Laser-Plasma Energetic Particle Production for Aneutronic Nuclear Fusion Experiments

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CELIA

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The collaboration

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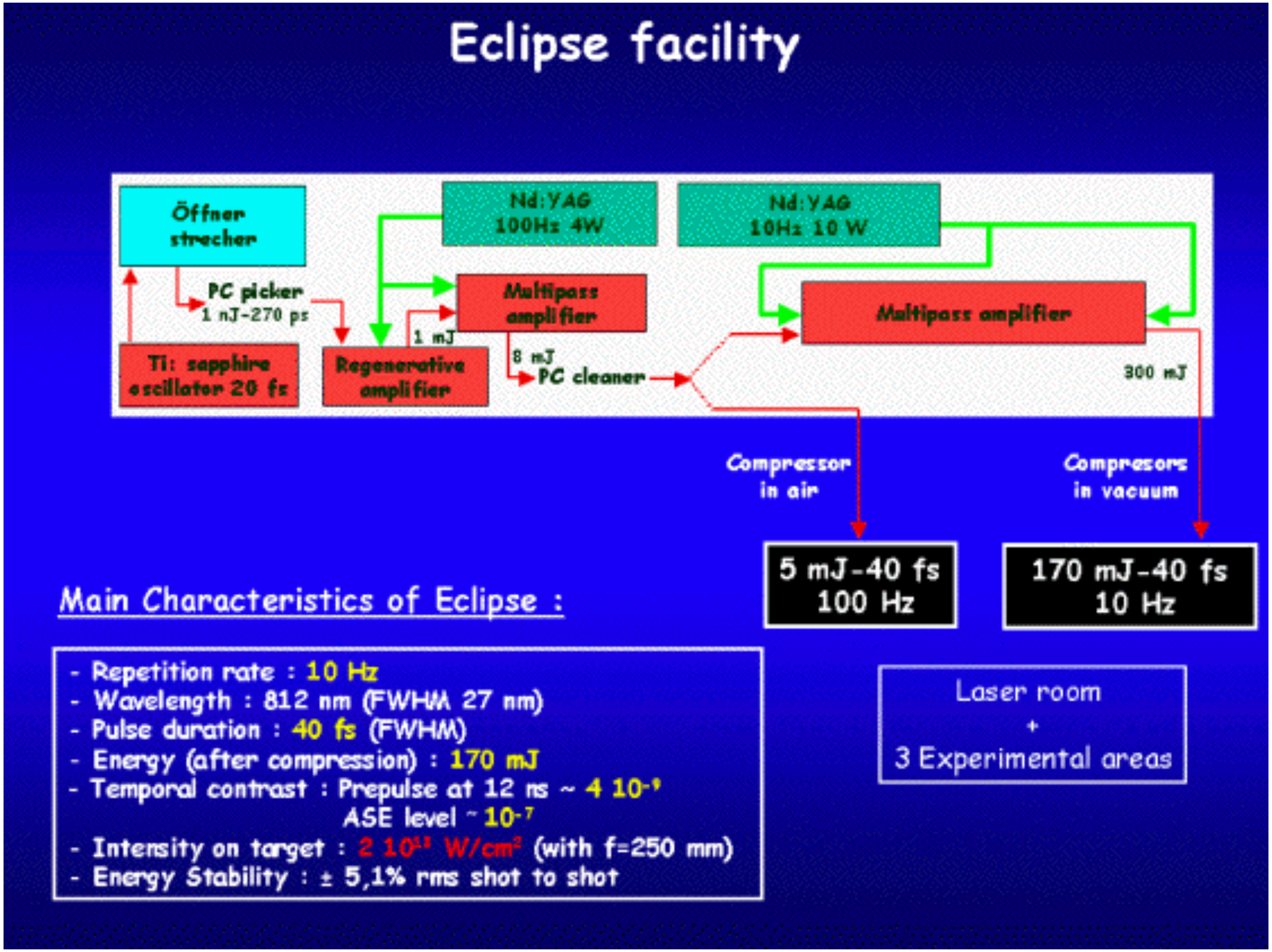
Summary

The main interest in the **aneutronic nuclear fusion reactions** for energy production concerns the possibility of greatly reducing the problems associated with **neutron activation** and related requirements for biological shielding, remote handling, and safety. Among the so called "advanced fusion fuels" the **proton-Boron fusion reaction** seems to be the most attainable from an experimental point of view, due to the relatively high cross section of the process exhibited at the centre of mass kinetic energy of 148 KeV and 580 KeV respectively. An experiment has been performed at **CELIA** in which a **multi-TeraWatt Ti:Sapphire laser** interacted at fairly relativistic intensities with different solid targets. The experiment aim was to investigate two fusion processes, **p-B and D-D**, the first of which aneutronic. Al thin foils were used to produce energetic protons to be addressed to a Boron target, while deuterated-plastic targets were used to induce the D-D fusion reaction. Several diagnostics were activated to monitor the effectiveness of the laser-target interaction, the energy spectrum of the accelerated particles and the release of charged particles related to the activated fusion processes.

PRESENTATION OUTLINE

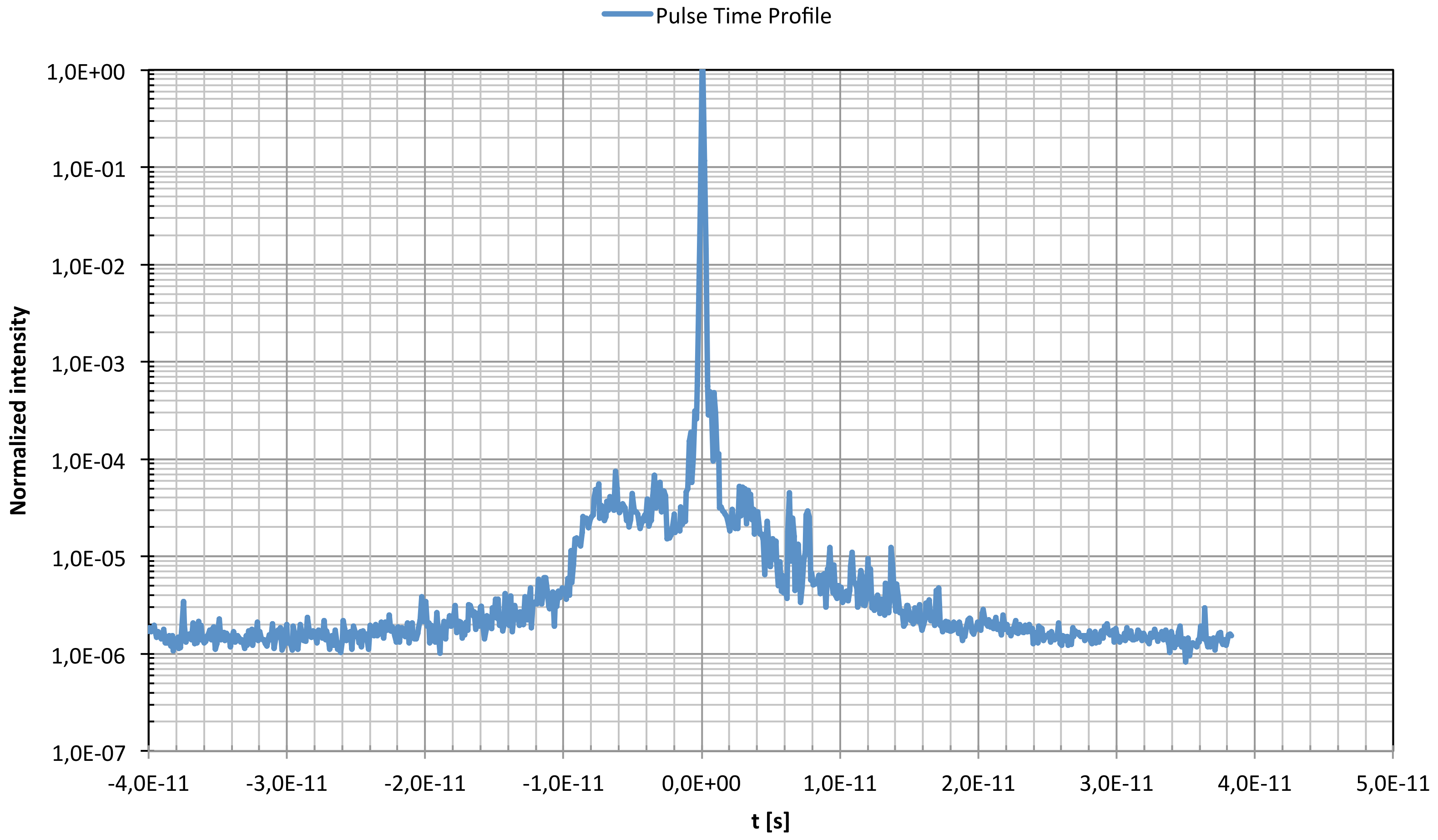
- Experimental set-up
- Energetic proton production by LPA
- P+^{11}B fusion reactions
- D+D fusion reactions
- Conclusions

The LASER

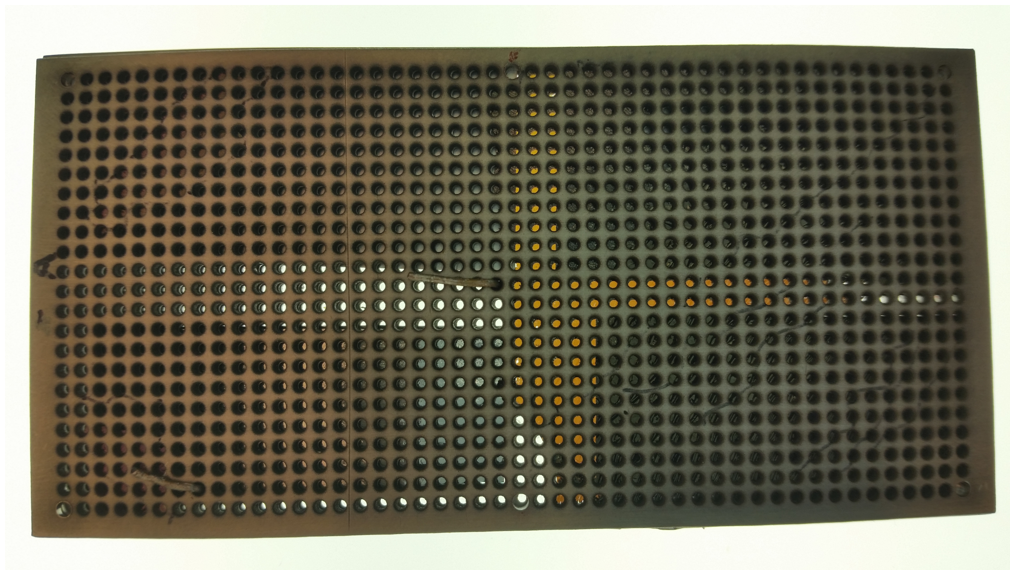


Eclipse facility
Öffner strecher
Nd:YAG 100Hz 4W
Nd:YAG 10Hz 10 W
PC picker
1 nJ-270 ps
Multipass amplifier
1 mJ
Ti: sapphire oscillator 20 fs
Regenerative amplifier
8 mJ
PC cleaner
Multipass amplifier
300 mJ
Compressor in air
Compresors in vacuum
5 mJ-40 fs
100 Hz
170 mJ-40 fs
10 Hz
Main Characteristics of Eclipse :
- Repetition rate : 10 Hz
- Wavelength : 812 nm (FWHM 27 nm)
- Pulse duration : 40 fs (FWHM)
- Energy (after compression) : 170 mJ
- Temporal contrast : Prepulse at 12 ns ~ 4 10^{-9}
ASE level ~ 10^{-7}
- Intensity on target : 2 10^{18} W/cm^2 (with f=250 mm)
- Energy Stability : ± 5,1% rms shot to shot
Laser room
+
3 Experimental areas

The ultra-short LASER pulse



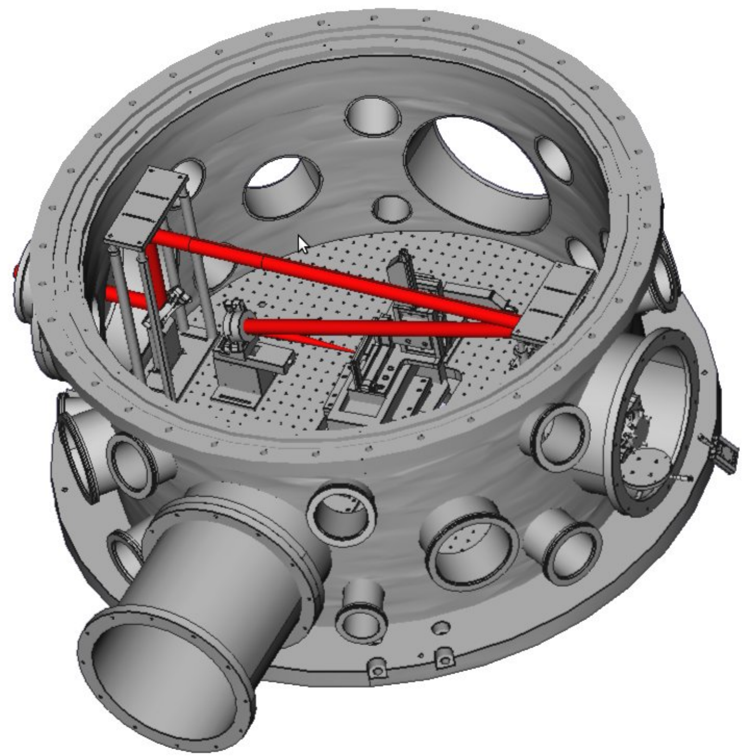
Deuterated plastic and Al foils on the target holder



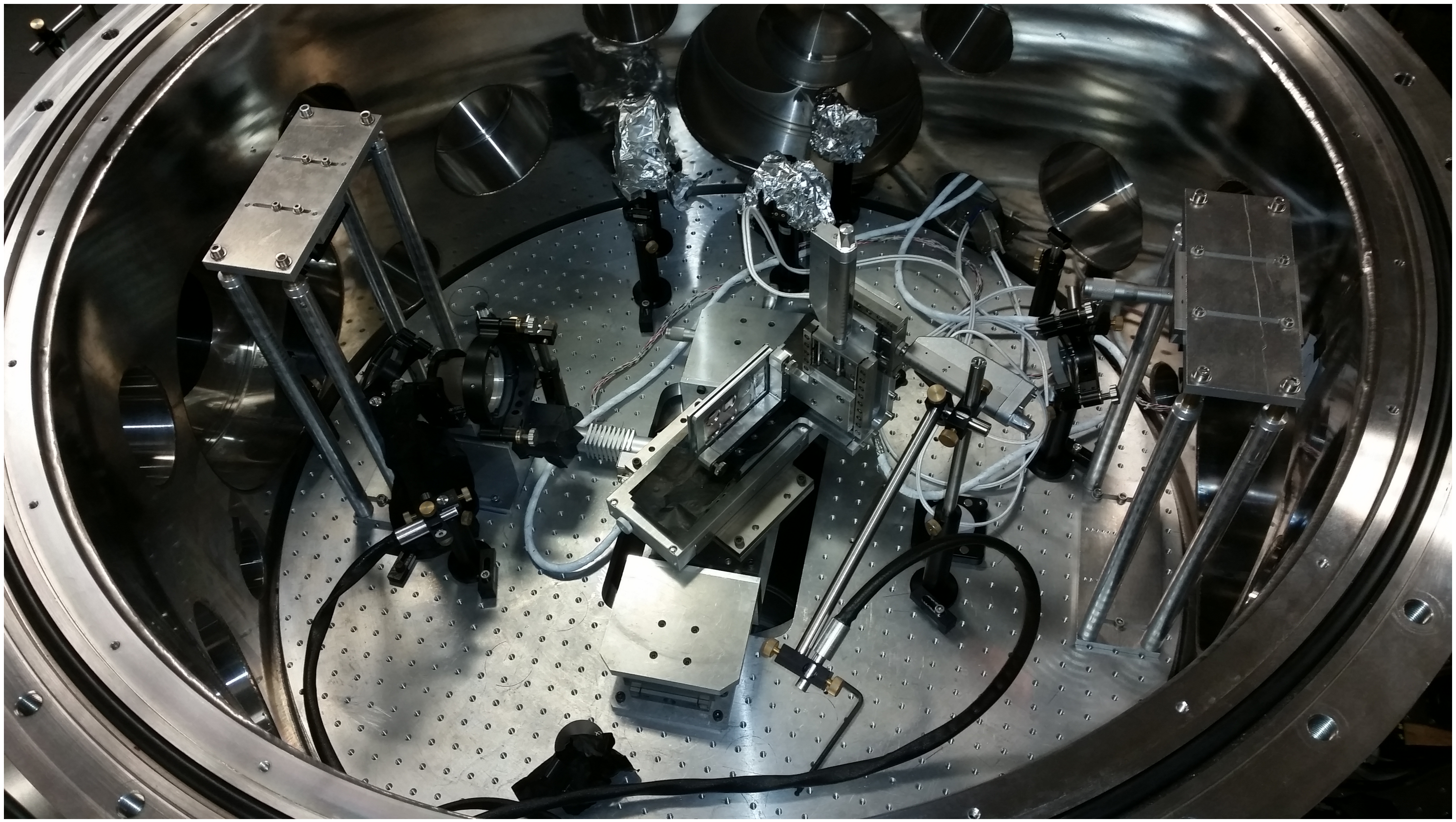
200 μm deuterated plastic, C_2D_4

6-10 μm Al

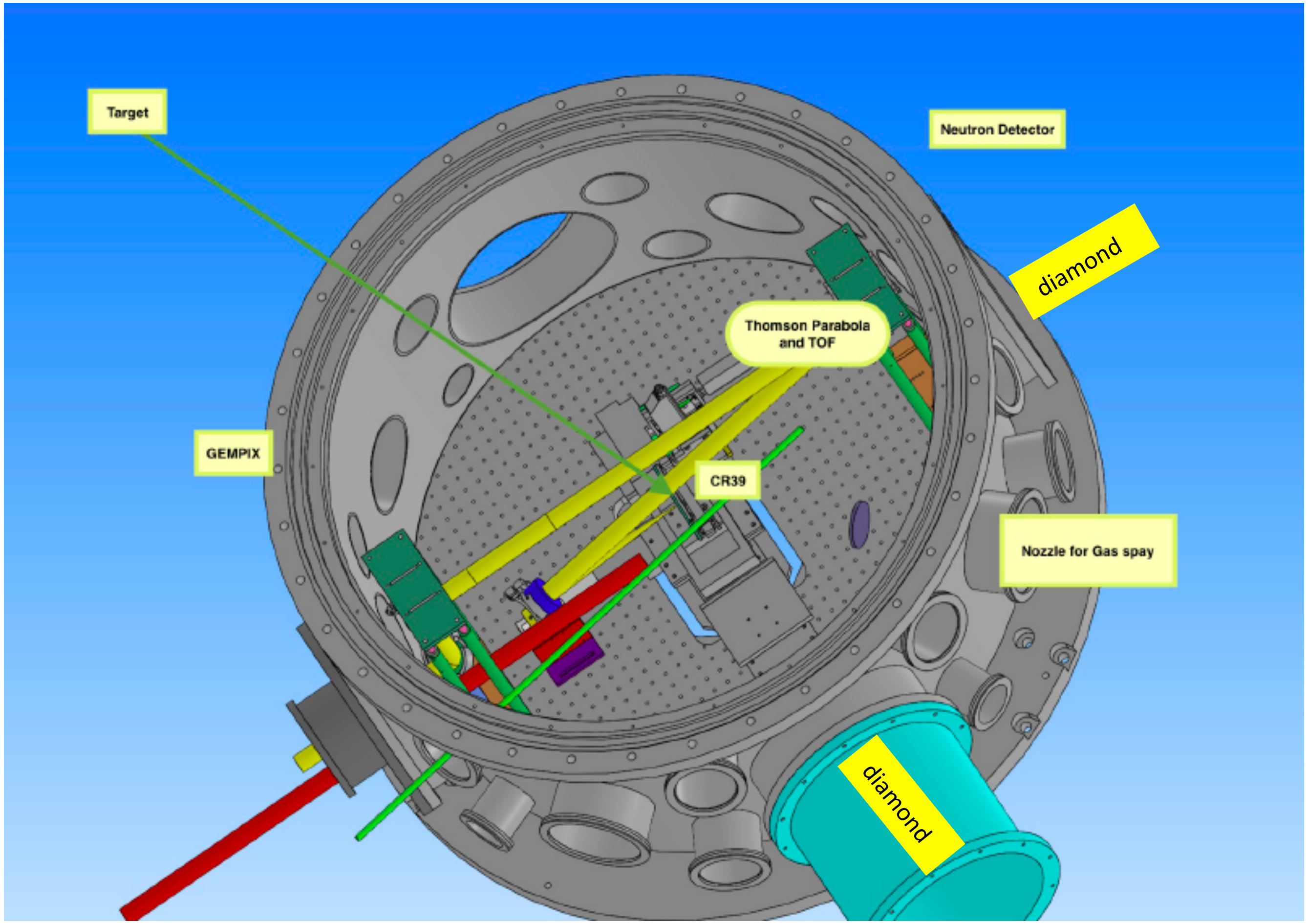
The interaction chamber



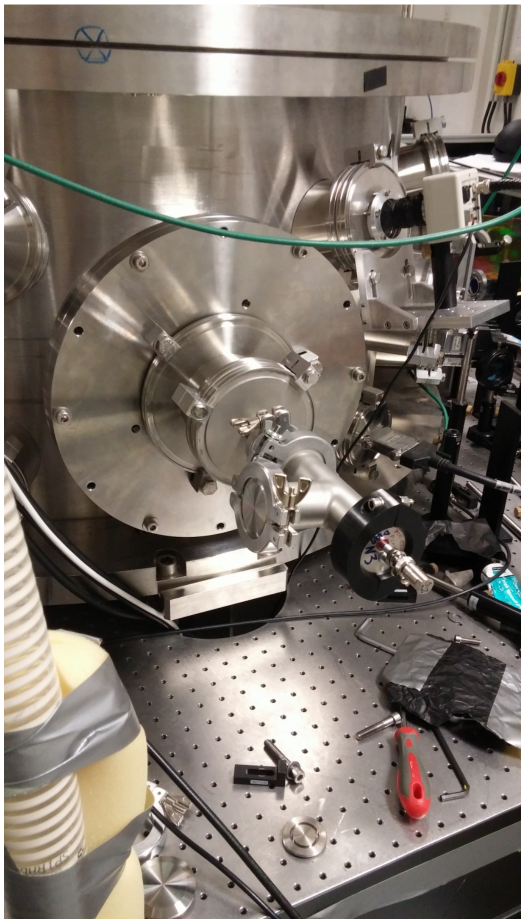
Interaction Chamber

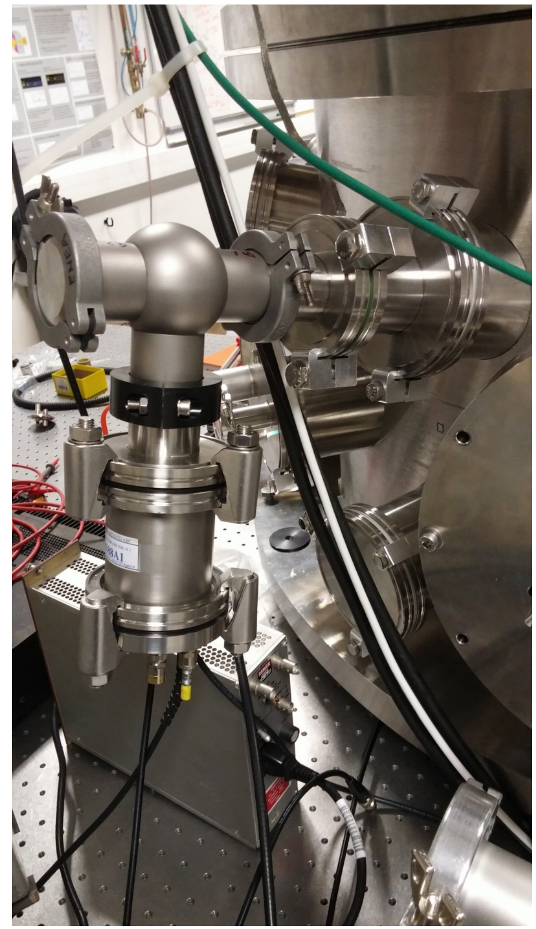


Interaction Chamber



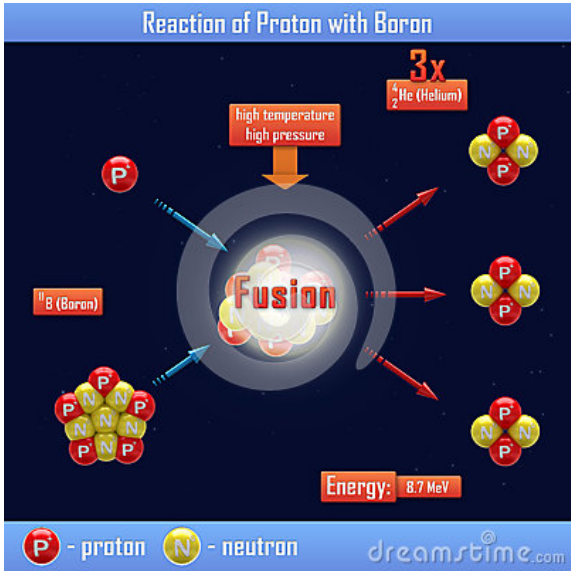
Diamond Detectors

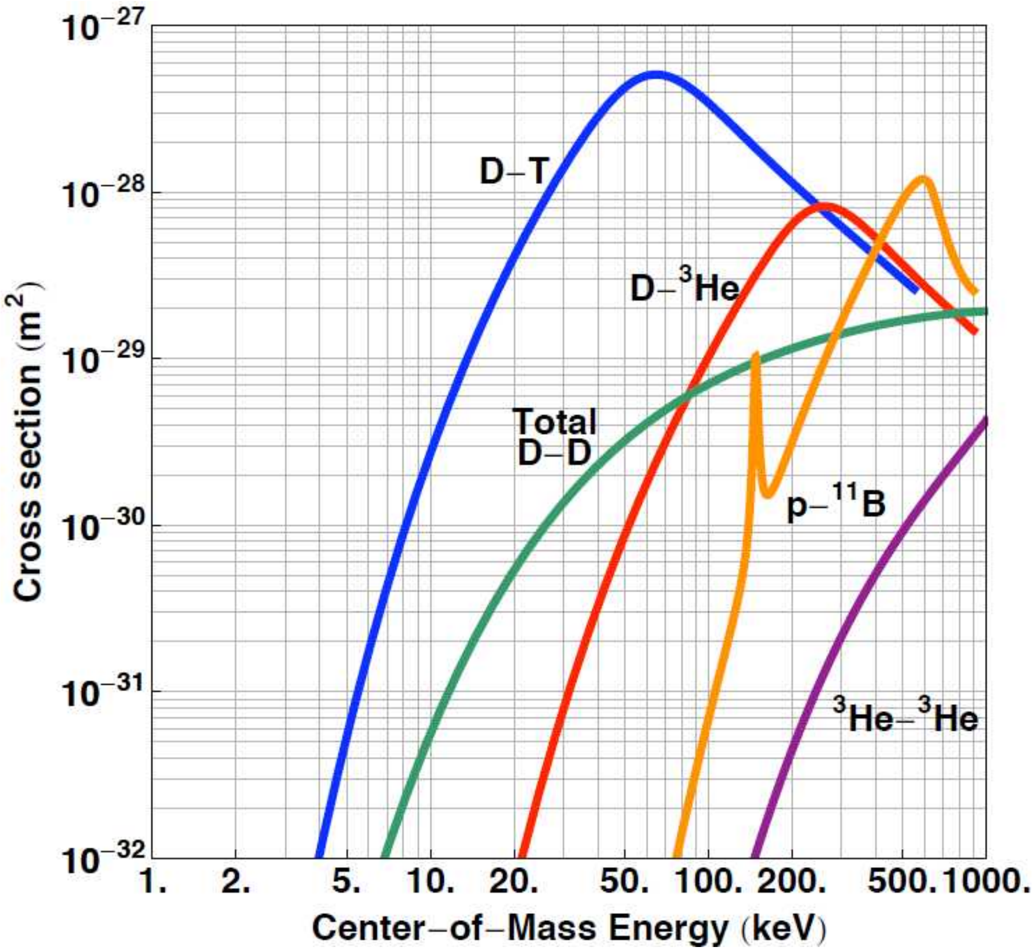




Proton-Boron reaction

$$p + {}^{11}B \rightarrow 3\ {}^{4}H_e\ (8.7 MeV)$$



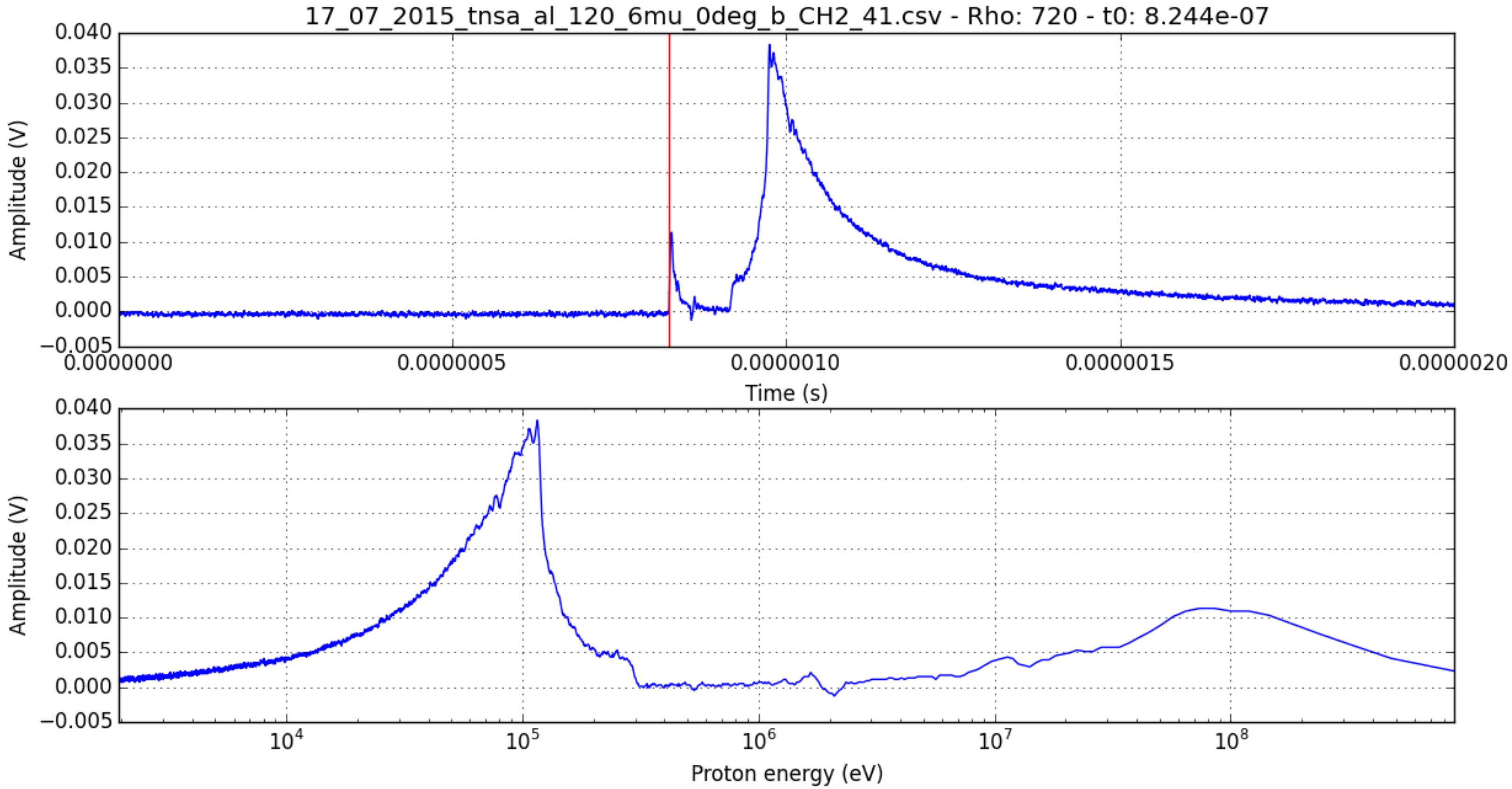


Cross section max. @ 148 - 580 KeV

Proton Laser-Plasma Acceleration

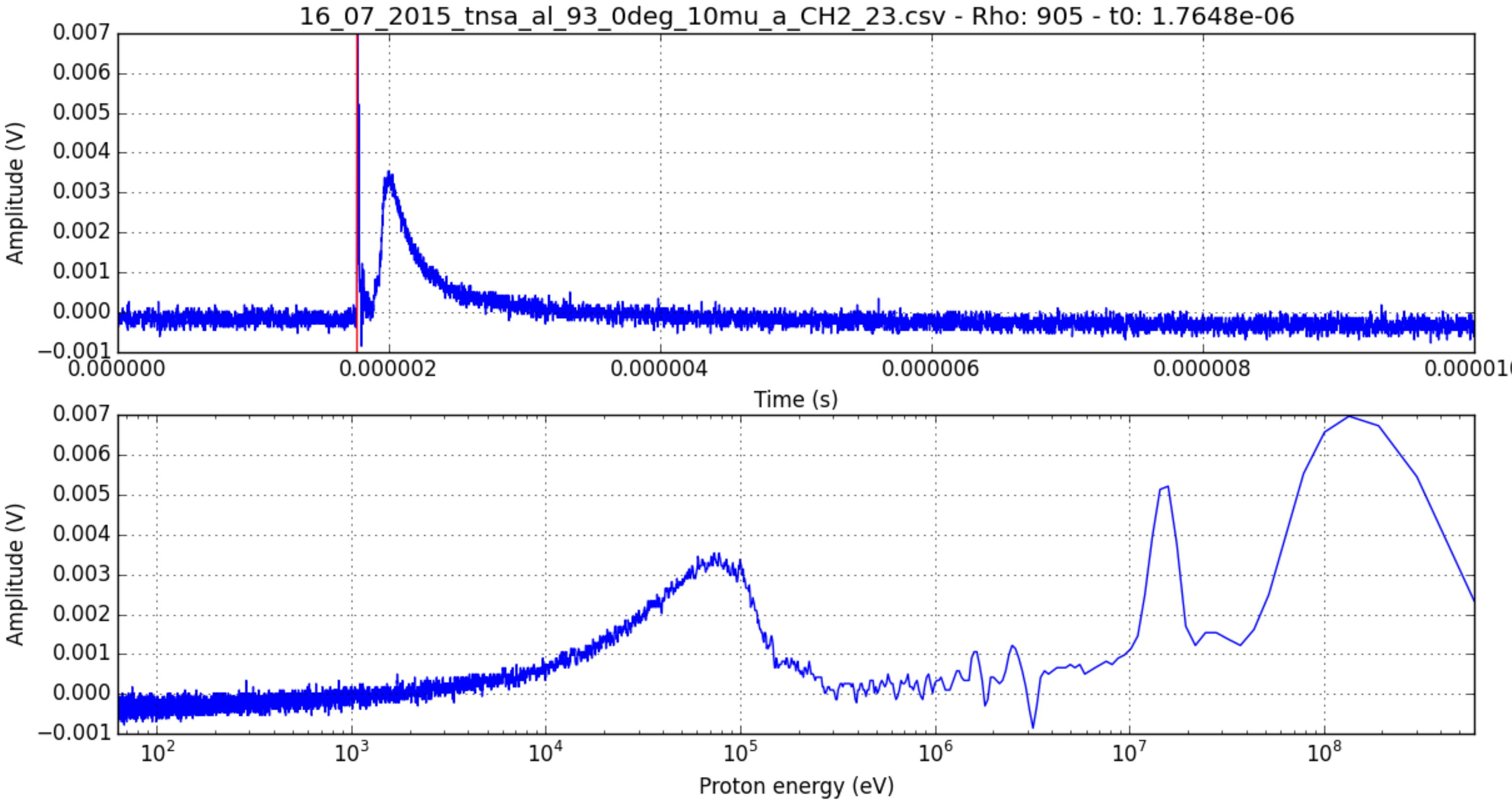
TIME OF FLY (TOF) MEASUREMENS

TOF



6μm Al foil, I=2x10^{18} W/cm^2

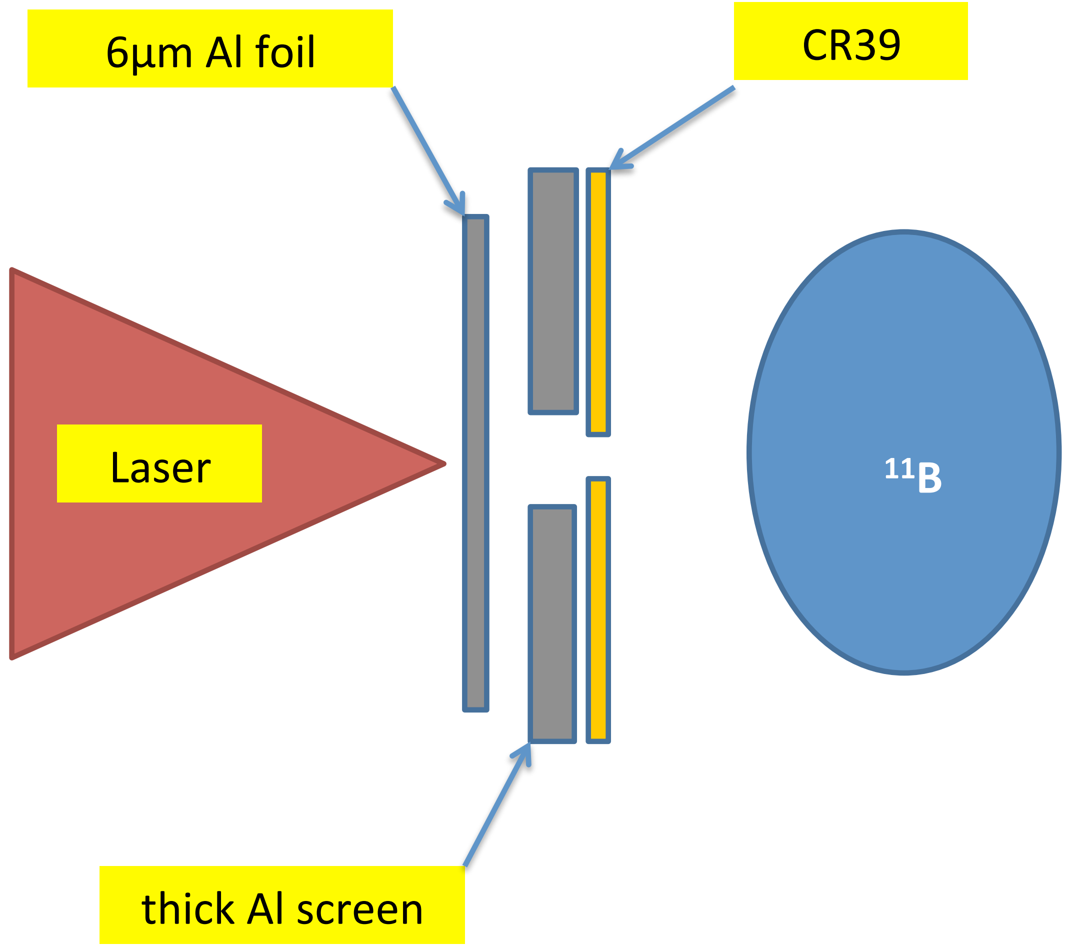
TOF



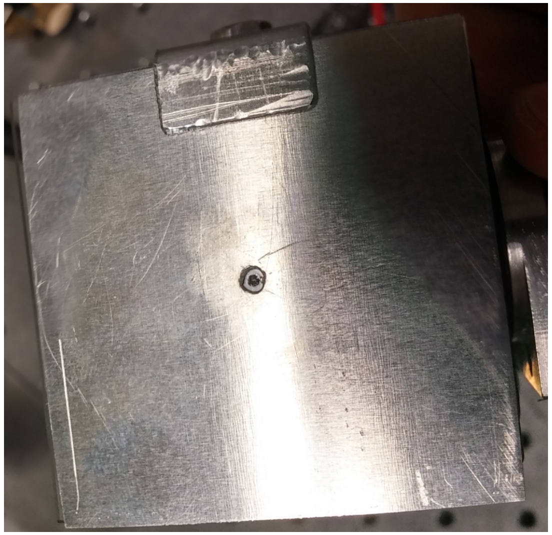
10µm Al foil, $I=1.6 \times 10^{18}$ W/cm^2

ENERGETIC PROTONS ON ^{11}B TARGET

CR39 set-up

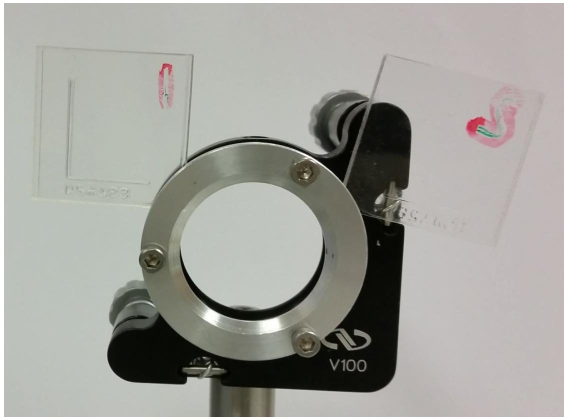


CR39 Set-up

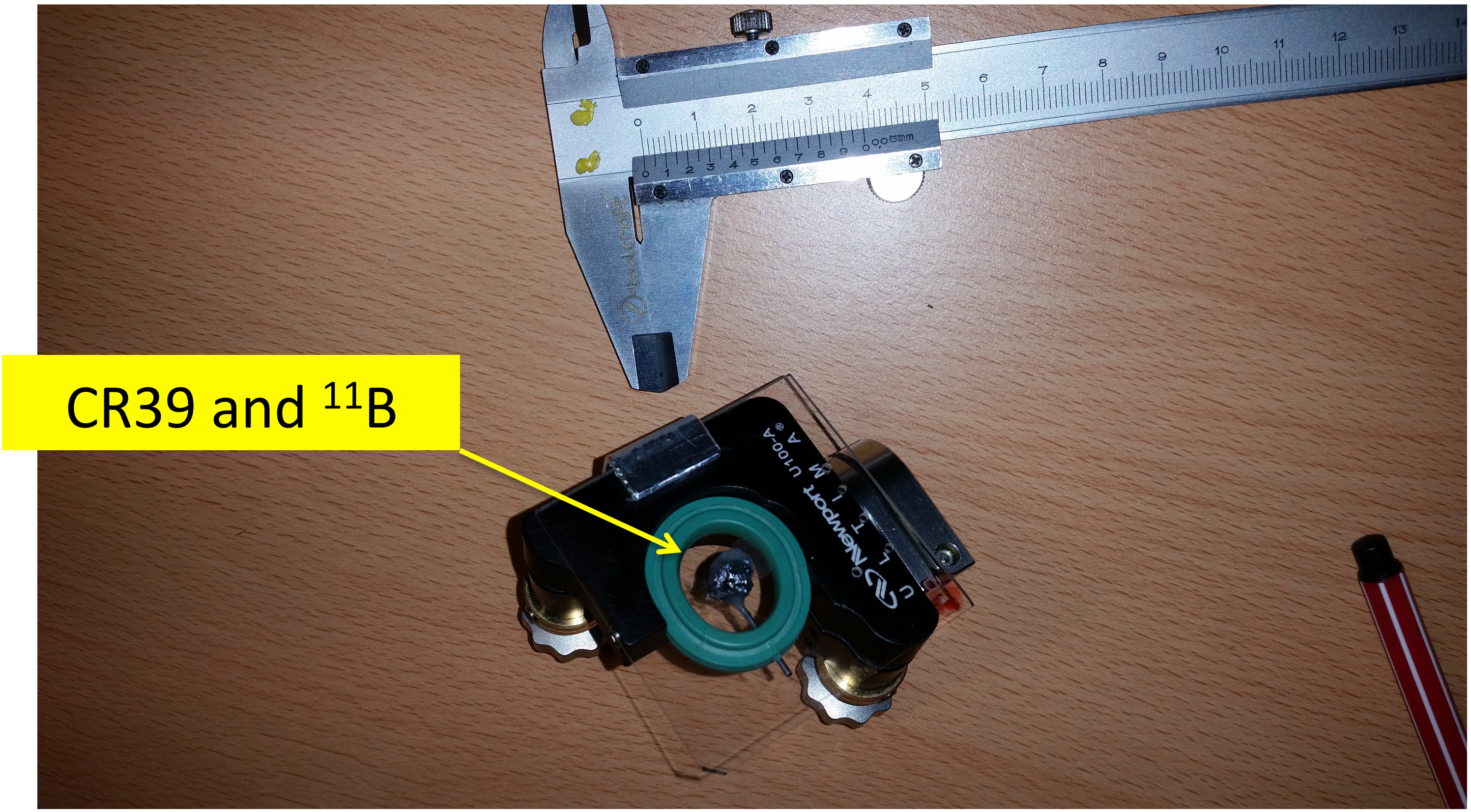


thick Al screen

CR39

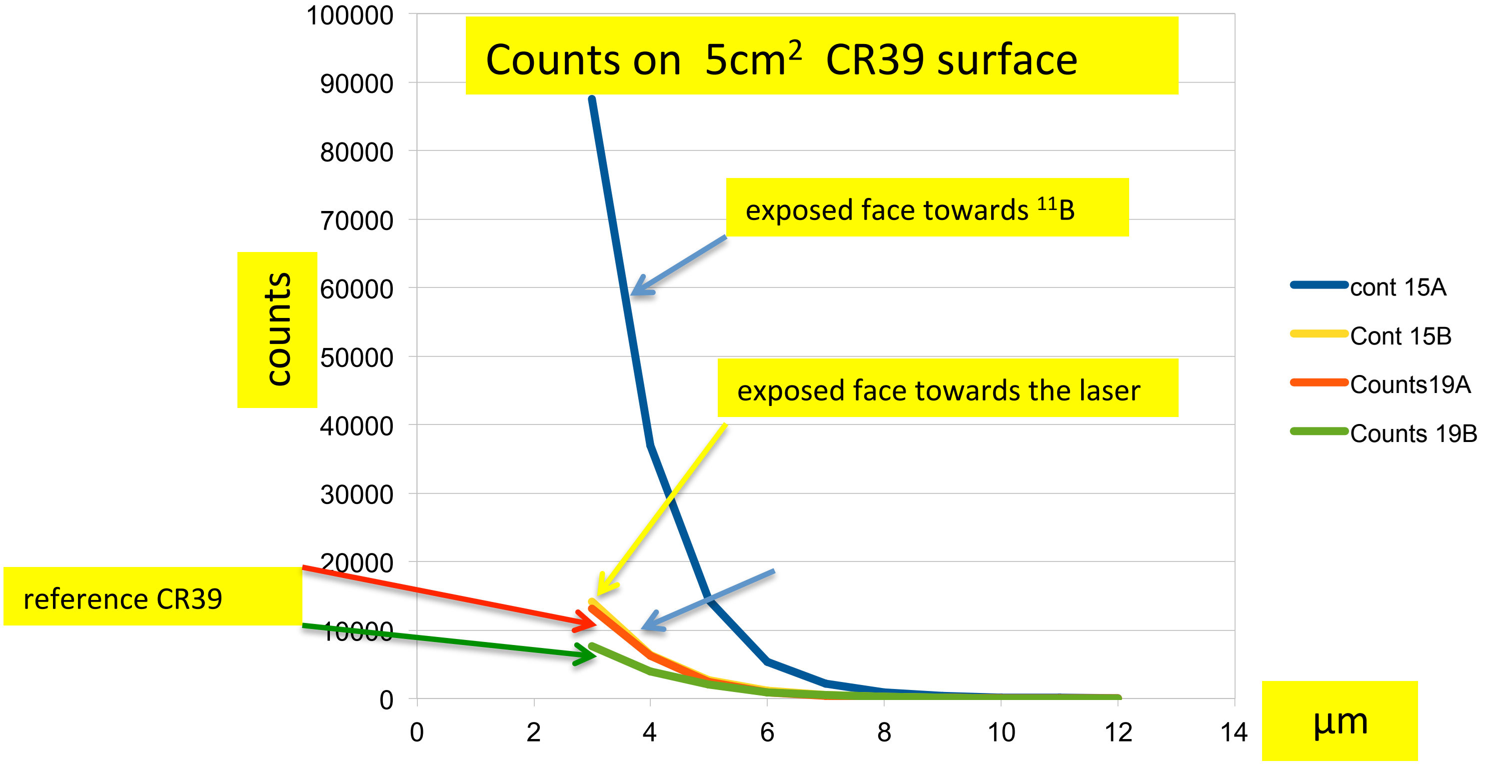


CR39 set-up



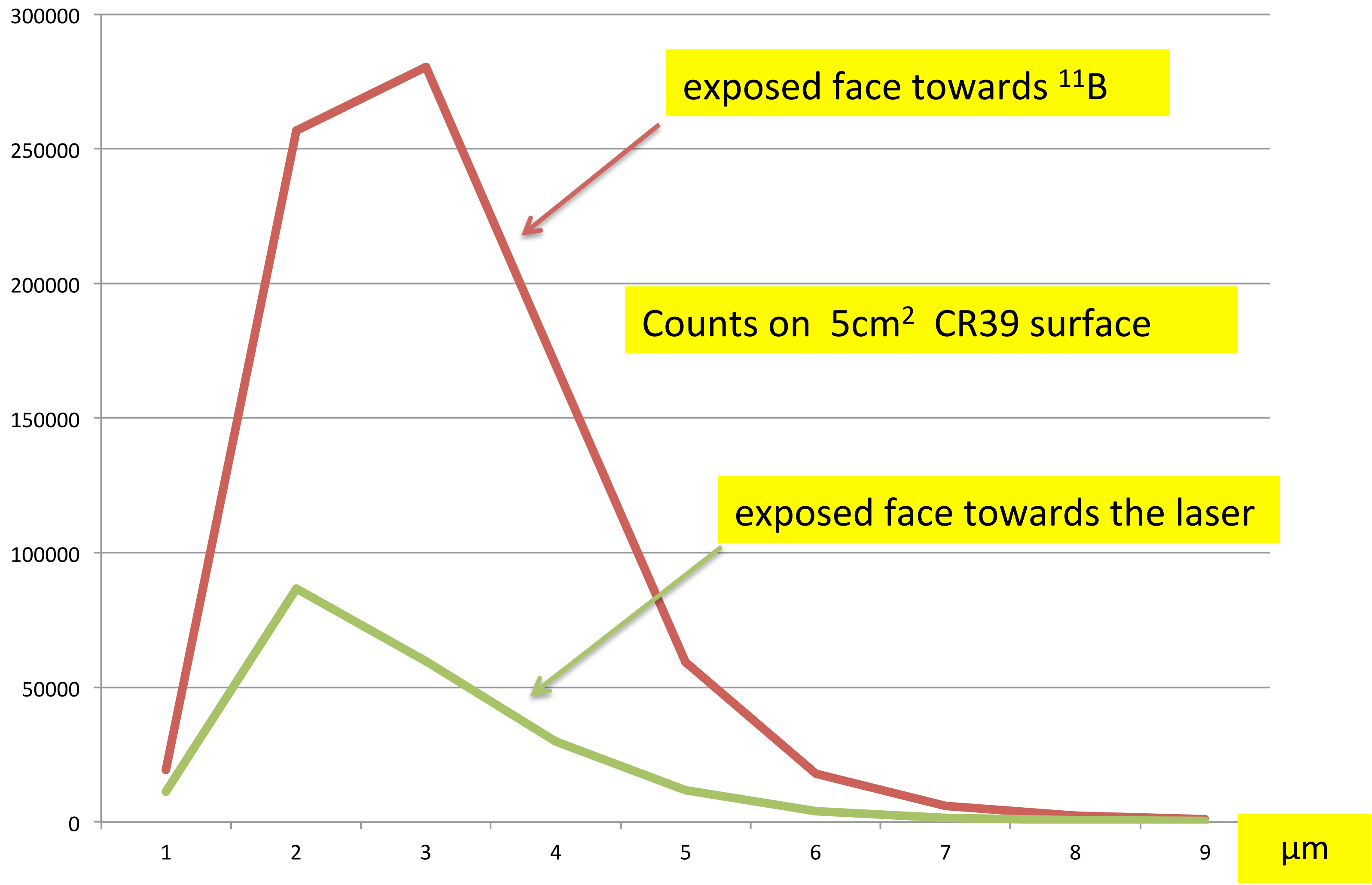
CR39 Data Analysis

CR39 a-COUNTS



19 Reference CR39
15 Exposed CR39
A face towards ^{11}B
B face toward the Laser

CR39 a-COUNTS

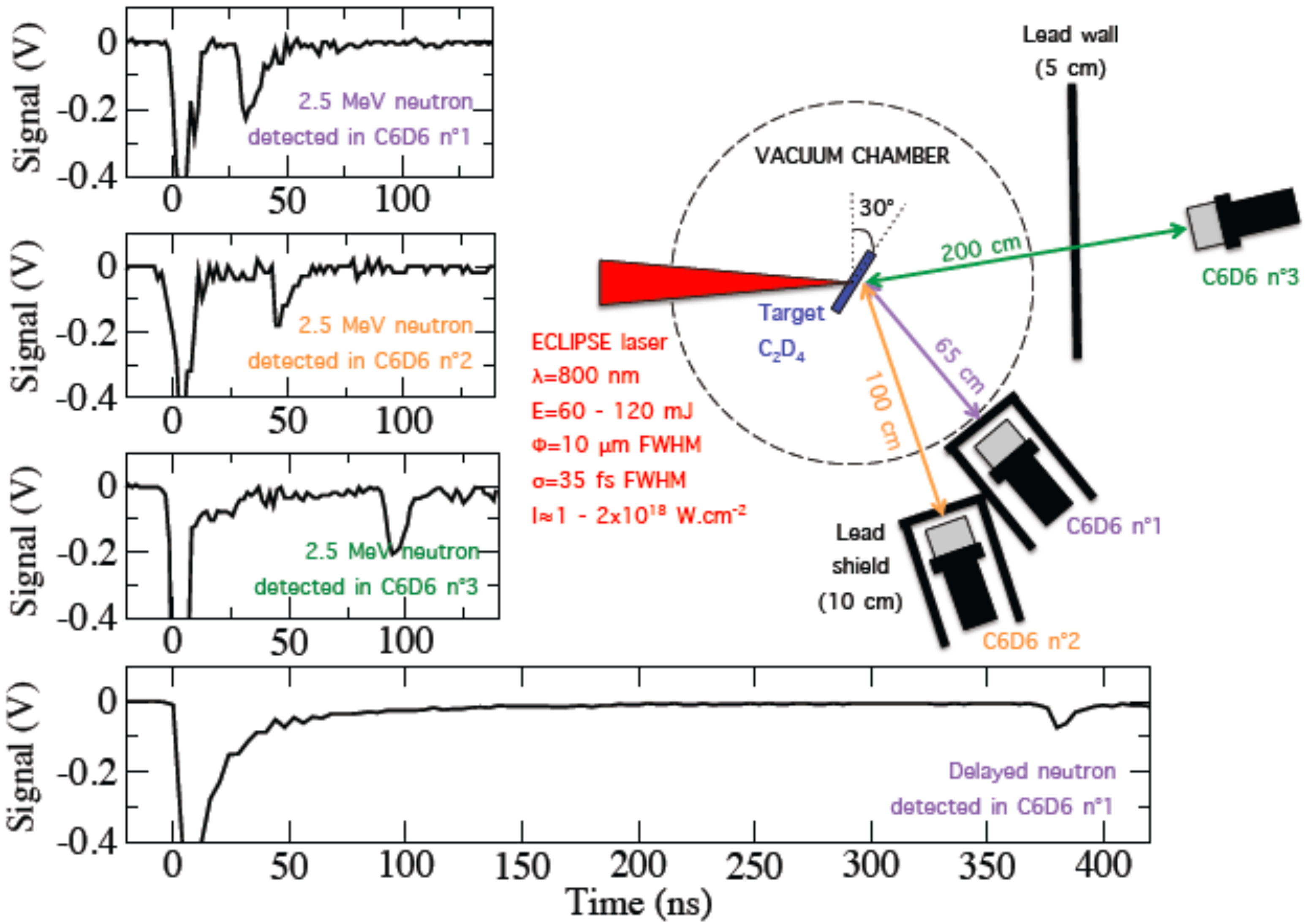


D+D reaction

$$ {}^{2}_{2}D + {}^{2}_{2}D \rightarrow {}^{3}_{1}T\ (1.01MeV) + p\ (3.02MeV) \qquad 50\% $$

$$ {}^{2}_{2}D + {}^{2}_{2}D \rightarrow {}^{3}_{2}He\ (0.82MeV) + n\ (2.45MeV) \qquad 50\% $$

TOF MEASUREMENTS

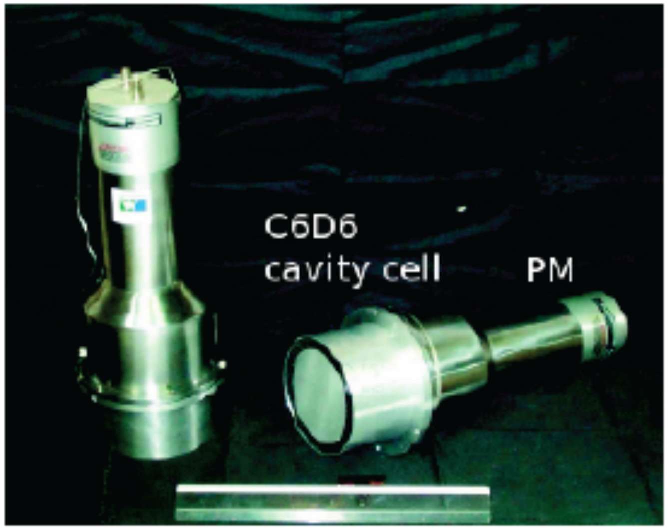


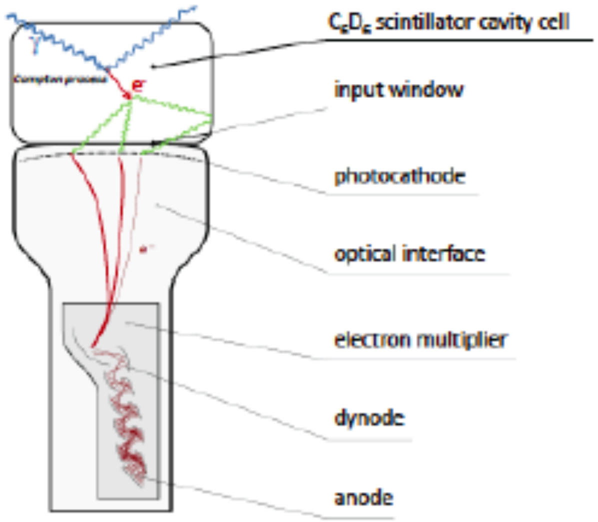
Scintillator and PM

C_6D_6 scintillators or NE-230:

→ Well-known detectors for photons and fast neutrons
→ Good pulse-shape-discriination (PSD), but not used here.
→ Fast detectors: less than 10 ns rising time.
→ Unambiguous detection of neutrons using Time-of-Flight:

$$TOF_{neutrons}(ns) = \frac{0.72295 \times d_n(cm)}{\sqrt{E_n(MeV)}}$$

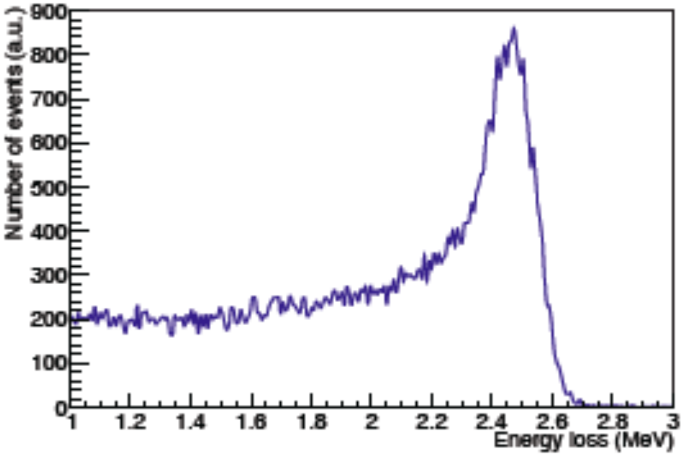


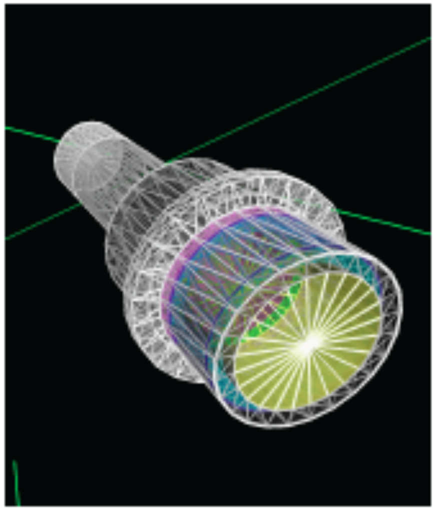


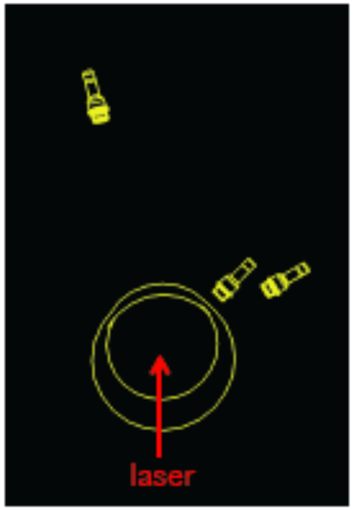
GEANT4 Simulations

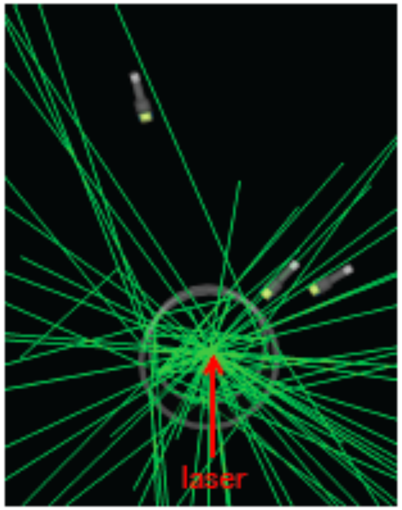
Monte-Carlo GEANT4 simulations :

→ Quasi-mono-energetic response to neutrons (actually recoiling protons), in good agreement with data (-200 mV signal, almost all the time)
→ Use simulations to infer detection efficiency.









Counting rates

Counting rates:

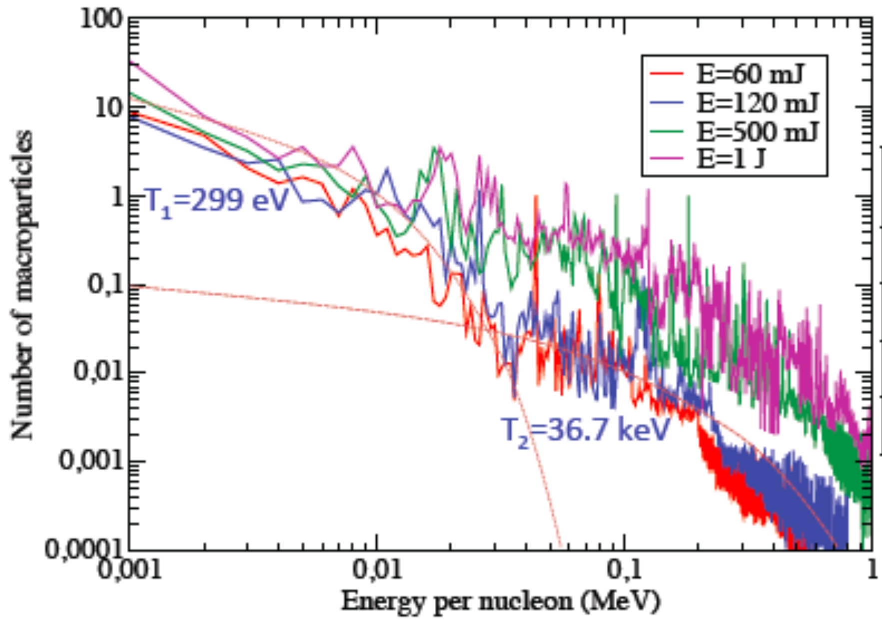
	Number of neutron events & number of shots	Detection efficiency	Number of fusion events
03/2016 – 60 mJ – detector 1	24 events / 1000 shots	7×10^{-4}	35 ±13
07/2016 – 120 mJ – detector 1	17 events / 400 shots	7×10^{-4}	61±24
07/2016 – 120 mJ – detector 2	18 events / 1000 shots	3×10^{-4}	60 ±23
07/2016 – 120 mJ – detector 3	3 events / 1000 shots	0.7×10^{-4}	43 ±25

PIC Simulations

Particle-in-Cell simulations:

C2D4 target, preplasma 25 microns

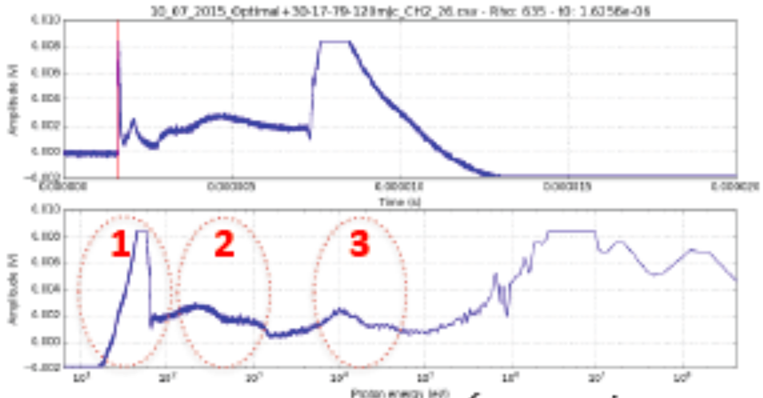
preplasma measured by polarimetry by P. Forestier et al., exponential 15 microns for 30 mJ



	T_1 (keV)	T_2 (keV)
60 mJ	0.13	23.7
120 mJ	0.29	36.7
500 mJ	1.84	81
1 J	2.67	92

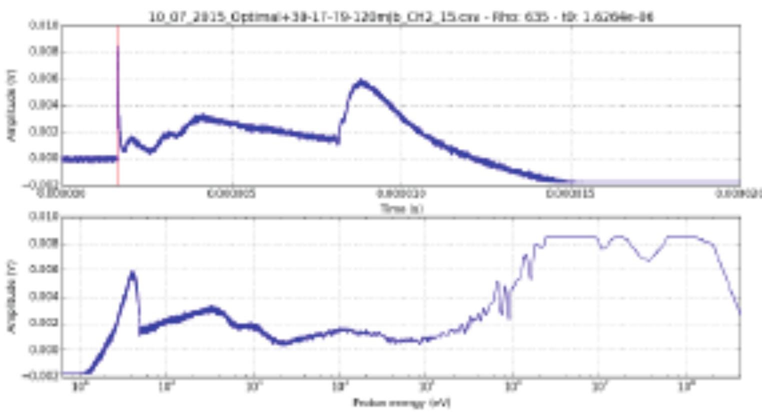
- No TNSA because of the thickness of the target (200 microns)
- Ion acceleration is due to the front-surface charge separation ($T_1 \approx$8.7 keV @ 120 mJ) and thermal expansion ($T_2 \approx$ 36.7 keV @ 120 mJ)

Comparison with ToF measurements (front side of the target):



Shot #26

(energy given per a.m.u)



Shot #15

→ Rather Good reproducibility

Three different contributions with two components (D and C ions):

1: A.eV ions; 2: 1A.keV ions (charge separation); 3: 20A.keV ions (thermal expansion)

→ Good agreement with PIC simulations

CONCLUSIONS

*Protons at energies up to a dozen MeV by irradiating thin Al foils have been accelerated

*Energetic protons sent on a massive ^{11}B sample induced $p+^{11}B$ fusion reactions and alpha particles have been detected

*Irradiating a deuterated plastic foil D+D fusion reactions have been induced and 2.5MeV neutrons detected