Investigations of a beam phase-space model for multi-leaf collimated electron fields.

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Abstract

The interest of using energy- and intensity modulated electron radiotherapy (MERT) for superficial targets have gained interest in recent years. While some have proposed using only the photon MLC (xMLC) for electron collimation, sharper penumbras can be achieved using an electron multi leaf collimator (eMLC) close to the patient. One of the problems associated with MERT is that the dose from bremsstrahlung leakage through the eMLC will be substantial when adding many fields. Having the photon MLC track the shape of the eMLC can greatly reduce this contribution. However, using this approach puts more strain on the treatment planning system’s ability to calculate absorbed dose in the patient. The coupled multi–source electron beam model in Oncentra Masterplan 3.2 starts with a parameterized description of the electron (source) phase–space in a plane below the secondary scattering foil and uses a dedicated Monte Carlo code (QMC) for electron transport through the treatment head. The model uses a fluence based formalism and currently needs measured dose to registered monitor units (Gy/MU) for each applicator–energy combination in order to normalise the dose engine. In this thesis the beam models ability to model a linear accelerator with a simple eMLC model together with xMLC tracking was investigated. Comparisons were made between the beam model (EBM) and BEAMnrc simulations of a Siemens Primus linear accelerator on account on several parameters. Good agreement between planar fluence profiles was found, although for 6, 15 and 18 MeV some disagreement can be seen in the flatness for some of the larger fields with the shortest SSD (85 cm, CSD 5 cm). Electron angular distribution was evaluated using the mean (effective source distance) and the standard deviation of the distribution. Results were in good agreement apart from minor differences seen for the smallest eMLC fields with the smallest xMLC tracking margins (maximum difference $Z_{eff} < 6$ cm, $\sigma_{\theta} < 0.1$ degrees). Differences in relative planar fluence output was lowest for 6 MeV and amounted to 2% or less for all the fields except the 2x2 cm$^2$ field where differences were < 4%. For 9, 12, 18 and 21 MeV results are within 3-4 % for field sizes of 7x7 to 20x20 cm$^2$. 15 MeV shows some larger disagreement and is within 5% for the 7x7 to 20x20 fields with the largest tracking margin. In general for all energies, small fields with small tracking margins are prone to the worst agreements. Also the Primus accelerator has an aluminium ring surrounding the secondary scattering foil which inadvertently acts as a secondary source of electrons. Using LATCH-bits to remove the ring-scattered electrons greatly improves the agreement between EBM and BEAM for fields larger than 10x10 cm$^2$. This shows that the discrepancy in relative fluence output for the larger fields can be attributed to the source phase–space parameterisation. For small fields however the discrepancy can currently not be explained.
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Abbreviations

IMRT  Intensity modulated radiation therapy
xIMRT  Intensity modulated radiation therapy with photons
MERT  Modulated electron radiation therapy

MLC  Multi leaf collimator
xMLC  Photon multi leaf collimator
eMLC  Electron multi leaf collimator

SSD  Source to surface distance
SCD  Source to collimator distance
CSD  Collimator surface distance

PSP  Phase space
SPS  Source phase space
EPS  Exit phase space
MC  Monte Carlo

ROF  Relative (planar fluence) output factor
MU  Monitor units
TPS  Treatment planning system
EBM  Electron beam model
1 Introduction

1.1 Electron treatment

In treating superficially located tumors with external radiotherapy, electrons in the MeV-range have advantages over MV-photon beams due to the well-defined energy dependent range, sparing distally located healthy tissue and sensitive organs (ICRU 35 1984, Hogstrom and Almond 2006). Traditional electron treatment is performed with a multi level collimating structure (applicator) that uses several thin scraper layers (diaphragms) to terminate peripheral scattered electrons. This approach is favorable since it minimizes collimator scatter which otherwise would produce a large number of large-angle, low-energy electrons (van Battum et al. 2003, ICRU 35 1984). The last scraper layer of the applicator is in close proximity to the patient surface to avoid degradation of the beam (penumbra widening) due to multiple scattering in air. Field sizes are fashioned with different sized applicators, capable of supplying square fields in the tens of centimeters. To form the desired field shape a custom-made insert (cut out) of a high-Z material is produced after the tumor outline and mounted on the last scraper layer of the applicator. In order to obtain an even distribution of collimator scattered electrons over the field and to minimize and photon leakage through the diaphragms, the jaws and/or photon MLC are set to fixed positions after applicator size and energy. The use of applicators with inserts is however, a limiting factor in electron therapy since new inserts have to be produced for every treatment field and patient. In addition, to compensate for patient curvature or to change the therapeutic range, boluses are sometimes added to the patient surface (Low et al. 1992, Vatanen et al. 2009).

With inverse dose planning using fluence modulated photon beams (IMRT), good target coverage of some superficial tumors can be achieved while high dose to sensitive organs and surrounding tissue can be minimized. Unfortunately, large volumes will usually suffer a low dose contribution (Fogliata et al. 2007, Webb 2001, Ma et al. 2003, Smitt et al. 1997). A multi leaf collimator particularly designed for electron fields (eMLC) have been suggested as an alternative to applicators with inserts (Gauer et al. 2006, 2008a,b, Karlsson et al. 1999, Lee et al. 2000, Ravindran et al. 2002, Vatanen et al. 2008, Eldib et al. 2008). In the same manner as with the photon MLC (xMLC), irregular fields could be shaped and the necessity for field shaping inserts would be eliminated. Several prototypes have been investigated, both as ad-ons to applicators mounted on the last scraper layer, or as separate modules without diaphragms, either at a fixed source-collimator distance (SCD) or variable in position along the beam axis. With the latter, standard SSD-, isocentric- and arc treatment would be possible (Hogstrom et al. 2004, Olofsson et al. 2005a).

1.2 Modulated electron radiation therapy

The ability to form almost arbitrary lateral shaped electron fields also opens up for modulated electron therapy (MERT) where the dose is delivered in segments with either fluence modulation or both fluence and energy modulation (Deng et al. 2002, Åsell et al. 1997, Olofsson et al. 2004). With an appropriate choice of segment sizes and weighted fluence and energy, dose conformity both laterally and distally
can be achieved (Ma et al. 2003). This could also eliminate the need for boluses in electron therapy since range modulation could be achieved by varying the energy (Vatanen et al. 2009). There has also been some interest in the possibility of using only the xMLC of a conventional dual-scattering foil linear accelerator to form the electron fields for both conventional electron treatment and MERT (du Plessis et al. 2006, Klein et al. 2009, Lee et al. 2000, Jin et al. 2008a,b, Lewis et al. 2008). This approach would however produce dose profiles with unacceptable large penumbras if the collimator to surface distance (CSD) is too large. However, Karnas et al. (2005) showed that the penumbra of electron fields shaped by the xMLC of a Varian 2100 CD (CSD 42 cm) could be improved by adding photon IMRT fields. Results yielded dose profiles similar to conventional electron treatment with cut-outs for the dose above 50%. Karlsson et al. (1999) concluded that replacing the air with helium in the treatment head, among other things, would decrease the penumbra and increase the effective source position of the electron field using the xMLC for shaping electron fields. Abutting segments of electron and photon fields would be easier to match with a common effective source distance.

Compared to treatment techniques used today for superficially located tumors, simulated MERT plans have shown promising results. Ma et al. (2003) compared conventional tangential photon beams, intensity-modulated tangential photon beams, multiple field IMRT and MERT for three breast cancer patients. Their results showed that the MERT-plans provided a large reduction in peak lung and heart dose compared to the tangential photon techniques. Multiple beam angle IMRT was also able to reduce the maximum dose to the heart and lung, but at the expense of a low and medium dose contribution to the healthy tissue. The MERT-plans also induced the lowest dose to the contralateral breast of all techniques. However, dose inhomogeneity was most significant for the MERT plans (10%). Surucu et al. (2009) reported a significant decrease in dose to organs at risk (OAR) comparing MERT with IMRT for parotid gland cancer treatment. They also showed a higher dose heterogeneity in the target with MERT. Jin et al. (2008a) compared energy and fluence modulated (xMLC) electron fields with conventional opposed photon beams for scalp irradiation, and found improved dose conformity to the target and a reduction of dose to the brain and less volume irradiated. Klein et al. (2007) investigated the use of MERT for chest wall (post mastectomy) and scalp irradiation. Using 8 segments and 2 energies with one gantry angle, they obtained a homogeneous dose distribution (±10%) in the chest wall with minimal dose (<5%) to the heart, lung and contralateral breast. The scalp simulation was done with 2 table and 3 gantry angles, 2 energies (6 and 9 MeV) and 11 segments and yielded a homogeneous coverage (±9%) and almost no irradiation of brain tissue. Gauer et al. (2008a) showed a reduction of high dose exposure to heart, lung and liver for funnel breast (post mastectomy) patients comparing xIMRT, Tomotherapy and MERT. With Tomotherapy, the dose to heart and liver was lower than with MERT, though the contralateral lung and breast received an average dose of 5 Gy (10% target dose). Ma et al. (2000) showed for breast treatment a better dose homogeneity with MERT in the target area compared to tangential photon beams and a reduction of maximum dose to the lung from 50 to 35 Gy. The volume of the lung receiving 8 Gy or more was reduced, although the part of the lung receiving 8 Gy or less was slightly increased. The dose to the surrounding tissue (1000 cm$^3$) was reduced by 10-30 Gy with MERT. Combined optimized electron and photon fields have been investigated for breast treatment and results showed a lower dose inho-
mogeneity in the target compared to conventional treatment methods (Xiong et al. 2004).

With all dual-foil linacs, bremsstrahlung production in the treatment head (mostly in the scattering foils) is unavoidable. This is usually of little concern in delivering single or a few electron fields. However, using several segments and energies as in MERT, the leakage through the eMLC could increase to unsatisfying levels (Olofsson et al. 2005a,b). The proposed and prototyped eMLCs are kept relatively thin for weight, clearance and in order to minimize leaf scatter. To reduce the contribution of eMLC bremsstrahlung leakage, the xMLC can be used to track the position of the eMLC leafs (Olofsson et al. 2005a). There is however a need for some margin between the xMLC and eMLC projected field sizes since the xMLC would otherwise perturb the electron field and degrade the penumbra if no, or to small of a margin is applied. Olofsson (2005) showed a large reduction in bremsstrahlung dose from eMLC leakage using this approach. The term 'tracking margin' in this thesis will be used to describe the margin of the xMLC’s projected field size (side of field in cm) to that of the eMLC at the given SSD.

1.3 Dose calculation

For dose calculation of electron fields, the Monte Carlo (MC) method is unprecedented in accuracy over other methods and is able to adroitly model dose distributions around inhomogeneities (Andreo 1991, Rogers 2006, Ma and Jiang 1999). It relies on random samplings of probability distributions of physical processes and usually requires a large number of generated electrons in order to achieve a low statistical uncertainty (Ma et al. 2005). In order to perform accurate dose calculations it is required to have knowledge of the phase-space (energy, position, direction, charge) of the electron beam (Ma et al. 1997). For newer linear accelerators, the narrow mm spot-sized electron beam exiting the vacuum window is modified by two scattering foils designed to widen the beam and ensure a flat fluence profile in a plane below the accelerator while minimizing bremsstrahlung production. The electrons will undergo multiple Coulomb scattering in the air in the treatment head hit collimating structures producing secondary particles and adding complexity to the beam. It is therefore required to have a detailed description of the geometry and material composition in order to correctly model the phase-space (PSP) propagation through the treatment head.

The MC code BEAMnrc (Rogers et al. 1995, 2009) using the EGSnrc code system (Kawrakow 2000, Mainegra–Hing et al. 2009), was developed as a part of the OMEGA-project in order to model clinical linear accelerators and have been widely used since (Rogers 2006). For phantom and in-patient dose calculations, the DOSXYZnrc code (Walters et al. 1939) has been shown to be within 1% of measurements under ample conditions. These MC programs are however not quite suitable for clinical purposes since calculation times usually are too long. The Voxel Monte Carlo Code (VMC++) developed by Kawrakow (2001), supplied the demand of a fast and accurate MC dose calculation engine for electrons and photons. It is in general 50-100 times faster than EGSnrc/DOSXYZnrc for dose calculation in a phantom and results are within 1% agreement with EGSnrc/DOSXYZnrc (Kawrakow 2001).
1.4 Aim of thesis

The electron beam model used in Oncentra Masterplan 3.2 (Ahnesjö et al. 2000, Traneus et al. 2001, 2006) was investigated regarding its potential use for modeling a Siemens Primus linear accelerator with an attached eMLC. Comparisons were made between this model and BEAM simulations for a number of energies, field sizes (square shaped), SSDs and tracking margins of the xMLC. Scoring planes were set under the secondary scattering foil for comparison of the source phase-spaces (SPS) and at SSDs of 85, 96 and 100 cm (iso-plane). The PSP was investigated with respect to the effective source position, angular distribution, planar fluence profiles and relative electron output in air (exit phase-space only). The main purpose is whether the beam model can handle changes in relative planar fluence output factors (ROF) with varying field size, SSD and tracking margin (cf Lewis et al. 2008).

The electron beam model is a coupled multi-source model consisting of a dedicated Monte Carlo code (QMC) developed by Traneus (Traneus et al. 2001, 2006) for transporting electrons in air in the treatment head (solely multiple coulomb scattering) and makes use of pre-calculated edge scatter kernels (EGSnrc) for every collimating structure (Ebert and Hoban 1995a,b, Traneus et al. 2001). Photon dose contamination as a result of bremsstrahlung production in the accelerator head is modeled with an analytical model fitted to depth dose and profile measurements. The in-patient electron transport and dose calculation is later performed by VMC++. The beam model starts in a plane below the secondary scattering foil as a parameterized description of the electron PSP. This constitutes the source phase-space (SPS) plane and is unique for every energy and accelerator. Electrons are sampled from the SPS parameterisation and propagated through the treatment head by QMC down to an exit phase-space (EPS) right above the last scraper of the applicator. The EPS is parameterized and sampled from on request by the dose calculation engine (VMC++). For each energy and applicator combination, the jaws and/or xMLC are set to fixed positions, the electron transport in the accelerator head only has to be performed once for every such combination (Nucletron 2006). A Monitor unit (MU) calculation is done for each applicator-energy combination without insert present. The parameterized EPS together with the MU calculation is then stored locally in the treatment planning system (TPS) with the customer. The electron beam model (abbreviated ‘EBM’ hereafter) is currently in use for applicators with inserts (Cygler et al. 2004, 2005, Wieslander and Knööö 2006, 2007) and has recently been tested with an add-on eMLC (Vatanen et al. 2008, 2009).

While using the xMLC to track the eMLC, dose to MU calculation (Gy/MU) cannot be performed in the same way as for applicators because each field shaped by the eMLC would require different xMLC leaf positions and the PSP would be altered upstream. Thus, the treatment head transport of electrons by QMC would have to be performed for each unique xMLC shape. For this reason, the EBM’s ability to model changes in relative fluence output factors with varying field size, SSD and tracking margin is investigated. If successful, global normalisation could be applied, i.e. only one absolute dose to MU measurement would be sufficient for all fields, tracking margins and SSD.

In the Siemens Primus linear accelerator, an aluminium ring used in the carousel mechanism for the second scattering foil and photon beam flattening is in close prox-
imity to the secondary scattering foil. The effect of this component on the SPS can currently not be adequately modeled in the beam model, and it is unclear which effect this has. Because of this, BEAM simulations were evaluated with and without electrons that had undergone interactions in this component. BEAM has an option to set tags (LATCH-bits) on particles that has interacted with certain components. In this work, LATCH bits were used to distinguish collimator-scattered electrons from the non-scattered, and to separate those that interacted with the aluminium ring. The beam model can produce the same type of binary phase-space files as BEAM and likewise tag collimator-scattered electrons with LATCH-bits. Issues regarding correct modeling of collimator scattered electrons and bremsstrahlung dose contribution will not be addressed here. The indirect electrons are entirely dependent on the direct electrons in EBM, the handling of the latter must first be correct before adding the scattered component.

2 Materials and method

2.1 Description of the geometry

A virtual model of a Siemens Primus linear accelerator was built in BEAM and in Oncentra Masterplan’s electron beam model (EBM) after vendor specifications of geometry and material composition. The accelerator incorporates a dual-foil scattering system for electrons with a primary scattering foil based on selected nominal energy (none for the lowest energy, 6 MeV) and one secondary scattering foil used for all energies. The secondary scattering foil is placed upon a thin kapton foil together with an aluminium ring used in the carousel mechanism. The aluminium ring is in close proximity to the scattering foil, yet not intended as a beam-modifying device. The beam monitor (ion chamber) is located directly below and is a part of the same structure (figure 1). For beam collimation, the Primus model has one pair of focusing jaws and a photon multi-leaf collimator (xMLC). The latter was modeled as a VARMLC tungsten component in BEAM at a distance of 28 cm (top surface) and a thickness of 7.6 cm. The leafs had a tongue- and groove design with non-rounded, double focusing edges. The xMLC in EBM was modeled without the tongue- and groove design, but otherwise incorporated the same geometry. An eMLC was modeled based upon preliminary data of an eMLC prototype, as a tungsten (W) component at an SCD of 78.5 cm (top surface) and thickness 1.5 cm with straight non-focusing leafs (Figure 2).

2.2 The coupled multi-source electron beam model

The electron beam model used in Nucletron Oncentra Masterplan 3.2 is a coupled multi-source model. There is a distinction made between electrons scattered solely in air (direct electrons) and those that interact with collimating structures such as jaws, multi leaf collimators, scraper layers and inserts (indirect electrons). The electron model is initiated with a parameterized description of the source phase-space (SPS) located in a plane below the secondary scattering foil and is propagated down to an exit phase-space (EPS) with a fast dedicated Monte Carlo code, QMC (Traneus et al.)
Figure 1: (a) Electron beam modifying components (not to scale). (1) exit/vacuum window, (2) primary scattering foil and primary collimator, (3) aluminium ring, (4) secondary scattering foil resting on a kapton foil. Beam monitor/ion chamber not shown in figure. (b) Illustration of the secondary scattering foil with surrounding aluminium ring.
Figure 2: Schematic diagram of a Siemens Primus accelerator with an electron MLC (not to scale). (1) Vacuum window and primary scattering foil, (2) secondary scattering foil, ion chamber and source phase-space plane (dashed), (3) block collimators (rotated, retracted), (4) photon MLC, (5) eMLC, (6) iso-plane. Figure also depicting the xMLC tracking margin (x cm) for the 100 cm SSD.
2001). The creation of secondary particles during transport in the accelerator head is not considered. Bremsstrahlung photons (mainly from the exit window and scattering foils) are handled with an analytical model with parameters extracted from depth and profile dose measurements and are described elsewhere (Nucletron 2006). The parameterisation of the EPS is only described here for consistency and was not performed in this work.

2.2.1 Accelerator characterisation measurements

The user of the TPS provides the geometry and material composition of the accelerator and of additional applicators and inserts. A number of measurements are required for each energy to characterize the accelerator and to verify the beam model. In-air cross-plane and in-plane profile scans are performed without applicator at SSDs of 70 and 90 cm, with a projected upper jaw opening of 8 cm and lower jaw (or xMLC) setting of 30, 20 and 8 cm (given at the isocenter, 100 cm SSD). An additional 30x30 cm$^2$ square-field measurement is also required. On-axis output factors measurements in air are performed for the above-mentioned fields and SSDs. Measurements in a water phantom consist of depth-dose measurements with and without applicator, in–plane cross–plane profiles and an absolute dosimetry calibration. Profile scans beyond the practical range of the electrons are also performed for bremsstrahlung measurement. In-air measurements are performed without any build-up cap.

The parameterisation of the SPS is done for every unique machine and energy available and performed by Nucletron personal. The parameters are manually tuned and fitted toward in-air profile measurements (figure 3). The electron energy spectrum used in the SPS parameterisation is determined by minimizing the difference between a measured open field (collimators maximally retracted, no applicator) depth dose and a calculated water depth dose. The spectrum is given by a weighted sum of monoenergetic depth doses. The small effect of energy degradation in air is neglected as the spectrum derived at the phantom surface (SSD of 100 cm) is used in the SPS parameterisation.

2.2.2 Source phase-space (SPS) parameterisation

The SPS ($\Phi_s$) is a parameterisation in five variables of the electron phase-space in a plane right below the secondary scattering foil. It has a rotational symmetry around the beam axis and can be described by

$$\Phi_s(E, \theta_\parallel, \theta_\perp, s) \propto \varphi(E) \times e^{\frac{s^2}{\sigma_s^2}} \times e^{\frac{(\theta_\parallel - \theta_s)^2}{\sigma_\theta^2}}$$

for $s \leq s_{\text{max}}$ \hspace{1cm} (1)

$$\Phi_s(E, \theta_\parallel, \theta_\perp, s) = 0$$

for $s > s_{\text{max}}$ \hspace{1cm} (2)

Where $E$ is a location-invariant energy spectrum and $s$ is the radial distance from the beam axis extending to a maximum $s_{\text{max}}$ (cut-off radius), defining the disc that is the extended source of the electrons in the model (figure 4(a)). The planar fluence is approximated with a (rotation symmetrical) gaussian distribution extending to the
Figure 3: Measured (red) and simulated (green jagged) center plane profiles for 12 MeV at SSD of 70 and 90 cm. Field sizes given at the iso-place (SSD 100 cm). Upper jaw set to 8 cm and lower jaw to 8, 20 and 30 cm. Profiles normalised to the 20x8 cm\(^2\) SSD 70 cm profile. Note the small disagreement in the edges of the 30x8 cm\(^2\) field.
cut-off radius and with an amplitude given by the variable $\sigma_s$ (standard deviation of the distribution) (figure 4(b)). The mean direction of the electrons is given by $\theta_s$, which is a function of $s$ through the location of the effective source position, $Z_{\text{eff}}$. The net effect on the angular distribution by the vacuum window, scattering foils, monitor chamber and air is approximated with gaussian functions, parallel and perpendicular to the radial direction ($\theta_\parallel$ and $\theta_\perp$ respectively) (figure 4(c)). Their widths are defined by $\sigma_\theta$ as a linear function of $s$.

2.2.3 Source phase-space transport

The electron transport is executed in a single step in air between each collimating layer in the treatment head utilizing the LLCA algorithm for multiple coulomb-scattering in air (Kawrakow 1996, Kawrakow and Bielajew 1998). Only electrons with a clear passage through each aperture will be transported further down. For thicker collimating structures, such as block collimators or photon MLCs, the transport is performed in an additional step between the top and the bottom surface.

2.2.4 Exit phase-space (EPS)

Using electron applicators, the exit phase-space is located right under the lowest collimating structure and the transport of the SPS only has to be performed once for every energy-applicator combination. Pre-calculated scattered kernels are used to handle interactions with the scraper layers and patient specific inserts. The direct component of the electron phase space is parameterized according to

$$\Phi_s(E, \theta_\parallel, \theta_\perp, x, y) \propto \varphi_E(E) \times \varphi_{xy}(x, y) \times e^{-\frac{\sigma_\theta^2 + (\theta_\parallel - \theta_r(r))^2}{\sigma_\theta^2/\sqrt{2}}}$$

where $r = \sqrt{x^2 + y^2}$ is the radius of the plane and $\varphi_{xy}(x, y)$ is a lateral fluence distribution. The mean angle $\theta_r(r)$ of the electrons and the variance of the angular distribution $\sigma_\theta^2(r)$, are defined by an effective source distance $Z_{\text{eff}}(r)$ dependent on the location radially in the EPS plane. Their respective values are determined by scoring the exit direction in concentric rings (figure 5). The electron energy spectrum derived from depth dose measurements, is used in both the SPS and EPS parameterisation. During dose calculation, the dose engine (VMC++) samples electrons from pre-calculated edge scatter kernels (Ebert and Hoban 1995a,b). The scatter kernels are differential in incident energy and beam angle and are generated for applicator scraper layers as part of the accelerator characterisation. With patient specific inserts the direct electrons are only generated over the open part of the insert.

2.2.5 Fluence based formalism

Oncentra Masterplan uses a fluence-based formalism to calculate dose and to determine the dose per monitor unit (MU). The ratio of reference fluence to monitor units is defined as

$$\frac{\Phi_0}{M_0} = \frac{(D/M)_{\text{calib}}}{d(r_{\text{calib}})}$$
Figure 4: (a) Parameterisation of the source phase-space (SPS) in a plane ($x, y$) below the secondary scattering foil with rotational symmetry around the beam axis ($z$). The mean angle ($\bar{\theta}_s$) of the electrons as a function of radius ($s$) is defined by the location of an effective point source position $Z_{eff}$ on the beam axis. The electron angular distribution is approximated with gaussian functions perpendicular ($\theta_\perp$) and parallel ($\theta_\parallel$) to the radial direction ($s$). (b) The planar electron fluence in the SPS is parameterized as a rotation symmetrical gaussian distribution with width and cut-off radius defined by $\sigma_s$ and $s_{max}$ respectively. (c) Electron angular distribution perpendicular to the radial direction ($\theta_\perp$). The figure shows the variation of $\sigma_\theta$ with radius in the plane of parameterisation.
**Figure 5:** In the EBM EPS parameterisation, the effective source distance ($Z_{\text{eff}}$) and the angular variance ($\sigma^{2}_{\theta}$) are derived from the electron exit direction in concentric rings in the EPS plane. Both variables are treated as function of the radius $r$.

where $(D/M)^{\text{calib}}_{\text{meas}}$ is the measured calibration dose per registered monitor unit and $d(r_{\text{calib}})$ is the dose value calculated by the dose engine at the calibration point $r_{\text{calib}}$. The procedure is performed for every applicator/energy combination with an electron applicator without insert.

### 2.3 Simulations

#### 2.3.1 Monte Carlo calculation details

All simulations were performed on a dual Intel Xeon and a Pentium IV CPU under the Windows XP operating system. Calculation times for the BEAM-simulations were between 1 and 30 hours depending on the number of histories, field size, SSD, tracking margin and energy. Intel’s Hyper-threading (HT) option was turned on, giving two logical CPUs per physical CPU, making it possible to run more (BEAM) simulations in parallel. It was found that this option was beneficial since calculation times were somewhat shorter (20%) as compared to running two consecutive simulations on one logical CPU with the HT-function turned off. All simulations were executed with scripted inputs. Simulations in Masterplans electron dose engine EBM, were executed
in a developer test-mode separate from the TPS. All the resulting phase-space files were evaluated using a software (‘JASA’) developed by Nucletron (Traneus 2009). The program had similar capabilities to BEAMDP (Ma and Rogers 1995a) but with an additional set of tools useful for exporting data.

BEAMnrcMP 2007 based on the EGSnrc code system was used in this work. Electron energy cut-off (ECUT) was 700 keV, photon energy cut-off (PCUT) was set to 10 keV. Maximal fractional energy loss/step (ESTEPE) 0.25. Maximum electron step (SMAX) was 5.0 cm. Boundary crossing algorithm PRESTA-I. Electron-step algorithm PRESTA-II. The initial electron beam was modeled as a parallel circular beam (ISOURC 0) with a radius of 1 mm. DOSXYZnrc dose calculations were used for the BEAM-model verification. Depth doses were performed in a water phantom of 40x40x16 cm³ (x, y, z) with a voxel size of 4x4x2 mm³.

2.3.2 BEAMnrc model verification

Gaussian distributions were used to approximate the electron energy spectra exiting the vacuum window of the accelerator (Table 1). Full BEAM and DOSXYZ simulations were performed in an open field geometry and compared to measured central axis water depth-dose distributions (SSD 100 cm, open field) until results were in reasonable agreement (R50 difference < 3%/1mm). The energy distributions were also compared to the calculated spectra used in EBM. The measurements were performed antecedently by a Nucletron customer and also served as input and verification to the parameterisation of the SPS in EBM. Approximately 20x10⁶ DOSXYZ histories were used for each energy and the BEAM PSP-files were recycled 2 times.

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</tbody>
</table>

2.3.3 BEAMnrc source phase-space

The BEAM simulations were performed in two steps. A scoring plane was placed under the secondary scattering foil and the transport through the vacuum window and scattering foils only had to be performed once for each energy, and in addition made it possible to compare the SPS in BEAM with that of EBM. Electrons used in the subsequent BEAM-simulations through the remaining part of the treatment head were read from the generated SPS files. LATCH-bits were set on the aluminium ring surrounding the secondary scattering foil for some of the simulations. Approximately 8x10⁸ histories were used in the creation of the BEAM SPS files. Several parameters were extracted from the BEAM SPS; electron energy spectrum, effective source position/mean angle, angular distribution width and planar fluence profiles.
2.3.4 Coupled multi-source model parameters

It is possible to obtain a good agreement with the in-air profile measurements using incorrect values of the SPS input parameters. For that reason and in order to minimize the number of free variables in the parameterisation, some results from the BEAM SPS simulations were used as input. Due to the proximity of the ring surrounding the secondary scattering foil, the cut-off radius in the parameterisation was set slightly smaller than the inner radius of the ring. The effective source distance calculated from the BEAM SPS was also used as input. Remaining variables were manually tuned until the simulated planar fluence profiles agreed with measurements.

2.3.5 Treatment head simulations

For each energy, seven square shaped fields were produced by the eMLC in both models at 85, 96 and 100 cm SSD, ranging from 2x2 to 20x20 cm$^2$. Tracking margins of 1-4 cm were applied to each field. Additional simulations were subsequently performed in BEAM with LATCH-bits set on the aluminium ring. For time saving purposes, only 96 and 100 cm SSD with 2 and 4 cm tracking margins were run. A total of 672 BEAM and 504 EBM simulations were performed.

The resulting PSP files were evaluated on several parameters. In-plane planar fluence profiles were extracted for each field. To improve statistics, the width of the profiles ranged from 0.2 to 4 cm depending on field size. Relative fluence output was calculated from the central part of each planar fluence surface and normalised to the number of sampled electrons from the SPS and to the 10x10cm$^2$ field with 2 cm tracking margin at SSD 96 cm. Mean angle direction, effective source distance ($Z_{\text{eff}}$) and angle distribution width ($\sigma_\theta$) was extracted from annular concentric rings covering the field (figure 5). The parameters were evaluated using back projection from the exit direction on the EPS plane. The effective source distance was calculated using $Z_{\text{eff}} = \arctan(\theta) \times r$ where $r$ is the radial distance from the field center in the scoring plane. This method has unfortunately been shown to be unreliable for determining effective source distance for small fields (Ma et al. 1995b), but may be useful for comparing two MC models. Note that the standard deviation and not the variance of the angular distribution was calculated.

3 Results and discussion

3.1 Source phase-space (SPS)

The source phase-space files of the BEAM and EBM simulations contained approximately $10^8$ electrons each.

3.1.1 Planar fluence profiles

The extracted BEAM planar fluence profiles are gaussian-like in shape and show a varying degree of interaction with the aluminium ring (figure 6). 15 and 18 MeV
Figure 6: Electron planar fluence profiles of the SPS under the secondary scattering foil for 6-21 MeV. The horizontal axis is the off-axis distance in centimeters. Vertical axis is planar fluence in normalised units. Results from the BEAM simulation (solid red) are almost gaussian-like in shape. EBM profiles (dashed blue) are by construction, gaussian shaped over the defined (cut-off) radius. The EBM profiles are overestimated for all energies, particularly for 6 and 9 MeV. Even so, a better agreement is seen with the BEAM profiles with the ring-scattered electrons removed (dash-dotted black).

shows a large portion of the fluence inherent of the ring, 9, 12 and 21 MeV shows a moderate contribution, and 6 MeV (no primary scattering foil) shows only a small interaction with the ring. With the ring-scattered electrons removed, the width of the profiles reflects the inner radius of the ring. The EBM profiles show a better radial agreement with the BEAM profiles without the ring-scattered electrons, although they are ubiquitously overestimated for all energies, most notably for 6 and 9 MeV.

### 3.1.2 Angular distribution

The angular distribution width as a function of field radius, $\sigma_\theta(r)$ (figure 7), shows a significant increase at the location of the ring due to the greater thickness. Note also the step-like shape over the secondary scattering foil and the slight decrease of $\sigma_\theta$ with increasing energy. EBM shows a slightly underestimated value for 6 MeV over the entire secondary scattering foil.

The straight-line approximation of $\sigma_\theta$ is in reasonably good agreement over the secondary scattering foil for the remaining energies. It is however exaggerated over the kapton foil and non-existing over the aluminium ring. For both BEAM and EBM, the effective source distance shows for the lowest energy (6 MeV, no primary
Table 2: The effective source distance at the SPS plane for BEAM and the EBM parameterisation. The average of $Z_{\text{eff}}$ along the radius is presented.

<table>
<thead>
<tr>
<th>Nominal energy</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>18</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{\text{eff}}$ BEAM (cm)</td>
<td>11.9</td>
<td>11.0</td>
<td>10.9</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>$Z_{\text{eff}}$ EBM (cm)</td>
<td>12</td>
<td>10.9</td>
<td>10.9</td>
<td>10.5</td>
<td>10.5</td>
<td>10.6</td>
</tr>
</tbody>
</table>

scattering foil) a good agreement with the physical distance to the vacuum window. For higher energies, $Z_{\text{eff}}$ agrees well with the location of the primary scattering foil within a few mm (table 2).

Figure 7: Angular distribution width $\sigma_\theta$ of the SPS for BEAM (red) and EBM/parameterisation (blue straight line) as function of field radius for 6-21 MeV. Note the jagged shape of the BEAM results and the large increase in $\sigma_\theta$ under the aluminium ring. The radius of the secondary scattering foil extends to approximately to 1.5 mm and its effect can clearly be seen in the figure as $\sigma_\theta$ sharply drops. The inner radius of the ring is 2.2 cm and extends to about 4 cm.

3.1.3 Energy distribution

The gaussian shaped energy spectra used in the BEAM simulations were tuned until measured depth dose distributions matched measurements within some degree of accuracy. The emphasis was on matching the $R_{50}$ depth, which corresponds to the mean energy. The peak width ($\Gamma$) of the BEAM energy spectra were set to match those in the EBM parameterisation. From figure 8 it can be argued that a gaussian energy distribution of the incident electron beam on the vacuum window, after passing through the scattering foils, gives a reasonably good approximation to the calculated spectrum used in EBM. Mean and most probable energy are listed in table 3.
3.2 Exit phase-space (EPS)

The number of histories in BEAM ranged from $10^7$ to $4 \times 10^8$ depending on field size and energy, with more histories used for the smaller fields. EBM had an option to keep generating electrons until the desired number of particles in the EPS was met. Each phase-space file produced by EBM contained $4 \times 10^6$ electrons.

3.2.1 Planar fluence profiles

In general the agreement between BEAM and EBM planar fluence profiles is very good for all energies, field sizes, tracking margins and SSDs (figures 9 – 14). However,

Table 3: Mean and most probable energy of the BEAM SPS/EPS and the EBM parameterisation

<table>
<thead>
<tr>
<th>Nominal energy</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>18</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{BEAM , SPS}$</td>
<td>6.0</td>
<td>8.3</td>
<td>10.9</td>
<td>13.5</td>
<td>16.5</td>
<td>19.2</td>
</tr>
<tr>
<td>$E_{P, , BEAM , SPS}$</td>
<td>6.4</td>
<td>9.0</td>
<td>11.8</td>
<td>15.3</td>
<td>18.6</td>
<td>21.4</td>
</tr>
<tr>
<td>$E_{BEAM , EPS}$</td>
<td>5.9</td>
<td>8.4</td>
<td>11.0</td>
<td>13.9</td>
<td>16.9</td>
<td>19.7</td>
</tr>
<tr>
<td>$E_{P, , BEAM}$</td>
<td>6.1</td>
<td>8.7</td>
<td>11.5</td>
<td>15.1</td>
<td>18.4</td>
<td>21.1</td>
</tr>
<tr>
<td>$E_{EBM}$</td>
<td>5.9</td>
<td>8.2</td>
<td>10.9</td>
<td>13.7</td>
<td>16.9</td>
<td>19.4</td>
</tr>
<tr>
<td>$E_{P, , EBM}$</td>
<td>6.1</td>
<td>8.8</td>
<td>11.6</td>
<td>15.2</td>
<td>18.4</td>
<td>21.2</td>
</tr>
</tbody>
</table>
for some of the larger fields a discrepancy can be seen in the edges of the profiles. In particular, the effect can most notably be seen for 6, 15 and 18 MeV for the shortest SSD (figures 9, 12,13). Differences amounted to at most 6.5, 2.9 and 3.3 % respectively, for the largest fields. For larger SSDs the effect is still present, but less patent. Since only direct electrons are considered in both simulations, collimator scatter cannot be attributed to this and the effected is believed to be inherent from differences in the source phase-space.

![Graphs showing planar fluence profiles for different SSDs and tracking margins](image)

**Figure 9:** Results from the BEAM (thin red) and EBM (thick blue) simulations of 6 MeV nominal energy depicting center in-plane planar fluence profiles for tracking margins of 1-4 cm and SSDs of 85, 96, 100 cm. The profiles have been scaled for clarity with each pair of fields locally normalised in the center of the plane. The horizontal axis shows the off axis distance in centimeters and the vertical axis is planar fluence in arbitrary units.
Figure 10: 9 MeV profiles. See figure 9 for caption.
Figure 11: 12 MeV profiles. See figure 9 for caption.
Figure 12: 15 MeV profiles. See figure 9 for caption.
Figure 13: 18 MeV profiles. See figure 9 for caption.
3.2.2 Angular distribution

The effective source distance was calculated from the mean angle of the electrons (relative the normal of the scoring plane) in a small circular region around the centre of each field. This method of back projection is however unreliable for small fields and serve only as a comparison of the two MC models. Regardless, calculated effective source distances from EBM correspond well with those of BEAM for all energies and field sizes (figures 15-17). There is however a slight difference for the smallest fields with the 1-2 cm tracking margins, were EBM gives a smaller $Z_{\text{eff}}$ (maximal difference $< 6$ cm). This is most pronounced for 15, 18 and 21 MeV.
Figure 15: SSD 85 cm effective source distance $Z_{\text{eff}}$ derived from the mean angle of electrons around a small disc centered in each field. EBM shows slightly lower values for the smallest fields and tracking margins for 15, 18 and 21 MeV. For clarity, only the 1 and 4 cm tracking margin is shown. The location of the primary (dashed) and secondary (dot-dashed) scattering foil is shown in figure.
Figure 16: SSD 96 cm effective source distance $Z_{eff}$. See figure 15 for caption.
The standard deviation of the electron angular distribution ($\sigma_\theta$) was constant over each field and only suffered some minor statistical noise. As with the effective source distance (mean angle), $\sigma_\theta$ is in good agreement comparing the two MC models. Results for 1 and 4 cm tracking margin are shown in figure 18. The 2 and 3 cm tracking margins were intermediate and omitted for clarity. Differences are on average less than 0.05 degrees and somewhat larger for the smaller field sizes. Per energy, the largest difference is found for 21 MeV and SSD 85 ($< 0.1$ degrees).
3.2.3 Relative planar fluence output in air

The relative planar fluence output was normalised per energy to the 10x10 cm$^2$ field, SSD 96 cm with the 2 cm tracking margin. Electrons scattered in the aluminium ring was removed using LATCH-bits for the 2 and 4 cm tracking margin and SSDs of 96 and 100 cm.

Relative planar fluence output for 6 MeV shows the best general agreement of all energies (figure 19). Differences (relative BEAM) are within 2% for all fields except for the smallest 2x2 cm$^2$ fields, were differences amount to 4% for the smallest and largest tracking margins and the 96 and 100 cm SSD. For 9 MeV (figure 20), results are within 2% for the 10x10 to 20x20 cm$^2$ fields for all tracking margins and SSDs. The agreement of the 4x4 and 7x7 cm$^2$ fields improves with increasing tracking margin and is less then 2% for the 4 cm tracking margin. The largest discrepancies (12-17%)
is seen for the 2x2 fields with the smallest tracking margins. For 12 MeV (figure 21), the 7x7 to 20x20 cm$^2$ fields are within 4%. The largest discrepancy is seen for the smallest field (12%) and SSD 100cm. With 3-4 cm tracking margin, all results are within 4%. For 15 MeV (figure 22), the 7x7 to 20x20 cm$^2$ fields are within 5%. The discrepancy of the smaller 2x2 and 4x4 cm$^2$ fields improves with increasing tracking margin and are within 5% for the 3-4 cm tracking margin. For the smallest tracking margin discrepancies of 13-21% is seen. Results of the 18 MeV fields (figure 23) are within 3% for 7x7 to 20x20 cm$^2$. Again, the smallest 2x2 cm$^2$ fields show the largest discrepancies with the smallest tracking margins (16-25%). Both the 2x2 and 4x4 fields improve considerably with increasing tracking margin and are within 4% for the 3-4 cm tracking margin. For 21 MeV (figure 24), the 7x7 fields are within 4% and the 10x10 to 20x20 cm$^2$ fields are < 2%. The discrepancies of the 2x2 and 4x4 fields improve with increasing tracking margin and shorter SSD (<6% for 3-4 cm tracking margin). The largest difference is seen for the 2x2 field with 1 cm tracking margin at 96 and 100 cm SSD (29%).

In general for all energies, differences between the relative planar fluence output decreases slightly with decreasing SSD and decreases largely with increasing tracking margin. The smallest fields are prone to the largest differences. The results of the BEAM simulations are consistently larger then those of EBM for the smallest and largest field sizes.

Removing the ring-scattered electrons using LATCH-bits (figures 19–24), an improvement can be seen between EBM and BEAM for the larger fields. 6 and 9 MeV BEAM simulations shows a moderate decrease in ROF for fields larger then 10x10 cm$^2$. 12 and 15 MeV shows the largest decrease in ROF of all energies. 18 MeV shows a slight decrease for large fields and 21 MeV shows no noticeable decrease what so ever. It should also be noted that the differences in ROF between EBM and BEAM for the smaller fields worsens with the ring-scattered electrons removed.
Figure 19: 6 MeV. Relative planar fluence output in air as a function of field size for BEAM and EBM simulations. Figure shows results for SSDs of 85, 96 and 100 cm with xMLC tracking margins of 1-4 cm (marked in figure). Additional BEAM simulations with the ring scattered electrons removed are shown for 96 and 100 cm SSD with the 2 and 4 cm tracking margin. Results are normalised to the 10x10 cm$^2$, SSD 96 field with the 2 cm tracking margin (marked by circle in figure). The planar fluence was extracted from (central) square-shaped regions averaged over 0.2x0.2 to 4x4 cm$^2$ depending on field size and flatness.
Figure 20: 9 MeV. See figure 19 for caption.
Figure 21: 12 MeV. See figure 19 for caption.
Figure 22: 15 MeV. See figure 19 for caption.
Figure 23: 18 MeV. See figure 19 for caption.
Figure 24: 21 MeV. See figure 19 for caption.
4 Conclusions

In this work the electron beam model used in Oncentra Masterplan 3.2 was evaluated for use with an electron multileaf collimator (eMLC) together with photon MLC (xMLC) tracking. Comparisons were made between the beam model (EBM) and BEAMnrc simulations of a Siemens Primus accelerator on account for non-collimator scattered (direct) electrons. Comparisons were performed at scoring planes at SSDs of 85, 96 and 100 cm for nominal energies of 6, 9, 12, 15, 18 and 21 MeV. The phase-space under the secondary scattering foil was also investigated since this location serves as the plane of parameterisation in EBM.

Considering the planar fluence profiles in air as shown in figures 9 - 14 the overall agreement between BEAM and EBM was excellent although there was a discrepancy for some of the larger fields were EBM underestimated the fluence at the shoulders of the profiles. Differences found were most notable for 6, 15 and 18 MeV with the largest fields and shortest SSD. The discrepancies also increased with increasing tracking margin and amounted to at most 6.5, 2.9 and 3.3 % respectively for the above mentioned energies (drop in fluence relative BEAM). Monte Carlo simulations of large electron fields have been shown to be sensitive to variations in scattering foil geometry and source parameters (Björk et al. 2002, Huang et al. 2005, Schreiber and Faddegon 2005). Thus, small variations in the parameterisation of the source phase-space in EBM would be more noticeable for large fields.

Exit phase-space angular distributions were evaluated with two parameters, the mean angle (effective source distance) and the standard deviation (width). The effective source distances were in good coherence apart from some of the smaller fields where EBM underestimated the distance of up to approximately 6 cm (21 MeV, SSD 85 cm). From figures 15-17 it is clear that the smallest tracking margins and highest energies (15, 18 and 21 MeV) produced the largest differences. The standard deviation of the angular distributions were in much better agreement and showed at most a difference of 0.1 degrees.

Results of the planar fluence output in air (figures 19-24) were somewhat unexpected since it was initially assumed that the high scattering power of the lower nominal energies would give the worst agreement due to approximations in EBM. On the contrary, the low and intermediate energies (6-12 MeV) gave the best overall agreement. It was also believed that the aluminium ring surrounding the secondary scattering foil would have no, or at most a marginal impact on fluence output. This was indeed true for 6 and 21 MeV, but not for the remaining energies. Evidently, when removing the ring-scattered electrons from the BEAM simulations the difference found earlier for larger fields was almost totally eliminated. From the planar fluence under the secondary scattering foil (figure 6) one can see that the interaction with the surrounding ring greatly varies from one energy to the next, with almost none for 6 MeV and a considerable amount for 15 MeV. At the phase-space scoring planes downstream, the electrons are however distributed fairly even over each field investigated and showed no noticeable impact on either fluence profiles, spectral or angular distributions. These results indicate that the parameterisation in EBM needs to be able to model the effects of the ring if accurate results in fluence output are sought for larger fields. Approximating the angular spread as a linear function of the radius is not sufficiently accurate in this case (figure 7). It should be noted that...
other major manufacturers such as Varian or Elekta do have similar structures in their design but these components are located either further away or are properly shielded by the primary collimator (Traneus 2009). They would most likely not suffer the same problem as with the Siemens Primus accelerator.

Discrepancies found for the smaller fields are not fully understood, but they could possibly be explained by that EBM does not fully encompass a 3D model of the collimating structure (Traneus 2010). As described earlier, the Monte Carlo code (QMC) in EBM transports electrons in steps between each collimating structure with an additional step over thick collimators (top to bottom). Electrons with a direction pointing to a surface of any collimator will not be transported further down but rather considered collimator hits and terminated. It is of course conceivable that an electron with an initial direction pointing to a collimator could scatter in air before reaching it. This could explain, at least partially, why the EBM direct fluence output is lower for most of the small fields. The fact that the differences found decreases with increasing tracking margin further endorses this belief. Using BEAM phase-space files generated under the secondary scattering foil as input to EBM could clarify if differences are due to simplifications in the SPS parameterisation or exists because of problems with the collimator model.

As currently implemented for applicators, the dose engine is normalized per applicator-energy combination with fixed block collimator and xMLC positions. Using xMLC tracking to reduce bremsstrahlung leakage through the eMLC has a large impact on fluence output and subsequently the absorbed dose. Since it is not possible to have absolute dose measurements for every possible xMLC-eMLC leaf position, energy and SSD combination, one would require the dose engine to be able to accurately calculate exit fluence from one single normalisation measurement at reference geometry in analogy with how MV photon beams can be modeled. To apply a global normalisation approach (i.e. one absolute dose to MU measurement) for electron beams requires improved beam model coherence over what was found in this work.

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First and foremost, I would like to thank my supervisor, Erik Traneus for his endurance and enthusiasm in tutoring me on the BEAM/DOSXYZ programs as well as the intricate text and GUI-based developer version of his multi source electron beam model. Thank you for listening to my numerous suggestions on how to run different simulations and help with evaluating the data. Your patience is without limits. A great “thank you all” to the Nucletron staff in Uppsala for being kind and supportive and for all the interesting conversations during the coffee breaks. Thank you for the ≈ 700 cups of free coffee I had, saved a lot of money there. A special thanks to Bo Nilsson for teaching me and my fellow students medical radiation physics. Finally, I would like to extend gratitude to my friends and family for their support.
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