Path towards a high-flux neutron source at ELI-NP

Siegfried H. Glenzer, *Stanford University / SLAC*

New opportunities and challenges in nuclear physics with high power lasers,

July 4th, 2024, Trento, Italy

Stanford University
U.S. DEPARTMENT OF ENERGY

The development of high-flux and high peak power ion and neutron sources are important for Basic Plasma Physics and Material Science

- **Validate simulations of the most extreme plasma phenomena** *Particle in Cell (PIC)* simulations predict laser-plasma interaction that are foundational to laser inertial fusion

Basic Plasma Science

F. Fiuza et al., Nature Physics (2020)

Demonstration of 1st order Fermi acceleration process in the laboratory

- **Understanding matter in extreme conditions and burning plasmas**
  Test Density Functional Theory (DFT) for alpha stopping, compression, and nuclear burn waves

Extreme Conditions

A. Kritcher et al., Nature (2020)

Calibrating cosmic clocks by testing EOS models at white dwarf interiors

- **Predict material behavior in fusion plasma environments**
  Knowledge of the *inter-atomic potential of Molecular Dynamics (MD)* modeling; support the design of new materials

Fusion Material Science

M. Mo et al., Science (2018), Nature C. (2024)

Heterogeneous to homogeneous melting of metals

- **Develop inertial fusion energy technologies and validate fusion designs in support of the Bold Decadal Vision**

Inertial Fusion Science

H. Abu-Shawareb et al. PRL 2022, 2024, A. Zylstra et al., Nature (2022)

Our efforts to develop ion and neutron beam sources are aimed at advancing the forefront of high-energy density science

High Power

Short-pulse (fs) lasers with multi-petawatt peak power

High Energy

Long-pulse (ps-ns) lasers with megajoule energy

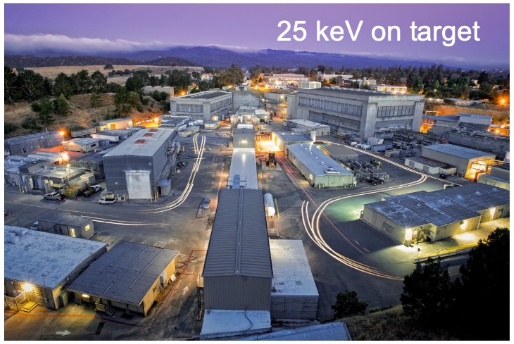
High Peak Brightness

Free-electron lasers produce short (<fs) intense X rays

Present capabilities

LLNL/ELI

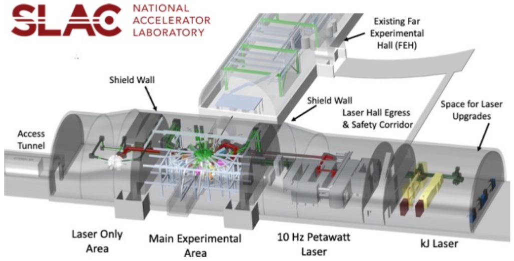
LLNL



SLAC

Future

ALEPH Upgrade — Colorado State University



MEC Upgrade — SLAC

NSF Opal Design — LLE, Rochester

The time scale for purpose-built facilities is accelerating motivated by the development of Inertial Fusion Energy

This work is the result of an international collaboration

Acknowledgements

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Stanford University

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LaserNetUS

NSF

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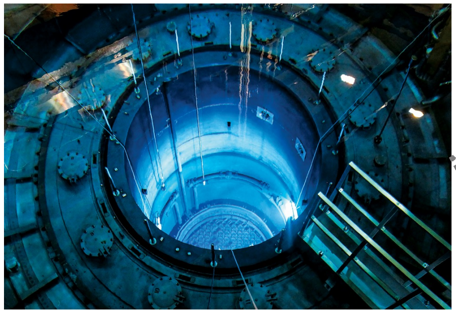
#1 Development of high-flux laser-driven neutron sources

Franziska Treffert (Ph.D thesis 2022)
Griffin Glenn
Girik Jain
Maxence Gauthier

Short-pulse laser driven neutron sources promise to fulfill source requirements

Reactors

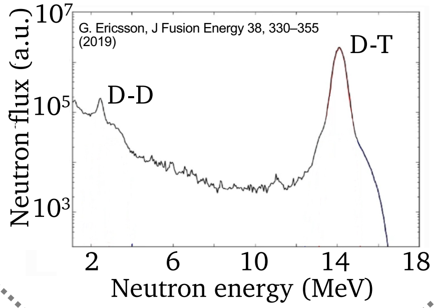


https://cen.acs.org/energy/nuclear-power/Combating-corrosion-worlds-aging-nuclear/98/i36

Accelerators

https://neutrons.ornl.gov/content/how-sns-works

Neutron source requirements:



G. Ericsson, J Fusion Energy 38, 330–355 (2019)

Multi-MeV energies

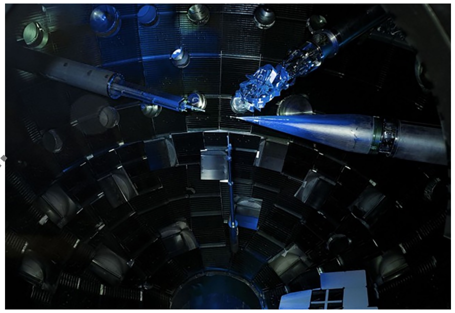
high peak flux

short pulses

high repetition rate

Alternative approach:
hybrid accelerators

Laser fusion (ICF)



https://lasers.llnl.gov/about/how-nif-works/target-chamber

Short-pulse lasers

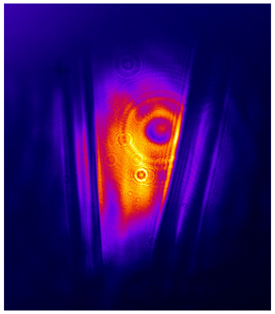
https://www.eli-beams.eu/facility/lasers/laser-3-hapls-1-pw-30-j-10-hz/

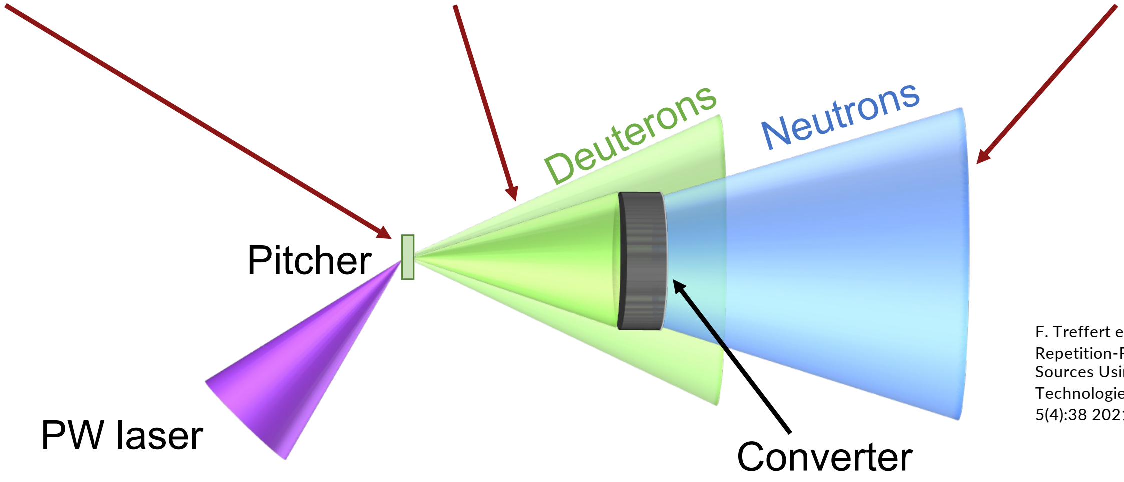
High average flux laser-driven neutron sources require HRR lasers and targets

Ambient temperature liquid jets

HRR high-flux deuteron generation

HRR Multi-MeV neutron generation

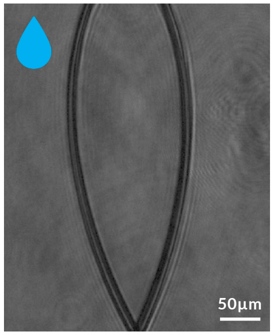




F. Treffert et al., Towards High-Repetition-Rate Fast Neutron Sources Using Novel Enabling Technologies, Instruments, 5(4):38 2021

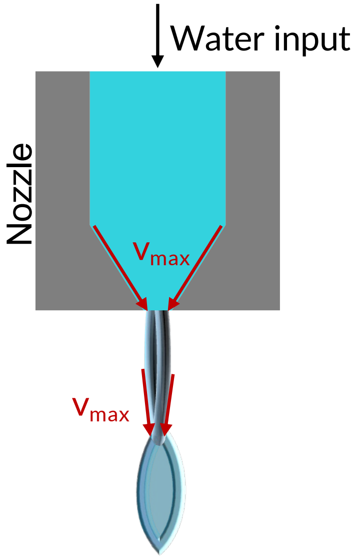
At SLAC we have developed novel ambient-temperature liquid jet targets with several- to sub-micrometer thicknesses

Sheet Jet

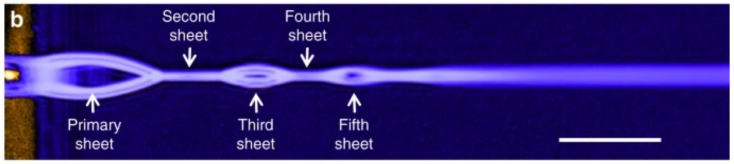


H_2O, D_2O, C_2H_5OH

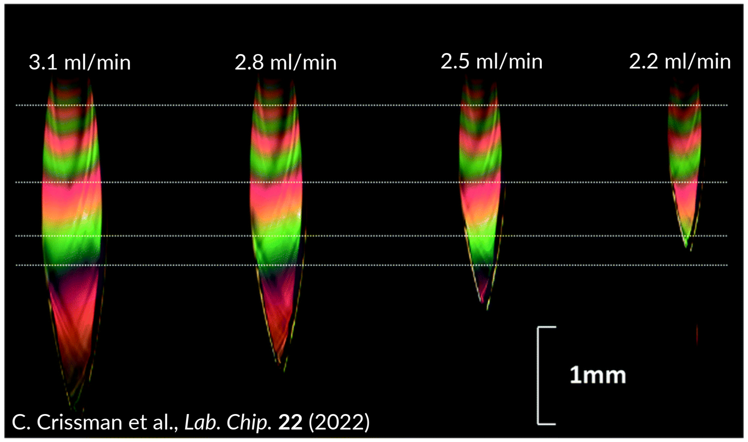
> 10 m/s



- Nozzle design is adaptable:
  - Different jet sizes and thicknesses
  - Multi-layer targets
- Fabrication in metal improves nozzle robustness
  - Survived >4000 shots with PW-class laser



J. D. Koralek et al., Nat Commun. 9, 1353 (2018)

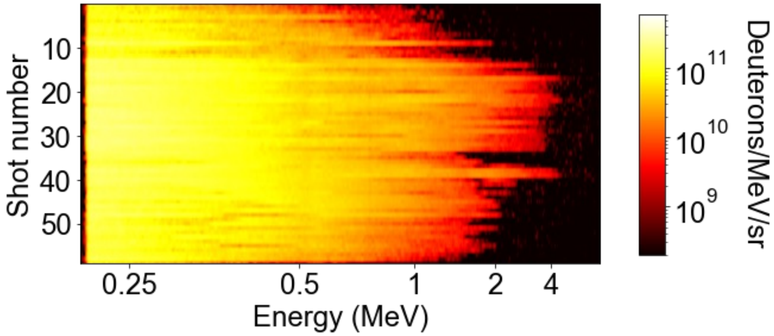


C. Crissman et al., *Lab. Chip.* **22** (2022)

Our previous LaserNetUS experiment at the ALEPH laser demonstrated high repetition-rate deuteron beam generation

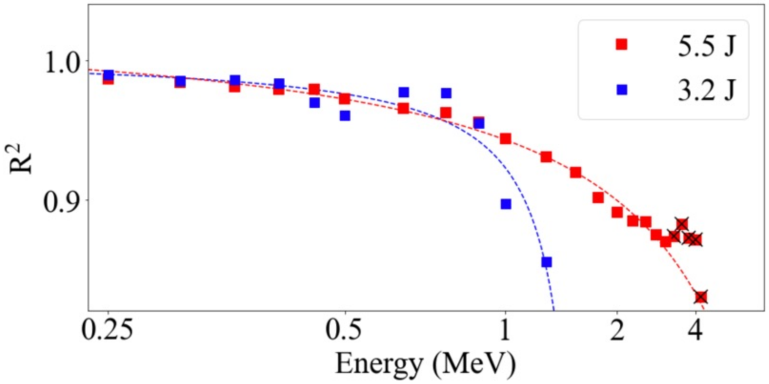
Experiment Information:

- 2ω ALEPH laser parameters:
  - (5.5 ± 0.1) J
  - 1.2 x 10^{21} W/cm^2
  - 45 fs
  - 0.5 Hz
- Deuteron acceleration to up to 4.4 MeV



F. Treffert et al., *Appl. Phys. Lett.* **121** (2022)

Fitness metric of linearity assumption for two spectra



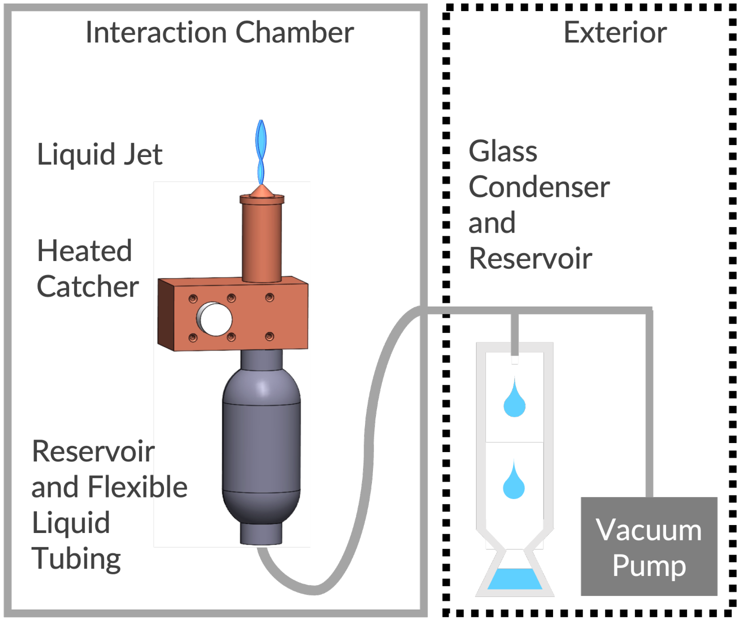
Identified several challenges:

- Instabilities in jet likely caused by decreased control over vacuum level
- Instabilities led to fluctuations in ion beam yield

Goals for K168: Improved stability and greater control over ion beam parameters

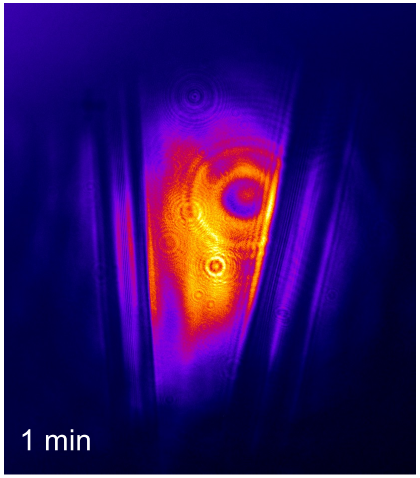
Improved catcher system led to high-stability continuous jet operation over multiple hours

Catcher system incorporated elements needed for sample recirculation



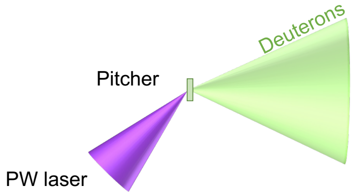
Successful continuous system operation for up to five hours

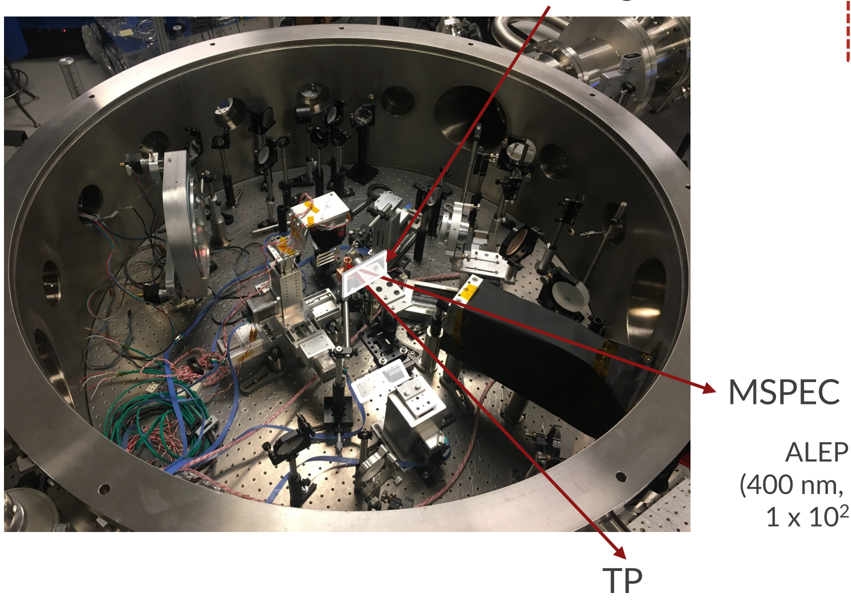
Defocused 2ω ALEPH laser beam on target



- Stable operation using both H_2O and D_2O
- Jet fully recoverable under vacuum if shut off or flow rate decreased
- Small fluctuations and rotations still observed

Ion beam pointing and energy spectrum were monitored using HRR-capable Thomson parabolas and an ion imager

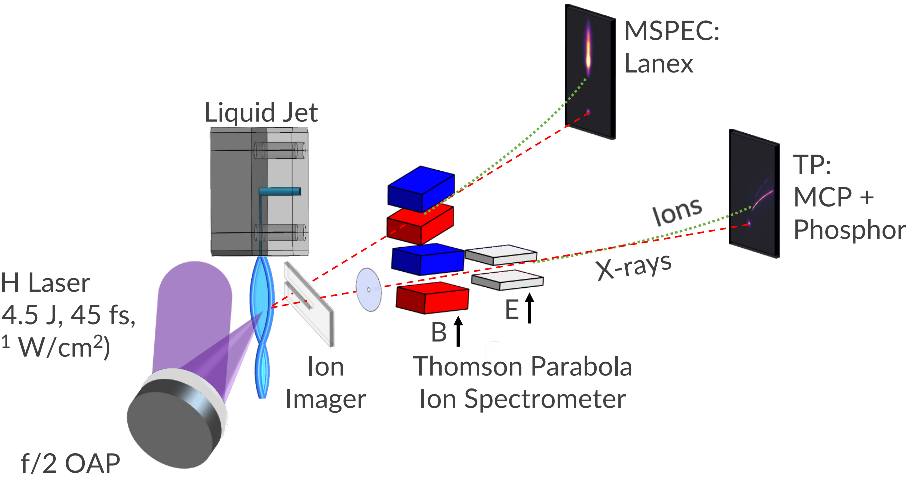




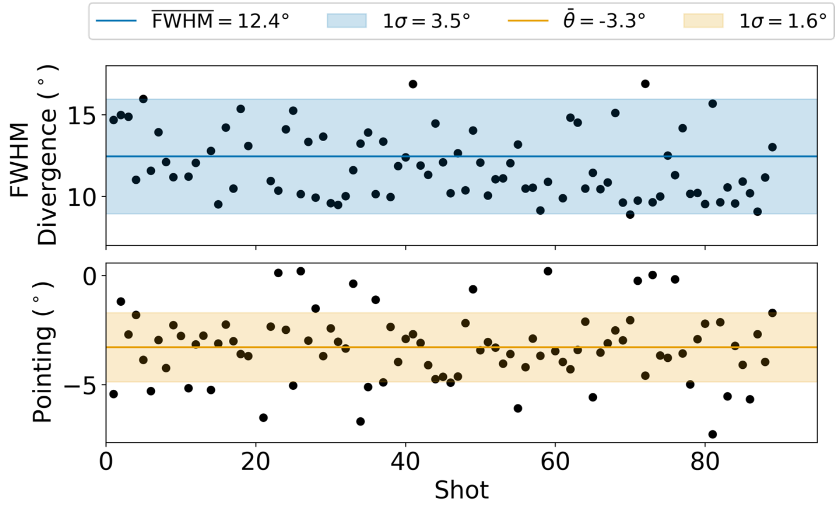
Ion Diagnostics:

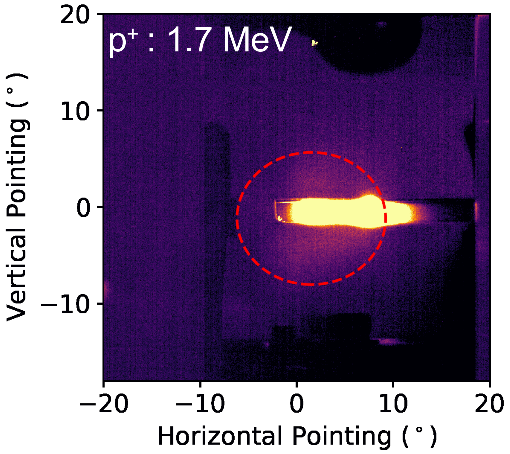
- Ion imager at 5.7 cm covering ±20°
- Thomson parabola (TP):
  - Target normal direction
- Magnetic spectrometer (MSPEC):
  - 22.5° from target normal direction

ALEPH Laser
(400 nm, 4.5 J, 45 fs,
1 x 10^{21} W/cm^2)

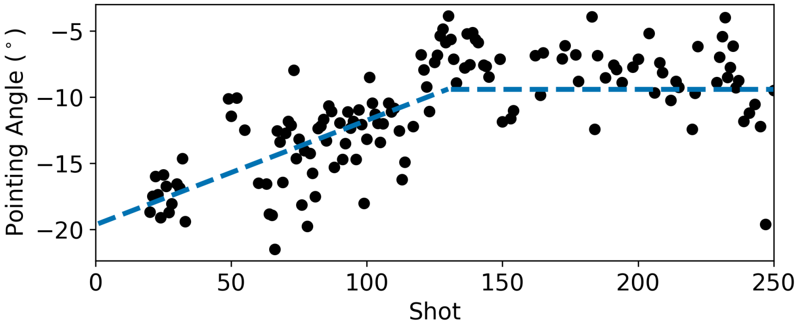


Multi-MeV proton beams exhibit narrow (12° FWHM) divergence and adjustable pointing

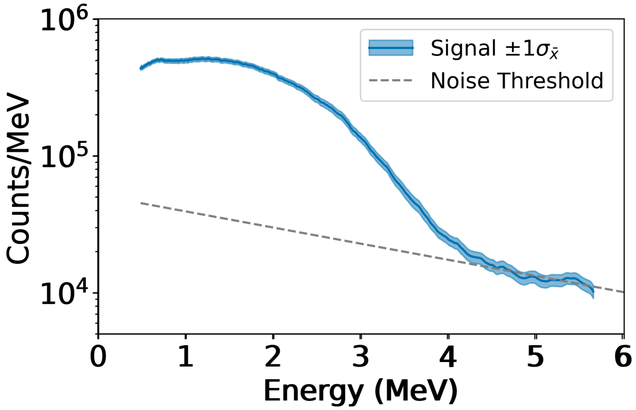


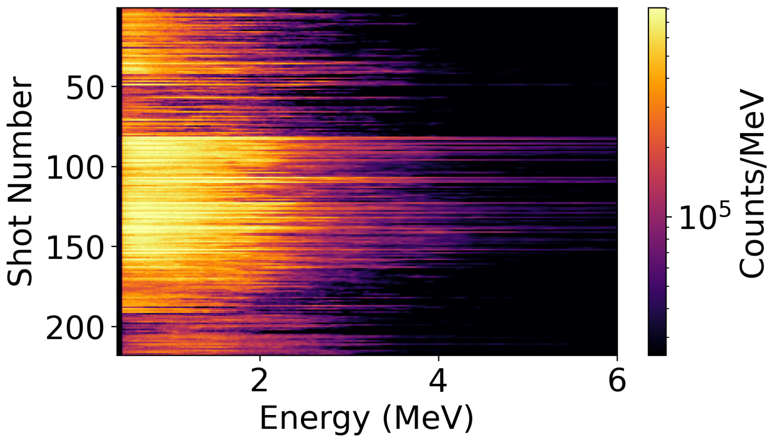


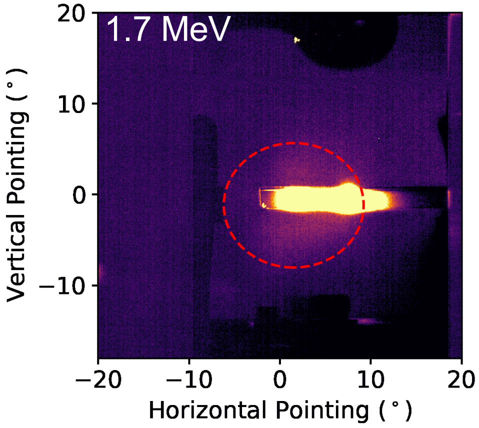
- Low divergence: 12.4° @ 1.7 MeV
- Similar divergences only observed at higher energies to date (P. L. Poole et al., *New J. Phys.* 2018)
- Stable pointing within ±1.6°
- 6-axis motorization allows precision alignment of target
- Ion beam pointing control through target rotation



Multi-MeV, low-divergence, high repetition-rate proton beams for radiography and hybrid accelerator applications







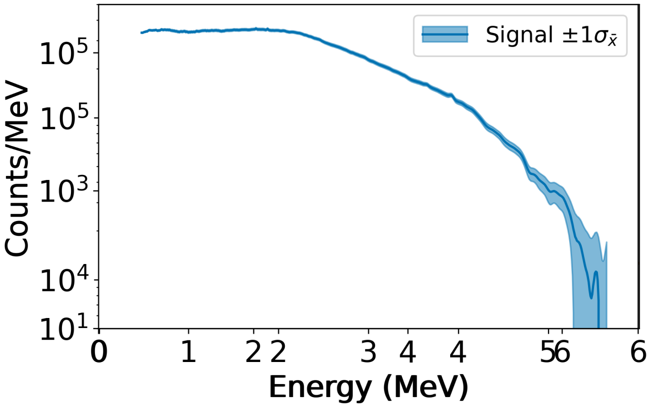
- Laser parameters:
  - 400 nm
  - 4.5 J
  - 1.2 x 10^{21} W/cm^2 (a_0 = 12)
  - 45 fs
  - 0.5 Hz

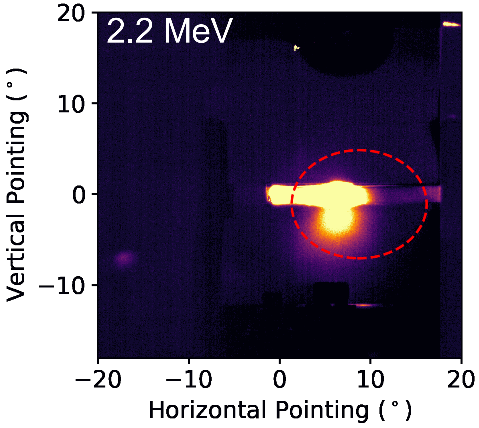
Proton beam:

- E_c: 4.2 MeV
- Standard error <10% for energies up to 3 MeV

Multi-MeV high repetition-rate proton beams are ideally suited to explore hybrid laser accelerators and flash radiography applications.

High stability, multi-MeV deuteron acceleration for reliable high repetition-rate neutron generation





- Laser parameters:
    - 400 nm
    - 4.6 J
    - 1.0 x 10^{21} W/cm^2 (a_0 = 11)
    - 45 fs
    - 0.5 Hz

Deuteron beam:

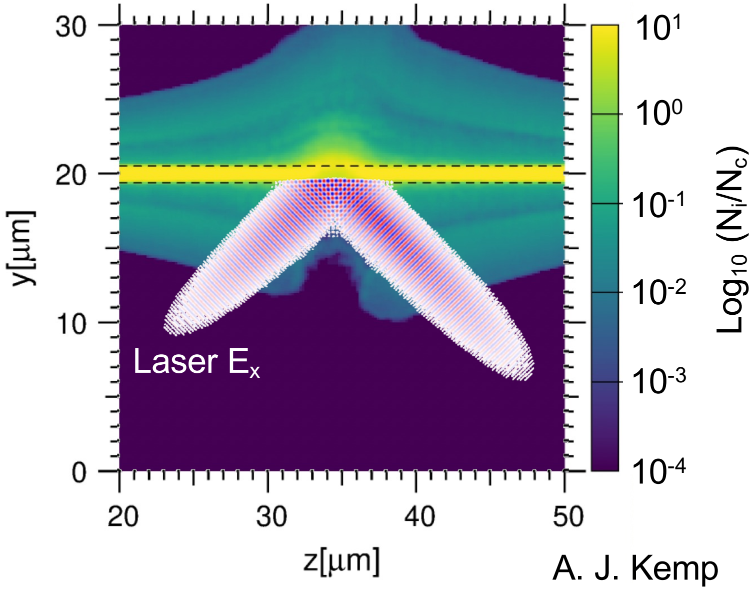
- E_c: 5.5 MeV
- Standard error <10% for energies up to 4.2 MeV

Multi-MeV, narrow divergence deuteron beams delivered at high repetition rate are ideally suited for laser driven neutron sources for IFE research and material science.

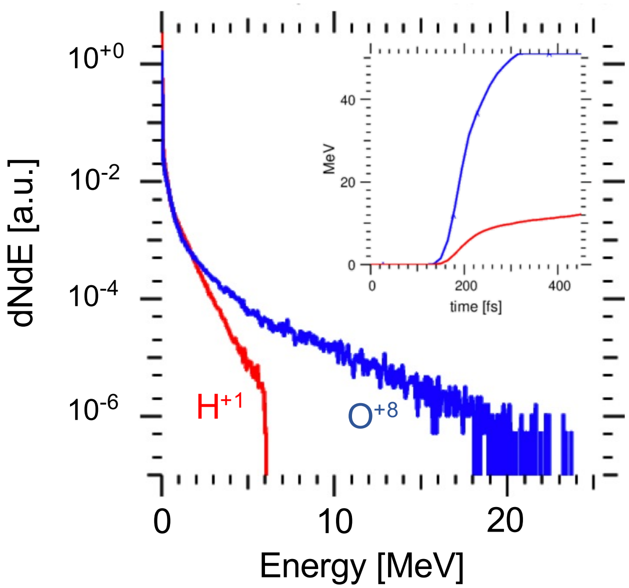
2D/3D PIC simulations will help understand the laser-target interaction and acceleration process

Simulation parameters:

- Laser: 45 fs FWHM, 8 x 10^{20} W/cm^2 (a_0 = 9.66), 400 nm, s-polarized, 2 µm FWHM Gaussian focal spot, paraxial beam, 45 deg
- Target: 1 µm H_2O, fully ionized n_e=3.3 x 10^{23} 1/cm^3, no preplasma

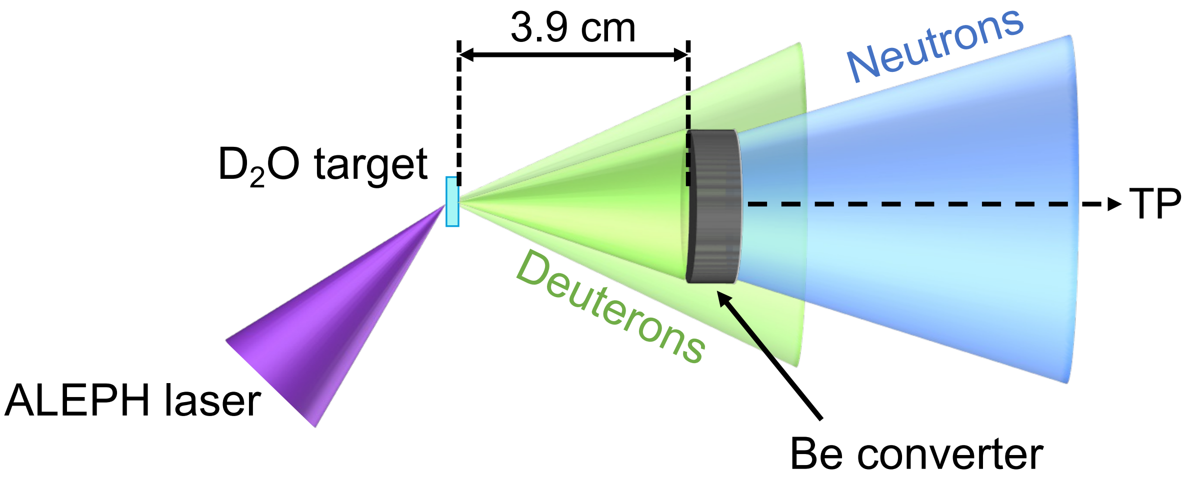


A. J. Kemp

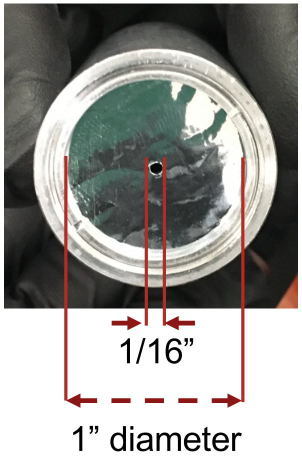


2D PIC simulations have been started to model the laser-target interaction during this experiment. Future efforts will investigate the mechanism at work leading to low divergence ion beams.

We have performed the first demonstration of a high repetition rate pitcher-catcher laser-driven neutron source



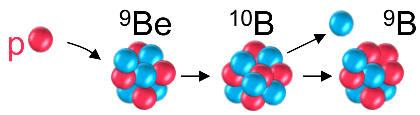
Converter front



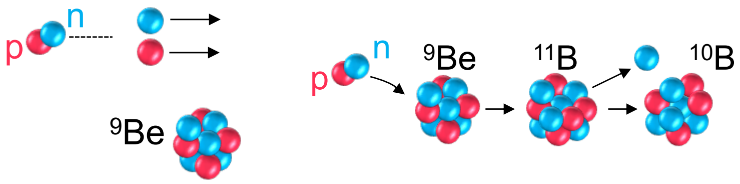
- Converter:
  - 10 µm Al + 1 mm Be disk with 1/16” on-axis pinhole
- Ion diagnostics:
  - 1 Thomson parabola (target normal direction)
- Neutron diagnostics:
  - 8 nTOFs (approx. -25°, -35°, 54°, -167° from target normal)
  - 26 BD-PND bubble detectors

Protons and deuterons generate neutrons through different reactions with a higher single shot yield for incident deuterons

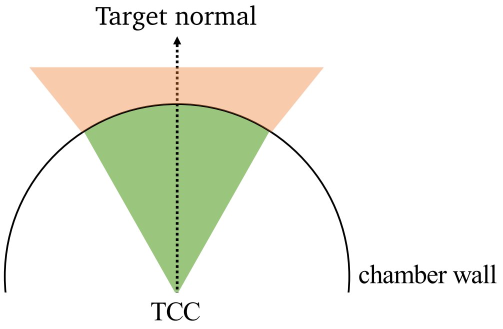
Proton induced neutron generation



Deuteron induced neutron generation



Neutron production in chamber wall



▮ Converter

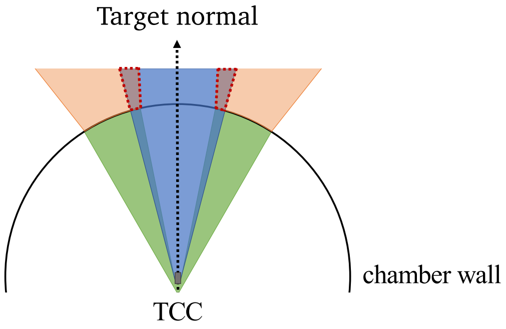
🟩 Deuterons

🟦 Neutrons (converter)

🟧 Neutrons (wall)

▨ Neutrons (wall + converter)

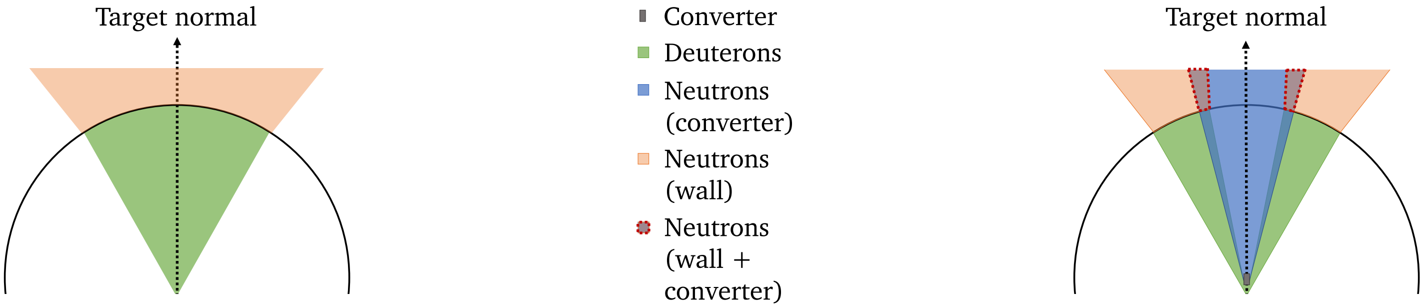
Neutron production in beryllium converter

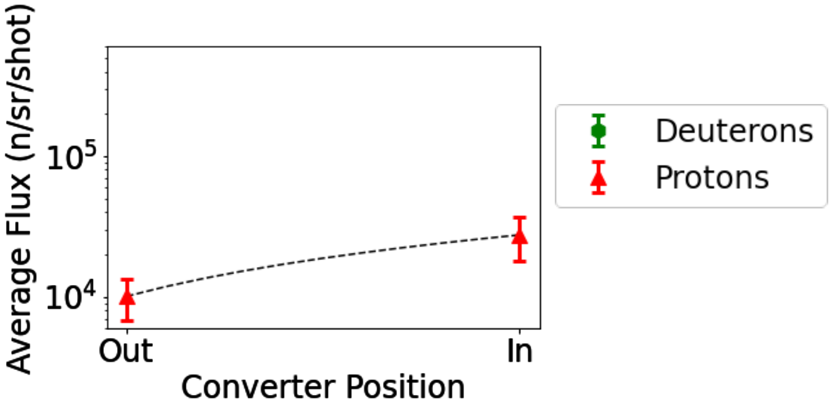


Protons and deuterons generate neutrons through different reactions with a higher single shot yield for incident deuterons

Neutron production in chamber wall

Neutron production in beryllium converter



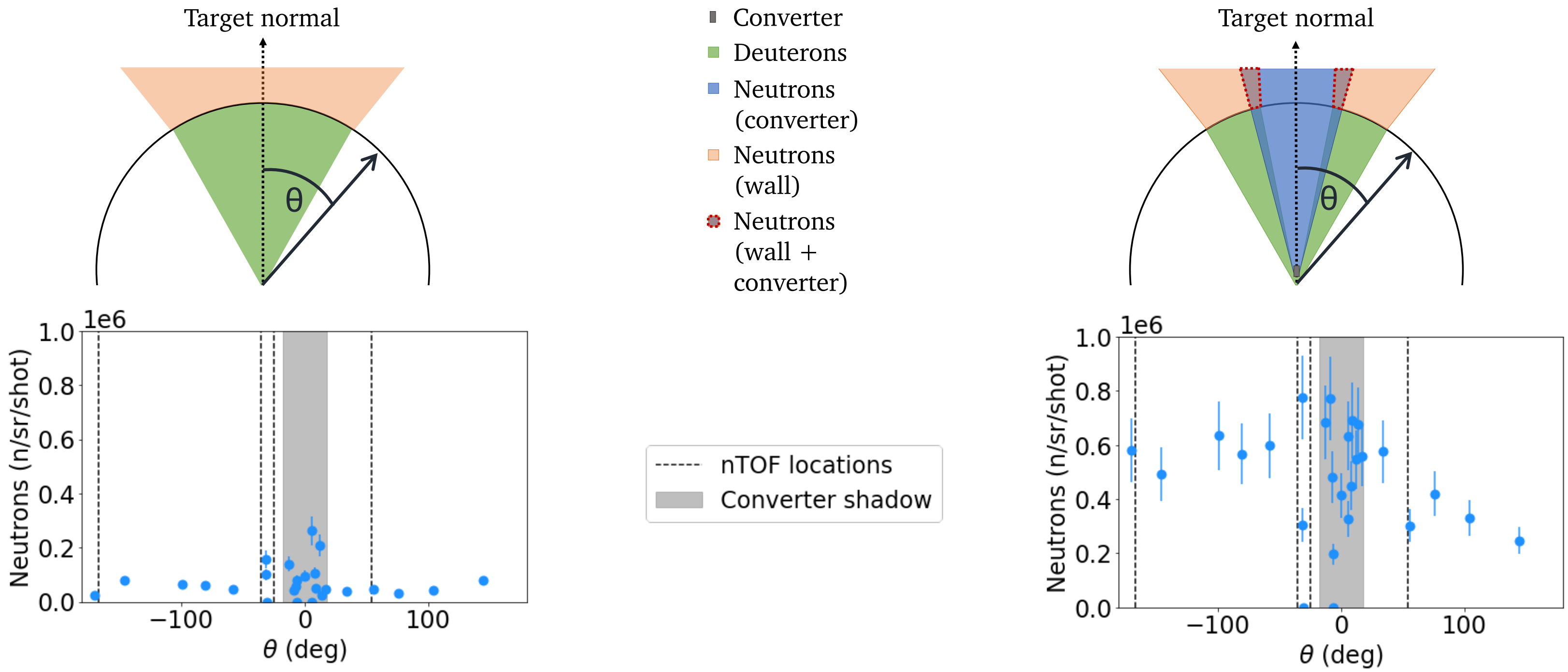


- Higher neutron yield from converter than stainless steel chamber wall
- No converter:
  - Higher neutron yield from deuterons
- With converter:
  - Larger increase in neutron yield for incident deuterons

Deuterons most efficiently generate neutrons in the beryllium converter, generating a semi-directional neutron beam

Neutron production in chamber wall (total shots: 492)

Neutron production in beryllium converter (total shots:



Average neutron yield: 0.7 x 10^5 n/sr/shot

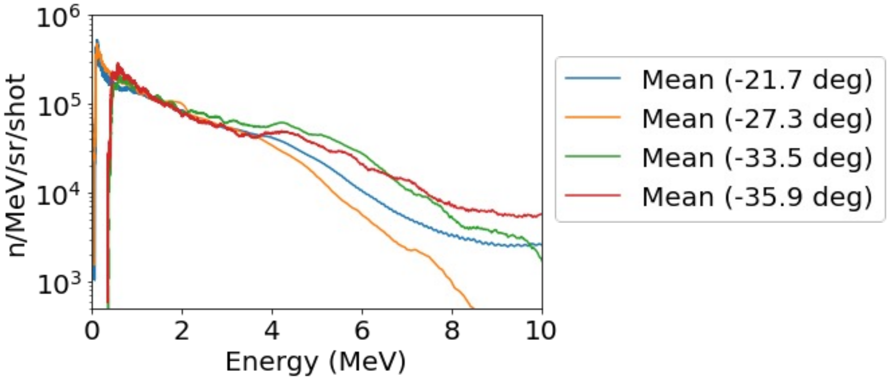
Average neutron yield: 5 x 10^5 n/sr/shot

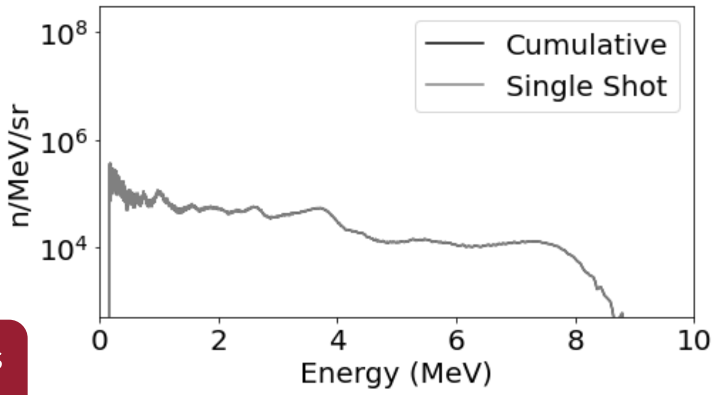
Neutron flux generated by converter is seven times higher than that generated within the target chamber wall.

First demonstration of a high repetition-rate laser-driven neutron source in pitcher-catcher configuration

- Laser parameters:
  4.6 J, 1.0 x 10^{21} W/cm^2 (a_0 = 11), 45 fs, 0.5 Hz
- Deuteron average cut-off energy E_c: 5.5 MeV
- Neutron average cut-off energy E_c: ~7 MeV
- ^{9}Be(d,n)^{10}B Q-value: 4.4 MeV
- First nTOF calibration with average neutron yield from BDs

- 27.3 deg

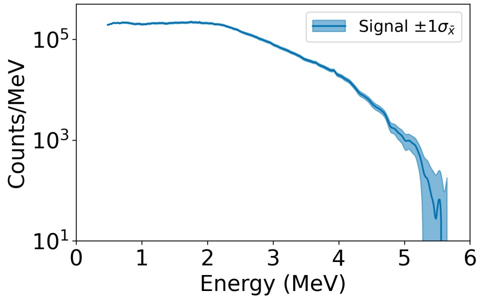


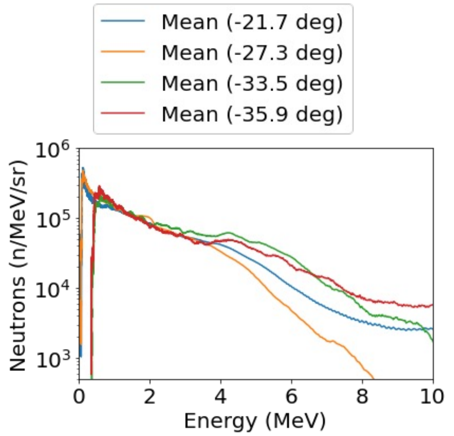


Stable shot-to-shot neutron generation up to 7 MeV demonstrates high repetition-rate capable source for applications.

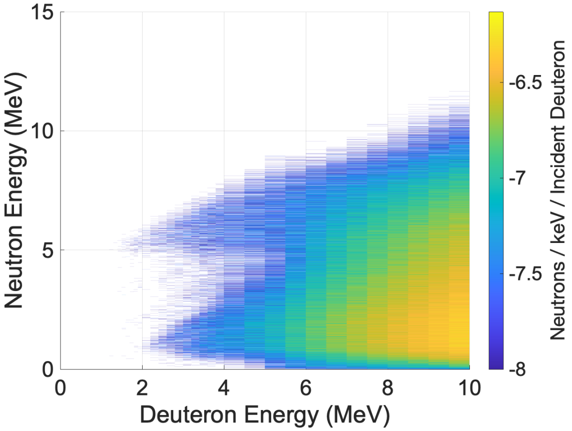
Geant4 simulations are utilized to model neutron production and enable reliable estimation of conversion efficiency

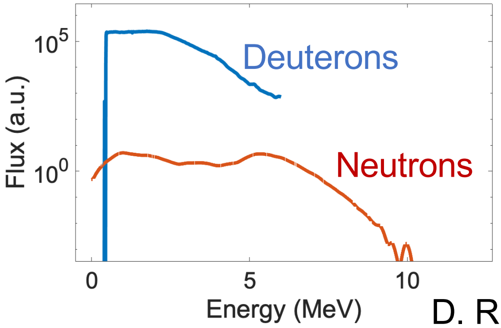
Experimental Results





Preliminary Simulation Results





D. Rusby

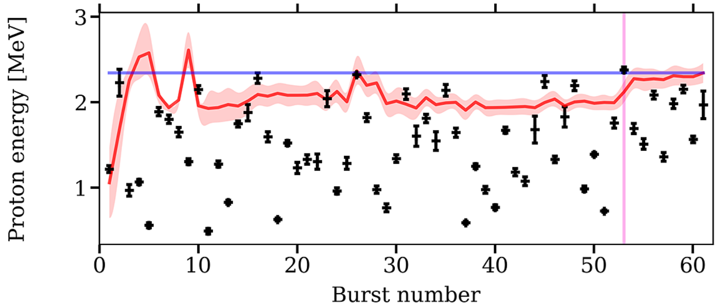
First Findings

- Neutrons predominantly generated by deuterons >2 MeV
- Double peak structure observed in simulations and experiment
- ^{9}Be(d,n)^{10}B Q-value: 4.4 MeV
  https://www.nndc.bnl.gov/qcalc/

Additional Geant4 simulations will target estimating the conversion efficiency from deuterons to neutrons.

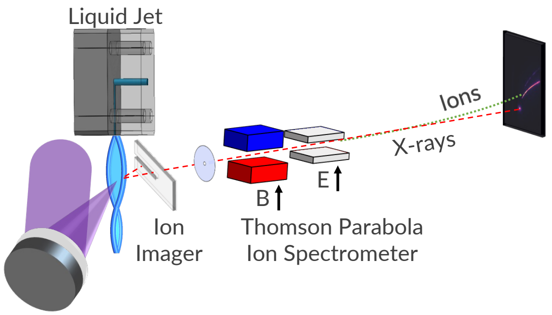
Our initial demonstration presents opportunities to address key questions in fusion energy science and other applications

Real-time optimization of secondary beams using machine learning (B. Loughran et al. (2023))

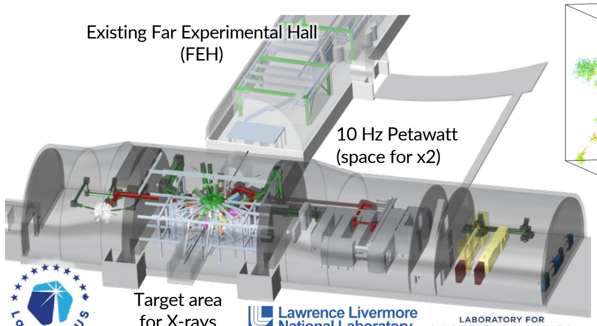


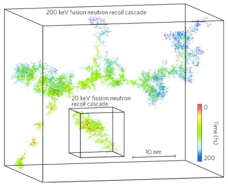
Loughran, B., et al. (2023). Automated control and optimization of laser-driven ion acceleration. High Power Laser Science and Engineering, 11, E35.

Further platform development (G. D. Glenn et al. (2024)) and scaling to >100 J laser energies



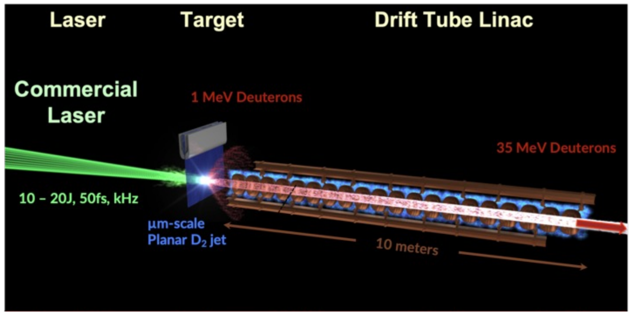
In-situ neutron damage studies using MEC-U



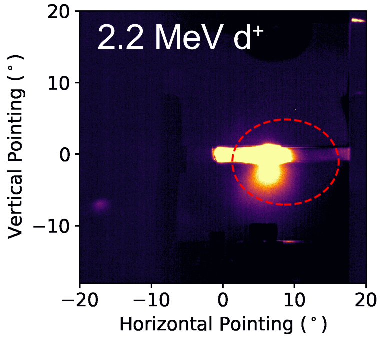


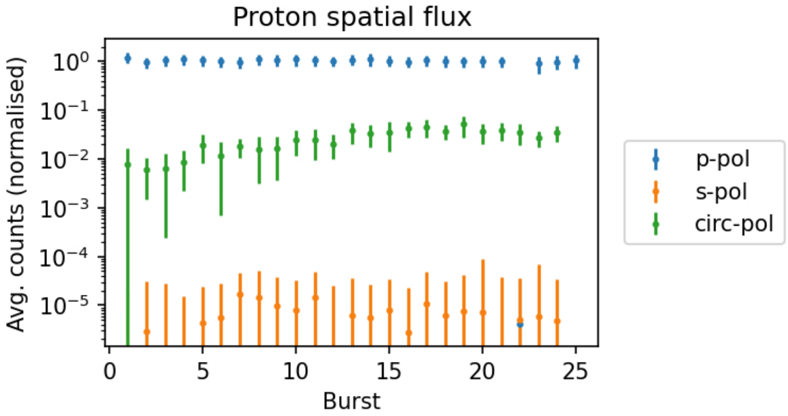
Knaster, et al. Materials research for fusion. Nature Phys 12, 424–434 (2016).

Development of a fusion prototypic neutron source using a hybrid laser-RF accelerator



Our initial demonstration presents opportunities to address key questions in fusion energy science and other applications





- **High repetition rate deuteron acceleration:**
  - Multi-MeV, low-divergence (11.7° FWHM)
- **High repetition rate (0.5 Hz) neutron generation in pitcher-catcher geometry:**
  - Neutron energies up to 7 MeV
  - Directional neutron beams with up to 8 x 10^5 n/sr/shot

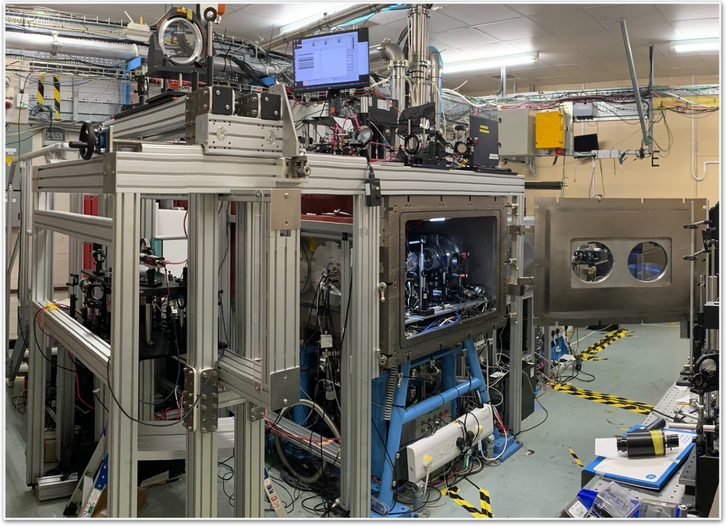
Outlook:

- Simulations and preliminary data from RAL on water sheet targets suggest much higher ion beam energy flux when using p-polarized beams
- In 2024, a new LaserNetUS experiment is planned to test these predictions
- Further increases in flux appear possible

#2 Recent advances and future investigations towards high-flux laser-driven ion and neutron beam sources

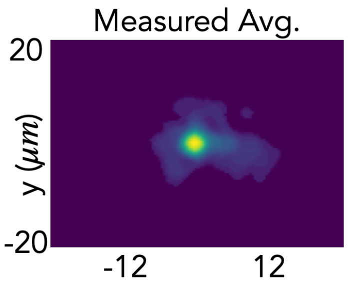
Christopher Schoenwaelder (Ph.D thesis 2024)
Maxence Gauthier

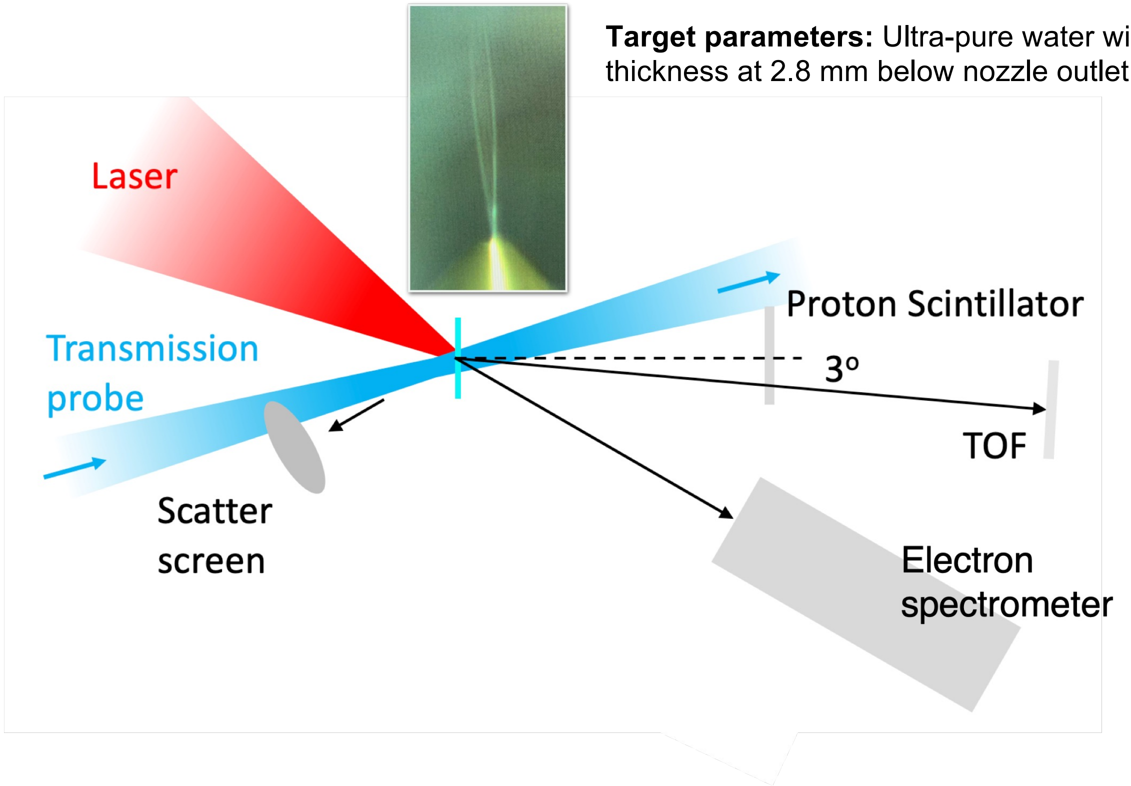
Experimental setup at CLF Astra Gemini TA2



Laser parameters: Up to 200 mJ on target in 60 fs focused with F/2.5 OAP delivered at 5 Hz.

Active control of wavefront, temporal pulse shape, delivered energy.





Target parameters: Ultra-pure water with thickness at 2.8 mm below nozzle outlet.

Vacuum parameters: Vacuum pressure of 0.1 mbar at approx. 1 m from liquid sheet.

Proton beams from the liquid sheet

Interaction produced proton beams extending up to 6 MeV with order of magnitude higher flux than comparison tape targets (13 micron thick Kapton).

High stability of proton spectrum with peak energies measured coincident with highest laser intensity.

Beam divergence was reduced to few degrees with stable pointing and peak dose delivered to scintillator over hundreds of shots.

New experiments at the Nuclear Photonics research group at Tel-Aviv university have demonstrated 10 Hz MeV ion beams

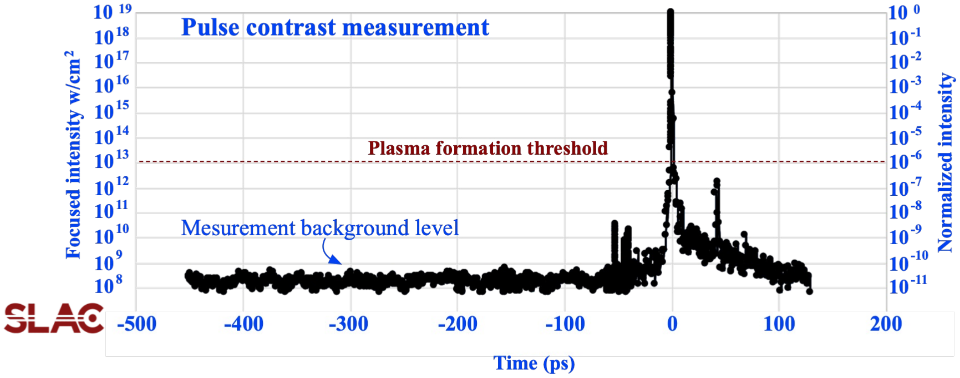
TEL AVIV UNIVERSITY אוניברסיטת תל אביב

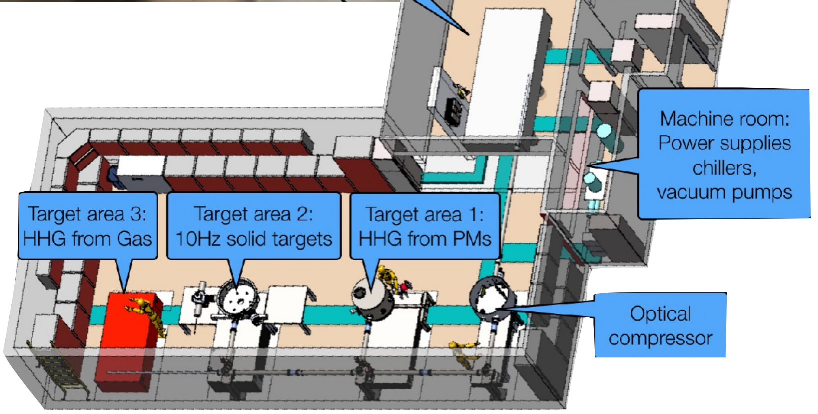
10 Hz / 500 mJ on-target / 25 fs

Front-end based on picosecond OPCPA

Contrast <10^{-11} @70 ps

THIRD ORDER CROSS-CORELLATION MEASUREMENT





A preliminary look at the data suggests that highly stable beams

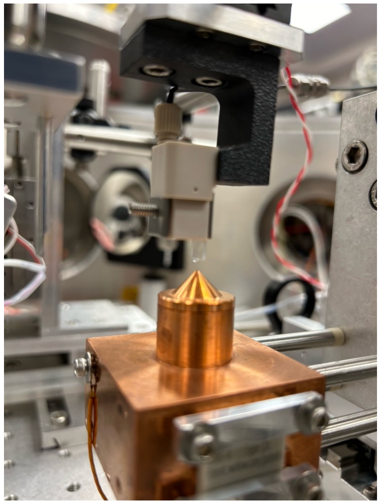
- Demonstration of 10 Hz acceleration of laser-driven proton beams from ~400 nm liquid H_2O target
- Preliminary highlights:
  Ion beams are highly stable both spatially and spectrally

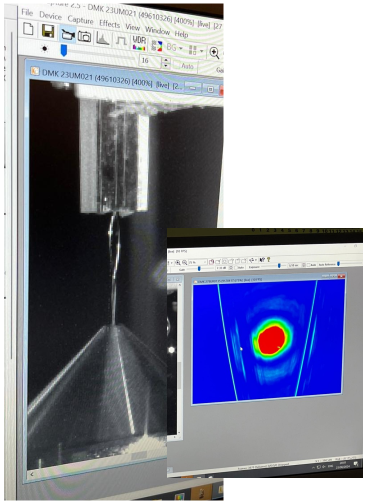
Jet and Catcher system

Laser – Jet alignment

Ion Beam image

Thomson Parabola data

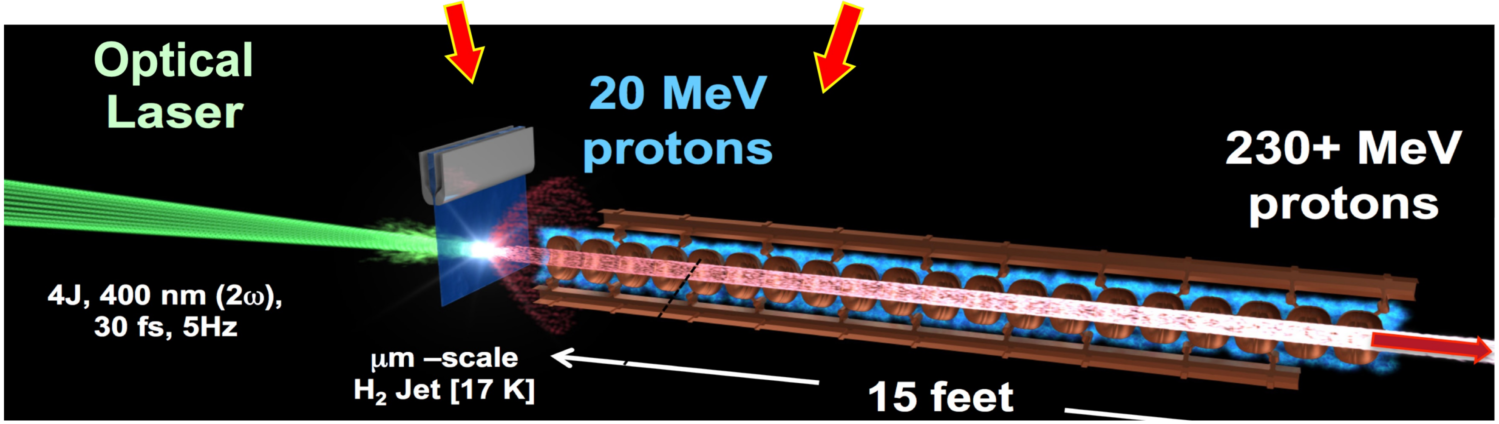




We are mow in the position to advance a high peak current hybrid accelerator

First Stage: Laser Plasma

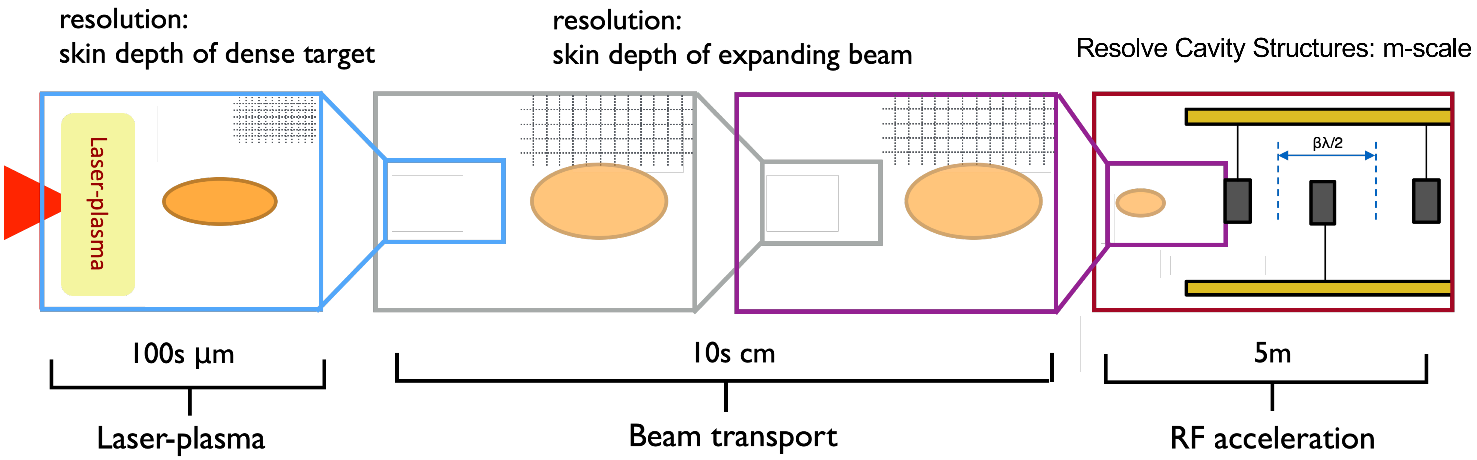
Second Stage: high-gradient RF linac



- Perform fully integrated simulations of this system
- Include beam transport and space charges

It is critical to optimize the different steps of the accelerator: laser-plasma source, beam transport, and RF-capture and acceleration

Multi-stage fully-kinetic simulations to enable end-to-end modeling of particle dynamics from micron to meter scale for the first time



resolution:
skin depth of dense target

resolution:
skin depth of expanding beam

Resolve Cavity Structures: m-scale

100s μm

Laser-plasma

10s cm

Beam transport

5m

RF acceleration

- Transport is ballistic
- Space charge at RF entrance must be smaller than the RF field

Jason Chou| PhD student | HEDS Division

An adaptive mesh refinement scheme has been implemented to enable self-consistent multi-stage simulations of hybrid (laser-RF) accelerators

End-to-end 3D simulations demonstrate a mono-energetic high-charge 250 MeV proton beam at RF exit

- Uses cryogenic hydrogen target with petawatt laser at 6 x 10^{21} W cm^{-2}

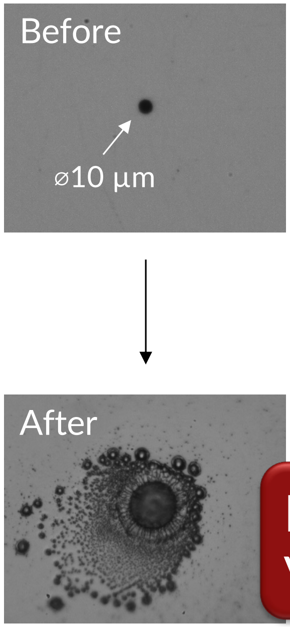
Jason Chou| PhD student | HEDS Division

The hybrid accelerator can access a new regime of high-energy ion beam interactions with matter with nC charges delivered in picoseconds

#3 Development of high-energy laser-driven ion beam sources

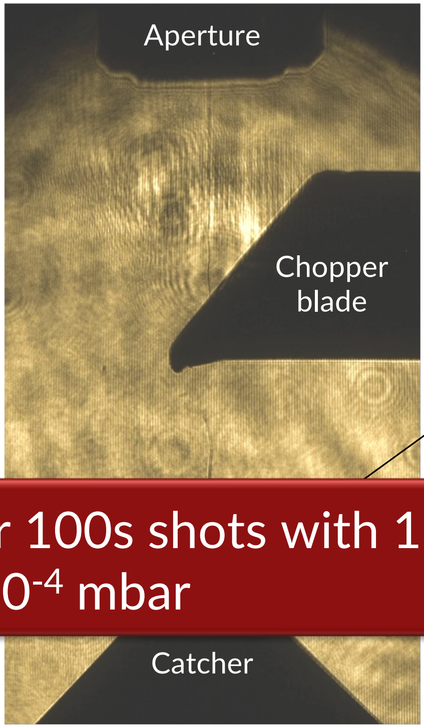
Christopher Schoenwaelder (Ph.D thesis 2024)
Maxence Gauthier
Martin Rehwald (Ph.D thesis 2023)
Lennard Gauss (Ph.D thesis 2023)
Thomas Kluge
Ulrich Schramm
Karl Zeil

We have developed a chopper-catcher system to ensure survivability of the nozzle and long-time operation

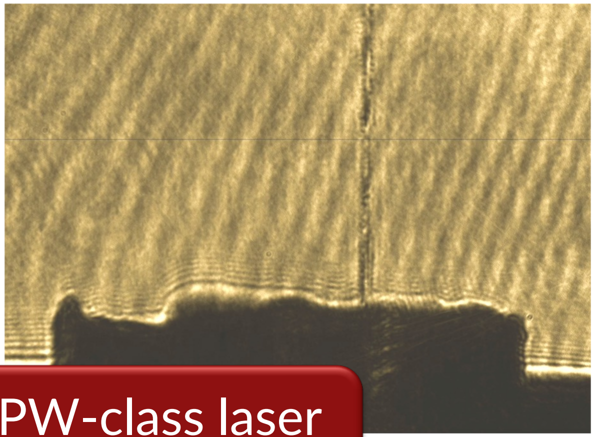


Texas PW (2017) ,
100J, 150fs

Solution



MEC LX35 (2021)



PAC'22 (2022)

No damage after 100s shots with 18J, PW-class laser
Vacuum ~ few 10^{-4} mbar

Pure high-Z ion beams have been produced with a 150 J short pulse laser at Phelix (GSI)

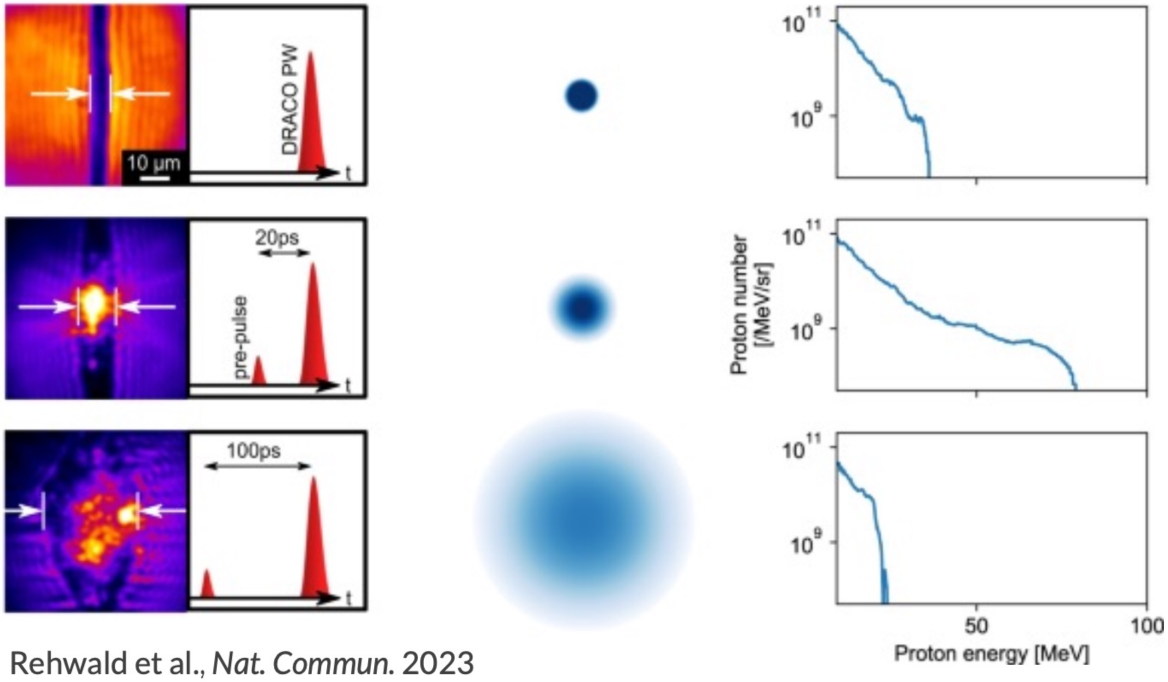
Demonstration of stable cryogenic argon jet driven by 150 J, 600fs laser

Experiment was performed at a single-shot PW - class laser at GSI

We envision to develop ion and neutron beams driven by the 10 Hz PW laser at MEC-Upgrade

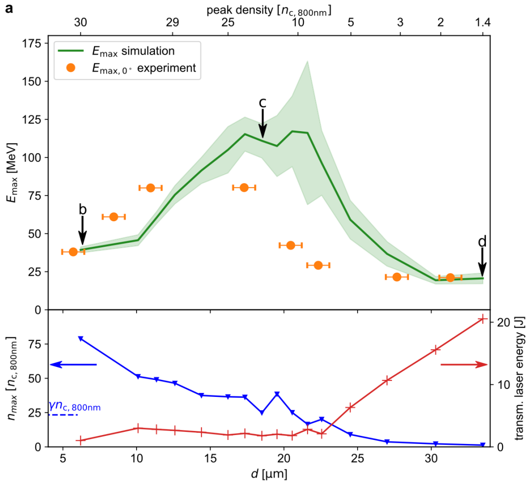
- We have demonstrated robust jet target suitable for 150 J lasers in single shot mode
- We aim developing high-repetition rate plasma diagnostics, e.g., Thomson Parabola, Ion Beam Imager, Neutron Time Of Flight
- This effort includes solving effects of EMP towards demonstration of a pump-probe experiment
- This program prepares us for future experiments at high doses produced by high repetition rate PW lasers (10 Hz)
- This capability is opening up future radiation damage experiments and heavy ion beam fusion studies

An early success with liquid hydrogen was achieved at HZDR where we accessed an advantageous acceleration regime

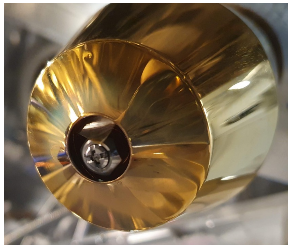


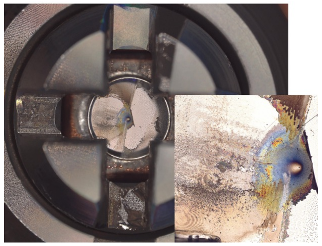
Rehwald et al., *Nat. Commun.* 2023

Reproduced by PIC simulations



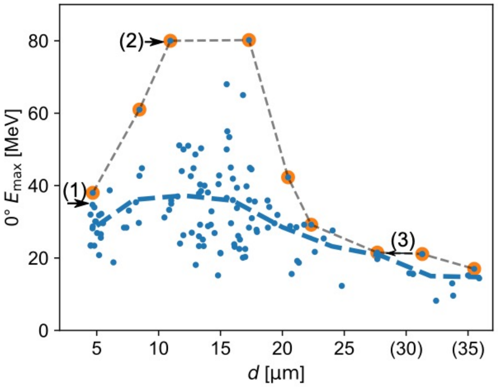
~50,000 shots in 7 hours

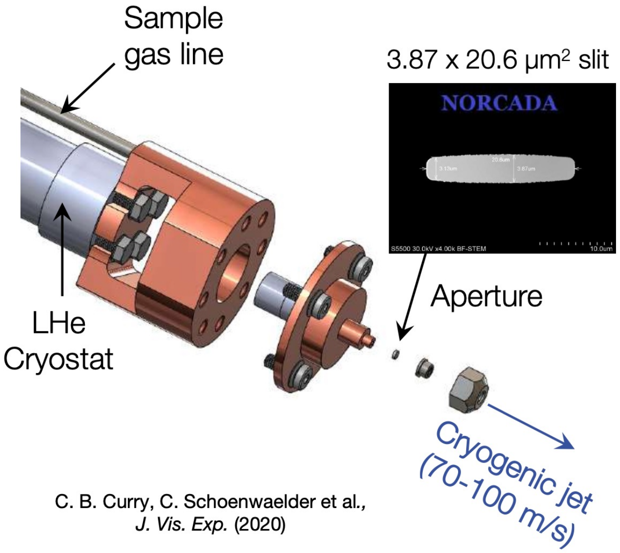




We will enhance the hit rate by going to a liquid planar cryogenic jet

Hit rate with 5 micron-meter diameter jets is not sufficient

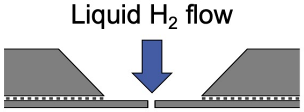




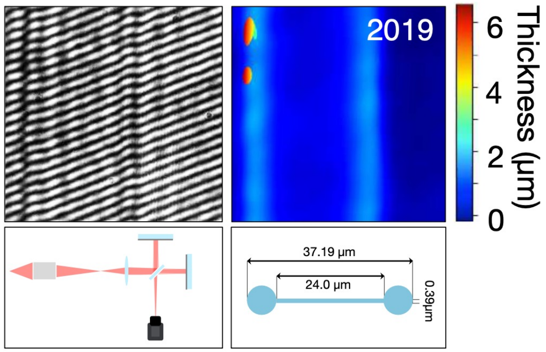
C. B. Curry, C. Schoenwaelder et al., *J. Vis. Exp.* (2020)

Works with liquid hydrogen, neon argon, krypton, etc.

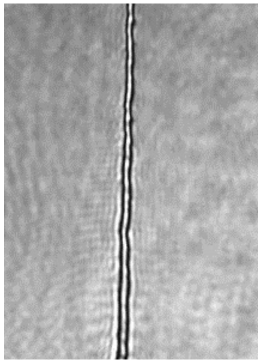
Demonstration at Texas PetaWatt laser



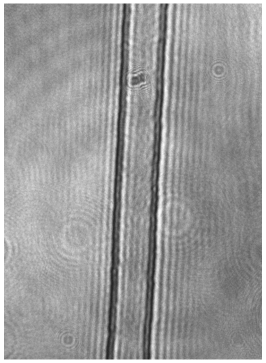
High magnification interferometry provides *in situ* target thickness of planar jets



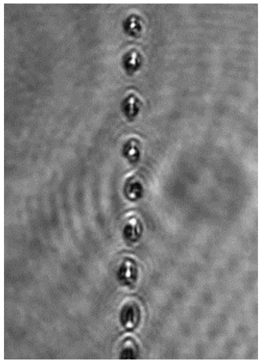
We have developed jets for high-repetition rate laser-plasma science



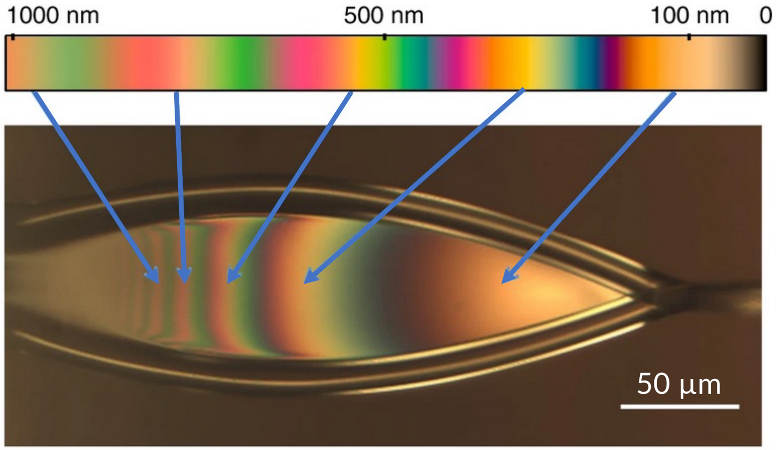
⌀ 2 - 10 μm



20 - 40 μm width,
0.5 - 4 μm thick



⌀ 10 – 19 μm



Cryogenic jets

- High purity
- Debris Free
- Mass limited
- Velocity: 40-200 m/s
- Demonstrated H_2, D_2, H_2/D_2, CH_4, Ne, Ar, Kr

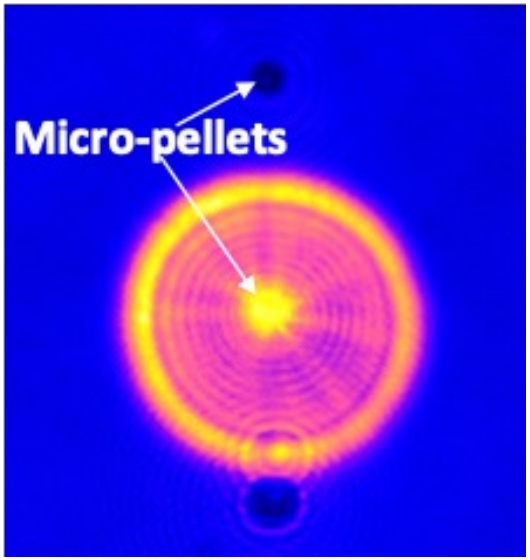
Ambient liquid jets

- Mixtures & multi-layered
- Access to various thickness
- Wide thickness range accessible
- Air and vacuum operation
- Velocity : 5-10 m/s

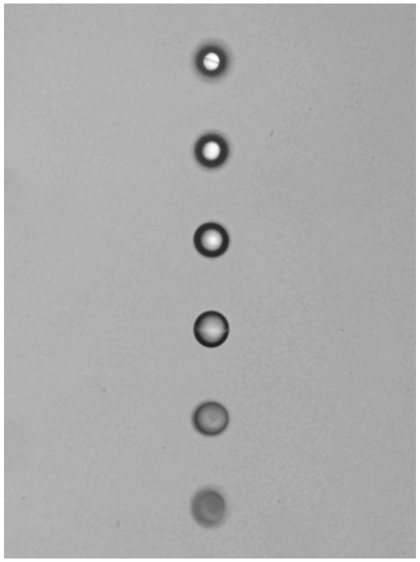
Challenge: from mJ to 150J high-intensity laser interaction

We are studying the target repetition rate limitations using Computational Fluid Dynamics simulation

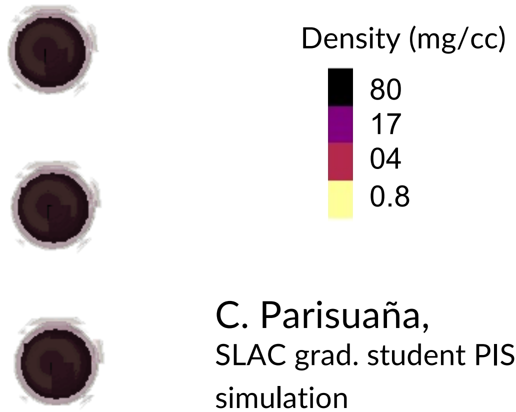
3D PISALE modeling



MEC, LQ85 (2017)



C. Stan, et al. Nature Physics, 2016

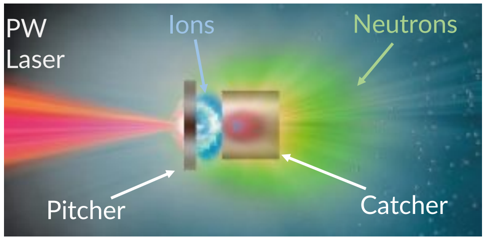


C. Parisuaña,
SLAC grad. student PISALE simulation

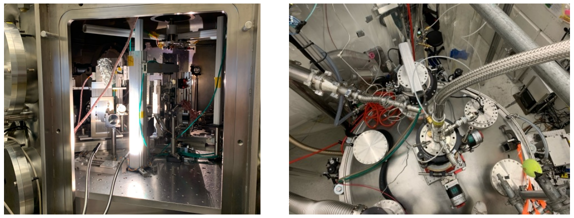
*Alice Koniges, et al. Plasma Science and Technology, 2015

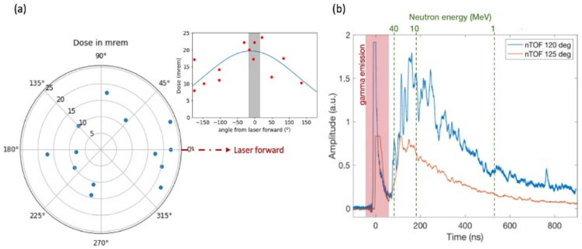
3D CFD simulations provides a way to determine repetition rate

High yield neutron beam generation



Texas Petawatt @ UT





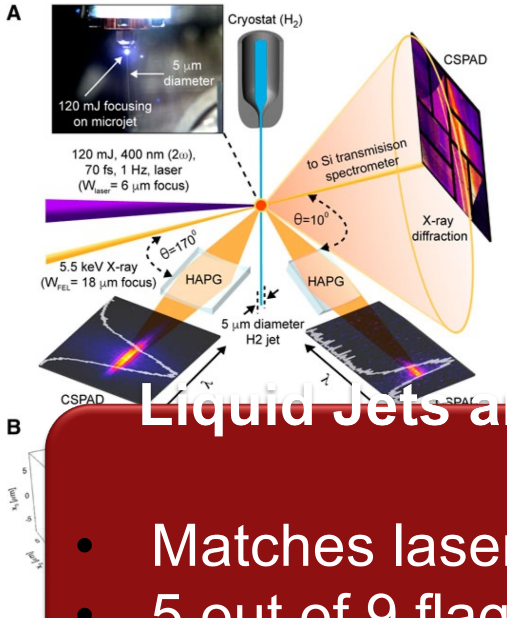
Deuteron acceleration and neutron generation using cryogenic jets

High flux, high energy directional deuteron beams.

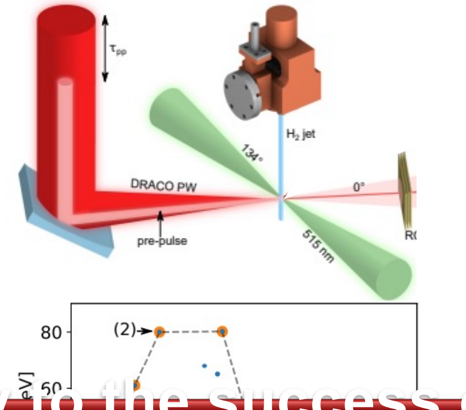
High yield (1 x 10^{10} neutrons/shot), directional neutron beams up to 25 MeV energies, relevant for DD/DT fusion.

HEDS has successfully delivered impactful results using high-repetition rate liquid jets

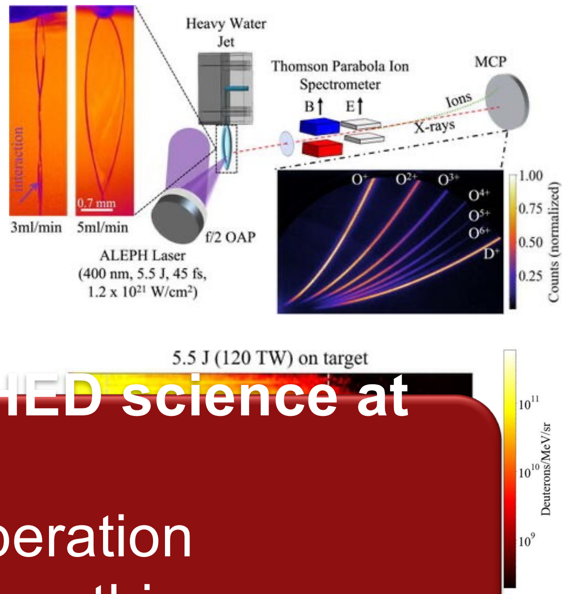
Dense plasma physics



Laser plasma physics



Accelerator physics



Liquid Jets are key to the success of HED science at MEC-U

- Matches laser repetition rate and shift operation
- 5 out of 9 flagships experiments depend on this technology

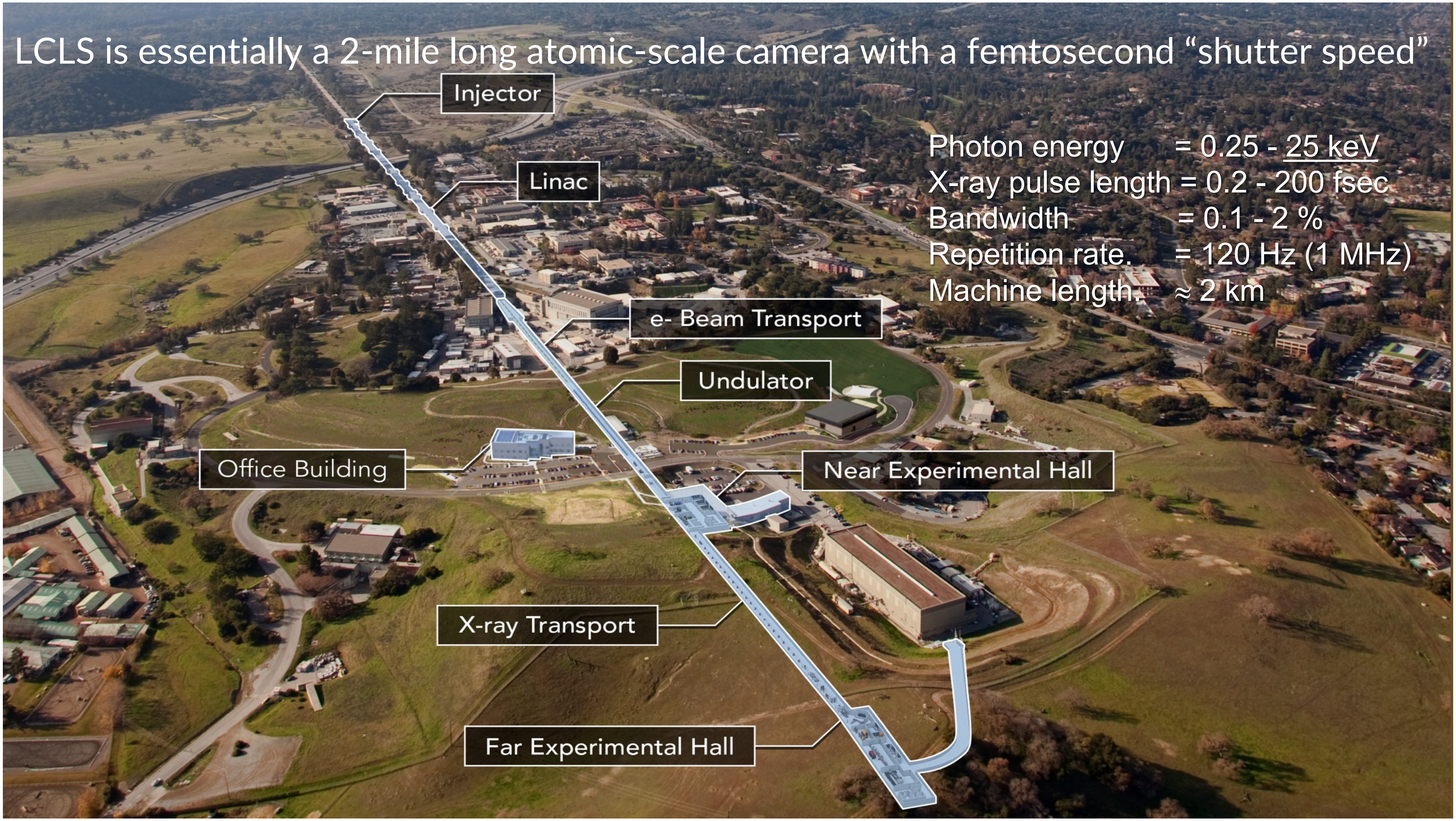
Elect

- ⌀5 μm H_2
- 1 Hz, 120 mJ

- ⌀10 μm H_2
- 18J, ~0.1 Hz, 5x10^{21} W/cm^2

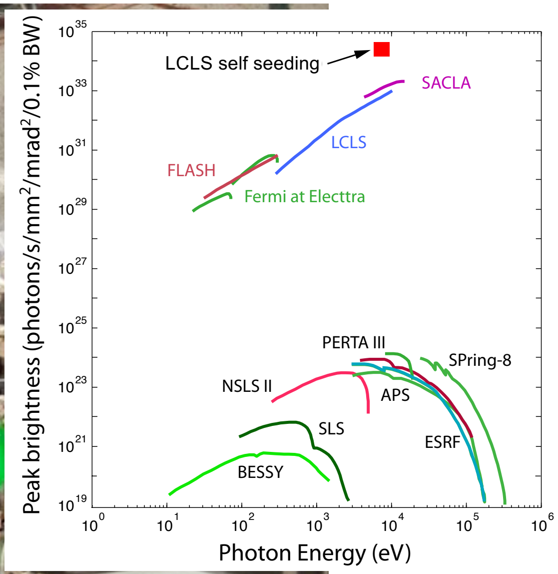
- 5 μm thick D_2O, 5J, 0.5Hz, 10^{21} W/cm^2
- 0.7 μm thick H_2O, 5Hz, 10^{20} W/cm^2

LCLS is essentially a 2-mile long atomic-scale camera with a femtosecond “shutter speed”



Photon energy = 0.25 - 25 keV
X-ray pulse length = 0.2 - 200 fsec
Bandwidth = 0.1 - 2 %
Repetition rate. = 120 Hz (1 MHz)
Machine length. ≈ 2 km

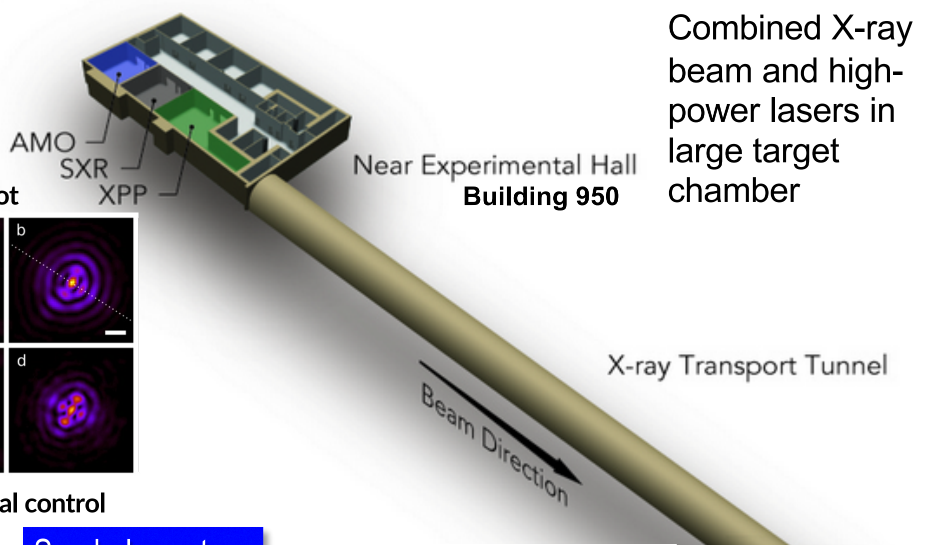
Laser action action occurs by Self Amplified Spontaneous Emission of radiation in the undulators (10^9 increase in brightness)



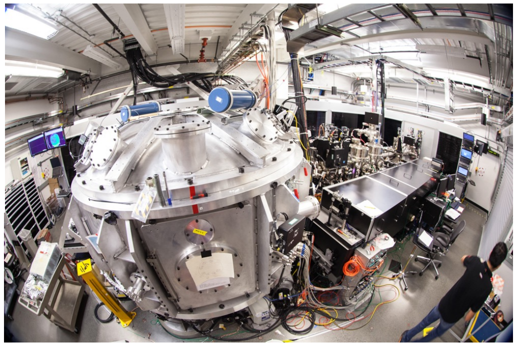
LCLS operates 24 hours/day
with 95% beam availability
as an open-access User Facility

- Undulator hall 2009

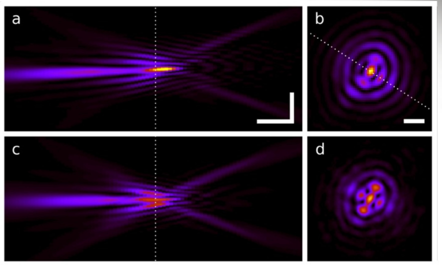
Combining high-intensity PW lasers with X-ray lasers (example LCLS) will greatly advance our scientific capabilities



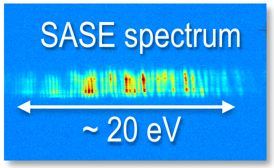
Combined X-ray beam and high-power lasers in large target chamber

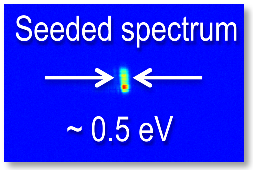


1 μm to 200 mm focal spot

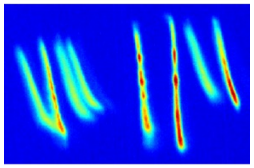


Fine spectral control

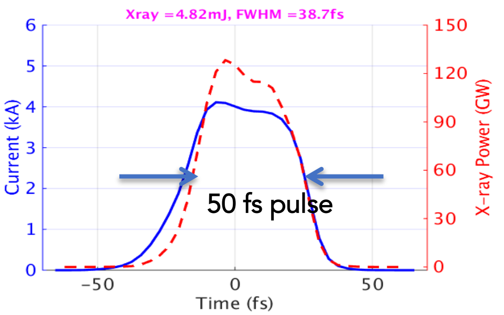


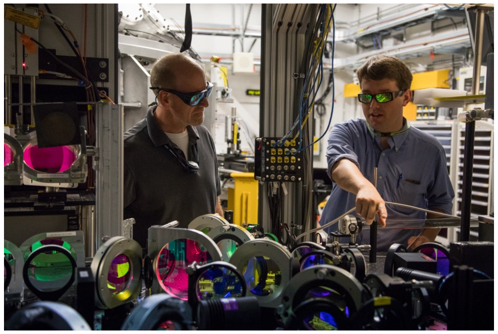


Up to 8 beams separated by 350 ps in a single pulse train



Ultra short pulses



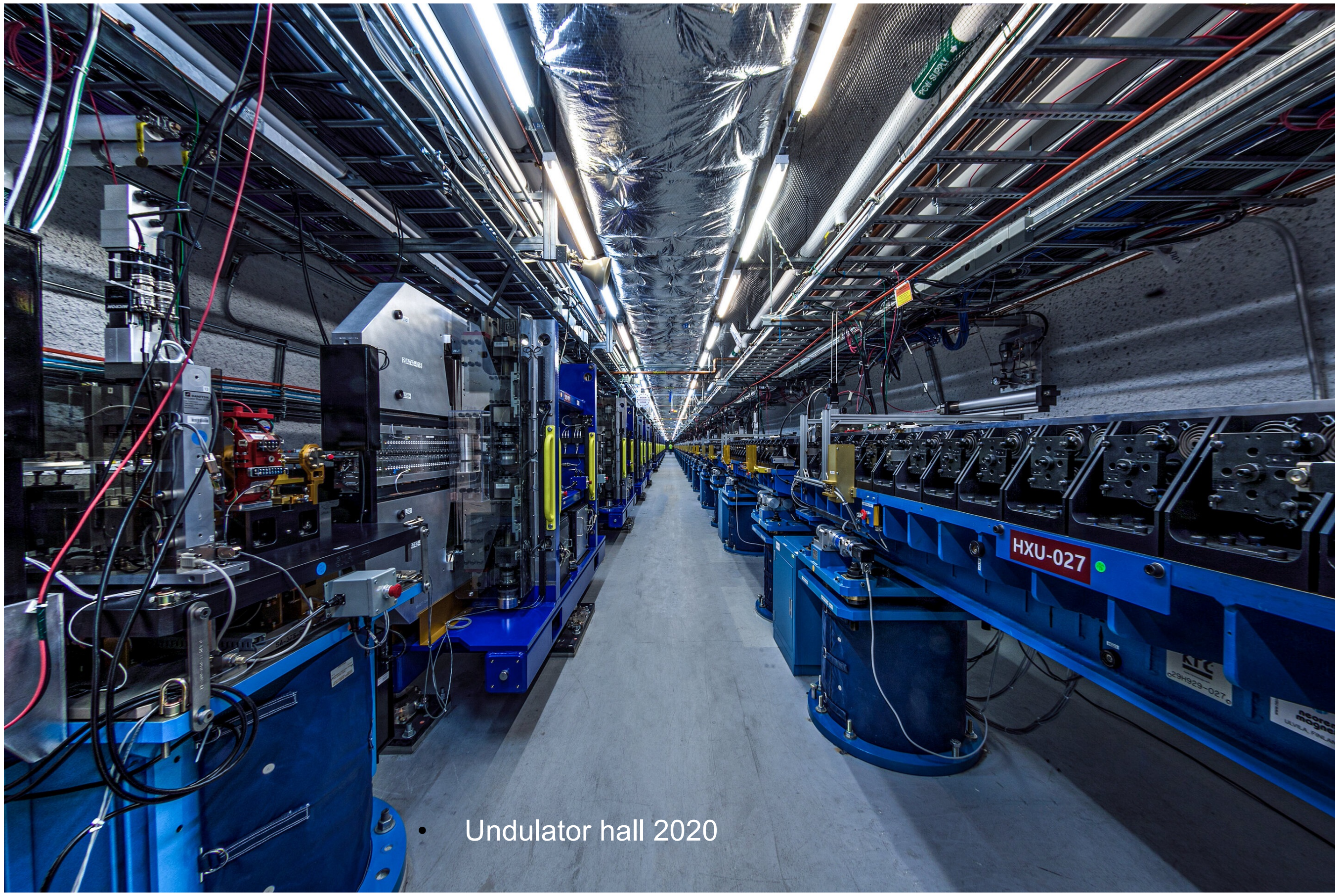


Compression Laser
100 J, 10 ns, 2ω

Short-pulse Laser
0.5 J, 50 fs, 2ω

Laser action action occurs by Self Amplified Spontaneous Emission of radiation in the undulators

- **Variable gap undulator**
- **250 eV to 5 keV**
- **Up to 1 MHz**



- Undulator hall 2020

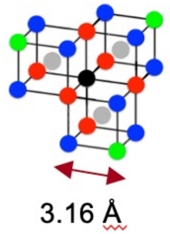
- **Variable gap undulator**
- **5 to 25 keV**
- **120 Hz**

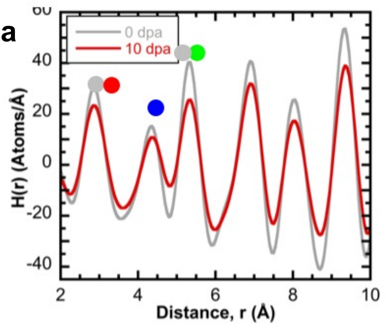
It is our goal to resolve PW laser driven radiation damage cascades by ultrafast X-ray and electron probes: example from LCLS

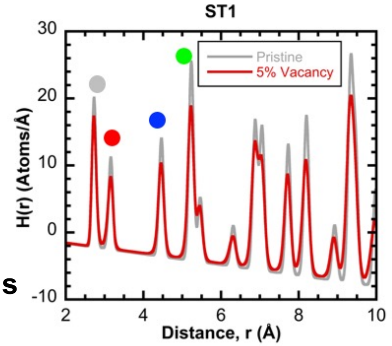
LCLS resolves defects in matter => observe damage cascade

LCLS UED data

BCC W



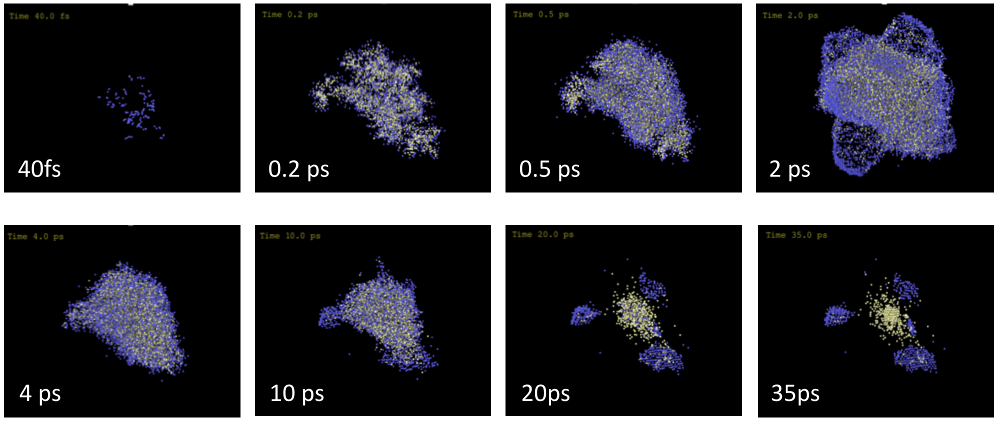




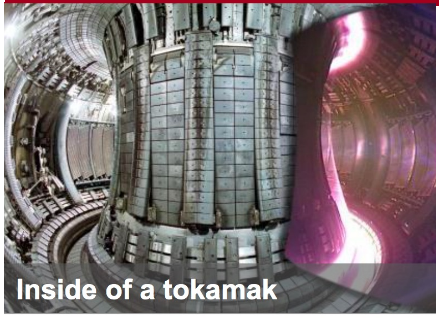
MD simulations

MD simulations of 150 keV Primary Knock on Atom [yellow dots: vacancies, blue dots: interstitials

With courtesy of A. Sand (2018)



Fusion Material Science

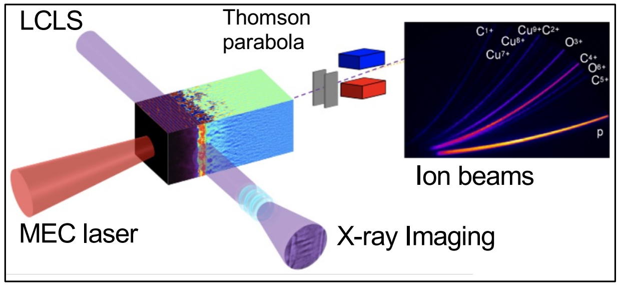


- We currently cannot resolve the cascade kinetics which would require a petawatt-class laser coupled to UED of XFEL
- Use ultrafast diffraction techniques to resolve the response of damaged materials to heat loads
- Fourier Transformation of the scattered intensity provides the Pair Distribution Function

Experiments have begun on pre-damaged samples

The LCLS X-ray beam can also be used to optimize the laser-, ion-, and neutron - beam - plasma interaction conditions

Development of X-ray imaging with unprecedented spatial (200 nm) and temporal resolution (2 – 50 fs)



Advancing XFEL-based discovery plasma science – 10x improvement over state of the art

- We are well-positioned to provide new high repetition rate diagnostics of ultra-intense laser driven plasmas (neutrons, ions, electrons & X-rays)
- R&D on ultrafast X-ray imaging systems for hot laser-driven plasmas
- Opportunity to drive development of multi-bucket experimental technique, through coordinated source, beamline, detector and science initiatives

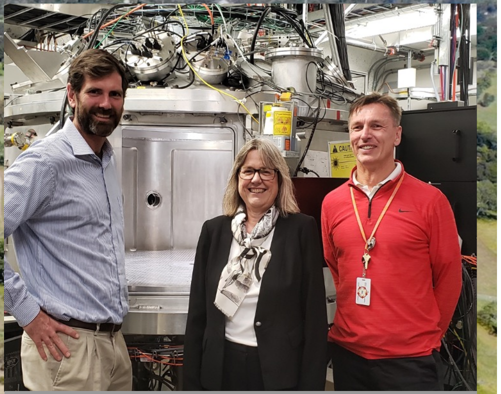
MEC experiments visualize kinetic plasma instabilities

MEC projects develop imaging and analysis techniques

High-resolution images of 1 MeV protons stopped in a solid Si slab

Reference: PI: E. McBride, M. Gauthier

The successes of these programs contributed to the science case motivating an Upgrade of MEC



Nobel laureate Donna Strickland visiting MEC at LCLS

SLAC NATIONAL ACCELERATOR LABORATORY

Lawrence Livermore National Laboratory

UR LLE

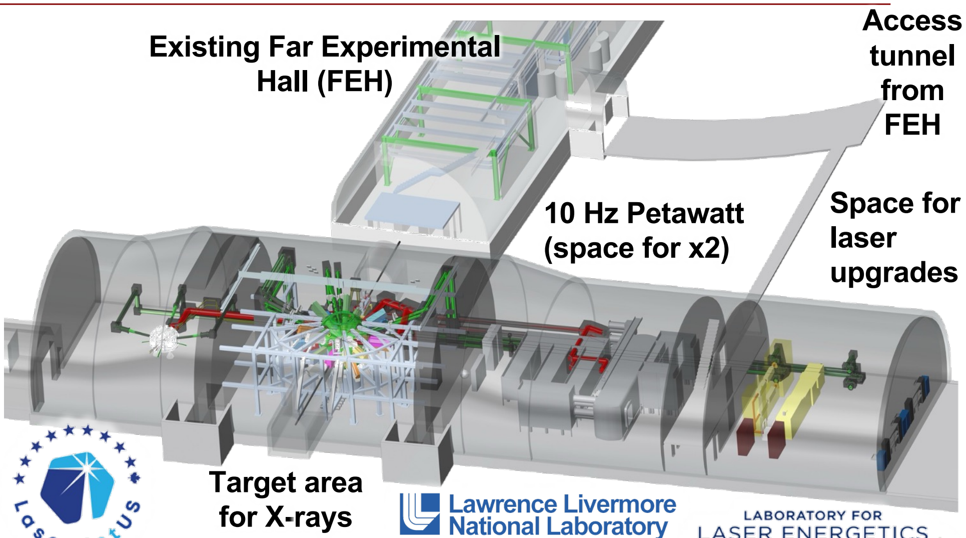
U.S. DEPARTMENT OF ENERGY

Stanford University

The MEC Upgrade project will move the frontier and exploit new research directions of importance to DOE

MEC-Upgrade is strongly endorsed by the community

- Recommendation: “Complete the design and construction of MEC-Upgrade.” page 47 of A Report of the Fusion Energy Sciences Advisory Committee-LRP (2020)
- *“the MEC-U facility* will leverage the diagnostic power of LCLS together with a kilojoule and Petawatt lasers, to provide a facility with capacity for **upgrades pursuant to IFE-relevant science**.” page 198 of IFE BRN Report (2022)



LaserNetUS

Lawrence Livermore National Laboratory

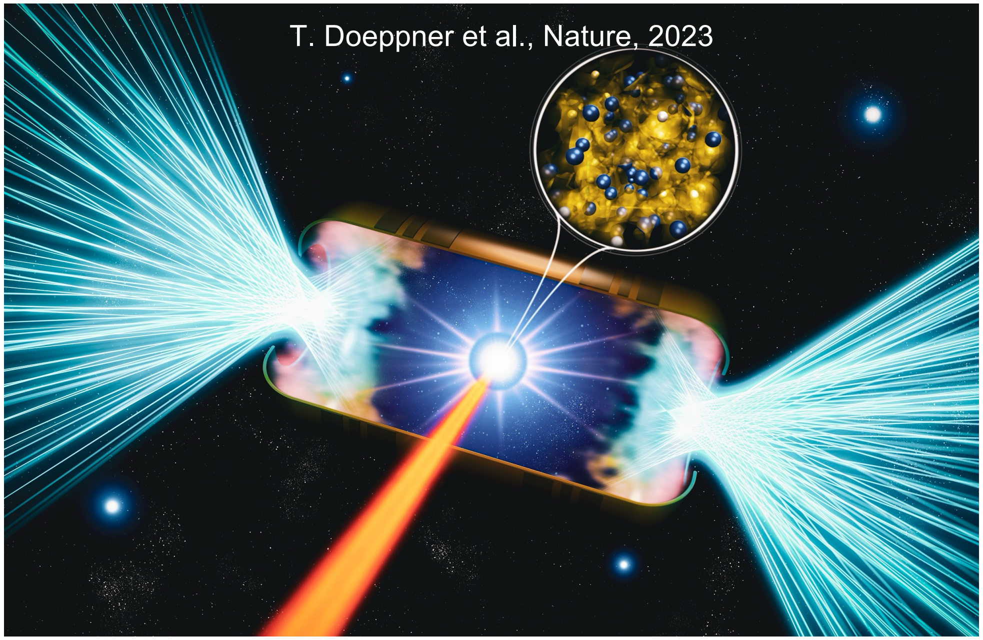
LABORATORY FOR LASER ENERGETICS
UNIVERSITY OF ROCHESTER

The MEC-Upgrade project:

- Collaboration with the Nation’s leading laser laboratories
- World-leading combination of high-power lasers with XFEL
  - 10x higher power @ 10 Hz (Petawatt)
  - 10x higher energy laser (kilojoule)

MEC upgrade at LCLS will provide world-leading capability in HED science

LCLS MEC and HED-led discovery science experiments are in the world's news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D. Kraus et al., Nature Comm (2016);
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D. Dattelbaum et al., Nat. Comm. (2021)
Z. He et al., Science Advances (2022);
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A. Gleason et al., Nature Comm (2015);
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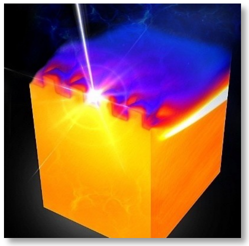
S. Brennan-Brown et al., Sci. Adv. (2019)
S. Pandolfi et al., Nat. Comm. (2022);

MEC is the most prolific instrument at LCLS

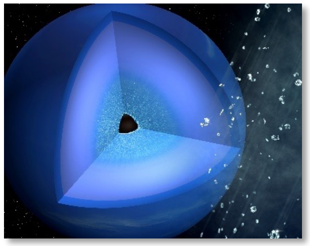
The Laser specs for the MEC upgrade are driven by the scientific missions within DOE

- **PW Laser:** **150J, 150 fs, 1 μm, 10 Hz**
- 10^{18} Pa light pressure, Bright ion beams, Collision-less shocks
  - Compared to international competition
    - 10x higher repetition rate
    - 6x higher energy
    - 2x higher power



Producing bright sources of ions, neutrons and magnetic fields for fusion material science

- **Compression Laser:** **1 kJ, 20 ns, 0.35 μm, shot/minute**
  - 10^{12} Pa material pressure, Ablator physics, Unearthly materials
  - Compared to international competition
    - 10x higher energy at shot/minute
    - 2x higher energy at 10 Hz



Producing extreme material states through near isentropic compression

These lasers provide unparalleled capabilities to access and probe new states of matter