Use of XR-QA2 radiochromic films for quantitative imaging of a synchrotron radiation beam

F. Di Lillo[a,b], D. Dreossi[c], F. Emiro[a,b], C. Fedon[d,e], R. Longo[d,e], G. Mettivier[a,b,*], L. Rigon[d,e], P. Russo[a,b], G. Tromba[c]

[a] *Università di Napoli Federico II, Dipartimento di Fisica, Via Cintia, I-80126 Napoli, Italy*
[b] *INFN, Sezione di Napoli, Via Cintia, I-80126 Napoli, Italy*
[c] *Elettra-Sincrotrone Trieste SCpA, Strada Statale S.S. 14 km 163.5, 34012 Basovizza, Trieste, Italy*
[d] *Università di Trieste, Dipartimento di Fisica, Via A. Valerio 2, I-34127 Trieste, Italy*
[e] *INFN, Sezione di Trieste, Via A. Valerio 2, I-34127 Trieste, Italy*
E-mail: giovanni.mettivier@na.infn.it

ABSTRACT: This work investigates the use of XR-QA2 radiochromic films for quantitative imaging of a synchrotron radiation (SR) beam. Pieces (200 × 30 mm^2) of XR-QA2 film were irradiated in a plane transverse to the beam axis, at the SYRMEP beamline at ELETTRA (Trieste), with a monochromatic beam of size 170 × 3.94 mm^2 (H × V) and energy of 28, 35, 38 or 40 keV. The response was calibrated in terms of average air kerma (1–20 mGy), measured with a calibrated ionization chamber. Films were digitized in reflectance mode using a flatbed scanner. The 16-bit red channel was used. The net reflectance was then converted to photon fluence per unit air kerma (mm^{-2} mGy^{-1}). The SR beam profile was acquired also with a scintillator (GOS) based, fiberoptic coupled CCD camera as well as with a scintillator based flat panel detector. Horizontal profiles obtained with the two modalities were compared, evaluated in a ROI of 17.71 × 0.59 mm^2, across the beam centre. Once corrected for flat field, the CCD profile was scaled in order to have the same average value as the normalized profile acquired with the gafchromic film. The same procedure was followed for the beam images acquired with the flat panel detector. Horizontal and vertical line profiles acquired with the radiochromic film show an uneven 2D distribution of the beam intensity, with variations in the order of 15–20% in the horizontal direction, while the statistical uncertainties evaluated for the radiochromic dose measurements were 6% at 28 keV. Larger variations up to 64% were observed in the vertical direction. The response of the radiochromic film is comparable to that of the other imaging detectors, within less than 5% variation.

[*] *Corresponding author*

NOT FOR DISTRIBUTION JINST_083P_0914 V1

KEYWORDS: Synchrotron radiation; Beam dosimetry; Radiochromic film.

NOT FOR DISTRIBUTION JINST_083P_0914 v1

Contents

1. Introduction

This work investigates the use of XR-QA2 radiochromic films – designed for quality control in diagnostic radiology [1] – for quantitative imaging of a synchrotron radiation (SR) beam. This experimental study has been performed within the project SYRMA-CT. The aim of this project, supported by INFN, is a pilot study at the SYRMEP beamline at ELETTRA[2,3] for producing the first in-line phase-contrast computed tomography (CT) scan of the female breast with monochromatic synchrotron radiation (~ 40 keV). The setup will include a photon counting CdTe imaging detector [4]. The assessment of the radiation dose to the breast is one of the critical issues in this context [5]. The dosimetric protocol will be based on the evaluation of the Mean Glandular Dose (MGD) and of the $CTDI_w$, the dose index used in CT exams. For this purpose, a dosimetric characterization of the SR beam was performed by using different dosimeters (ionization chamber, TLD and radiochromic film). In particular, radiochromic films were used to obtain a 2D distribution of the photon fluence at isocenter, in a plane orthogonal to the beam axis. Radiochromic films have been used in the past for dose verification purposes with synchrotron-produced monochromatic x-ray beams [6]. Use of radiochromic film was also reported for dosimetry of synchrotron microbeam radiation therapy [7]. The goal of this method is to determine the photon fluence per unit area over the whole transverse surface of the SR beam, after calibration with an ionization chamber in terms of air kerma.

2. Materials and Methods

The Gafchromic™ XR-QA2 film (Ashland, NY) is a reflective-type film with an asymmetric geometrical structure, composed of one active layer of 25 μm thickness separated by an adhesive layer of 20 μm, sandwiched between two 97-μm thick polyester layers, one with an orange color on the front and the other with a white color on the back. By specifications, the film is sensitive in the dose range 1–200 mGy and energy range 20–200 keV. Pieces of film (200 × 30 mm^2) were cut from a single sheet (lot #A10071003A) and irradiated in a plane transverse to the beam axis. The front orange layer of the film was facing the X-ray beam. Measurements were performed at the SYRMEP (SYnchrotron Radiation for MEdical Physics) beamline at the ELETTRA facility in Trieste, Italy [2,3]. A monochromatic, laminar beam of transverse size 170 × 3.94 mm^2 (H × V) and energy of 28, 35, 38 or 40 keV, irradiated the film at a distance of about 23 m from the source. The beam cross section was define by a

NOT FOR DISTRIBUTION JINST_083P_0914 V1

micrometric slits system. During the measurements, the electron energy was 2.4 GeV and the ring current was 160 mA. The response of radiochromic film was calibrated in terms of average air kerma, K_{air} (mGy), measured with a calibrated ionization chamber (Radcal 10X6-3CT connected to the dosimeter Radcal AccuPro). The 100-mm long chamber was positioned along the vertical direction at the centre of the beam, so that its 3 cm^3 sensitive volume was covered only partially by the SR beam. Hence, its reading was scaled by a factor 100/L, where L (mm) is the vertical height of the beam at the position of the chamber, as determined by the vertical collimation of the beam. This correction is intended to provide an air kerma averaged along the vertical direction (determined by the central height of the beam), as well as along a horizontal beam span of 13 mm (determined by the diameter of the CT ion chamber with the build-up cap used for the measurements). This value of air kerma was taken as the reference value for normalization of the radiochromic film response.

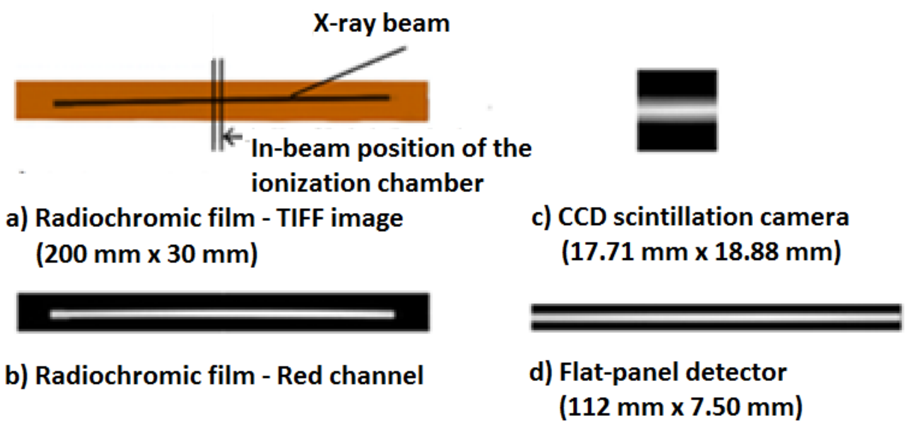

Figure 1: a) Raw image (TIFF format) of the SR beam (photon energy = 28 keV) acquired with the radiochromic film. b) The red channel of the raw TIFF image of the radiochromic film. c) Image of the SR beam acquired with the scintillator based CCD camera. d) Image acquired with the flat panel detector. The white zones in the middle of images 1b), 1c), 1d) correspond to the irradiated area.

For calibration, eleven 50 × 50 mm^2 pieces of film were irradiated in air obtaining a dataset of eleven air kerma values ranging from 1 to 20 mGy (Figure 1). This irradiation was performed by translating the film through the beam at constant speed, thus obtaining a uniform film exposure along the vertical direction. This procedure allowed us both to average the vertical beam profile and to obtain a sufficiently wide area for film digitization and analysis [5]. Films were digitized in reflectance mode using a flatbed scanner (Epson 750V Pro, EPSON Scan readout software) with an image resolution of 150 dpi in 48 bit RGB mode and saved as tagged image file format (TIFF) files. The 16-bit red channel of the RGB image was used for the film processing. According to approach suggested by Menegotti et al. [8] in order to obtain stable values from the scanned image, each scan was repeated five times and only the last one was analysed. The analysis was performed by using the open software ImageJ (National Institutes of Health, Bethesda, MD). Following Tomic et al. [9], the film response was evaluated, at each beam energy E (keV), in terms of net reflectance, netΔR; its value (mean pixel value ± std. dev.) in a Region Of Interest (ROI) of 10 × 10 mm^2 was plotted versus the (collisional) air kerma, K_{air}, and a function of the form $K_{air} = a + b[\text{net}\Delta R/\ln(\text{net}\Delta R)]$ was fitted to the data using the software Origin 5 (OriginLab Corporation, Northampton, MA) with a and b as fitting parameters. The netΔR was then converted to photon fluence ϕ (mm^{-2}), using the relationship

NOT FOR DISTRIBUTION JINST_083P_0914 V1

between K_{air} (mGy) and ϕ, given by $K_{air} = c \cdot \phi \cdot E \cdot \mu_{en}/\rho$, where μ_{en}/ρ (cm^2/g) is the mass energy absorption coefficient of air at photon energy E (keV) and where c (= 1.6×10^{-14}) a scaling factor. Here μ_{en}/ρ (cm^2/g) is used instead of μ_{tr}/ρ (cm^2/g) since for low Z materials in this energy range the two coefficients are virtually identical [10]. This permits to express quantitatively the calibrated pixel value of the radiochromic image of the SR beam, normalized to air kerma, in mm^{-2} mGy^{-1}.

The SR beam profile was acquired also with a CMOS flat panel detector (Hamamatsu, model C7942CA-02) featuring a 50 μm pitch and a 150-μm thick CsI:Tl scintillator, as well as with a scintillator based CCD camera having a field of view of 17.71 × 11.88 mm^2. It is a water cooled CCD camera by Photonic Science, model VHR, 4008 × 2672 pixel full frame, used in 4 × 4 binning mode resulting in a pixel size of 18 μm by side, coupled to a 3 mg/cm^2 Gadolinium Oxysulphide (GOS) scintillator placed on a fiber optic taper. This camera was used to analyse the 2D intensity distribution at the center of the 170-mm wide SR beam. The CCD camera response was not uniform in the horizontal and vertical directions, due to the optical coupling between the phosphor layer and the CCD chip. The image acquired with the CCD detector was corrected for the flat field acquired with a uniform illumination with a 40 kV X-ray tube beam. Then, the horizontal beam profiles obtained with the three modalities (radiochromic film, CCD camera and Flat panel) were compared (at 28 keV). For beam energy of 35, 38 and 40 keV only radiochromic and CCD images have been acquired.

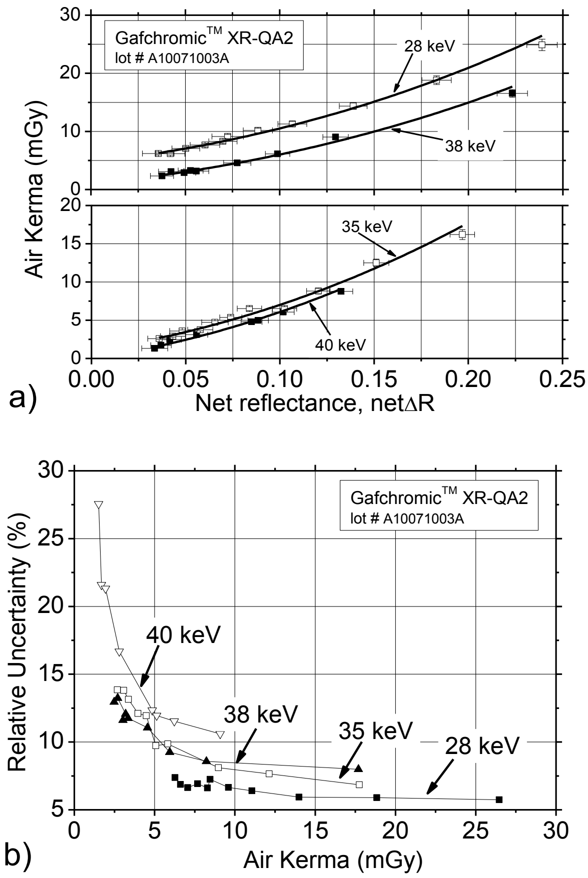

Figure 2: a) XR-QA2 radiochromic film calibration curves and b) corresponding uncertainties.

NOT FOR DISTRIBUTION JINST_083P_0914 V1

3. Results and discussion

Figure 1a shows the raw image of the SR beam acquired with a piece of gafchromic film (200 × 30 mm^2), and the SR beam image acquired with scintillator-based CCD camera (17.71 × 11.88 mm^2) (figure 1c). The red channel of the image acquired with the radiochromic film (figure 1b) was calibrated in terms of photon fluence per unit air kerma at the beam centre, where the ionization chamber was placed. Calibration curves obtained at the various energies are shown in figure 2a, while corresponding experimental uncertainties (obtained via error propagation) are shown in figure 2b: they decrease to less than 10% for air kerma values above 10 mGy.

Figure 3 shows the horizontal and vertical profiles evaluated from the radiochromic images in a rectangular ROI of size 0.68 × 176.6 mm^2 and 8.97 × 22.69 mm^2 for the horizontal and vertical direction, respectively, across the beam centre.

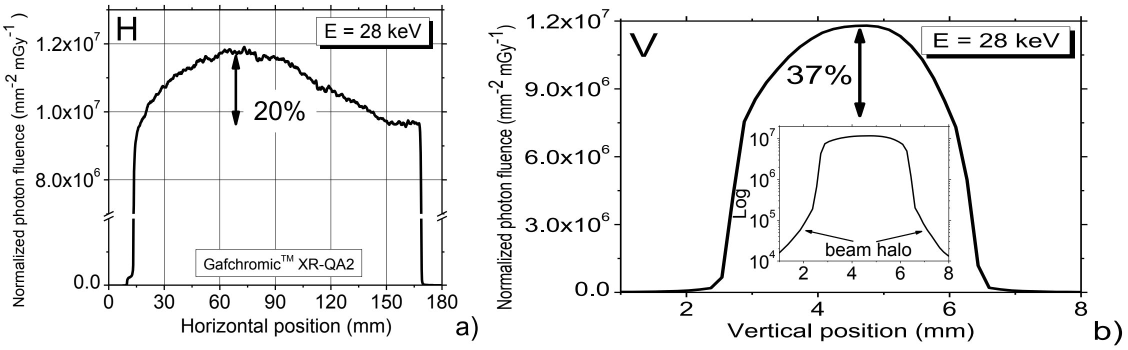

Figure 3: a) Horizontal (H) and b) vertical (V) beam line profiles at 28 keV, obtained from the image of the radiochromic film . The line profile was averaged along vertical direction. Maximum variation of 20% (H) and 37% (V) were observed, with respect to the peak value. The inset in b), in log scale, highlights a low-intensity scatter signal.

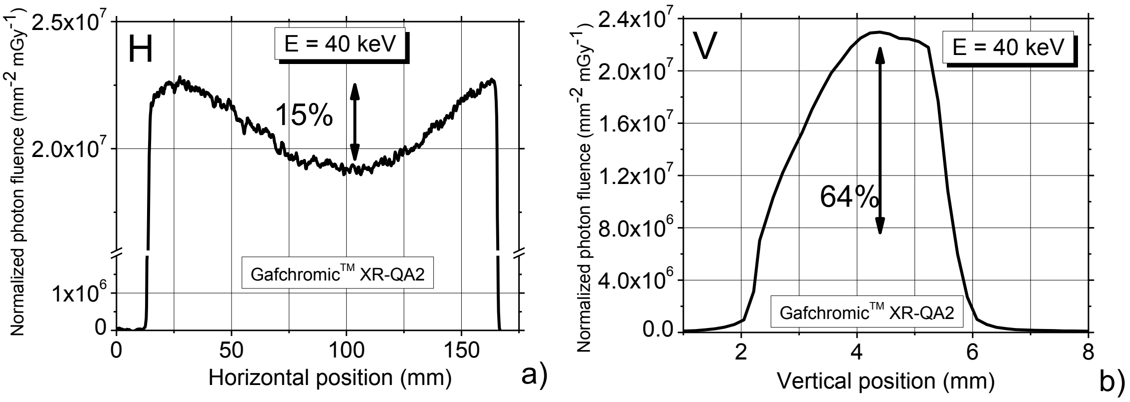

Figure 4: a) Horizontal and b) vertical average beam line profiles at 40 keV, obtained from the radiochromic image. Maximum variations of 15% (H) and 64% (V) were observed.

The beam uniformity at 28 keV, in terms of percent variation from the peak value of the line profile, is over 20% (in the horizontal direction) and 37% (in the vertical direction) as observed in figure 3. Interestingly, as shown in the insert in figure 3b, the vertical profile of the radiochromic image of the beam shows a beam halo, whose signal is up to two orders of magnitude less intense than the main peak intensity.

NOT FOR DISTRIBUTION JINST_083P_0914 V1

The beam line profiles obtained with radiochromic imaging at 40 keV are shown in figure 4; in this case the maximum non-uniformity of the beam was 15% along the horizontal direction. The 64% non uniformity in the vertical direction is essentially due to the misalignment of the slits system with the peak. Horizontal beam profiles obtained with the three modalities (radiochromic film, CCD camera and Flat panel detector) were compared in figure 5. The profiles were evaluated in a rectangular ROI of size 17.71 × 0.59 mm^2: at 28 keV in figure 5a and at 40 keV in figure 5b, respectively. The CCD profile was scaled in order to have the same average value as the normalized profile acquired with the radiochromic film. Moreover, given the higher sampling of the CCD detector (1411 pixel per inch) with respect to the radiochromic image (150 dot-per-inch scan), the profile corresponding to the CCD detector was smoothed by a 10 point moving average second order polynomial.

The relative variation [(max-min)/mean] of the normalized photon fluence obtained with radiochromic film over the 18-mm wide SR beam (figure 5) was about 3% for all profiles, well within the statistical uncertainties evaluated for the radiochromic dose measurements (6% at 28 keV). The difference in the response of the radiochromic film with that of the other imaging detectors was less than 5%.

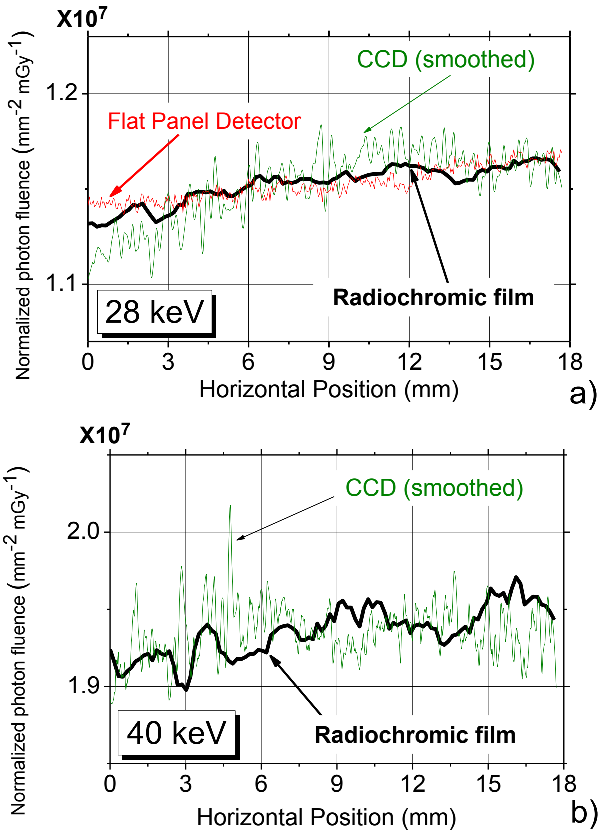

Figure 5: The average horizontal line profiles along a ROI of size 17.71 × 0.59 mm^2 of the image of the beam acquired with the radiochromic film, with a CCD detector and with the Flat Panel detector, at a) 28 keV, b) 40 keV. Profiles were scaled vertically in order to have the same average value as the average line profile acquired with the calibrated radiochromic film. The response of the radiochromic film is comparable to that of the other imaging detectors, within less than 5% difference. The image of the flat panel detector was not available at 40 keV.

NOT FOR DISTRIBUTION JINST_083P_0914 V1

A set of exposures (figure 6a) was made by inserting thin foils of pure aluminum (from 1 mm up to 5 mm) consecutively in the beam, which determined an increasing attenuation of the beam intensity. From the average value of the calibrated response of the film in a ROI centered on each Al foil of varying thickness (figure 6b), an attenuation curve was derived (figure 6c). The half value layer (HVL) evaluated from the exponential fit of the data points was 1.75 ± 0.15 mm Al: at the given beam energy (28 keV) the HVL expected was 1.9 mm Al, a reasonable agreement.

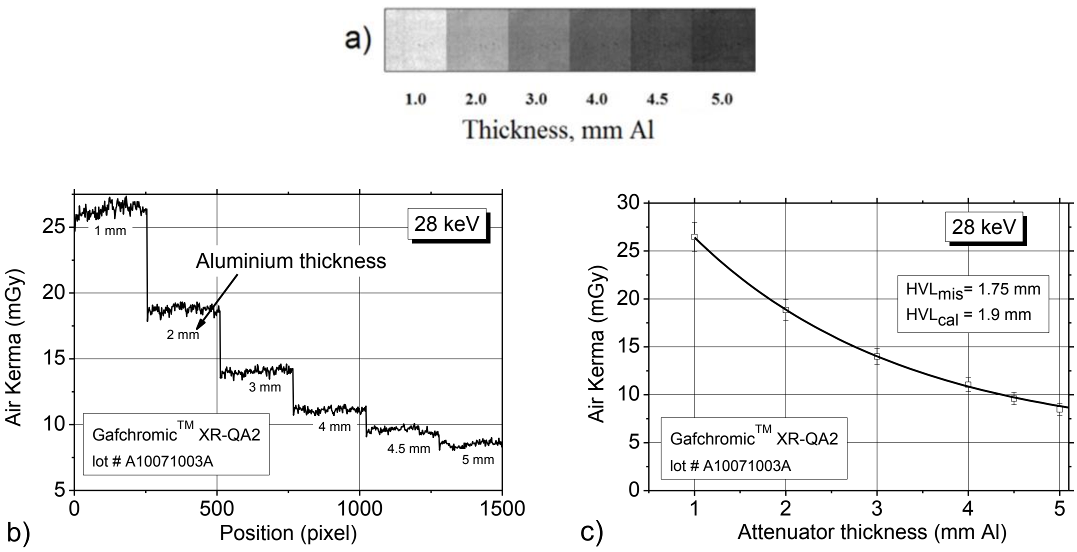

Figure 6: a) Composite image of radiochromic film pieces exposed to the SR beam at 28 keV, attenuated by varying thicknesses of Al foils. b) Average line profile of the calibrated film response in (a). c) Attenuation curve from the data in (b) (data points shown as mean ± std. dev. in a ROI), along with an exponential fit (continuous line). Measured and expected HVL values (mm Al) are also indicated.

4. Conclusions

The images of the SR beam produced with the Gafchromic™ films have been calibrated in terms of air kerma free-in-air, using a standard 100-mm-long CT ion chamber. Once expressed in units of photons mm^{-2} mGy^{-1}, the radiochromic film provides the 2D distribution of the beam intensity in a plane transverse to the beam axis in terms of photon fluence per unit air kerma. The radiochromic films provided a 2D map of the beam intensity in a transverse plane, showing beam intensity variations which were down to four orders of magnitude lower than the maximum beam intensity. Observed variations of the beam intensity were from 15% to 64% over the whole beam. The comparison with images acquired with a CCD scintillator camera and with a flat panel detector shows that the performance of the film is comparable within 5%, but the film is expected to provide an unsaturated response in a larger range of air kerma values. Moreover, the radiochromic film may have a larger sensitive area than CCD or flat panel detectors and it does not require any flat field correction, but it requires an offline processing.

NOT FOR DISTRIBUTION JINST_083P_0914 v1

References

[1] N. Tomic et al., *Characterization of calibration curves and energy dependence GafChromicTM XR-QA2 model based radiochromic film dosimetry system*, Med. Phys. **41** (2014) 062105.

[2] D. Dreossi et al., *The mammography project at the SYRMEP beamline*, Eur. J. Rad. **685** (2008) s58-62.

[3] Abrami et al., *Medical applications of synchrotron radiation at SYRMEP beamline of ELETTRA*, Nucl. Instr. Meth. Phys. A **548** (2005) 221-227.

[4] R. Bellazzini et at., *Chromatic x-ray imaging with a fine pitch CdTe sensor coupled to a large area photon counbting pixel asic*, J. Inst. doi:10.1088/1748-0221/8/02/C02028

[5] J. M. Boone et al., *Dedicated breast CT: Radiation dose and imaging quality evaluation*, Radiology **221** (2001) 657-667.

[6] T. A. D. Brown et al., *Dose-response curve of EBT, EBT2, and EBT3 radiochromic films to synchrotron-produced monochromatic x-ray beams*, *Med. Phys*. **39** (2012) 7412–7417.

[7] J. C. Crosbie et al., *A method of dosimetry for synchrotron microbeam radiation thereapy using radiochromic films of different sensitivity*, Phys. Med. Biol. **53** (2008) 6861–6877.

[8] L. Menegotti et al., *Radiochromic film dosimetry with flatbed scanners: A fast and accurate method for dose calibration and uniformity correction with single film exposure*, Med. Phys, **35** (2008) 3078-3085

[9] N. Tomic et al., *Reference radiochromic film dosimetry in kilovoltage photon beams during CBCT image acquisition*, *Med. Phys.* **37** (2010) 1083–1092.

[10] H. E. Johns and J. R. Cunningham, *Physics of Radiology*, Charles C. Thomas Publisher, Springfield, Illinois

NOT FOR DISTRIBUTION JINST_083P_0914 V1