IGFAE workshop on technologies and applied research at the future Galician proton-therapy facility, Santiago de Compostela, May 9-10, 2023

Neutron dosimetry in particle therapy facilities: status of the LINrem project

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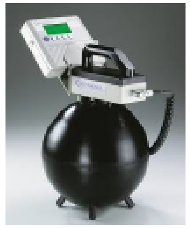
- **Big science projects**
- **Particle therapy facilities**
- **Industrial applications**

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**).

Limitations current commercial solutions:

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

Market price **10 – 15 k€** per unit.



Berthold GmbH.

Ludlum Inc.

Thermo Fisher

Studsvik

Some challenges:

+ High energy neutron fields in particle therapy facilities.

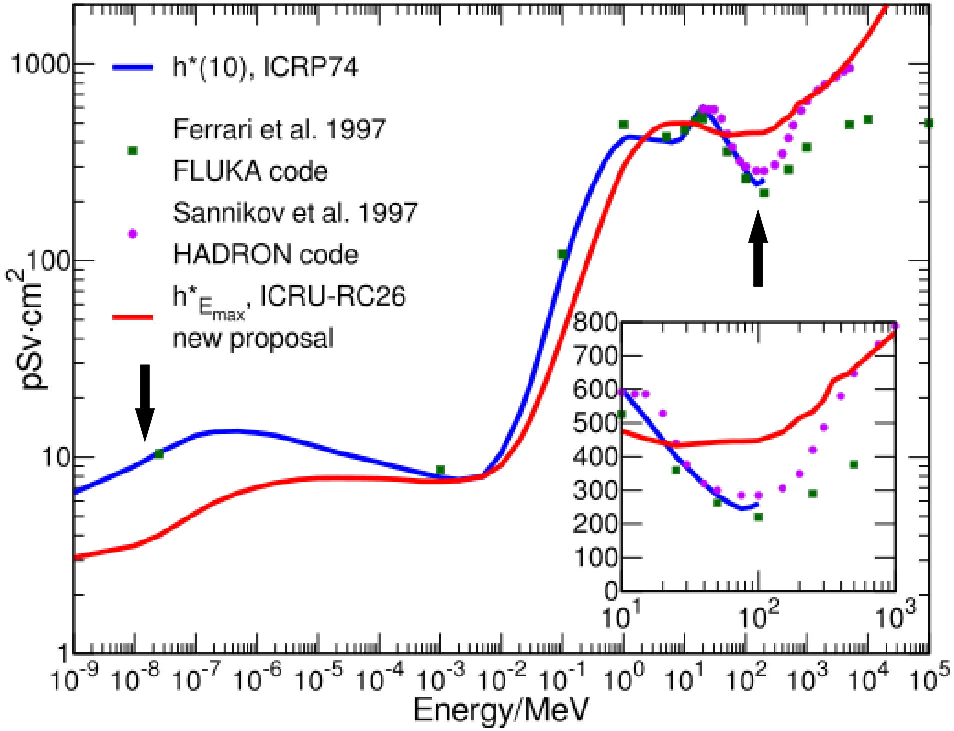
+ Pulsed neutron fields by beam losses in synchrotron or cyclotron facilities.

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

"The development of new neutron dosimetry techniques" / Second priority among nineteen challenges identified in 2018 by EURADOS.

ICRU Report 95: Operational Quantities for External Radiation Exposure

N.E. Hertel et al. Journal of the ICRU 20:1 (2020) 7-130.



Some designs become obsolete *as soon as ICRU95 is incorporated into legal frameworks (5-10 years)*

NEEDS ⟶ Opportunities for R&D+i

- Industry and workers: cost reduction and optimization of processes in routinary radiation protection
- Patients: risk control of secondary cancers in modern medical facilities (proton therapy)
- New facilities: radiation protection challenges associated to big science projects

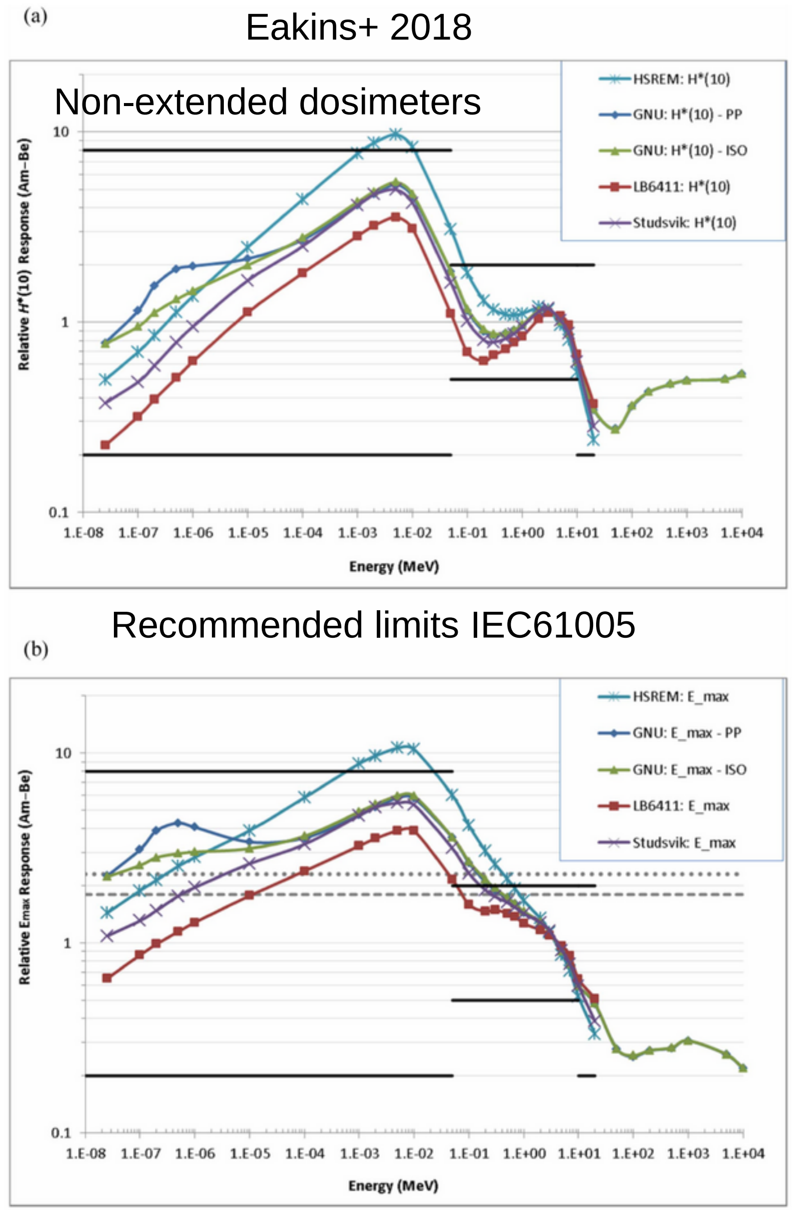
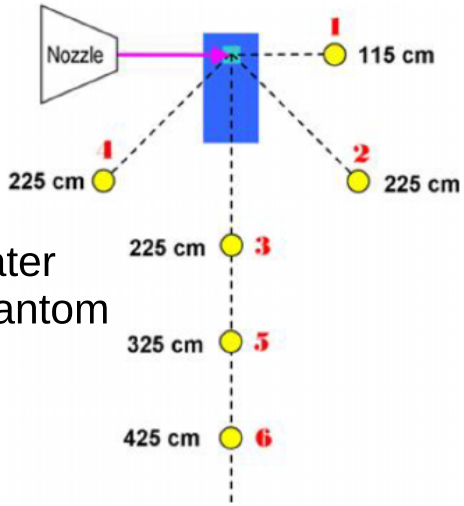


Figure 3. Relative (a) $H^*(10)$ and (b) E_{max} responses of the LB6411, Studsvik 2202D HSREM and GNU, normalized to their respective responses to ^{241}Am-Be. Recommended limits (*solid lines*), and the effects of recalibrations to the response at 144 keV (*dotted line*) and 565 keV (*dashed line*), are also indicated.

Farah et. al. 2015:
"Measurement of stray radiation within a scanning proton therapy facility: EURADOS WG9 intercomparison exercise of active dosimetry systems", Med. Phys. 42 (5), pp. 2572-2584 (2015)
http://dx.doi.org/10.1118/1.4916667



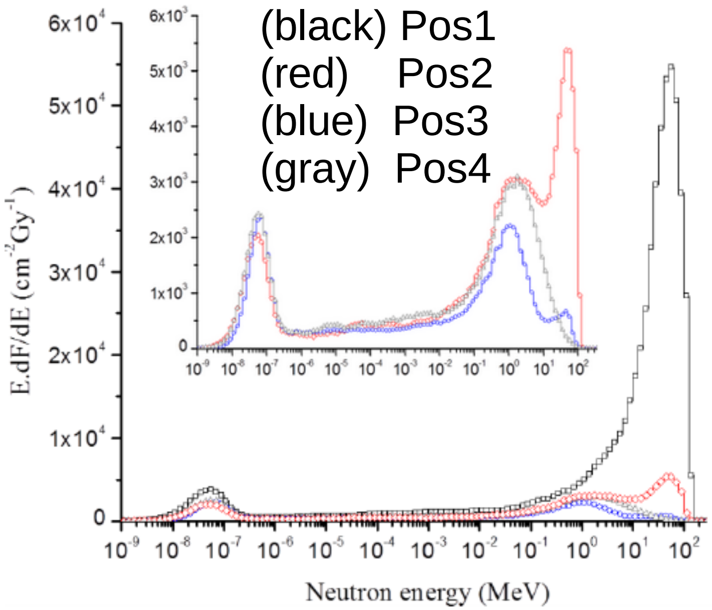
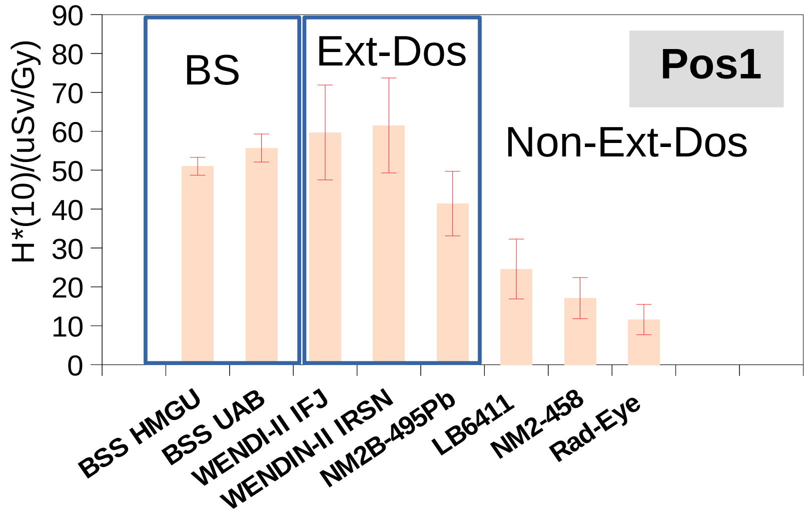


FIG. 1. Schematic view of measurement positions around the water tank phantom (left) and picture of the actual setup within the Trento gantry room (right).



- Measurements with average delivery dose rate < 0.5 Gy/min **in order to avoid deadtime effects**. Delivery dose rate at clinical conditions ~ 2 - 5 Gy/min.
- Bonner spheres provides dose measurements with an accuracy within 5%.
- WENDI-II is the gold standard extended neutron dosimeter for high energy fields (up to 30% including uncertainties)
- Non-extended dosimeters provides underestimated dose measurements 20-50% from the expected value.

LINrem project: status

LINrem solution:

→ **Modern design technology**: Numerically assisted optimization of the detection module.
→ **Novel concept**: Implementation of data acquisition technology suited for complex radiation fields (pulsed & quasi-continuous).
→ **Make it digital**: Acquisition and readout based on digital electronics and apps.

Electronics module:
+ Power source
+ Signal shaping
+ Data acquisition

Cloud data:
+ Databases
+ Data mining
+ Local or remote display

Detection module:
+ Lightweight
+ Based on thermal neutron detector
+ Moderator
+ Absorption/converter materials
+ Detector designs:
  → LINrem/LINremext (ICRP74)
  → LINdos/LINdosext **(new ICRU95)**

Sensor read-out:
+ Wireless data transfer
+ Remote controlling
+ Smart monitors (App based)

Detector performance:
+ Good compromise between sensitivity & portability for industrial and high energy neutron fields
+ Suited for continuous and pulsed neutron fields
+ Able to provide time resolved dosimetry in medical applications.

*Demonstrator prototypes for LINrem/LINremext already developed
*Prototypes have been tested in relevant environments (TRL6)
*Patent **PCT/EP2021/052074** (focus on pulsed neutron fields). Now in national phases (EU, USA)
*LINdos/LINdosext designs under development

LINrem project: status

LINrem project

LINrem
Non-extended dosimeter
Thermal up to 10 MeV

Version 1: 3.3 kg
Design focused on pulsed fields (up to 200 nSv/bunch) and fast neutrons

Version 2: 3.5 kg
Improved response for pulsed fields (up to 2000 nSv/bunch) and thermal/epithermal energy region

LINremext
Extended dosimeter
Thermal up to GeV

Version 1: 10 kg
Design focused on proton therapy facilities

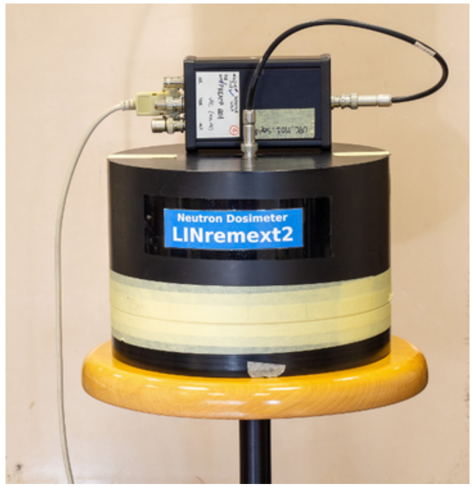
Version 2: 10.5 kg
Improved response in the thermal/ epithermal energy region, pulsed fields up to 1000 nSV/bunch

This talk!
Demonstration in **PBS proton therapy for PBS & DS modes** at **clinical delivery dose rates (H*(10), ICRP74)**

TRL6
(Demonstrated)

TRL7 (work in progress): System prototype, including dedicated digital electronics and readout, demonstrated in relevant enviroments (proton therapy, continuous and pulsed fields)

GASIFIC7**
IFIC
Digital
AcQuisition
system

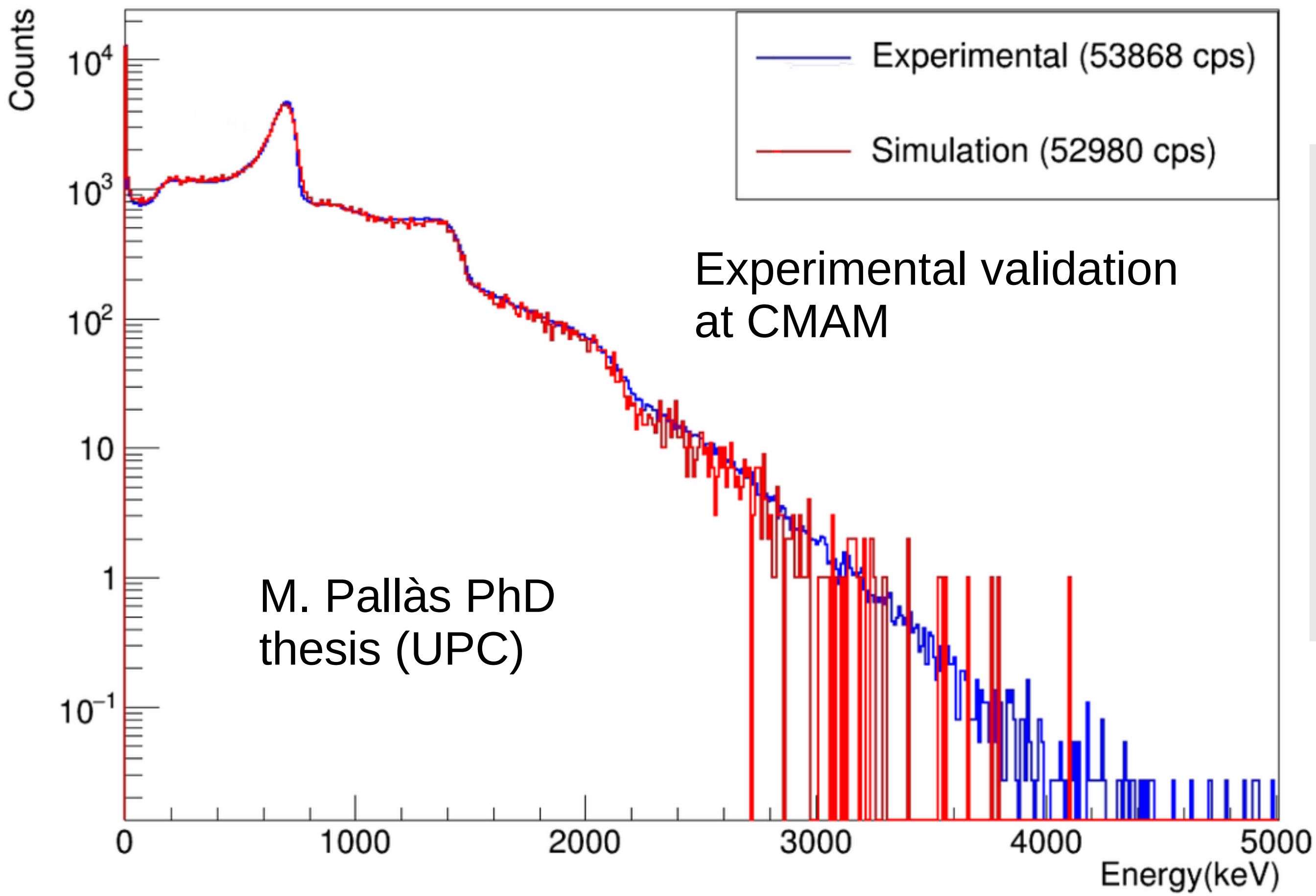


Demonstration activities achieved using:
- LINrem/LINremext prototypes
- Modular nuclear electronics
- Struck SIS3316 digitizer
- GASIFIC7 DAQ (list mode & sample digitizer)

****J. Agramunt et al. NIM 807 (2016) 69–78**

Deatime correction for LINrem: Event pile-up reconstruction

- Our DAQ (GASIFIC7) is a non-paralizable system by construction.
- We successfully emulate the firmware.
- The data stream is reconstructed by assuming a event time difference distribution ~ Exp(-R·t).
- The true event rate (R) is obtained by fitting the experimental amplitude spectrum of the neutron counter.



Good agreement with the reconstruction at large counting rates (>100 kcps)!

Experimental rate: 53868 cps

Simulation rate: 52728 cps

True rate: 111985 cps

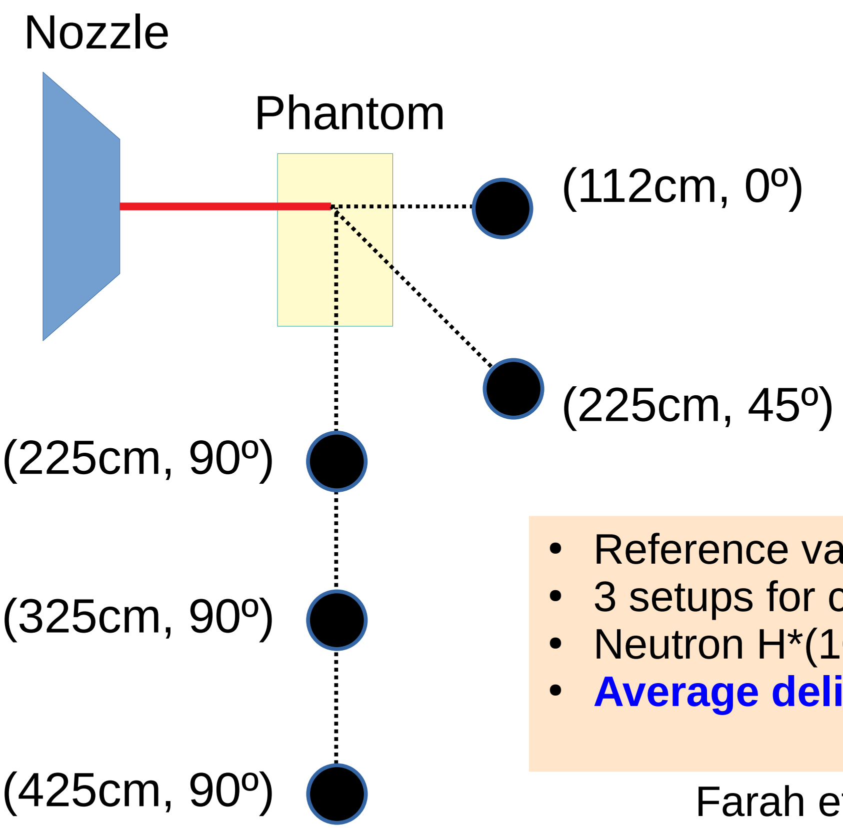
LINremext1: Demonstration in PBS (WPE, Germany)

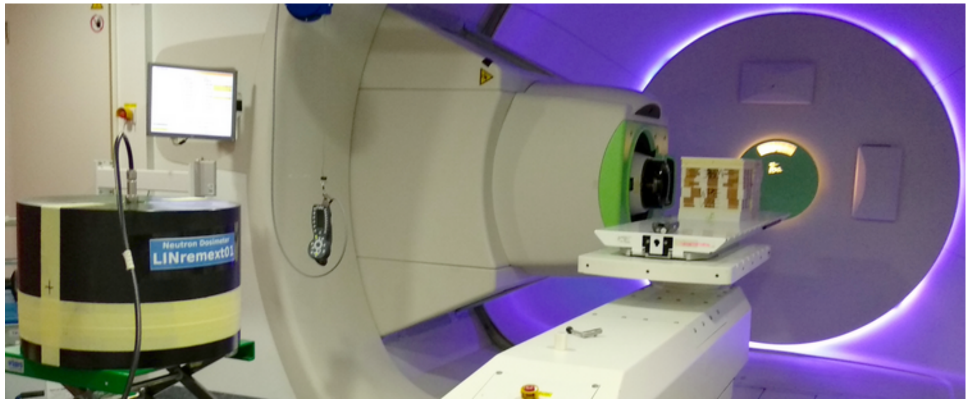
- Prototype of extended range dosimeter: **LINremext1, 10kg, sensitivity from thermal up to GeV's.**
- LINremext1 designed focusing on the application in proton therapy facilities. Uncertainties in dose determination estimated to be ~10% by detector energy response (systematic).
- Time resolved measurements of the out-of-field secondary neutron dose in PBS proton therapy achieved.

LINrem detectors @ WPE @ Dec. 18

- Phantom 30x30x60, water equivalent RW3 material.
- R20M10

Angle/deg	D/cm	Eq_Setup
0	112	Farah.Pos1
45	225	Farah.Pos2
90	225	Farah.Pos3
90	325	Farah.Pos5
90	425	Farah.Pos6

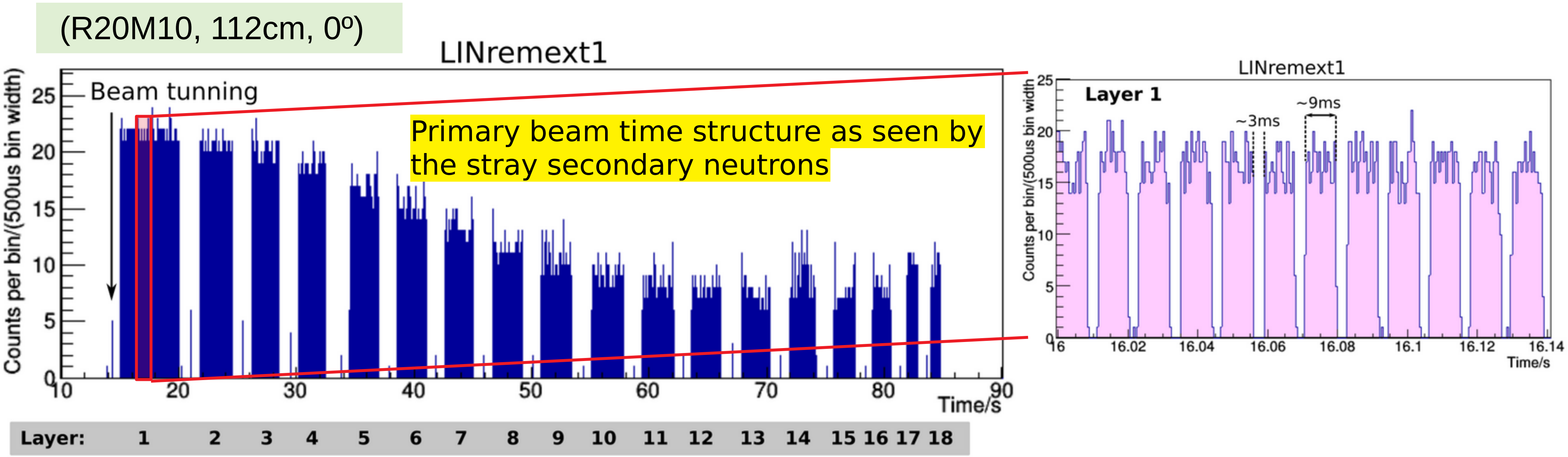




- Reference values from Bonner sphere spectrometers (EURADOS).
- 3 setups for comparison.
- Neutron H*(10) from BS in Pos. 5 and 6 is not provided in the article.
- **Average delivery dose rate ~ 5 Gy/min (clinical).**

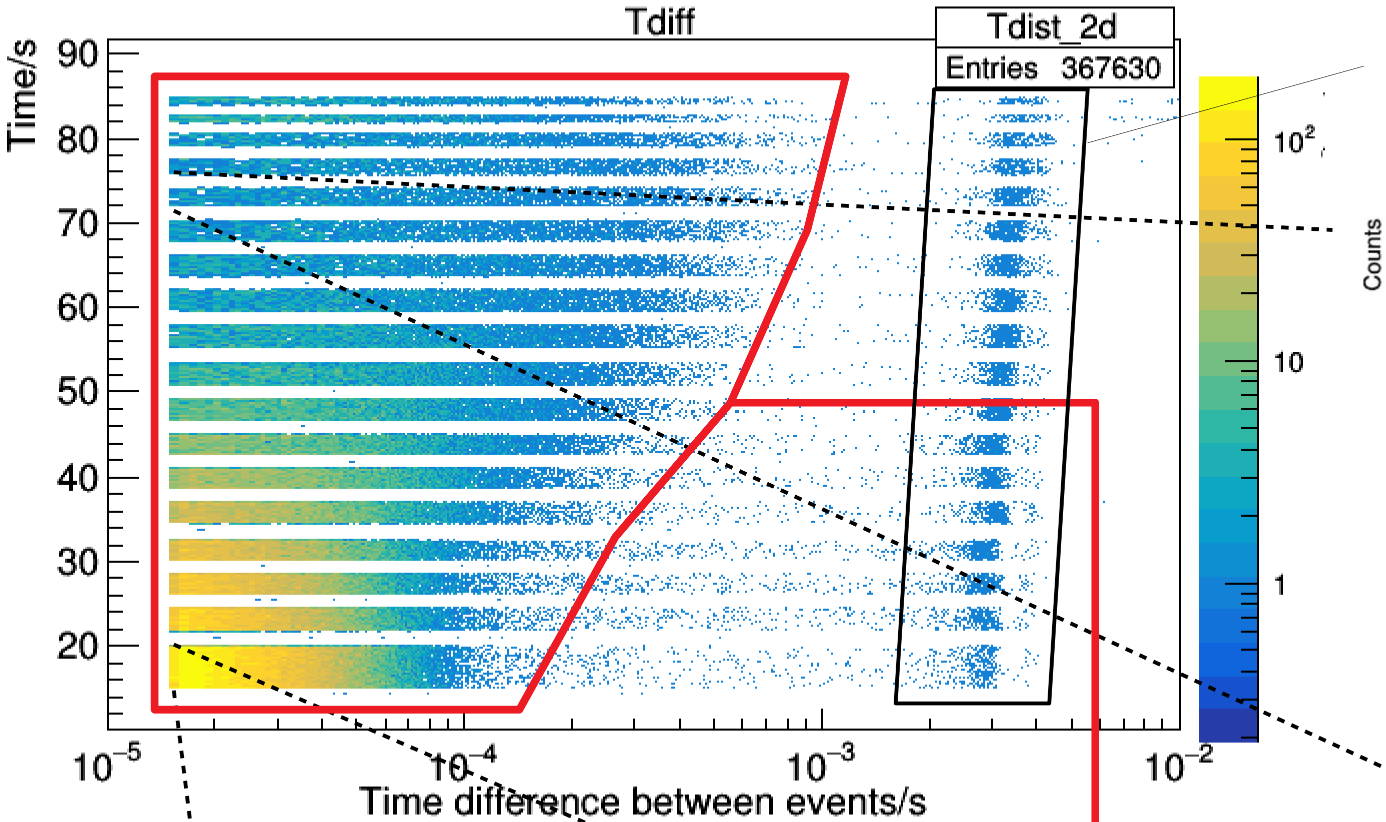
Farah et. al. Med. Phys. 42 (5), pp. 2572-2584 (2015)

Time resolved measurements in PBS

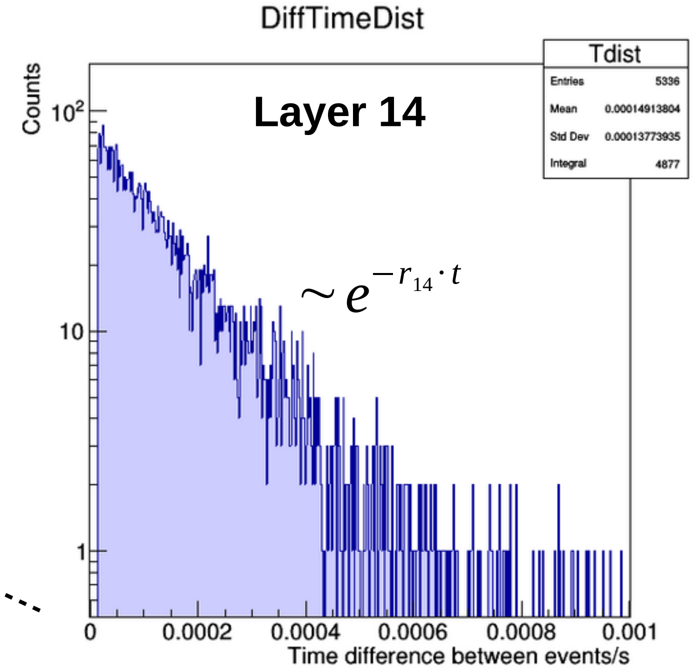


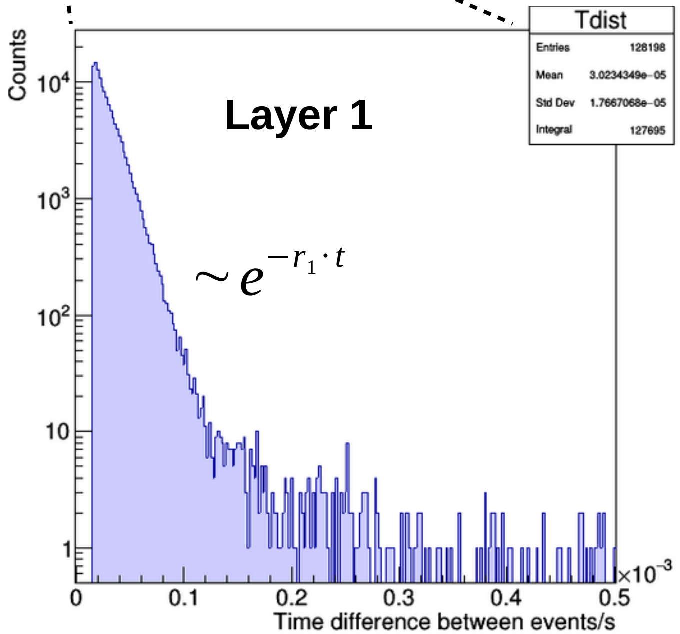
- **Complex time structure (quasi-continuous neutron field).**
- 18 "layers" identified, each layer separated by time periods of seconds.
- A flash of neutron emission is observed between layers due to the beam tunning.
- Blocks of "stable" neutron emission are observed inside the layers ("spots"). Each spot is separated by periods of no emission (~ms).
- **Dead-time and pile-up correction methods should be applied.**

Time structure: distribution of events time differences



Time difference between spots

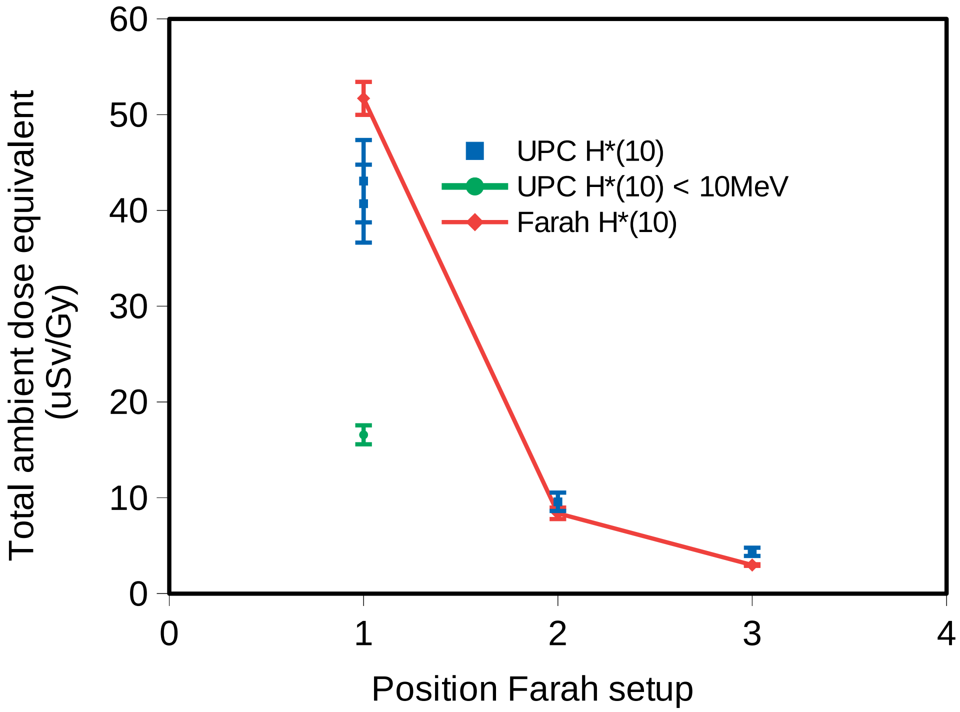


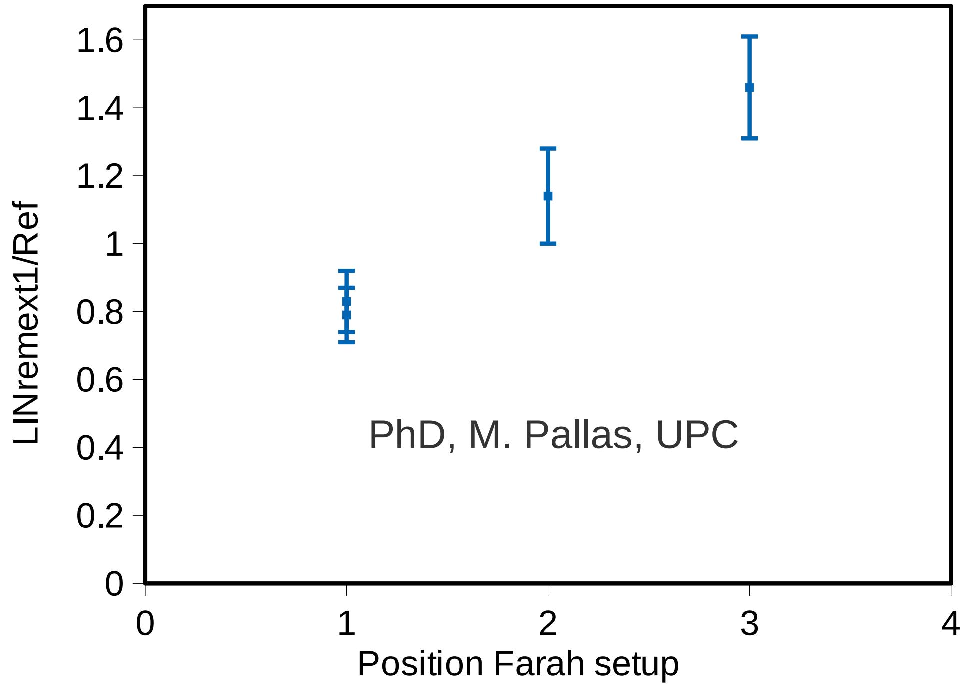


CUT on the waiting time distribution for the different layers

- The counting rate for the different layers is obtained by applying a cut on the 2D-waiting time distribution.
- For the different layers, the WTD shows an exponential shape. This is expected since the WTD is modulated by the moderation time of fast neutrons.

Dose measurements results: H*(10)

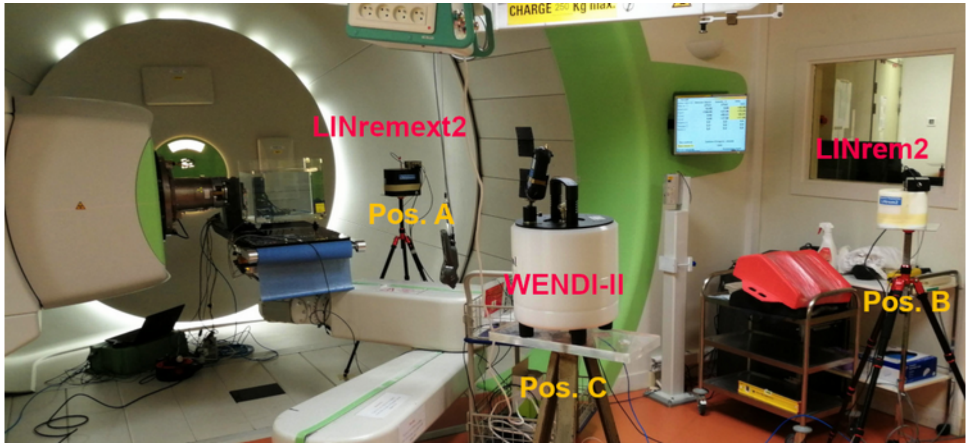


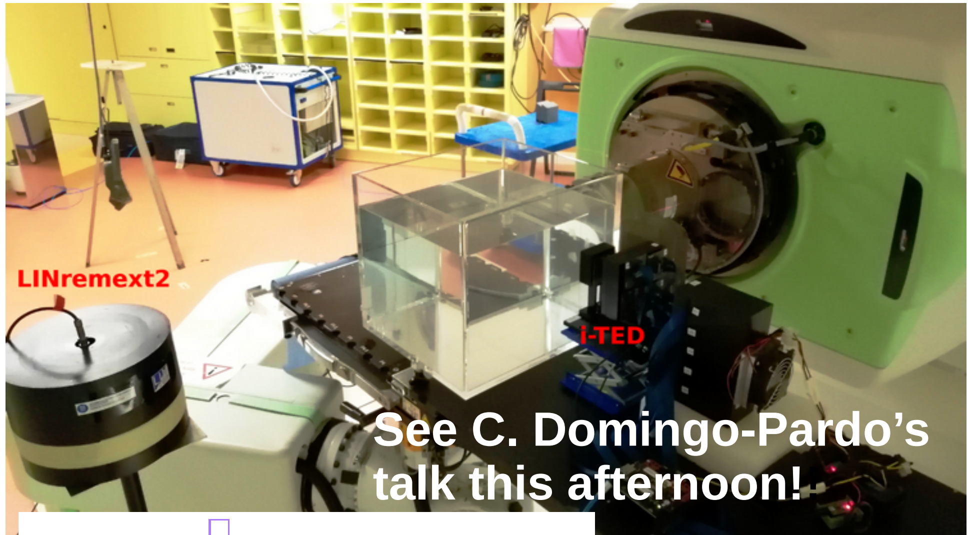


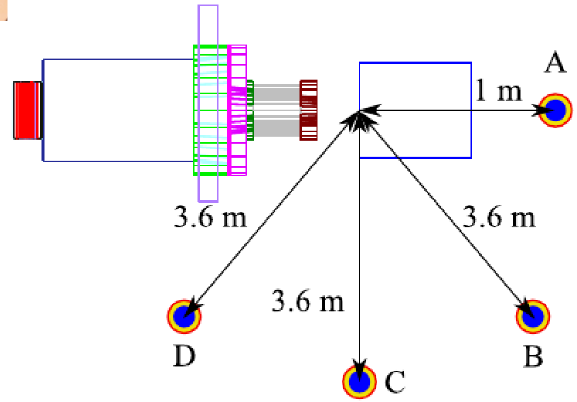
- **Deadtime correction method applied**: Dead-time + pile-up cascades (M Pallas, UPC)
- **Agreement with literature H*(10) values is found** (Farah et al 2015). Comparison of LINremext1 and the reference values from Bonner spheres in intercomparison studies.
- Using LINrem1 detector (thermal – 10 MeV), the contribution from high energy neutrons (En > 10 MeV) to H*(10) is estimated to be as high as 65% on the downstream position (Pos1).

LINremext2: Demonstration in Double Scattering (ICPO, Orsay)

- Prototype of extended range dosimeter: **LINremext2, 10.5 kg.**
- Validation of deadtime correction algorithm: continuous beam at Y1 room (100 & 130 MeV).
- Validation of response after upgrade to detector design (version 2): DS at Gantry room.
- DS setup: 34×40×35 cm³ water phantom. A brass collimator of 65mm thickness and 55 mm circular aperture was used. Beam energy of 100 MeV.







Reference setup: Leite et al. 2021

IOP Publishing Phys. Med. Biol. 66 (2021) 225010 https://doi.org/10.1088/1361-6560/ac3209

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RECEIVED 22 July 2021
REVISED 18 October 2021
ACCEPTED FOR PUBLICATION 21 October 2021
PUBLISHED 24 November 2021

PAPER

Secondary neutron dose contribution from pencil beam scanning, scattered and spatially fractionated proton therapy

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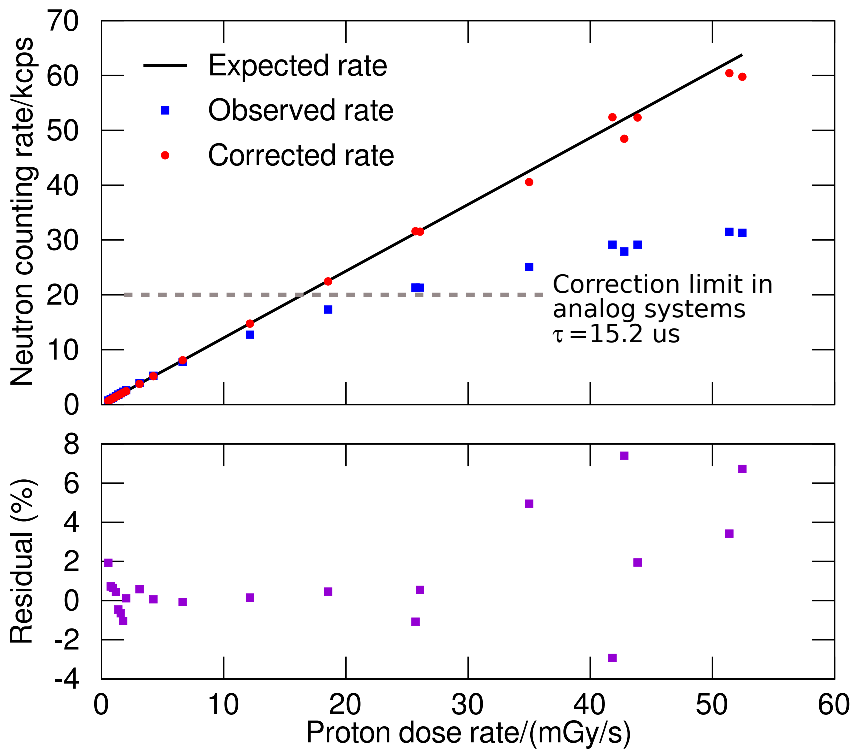
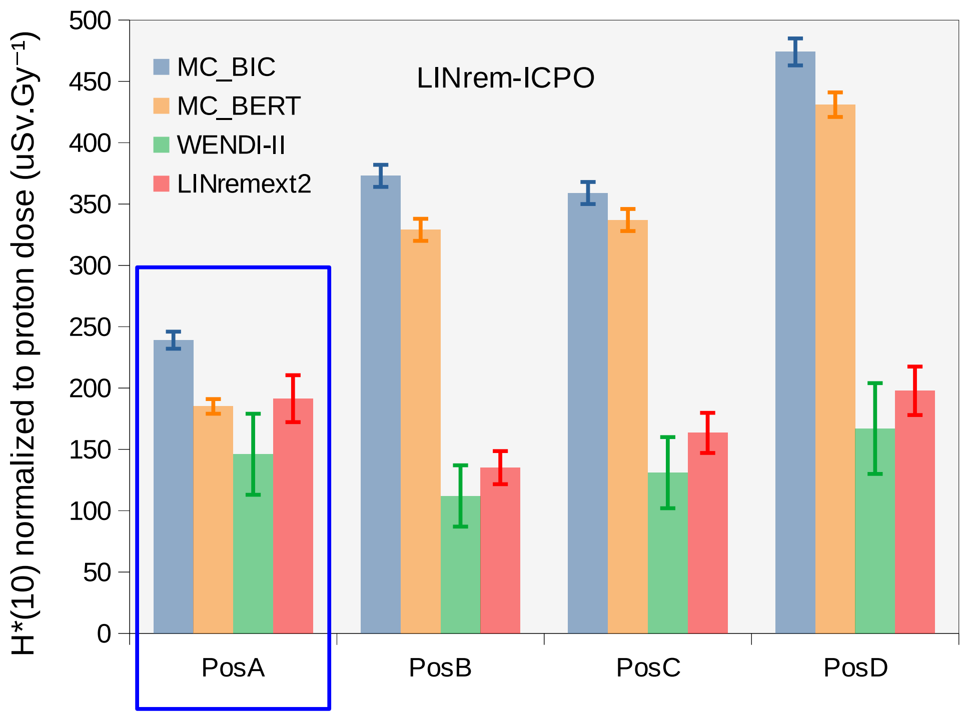
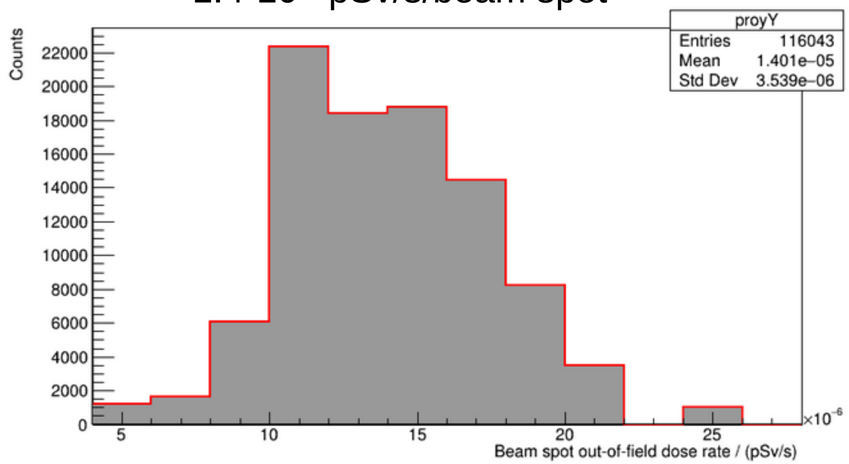
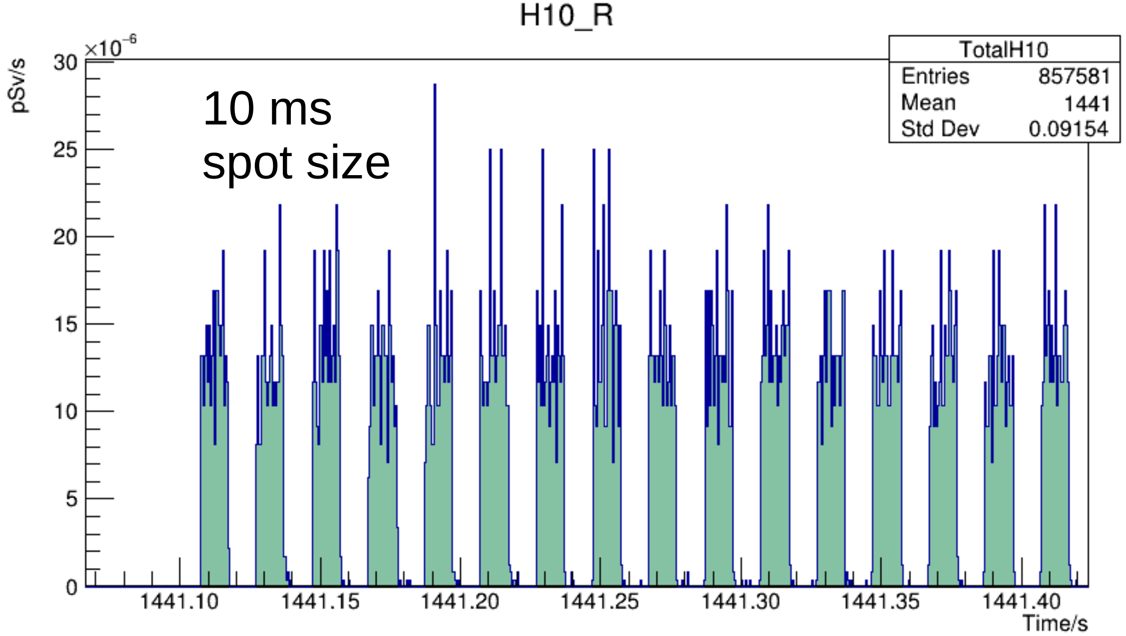
LINremext2: Demonstration in Double Scattering (ICPO, Orsay)





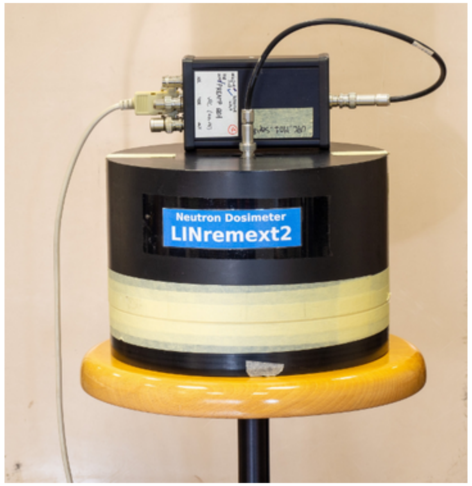
1.4·10^{-5} pSv/s/beam spot





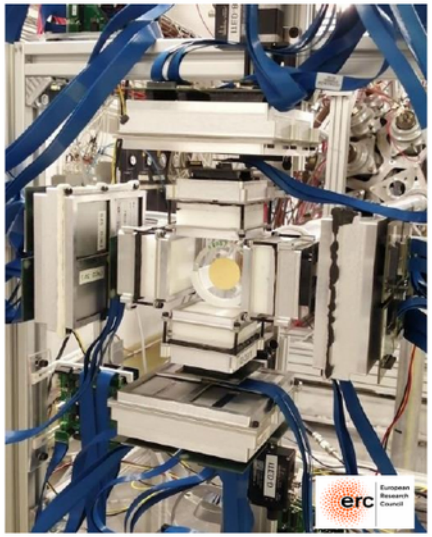
What is next?

- **LINrem prototypes able to be transfer to users (TRL>=7)**: I+D for integration of electronics, DAQ and front-end into a single/portable module (continuous & pulsed fields).
- **LINdos**: detector design adapted for ICRU95 (new recommendation) on-going.
- **SINERGY4HT**: **SI**multaneous **NE**ut**R**on and prompt **G**amma-ra**Y** imaging system for in-vivo diagnosis in **H**adron-**T**herapy



LINrem/LINdos

+



i-TED

Next talk C. Domingo-Pardo @ 16:15!

List of LINrem collaborators (experiments, validations, etc)

C. Bäumer, M. Barbagallo, F. Molina, J. Agramunt, P. Aguilera, A. Albert, H.F. Arellano, G. Avaria, B. Bora, A. Casanovas, E. Chiaveri, S. Davis, J. Jain, V. Juarros, A. Lázaro, A. M. M. Leite, F. López-Usquiano, D. Macina, L. De Marzi, J. Moreno, L. Orellana, S. Parra, A. Patriarca, C. Pavez, J. Romero-Barrientos, A. Ruiz, L. Soto, B. Timmermann, J. Wulff, M. Zambra, M. Zorondo

Acknowledgments

Spanish Ministerio de Economía y Competitividad under Grants nos. FPA2014-52823-C2-1-P, FPA2014-52823-C2-2-P, FPA2017-83946-C2-1-P, FPA2017-83946-C2-2-P and grants from Ministerio de Ciencia e Innovacion nos PID2019-104714GB-C21 and PID2019-104714GB-C22. INSPIRE project TNA (LINrem-ICPO).

Thanks!