# Ion acceleration and neutron production based on relativistic transparency of solids

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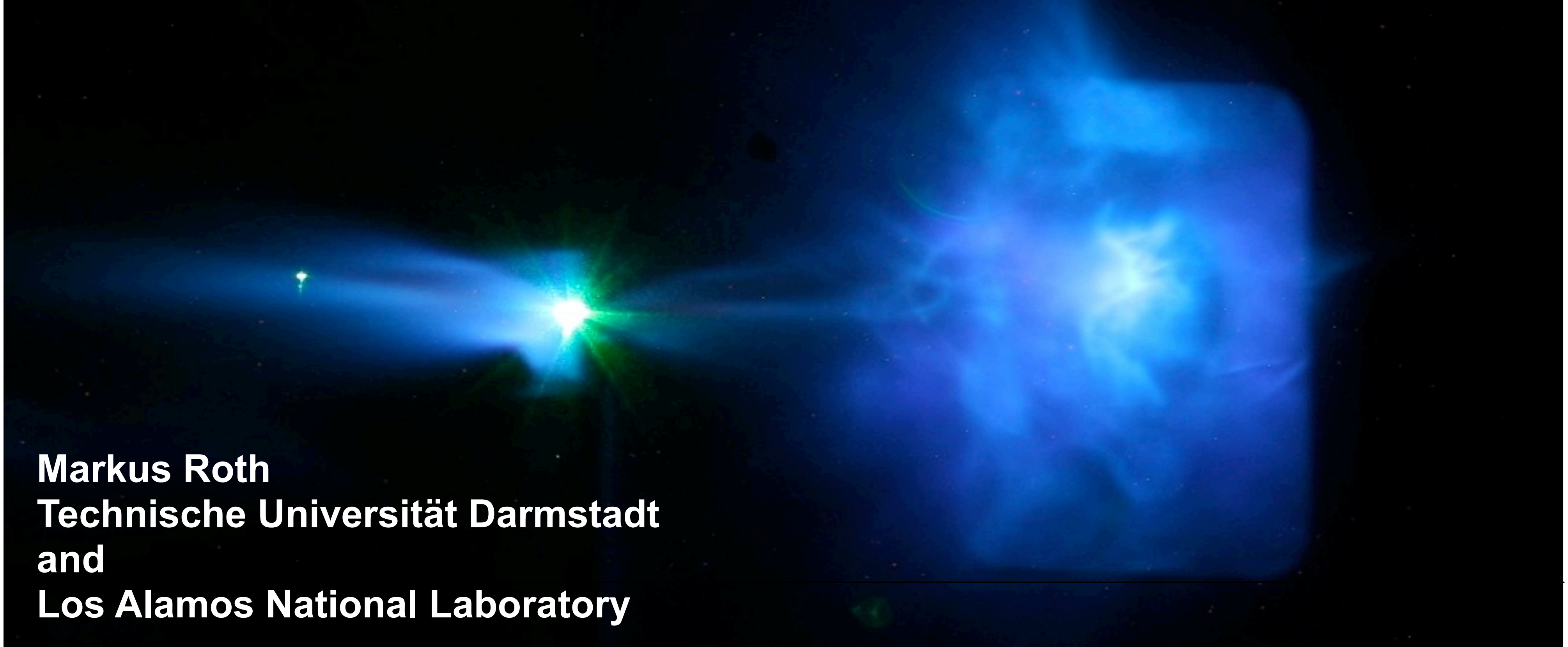
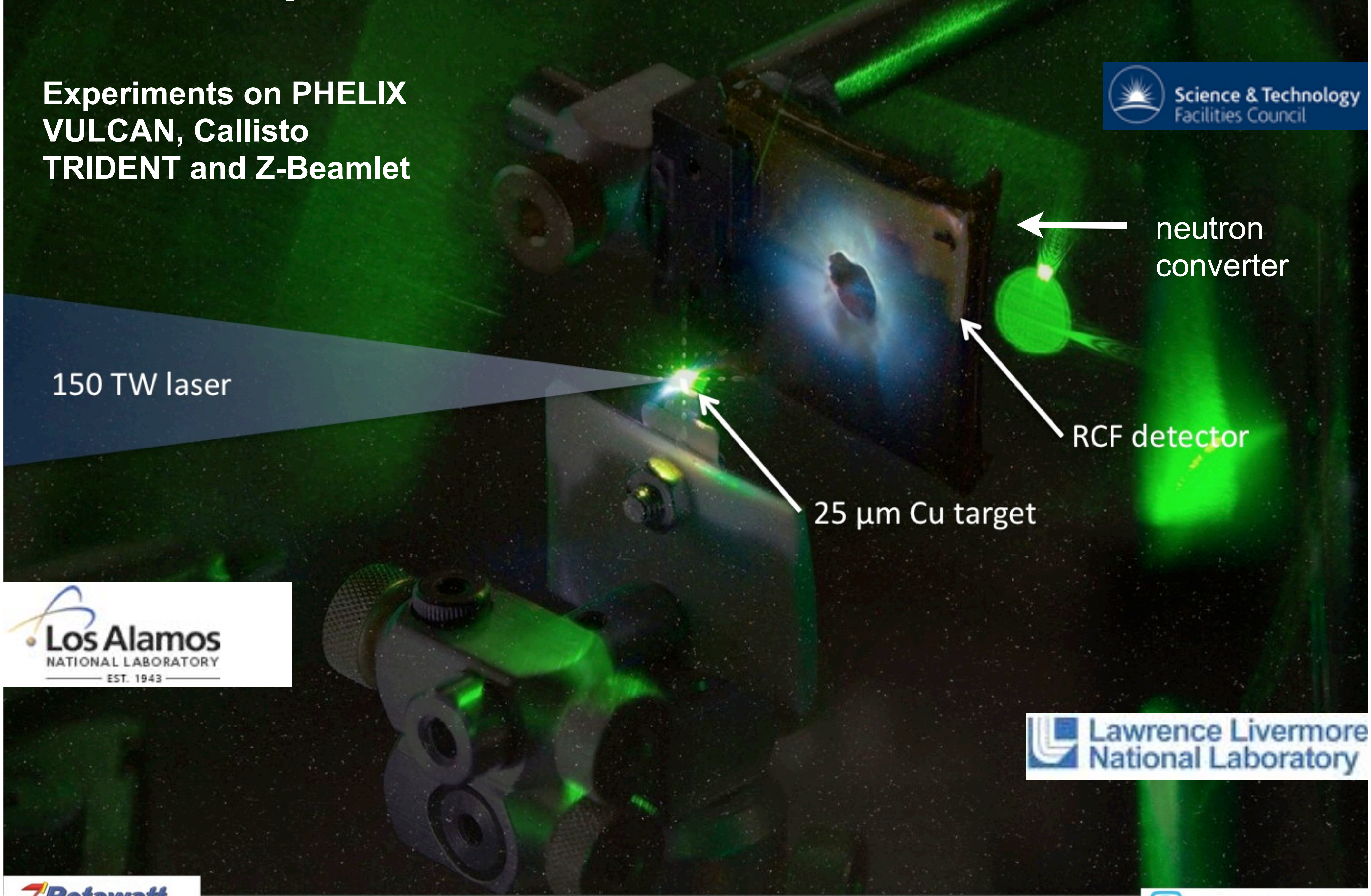
D. Jung, K. Falk, N. Guler, O. Deppert, M. Devlin, A. Favalli, J. Fernandez, D. Gautier, M. Geissel, R. Haight, C. E. Hamilton, B. M. Hegelich, R. P. Johnson, F. Merrill, G. Schaumann, K. Schoenberg, M. Schollmeier, T. Shimada, T. Taddeucci, J. L. Tybo, F. Wagner, S. A. Wender, C. H. Wilde and G. A. Wurden



**Markus Roth**
**Technische Universität Darmstadt**
**and**
**Los Alamos National Laboratory**

# Secondary radiation: Neutrons

**Experiments on PHELIX**
**VULCAN, Callisto**
**TRIDENT and Z-Beamlet**

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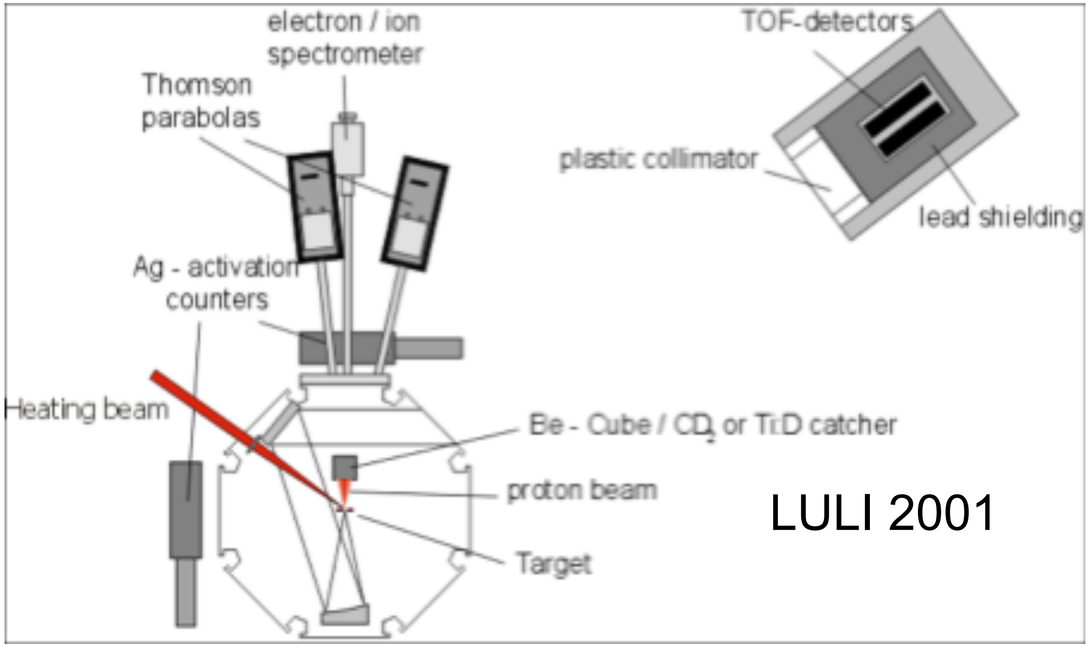
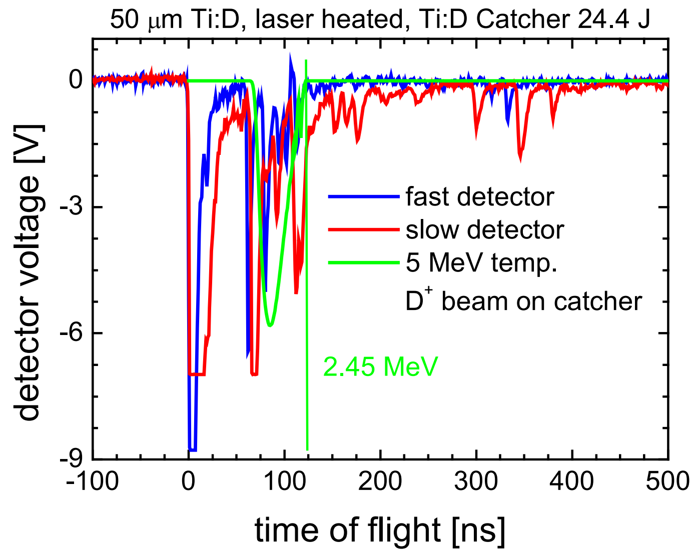
Z Petawatt

Sandia National Laboratories

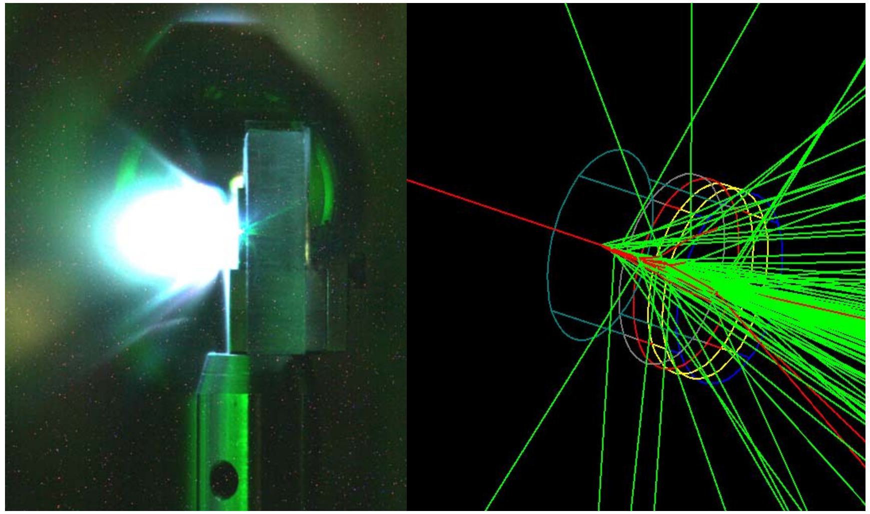
# Neutron Source



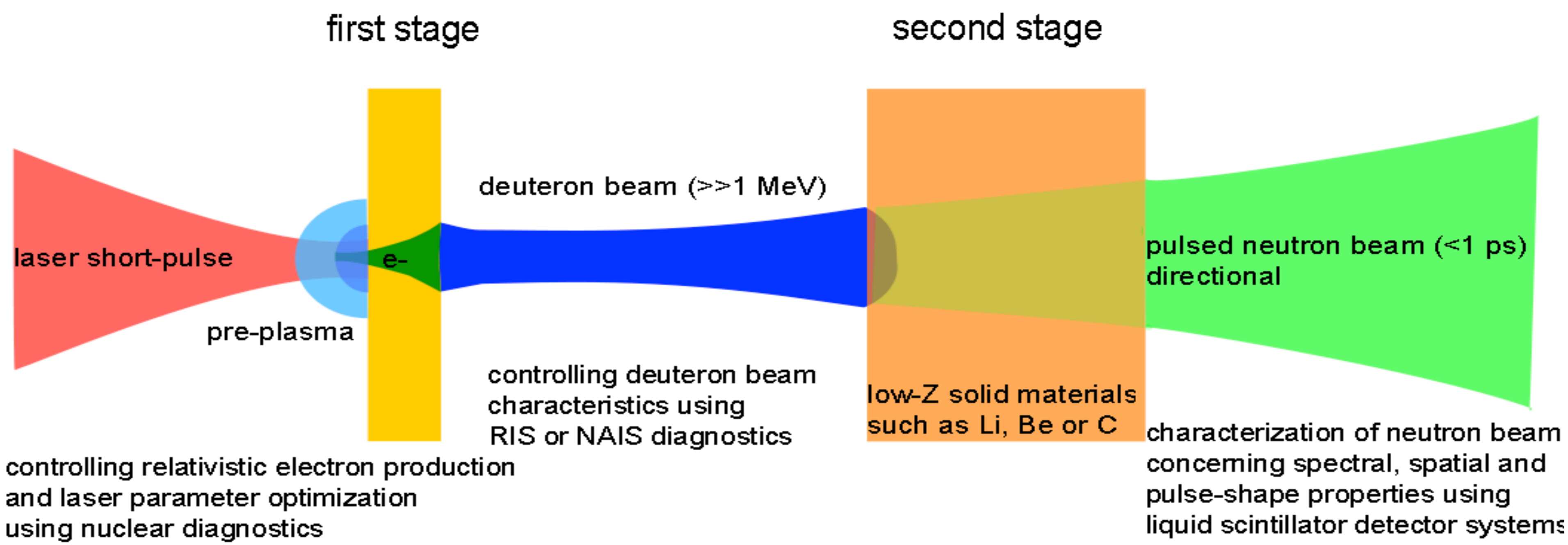




Pulsed neutron sources:

$4 \cdot 10^8$ /puls beamed d-d fusion



# Idea of laser driven neutron source



# Nuclear activation imaging spectroscopy (NAIS)

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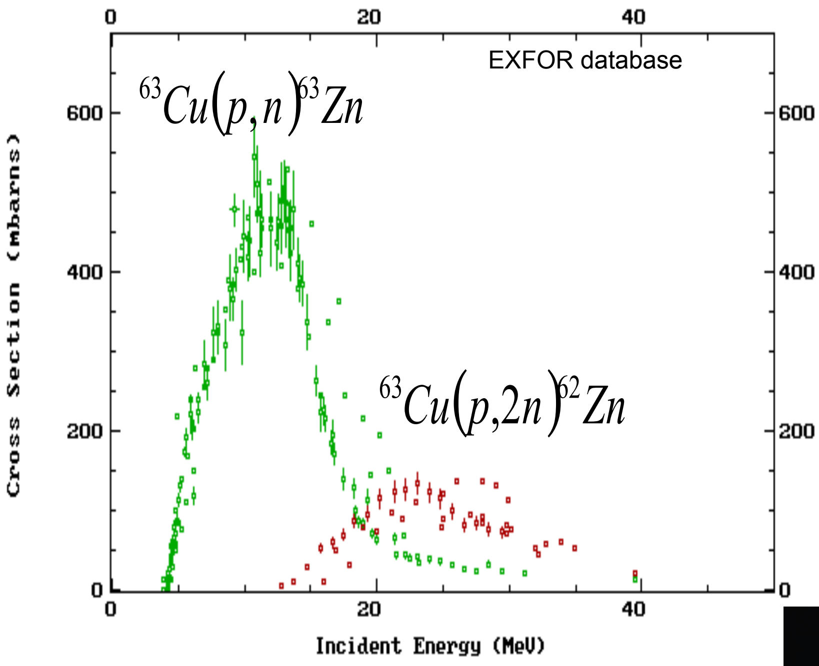
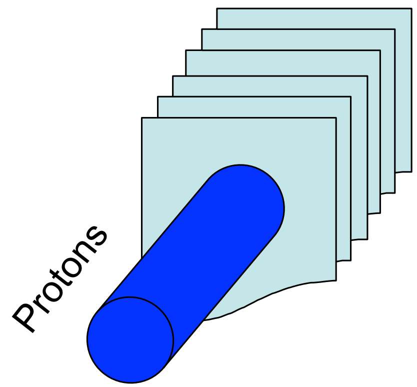
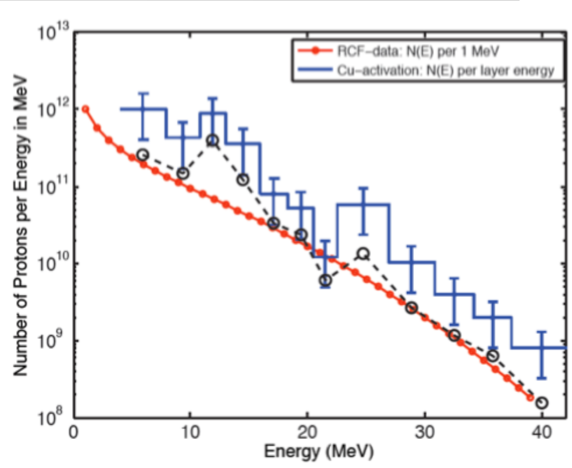
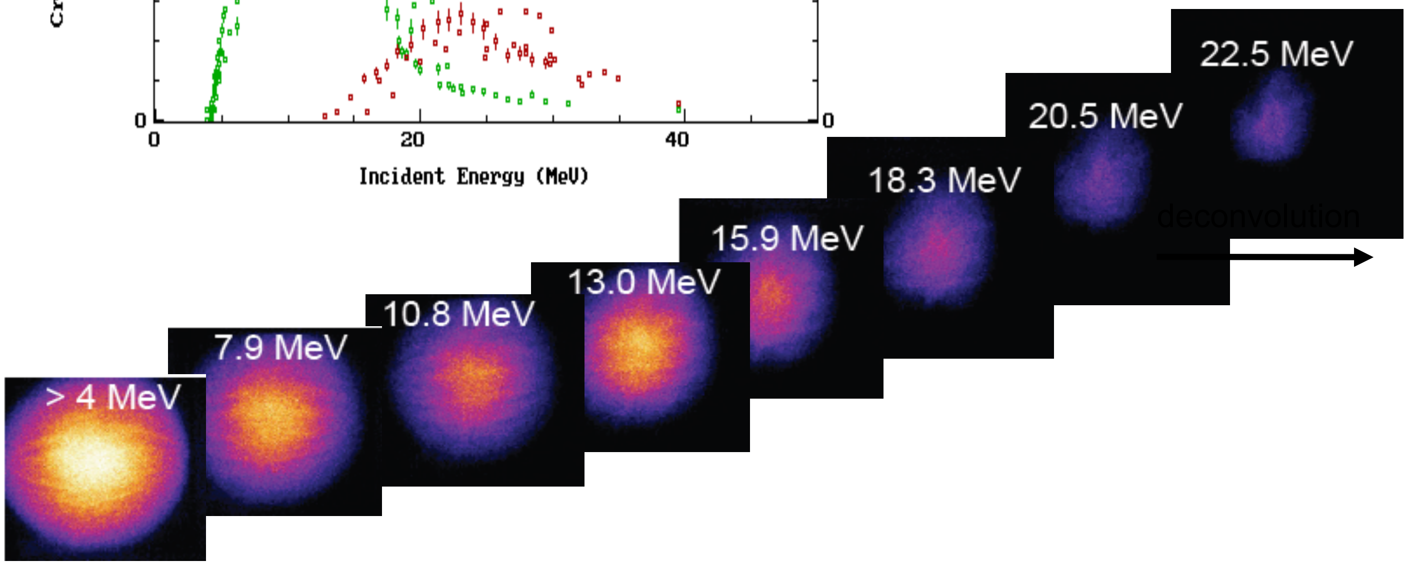
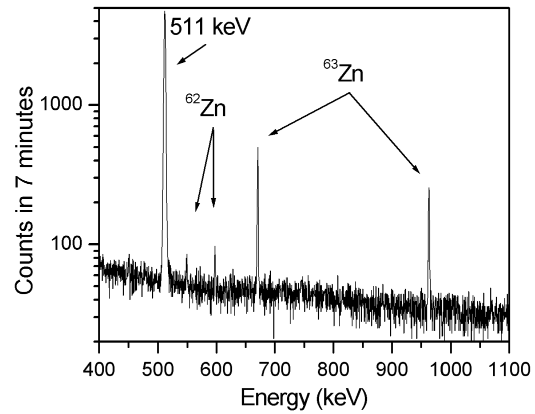



$$Y = N_T \int_{S_n}^{\infty} \sigma(E_p) N_p(E_p) dE_p$$






- Neutrons

# Neutrons are a unique tool to probe and alter material properties

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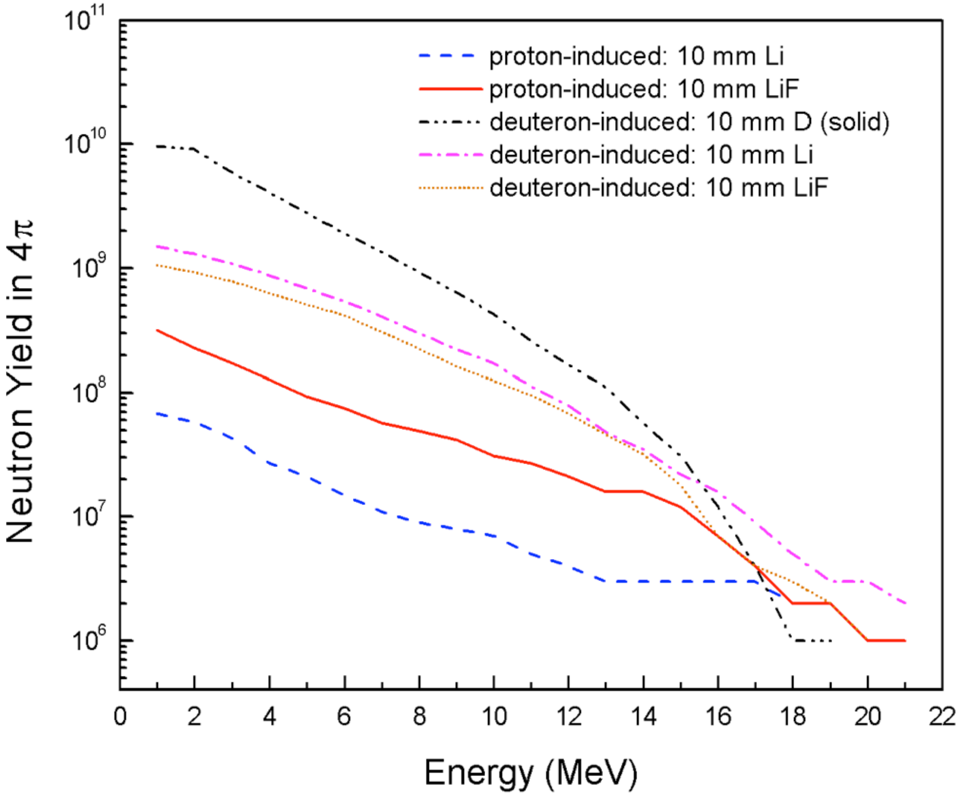
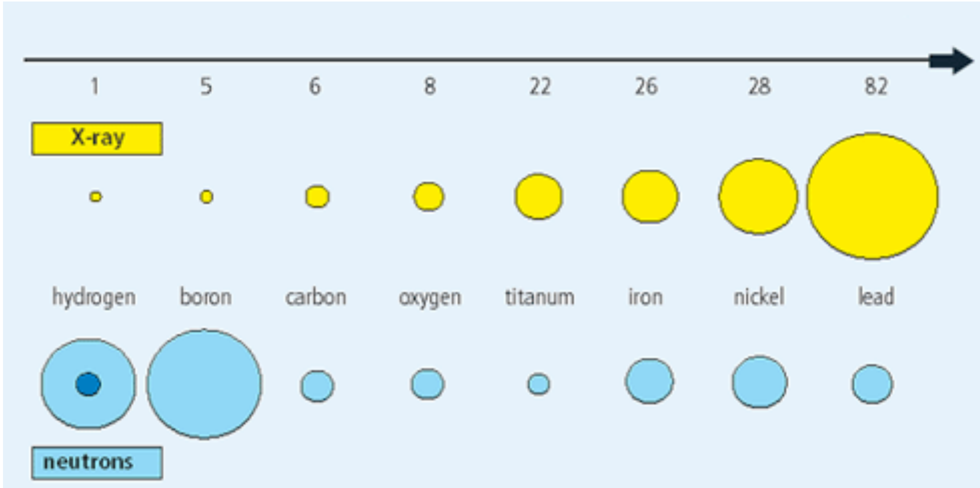
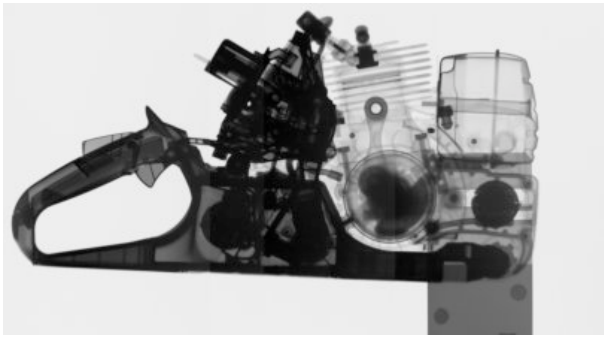
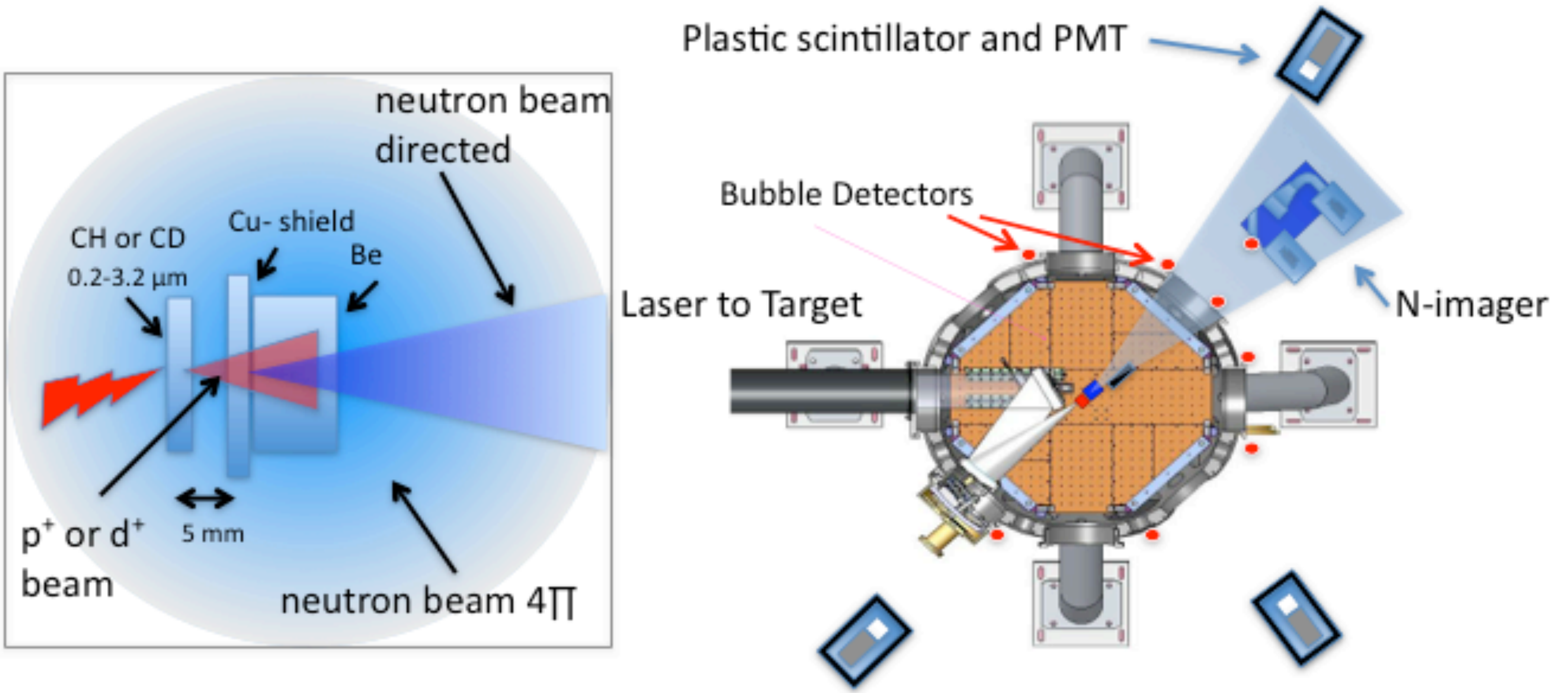



**New Diagnostics: fast neutron radiography of transient phenomena**



# Experimental setup



# Proton acceleration with lasers : Static electric fields

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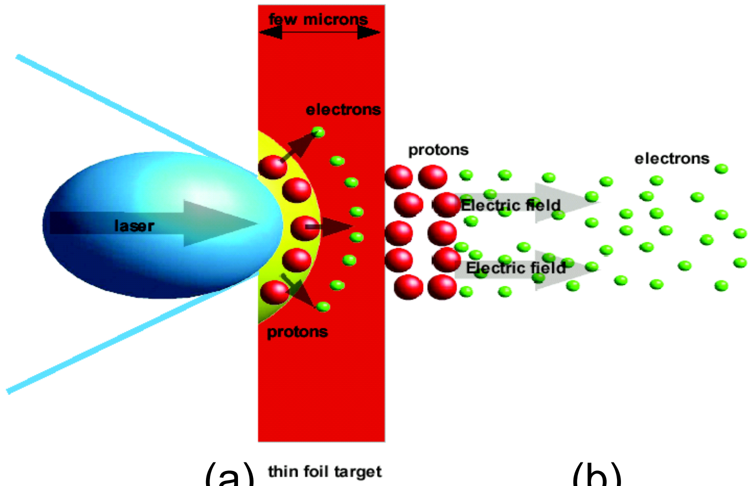


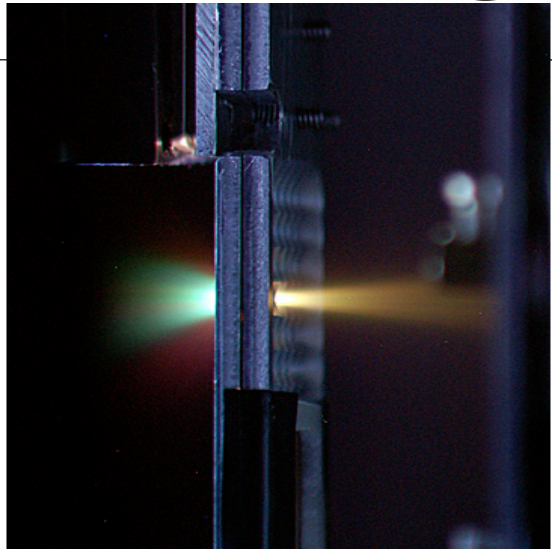

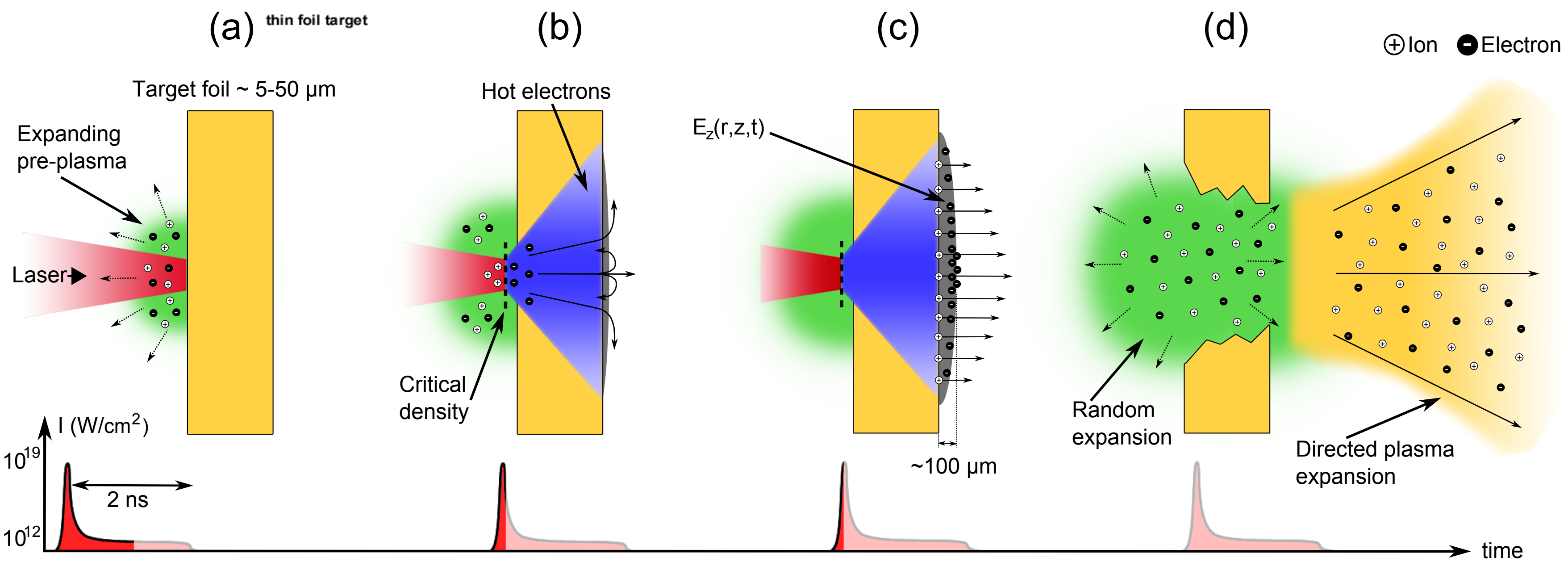


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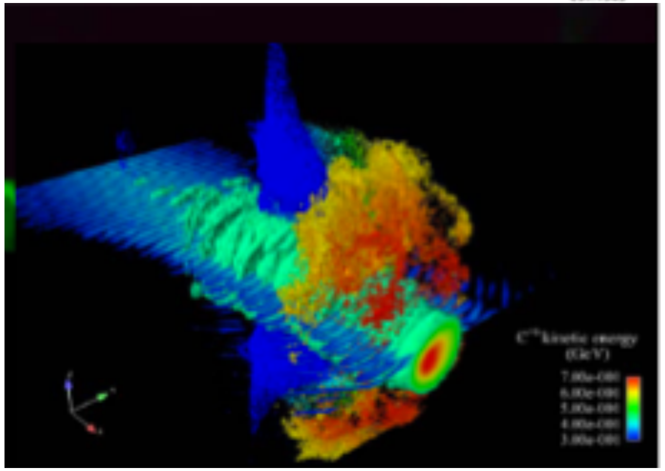
# TNSA vs. BOA

Accessible with moderate contrast lasers
Micrometer sized targets
Spectrum limited to 70 MeV
Surface acceleration

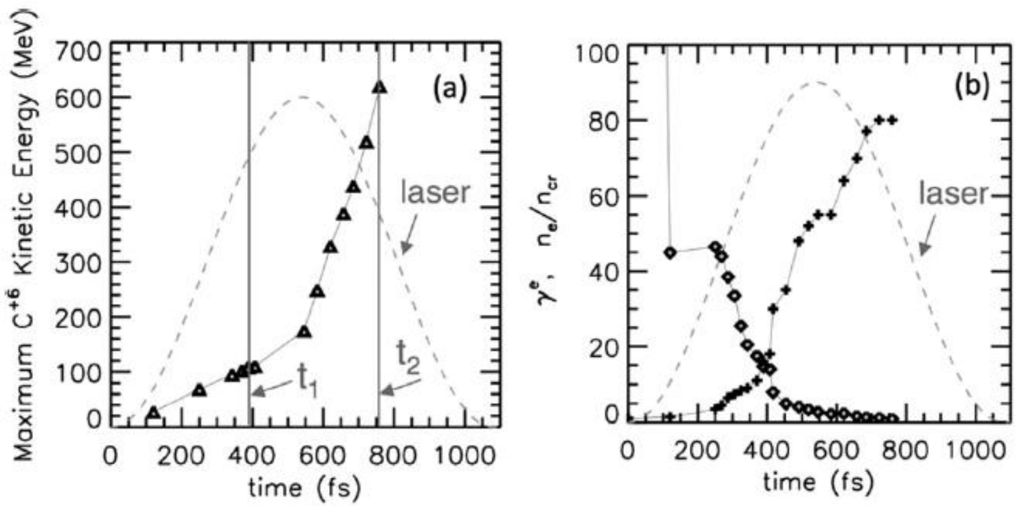
High contrast lasers needed
Sub-Micrometer sized targets
Ion energies exceeding 120 MeV
Volume acceleration
Heavy ions (deuterons) at same speed as protons
Lower EMP and less debris

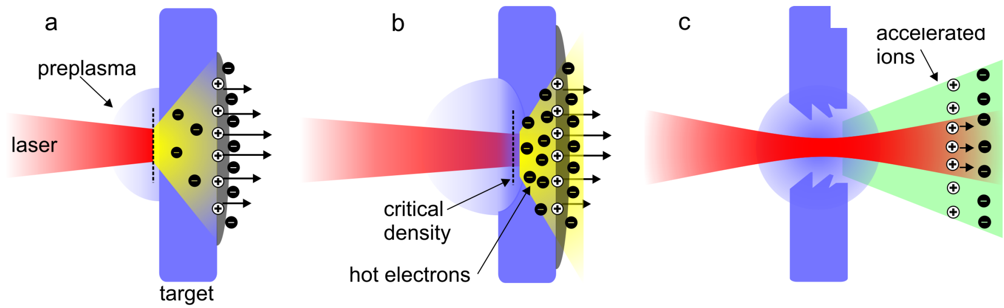
# Break out Afterburner (BOA)

L.Yin et al., LPB, 24, 291 (2006); POP, 14, 056706 (2007); POP, 18, 063103 (2011)



**2D-VPIC: 58nm DLC target & Trident laser with $5x10^{20}W/cm^2$**




**a)** Target Normal Sheath Acceleration (TNSA) phase
**b)** Intermediate phase
**c)** Laser Breakout Afterburner (BOA) phase

**VPIC: 100nm CH2 target & Trident laser with $2x10^{20}W/cm^2$**

| Max. energy | proton | carbon |
|---|---|---|
| Ideal laser | 132 MeV | 450 MeV |
| Real laser | 121 MeV | 447 MeV |

# Targets for BOA

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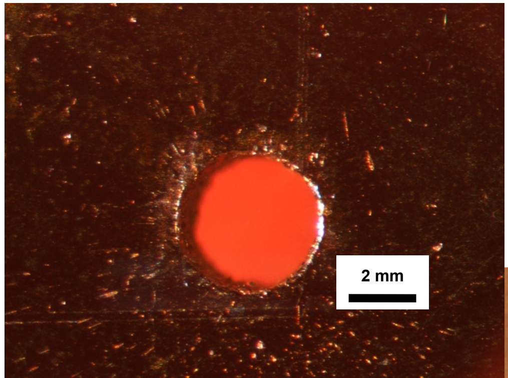
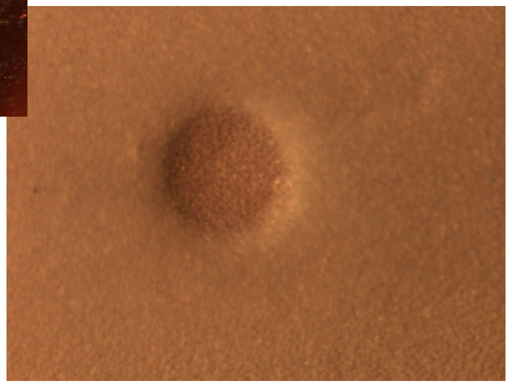
## $CH_2$ Targets

- Poly(4-methyl-1-pentene), trade name TPX (Mitsui, Inc.)
- Soluble in cyclohexane
- Full density films (800 mg/mL) dip- or spin-cast (<200 nm – 1 um)
- Low density foams (5 – 50 mg/mL) produced by freeze-dip-casting, freeze drying (~50 um)

Full-density film

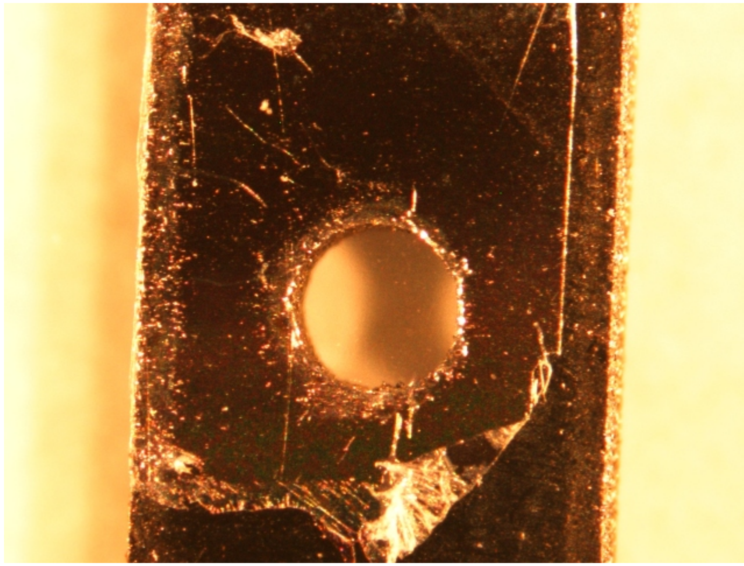



Low-density film



## $CD_2$ Targets

- Deuteropolyethylene(85% D content)
- Soluble in hot toluene/ xylenes
- Full density films (940 mg/mL) drop-cast onto warm Si wafers (300 nm- 1um)



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# Volume instead of surface acceleration

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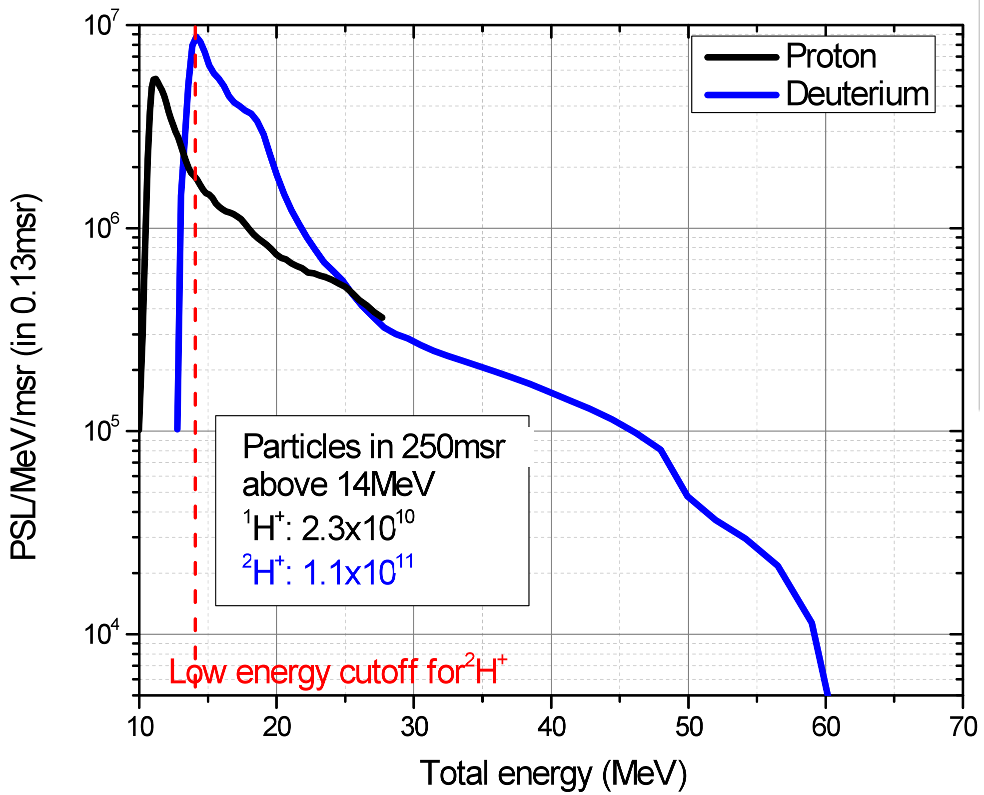


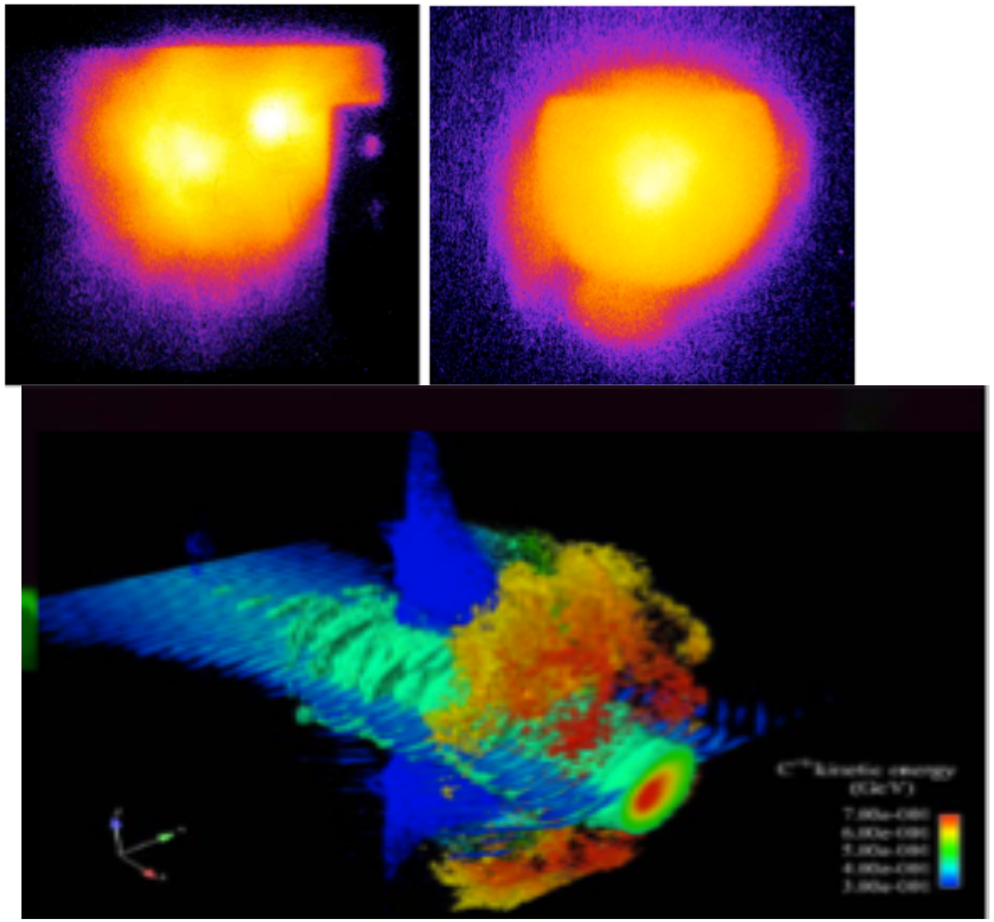

Using CD targets: No cleaning needed
one order of magnitude more deuterons than protons when using BOA



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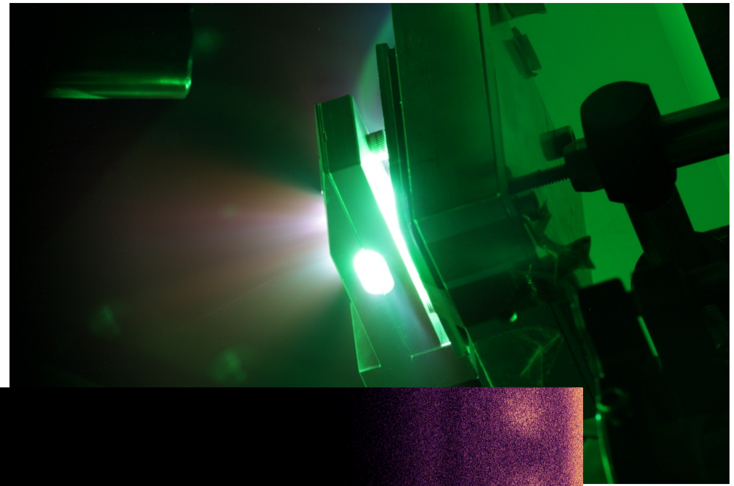
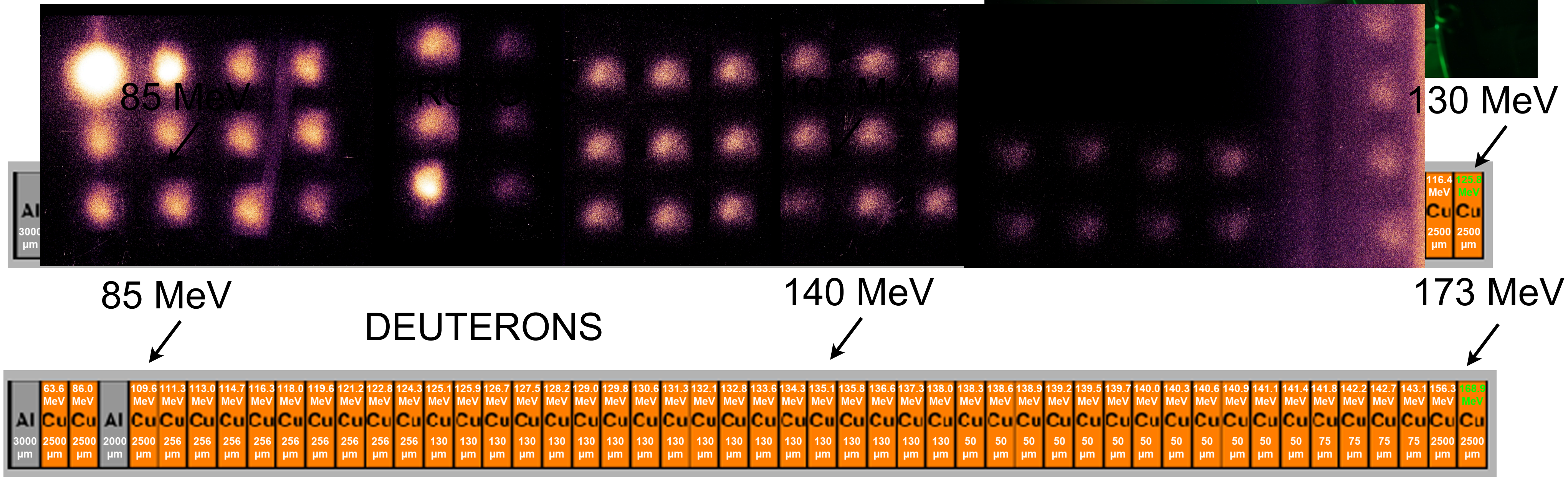
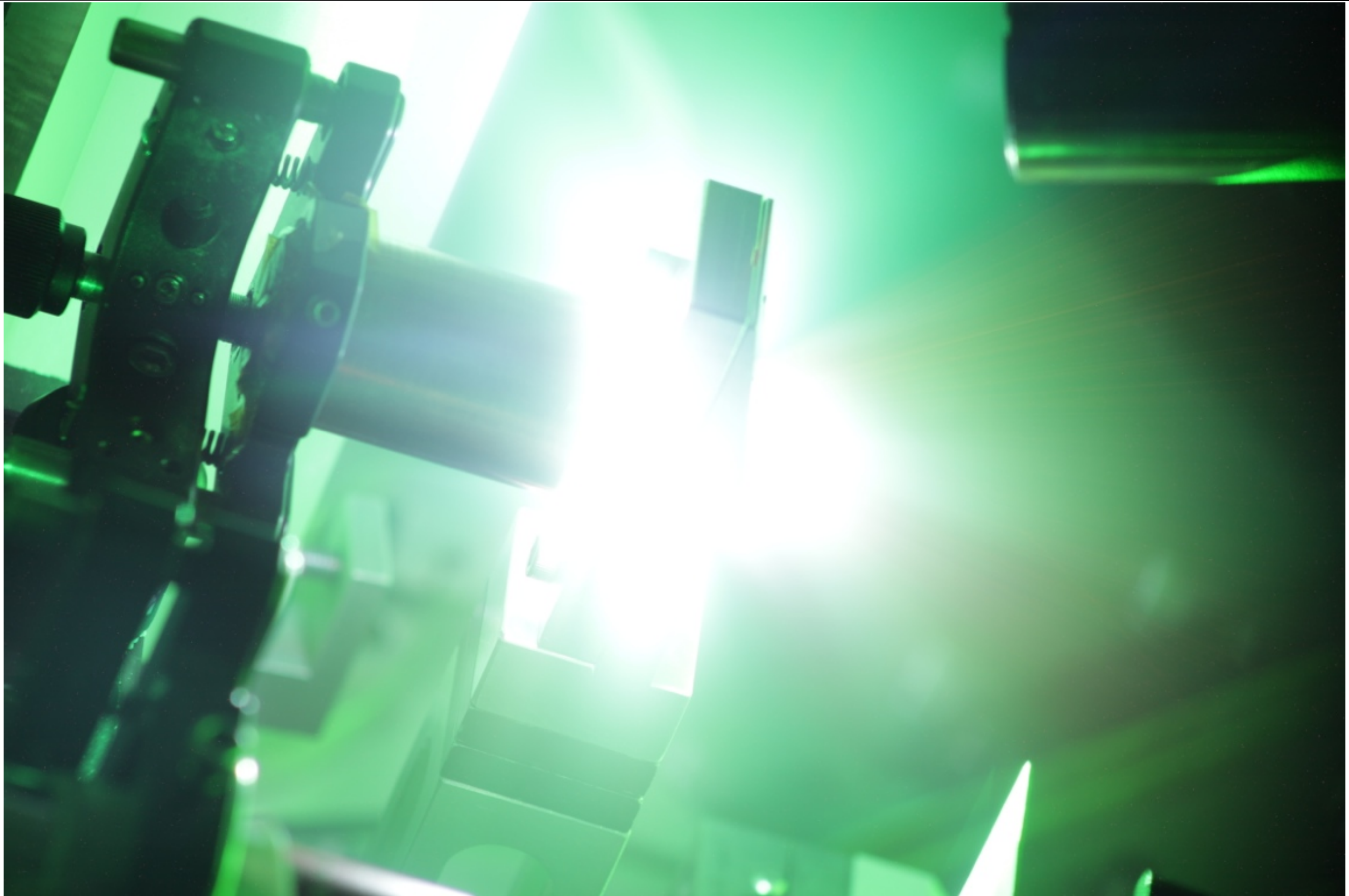
# BOA does really work

Ultimate test of ion energies using NAIS





# Be-Converter in Copper shielding



# Up to 25 cm of lead shielding

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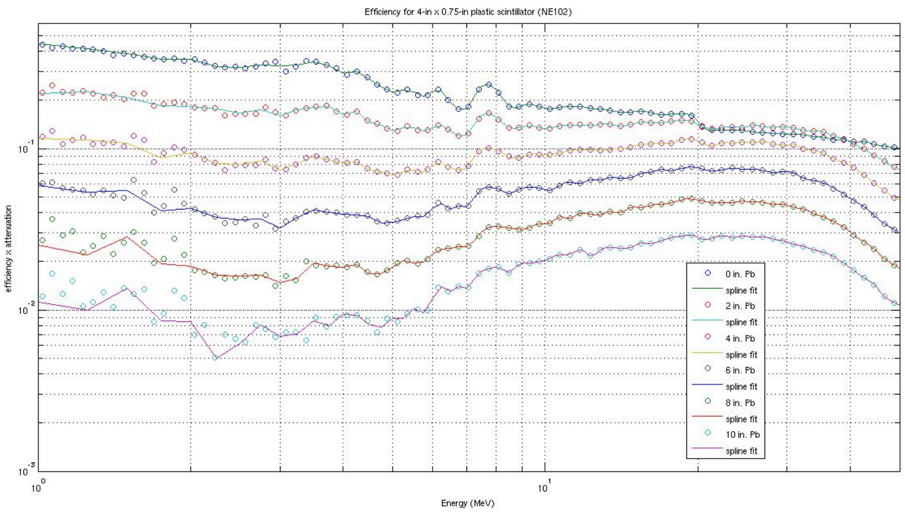


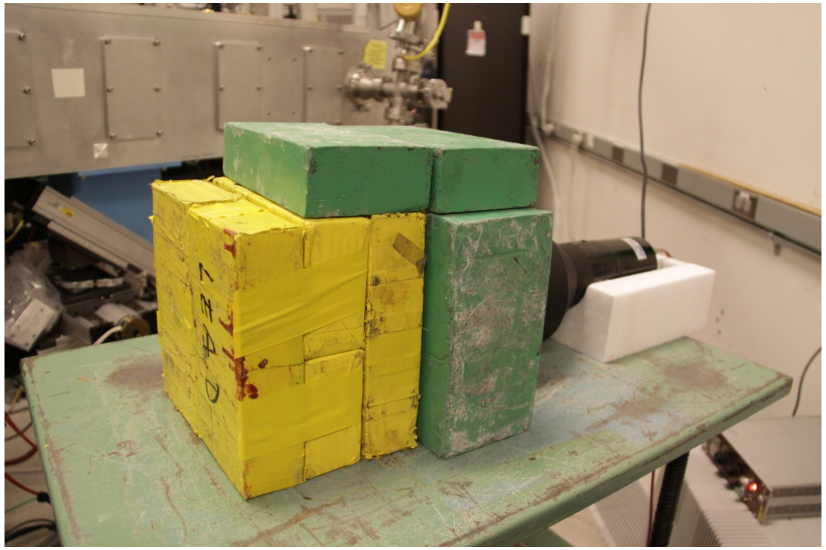

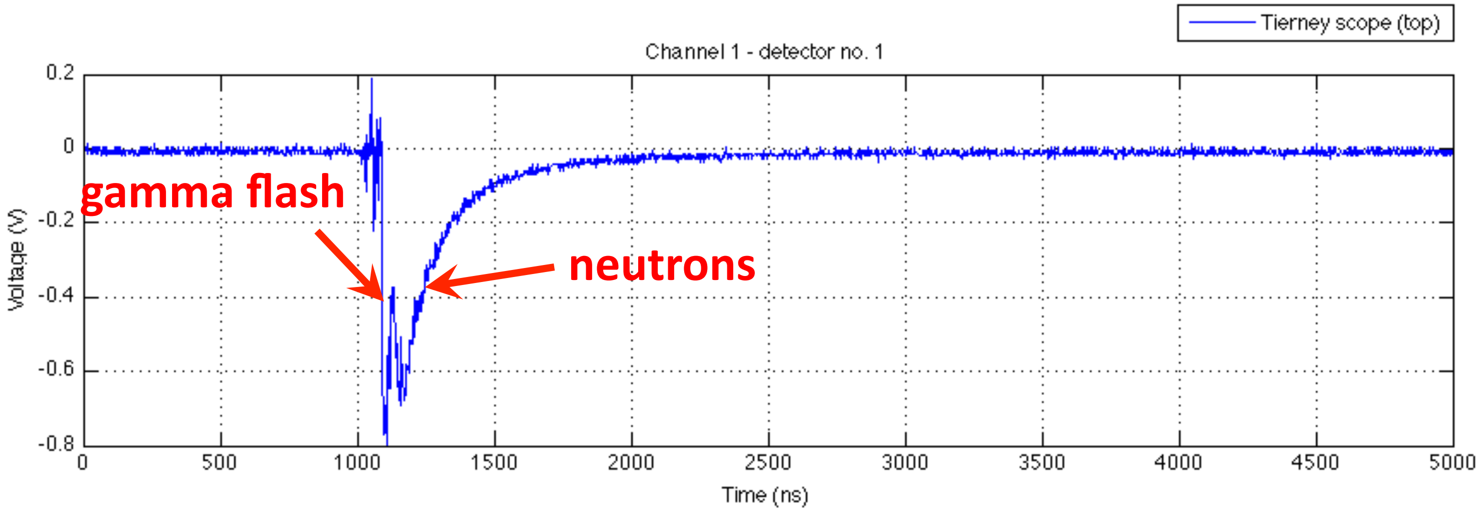

# Bubble detectors for neutron yield measurement

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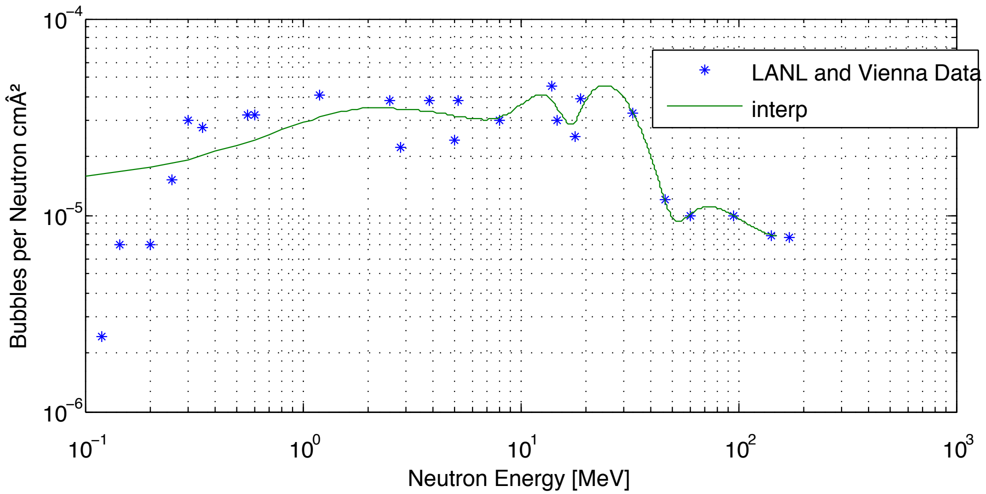
Insensitive to gamma rays

easy to field and to read out

reusable




for 1 bub/mrem



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# BOA vs. TNSA

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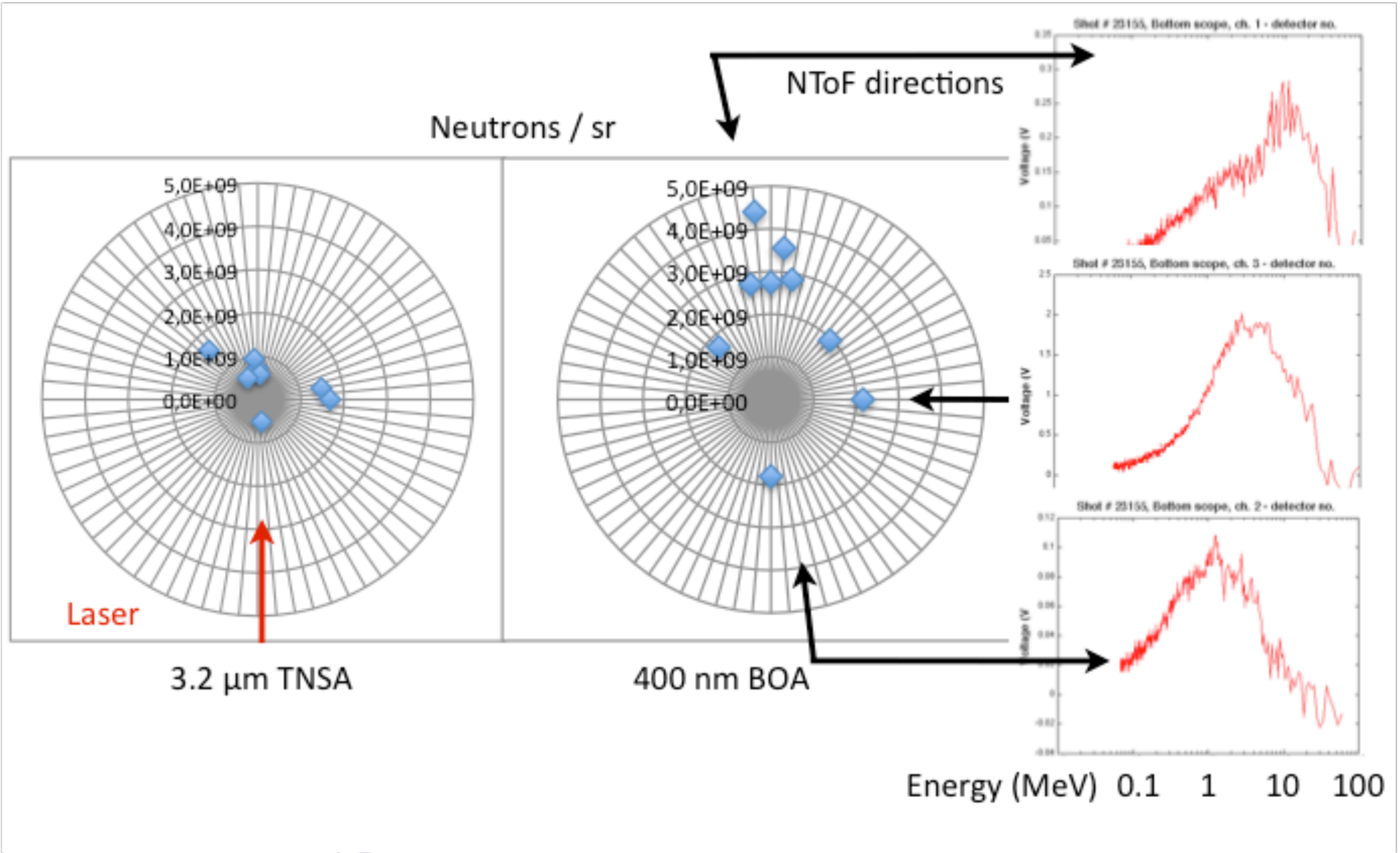
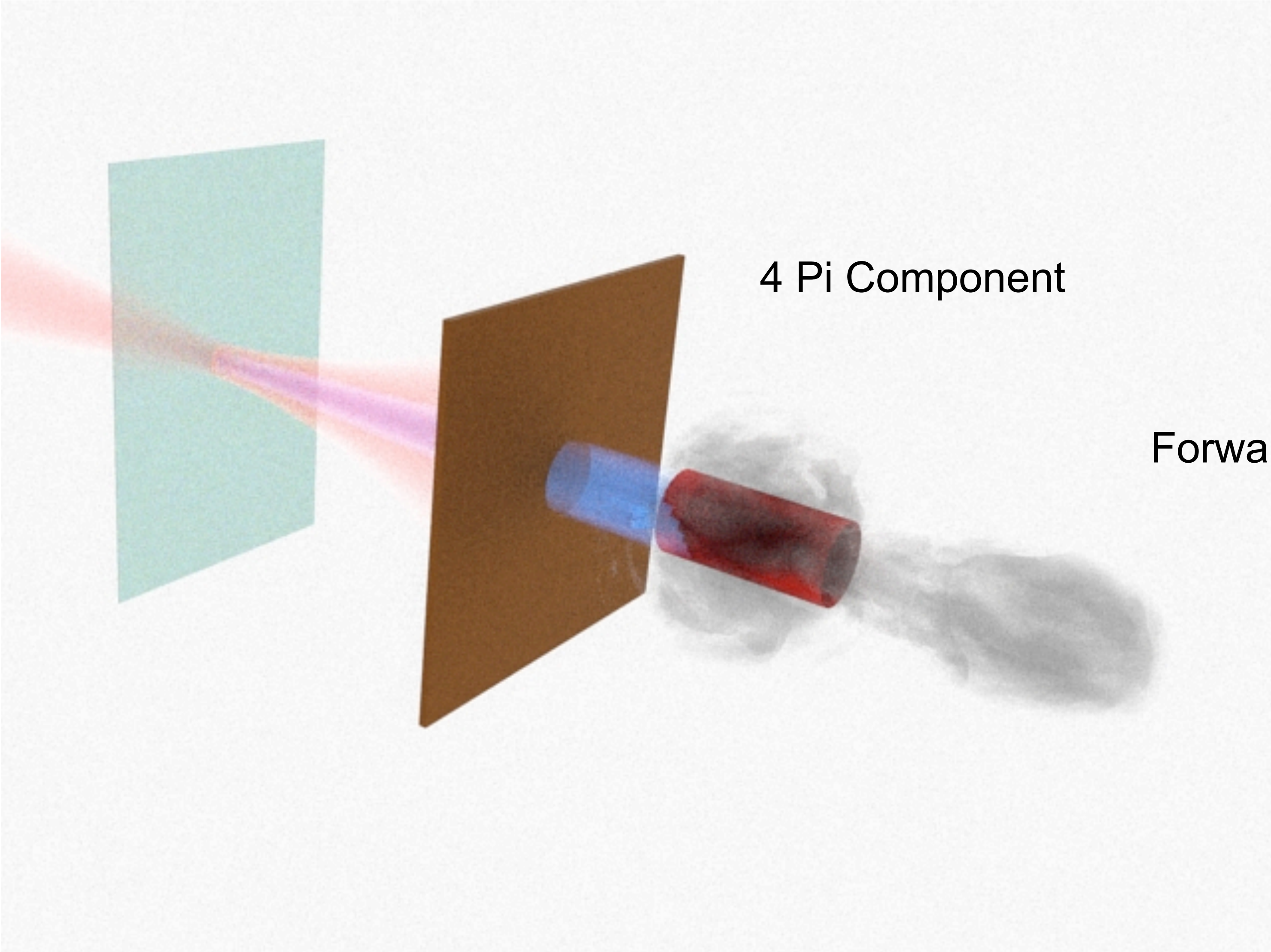


# Change in directionality



4 Pi Component

Forward component

# Results using the f 1.5 parabola and $10^{21}$ W/cm$^2$

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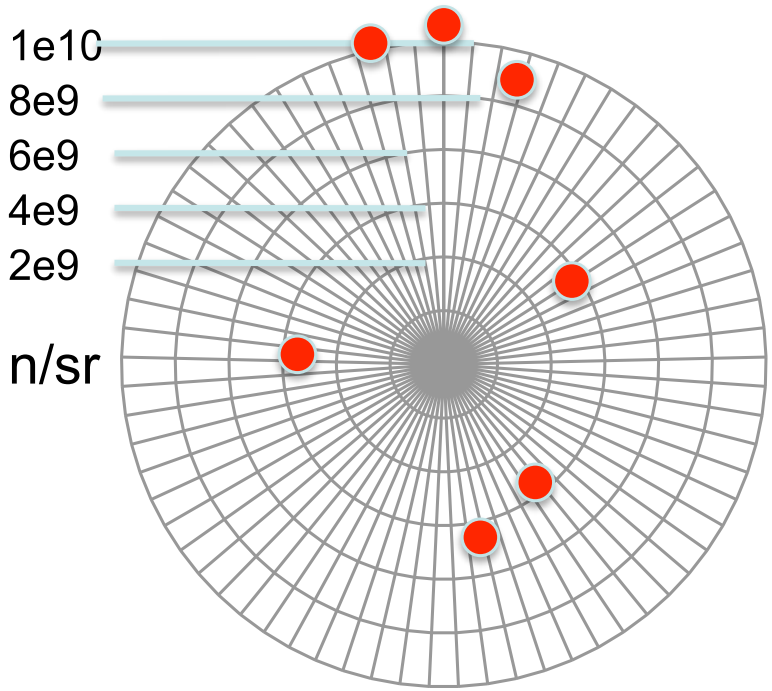
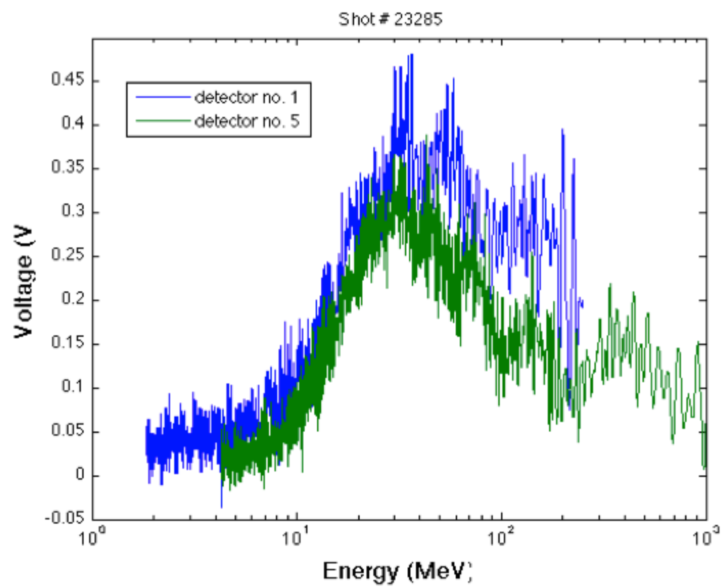


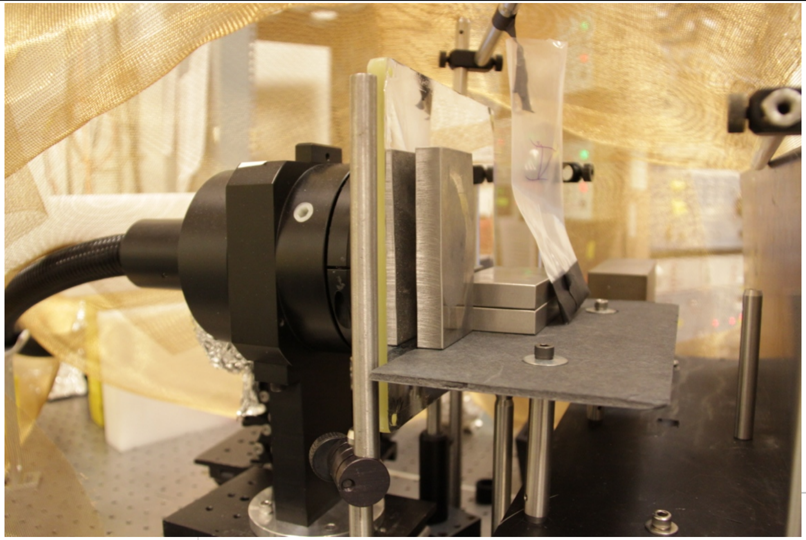

Neutrons:
$>10^{10}$/sr
>200 MeV
Peak @ 70 MeV

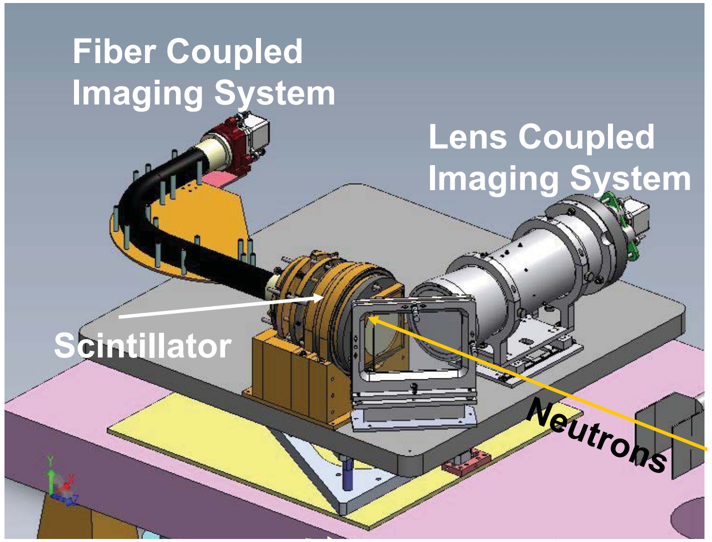
60 J of Laser energy
$1\times10^{21}$ W/cm$^2$
PHELIX has four times the energy available

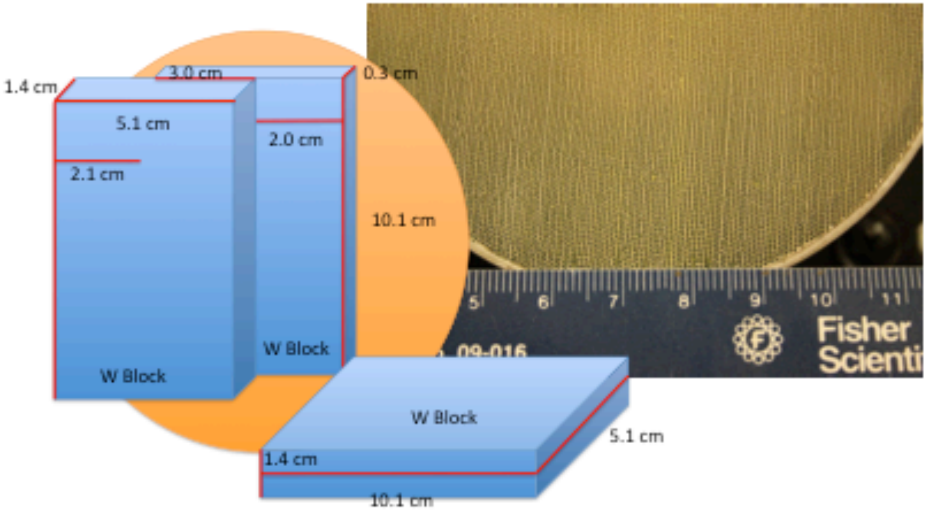


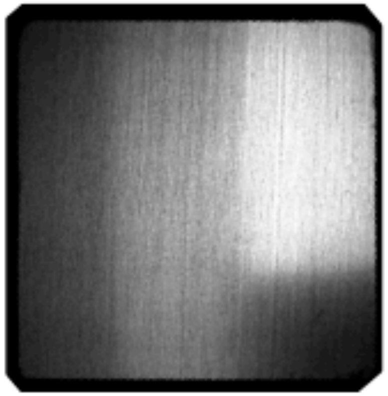

**A recent test experiment at lower energies (April 13) has shown the presence of ion beams driven by BOA higher than 60 MeV comparable to the first TRIDENT campaign!**

# Gated Neutron Imager





# First short pulse laser driven fast neutron radiography

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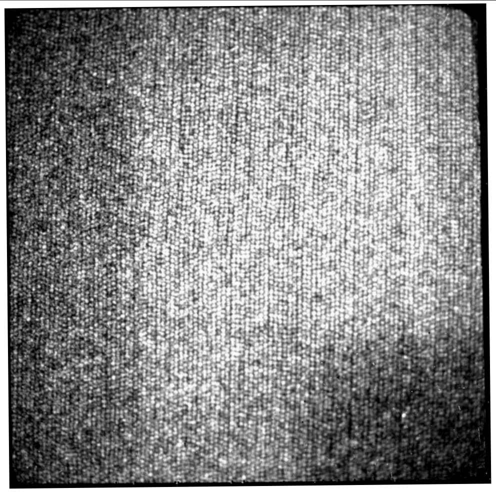
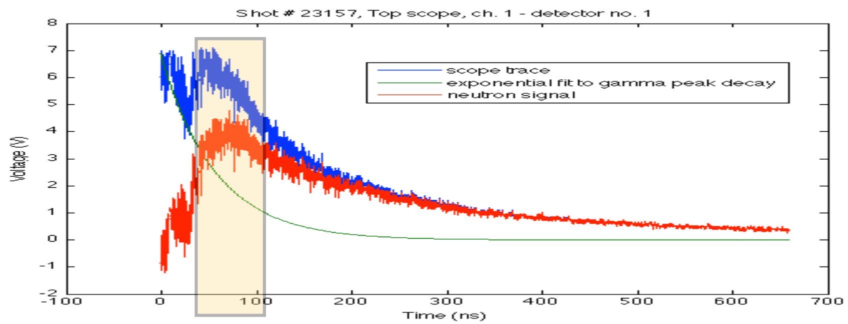
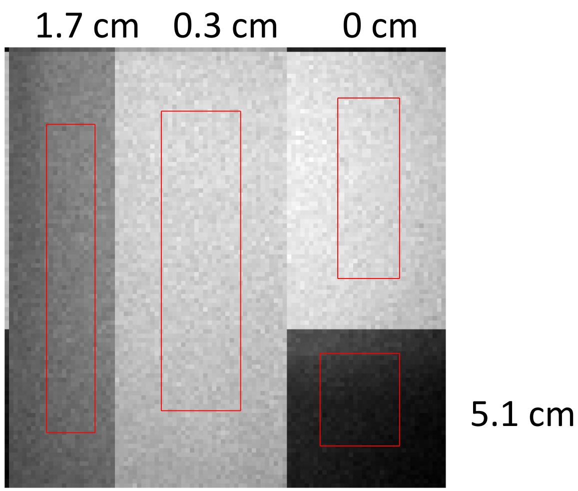
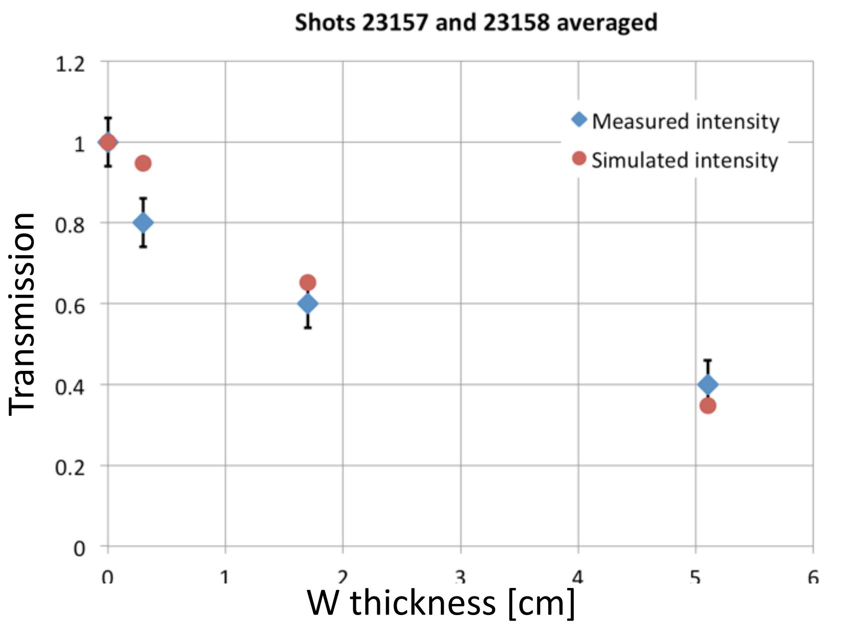





W thickness and simulated image



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# Prospect

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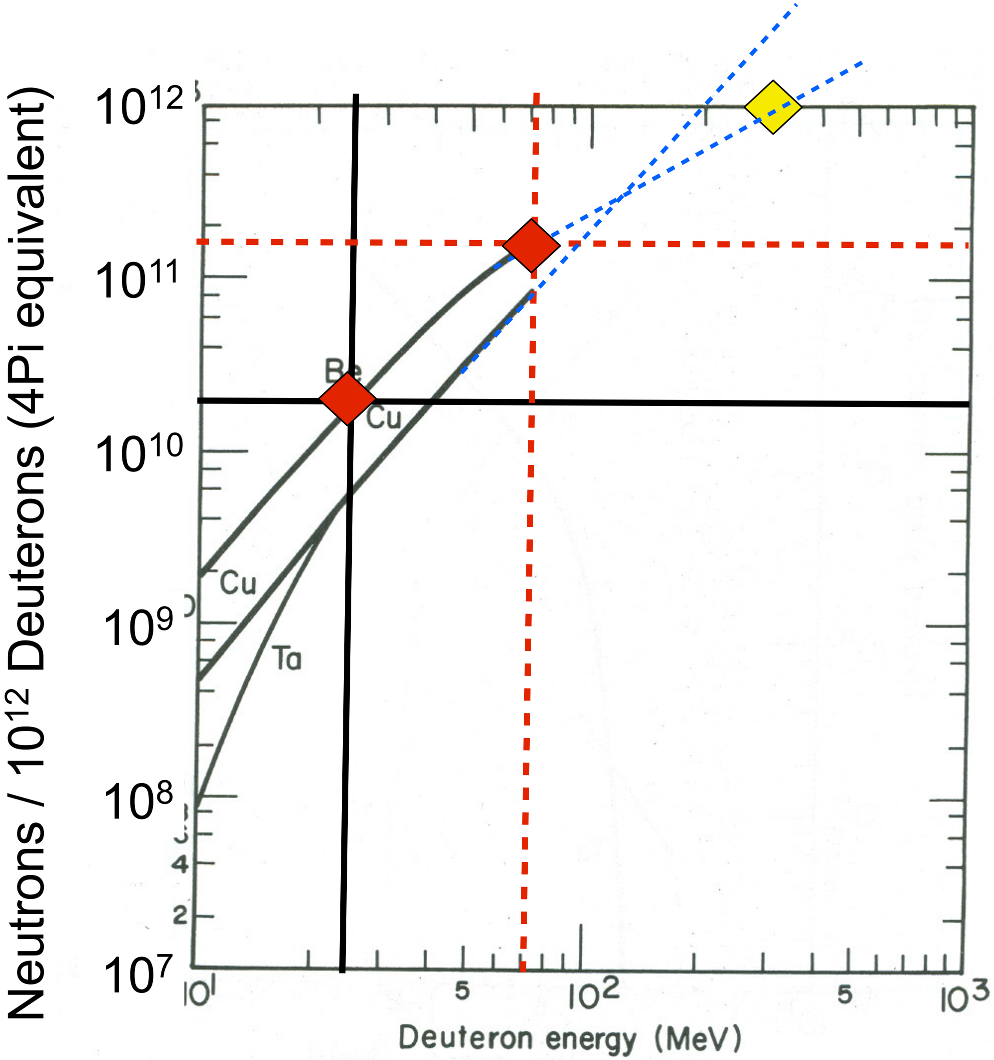


Using BOA:
$10^{12}$ deuterons @ 20 MeV
yield is consistend with data from 1975

Second campaign: Higher energies and higher $D_2$ resulted in more than $10^{11}$ neutrons @ 70 MeV and up to energies of 200 MeV

The forward $D_2$ breakup is already comparable to $2\times10^{11}$ n

Using BOA and novel Targets (cryo) VPIC indicate 200 MeV/u ...

Changing to Ta or Cu converter reduces safety hazards on the converter

@ 10 Hz: 1 kW HESP laser, diode pumped, 20 kW electrical input > $10^{13}$ n/s possible

# Summary

- First laser driven neutron radiography

- Using gated imager and gamma flash objects can be probed with x-rays and neutrons at different energies --> material identification

- Using BOA instead of TNSA results in 20 times higher neutron yield and increased directionality ($2 \times 10^{10}$ n/sr) with only 80 J of laser energy

- Two components observed: beryllium excitation and deuteron breakup

- Neutrons with more than 200 MeV observed (Pre-compund reaction)

- In 1 cm behind the converter: 200 n/$\mu m^2$ and $2 \times 10^{19}$ n/$cm^2$s to alter material

- Neutron science becomes available to universities using short pulse lasers

# Thanks to

Oliver Deppert[1], Matthew Devlin[2], Katerina Falk[2], Andrea Favalli[2], Juan Fernandez[2], Cort Gautier[2], Mattthias Geissel[3], Nevzat Guler[2], Robert Haight[2], Chris Hamilton[2], Manuel Hegelich[2], Randall P Johnson[2], Daniel Jung[2], Frank Merrill[2], Gabriel Schaumann[1], Kurt Schoenberg[2], Marius Schollmeier[3], Tsutomu Shimada[2], Joshua L. Tybo[2], Stephen A Wender[2], Carl, H Wilde[2], Glen Wurden[2]

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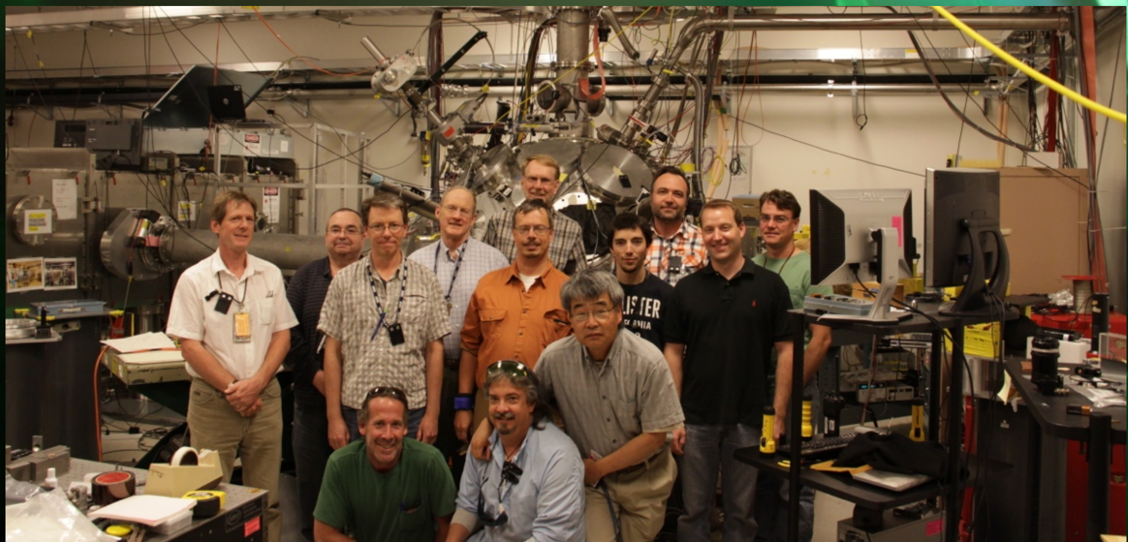
ndia National Laboratory, Albuquerque, New Mexico 87185, USA



The LANL for the Rosen Scholar award

TUD for the sabbatical