Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

SANDA
Supplying Accurate Nuclear Data for energy and non-energy Applications

HORIZON2020

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847552 (SANDA).

Experiment for Double-Differential Cross Section Measurement with the Emission of Light Charged Particles from High Energy Neutrons on Carbon at n_TOF

nBHEAM Workshop 2025, IAEA Vienna

R. Beyer, A. Di Chicco, M. Dietz,
A. Junghans, R. Nolte, E. Pirovano,
and the n_TOF collaboration

Motivation in Neutron Dosimetry

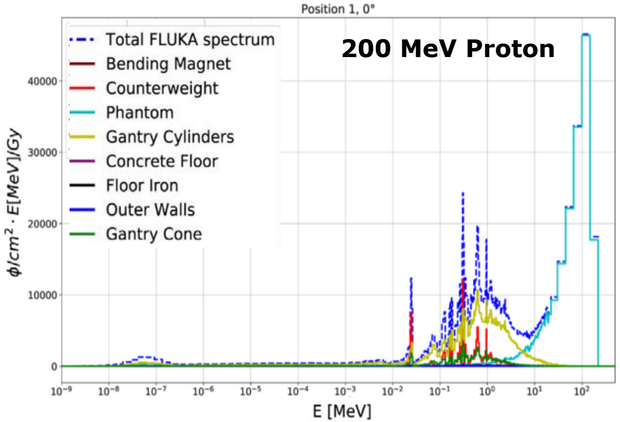
Where are high-energy neutrons produced?

- by cosmic radiation: E_n up to GeV
- in hadron therapy: E_n up to 200 MeV / 430 MeV for proton / carbon beams

Absorbed dose calculations require

- DDX data for (n, px) (n, dx) (n, αx) …
- for tissue constituents (C, N, O)
- ➤ Particularly important for young patients of radiation therapy

(Si: Radiation damage in aircraft and space instrumentation)



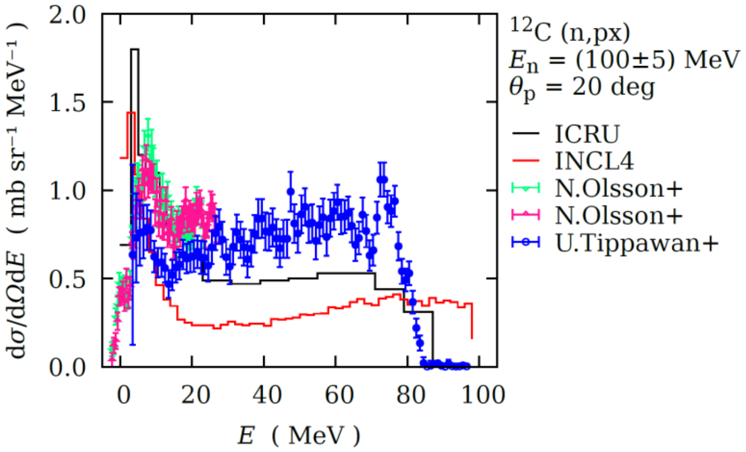
[1] https://doi.org/10.1016/j.zemedi.2021.01.001

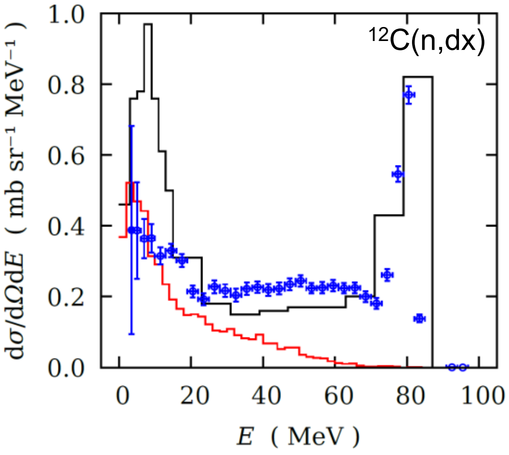
Main problems related to high-energy neutrons (DDX)

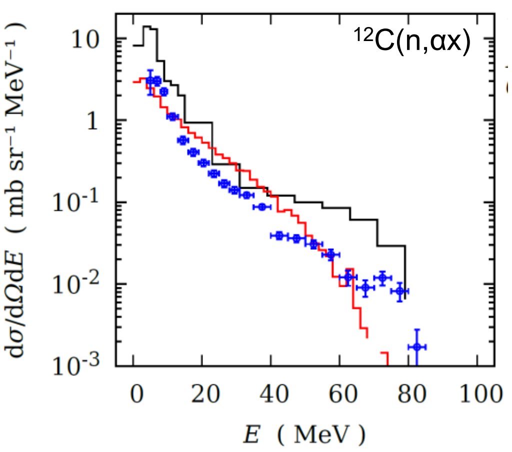
For a precise neutron absorbed dose calculations we require Double diff. cross section (DDX) data (C, N, O etc.) for (n, p d t ^{3}He ^{4}He), but:

- Few datasets, at selected neutron energies, only up to 100 MeV (for Carbon).
- Evaluations not based on experimental data but model calculations (INC models):

  - ➢ Big discrepancies with experimental data;
  - ➢ New data are necessary for benchmarking, especially in the range **100-200 MeV or higher** and for the emission of compound ejecticles;

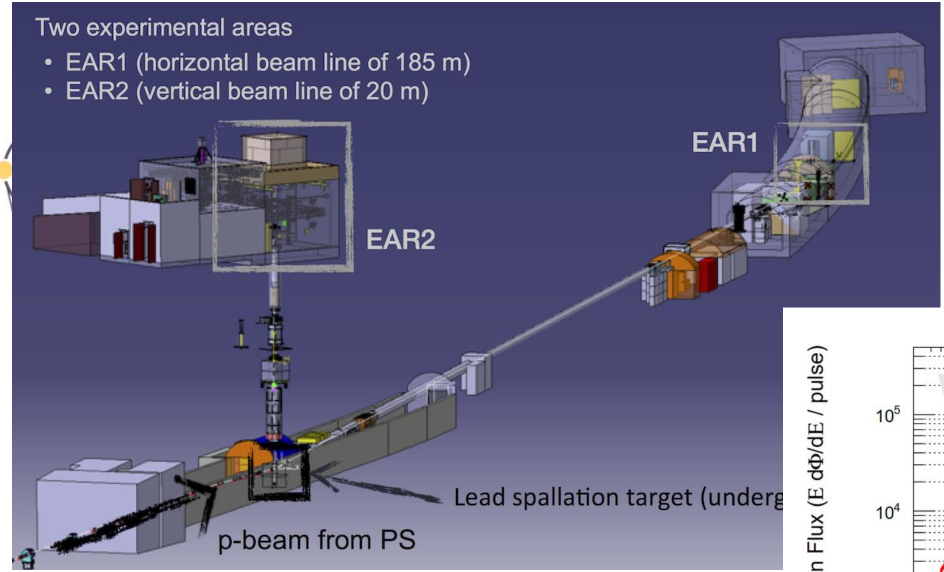


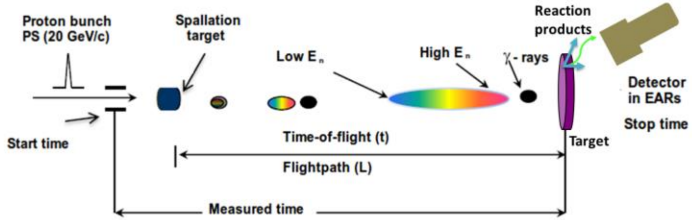




n_TOF @ CERN

Only pulsed neutron source >100 MeV in Europe!



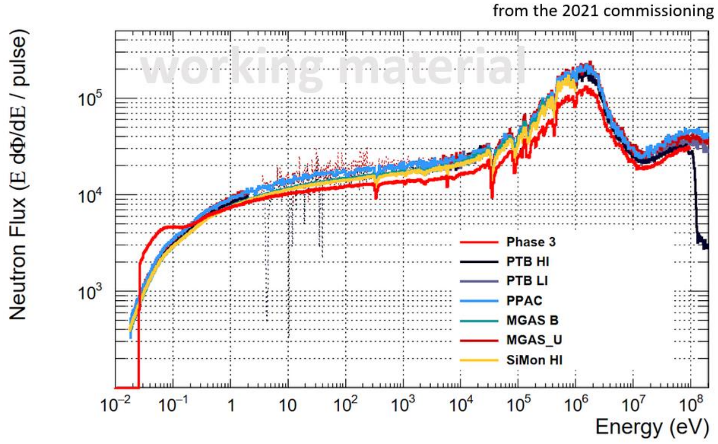


$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1-\beta^2}} - 1 \right) \quad \text{with} \quad \beta = \frac{L}{t_n c}$$

n_TOF EAR1:

- large energy range: 25 meV – 1 GeV
- high energy resolution: $\Delta E/E=10^{-4}$
- low repetition rate < 0.8 Hz → low average flux
- high instantaneous flux

  typical bunch: $7 \cdot 10^{12}$ protons × 300 neutrons/proton



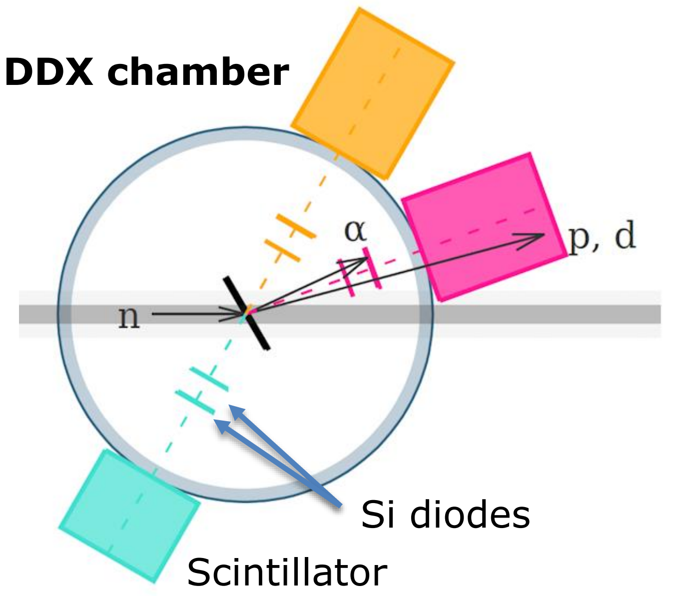
⇒ Prototype experiment of ^{12}C(n, lcp) to evaluate feasibility of DDX measurements above 100 MeV @ n_TOF

	tof_n / ns	En / MeV
	614	γ-flash
	720	8.58E+02
	900	3.45E+02
	1200	1.54E+02
MeV	2000	4.76E+01
	5000	**7.16E+00**
	8000	2.78E+00
13µs →	13000	1.05E+00
	15000	7.88E-01
	20000	4.43E-01
keV	50000	7.08E-02
	80000	2.77E-02
	100000	1.77E-02
420µs →	500000	7.08E-04
eV	1.00E+06	1.77E-04

DDX chamber Concept for C(n,lcp) at n_TOF

Proof-of-principle experiment with the new DDX chamber with 6 meas. angles (± 20°, 60°, 120°), in the energy range between 20-250 MeV:

- Measurement of the energy distribution of the neutron-induced emission of p, d, t, α, ^{3}He;
- Particle identification with the Δ*E*-*E* telescope technique and the Time-of-Flight technique:
  - ➤ (For each angle) 1 thin Si diode, 1 thicker Si diode and 1 Scintillator (EJ-204)
  - ➤ Different combination of Δ*E*-*E* telescope and electronics



Beamtime in September/October 2024 (30 days measurement):

- 2 Carbon targets (2 mm and 75 µm).
- 1 Polyethylene target.

CERN-INTC-2023-007, INTC-P-651, https://cds.cern.ch/record/2845911

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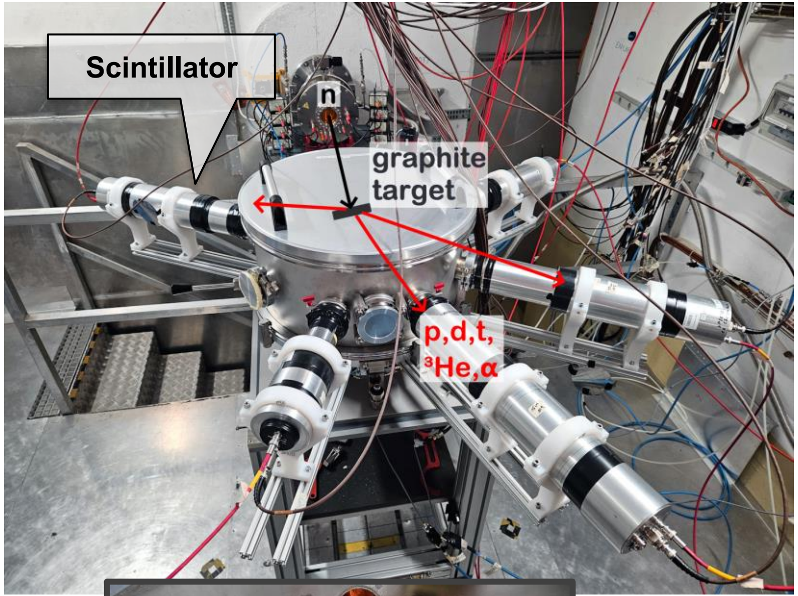

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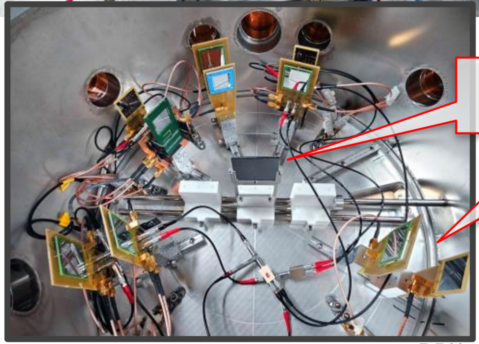
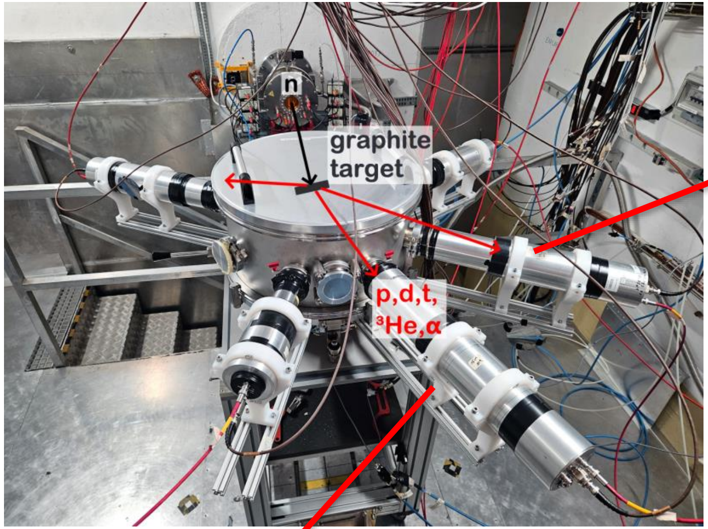
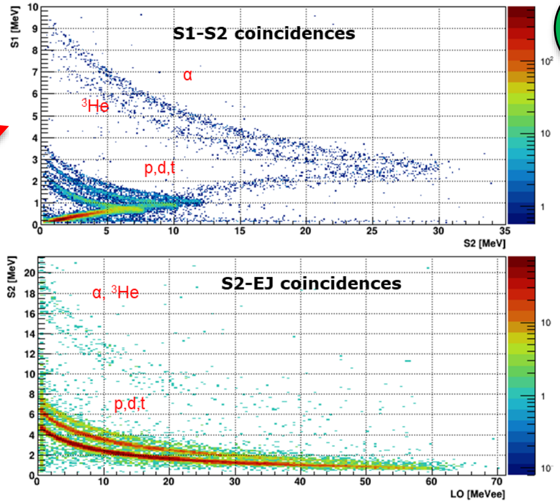
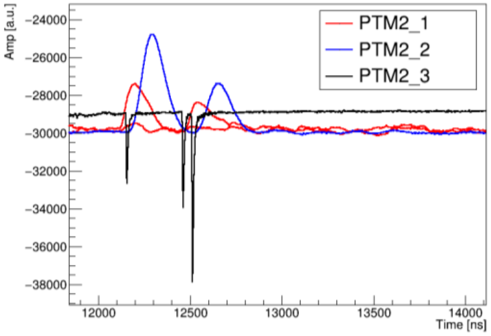
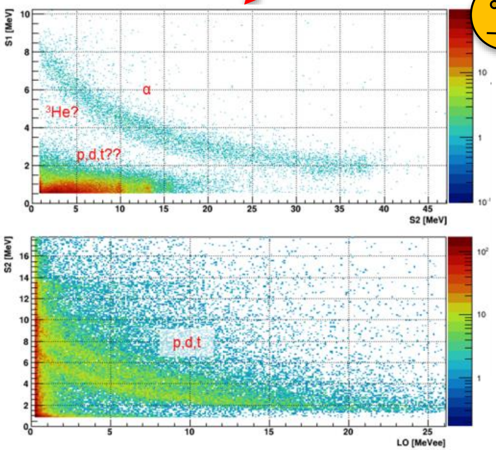




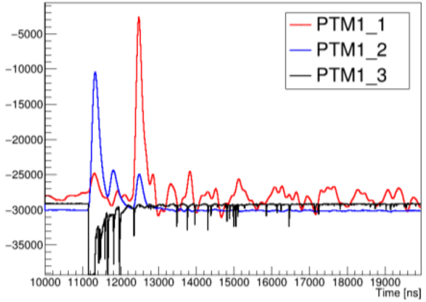


Pos: -60°





Pos: -20°

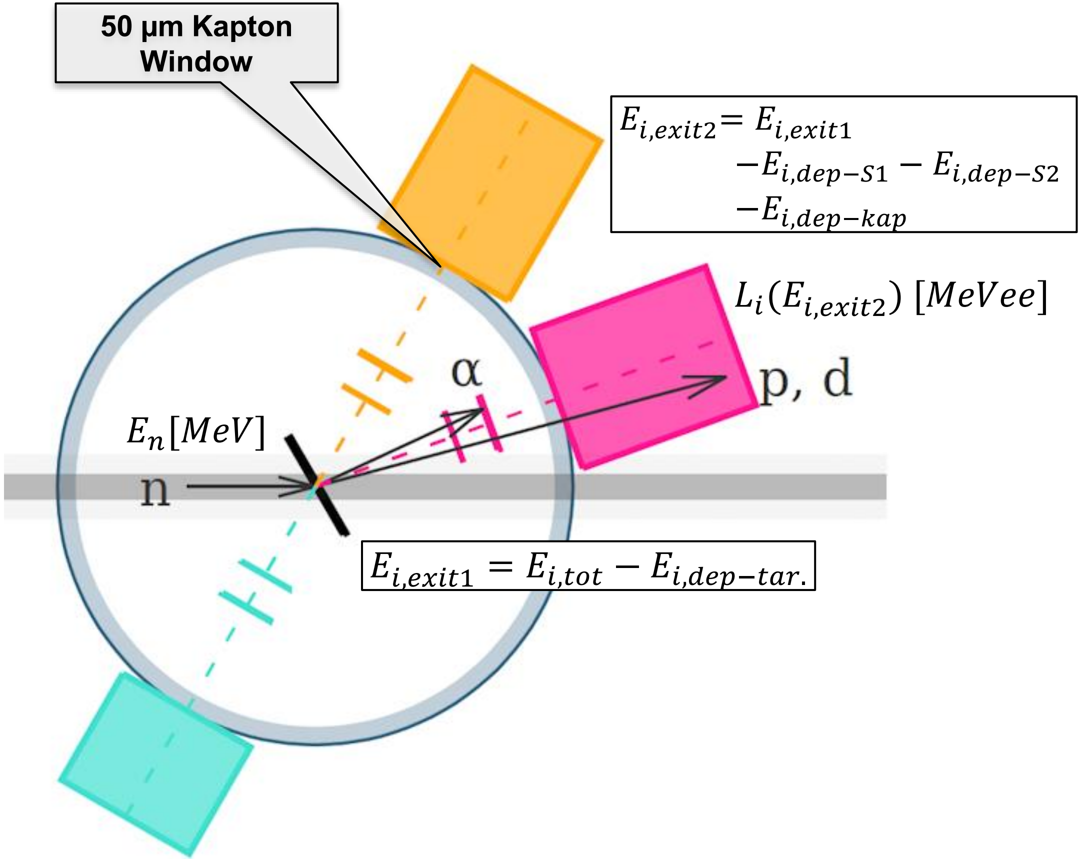


- Energy calibration of detectors with alpha (for Silicon diodes) and gamma (for scintillators) sources.
- Coincidences selection:
  - E_n> 20 MeV; Coinc. Window: 11 ns;

➢ Pos -60° and -120°, Excellent particle identification;

➢ Pos ±20° and 120°, Bad particle identification:
  - ❖ 1st Si diode signal really noisy;
  - ❖ Low Light Output for the EJ204 (15 cm) and $CeBr_3$

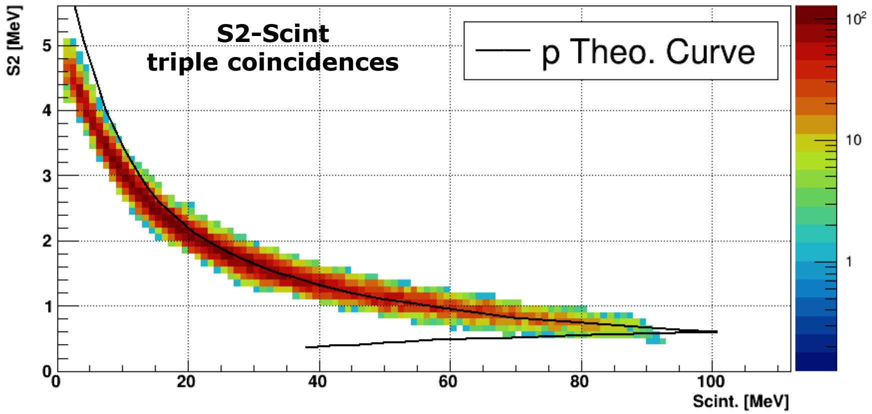
Reconstruction of total energy of emitted charged particles



For the DDX characterization we need the total energy of the emitted ion $E_{i,tot}(E_n, \theta)$:

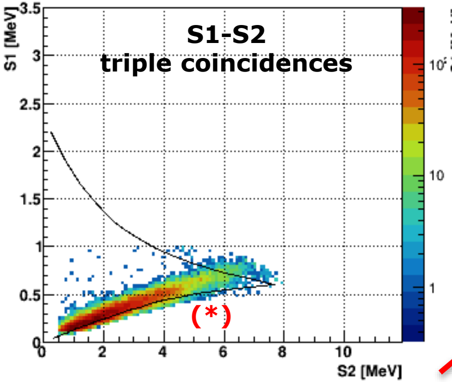
- Energy self-absorbed within the target ($E_{i,dep-tar.}$);
- In the pair of Silicon diodes we measure lower energy than what is actually emitted;
- Energy loss in Kapton windows (between the second silicon and scintillator)
- Ion-dependent light-output (L_i[MeVee]) conversion of the EJ-204 scintillators into energy;

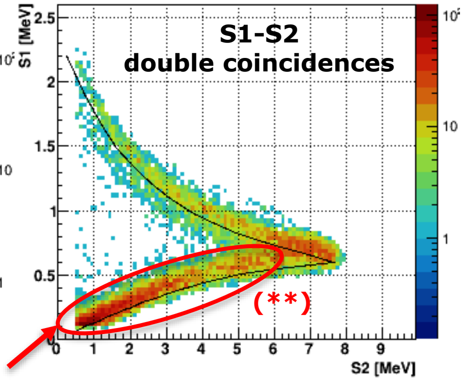
Preliminary results at 60° S1: 60 µm S2: 500 µm, E: EJ 10 cm



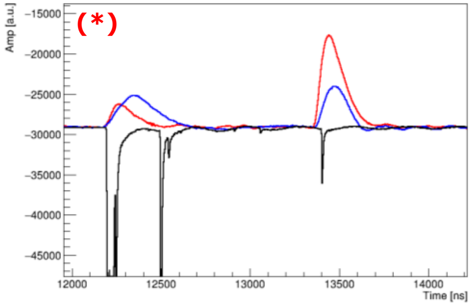
Proton contributions from 2 mm Carbon target:

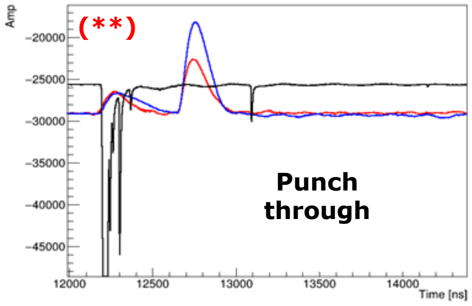
- ➢ Update and improvement of the code for finding coincidences (double and triple) according to ion species;
- ➢ Incorporation of energy loss corrections in Kapton windows
- ➢ Conversion of scintillator light output (LO) into deposited energy according the ion species;
- ➢ Excess of high-energy proton contributions in the S1-S2 pair
- ➢ Absence of such contributions in Geant4-INCL simulations





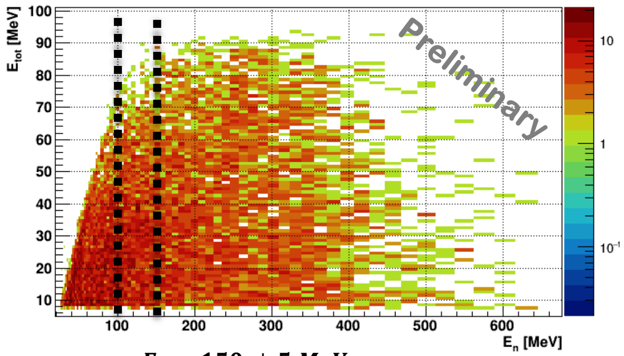
High energy protons
(they should not be there!!!)





Preliminary results at 60° S1: 60 µm S2: 500 µm, E: EJ 10 cm

$E_n = 100 \pm 5\ MeV$

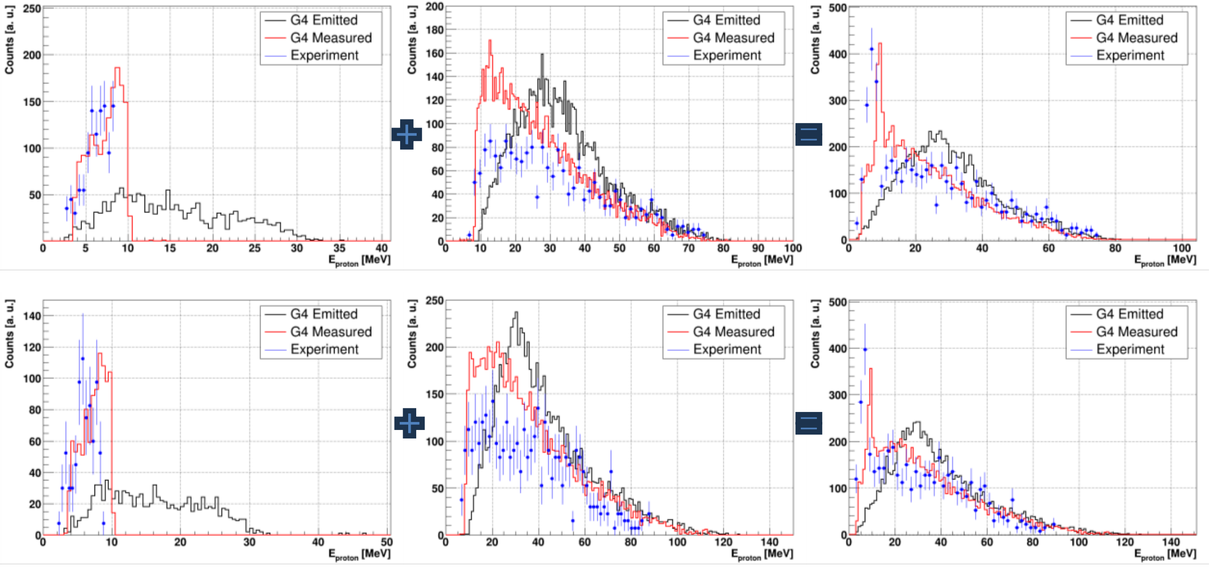


$E_n = 150 \pm 5\ MeV$

E. Dep sum in S1-S2

E. Dep sum in S1-S2-Scint

E. Dep sum in Double + Triple coinc.

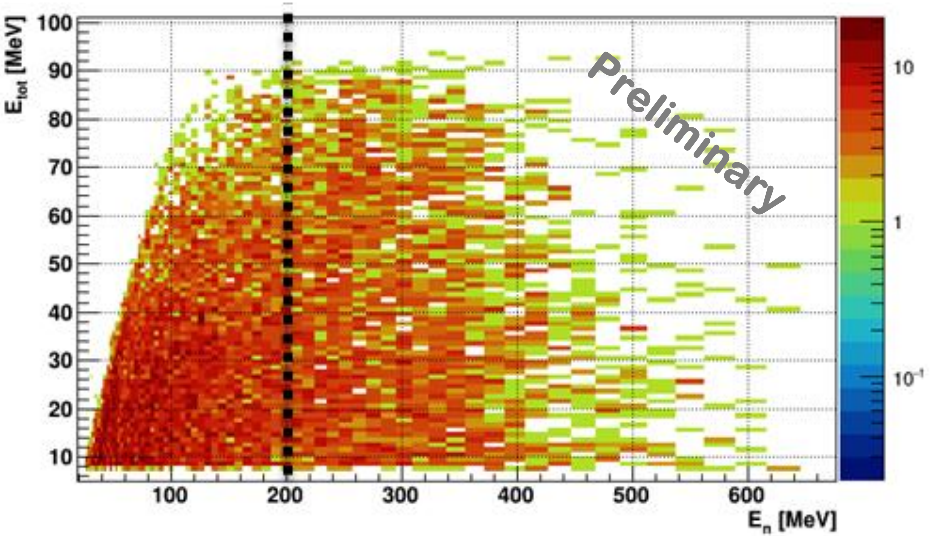


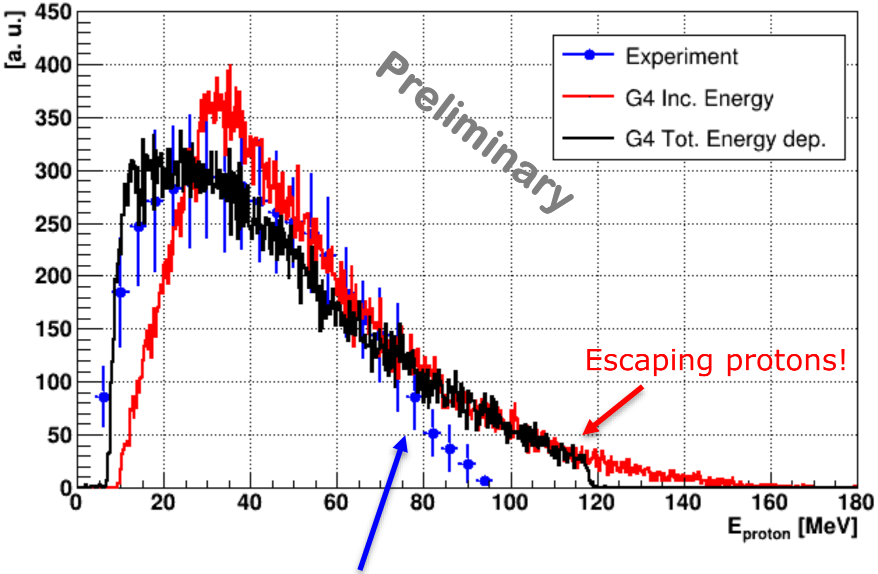
Preliminary analysis of proton emission spectra:

- Applying a punch-through cut improves the agreement between the experimental and simulated proton emission spectra (This effect observed in results at –120°, too);
- A proper interpretation of the experimental spectra requires identifying the origin of the excess contributions;
- This step is also essential when analyzing the polyethylene target, in order to subtract the proton contribution from carbon and to perform an accurate normalization.

Preliminary results at 60° S1: 60 µm S2: 500 µm, E: EJ 10 cm

$E_n = 200 \pm 5\ MeV$





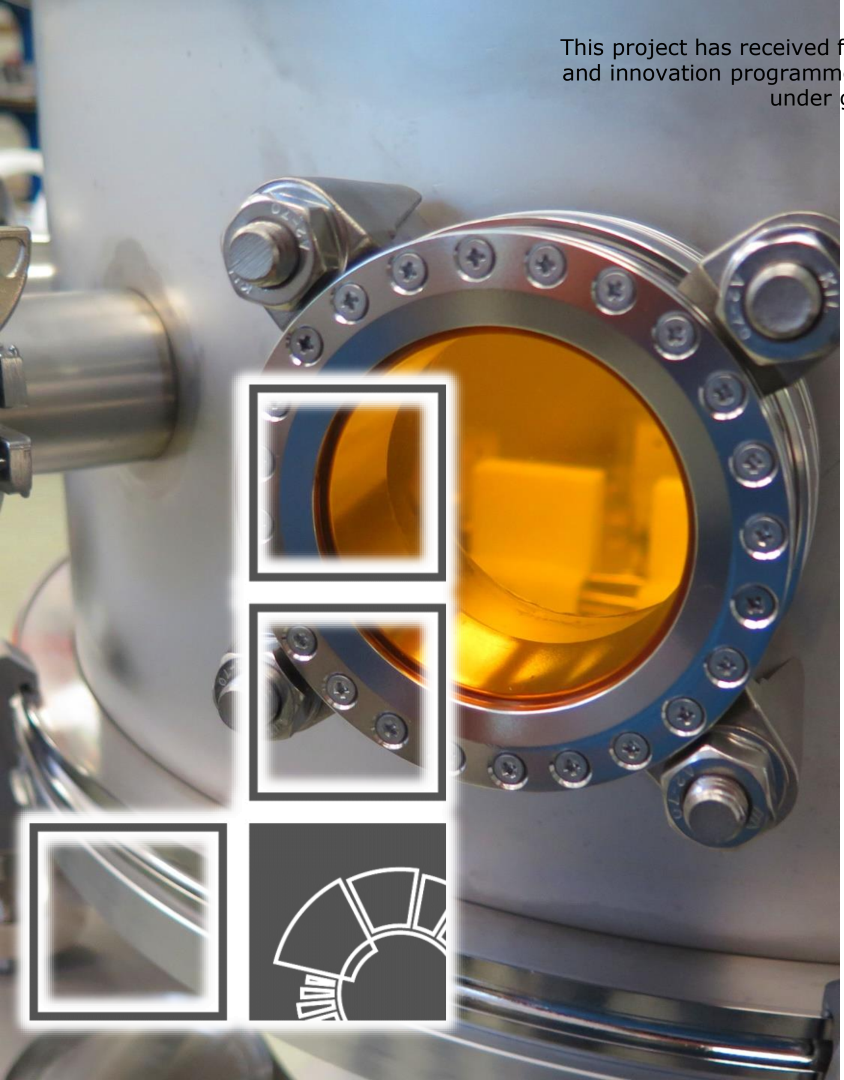
High-energy protons may escape or deposit too little energy to scintillate (This could result in an underestimation of the proton yield, particularly at higher energies.)

✓ Conclusion, future ❖ Works & Outlook ➢

- ✓ **<u>The proof-of-principle experiment with new DDX chamber showed good potential for identifying emitted secondary particles, but also needs further development to optimise its performance</u>;**
- ✓ Presence of **excess** contributions in the silicon diode pair;
- ✓ Exp. total proton spectra induced by neutrons having $\mathbf{E_n > 150}$ **MeV** show lower intensity than simulations (possible energy underestimation due to insufficient scintillation by high-E protons);

- ❖ Corrections for energy loss within the carbon target (especially important for alpha particles)
- ❖ Investigation of experimental challenges (deterioration of energy resolution of some thin Si diodes, low light-output of some E-detectors)
- ❖ Verification / validation of the EJ-204 charged particles response functions → beam times at PTB planned

- ➢ Normalisation of experimental data with Polyethylene target data
- ➢ **Characterization of DDX of light charged particle emission for the energy range of 20-150 MeV and comparison with verified experimental data**
- ➢ Planning of future experiments on other tissue constituents like N, O, …



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Thank you!

- HZDR colleagues
- PTB Transport Service
- PTB Workshop and electricians
- Local team
- Shifters
- n_TOF
- RP (PTB + CERN)

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Appendix