High energy ion acceleration and neutron production using relativistic transparency in solids

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Introduction And Motivation

The generation of neutrons by the interaction of accelerator driven ion beams has gained substantial interests over the last decades. Especially in the field of nuclear and material science [1], biology [2] or even in medicine [3] low energetic and thermal neutrons are used to alter material properties or to treat cancer diseases, respectively. On the other hand, high energetic neutrons as diagnostic for exotic material states, like Warm Dense Matter (WDM) [4] as well as a complimentary diagnostic for High Energy Density Matter (HEDM) [5] open very promising insights to these plasma conditions. With scope on neutron production, laser driven ions offers **highest brilliance**, **very short pulse lengths** (ps-ns) and **very intense beams** (up to 10^{13} particles).

The investigation of alternative laser driven acceleration schemes has opened new possibilities to the topic of neutron generation. One promising candidate to effectively accelerate light to heavier ions is the **laser Break-Out Afterburner** (BOA) mechanism [6]. It is able to efficiently accelerate ions from the whole target volume by the interaction in the relativistic transparency regime.

Laser Break-out Afterburner – BOA [6]

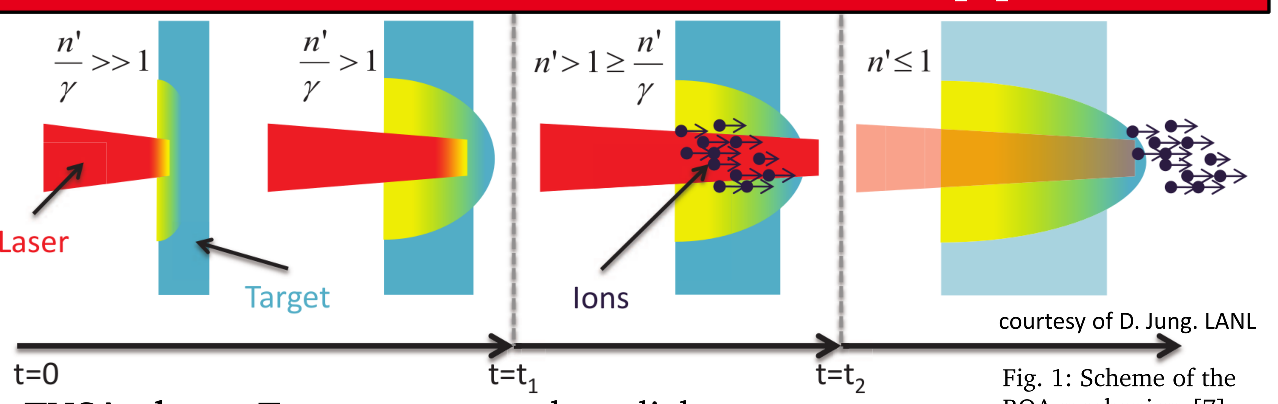


Fig. 1: Scheme of the BOA mechanism [7]

- **TNSA phase:** Target opaque to laser light
  - "Heating" => initial density decreases
  - Higher inertia of rel. electrons => critical density increases
- **Intermediate phase:** Laser propagates "behind" classical critical density
  - Volume-Heating
- **BOA phase:** Target relativistic transparent
  - Laser interacts with electrons in under-dense plasma
  - Buneman-Instability: Energy transfer from electrons to ions
  - But: Electrons still gain energy in laser field
  - Indirect coupling between laser-energy and ion-momentum

Neutron Generation

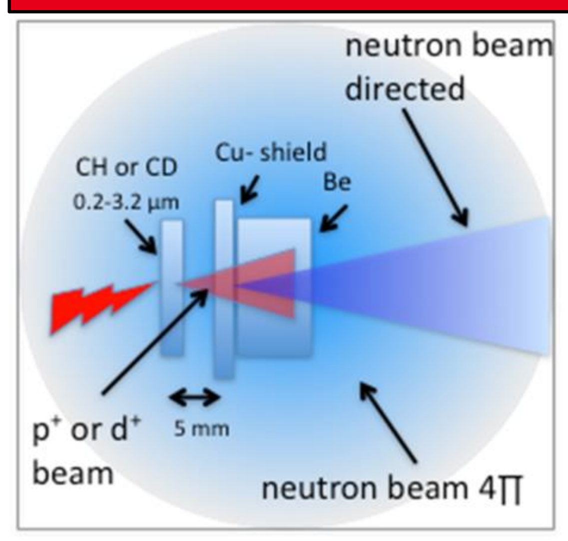


Fig. 2: Sketch of neutron beam generation; adapted from [10]

- Laser driven projectiles (e.g. protons or deuterons) interact with **thick** catcher target (e.g. Beryllium converter)
  - Inelastic nuclear reactions
- **Prompt** emission of neutrons
  - direct channels (e.g. **break-up** [8])
  - **pre-equilibrium** emission [9]
  - **equilibrium** emission
- **Delayed generation** of neutrons
  - after "underlying" radioactive decay
- Generation of a **high energetic** (up to 100 MeV) and **forward directed** neutron beam
- Accompanied by **low energetic** neutrons **homogenous** distributed over the whole solid angle

Addressed Applications

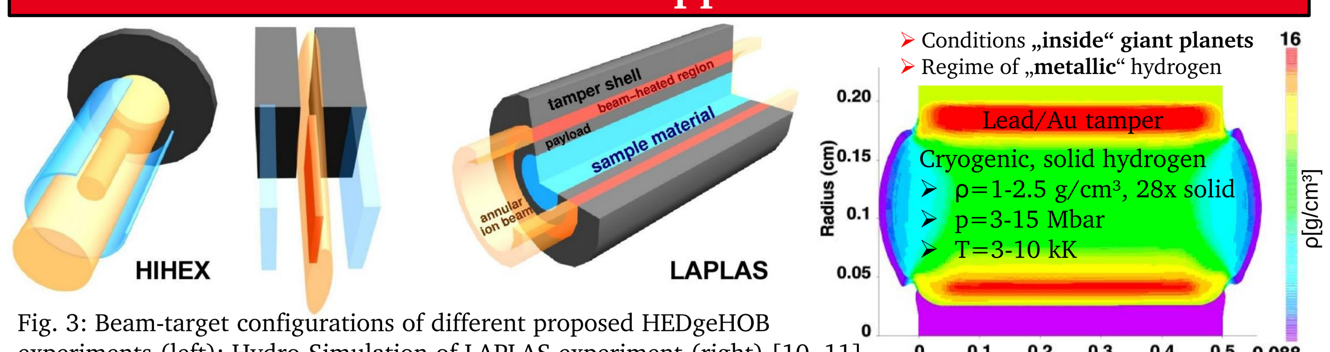


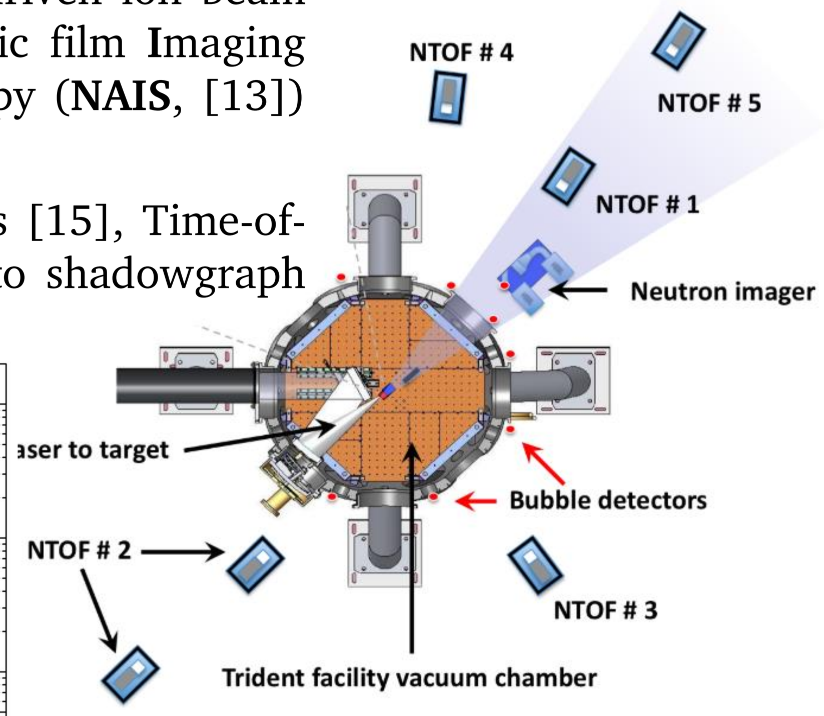
Fig. 3: Beam-target configurations of different proposed HEDgeHOB experiments (left); Hydro-Simulation of LAPLAS experiment (right) [10, 11]

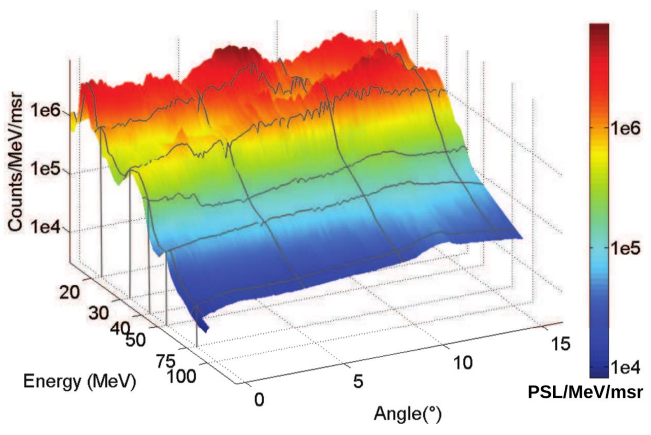
- High Energy Density Matter (HEDM) and "fast" neutron radiography
  - Complementary to x-ray radiography/scattering
- Diagnostic for **LA**boratory **PLA**netary **S**cience (**LAPLAS**) and **H**eavy **I**on **H**eating and **EX**pansion (**HIHEX**) campaigns at FAIR (HEDgeHOB, [11])
  - Low-entropy cylindrical compression and **WDM** (**W**arm **D**ense **M**atter) created by dynamical confinement
  - EOS measurement by quasi-isochoric heating and isentropic expansion

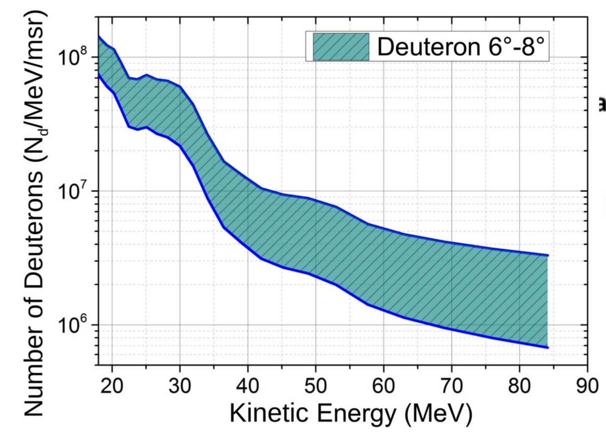
Experimental Methods and Results - published in [17] and [18]

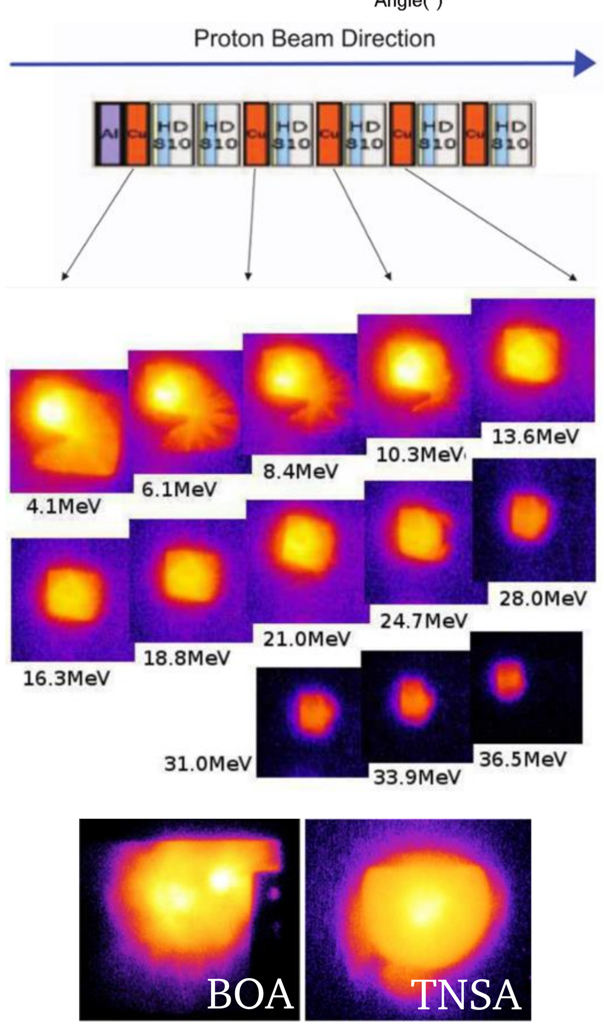
We have carried out **three** experimental campaigns at the TRIDENT laser-facility at LANL to characterize and optimize the neutron generation with scope on **neutron energy**, **yield** and angular **directionality**.

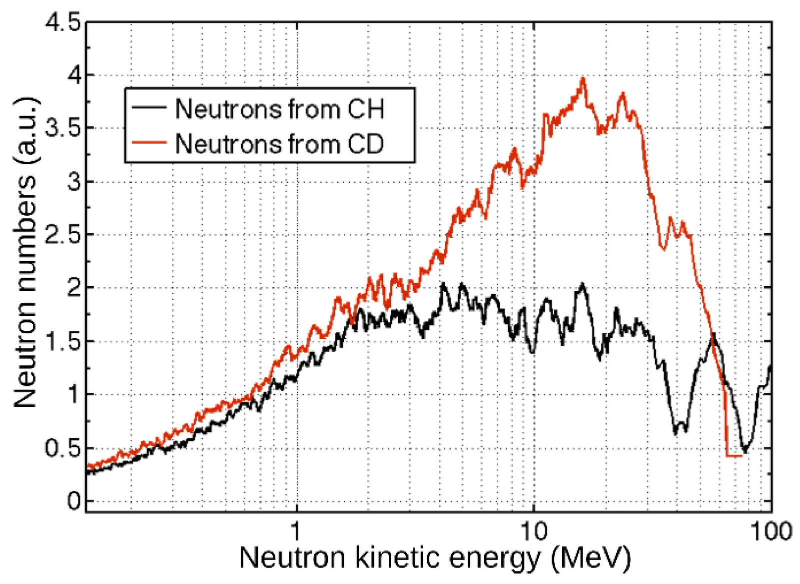
- The optimization and characterization of the primary laser driven ion beam plays an important role and was conducted by **R**adiochromic film **I**maging **S**pectroscopy (**RIS**, [12]), **N**uclear based **I**maging **S**pectroscopy (**NAIS**, [13]) as well as an **i**on **W**ide **A**ngle **SP**ectroscopy (iWASP, [14]).
- For neutron beam characterization we used **Bubble** detectors [15], Time-of-Flight (**nToF**) detectors [16] as well as a **neutron imager** to shadowgraph different objects.

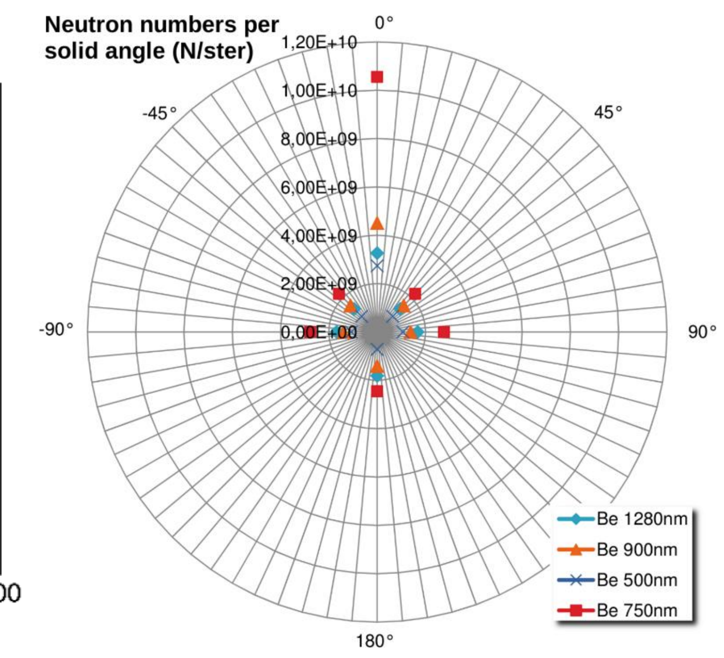








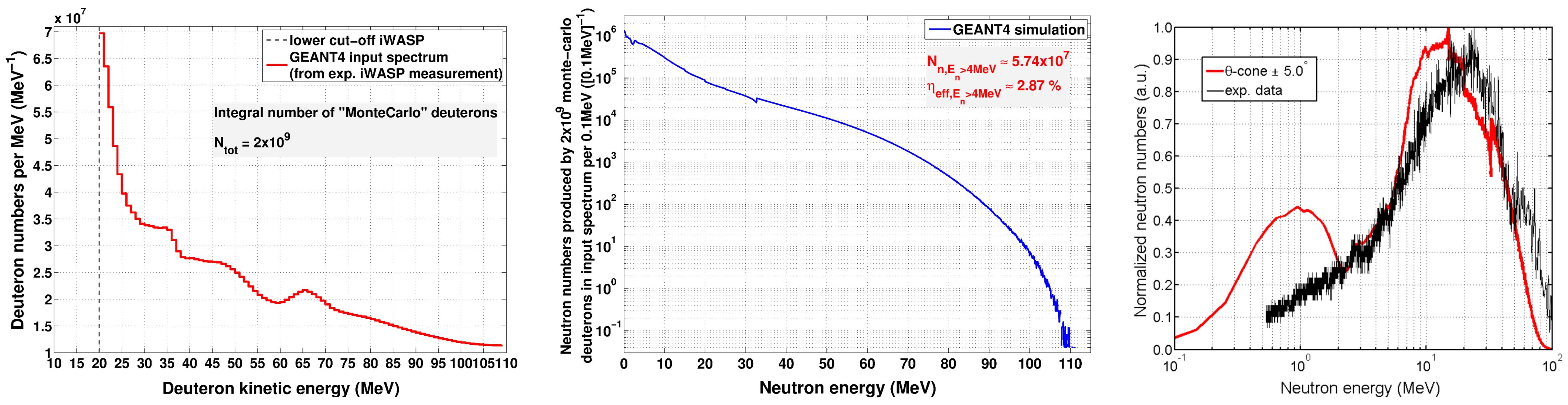


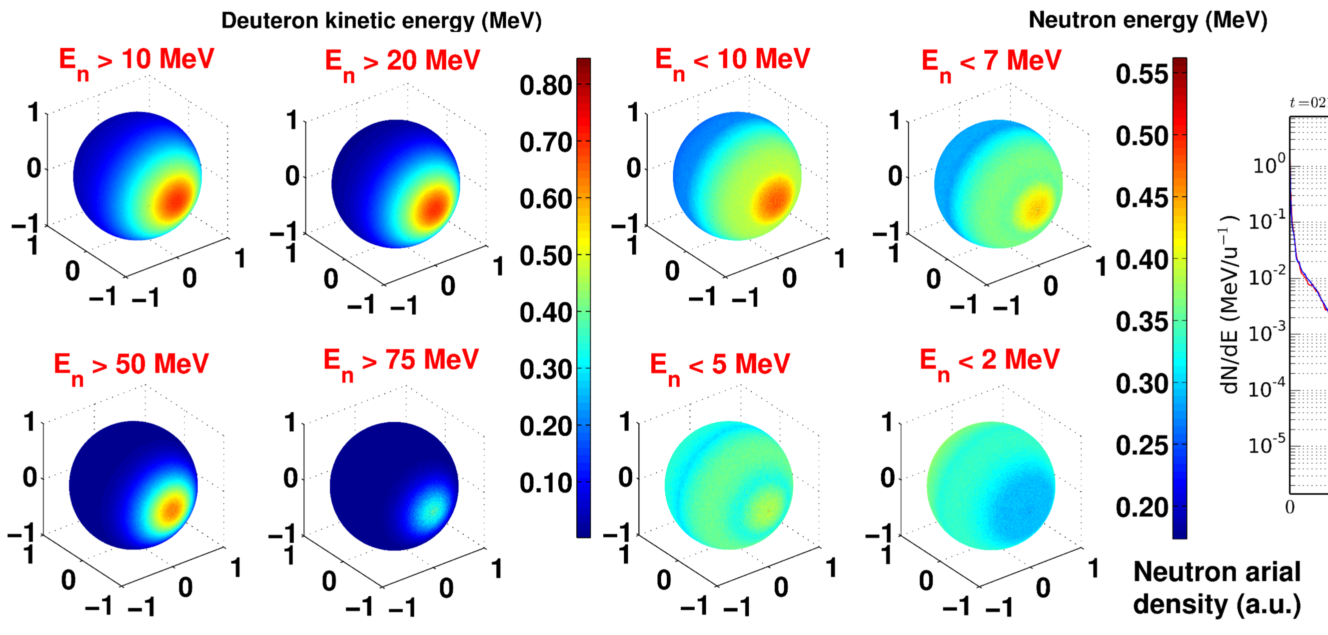


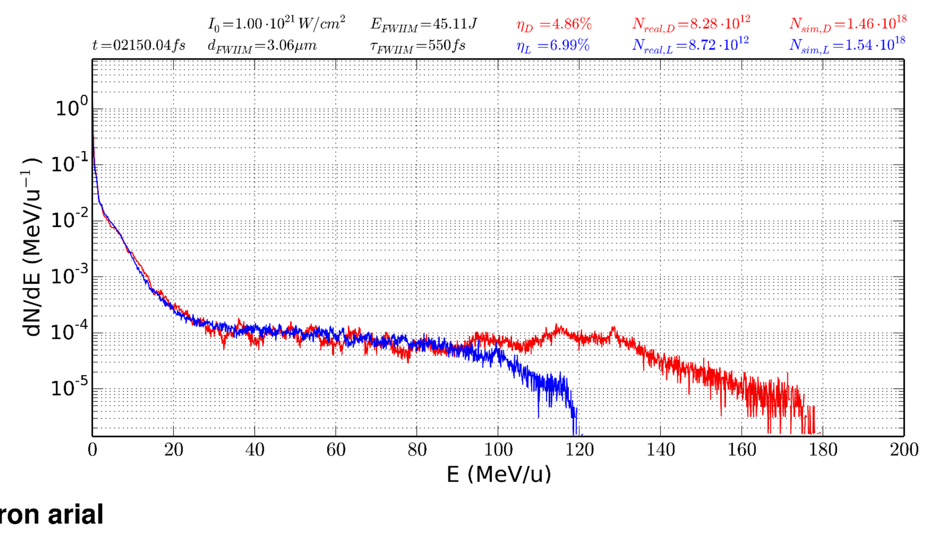
- Protons **>126 MeV** and Deuterons **>110 MeV** accelerated via BOA
- Characteristic "lobes" in spatial beam profile observed for BOA scheme
- Up to **1.19 ·10¹⁰ N/ster** in forward direction measured
- Forward emission with energies up to **110 MeV** (pre-equilibrium)
- **"Peak" at 30 MeV** for "small" forward directed cone (break up)
- **Homogenous 4π component** at lower energy peaking around 3-5 MeV (equilibrium) with **~2 ·10⁹ N/ster**

Monte Carlo And Particle-in-Cell Simulations – Roadmap

To model the experimental results, simulations with the Monte Carlo framework **GEANT4** [19] where carried out. To precisely model the low energetic hadronic interactions for energies up to 200 MeV we have patched GEANT4 with the **particle HighPrecision** package [20]. It allows to incorporate purely data base driven nuclear models for inelastic interactions of light projectiles from the **TENDL** data base [21].







Future exploration of this **compact**, **bright** and **temporally short** laser driven neutron source

- Scheduled experiment at PHELIX laser to **demonstrate** its capabilities for the HEDgeHOB experiments.
- Proposal: TRIDENT laser to generate **(d,d) and (T,d) fusion neutrons** by using deuterated Lithium laser/catcher targets and to characterize the **first time a laser driven Triton beam**.

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