National Laser-Initiated Transmutation Laboratory
University of Szeged

HUNGARIAN NATIONAL LABORATORY

Proton and deuteron acceleration with few-cycle, relativistic intensity laser pulses

Károly Osvay

EUROPEAN NETWORK FOR NOVEL ACCELERATORS
EuroNNAc4
NPACT supported by EU via I-FAST

21st September 2022

National Laser-Initiated
Transmutation Laboratory
University of Szeged

Outline

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Motivation – neutrons for transmutation

Experiment I – *Physics* of ion acceleration with single shots

Experiment II – *Optimisation of* p and D^+ acceleration at 1 Hz

Experiment III – *Stability* of proton generation performance

Neutrons generated

Outlook

The Tajima-Mourou Scheme of a Neutron Source for a Laser-based Transmutator

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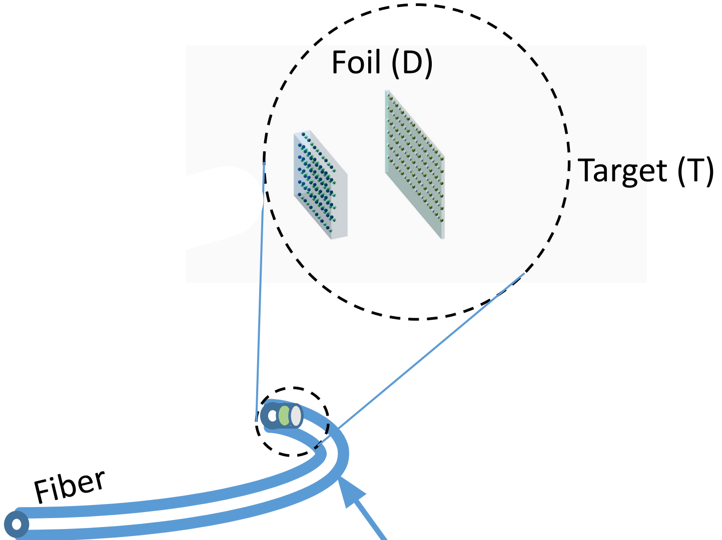

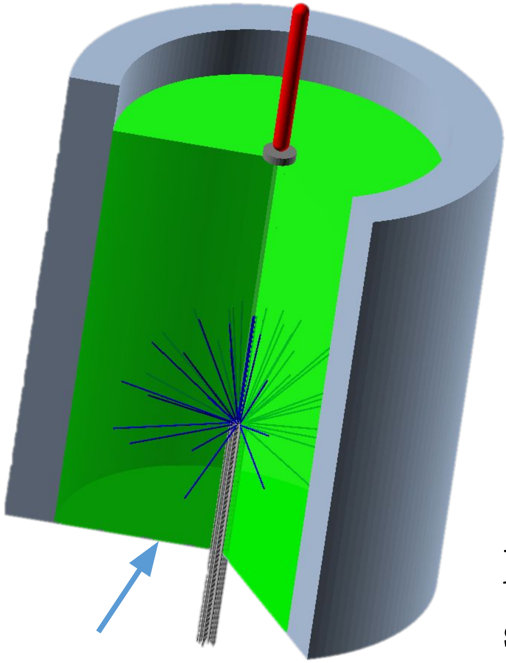

Laser-based fusion neutron source (DT / DD)

Molten salt sub-critical reactor

Tajima et al., Fus.Sci.Tech., **77**, 251 (2021)

Neutron needs and lasers – energy conservation

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Sub-critical reactor, *k>0.99* -> 10^{16} n/s, >1 MeV/n

Average power of the neutrons: 1.6 kW (1.6 kJ /s)

Laser needs

1% conversion from laser to neutron: 160 kW laser

0.1% conversion from laser to neutron: 1.6 MW laser

10% plug-in laser efficiency: 16 MW consumption

Laser-based neutron sources
PW class lasers – current situation

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PhotoFusion

- Accelerate ion (proton, deuterium)
- Make fusion: Be(p,n), Li(p,n), D(d,n) (T)d,n)

Highest efficiency experiment

3.1×10^9 n/J

0.05% laser->neutron

Günther et al., Nat. Com.13, (2022) 170

Photonuclear

- Accelerate electrons
- Brehmstralung and high Z converter: (γ,n), Li(p,n), D(d,n) (T)d,n)

7×10^8 n/J

0.02% laser->neutron

Average power of such lasers is <1W

Laser spallation

- Accelerate proton
- Make fusion: Be(p,n), Li(p,n), D(d,n) (T)d,n)

Predicted efficiency

$\sim8\times10^{10}$ n/J

~1% laser->neutron

Martinez et al., MatRadExt 7 (2022) 024401

High average power lasers

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Average power of industrial ps lasers is >(>)1kW

See Metzger's talk today!

Average power of scientific, few cycle pulse lasers (ELI) is >>100W.

See Limpert's and Labate's talk today!

Current laser technology supporting high average power and relativistic pulse intensity is the high repetition rate, few TW peak intensity one.

↓

Let's investigate ion acceleration with few cycle pulses!

Experiment I – *Physics*

Single shot experimental campaigns in ELI-ALPS

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Shooting on target: 26 and 14 working days
>1500 single shots

Target materials:

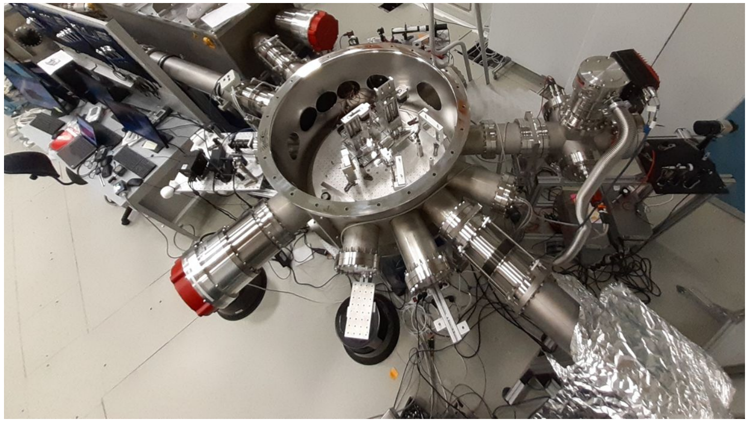
Commercial: Al, C, CH, DLC, PET
Home-made: formvar, dPE

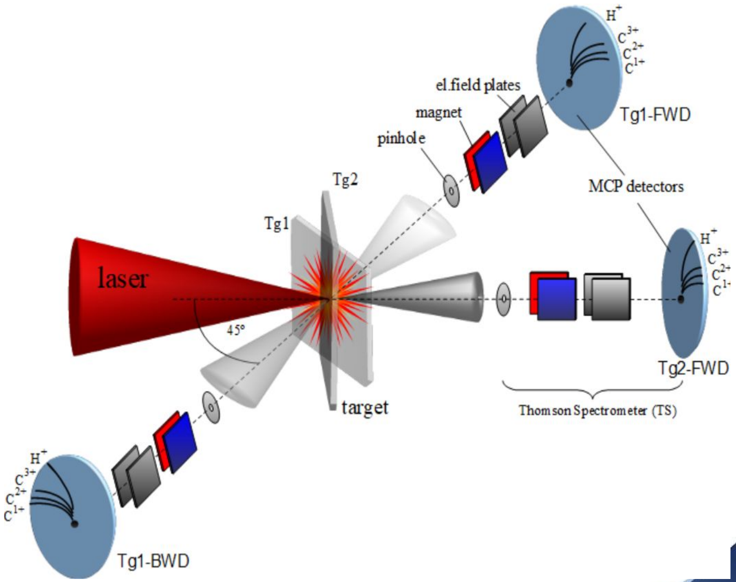
Target thickness:

5nm, 10nm, 20nm, 50nm, 100nm, 200nm, 500nm, 2µm, 9µm

Diagnostics

Thomson ion spectrometers (BWD, FWD)





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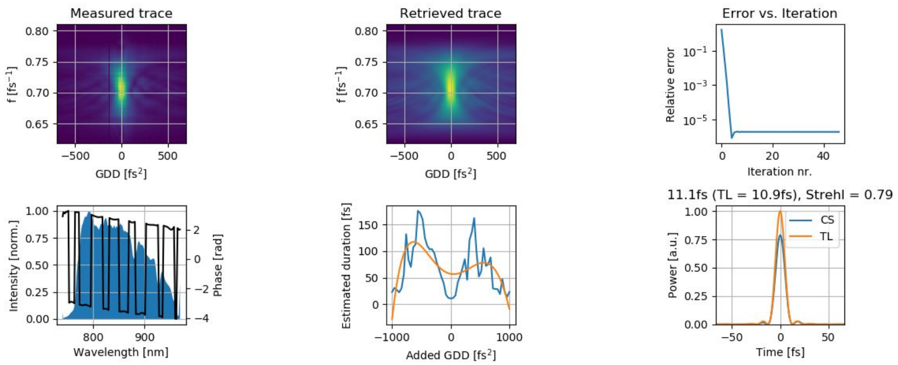
EuroNNAc Special Topics Workshop
21st September 2022

SEA laser (10Hz, OPCPA) of ELI-ALPS parameters *on target*

Pulse energy: *~35 mJ*
(measured for each shot)

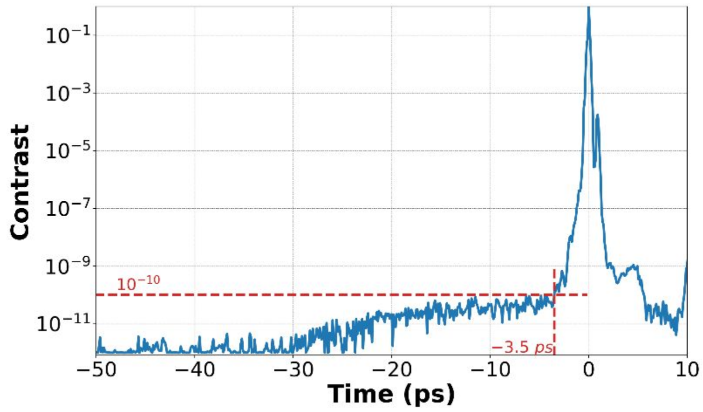
Laser pulse duration: *11.6 fs*
Measured in vacuum, after OAP, with disp scan



Focal spot FWHM: $2.9\times3.5\ \mu m^2$,
Strehl ratio: >0.8

Peak intensity in focus:
$\sim10^{19}$ W/cm^2 (a_0=2.3)

Temporal contrast



Toth, et al., Photonics **2**, 045003 (2020)

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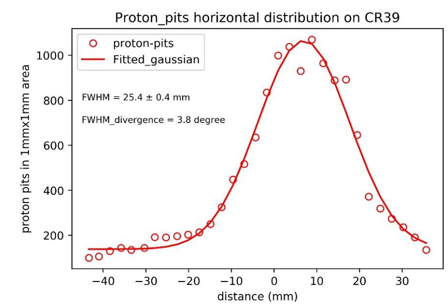
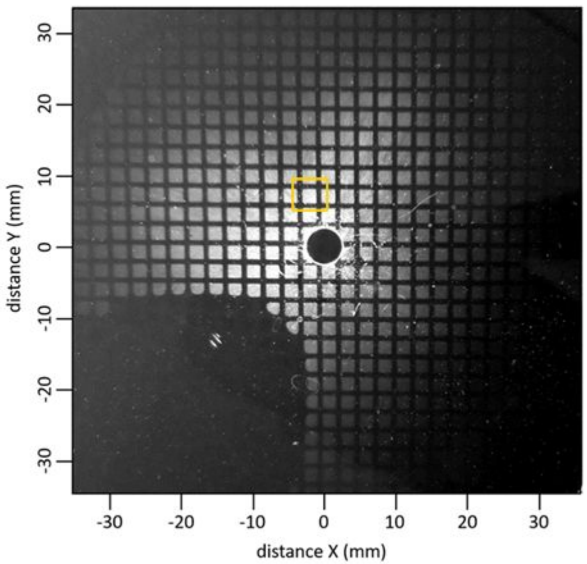
Dr. Károly Osvay
ELISS 2022
31st August 2022

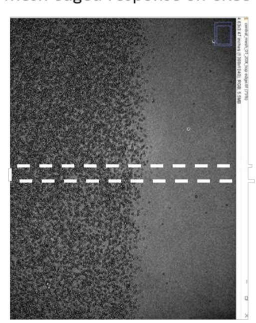
Study of ion acceleration by few cycle laser pulses

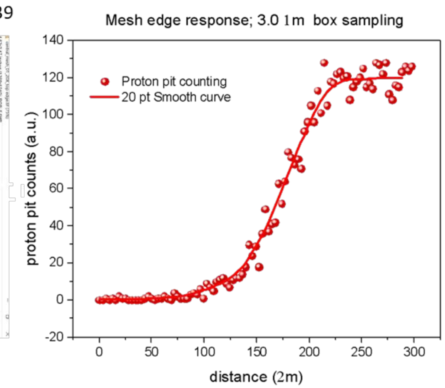
Proton acceleration results – proton beam characterisation

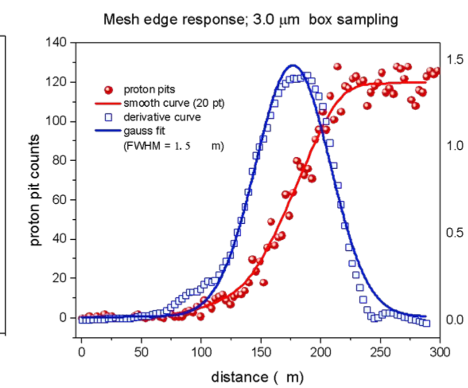
- Large number of protons (above 100keV: 10^{10}/shot);
- Small beam divergence (<65mrad for protons > 250 keV)
- Small emittance   0.00032 π-mm-mrad











Singh et al., Sci. Rep. 12, 8100 (2022)

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Study of ion acceleration by few cycle laser pulses

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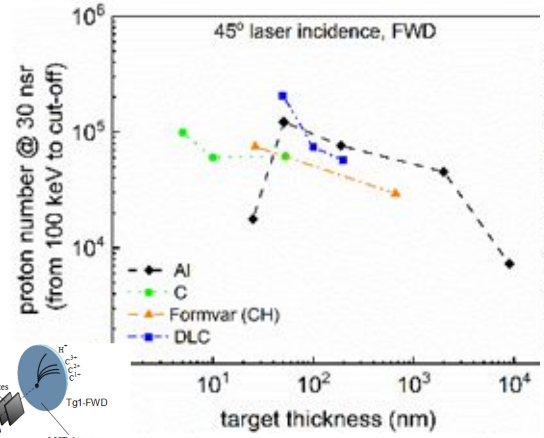
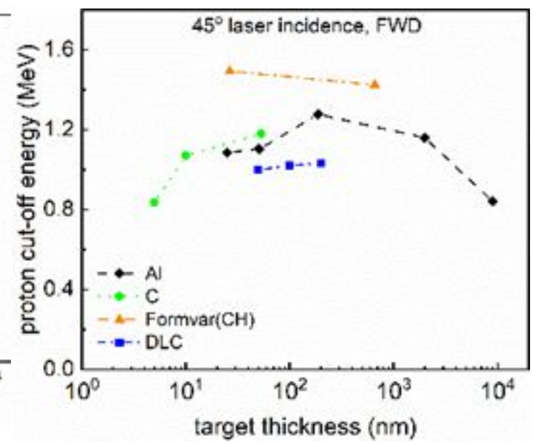
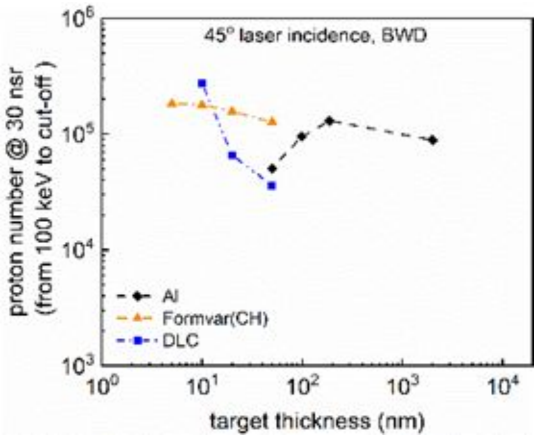
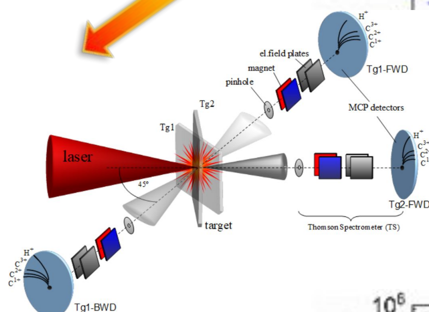
Proton acceleration results – target material and thickness





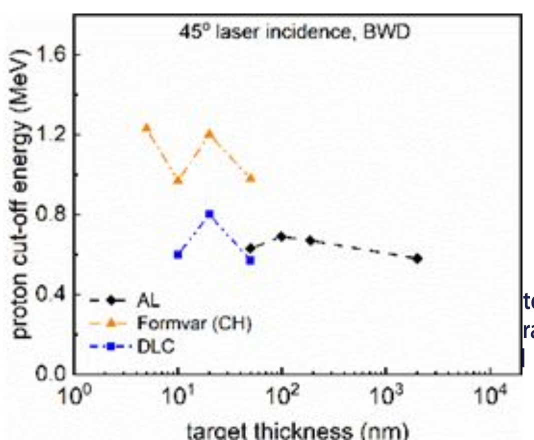
Particle number 1/4



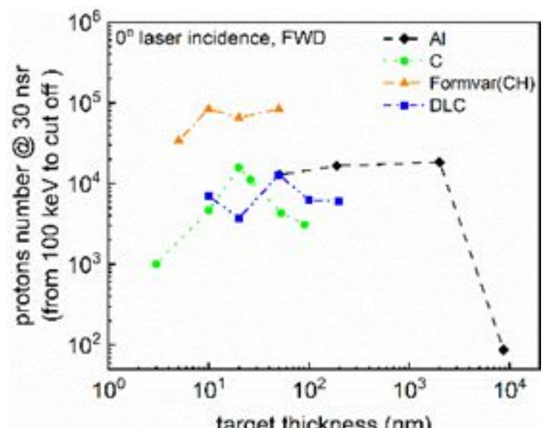


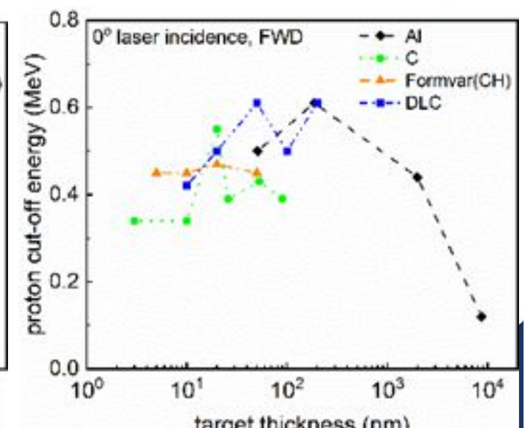
Particle number 1/10 (exc. CH)

Cut-off Energy 1/2



Cut-off Energy ~2/3





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Physics

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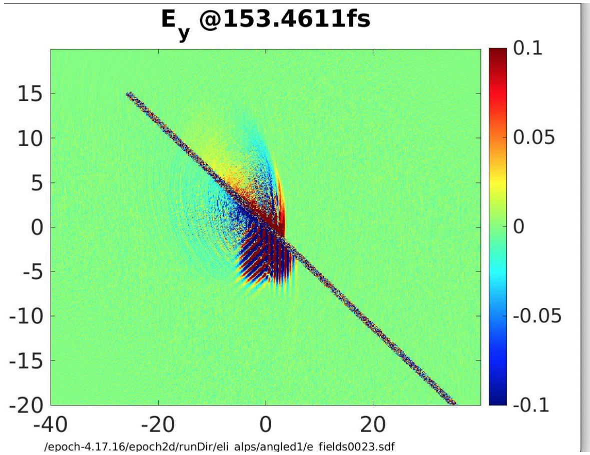
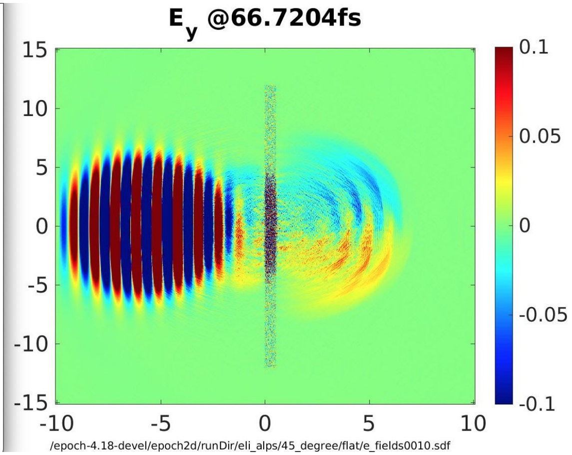
- High cut-off energy protons (compared to the pulse energy)
- Reasonable conversion efficiency (1% – 1.5%)
- Dominant acceleration from thick targets: TNSA and TNSA(+Coulomb)
- Acceleration from ultrathin targets:
  LS or CAIL and (TNSA+)Coulomb;
- Acceleration FWD at 45°: Brunnel-type heating of electrons

Veltcheva et al.,PRL 108, 075004 (2012)





PF + Brunel

E_y is large on the backside

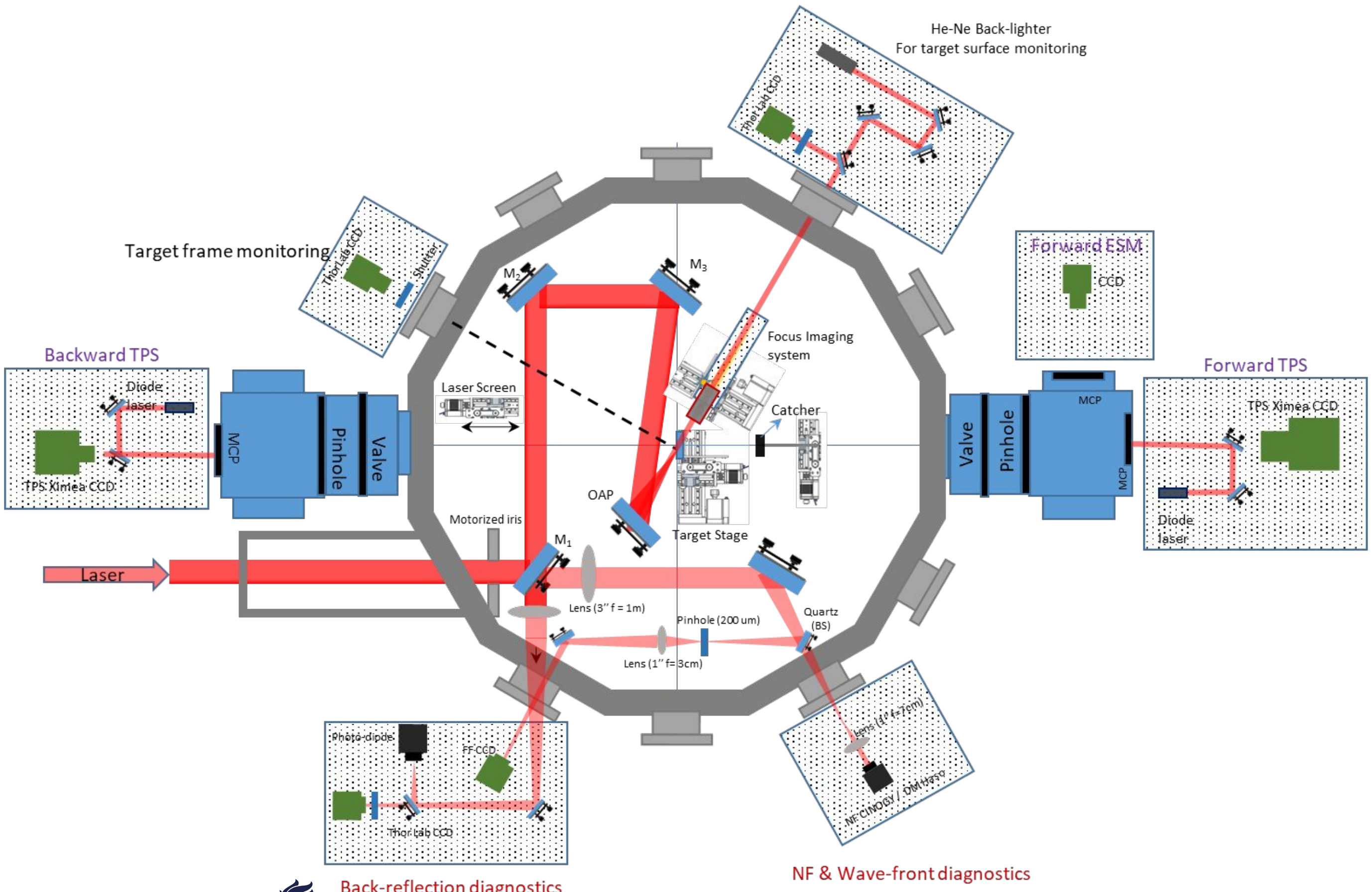
Purely PF driven electrons

E_y is small on the backside

Ter-Avetisyan et al., *in preparation (2022)*

Experiment II – *Optimisation (attempt) at 1 Hz repetition rate*

Laboratory time in ELI-ALPS
10.6.22-23.06.22, 7 laser days, ~4000 shots



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Rotating wheel target

In collaboration with Universidad Santiago de Compostela

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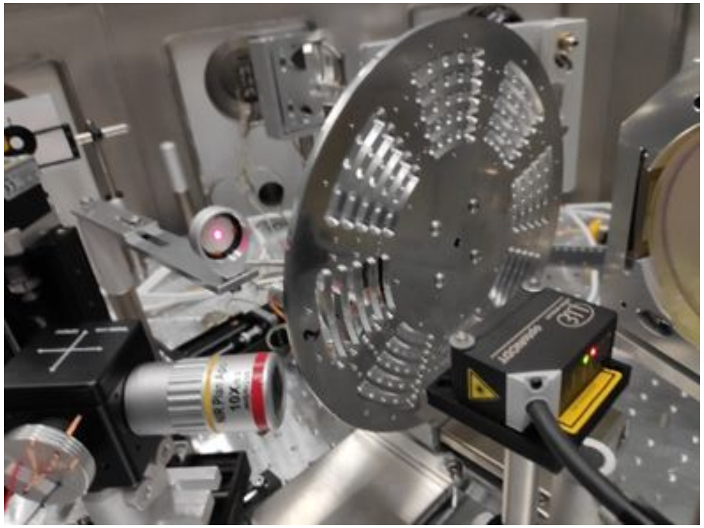
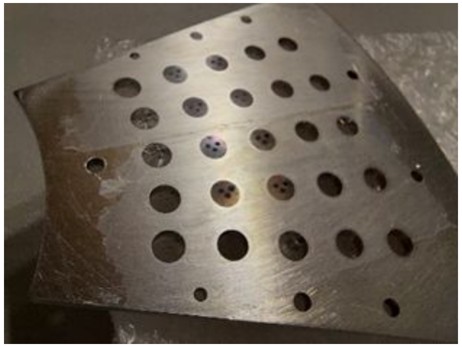


UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

7 (+1) segments
25 holes per segment (5x5)

Home-made dPE foil ~200nm
Bar et al., RSI **91**, 103302 (2020)

Prior to shoot - mapping
- target foil position in the center of each hole (5μm precision in *z*)
- 3 shots in each hole



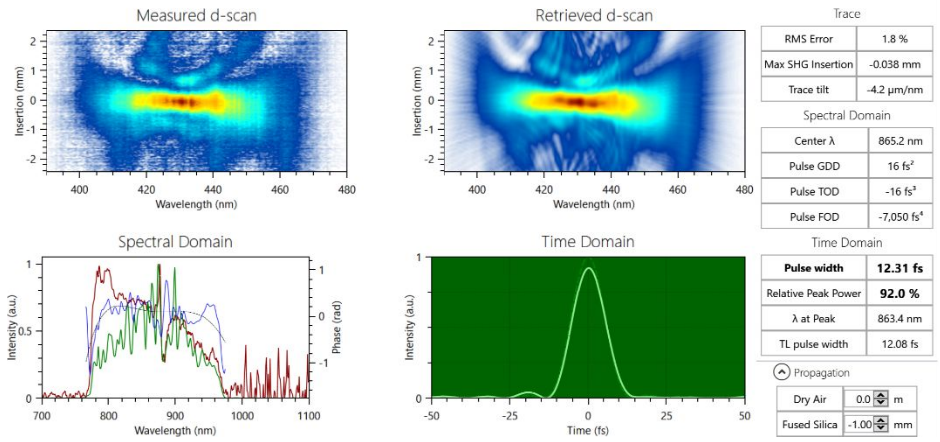
1 Hz operation in burst mode
Bursts: up to one segment (75 shots)

LASER

SEA laser (10Hz, OPCPA) of ELI-ALPS parameters *on target*

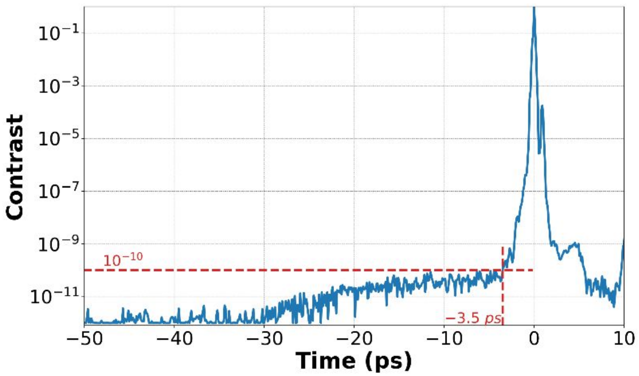
Pulse energy: 20 mJ
(measured for each shot)

Laser pulse duration: 12.3 fs
Measured in vacuum, after OAP, with disp scan



Focal spot FWHM: $2.9\times3.5\ \mu m^2$,
Strehl ratio: >0.8

Temporal contrast



Peak intensity in focus: **~3×10^{18}** W/cm^2

Toth, et al., Photonics **2**, 045003 (2020)

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Proton and Deuterion and acceleration at 1 Hz repetition rate

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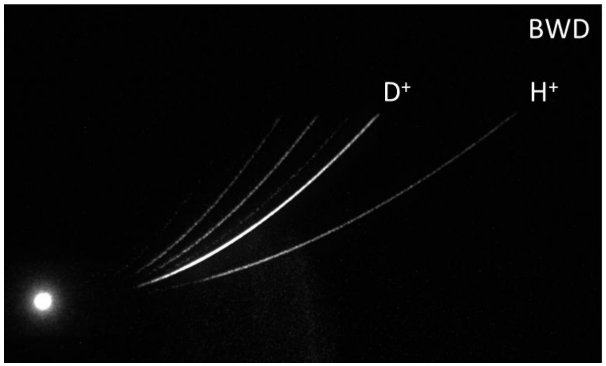
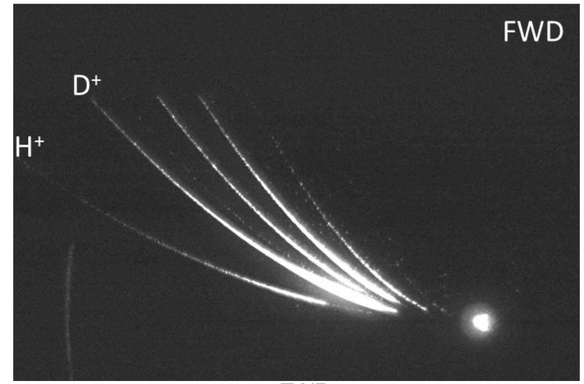
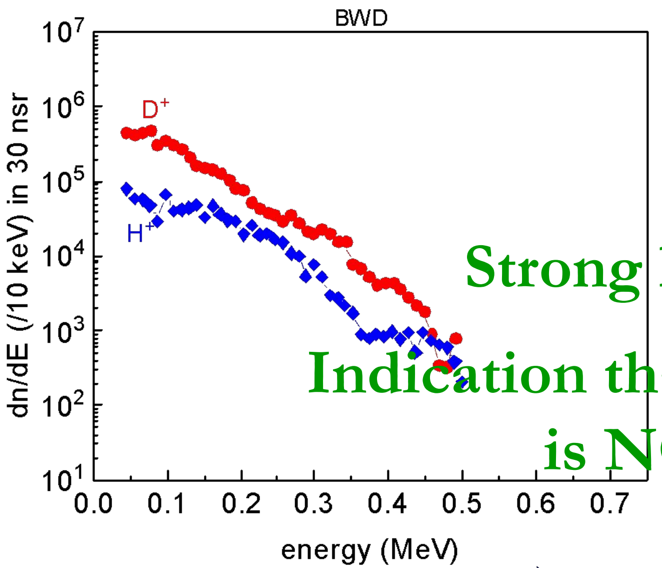
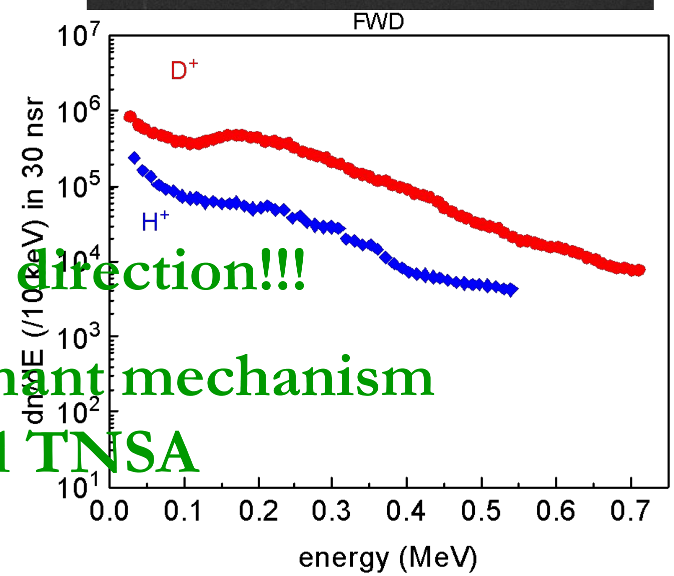
Each shot is recorded and stamped – example shot #976









Strong D+ in FWD direction!!!

Indication that the dominant mechanism is NOT classical TNSA

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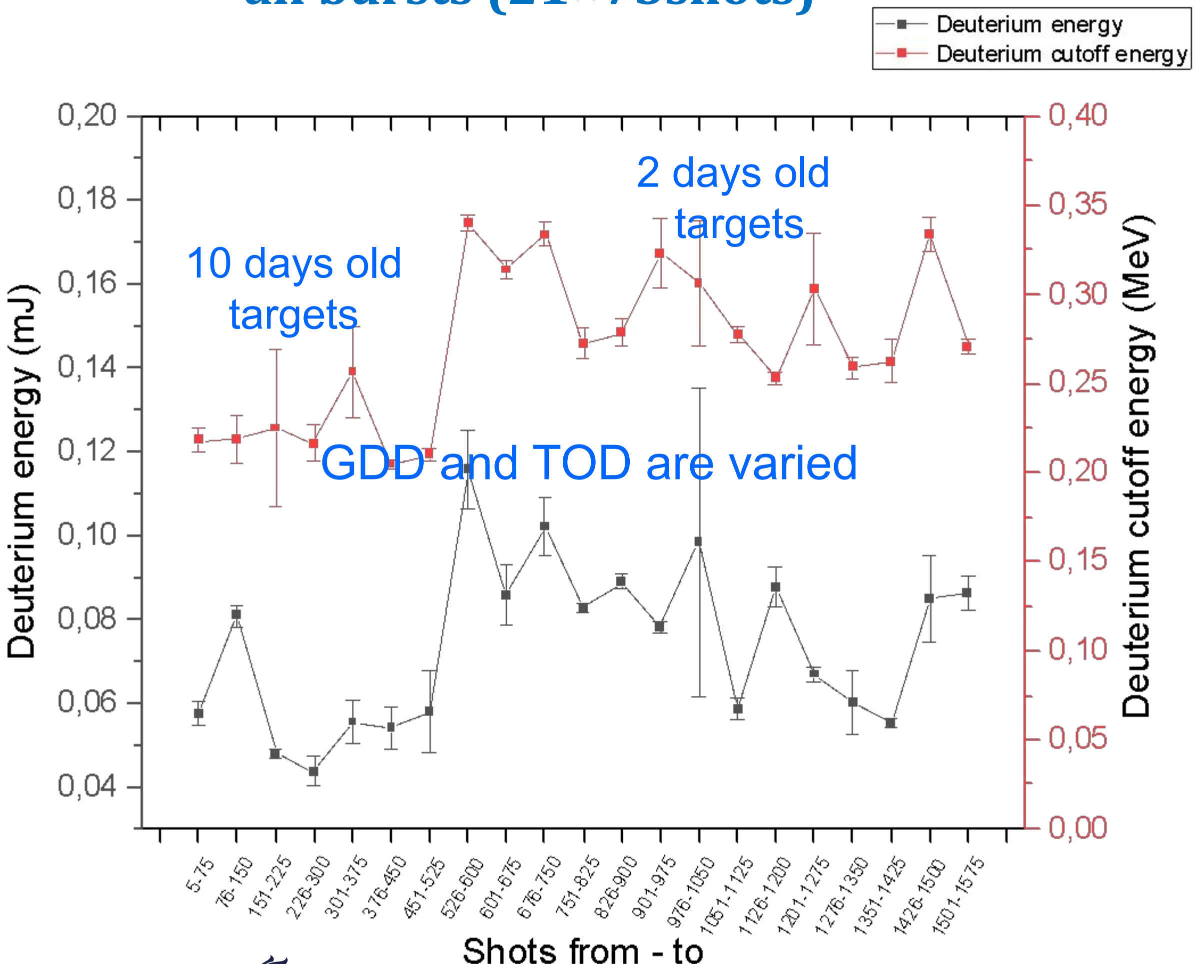
Deuterion acceleration at 1 Hz repetition rate

Deuteron in FWD direction, 23rd June all bursts (21×75shots)



FWD Proton and deuterion acceleration GDD and TOD scan

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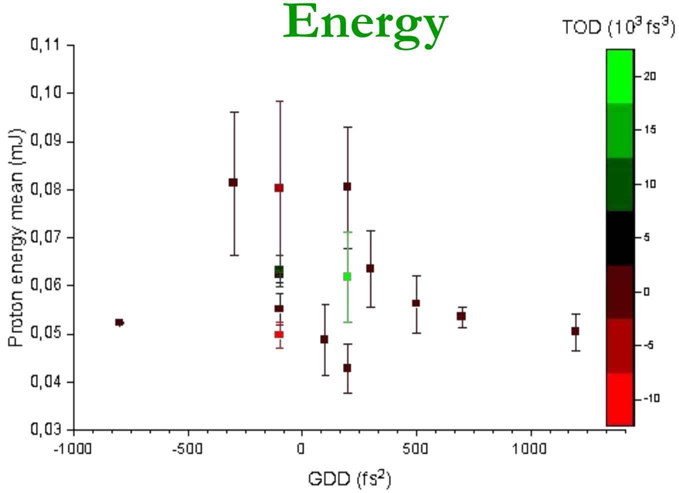
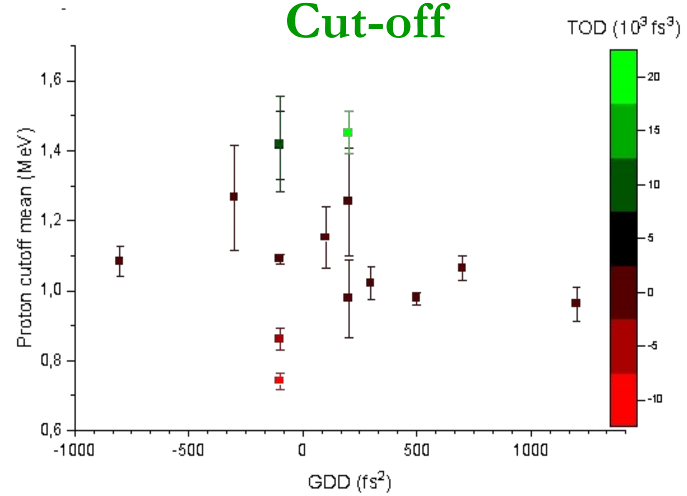
22nd June, top 3 bursts (each of 75shots)

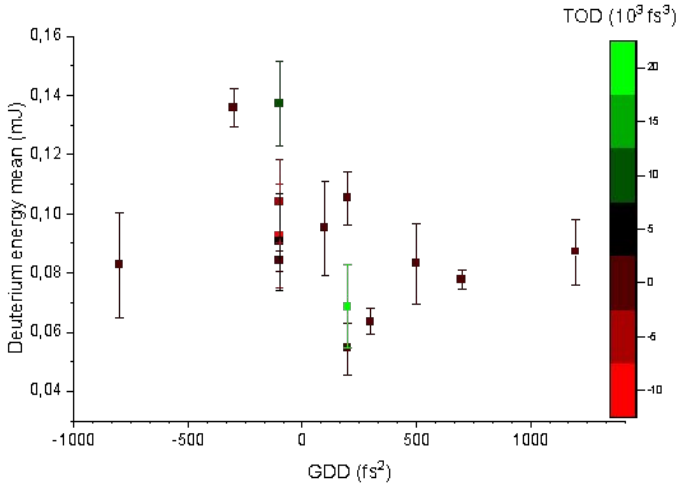
Energy **Cut-off**

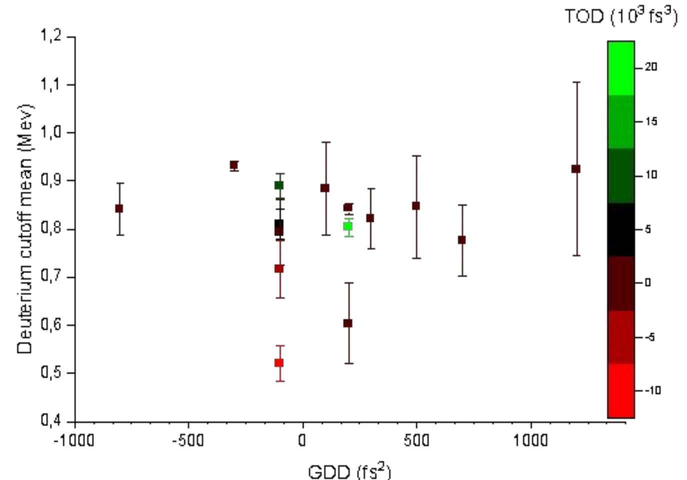
Proton





Deuteron





Full evaluation is in progress

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BWD Proton and deuterion acceleration GDD and TOD scan

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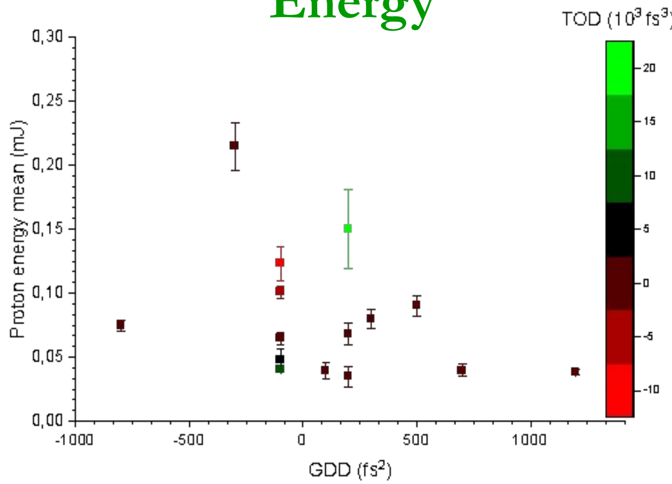
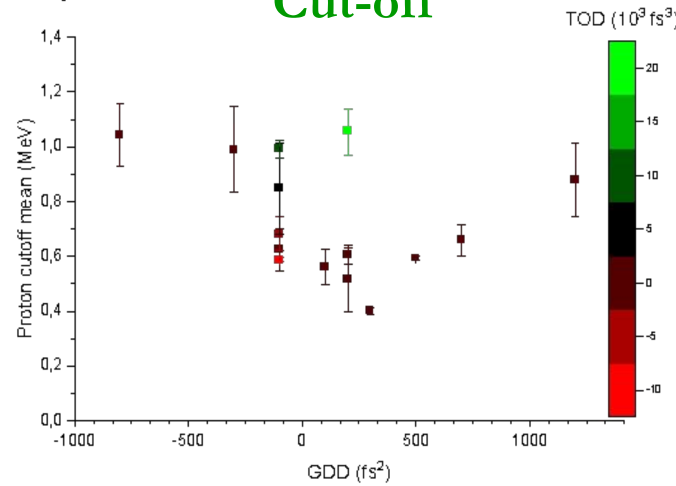
22nd June, top 3 bursts (each of 75shots)

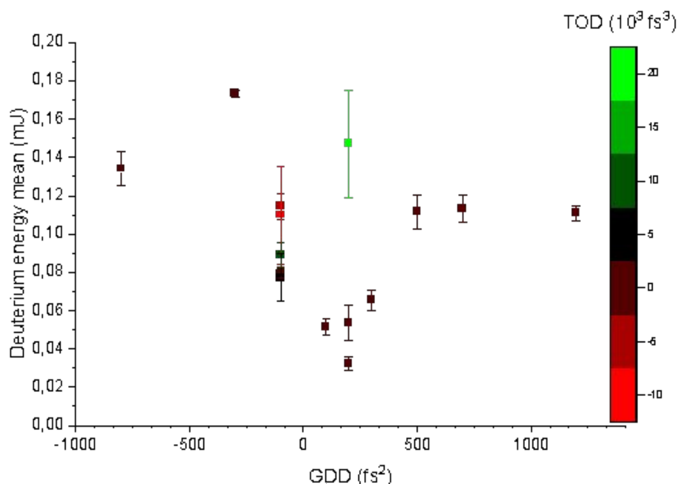
Energy | **Cut-off**

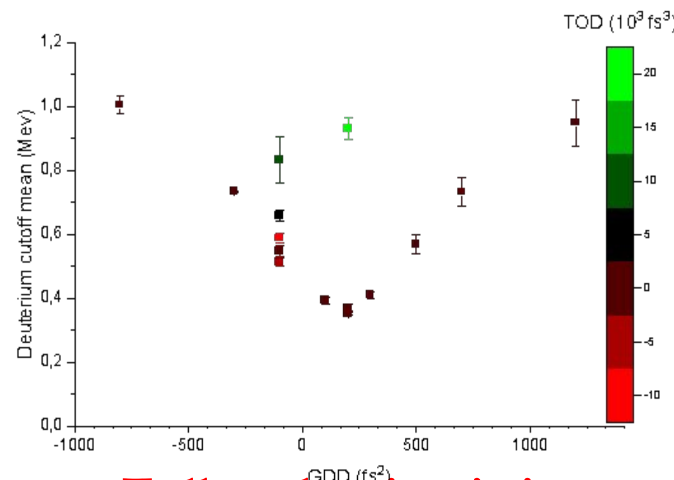
Proton





Deuteron





Full evaluation is in progress

BWD Proton and deuterion acceleration
GDD and TOD scan

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Preliminary observations

- **BWD p and D^+ energy and cut-off scale together with GDD & TOD;**
- **BWD the major effect is the GDD one.**
- **FWD p and D^+ energy and cut-off scale differently with GDD & TOD;**
- **Effect of GDD can be decreased by opposite sign TOD**
  Various regimes under optimal operation.
- **With the tune of GDD and TOD, the p / D^+ ratio could be varied.**
- **Some of these in agreement with recent works, some are new.**

Ziegler, et al., Sci.Rep. 11, 7338 (2021)
Permogorov, et al., Sci.Rep. 12, 3031 (2022)

- **The error of energy and cut-off is large (~25%) within a burst.**
  (probably due to the error in preparation of targets and focusing)

Experiment III – *Stabilisation (attempt) at 1 Hz repetition rate*

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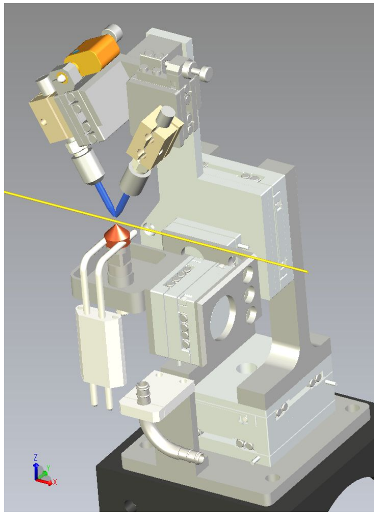
(Ultra)thin liquid leaf

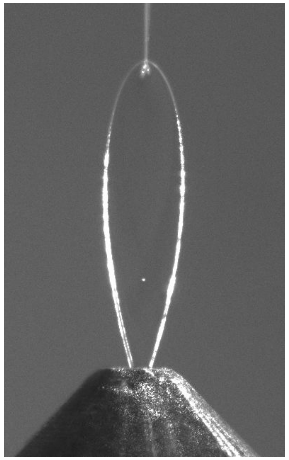
Advanced Microfluidic Systems GmbH

- **Two liquid jets collide from two nozzles**
- **Stable leaf with length of 1.5 mm**
- **Pulsation damping system**
- **Recirculation system enables continous operation**
- **Cold finger**



First attempt

- nozzles of ∅ 21 μm
- Leaf thickness in the middle: ~540nm
- vacuum in target chamber kept at 10^{-4} mbar



Experiment III – *Stabilisation (attempt) at 1 Hz repetition rate*

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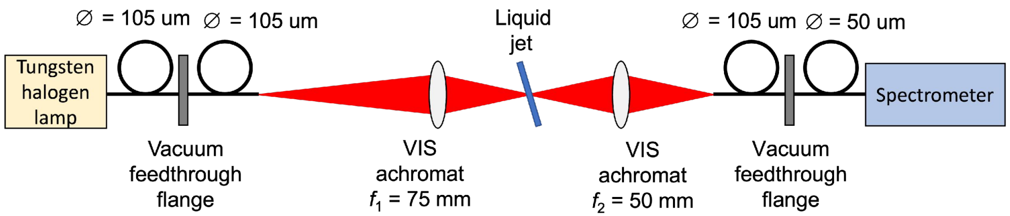
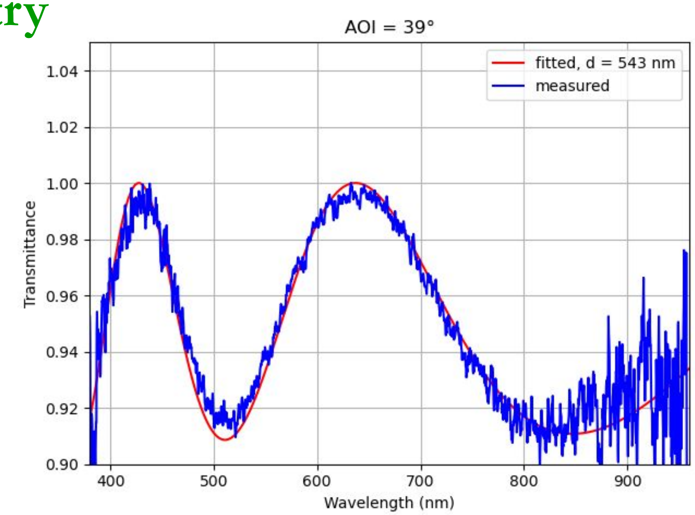
Liquid leaf characterisation

Thickness measurement with spectral interferometry

Vacuum compatible

The current measurement limit is ~150 nm.





Spatial measurement with stabilised HeNe

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FWD & BWD Proton acceleration

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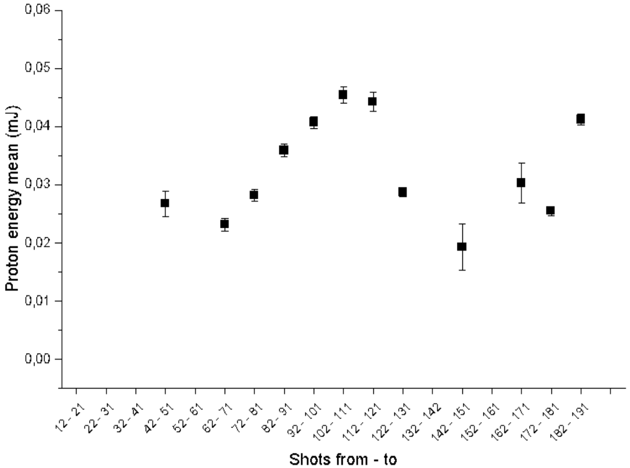
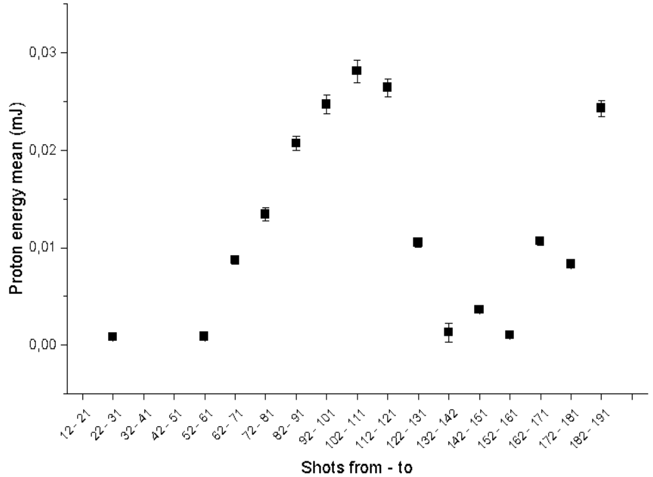
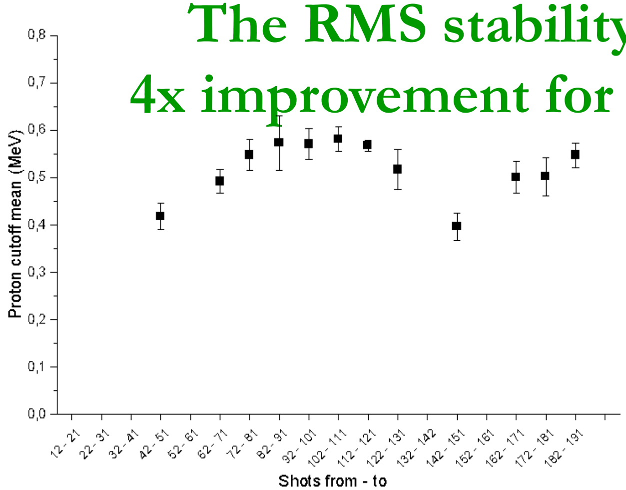
Bursts with 10 shots, optimisation for target position

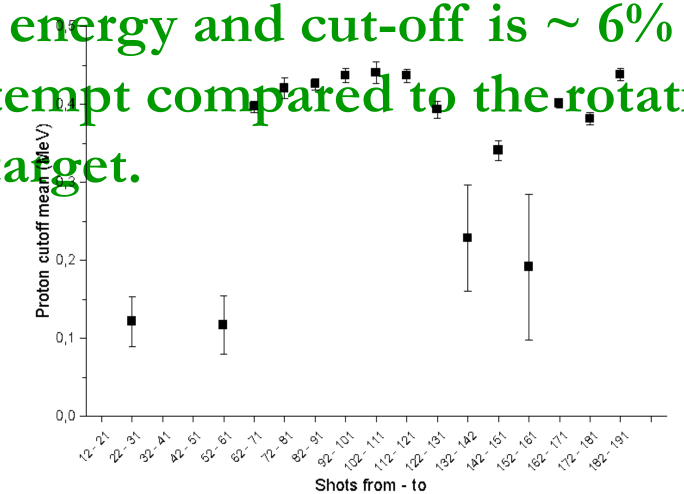




The RMS stability of proton energy and cut-off is ~ 6%

4x improvement for the first attempt compared to the rotating wheel target.





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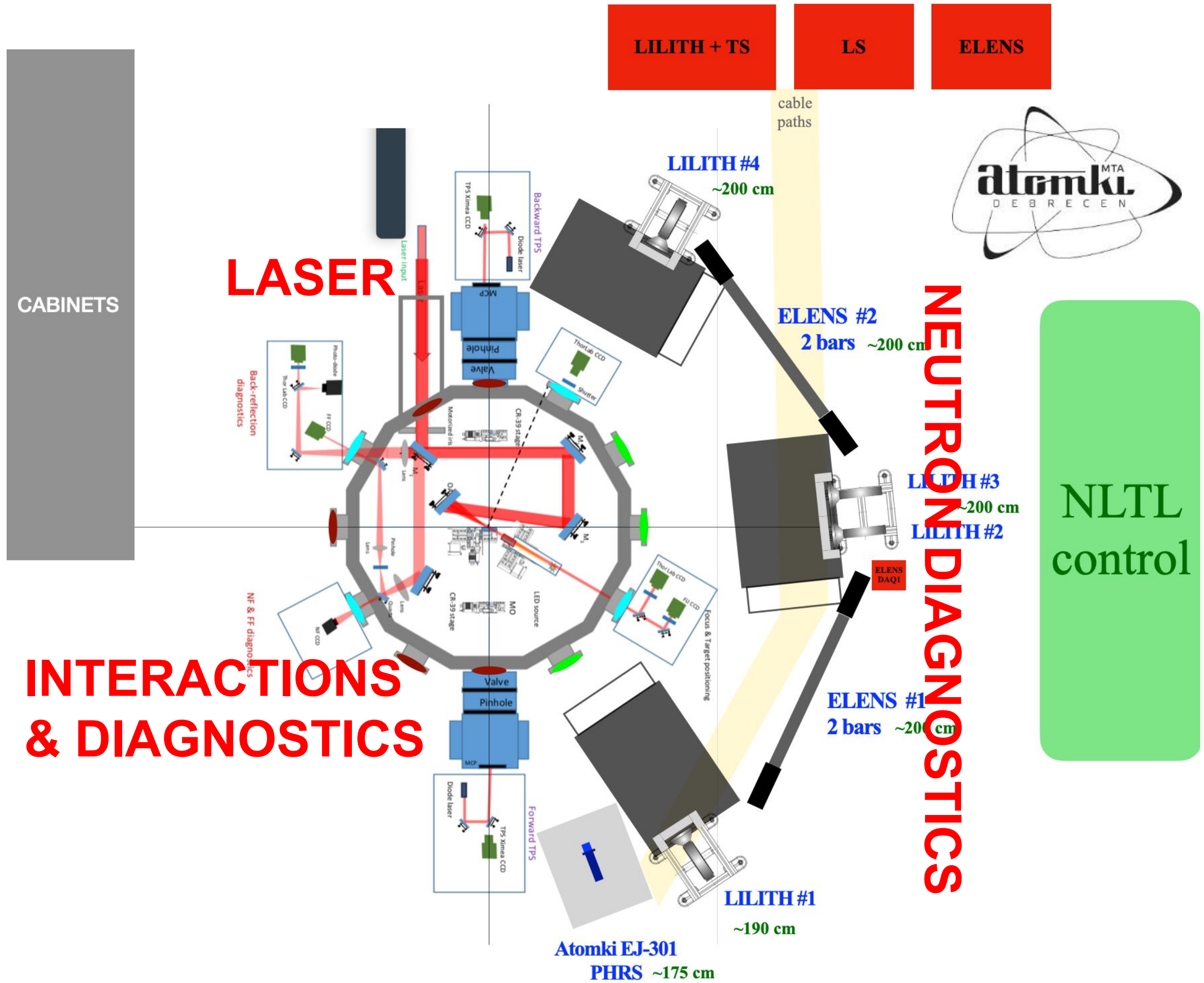
Neutron generation

Laboratory time in ELI-ALPS

10.6.22-23.06.22, 7 laser days, ~3000 shots in 3 days



INTERACTIONS

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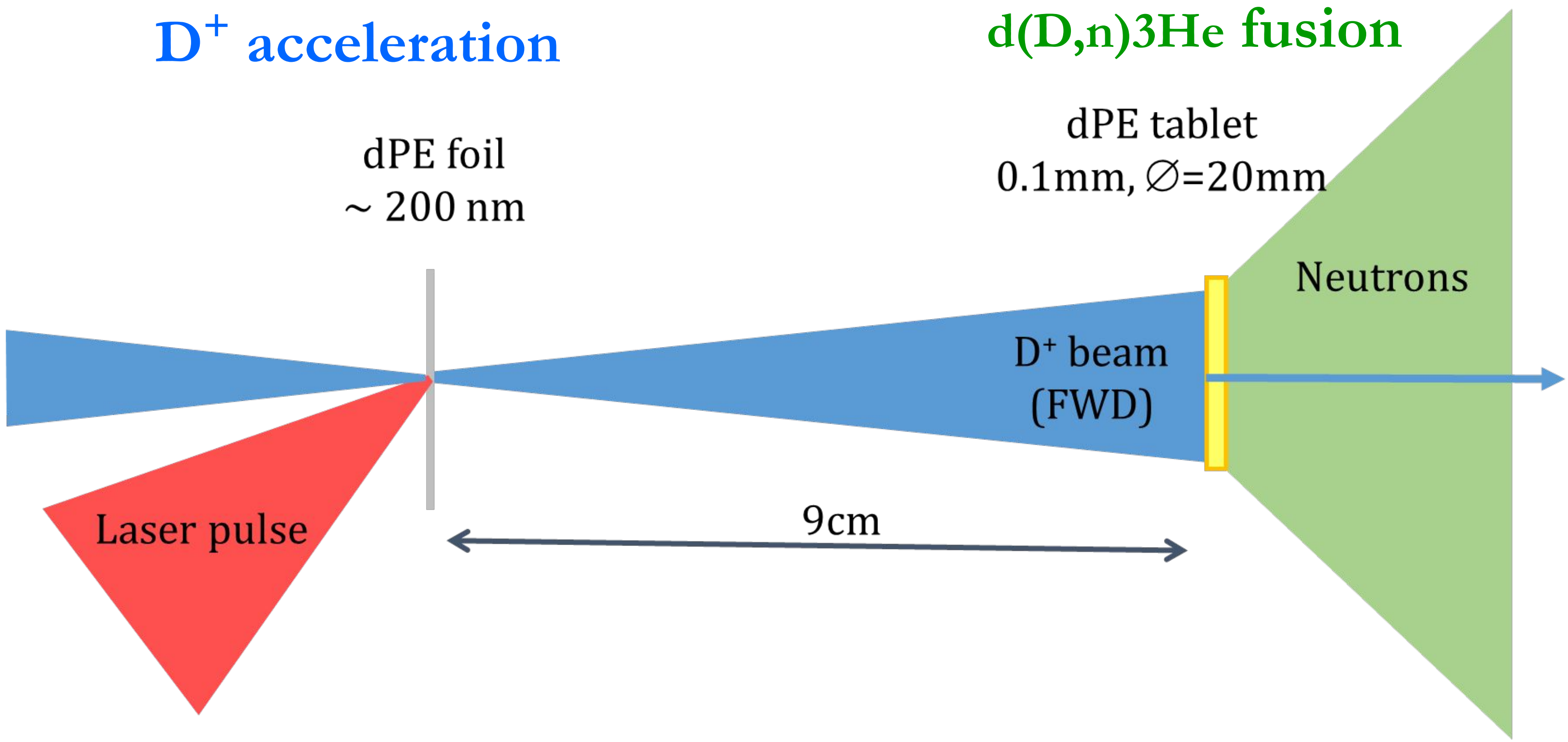

Primary target (pitcher)

Home-made

Bar et al., RSI **91**, (2020) 103302

Secondary target (cathcer)

from dPE powder, press-machine

Fast neutron generation with 1 Hz repetition rate

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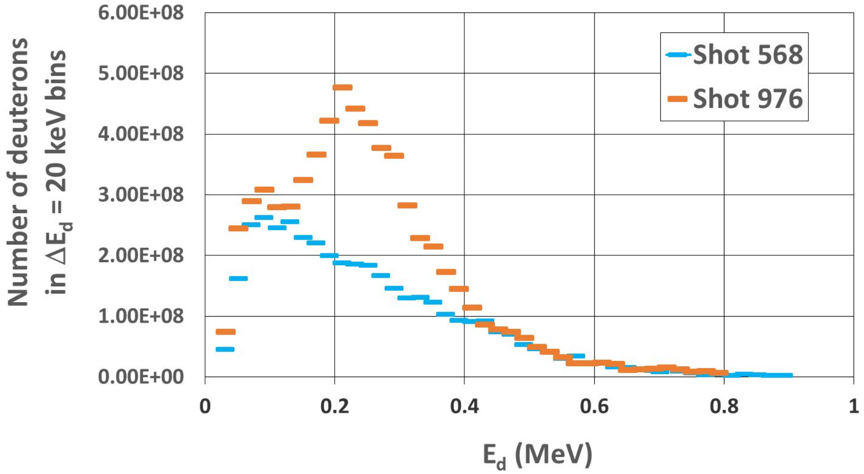
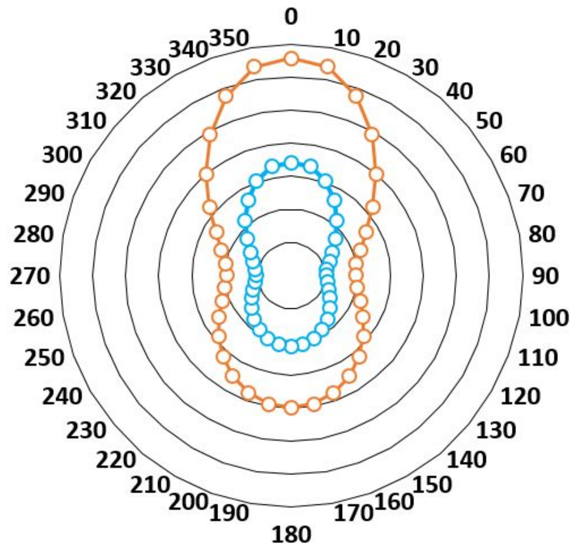
For simulations, so far two typical spectra were considered

one with high cut-off energy
one with high total D+ energy





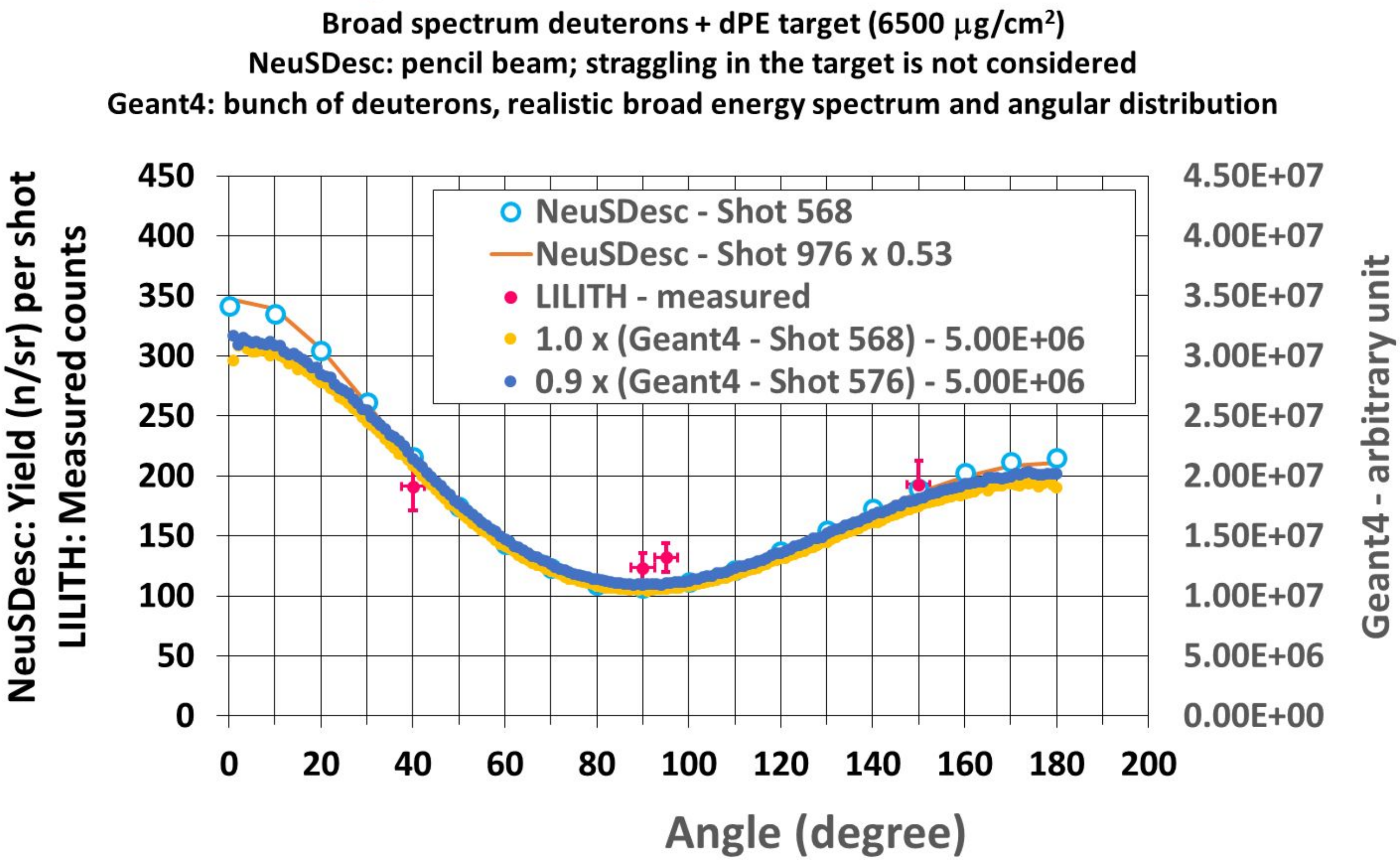
Neutron yields for $\Theta = 4\pi$

Shot 568: 1978 neutrons per shot

Shot 976: 3649 neutrons per shot

Fast neutron generation with 1 Hz repetition rate

Angular distribution – measurement and simulations



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Conclusion and outlook

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Proton acceleration with few cycle pulses is a mixed process

D^+ yield depends on the chirp of the pulse

Generated neutrons at 1 Hz (first results) **>2000 n/shot**
~ 2MeV/n

Next steps: ***thinner dPE foil*** (<10nm) – to reach "RPA / LS" regime
optimise D yield for neutron via chirp, etc.
improve focusing
go for <6fs – pulse compression
go for kHz - further target system developments
deep learning

Pulse compression towards single-cycle pulses up to 1 khz

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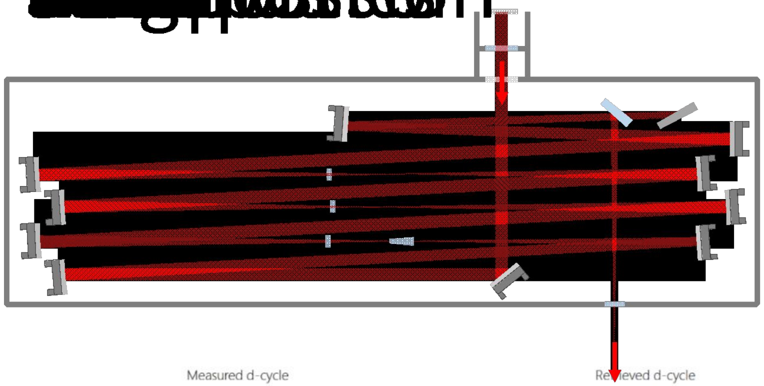
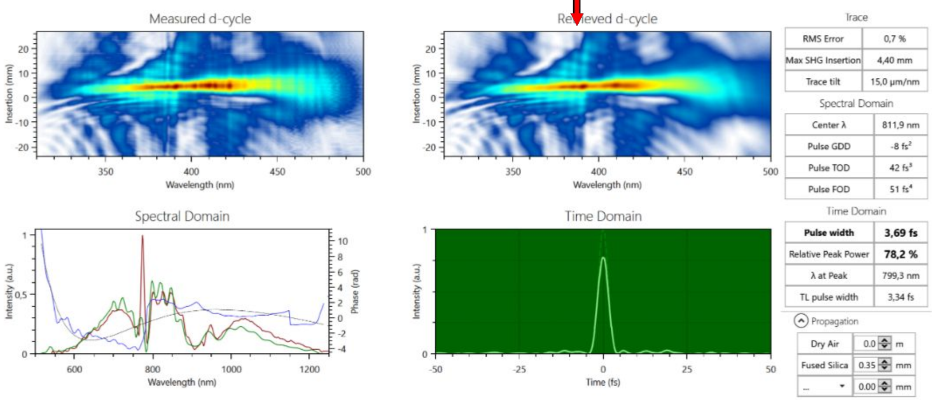
Implementation based on a multi-plate pulse compressor



Results (state of the art):
- Pulse shortening: 12 fs -> 3.7 fs
- Transmission: >90%
- Outcoming energy: 13 mJ

Probably the current energy record for single cycle pulse!



Nagymihaly et al, (2022), under submission

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Grants

- ITM szerződés: ITM 1096/2019. (III.8.) kormányhatározat

- NKFIH szerződések:
  1. NKFIH-877-2/2020
  2. NKFIH-476-4/2021
  3. NKFIH-476-16/2021

Thank you for your attention

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