$^{12}C+^{12}C$ status update

LUNA Collaboration meeting

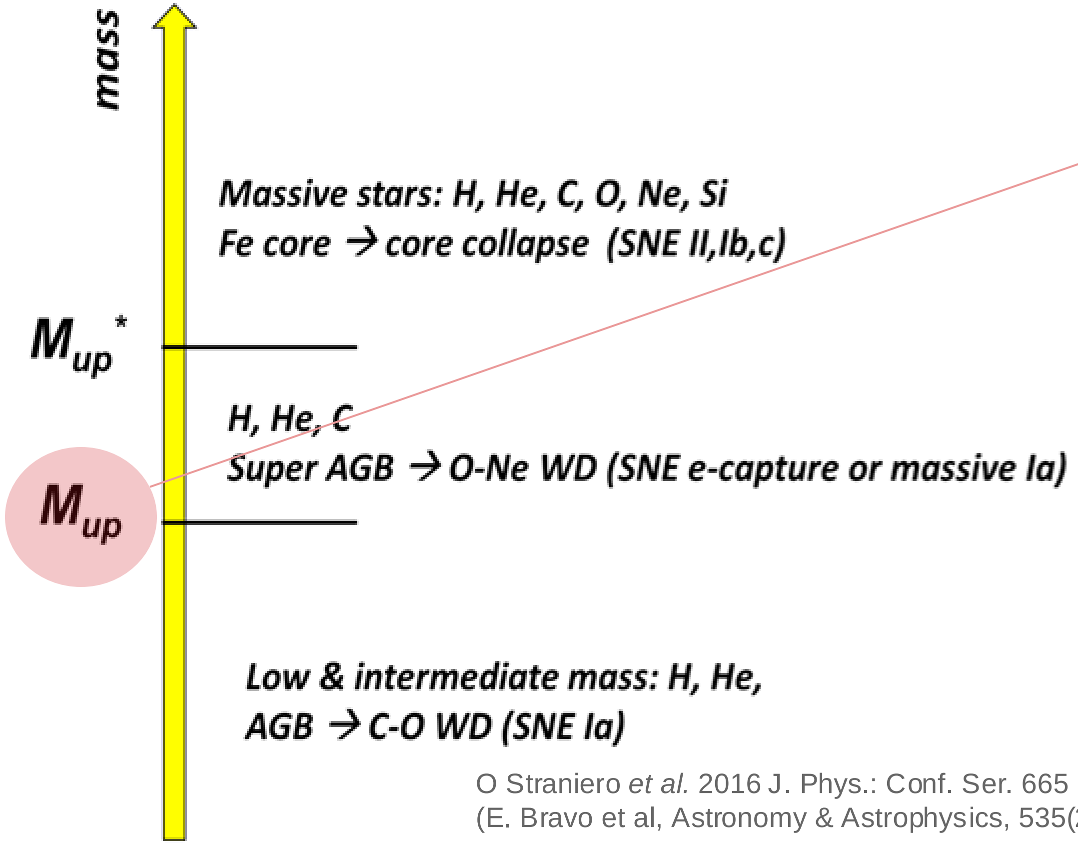
2 July 2024

Outline

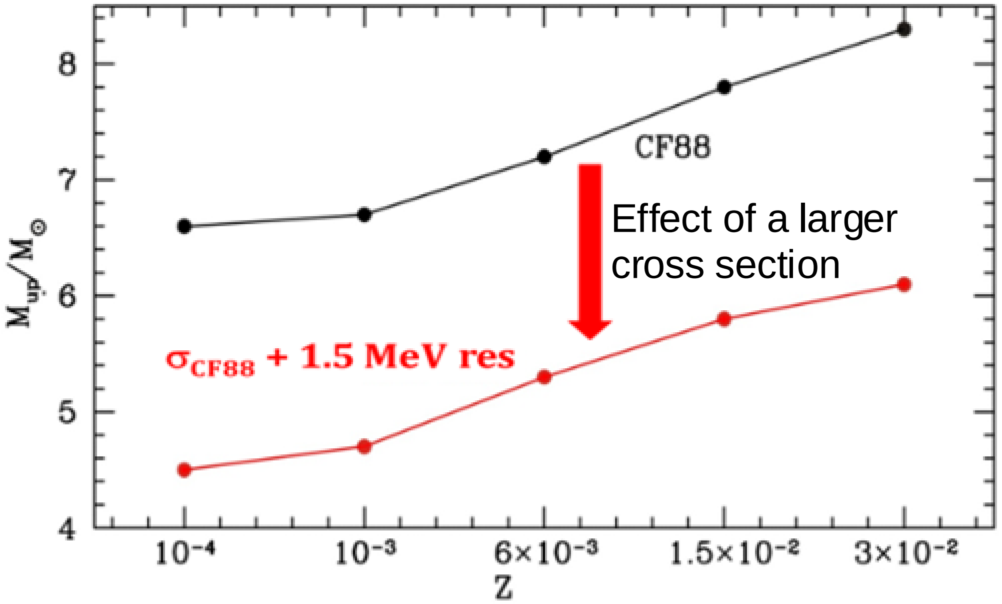
- Motivation and present status
- Integration tests
- Beamline control system
- Targets and target holders
- GePD2
- NaI detector
- Simulations
- Application to the new call of the Bellotti IBF

Motivation and present status

Motivation & present status



$M > M_{up}$	⇒	quiescent C burning (ONe-WD, CC-SN, NS, BH)
$M < M_{up}$	⇒	no C burning (CO-WD, Novae, **SN-Ia**)



O Straniero *et al.* 2016 J. Phys.: Conf. Ser. 665 012008
(E. Bravo et al, Astronomy & Astrophysics, 535(2011)A114)

Moreover:

- **p and α produced in hot environment** as a result of $^{12}C+^{12}C$ fusion ⇒ reactions induced by p and α
- increase of the cross section ⇒ decrease of the **superburst** ignition depth (triggered by $^{12}C+^{12}C$ fusion)

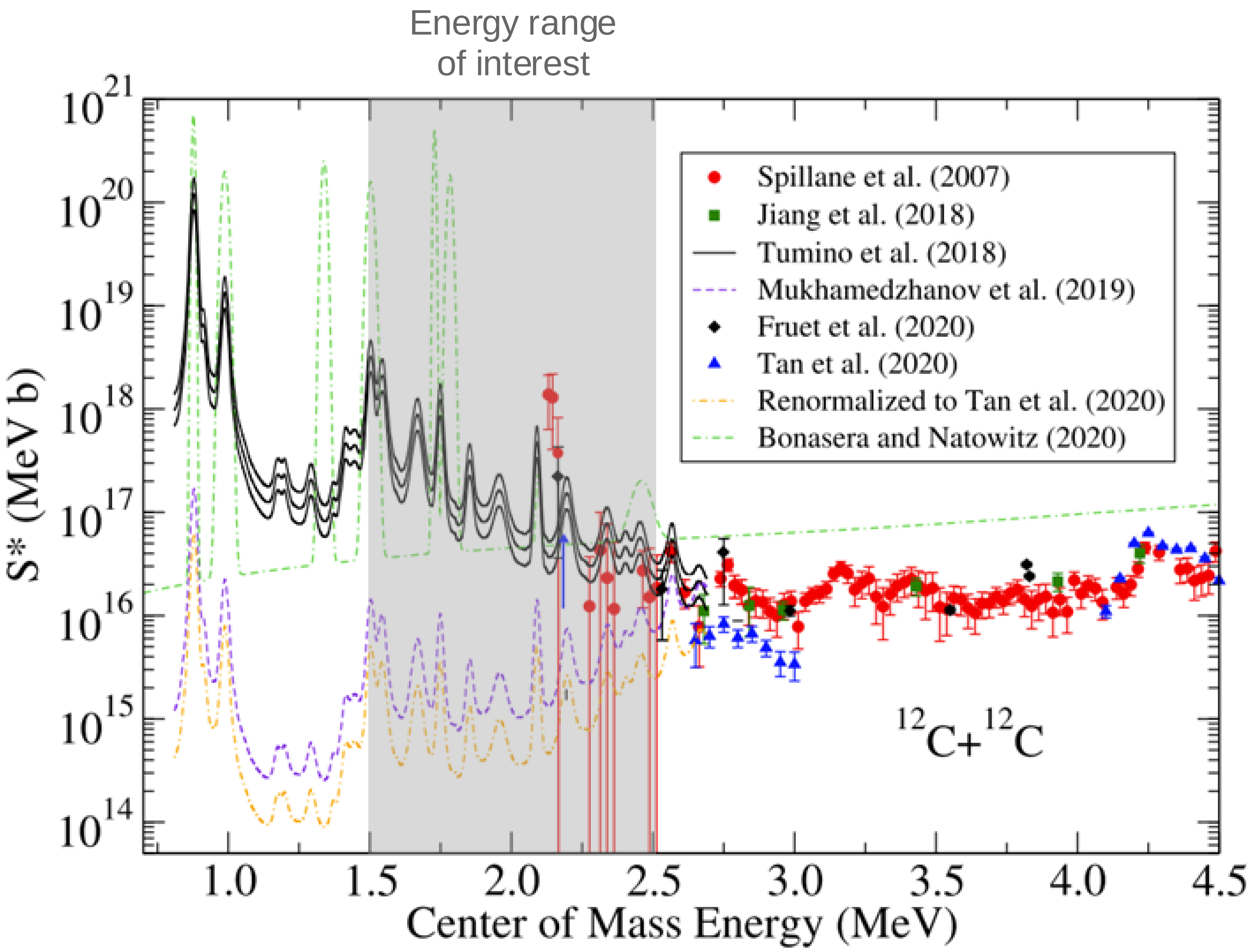
Motivation & present status

Several models

- **Tumino** states that Coulomb interactions are negligible and uses PWA
- **Mukhamedzhanov** states that Coulomb interactions are non-negligible and uses DWBA
- Bonasera and Natowitz extended the Neck Model to sub barrier energies within the Feynman Path Integral Method framework.

Different normalizations

- **Mukhamedzhanov** (renormalized to Tan)



M Aliotta et al 2022 J. Phys. G: Nucl. Part. Phys. 49 010501

Integration tests

Federico, Matthias, Riccardo

Integration test

IKEA-like list of instructions to assemble the shielding will take into account what we learnt during the test

Integration test results: shielding

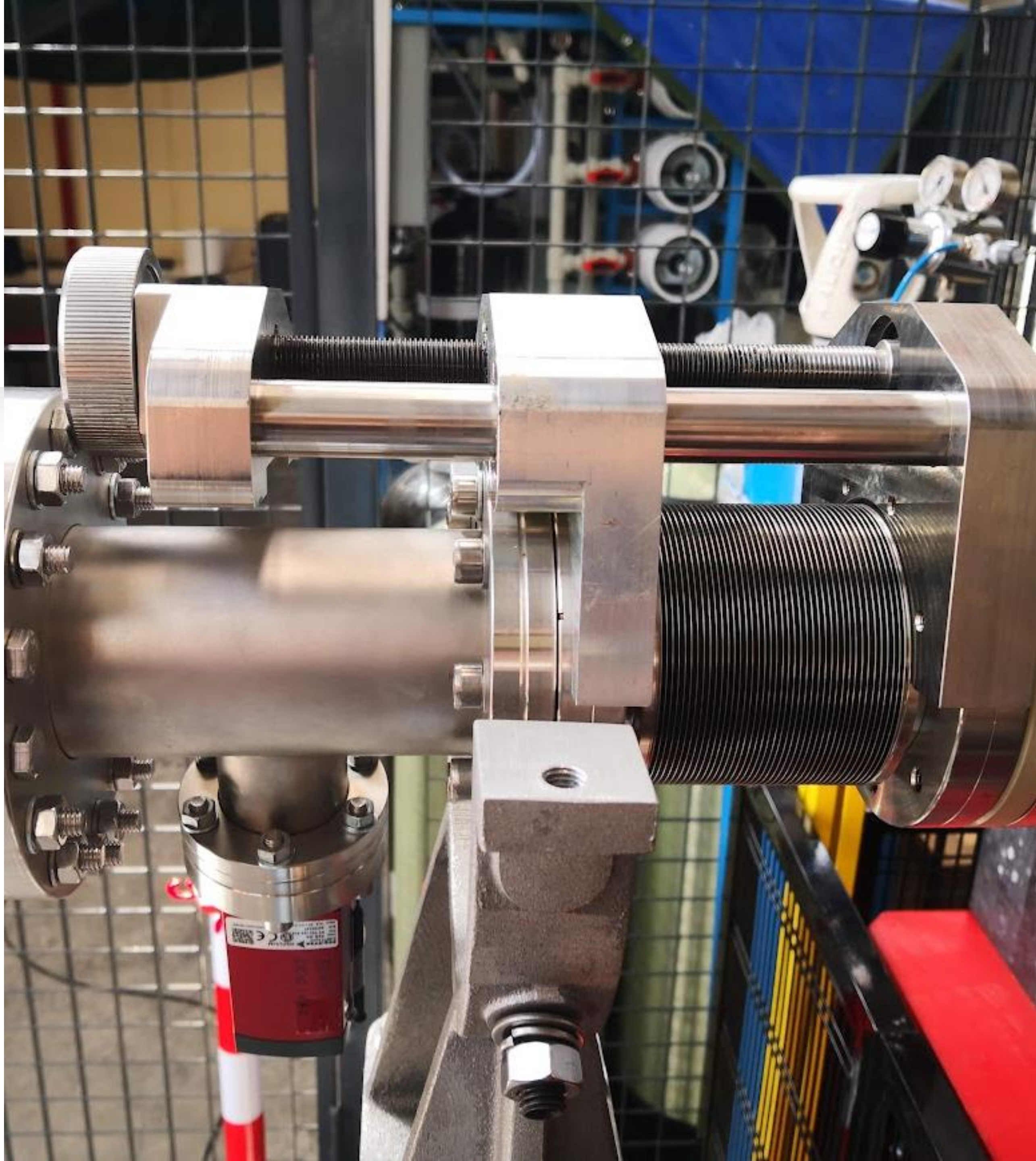
Colors indicate the readyness level

- Reduce the diameter of the spines in the top posterior internal wall.
- Replace stainless steel screws on the bottom of the Cu box with brass screws
- HPGe cold finger touches the Pb shielding:
  - Enlarge the hole
  - Make the table for the Dewar adjustable
- Prepare shims to ease the copper box positioning
- Prepare a copper disc to close the hole downstream in the copper box
- Refine the Cu handles (they touch the Pb door)
- Check the dimensions of the crane and lifting tools to be used underground
- Produce staging and procure stairs for the assembly of the shielding underground
- Modified downstream walls and new Pb inserts will be delivered at LNGS by the end of the first week of July

Integration test results: beamline

Colors indicate the readyness level

- Use insulated screws for insulating part (find insulating spacers)
- Rotate the four-way cross perpendicular to the beam line
- Produce a support for the beam line to be placed inside the shielding
- Purchase a longer drift with a smaller diameter
- Ask for accurate position of the GV in the accelerator room
- Prepare rigid aligning tools to be mounted on the table
- Procure components for automatic control
- Program automatic control
- Test automatic control



Beamline control system

David, Federico, Riccardo

Beamline control system

- **Elements**
  cryopump system (communication: RS485)
  scroll pump (RS485)
  maxi gauge (RS485)
  gate valves (NI relay module)
  1 - line gate valve (IBF one)
  2 - cryo-pump valve (24VDC + relay, DIO module)
  3 - beam line bypass (24VDC + relay, DIO module)
  4 – venting (24VDC + relay, DIO module)
- **Procedures**
  Start vacuum (tested manually in Lab7, procedure available)
  Stop Vacuum (tested manually in Lab7, procedure available)
  Change Target (procedure need to be produced)
  Venting (procedure need to be produced)
  Manual operation (expert users)
- **Interlocks**
  Vacuum levels
  Pumps in operations
  Procedure status

NOTE
IBF requirement to have a venting procedure status to avoid mistakes and a vacuum level acknowledgement. Will be done with NI relay and maxi gauge relay port (as for SHADES)

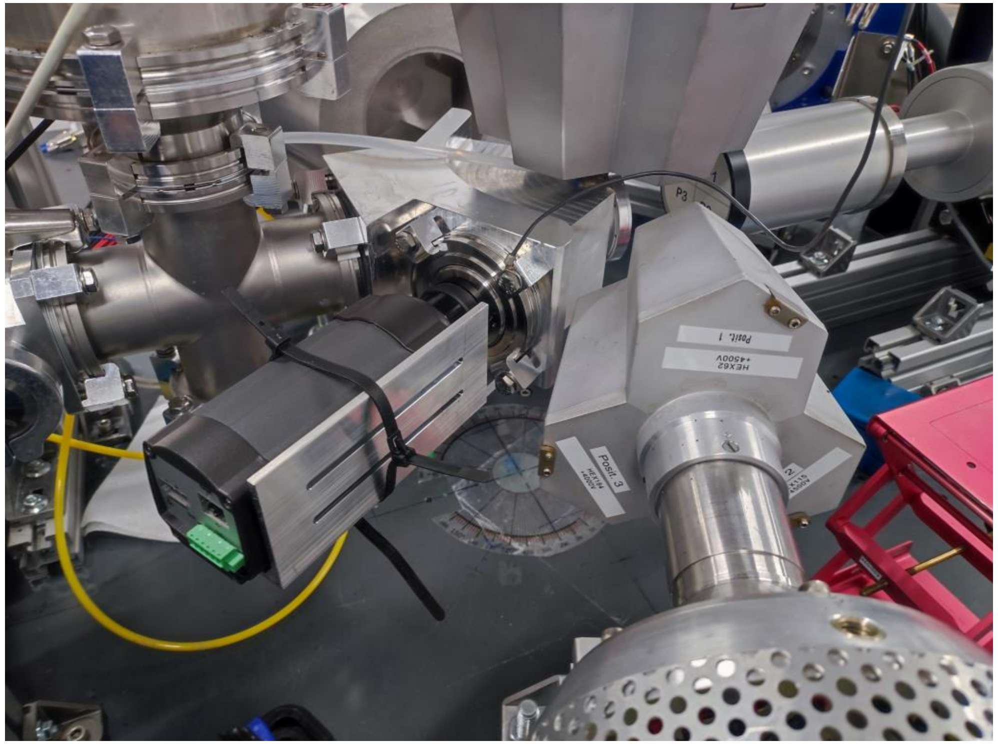
OPTION
HPGe temperature and electron suppression controls could be added

Targets and target holder

Denise, Eliana, Federico, Sumittra, Matteo, Valentino, Steffen, Linus

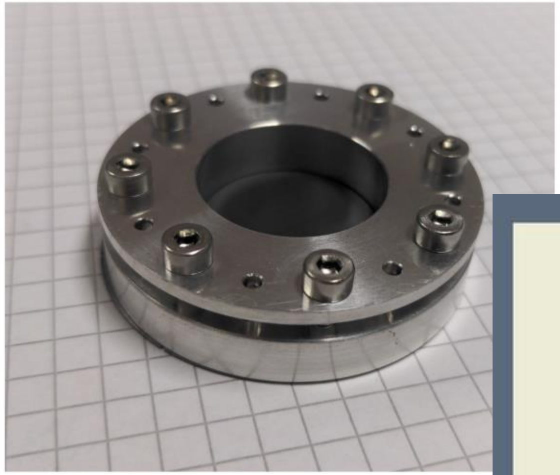
Aims

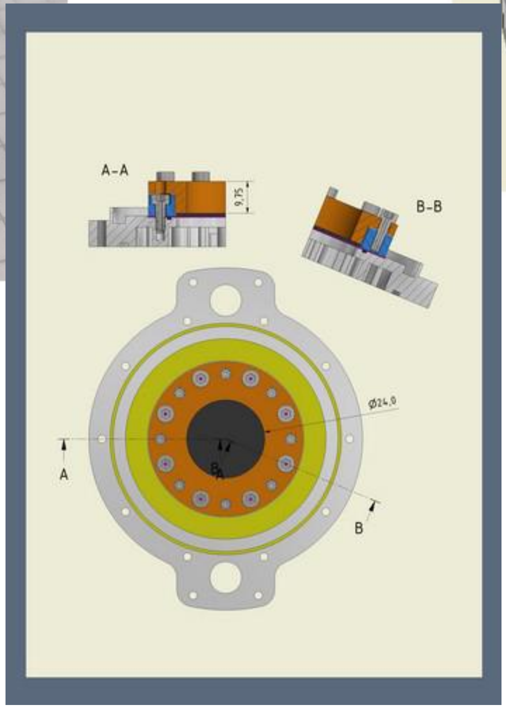
- test degradation of different targets
- test the vacuum and thermal features of target+holder assembly
- test contamination in targets



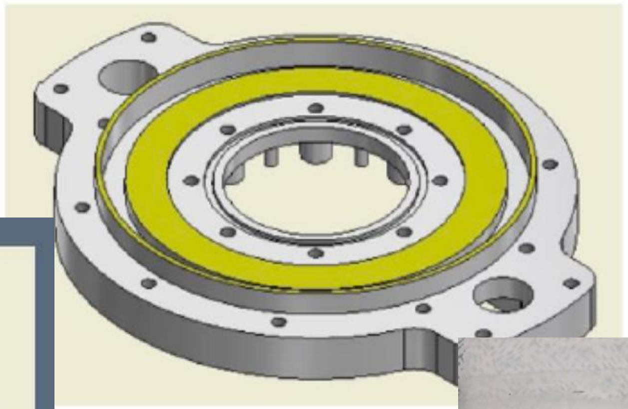
- First phase (tests performed at Felsenkeller - low beam intensity)
    - we tested different target holder options finding a good **baseline design**

Rings to hold the Ta backing and the C target

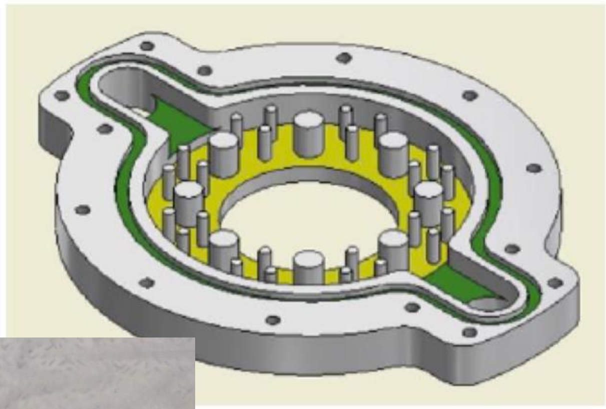


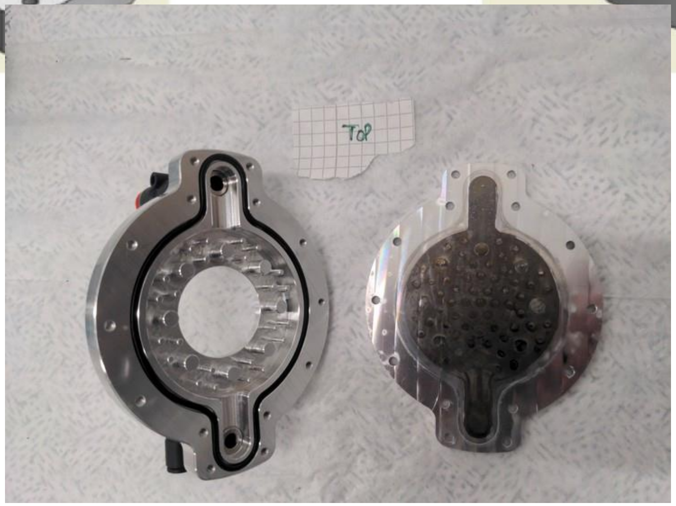


New machined target holder - front

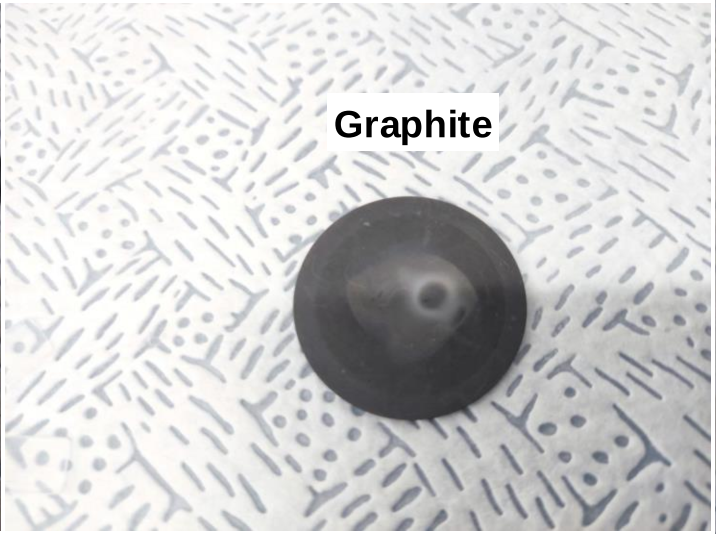


New machined target holder - back



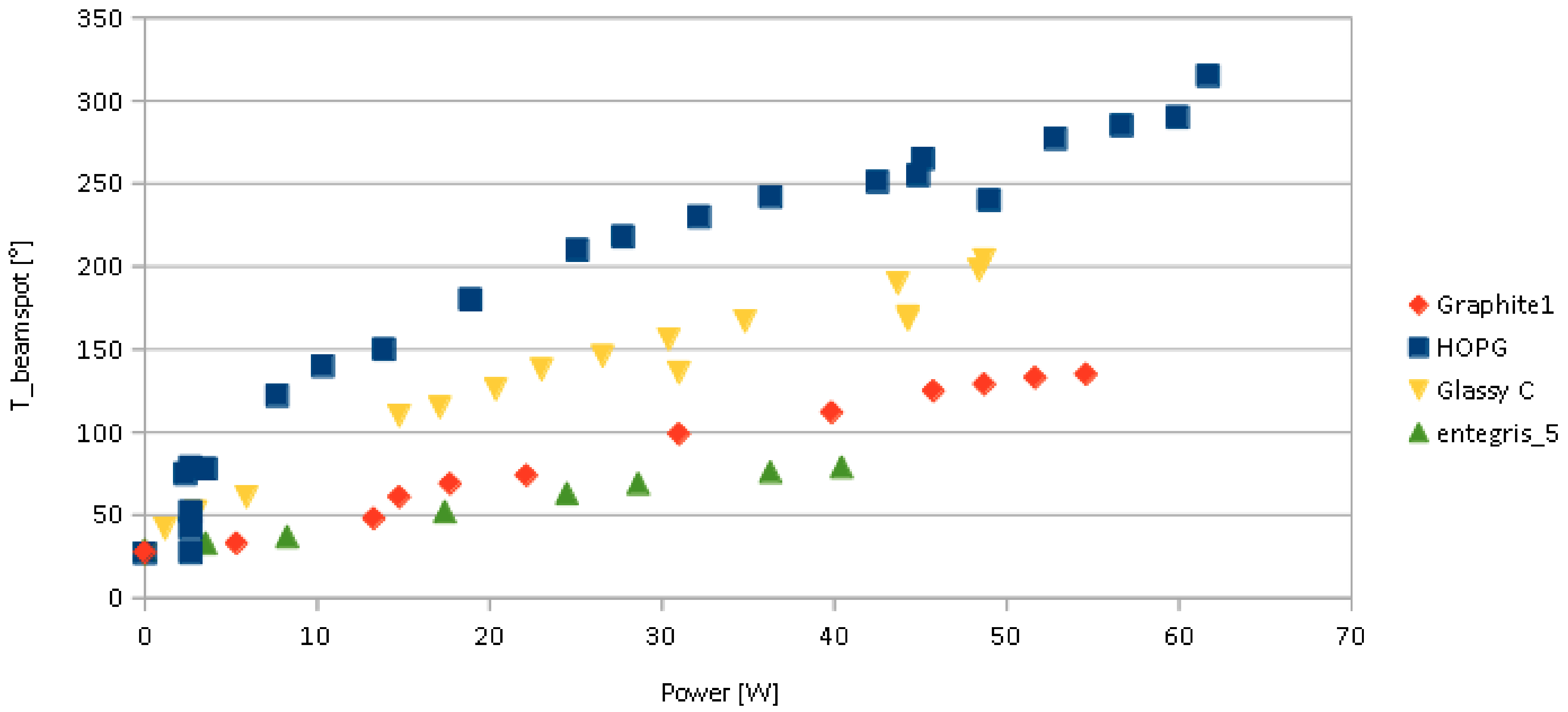


- First phase (tests performed at Felsenkeller - low beam intensity)
  - we tested different target holder options finding a good **baseline design**
  - we tested different target types

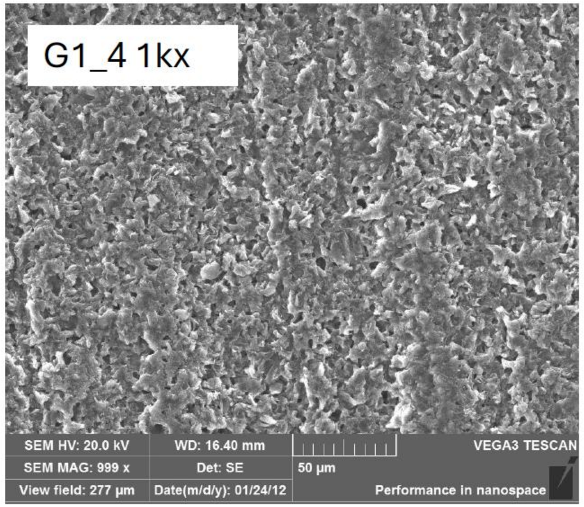


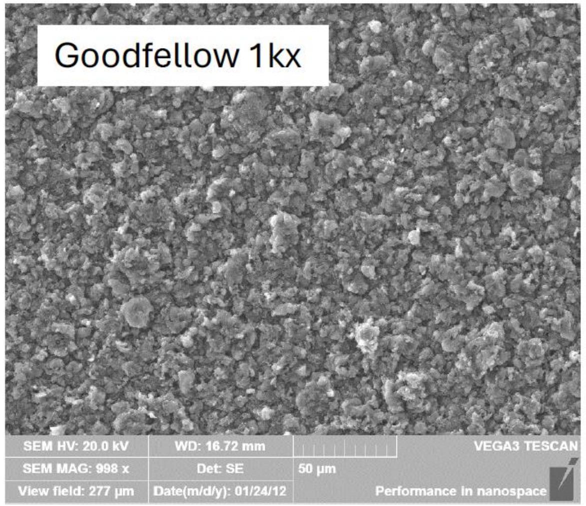
- All irradiated up to 1 C of accumulated charge
- All 1 mm thick

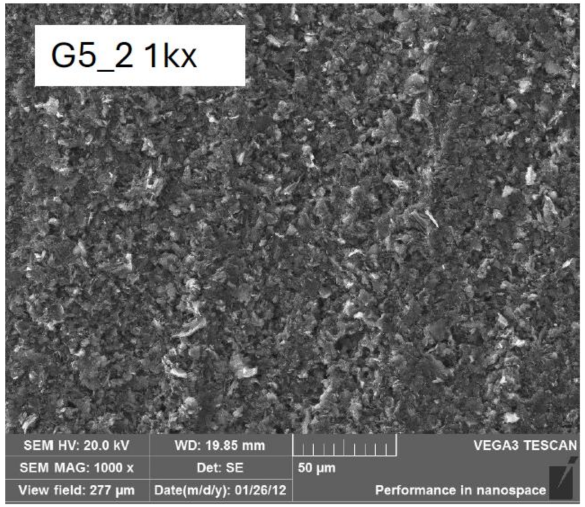
- First phase (tests performed at Felsenkeller - low beam intensity)
  - we tested different target holder options finding a good **baseline design**
  - we tested different target types

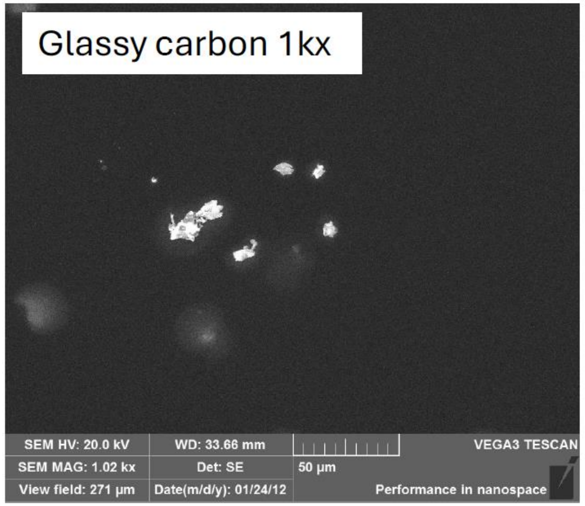


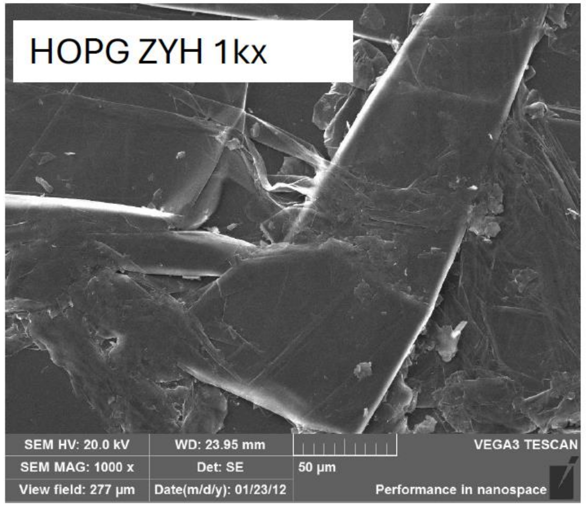
- Second phase (ongoing analysis - SEM)
  - analysis of the irradiated target via SEM (scanning electron microscope)

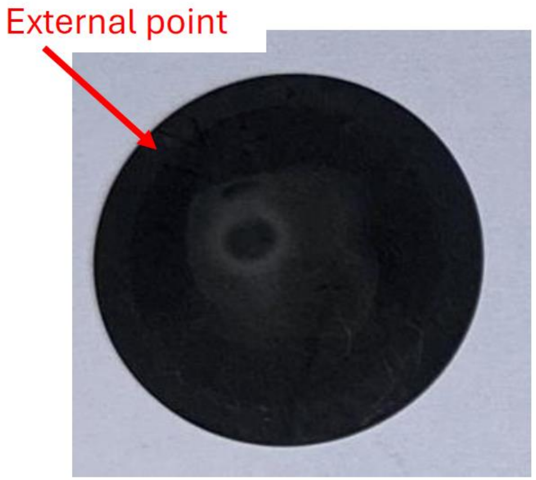




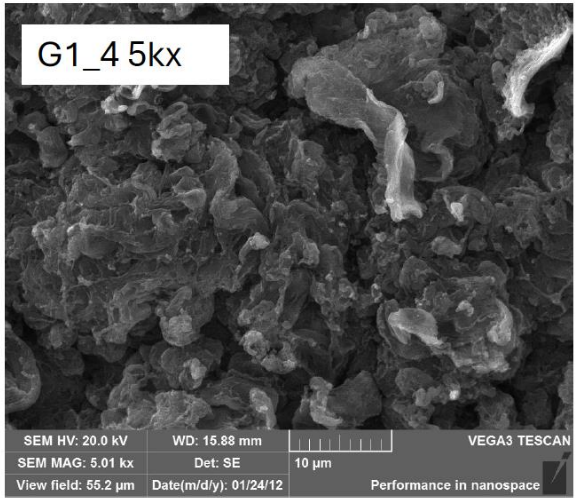


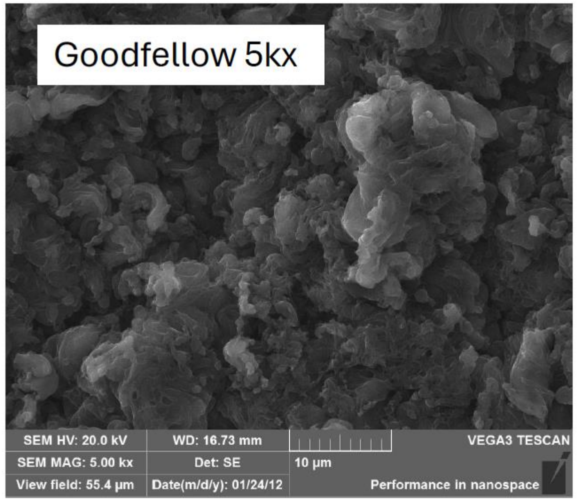


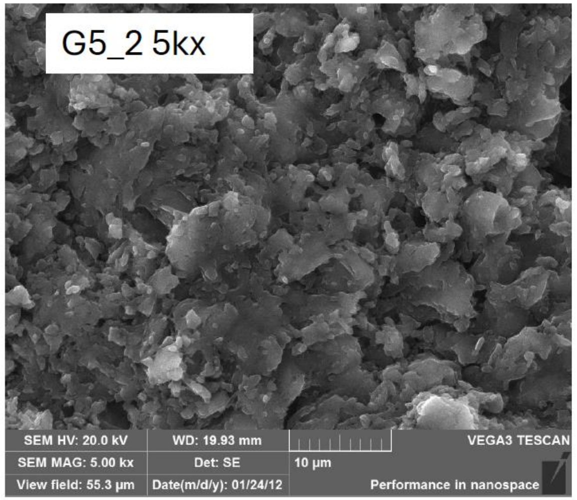


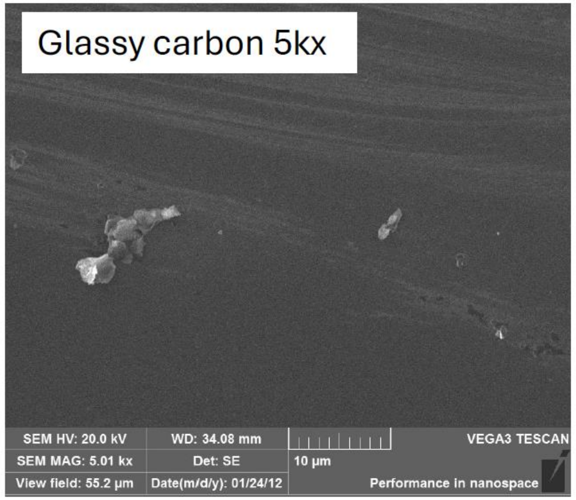


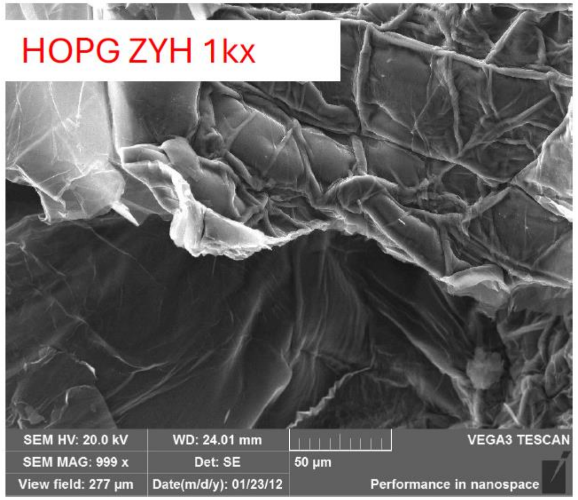
- Second phase (ongoing analysis - SEM)
  - analysis of the irradiated target via SEM (scanning electron microscope)

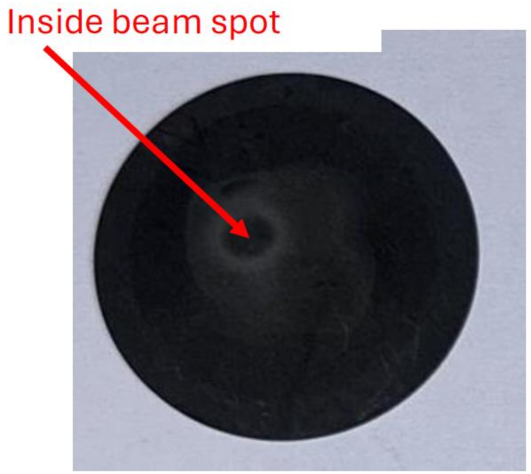






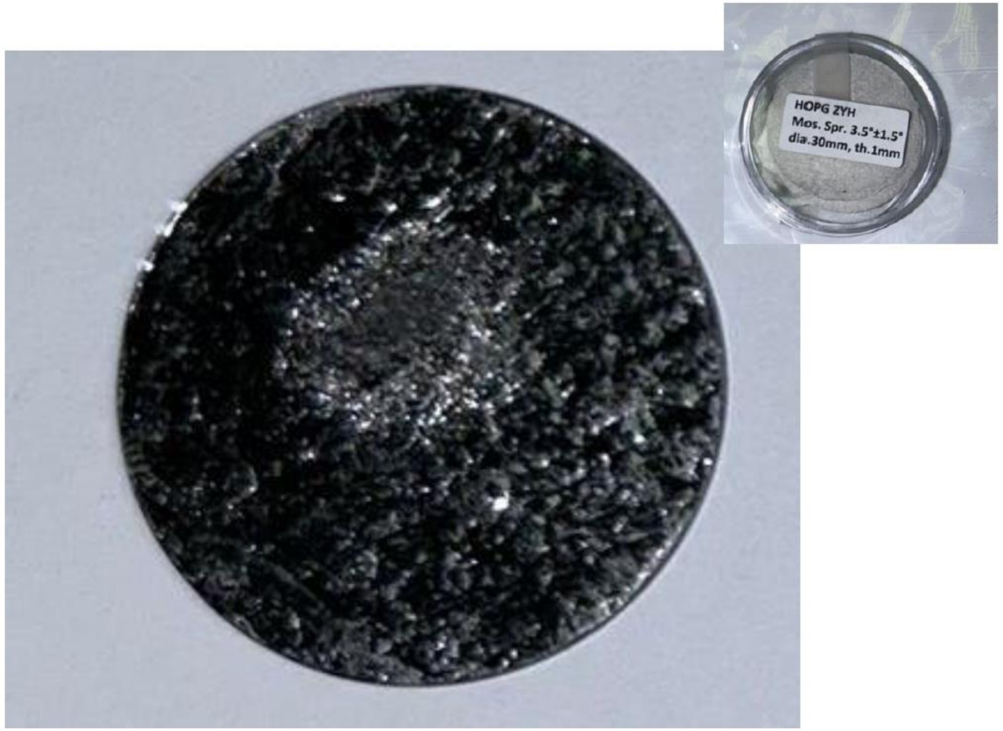


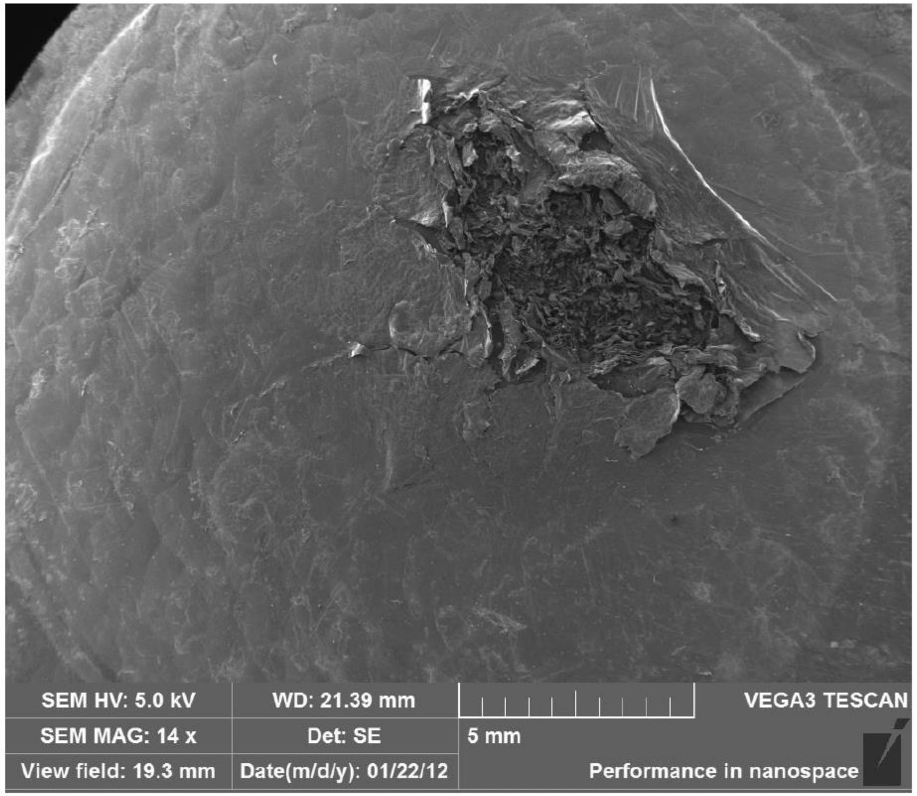




- Second phase (ongoing analysis - SEM)
  - analysis of the irradiated target via SEM (scanning electron microscope)

HOPG_ZYH -> swelling + flaking effect





- Second phase (ongoing analysis - SEM)
  - analysis of the irradiated target via SEM (scanning electron microscope)

Sigradur_Glassy carbon

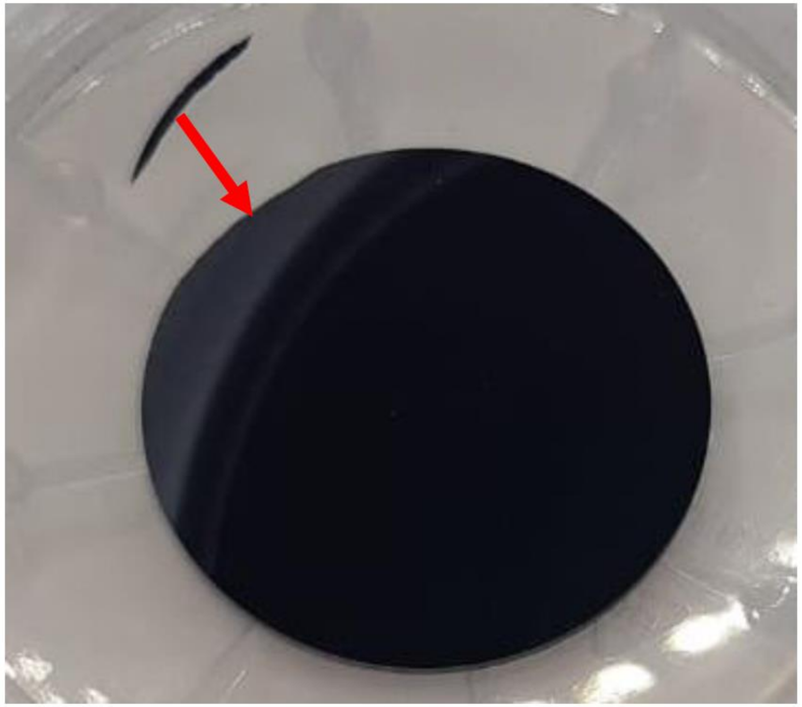
Surface roughness line (step like)

Could be a first step of brittle cracks

➔ Implantation induces stress due to density change

➔ The local stress could evolve in cracks (surface or subsurface)

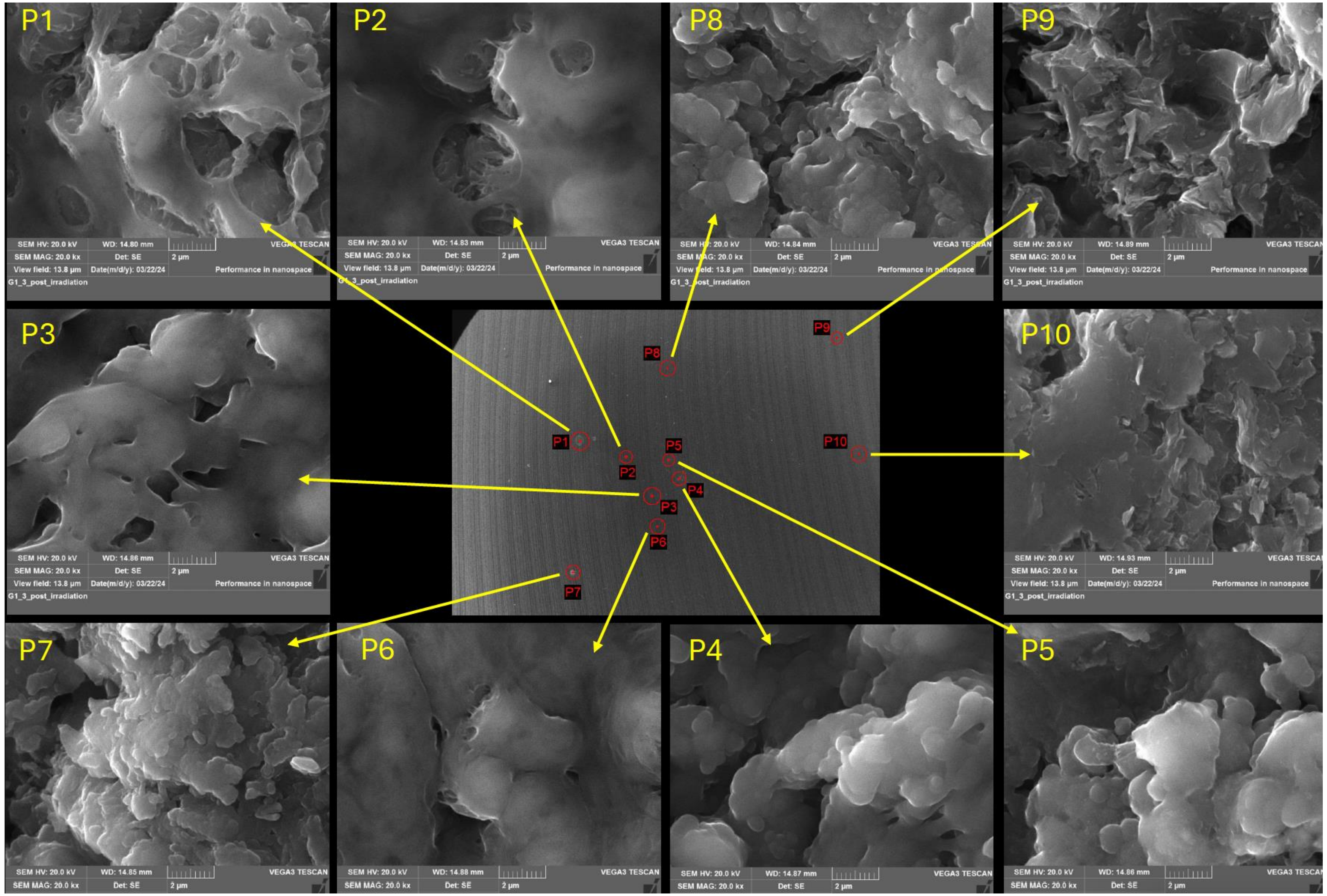
➔ Crack+stress = brittle fracture -> like cocktail glass



- Second phase (ongoing analysis - SEM)
  - analysis of the irradiated target via SEM (scanning electron microscope)

G1_3
~ 3C

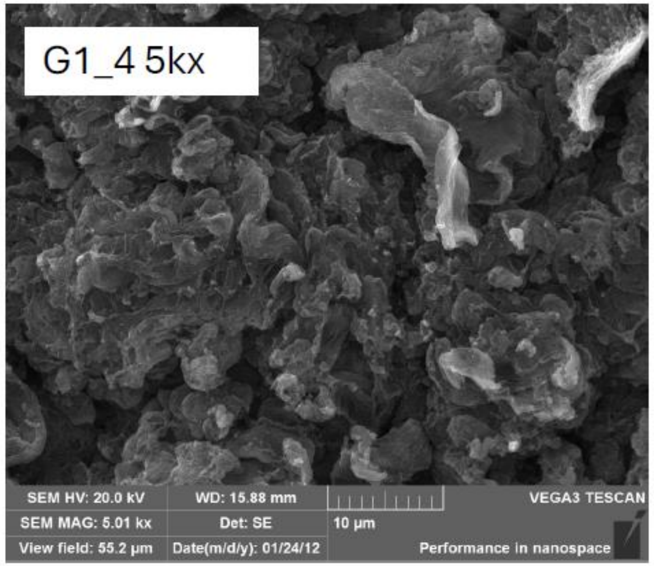
MAG
20kx

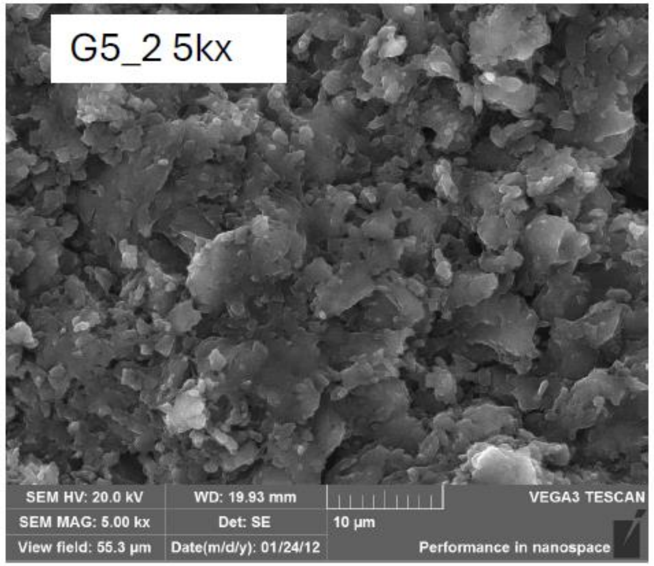


Damage ascribable to material amorphization

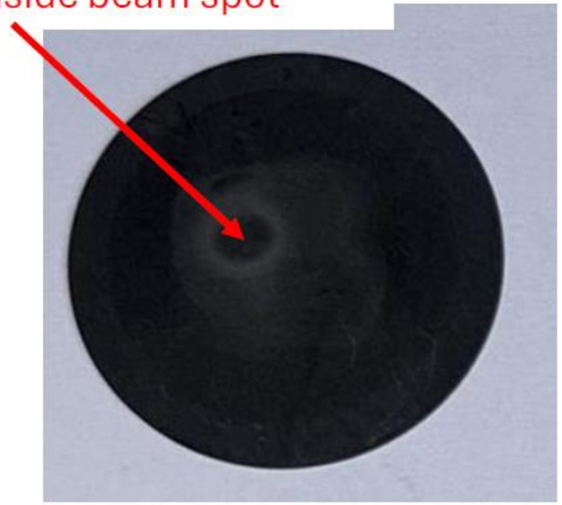
Surface fusion excluded by online thermal measurements

- **Second phase** (ongoing analysis - SEM) …long story short…

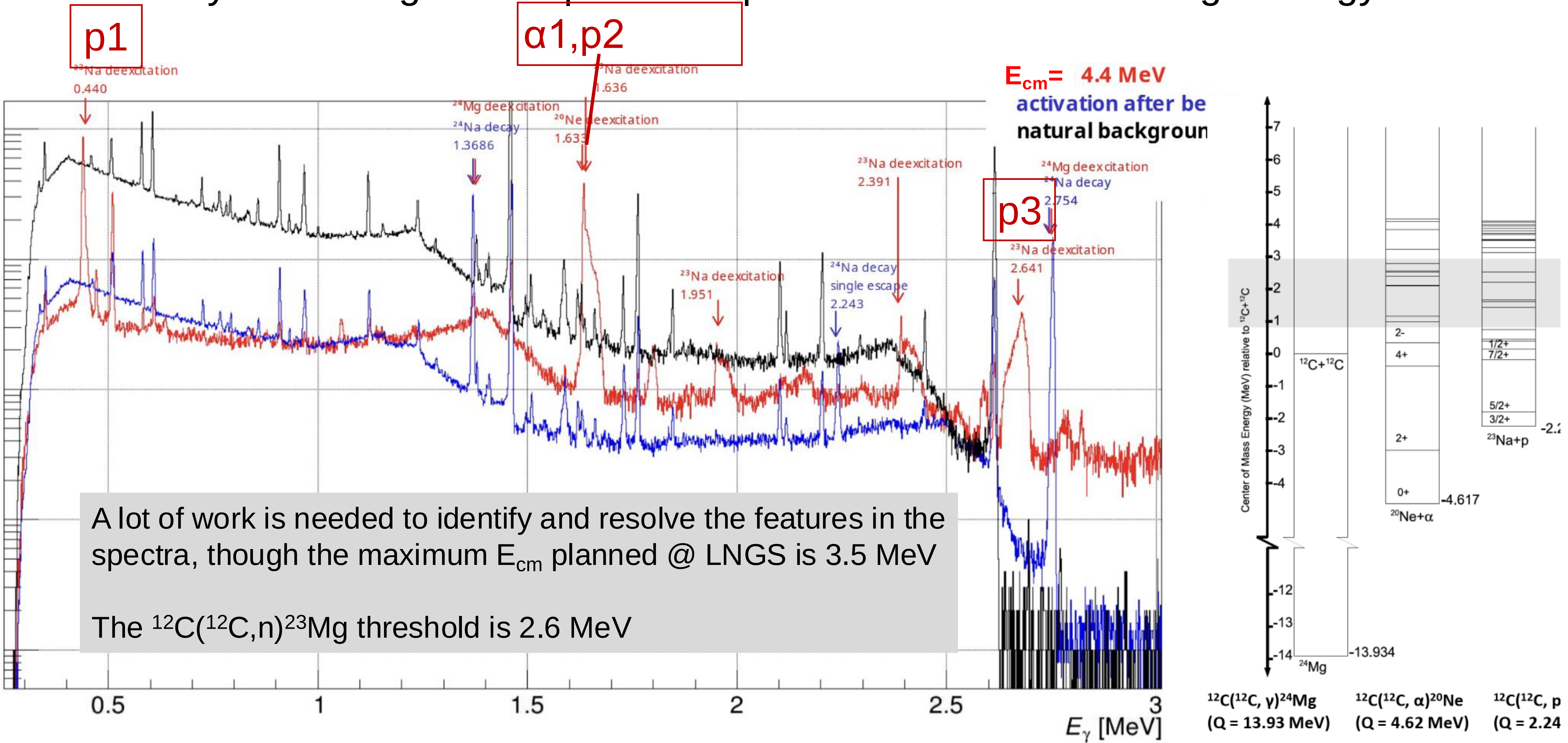




Inside beam spot



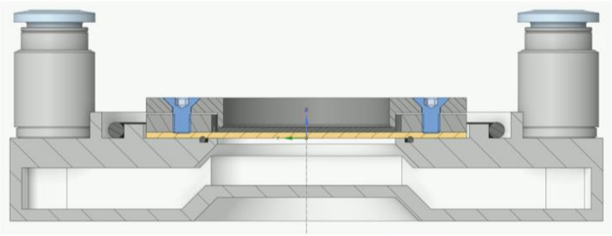
- Second phase (ongoing analysis - gamma spectra)
  - analysis of the gamma spectra acquired at Felsenkeller at high energy

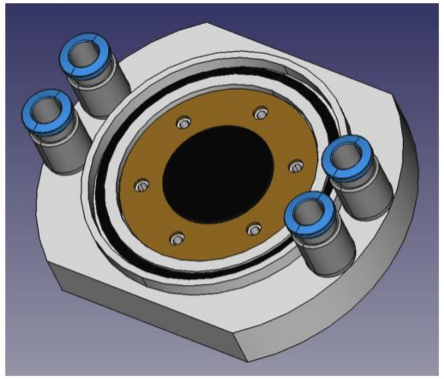


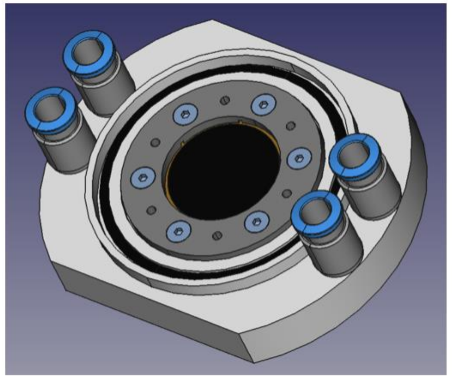
A lot of work is needed to identify and resolve the features in the spectra, though the maximum E_{cm} planned @ LNGS is 3.5 MeV

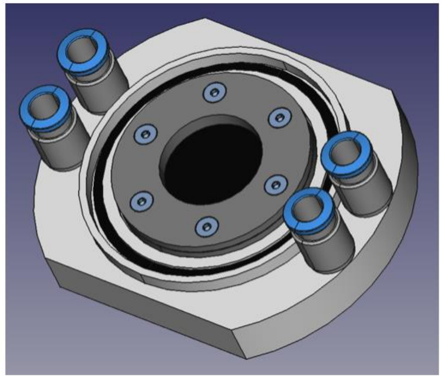
The $^{12}C(^{12}C,n)^{23}Mg$ threshold is 2.6 MeV

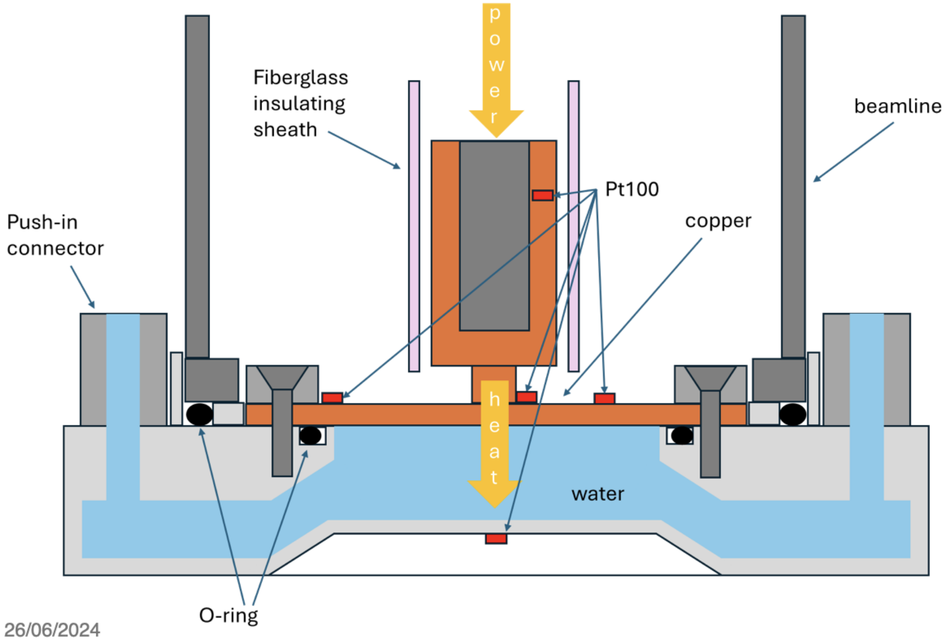
- Third phase (present and close future – moving to higher beam power)
  - production of vacuum-proof target holder via Additive Manufacturing
  - thermal test (mimick beam heating and test water cooling at the B-IBF)
  - test beam at the B-IBF











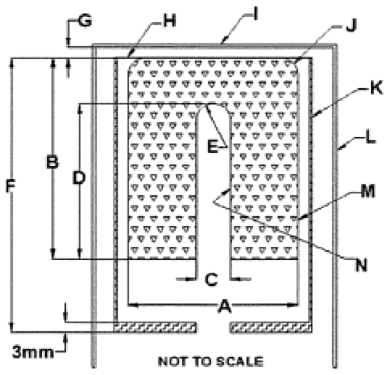
- **New target holder produced via AM at LNGS is vacuum proof (finally!)**
- Thermal tests in preparation right now (will be probably performed next week)

GePD2

Riccardo, Steffen, Gianluca, Benedetto

Active volume characterization

- Active volume characterization via radioactive sources scans:
  - 137Cs -> E_γ = 661 keV -> sensitive to macroscopic characteristics (i.e. hole dimensions), single photon
  - 133Ba -> E_γ = 81 keV and E_γ = 356 keV -> sensitive to macroscopic and microscopic characteristics, multiple photons
- During a month-long measurement scanned:
  - Front of the detector, along the diameter and 3 cm above the diameter (both ^{137}Cs ad ^{133}Ba)
  - Side of the detector, along the axis (only ^{137}Cs)
  - Side of the detector, vertically (only ^{137}Cs)
- Results used to fine-tune the simulations



E: NOMINAL 5-mm RADIUS

F: 130-mm CUP LENGTH

G: 5-mm SPACE

H: 0.03-mm Al-Mylar FILM

I: 1.5-mm Cu

J: NOMINAL 8-mm RADIUS

K: 0.8-mm Cu

L: 1.5-mm Cu

M: 0.7-mm Ge/Li DEAD LAYER

N: 0.3-micron Ge/B DEAD LAYER

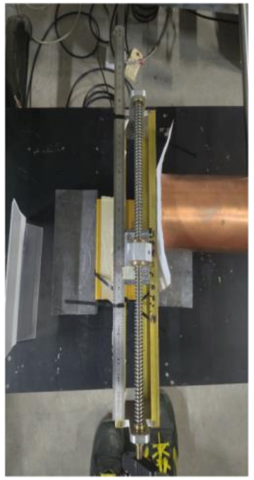
A= 92 mm (Crystal Diameter)

B= 94.8 mm (Crystal Length)

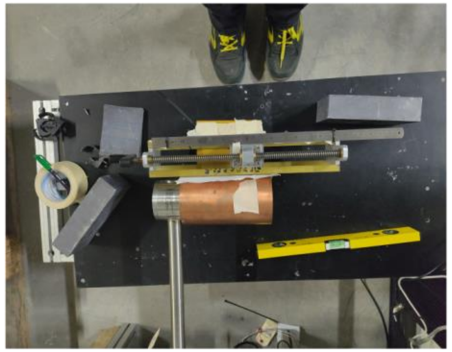
C= 8.8 mm (Hole Diameter)

D= 80.8 mm (Hole Depth)

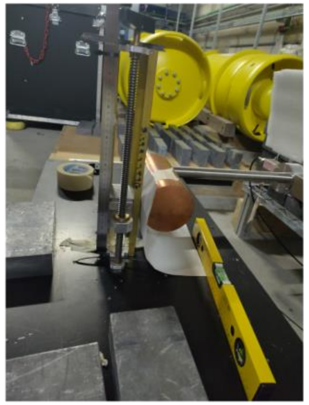
Frontal scan



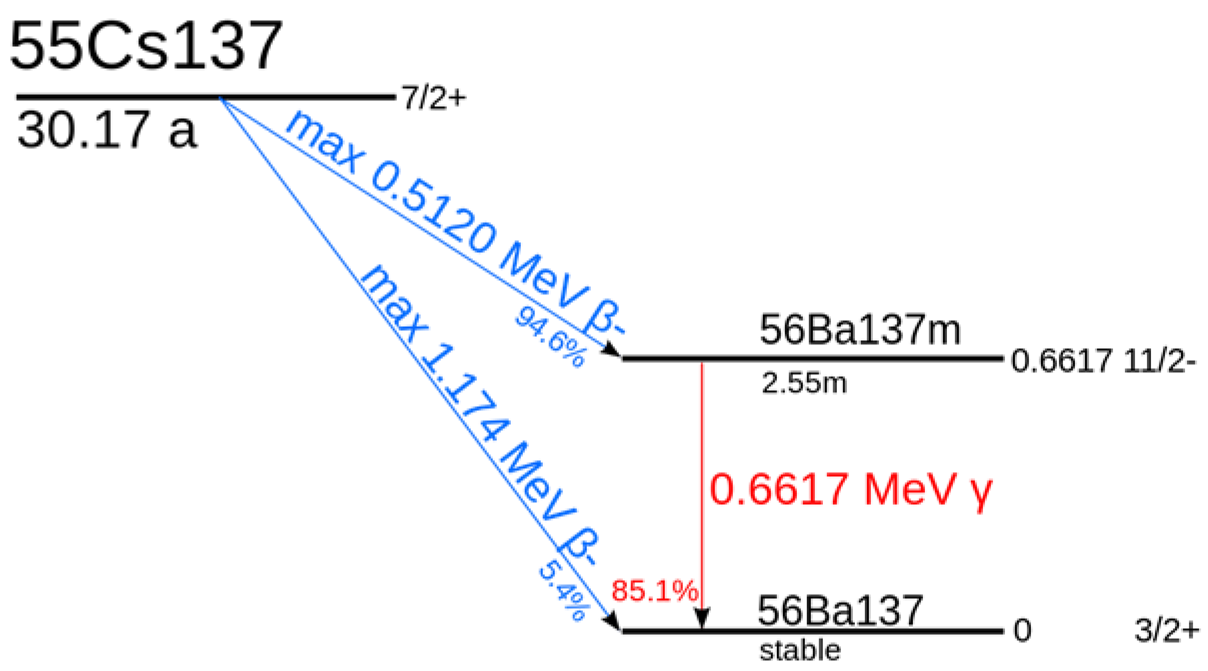
Horizontal side scan

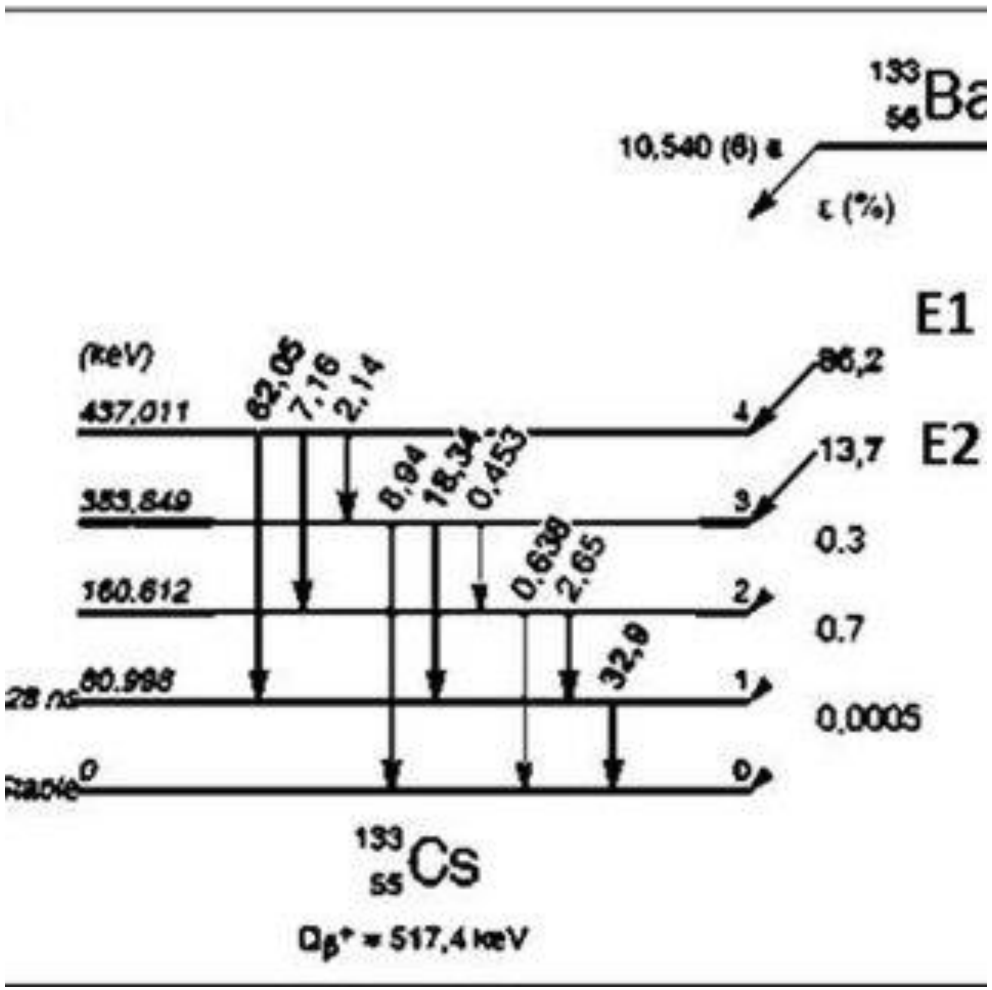


Vertical side scan



Scans with collimated radioactive sources

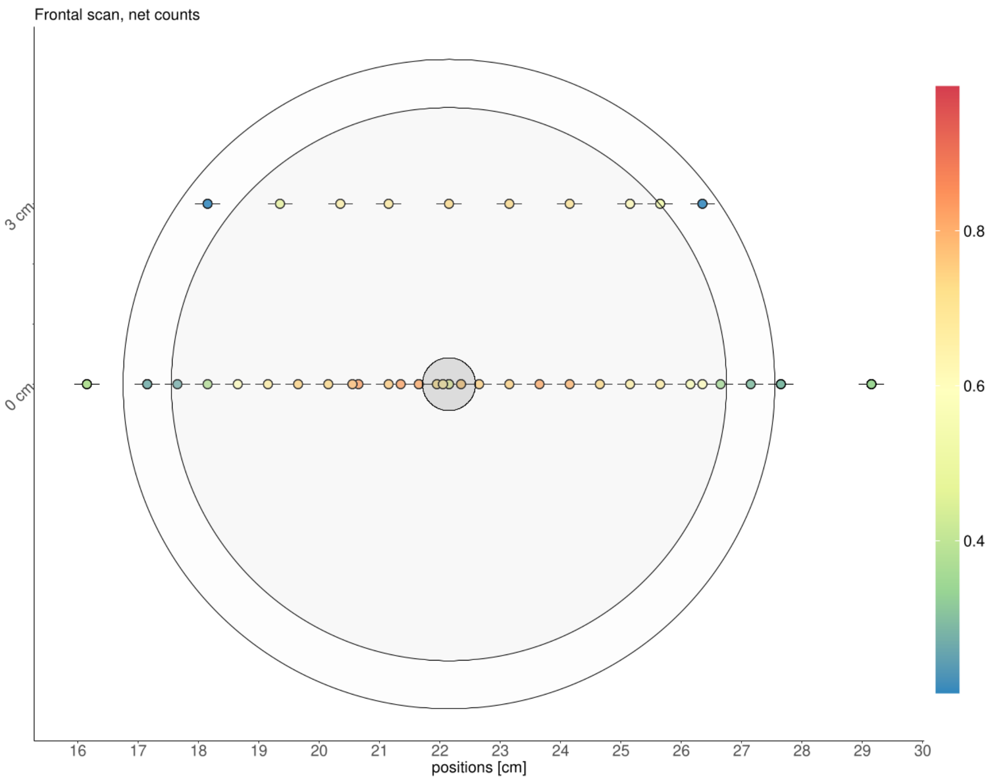


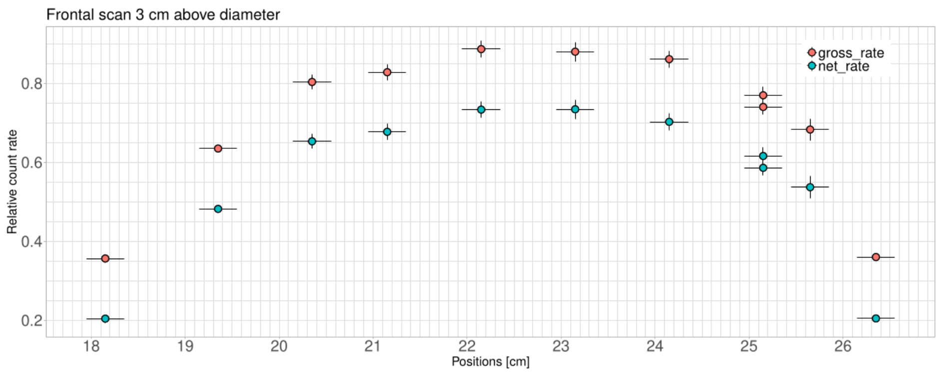


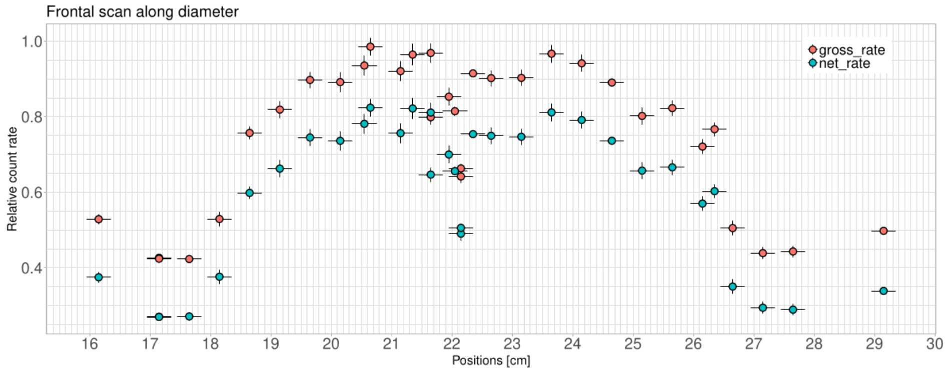
Active volume characterization: frontal scans

- Along the diameter: effect of the hole visible with higher energy gamma.
- 3 cm above the diameter: hole not visible anymore and effects possibly due to crystal position
- Hole not visible anymore at E_γ = 81 keV, more sensitive to crystal edges

137Cs

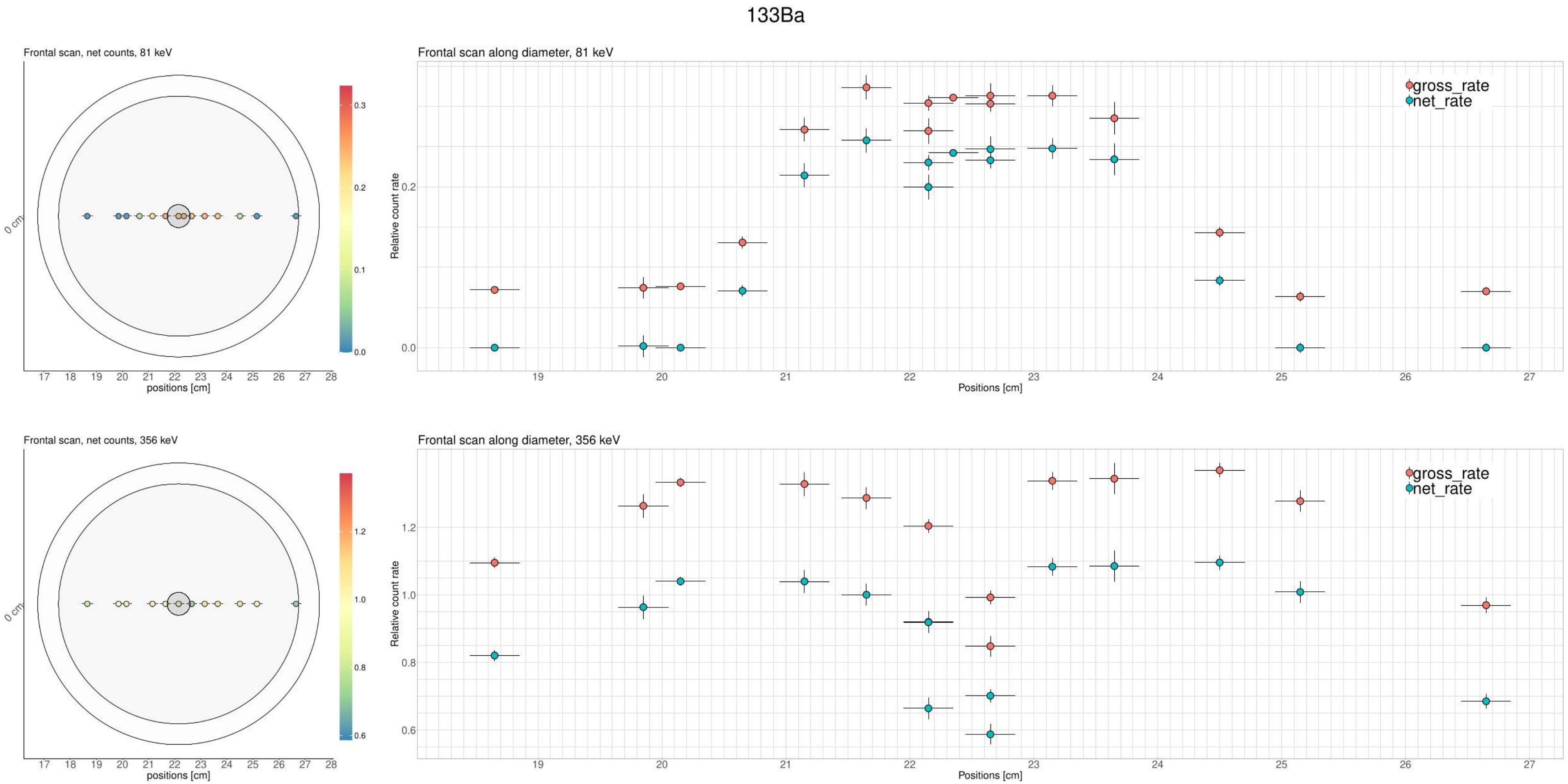






Active volume characterization: frontal scans

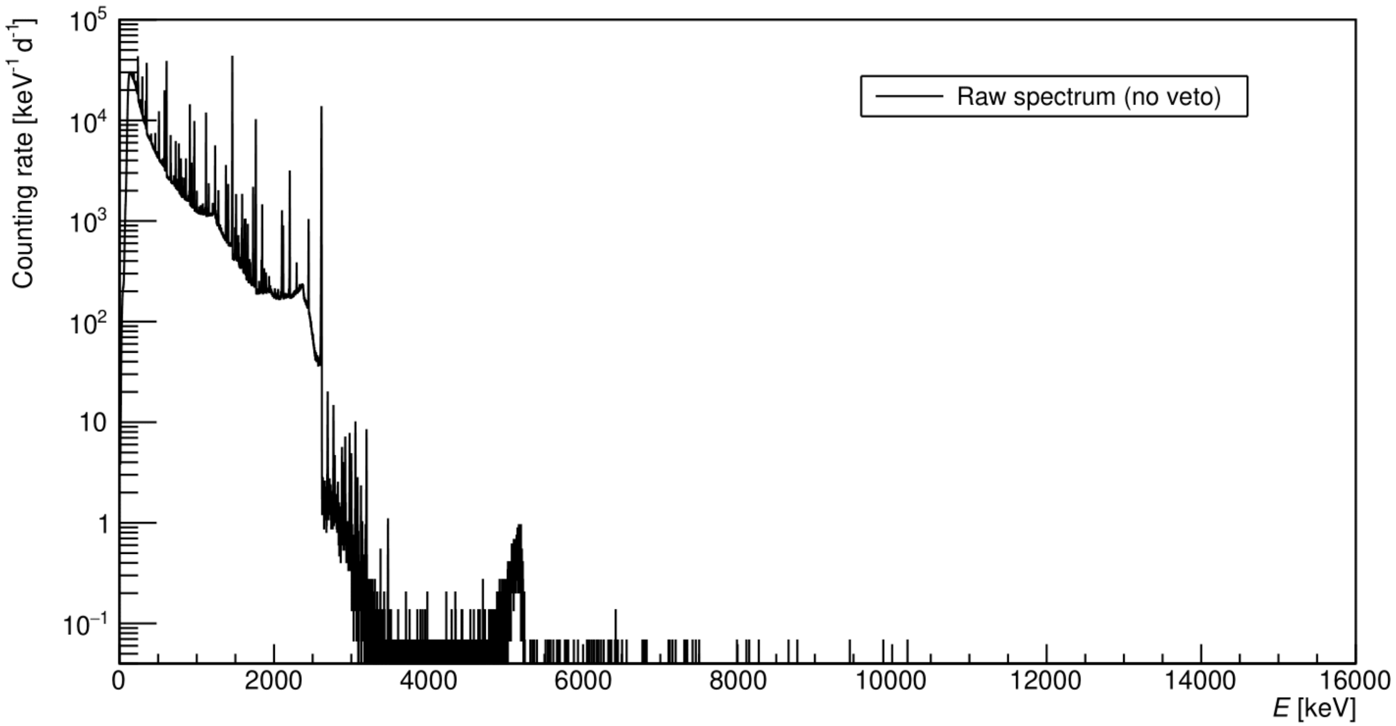
- Along the diameter: effect of the hole visible with higher energy gamma.
- 3 cm above the diameter: hole not visible anymore and effects possibly due to crystal position
- Hole not visible anymore at E_γ = 81 keV, more sensitive to crystal edges

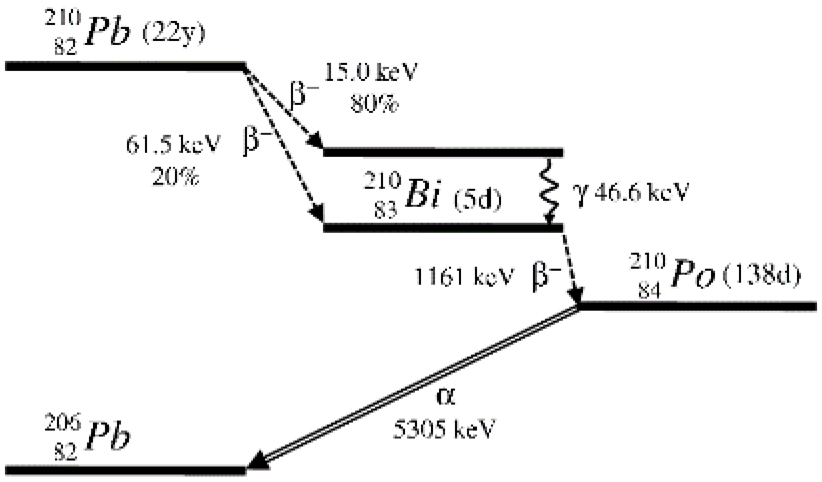


GePD2 features

Intrinsic contamination of ^{210}Pb

- Most likely located in the soldering close to the crystal
- Half-life of ^{210}Pb: $T_{1/2}=22\,a$
- Daugther ^{210}Po emits E = 5.3 MeV alpha





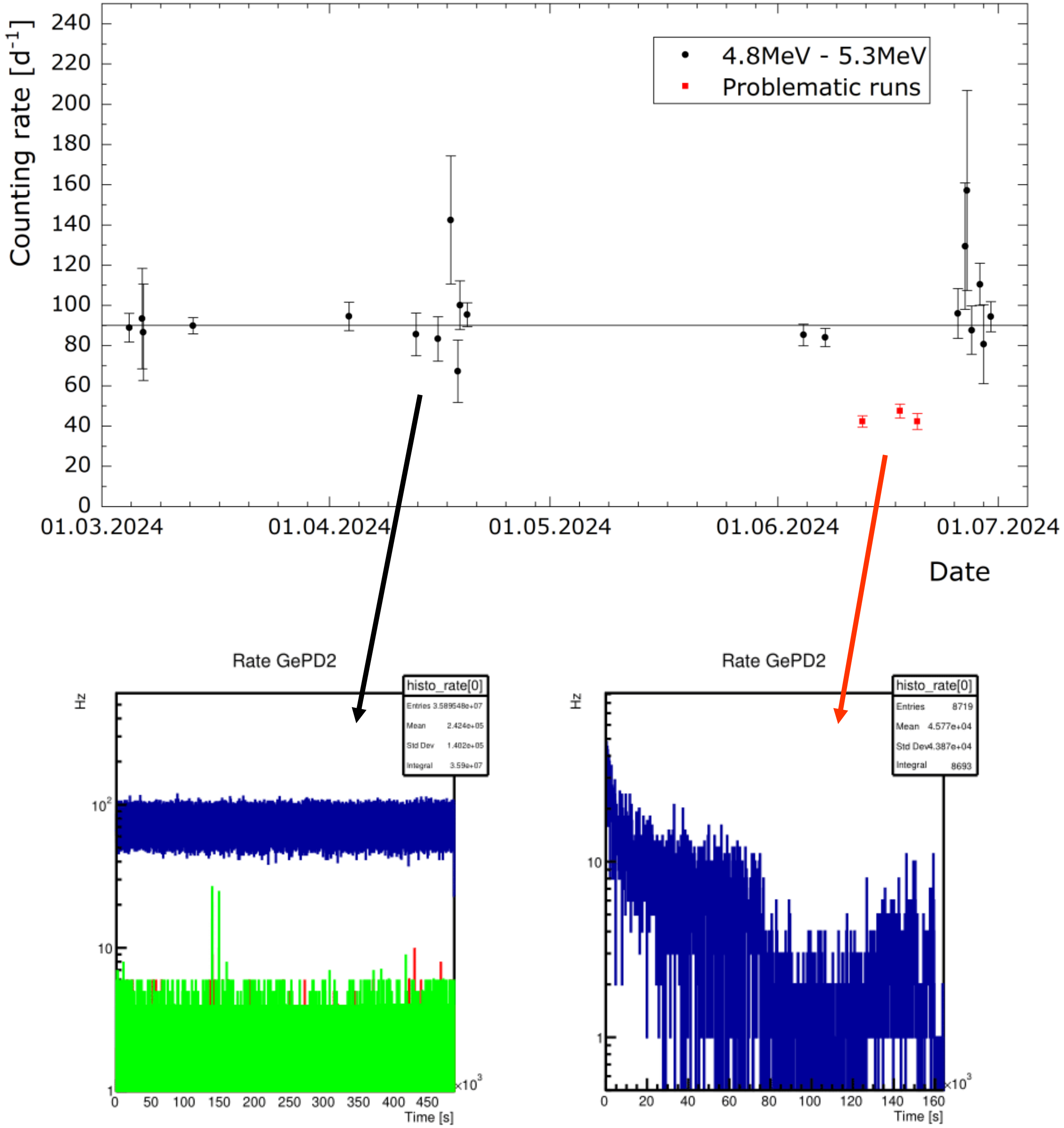
GePD2 features

Intrinsic contamination of ^{210}Pb

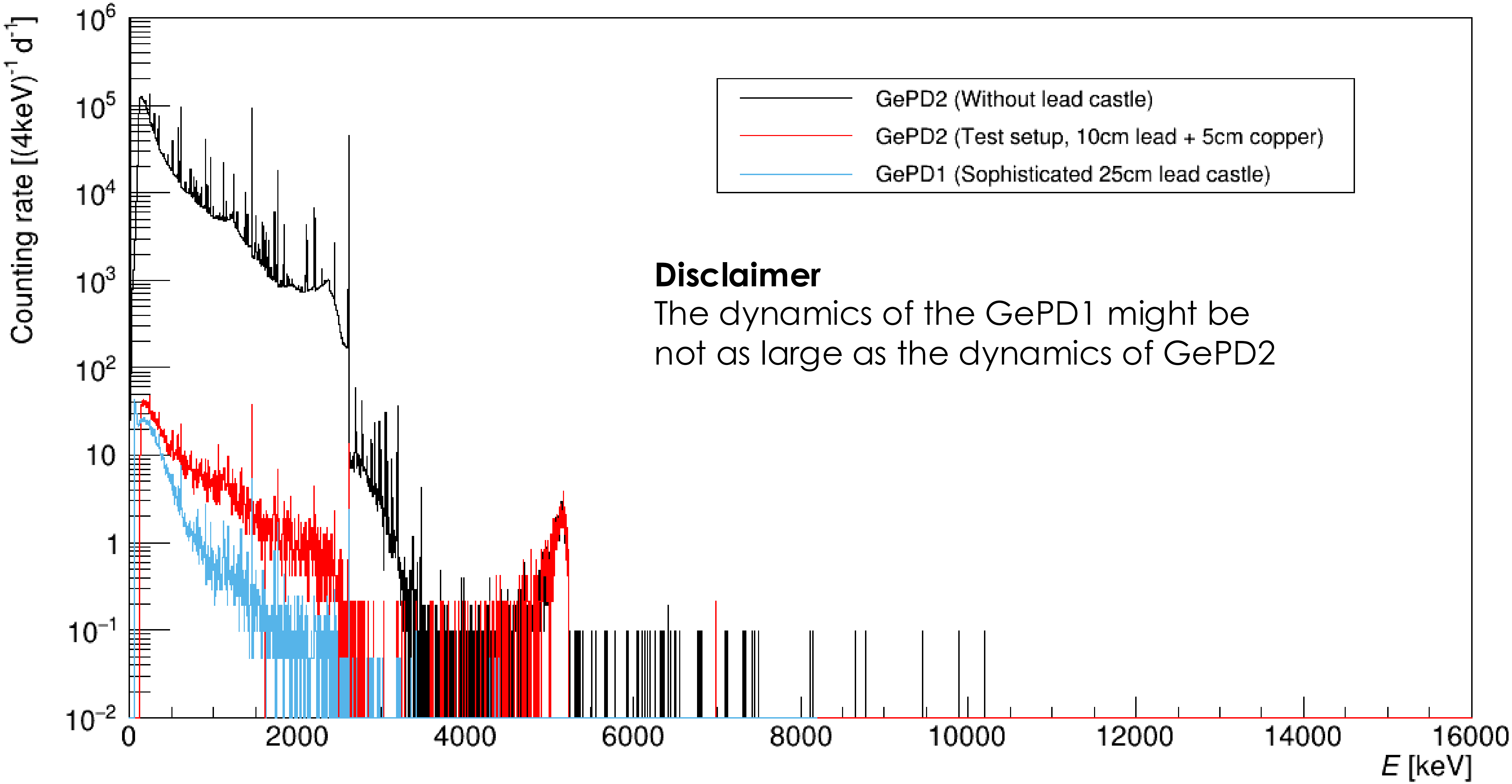
- Contamination can be used for stability tests
- Counting rate independent of setup & location

Issues with GePD2

- Intense noise & oscillations resulted in non-reliable data
- Significant loss of real data
- Problem solved and resilience tests ongoing
- Origin both due to UPS line and grounding issues



Comparison with one of LUNAs best BG spectra



Disclaimer
The dynamics of the GePD1 might be not as large as the dynamics of GePD2

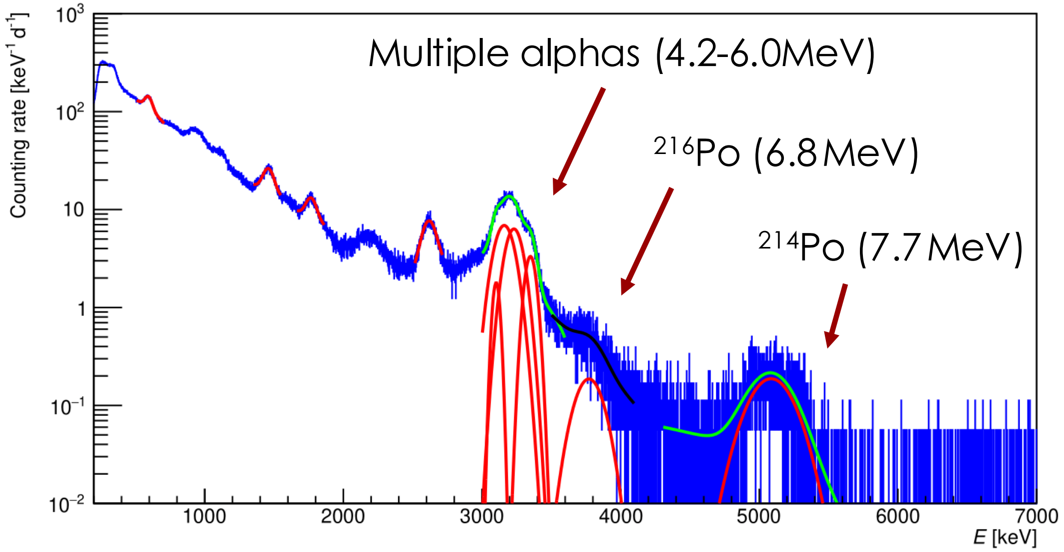
NaI detector

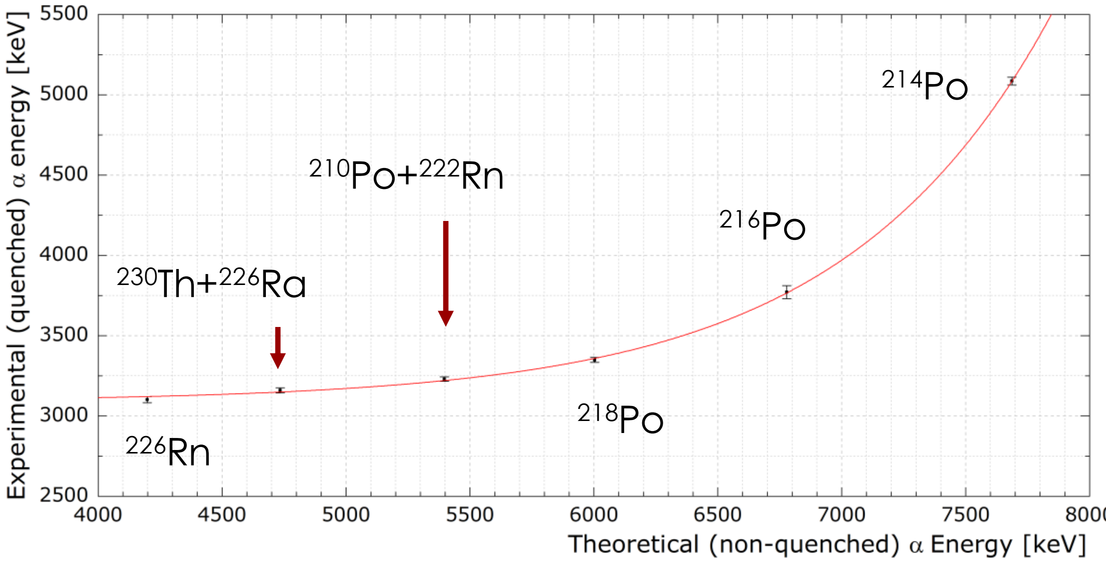
Riccardo, Steffen, Gianluca, Benedetto

Current status of the NaI prototype

Background study

- Gammas from enviromental BG (^{40}K, ^{214}Bi, ^{208}Tl, etc.)
- Intrinsic alpha contamination
  - ^{232}Th and ^{238}U inside NaI crystal





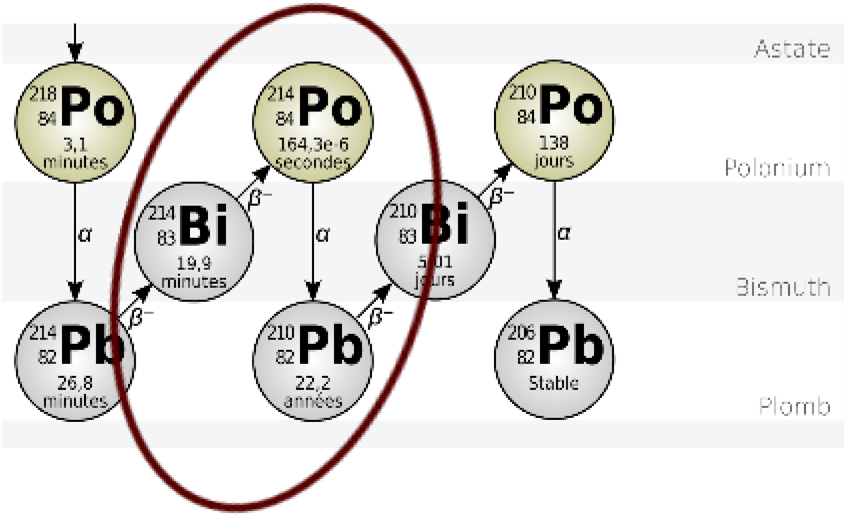
Alpha contamination

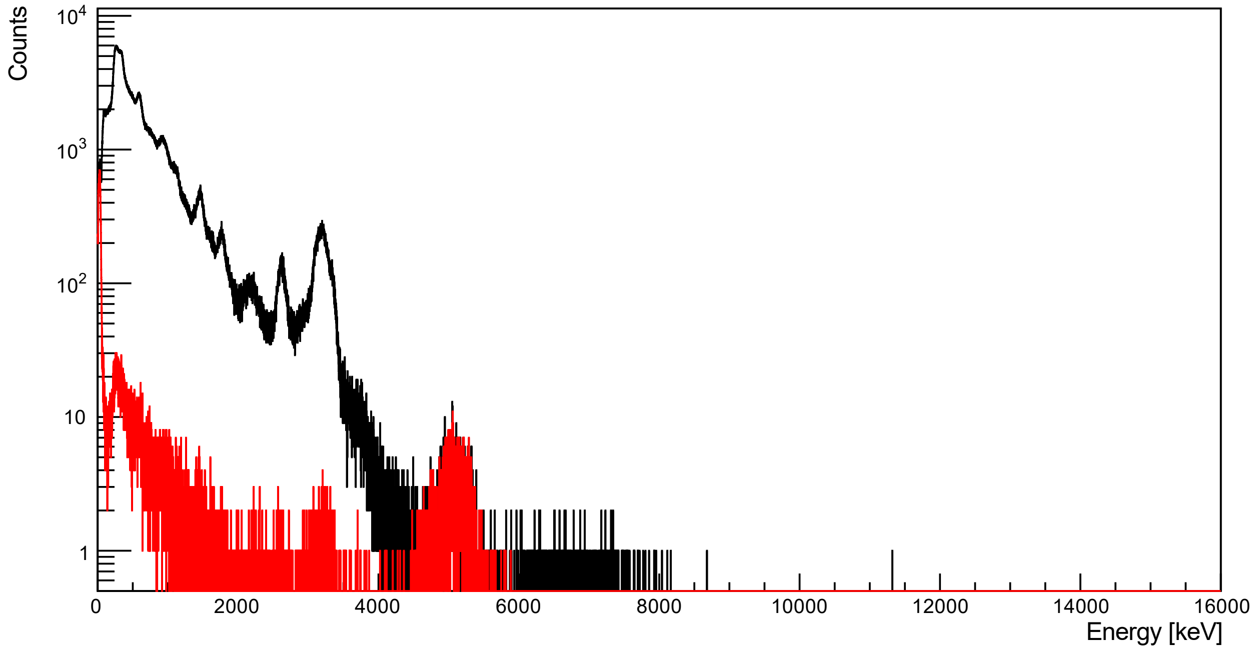
- Quenched energy calibration
- Simulations ongoing

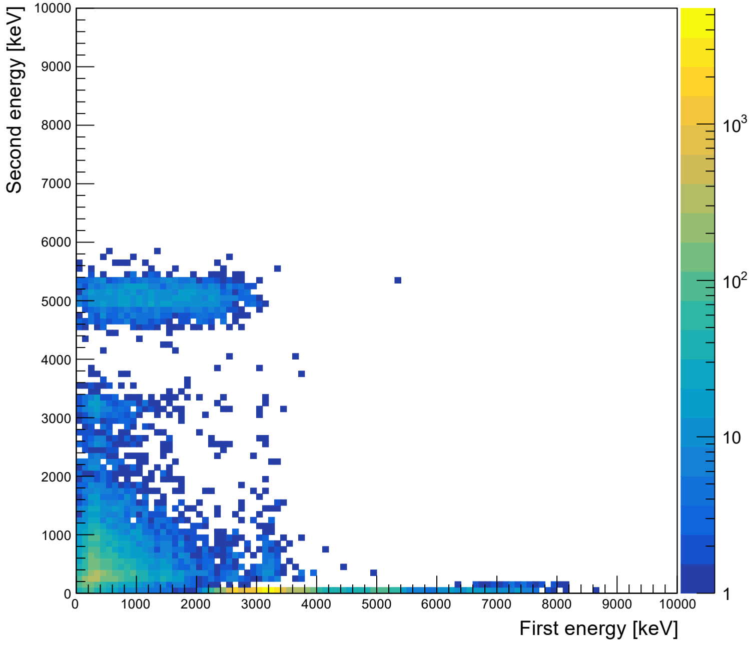
Current status of the NaI prototype

Intrinsic alpha contaminations

- Self-coincidence analysis with
  - Beta from ^{214}Bi
  - Alpha from ^{214}Po ($T_{1/2}$=163μs)

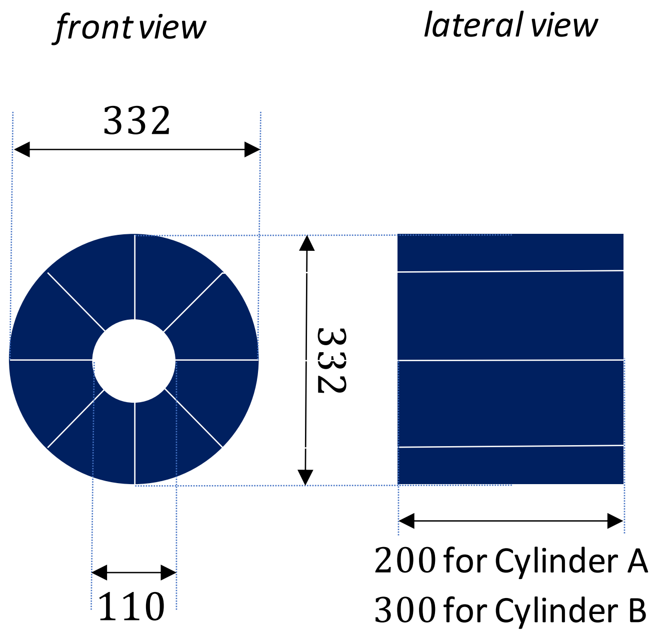


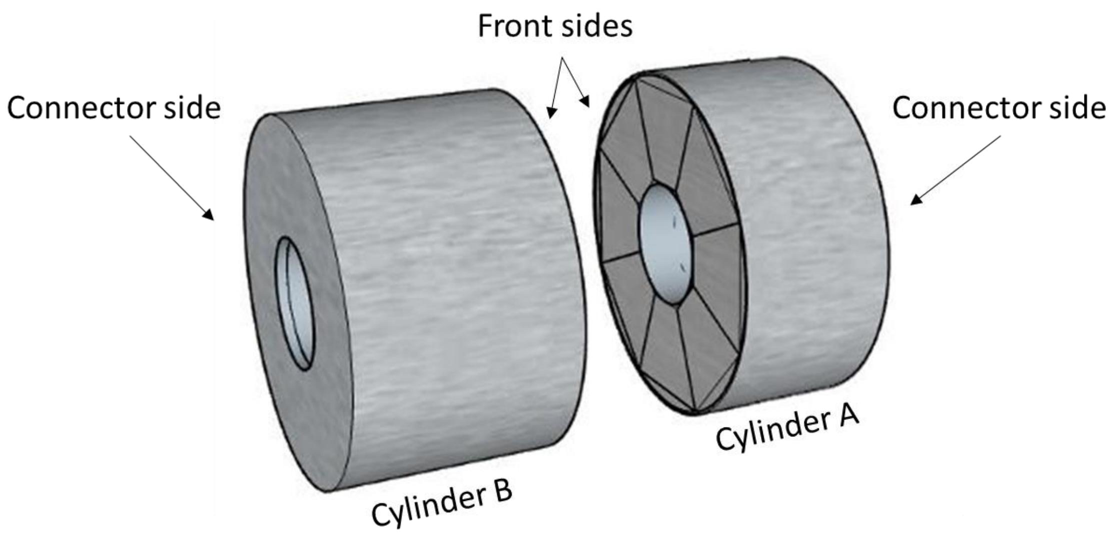




Specifications of the NaI array

The following specifications are for the tendering procedure of 16 NaI(Tl) crystals, encapsulated into two aluminum cylinders, for the setup needed for the $^{12}C + ^{12}C$ fusion cross section experiment as a part of the LUNA scientific program at the "E. Bellotti" Ion Beam Facility, located at Underground Gran Sasso Laboratory.





RADIOCHEMICAL PURITY:

- 40-K counting rate: < 0.01 counts per second per liter of NaI;
- Counting rate in the 400 keV – 3 MeV energy region: < 1 counts per second per liter of NaI.

SEGMENTATION:

Each crystal could be additionally segmented into a maximum of 4 segments, optically insulated to each other to avoid cross-talk. In such a case, the readout described above should be replicated individually for each segment of a crystal; it is not mandatory that the preamplifiers are located inside the aluminum case in this configuration. If this configuration is adopted, the company needs to quantify the worsening of the energy resolution achievable if the preamplifiers are located outside the case.

- LUNA3: euro 211.721,31, oltre IVA, per un totale complessivo di euro 258.300,00;
- DOTAZIONI GR.3: euro 3.278,69, oltre IVA, per un totale complessivo di euro 4000,00.

La gara è stata inserita nel piano biennale degli acquisti ed ha CUI F84001850589202300119.

Considerata la specificità della fornitura, l'ambiente sotterraneo in cui si dovrà posizionare il materiale e non ultima la tecnologia richiesta, dopo un'attenta indagine di mercato, effettuata anche alla luce delle informazioni acquisite da un acquisto analogo, ti comunico che le ditte che possiedono le qualificazioni e le maestranze idonee per poter fornire rivelatori NaI con adeguati standard di rumore intrinseco sono le seguenti:

1. Scionix;
2. Luxium-Solutions (Saint-Gobain);
3. TNE – Technology Nuclear Electronics;
4. Alpha-spectra, Inc.

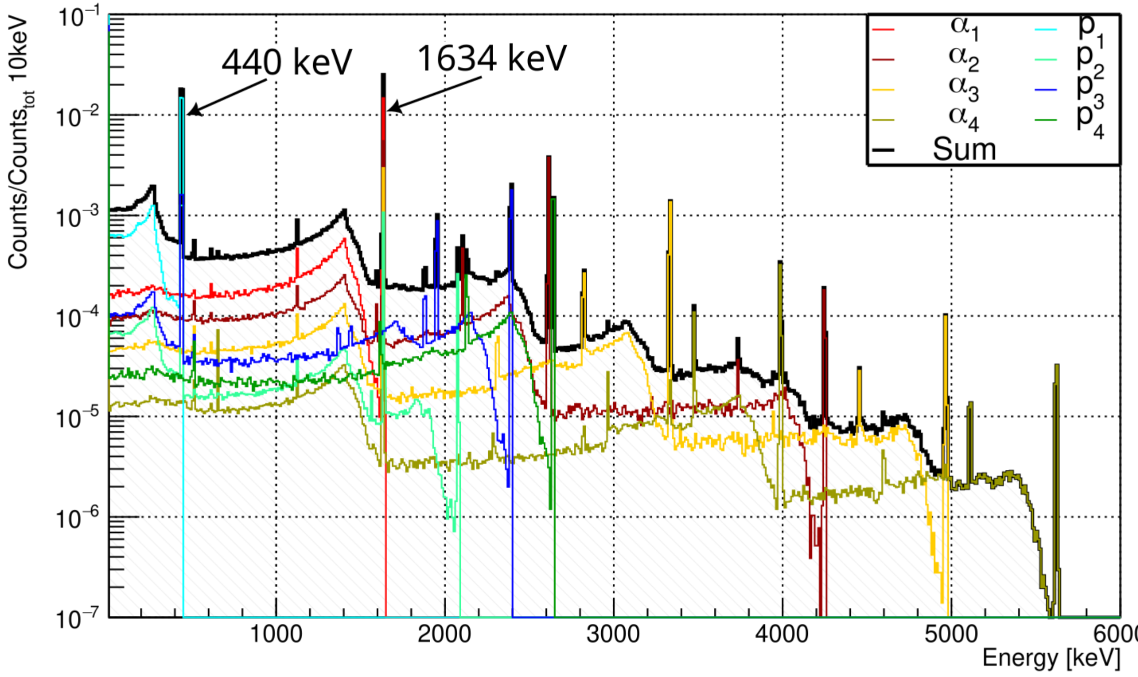
4 companies have been invited

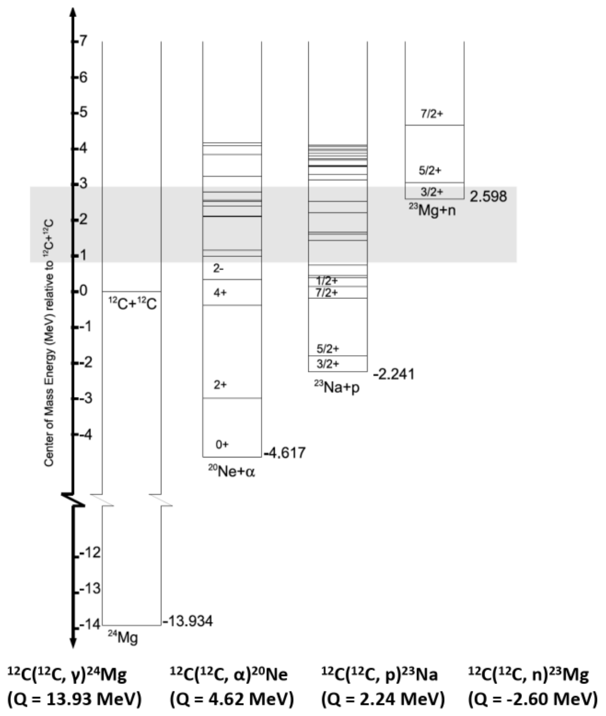
Simulations

Riccardo, Benedetto, Linus

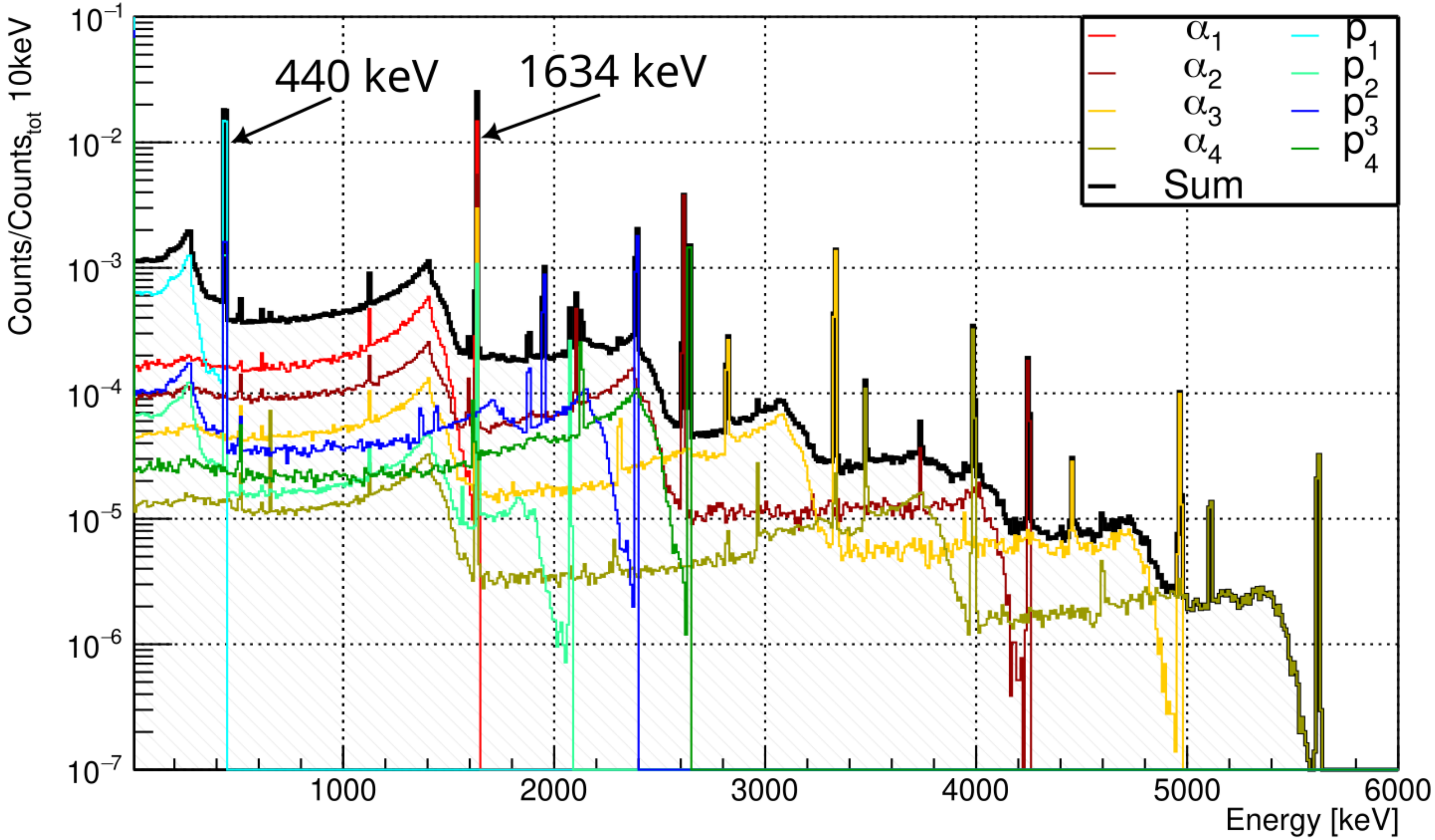
GePd2 simulations

- Accurate model of GePD2 implemented -> based on technical drawing
- Simulation ready for implementation of NaI array when the definitive geometry will be decided
- Simulated $^{12}C + ^{12}C$ gamma based on branching ratios from Becker et al., 1981:
  - Ecm ≥ 3.1 MeV contribution up to α_4, p_4
  - Ecm ≤ 3 MeV, α_1 and p_1 by far the dominant contribution
- Critical for determination of setup's geometrical efficiency and branching ratio measurement

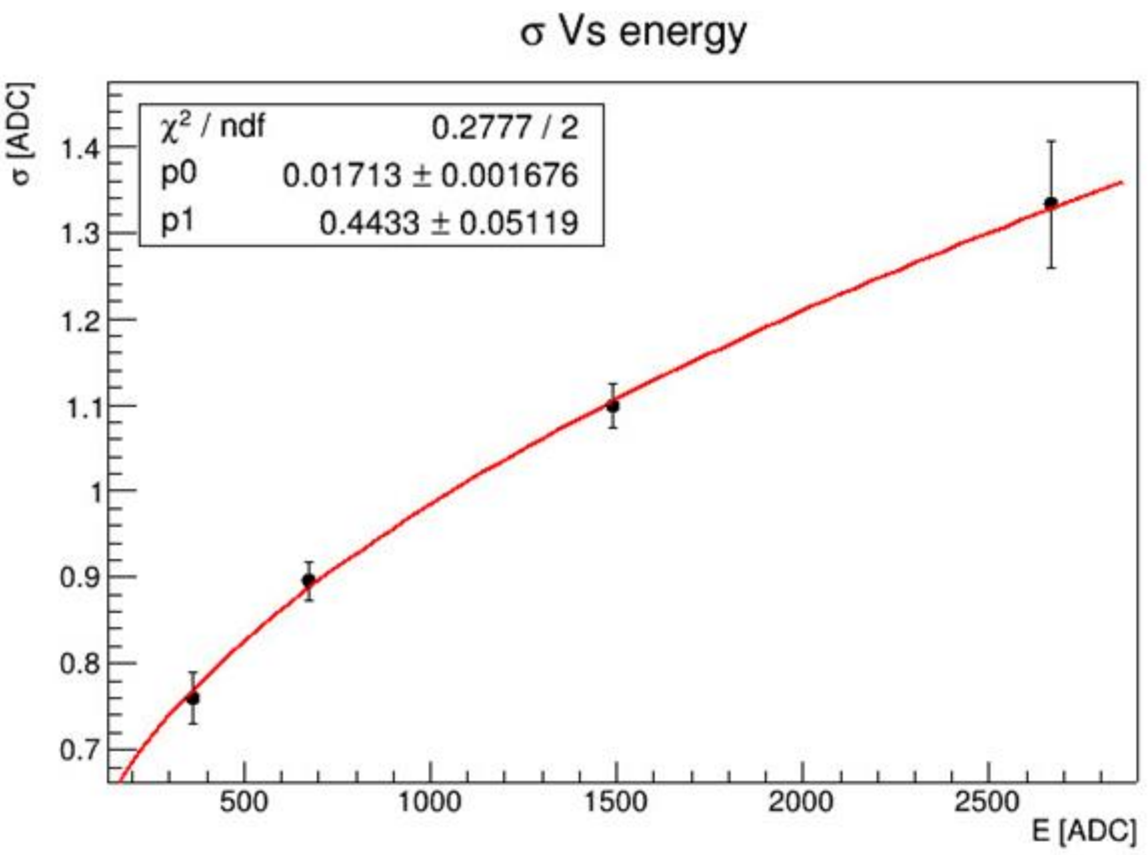


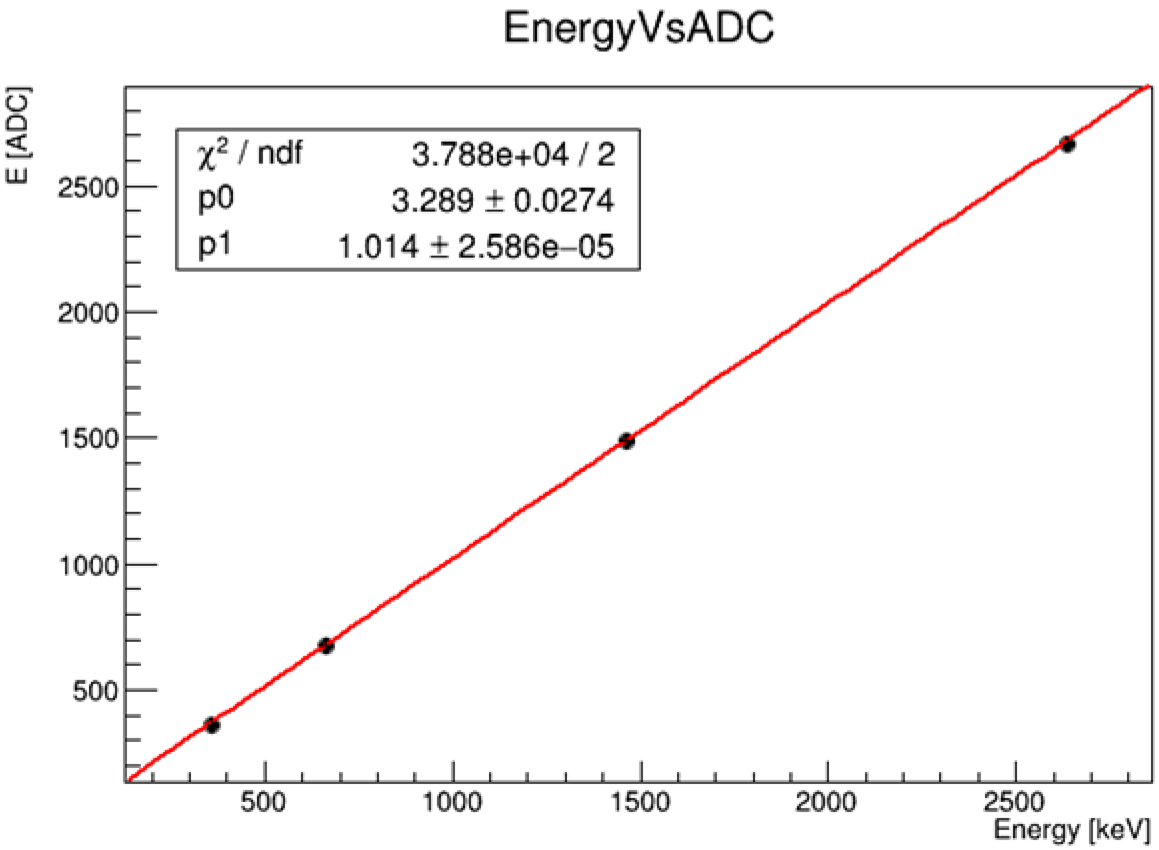


GePd2 simulations



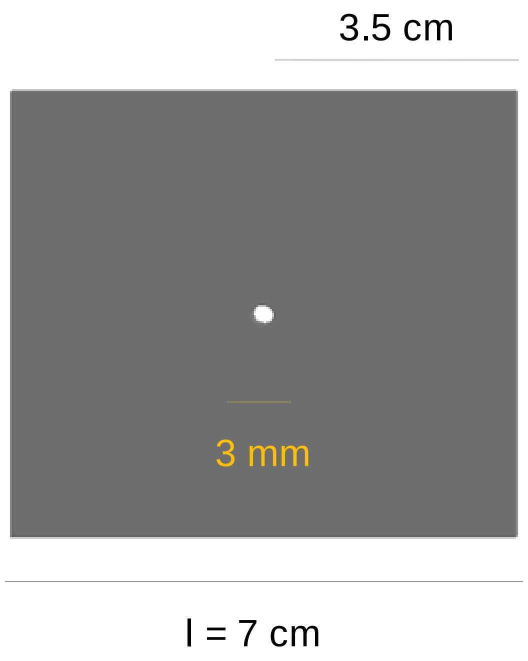
Energy calibration and resolution





Energy resolution was applied to the simulated events according to the equation: $\sigma = p_0 + p_1\sqrt{x}$.

Geometry



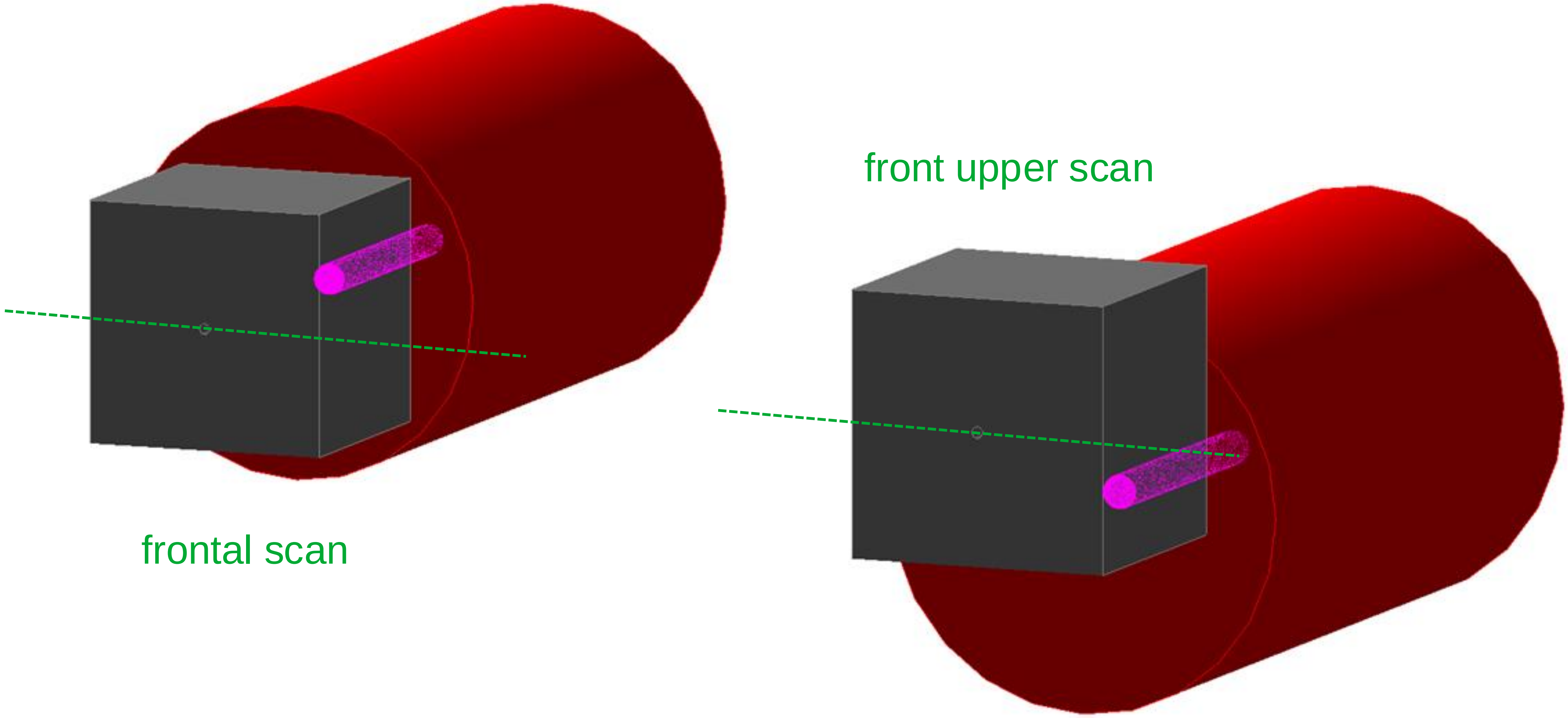
The collimator is a cubic lead block with a cylindrical through hole in the center

The collimator is 0.05 cm far from the detector (thickness of a sheet of paper)

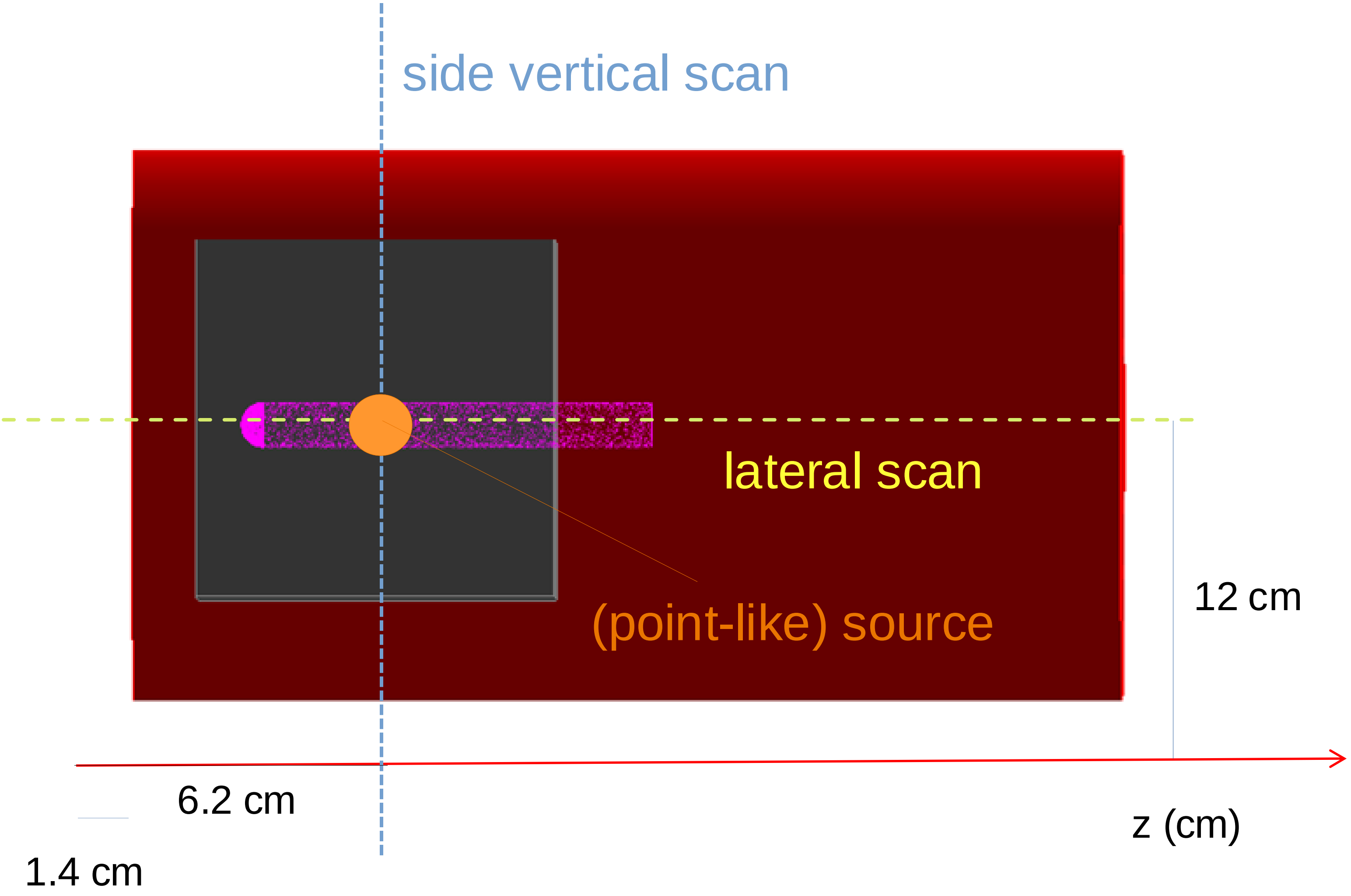
For all the simulated scans, a point-like, isotropic source was placed in direct contact with the collimator face on the side opposite to the detector

The collimator always points toward some part of the detector

Scans with collimated radioactive sources



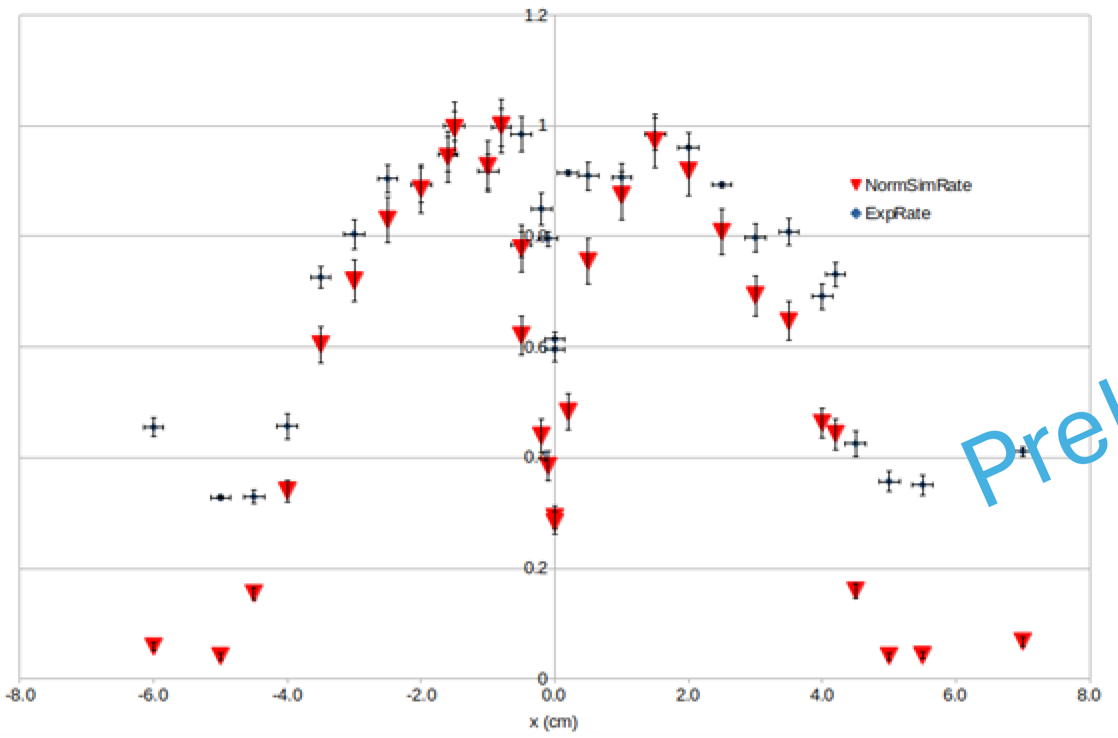
Scans with collimated radioactive sources



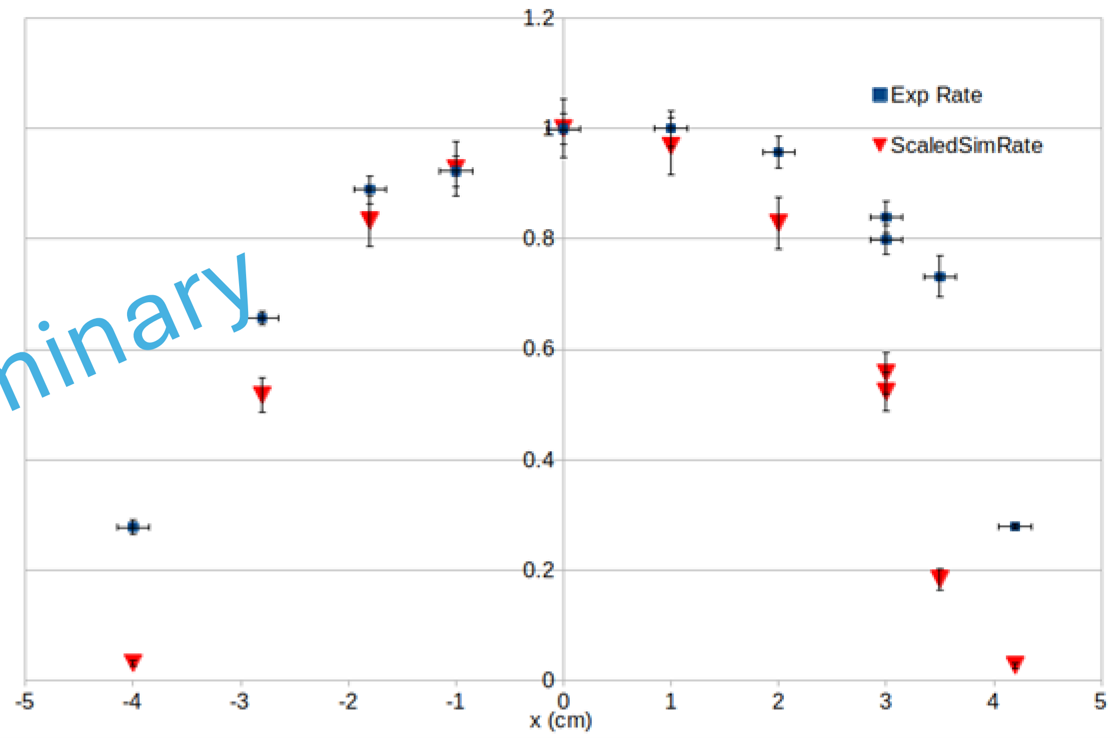
Scans with collimated radioactive sources – experiment vs simulation

^{137}Cs

frontal scan



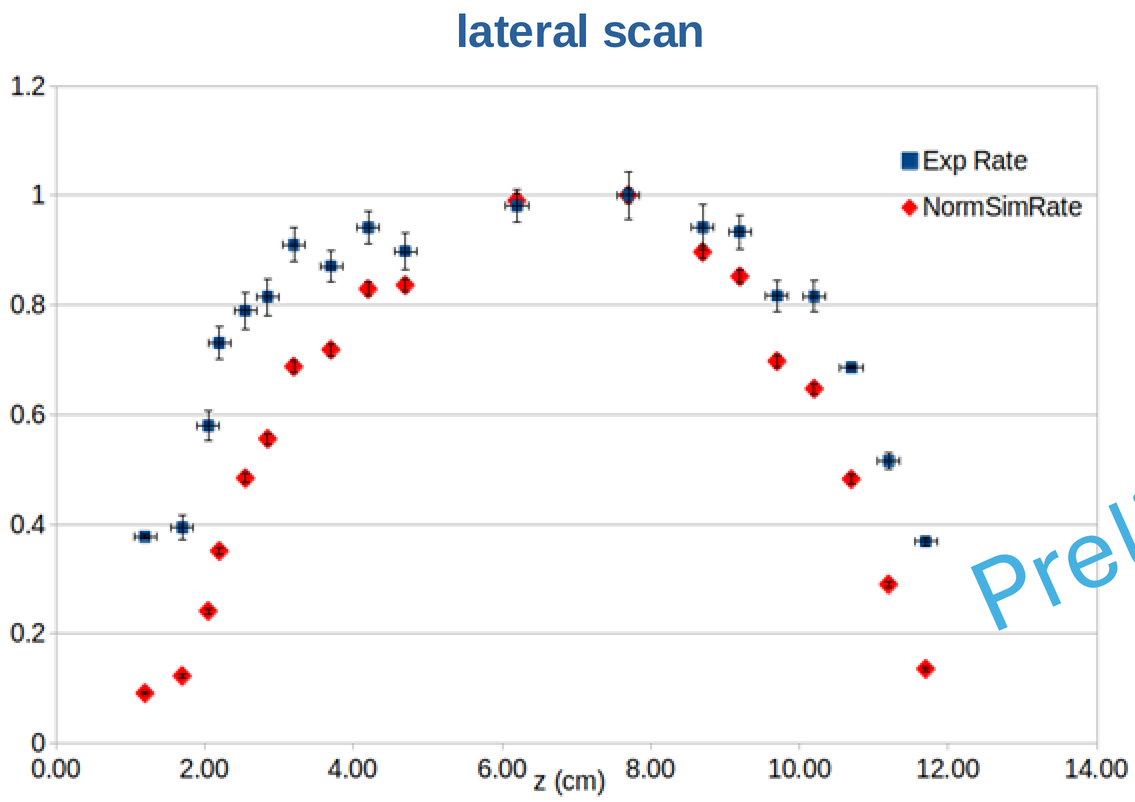
front upper scan

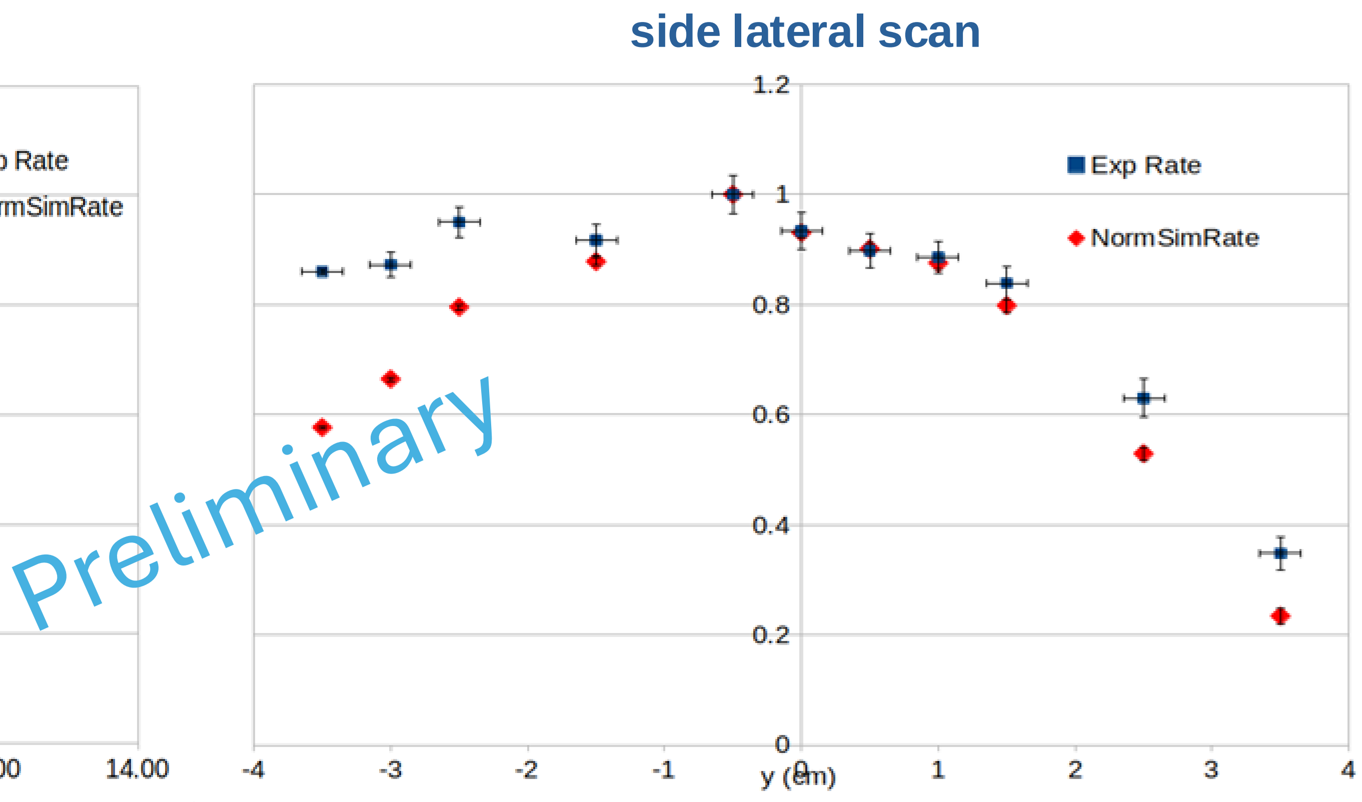


Preliminary

Scans with collimated radioactive sources – experiment vs simulation

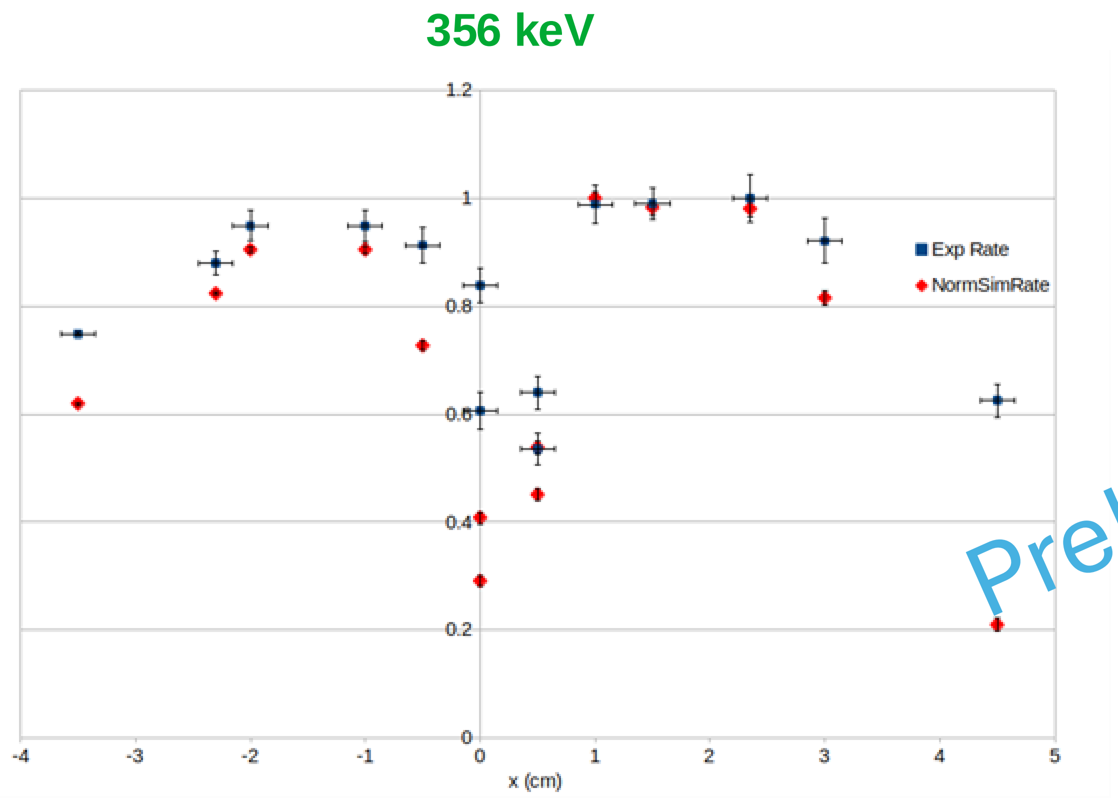
^{137}Cs

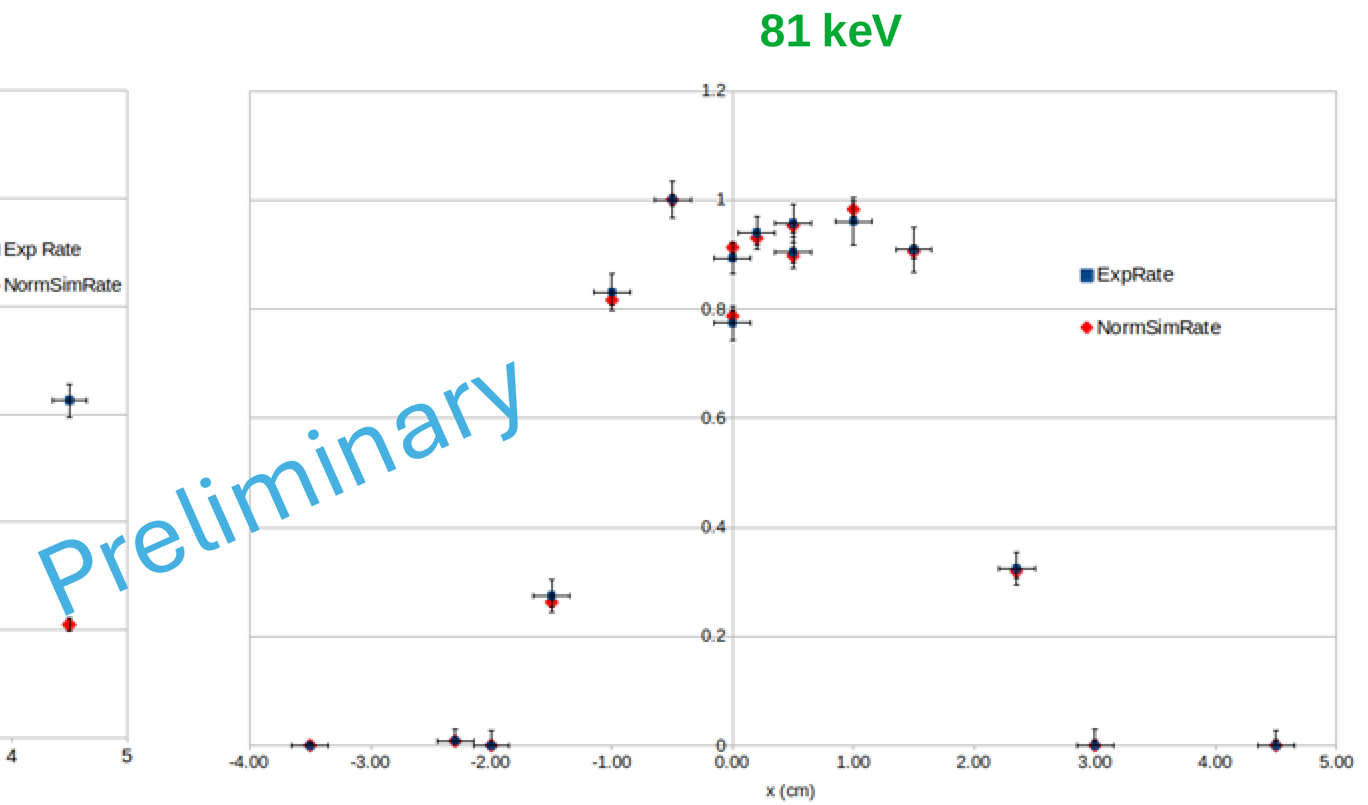




Scans with collimated radioactive sources – experiment vs simulation

^{133}Ba





Application to the new call of the Bellotti IBF

Application to the new call of the Bellotti IBF

We need to apply to the new call of the Bellotti IBF

- the call will open very soon and will most probably close in mid-August
- the proposal should be focused on the measurements below 2.1 MeV (phase 4 and 5) with the HPGe+NaI setup, but should also mention previous phases, that we were not yet able to complete due to rescheduling at the Bellotti IBF
- we must have the proposal complete by the end of July (to allow its integration into the larger LUNA proposal)

however

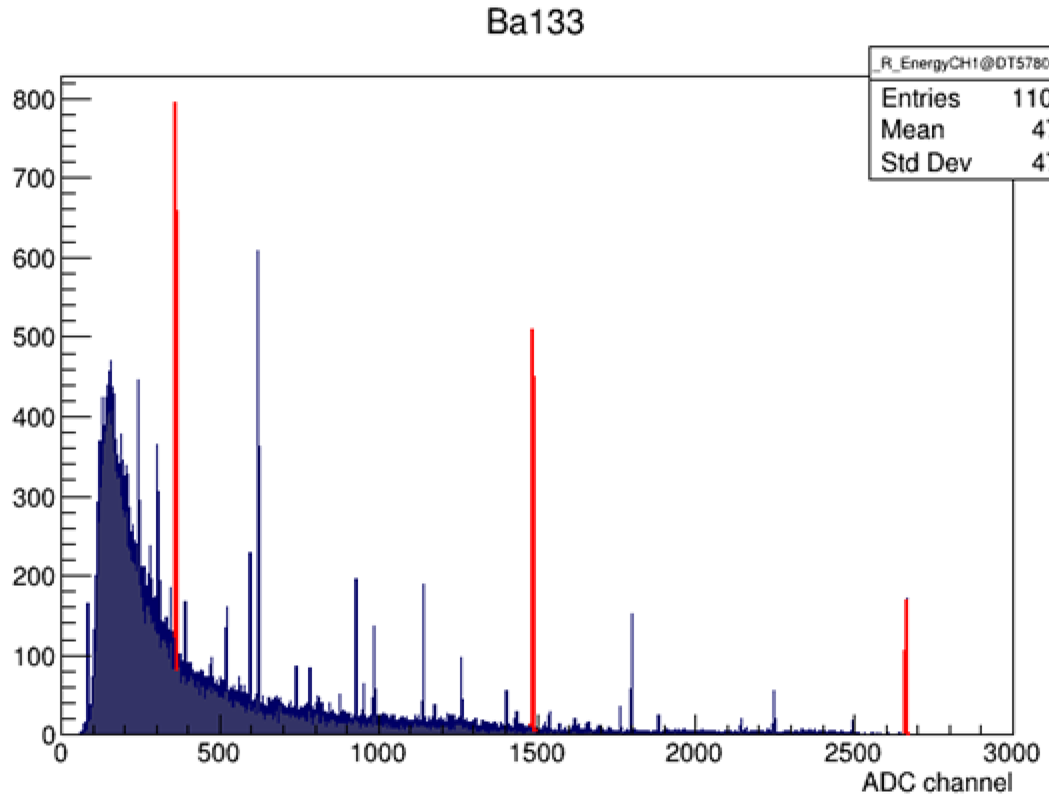
- we have not mounted the setup in the accelerator room yet
- we have no data on the $^{12}C+^{12}C$ from the beamtime that has been assigned to us after the last call (and we won't have any by the application deadline)
- after the last call we have been assigned only 12 BTU for phase 2 (out of 37)
- The PAC expected to have a report from the Accelerator Service in October 2024 about a realistic time for changing energy and the beam setup to evaluate BTU assignment for phase 2 completion (25 BTU) and phase 3 (60 BTU) assignment

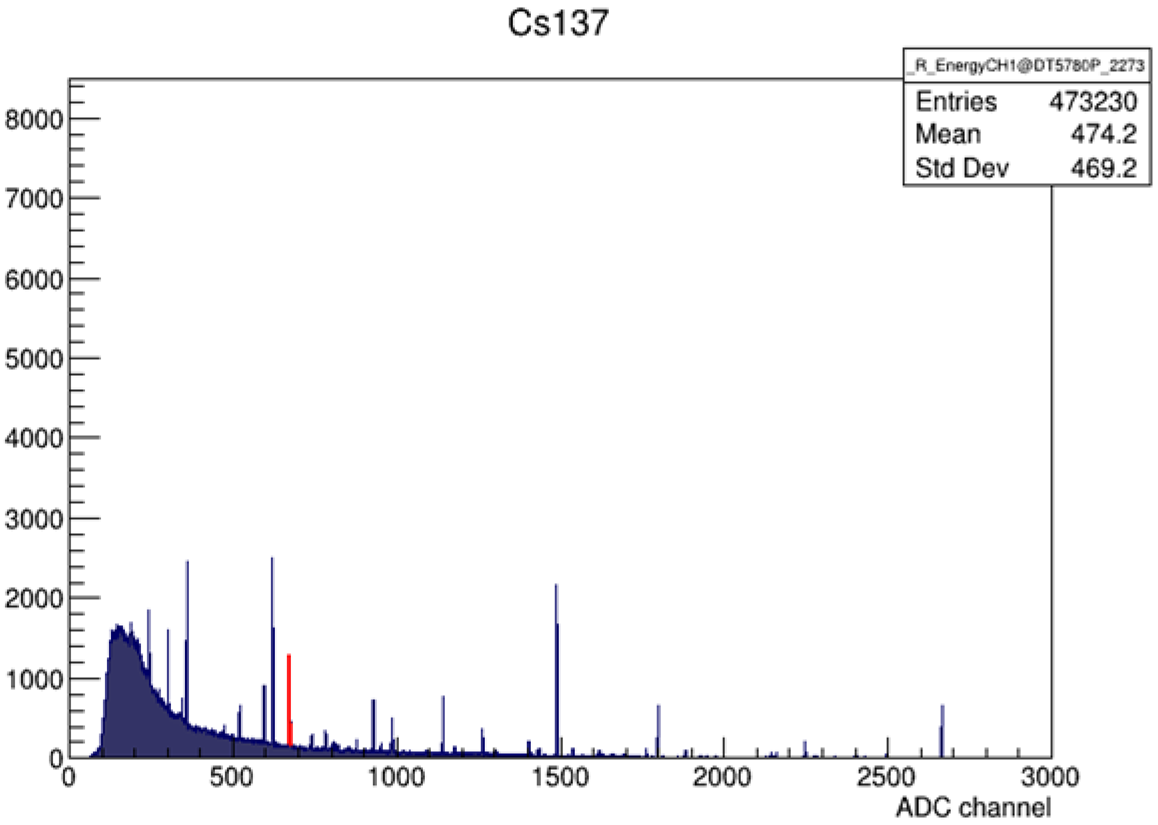
but

- due to some problems with the MV accelerator, the situation changed already a lot and will probably change again, causing further rescheduling
- we do not have to relax and we must use this time wisely

Backup slides

Energy calibration and resolution



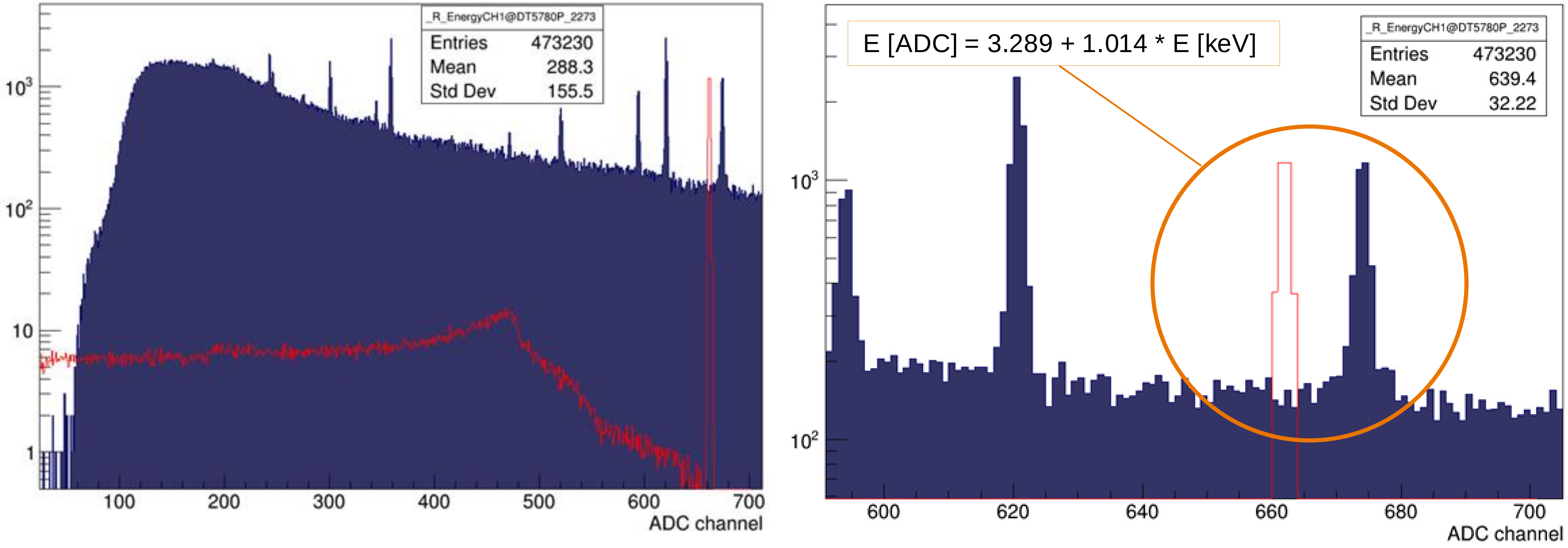


By fitting the peaks expected at 356 keV (^{133}Ba), 662 keV (^{137}Cs), 1461 keV (^{40}K) and 2614 keV (^{208}Tl),

- σ vs ADC channel -> energy resolution
- E vs ADC channel -> energy calibration

were evaluated

Energy calibration and resolution



Resolution was applied to the simulated events according to the equation: $\sigma = p_0 + p_1\sqrt{x}$.

For comparison, the simulated spectrum was normalized with respect to the most populated photopeak bin

L. Barrón-Palos et al. Nucl. Phys. A 779, 318 (2006)