foil defined as

$$h(r) = H\exp\left(-\frac{r^2}{R^2}\right). \quad (1)$$

The new design method, while minimizing the involvement of the designer, delivers high quality results as all the relevant physics and geometry details are naturally accounted for. It may, however, seem that the new method is infeasible due to potentially very large number of lengthy Monte Carlo calculation runs. To prove otherwise, we present here a real life example of application of this new method.

The paper is organized as follows. We start with a presentation of a prototype software tools that were constructed to test the feasibility of the new method. We then follow with description of an electron beam irradiation device that was designed according to the new method with use of the above mentioned tools. We then present the results of design optimization and discuss practical aspects of the new design method implementation.

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2. Tools for practical implementation of the new design method

2.1. Geant4 based application

An application, utilizing Geant4 toolkit [2,3], was developed to calculate off-axis dose profile deposited in water by electron beam transported through a model of a beam forming system.

2.1.1. Model geometry

The geometry of the system is defined in a mandatory Geant4 class DetectorConstruction. In particular, objects representing an exit window of an electron accelerator, a scattering foil, a flattening foil and a water phantom are defined in this class. Fig. 1 shows an illustration of the most simple beam forming system consisting of those elements only. The designer may extend the geometry model by adding a custom beam collimation system. Geant4 offers a rich library of geometrical solids as well as methods for constructing new solids. With these facilities a model of a collimation system geometry may be implemented quickly. In Section 3, an example of a system including a specialized collimation system is presented (see Fig. 4). The exit window and the scattering foil are made of G4Tube solids. The flattening foil is modeled as a G4GenericPolycone and closely approximates a Gaussian defined with Eq. (1) (see also Eq. (3) in Part I [1]). The approximation used is shown in top part of Fig. 2. The polycone consists of up to 10 segments and is scaled, on the run time, accordingly to actual values of the parameters H and R. The model of the flattening foil also includes a realistic backing plate. The exactly same numerical description of the flattening foil thickness profile as implemented in the Geant4 simulation is also used to program the Computer Numerical Control (CNC) turning machines used at the National Centre for Nuclear Research (NCBJ) to actually produce the flattening foil. An example of a Gaussian shaped flattening foil with a backing plate machined as a single detail is presented in the bottom part of Fig. 2.

Properties of geometrical objects, such as material, dimensions, position in space, can be modified interactively. This is done by means of a set of new interface commands defined with G4UImessenger methods. For defining materials a rich library of Geant4 materials is used. Position in space of the scattering and the flattening foils are defined as separation distances between the back plane of the exit window and of a respective foil. A foil (including the exit window) can be removed from the model by setting its thickness to zero. This functionality is included to allow optimization of the scattering foil according to Kozlov and Shishov method (see Sec. 6.7 in Part I [1]). Similarly, the backing plate of the flattening foil may be removed by setting its thickness to zero.

2.1.2. Primary beam

For defining a primary beam, the Geant4 General Particle Source facility is used. This allows for simple, command based, setup of a nearly arbitrary complex particle source without any modifications of the application code.

2.1.3. Dose scoring

The geometry model of the system includes a model of a water phantom for calculation of the off-axis dose profile and its flatness, as defined in Section 5 in Part I [1]. The phantom is positioned such that its upper base is at distance *SSD* from the accelerator exit window.

To study the performance of the prototype application, two methods for calculation of the off-axis dose profile in water were implemented. The first one relies on a generic Geant4 dose scorer, while in the second one the dose is derived from an electron and photon planar fluence.

To reduce the number of voxels in the phantom used with the generic Geant4 dose scorer, and thus to reduce the calculation time, the scoring is done in concentric rings. This is appropriate for axially symmetric systems, as the one presented later. Schematic illustration of the phantom segmentation is shown in Fig. 1. In what follows, the active space of the water phantom was divided into a central disk of 10 mm diameter, and 39 concentric rings of 5 mm width. All segments are 5 mm thick. Flatness of the dose distribution registered in this phantom is calculated at the end of a run according to Eq. (7) in Part I [1].

In the second method, an approximate dose profile in water is calculated based on planar particle fluence. This method is expected to be faster in terms of calculation time since it does not introduce any additional geometrical region boundaries for particle tracking (as opposed to a segmented phantom). The planar fluence is calculated separately for electrons and photons, per concentric radial bins, on a plane perpendicular to the beam axis at a user defined depth in water. For proper normalization of the planar fluence, the edges of the bins are setup such that the area of each bin is the same. The binning can be changed interactively by setting the radius of the center bin and the maximum radial extension of the data collection area. The fluence is calculated directly by counting particles passing through the plane. At the same time, energy spectra are accumulated.

For calculation of the relative off-axis dose profile, first the energy deposited in a thin layer of water of thickness ΔZ is estimated for each registered particle. In case of electrons, the deposited energy is calculated as

$$\Delta E_e = S_{col}(E)\Delta Z \tag{2}$$

where $S_{col}(E)$ is the energy dependent collision stopping power

Fig. 1. Geant4 model of the most simple system geometry. From left to right: exit window, scattering foil, flattening foil, water phantom. The dimensions of foils were set unrealistically large in order to improve readability of the illustration. For the same reason also the number and dimensions of radial segments of the water phantom are for illustration purposes only, and do not reflect the actual system geometry.