A fast neutron source driven by an 80W average-power laser and its application in radiobiology

Károly Osvay

EAAC ’25, Isola d’Elba

25th September, 2025

Outline

Motivations

Laser-based neutron sources

Neutron generation at 10 Hz

Optimisation of the temporal shape

Neutron generation at 1kHz

Irradiation of zebrafish embryos

Motivation

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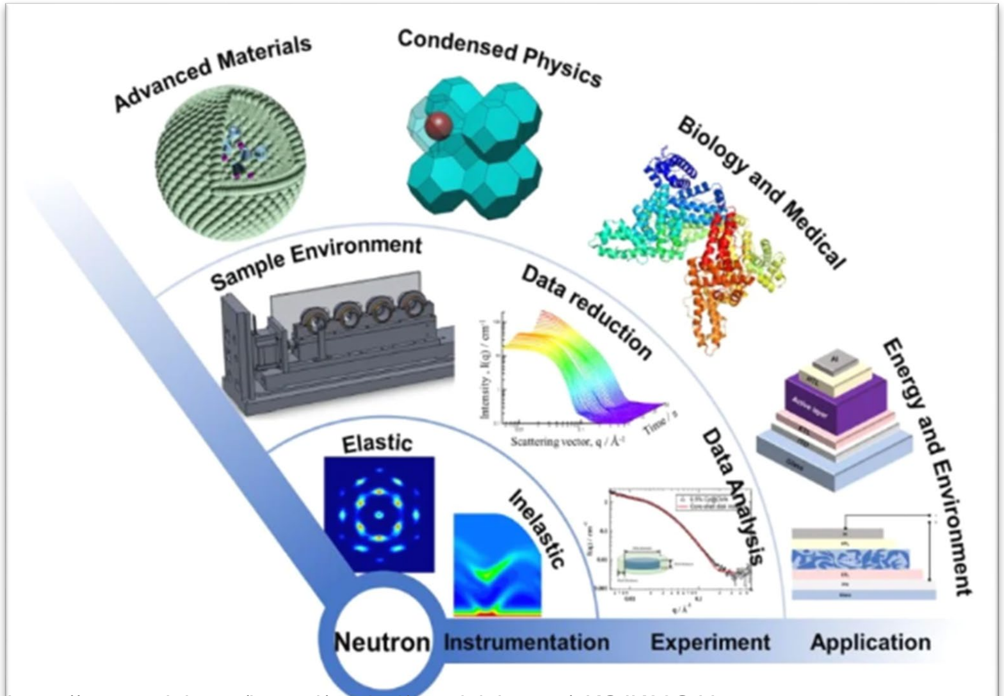
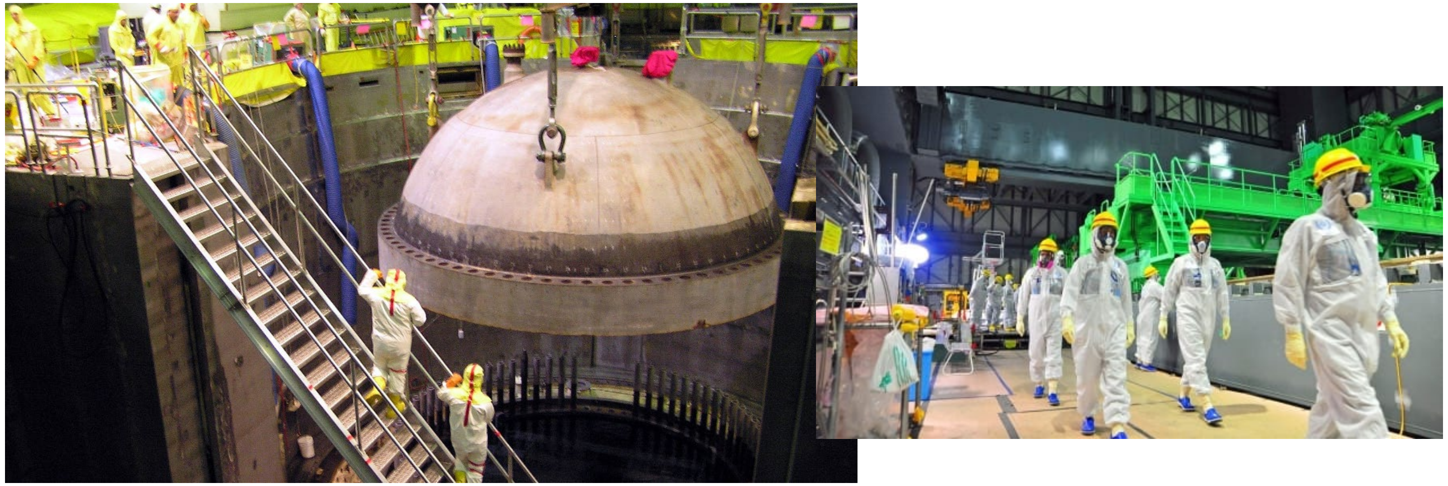
Neutron
- High penetration in material
- Direct interact with nuclei

The number of neutron facilities sources is decreasing
- reactors are aging, and closing down.
- big sources are delayed.



https://www.mdpi.com/journal/applsci/special_issues/7KCJK80OJJ



Specialities of a laser-based neutron source
- neutrons are generated in ultrashort bunches
- the ”machine” (laser) and the ”source” can be separated
- the laser is not a nuclear device

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Strategies ”*en large*” for a laser driven particle (neutron) source

NLTL approach

Use T(P)W lasers from single shot mode
Contrast issues

Increase laser repetition rate
Target development

Start from ”ideal”, ”Dirac”-pulse
Investigate interactions and optimise yields

High repetition rate target development
Purpose designed laser
Increase pulse energy

Both paths would lead to a laser accelerator based particle source…
… with differences especially in early stage

Common challange, where we meet down the road:
High Repetition Rate Targets

Ion Acceleration and Neutron Generation with Few-Cycle Lasers

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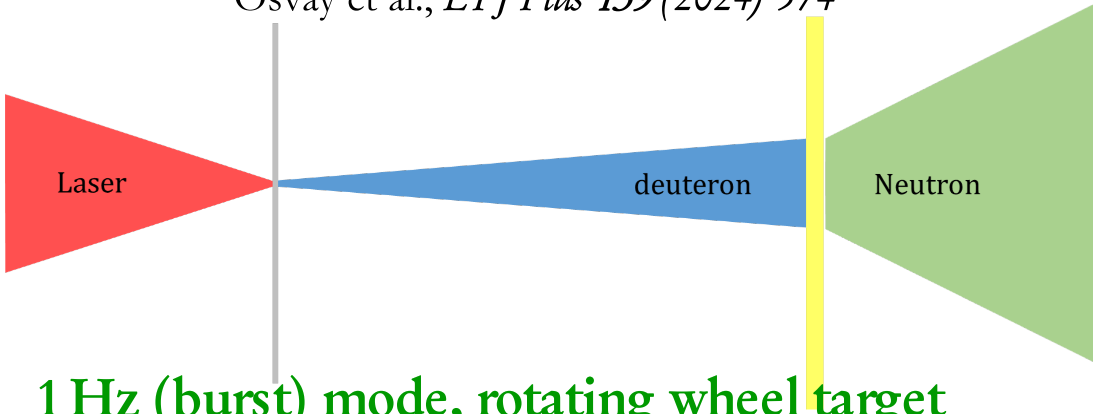
D^+ acceleration

d(D,n)3He fusion

Osvay et al., *EPJ Plus* *139* (2024) 574



1 Hz (burst) mode, rotating wheel target
Deuteron acceleration from foils and neutron generation

Osvay et al., Sci.Rep. **14** (2024) 25302

Single shot, few-cycle, single cycle pulses
Study of ion acceleration on ultrathin foils

Singh et al., Sci.Rep. **12** (2022) 8100
Varmazyar et al., Rev.Sci.Instr. **93** (2022) 073301
Ter-Avetisyan et al., PPCF **65** (2023) 085012
Toth et al., Opt. Lett. **48** (2023) 57
Hadjikyriacou et al., in prep.

Development of an ultrathin liquid leaf target system

Füle et al, HPLSE **12** (2024) e37

Deuteron acceleration from liquid leaf and neutron generation

Varmazyar et al, Comm.Phys. **8** (2025) 350
Stuhl et al, PRR **7** (2025) 023137

Neutron generation at 10 Hz repetition rate

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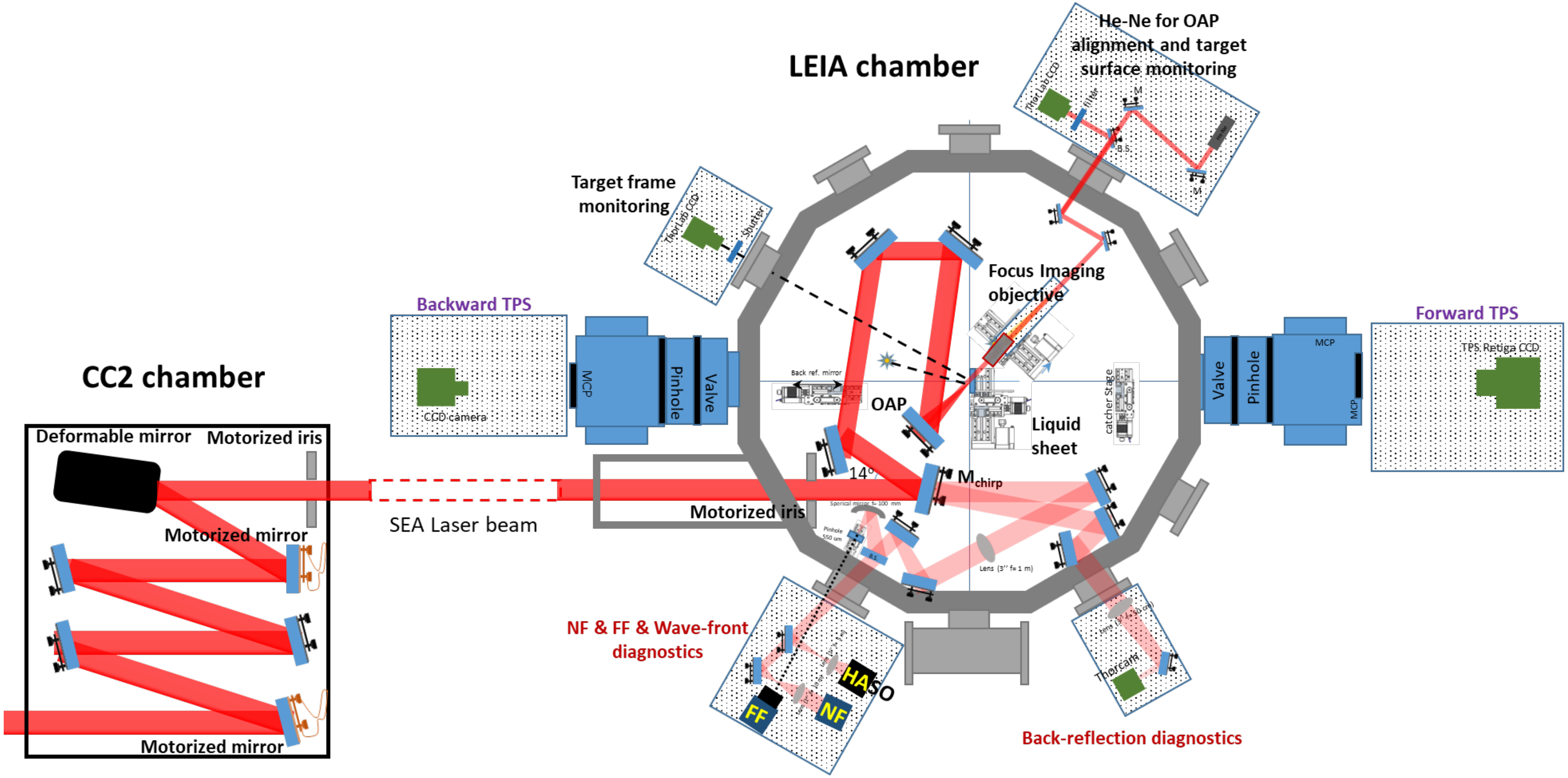

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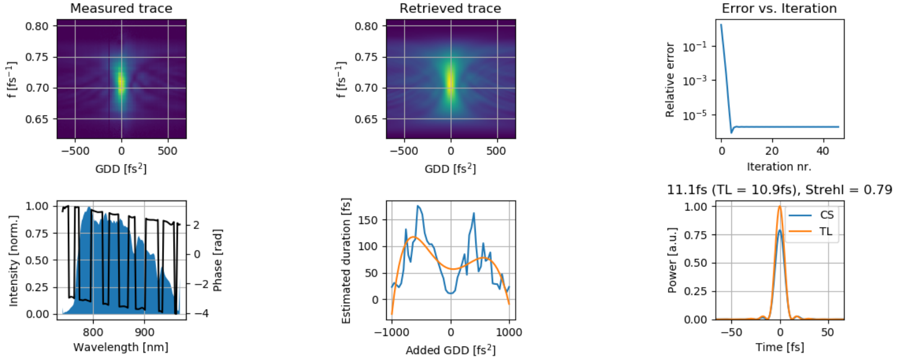
SEA laser (10Hz, OPCPA) of ELI-ALPS parameters *on target*

Pulse energy: ~21 mJ (35mJ at laser)
(measured for each shot)

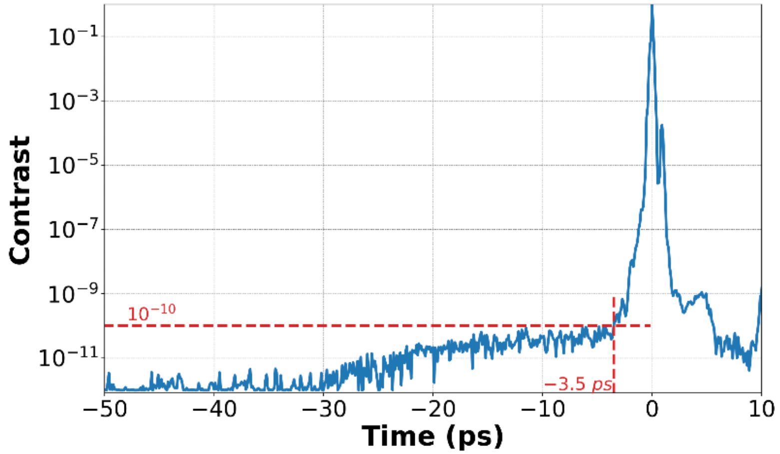
Laser pulse duration: 12.3 fs
Measured in vacuum, after OAP, with disp scan

Focal spot FWHM: $3.2\times3.8\ \mu m^2$

Peak intensity in focus:
4×10^{18} W/cm^2 ($a_0\sim1$)



Temporal contrast



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

Development of a sub-200nm liquid leaf target

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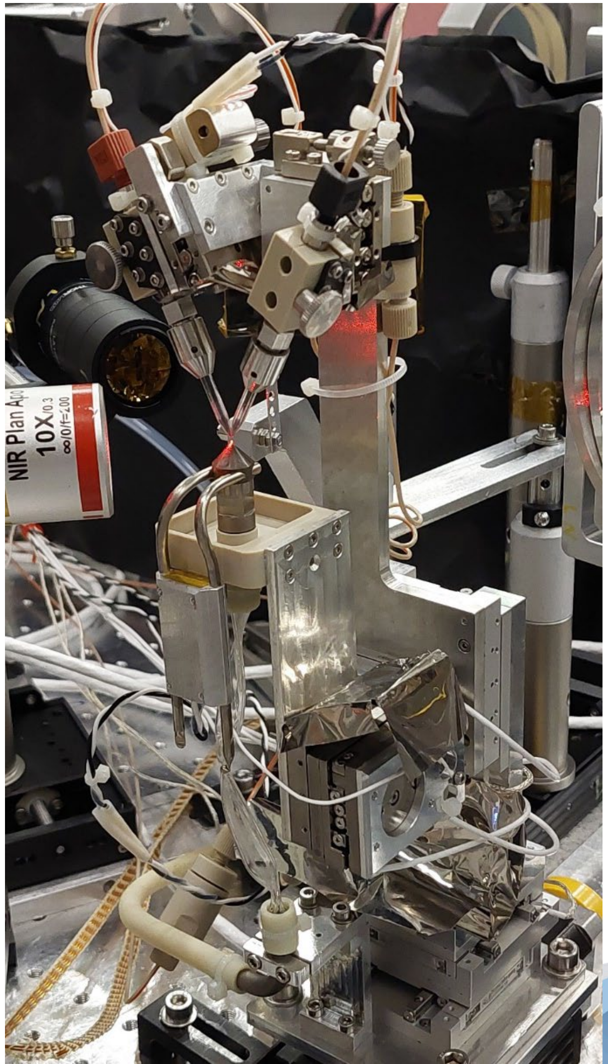
Advanced Microfluidic Systems GmbH

- Two liquid jets collide from two glass nozzles
- Pulsation damping system for *stability*
- Recirculation system for *continous operation*
- Cold finger for 10^{-4} mbar *vacuum*
- Thicknesses measured *in vacuum* (!), and used here: ***~230nm, ~440 nm***

Füle et al., *HPLSE* **12** (2024) e37



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Interaction optimization, liquid leaf

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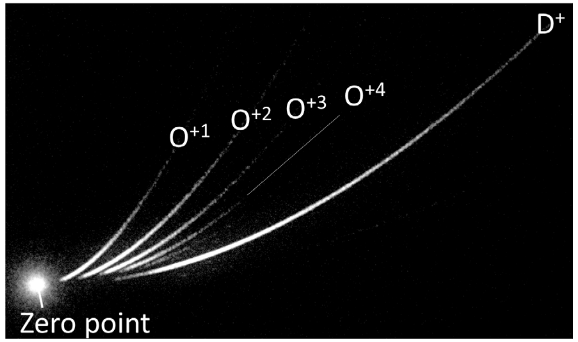
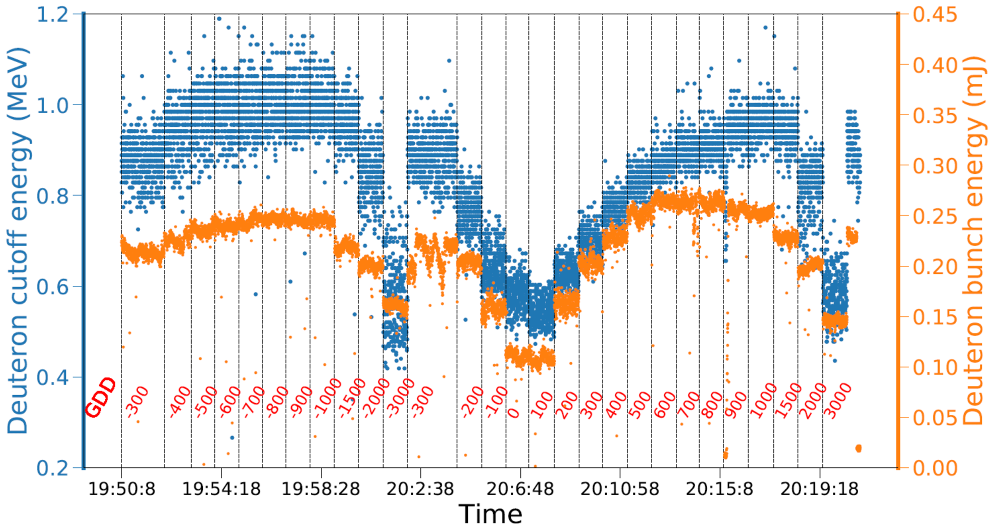
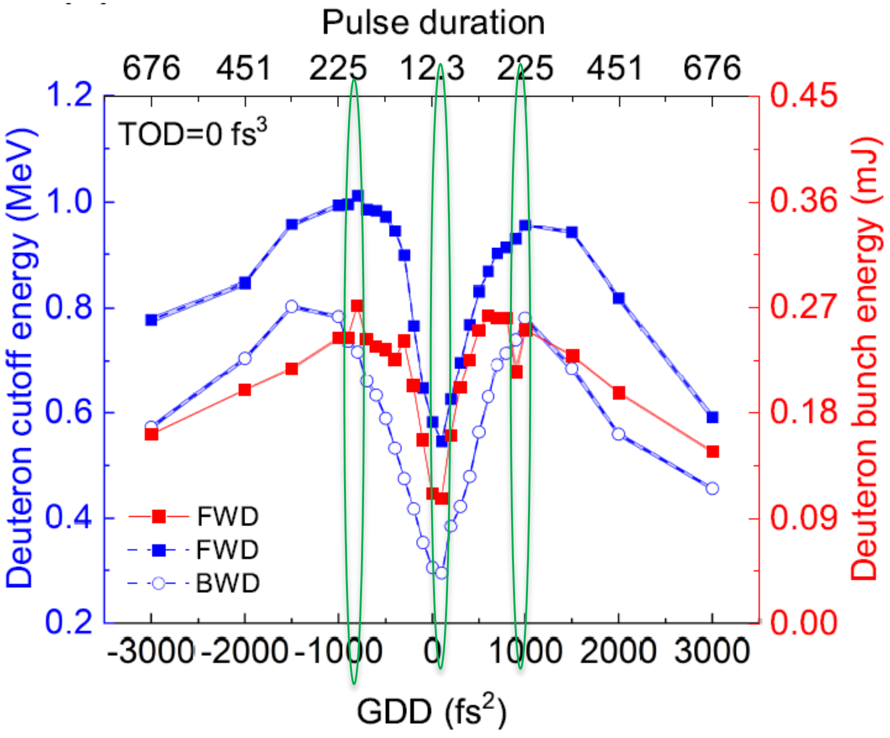
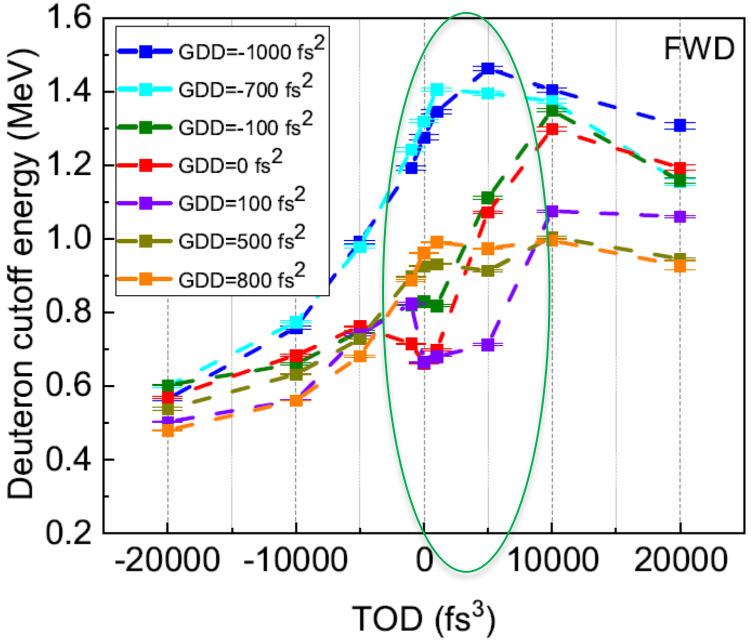
@10 Hz
Liquid leaf of heavy water: 230 nm
Each point: average of 600 shots









Varmazyar et al, Comm.Phys. **8** (2025) 350

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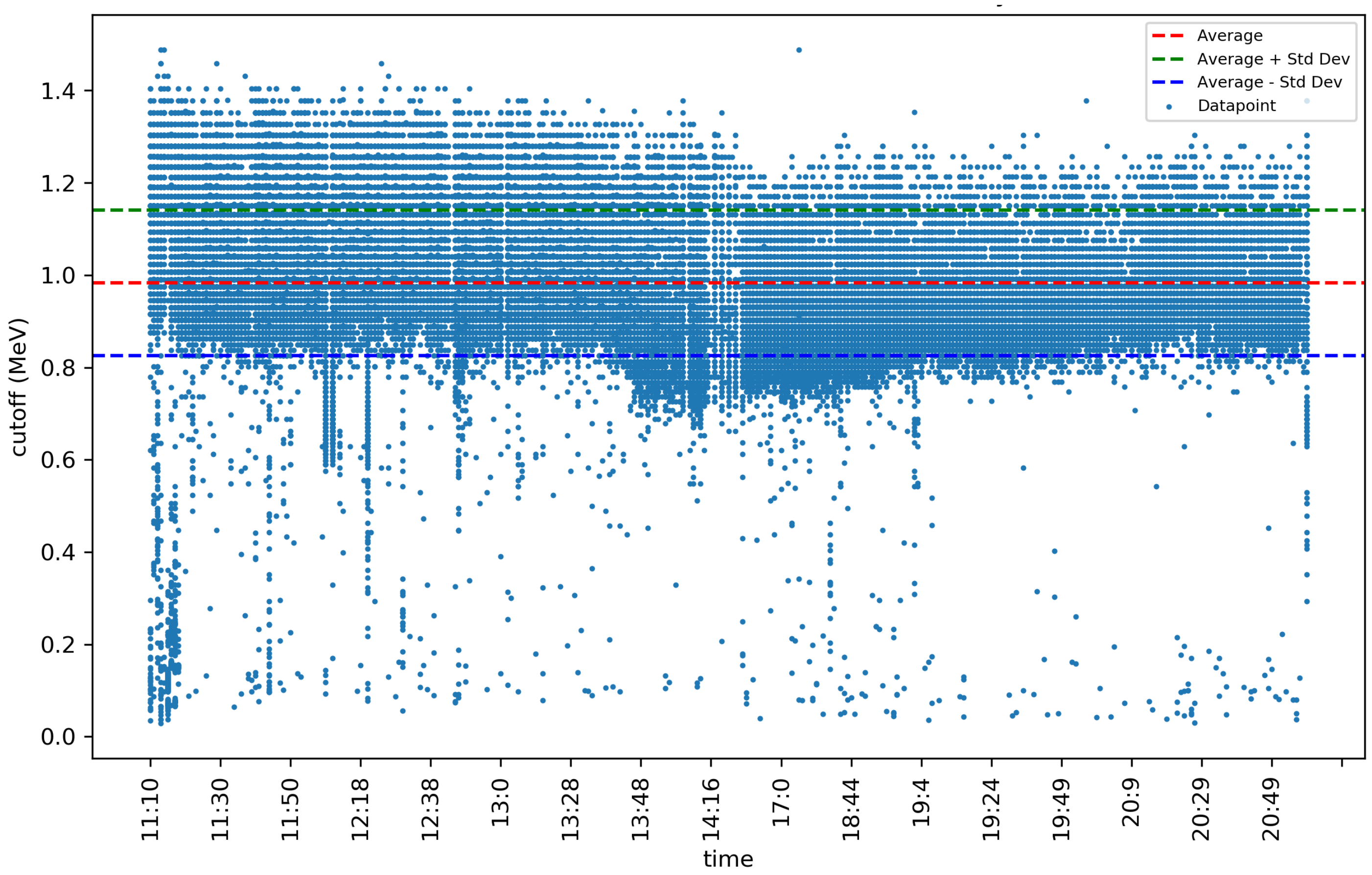
Deuterion acceleration at 10 Hz repetition rate

One of the four days – stability studies

cut-off morning: 1.06±0.12 (MeV)

cut-off afternoon: 0.95±0.087 (MeV)



Stuhl et al, PRR **7** (2025) 023137

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Neutron measurements

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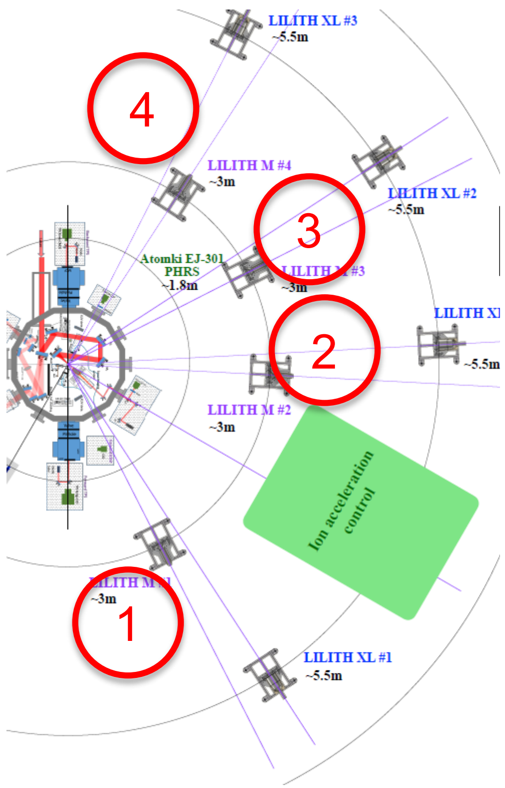
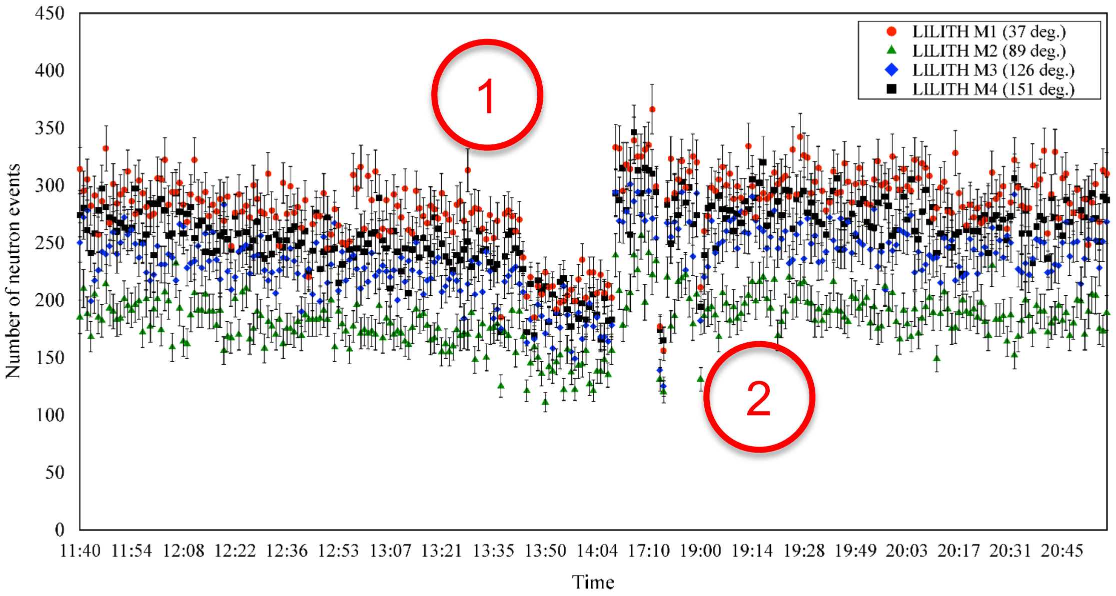
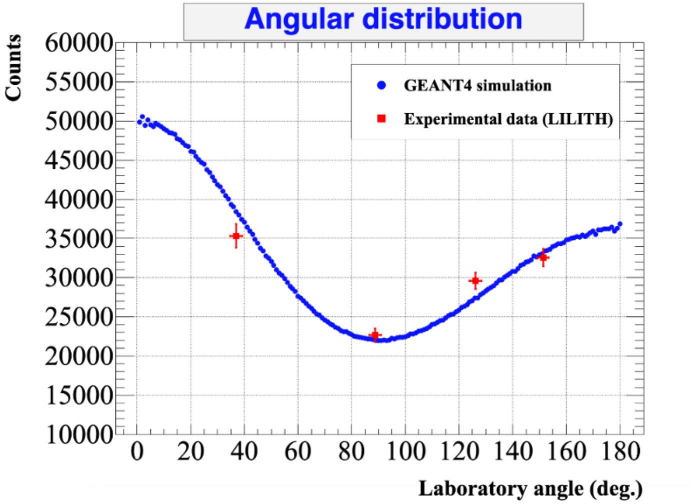
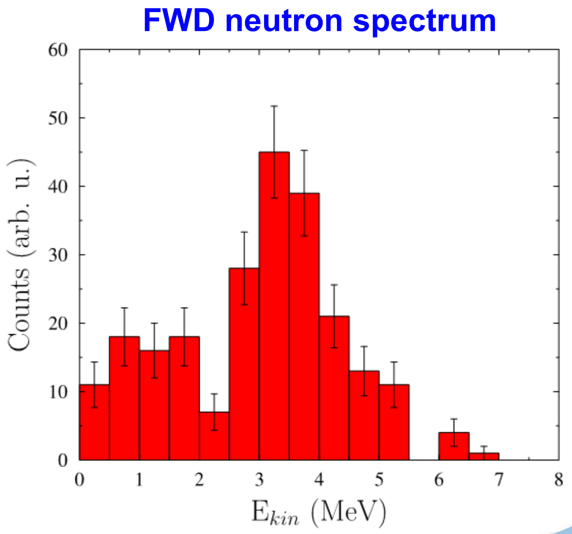




Stuhl et al, PRR **7** (2025) 023137





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State of the art **neutron** generation at **10Hz** repetition rate (~6 hours)

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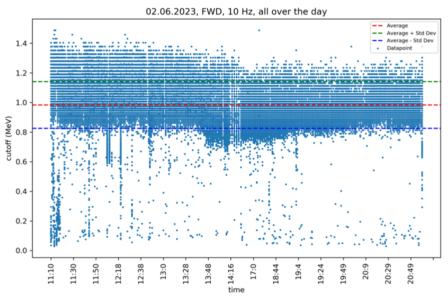
Deuteron acceleration from liquid

- at 10 Hz, SEA laser
- at *230mW* average power
- 430 nm D_2O leaf

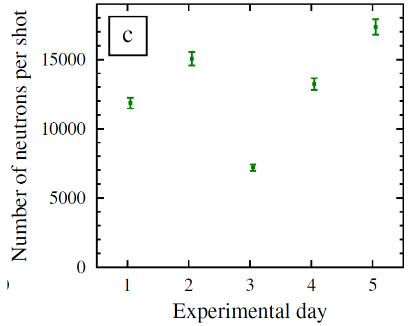
Stuhl et al, *Phys.RevRes.* **7** (2025) 023137

cut-off for the day: 0.98±0.16 (MeV)



Neutron generation

- 430nm D_2O leaf + 1mm C_2D_4
- fusion neutron spectra peaks ~3 MeV



~1.8×10^5 n/s, rms 5%

Laser-Neutron conversion rate:

7.8×10^5 neutron/J

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attosecond

LASER

EKSPLA

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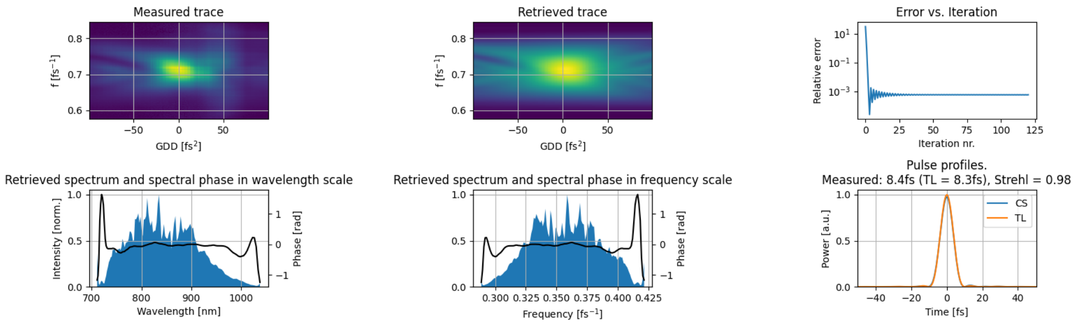
S3 laser (1 kHz, OPCPA) of ELI-ALPS parameters *on target*

Pulse energy: ~80 mJ
(105 mJ in laser)

Laser pulse duration: 8.4 fs
(measured in vacuum, after OAP, with disp scan)

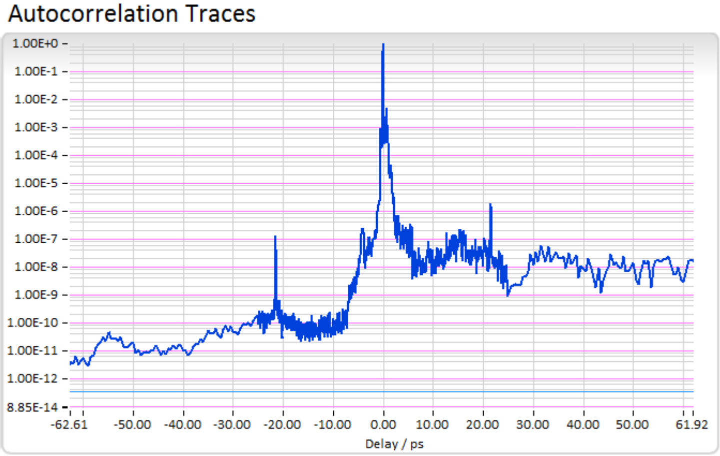


Central wavelength: 826nm

Focal spot FWHM: 2.9×2.6 μm^2

Peak intensity in focus:
2×10^{19} W/cm^2 (a_0~2.2)

Temporal contrast



**peak at +-22ps is estimated to be post-pulse from the variable density filter in the diagnostics arm, not in the main output*

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Neutron yield optimization at 1 kHz repetition rate
80 mJ energy on target

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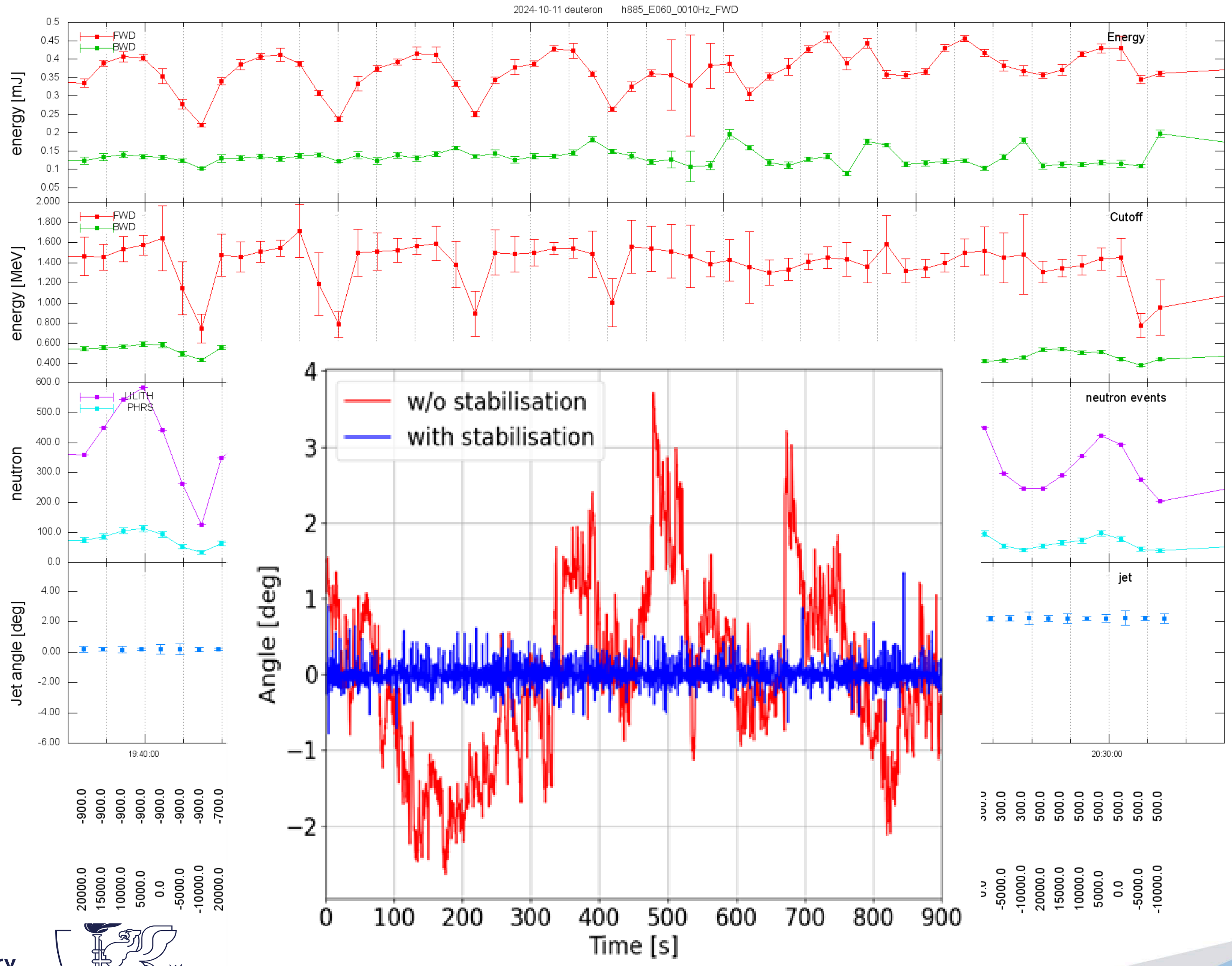
Bunch energy of deuteron

Cutoff energy deuterons

Neutron event LILITH
Liquid Scint

Stability of liquid jet



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State of the art deuteron generation at 1kHz repetition rate (~ 6 hours continous operation)

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Deuteron acceleration from liquid

- at 1 kHz, SYLOS 3 laser
- at ***80W*** **average power** on target
- 450nm D_2O leaf

Deuteron (full) ion beam intensity in Nov ’24 at 1kHz :

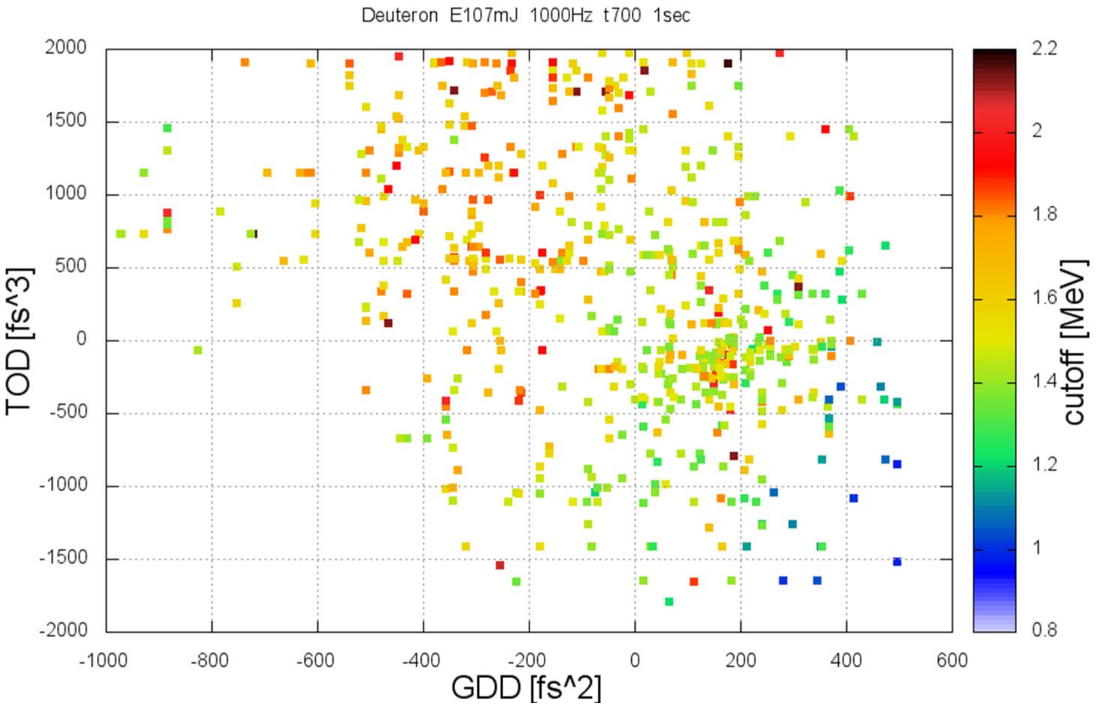
>4 W (10W) → > 15×10^{12} deuteron/sec →

> 2.5 μC /sec
> 2.5 nC / shot
> 2.5 kA peak current

See also the challanges in KALDERA and the Beetle program! (A. Maier’s and T. Eichner’s talks, Monday)

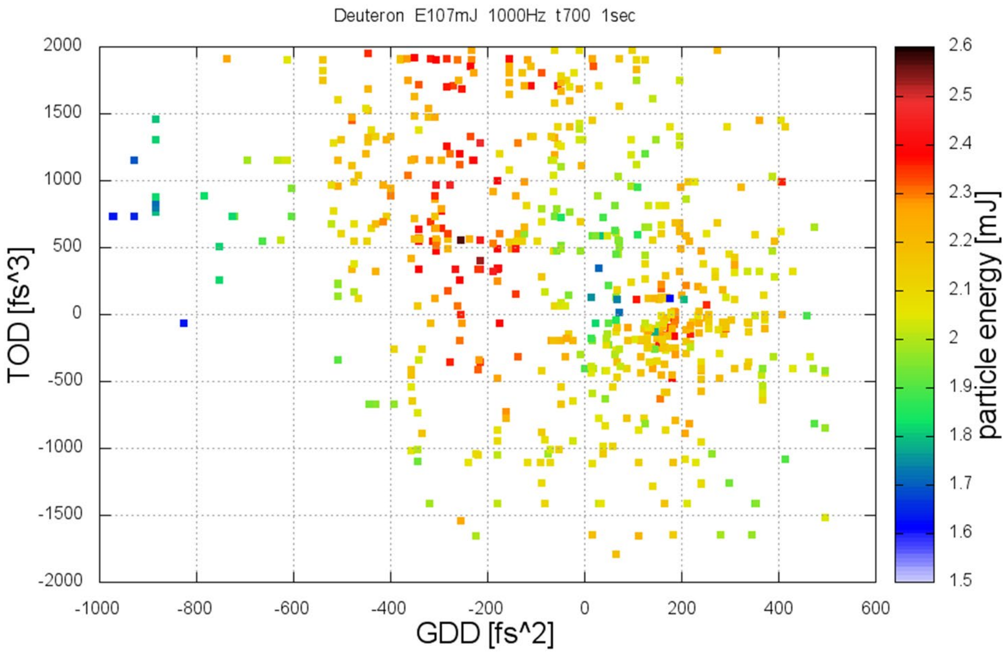
New optimisation – deuteron, kHz
Markov-Chain Monte-Carlo scanning

For deuteron cutoff



Heavy water sheet jet, 700nm
SYLOS3 laser, 80mJ, 1kHz
(15 min, 900 points)

For deuteron bunch energy

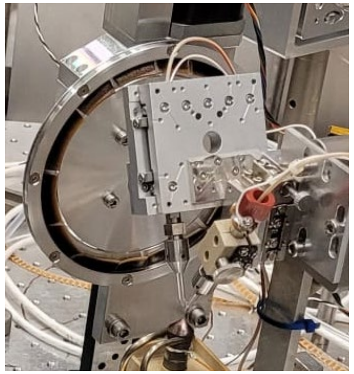


State of the art neutron generation at 1kHz repetition rate (~ 3×2 hours)

Neutron **generation:** 450nm D_2O leaf + 1mm C_2D_4

Peak yield detected in Nov ’24 at 1kHz : **~10^8 n/s**

Average yield over 2 hours in Nov ’24 at 1kHz : **~10^7 n/s**



Average neutron flux at 1kHz : **2×10^7 n/cm^2/s**

Peak neutron *flux rate* / shot: **> 10^{13} n/cm^2/s**

Laser-based neutron sources for applications

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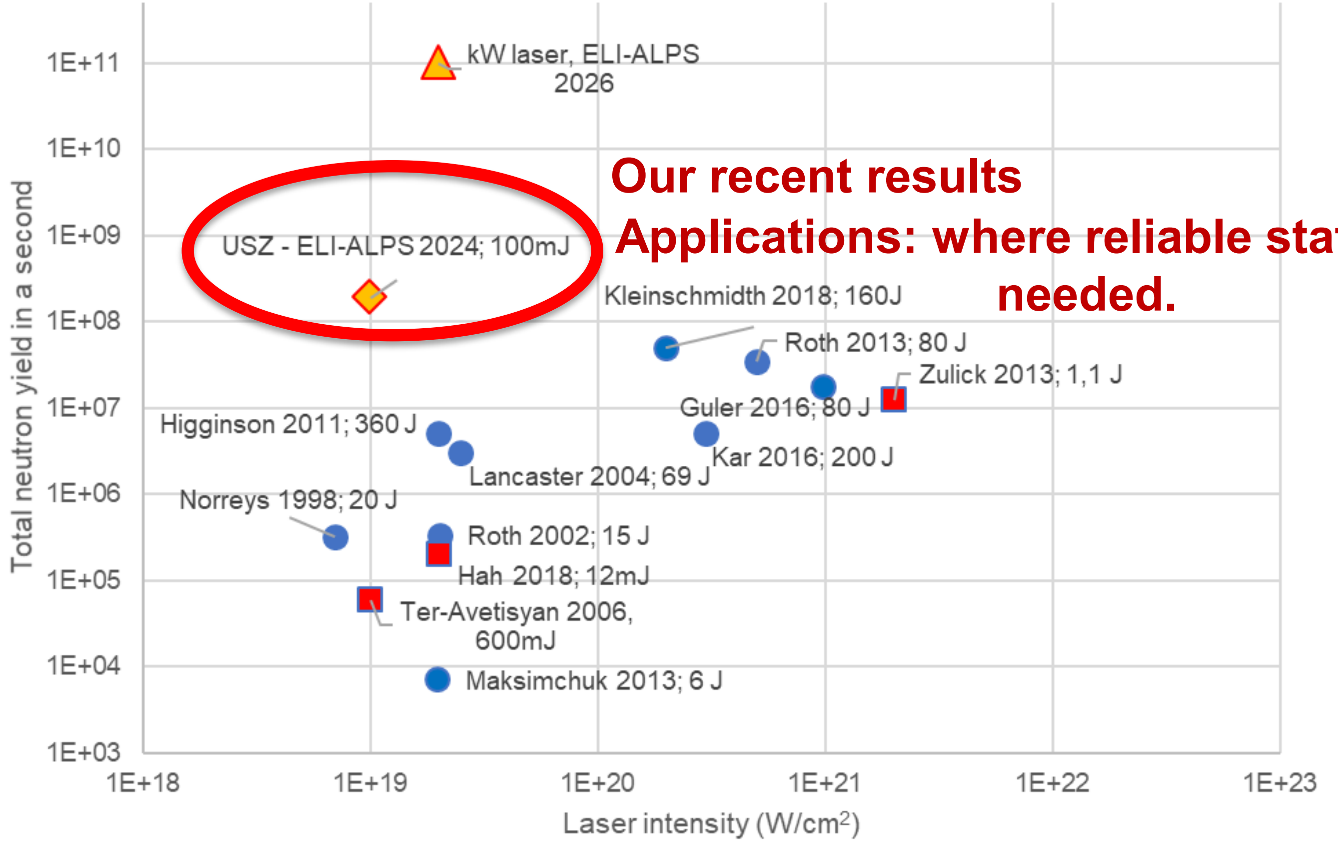

Our recent results

Applications: where reliable statistics are needed.

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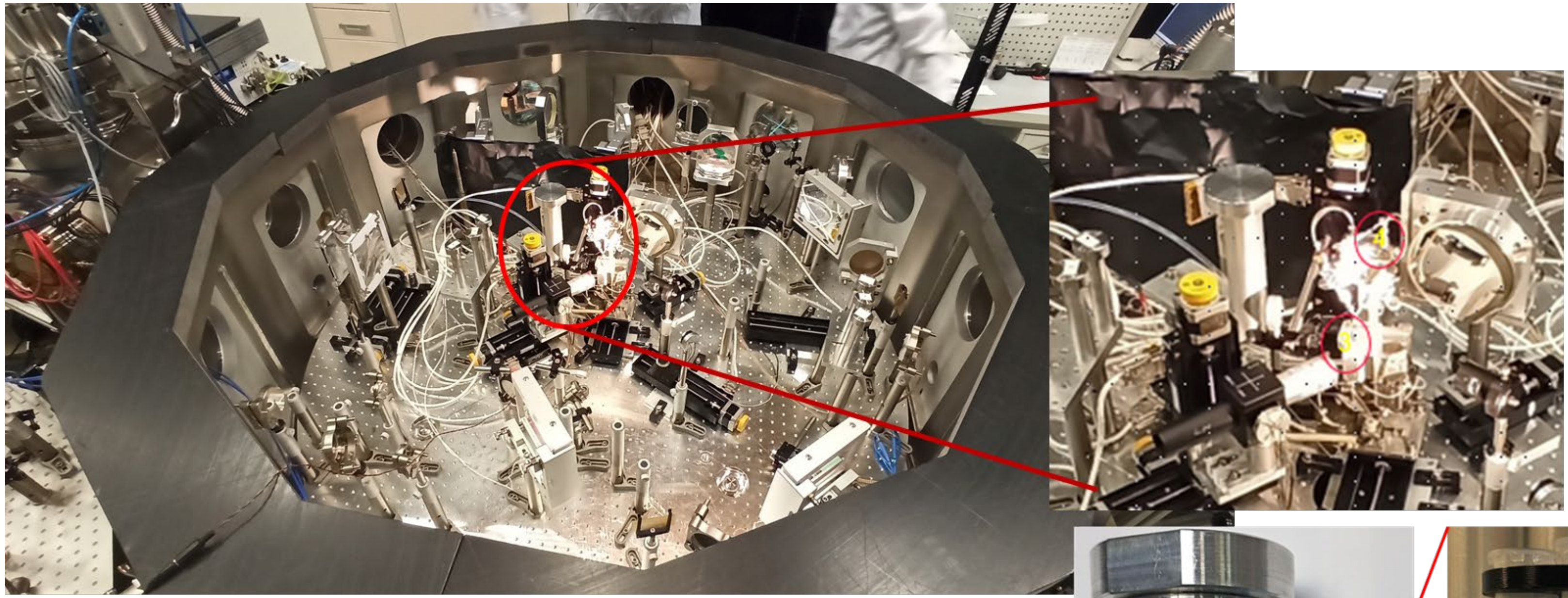
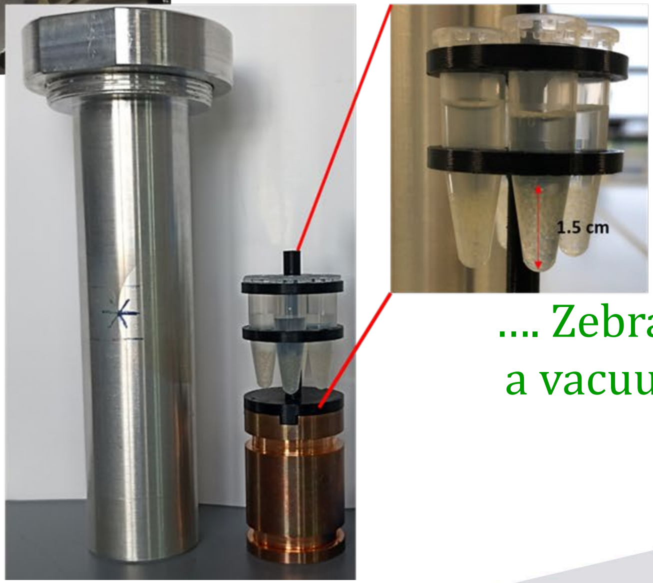
First radiobiology experiments with laser-generated neutrons



Experimental chamber…



…. Zebrafish embryos in
a vacuum tight container

Procedures - challenges

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Irradiation parameters

Particle

Enegy (range)

Dose rate/shot; mean

Beam dir./size/alignm

Dose levels

Biological samples

Sample type(s)

Conditions (temp, media)

Sample holder

Sample size

Endpoints

Calculation/ dosimetry

MCNP simulation of dose distribution based on particle intensity, energy, materials

Dosimetry

Offline/online

Irradiation

Sample prep.

Sample positioning

Beam alignment

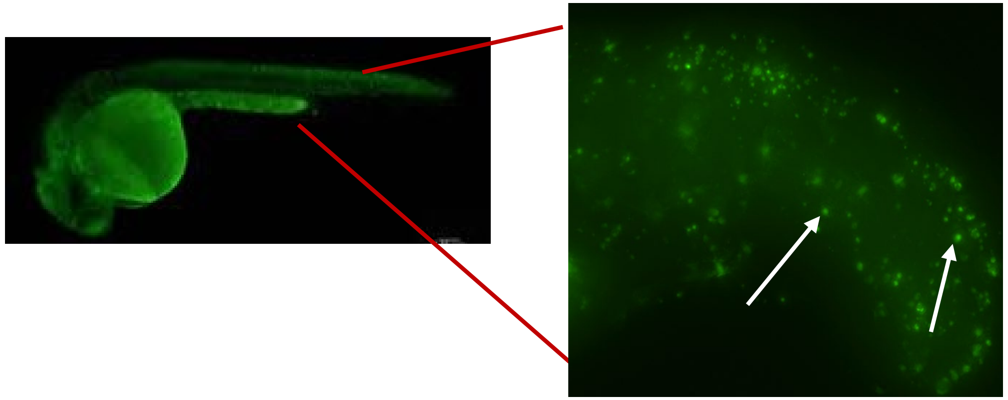
Dose delivery

amples for endpoints

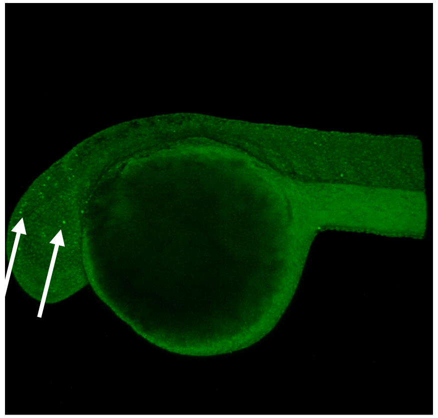
Reference Irrad. → **Evaluation, comparison of the effects** ← Dosimetry films-, Biol. Sample analysis

Development of endpoints for low dose RT

Apoptosis: Acridine orange staining/Caspase staining

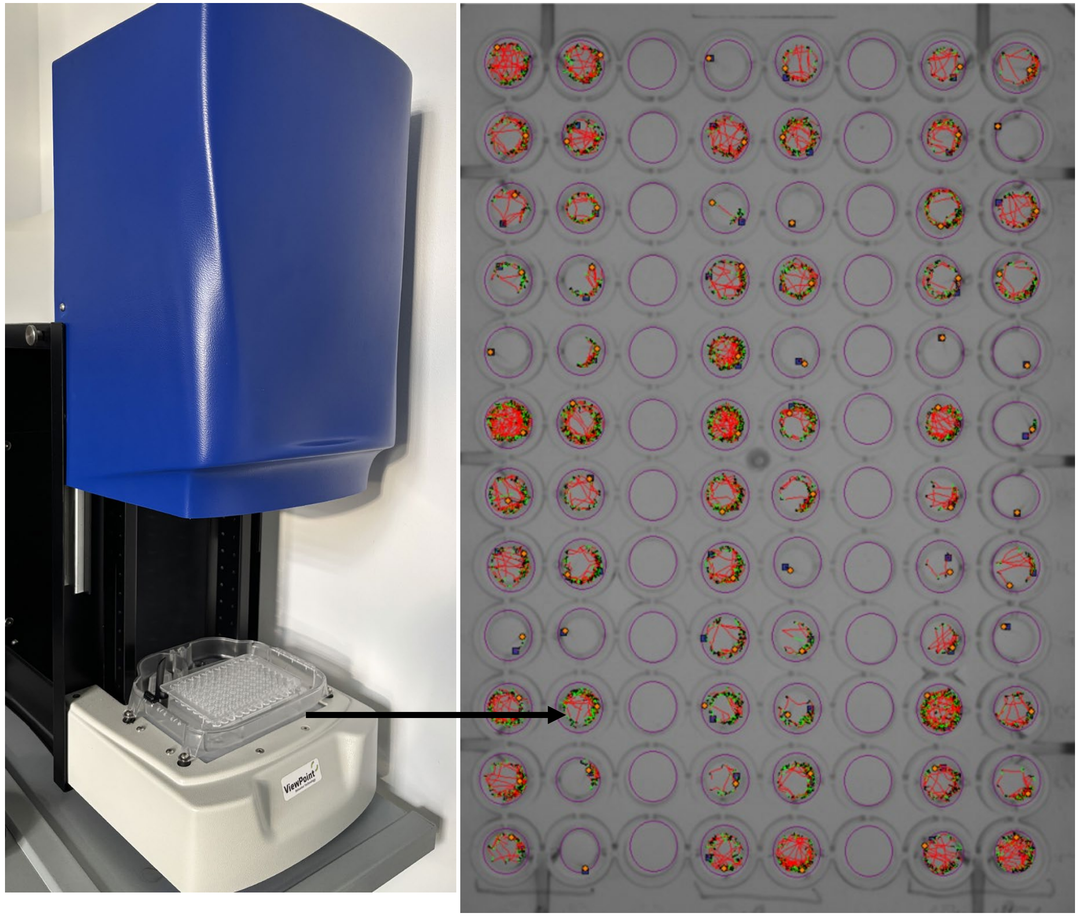


DNA DBS: γH2AX staining



DNA Expression profile changes- RTPCR

Behaviour analysis- photomotor response



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Dose delivered to the samples

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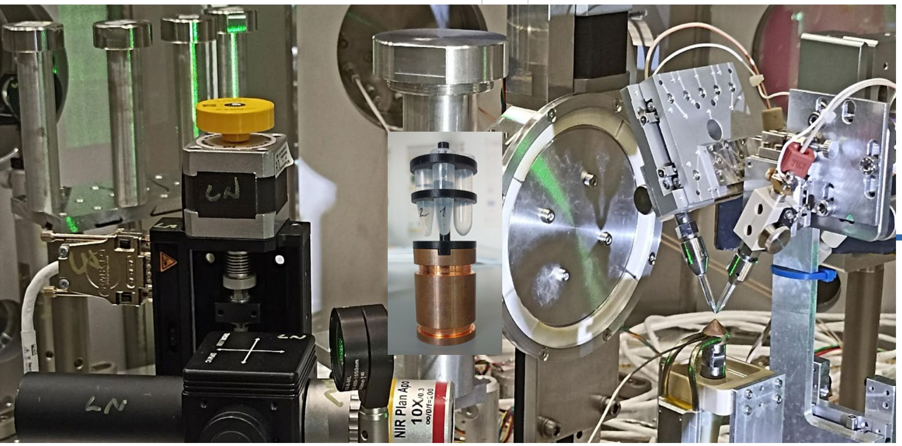
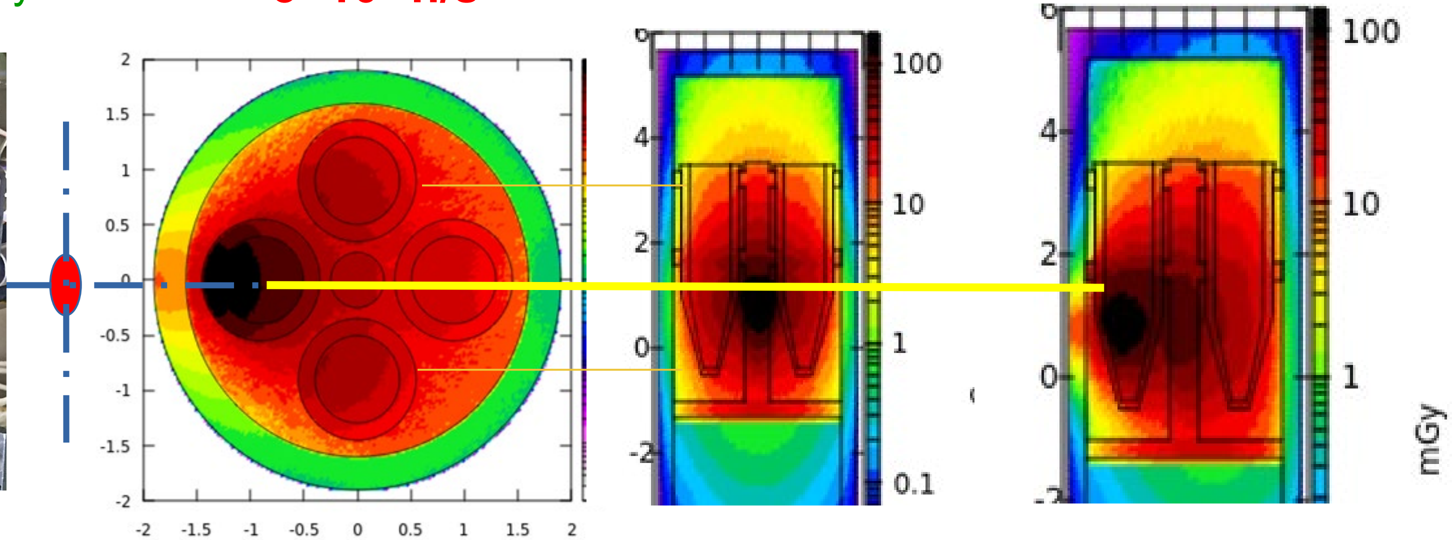
4 mm

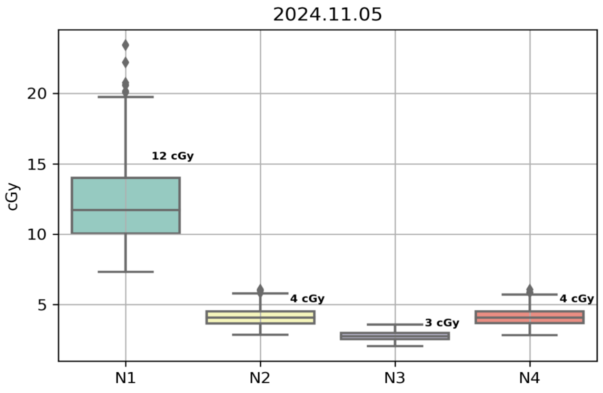
Peak neutron yield / sec: **~ 3×10^{8} n/s**

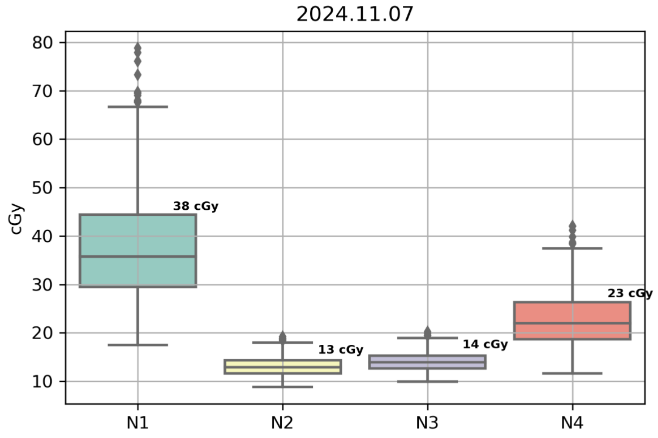


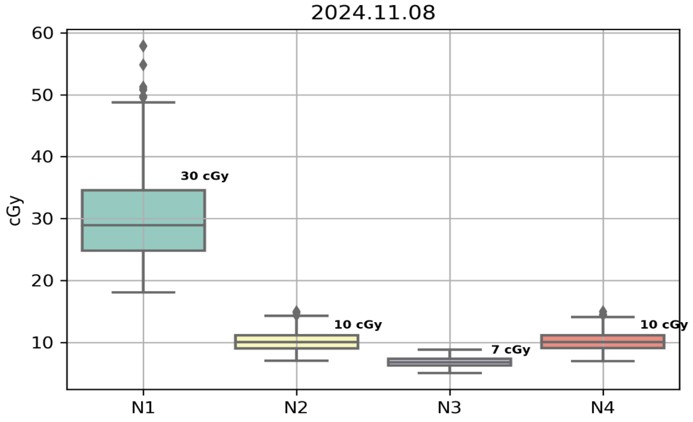


3,2 Mev fast neutron   100 Hz, 1 kHz

Irradiation time: **3×120 min,** MC-mean dose on the samples: **3 cGy- 38 cGy**







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Zebrafish embryo irradiation with laser-induced neutrons

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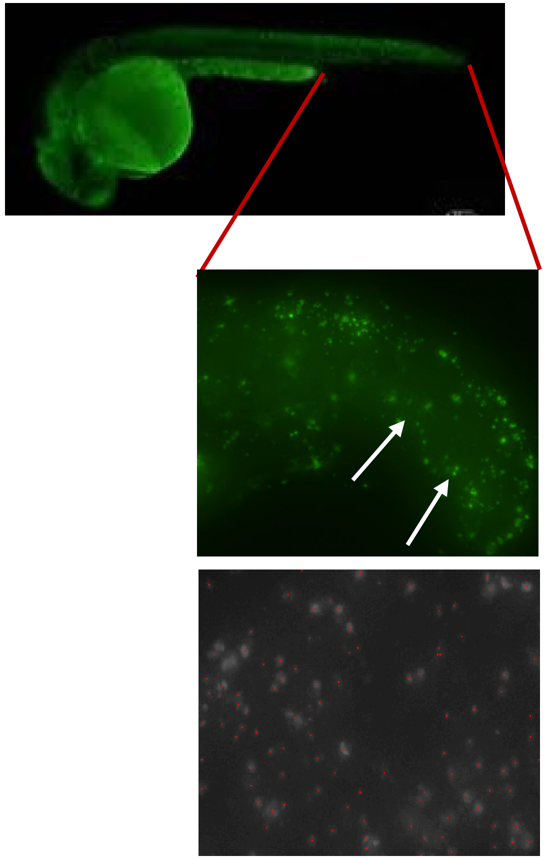
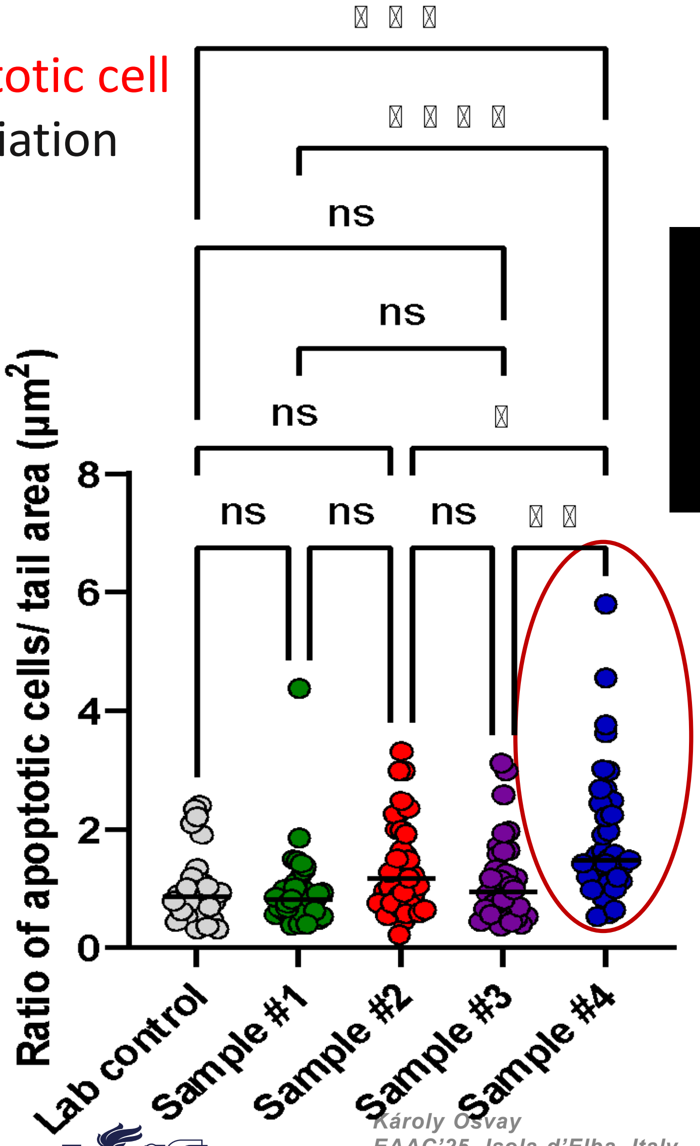
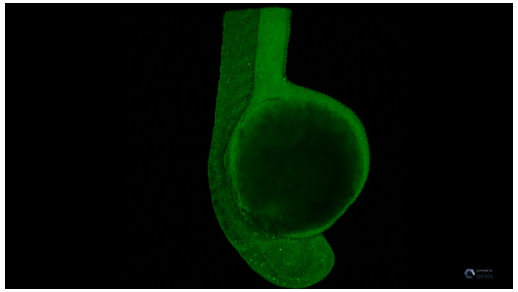
Acridine orange staining for apoptotic cell density measurement after irradiation

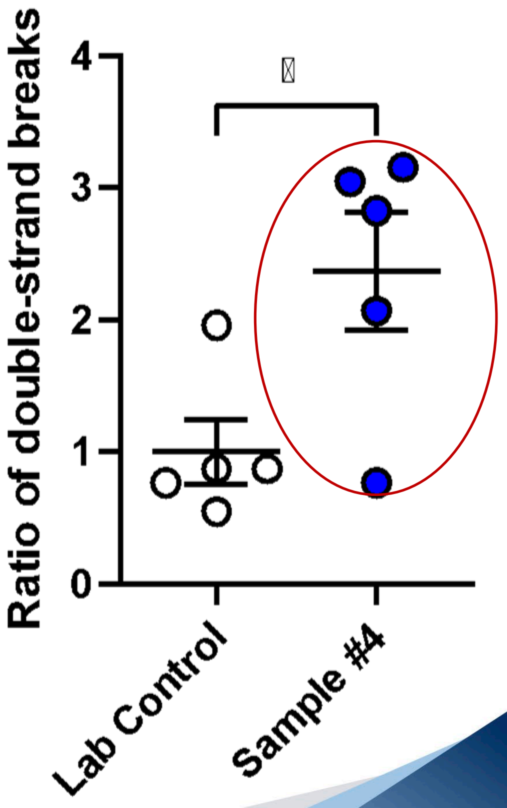




Mean dose: 27cGy
Dose inhomogeneity (90%): 10 cGy- 30 cGy



GammaH2AX whole body mounting



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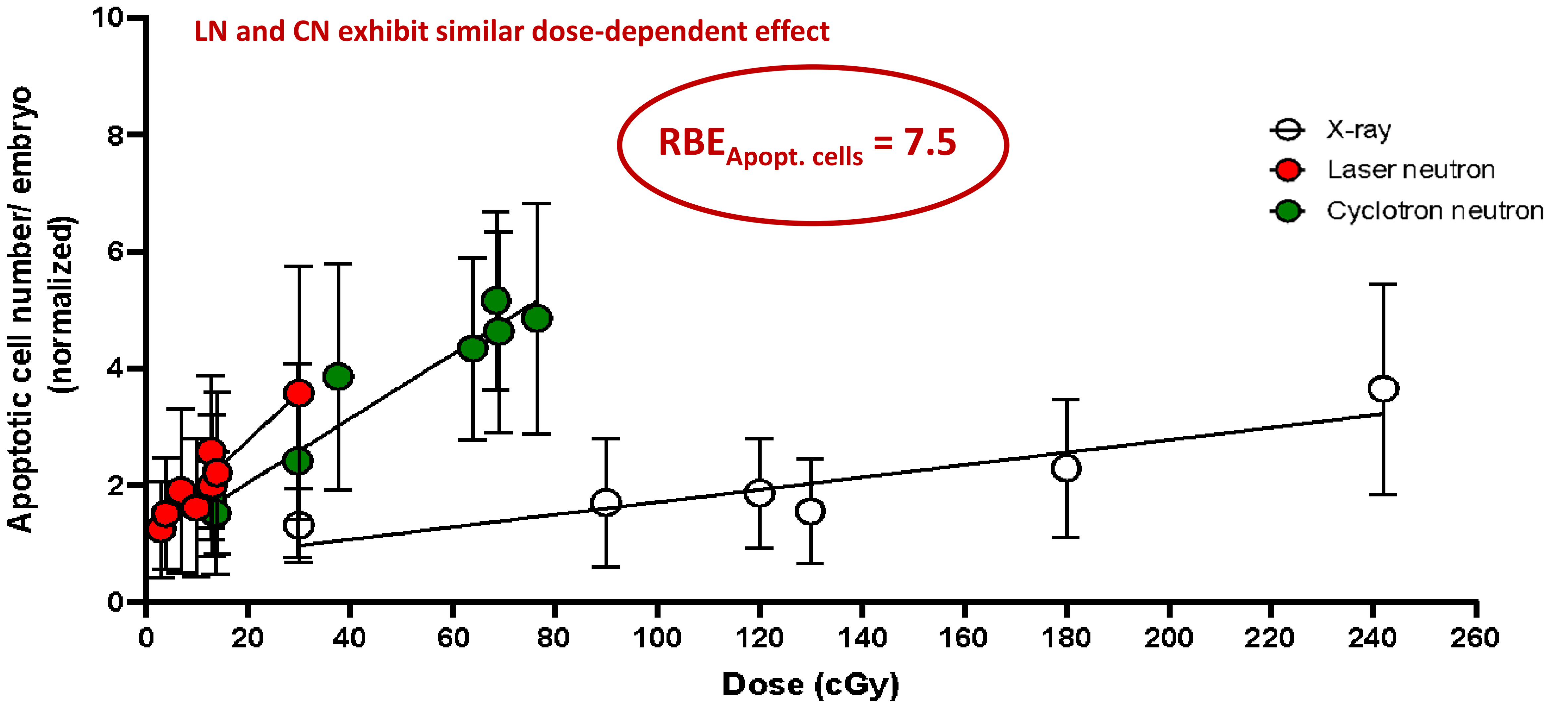
Zfe: Apoptotic cell density



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Summary

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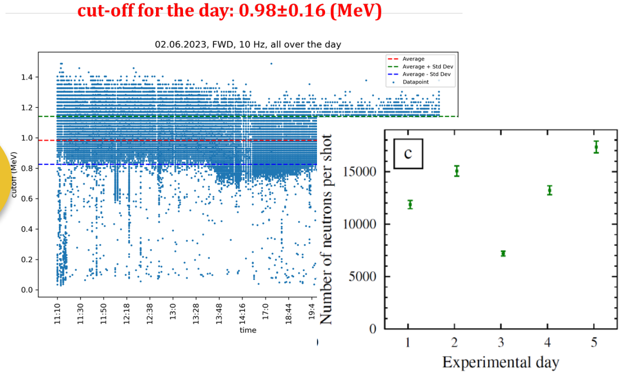
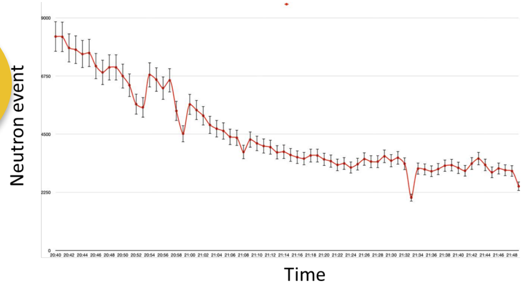
- **Neutron generation from liquid @ 10 Hz**
  - at 10 Hz (continous)
  - 450 nm D_2O leaf + 0.1mm C_2D_4

~7.8×10^5 n/J
~1.8×10^5 n/s, 6h

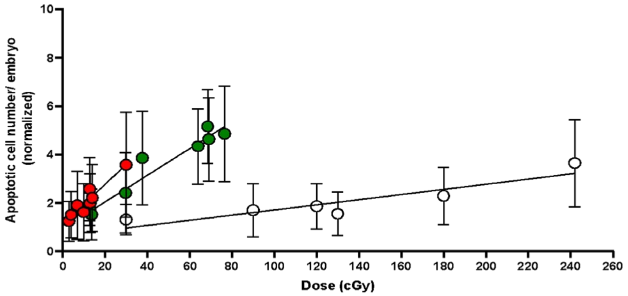


- **Neutron generation from liquid @ 1 kHz**
  - at 10 Hz (continous)
  - 450 nm D_2O leaf + 0.1mm C_2D_4

Peak yield: 10^8 n/s
~10^7 n/s, 3x2h



- **Zebrafish Embryo irradiation (low-dose, high dose rate)**
  - $RBE_{Apopt\ cell}=7.5$
  - $RBE_{DNA-DSB}=2.5$



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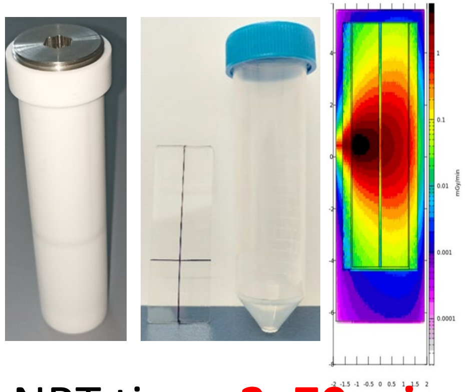
Irradiation campaigns with laser-based fast neutron beam

3,2 MeV
5 Hz, 10 Hz
1.7×10^{5} n/s (av.)

2023 May

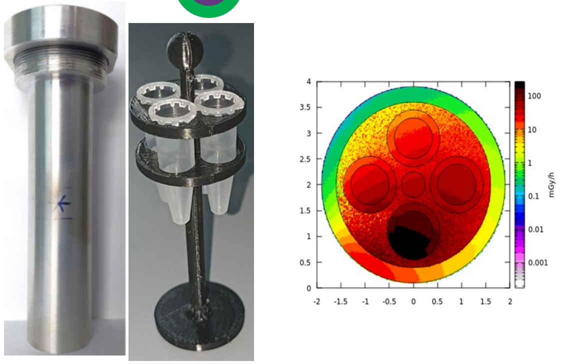


NRT time: **3×70 min**

NRT **dose: 0.3-13cGy**

3,2 MeV
100 Hz, 1 kHz
1×10^{7} n/s (peak)

2023 December

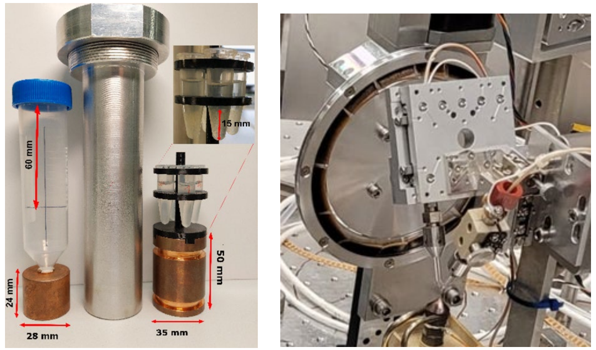


NRT time: **2×30 min**

NRT **dose: 1-27 cGy**

3,2 MeV
100 Hz, 1 kHz
1×10^{8} n/s (peak)

2024 Novembe

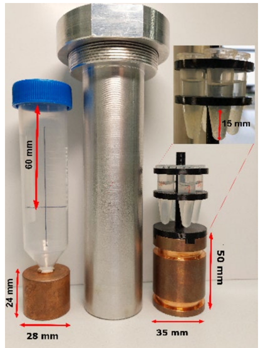


NRT time: **3×120 min**

NRT dose: **3 - 155 cGy**

3,2 MeV
1 kHz
3×10^{8} n/s (peak)

2025 Novemb



NRT time: **420 min**

NRT dose: **~10 Gy**

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Thank you for your attention

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