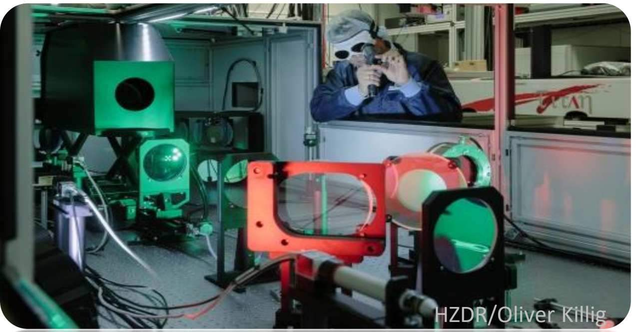
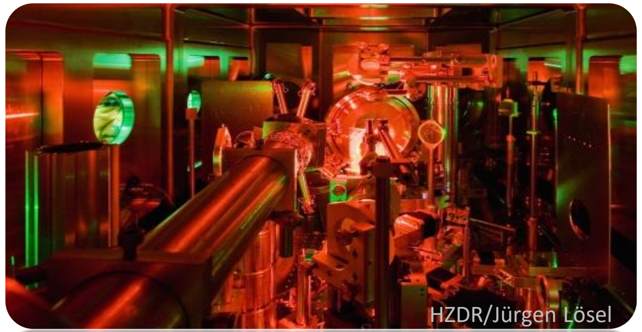
Laser proton acceleration and neutron generation for nuclear reaction studies at the Draco PW facility





Karl Zeil

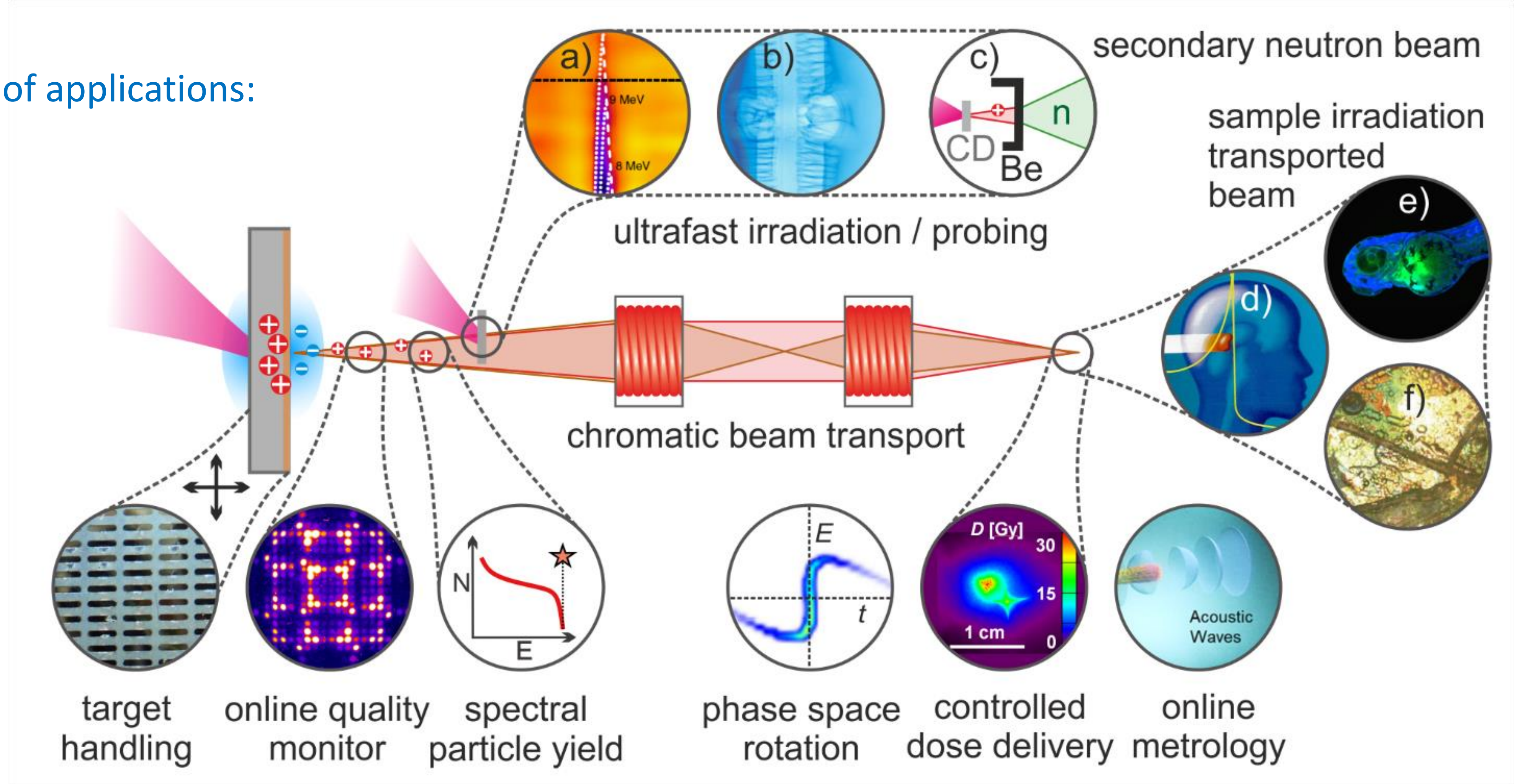
LENS Workshop on Laser-driven Neutron Sources
ESS Lund, 01.03.2023

Universidad de Sevilla · CNA Centro Nacional de Aceleradores · ARIEL · OncoRay National Center for Radiation Research in Oncology Dresden · IGFAE Instituto Galego de Física de Altas Enerxías · USC · XUNTA DE GALICIA · HZDR · cividec Instrumentation · Technische Universität Darmstadt · Partner von DRESDEN concept

Institute of Radiation Physics · Laser Particle Acceleration · Dr. Karl Zeil · k.zeil@hzdr.de · www.hzdr.de

Laser-driven proton acceleration – Identifying the most impactful field of research

Status of applications:



Successful demonstration of application capability always serves as a benchmark of the accelerator development status.

2020 Roadmap on Plasma Accelerators, NJP 2021

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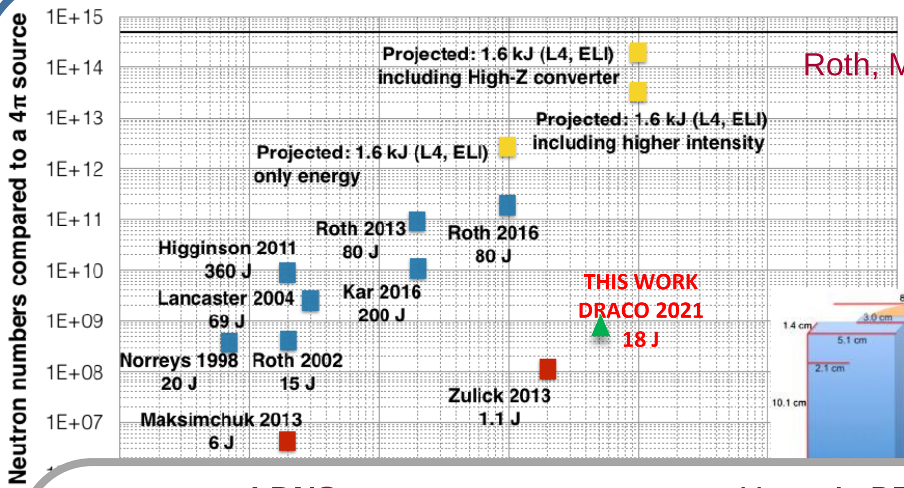
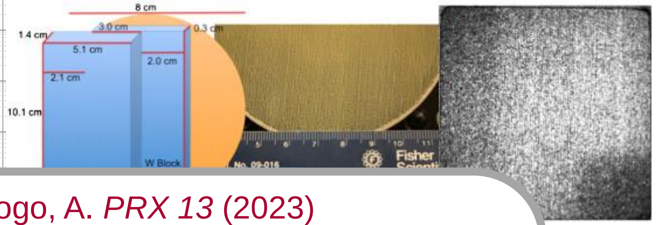
Laser-driven neutron sources – compact neutron sources for life science

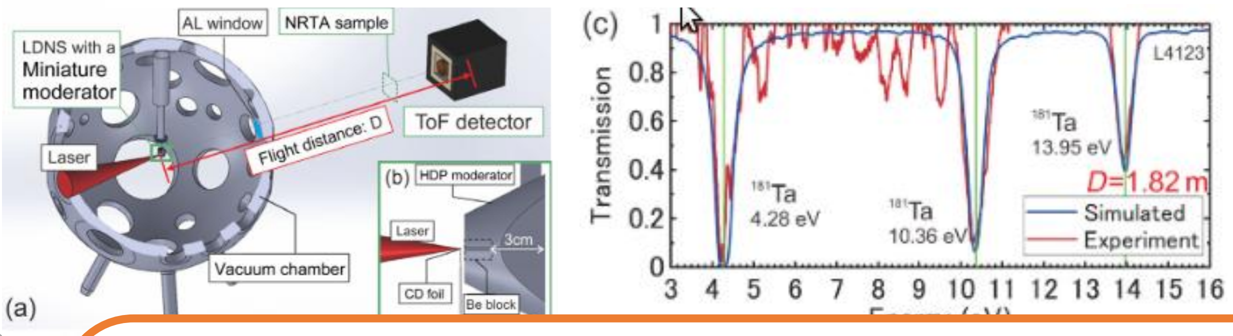


Roth, M. *LANL Technical Report.* LA-UR-17-23190. (2017).

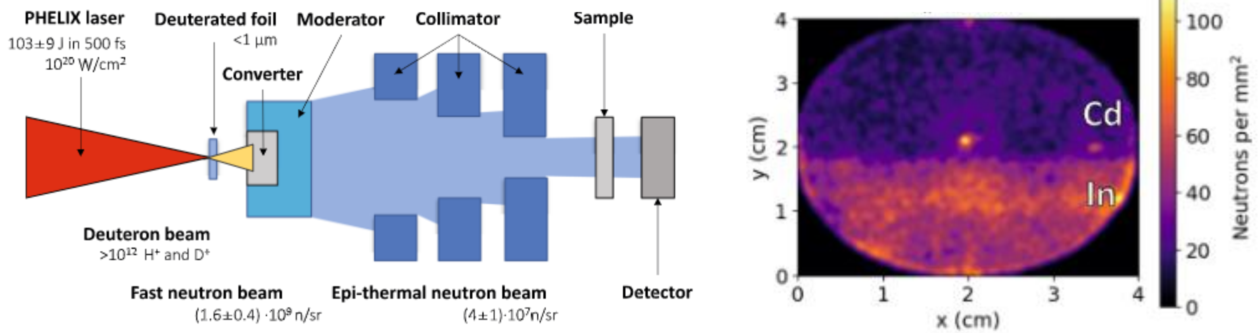
LDNS Radiography
Roth, M. *PRL 110* (2013).



LDNS resonance spectroscopy Yogo, A. *PRX 13* (2023)



LDNS resonance imaging Zimmer, M. *NatComm 13* (2022)



Mission of our Ariel collaboration

(C. Guerrero, A. Junghans, M. A. Millán-Callado et al.)

- Establish link between the laser acceleration community and the neutron-user community
- Spectroscopy with fast (MeV) neutrons for nuclear physics studies (nuclear data basis)
- Compact LDNS time-of-flight setup with high temporal resolution and high pulse intensity
- Single neutron detection necessary for reaction kinematics
- enormous challenges due to the harsh environment (EMP and secondary radiation)
- Demand: repetitive system delivering 10s of MeV laser driven ions (protons/deuterium)
  → TiSa PW-class systems?

ELBE Center for high power radiation sources and high power lasers at HZDR

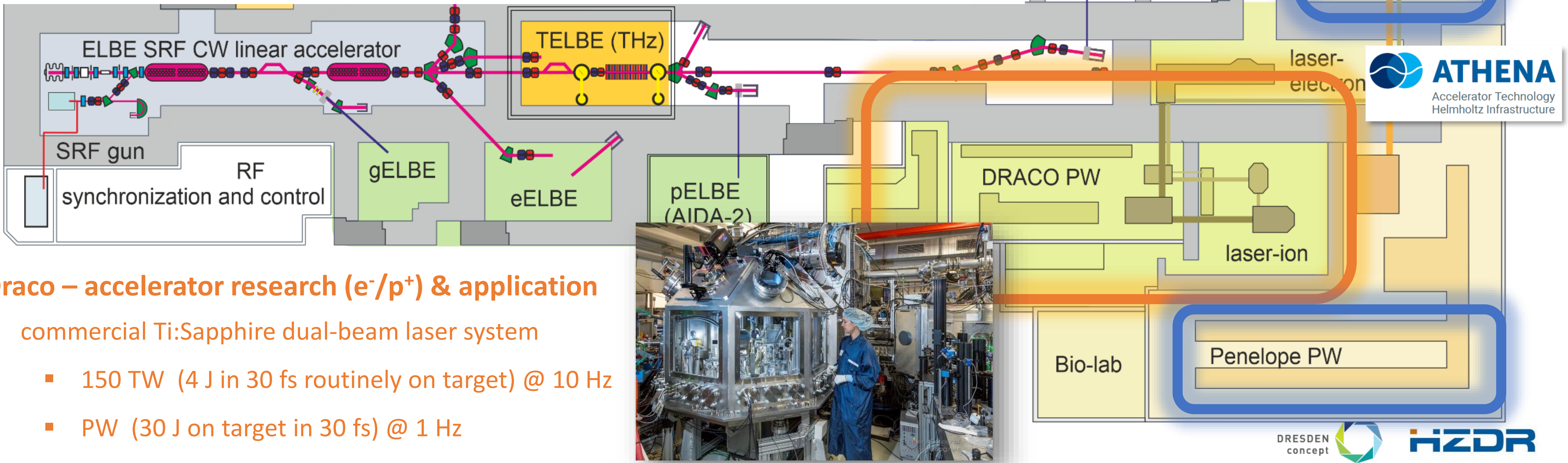
1mA, 40MeV CW electron accelerator

PENELOPE – prototype driver for radiobiology with protons

- diode-pumped, energy-efficient 150 J / 150 fs laser @ 1Hz

Neutron Time-of-Flight
0 – 10 MeV

nuclear data
A. Junghans et al.



Draco – accelerator research (e⁻/p⁺) & application

- commercial Ti:Sapphire dual-beam laser system
  - 150 TW (4 J in 30 fs routinely on target) @ 10 Hz
  - PW (30 J on target in 30 fs) @ 1 Hz

DRESDEN concept HZDR

Member of the Helmholtz Association
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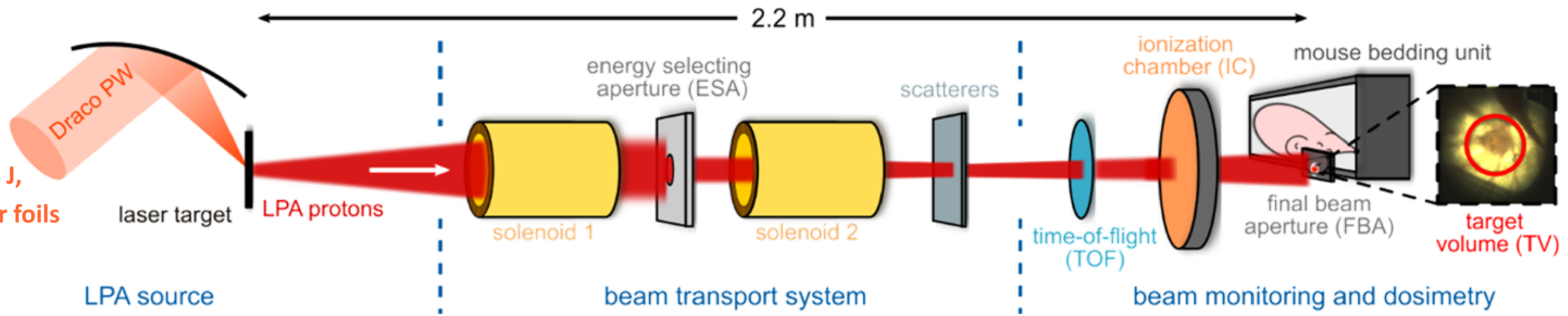
Small animal pilot study with laser-driven proton pulses

Setup at Draco PW

τ = 30 fs, E_L = 18 J,
200 nm Formvar foils



***In vivo* 3D irradiation**
proof-of-principle experiments

10 % homogeneous dose
within 5×5×5 mm³

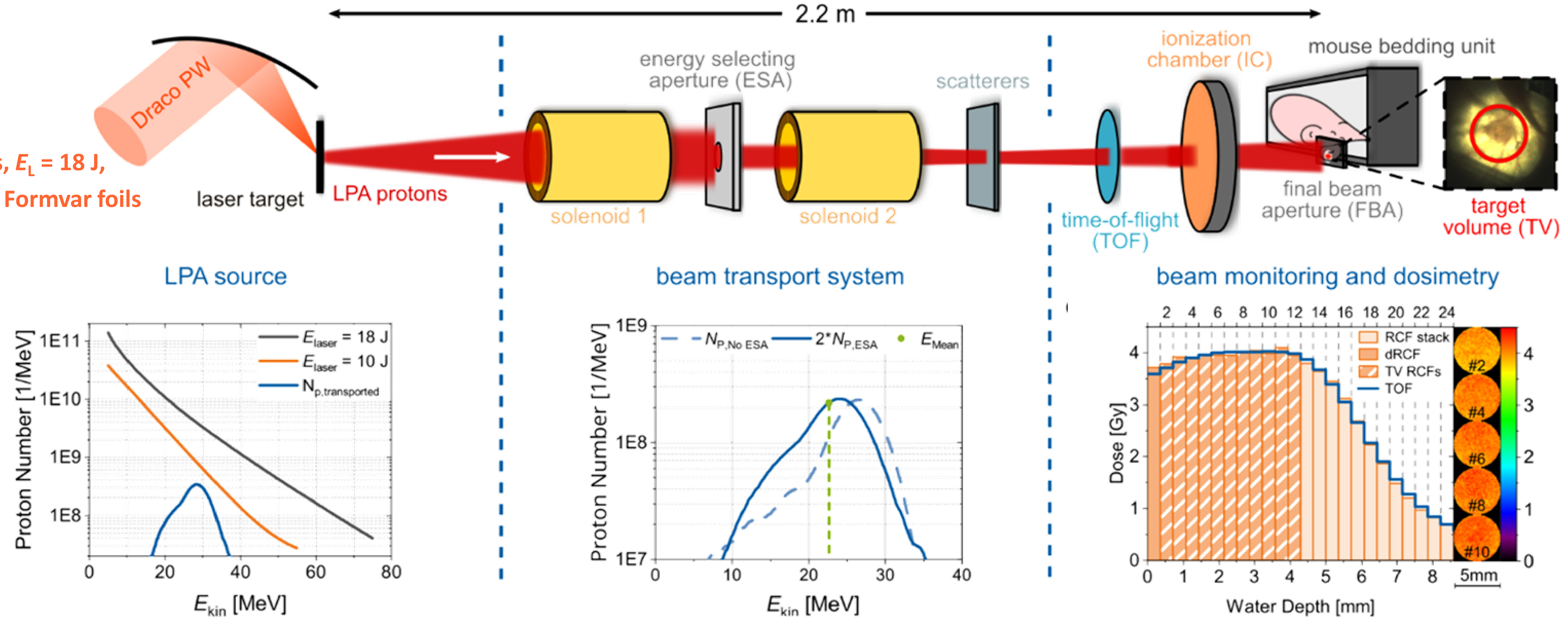
E. Beyreuther *et al.*, 2017 PLOS ONE 12

Small animal pilot study with laser-driven proton pulses

Setup at Draco PW

τ = 30 fs, E_L = 18 J,

200 nm Formvar foils

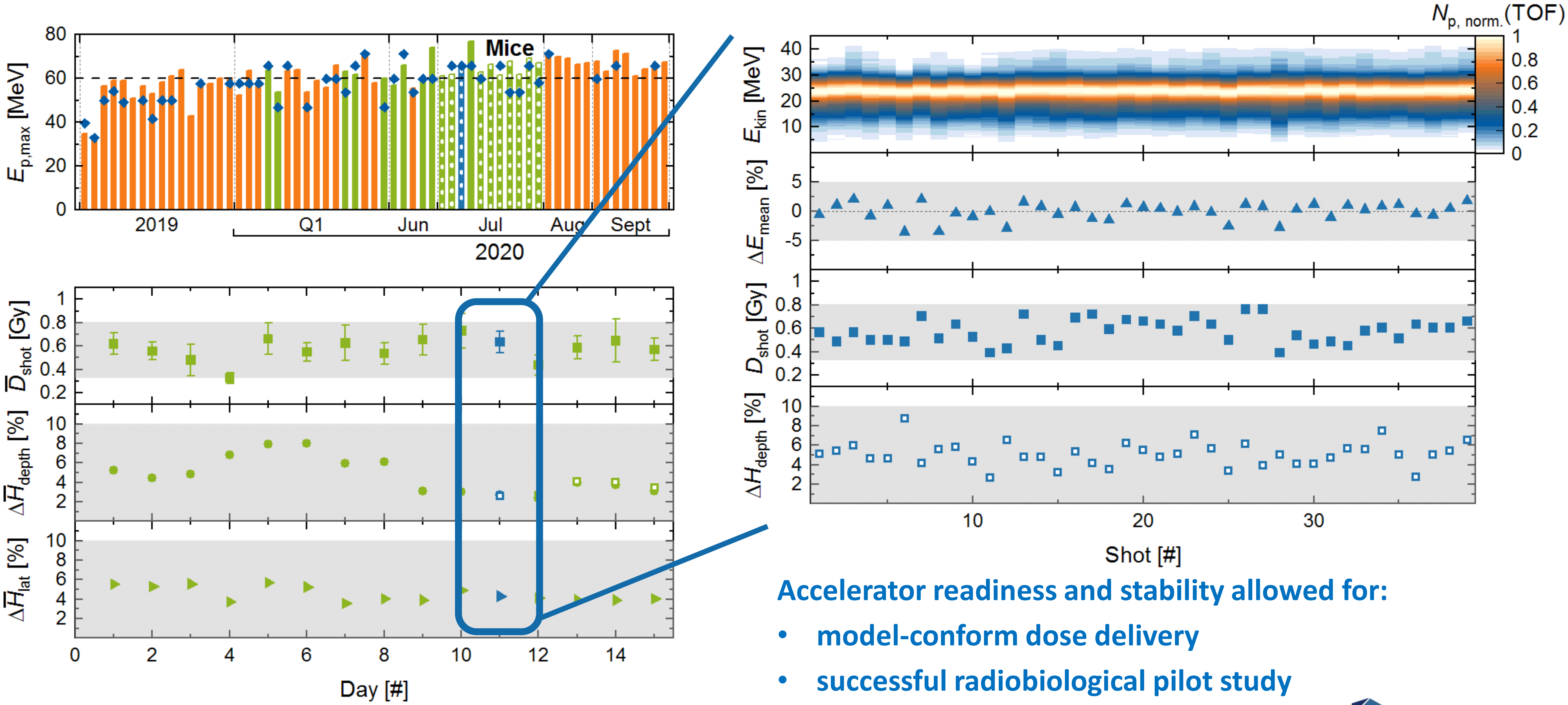


platform enables single-shot delivery of mm-scale 3D tumor-conform dose distributions making perfect use of the broadband LPA proton spectrum

T. Ziegler *Sci Rep* 11 (2021); F.-E. Brack *Sci Rep* 10 (2020); M. Reimold *Sci Rep* 12 (2022); F. Kroll *Nature Physics* 18 (2022)

Small animal pilot study with laser-driven proton pulses

Accelerator readiness and stability benchmarked via application-specific parameters



Accelerator readiness and stability allowed for:

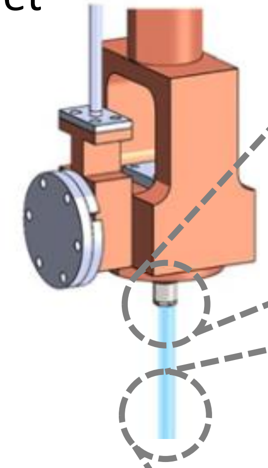
- **model-conform dose delivery**
- **successful radiobiological pilot study**

F. Kroll, et al., Nature Physics 18, 316 (2022)

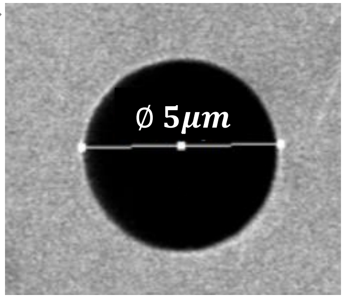
Cyrogenic jet based repetitive laser proton platform

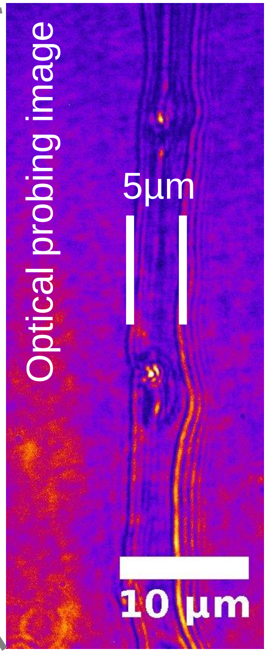
European XFEL | SLAC

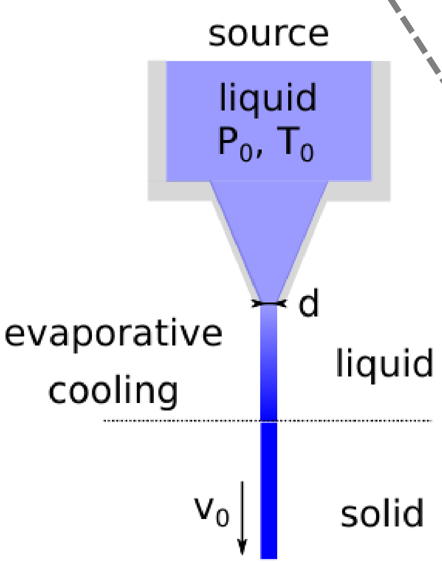
Cryogenic solid hydrogen jet



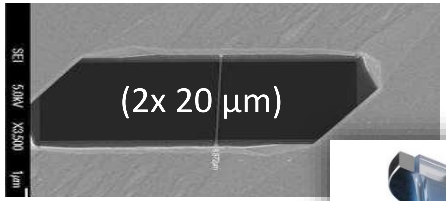
cylindrical jet

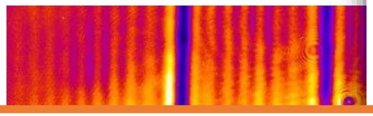






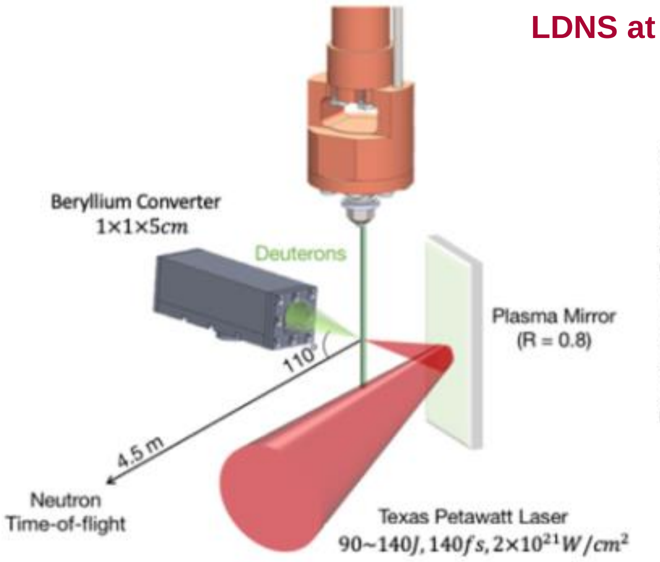
Sheet jets

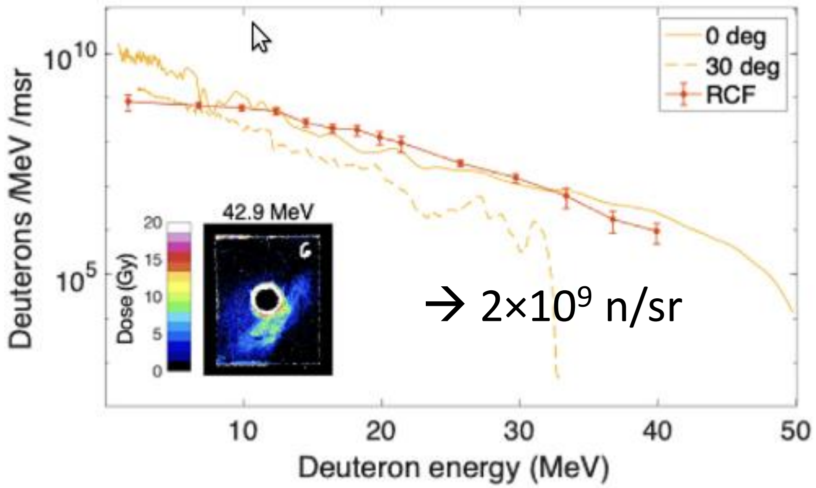




- debris free, high rep rate target
- single species, simple ionization dynamics, low density → facilitates quantitative modelling
- small geometries enable optical probing

LDNS at TPW with jets Jiao, X. *Frontiers in Physics* (2023)



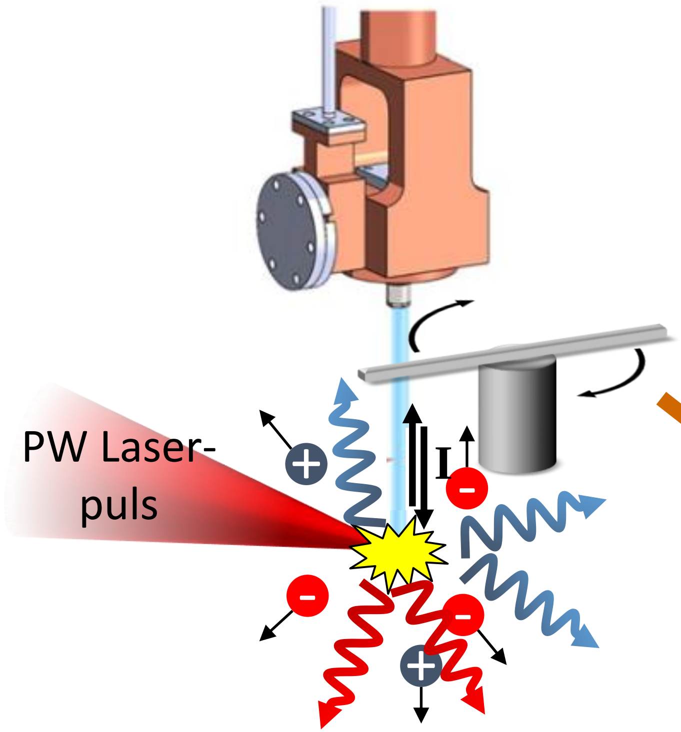


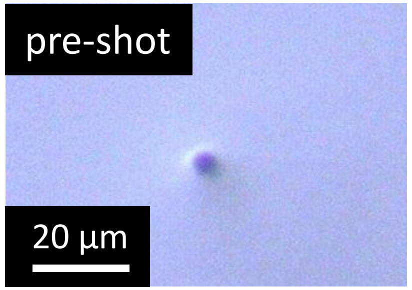
→ 2×10^9 n/sr

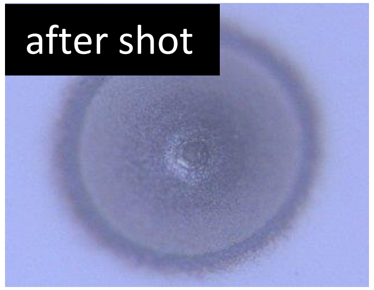
L. Obst Scientif...
S. Göde et al. Pr...

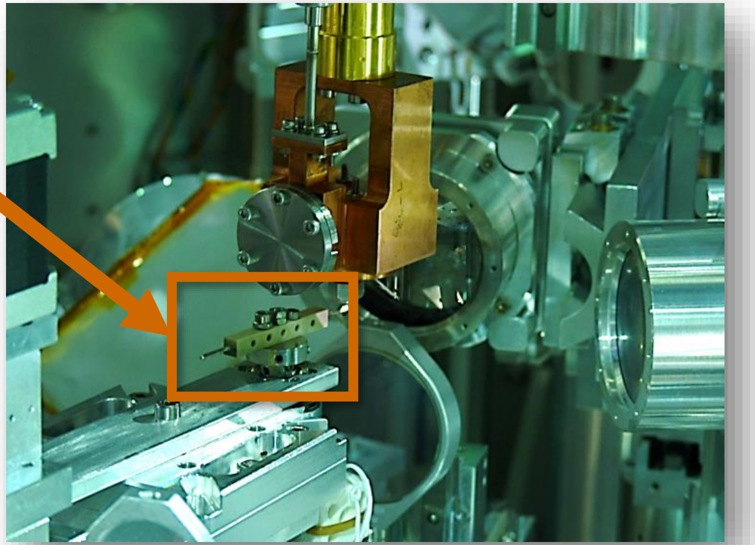
Developments - towards experiments @ high rep rate

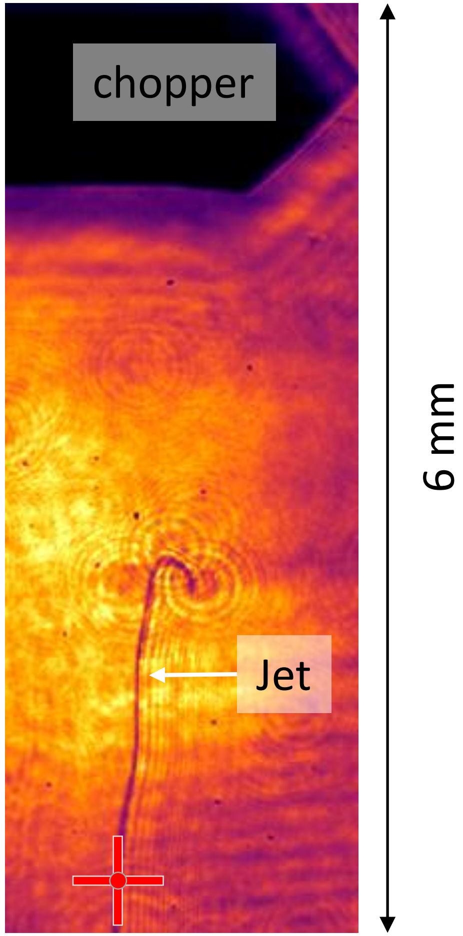
Rehwald IOP J. Phys.: Conf. Ser. (2023), Curry JoVE (2020), Bernert Scientific Reports (2022), Bernert Scientific Reports (2023)





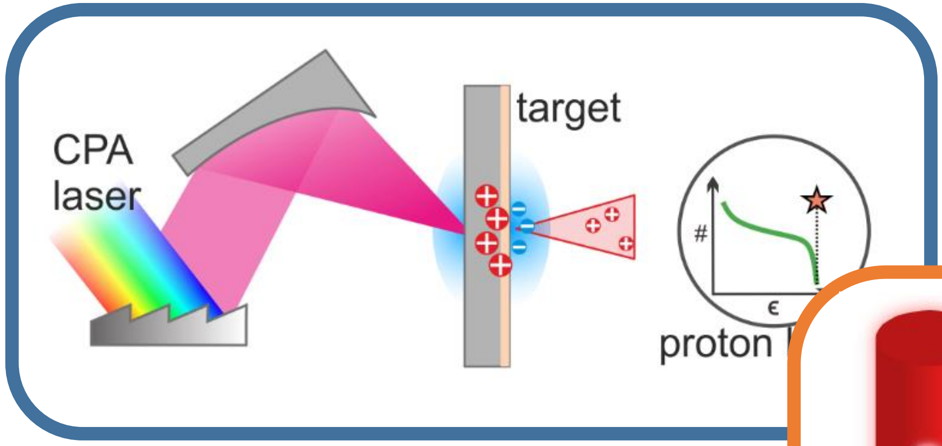


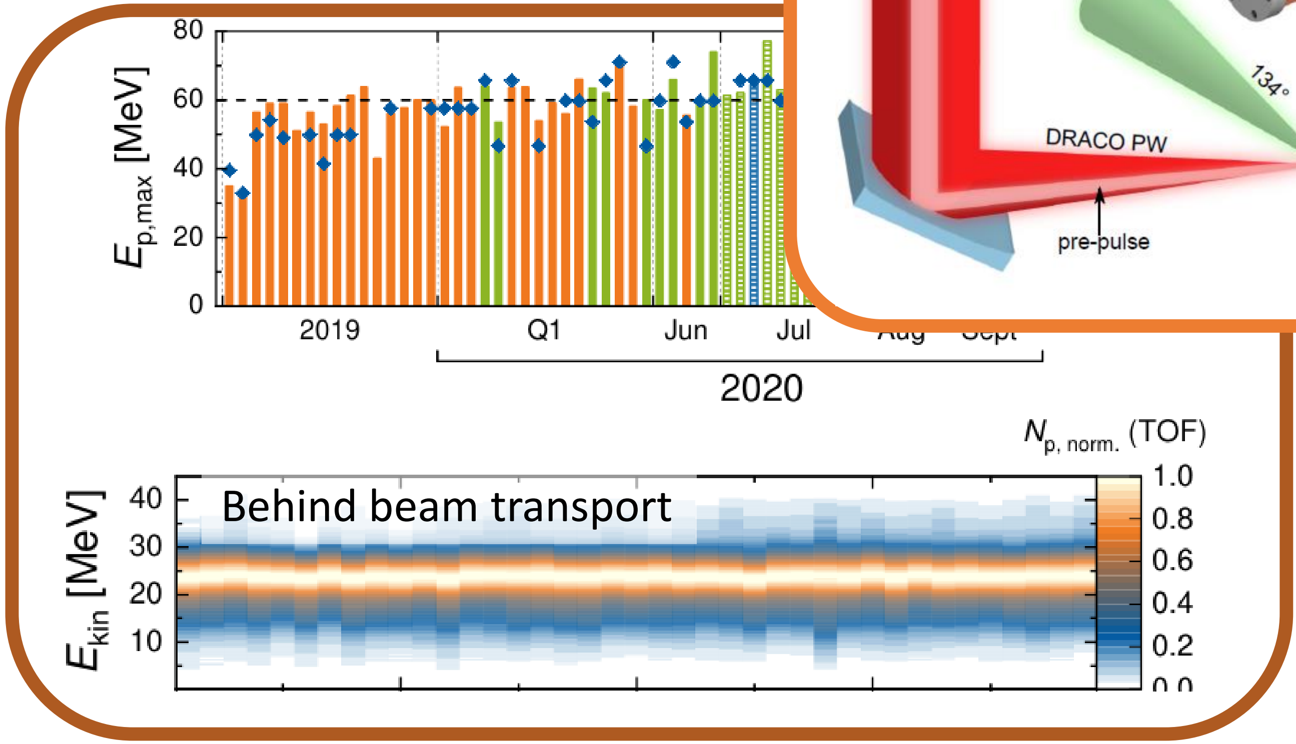


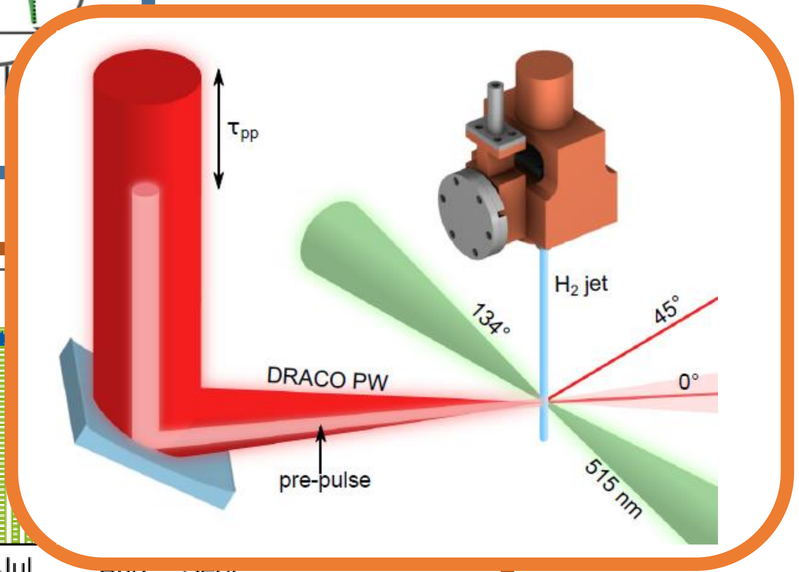


- Rotating mechnanical chopper blade to protect sensitive extrusion nozzle
- Experience in implementing off-harmonic, multiple optical probing beam paths
- Platform realized on many systems: Draco PW, Phelix GSI, SLAC-MEC, XFEL-HED, Texas PW

Intermediate summary – laser proton source







- Stable beam generation >60MeV and accelerator readiness demonstrated
- First animal irradiation → platform ready for translational research with laser-driven protons
- Cyrogenic jet based repetitive laser proton platform (up to 80 MeV)
- Pre-expanded plastic foils with >100 MeV
- Control of laser contrast and target density profile is key
- LPA source delivering 100 MeV at 1 Hz seems feasible with present laser technology

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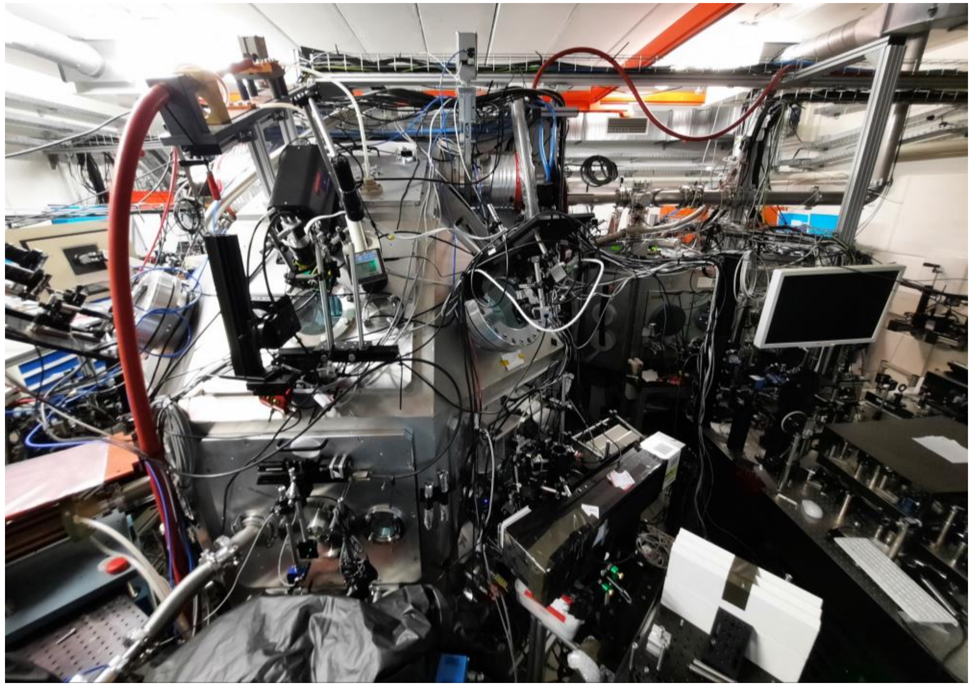
Part 2: Laser driven neutrons at Draco PW for fast neutron spectroscopy



GOALS of Experiment:

- Test neutron diagnostics in laser plasma environment
- Single neutron detection with diamond detectors
- Multiple detectors for protons, neutrons and various background sources

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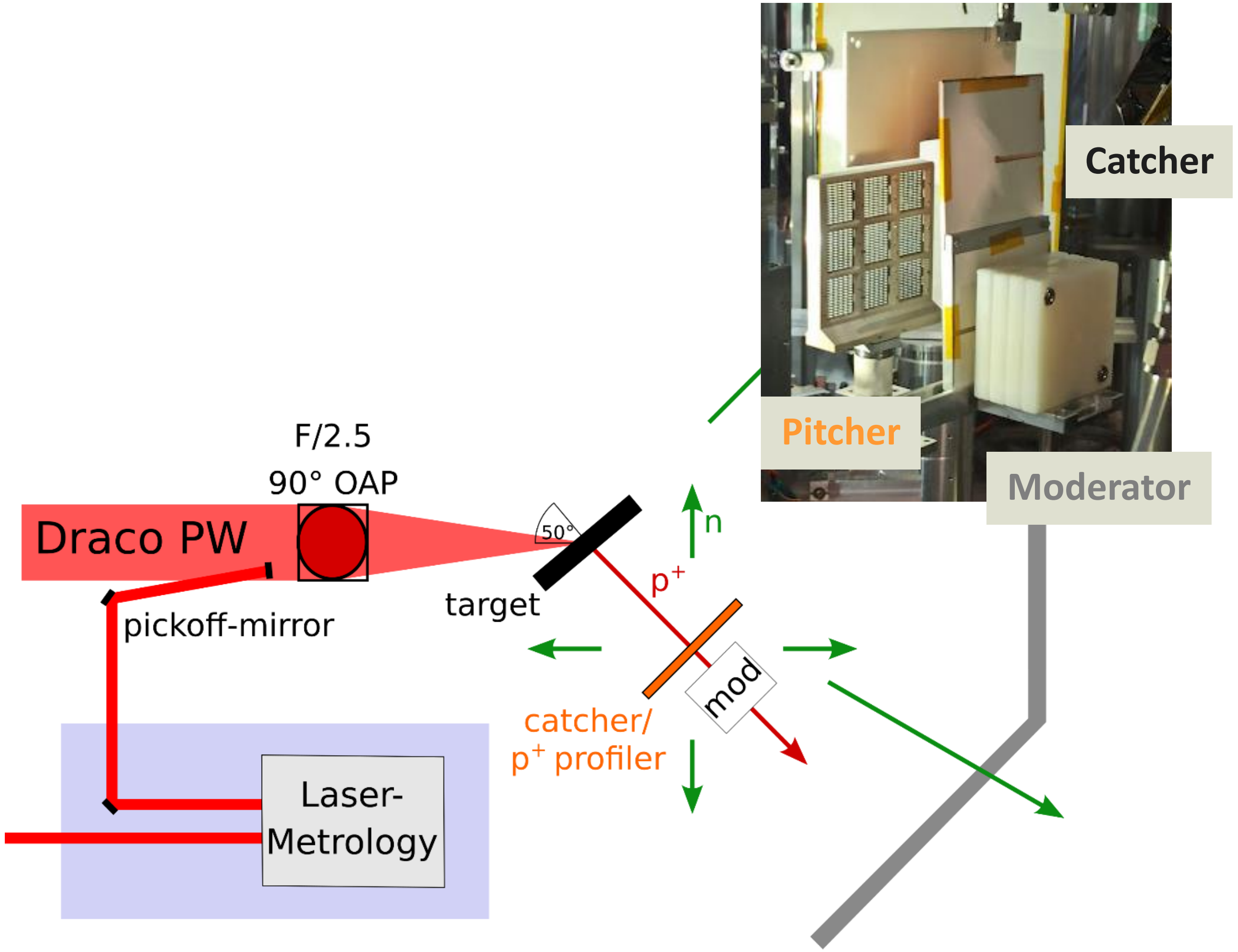
Experiment setup and diagnostics

Laser, pitcher, catcher, moderator



Laser:

- Single plasma mirror (PM)
- up to 18 J in 30 fs
- input spectrum before PM, spectrum and SPIDER after PM for spectral phase optimization

Pitcher:

- FV ~250 nm (1300 shots in 8 days)
- deuterated PS ~180 nm (>110 shots)

Catcher:

- Cu (3mm) or LiF (25 mm)

Moderator (beam dump):

- PE block

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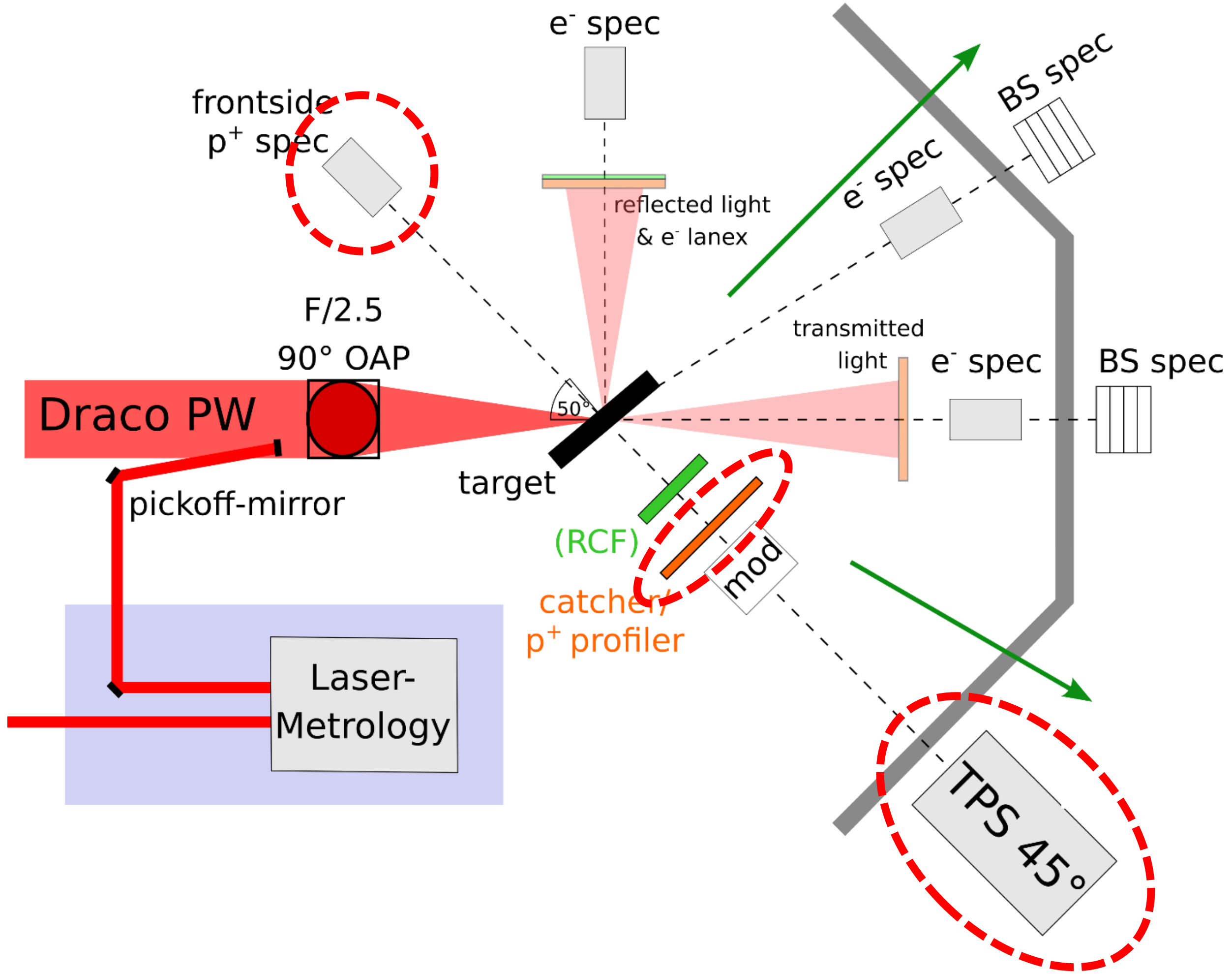
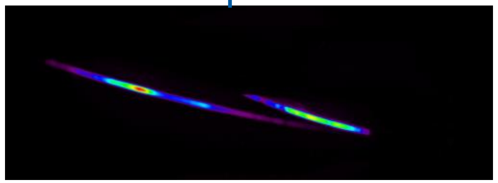
Experiment setup and diagnostics

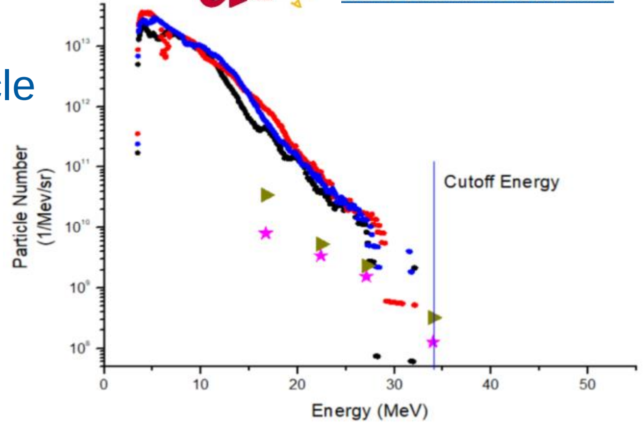
Protons



Thomson parabola spectrometer (TPS)

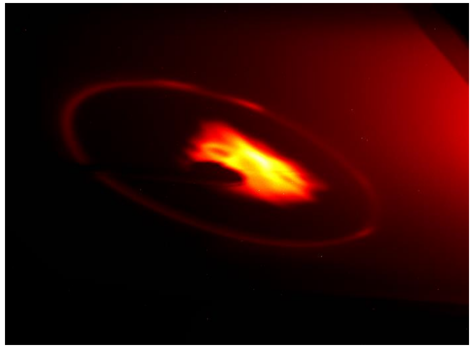
- Lanex for absolute particle number spectrum





Proton profiler

- Lanex screen on the back side of the catcher
- Shows proton beam profile for ≥ 40 MeV

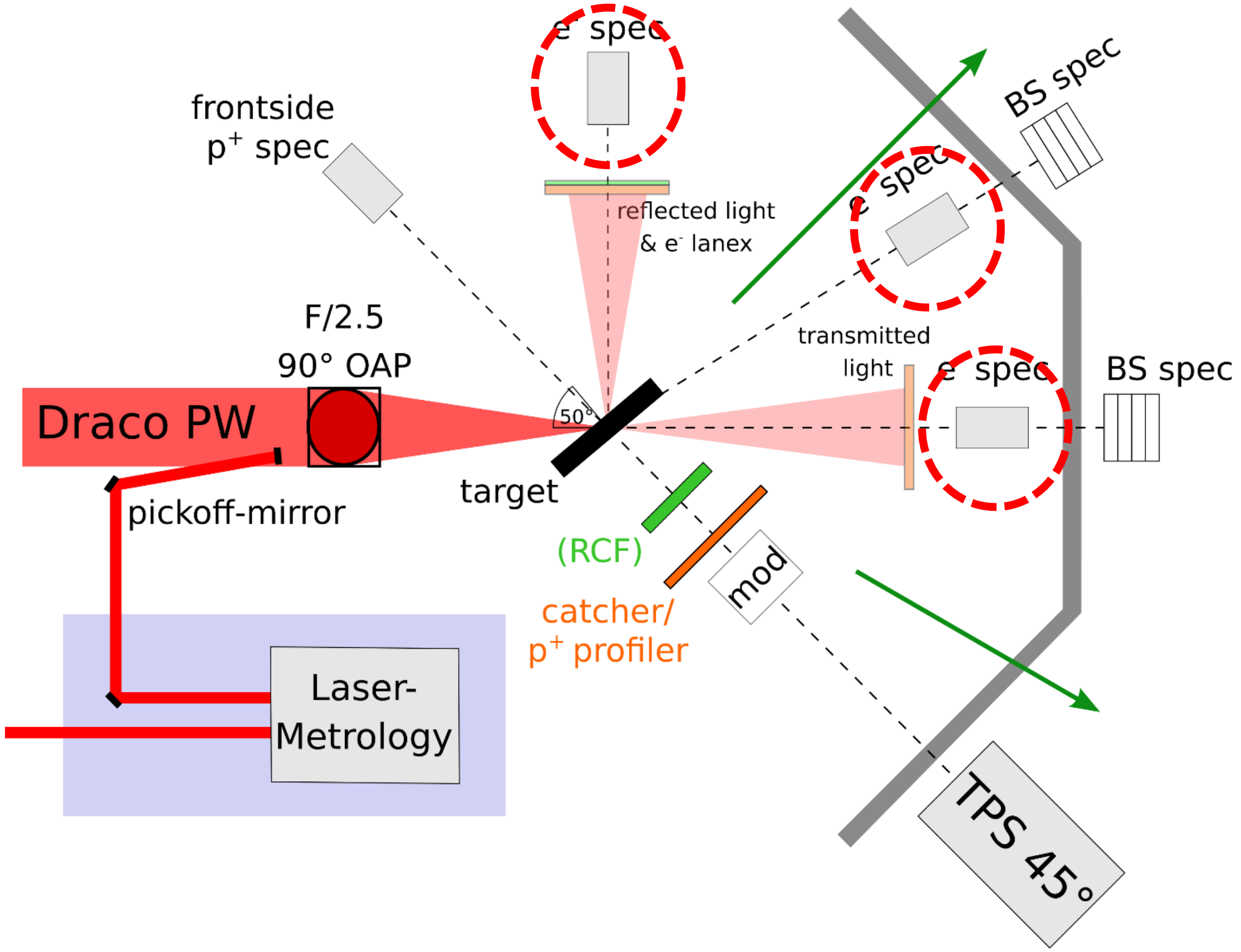


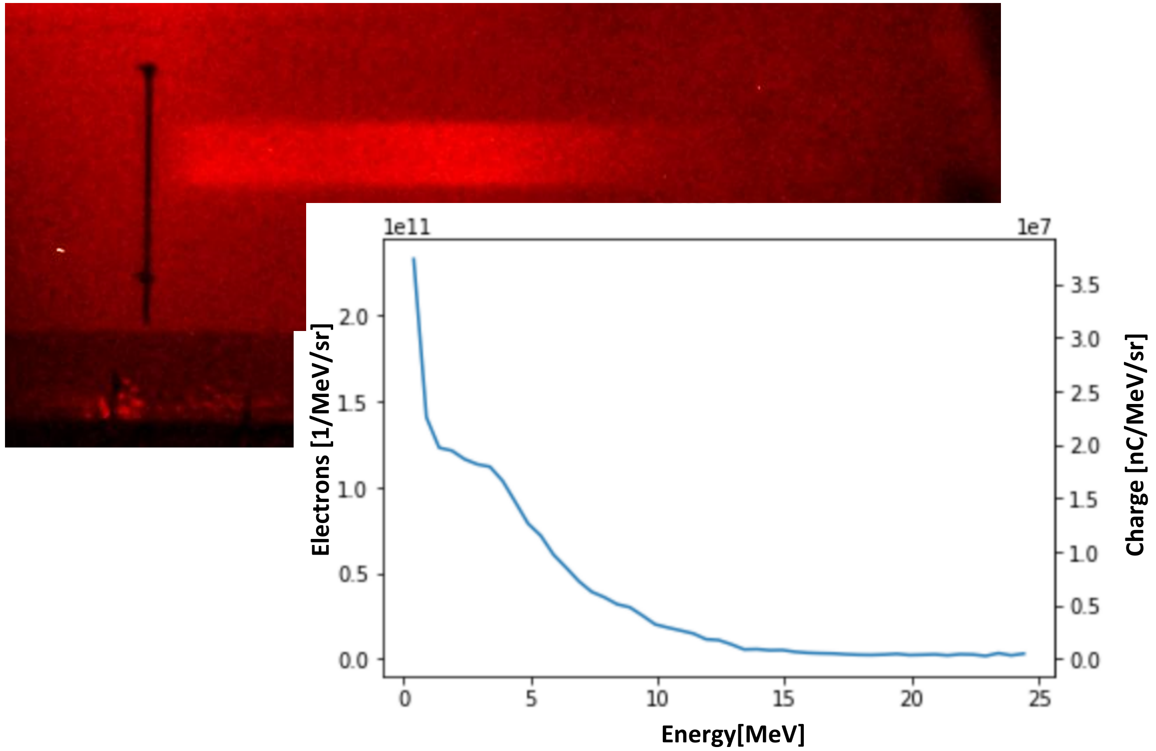
p^+ frontside spectrometer:

- Frontside protons able to drive a “parasitic” neutron source?

Experiment setup and diagnostics

Electrons



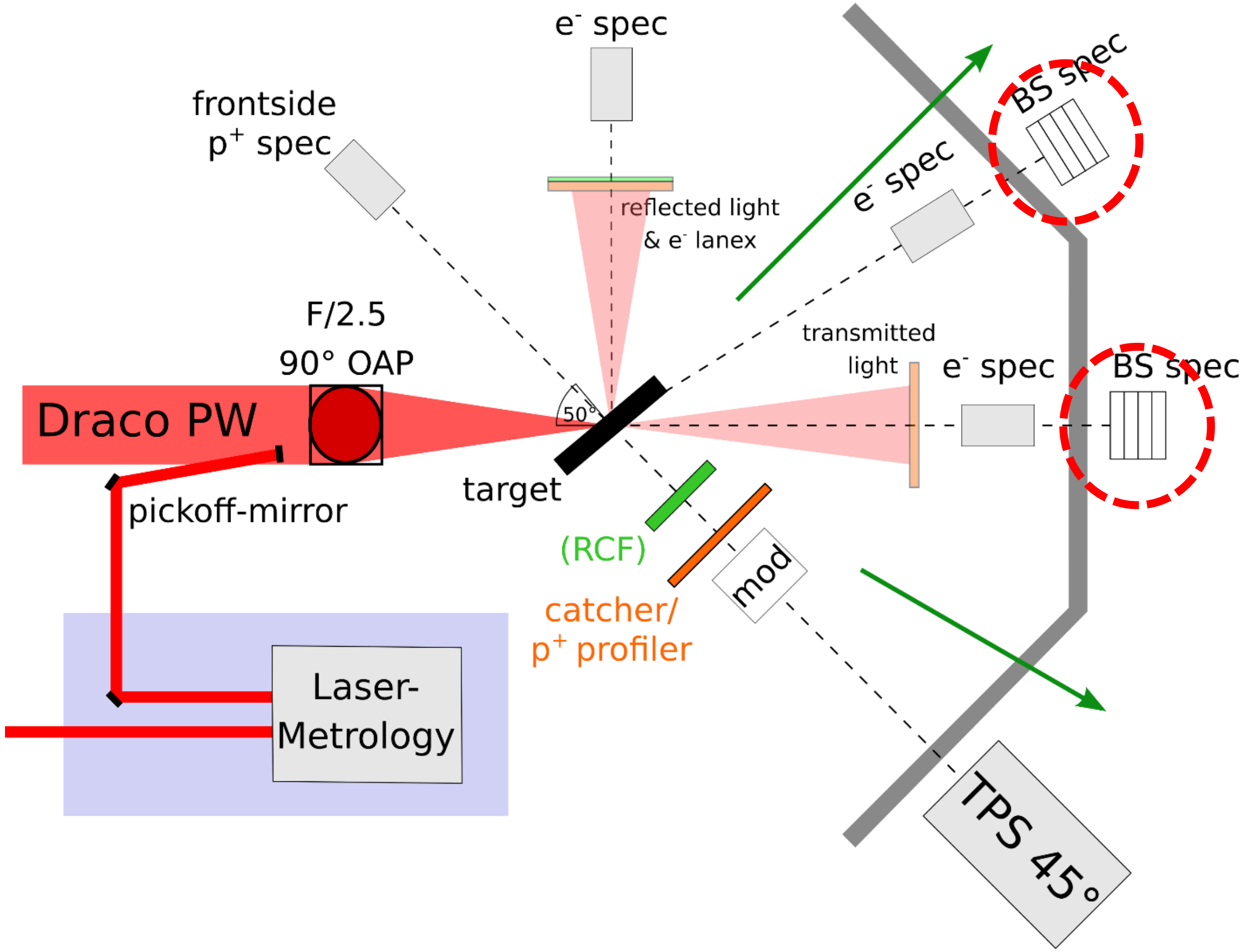


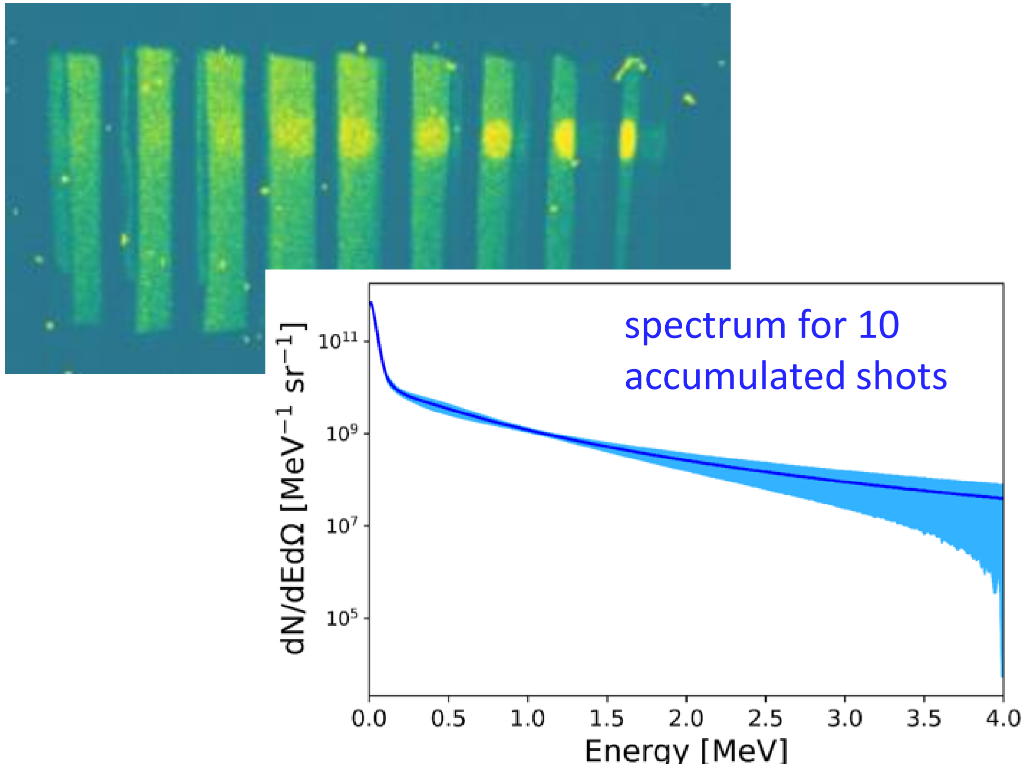
e^- spectrometers:

- Measurements in multiple directions
- Electrons magnetically deflected impinging on Lanex
- Spectra and temperatures of front and backside electrons

Experiment setup and diagnostics

Bremsstrahlung





BS spectrometer:

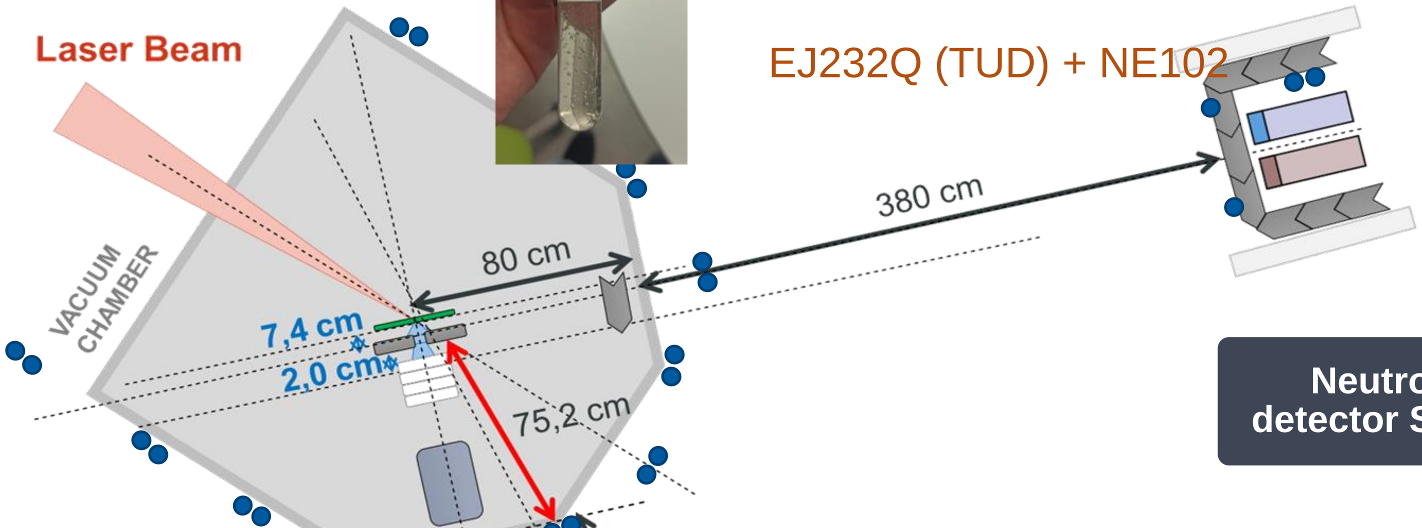
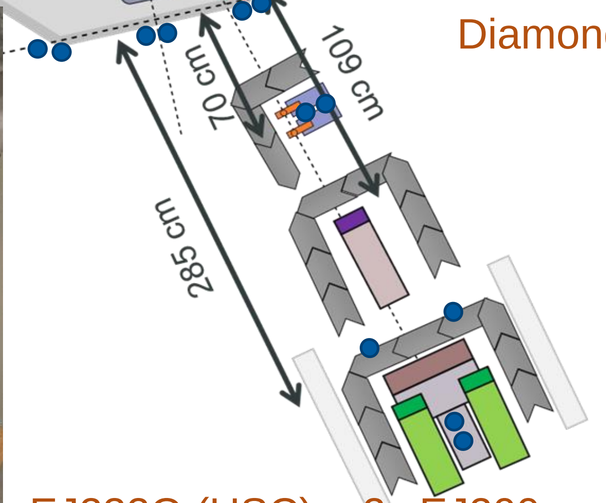
- Measurements in multiple directions
- Electrons magnetically deflected
- Absolutely calibrated via IP stack

A. Laso et al. Rev. Sci. Instrum. 93, 043102 (2022)

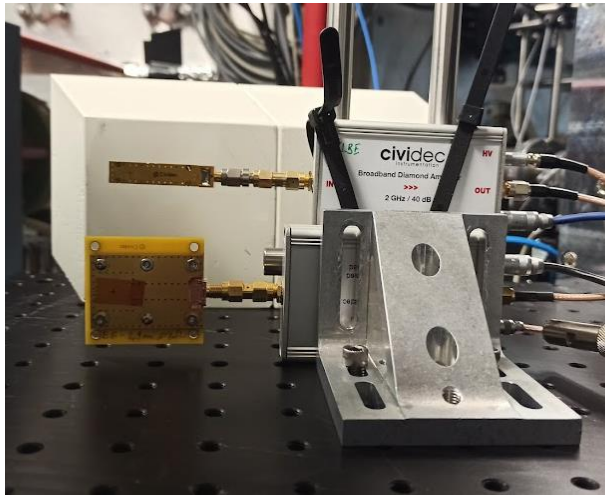
Neutron detection setup: gamma sensitivity versus shielding

Bubble detectors

EJ232Q (TUD) + NE102

Diamond detectors



EJ232Q (USC) + 2x EJ200
+ Gated PMT EJ232Q

Neutron detector Setup

- **Scintillators**
  - 2 x EJ200 (US)
  - NE102 (TUD)
  - 2 x EJ232Q (TUD + USC)
  - Li-Glass (US)
  - EJ232Q + Gated PMT (HZDR)
- **Particle detectors**
  - 2 x diamond detector (CIVIDEC + HZDR)
- **Passive detectors**
  - 13 x Bubble detectors (TUD + USC)

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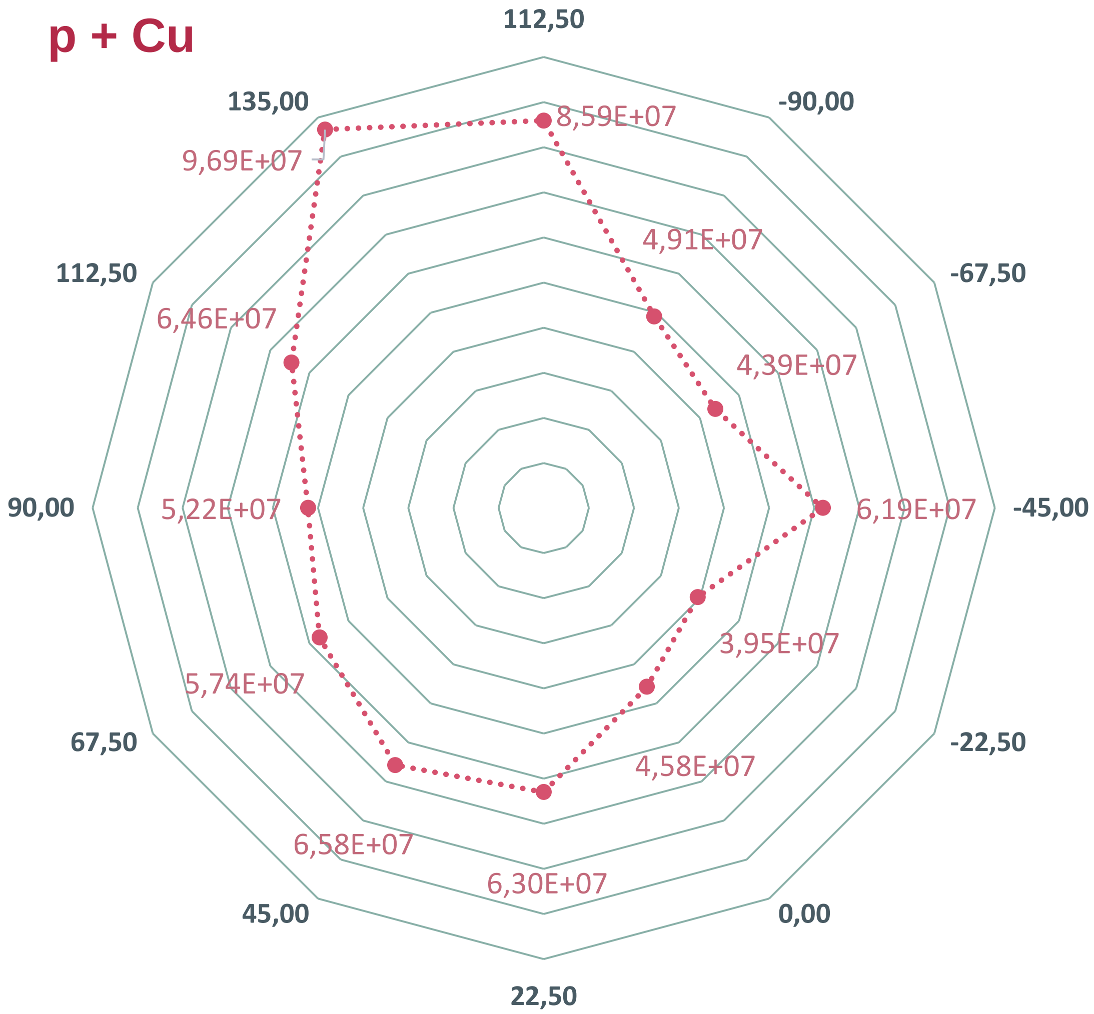
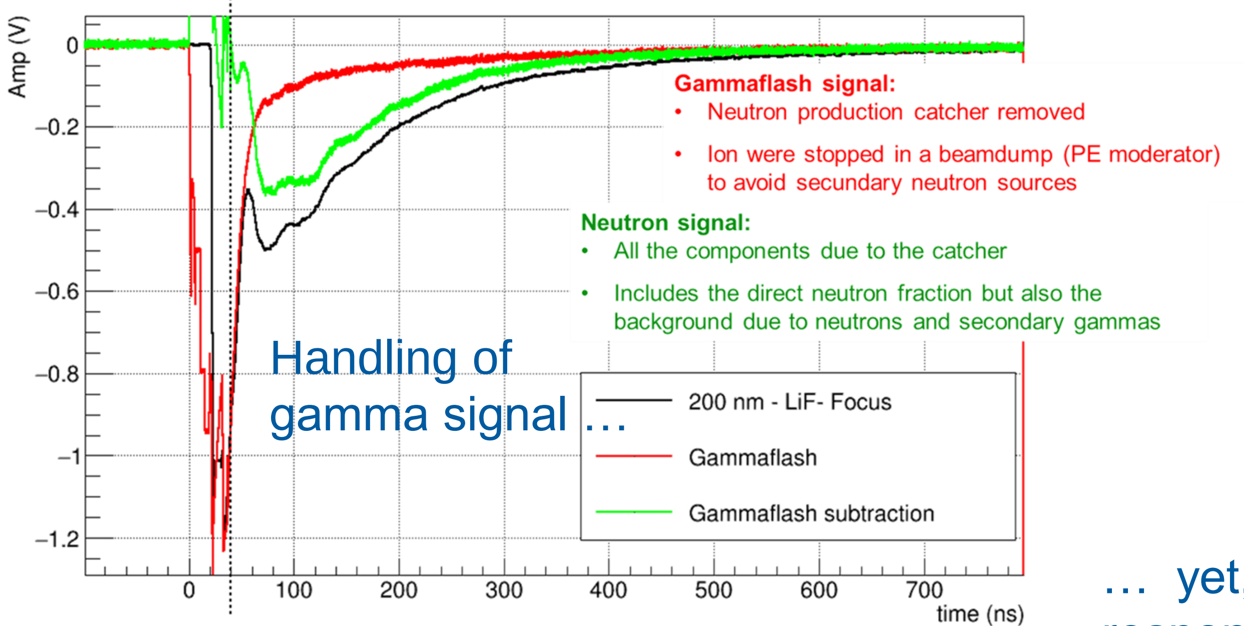
Neutron production: Bubble detectors



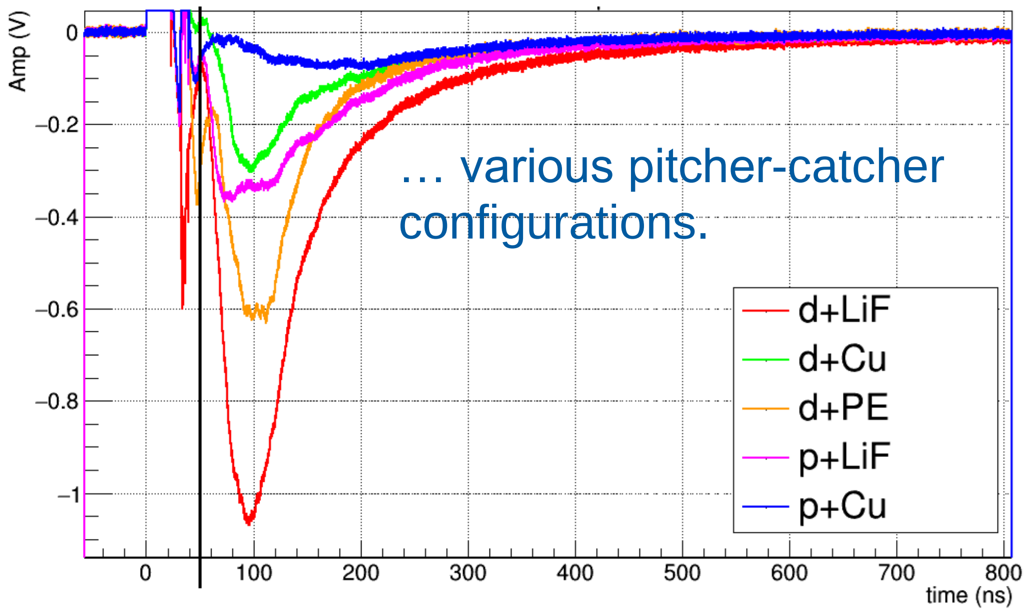
Configuration	Neutrons per shot (Forward direction)
p + Cu	~ $59(3)\cdot10^6$ neutrons/sr
d + Cu	~ $51(5)\cdot10^6$ neutrons/sr
d + PE	~ $46(6)\cdot10^6$ neutrons/sr
p + LiF	~ $60(7)\cdot10^6$ neutrons/sr
d + LiF	~ $81(8)\cdot10^6$ neutrons/sr

- Assuming isotropic emission **$7.5\cdot10^8$ neutrons/shot consistent with estimation from proton spectrum**
- Yet open questions concerning backward emission and spectral sensitivity wrt scintillators
- To be evaluated with the help of simulations

Time of light signal from scintillators

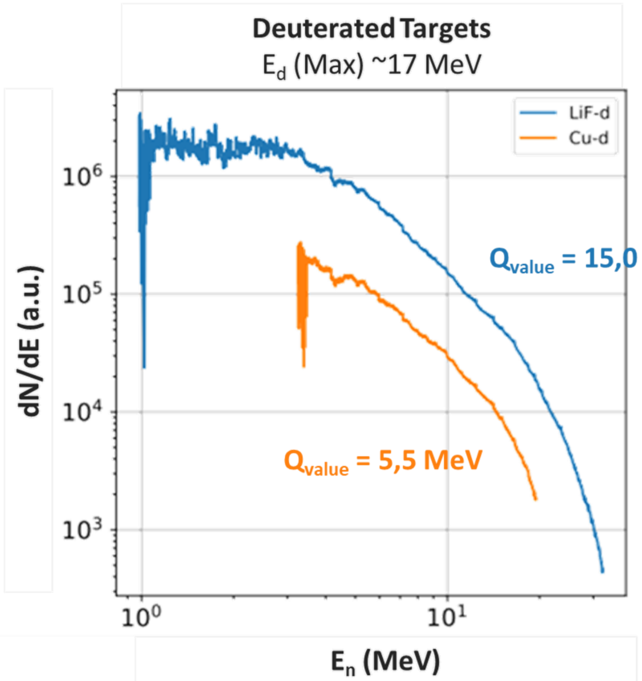


Handling of gamma signal …

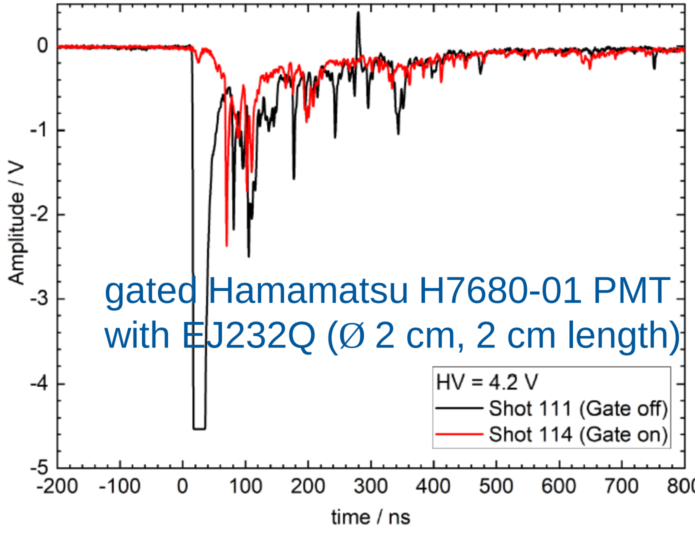


… various pitcher-catcher configurations.

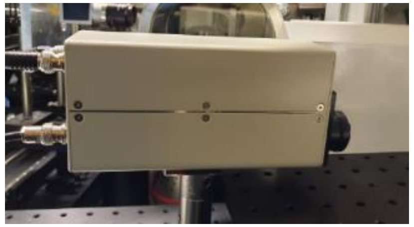
… deconvolution of TOF signal,



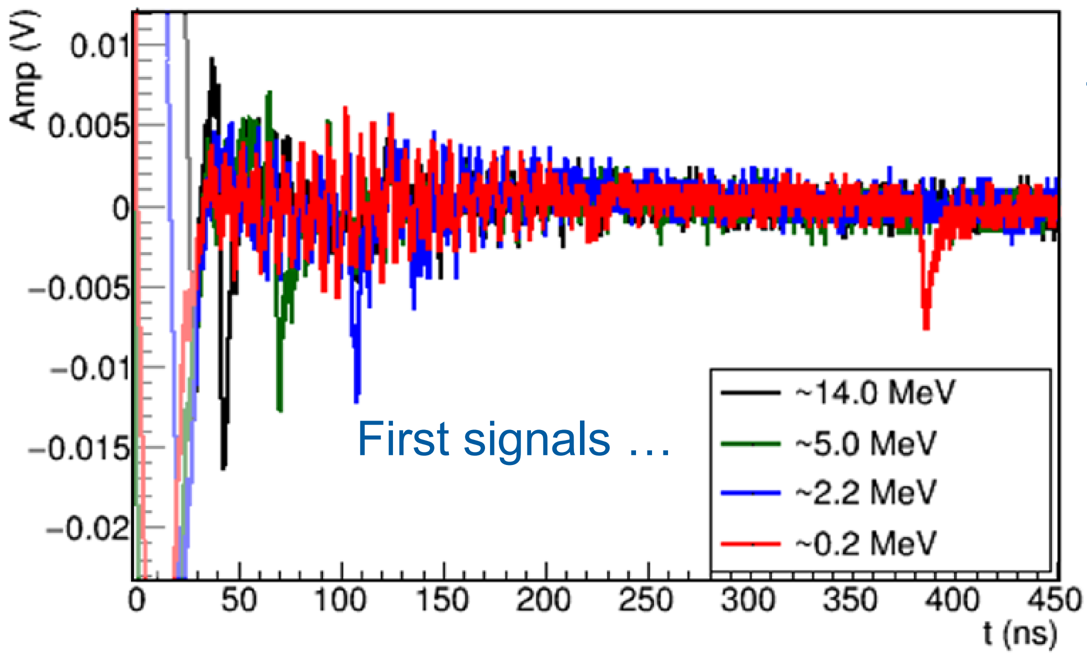
… yet, contribution of gamma induced effects, detector responses and influence of shielding to be investigated with detailed MC simulations.



gated Hamamatsu H7680-01 PMT with EJ232Q (Ø 2 cm, 2 cm length)

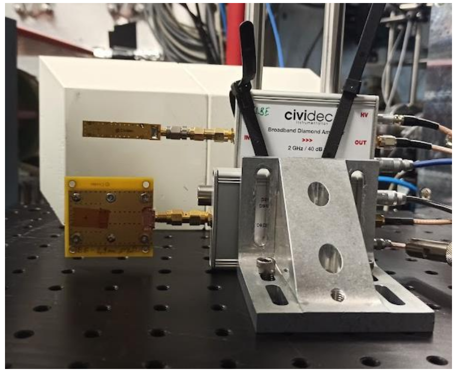


Single event detection with Diamond detectors



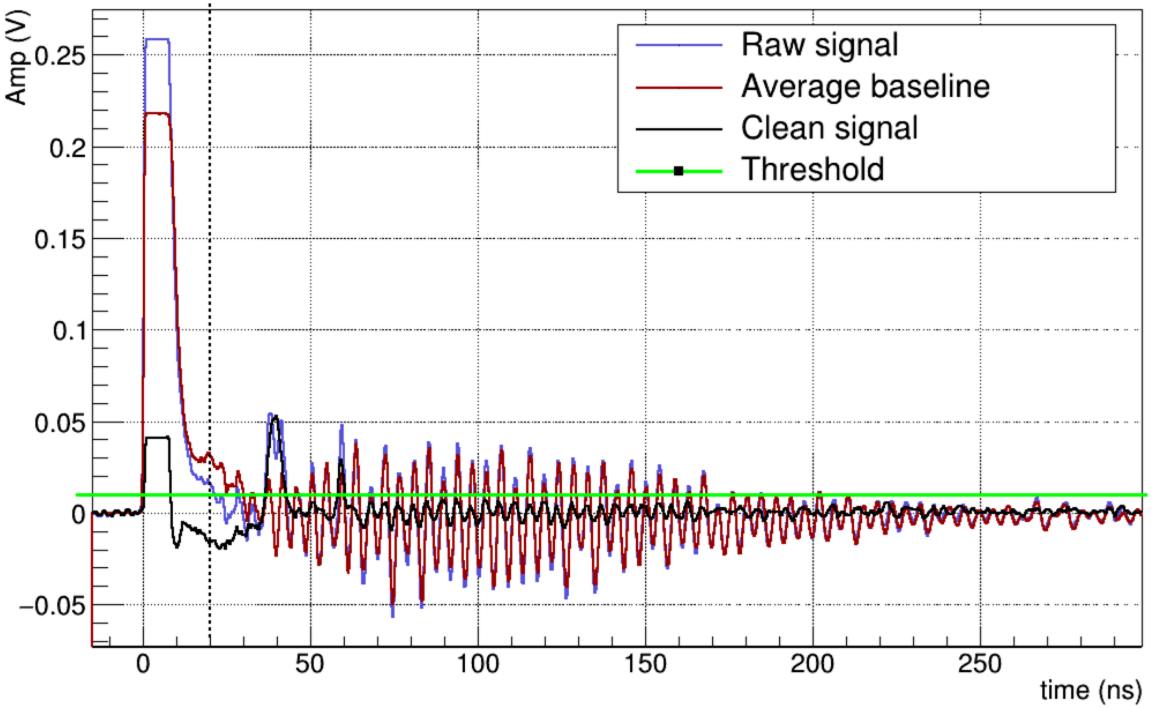
First signals …

Size: 4x4 mm
Thickness: 140µm and 500 µm

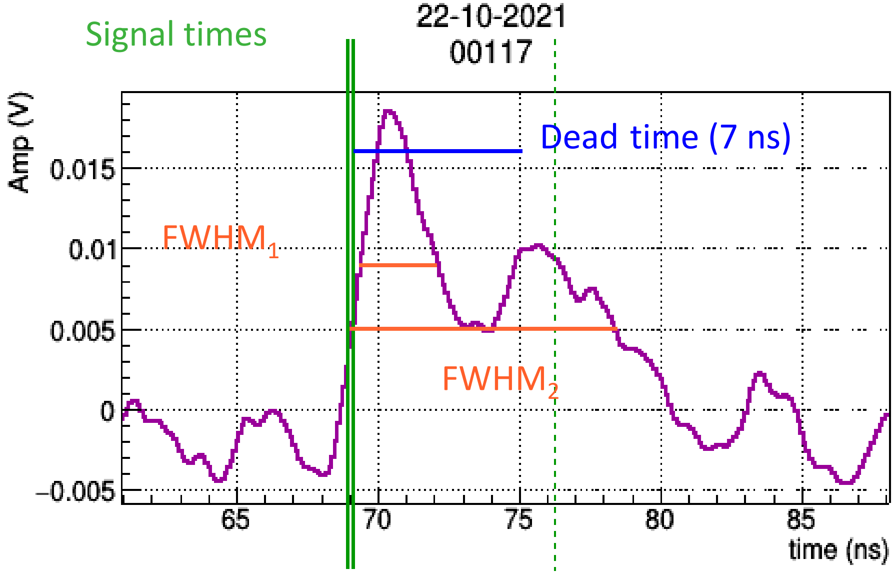


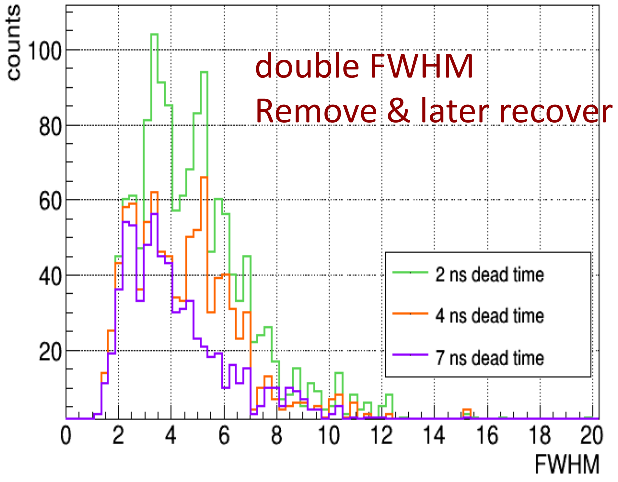
- Sensitivity **low** for gamma, **high** for charged particles (n, chp) reactions
- **Fast response sub-ns rise time, fast recovery**
- Operated with a 2 GHz Broadband Amplifier (40dB), **EMP mitigation important**

… subtraction of gamma signal and cleaning of constant EMP noise. Signal classification via threshold.



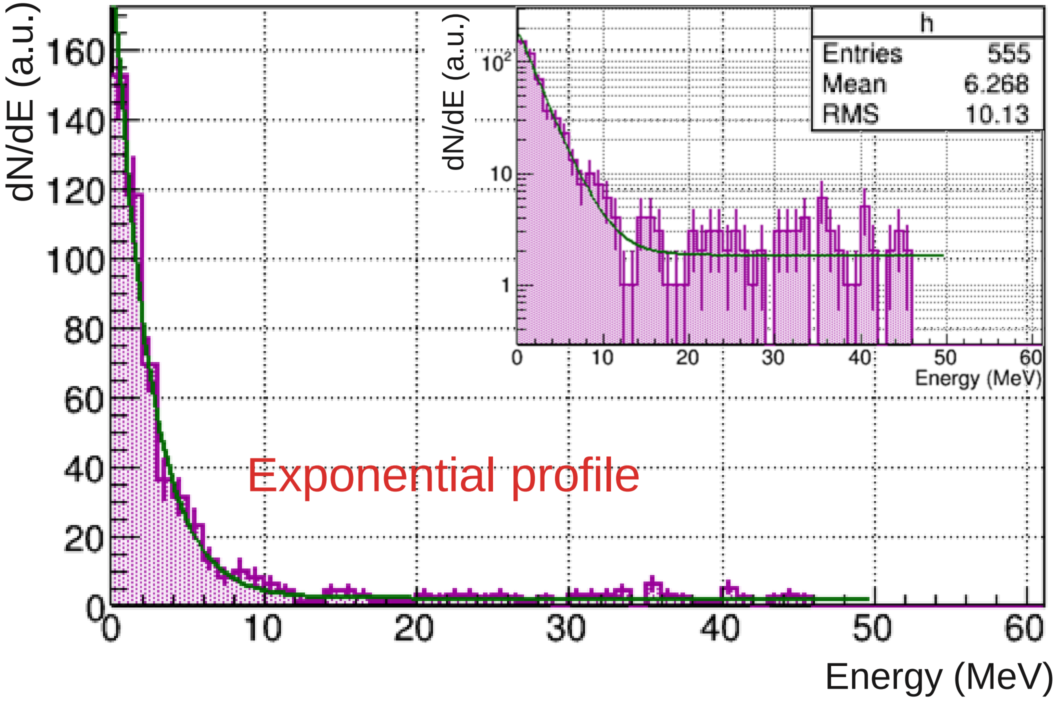
Single event detection with Diamond detectors





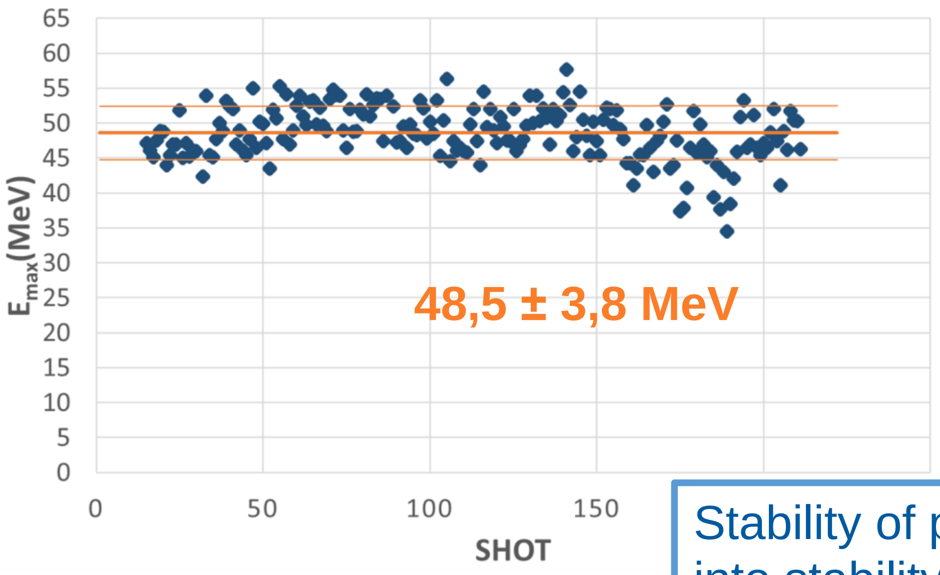
Timing correction, quality checks via signal shape analysis and amplitude-energy correlation ongoing …

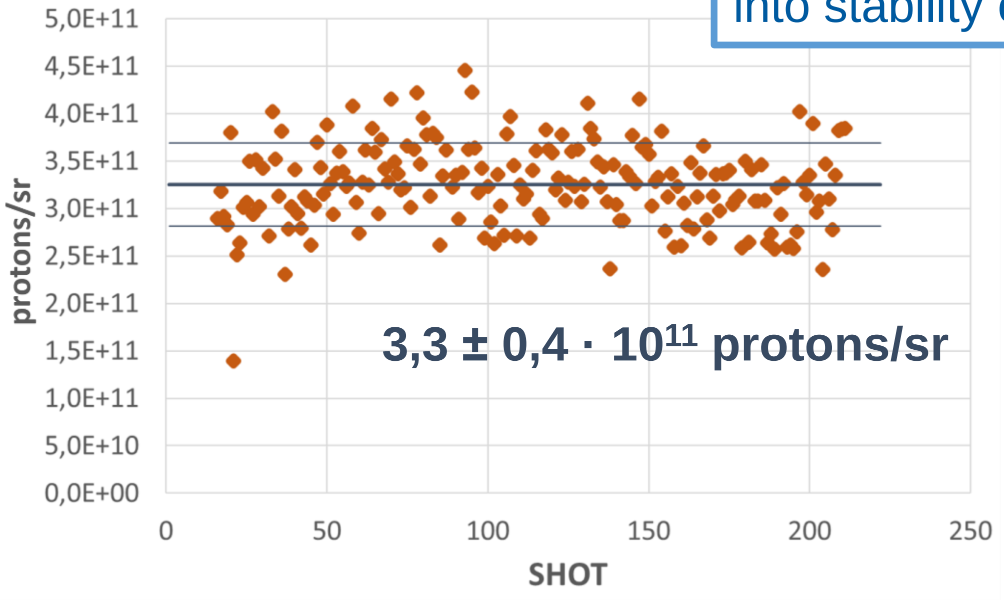
… preliminary spectrum for (protons + Cu catcher), includes 555 counts from 194 shots.

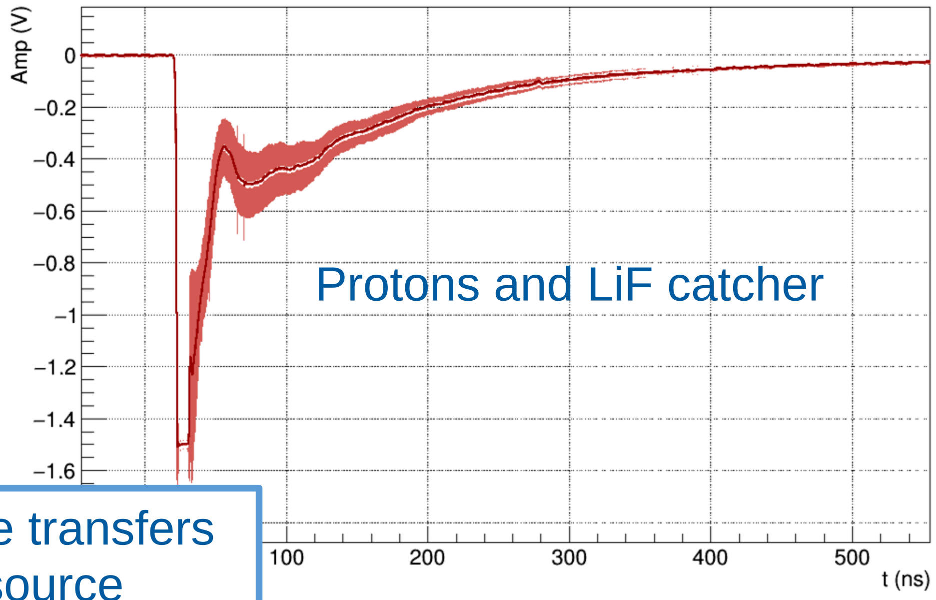


Proton source stability

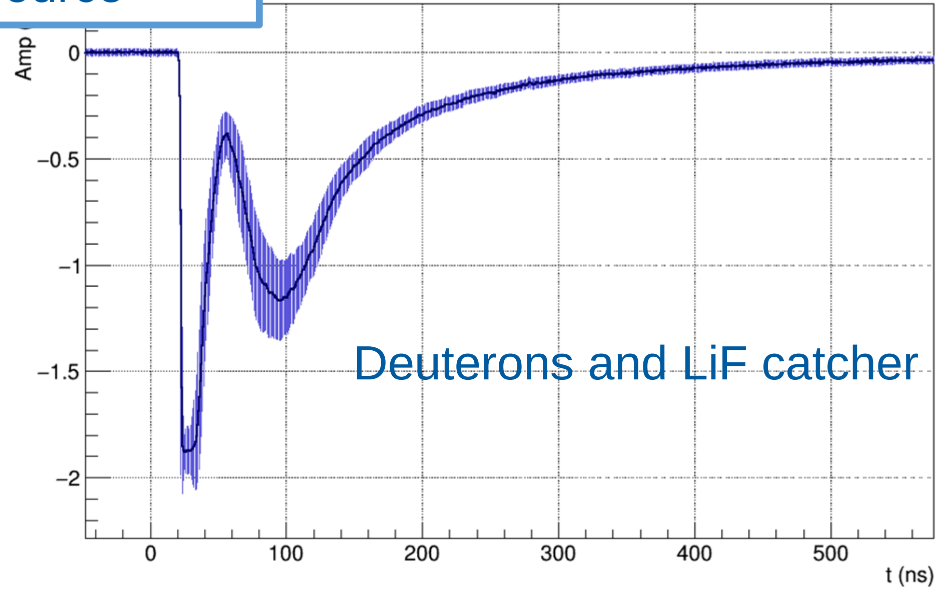
Stability of the laser-driven particle sources determines the validity of the neutron spectrum.



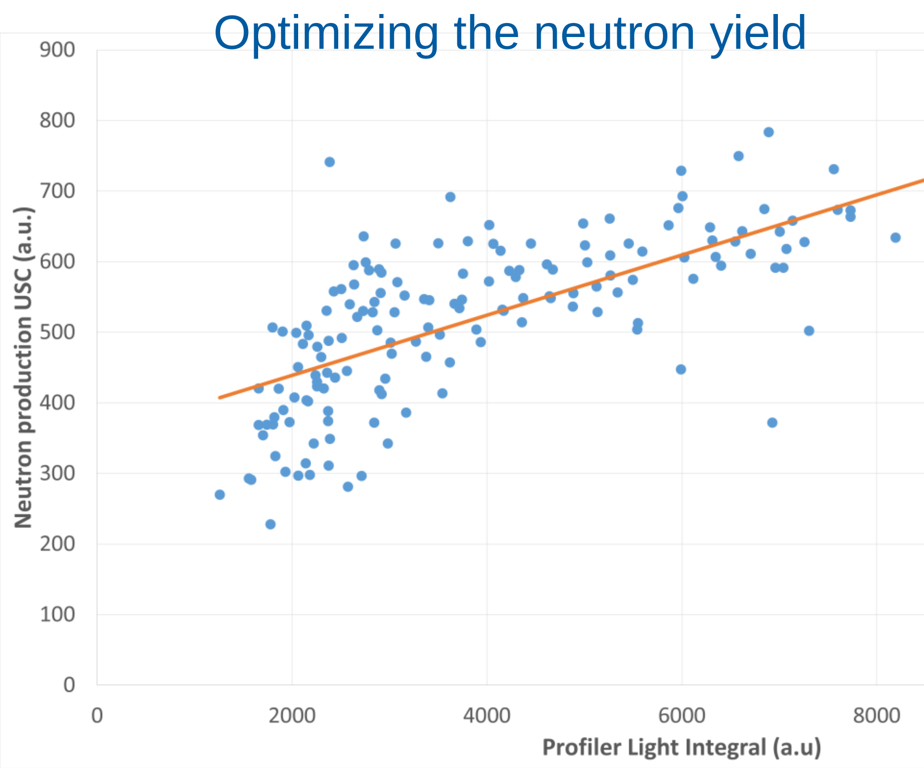


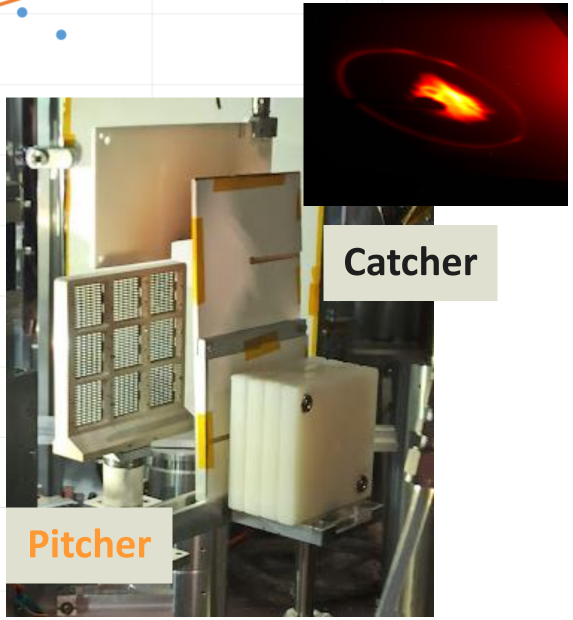


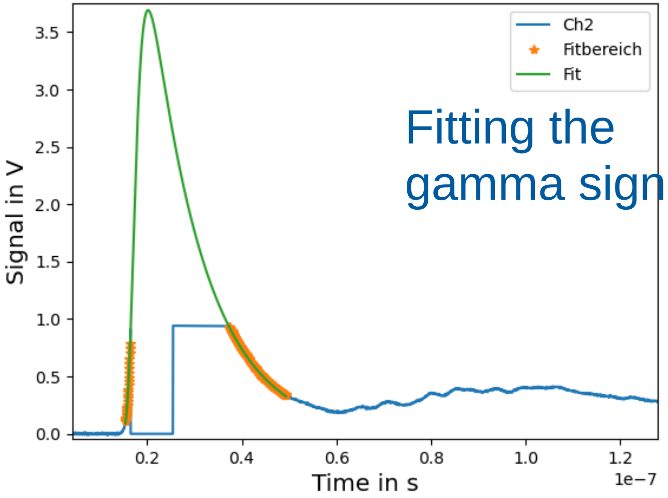
Stability of proton source transfers into stability of neutron source



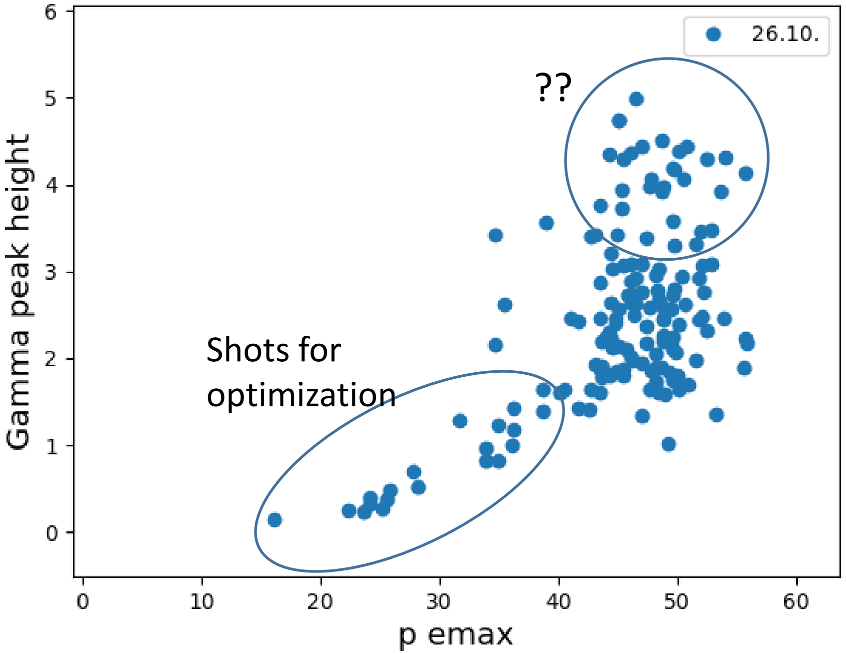
Correlations for varied laser target configurations







LiF & Cu



- Correlation between particle and plasma diagnostics – work in progress
- Compromise between neutron yield and gamma signal
- Study scaling of secondary sources and EMP background

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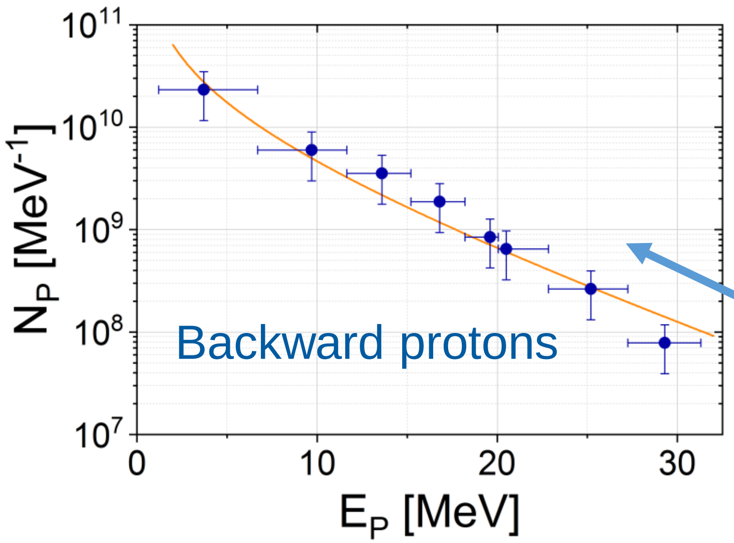
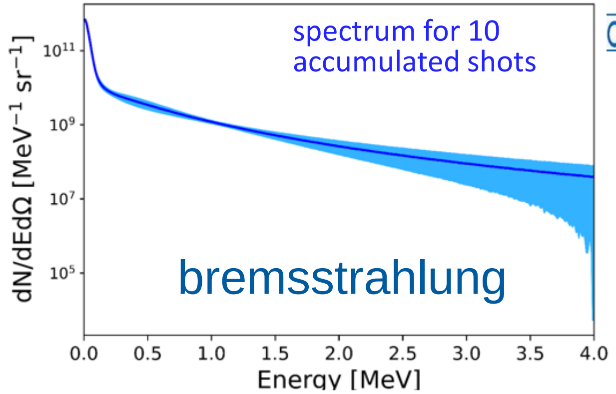
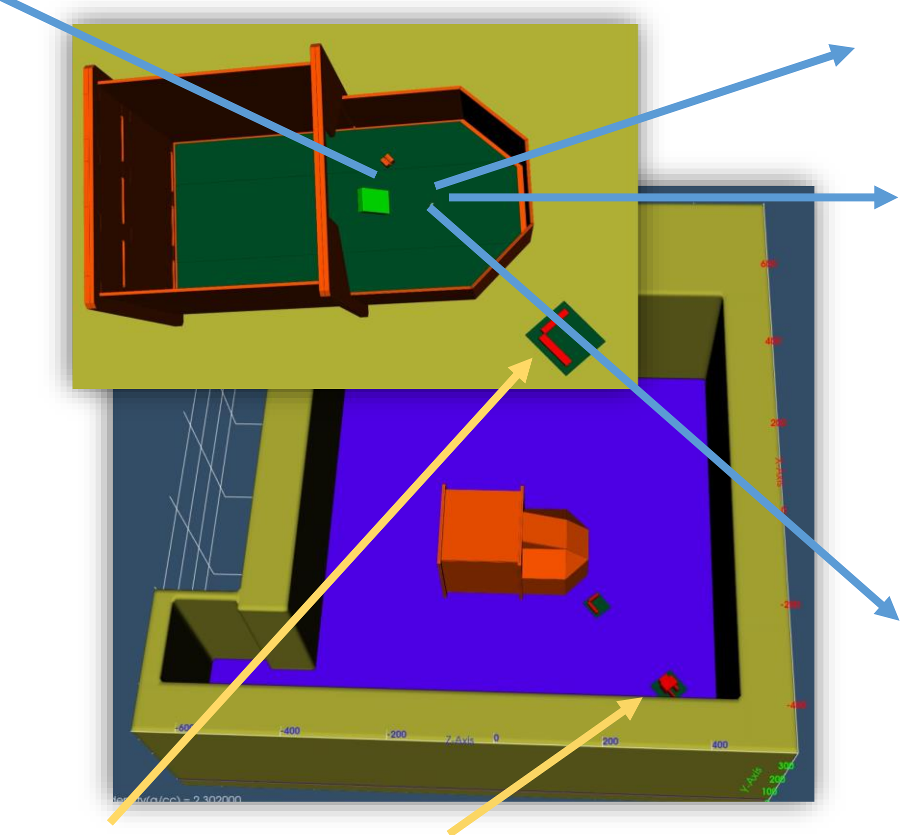
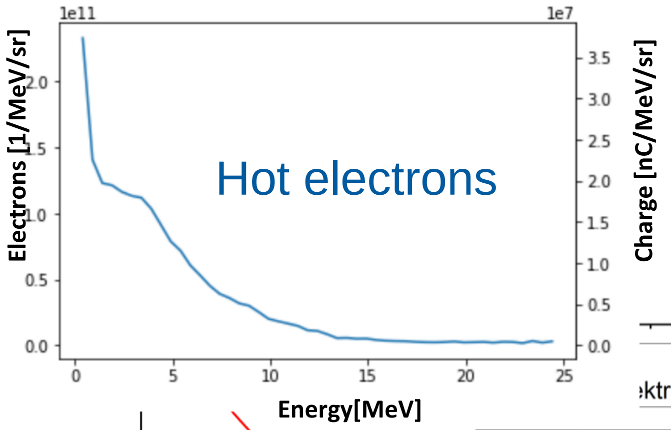
Monte Carlo simulations

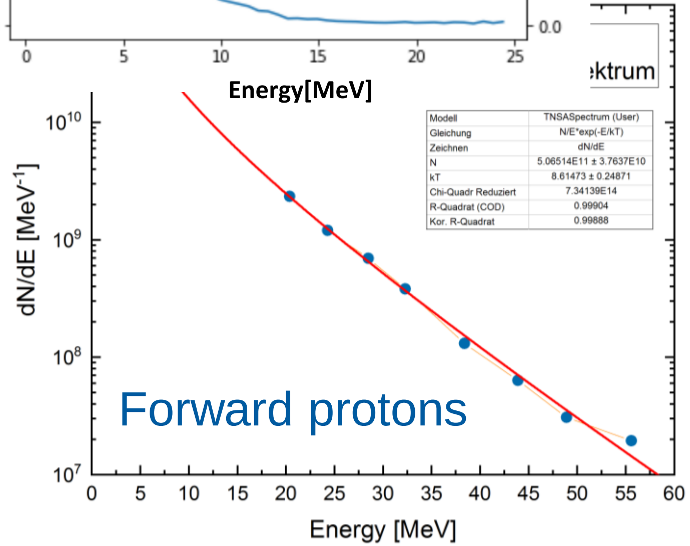


- Full model of experimental setup used at DRACO
- PHITS Monte Carlo code developed by JAEA



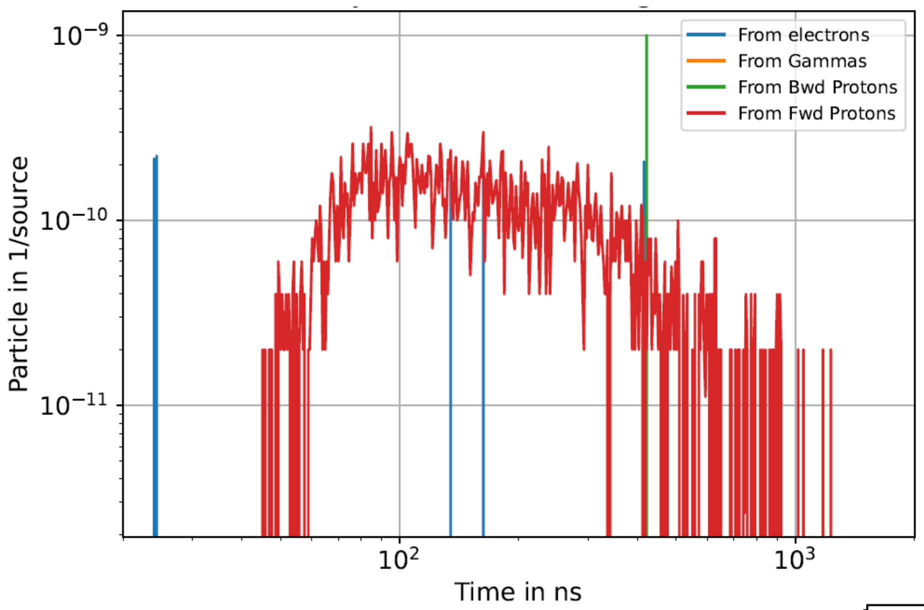




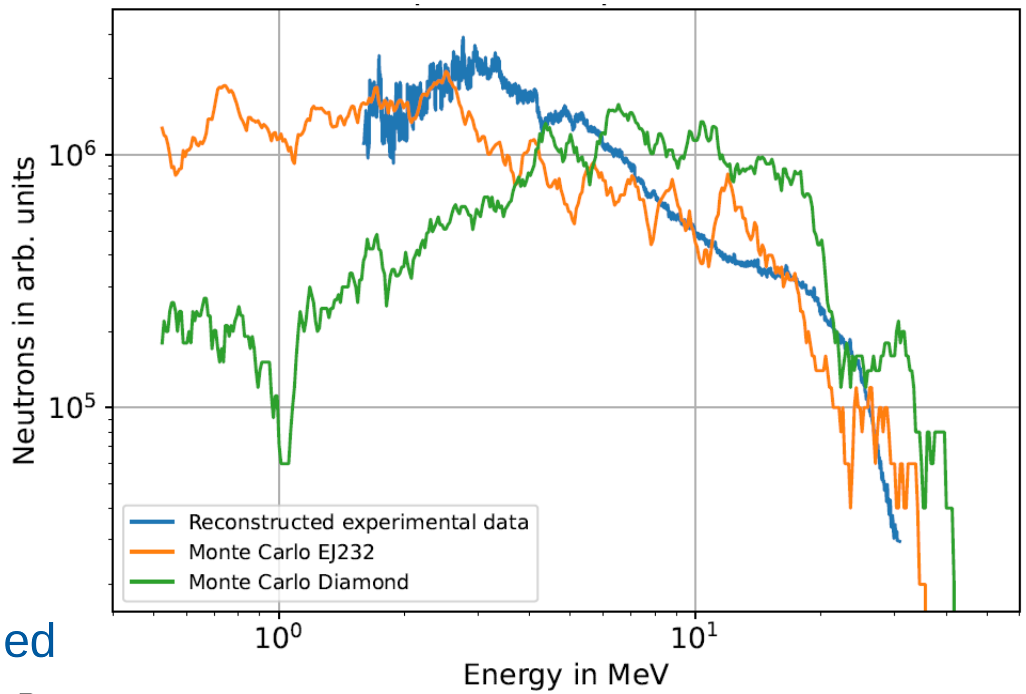


- Scoring of photons and neutrons by time of flight and energy
- Investigate contribution of gamma flash to neutron signal
- Investigate potential other neutron sources (backwards protons, hot electrons, etc.)
- Contribution of shielding

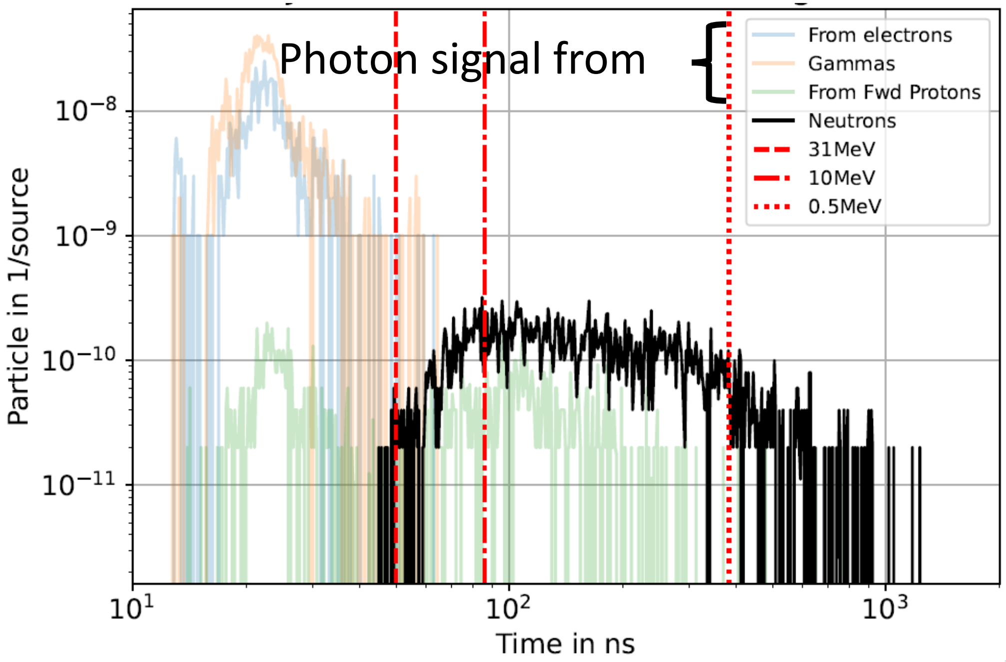
Monte Carlo simulation results – work in progress



- Secondary photons in scintillator
- Input spectra to be scaled



- Neutron signal induced in scintillator from different sources
- Main signal from catcher
- Input spectra to be scaled



- Comparison scintillator signal with MC – similar shape
- Difference between scintillator and diamond → WIP

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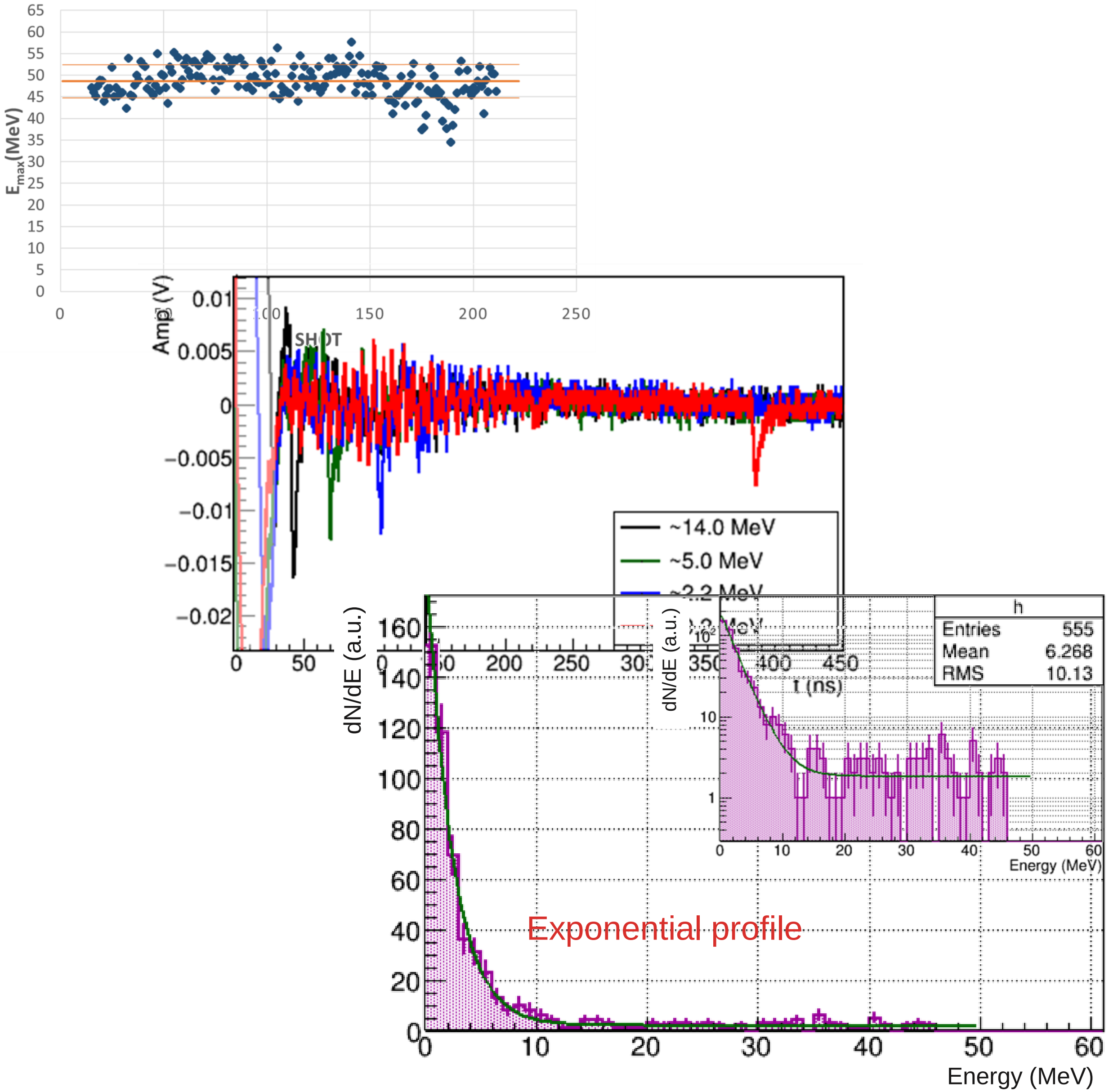
Conclusion



- **Almost 1300 shots & laser-plasma source setup mostly unchanged** → Statistical analysis of shot-to-shot fluctuations and proton acceleration stability
- **Harsh radiation environment:** → Need of huge shielding (extra source of background) or ultrafast detectors with low efficiency (e.g. diamonds. Need of a high repetition source).
- **Strong EMP:** High-frequency noise ringing in detector signals. → Reduced, but not avoided, with EM shielding.
- **Single event fast neutron ToF spectrum in a PW laser system!** → First steps for nuclear reactions measurements in a laser facility.

Big Thanks to the Dresden Team

Laser radiooncology

Laser particle acceleration

reference beams

biological infrastructure

biological models

beam transport/ dose delivery

beam monitoring/ dosimetry

laser-driven ion acceleration

high power lasers Draco and PENELOPE

computational radiation physics

J. Pawelke, E. Beyreuther, K. Brüchner, E. Bodenstein, L. Karsch, E. Lessmann, M. Krause, E. Troost, N. Cordes, C. Richter, et al.
K. Zeil, J. Metzkes-Ng, F. Kroll, C. Bernert, E. Beyreuther, L. Gaus, S. Kraft, A. Nossula, M.E.P. Umlandt, M. Rehwald, M. Reimold,
H.-P. Schlenvoigt, M. Sobiella, T. Ziegler, S. Bock, R. Gebhardt, U. Helbig, T. Püschel, U. Schramm, T. Cowan, et al.
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DRESDEN concept

Big Thanks to the Neutron Team

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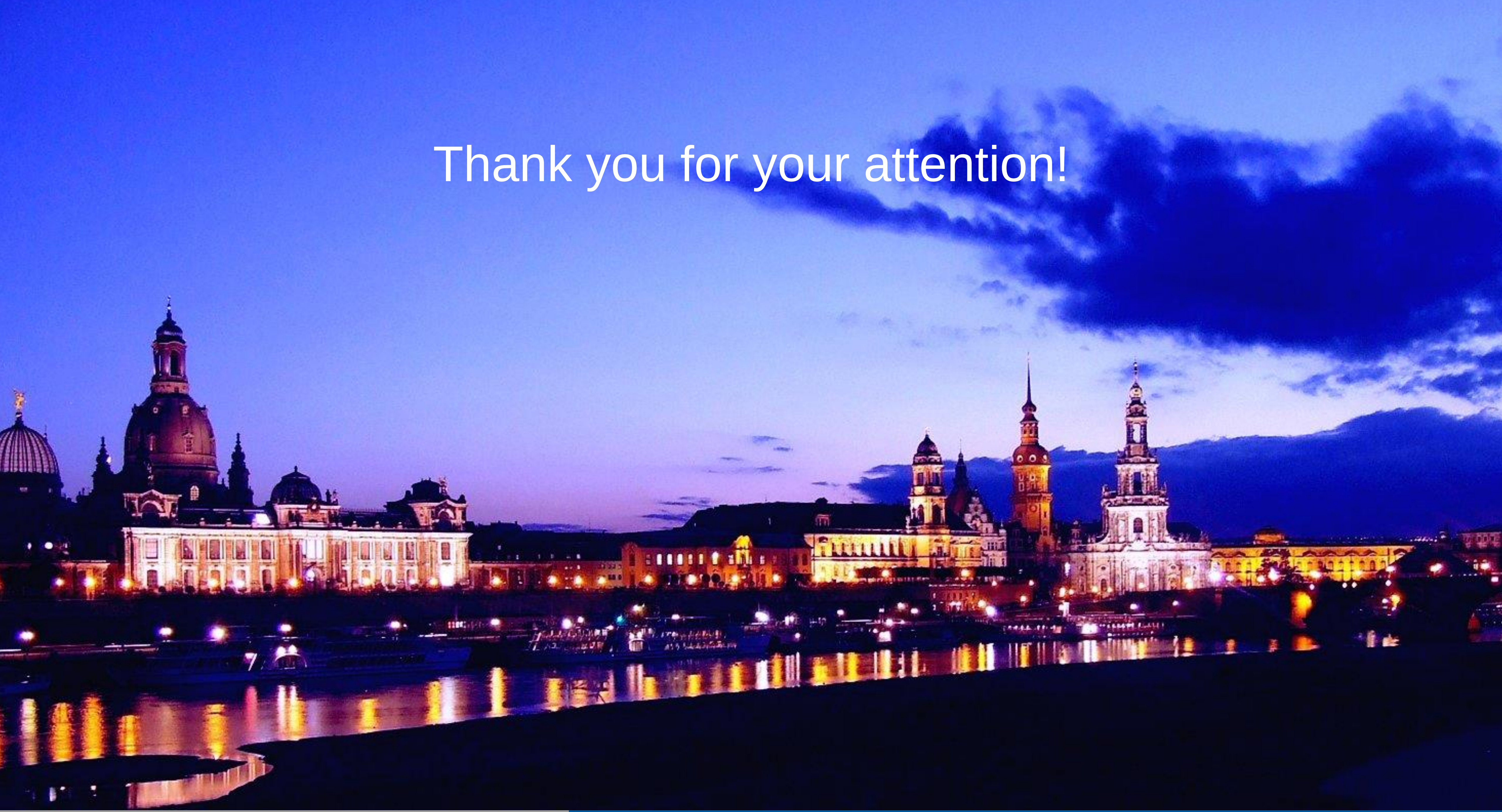
ARIEL IGFAE Instituto Galego de Física de Altas Enerxías USC XUNTA DE GALICIA cividec Instrumentation TECHNISCHE UNIVERSITÄT DARMSTADT UNIVERSIDAD DE SEVILLA CNA Centro Nacional de Aceleradores DRESDEN concept HZDR

Thank you for your attention!



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