# Dosimetric calibration of GAFCHROMIC HD-V2, MD-V3, and EBT3 film for dose ranges up to 100 kGy

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(Dated: 9 April 2021)

A dosimetric calibration of three types of radiochromic film (GafChromic™HD-V2, MD-V3, and EBT3) was carried out for absorbed doses ($D$) ranging up to 100 kGy using a 130 TBq $^{60}$Co $\gamma$-ray source. The optical densities (OD) of the irradiated films were acquired with the transmission-mode flatbed film scanner EPSON GT-X980. The calibration data was cross-checked using the 20-MeV proton beam from the AVF cyclotron at Research Center for Nuclear Physics in Osaka University. Those experimental results not only present the measurable dose ranges of the films depending on the readout wavelength, but also show consistency with our hypothesis that the OD response curve (log($OD$)-log($D$) curve) is determined by volumetric average of the absorption dose and does not strongly depends on type of radiation for the excitation.

## I. INTRODUCTION

Radiochromic films (RCFs) have been extensively used for ionizing radiation dosimetry and imaging in medical, nuclear, and plasma science. RCFs are generally a semi-transparent plastic film with a thin active layer composed of monomers suspended in gelatin, which polymerizes to form a darker dye upon exposure to ionizing radiation. Since the optical density (OD) of irradiated films is related to the energy deposited in the film, RCF can be used for dosimetry by characterizing the response of the OD to radiation. Proton dosimetry using a stack of RCFs has been a standard diagnostic in the experiments on laser particle acceleration. Various mechanisms of particle acceleration by laser has been reported including the Target Normal Sheath Acceleration (TNSA)[1]. The resulting protons in many cases are known to have a broad energy distribution and a divergence with an energy-dependent envelope angle, which has not been fully understood[2,3]. RCFs in a stack configuration makes it possible to capture the entire beam of protons a few centimeters away from the source, providing full information about proton flux as a function of energy and angle with a high dynamic range. The drawbacks of this diagnostic are difficulty in spectral reconstruction and poor energy resolution, which is defined by the thickness of the film and typically limited to a few Mega-electron-volts (MeV). However, recent three-dimensional (3D) unfold techniques published by M. Schollmeier *et al.*[4] have demonstrated practical analysis of laser-accelerated protons using well-characterized RCFs. These technical advances have gained renewed attention to this diagnostic method.

Characterization of various types of RCF, *i.e.* calibration of OD against exposed dose, has been conducted in the world[5–7]. However, information of those films is still limited especially on their optical saturation property at high dose levels. In addition, readout wavelength makes a significant difference of one or more orders of magnitude in the resulting OD[5], and batch-to-batch variation in the sensitivity of RCF can be as high as 10% (from manufacturer's specifications). Therefore, it is desirable to calibrate owned films with on-site readout systems for the use of RCF. GafChromic™HD-V2, MD-V3, and EBT3 films are widely used for dosimetry in laser-plasma experiments. Since they have different optical sensitivities, HD-V2 is generally used for high doses, MD and EBT are used for middle and low doses respectively. In this paper, we present their response curves for dose ranges up to 100 kilo-gray (kGy) and describe our technical scheme of dosimetric calibration using a $^{60}$Co $\gamma$-ray source.

## II. EXPERIMENT-I

The calibration experiment was carried out using a 128.94-TBq $\gamma$-ray source at the Institute of Scientific and Industrial Research (ISIR) of Osaka University. The radioactive source is composed of a $^{60}$Co pellet enclosed in an aluminum cylindrical container with an outer diameter of 2 cm, a height of 20 cm, and a wall thickness of 2 mm. The $^{60}$Co pellet emits two photons with energies of 1.17 and 1.33 MeV every nuclear decay event and provides a constant photon flux of $2.58\times10^{14}$ photon/$4\pi$/sec. As schematically shown in Fig. 1, five sets of HD-V2, MD-V3, and EBT3 film array were aligned in a straight line and located respectively at 17, 50, 100, 141, 200 cm away from the radioactive source. The film configurations are shown in Fig. 1 (a). Each film was cut into a sheet of $5 \times 2$ cm$^2$ size and embedded in a lead shield, which defended films against unwanted radiation caused by scattered $\gamma$-rays and secondary electrons coming from the side wall and ceiling of the experimental area. The

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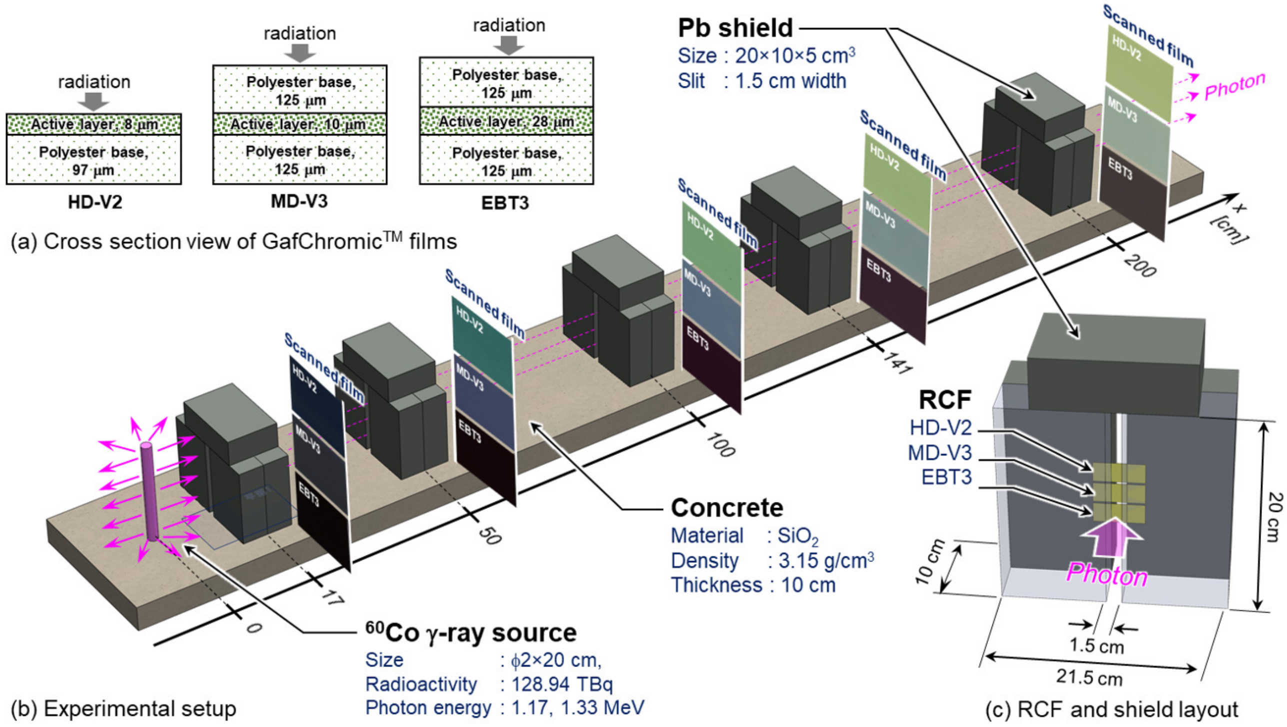

FIG. 1. Schematic view of the experimental setup. (a) Cross sction view of the GafChromic HD-V2, MD-V3, and EBT3 film, (b) geometric setup applied to the experiment and Monte Carlo simulation, (c) RCF and lead shield layout. Scanned image of each film at each location shows an uniform irradiation by perfectly isotropic $\gamma$-rays.

lead shields have a 1.5-cm wide slit, and a $2 \times 1.5$ cm$^2$ area of each film was exposed to radiation (see Fig. 1 (c)). This experimental setup allows to obtain multiple data points with different doses in a single irradiation session, that is useful for the experiment with limited facility usage time. In addition, this setup also allows to reduce the size of simulation box mentioned later. The provided radiation is perfectly isotropic and thus irradiates RCFs uniformly as shown in Fig 1. This feature is convenient for relating dose and OD of the film. All films were exposed to the radiation for 46 hours in total across eight separate irradiation sessions of 10, 10, 115, 80, 200, 950, 400, 1000 minutes, and were scanned after every session. The resulting dose range was approximately 0.5 mGy - 100 kGy. The radiation source was moved from the shielding tank to the irradiation position using a robot arm in the experimental area and returned to the tank immediately after the irradiation session. The uncertainty of irradiation time due to this work process is less than 1%.

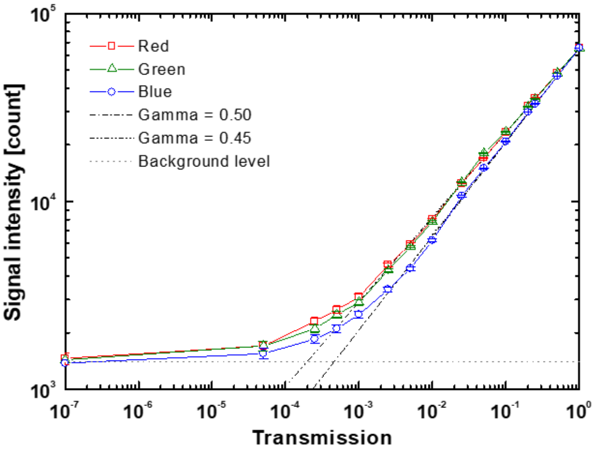

FIG. 2. Output signal intensity of the scanner EPSON GT-X980 as a function of probe light transmission, showing logarithmic response for all color channels.

OD values of the irradiated films were measured using the transmission-mode flatbed scanner EPSON GT-X980 operated by the standard driver EPSON Scan 4.0.1.0. RGB-positive images were recorded in TIFF format at a depth of 16 bits per color channel with a spatial resolution of 600 dpi and gamma sets of $\gamma = 0.5$ for blue, $\gamma = 0.45$ for red and green channel. The obtained images were processed using the free image analysis program ImageJ (National Institute of Health, Bethesda, MD, USA) for a region-of-interest (ROI) of $1.5 \times 1.0$ cm$^2$, where a median filter was applied to reduce the effect of scratches

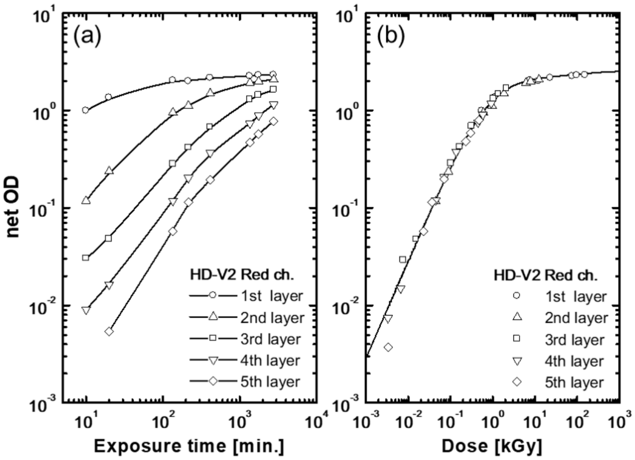

FIG. 3. Calibration result for GafChromic HD-V2 film, showing (a) net-OD as a function of exposure time for five films located at different distance from the radiation source and (b) overall dose response curve, where the data points of five films trace a single curve with a good accuracy, showing a high reliability of the experiment and dose calculation by PHITS.

and small debris on the film. Figure 2 shows the response of the scanner as a relationship between the output signal intensity $I$ and transmittance $T$ of the probe light, which was obtained by scanning well-characterized neutral density (ND) filters with the same readout setup. The output signal intensity ranges from $I_{\min} = 1,600$ to $I_{\max} = 65,500$, and the upper limit of measurable OD is aproximately 3.0 ($T > 10^{-3}$). Here, $I_{\min}$ and $I_{\max}$ are the signal intensities for 0% and 100% transmission respectively. The transmittance of the proble light is given by $T(I) = (I/I_{\max})^{1/\gamma}$, and the OD value is obtained by

$$\mathrm{OD} = -\log_{10}\left(\frac{I_{\mathrm{film}}^{1/\gamma} - I_{\min}^{1/\gamma}}{I_{\max}^{1/\gamma} - I_{\min}^{1/\gamma}}\right) \tag{1}$$

Consistent with the analysis procedure outlined by Devic *et al.*[7], OD value measured before irradiation ($\mathrm{OD_{unexp}}$) was subtracted from the OD measured after irradiation ($\mathrm{OD_{exp}}$) in order to give the net optical density ($\mathrm{netOD} = \mathrm{OD_{exp}} - \mathrm{OD_{unexp}}$).

The absolute energy deposition to each film was calculated using a Monte Carlo (MC) particle tracking code PHITS (ver.3.02) as listed in Table I. MC codes are necessary to estimate the exact dose on each film taking into account the energy deposition by secondary $\gamma$-rays and electrons from the surrounding materials. A slightly simplified geometry was described in the input cards, where no detail about the outside concrete wall and ceiling was included since they would have negligible influence on the dose characteristics in this experimental geometry. Figure 1 also presents the geometric setup of the simulation. The active layer and substrate layers were assumed to be $C_1H_1$ ($\rho = 0.9$ g/cm$^3$) and $C_2H_2O_1$ ($\rho = 1.3$ g/cm$^3$) respectively. An energy cut-off of 1 eV was used for both photon and electron transport, overriding their default cut-off of 1 keV, in order to calculate absolute dose and its spatial distribution precisely. An overall dose on a film is derived from Dose [Gy] = $2R_a t D_r/\rho L$, where each variable means $R_a$: radioactivity [Bq], $t$: exposure time [sec], $D_r$: deposit energy per source photon [MeV/cm$^2$/photon], $\rho$: density [kg/cm$^3$] and $L$: thickness [cm] of the active layer.

TABLE I. Estimated energy deposition per source particle at each RCF layer

| Layer No. | Distance | Dose [MeV/cm$^2$/photon][a] | | |
|---|---|---|---|---|
| | [cm] | HD-V2 | MD-V3 | EBT3 |
| 1st | 17 | $1.1 \times 10^{-8}$ | $1.2 \times 10^{-8}$ | $3.3 \times 10^{-8}$ |
| 2nd | 50 | $1.1 \times 10^{-9}$ | $1.1 \times 10^{-9}$ | $3.2 \times 10^{-9}$ |
| 3rd | 100 | $1.6 \times 10^{-10}$ | $1.7 \times 10^{-10}$ | $5.8 \times 10^{-10}$ |
| 4th | 141 | $5.1 \times 10^{-11}$ | $1.2 \times 10^{-10}$ | $2.7 \times 10^{-10}$ |
| 5th | 200 | $3.6 \times 10^{-11}$ | $3.4 \times 10^{-11}$ | $1.5 \times 10^{-10}$ |

[a] The dose value is in the unit of MeV per unit film area in cm$^2$ and per single photon emitted from the $^{60}$Co.

The experimental results on HD-V2 are summarized in Fig. 3(a), where five net-OD curves from different films are presented as a function of exposure time. Those 5 samples cover different dose level and enable to obtain wide range of exposure response as shown in Fig. 3(b) with limited number of trials. The excellent agreement of the dose response curves between films indicates the accuracy of absolute dose calculation by MC simulation.

The dose response curves of HD-V2, MD-V3, and EBT3 for all color channels were obtained in the same process and presented in Fig. 4. The fit curve was given by the following function:

$$\mathrm{netOD}(D) = \frac{c_1 D + c_2 D^2}{c_3 + c_4 D + c_5 D^2} \tag{2}$$

where $D$ is the absorbed dose in kGy and the best fit coefficients $c_1 \sim c_5$ for each film are listed in Table II. EBT3, the most sensitive film discussed here, is saturated at 0.1 - 1 kGy for all color channels, but the blue channels of HD-V2 and MD-V3 are not fully saturated and show perceptible contrast even over 10 kGy exposure. The obtained dose response curves are consistent with previous works reported by Y. Feng *et al.*[5]. Figure 4 (a) and (c) also present their typical results for HD-V2 and EBT3 exposed to 20-MeV protons and read at 402 nm, showing good agreement with our results in blue channel. This agreement shows the reliability of our calibration results, as well as indicates that the obtained response curves don't depend on the type of radiation source.

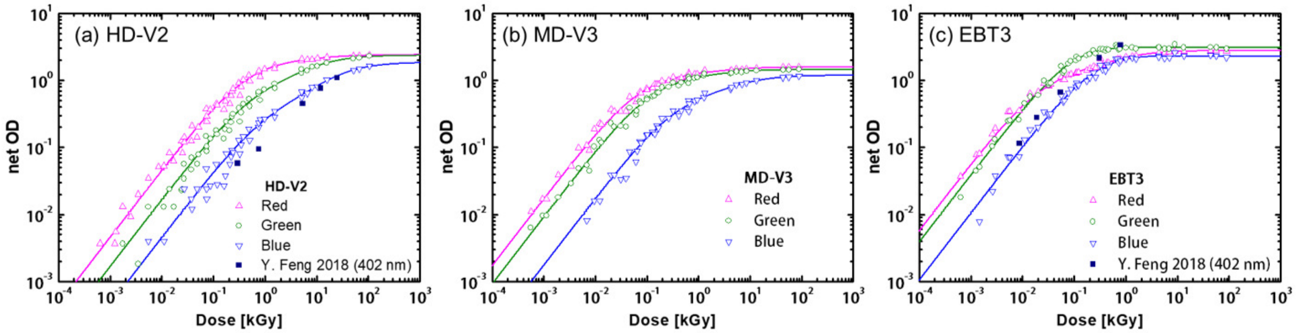

FIG. 4. Dose response curves of (a) HD-V2, (b) MD-V3, and (c) EBT3 for all color channel. EBT3 film is saturated around 0.1 - 1 kGy for all color channels, but HD-V2 and MD-V3 films are not totally saturated and show perceptible contrast even over 100 kGy exposure. The obtained OD response curves for HD-V2 and EBT3 are consistent with the results from proton excitation (Y. Feng 2018[5]), indicating that the dose value are universal for any other radiation sources.

TABLE II. The resultant coefficients for the best fit curves, $netOD(D) = (c_1D + c_2D^2)/(c_3 + c_4D + c_5D^2)$, shown in Fig. 4.

| Film type | | HD-V2 | | | MD-V3 | | | EBT3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Color channel | unit | Red | Green | Blue | Red | Green | Blue | Red | Green | Blue |
| $c_1$ | $\times 10^6$ kGy$^{-1}$ | 4.358 | 1.514 | 1.937 | 3.231 | 3.450 | 3.512 | 23.95 | 22.08 | 66.89 |
| $c_2$ | $\times 10^6$ kGy$^{-2}$ | 0.391 | 0.477 | 0.379 | 1.332 | 1.345 | 1.096 | 70.56 | 73.96 | 35.30 |
| $c_3$ | $\times 10^6$ | 0.951 | 0.910 | 4.279 | 0.188 | 0.376 | 2.009 | 0.421 | 0.571 | 6.409 |
| $c_4$ | $\times 10^6$ kGy$^{-1}$ | 2.187 | 1.731 | 4.491 | 2.591 | 3.020 | 5.946 | 17.62 | 6.881 | 27.91 |
| $c_5$ | $\times 10^6$ kGy$^{-2}$ | 0.162 | 0.201 | 0.204 | 0.840 | 0.921 | 0.919 | 25.29 | 23.84 | 15.32 |
| Fit range | kGy | 0.001 – 100 | | | 0.001 – 100 | | | 0.001 – 100 | | |
| Fit error | | 5.6% | 7.1% | 11% | 4.8% | 5.9% | 8.5 % | 7.3% | 5.1% | 8.2% |

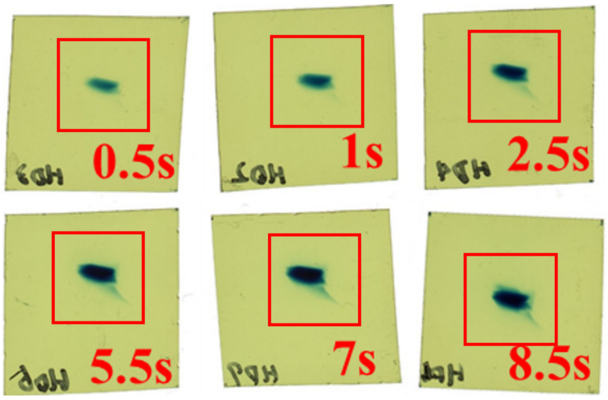

FIG. 5. Scanned view of HD-V2 films irradiated with a 20-MeV proton beam for different exposure times (written as red letters), showing the non-uniformity of the spatial profile of the proton beam. The total dose in the area surrounded by the red square was evaluated using the OD response curve obtained with the $\gamma$-ray source.

## III. EXPERIMENT-II

The dose calibration results were cross-checked using a 20-MeV proton beam from the azimuthally varying field (AVF) cyclotron at the Research Center for Nuclear Physics (RCNP) in Osaka University. The purpose of this experiment was to ensure that the response curves for gamma-ray excitation and proton excitation were scalable. The AVF cyclotron provided an approximately 5 mm diameter beam of protons with the energy of 20 MeV with excellent stability. The beam current on-target was monitored with a Faraday cup and maintained at 1 nA throughout the experiment. The proton beam transmitted a 50 $\mu$m thick Mylar vacuum window and traveled about 5 mm through ambient air before reaching the RCF. Six HD-V2 films were exposed to the beam for 0.5, 1.0, 2.5, 5.5, 7.0 amd 8.5 second and scanned with the same scanner. The resulting proton dose in the active layer of HD-V2 was calculated to be $D_\mathrm{r} = 0.0277$ MeV/proton taking into account the energy loss of protons before reaching the film. The stopping range of 20-MeV proton is sufficiently longer than the thickness of RCF, allowing to minimize the uncertainty in absorbed dose due to protons near the Bragg peak. Figure 5 represents the irradiated HD-V2 films, showing

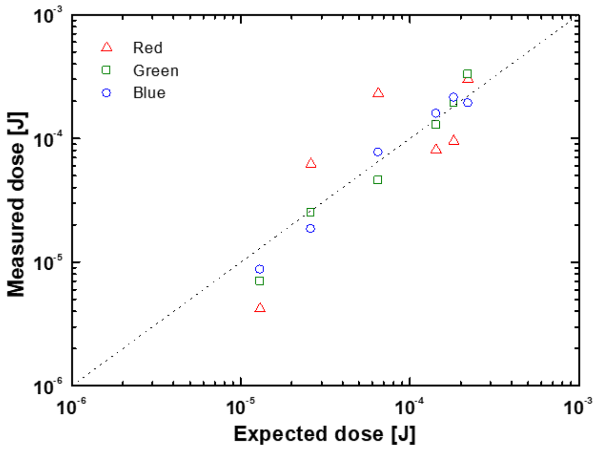

FIG. 6. The dose of HD-V2 film irradiated with the proton beam at RCNP in Osaka University. Dose values of all data points were calculated from the dose response curves obtained with the $\gamma$-ray source (Fig. 4(a)). The agreement between the experimental results and actual dose value estimated from the beam current shows that the obtained film response functions to dose are universal for any other radiation sources

a significant non-uniformity of the proton beam. The total dose of each film was successfully measured from the non-uniform color profile of the films using the dose response curves shown in Fig. 4. Figure 6 shows the relation between the measured dose and expected dose. The expected dose was estimated from the beam current $I_{\rm p}$, dose per proton $D_{\rm r}$, exposure time $t$, proton charge $q$, and given by $D = I_{\rm p}D_{\rm r}t/q$. Here, the dose value of all pixels surrounded by the red square in Fig. 5 was accumulated. As shown in Fig. 6, the blue and green channel showed a good agreement with the expected dose within the error of 50%. The red channel also agrees with the theoretical curve, but the accuracy is not good because it's already saturated at these dose values. The experimental results are consistent with our hypothesis that the OD response curve (log($OD$)-log($D$) curve) is determined by volumetric average of the absorption dose and does not strongly depends on type of radiation for the excitation. That means quenching due to high local excitation density of the latent track of heavy charged particles (especially near the Bragg peak energy) does not explicitly affect the relative sensitivity of gamma rays and protons.

## IV. CONCLUSION

Dosimetric characterization was performed for the GafChromic™HD-V2, MD-V3, and EBT3 film with the flatbed scanner readout, which is way more accessible compared to traditional microscope-based densitometers. Our experimental results present OD response functions for those films that cover the high-dose regions up to 100 kGy, where those films are optically saturated. In the high dose region, blue channel is the most sensitive of the three readout color channels. The maximum OD that can be read by the EPSON GT-X980 scanner is around OD 3.0, which limits the measurable dose up to 1 kGy for EBT3, 10 kGy for MD-V3, and 100 kGy for HD-V2. The OD response functions of those films are primarily determined by volmetric average of the absorbed dose and therefore universal for all types of radiation sources (photons, electrons, protons *etc.*). The presented calibration scheme allows to obtain a wide range of exposure response with limited number of trials and could be an effective way of on-site calibration.

## V. ACKNOWLEDGEMENT

The authors gratefully acknowledge the technical support of S. Tojo, Y. Okada, N. Aoi and other staffs in ISIR and RCNP in Osaka University. This work was performed under the auspices of the Collaboration Research Program between the National Institute for Fusion Science and the Institute of Laser Engineering (No. 2018NIFS12KUGK057, 2019NIFS12KUGK057, 2020NIFS12KUGK057), and the Japanese Ministry of Education, Science, Sports, and Culture through Grants-in-Aid (KAKENHI) (Grant No. 19K14681, 19H01876).

## VI. DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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