Co-financed by the Connecting Europe Facility of the European Union

CHARACTERIZATION OF DOSIMETRIC SENSORS FOR PROTON AND NEUTRON BEAMS

JUAN ANTONIO MORENO PÉREZ

October 2022

3rd ELICSIR Training School

Table of Contents

1. ECsens Research Group

ECsens
Electronic and Chemical sensing solutions

Ciemat

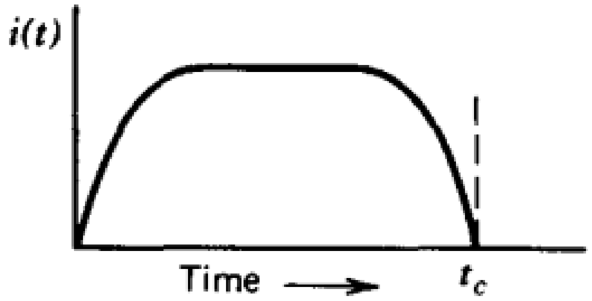
UNIVERSIDAD DE GRANADA

elicsir

IFMIF-DONES ESPAÑA

2.1. General Properties of Radiation Sensors

- The net result is usually an electric charge from the interaction of a particle, which is collected through the imposition of an electric field that causes the positive and negative charges to flow in opposite directions.
- In a simplified model, a current flows for a time equal to the charge collection time, being the integral over its duration equal to the total charge.

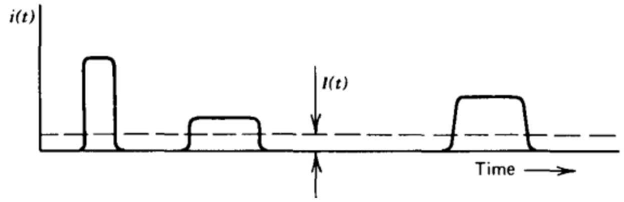


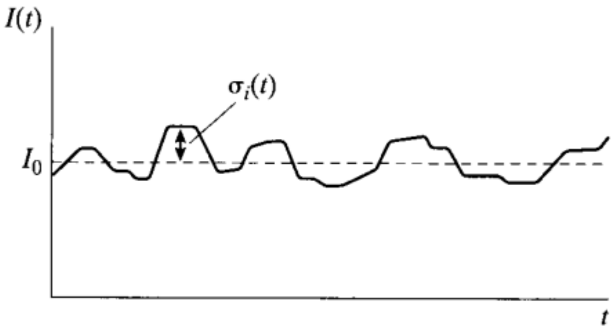
$$\int_0^{t_c} i(t)\, dt = Q$$

2.1.1. Typical operating modes of radiation detectors

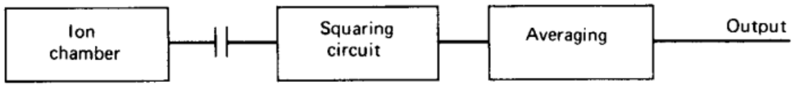
Current mode

- A current-measuring device is connected to the detector, recording the average current, that depends on the product of the interaction rate and the charge per interaction.
- There is an statistical uncertainly due to random fluctuations.





Mean square voltage mode



- This type of detector works with a circuit capable of blocking the average of the current signal and passing the fluctuating component.

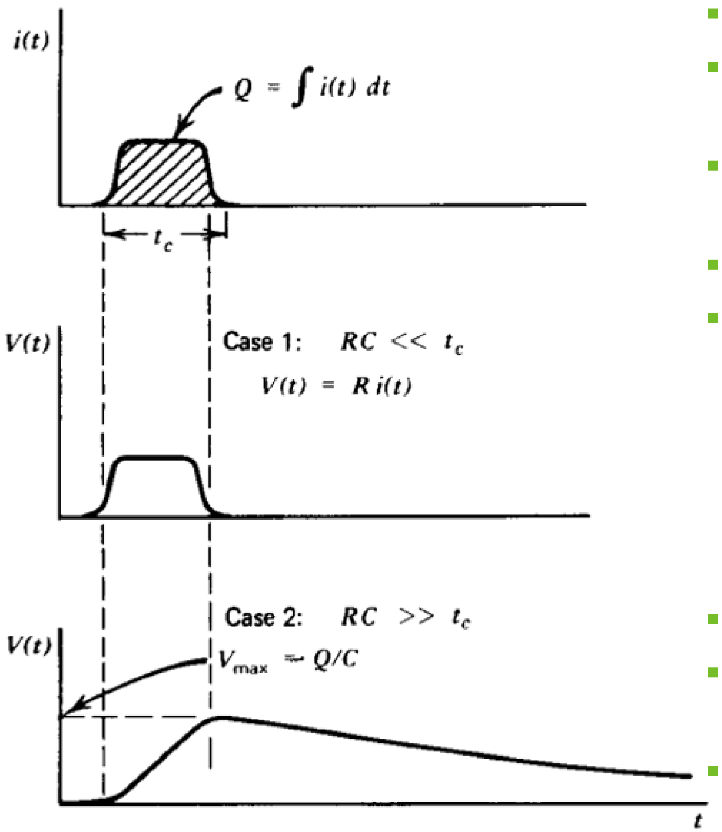
$$\overline{\sigma_I^2(t)} = \frac{rQ^2}{T}$$

- The signal is directly proportional to the event rate (r) and the square of the charge of each event.
- It is useful with mixed radiation environment with charges produced by different types of radiation.

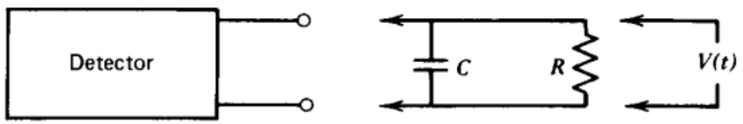
UNIVERSIDAD DE GRANADA

2.1.1. Typical operating modes of radiation detectors

Pulse mode



- It is the most commonly used.
- Design to record each individual quantum of radiation that interacts the detector.
- Sometimes it record the time integral of each burst, and other times it use a simplier approach (pulse counting).
- Fails at very high event rate.
- The pulse produced from an event depends on the circuit to which the detector is connected.



- The rise time is determined by the detector itself.
- The decay time is determined by the time constant of the circuit.
- The amplitude of the pulse is determined by the ratio of the total charge created
- The sensitivity is great and each pulse carries some information.

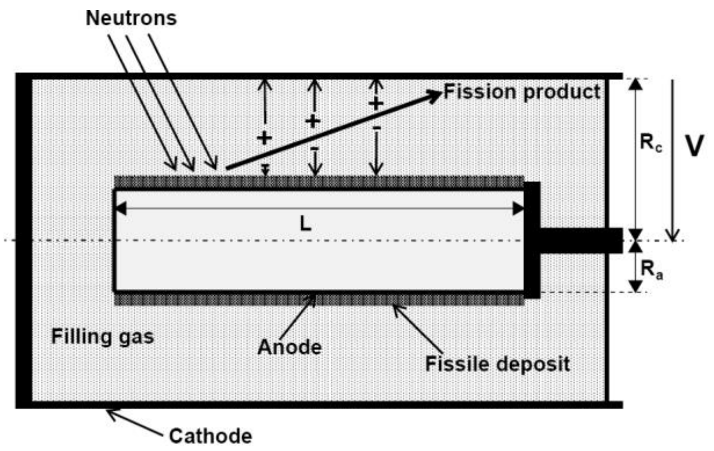
2.1.2. Radiation detectors

Ionization Chambers

- Used to measure **ionizing radiation**.
- Based on **ionization** and excitation of **gas molecules along a particle track**.
- Their normal operation is based on **collection of all charges** created by direct ionization **within the gas** through the application of an **electric field.**
- The **fast charged particles ionized neutral molecules** resulting in a **positive ion** and a **free electron**.
- The particle must transfer an amount of **energy equal to the ionization energy** of the gas molecule **at mínimum**, but often it takes even more due to the energy lost within the gas.

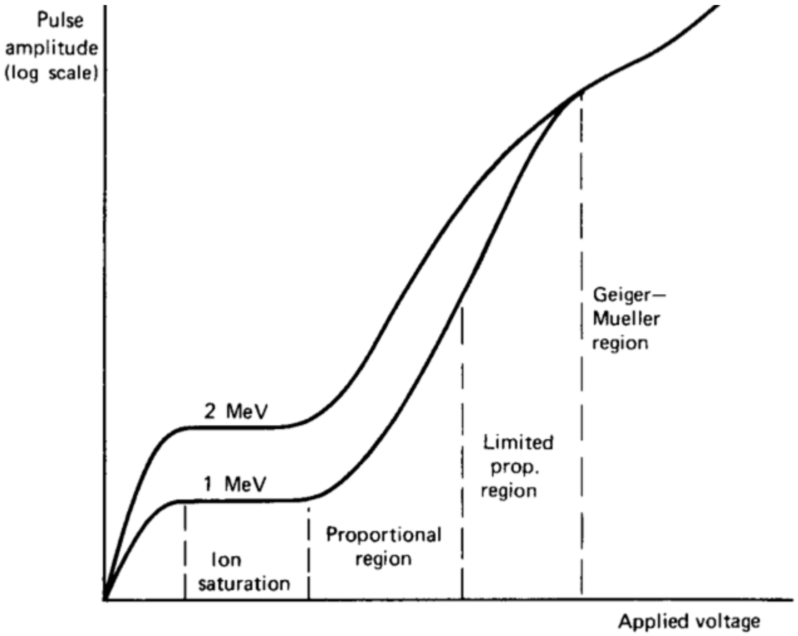
Fission Chambers

- Are ionization chambers with a **fissile deposit**.
- Capable of **discriminating** a **neutron flux against** a **gamma** one.
- **Two coaxial electrodes**: the outer one (**cathode**) and the inner one (**anode, fissile material**).



Fission Chambers

- **Generate** two charged **ions** that ionized the filling gas and get **separated** due to the **bias voltage** applied.
- To have the **neutron-induced current** signal **proportional to the fission rate**, it has to work in **saturation regime**.
- The **fissile material** is typically either **U-235** or **U-238**.
    - U-235 based ones are typically used in the detection of **thermal neutrons**.
    - U-238 works solely with **neutrons above a threshold energy level**.



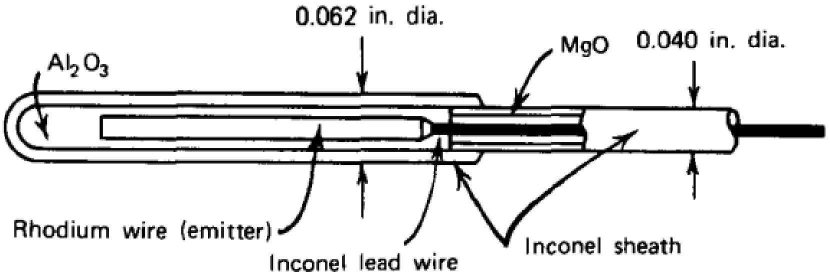
Self-Powered Neutron Detectors (SPNDs)

Basic background concepts

- The process in which an unstable atomic nucleus loses energy by radiation is the radioactive decay, which can be, for example, beta or gamma.
- For neutrons, the probability per unit path length is a constant for any of the interaction mechanism, and it is usually express as the cross section (σ) per nucleus for each type of interaction, which have a macroscopic version when it is multiplied by the number of nucleus (Σ).
- The neutrons can have different interactions with the environment, such as:
  - Elastic scattering, in which neutrons collides with an atomic nucleus without being absorbed by.
  - Radiative capture, in which the incident neutron is completely absorbed and a compound nucleus is formed.
  - …

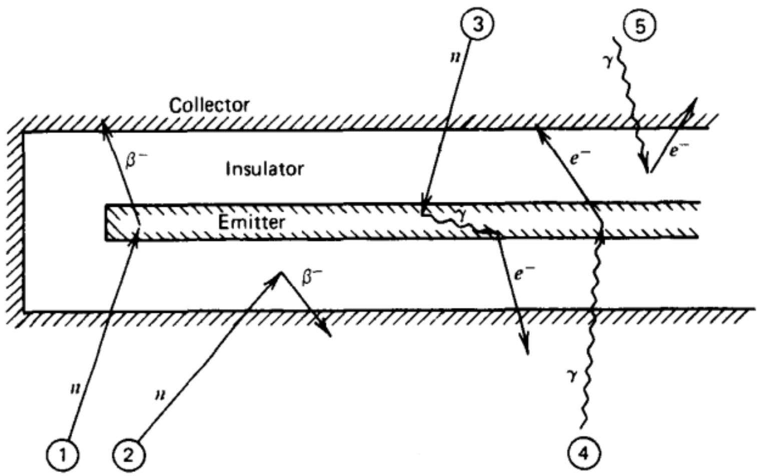
$$\Sigma = N\sigma$$

$$\Sigma_{\text{tot}} = \Sigma_{\text{scatter}} + \Sigma_{\text{rad. capture}} + \ldots$$



Self-Powered Neutron Detectors (SPNDs)

- SPNDs are neutron detectors that incorporates a material chosen for its relatively high cross section for neutron capture, leading to beta of gamma decay.
- The first type one operates by measuring the beta decay current directly, being proportional to the rate at which neutrons are captured in the detector, and no bias voltage is needed.
- In the latter, some of the gamma rays emitted can interact to form secundary electrons through Compton effect, photoelectric mechanism…, being the current produced the basic detector signal.
- Advantages: small size, low cost and simple electronics.
- Disadvantages: low current level, so it needs high sensitivity, and slow response time.
- Always operate in current mode.

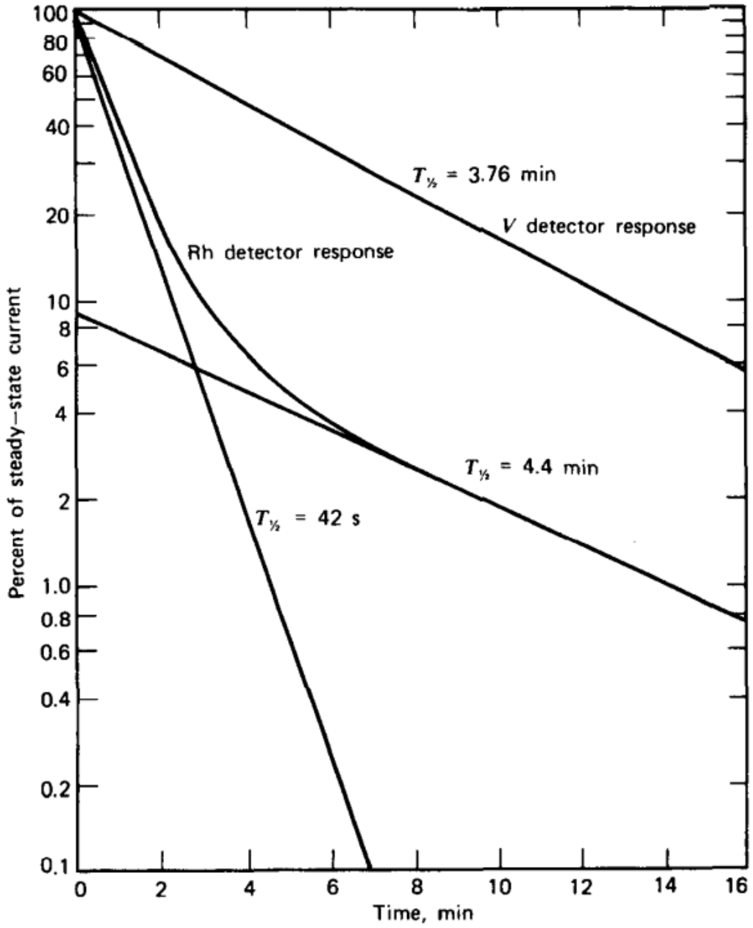


Self-Powered Neutron Detectors (SPNDs)

Detector based on β decay

- The emitter is made from a material chosen for its relatively high cross section for neutron capture.
- The current is measured between the emitter and the outer shell called the collector (high purity stainless steel or Inconel).
- The intervening space is filled with an insulator (typically Mg or metalic oxides).
- Low cross section leads to low sensitivity, while a high one result in rapid burnup of the emitter.
- The beta rays must have enough energy to avoid self-absorption and the half-life of the induced activity should be as short as posible.
- Most popular options Rhodium and Vanadium.

$$I(t) = Cq\sigma N\varphi(1 - e^{-\lambda t}) \qquad I_{sat} = Cq\sigma N\varphi$$



2.1.2. Radiation detectors

Self-Powered Neutron Detectors (SPNDs)

Detector based on γ decay

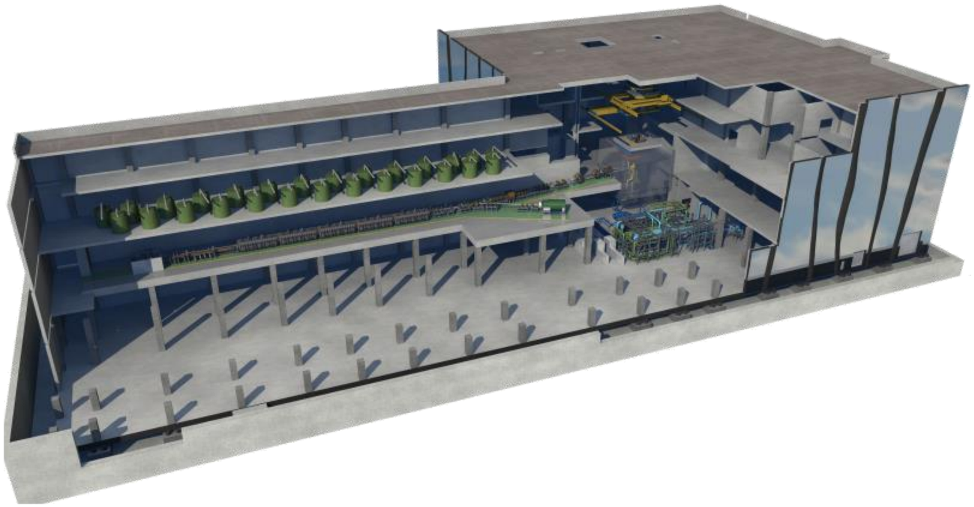
- The response time is faster, relaying on the secondary electrons produced by prompt capture gamma rays.
- Even in Vanadium and Rhodium, there is a small prompt component of the signal, much smaller than the beta current.
- Cadmium and Cobalt usually used as a prompt emitter.
- The response is faster but the sensitivity, lower.

General considerations of both detectors

- The effect of the cable used can be significant.
- The usual solution is to use twin signal leads:
  - One lead is connected to the emitter
  - The other is physically near but without electrical contact.
- With the two signals, the cable interaction can be nearly cancelled out.

3. IFMIF-DONES: Characterization of a neutron beam

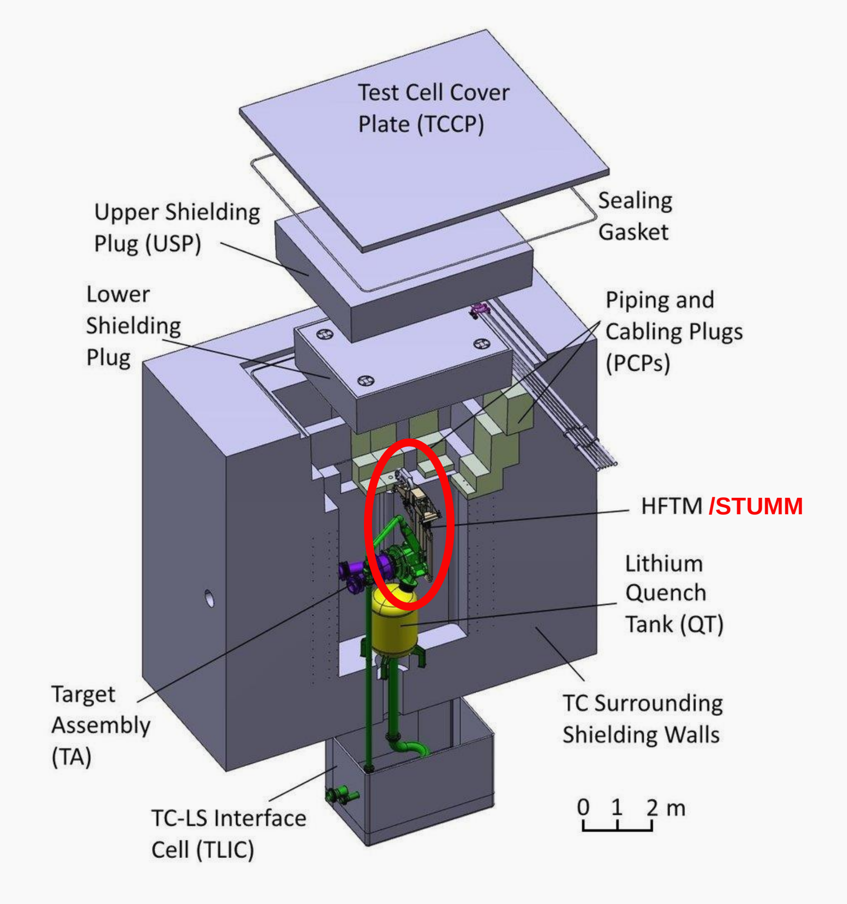
- **IFMIF-DONES** stands for **International Fusion Materials Irradiation Facility DEMO Oriented Neutron Source**.
- Project that aims to build a **neutron source**, which is expected to generate a **fast neutron flux** density of $\mathbf{10^{15}}$ **n/s/**$\mathbf{cm^2}$, producing a temperature close to **550ºC**.
- Based on **deuteron – lithium target reaction**.
- Dedicated mainly to the **irradiation of materials** (testing and validating them).



UNIVERSIDAD DE GRANADA

3.1. STUMM Basics

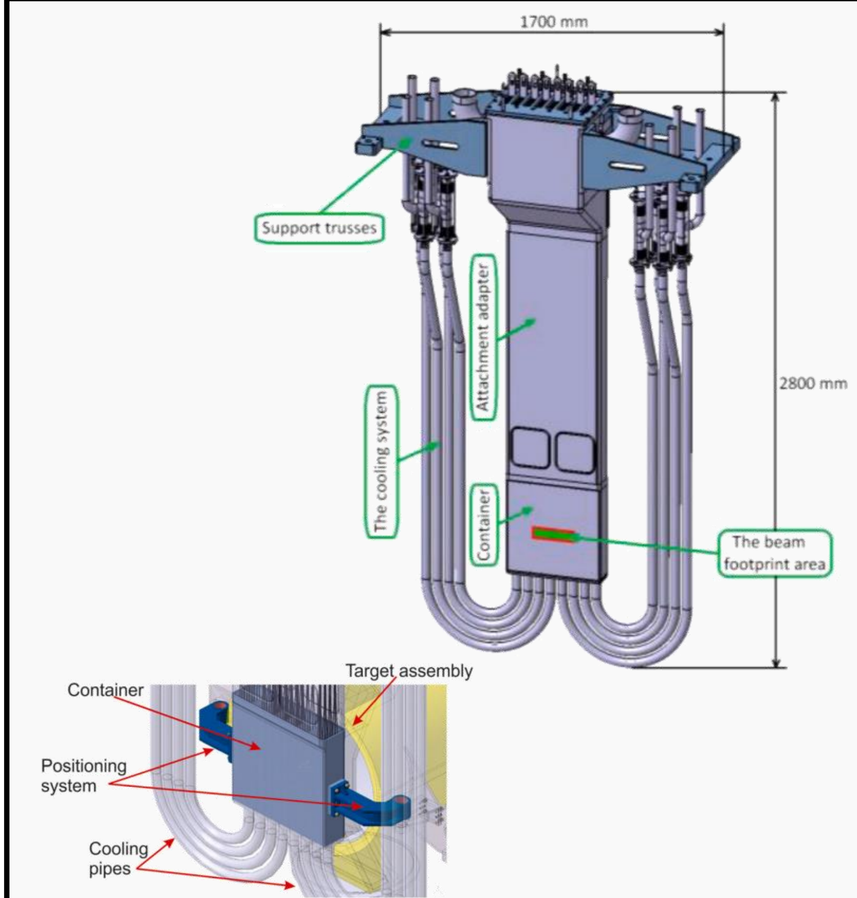
Test Cell Design



- One of the modules of the accelerator.
- Located about **2 mm from the target**.
- Very **similar to** the **High Flux Test Module** (HFTM), but during the commissioning and **testing phase**.
- Its main objectives are:
  - **Monitor** radiation and thermal conditions during the commissioning pase.
  - **Characterize** the neutron flux.
  - **Validate** the neutronic modelling of the facility.

3.1.1. External design and location

STUMM module in detail

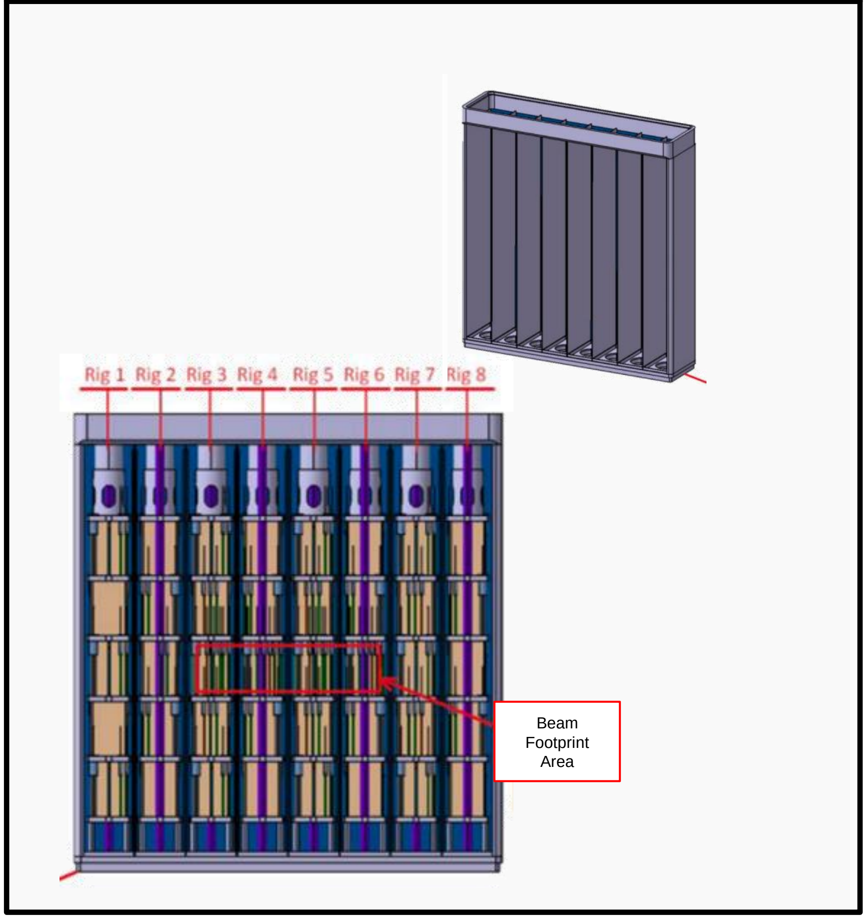


- The **casing** structure will be made of **austenistic stainless steel** (CrNiMo 17-12-2).
- Main parts will be:
  - **Container** (with the **measuring systems** placed inside).
  - **Support Trusses**, to transport the module.
  - **Attachment Adapter**, that guide the cables and transport the cooling gas.
  - **Helium Cooling System**, which ensure the proper operation condition for the sensors.

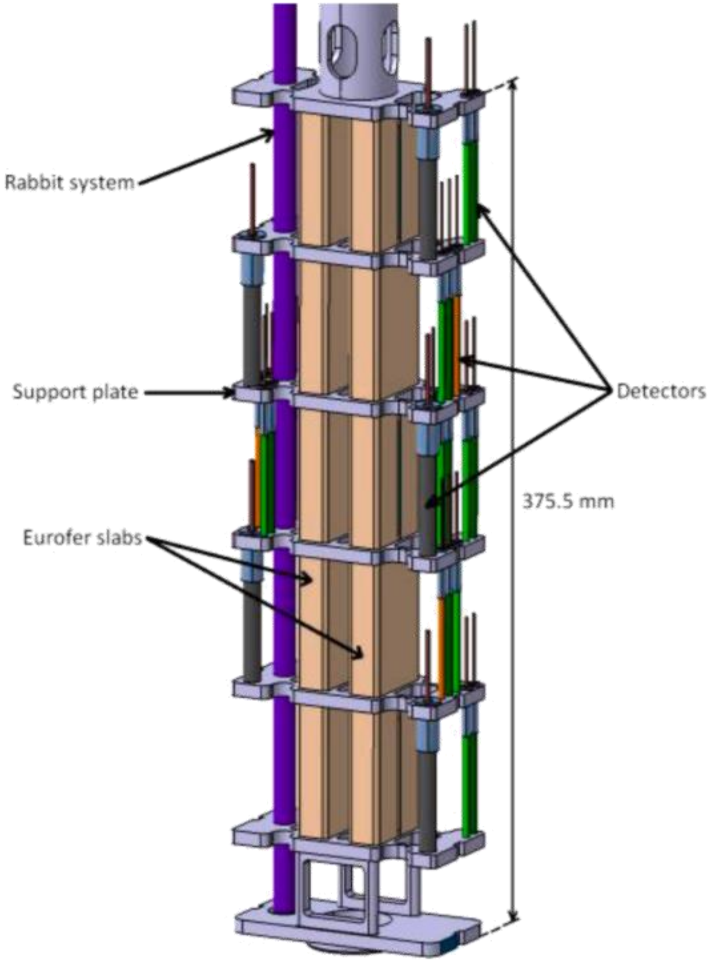
3.1.2. Container Basics

- The internal structure is divided in **8 rigs**.
- The **area with the detectors** inside the container is called the **active area**, in which the rigs are **separated in 5 levels**.
- Space divided in:
  - **Central region**, also called the **beam footprint area**.
  - **Front area**: gives information about the **distribution** of neutrons and gamma flux.
  - **Rear area**: collects information about radiation **conditions similar to** the ones on **HFTM**.

Container design



3.2. Radiation Detectors and Sensors of the STUMM



- The **active part** of the rig consist of:
  - Supporting plates
  - Connecting elements
  - Eurofer slabs
  - Measurement systems
- The **expected sensors** are:
  - A Rabbit System (RS)
  - Pairs of Micro Fission Chambers (U-235 and U-238)
  - Ionization Chambers
  - Gamma Thermometers
  - Thermocouples.
  - Self-Powered Neutron Detectors (SPNDs).

3.3. Analysis of the sensors behaviour

Fission Chambers

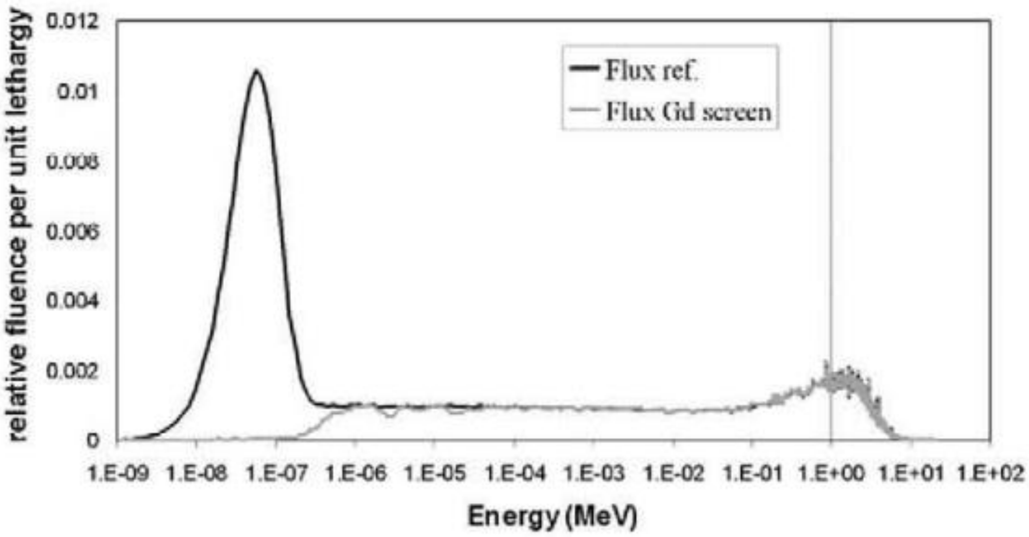
- In the framework of IFMIF tasks, CIEMAT made some studies for the selection of the detectors.
- An fission chamber and an ionization chamber were studied, performing the experiment in the BR2 reactor.

Channel	Φ_{th} (n/cm^2/s)	$\Phi_{E>0.1\,MeV}$ (n/cm^2/s)	GHR (kGy/s)
L120 (1stcycle)	1.0×10^{14}	0.12×10^{14}	1.7
G60 (1st cycle)	1.9×10^{14}	0.6×10^{14}	3.0
F46 (2nd cycle)	2.3×10^{14}	0.8×10^{14}	3.6

- The gamma rays contribution were measured with the ionization chamber.
- In BR2 the thermal component dominates, so to make conditions more similar to those of IFMIF-DONES, the chambers were surrounded by gadolinium (Gd).

Fission Chambers

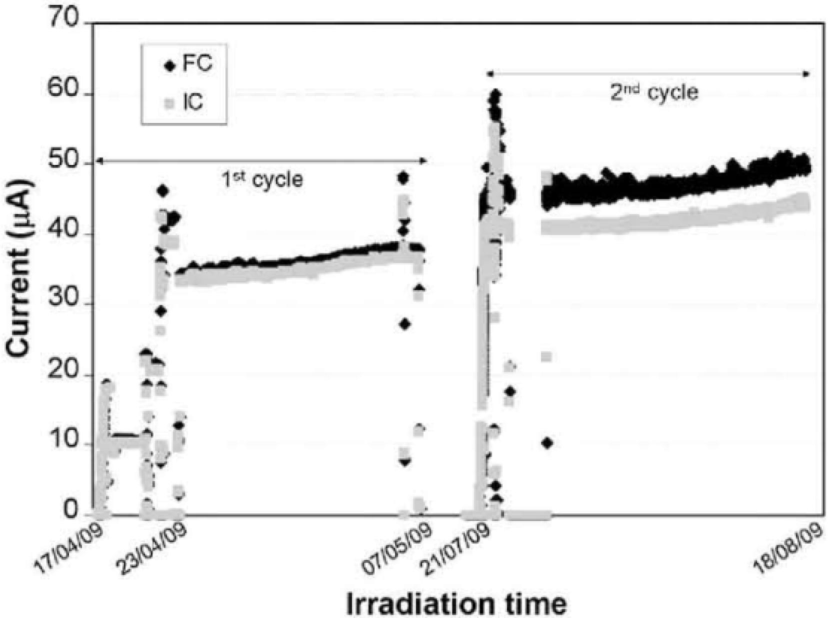
- The efficiency of the gadolinium screen is not a problema since it remains constant during all its lifetime, which is not planned to be exceed.
- The local nuclear heating is negligible, but the gamma rays emitted after the neutron is caputed not.
- Currents were measured and stored once per minute.

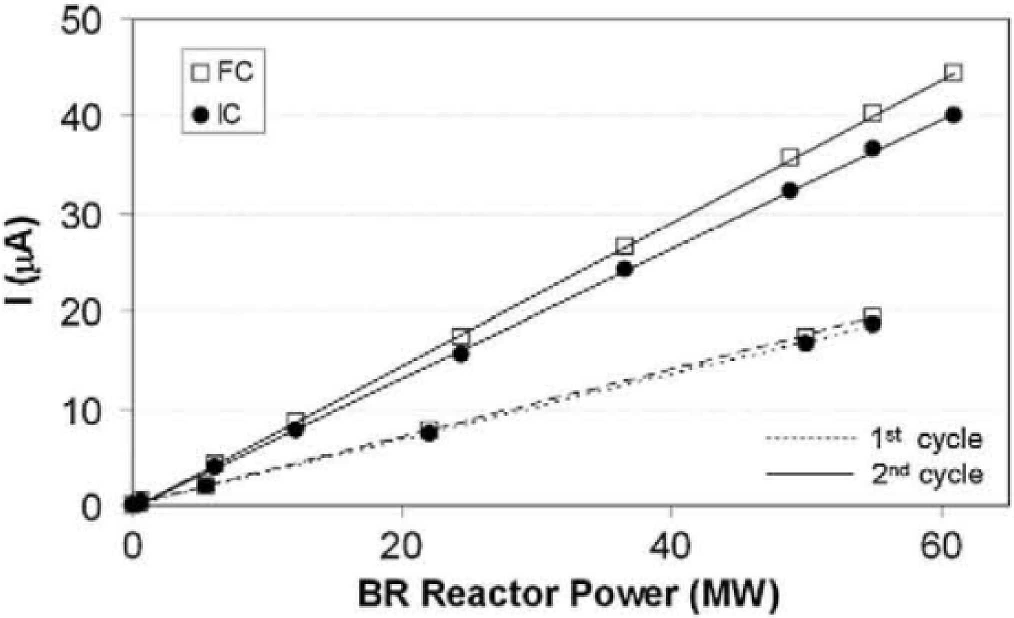


- The detectors were irradiated during two cycles.
- The integrated gamma dose absorbed was about 4×10^{10} Gy, and the fast neutron fluence, 4×10^{20} n/cm ^{2}.

3.3. Analysis of the sensors behaviour

Fission Chambers



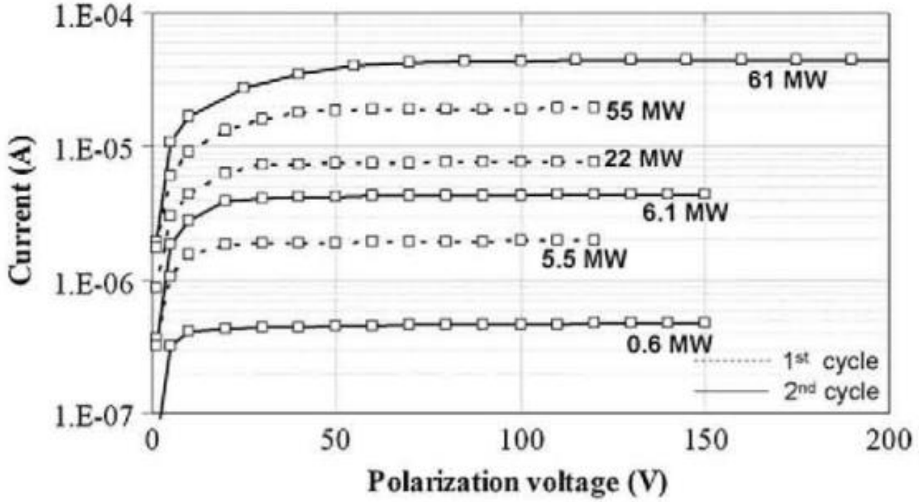


- Fission chamber in black diamonds and the ionization in grey.
- Differences due to the neutron induced component and the position.

- The different slopes are due to the change of channels between cycles, and the neutron and flux levels are also different.

3.3. Analysis of the sensors behaviour

Fission Chambers

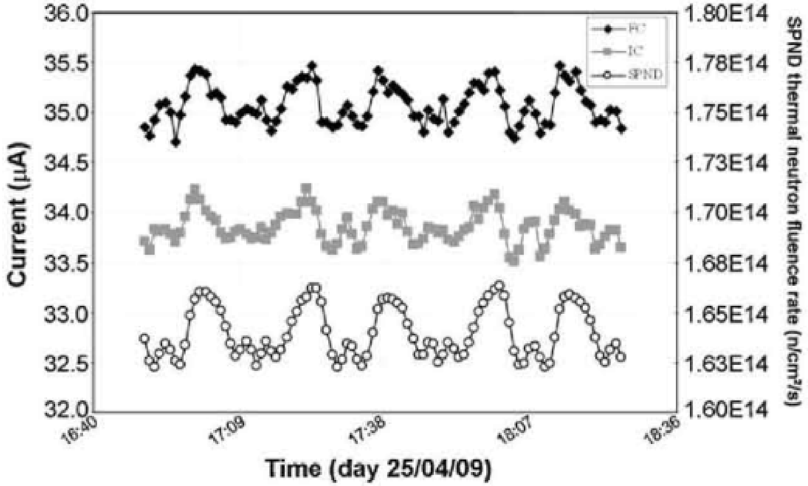


- Current-to-voltage characteristics for different neutron fluence, showing normal behaviour.
- Ionization chambers results are not displayed.
- Voltage was increased to 400 V to study the breakdown.
- Influenced by secondary ionization beyond 250 V and breakdown at 340 V.

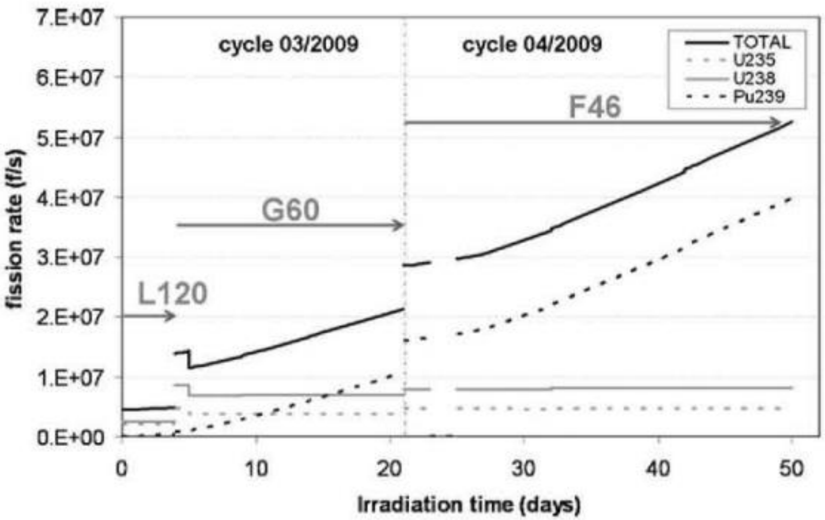
- Another parameter to consider is the isolation resistance, since it determined the leak current.
- It can drop depending on the radiation field seen by the detector cable.
- In the experiment, it was about 0.3 GHz, which represent < 2% of the signal of the detector.

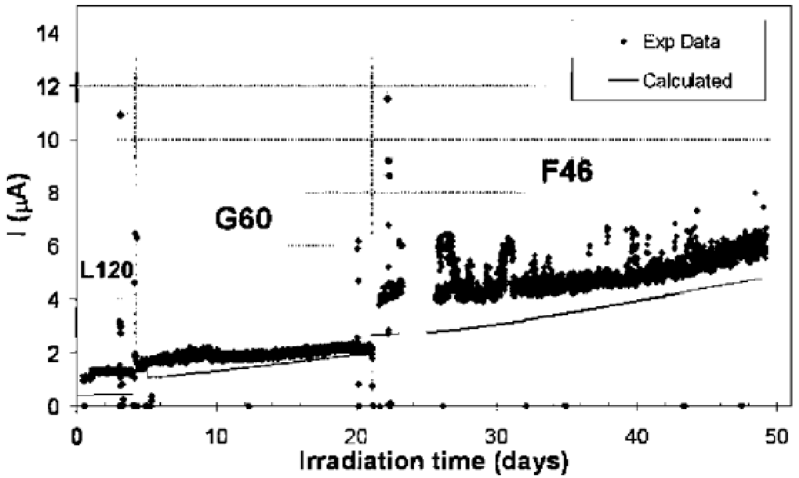
3.3. Analysis of the sensors behaviour

Fission Chambers



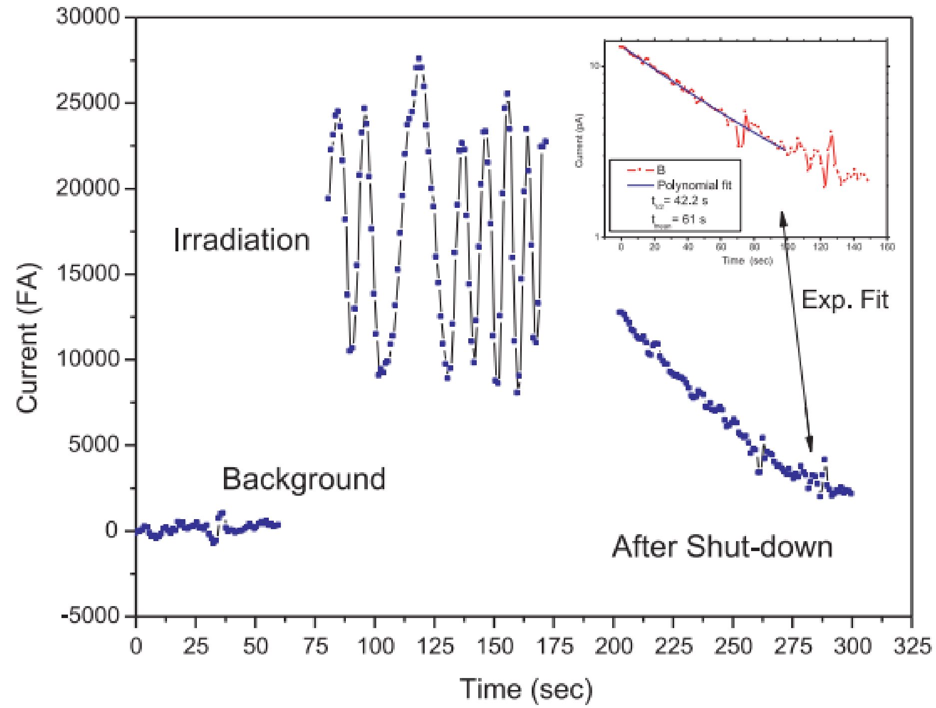
- Shows periodic flux variations
- Error of 0.2 % for an absolute current of 35 μA.
- ACAB code for the prediction.
- Growing fission rate due to Pu.
- Purely neutron signal obtained by substracting the currents from each detector.





Self-Powered Neutron Detectors

- The idea is that SPNDs has the lower possible sensitivity to gamma radiation, for which the emitter should have a high atomic number while the collector a low one.
- Some groups have made researches in neutron fields, with some materials such as Rh, V and Co.
- The hardening of the neutron spectrum greatly reduces the cross section and produces isotopes that reduces the beta activity and thus the current.
- Necessary to perform more tests in other environments and with other materials.



- Result of Rh showed good agreement, but neither the Co nor the V did.

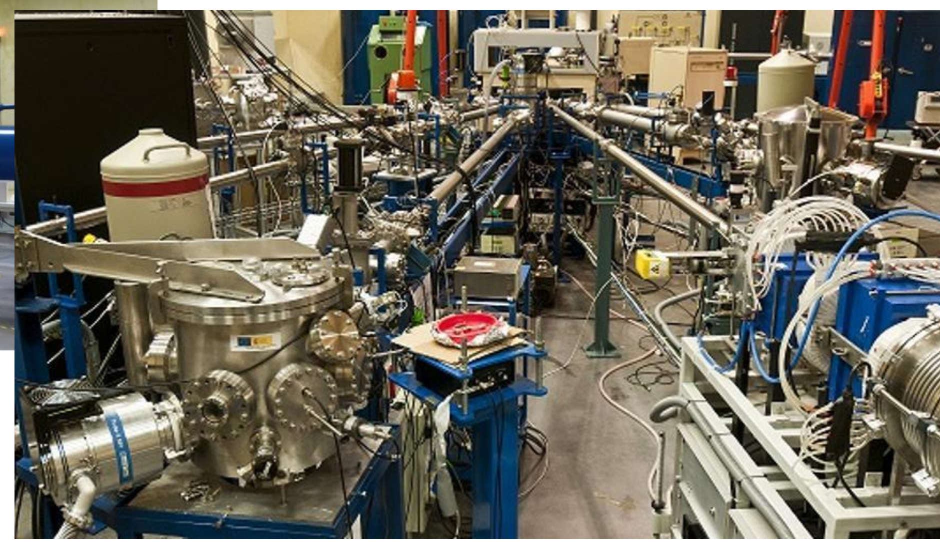
4. Proton Dosimetry

Background

- The use of protons in radiotherapy treatments has increased in recent years.
- It has a large spatial accuracy in the dose delivery.
- The relative uncertainties in the absorbed dose distribution must be below 5% in the external beam radiotherapy, according to the ICRU.
- Some commercial options are the already explained ionization chambers, or devices based on semiconductors.
- MOSFETS can have an increased sensitivity by having the gate fabricated under special conditions, thus creating the so-called RADFETs.
- Commercial MOSFETs are presented as dosimetric sensors, using the threshold voltage as the parameter measured.
- It works at a constant current to reduce the thermal effects.
- The MOSFET chosen for those initial tests is the 3N163, which has already been studied by our research group.

4. Proton Dosimetry

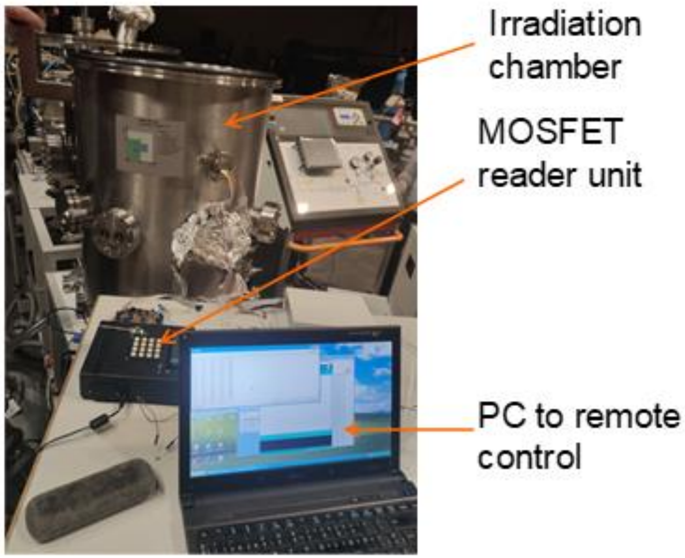
Facilities



- Tests were carried out in the National Center of Accelerators (CNA) in Seville, with the Tandem Accelerator, capable of generating a proton beam of 5,6 MeV.

4. Proton Dosimetry

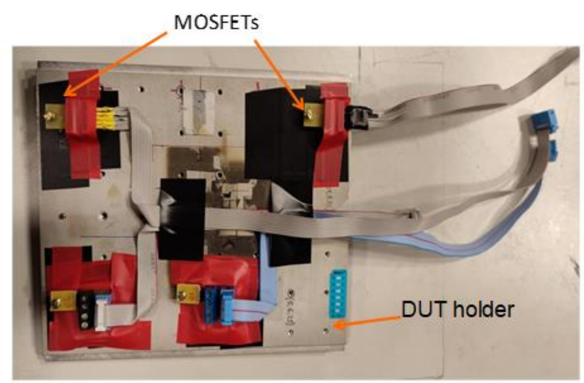
Reader unit



- It was developed by our research group, and it is capable of measuring with 0,1 mV of resolution and can bias the transistor with a current from 10 μA to 1 mA.

Sensor Module

- Composed by the MOSFET and two JFETs, and has three different states:
  - Storing State: all JFETs on and terminals of the MOSFET shortcircuited.
  - Readout State: source to current source and voltage measured.
  - Sensing State: gate is biased.

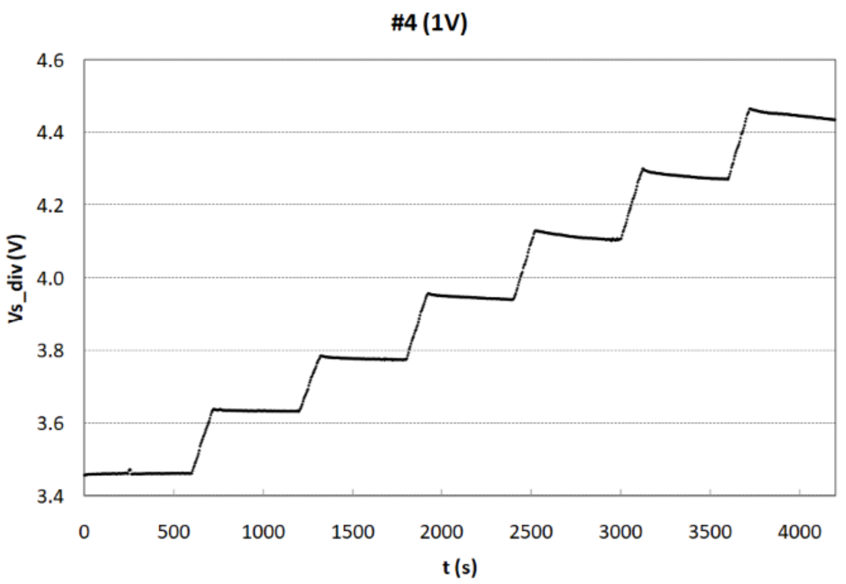


4. Proton Dosimetry

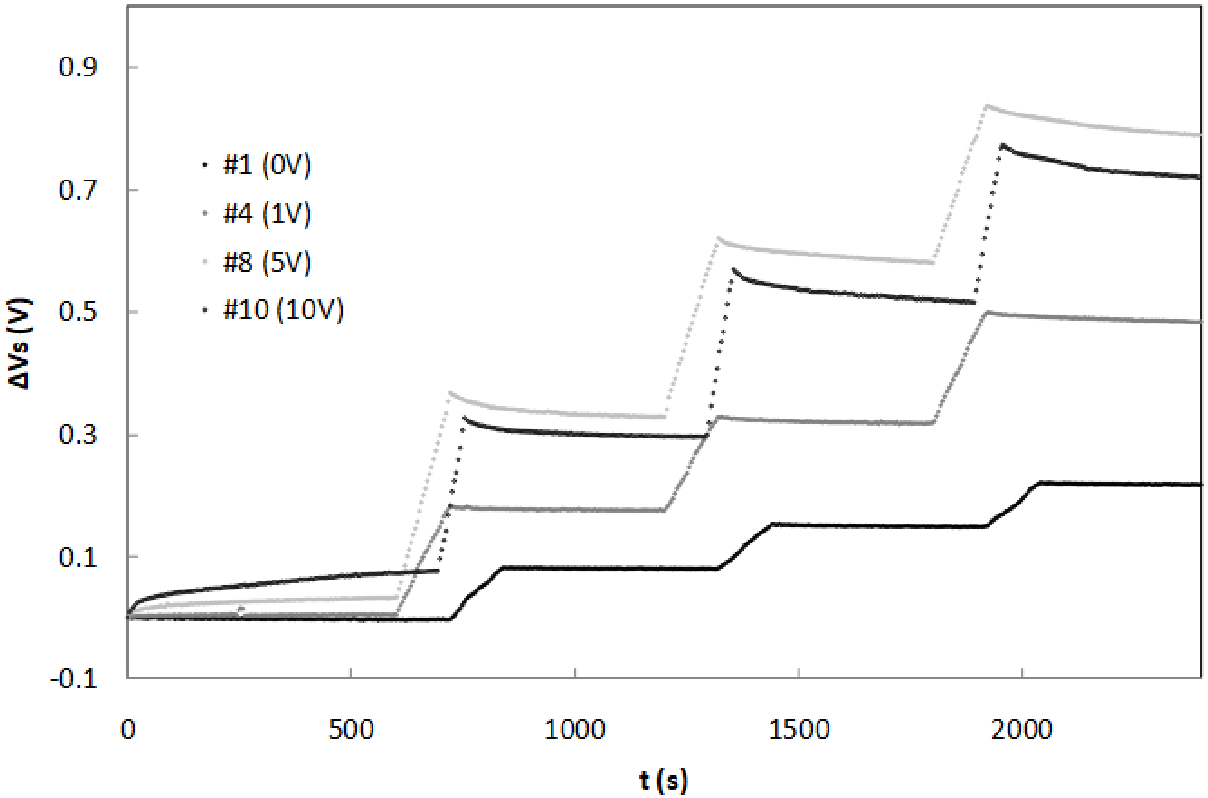
Results

- It consist of four voltage measurements: forward voltage, source voltage and the drain current.
- The housing was removed due to the low penetration power of the proton beam used.
- Four sets of three samples were made with different bias voltage.
- Irradiation sessions of two minutes, with an average dose of 13.4 Gy, with a rest period of 8 minutes.
- The parameter analized was the source voltage without amplification.
- Average sensitivity as a slope of the accumulated voltage shift, and instant one as the one during irradiation between dose-rate.

- To prevent the degradation, samples were irradiated until the source voltage was shifted 1 V from its original value
- The number of shots performed to each sample depended on the bias.



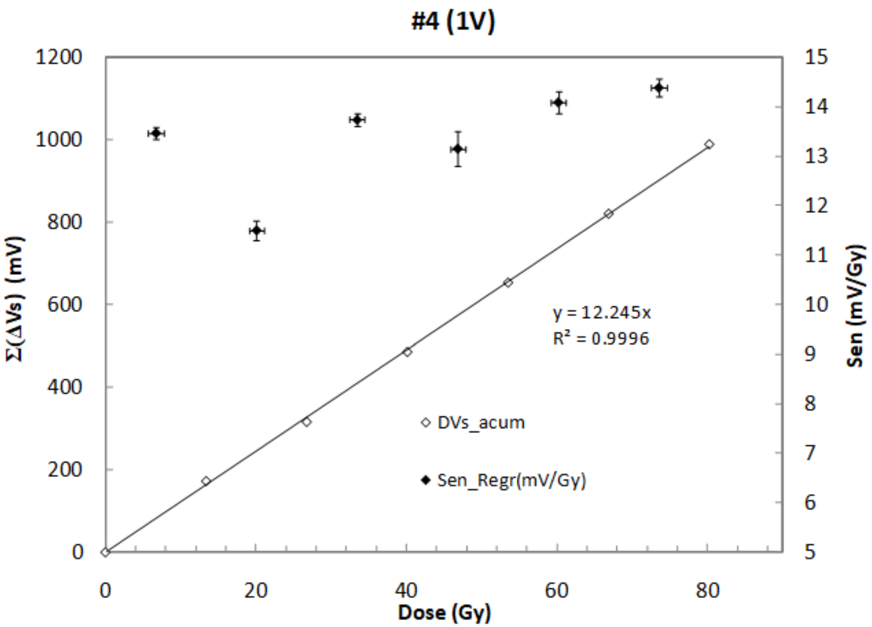
Results



- Source voltage increment during three irradiation sessions of four samples biased at different voltages.

4. Proton Dosimetry

Results



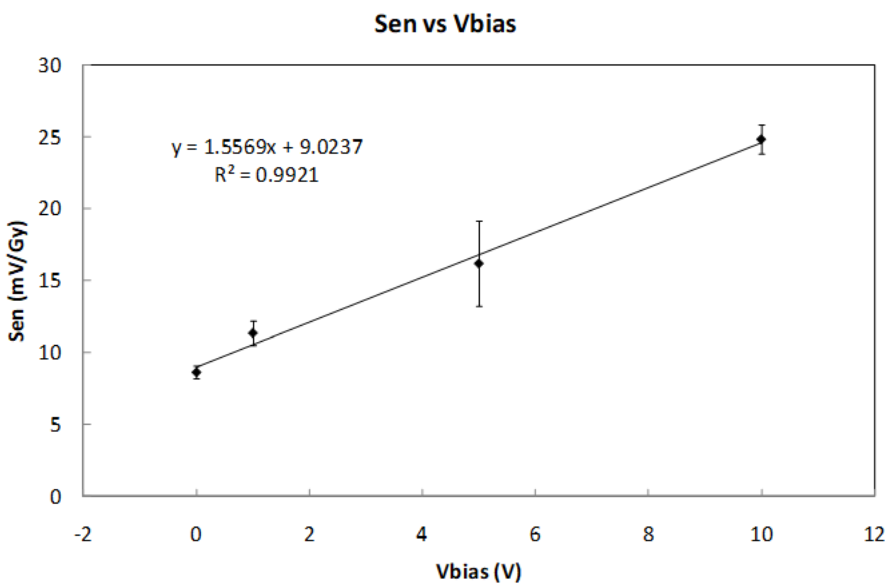
MOSFET	Sen (mV/Gy)	σ_Sen (mV/Gy)	Vbias (V)	Avg_Sen (mV/Gy)	σ_AvgSen (mV/Gy)
#1	8.18	0.24			
#2	8.66	0.15	0	8.6	0.4
#3	9.08	0.09			
#4	12.24	0.05			
#5	11.31	0.09	1	11.4	0.9
#6	10.5	0.3			
#7	19.3	0.4			
#8	13.4	0.4	5	16.2	3.0
#9	15.81	0.23			
#10	23.6	0.5			
#11	25.50	0.05	10	24.8	1.0
#12	25.3	0.3			

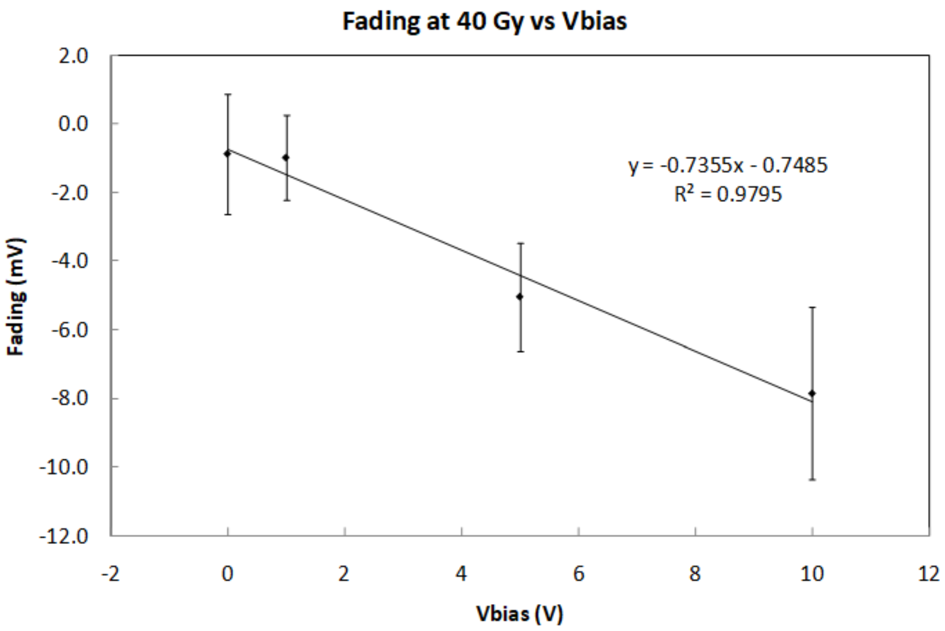
- Accumulated source voltage shift as a dose function.
- Instant sensitivity per irradiation shoot.

- Highest sensitivity with the highest bias voltage.
- A linear dependance has been found.

UNIVERSIDAD DE GRANADA

Results





- There is a linear dependence of the sensitivity with the bias voltage.
- It is also important to consider the short-term fading, which was calculated with four samples at different bias and 5 minutes after the third irradiation session.
- Considering the error due to the fading, the best choice is the 1 V bias.

V bias (V)	Fading Dose error (Gy)		
0	-0.10	±	0.20
1	-0.09	±	0.11
5	-0.31	±	0.11
10	-0.32	±	0.10

References

[1] U. Wiącek, F. Arbeiter, B. Bieńkowska, D. Bocian, J. Castellanos, A. Igielski, J. Kotuła, W. Królas, A. Kurowski, G. Madejowski, R. Prokopowicz, R Ortwein, J Świerblewski. (2021). New approach to the conceptual design of STUMM: A module dedicated to the monitoring of neutron and gamma radiation fields generated in IFMIF-DONES, Fusion Engineering and Design. 172. https://doi.org/10.1016/j.fusengdes.2021.112866.

[2] D. Rapisarda, L. Vermeeren, A. GarcÍa, O. Cabellos, J.M. García, A. Ibarra, J.M. Gómez-Ros, F. Mota, N. Casal, V. Queral. (2011). Study on the response of IFMIF fission chambers to mixed neutron-gamma fields: PH-2 experimental tests. Fusion Engineering and Design. 86. 1232-1235. 10.1016/j.fusengdes.2011.03.079.

[3] D. Rapisarda, A. García, O. Cabellos, F. Mota, J.M. Gómez-Ros, A. Ibarra, N. Casal, V. Queral, J. Sanz. (2009). Feasibility of fission chambers as a neutron diagnostic in the IFMIF—Test Cell, Fusion Engineering and Design. 84. 7–11. 10.1016/j.fusengdes.2009.02.004.

[4] V. Verma, L. Barbot, P. Filliatre, C. Hellesen, C. Jammes, S. Jacobsson Svärd. (2017). Self powered neutron detectors as in-core detectors for Sodium-cooled Fast Reactors, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 860. 6-12. 10.1016/j.nima.2017.04.011.

[5] M. Angelone, A. Klix, M. Pillon, P. Batistoni, U. Fischer, A. Santagata. (2014). Development of self-powered neutron detectors for neutron flux monitoring in HCLL and HCPB ITER-TBM, Fusion Engineering and Design. 89. 2194-2198. 10.1016/j.fusengdes.2014.01.077.

[6] Jammes, C., Filliatre, P., Geslot, B., Oriol, L., Berhouet, F., Villard, J., & Vermeeren, L. (2009). Research activities in fission chamber modeling in support of the nuclear energy industry. *2009 1st International Conference on Advancements in Nuclear Instrumentation, Measurement Methods and their Applications*, 1-5.

[7] G.F. Knoll (2000). Radiation Detection and Measurement