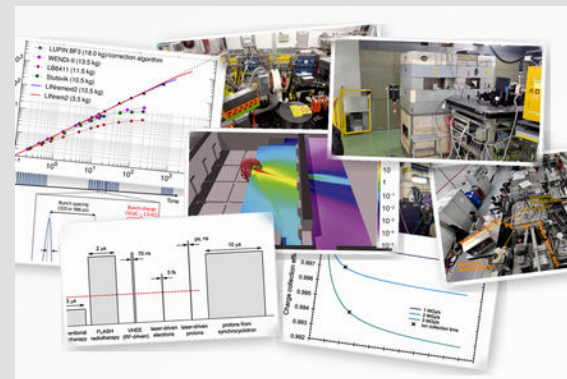




Addressing Modern Challenges in Neutron Dosimetry: The LINrem Approach

Ariel Tarifeño-Saldivia, PhD

Instituto de Física Corpuscular (IFIC)
CSIC – Universidad de Valencia
Valencia, Spain

Contact: atarisal@ific.uv.es

Coordinated Spanish R&D project



www.linrem.tech

GAPS AND CHALLENGES ACTIVE REM-COUNTERS



- Big science projects
- Particle therapy facilities
- Industrial applications

Examples of REM meters:

Neutrons can dominate the total radiation dose received by workers, patients and public. **Proper detection techniques of neutrons are required** (energy sensitivity, time structure, real time monitors).

Gaps in most commercial solutions:

- Classical technology: radiation sensor (60's), acquisition/read-out (90-2000's)
- **Portability, 9-18kg** per unit.
- **Poor response** for high neutron energies ($> 20\text{MeV}$).
- **Not well suited for complex quasi-continuous or pulsed neutron fields.**

See talk by M. Caresana!

Some challenges & needs:

+ **High energy neutron fields in particle therapy facilities** (complex time structure).

+ Beam losses in synchrotron or cyclotron facilities (**sudden pulsed fields**).

+ Pulsed sources for fundamental research and applications (spallation, fusion neutron sources or **high intensity lasers, flash therapy**)

+ **New recommendations for operational quantities (ICRU 95, 2020)**

See talks by V. Olšovcová, A. Leuschner, A. Malyzhenkov!



Berthold
LB6411



Studsvik
2222A



WENDI-2



LUPIN
BF3-NP



LINrem project

LINrem dosimeters: two detector designs



LINrem:

Lightweight system

- + Thermal up to **10 MeV**
- + Portability: **3.6 kg**

LINrem: active versions

- **$\pm 10\%$ overall accuracy** from experimental benchmarks.
- **Sub-millisecond** time response
- **Pulsed field:** linear response up to **1 $\mu\text{Sv/bunch}$**



LINremext:

Extended energy range

- + Thermal up to **10 GeV**
- + Portability: **10.6 kg**

MAIN APPLICATIONS: active versions

LINrem3

- + Nuclear power plants
- + Industrial applications with neutrons
- + D-D Fusion and Laser-driven neutron sources
- + Small accelerators & research laboratories
- + Radiotherapy facilities

LINremext3

- + Proton and light ion therapy
- + Ultra-high dose rate (FLASH) therapy
- + D-T Fusion
- + Large and high intensity particle accelerator facilities
- + Aircrew and Space crew dosimetry



LINpass: passive versions

- + **Absolute $H^*(10)$** measurement with direct traceability for radioprotection
- + **Dual TLD configuration** for low and high dose rate environments
- + No batteries, zero dead-time, reliable in mixed fields (γ/n)

LINpass main applications

- + Nuclear power plants
- + Research facilities
- + Radiotherapy facilities
- + Aircrew and Space crew dosimetry



PRECISION DOSIMETRY



TIME-RESOLVED DOSIMETRY



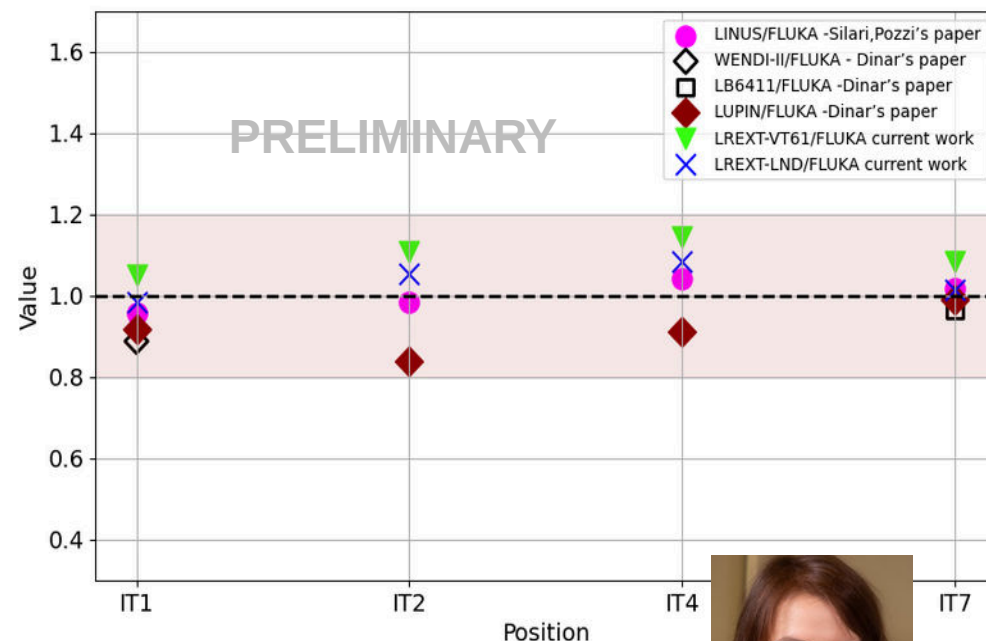
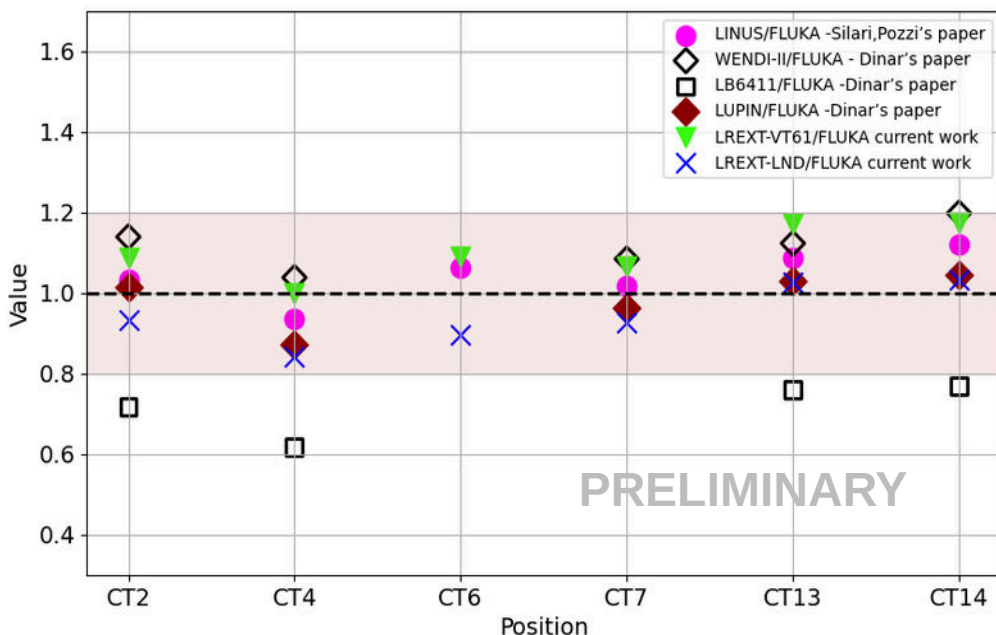
PULSED FIELD RESPONSE



SUPERIOR PORTABILITY

RESPONSE OF REM-COUNTERS IN WIDE ENERGY NEUTRON FIELDS

REM counters over the concrete (CT) and iron roof (IT) normalized to CERF reference values



Detector	CT Average Relative Error %	IT Average Relative Error %
LREXT-VT61	8.4	9.8
LREXT-LND	6.8	3.4
WENDY-II	10.9	11.9
LUPIN	5.3	15.4
LINUS	6.3	2.8
LB6411	33.3	20.3

LINrem data:

Benedetta Brusasco
PhD thesis (UPC)



CERF Facility (Pozzi & Silari, 2020):

[10.1016/j.nima.2020.164477](https://doi.org/10.1016/j.nima.2020.164477)

Instrument intercomparison (Dinar et al, 2018):

[10.1016/j.radmeas.2018.05.008](https://doi.org/10.1016/j.radmeas.2018.05.008)

- Maximum relative response deviation is within $\pm 20\%$. This sets the **maximum acceptable irradiation tolerance** when the energy spectrum/distribution is unknown.
- Any deviation $>20\%$ should be treated as a **systematic effect** (instrument performance), e.g., due to **non-standard conditions such as pulsed radiation fields**.



Contents lists available at ScienceDirect

Nuclear Instruments and Methods in
Physics Research A

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



2014

EURADOS
intercomparison
exercise



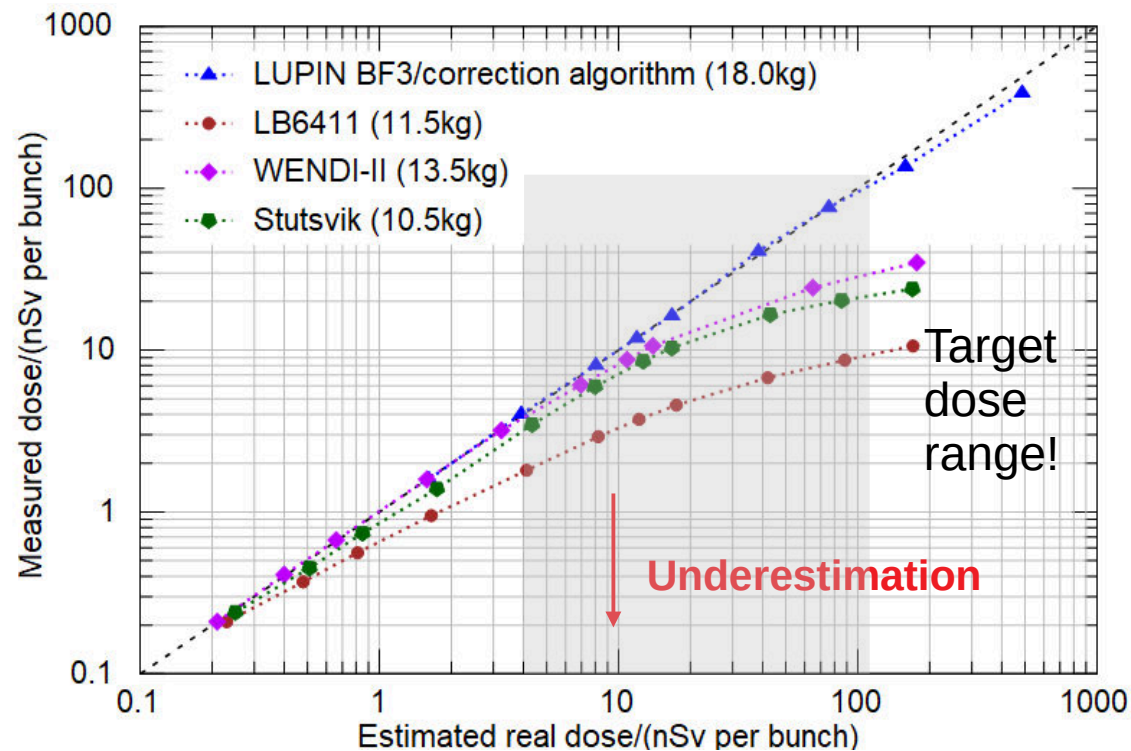
Intercomparison of radiation protection instrumentation in a pulsed neutron field

M. Caresana^{a,*}, A. Denker^b, A. Esposito^c, M. Ferrarini^d, N. Golnik^e, E. Hohmann^f,
A. Leuschner^g, M. Luszik-Bhadra^h, G. Manessi^{i,j}, S. Mayer^f, K. Ott^k, J. Röhrich^b, M. Silariⁱ,
F. Trompieri^l, M. Volnhals^m, M. Wielunski^m

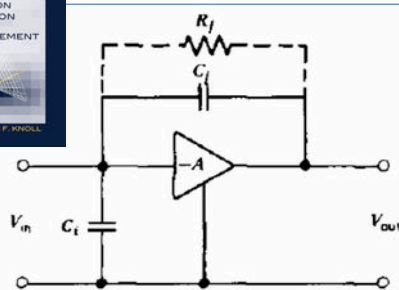
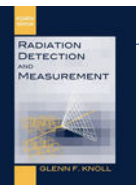
- Most of the commercial dosimeters are not suited for pulsed neutron fields (pile-up effect). **They present underestimation of the dose beyond 10 nSv/burst.**
- Dosimeters based on activation (AGREM, REM-2) do not suffer pile-up effect; however they do not provide online shot-to-shot monitoring.
- Latest dosimeters based on proportional counters rely on LOG-current preamplifiers and make use of pile-up correction models.

$$D_{ref} = \frac{D_{meas}}{1 - (D_{meas}/D_{half})} \quad (5)$$

The response curves were fitted by expression (3) in order to deduce D_{half} for each detector. The results are listed in Table 5 and the experimental data corrected by Eq. (5) are plotted in Fig. 4. Starting from D_{half} one can calculate the half response signal (HRS)



COUNTING NEUTRONS BY CHARGE INTEGRATION



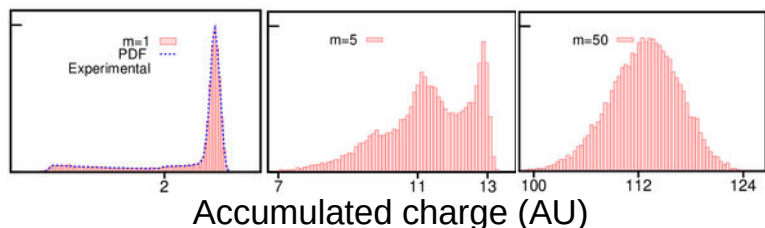
Assume $A \gg (C_i + C_f)/C_f$

$$V_{out} = -A V_{in}$$

$$V_{out} = -A \frac{Q}{C_i + (A+1)C_f}$$

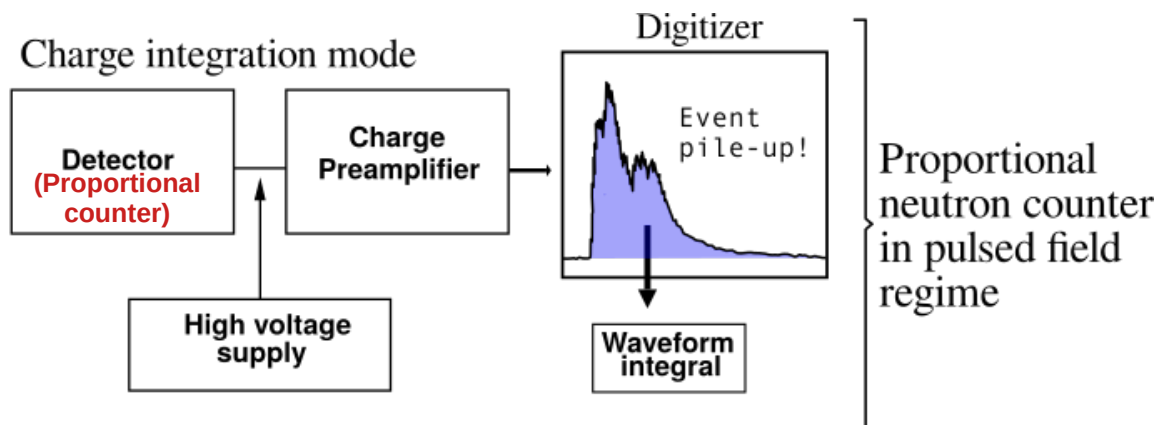
$$V_{out} \approx -\frac{Q}{C_f}$$

Figure 17.2 Simplified diagram of a charge-sensitive preamplifier configuration. If the conditions indicated are met, the output pulse amplitude becomes independent of the input capacitance C_i . The time constant given by the product $R_f C_f$ determines the decay rate of the tail of the output pulse.



Concept proposal by R. Mayer (CAB, Argentina)

$$\langle N_{events} \rangle = Q_{Total} / \bar{q}_{single}$$



Moreno+ 2008, Tarifeño-Saldivia+ 2010, Tarifeño-Saldivia+ 2014

IOP PUBLISHING

Meas. Sci. Technol. **19** (2008) 087002 (5pp)

MEASUREMENT SCIENCE AND TECHNOLOGY

doi:10.1088/0957-0233/19/8/087002

TECHNICAL DESIGN NOTE

System for measurement of low yield neutron pulses from D-D fusion reactions based upon a ^3He proportional counter

José Moreno^{1,2}, Lipo Birstein¹, Roberto E Mayer^{3,4}, Patricio Silva¹ and Leopoldo Soto^{1,2}

Practical implementation: neutron detectors for pulsed fusion neutron sources

REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 013502 (2014)



Calibration methodology for proportional counters applied to yield measurements of a neutron burst

Ariel Tarifeño-Saldivia,^{1,a)} Roberto E. Mayer,² Cristian Pavez,¹ and Leopoldo Soto¹

¹Comisión Chilena de Energía Nuclear, Casilla 188-D, Santiago, Chile; Center for Research and Applications in Plasma Physics and Pulsed Power, P¹, Santiago, Chile; and Departamento de Ciencias Físicas, Facultad de Ciencias Exactas, Universidad Andres Bello, Republica 220, Santiago, Chile

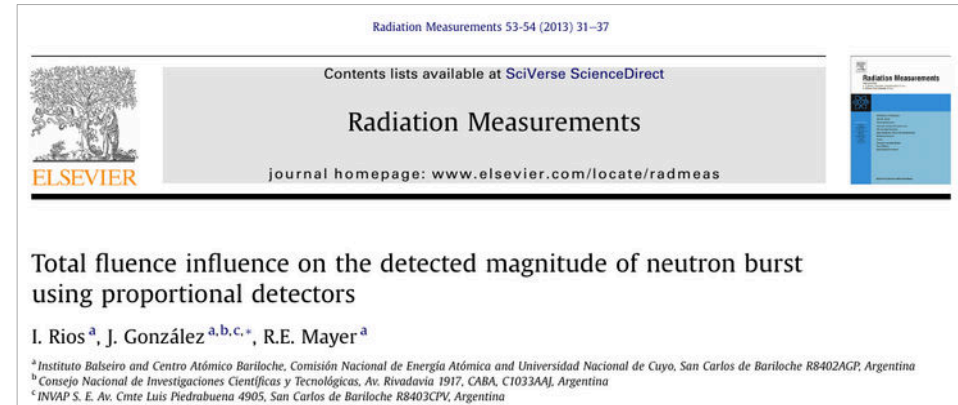
²Instituto Balseiro and Centro Atómico Bariloche, Comisión Nacional de Energía Atómica and Universidad Nacional de Cuyo, San Carlos de Bariloche R8402AGP, Argentina

(Received 25 April 2013; accepted 23 November 2013; published online 6 January 2014)

Formal concept for proportional neutron counters: Counting statistical model, single-shot uncertainties, etc.

NON-LINEAR EFFECTS IN PROPORTIONAL NEUTRON COUNTERS

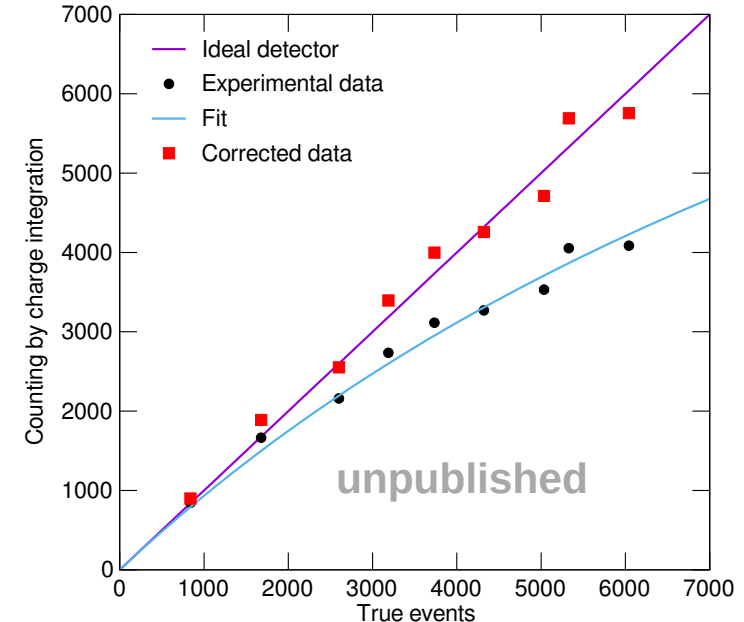
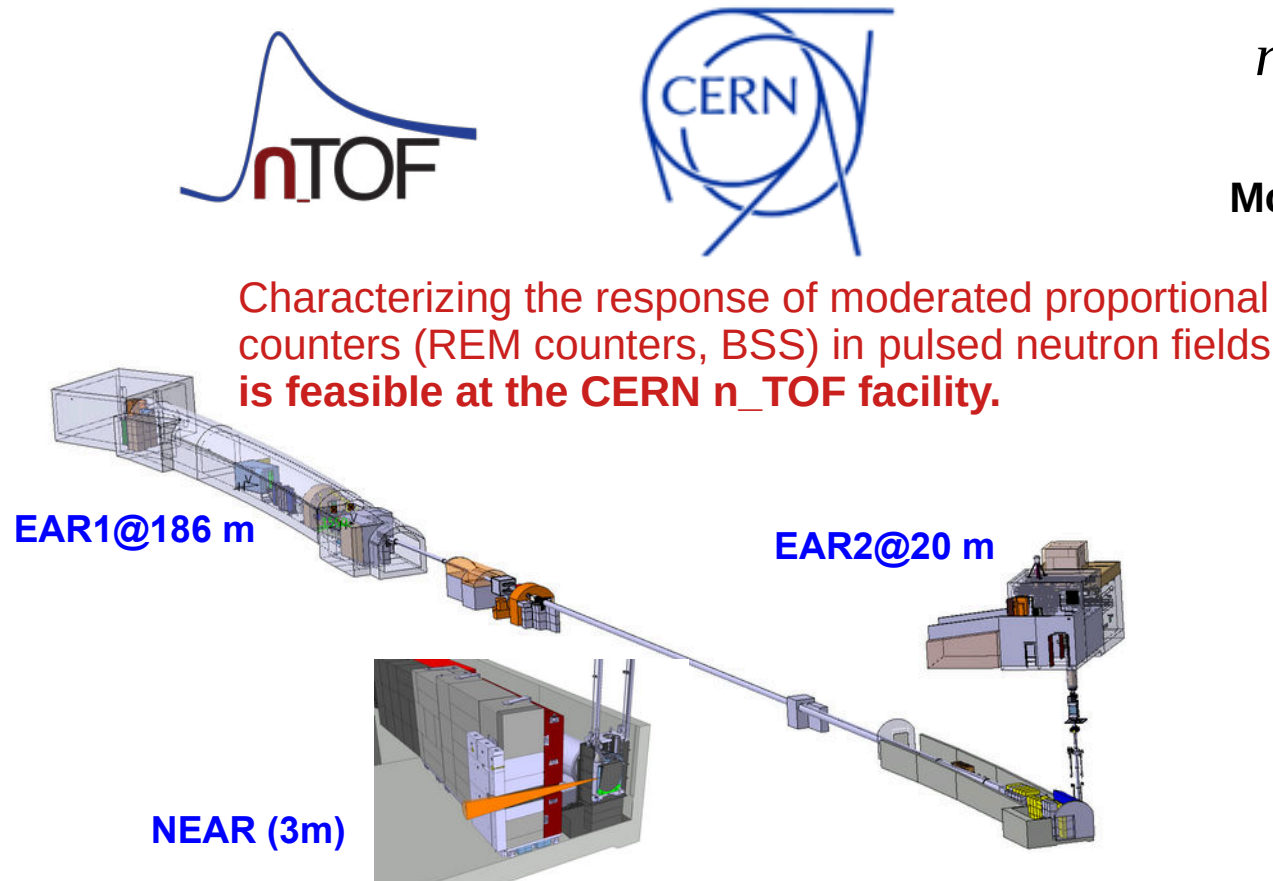
- At very high burst doses, space-charge accumulation in the proportional counter reduces gas gain → non-linear response
- Correction model (Ríos et al., 2013) enables restoring linearity, **but a pulsed facility for detector characterization is required.**



Correction model by loss of linearity (space-charge effects)

$$n_{obs} = n_{true} / (1 + c \cdot n_{true})$$

Moderated ^3He -filled neutron counter



Ambient dosimetry in pulsed neutron fields with LINrem detectors

Ariel Tarifeño-Saldivia^{a,b,*}, Francisco Calvino^b, Alfredo De Blas^b, Benedetta Brusasco^b, Adrià Casanovas-Hoste^b, Ana M. Cives^c, Guillem Cortés^b, Roger García^b, Francisco Molina^{d,f}, Nil Mont-Geli^b, Max Pallàs^b, Cristian Pavez^{e,f}

^a Instituto de Física Corporal (CSIC-UV), Catedrático José Beltrán 2, Paterna, E-46980, Spain

^b Institut de Tècniques Energètiques, Universitat Politècnica de Catalunya, Av. Diagonal 647, Barcelona, E-08028, Spain

^c Centro de Estudios Prolados (CEPU), Edificio MS, Parque Científico, C/Adolfo, 8, Villanueva, Salamanca, 37185, Spain

^d Centro de Investigación en Física Nuclear y Espectroscopia de Neutrones CEPNN, Comisión Chilena de Energía Nuclear, Nueva Bilbao 12501, Las Condes, Santiago, Chile

^e Comisión Chilena de Energía Nuclear, Center for Research in the Intersection of Plasma Physics, Matter and Complexity, P2nc, Nueva Bilbao 12501, Las Condes, Santiago, Chile

^f Departamento de Ciencias Físicas, Facultad de Ciencias Exactas, Universidad Andrés Bello, República 220, Santiago, Chile

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Pulsed fields
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ABSTRACT

The status of the LINrem project is presented, focusing on the development of innovative neutron dosimeters with enhanced energy sensitivity, time resolution, and portability. Designed to meet the technical demands of radiation protection in modern particle and nuclear facilities, these dosimeters are discussed in detail. Results from experimental campaigns showcasing their efficacy in pulsed fields generated by fusion plasmas and high-intensity pulsed lasers are presented. Additionally, prospects and future plans for the LINrem project are outlined.

1. Introduction

Monitoring neutron dose rates is crucial to ensure minimal risks for workers, patients, and the public in different facilities. At the level of operational radiological protection, the most common monitors are known as ambient neutron dosimeters. These systems employ typically a thermal neutron sensor embedded in a High Density Polyethylene (HDPE) moderator. Commercial devices typically utilize proportional neutron counters, gas ionization detectors employing ³He or BF₃ as the active medium, and operating in the proportional region. The ideal ambient neutron dosimeter has an energy response that mimics the energy-dependent function of the recommended conversion factor from fluence to ambient dose equivalent ($H^*(10)$), ensuring that the recorded dose is proportional to the number of detected events. Therefore, the design criterion for the moderator geometry is to match this energy-dependent shape. However, achieving a perfect match between the response of a moderated proportional neutron counter and the shape of the conversion factor function is unattainable in practice. Generally, commercial dosimeters tend to overestimate the dose in the intermediate energy region (0.1 eV–100 keV) and significantly underestimate doses for energies exceeding 10 MeV or 20 MeV (Tanner et al., 2007b), depending on their design. Certification standards account for these

potential deviations by specifying tolerance ranges in the energy response of such dosimeters (International Electrotechnical Commission, 2017). To address energies greater than 20 MeV (high-energy facilities), extended energy range dosimeters employ high atomic number neutron multiplying materials thereby enhancing dosimetric sensitivity for energies larger than 20 MeV (Burrattari et al., 1998). In Table 1 is provided a compilation of the main commercial dosimeters routinely used in industrial facilities, such as nuclear reactors, processing or storage plants for combustible materials, irradiation laboratories, as well as in research facilities, such as particle accelerators, or medical facilities. Despite compilation in Table 1 is not exhaustive, it provides a summary of the state-of-the-art technology in ambient neutron dosimeters.

In this work, we present a brief overview of the LINrem project, which focuses on enhancing neutron dosimetry, particularly for pulsed neutron fields and applications in medical facilities such as proton therapy centers. The LINrem project aims to develop innovative neutron dosimeters with enhanced energy sensitivity, time resolution, and portability. Although a detailed description of the development of the LINrem detectors will be reported in a separate publication, a brief description is provided here. This manuscript highlights the utilization of Monte Carlo numerical optimization techniques, digital electronics,

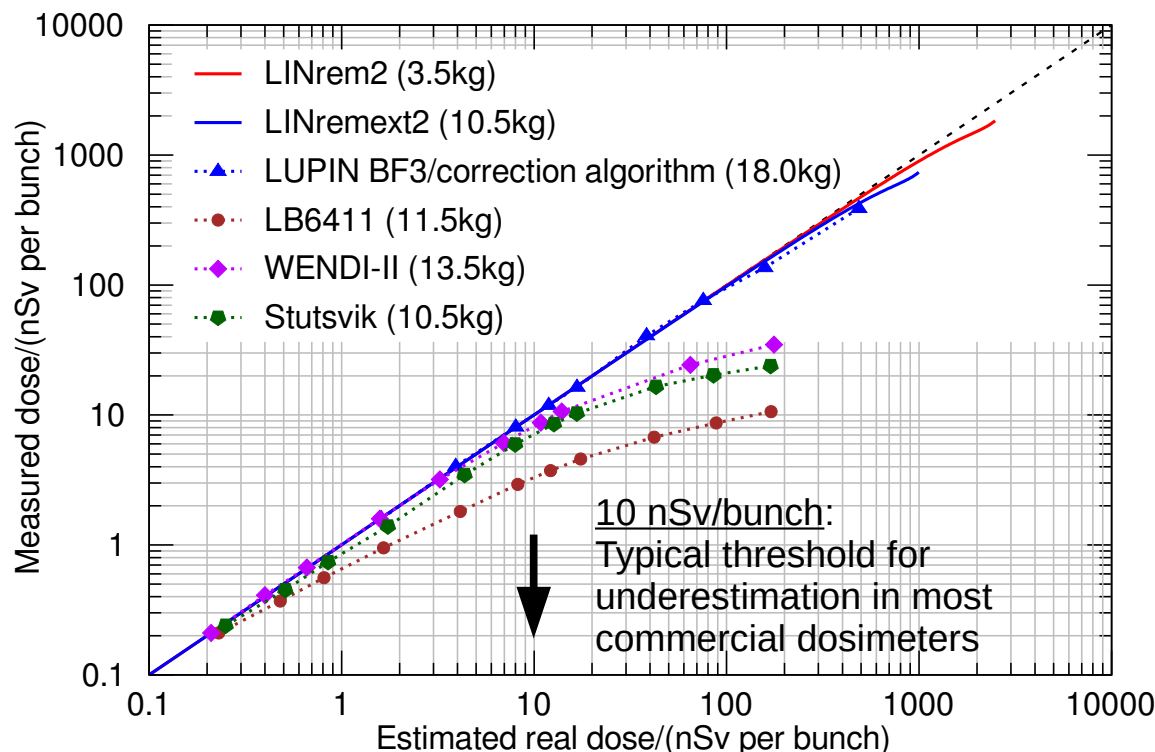
* Corresponding author at: Instituto de Física Corporal (CSIC-UV), Catedrático José Beltrán 2, Paterna, E-46980, Spain.
E-mail address: atarisai@ific.uv.es (A. Tarifeño-Saldivia).

<https://doi.org/10.1016/j.radphyschem.2024.112101>

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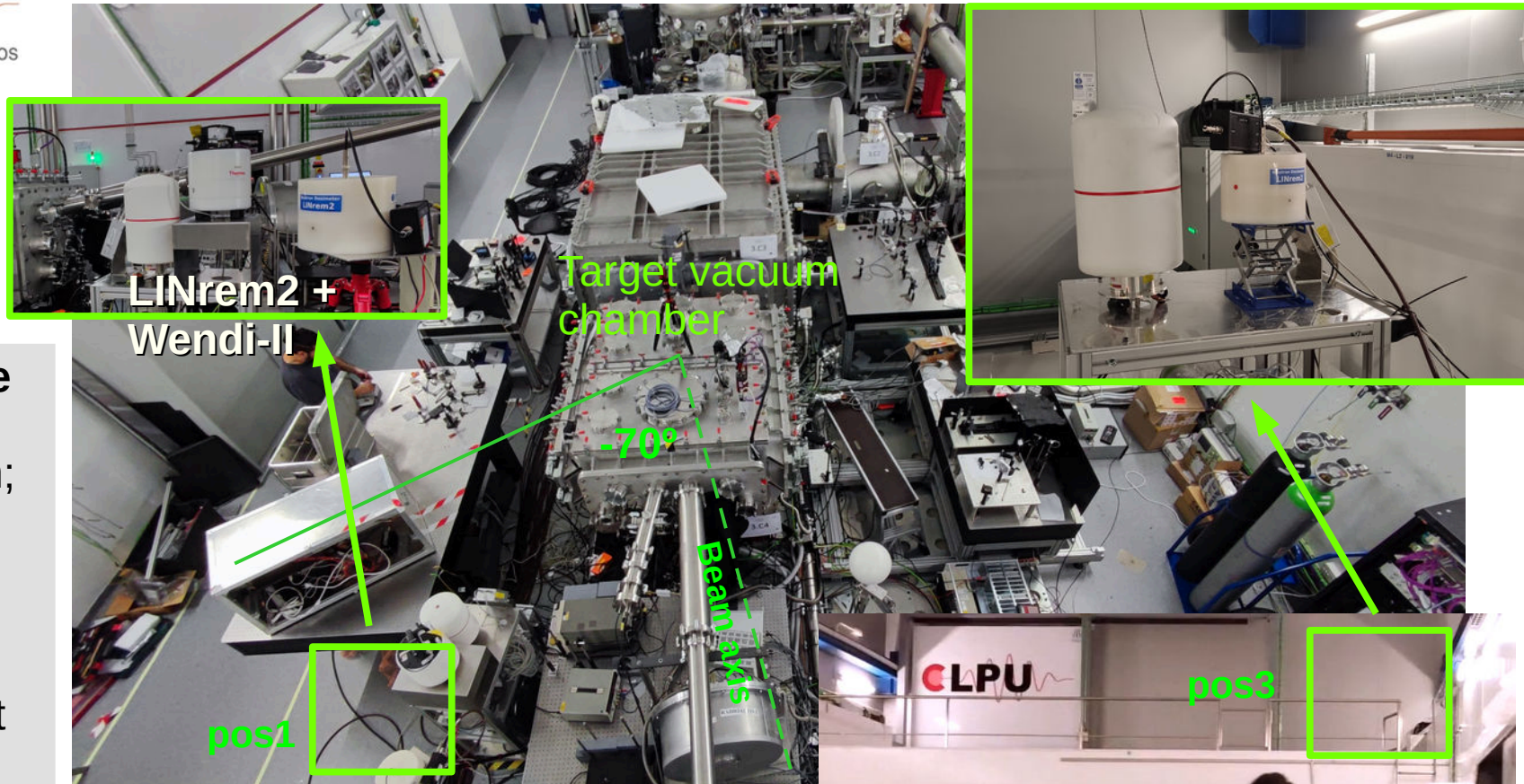


Dosimeter data from EURADOS intercomparison exercise, NIMA 737 (2014) 203-213

<https://doi.org/10.1016/j.radphyschem.2024.112101>

APPLICATION EXAMPLE: Dosimetry in laser-driven neutron sources

Experiment: *"Laser-driven neutrons for nuclear physics experiments and applications at CLPU"*, ref: 00458-0101 , Spokesperson: C. Guerrero (US, CNA)



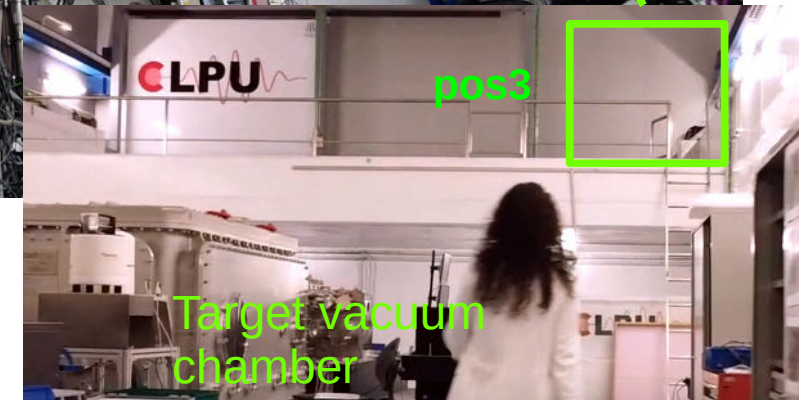
Neutron source at CLPU:

$7\text{Li}(p,n)$ reaction; significant neutron production expected from 100 keV up to at least ~ 5 MeV.

VEGA3 (1 PW):

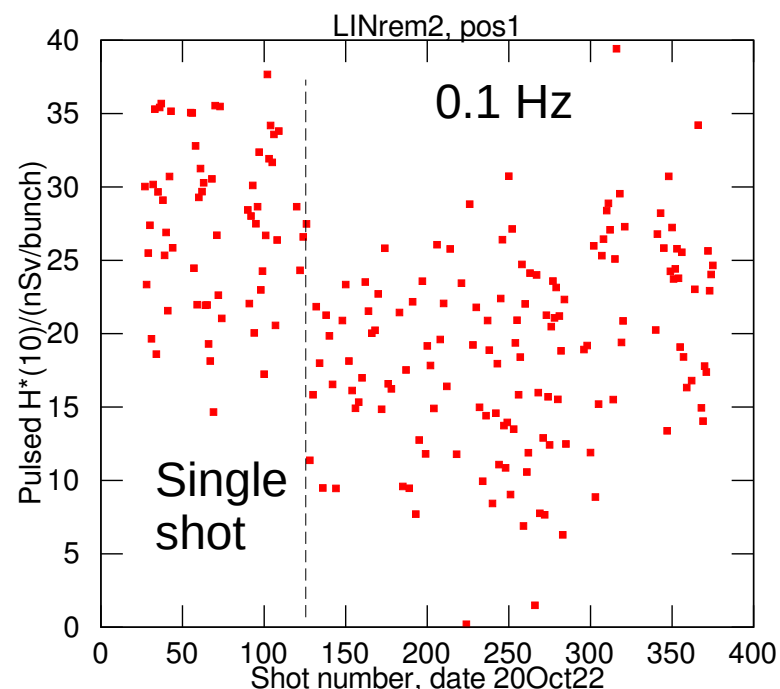
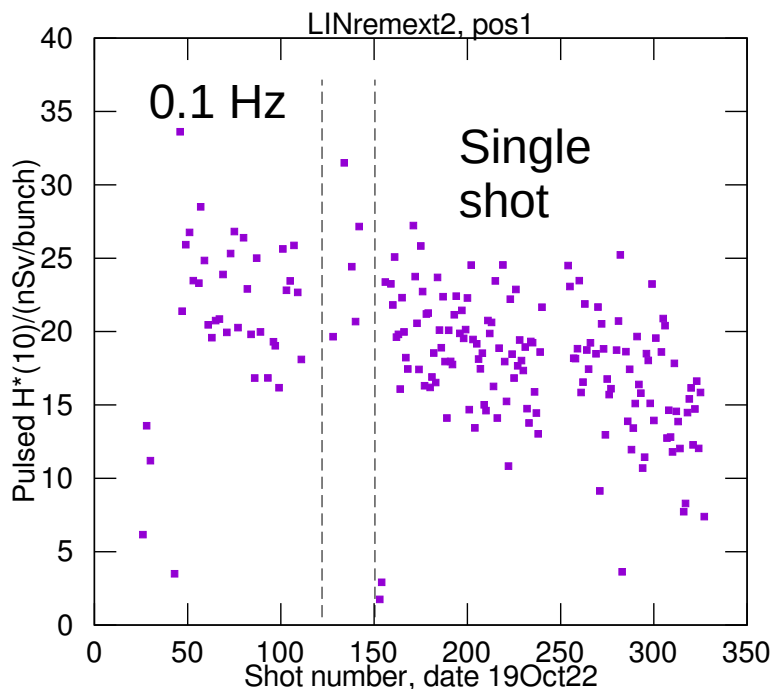
Exp: 25 J, 200 fs, 0.125 PW.

- Three positions inside the experimental room
- WENDI-II + bubble detector (CLPU)
- LINrem2 + LINremext2 (IFIC/UPC)

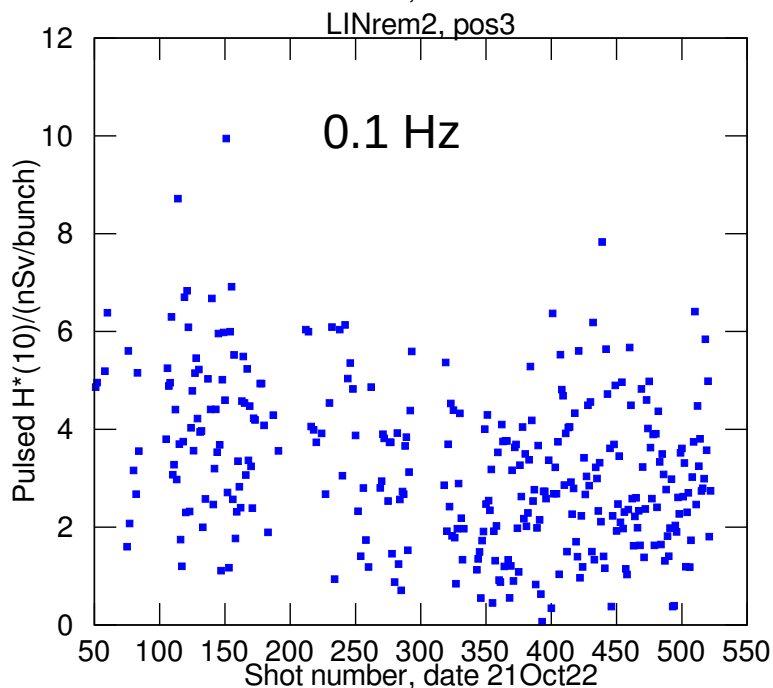


PULSED DOSE-RATE AT CLPU NEUTRON SOURCE

pos1



pos3



Pos1:

- Pulsed dose rates typically spanning from 10-30 nSv/bunch.
- Recommended value **20 nSv/bunch**.
- Affected by the laser repetition rate.

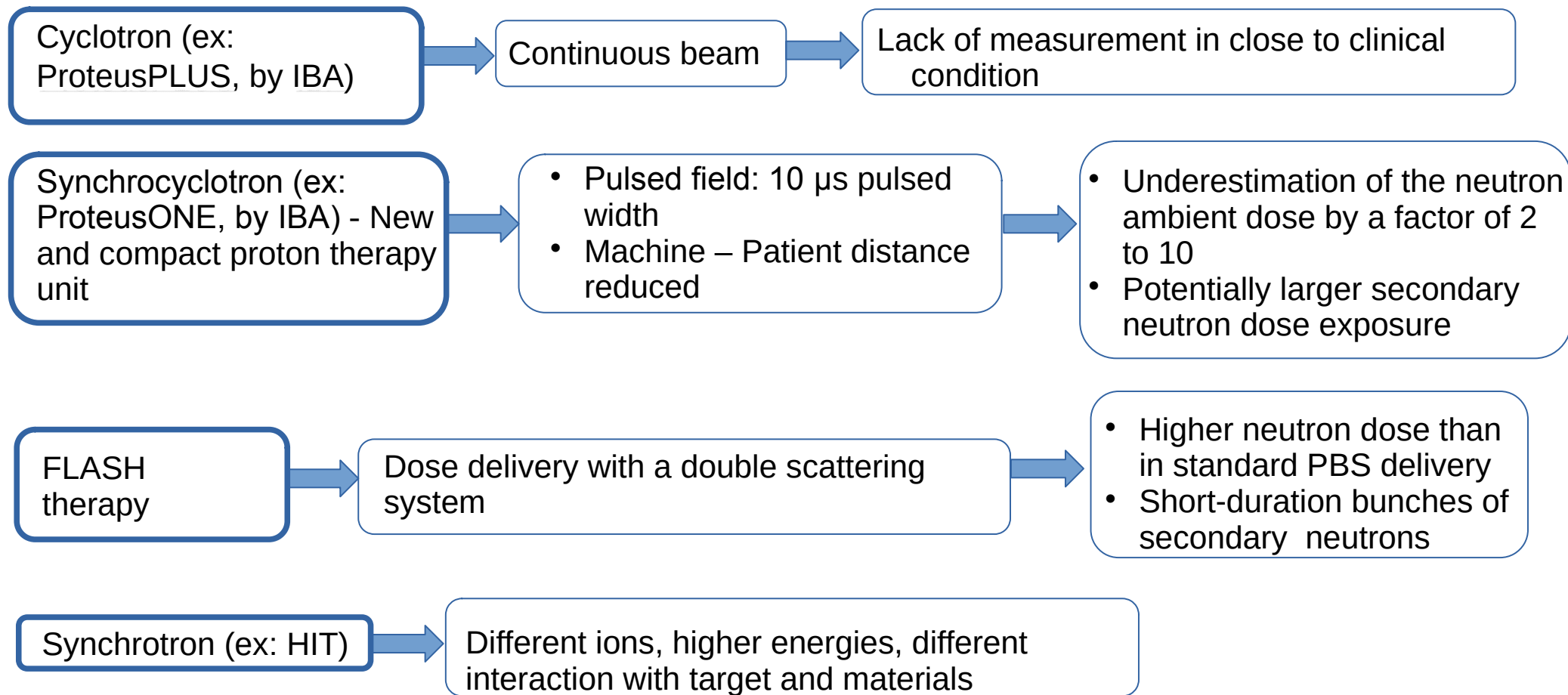
Pos3:

- Pulsed dose rates spanning typically from 1-5 nSv/bunch.
- Recommended value **3 nSv/bunch**.

<https://doi.org/10.1016/j.radphyschem.2024.112101>

APPLICATION EXAMPLE: secondary neutrons in hadron therapy

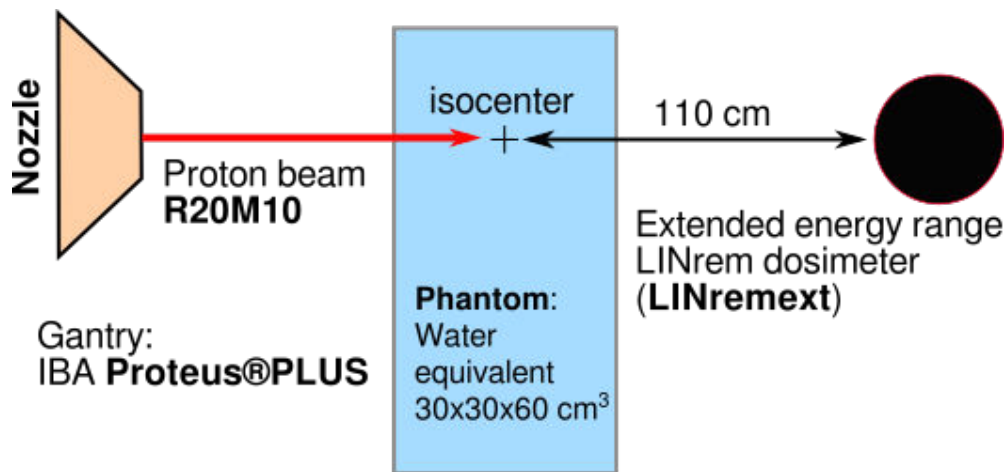
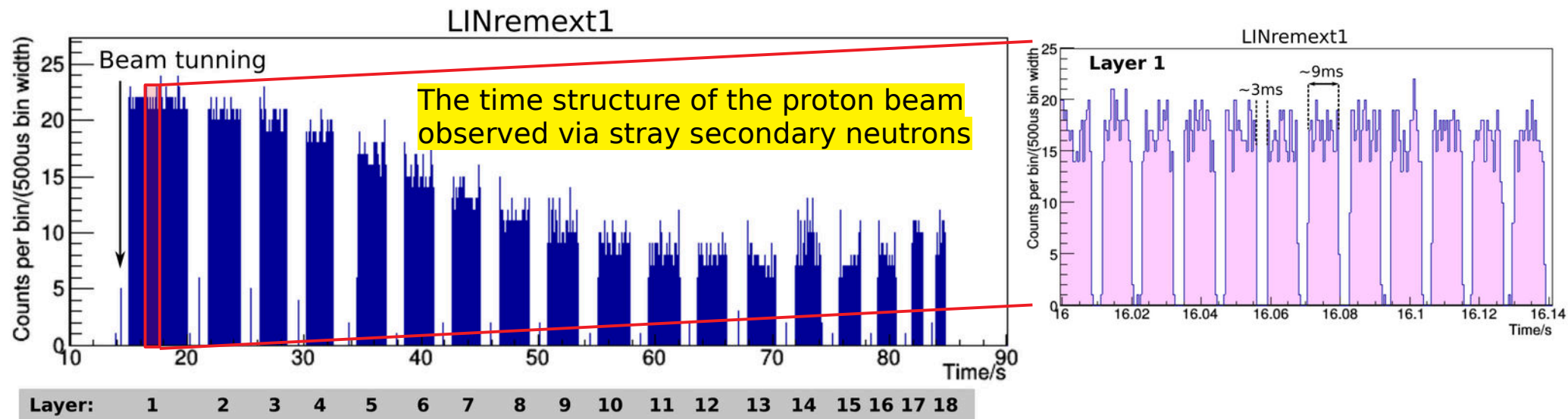
Secondary neutrons is quite a **complex problem**: Different technologies are involved to the dose delivery, for example:



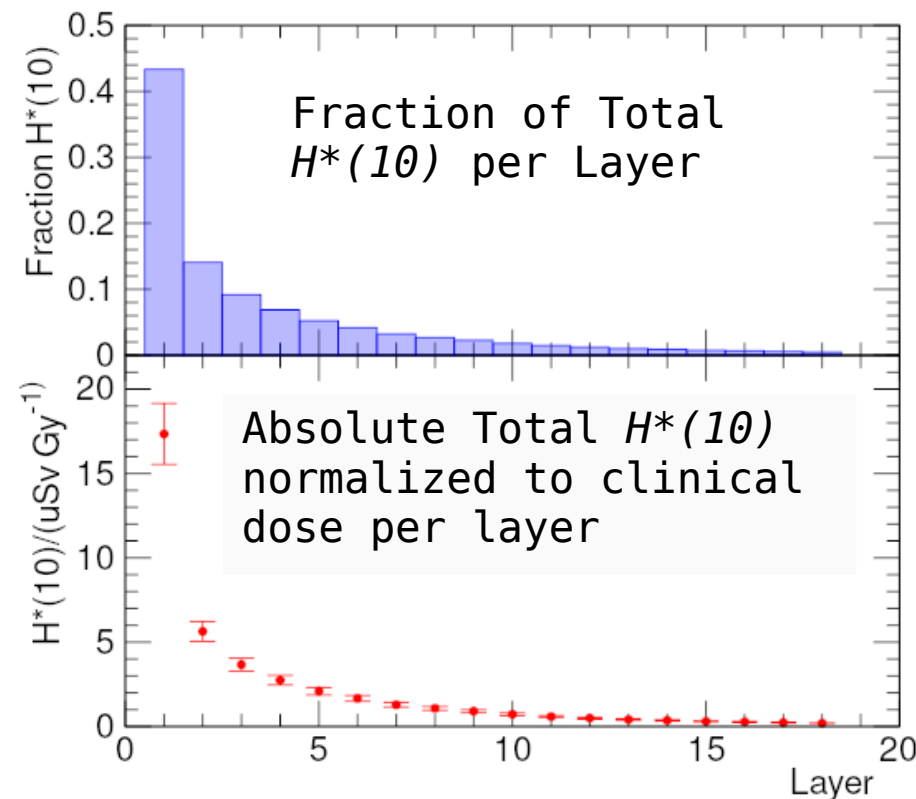
Each machine requires proper characterization of secondary neutrons — and data is lacking for new technologies.

INSTRUMENTATION MUST EVOLVE WITH THE TECHNOLOGY

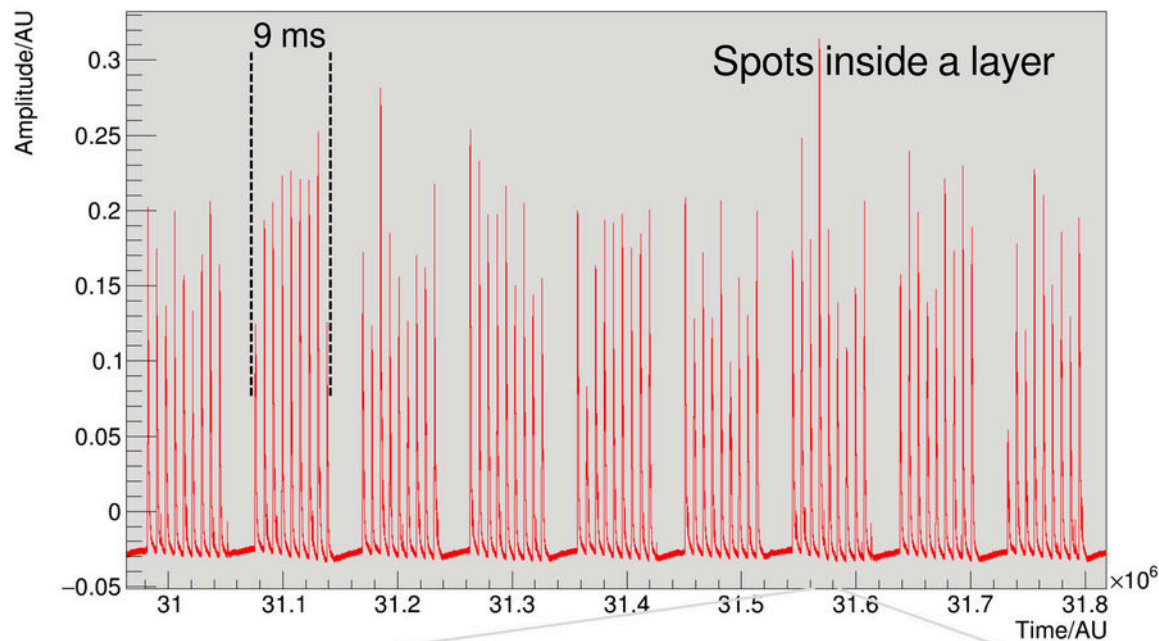
TIME-RESOLVED DOSIMETRY IN PBS (CYCLOTRON)



- 80 % of the out-of-field neutron ambient dose equivalent ($H^*(10)$) is produced by the first 5 layers.
- The first layer produces 45 % of the total $H^*(10)$.



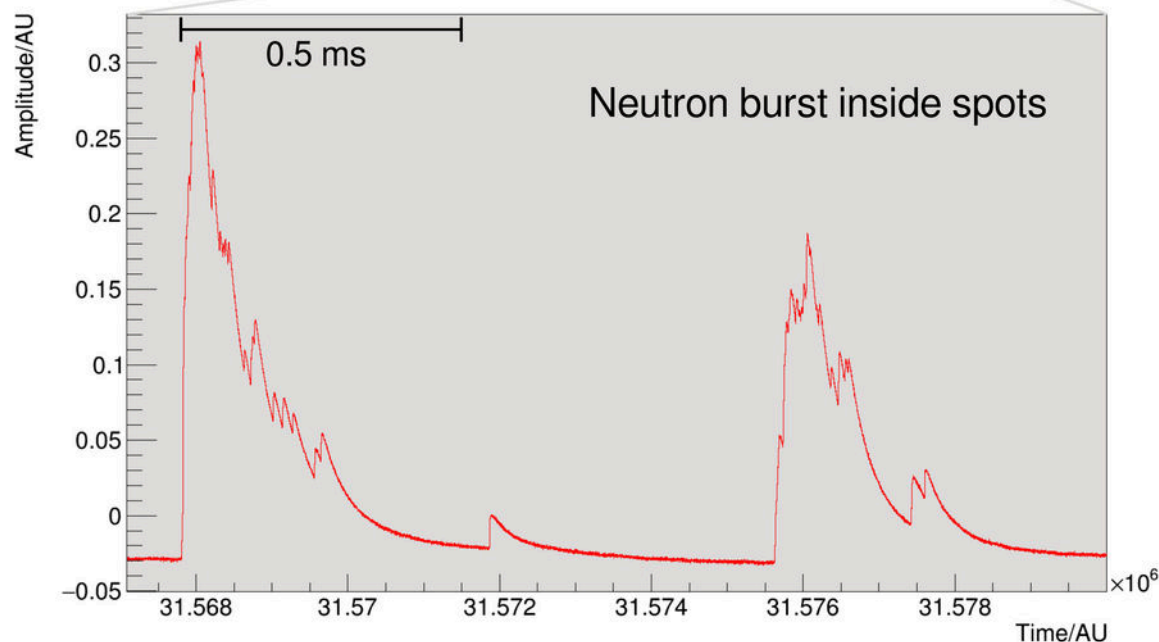
TIME-RESOLVED DOSIMETRY IN PBS (SYNCHROCYCLOTRON)



Gantry:
IBA Proteus®ONE

Phantom:
RW3, 30x30x60 cm³

Dosimeter:
LINremext3, 115 cm, 0 deg



Intercomparison of out-of-field doses ProteusPLUS vs ProteusONE to be released in 2026 (B. Brusasco, PhD thesis, UPC-Barcelona)

Core system specifications:

- **Adaptive signal processing:** single firmware integrating single-event detection and charge-integration analysis
- **Sub-millisecond temporal resolution:** common specification enabling operation across the full temporal spectrum (continuous, quasi-continuous, pulsed)
- **Energy response** ICRP 74 compliant; ICRU 95 conceptual design in place
- **Active and passive variants** share moderator geometry and energy response, providing direct traceability

Project status:

- Transitioning from prototype validation to integrated standalone system (detector + electronics + digital readout)
- <12-month horizon for a first integrated system suitable for transfer to early users
- Passive version validation expected autumn 2026
- Ongoing experimental work with CERN n_TOF toward a pulsed-field irradiation setup
- IP protected in EU, USA, Japan
- **Open to collaboration and joint validation efforts**

THANKS

