MONTE CARLO MODELLING OF A-SI EPID RESPONSE: THE EFFECT OF SPECTRAL VARIATIONS WITH FIELD SIZE AND POSITION

Laure Parent, Joao Seco[†], Phil M Evans

5 *Joint Department of Physics, The Institute of Cancer Research and The Royal Marsden NHS Foundation Trust, Downs road, Sutton, SM2 5PT, United Kingdom*

Andrew Fielding

10 *School of Physical and Chemical Sciences, Queensland University of Technology, Q337 Gardens Point Campus, Brisbane, Queensland 4001, Australia*

David R Dance

15 *Joint Department of Physics, The Institute of Cancer Research and The Royal Marsden NHS Foundation Trust, Fulham road, London, SW3 6JJ, United Kingdom*

[†] Present address:

Department of Radiation Oncology, Francis Burr Proton Therapy Center, Massachusetts General Hospital, Harvard medical school, Boston, USA

20 ABSTRACT

Electronic portal imaging detectors (EPID) have initially been developed for imaging purposes but they also present a great potential for dosimetry. This is of special interest for intensity modulated radiation treatment (IMRT), where the complexity of the delivery makes quality assurance necessary. By comparing a predicted EPID image of
25 an IMRT field with a measured image, it is possible to verify that the beam is properly delivered by the linear accelerator and that the dose is delivered to the correct location in the patient. This study focused on predicting the EPID image of IMRT fields in air with Monte Carlo methods. As IMRT treatments consist of a series of segments of various sizes which are not always delivered on the central axis, large spectral
30 variations may be observed between the segments. The effect of these spectral variations on the EPID response was studied. A detailed description of the EPID was implemented in a Monte Carlo model. The EPID model was validated by comparing the EPID output factors for field sizes between 2x2 and 26x26 cm² at the isocentre. The Monte Carlo simulations agreed with the measurements to within 0.5%. The effect of

35 spectral variations on the EPID response, with field size and position, was studied for
three field sizes (2x2, 6x6 and 10x10 cm² at the isocentre) with various offsets (from 10
to 19 cm). The Monte Carlo model succeeded in predicting the EPID response to within
1% of the measurements. Large variations of the EPID response were observed
between the various offsets: 29%, 29% and 25% for the 10x10, 6x6 and 2x2 cm² fields
40 respectively. The EPID response increased with field size and with field offset for most
cases. The Monte Carlo model was then used to predict the image of an IMRT field
consisting of four segments. The field was delivered on the beam axis and with offsets
of 15 and 12 cm on X- and Y-axes respectively. Good agreement was found between
the simulated and the measured images. A variation up to 30% was found between the
45 on and off-axis delivery. The feasibility of using Monte Carlo methods to predict portal
images is thus demonstrated. The model predicted accurately the EPID response in air
for the large spectral variations observed with field offsets.

INTRODUCTION

Electronic portal imaging devices (EPIDs) were first introduced in external beam radiotherapy to replace film cassettes for patient position verification. Indeed they present significant advantages over film technology¹. As the image is instantly
55 obtained, there is no need to process a film and therefore it is possible to verify the accuracy of positioning during the course of the field delivery. As the technology develops, EPIDs are not only used for patient positioning verification but also for a variety of other applications, including patient dosimetry. This is of special interest for intensity modulated radiation treatments (IMRT). As the delivery gets more
60 complex, it becomes necessary to develop quality assurance techniques to verify the treatment beams. EPIDs can be used for this purpose.

The use of EPIDs for dosimetric applications requires the implementation of a procedure to convert the pixel intensity to dose, either at the level of the EPID, or in the patient. Three approaches have been considered: empirical methods,
65 superposition/convolution methods and Monte Carlo methods. Empirical methods use a set of measurements in standard conditions to define an algorithm allowing the prediction of a portal dose image. The simplest method consists of expressing the relationship between pixel value and dose for a fixed field size by an analytic relation². Various corrections are then applied to correct for the non-linearity of the
70 EPID response and for the light scatter in fluoroscopic systems³ or to incorporate the EPID scatter variation with field size in the calibration curve⁴. The superposition/convolution methods generate kernels, either by an extensive set of measurements^{5,6} or by Monte Carlo simulations⁷⁻¹⁰, that are then used in an analytic model. These two methods generally assume that the kernel describing scatter

75 contributions to points on the beam axis can also be used for calculation of scatter contribution at off-axis points. This approximation might not always be valid.

Only a few studies^{11,12} have been published using a full Monte Carlo method to predict the EPID response. Spezi *et al*¹¹ have modelled the Varian SLIC EPID but have only looked at a single field size. Siebers *et al*¹² have modelled the Varian a-Si
80 EPID and successfully predicted the EPID response for various field sizes delivered on the central axis. Although full Monte Carlo simulations are time consuming and computer resource intensive, this is the only method allowing accurate calculations for heterogeneities, at interfaces and for small fields¹³. This study focuses on the Elekta (Crawley, UK) a-Si EPID. The active part of the detector is mainly made of a
85 copper plate and a terbium-doped gadolinium oxysulphide ($Gd_2O_2S:Tb$) screen, materials of high atomic number. It is therefore not necessarily correct to approximate the EPID by a water model. Monte Carlo techniques (using a complete description of material composition), are expected to provide an accurate tool for EPID image prediction.

90 This study aimed at building a Monte Carlo model to predict EPID images in the particular case of IMRT treatment. A model of the EPID was first built and commissioned by comparing simulated and measured EPID output factors for various field sizes. IMRT treatment delivery, whether it is static or dynamic, follows the principal of the sliding aperture technique: the first segment is usually at one end of
95 the treatment field and the last segment at the other end^{14,15}. Thus the beam is generally not delivered on the central axis. Furthermore the sizes of the segments of an IMRT beam vary. As there is a spectral variation across the axes on the linac because of the flattening filter design and the collimation system, it is expected that the EPID response will vary with field size and offset. In order to investigate the

EPID response variation due to spectral changes in the beam, simulations were compared with the measurements for a series of fields with various sizes and offsets and for an IMRT field.

MATERIAL AND METHODS

Materials

All measurements were performed on a Precise linac (Elekta Ltd, Crawley, UK), operating at 6 MV. In the Elekta coordinate system, the crossplane and inplane directions are defined respectively by the Y- and the X-axes. Precise linacs are equipped with a 40 leaf pair multileaf collimator (MLC). The leaf edge is rounded in the Y direction and stepped in the X-direction¹⁶. Each leaf travels parallel to the Y-axis. All leaf widths are identical and such that the projection of the central leaves is 1 cm wide at the isocentre.

All images were produced with an iViewGT amorphous silicon EPID (Elekta Ltd, Crawley, UK). A schematic representation of the EPID detection panel is given in figure 1. The copper plate converts the incident x-rays to high energy electrons and blocks low-energy scattered photons that would otherwise decrease the contrast in the images. The phosphor screen also converts the incident x-rays to high energy electrons and transforms a fraction of the energy of the electrons into light. The light is then detected by an amorphous silicon photodiode array. The active area of the detector is $41 \times 41 \text{ cm}^2$ and is located at 160 cm from the source. There are 1024×1024 pixels in the image. The pixel size of the detector is 0.25 mm at the isocentre.

125 **Studied fields**

Three different field sizes were studied: 10x10 cm², for reference conditions, 6x6 cm², which corresponds to the size of a typical IMRT segment, and 2x2 cm², to study the extreme case that might happen at the beginning and the end of the delivery when the sliding window technique is used. In order to test the Monte Carlo model in the most challenging situations, the maximum achievable leaf displacements of the MLC for a given field size were studied. It was necessary to take into account the limits imposed by the design of the jaws and the MLC:

- The X jaws cannot cross the central axis.
- The leaves cannot cross the central axis by more than 12.5 cm.
- 135 - There is a minimum distance of 1 cm between opposite leaves and adjacent leaves from different leaf banks.

As the X-jaws cannot travel over the central axis, the offsets achievable on the X-axis are limited. For example, it is not possible to shift the field centre on the X-axis by more than 5 cm for a 10x10 field. To increase the offset in this direction, the so-called “flag pole” technique is used, as it is illustrated in figure 2. When this technique is used, the collimation in the X direction towards the central axis is only achieved by the MLC.

Table 1 summarizes the field sizes and offset positions studied, as well as the names they are referred by in the rest of this paper. As the offset in the Y direction is parallel to the leaf travel direction and the offset in the X direction is orthogonal, the fields are not symmetrical. For example, because of the MLC constraints, the maximum achievable offset is 17 cm on the X-axis and 14 cm on the Y-axis for the 6x6 cm² field. In that case, an offset of 14 cm on X-axis was also studied to investigate whether the EPID response was equivalent on both axes for a given offset.

150 Finally the model was tested for a more complex IMRT field, delivered by a series of 4 segments (figure 3). The field was delivered on the beam axis and with offsets of 15 and 12 cm on X- and Y-axes respectively.

Monte Carlo modelling

155 Monte Carlo simulations were performed using the BEAMnrc¹⁷ and DOSXYZnrc¹⁸ codes developed by the National Research Council (NRC) in Ottawa, Canada. BEAMnrc was used to model the radiation source and the treatment head of the accelerator while DOSXYZnrc was used to predict the EPID response. A detailed description of the geometry of the linac head and the EPID was used in the Monte
160 Carlo model, based on information supplied by Elekta.

The linac head was modelled and commissioned with a similar method to Seco and al¹⁹. Percentage depth dose (PDD) curves and profiles in water were simulated and compared to measurements. The simulations reproduced the measurements to within 2% for the PDDs and 3% for the profiles.

165 Munro and Bouius²⁰ showed that for an a-Si EPID, in which the x-ray detector is made of a 0.1 cm Cu buildup plate and a phosphor screen, the signal detected by the light sensor is almost entirely due to photon and electron interactions within the copper and the phosphor layers. Furthermore, the response of the light sensor is proportional to the energy deposition in the phosphor²¹. As a consequence, the full
170 geometry of the EPID was described in the Monte Carlo model to account properly for scatter and the EPID response was simulated by scoring the dose deposition in the phosphor layer.

For IMRT beams, the modelling of the MLC is an important stage. In the crossplane direction, a 0.2 cm tolerance exists on the leaf positions²², leading to a

possible range of 0.4 cm for a given position. Such a variation could introduce a significant difference in terms of the intensity and position of the dose delivered. A method to predict the leaf positions for all the MLC leaves, that we have developed²³, was used in this study. It involved the measurement of two positions for each leaf (-5 and +15 cm) and the interpolation and extrapolation between these two points for any other given position. The method was implemented in our Monte Carlo system to predict EPID images and succeeded in predicting the field edges in the crossplane direction with a precision of 0.043 cm on average for the cases tested²³.

In BEAMnrc, the geometry is built from a series of component modules, each dealing with a specific class of geometric shape. The MLCE component module^{24,25} was used to model the MLC. The rounded shape of the leaf tip in the crossplane direction, as well as the tongue-and-groove design in the inplane direction, are modelled in this component module.

Commissioning of the Monte Carlo EPID model

The EPID model was commissioned by comparing the EPID output factors generated by the model with measurements performed on the linac for the following field sizes: 2x2, 6x6, 10x10, 14x14, 20x20 and 26x26 cm² at the isocentre. The EPID response was normalised to the response at the centre of the 10x10 field.

It was necessary to introduce into the model the number of monitor units (MU). In order to do so, the EPID response was first normalised to the response obtained at the centre of a 10x10 field and then multiplied by the number of MU.

In order to obtain a standard deviation of 1% in 0.2x0.2 cm² pixels at the isocentre, it was necessary to run 2.10⁶ histories for a field of 2x2 cm² at the

isocentre. This corresponds roughly to a simulation time of four hours on an Intel
200 Xeon 2.8 GHz processor.

EPID gain calibration

In clinical use, the EPID is calibrated by using two images for a given energy and
dose rate:

- 205 - A dark field image (*DFI*), which is an image acquired in the absence of
any radiation. This image is used to correct for additive electronic noise.
- A flood field image (*FFI*), which is an image acquired with a field
covering the entire area of the detector (26x26 cm² for example). This image
is used to correct the gain for each individual pixel.

210 Any image acquired with the EPID (*raw_image*) is then corrected by the
following process (x and y represent the coordinates of a pixel in the EPID):

$$Corrected_image(x, y) = \frac{Raw_image(x, y) - DFI(x, y)}{FFI(x, y) - DFI(x, y)} \quad (1)$$

The drawback of this method is that it uses a field, with high dose horns off-axis,
which is not flat at shallow depth. This is due to the changing beam quality across the
215 x-ray beam of the linear accelerator. Different solutions to take into account the beam
heterogeneity during the gain calibration can be found in the literature: the beam
profile can be corrected based on an ion chamber measurement in water²⁶, a film
measurement²⁷ or using a flood field image generated with a model^{17,28}. However, ion
chambers and films have a different response to the EPID thus a beam profile
220 measured with either of these detectors is not representative of the EPID and cannot
be used to calibrate the EPID.

Because the series of measurements described in table 1 was intended to further
validate the Monte Carlo model, it was difficult to use the Monte Carlo model to

predict the flood field image, without introducing any bias in the comparison between
 225 the measurements and the simulations. It was therefore necessary to develop a new
 method of setting the pixel gains that would not be affected by the EPID position and
 that would use an equivalent spectrum in all the areas of interest of the EPID.

The calibration method developed consisted of irradiating the different
 measurement areas of the EPID with an identical 10x10X0Y0 field. This field was
 230 chosen as it is expected to be flat over such an area. The calibration was achieved by
 keeping the field fixed and moving the EPID to four positions, so that the field
 covered each corner of the EPID in turn (figure 4). All the measurement areas of the
 EPID were thus calibrated with equivalent irradiation. The four images were then
 combined into a unique image, called *gain_image*, and used according to eq.2.

$$235 \quad \text{Corrected_image}(x, y) = \frac{\text{Raw_image}(x, y) - \text{DFI}(x, y)}{\text{Gain_image}(x, y) - \text{DFI}(x, y)} \quad (2)$$

The *gain_image* was obtained for 100 MU. This image was divided by 100 in
 order to obtain the EPID response per MU. By using this new image in equation 2, a
 response of 1 will be obtained at the centre of the image of a 10x10 field for 1 MU.

For all the fields described in table 1, the irradiations were performed with 100
 240 MU. For the IMRT field, the four segments were delivered for 25 MU each.

Data processing

In order to decrease the calculation time for the simulations, a variable voxel size
 was used to describe the EPID geometry: a larger voxel size was used in the low
 245 gradient region and a smaller one was used in the high gradient region. For all
 simulations, the pixel size ranged between 0.2 and 1 cm at the isocentre.

The measured images were processed using equation 2. The image size was reduced from 1024x1024 to 512x512 pixels to speed up the processing, thus increasing the pixel size at the isocentre to 0.05cm. This was acceptable compared with the resolution of the Monte Carlo simulations. The response at the centre of each field was measured by averaging the pixel values in a region of interest (ROI) of 400 pixels for the 10x10 field, 200 pixels for the 6x6 field and 50 for the 2x2 field. The ROI was located at the centre of the field.

RESULTS

Commissioning of the Monte Carlo model

The simulated and measured EPID output factors are presented in figure 5. The simulation values are within 0.5% of the measurements.

Comparison of the Monte Carlo simulations with measurements for fields of various sizes and positions

To illustrate the results obtained with the Monte Carlo model compared to the measurements, figure 6 presents crossplane and inplane profiles across the 2x2X0Y0 and 6x6X+14Y+14 fields. A good match was obtained between measured and simulated values in term of intensity (to within 2% in the high dose-low gradient regions), as well as field edge positions (to within 2 mm in the high gradient regions). Table 2 summarizes the results in term of beam intensity at the centre for all of the beams described in table 1. All the simulated values are within 1% of the measured values. Large variations of the EPID response are observed between the various offsets: 29%, 29% and 25% for the 10x10, 6x6 and 2x2 fields respectively. The EPID response increases with field size and with field offset. When the field is offset on

both axes, the response is higher than for a single axis offset, except for one case (2x2 field with an x-offset of 19 cm).

275 **IMRT field**

The measured and simulated images for the IMRT field are presented in figure 7. Simulated images are more pixelated than the measured images because of the difference of pixel size (0.18 cm for the simulations, 0.05 cm for the measurements). The efficacy of the leaf position prediction method is particularly visible in the lower
280 left part of the images for the off-axis delivery (figure 7c and 7d). The difference in positions of the two lower leaves is well reproduced. In the inplane direction, an asymmetry between the left and the right of the image is observed in the measured image of the off-axis field. This asymmetry is well reproduced on the simulated image.

285 The crossplane and inplane profiles across the fields, defined in figure 3, are presented in figure 8. The simulated values reproduced the measured values to within the uncertainties of the simulations (2%). The simulated field edges were within 1 mm of the measured field edges. For a given profile, a variation of response between 20 and 30% was observed between the delivery on-axis and off-axis.

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DISCUSSION

This study aimed at building a Monte Carlo model to predict EPID images in the particular case of IMRT treatment. The first step consisted of commissioning the Monte Carlo model of the EPID with simple square open fields. EPID output factors
295 measured with the EPID were reproduced to within 0.5% of the measurements, showing that the Monte Carlo model can be used for absolute dose simulations.

In order to further commission the Monte Carlo EPID model and study the variation of its response with off-axis position, three field sizes with various offsets were simulated and compared with EPID measurements. Profiles across the fields showed a good match between the measurements and the simulations. All the simulated values at the centre of the fields were within 1% of the measured values. The response variations with field offset were larger than the variations with field size. Figure 9 presents the spectra simulated for the three field sizes delivered on axis and for the different offsets of the 10x10 field. The largest difference between spectra occurs at the lowest energy (less than 1 MeV). This is where the efficiency of the EPID is the highest.

When the field was offset on both axes, the response was higher than for a single axis offset. This is a consequence of the radial beam softening, due to the angular distribution of the Bremsstrahlung photons created in the target and the differential hardening of the beam by the cone-shaped design of the flattening filter²⁹. In table 2, two values cannot be explained by the radial softening of the beam: the EPID response for the 6x6X+17Y+14 field was lower than for the 6x6X+14Y+14 field and the response for the 2x2X+19Y+12 field was lower than the 2x2X+19Y0 field. These values can be explained by the fact that the flattening filter is enclosed in a tubular structure, which provides additional attenuation at the periphery. The fluence is therefore reduced at the very edge of the beam aperture, resulting in a lower response for the largest offsets.

Visual comparison of the measured and simulated images of the IMRT field demonstrates the efficacy of the leaf position prediction method. In the inplane direction, an asymmetry between the left and the right of the image was observed in both the measured and simulated images of the off-axis field. This is a consequence

of the tongue-and-groove design of the MLC, as illustrated in figure 10. In the inplane direction, the leaf edge projects at a variable position, depending of the position of the leaf. For large offsets of the leaf, the field is defined only by the upper or lower part
325 of the leaf. Because of the tongue-and-groove design of the leaf, this results in different projections of the leaf edge. The variation in leaf projection is minimal close to central axis, where both upper and lower parts of the leaf define the field edge.

The delivery of the IMRT field with an offset on both axes demonstrated the benefit of using a component module describing the tongue-and-groove geometry,
330 such as MLCE, to model the MLC. We found that the asymmetry in the simulations could not be reproduced with a simpler component module, such as MLCQ¹⁷, for which the leaves have straight edges in the inplane direction (data not presented). The cost of modelling a more complex geometry is an increase of calculation times for the linac simulations by a factor of 5 compared to simulations using MLCQ.

335 As for the simple fields, a variation of response between 20 and 30% was observed between the delivery on-axis and with offsets of 15 and 12 cm on X- and Y-axes for the IMRT beams.

The Monte Carlo model of the linac and the EPID succeeded in predicting the EPID response for the three different field sizes with various offsets and for the
340 IMRT fields. These cases were chosen to produce large spectral variations: large offsets were used and the beam was imaged directly in air without any patient attenuation. This would be typically the case of pre-treatment beam verification. It is to be expected that when an attenuation material (i.e.. the patient) is placed between the beam and the EPID, it will act as a filter for low energy photons and thus decrease
345 the spectral variations between the different offsets.

CONCLUSIONS

This study aimed at building a Monte Carlo model to predict EPID images in the particular case of IMRT treatment. The portal dose prediction method developed
350 showed good agreement between the calculated and measured portal dose values. The model was used to assess the effect of spectral variations with field size and position on the EPID response. It was shown that offsets of the beam led to variations up to 30% compared to the response on central axis. This emphasizes the need for consideration of spectral variation in portal image prediction methods.

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TABLES

470 Table 1: Summary of the fields studied. X and Y offsets refer to the beam central axis
and are expressed in centimetres at the isocentre. The use of the flagpole technique to
design the field is specified with an “F” in the flagpole column.

	Field size	X offset	Y offset	Flagpole	Name
475	10x10	0	0		10x10X0Y0
	10x10	0	+15		10x10X0Y+15
	10x10	+15	0	F	10x10X+15Y0
	10x10	+15	+15	F	10x10X+15Y+15
480	6x6	0	0		6x6X0Y0
	6x6	0	+14		6x6X0Y+14
	6x6	+14	0	F	6x6X+14Y0
	6x6	+17	0	F	6x6X+17Y0
	6x6	+14	+14	F	6x6X+14Y+14
	6x6	+17	+14	F	6x6X+17Y+14
	2x2	0	0		2x2X0Y0
	2x2	0	+12		2x2X0Y+12
485	2x2	+12	0	F	2x2X+12Y0
	2x2	+19	0	F	2x2X+19Y0
	2x2	+12	+12	F	2x2X+12Y+12
	2x2	+19	+12	F	2x2X+19Y+12

Table 2: Measured and simulated values at the centre of each field described in table 1.

Values are normalised to the 10x10X0Y0 field.

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Field	Measurement	SD(%)	Simulation	SD(%)	Difference
10x10X0Y0	1.000	0.0	1.000	1.1	0.0%
10x10X0Y+15	1.202	0.5	1.202	0.9	0.0%
10x10X+15Y0	1.217	0.5	1.213	0.9	-0.3%
10x10X+15Y+15	1.279	0.4	1.286	0.9	0.5%
6x6X0Y0	0.949	0.3	0.951	2.0	0.2%
6x6X0Y+14	1.123	0.4	1.127	1.2	0.3%
6x6X+14Y0	1.132	0.5	1.142	1.3	0.9%
6x6X+17Y0	1.176	0.4	1.178	1.2	0.1%
6x6X+14Y+14	1.222	0.4	1.230	1.2	0.6%
6x6X+17Y+14	1.193	0.5	1.192	1.0	0.0%
2x2X0Y0	0.850	0.4	0.847	1.3	-0.4%
2x2X0Y+12	0.967	0.6	0.973	1.2	0.7%
2x2X+12Y0	0.973	0.5	0.967	1.2	-0.7%
2x2X+19Y0	1.056	0.7	1.055	1.2	-0.2%
2x2X+12Y+12	1.023	0.4	1.032	1.2	0.9%
2x2X+19Y+12	1.030	0.5	1.020	1.2	-0.9%

FIGURE CAPTIONS

495 Figure 1: Construction of the Elekta a-Si EPID detection panel (not to scale)

Figure 2: The flag pole technique. The grey area, the thin and the bold lines represent the field aperture, the MLC and the jaw positions respectively. The X2 jaw is on central axis. The flag pole area is only covered by the backup Y2 jaw.

500 Figure 3: Intensity map of the modelled IMRT field. The arrows represent the positions of the profiles plotted in figure 8. Each individual square is $1 \times 1 \text{ cm}^2$ at the isocentre. The field centre is located at the intersection of profiles 1 and 3.

505 Figure 4: EPID gain calibration. The field is fixed and the EPID is moved, so that the field covers each corner of the EPID in turn. The different positions of the beam on the EPID are represented in grey, while the EPID is represented by the larger white square. The cross denotes the position of the central axis of the beam. The robotic arm is represented at the top of each component diagram.

510 Figure 5: Output factors measured (continuous line) and simulated (dots) with the EPID. The error bars represent $\pm 1 \text{ SD}$ for the simulations and are 2% or less of the response.

Figure 6: Crossplane and inplane profiles across $2 \times 2 \text{ X0Y0}$ and $6 \times 6 \text{ X+14Y+14}$ fields. Measured and simulated values are represented by bold lines and histograms respectively. The response is normalised to the central intensity of a $10 \times 10 \text{ cm}^2$ field. The errors bars on the simulation results represent $\pm 1 \text{ SD}$.

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Figure 7: Measured (a,c) and simulated (b,d) images of the IMRT field delivered on central
axis (a,b) and off-axis (c,d). For the off-axis beam, the solid circles highlight the area where
the efficacy of the leaf position prediction method is particularly visible. The dotted circles
highlight one of the areas where an asymmetry between the two banks is present.

Figure 8: Profiles across the IMRT field as shown in figure 3. Measurements and simulations
are represented respectively by bold lines and histograms. The EPID response is normalised
to the central intensity of a $10 \times 10 \text{ cm}^2$ field for 1 MU. The errors bars on the simulation
results represent $\pm 1 \text{ SD}$.

Figure 9: Spectra obtained at the centre of the fields in a region of $1 \times 1 \text{ cm}^2$ at the isocentre for
(a) different field sizes and (b) different offsets for the 10×10 field.

Figure 10: Variable leaf edge projection. For large offsets of the leaf, the field is defined only
by the upper or lower part of the leaf. Because of the tongue-and-groove design of the leaf,
this results in different projections of the leaf edge. Positions A and B are on either sides of
the central axis. The variation in leaf projection is minimal close to central axis, where both
upper and lower parts of the leaf define the field edge.

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Aluminium cover

0.1cm Copper plate

Phosphor screen

Glass and a-Si
photodiode array

Supporting material
(Carbon fibre,
Aluminium)

Printed circuit board

Aluminium cover

545

560

Profile 1

Profile 2

Profile 3

565

570

580

On-axis

Off-axis

Profile 1

Profile 2

Profile 3

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590

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