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Contribution of X-ray tomography for primary references and their transfer for ionizing radiation doses.



Introduction

Until now, X-ray tomography is used sometime in addition to X-ray radiography to check the final assembly of detectors. Advances in X-ray tomography suggest that a direct determination of key parameters after mounting is possible. Tests were carried out with the means and the personnel of the NIKON company on prototypes of ionization chamber in order to highlight the interest and the limits of this method.

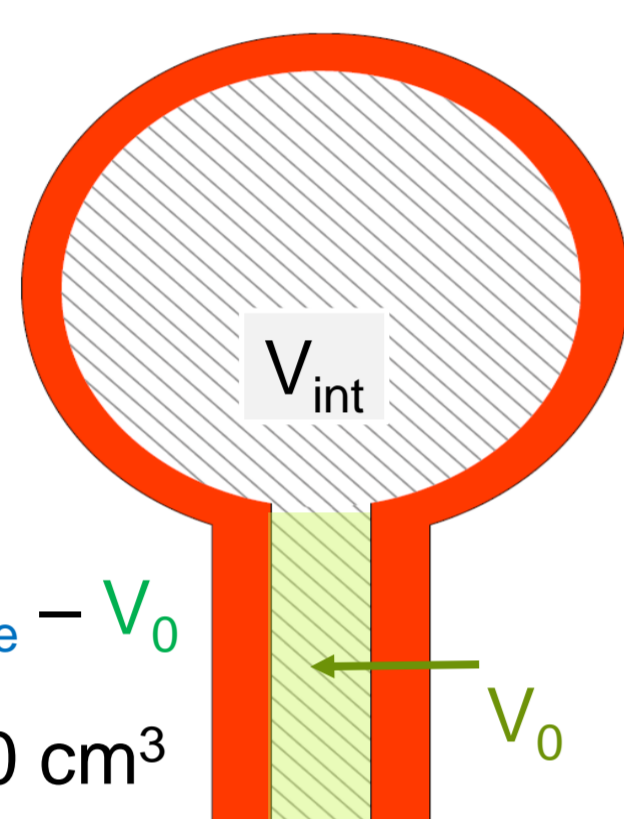
Introduction (air kerma primary measurements)

The effective charge collection volume, V , created inside the primary ionization chamber is a key parameter for the traceability of air kerma national references to the S.I.

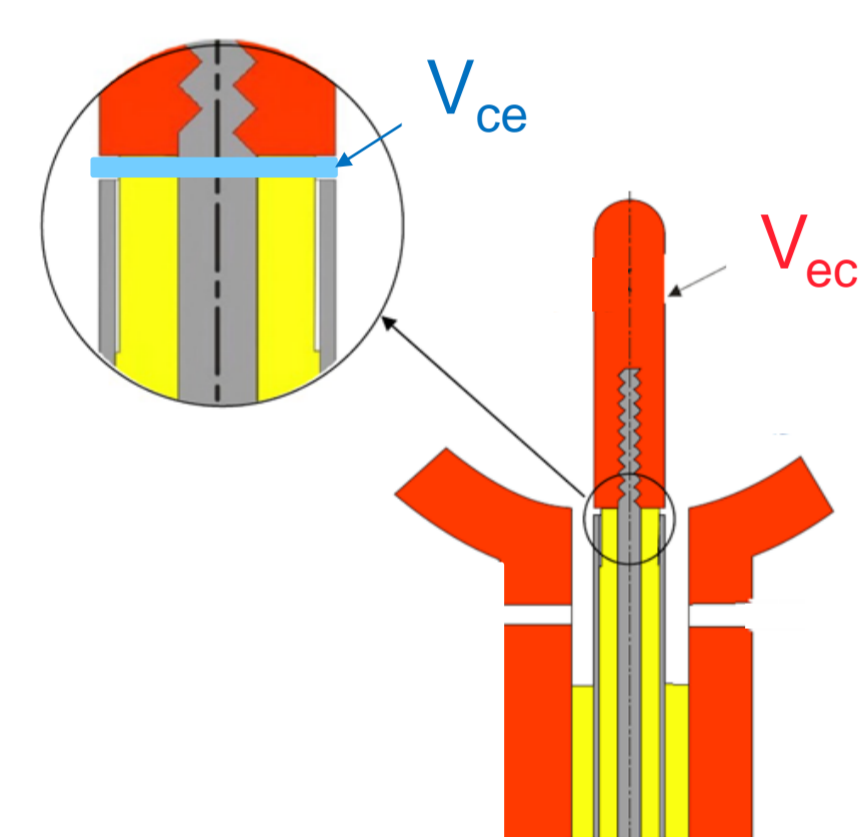
$$K_{air} = \frac{(Q w/e)}{(V \rho_{air}) \sum_i k_i} \quad \begin{array}{l} Q \text{ collected charge ; } w/e \text{ average energy to create an ion pair in air ; } V \text{ effective charge collection volume} \\ \rho_{air} \text{ air density ; } k_i \text{ correction factors for materials composition and experimental conditions} \end{array}$$

The primary ionization chambers (LNHB's design) are made of graphite (electrodes), metal (guard electrodes and wires) and plastic material for insulator. Until now, V comes from dimensional and volume measurements of the chamber components (electrodes, insulator, shells) before the final assembly.

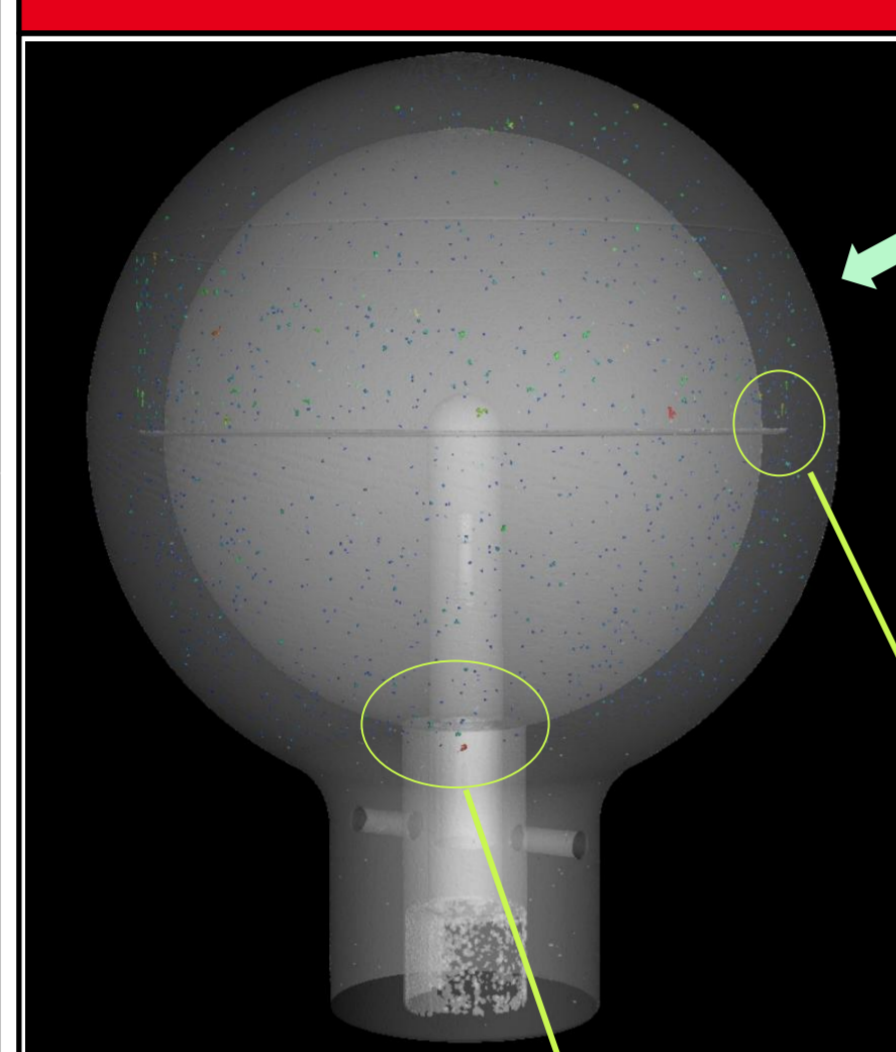
Method based on dimensional and volume measurements



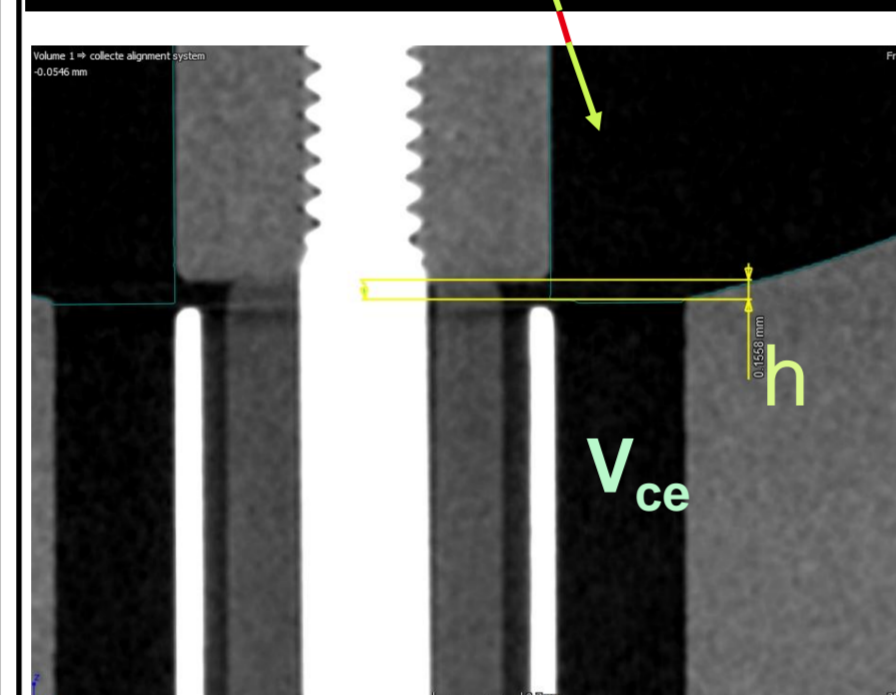
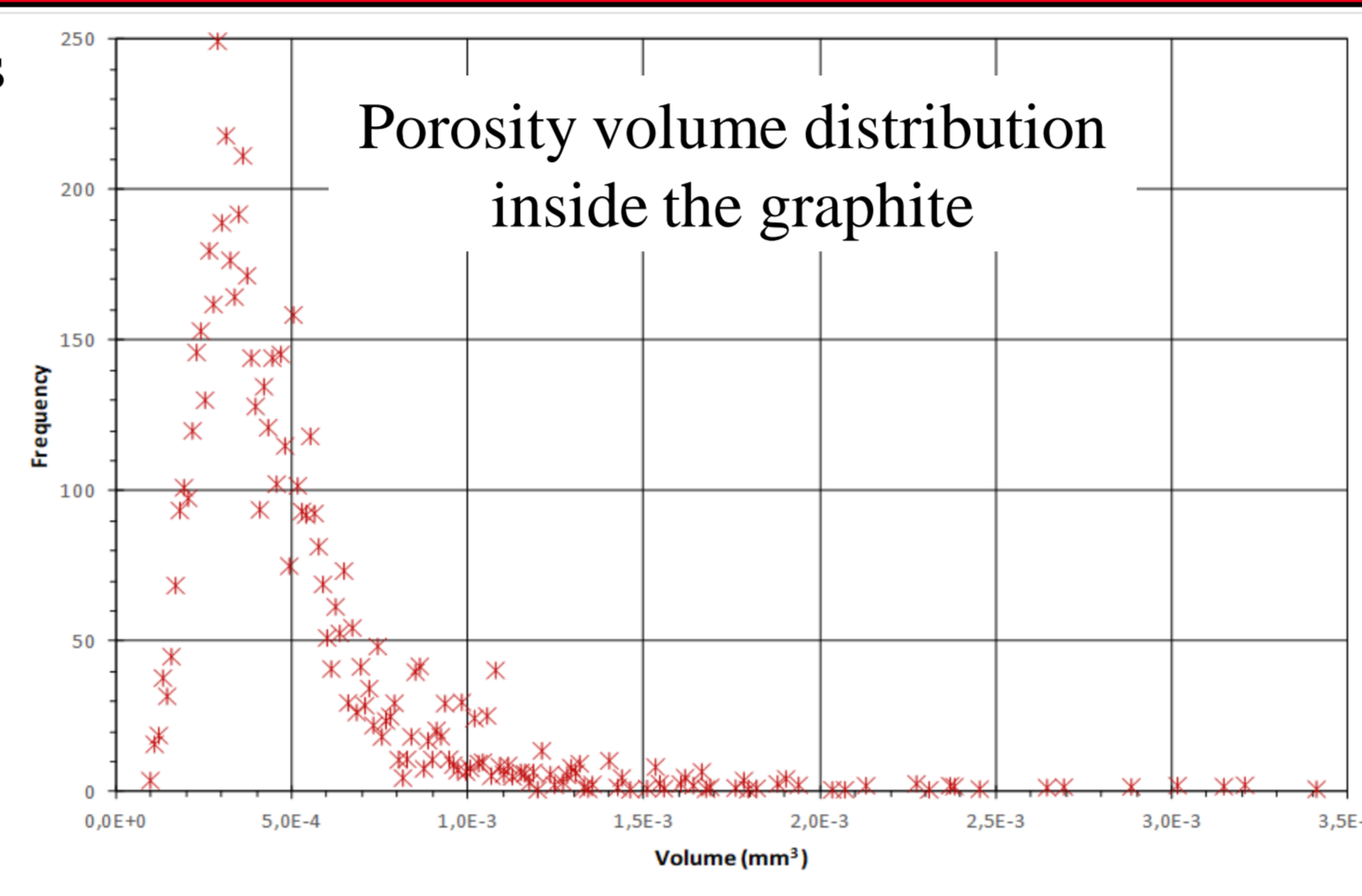
$$V = V_{int} - V_{ec} - V_{ce} - V_0$$



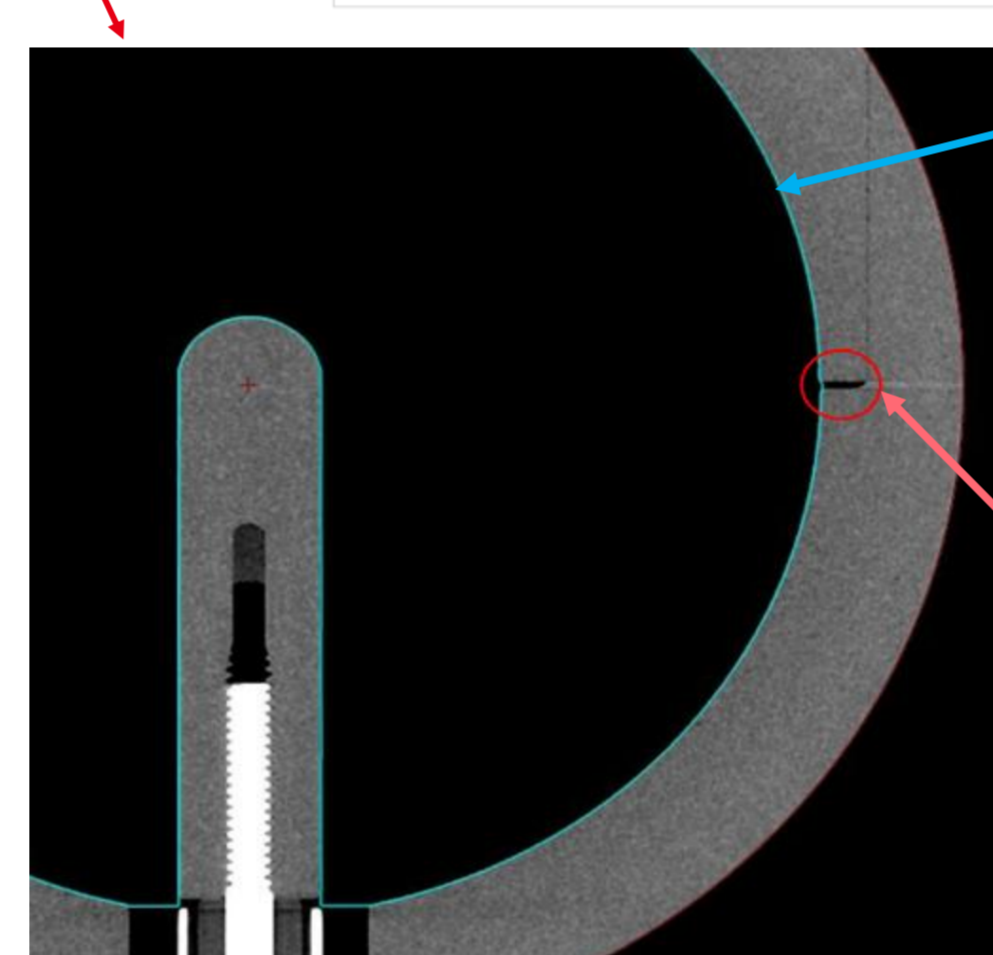
Tomography method



Colored dots are porosity uniformly distributed inside the graphite walls and central electrode



V_{ce} is a little larger than expected $h = 0.156$ mm instead of 0.1 mm, so 0.41 mm³ larger than expected



The blue line surrounds the volume calculated with VGL software. it encompasses 600666527 voxels (7182.533 mm³). A parasitic toric volume (12.573 mm³) is seen at the junction of the upper and lower shells. It might be added because, at least partly, this volume contribute to the effective volume.

Uncertainties are sorted in 3 categories:

The resolution of the images includes the operator (object position, choice of energies), digital and data files sizes, segmentation, display resolution, and resolution of the sensor.

During segmentation, the precision of the interface between two media is the fifth of the voxel side, i.e. $4.6 \mu\text{m}$.

The standard uncertainty associated with the tomograph calibration is due to the test object uncertainty ($3 \mu\text{m}$), to which one needs to add the above resolution during calibration, i.e. $(3 + 4.6 / 2\sqrt{3}) \mu\text{m}$.

An empirical formula, $u = 6 + L / 50 \mu\text{m}$, give the standard uncertainty on the acquisition parameters; L is the dimension in mm of the calibration object (100 mm).

$$u_c = \sqrt{1.32^2 + 4.32^2 + \left(6 + L/50\right)^2} = 9.2 \mu\text{m}$$

the following expression allows to calculate the volume evaluated by the tomograph, V_{Tomog} , according to the inner radius of the shells, R_s , and of the internal electrode, R_c .

$$u(V_{Tomog}) = \sqrt{\left[\left(\frac{\partial V_{Tomog}}{\partial R_s}\right)^2 + \left(\frac{\partial V_{Tomog}}{\partial R_c}\right)^2 + \left(\frac{\partial V_{Tomog}}{\partial h}\right)^2\right] u_c^2}$$

$$V_{tomog} = (V_{int} - V_0) - V_{ec} - V_{ce} = \frac{4}{3}\pi R_s^3 - \pi h R_c^2 - \frac{4}{6}\pi R_c^3 = 7195,1 \text{ mm}^3 \quad u(V_{Tomog}) = \sqrt{[(4\pi R_s^2)^2 + (\pi R_c^2)^2 + (2\pi h R_c)^2 + (2\pi R_c^2)^2] u_c^2} = 20,7 \text{ mm}^3 (0.29\%)$$

The uncertainty associated with X-ray tomography (0.29%) is 10 time higher than the one associated with the former method (0.029%), the difference between V and V_{tomog} being 0.29%, the results would be compatible at $k=1$. Even if today, one still relies on dimensional methods, the significant progress made in recent years allows hoping for even better performance in the future.

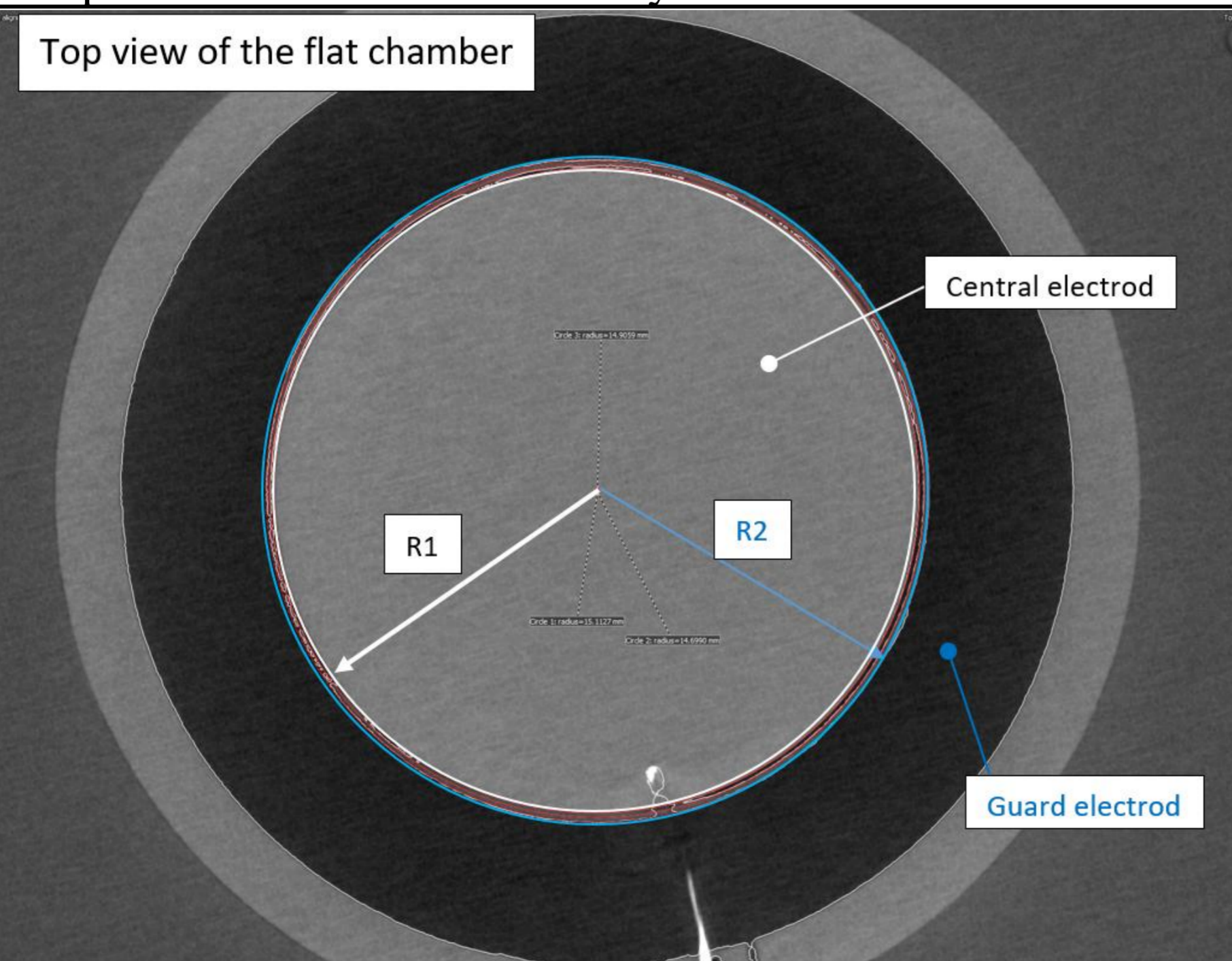
Introduction (Dose Area Product for radio-therapy)

Today, the traceability to the S.I. of "doses" delivered to the patient's tumor in radiotherapy is based on the measurement of the absorbed dose at a point in a field of $10 \times 10 \text{ cm}^2$ (IAEA protocol 398). The national reference for this quantity is obtained by means of calorimeters and the transfer to hospitals is done using ionization chambers. In both cases the detector is small compared to the size of the radiation field.

Clinical practice has evolved in recent years towards a drastic reduction in radiation field sizes in order to conform the irradiated volume as closely as possible to that of the tumor while sparing surrounding healthy tissue. Thus, the field size becomes in a majority of cases smaller than to the cross-sections of the calorimeter and the transfer ionization chamber. To overcome this problem, the current approach is to correct the measurement (IAEA 483), which drastically increases the uncertainty associated with the amount of radiation delivered during the treatment.

A new paradigm is explored by the CEA LIST LNHB, by replacing the absorbed dose at a point by an integrated absorbed dose measurement over a given surface. This new quantity is called the dose-area product, it is defined using graphite calorimeter (primary detectors) and transferred using flat ionization chamber whose detection areas are larger than the field size. Thus, the determination of the effective collection area becomes the critical parameter for the traceability of doses delivered in radiotherapy.

The ionization chambers designed and manufactured by CEA LIST LNHB are flat cylinders, the value of the effective collection area depends on the machining of the graphite pieces and their assembly; the radius of this area, R , is set at mid-distance of the radii of the central electrode (R_1) and the guard electrode (R_2).



The uncertainty on the radii, based on the machining tolerance ($\pm 50 \mu\text{m}$), is $u(R) = 0.05 / 2 / \sqrt{3} = 0.015 \text{ mm}$

The combined uncertainty, u_c , of the tomographic measurements is computed as it is for the above example, in the present case the voxel side is $71 \mu\text{m}$.

$$u_c = \sqrt{4,1^2 + 7,1^2 + \left(6 + L/50\right)^2} = 11.5 \mu\text{m}$$

$$S_{Tomog} = \pi R^2 = \pi \left[\frac{R_1 + R_2}{2}\right]^2 = \frac{\pi}{4} (R_1^2 + R_2^2 + 2R_1 \cdot R_2)$$

$$u(S_{Tomog}) = \sqrt{\left[\left(\frac{\partial S_{Tomog}}{\partial R_1}\right)^2 + \left(\frac{\partial S_{Tomog}}{\partial R_2}\right)^2\right] u_c^2} \quad u(S_{Tomog}) = \frac{\pi}{\sqrt{2}} (R_1 + R_2) u_c$$

Based on the machining tolerance $u(S_{Tomog}) = 0.14\%$; based on X-ray Tomography $u(S_{Tomog}) = 0.11\%$

The difference between the nominal radius value of R (15 mm) and the one obtained by tomography (14.92 mm) leads to a deviation on the effective collection area of 0.5%. The standard uncertainties based on the machining tolerances and on the tomographic measurements are similar: 0.14% and 0.11% respectively. The difference in area values is therefore significant. The evaluation by X-ray tomography being carried out after the final assembly of the detector, this last value is retained especially since during the assembly mechanical adjustments had to be made.

Conclusions & perspectives

In both cases studied (surface and volume) significant differences are found for the values of the parameters calculated according to the usual methods and the X-ray tomography. While in the case of the volume the analysis leads to favor the classical measurements, in the case of the surface it is the opposite. The uncertainty analysis also leads to different conclusions depending on the case. Thus, for the evaluation of the volume the traditional techniques are much more precise whereas for the measurement of surface the results in terms of uncertainties are equivalent but with the advantage of an analysis in situ. These results were made possible thanks to the very good quality of the images acquired by NIKON which allow a precise analysis after assembly.