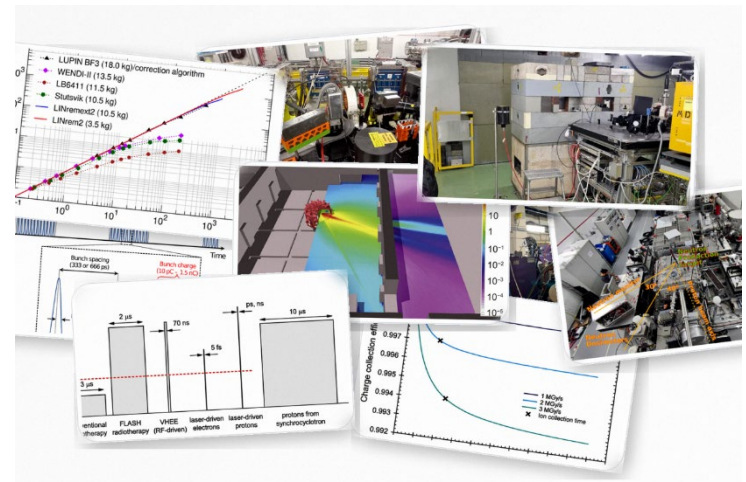


**EURADOS WG11 - Webinars “Pulsed radiation fields:
Methods of production and Dose measurements”**

Ionization Chambers in (Ultra) High Dose per Pulse conditions

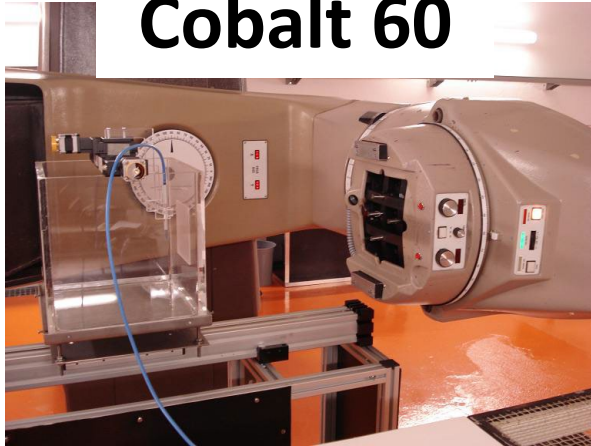
**Faustino Gómez & Jose Paz-Martin
University of Santiago (Spain)**

EURADOS →



The challenge

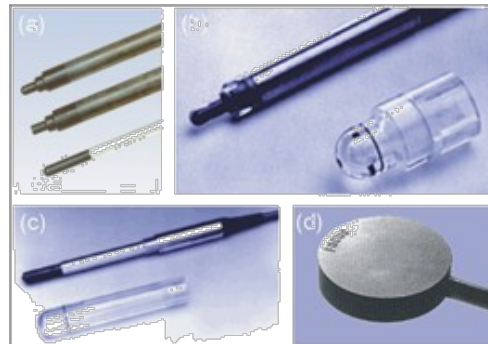
Cobalt 60



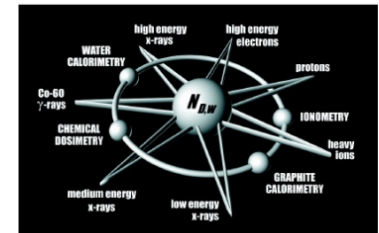
- Ionization chambers have been the gold standard for dosimetry in the last century.
- Current CoP take these detectors as the fundamental secondary standards for dosimetry traceability (i.e. TG51 or TRS398).
- Essentially this talk covers UHDP electron beams and basically air ionization chambers.

IAEA TRS-398

Medical linac



*Absorbed Dose Determination in
External Beam Radiotherapy:
An International Code of Practice for Dosimetry
based on Standards of Absorbed Dose to Water*



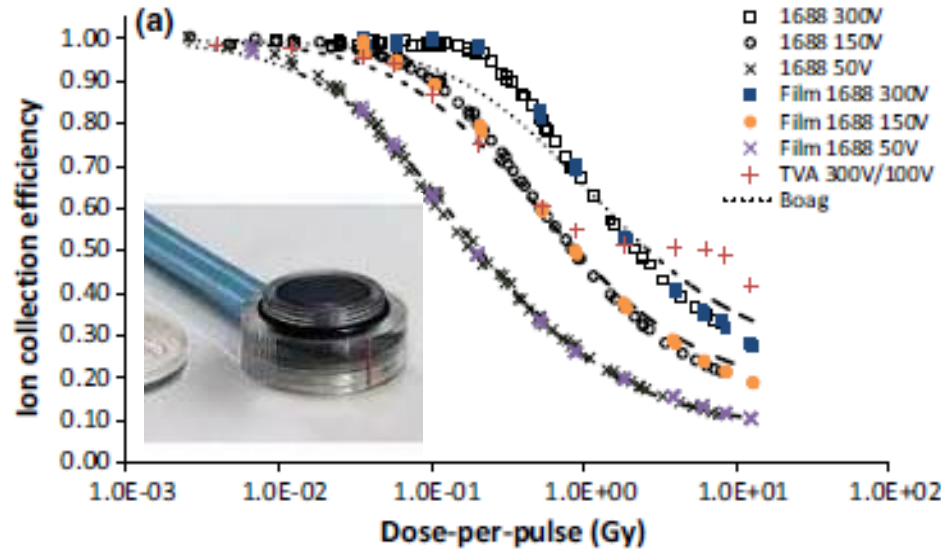
Pedro Andreu, Dosimetry and Medical Radiation Physics Section, IAEA
David T. Burns, Bureau International des Poids et Mesures (BIPM)
Klaus Hohfeld, Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
M. Saif-ud-Din, Thomas Jefferson University, Philadelphia, USA
Masahiko Kashi, National Institute of Radiological Sciences (NIRS), Chiba, Japan
Fedeo Laitano, Ente per le Nuove Tecnologie, l'Energia e l'Ambiente (ENEA), Rome, Italy
Vere Smyth, National Radiation Laboratory (NRL), Christchurch, New Zealand
Stefan Vynnyck, Catholic University of Louvain (UCL), Brussels, Belgium

PUBLISHED BY THE IAEA ON BEHALF OF IAEA, WHO, PAHO, AND ESTRO



INTERNATIONAL ATOMIC ENERGY AGENCY **IAEA**
05 June 2006 (V.12)

The challenge



Recent developments of ultra-high dose per pulse (UHDP) beams have shown that standard ionization chambers may exhibit important recombination corrections.

For example, FLASH electron linacs can produce an instantaneous dose rate of several MGy/s.

Advanced Markus chamber (gap 1 mm). (K. Petersson et al.)

Boag formalism is unable to reproduce the Charge Collection Efficiency (CCE) (denoted here as f).

K. Petersson et al. Med Phys; 44(3):1157-1167 (2017)

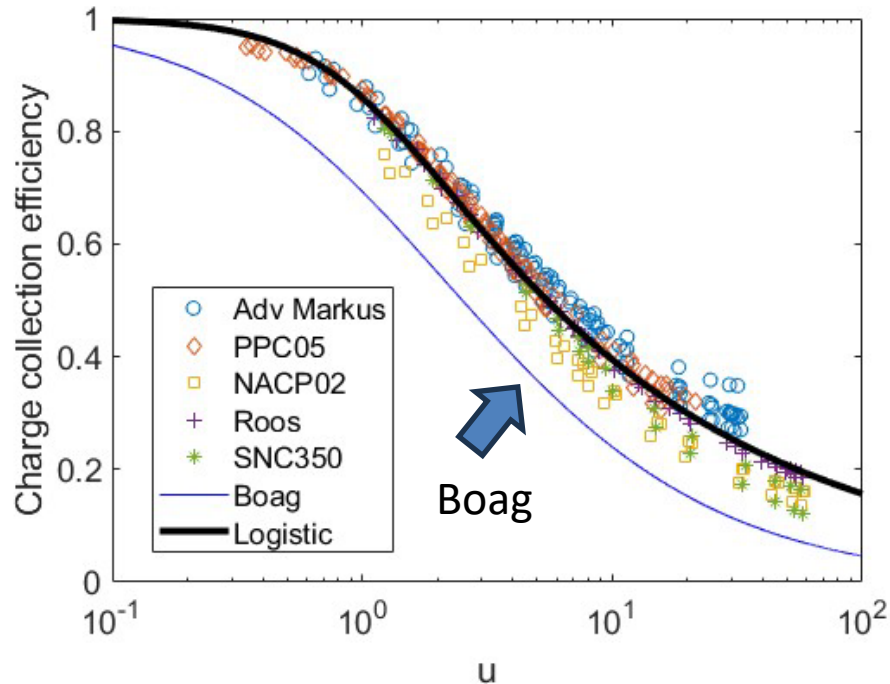
McManus, M., Romano, F., Lee, N.D. et al. Sci Rep **10**, 9089 (2020)

Rafael Kranzer et al. Med Phys; 48(2): 819-830 (2020)

$$f = (k_s)^{-1} = \frac{M_Q N_{D,w,Q_0} k_{Q,Q_0} k_{PT} k_{pol} k_{elec}}{D_{w,Q}}$$

M_Q	chamber readout
N_{D,w,Q_0}	calibration coefficient at ref. beam
k_{PT}	correction for air mass density
k_{Q,Q_0}	beam quality correction factor
k_{pol}	polarity correction factor
k_{elec}	electrometer correction factor

The challenge



Advanced Markus, PPC05, NACP02, Roos and SNC350 measurements in Ultra High Dose per Pulse 20 MeV electron beam at PTB. Data from nominal electric field around 225 V/mm (*). Dose per pulse from 0.1 Gy up to 6 Gy and pulse duration 2.5 μ s. Continuous line for logistic function fit ($a = 1.84$; $b = 0.22$).

Other phenomenological models, like the logistic model, are used to describe the chamber behavior.

$$f_{log} = \frac{1}{\left[1 + \left(\frac{D_p}{U} g\right)^a\right]^b} \approx \frac{1}{[1 + u^a]^b}$$

$$f_{Boag} = \frac{\log(1 + u)}{u} \quad u = \alpha \frac{n_0}{(\mu_+ + \mu_-)} \frac{1}{U} g$$

α ion recombination coefficient ($\sim 1.25 \cdot 10^{-12} \text{ m}^3 \text{ s}^{-1}$)
 n_0 charge carriers per unit volume
 g geometrical factor (i.e. d^2 parallel plate chamber)
 μ_+, μ_- average ion mobilities
 U chamber polarization voltage

(*) Alexandra Bourguin *et al* 2022 *Phys. Med. Biol.* **67** 085013

K. Pertersson *et al.* *Med Phys*; 44(3):1157-1167 (2017)

Boag J W 1950 *Br. J. Radiol.* 23 601-11

The challenge

Boag basic formalism does not take into account the existence of free electrons. Boag tried to modify the formalism in 1996 accordingly:

$$f_{Boag} = \frac{\log(1+u)}{u} \quad u = \alpha \frac{n_0}{(\mu_+ + \mu_-)} \frac{1}{U} g$$

$$f' = \frac{1}{u} \log \left[1 + \frac{e^{pu} - 1}{p} \right]$$

$$f'' = p + \frac{1}{u} \log[1 + (1-p)u]$$

$$f''' = \lambda + \frac{1}{u} \log \left[1 + \frac{e^{\lambda(1-\lambda)u} - 1}{\lambda} \right] \quad \lambda = 1 - \sqrt{1-p}$$

Where p stands for the free electron fraction.

$$p = \frac{(1-e^{-\delta})}{\delta}; \quad \delta = \frac{\gamma g}{\mu_e U}$$

α ion recombination coefficient ($\sim 1.25 \cdot 10^{-12} \text{ m}^3 \text{ s}^{-1}$)

n_0 charge carriers per unit volume

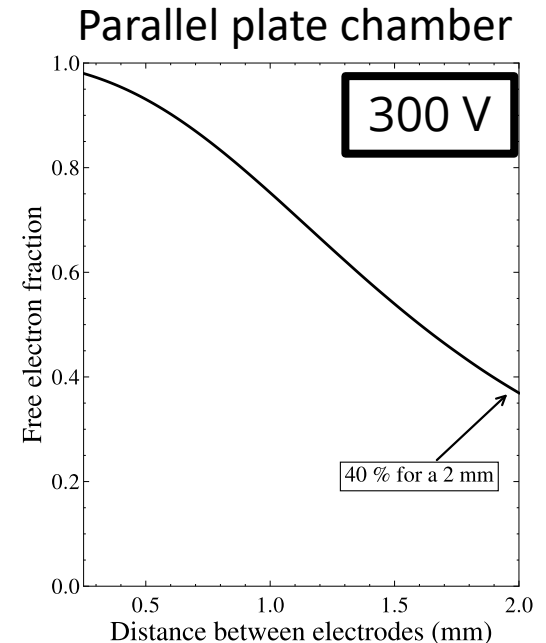
g geometrical factor (i.e. d^2 parallel plate chamber)

μ_+, μ_- average ion mobilities

μ_e electron mobility

γ electron attachment rate (inverse of e lifetime)

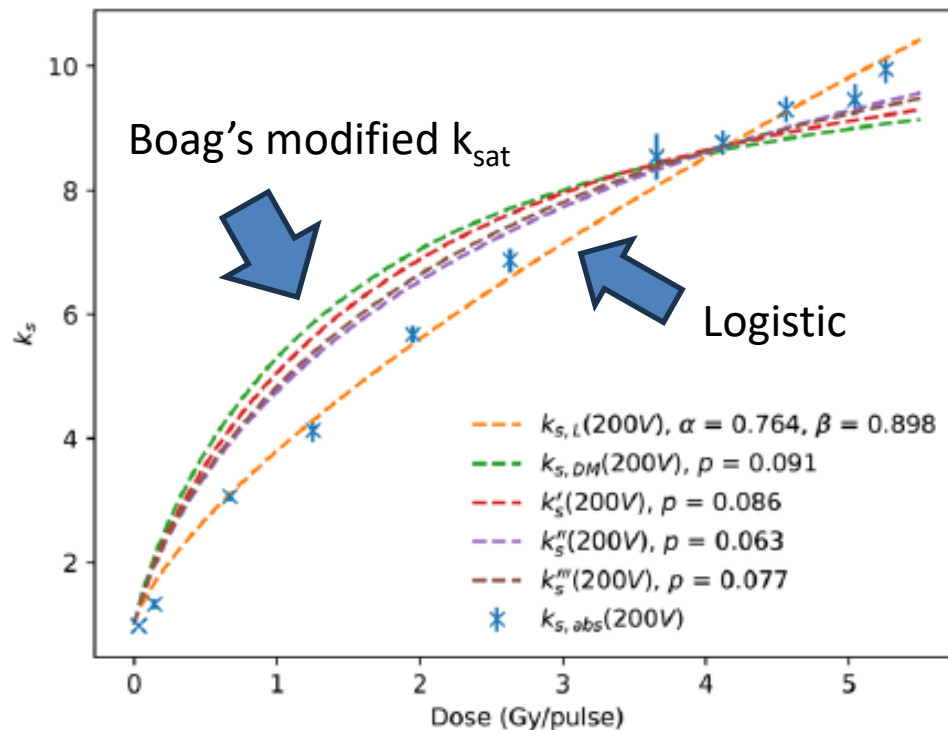
U chamber polarization voltage



J W Boag, E Hochhauser, O A Balk The effect of free-electron collection on the recombination correction to ionization measurements of pulsed radiation Phys. Med. Biol. 41 885 (1996).

The challenge

Even Boag's modified formalism have substantial problems to account for the actual recombination effect in UHPD conditions



Roos chamber saturation factor obtained in CLEAR (CERN). Saturation factor was evaluated against a graphite calorimeter (NPL).

The problem

The basic transport problem can be seen as a coupled system of partial differential equations that describe the charge transport of positive and negative ions plus free electrons. For a parallel plate chamber this gives an equivalent one-dimensional problem:

$$\frac{\partial}{\partial t} n_+(x, t) = N(x, t) - \alpha n_+(x, t) n_-(x, t) - \theta n_+(x, t) n_e(x, t) - \frac{\partial}{\partial x} \{E(x, t) \mu_+ n_+(x, t)\}$$

$$\frac{\partial}{\partial t} n_-(x, t) = \gamma n_e(x, t) - \alpha n_+(x, t) n_-(x, t) + \frac{\partial}{\partial x} \{E(x, t) \mu_- n_-(x, t)\}$$

$$\frac{\partial}{\partial t} n_e(x, t) = N(x, t) - \gamma n_e(x, t) - \theta n_+(x, t) n_e(x, t) + \frac{\partial}{\partial x} \{E(x, t) \mu_e n_e(x, t)\}$$

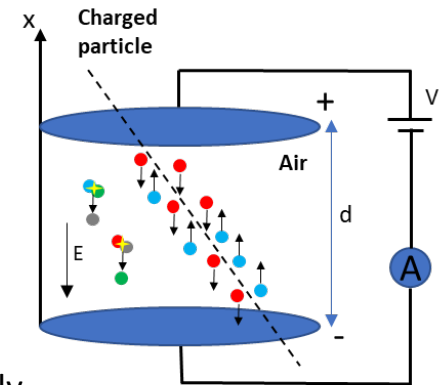
$n_+(x, t)$, $n_-(x, t)$, $n_e(x, t)$ densities of positive and negative ions and electrons respectively.

$N(x, t)$ number of electron-ion pairs released in the chamber per unit time and volumen.

α ion-ion recombination coefficient , θ electron-ion recombination coefficient

μ_+ , μ_- , μ_e mobilities of ions and electrons

γ electron attachment rate



- Positive charged ion
- Electron
- Negative charged ion
- Neutral molecule

New approaches

Recently **Fenwick and Kumar** have obtained an analytical solution to the problem with free electron transport (here for parallel plate chambers (PPIC)):

$$f = \frac{1}{u} \log[1 + u h(u, \delta)]; \quad h(u, \delta) = \frac{1}{\delta} e^{u/\delta} \left[E_1 \left(\frac{u}{\delta} e^{-\delta} \right) - E_1 \left(\frac{u}{\delta} \right) \right]$$

where E_1 stands for the exponential integral function:

$$E_1(x) = \int_x^\infty \frac{e^{-t}}{t} dt; \quad 0 < x \qquad \delta = \frac{\gamma g}{\mu_e U}; \quad u = \alpha \frac{n_0}{(\mu_+ + \mu_-)} \frac{1}{U} g$$

Unfortunately, this solution is computed for the nominal electric field $E(x, t) = \frac{U}{d}$ and constant mobilities. **No screening of the electric field is considered** since the solution is non-linear in that situation. **Radiation pulse delivery is instantaneous.**

New approaches

The introduction of the free electron fraction in the transport equations gives some new results for the evaluation of the saturation factor (even at low dose per pulse!).

The expansion of Boag's formalism gives:

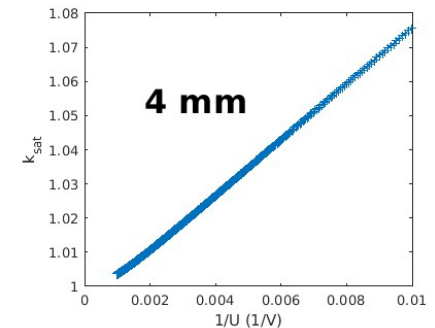
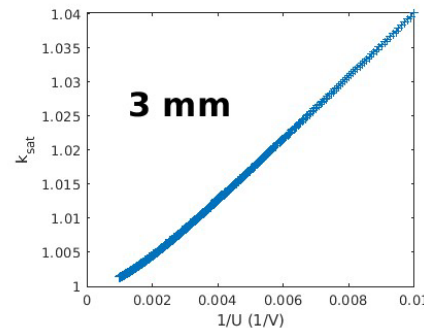
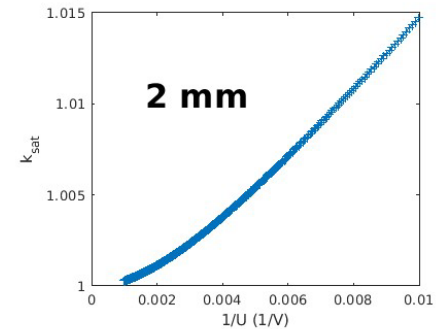
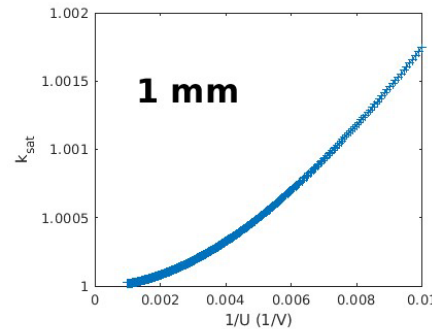
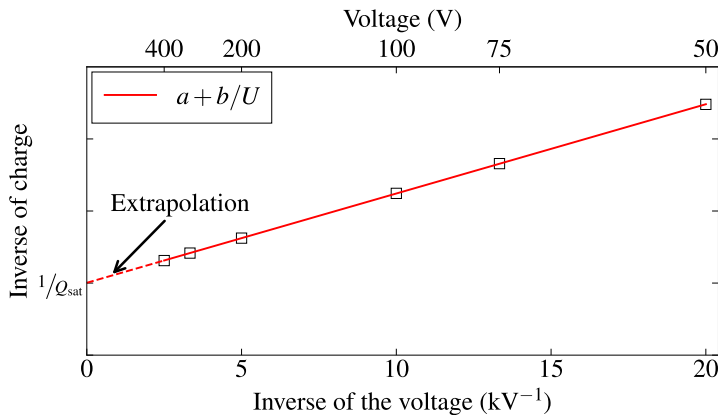
$$\frac{1}{Q} = \frac{1}{Q_{sat}} \left\{ 1 + \frac{u}{2} - \frac{u^2}{3} + \dots \right\} \approx \frac{1}{Q_{sat}} \left\{ 1 + \frac{u}{2} \right\}$$

Fenwick and Kumar model for a PPIC.



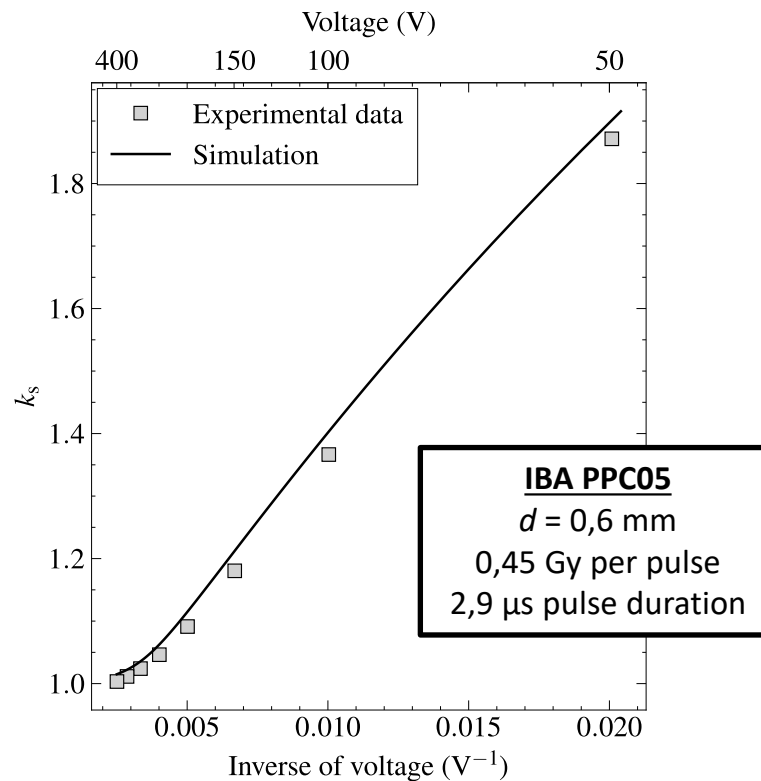
1 mGy

This has justified the use of the “so called” Jaffe diagrams:



New approaches

Whenever we compare with data of some small electrode distance chamber (i.e. PPC05 with 0.6 mm) we find that, even for low dose per pulse, there is a deviation from the linear expected behavior in the Jaffe diagram:



Numerical Method for Recombination (NMR)

We may solve numerically the problem associated to recombination, by using state of the art parametrizations of the fundamental physical processes:

Considering symmetry along the transverse dimensions (y and z), the system of differential equations can be written as a one-dimensional effective problem along the coordinate (x) perpendicular to the electrode planes,

$$\begin{aligned}
 \frac{\partial n_+(x, t)}{\partial t} &= I(x, t) - \alpha n_+(x, t) n_-(x, t) - \theta n_+(x, t) n_e(x, t) + g(x, t) v_e(x, t) n_e(x, t) + \\
 &\quad + \frac{\partial}{\partial x} \left[D_+(x, t) \frac{\partial n_+(x, t)}{\partial x} \right] - \frac{\partial}{\partial x} [E(x, t) \mu_+ n_+(x, t)], \\
 \frac{\partial n_-(x, t)}{\partial t} &= \gamma n_e(x, t) - \alpha n_+(x, t) n_-(x, t) + \\
 &\quad + \frac{\partial}{\partial x} \left[D_-(x, t) \frac{\partial n_-(x, t)}{\partial x} \right] + \frac{\partial}{\partial x} [E(x, t) \mu_- n_-(x, t)], \\
 \frac{\partial n_e(x, t)}{\partial t} &= I(x, t) - \gamma n_e(x, t) - \theta n_+(x, t) n_e(x, t) + g(x, t) v_e(x, t) n_e(x, t) + \\
 &\quad + \frac{\partial}{\partial x} \left[D_e(x, t) \frac{\partial n_e(x, t)}{\partial x} \right] + \frac{\partial}{\partial x} [v_e(x, t) n_e(x, t)],
 \end{aligned} \tag{1}$$

Symbol	Unit	Definition
n_+, n_-, n_e	m^{-3}	Positive ion, negative ion and electron density, respectively
I	$\text{m}^{-3} \text{s}^{-1}$	Charge liberated per unit time and volume that escapes initial recombination
α	$\text{m}^3 \text{s}^{-1}$	Volume recombination coefficient between ions
θ	$\text{m}^3 \text{s}^{-1}$	Volume recombination coefficient between electron and positive ions
g	m^{-1}	First Townsend coefficient
γ	s^{-1}	Electron attachment coefficient
μ_+, μ_-	$\text{m}^2 \text{V}^{-1} \text{s}^{-1}$	Positive and negative ion mobility, respectively
v_e	$\text{m} \text{s}^{-1}$	Electron drift velocity
D_+, D_-, D_e	$\text{m}^2 \text{s}^{-1}$	Positive, negative ion and electron diffusion coefficient
E	$\text{V} \text{m}^{-1}$	Electric field across the ionization chamber
V	V	Voltage applied to the ionization chamber
d	m	Distance between electrodes
e	C	Elementary charge
ϵ	$\text{C} \text{V}^{-1} \text{m}^{-1}$	Air permittivity

The recombination problem

Mathematical description of charge carrier transport

The electric field dependence across the chamber can be computed solving the one dimensional *Poisson* equation:

$$\frac{\partial E(x, t)}{\partial z} = \frac{e}{\epsilon} [n_+(x, t) - n_-(x, t) - n_e(x, t)] , \quad (2)$$

If we assume that the behaviour of high voltage supply do not disturb the ideal potential between the electrodes separated by the distance d , then

$$\int_0^d E(x, t) dz = V \quad \forall t \quad (3)$$

The instantaneous current produced at any time may be calculated using the Shockley-Ramo theorem

$$I_{IC}(t) = \frac{e}{d} \Delta x \sum_{i=0}^N [\mu_+ E(x_i, t) n_+(x_i, t) + \mu_- E(x_i, t) n_-(x_i, t) + v_e(x_i, t) n_e(x_i, t)] . \quad (4)$$

Available in Github:

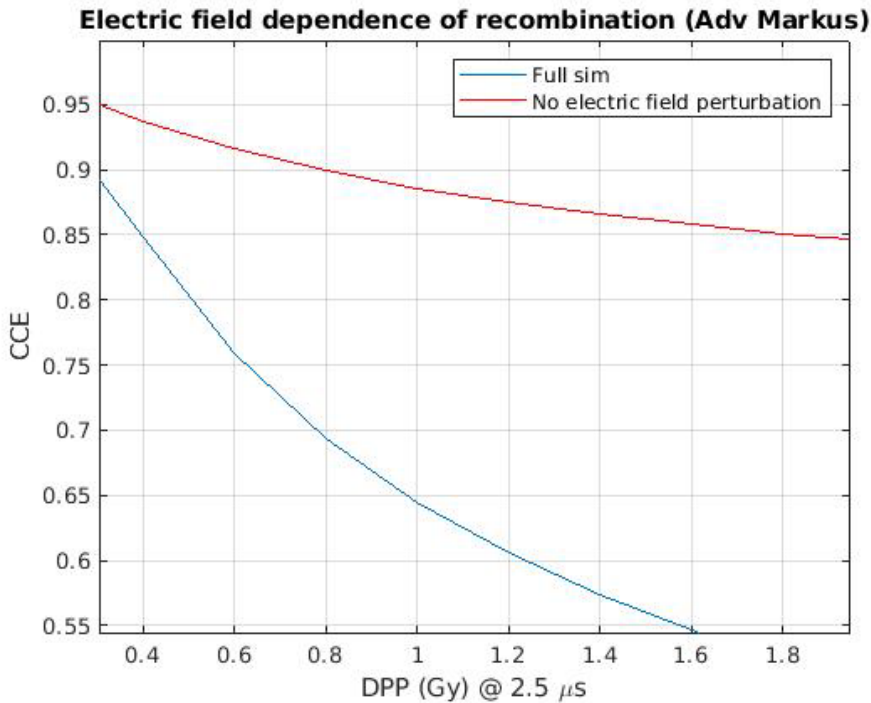
<https://github.com/JPazMartin/PPICSimulation>

<https://github.com/JPazMartin/ICSimulation>

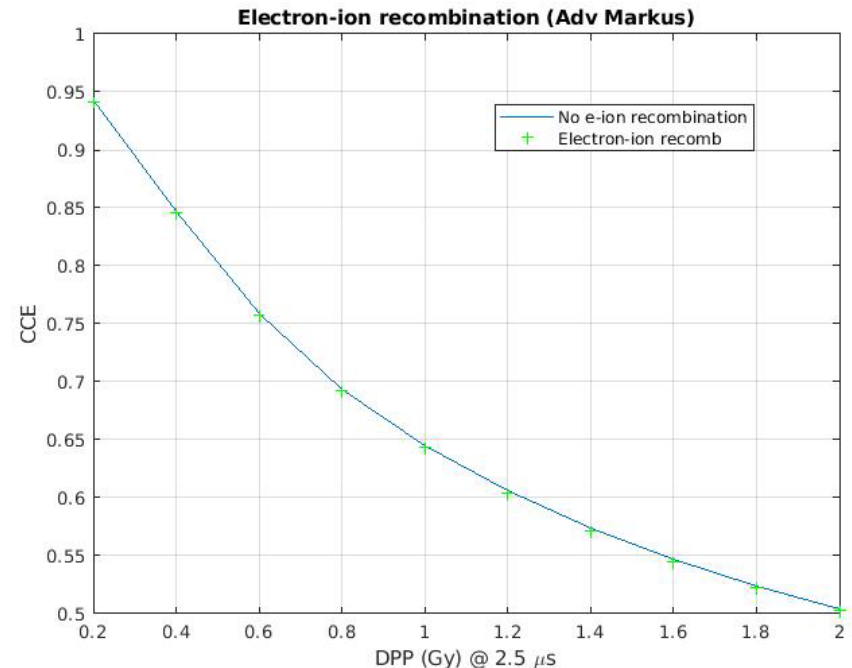
Parallel Plate Chambers (Finite differences)

All chambers (Finite elements)

Electric field screening & electron-ion recombination

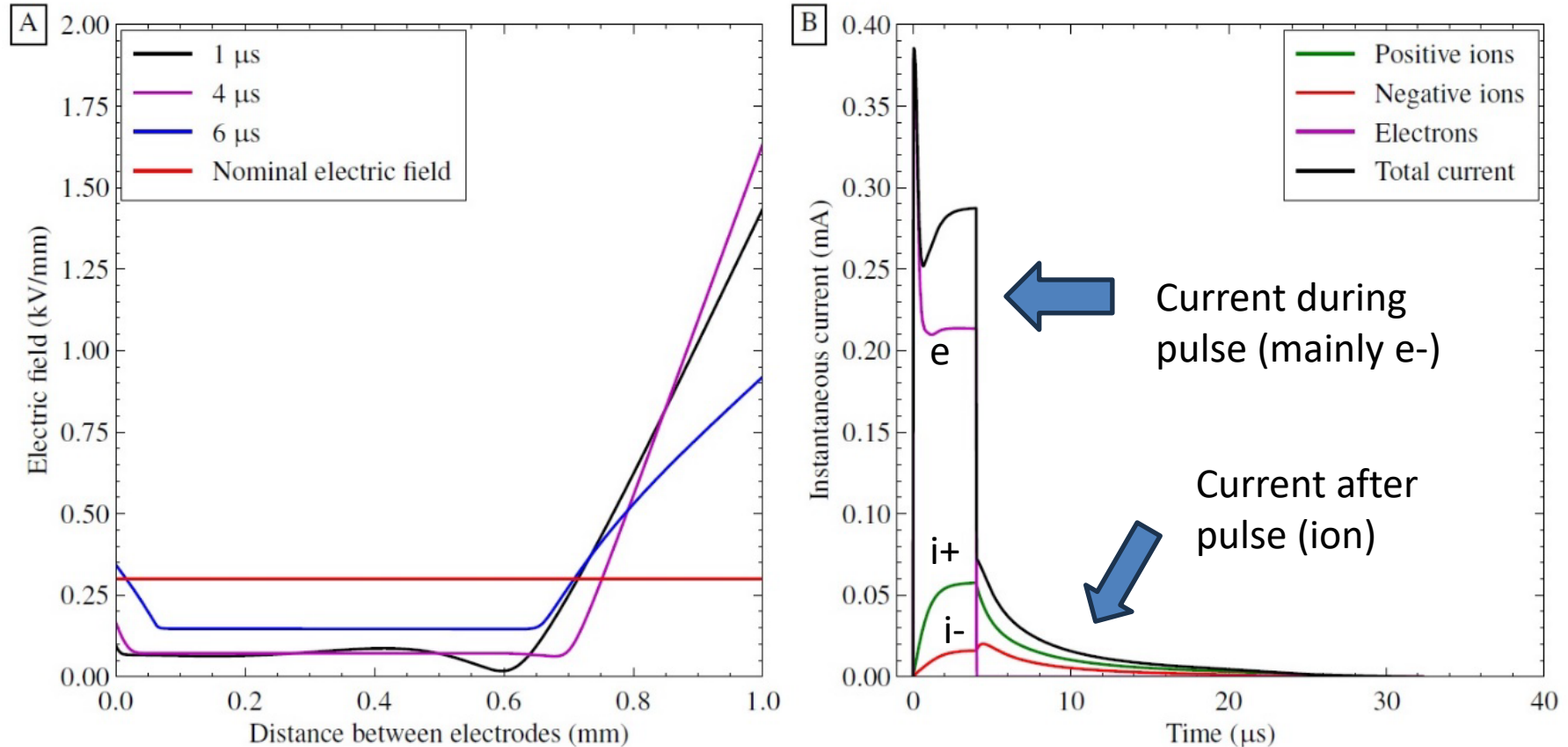


Models without electric field perturbation can not reproduce the problem in an accurate way.



Electron-ion recombination typical contribution to CCE is below 1% ($\theta = 4.45 \times 10^{-12} \text{ m}^3 \text{ s}^{-1}$)

PPIC under Ultra High Dose per Pulse (simulation)



Advanced Markus (1 mm gap) @ 300 V 20 °C and 1013.25 hPa

Dose per pulse 5 Gy. Pulse duration 4 μ s.

- Electric field perturbation for different time (1 μ s, 4 μ s and 6 μ s from pulse start).
- Instantaneous electrical current (electron+positive ion+negative ion)

Free electron fraction

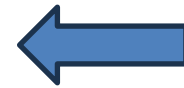
$$FEF_{Boag} = \frac{v_e \tau}{d} \left[1 - \exp \left(-\frac{d}{v_e \tau} \right) \right] = p = \frac{Q_e}{Q_{sat}}$$

$$\lim_{\tau \rightarrow \infty} FEF_{Boag} = 1$$

$$FEF_{Ind} = \frac{v_e \tau}{d} [1 - FEF_{Boag}] = \frac{Q_e^{ind}}{Q_{sat}}$$

$$\lim_{\tau \rightarrow \infty} FEF_{Ind} = 0.5$$

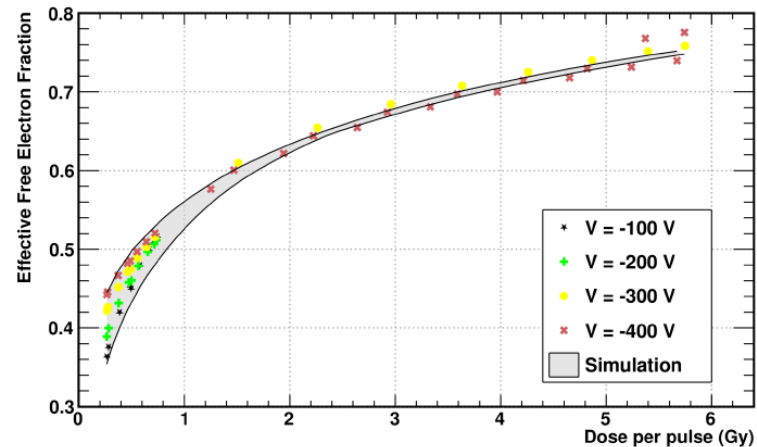
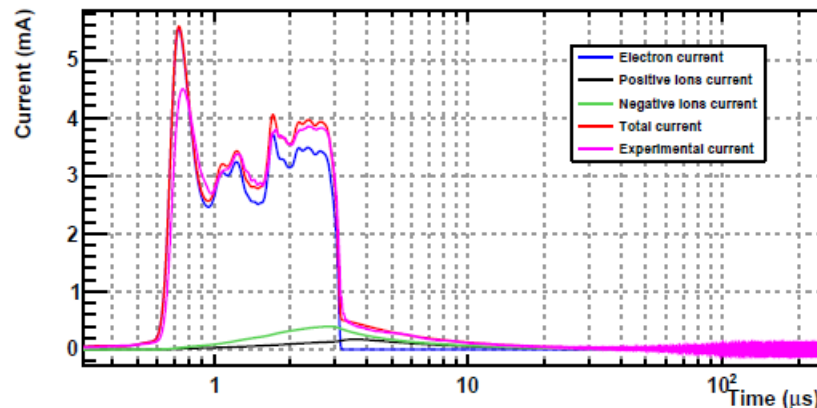
$$FEF'_{Ind} = \frac{Q_e^{ind}}{Q_{coll}} = \frac{Q_{sat}}{Q_{coll}} \frac{Q_e^{ind}}{Q_{sat}} = \frac{FEF_{Ind}}{CCE}$$



**Actually
measurable**

Experimental data (Roos)

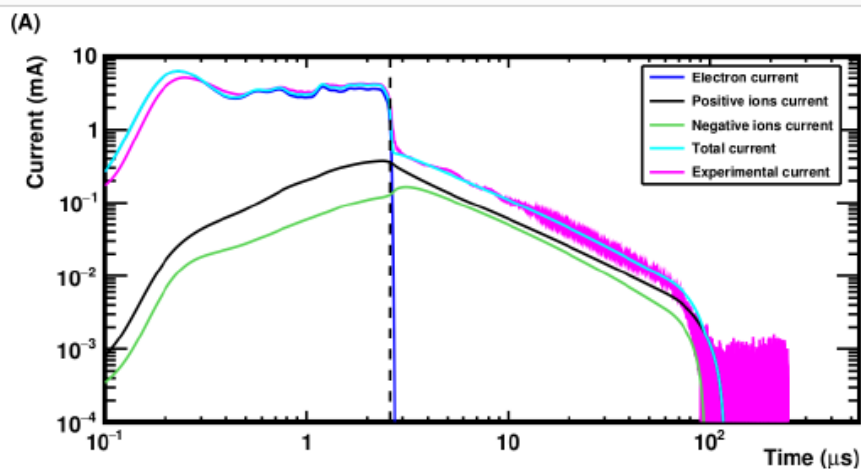
Current vs time 2.5 μ s pulse in 20 MeV electron beam MELAF (PTB) (simulation+measurement).



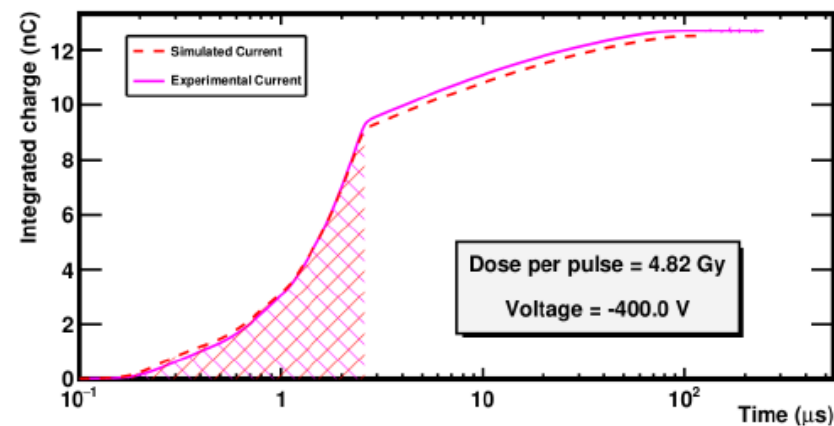
Phys Med. 2022 Oct 28;103:147-156. doi:
10.1016/j.ejmp.2022.10.006.

Simulation vs. data (Roos)

Data from 4.82 Gy per pulse, 2.5 μs pulse duration of 20 MeV electron beam MELAF (PTB). Chamber bias -400 V.



Experimental vs simulated instantaneous electrical current.

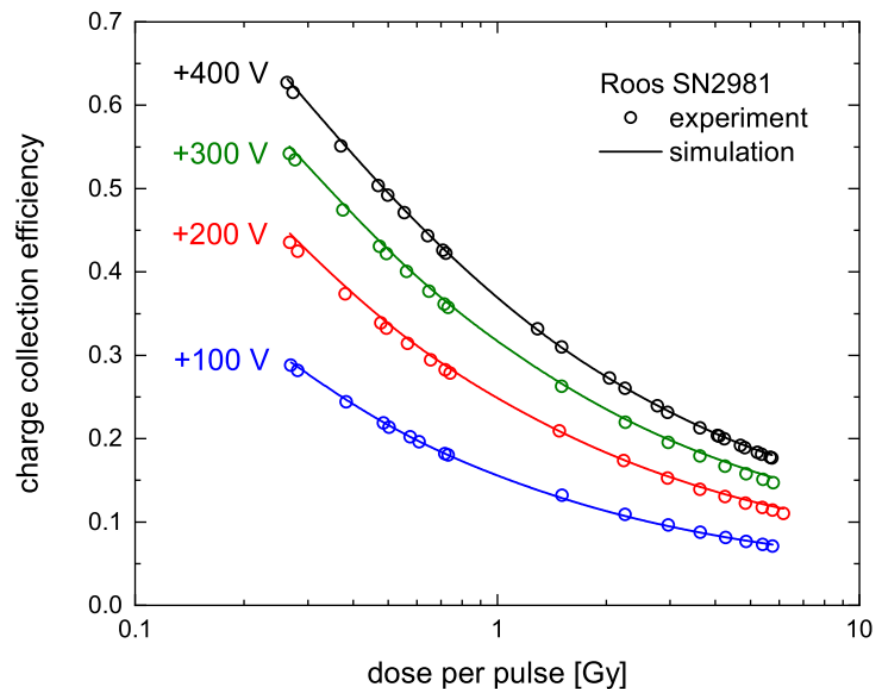
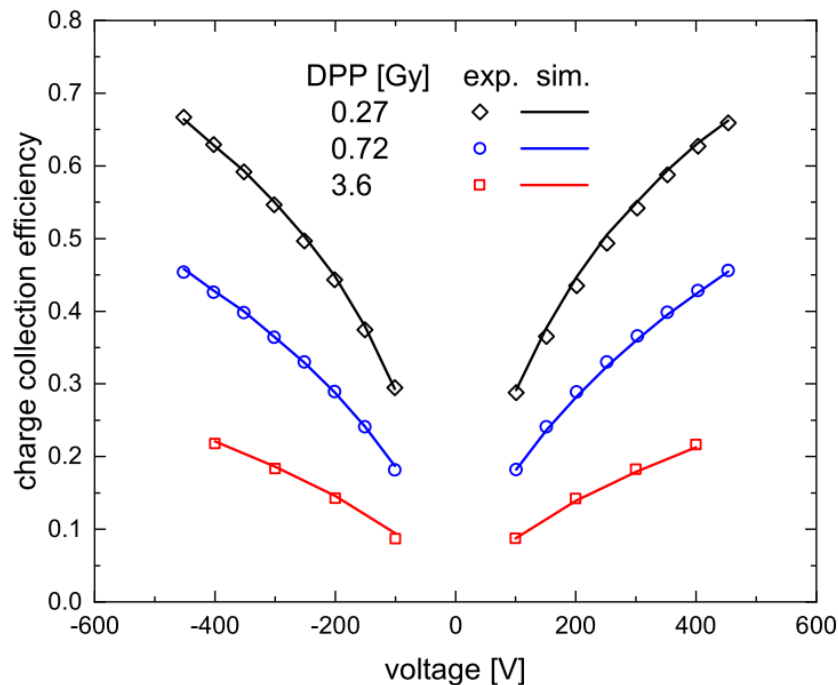


Experimental vs simulated integrated electrical charge.

Instantaneous dose rate was approximated from ICT readout.

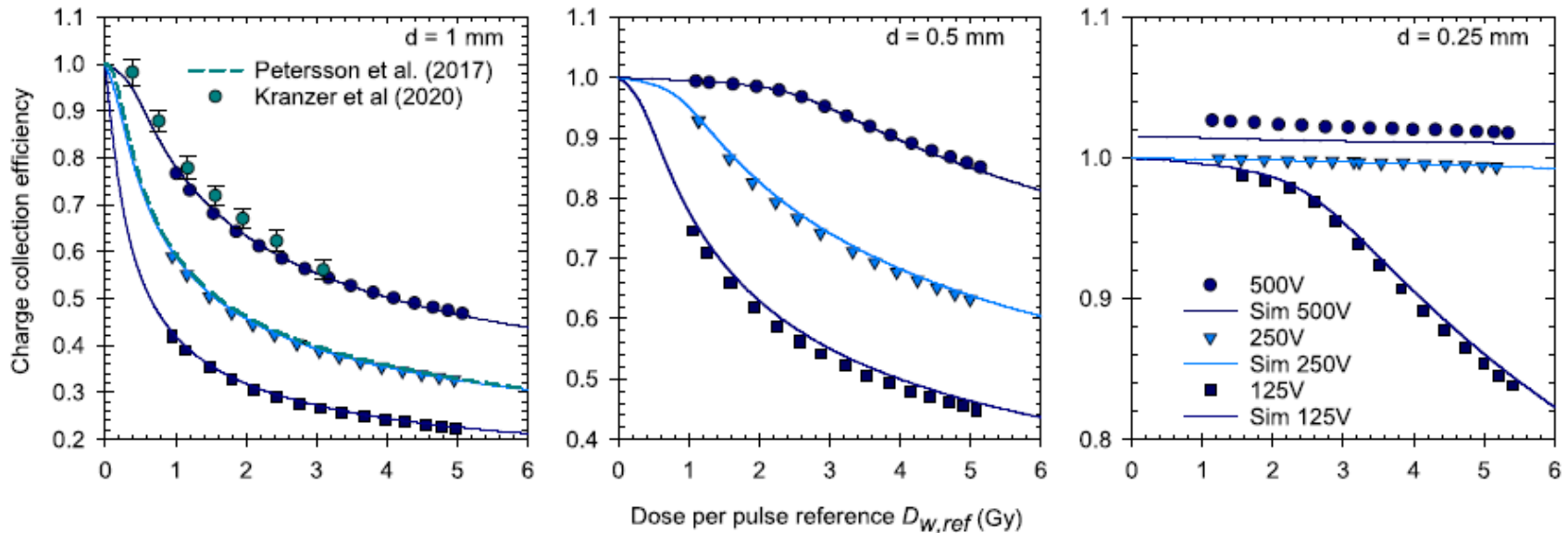
Simulation vs. data (Roos)

2.5 μ s pulse duration of 20 MeV electron beam MELAF (PTB)



Numerical simulation approach does not only yield CCE values, but also instantaneous current can be obtained and compared with experimental data

The importance of electrode distance

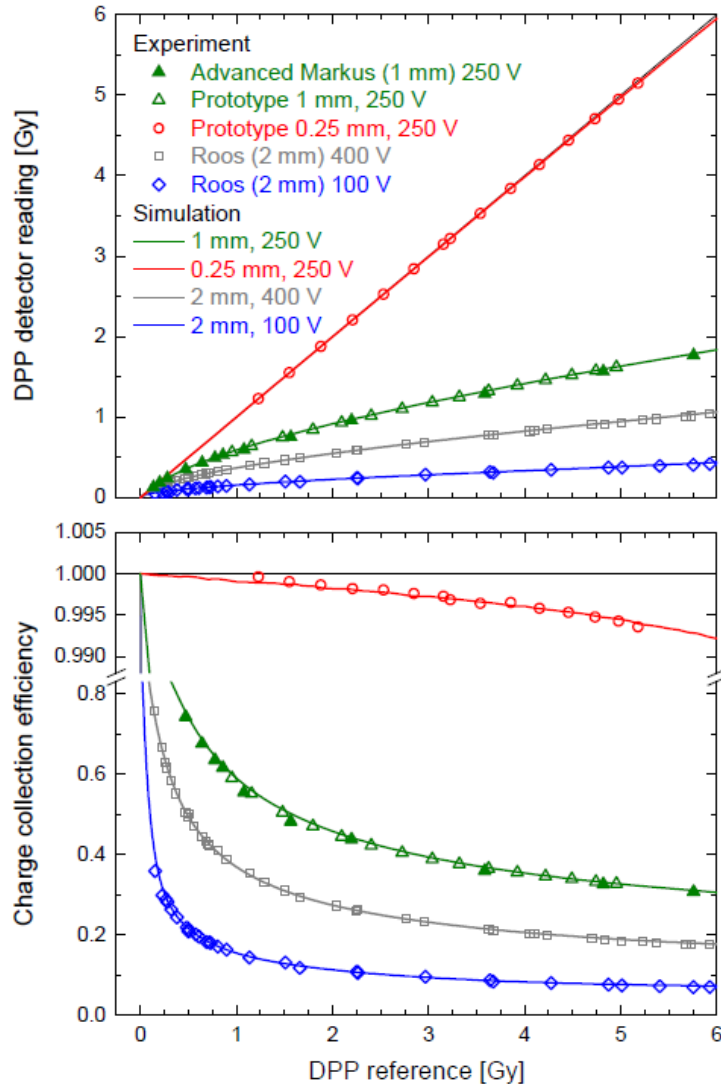


Charge collection efficiency of the PPICs with different electrode distances and three different chamber voltages. From left to right $d = 1$ mm, 0.5 mm, 0.25 mm. Experimental and simulated data as well as comparative data from the literature are presented.

Gómez, F, Gonzalez-Castaño, DM, Fernández, NG, Pardo-Montero, J, Schüller, A, Gasparini, A, Vanreusel, V, Verellen, D, Felici, G, Kranzer, R, Paz-Martín, J. Development of an ultra-thin parallel plate ionization chamber for dosimetry in FLASH radiotherapy. *Med Phys*. 2022; 49: 4705– 4714. <https://doi.org/10.1002/mp.15668>

“Charge collection efficiency, underlying recombination mechanisms, and the role of electrode distance of vented ionization chambers under ultra-high dose-per-pulse conditions”
Phys Med. 2022 Nov 7;104:10-17.
doi: 10.1016/j.ejmp.2022.10.021.

Ultra-Thin Ionization Chamber (UTIC)



The use of 0.25-0.30 mm electrode distance has allowed the use of ionization chambers with small recombination losses under UHDR/UHDP. Only parallel plate model available commercially is Standard Imaging A30.



PTW T34093
prototype

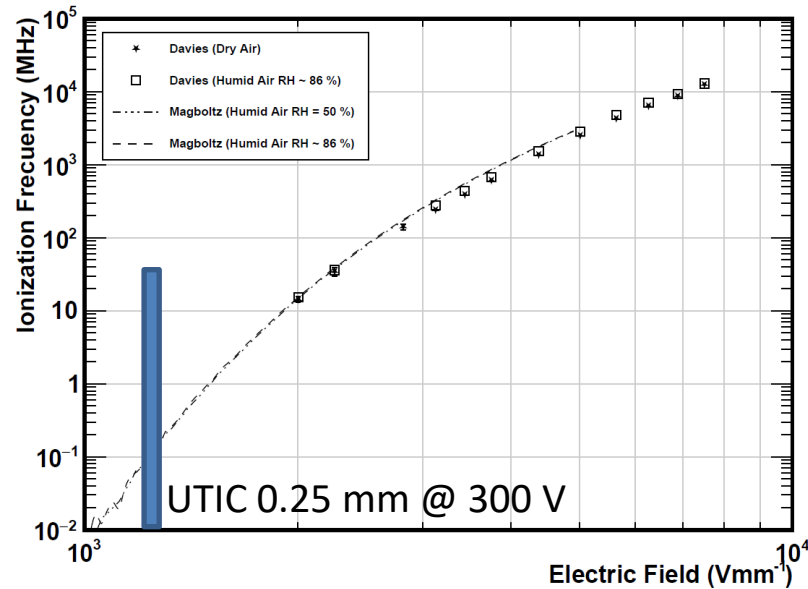
Gómez F et al. "Development of an ultra-thin parallel plate ionization chamber for dosimetry in FLASH radiotherapy". Med Phys. 2022 Jul;49(7):4705-4714.

"Metrology for advanced radiotherapy using particle beams with ultra-high dose rates" Anna Subiel et al 2024 Phys. Med. Biol. 69 14TR01

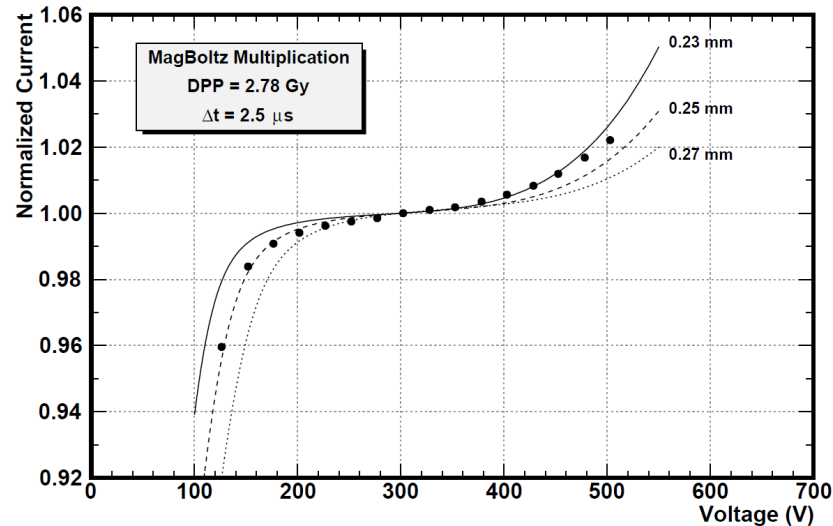
"Reconfiguring a Plane-Parallel Transmission Ionization Chamber to Extend the Operating Range into the Ultra-High Dose-per-pulse Regime" Elise Konradsson et al. Radiat Res. 2024 Mar 1;201(3):252-260.

"The model to correct for the ion recombination of micro-thin cylindrical ionization chamber in high dose-rate and frequency pulses X-ray beams" Yanmei Hao, Sen Bai, Wanchang Lai NIM A Vol. 1075 (2025), 170434

Charge multiplication



First Townsend coefficient has very limited experimental data in the region of electric field used in ICs. Figure shows MonteCarlo method results from Magboltz.

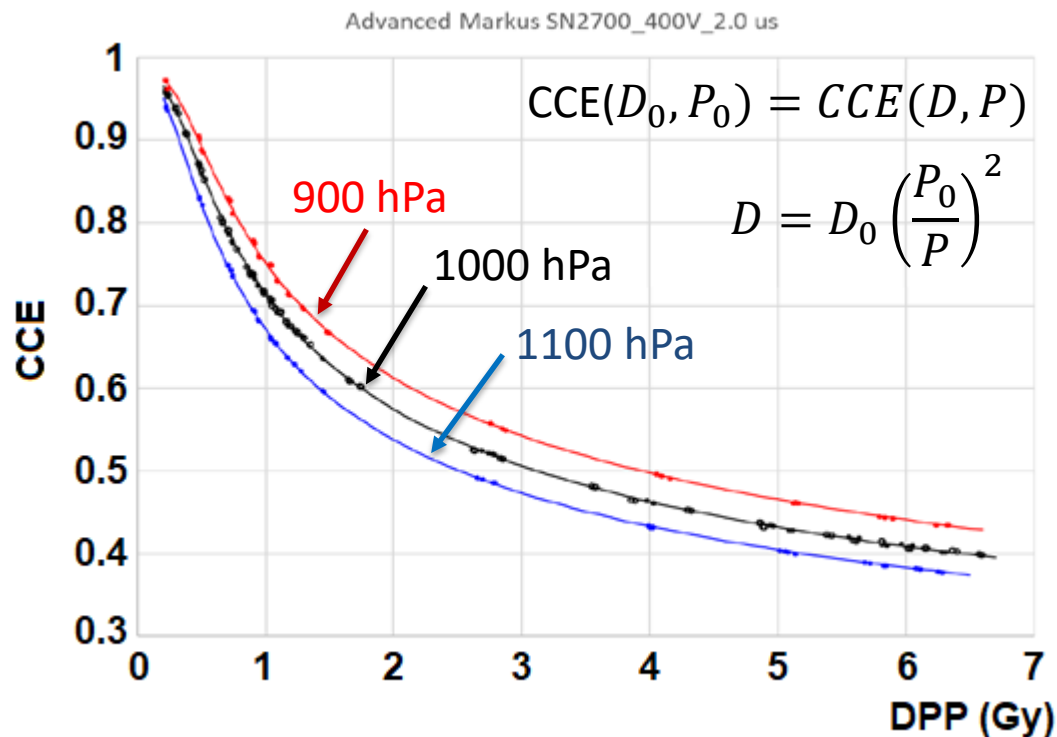


Simulation of charge multiplication for the Ultra Thin Ionization Chamber (0.25 mm) chamber. Data from Rafael Kranzer (PTW).

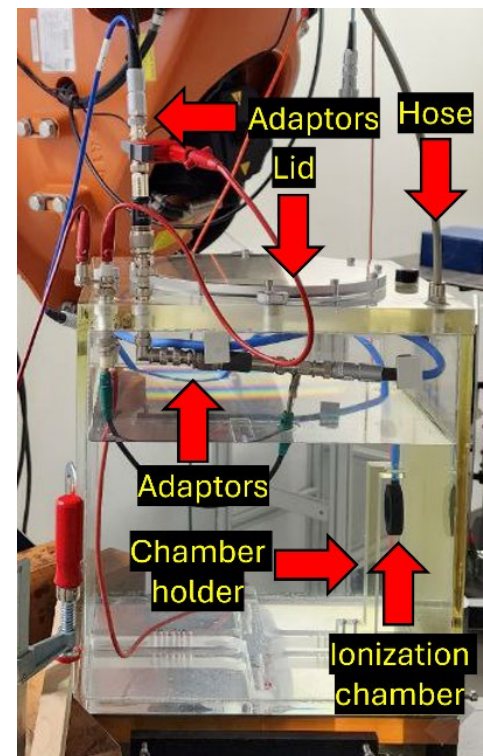
Pressure dependence of recombination

Predicted from current numerical models, PTB has performed measurements to study the effect of influence magnitudes on saturation effect in collaboration with USC and Wisconsin University. The evaluation of CCE is obtained after k_{PT} correction.

Advanced Markus @ 400 V pulse duration 2 μ s



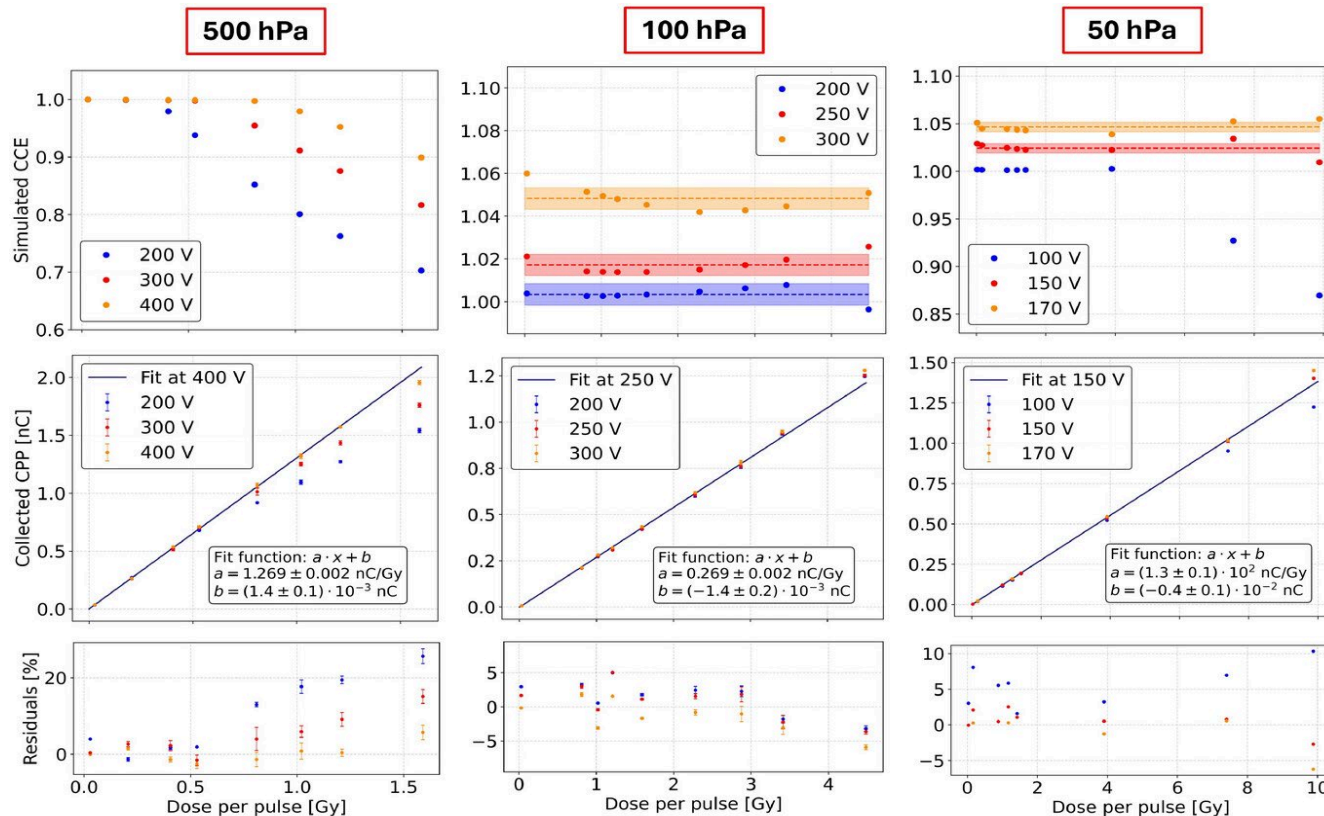
Miguel Angel Flores-Mancera *et al* 2026 *Phys. Med. Biol.* **71** 085013 DOI 10.1088/1361-6560/ae556b



Pressurized
water phantom
at PTB

Low pressure approach

Another alternative approach to UTIC air vented ionization chamber is the **ALLS ionization chamber** based in low pressure ionization detector for UHDP. Eventually the first prototype was a nitrogen filled chamber working at ~ 50 hPa.

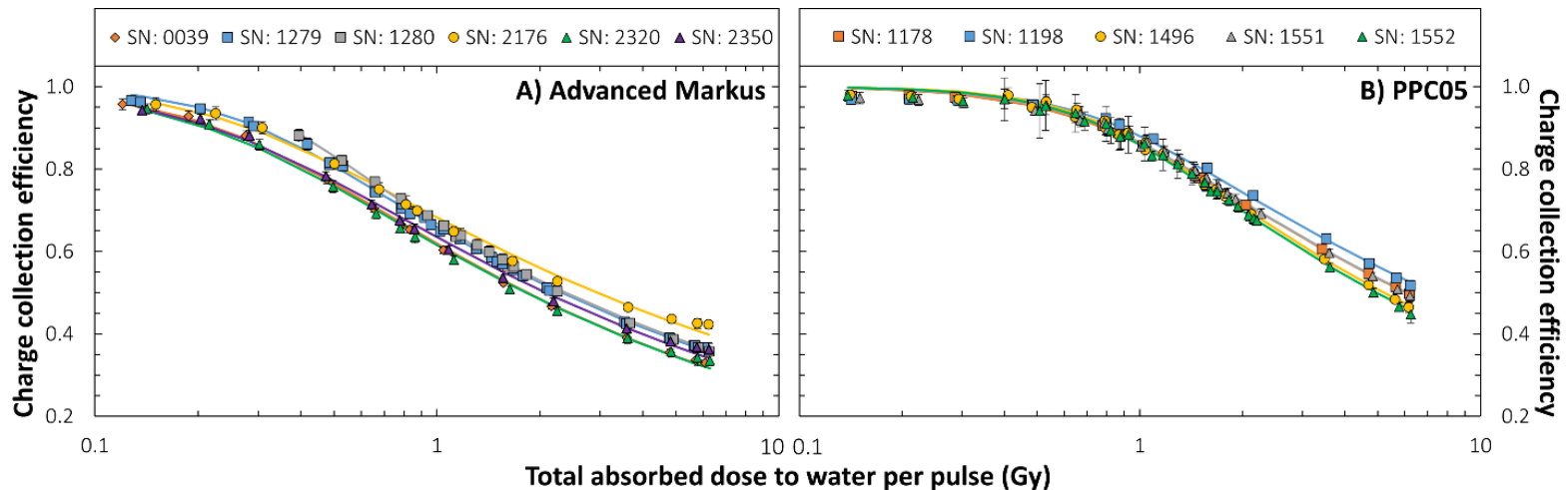


Parallel plate chamber with 1 mm electrode distance operated with 150-170 V external bias.

Di Martino F et al. "A new solution for UHDP and UHDR (Flash) measurements: Theory and conceptual design of ALLS chamber" Physica Medica: European Journal of Medical Physics, 2022; 102, 9-18
 Montefiori M, Baldini L, Bisogni MG, et al. First experimental characterization of a low-pressure nitrogen filled parallel-plate ionization chamber for UHDP electron beam dosimetry. Med Phys. 2026;53:e70287. <https://doi.org/10.1002/mp.70287>
 Marco Montefiori et al 2026 Phys. Med. Biol. 71 025010

Generic CCE correction under UHDP

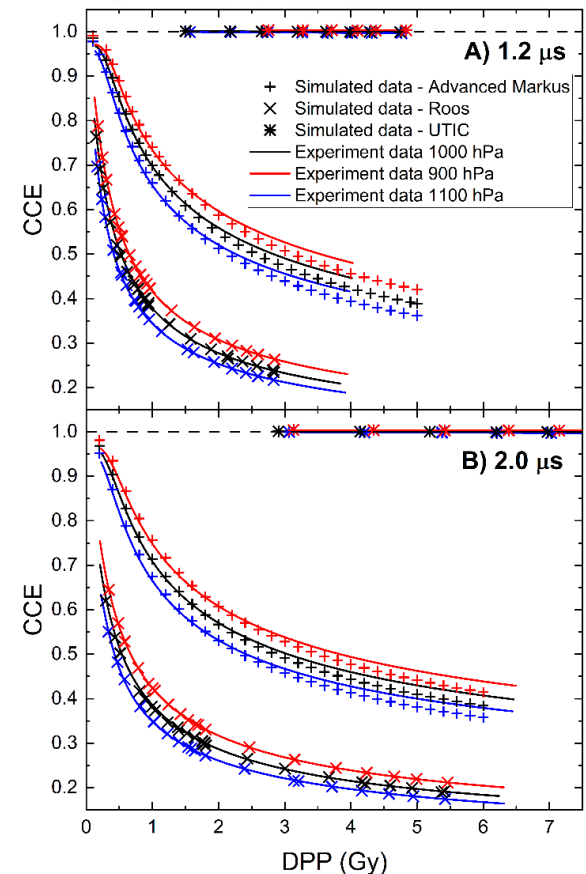
- Can we correct commercial ionization chambers under UHDP in a **reproducible** way for saturation losses?
- Experimental campaigns for 22 ionization chambers performed at PTB during the UHDPulse project.



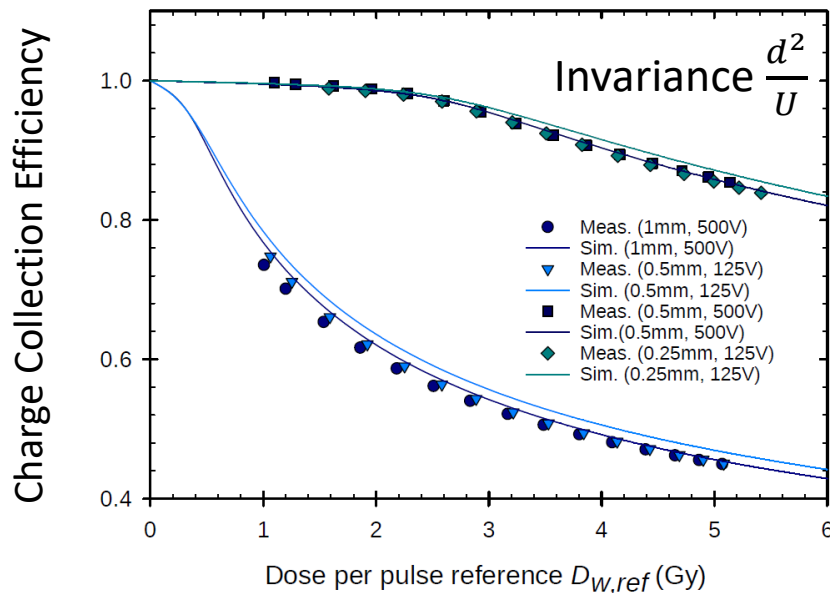
Intra-model variations are very important under large saturation conditions:
i.e. up to 8 % (PPC05) and 16 % (Advanced Markus)

Air ionization chamber limitations

- **Observed CCE relative variation** of commercial ionization chambers (large gap) units of the same model (and/or analogous geometry) under fixed UHDR/UHDP irradiation can be quite large, exceeding 2 %.
- The use an **effective empiric correction factor** for saturation under UHDR/UHDP for situations when $k_{\text{sat}} > 1,05$ implies **important uncertainties usually in excess of 1 %**.
- **Saturation factor depends also on air density** (after k_{pT} correction), and thus measurements with large recombination effects should also report (or correct !!) ambient conditions.



Scaling rules



Parallel plate ionization chamber CCE

$$CCE(D, U_0, d_0) = CCE(D, U_1, d_1)$$

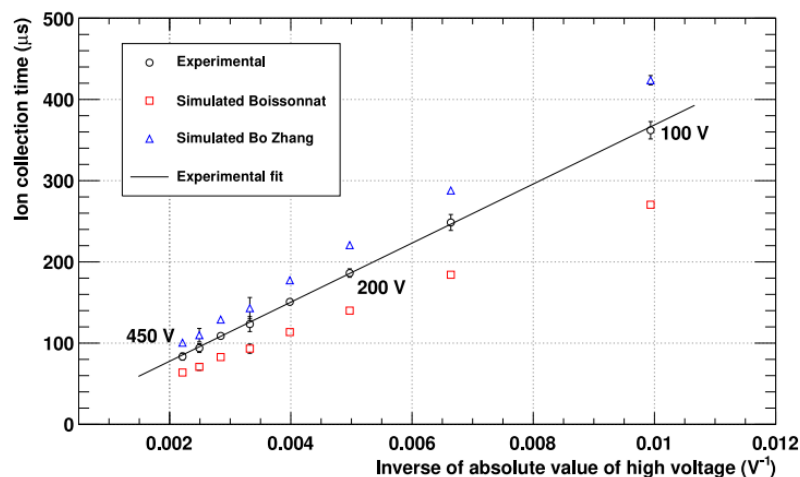
when

$$\frac{d_0^2}{U_0} = \frac{d_1^2}{U_1}$$

Phys Med. 2022 Nov 7;104:10-17.
doi: 10.1016/j.ejmp.2022.10.021.

Parallel plate ionization chamber
charge collection time Δt

$$\Delta t \propto \frac{1}{U}$$

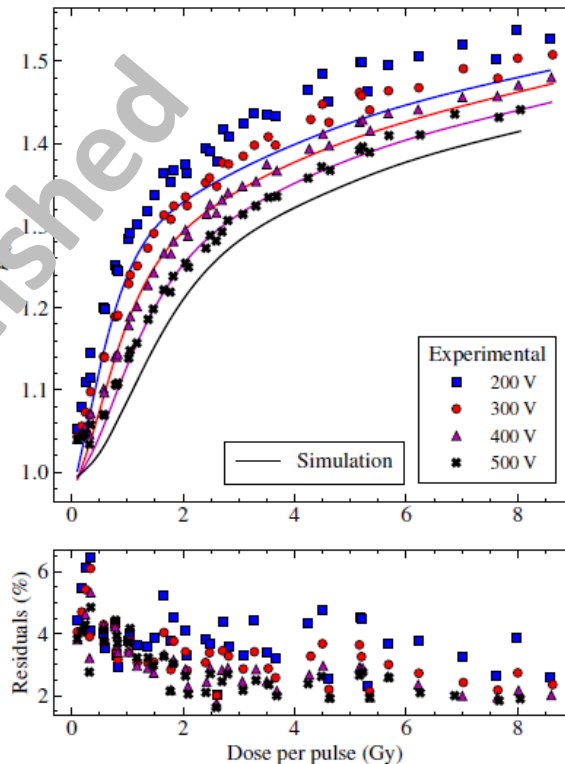
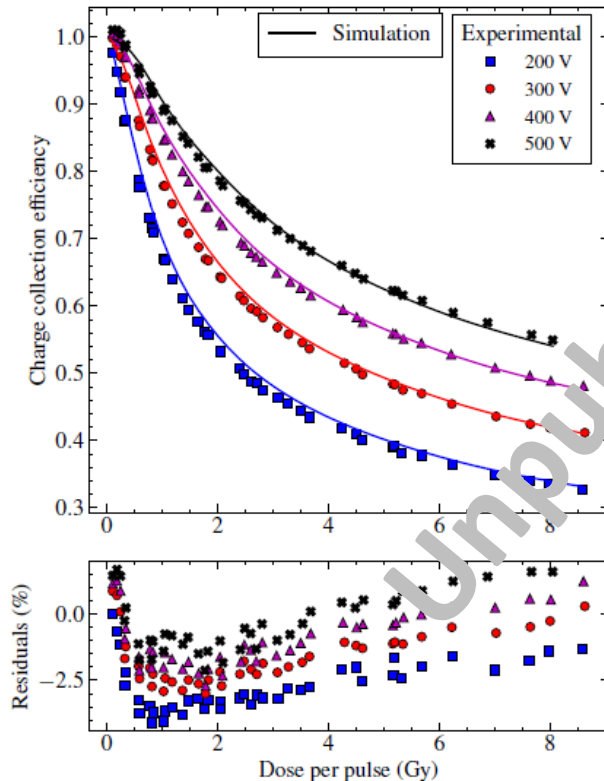


Roos chamber
DPP from 0.2 Gy to 5.8 Gy

Thimble ionization chambers

Cylindrical ionization chambers can also be solved through numerical methods (finite elements).

B) PinPoint T31023 SN170313



PinPoint chamber T31023

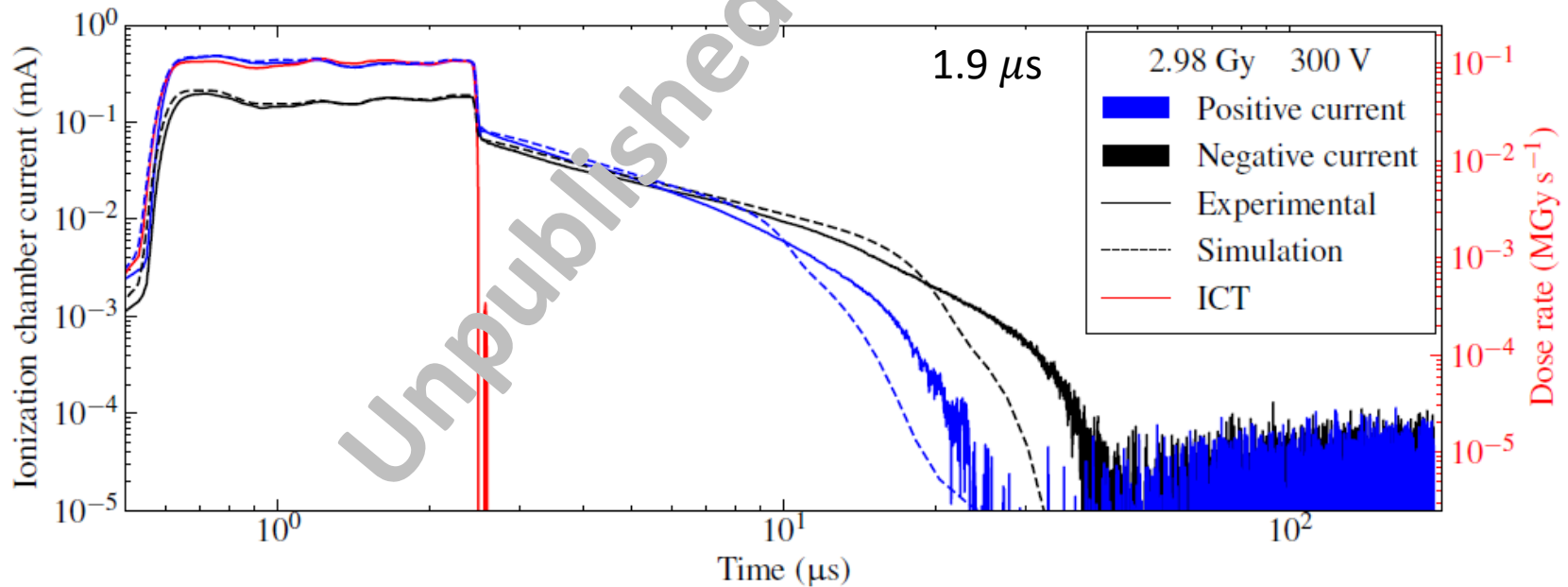


Polarity dependent recombination that is mixed with standard polarity effect!

J. Paz-martin et al. "Charge collection efficiency of thimble ionization chambers exposed to ultra-high dose per pulse" Submitted to Physica Medica

Thimble ionization chambers

Time resolved instantaneous currents for a PinPoint 3D T31022.



CCE is larger when negative charge is collected at the central electrode!!
This contributes to an effective $k_{pol} > 1$ produced by general recombination effect.

Methodologies to determine saturation correction

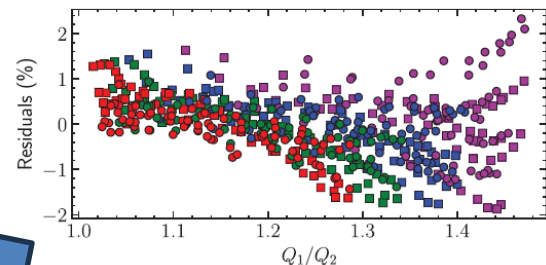
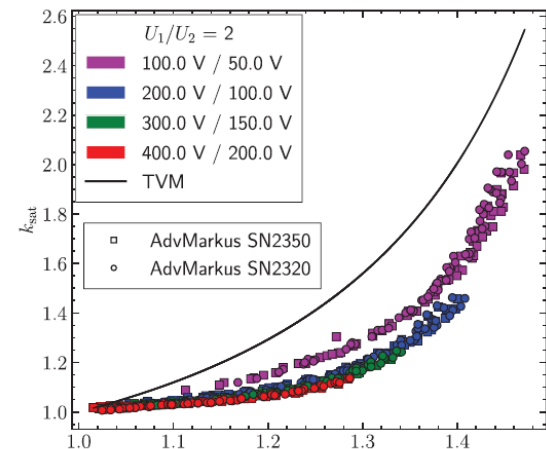
- Boag's theory does not account for free electrons drifting in the IC's volume.
- This free electron fraction might be large, even for ICs with large distance between electrodes.
- The free electron fraction is a function of the voltage. Therefore, the Jaffe's linear relationship is broken. **Also, k_s is not longer a function of the voltage ratio.**

~~$$k_s = a_0 + a_1 \left(\frac{M_1}{M_2} \right) + a_2 \left(\frac{M_1}{M_2} \right)^2 \quad a_i = a_i \left(\frac{V_1}{V_2} \right) \quad \text{Boag}$$~~

but

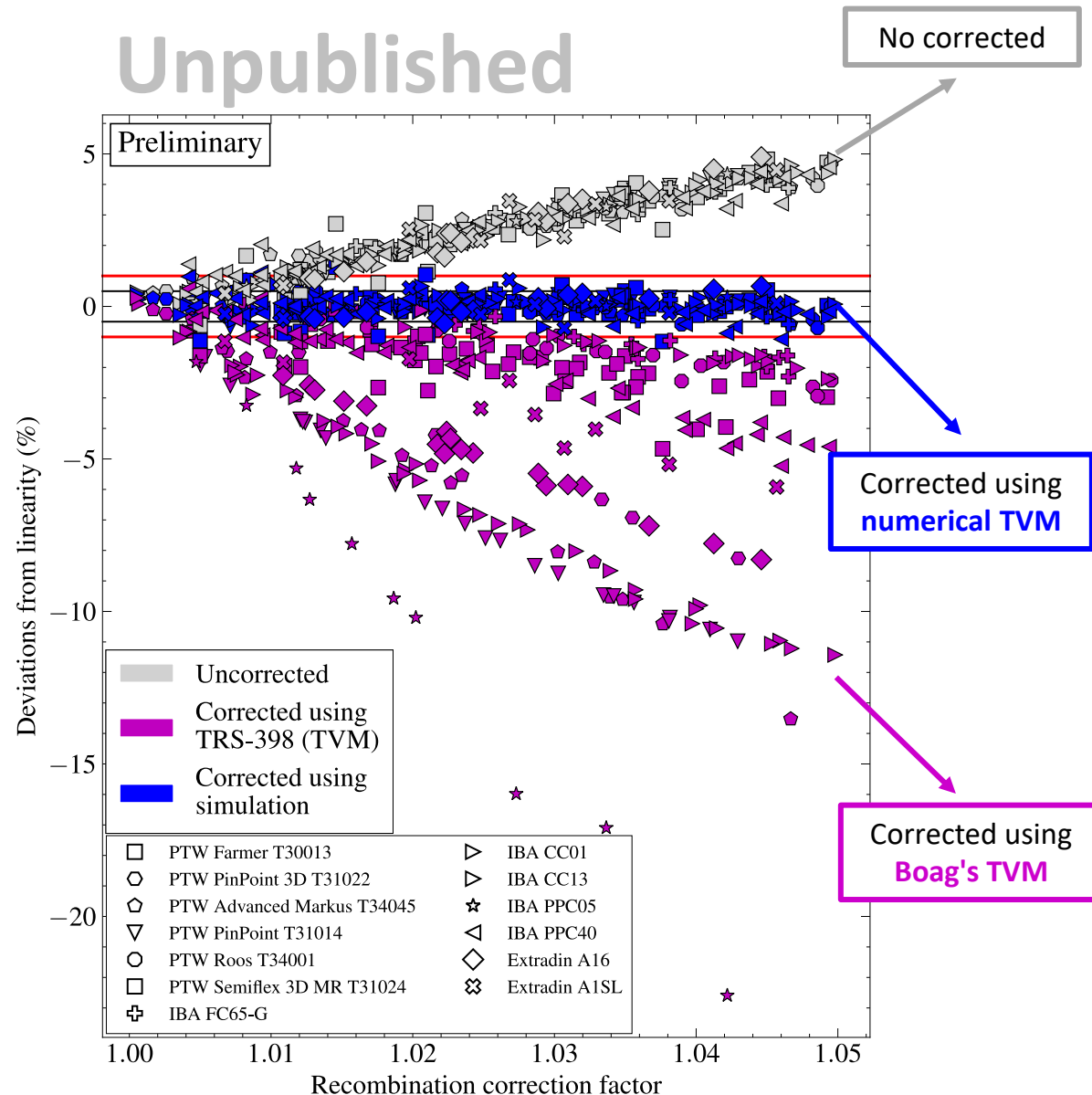
$$k_s = \sum_{i=0}^n a_i(V_1, V_2, d, \Delta t) \left(\frac{M_1}{M_2} \right)^i \quad \text{Numerical}$$

Now a_i depend on V_1 and V_2 and might also depend on other parameters like pulse duration Δt and geometry. Typically $i \leq 4$.



Methodologies to determine saturation correction

- The TVM based on Boag's method **tends to overestimate** the k_s up to 20 %.
- The correction based on the numerical model accounts (~ 1 %) for the recombination correction factor for **all** the ICs.
- The smaller the distance between electrodes the largest the deviation*



Methodologies to determine saturation correction

PTW Farmer T30013 dimensions

$$r_{\text{in}} = 1.15 \text{ mm}$$

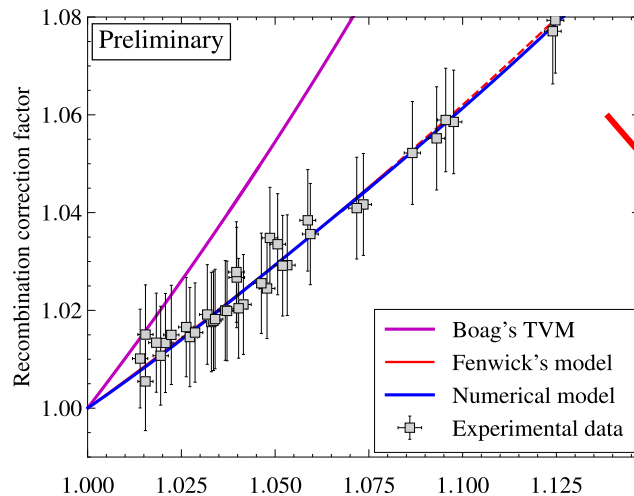
$$r_{\text{out}} = 3.05 \text{ mm}$$

Unpublished

PTW Advanced Markus T34045 dimensions

$$d = 1.0 \text{ mm}$$

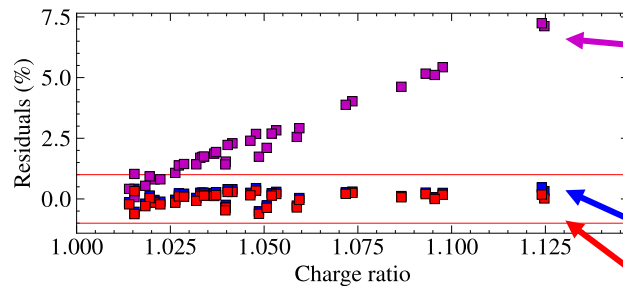
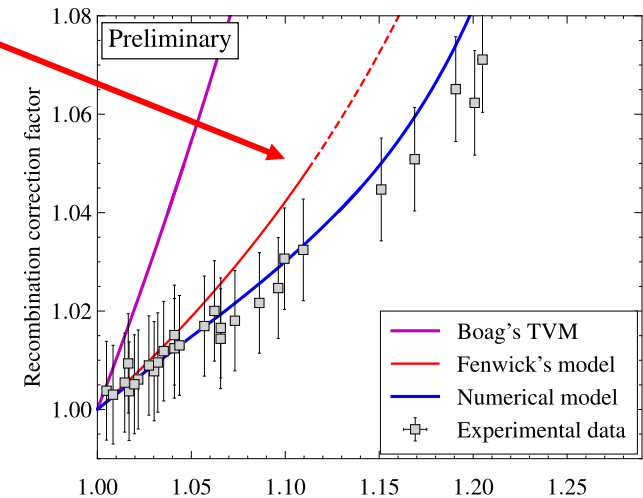
PTW Farmer T30013 500 V / 250 V



Here electric field perturbation effect becomes noticeable.

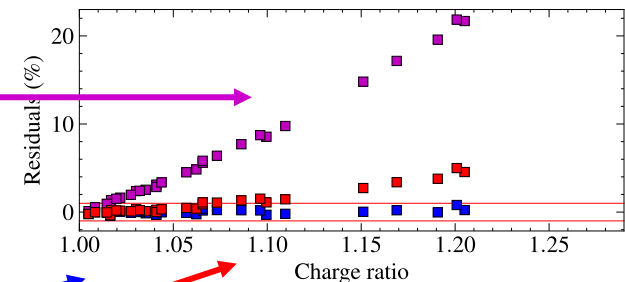
The maximum dose per pulse is 18 mGy, away from UHDPP conditions!

PTW Advanced Markus T34045 400 V / 200 V



Residuals from Boag's TVM

Residuals from numerical model and Fenwick's model



Conclusions

- The implementation of UHDR and UHDP beams presents significant challenges for dosimetry using commercially available ionization chambers.
- The application of generic correction factors developed for standard chambers introduces substantial uncertainties ($>1\%$), and the **use of chambers requiring saturation correction factors greater than 1.05 is therefore discouraged**.
- Vented parallel-plate ionization chambers (PPIC) **with small electrode spacing, such as UTIC**, or chambers operated at reduced pressure, have been demonstrated as **viable alternatives** for reference dosimetry under these conditions.
- These findings have necessitated a **re-examination of the traditional recombination formalism for pulsed beams (Boag theory)**, leading to the development of new approaches, including numerical recombination models.
- Furthermore, **standard methods for calculating saturation correction factors**—even at conventional dose-per-pulse levels in the mGy range—**are currently under critical review**, including a re-evaluation of the two-voltage method (TVM).
- Finally, it has been observed that the **charge collection efficiency (CCE) of vented ionization chambers** exhibits a **quadratic dependence on ambient pressure**, even after applying the conventional pressure–temperature correction factor (k_{PT}).

Acknowledgments

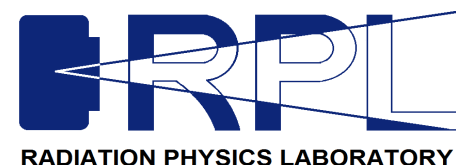
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