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Ultra-intense neutron source generation from (p,xn) and (γ,xn) reactions driven by the PETAL laser

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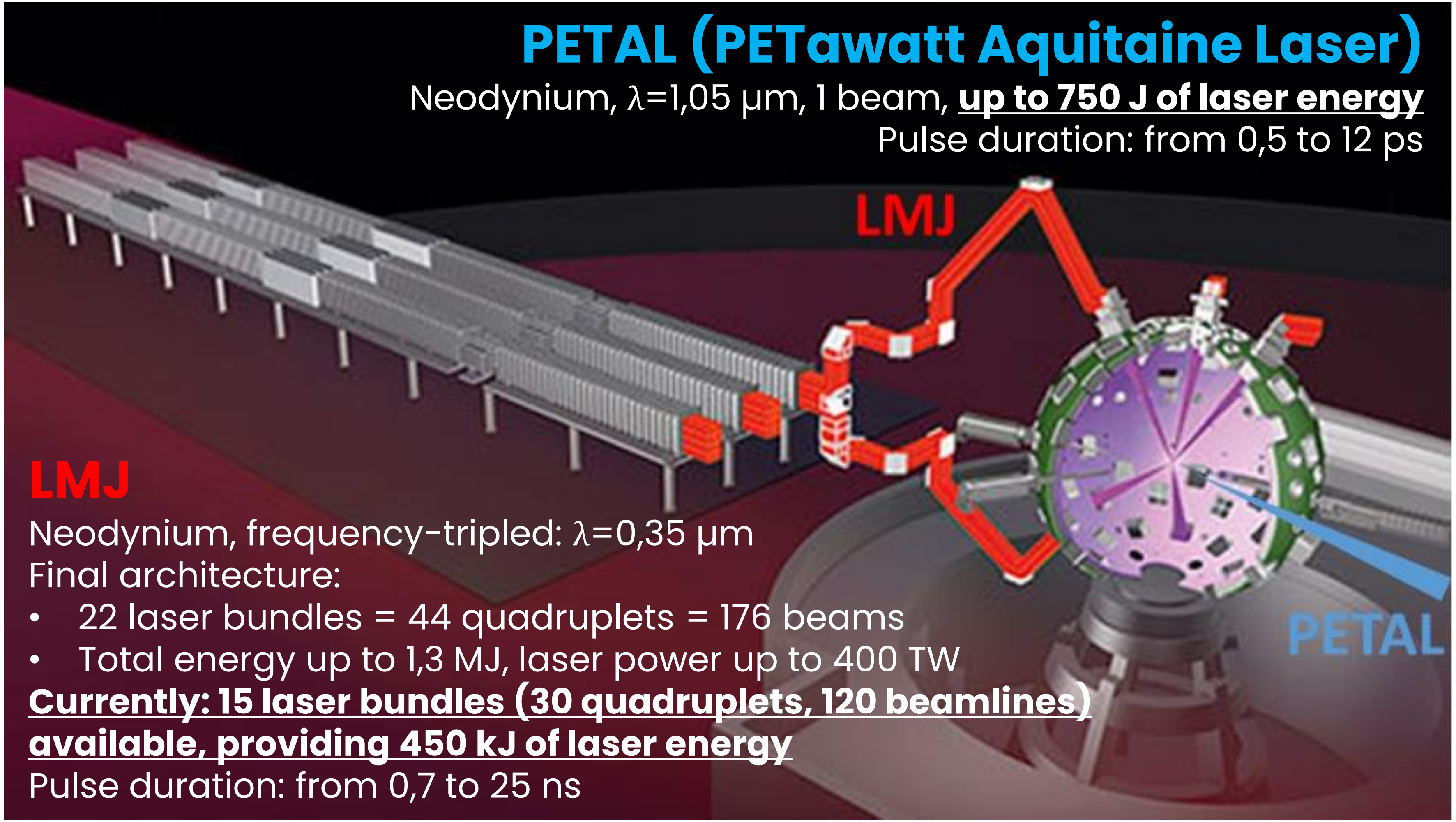
1. LMJ/PETAL

LMJ/PETAL – Laser architecture and main characteristics



PETAL (PETawatt Aquitaine Laser)

Neodynium, λ=1,05 µm, 1 beam, **up to 750 J of laser energy**
Pulse duration: from 0,5 to 12 ps

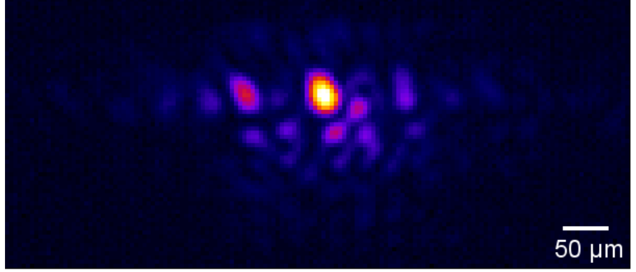
LMJ

Neodynium, frequency-tripled: λ=0,35 µm
Final architecture:

- 22 laser bundles = 44 quadruplets = 176 beams
- Total energy up to 1,3 MJ, laser power up to 400 TW

Currently: 15 laser bundles (30 quadruplets, 120 beamlines) available, providing 450 kJ of laser energy
Pulse duration: from 0,7 to 25 ns

Up to 1 PW & 2x10^{19} W/cm^2



[1 shot per day]

ICF design at LMJ and current fusion-neutron generation

- LMJ is a tool for high-energy density physics in hot and dense plasma, namely at temperature of **millions of K** as well as pressures in the **Mbar-Gbar range**.
  - Radiative hydrodynamics
  - EoS and atomic physics
  - Thermonuclear fusion physics

The ICF campaigns are tied to the facility developments:

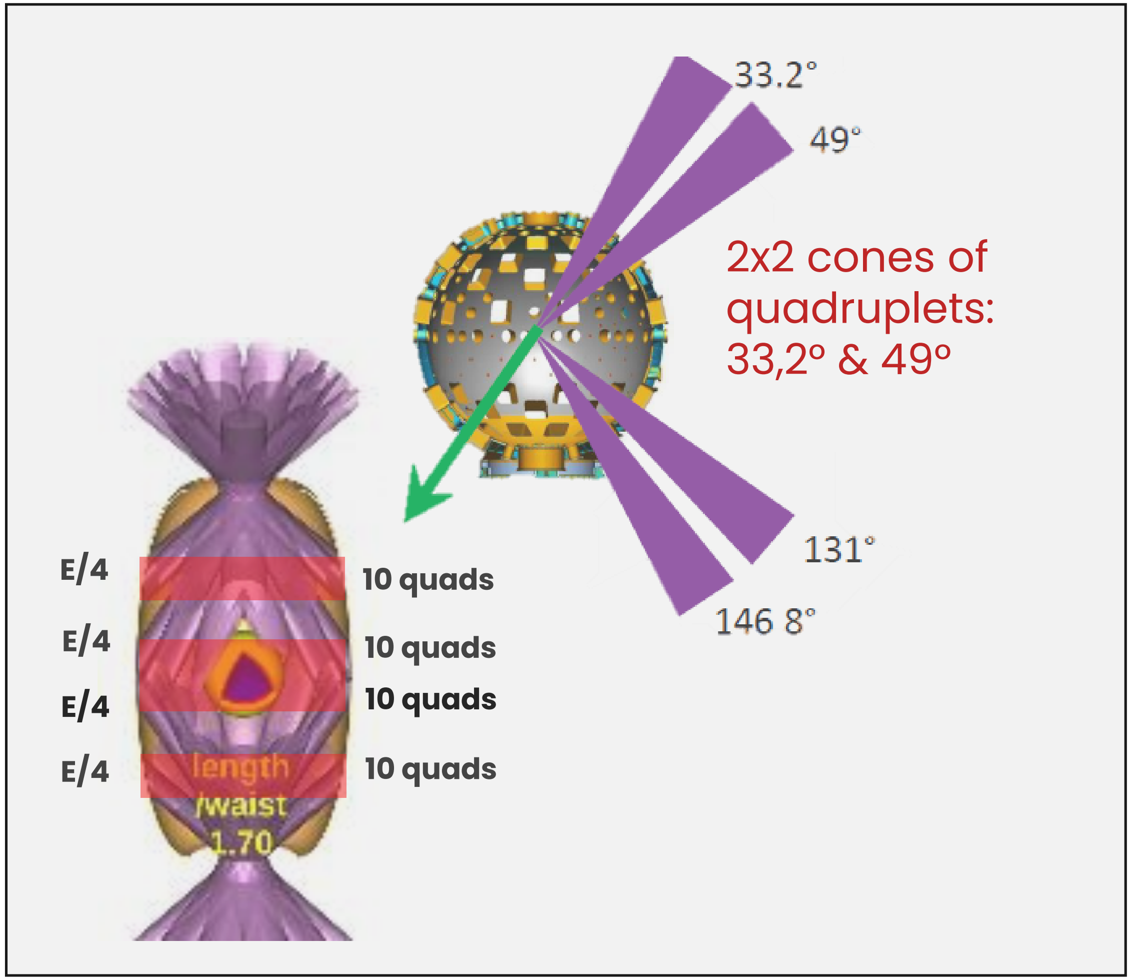
- Currently DD fusion with 300 kJ laser

  $D + D \rightarrow {}^3He$ (0.82 MeV) + n **(2.45 MeV)**

  Neutron yield ≈ 5×10^{11} n

- 600 kJ in 2027
- Cryo DT in the middle of the next decade and energy ramping up to 1,3 MJ.

In the remaining of the talk, we will talk about non-fusion neutrons using PETAL as driver.



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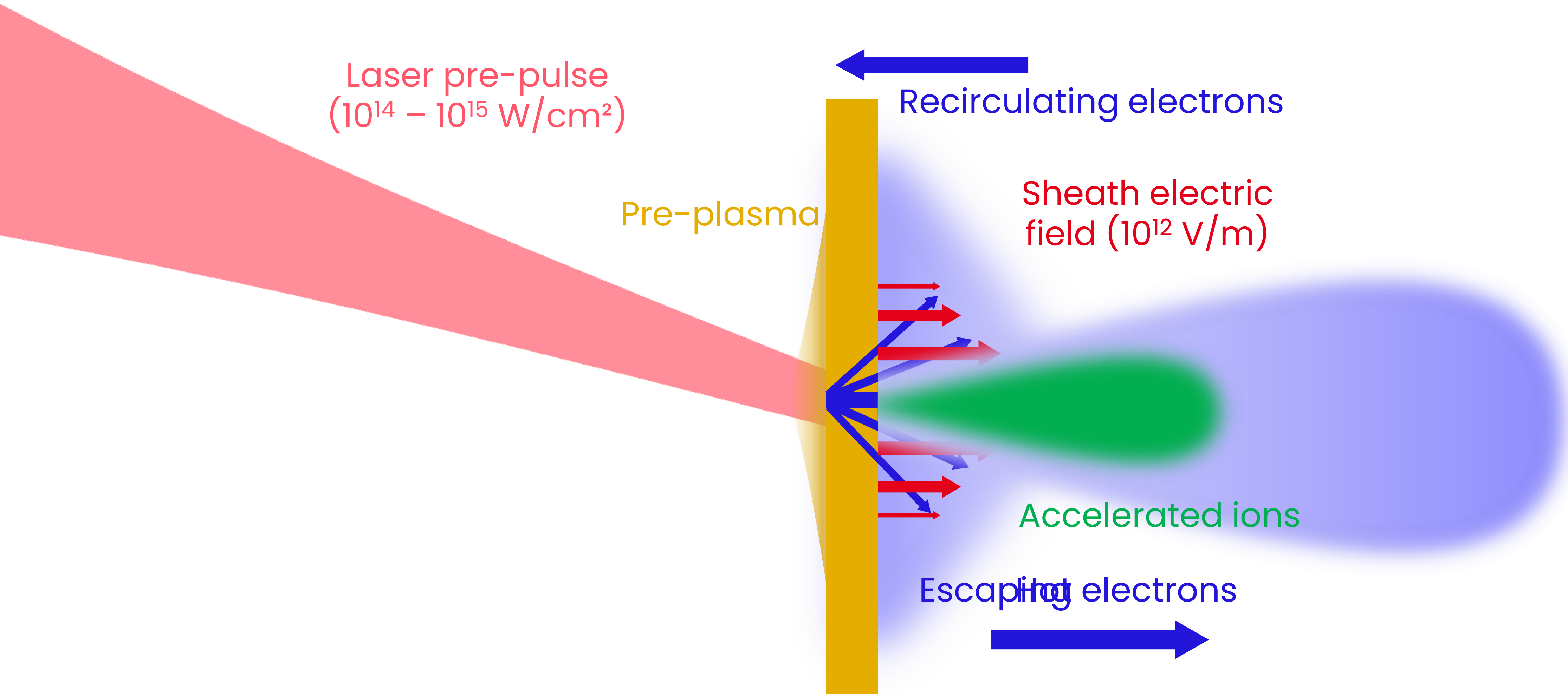
2. Primary sources

TNSA protons and SMLWA electrons using PETAL

High-energy protons can be generated using the Target Normal Sheath Acceleration (TNSA) mechanism

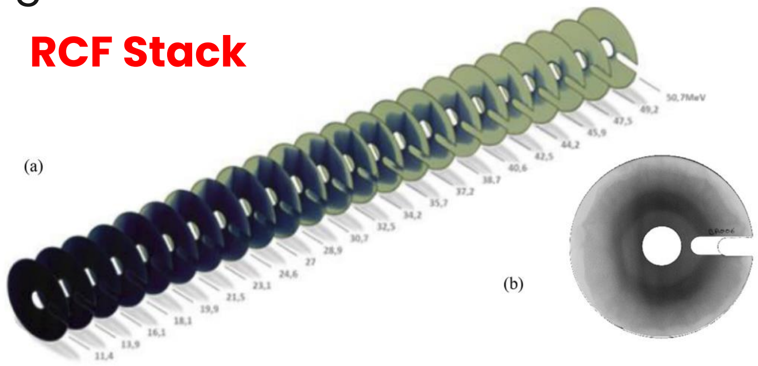


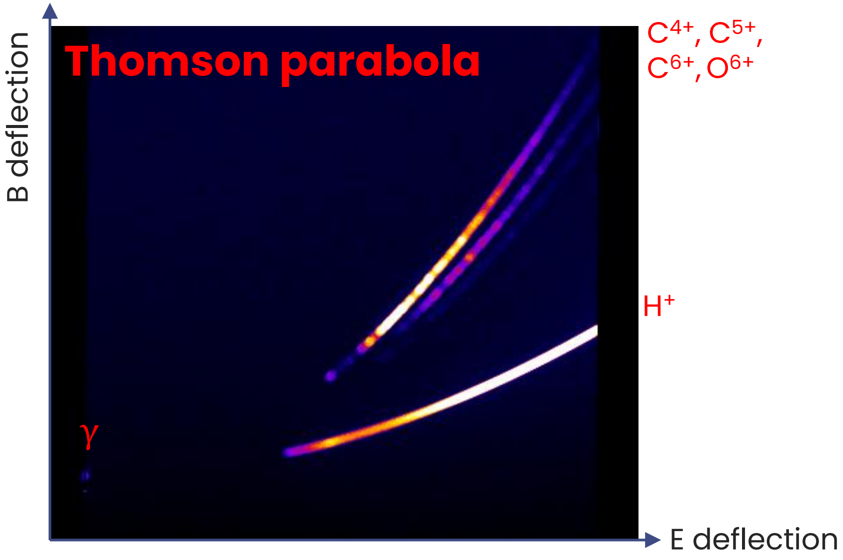
Thin target (nm, μm)

We have demonstrated robust TNSA proton generation driven by PETAL using CH target

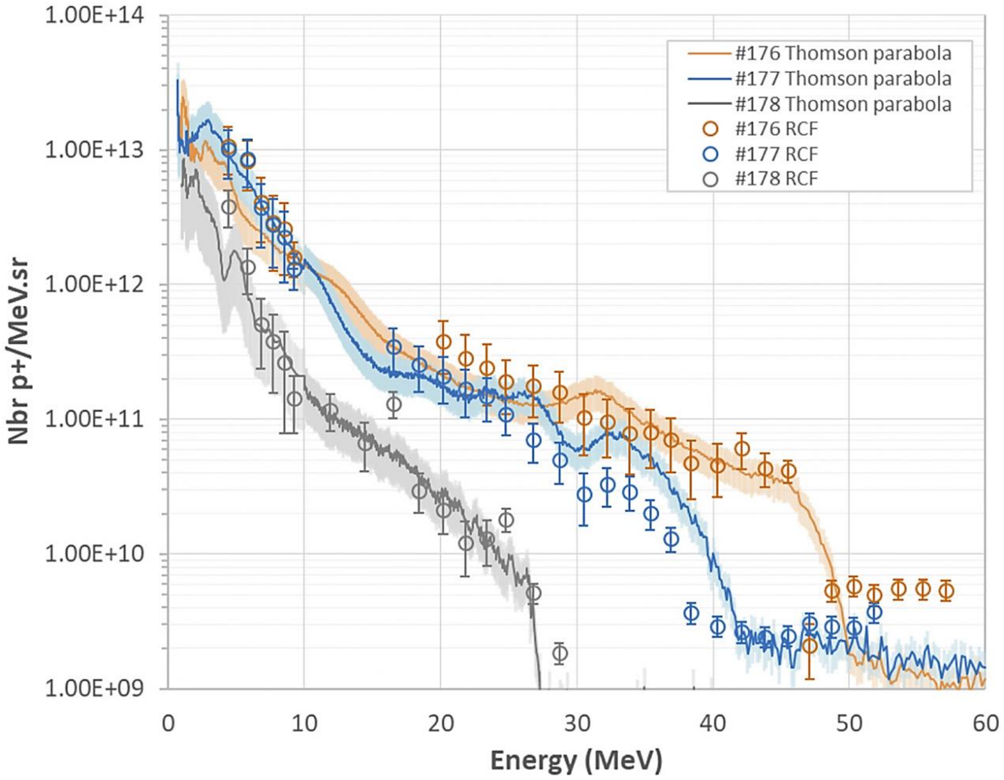
- Diagnostics:

RCF Stack





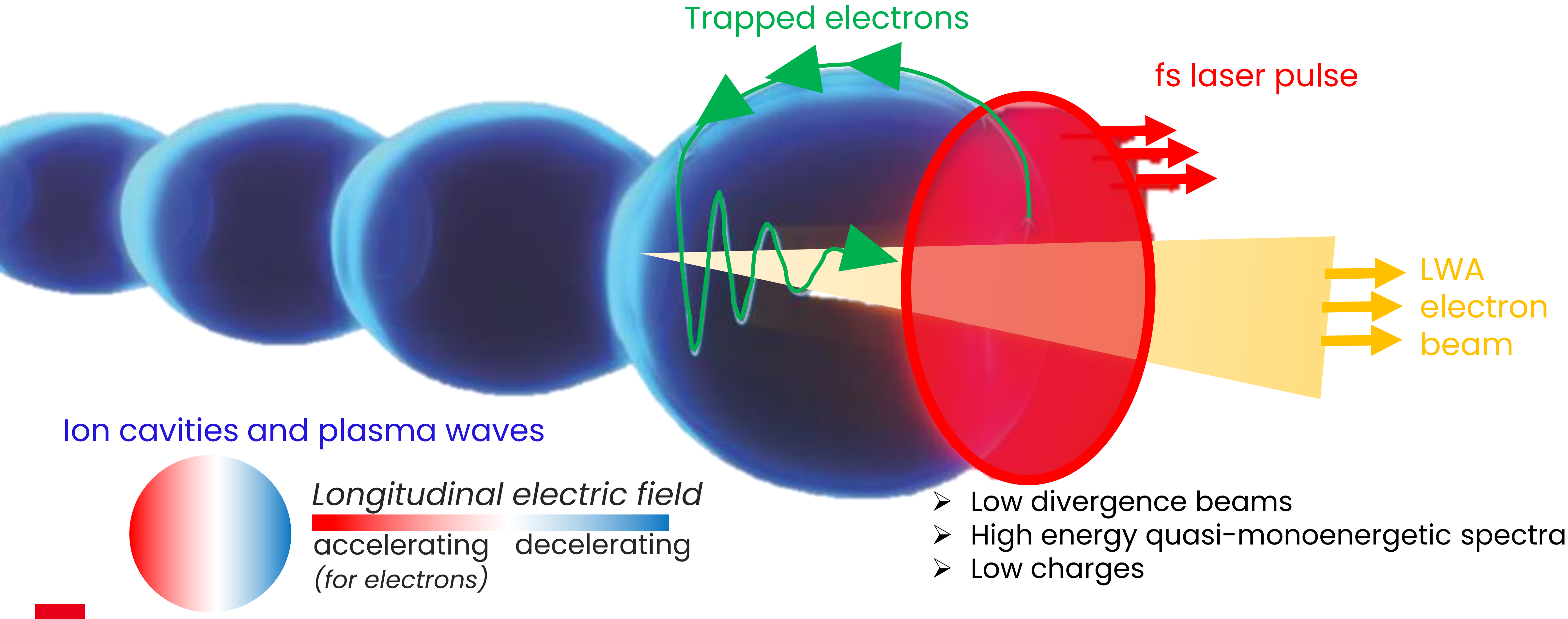
Shot #	Energy	Compression	Intensity	TNSA target
SR176	450 J	0.610 ps	7.9×10^{18} W/cm²	1 µm Al + 50 µm CH
SR177	409 J	0.660 ps	6.6×10^{18} W/cm²	10 µm CH
SR178	187 J	0.610 ps	3.3×10^{18} W/cm²	10 µm CH



- Protons cut-off energy ≈ 50 MeV
- Laser-to-proton conversion efficiency ≈ 3 %

High –energy e- beams are commonly produced by Laser Wakefield Acceleration using underdense targets (gas jet)

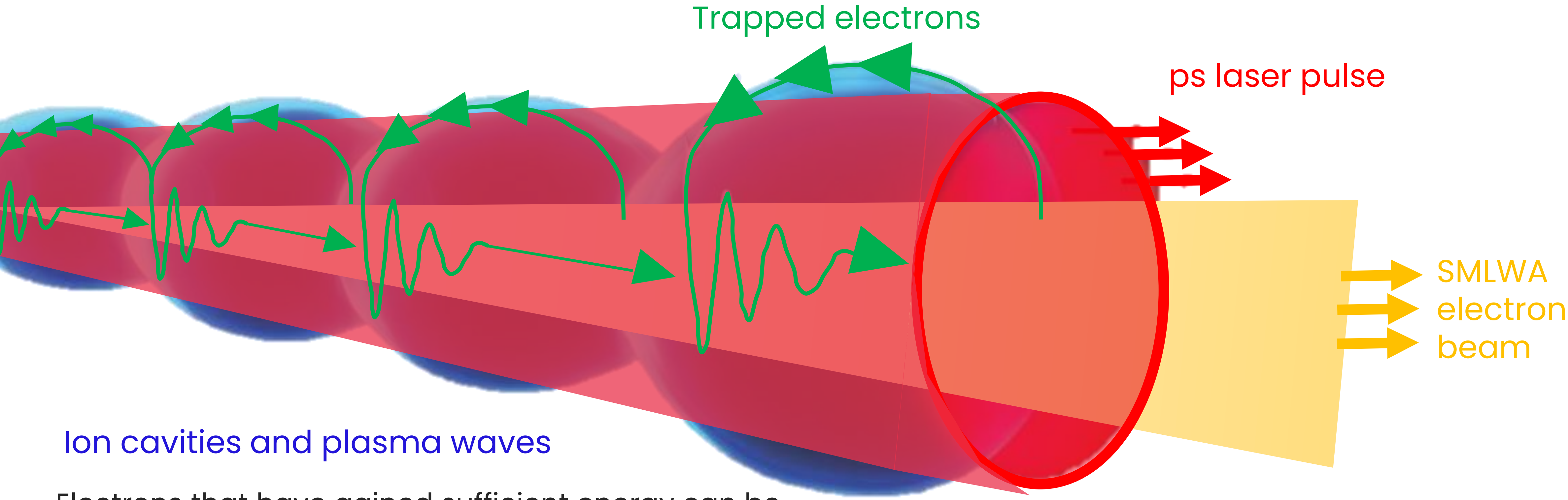
Using fs laser with high intensity $(> 10^{18}\ W.cm^{-2})$ and underdense plasma $(n_e \sim 10^{19}\ cm^{-3})$, the laser pulse duration is smaller than the plasma period. A longitudinal plasma wave is induced in the wake of the pulse, able to accelerate trapped electrons to relativistic energies in ion cavity structures → blowout regime



- Low divergence beams
- High energy quasi-monoenergetic spectra
- Low charges

Using PETAL, a regime of Self-Modulated Laser Wakefield Acceleration occurs.

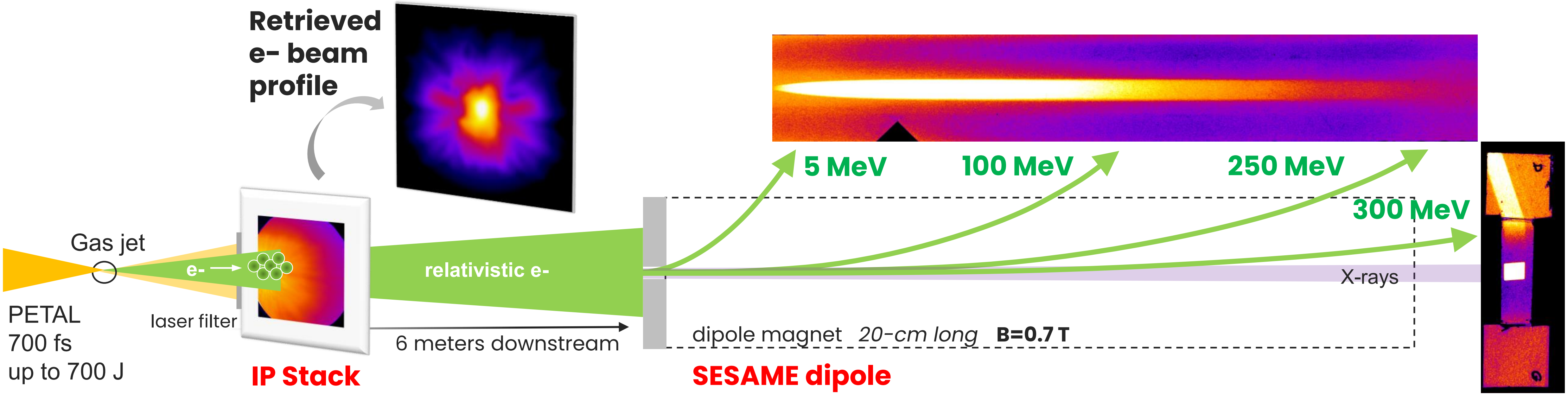
For a ps laser at $n_e \sim 10^{18-19}\ cm^{-3}$, the pulse overlaps with several plasma periods.
Energy exchange between the plasma wave and the laser field (stimulated Raman scattering) yields a modulated laser pulse.



Electrons that have gained sufficient energy can be trapped into the preceding cavity, and thus be accelerated, until dephasing

- High divergence beams
- Broad energy distribution
- High accelerated charges

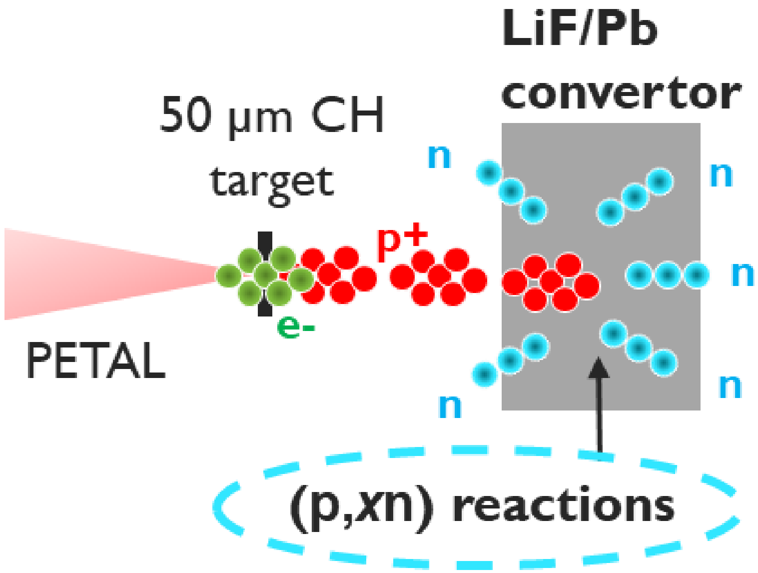
μC-class relativistic electron beams with moderate divergence have been measured at LMJ/PETAL

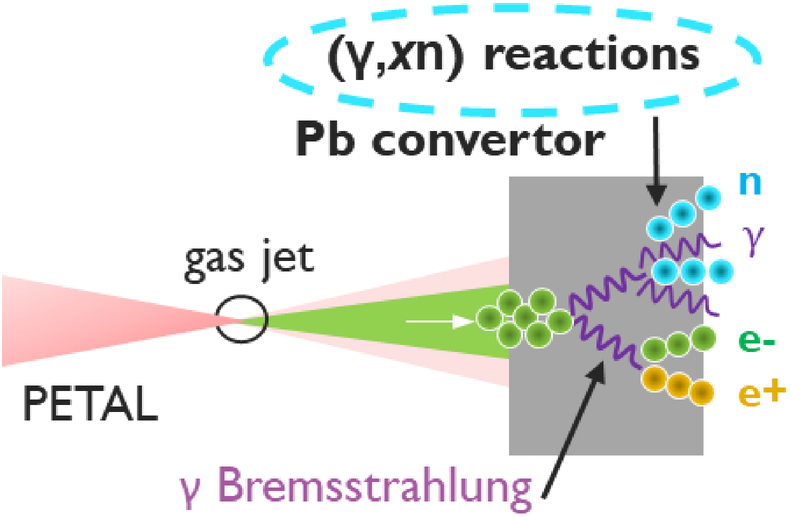


→ Electrons with **≈ 1.5 μC total charge** and **200 mrad divergence angle**
→ Electrons cut-off energy ≈ **300 MeV**
→ Laser-to-electron conversion efficiency ≈ **5 %**
→ Comparable to the state-of-the-art (0.7 μC @ OMEGA-EP, Sci. Rep. 2021)

We coupled these primary proton and electron sources to a convertor to produce nuclear reactions and secondary neutrons

- Pitcher-catcher schemes:





- Primary sources diagnostics: already mentioned detectors (i.e. RCF stacks, IP stacks , SESAME dipole)
- Neutron diagnostics: GPMT nToF + activation samples

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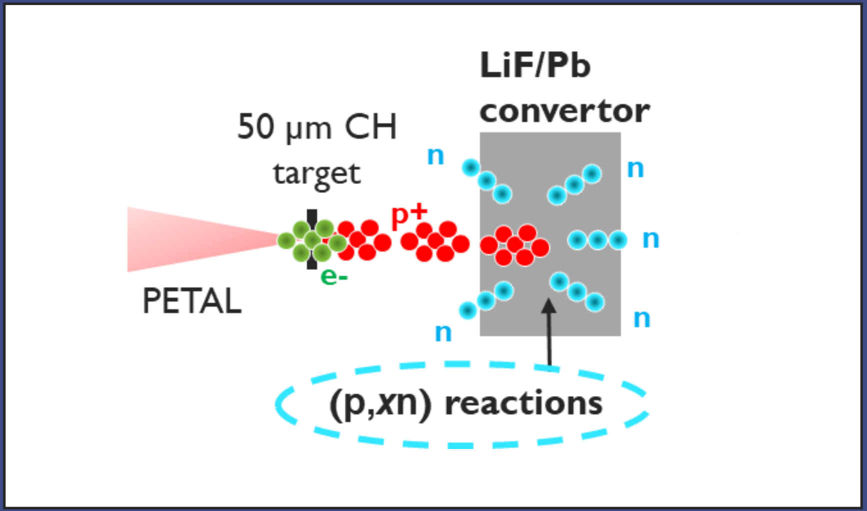
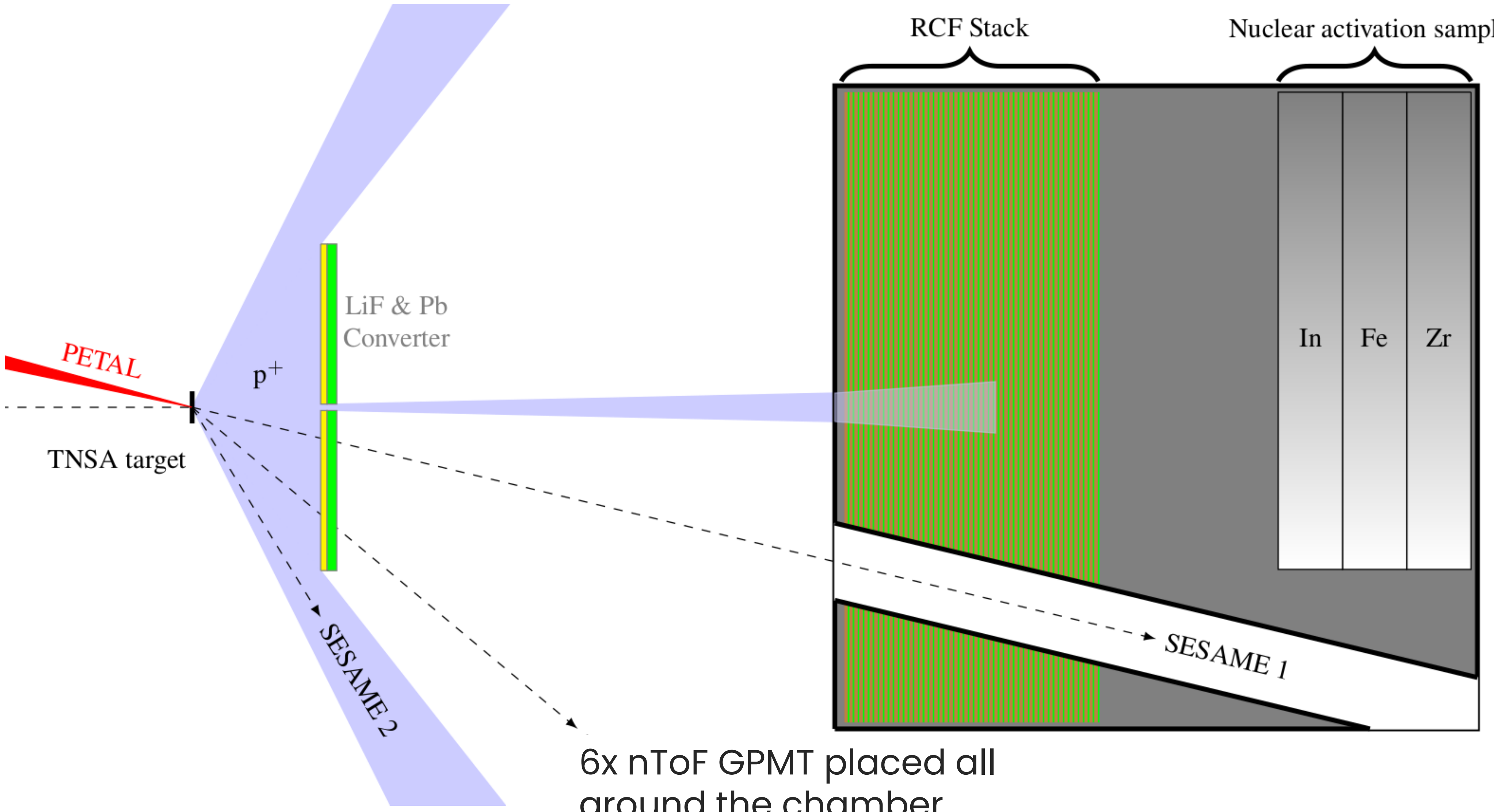


3. (p,xn) reactions

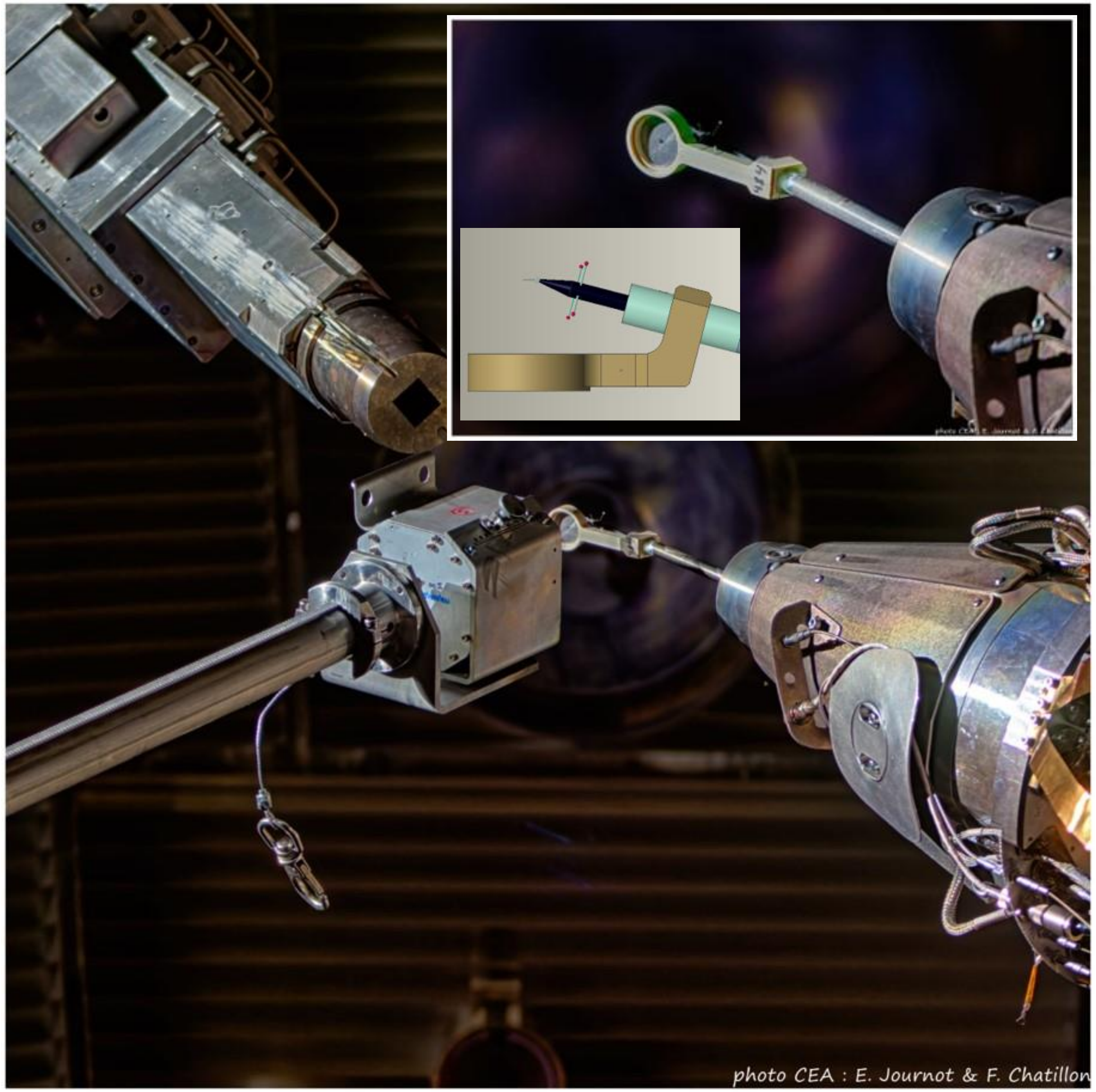
Pitcher-catcher scheme using TNSA protons as primary source

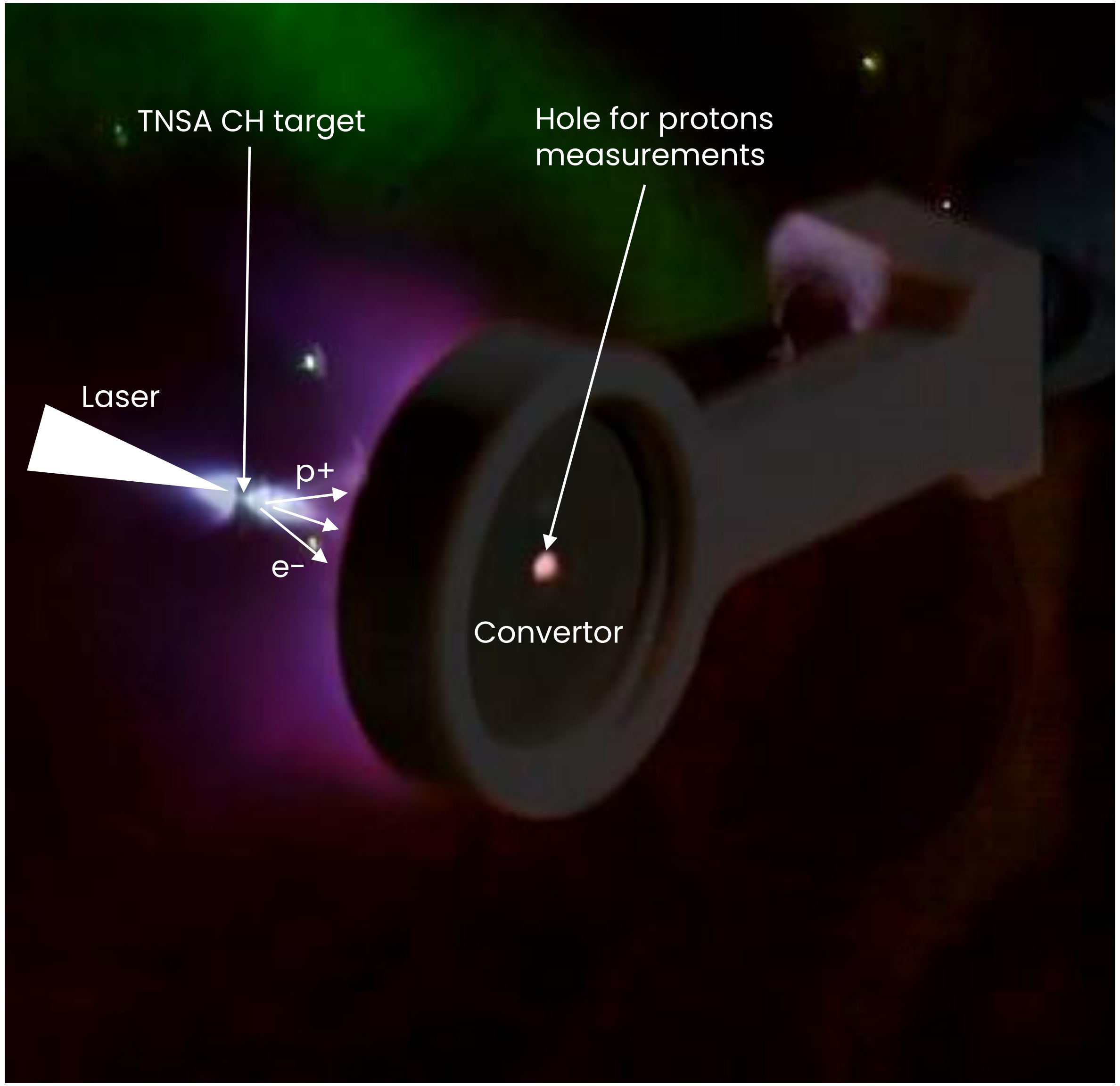
TNSA pitcher-catcher experimental setup



6x nToF GPMT placed all around the chamber

Experimental setup



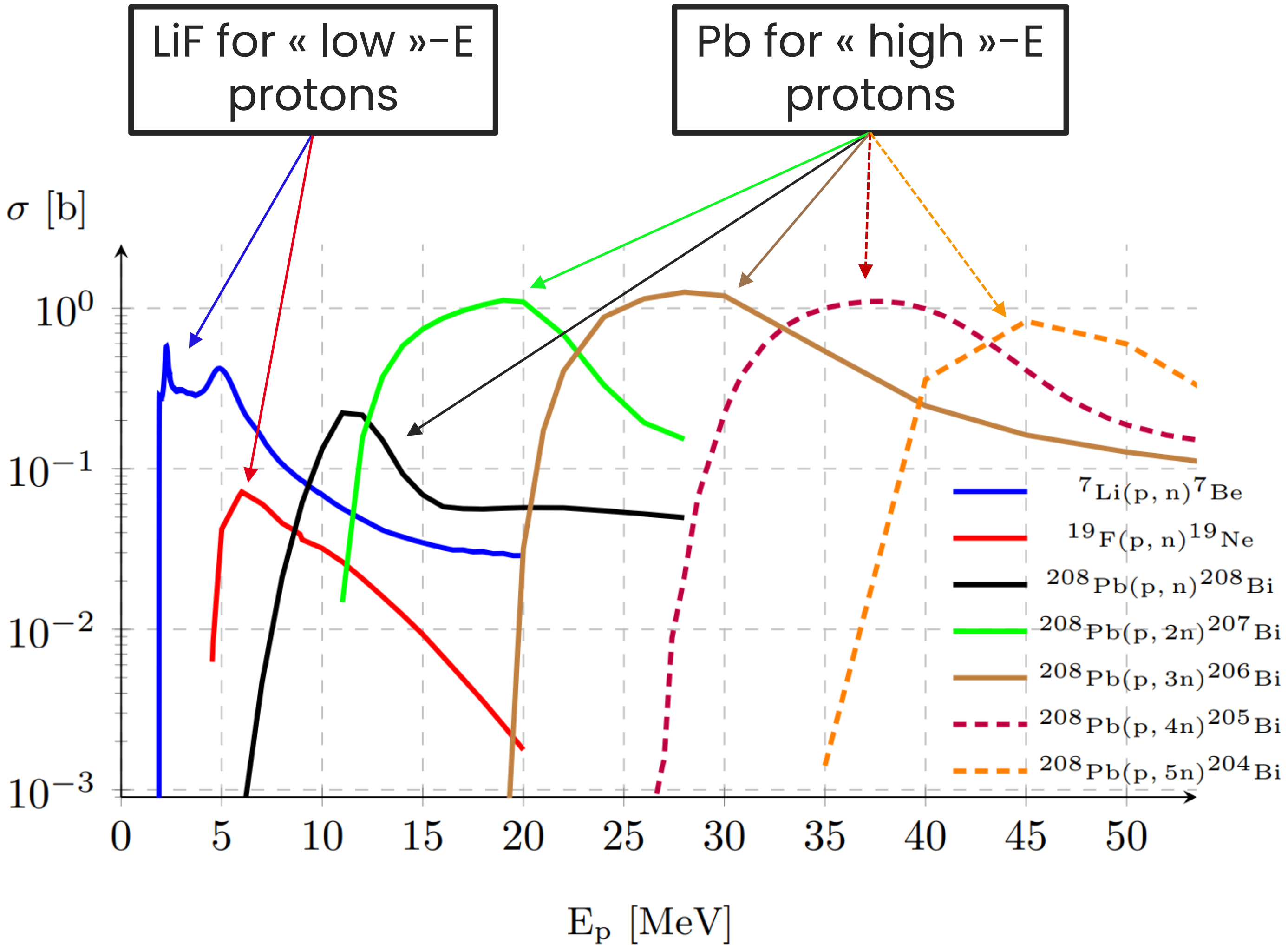


We used double-layer convertors to increase the neutron yield

Classical convertors: Be, LiF, Pb or deuterated CH

Our proton energies: 0 – ≈50 MeV

→ **Double-layer convertors (LiF + Pb)** should increase the total neutron output



Shot plan and main results

Shot #	Energy	Intensity	Convertor	N[E>1 MeV] (nToF)
SR420	334 J	3.43×10^{18} W/cm²	2 mm Pb	1.7×10^{9}
SR421	345 J	4.72×10^{18} W/cm²	4 mm LiF	2.3×10^{9}
SR422	332 J	2.86×10^{18} W/cm²	1 mm LiF + 1.5 mm Pb	4.6×10^{9}
SR425	328 J	9.4×10^{18} W/cm²	1 mm LiF + 1.5 mm Pb	7.5×10^{9}
SR511	476 J	4.93×10^{18} W/cm²	1 mm LiF + 3 mm Pb	1.9×10^{10}
SR512	558 J	6.38×10^{18} W/cm²	1 mm LiF + 3 mm Pb	2.9×10^{10}
SR514	639 J	1.29×10^{19} W/cm²	1 mm LiF + 3 mm Pb	5.5×10^{10}

Convertor impact

Better compression & focal spot

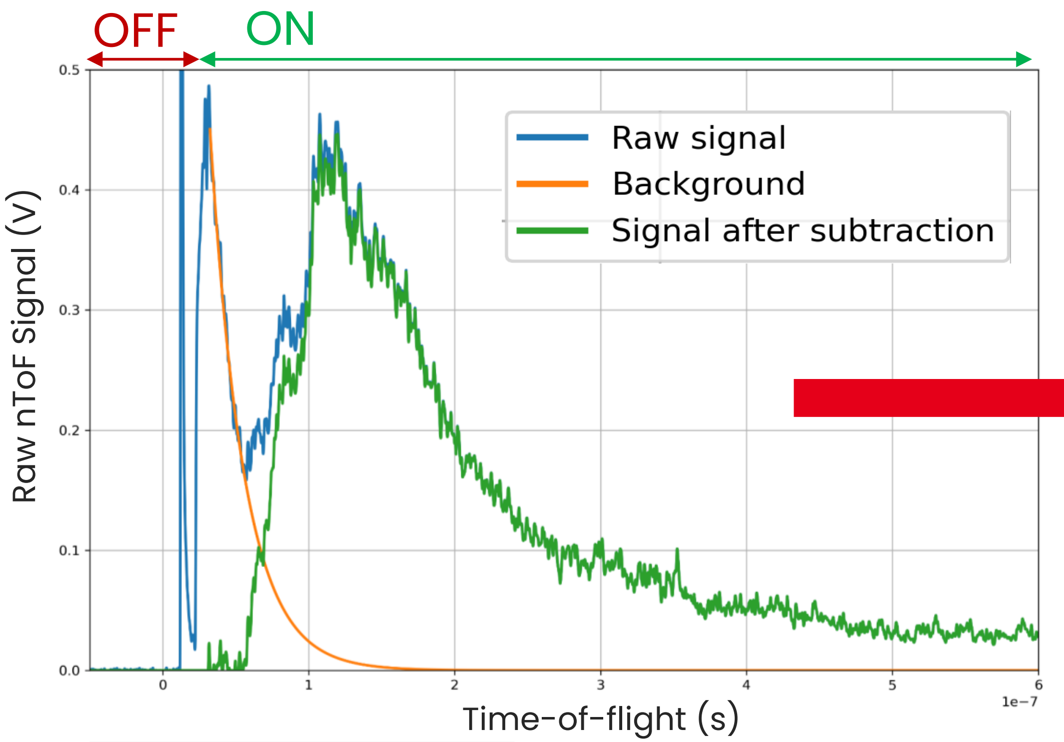
Increasing laser energy

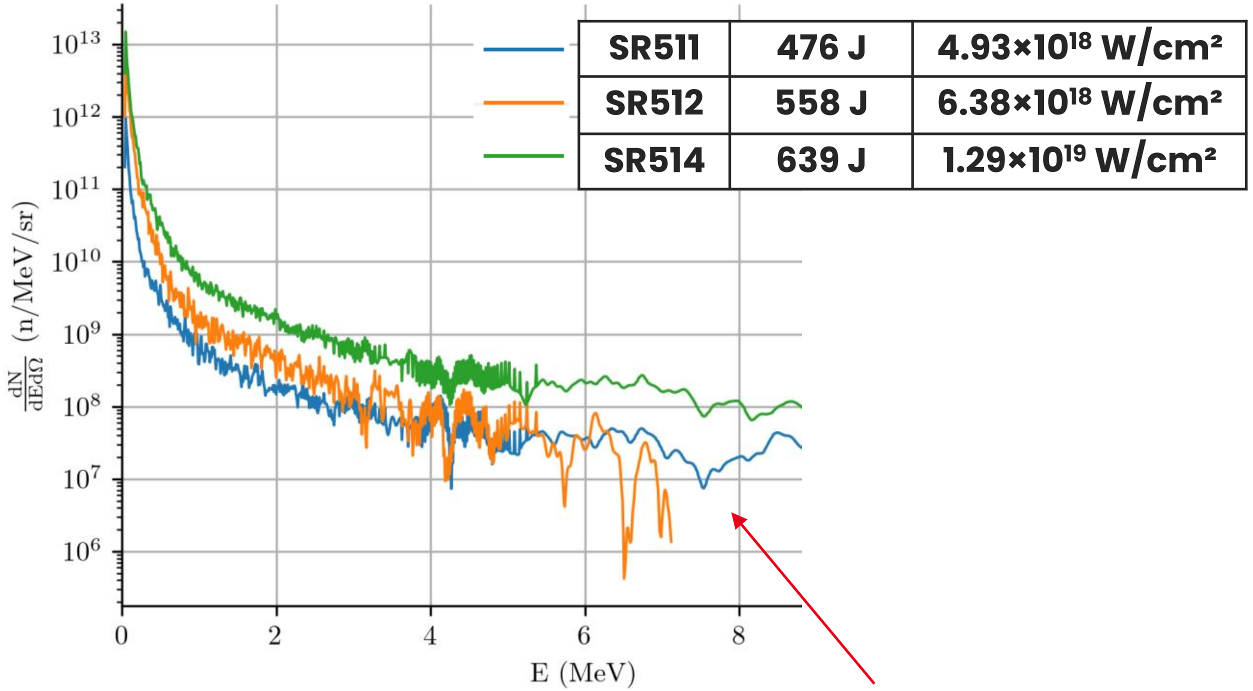
→ the role of the double layer convertor is experimentally demonstrated

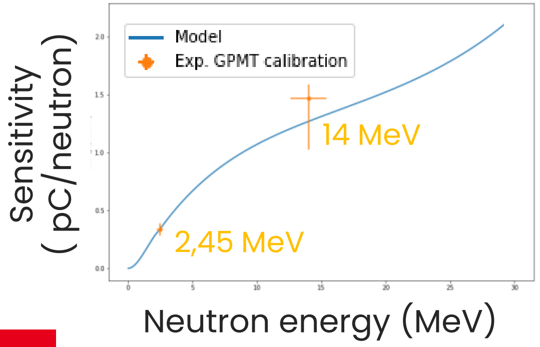
→ more neutrons as intensity and energy increase

→ up to 5.5×10^{10} neutrons above 1 MeV produced in our best shot

nToF neutron spectra are inferred at several angles and show a quasi-isotropic neutron emission







→ Gated PMT (GPMT) prevent from γ flash

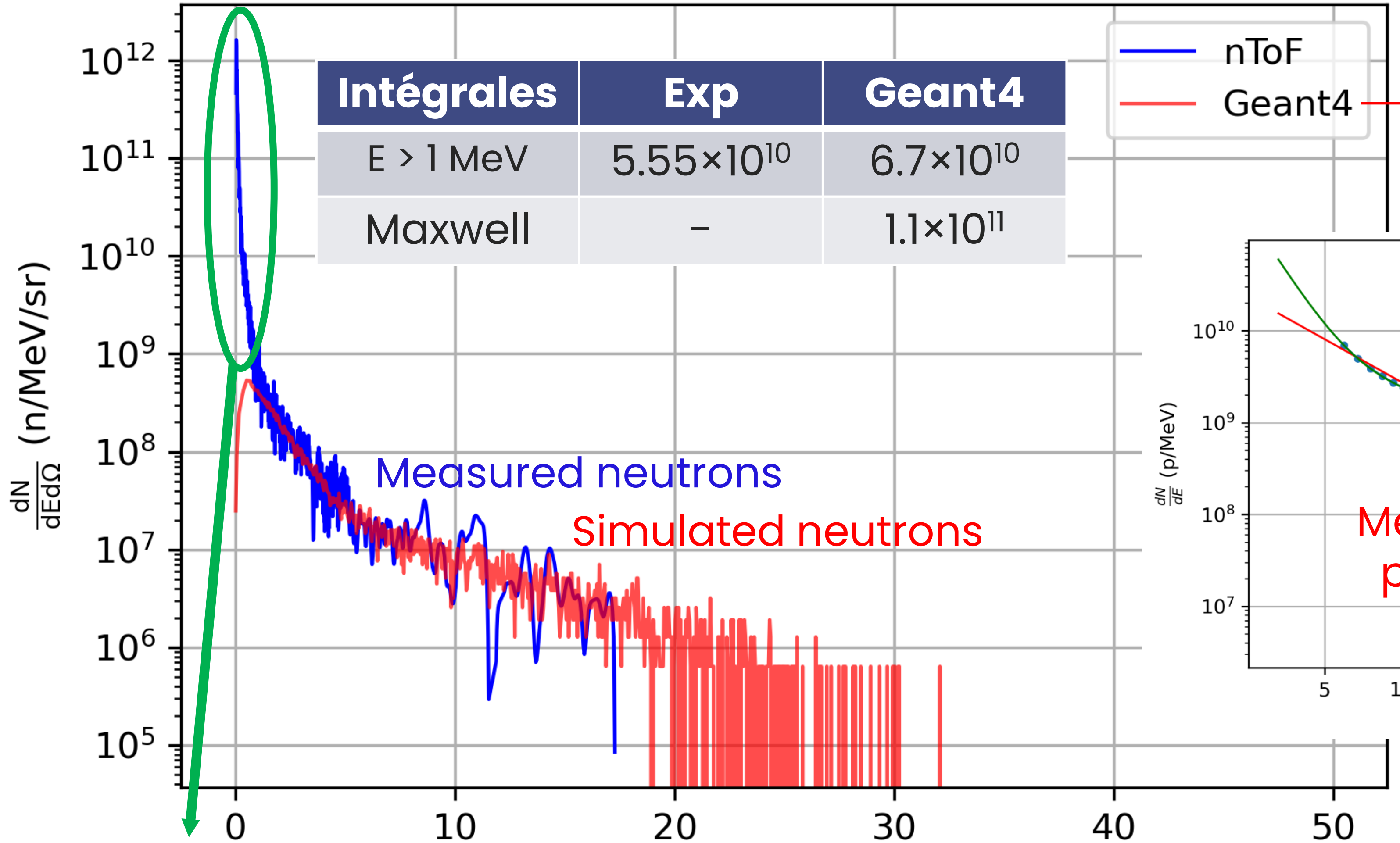
→ Birk's sensitivity model constrained by absolutely calibration @ 2,5 MeV and 14 MeV

→ Unfolding of GPMT transfer response (σ = 0.5 ns, τ = 4 ns) is needed

This illustrates how the neutron spectra evolves with laser energy and laser intensity

But is it quantitative?

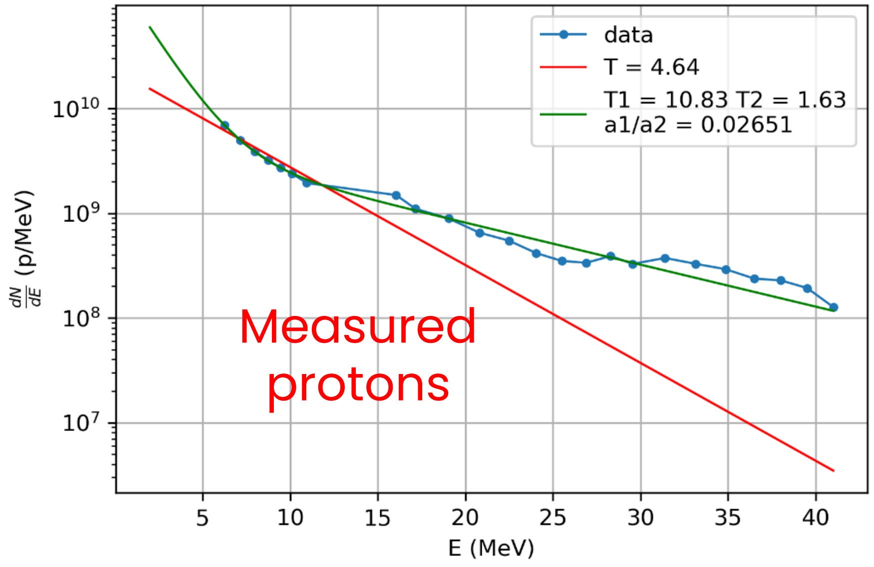
nToF data well reproduced by GEANT4 simulations using measured proton spectra as input



Intégrales	Exp	Geant4
E > 1 MeV	5.55×10^{10}	6.7×10^{10}
Maxwell	–	1.1×10^{11}

Neutron scattering in the experimental chamber + nToF background noise at longer time

RCF Spectra as Geant4 input

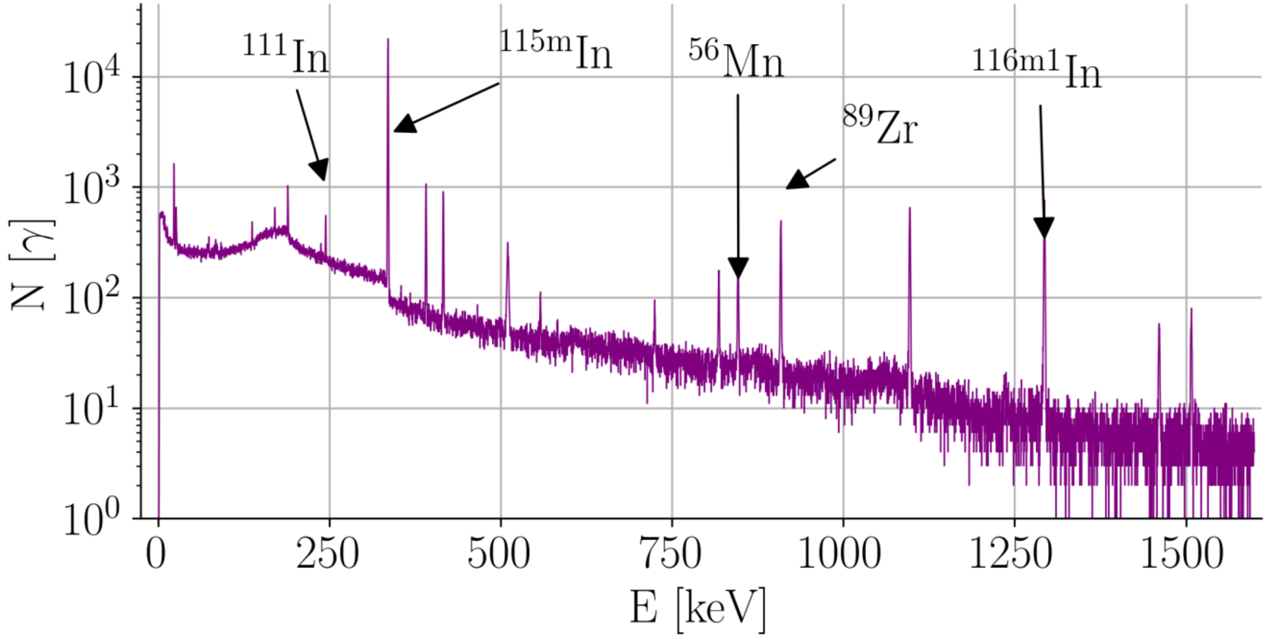


Simulations corroborate the nToF measurements above 1 MeV and enable to infer the primary neutron spectra.

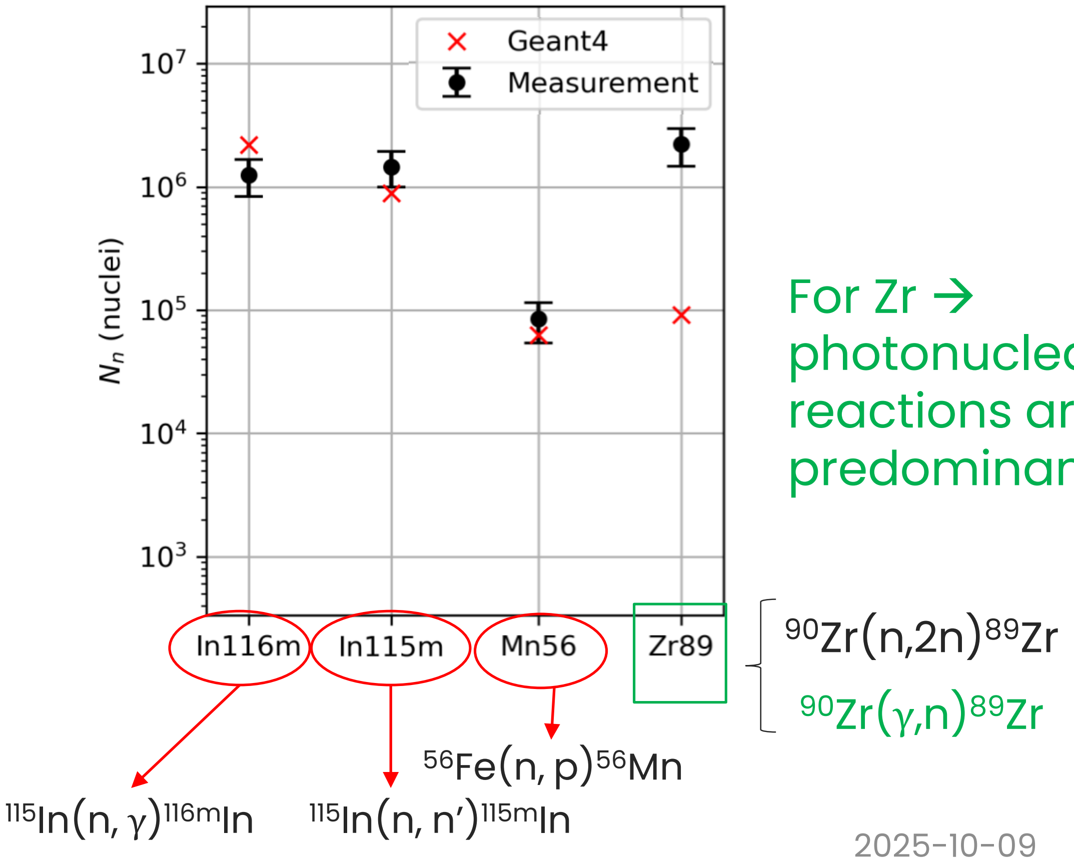
γ spectrometry of Indium – Iron and Zirconium activation layers in agreement with GEANT4 using measured nToF spectrum as input

- HPGe γ spectrometer (Canberra BE5030)
- $\delta t \approx$ 1–2 h extraction time
- Δt = 22–24 h acquisition time
- Range: 0–1600 keV

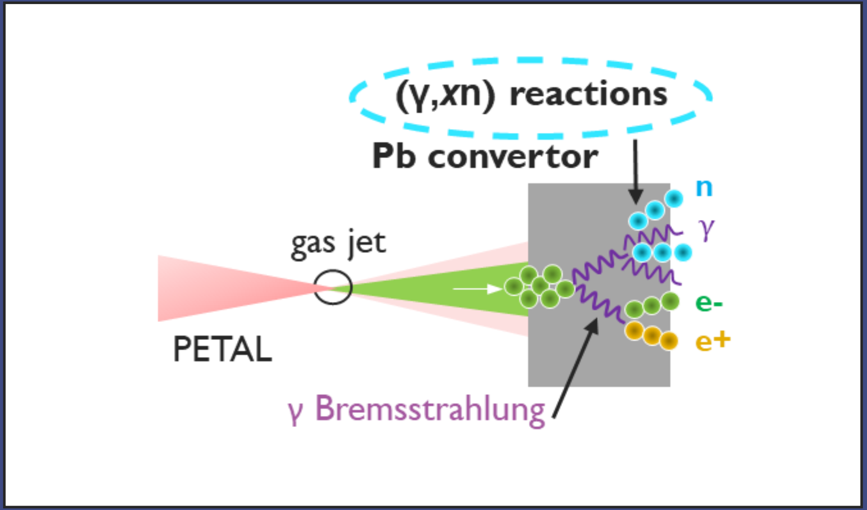
GEANT4 simulations using measured nToF spectrum as input can be compared to activation measurements
→ fair agreement for single neutron reaction



→ Number of activated nuclei in each sample



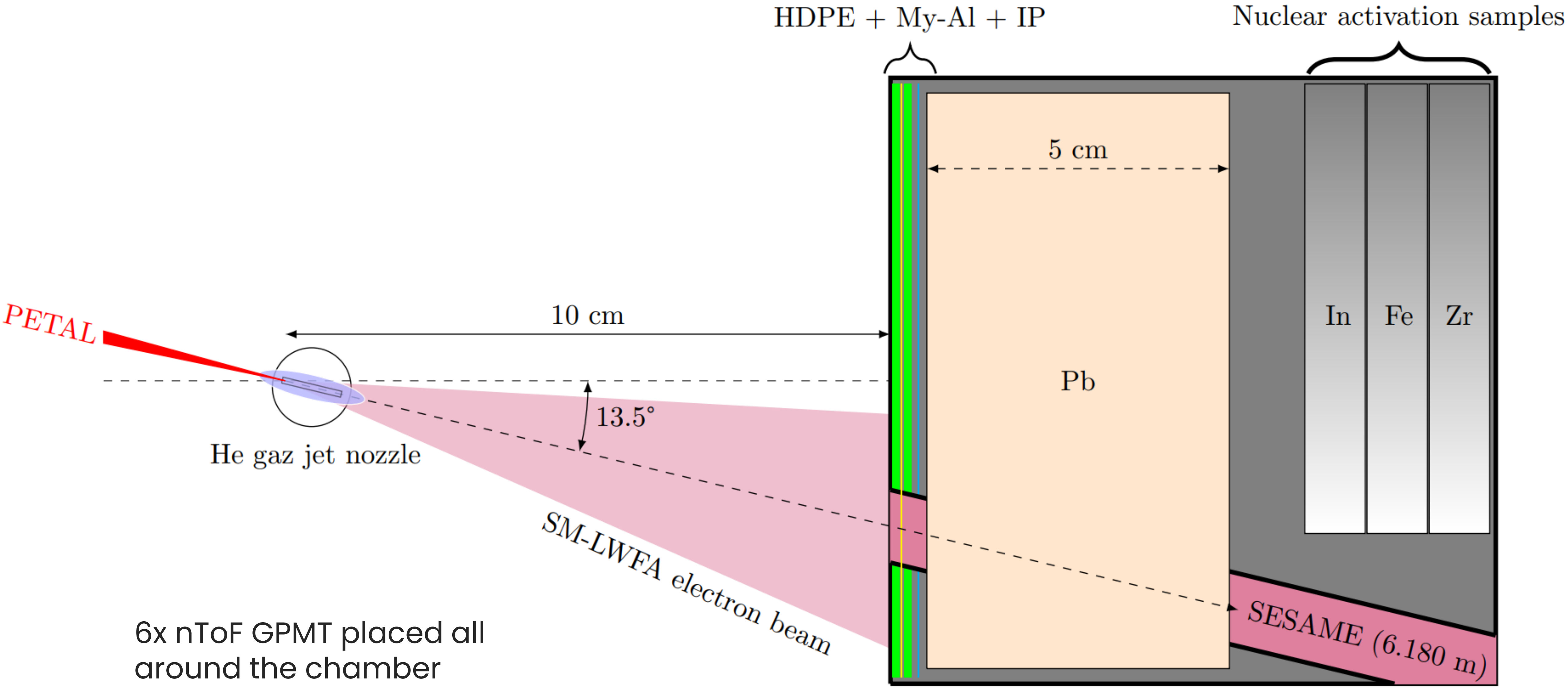
For Zr → photonuclear reactions are predominant



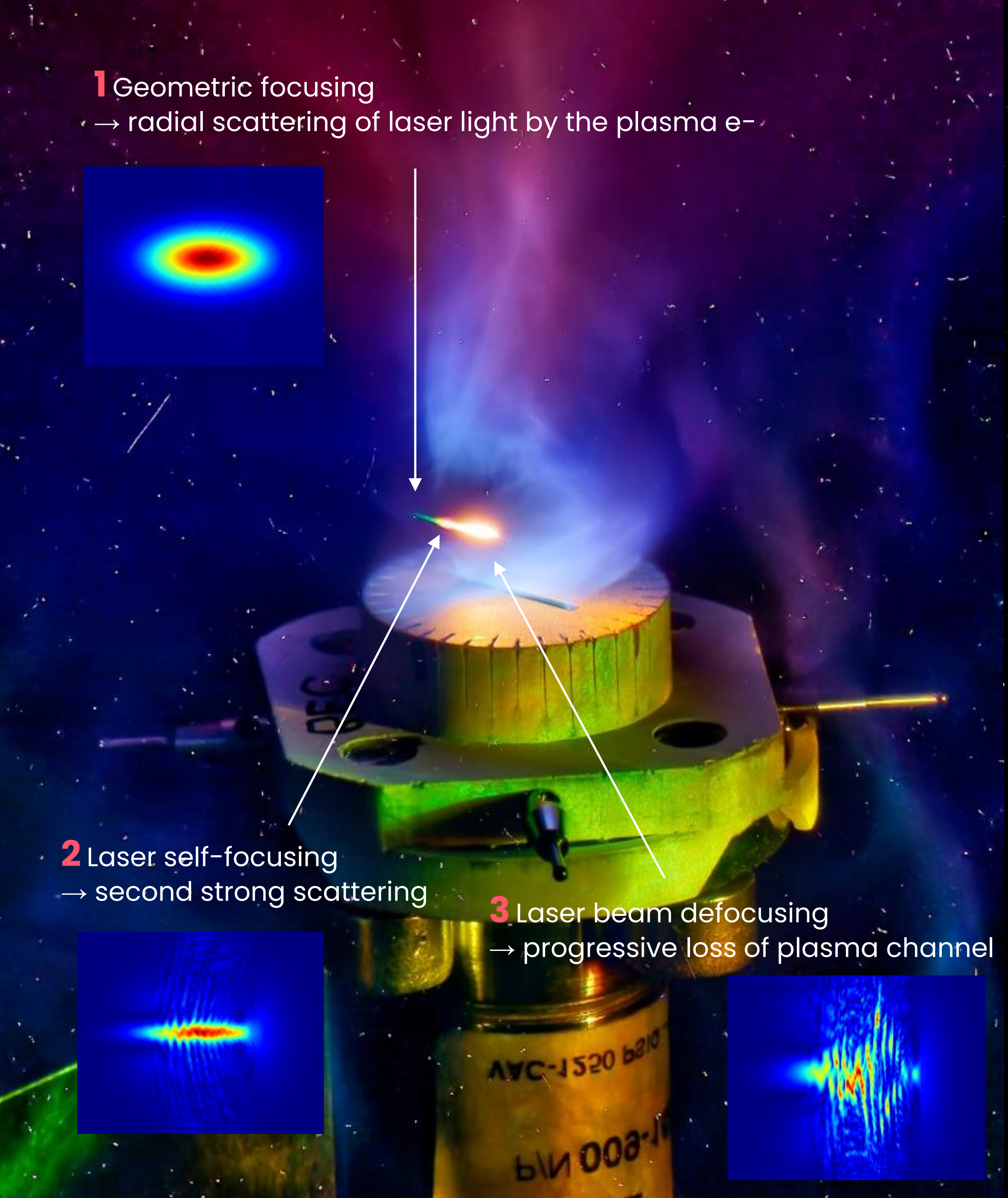
4. (γ,xn) reactions

Pitcher-catcher scheme using SMLWFA electrons as primary source

SMLWFA pitcher-catcher experimental setup



6x nToF GPMT placed all around the chamber


1 Geometric focusing
→ radial scattering of laser light by the plasma e-
2 Laser self-focusing
→ second strong scattering
3 Laser beam defocusing
→ progressive loss of plasma channel

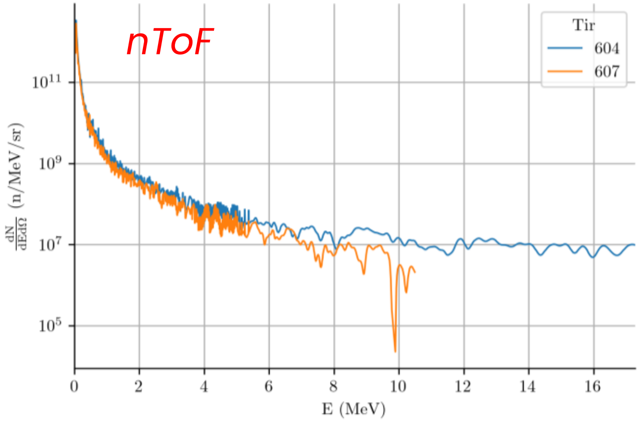
Preliminary results

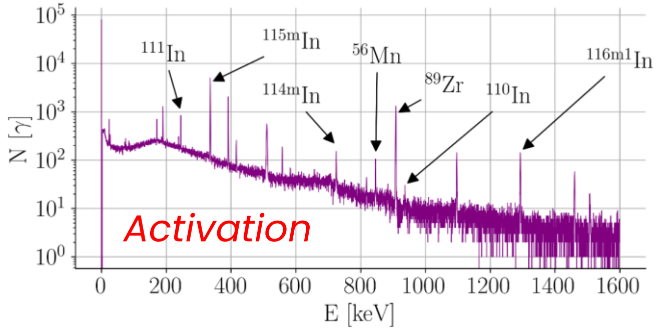
Shot #	Energy	Compression	Intensity	Nozzle	Convertor	N[E>1 MeV]
SR604	≈ 542 J	≈ 0.809 ps	1.20×10^{19} W/cm²	10 mm	5 cm Pb	2.2×10^{10}
SR607	≈ 718 J	≈ 0.682 ps	2.23×10^{19} W/cm²	10 mm	5 cm Pb	1.3×10^{10}

PRELIMINARY WORK

- nToF preliminary results:
  - Again **quasi-isotropic** distribution
  - **≈ 2.2×10^{10} neutrons above 1 MeV** at best
  - **≈ 5×10^{10} total neutrons** using maxwellian extrapolation
    → ≈ 4×10^{9} n/sr

- **Massive Bremsstrahlung** production:
  - ≈ 10^{12-13} γ / sr with T_{hot} ≈ 6 MeV





Bremsstrahlung spectrometer

5. Conclusion

Conclusion

- Implementation of the first non fusion-based neutron source on LMJ-PETAL, within **Academic Access**

- **TNSA proton** energies up to **53 MeV**
- Neutron yields = **$8{,}7\times10^9$/sr** using **(p,xn)** reactions in a pitcher-catcher scheme
- Demonstration of the impact of the double-layer convertor
- Comprehensive agreement between nToF / activation data with Geant4 simulations

- **SMLWA electrons** up to **300 MeV** and **1,5 µC** total charge
- Neutron yields ≈ **4×10^9/sr** using **(γ,xn)** reactions in a pitcher-catcher scheme

- Potential applications for nuclear photonics are under evaluations, including new applications to probe HED plasmas produced by LMJ (e.g. Betatron, Inverse Compton Scattering for phase-contrast imaging or dual X-ray/neutron imaging)

- Academic access – call for proposals each 3 years
- You can apply and propose amazing nuclear photonics experiments!

PETAL acknowledgments:

The PETAL project has been performed by the CEA ("maître d'oeuvre") under the financial auspices of the New Aquitaine Region in France ("maître d'ouvrage," project owner), the French Government, and the European Union. This work is supported by the Region Nouvelle-Aquitaine through the PETAL-Upgrade project (contracts #13532820, #22577420 and #42979220).

Thanks for your attention. Questions?

Thank to all collaborators ☺.

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