Novel approaches for UHDR-VHEE through ionization chambers

Marco Montefiori

Department of Physics E. Fermi, University of Pisa

VHEE25

15-17 set. 2025 – STFC, Daresbury Laboratory

Outiline

- Introduction
- Theory and conceptual design of the ALLS chamber
- Numerical simulations of charge transport in noble gases
- Practical realization of the first air-filled prototype
- Experimental characterization
- Conclusions and future steps

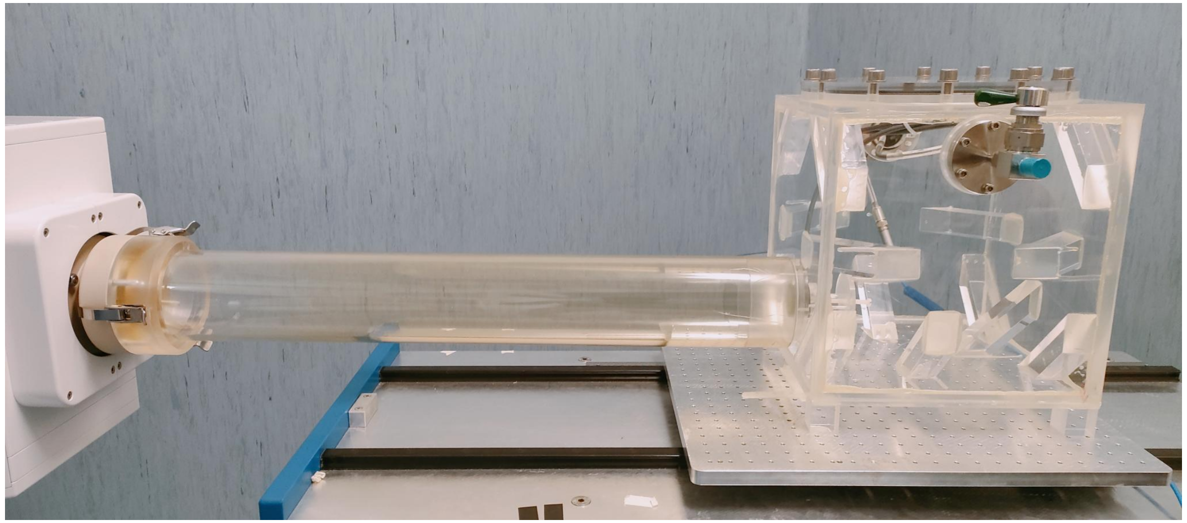
Introduction

Ionization chambers in Ultra-High Dose Rate and Ultra-High Dose per Pulse regime

- Problems related to the large charge density in the active volume
- Need for new design to overcome saturation problems

Our proposed model: ALLS chamber

- Theoretical design based on a low-pressure filling gas
- Development and characterization (my PhD work) → reliable solution for UHDP (≤ 10 Gy) dosimetry
- Experimental measurements with 9 MeV electrons → promising solution for VHEE applications

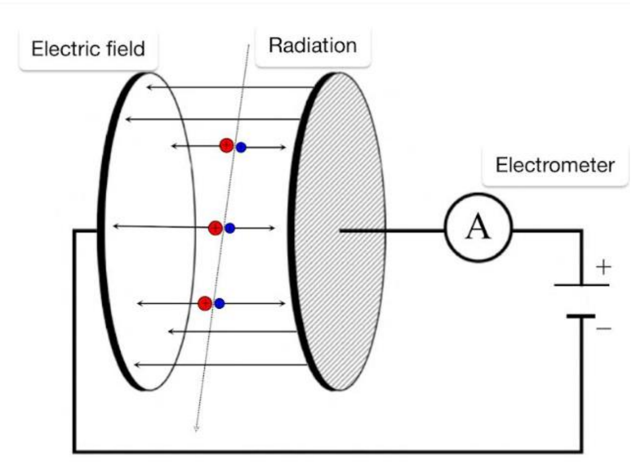


Ionization chambers (ICs) for RT dosimetry

Reference dosimeter in CONV-RT:

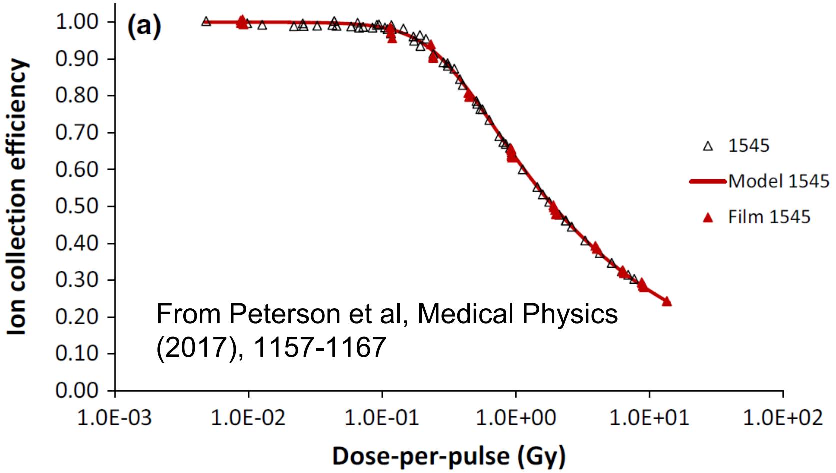
- High accuracy and stability
- Gold standard in dosimetry protocols

$$D_W = N_{D,w}\, M\, k_{Q,Q_0} k_{TP}\, k_{pol}\, k_{sat}$$



Issues with volume recombination:

- D_p → UHDP (> 1 Gy)



Perturbation of the bias electric field:

- Nullify the overall field → total recombination
- Very high values → secondary charge production

Alternative approaches:

- Other kind of dosimeters (semiconductors, scintillators, calorimeters)
- **Modification of the design of ionization chambers to make them suitable for UHDP dosimetry**

Ionization chambers in UHDP regime

Proposed solutions for new designs of parallel-plate ionization chambers (PPICs) for UHDP applications

RESEARCH ARTICLE

MEDICAL PHYSICS

Development of an ultra-thin parallel plate ionization chamber for dosimetry in FLASH radiotherapy

Faustino Gómez[1,2] | Diego M. Gonzalez-Castaño[2] | Nicolás Gómez Fernández[2] | Juan Pardo-Montero[3,4] | Andreas Schüller[5] | Alessia Gasparini[6,7] | Verdi Vanreusel[6,7,8] | Dirk Verellen[6,7] | Giuseppe Felici[9] | Rafael Kranzer[10,11] | Jose Paz-Martín[1]

Physica Medica 102 (2022) 9–18

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

ELSEVIER

A new solution for UHDP and UHDR (Flash) measurements: Theory and conceptual design of ALLS chamber

Fabio Di Martino[a,b,d,*], Damiano Del Sarto[b], Maria Giuseppina Bisogni[b,c,d], Simone Capaccioli[b,c], Federica Galante[e], Alessia Gasperini[f,g], Stefania Linsalata[a], Giulia Mariani[e], Matteo Pacitti[e], Fabiola Paiar[b,d,h], Stefano Ursino[b,d,h], Verdi Vanreusel[f,g], Dirk Verellen[f,g], Giuseppe Felici[e]

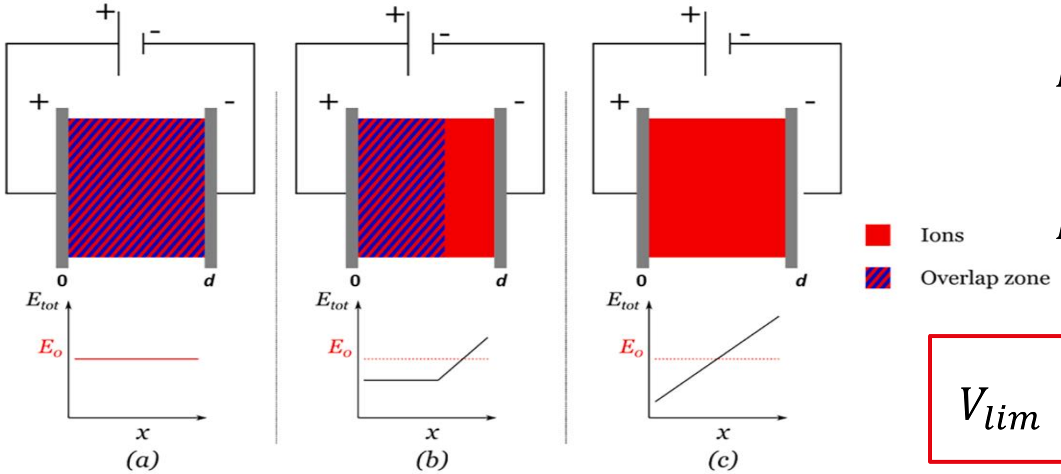
Conceptual design of the ALLS chamber

1. Avoid recombination

- Use of a noble gas in place of air
- Ensure E(x) > 0

2. Avoid uncontrolled discharges

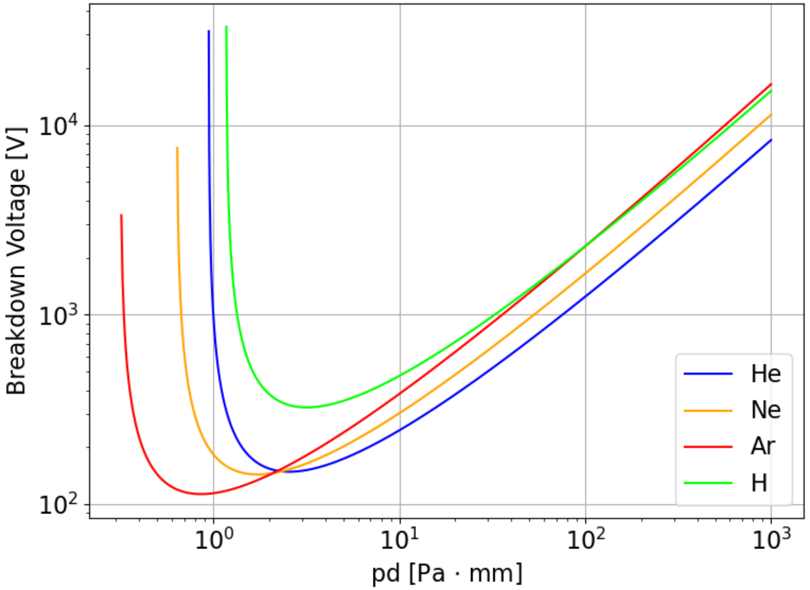
- Low pressures to avoid breakdown



$$E(x) = E_0 + E_{ION}$$

$$E_{ION}(x) = \frac{q_V{}^{gen}}{\varepsilon_0 \varepsilon_r}\left(x - \frac{d}{2}\right)$$

$$\boxed{V_{lim} = \frac{q_V{}^{gen} d^2}{2\varepsilon_0\varepsilon_r} = \frac{D_p \bar{S}_w{}^{gas} \rho}{2\varepsilon_0\varepsilon_r} d^2}$$

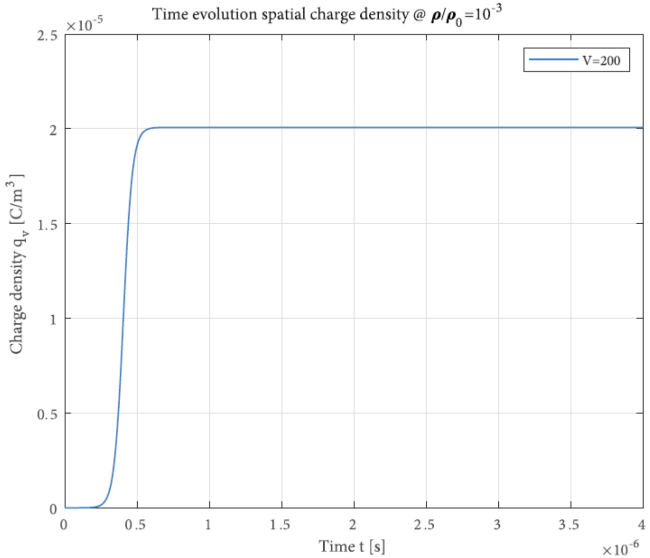


3. Analytical description of the charge collection

- Filling gas: argon at 1 hPa
- Distance between electrodes: 1 mm
- Applied voltage: 200 V

$$\dot{q}_V^{tot} = \frac{D_p \bar{S}_w^g \rho}{T w_e}\frac{\rho}{\rho_0} + \frac{\mu_{ion}}{2\epsilon_0\epsilon_r}\frac{\rho_0}{\rho}(q_V^{tot})^2 - \frac{\mu_{ion} V}{d^2}\frac{\rho_0}{\rho} q_V^{tot}$$

$$(q_V^{tot})^{MAX} = -\frac{\frac{\mu_{ion}V}{d^2}\frac{\rho_0}{\rho} + \sqrt{\left[\frac{\mu_{ion}V}{d^2}\frac{\rho_0}{\rho}\right]^2 - 4\frac{\mu_{ion}}{2\epsilon_0\epsilon_r}\frac{D_p\bar{S}_w^g\rho}{Tw_e}}}{2\frac{\mu_{ion}}{2\epsilon_0\epsilon_r}\frac{\rho_0}{\rho}}$$



Aim

Practical realization and the experimental characterization of an ALLS-like IC to provide a new active device for UHDP absolute dosimetry

- Study of experimental configurations → numerical simulations
- Research of materials suitable for low-pressure applications to realize the chamber body and electrical components
- Practical realization of a first air-filled prototype to reproduce a standard IC and preliminary tests in conventional conditions
- Realization of a sealed environment to explore different configurations
- Experimental measurement with FLASH pulsed electron beams at Centro Pisano FLASH Radiotherapy (CPFR)

FONDAZIONE PISA

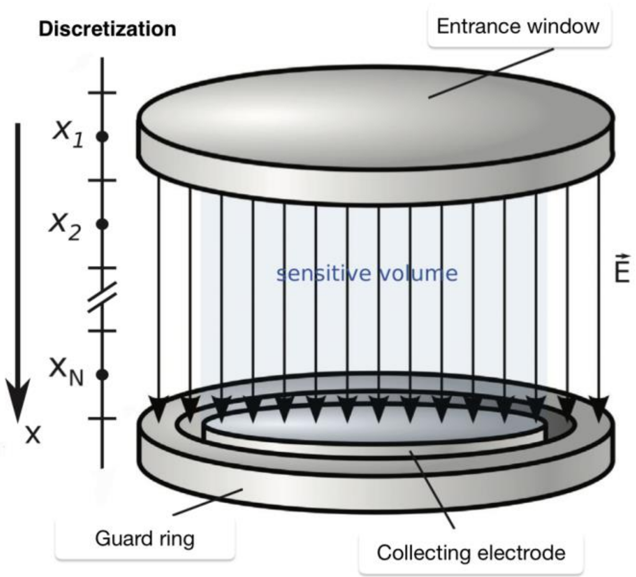
Centro Pisano Flash Radiotherapy CPFR

Numerical model of charge transport in noble gases

Transport equations in noble gases

$$\frac{\partial n_+(x,t)}{\partial t} = R(x,t) + \alpha(x,t)v_e(x,t)n_e(x,t) - \theta n_+(x,t)n_e(x,t) - \frac{\partial}{\partial x}\left[E(x,t)\mu(x,t)n_+(x,t)\right]$$

$$\frac{\partial n_e(x,t)}{\partial t} = R(x,t) + \alpha(x,t)v_e(x,t)n_e(x,t) - \theta n_+(x,t)n_e(x,t) + \frac{\partial}{\partial x}\left[v_e(x,t)n_+(x,t)\right]$$



Poisson equation

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

Boundary condition

$$\int_0^d E(x,t)dx = V$$

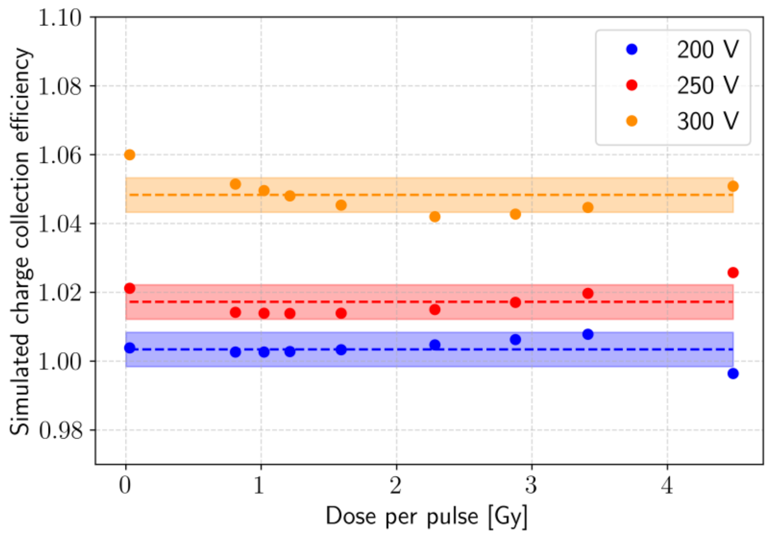
Chamber design: parallel-plate:

- Electrode distance: 1 mm
- Collecting electrode: 1 cm Ø
- Active volume: 78.5 mm^3

Output

- Collected charge (positive ions)
- Charge collection efficiency:

$$\boxed{CCE = \frac{q_v^+}{e\ n_0\ T_{pulse}\ d}}$$



Structural requirements and proposed solutions

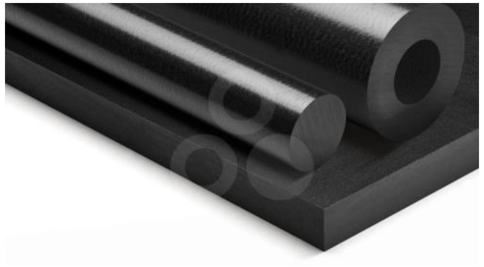
Dosimetric requirements:

- Water equivalence
- Reduced thickness
- Low-*Z* material for electrodes

Low-pressure application requirements:

- Low outgassing and porosity
- High mechanical rigidity
- Radiation resistance

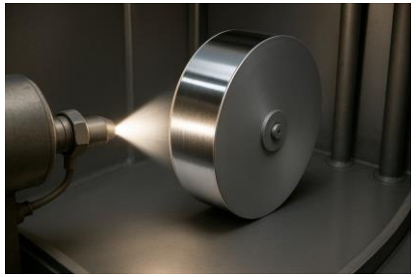
PolyEther Ether Ketone (PEEK)

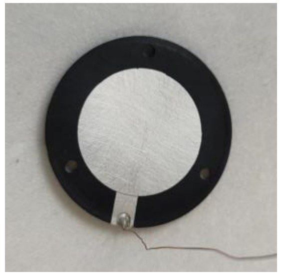


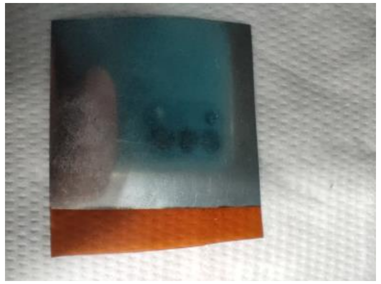
- Density 1.31 g/cm^3
- Elastic modulus 4.2 GPa

Body and inner components

Metallization technique



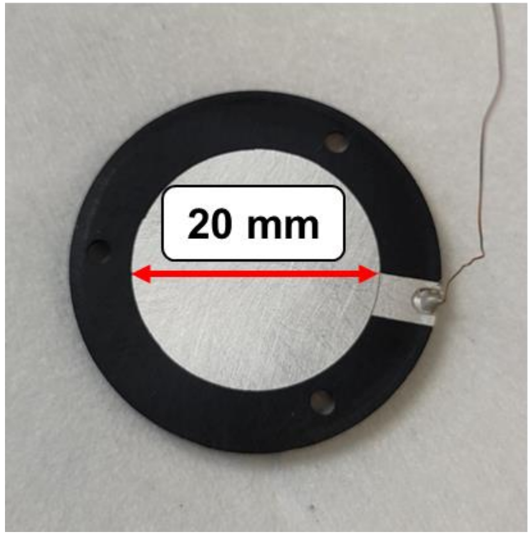


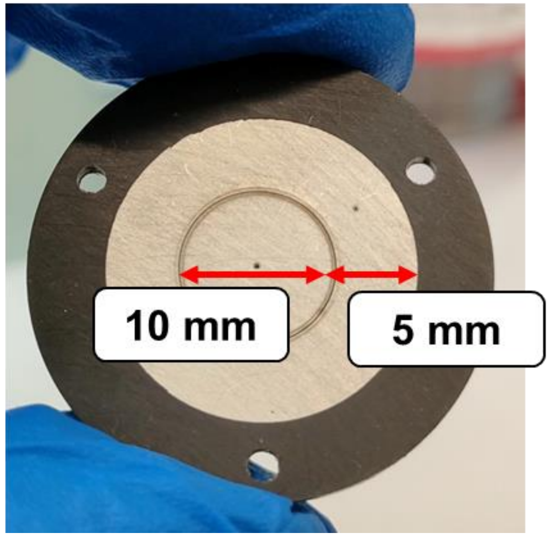


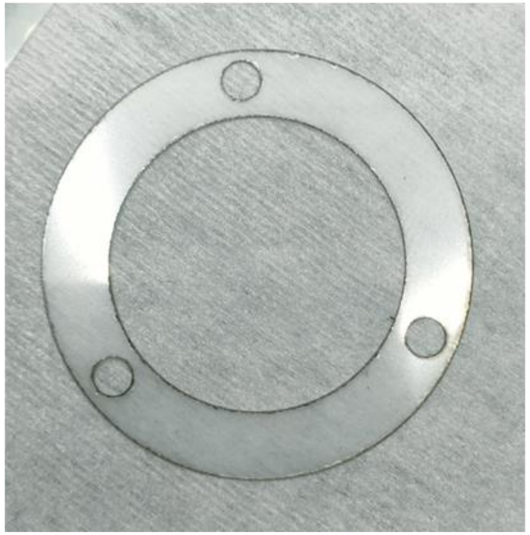
- Achievable thickness < µm
- Limitation of polarity effect

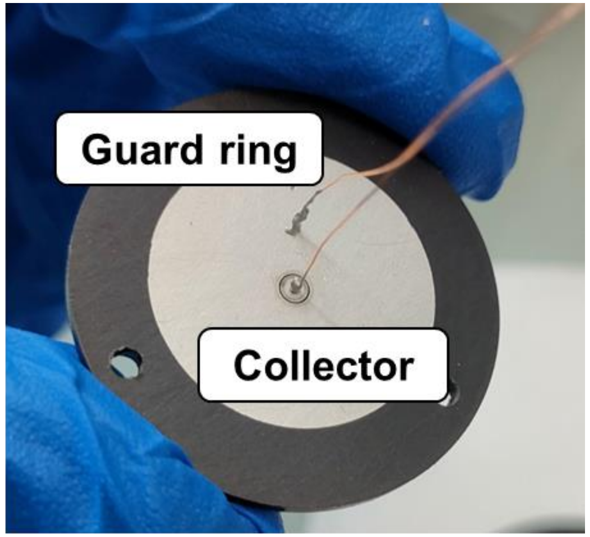
Electrodes

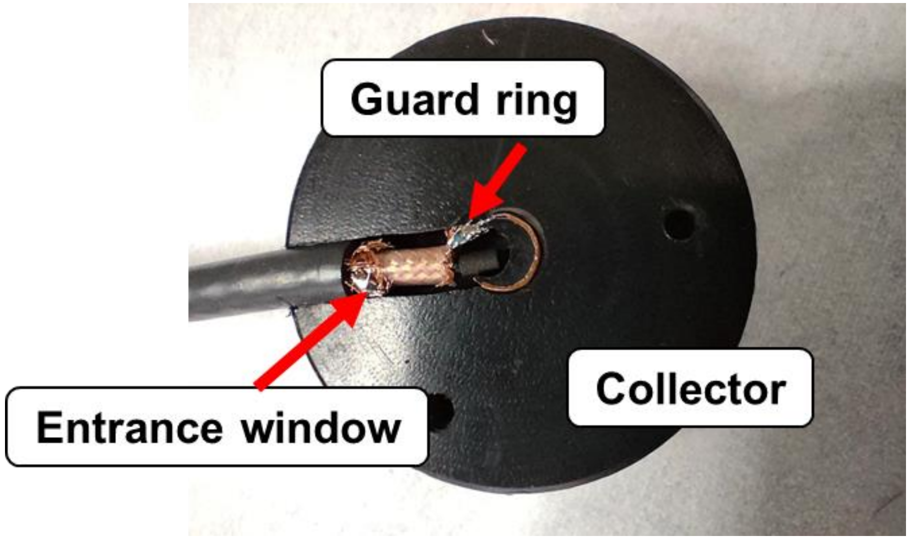
The USC prototype: structure and components







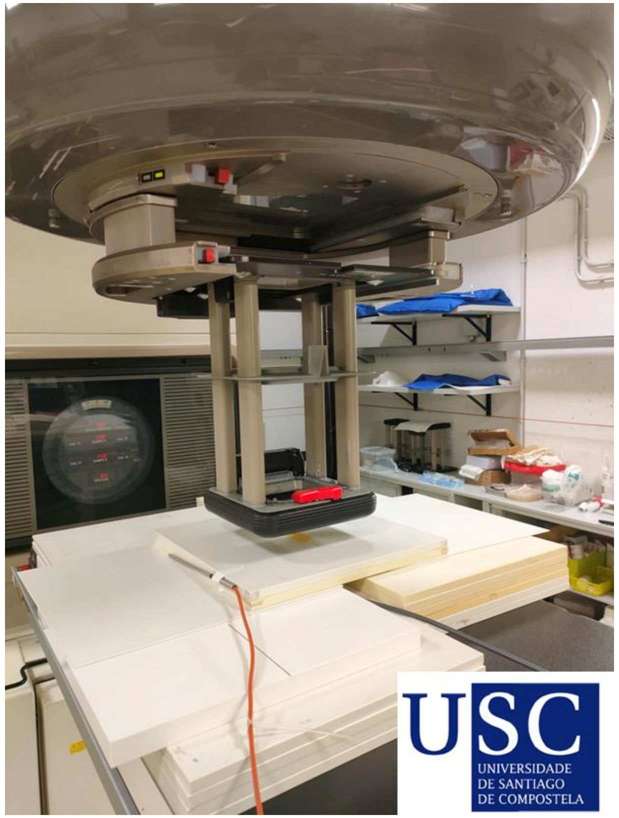




Metallized Al for electrodes:

- PEEK support thickness: 2 mm
- Electrode thickness: 0.3 μm
- Electrode distance: 1 mm
- Connections: Epoxy glue

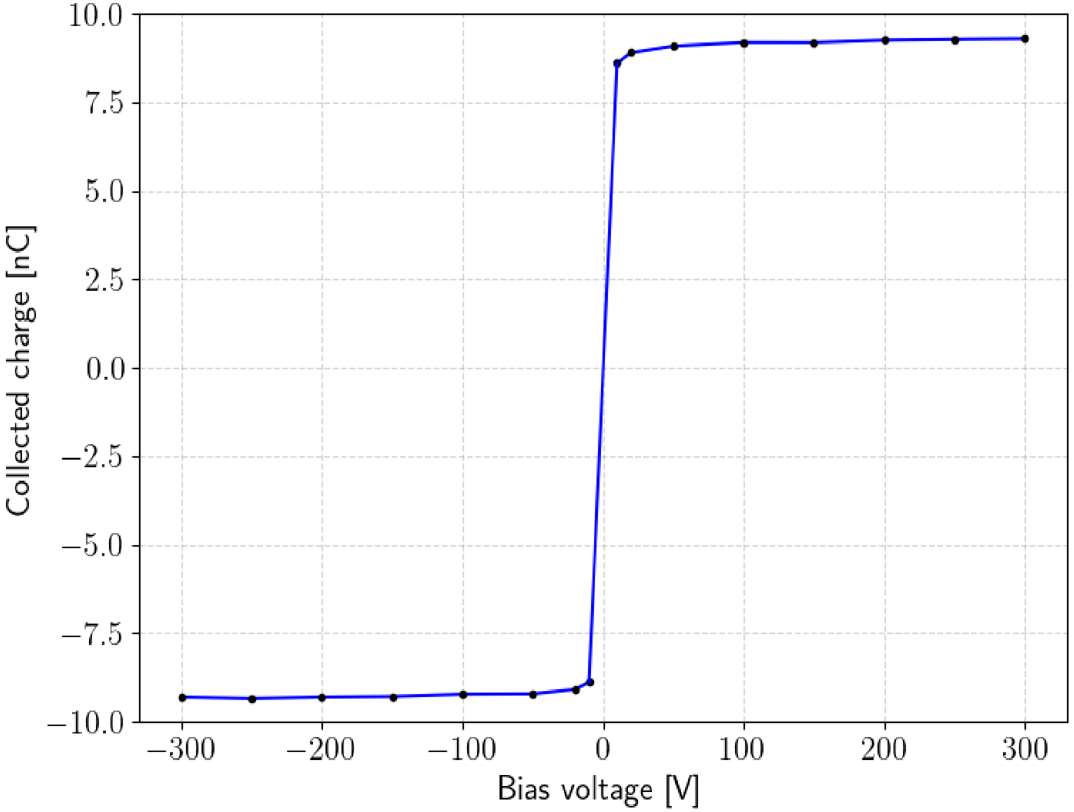
The USC prototype: preliminary test with pulsed electrons



Laboratorio de Radiofìsica, USC

Varian Clinac 2100 linear accelerator

Air-filled prototype



Beam energy: 18 MeV

PRF: 180 Hz

Pulse duration: 3 μs

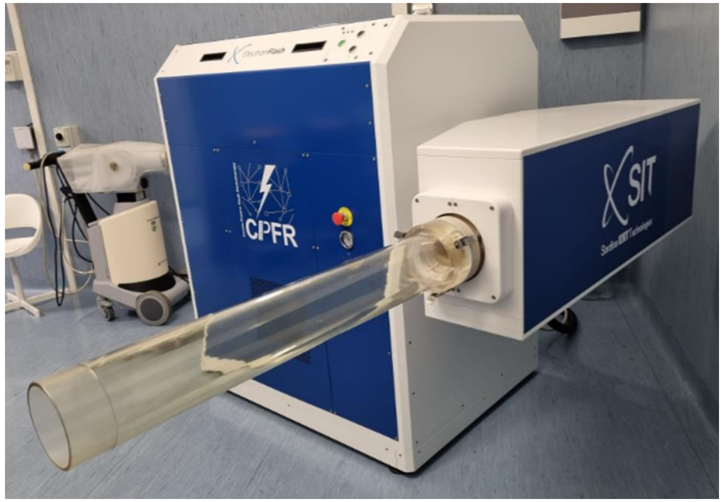
Dose rate: 6 Gy/min

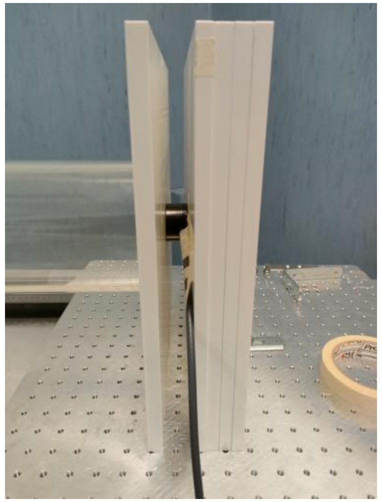
DPP: 1 mGy

Solid water thickness: 4 cm

$$\boxed{k_{pol} = \frac{|Q_+ - Q_-|}{2Q_+} = 1.003 \pm 0.001}$$

The USC prototype: preliminary test @ CPFR





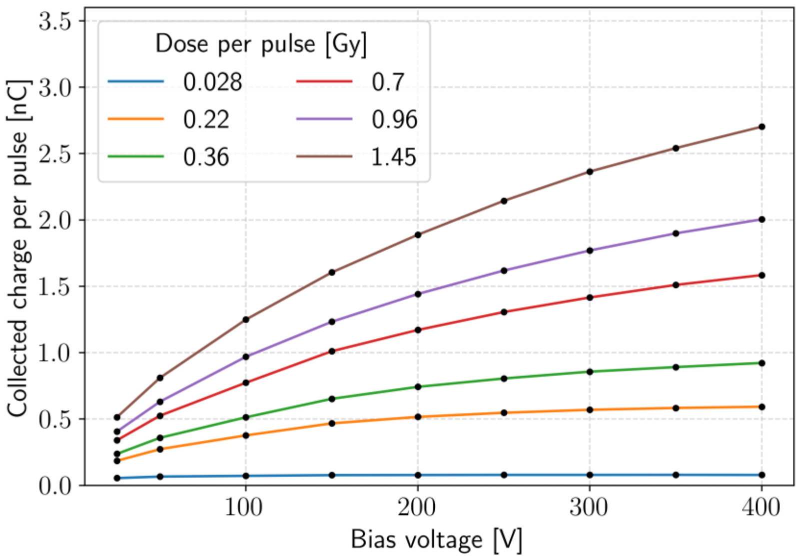
EF parameters :

- Beam energy: 9 MeV
- Pulse frequency: 20 Hz
- Pulse duration: 4 μs

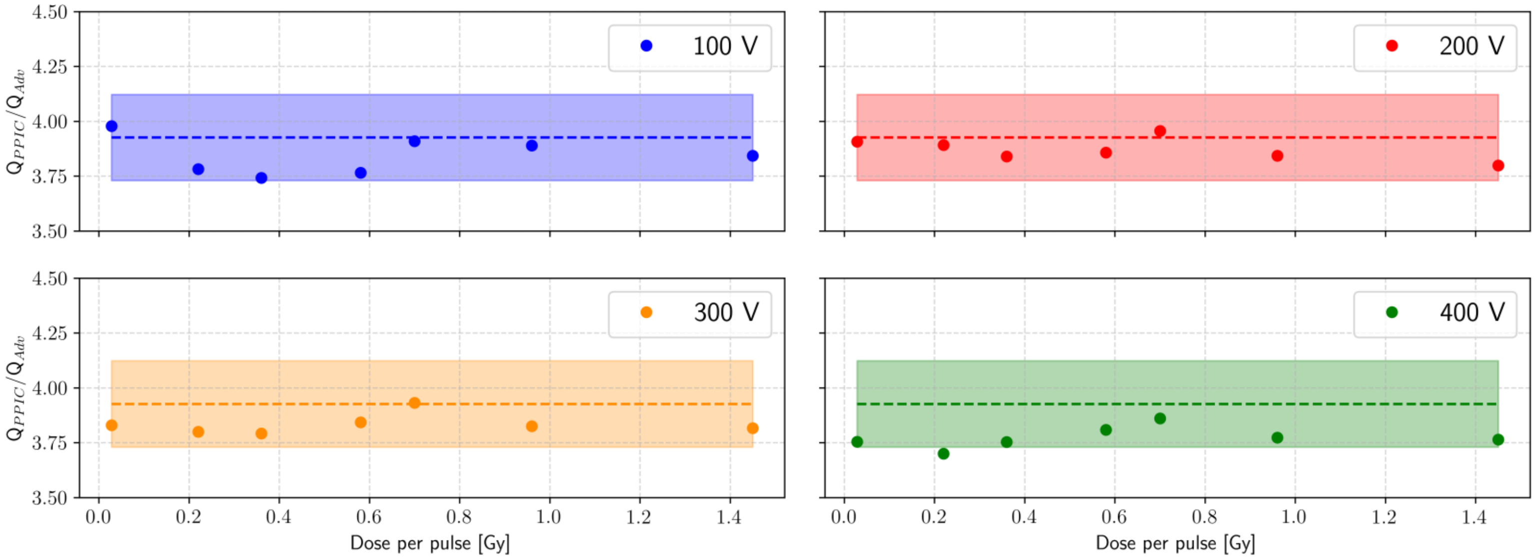
Experimental setup:

- Solid water build-up: 12 mm
- Collimator: 120 mm Ø
- PTW UNIDOS Romeo

Saturation curves



Comparison with PTW Adv. Markus



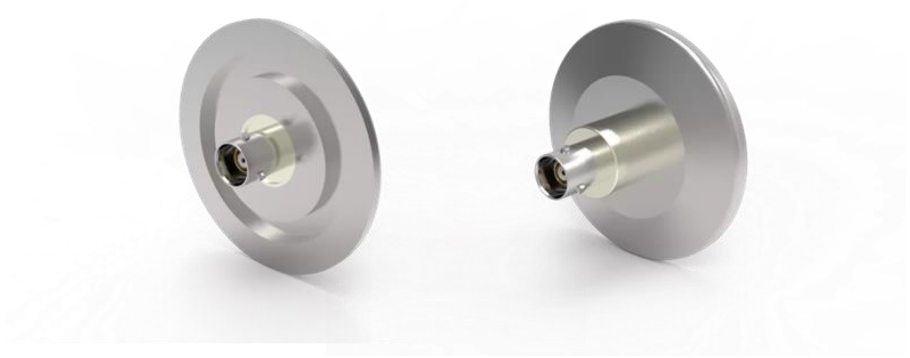
Sealed vessel: structure and components

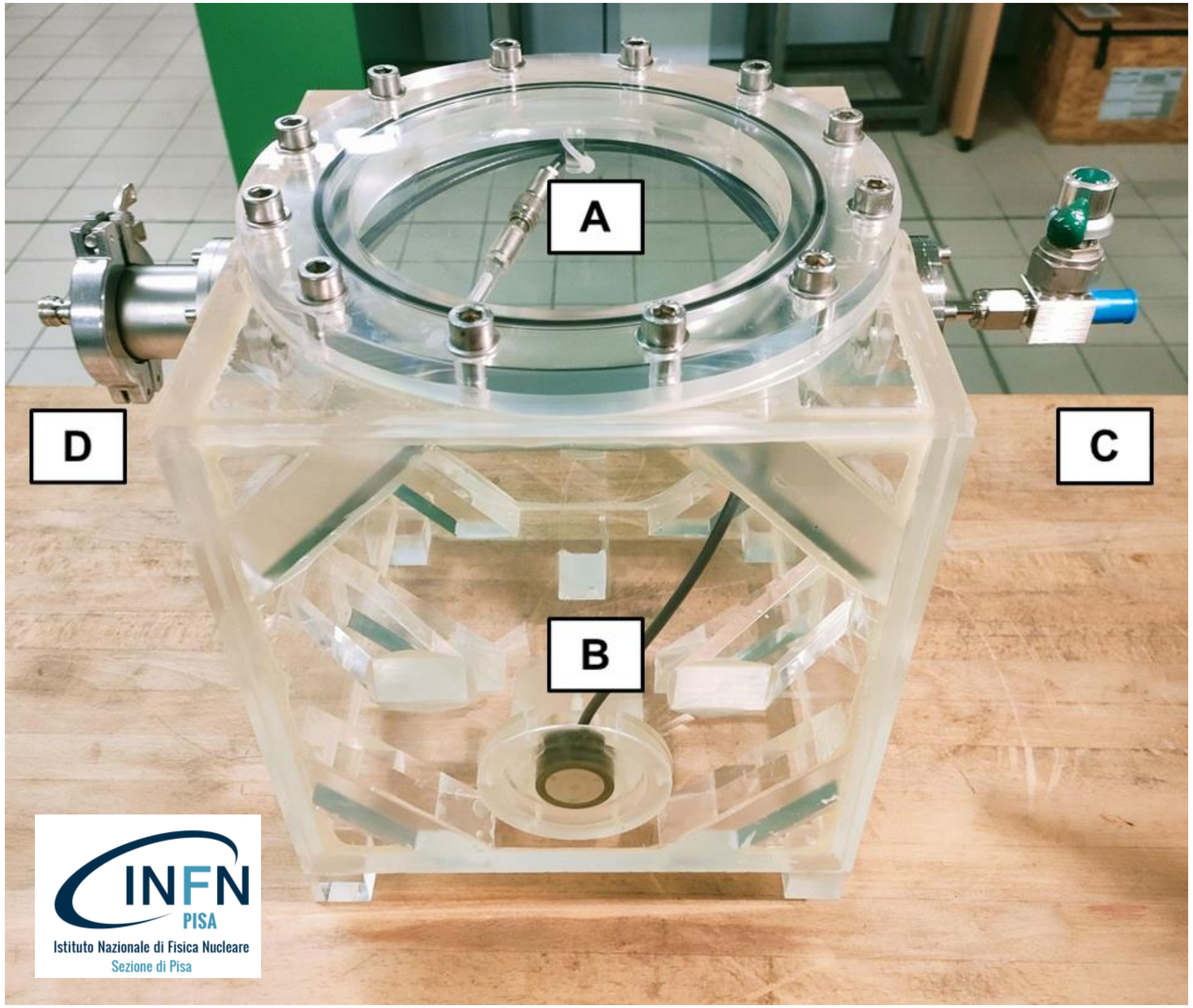
PMMA walls

- Thickness: 12 mm
- Dimensions: 294 x 394 x 309 mm3
- Bonding: Araldite 2011

Components

A. Circular PMMA flange (ISO-F 200)
B. IC holder (10 mm PMMA + 2 mm PEEK)
C. Valve for the gas filling
D. Electrical feedthrough (KF 40, Vacom)





Measurements in nitrogen

Filling gas: nitrogen at 99.99999% purity

- Similarity with air (density, *Z*) → direct comparison with measurements in air
- Easy to handle

Four different pressures: 1000 (atmospheric pressure), 500, 100 and 50 hPa

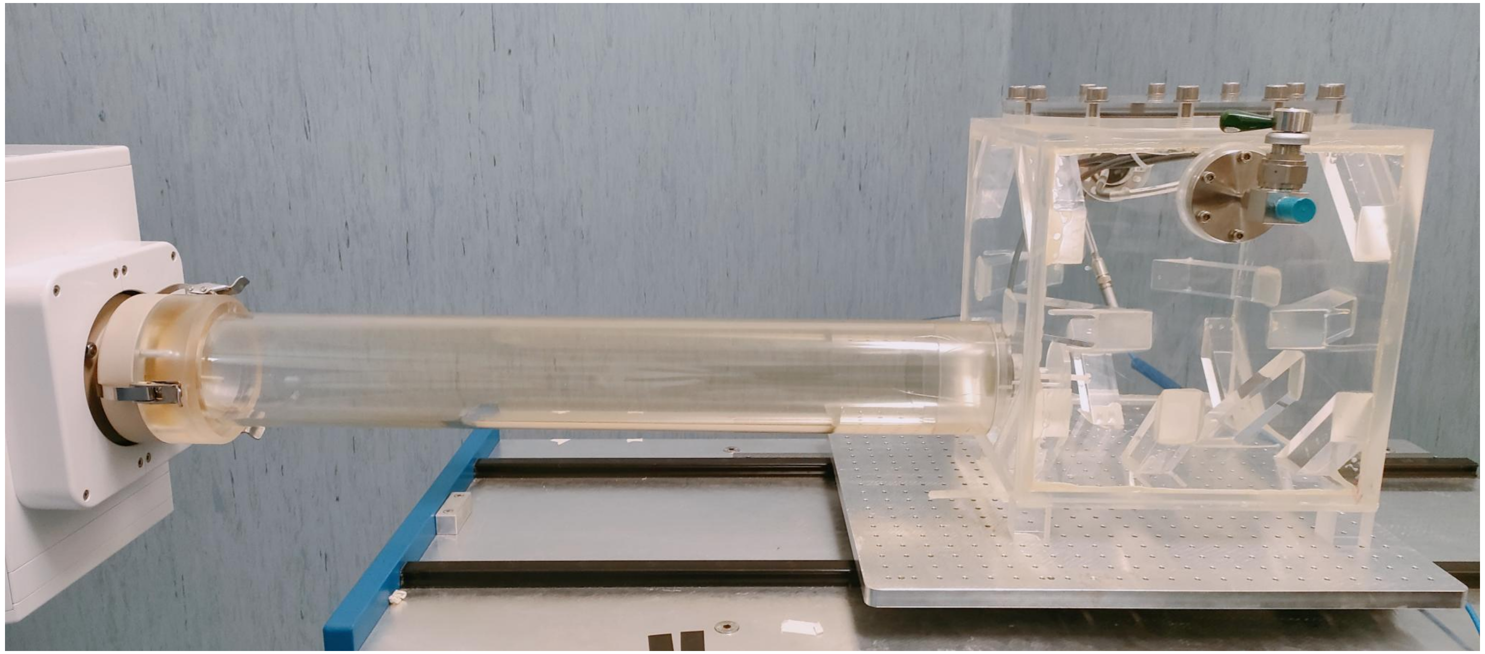
Performance assessment

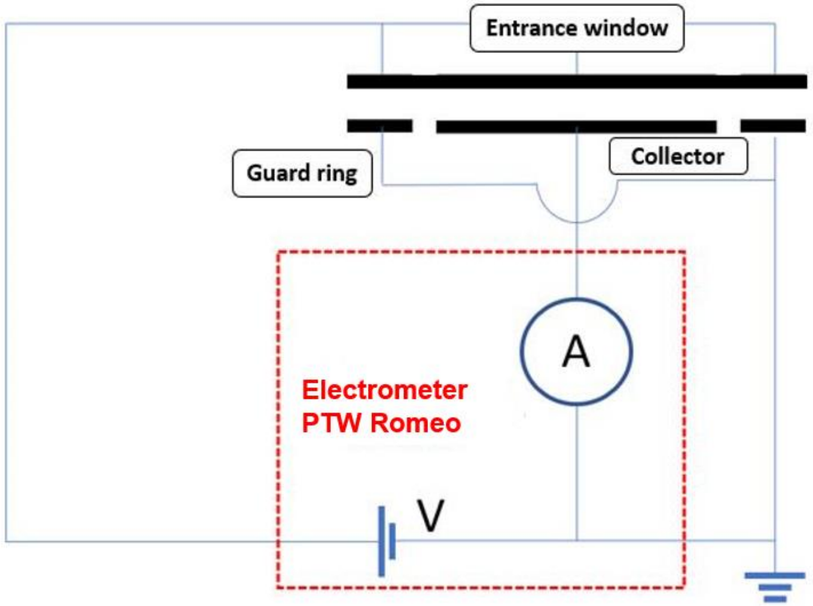
- Comparison with simulated saturation curves → experimental validation of the numerical model
- Linearity of response as a function of the dose per pulse (only for low pressures)

Measurements in nitrogen: experimental setup

ElectronFlash linear accelerator:

- Beam energy: 9 MeV
- Pulse repetition frequency: 20 Hz
- Pulse duration: 4 μs
- No build-up needed

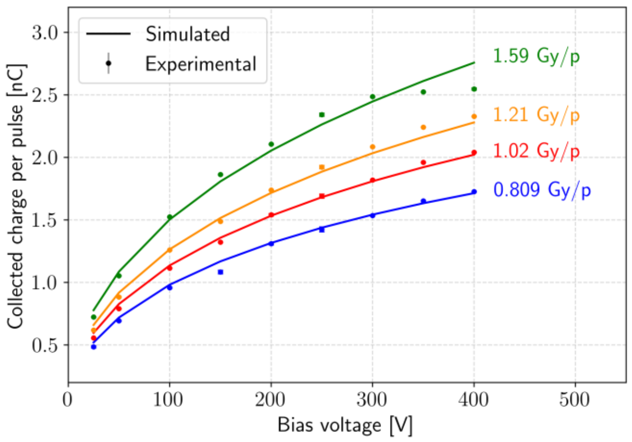


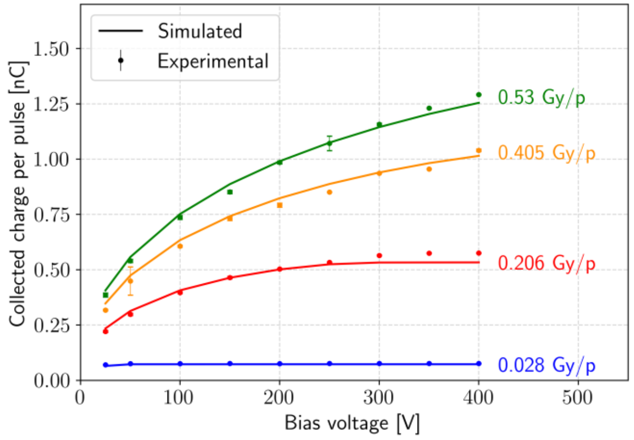


Applicator diameter [mm]	Dose per pulse [Gy]							
100	0.028	0.206	0.405	0.53	0.809	1.02	1.21	1.59
50	0.079	0.581	1.142	1.495	2.28	2.88	3.41	4.48
30	0.17	1.16	2.51	3.86	5.02	6.32	7.4	9.88

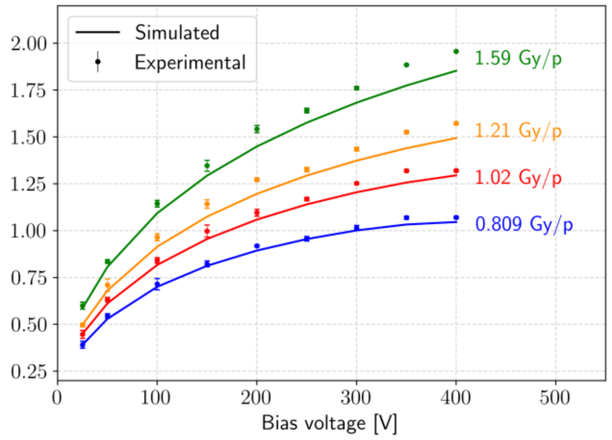
Measurements in nitrogen: comparison with simulations

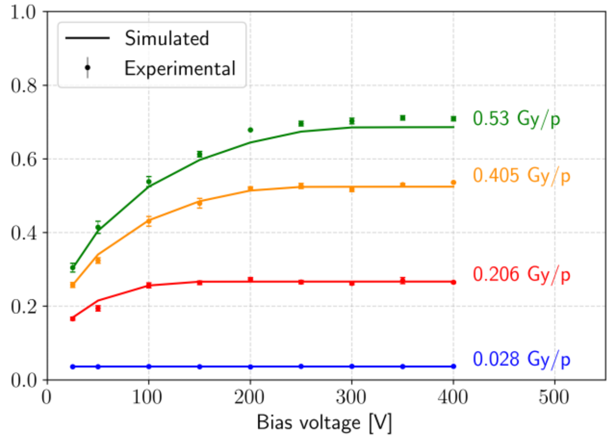
1000 hPa



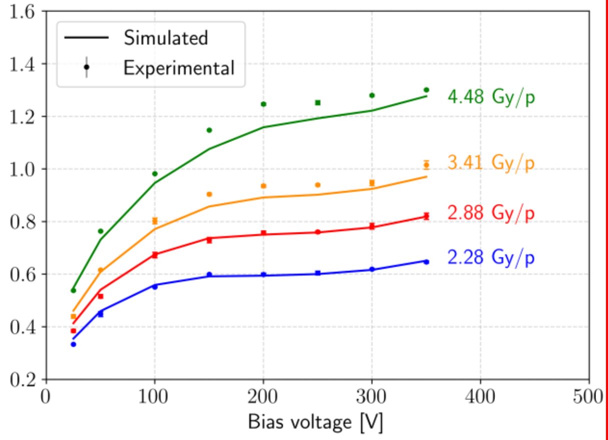


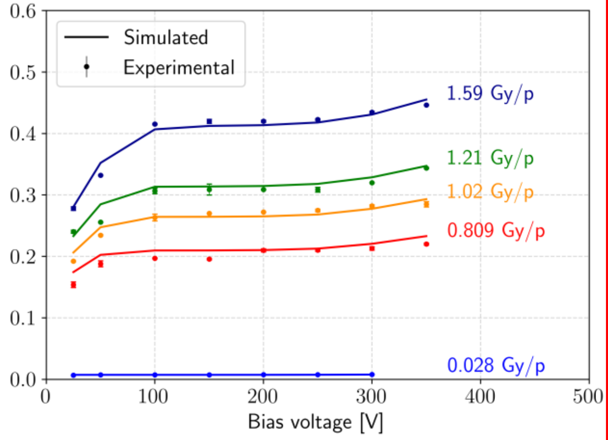
500 hPa



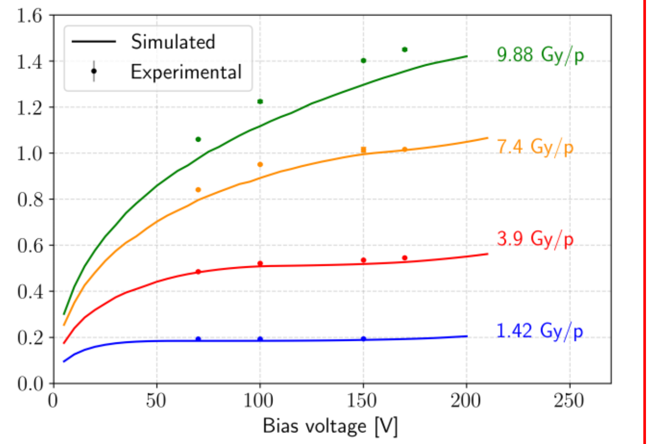


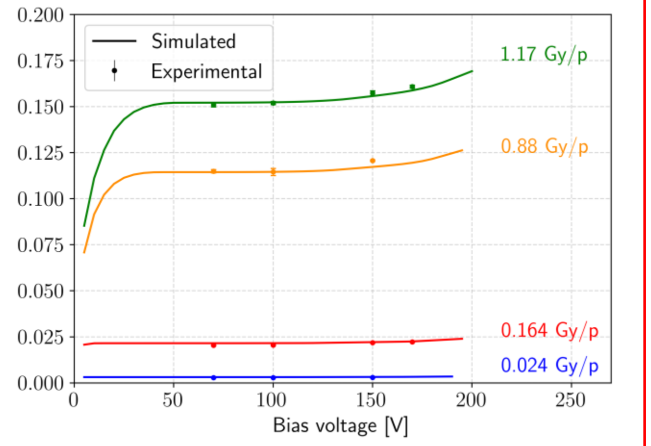
100 hPa





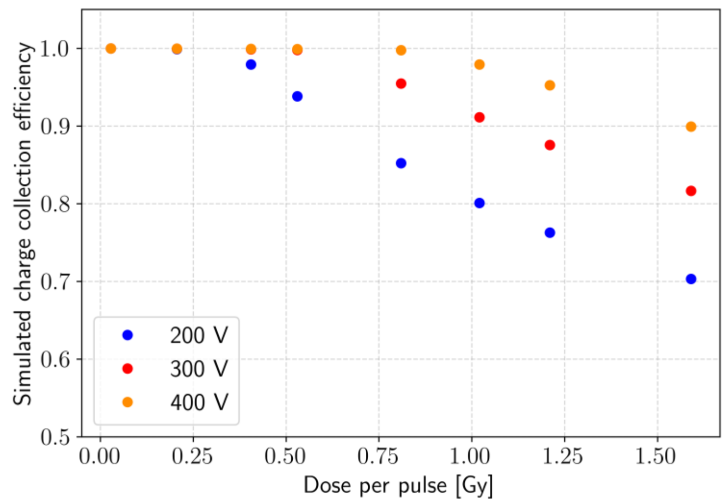
50 hPa

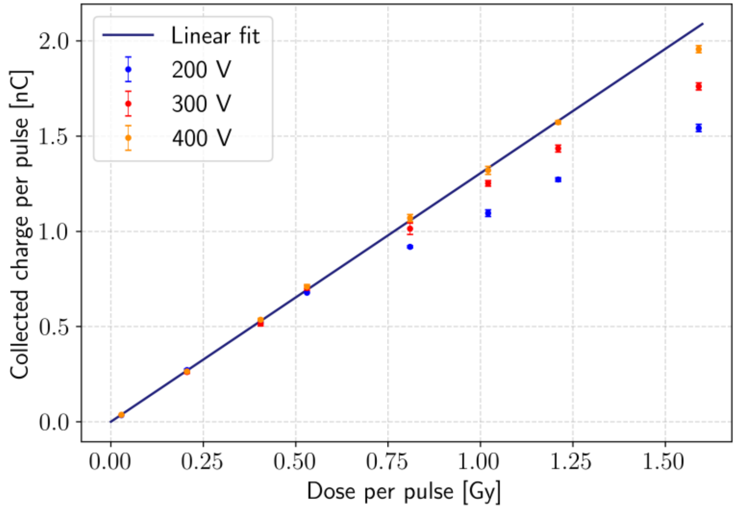




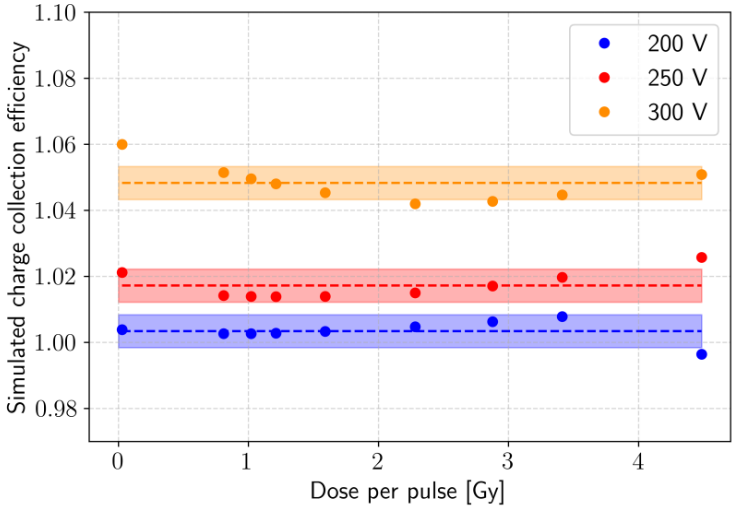
Measurements in nitrogen: assessment of linearity

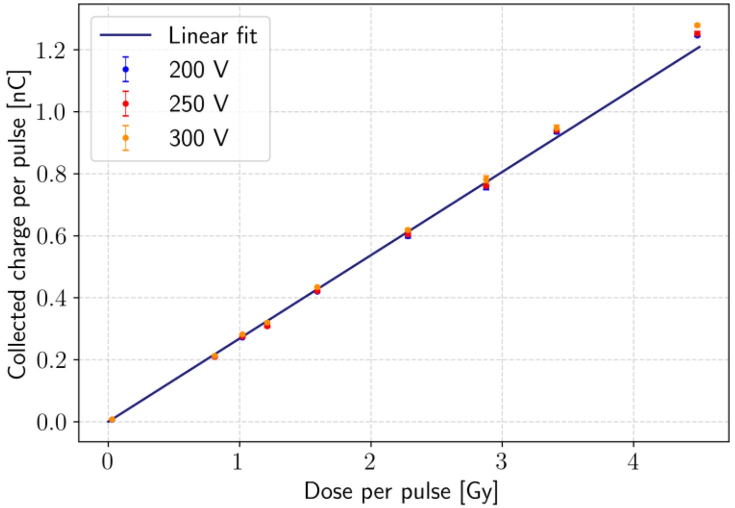
500 hPa



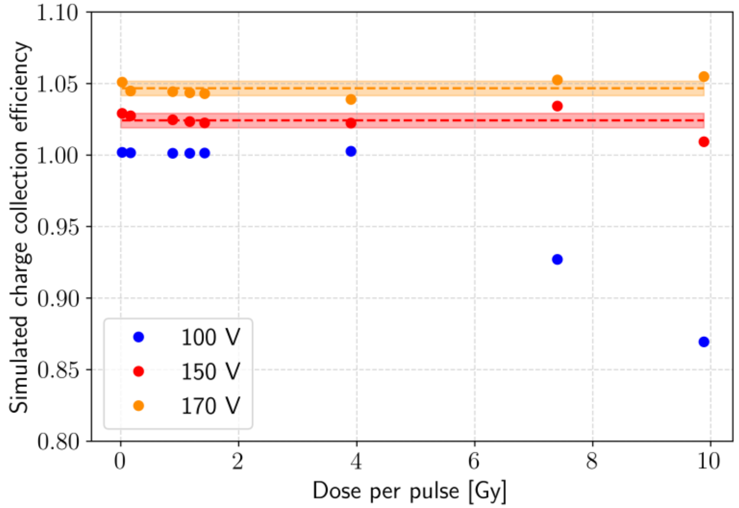


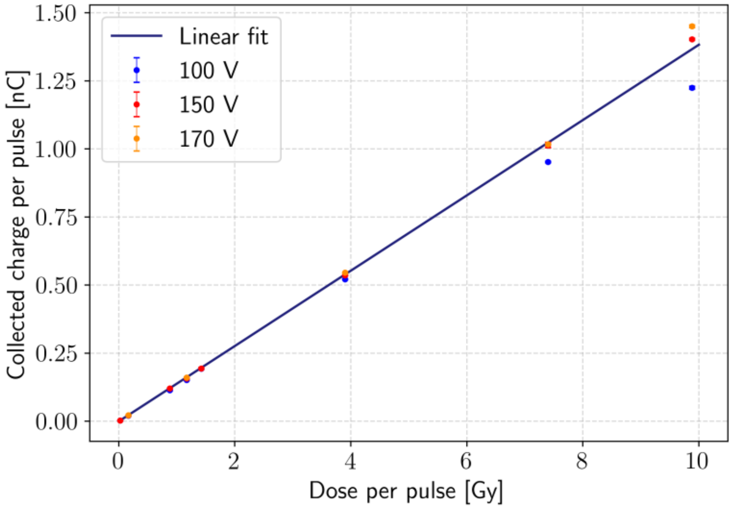
100 hPa





50 hPa





Conclusions

First experimental characterization of a low-pressure N_2 filled PPIC:

✅ Positive assessment of the theoretical design of the ALLS chamber for UHDP measurements

✅ Possibility to use fewer extreme depressurizations

✅ Reliable solution for UHDP dosimetry → promising approach for VHEE future applications

Publications in preparation (under review):

- M. Montefiori et al. “Numerical simulations of charge transport in depressurized noble gases for ultra-high dose per pulse applications” to *Phys. Med. & Biol*.
- M. Montefiori et al. “First experimental characterization of a low-pressure nitrogen filled parallel-plate ionization chamber for UHDP electron beam dosimetry” to *Medical Physics*

Future perspectives:

- Test of other gases and gas mixtures at different pressures
- Further developments toward the ultimate realization of the ALLS chamber

Thank you for your attention!

Marco Montefiori

Department of Physics E. Fermi, University of Pisa

marco.montefiori@phd.unipi.it

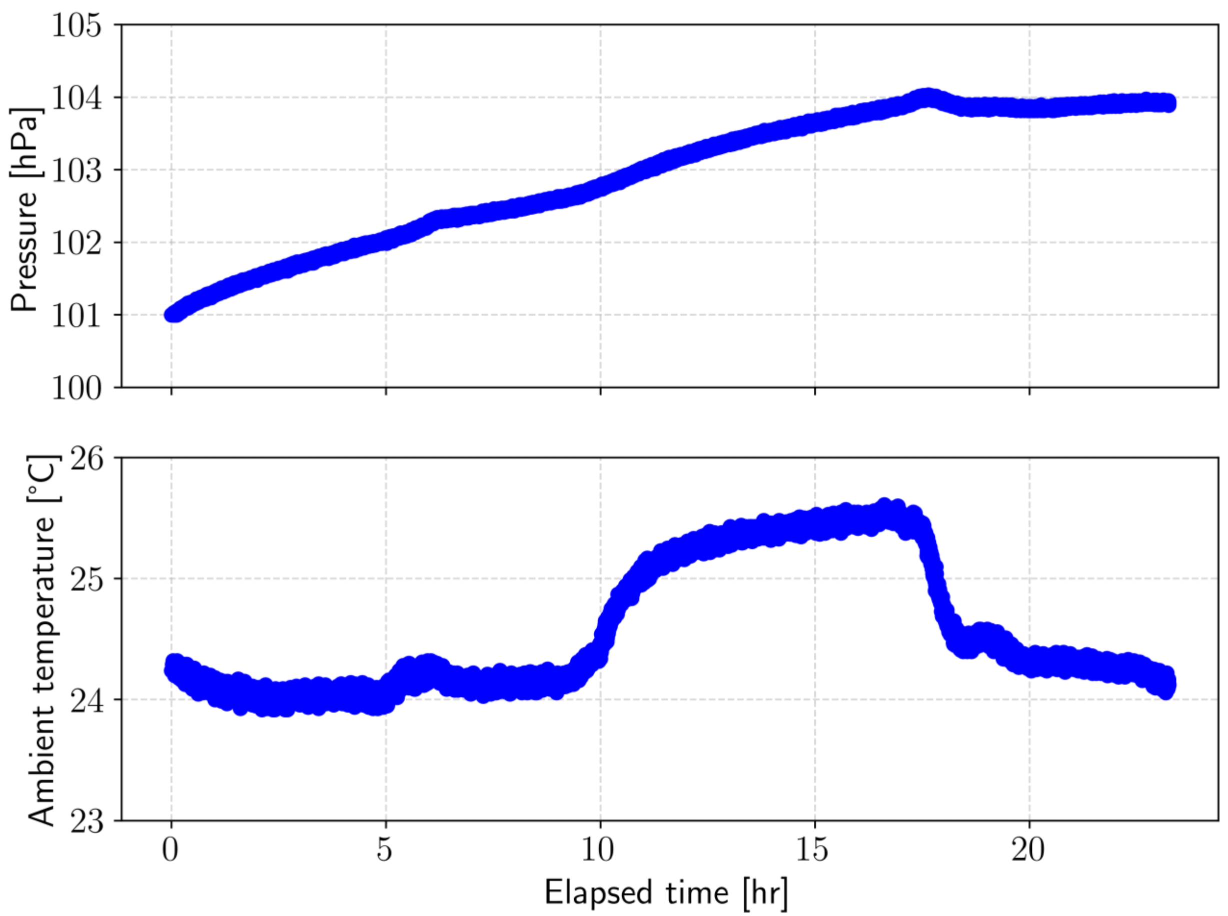
Supporting material

Test of pressure tightness and outgassing

Tested system: vessel + USC prototype + inner components

Estimation of the leak rate

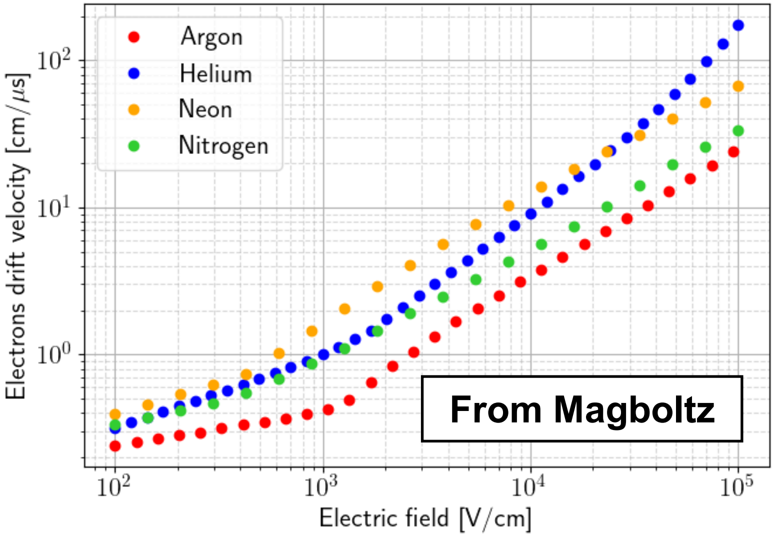
$$\left.\frac{\Delta P}{\Delta t}\right|_{vessel} \simeq 2.8 \cdot 10^{-10}\ \mathrm{hPa} \cdot \mathrm{s}^{-1}$$

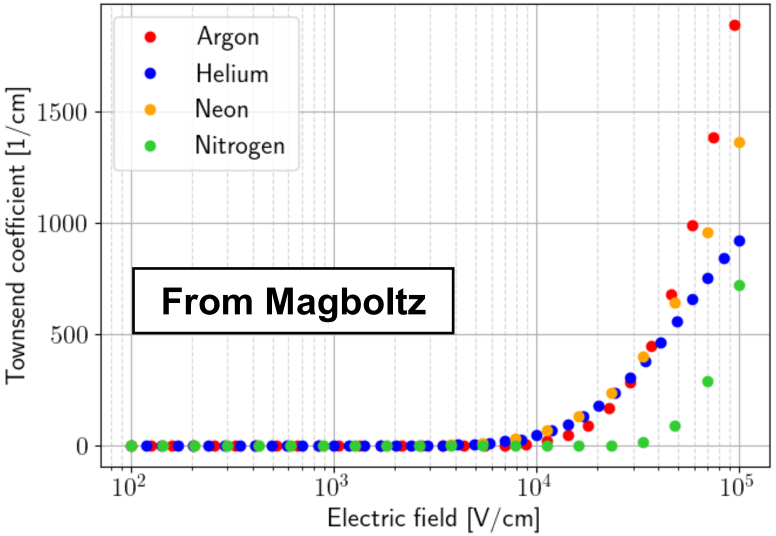


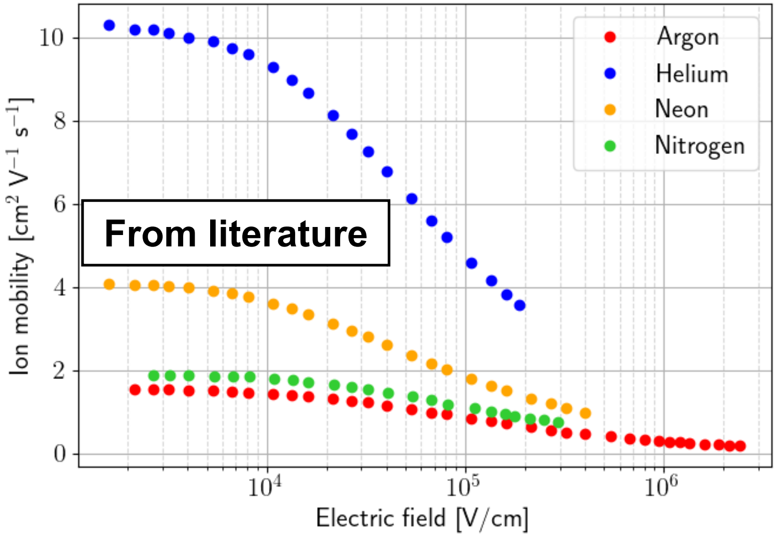
Test of the outgassing

- Filling with 100 (+1 offset) hPa of He
- Monitoring of the inner pressure over 24 h
- Trend: 1 hPa / 5 hours
- Maximum variation: 3 hPa after 17 h

Gas transport parameters: Ar, Ne, He, N







Gas	ρ_0 [kg/m^3]	w_e [eV]
Argon	1.66	26
Helium	0.167	41.8
Neon	0.899	36.2
Nitrogen	1.165	34.8

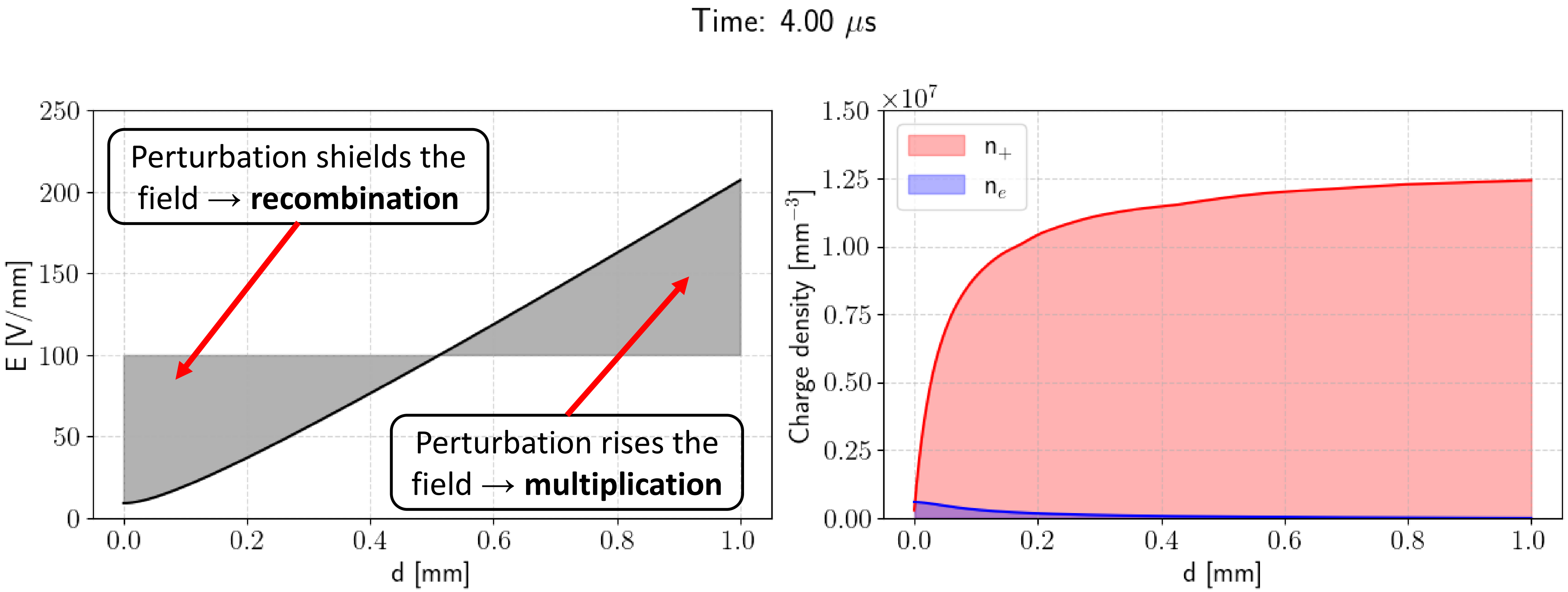
Scaling factor for gas temperature and pressure:

$$k_{TP} = \frac{T}{T_0} \cdot \frac{P_0}{P}$$

Transport parameter	Scaling (vs. E/k_{TP})
Electron drift velocity	v_d
Multiplication coefficient	α/k_{TP}
Ion mobility	$\mu \cdot k_{TP}$

The effects of the electric field perturbation

- Gas: nitrogen, P = 100 hPa, T = 20°
- Beam: 1 Gy/pulse, pulse duration 4 μs
- Chamber: d = 1 mm, 100 V of bias voltage



Preliminary analysis

Aim: study of possible sets of experimental parameters available for UHDP beams

Performance assessment:

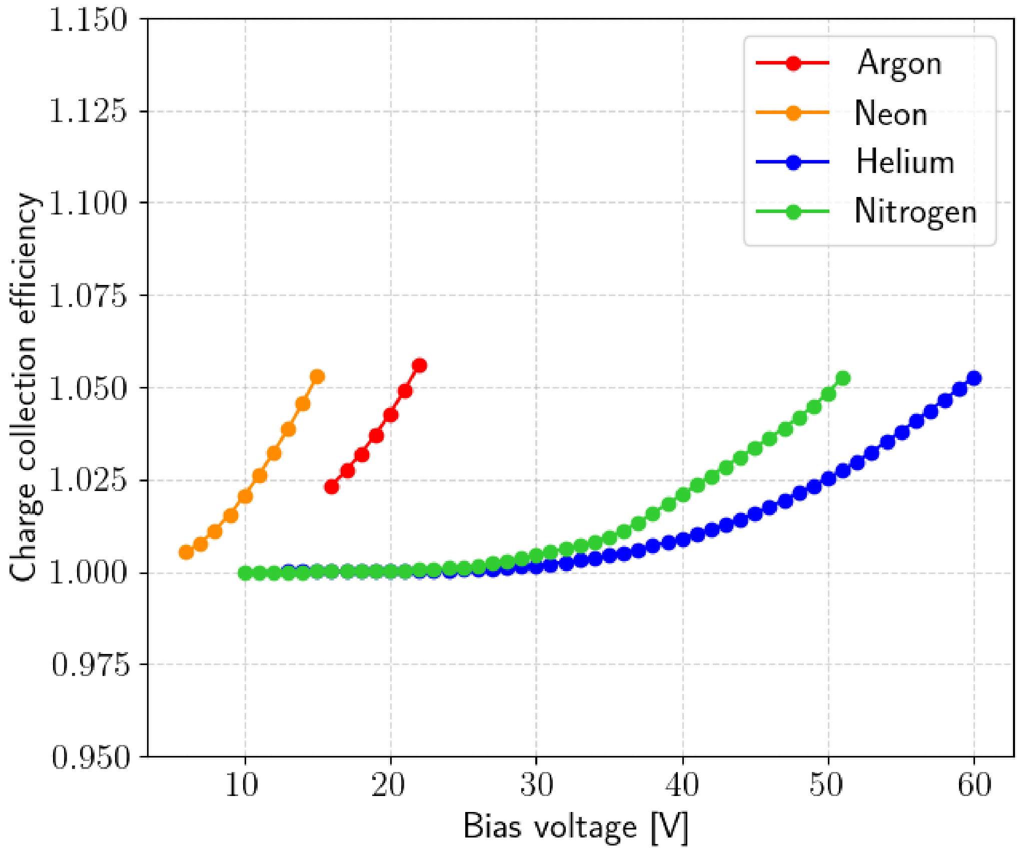
- CCE vs bias voltage
- Explore the operation regime of a PPIC

Evaluation of the impact of the gas properties:

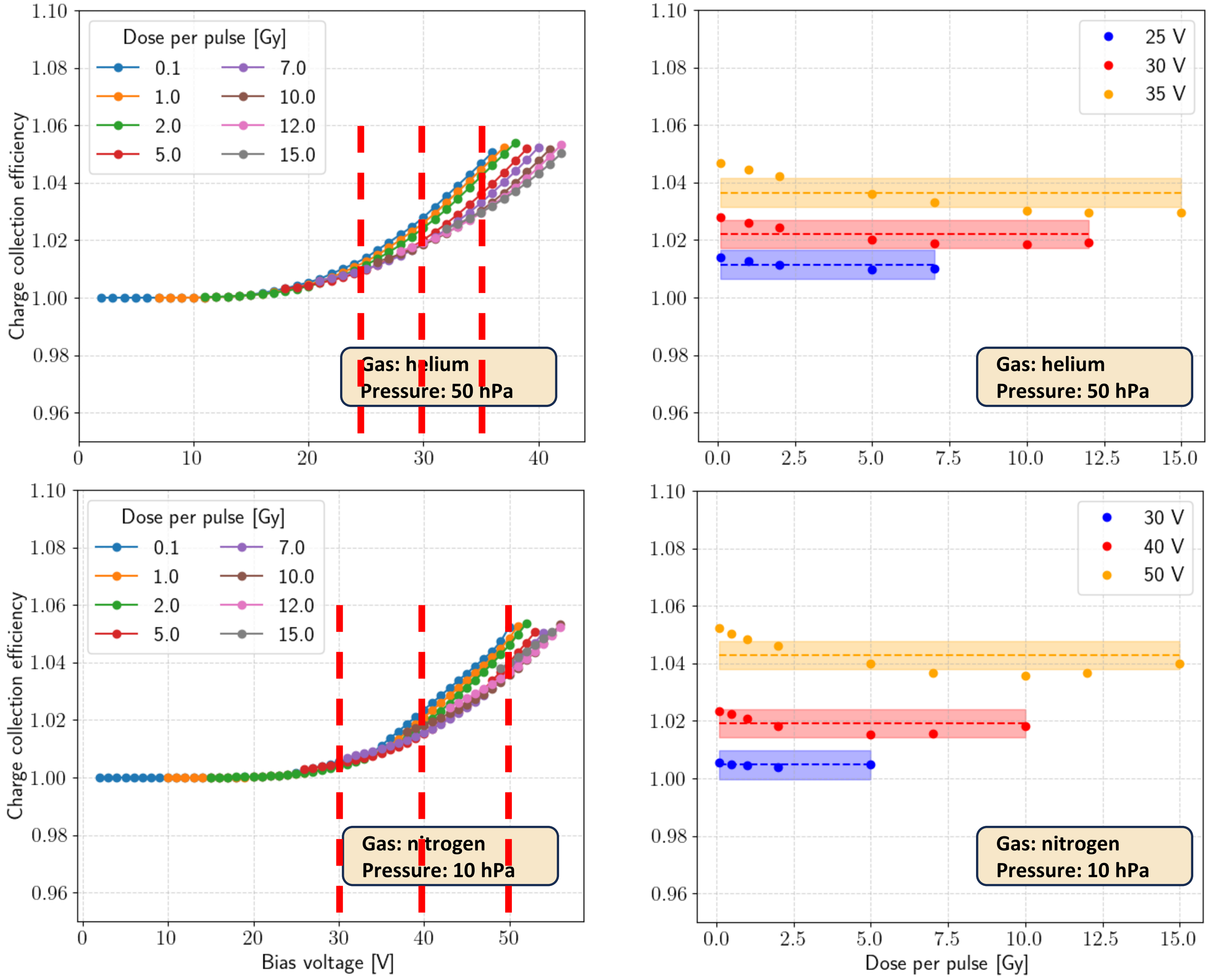
- 1 Gy/pulse, pulse duration 4 μs, d = 1 mm
- 100 hPa for He, 10 hPa for Ar, Ne, N_2

Outcome:

- High presence of multiplication regime
- He and N_2 best candidates for further analysis



Charge collection efficiency as a function of the dose per pulse



Helium at 50 hPa

- Field shielding close to entrance
- Stability up to 12 Gy/p at 30 V

Nitrogen at 10 hPa

- Multiplication close to collector
- Stability up to 10 Gy/p at 40 V