LA-UR-23-22495

Title: Short-pulse Laser-driven Moderated Neutron Source

Author(s): Vogel, Sven C.; Fernandez, Juan Carlos; Gautier, Donald Cort; Hollinger, Reed; Hunter, James F.; Kleinschmidt, Annika; Knickerbocker, Kelly L.; Losko, Adrian Simon; Mitura, Nikodem; Nelson, Ronald Owen; Rocca, Jorge J.; Roth, Markus; Schoenberg, Kurt Francis; Tremsin, Anton S.

Intended for: LENS Workshop on Laser driven Neutron Sources, 2023-03-01/2023-03-03
(Lund, Sweden)

Issued: 2023-03-09 (Draft)

Short-pulse Laser-driven Moderated Neutron Source

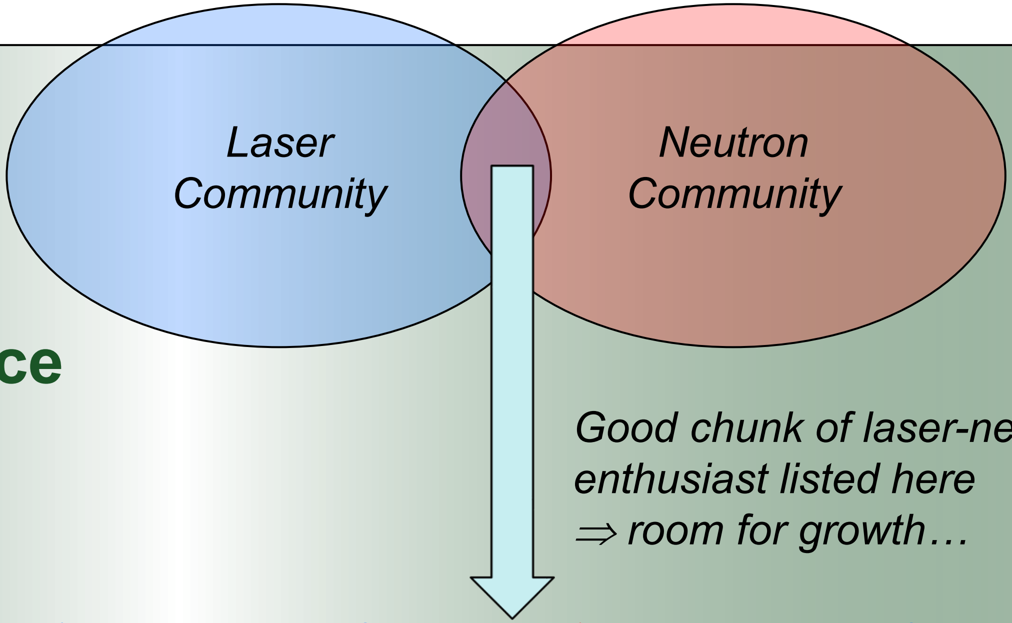
Sven C. Vogel[1]**,** J. Fernandez[1], C. Gautier[1], R.C. Hollinger[3], J. Hunter[1], A. Kleinschmidt[2], K. Knickerbocker[1], A.S. Losko[4], N. Mitura[2], R. Nelson[1], J.J. Rocca[3], **Markus Roth**[2], K. Schoenberg[1,2], A.S. Tremsin[5]

[1]Los Alamos National Laboratory, Los Alamos, NM, U.S.A.

[2]TU Darmstadt, Darmstadt, Germany
[3]Colorado State University, Fort Collins, CO, U.S.A.

[4]FRM-2, TU München, München, Germany
[5]University of California at Berkeley, Berkeley, CA, U.S.A.

LA-UR 16-24633, 16-23796, 18-24935, 18-28584, 18-28739



Short-pulse Laser-driven Moderated Neutron Source

Good chunk of laser-neutron enthusiast listed here ⇒ room for growth…

Sven C. Vogel[1], *J. Fernandez*[1], *C. Gautier*[1], *R.C. Hollinger*[3], *J. Hunter*[1], *A. Kleinschmidt*[2], *K. Knickerbocker*[1], *A.S. Losko*[4], *N. Mitura*[2], *R. Nelson*[1], *J.J. Rocca*[3], ***Markus Roth***[2], *K. Schoenberg*[1,2], *A.S. Tremsin*[5]

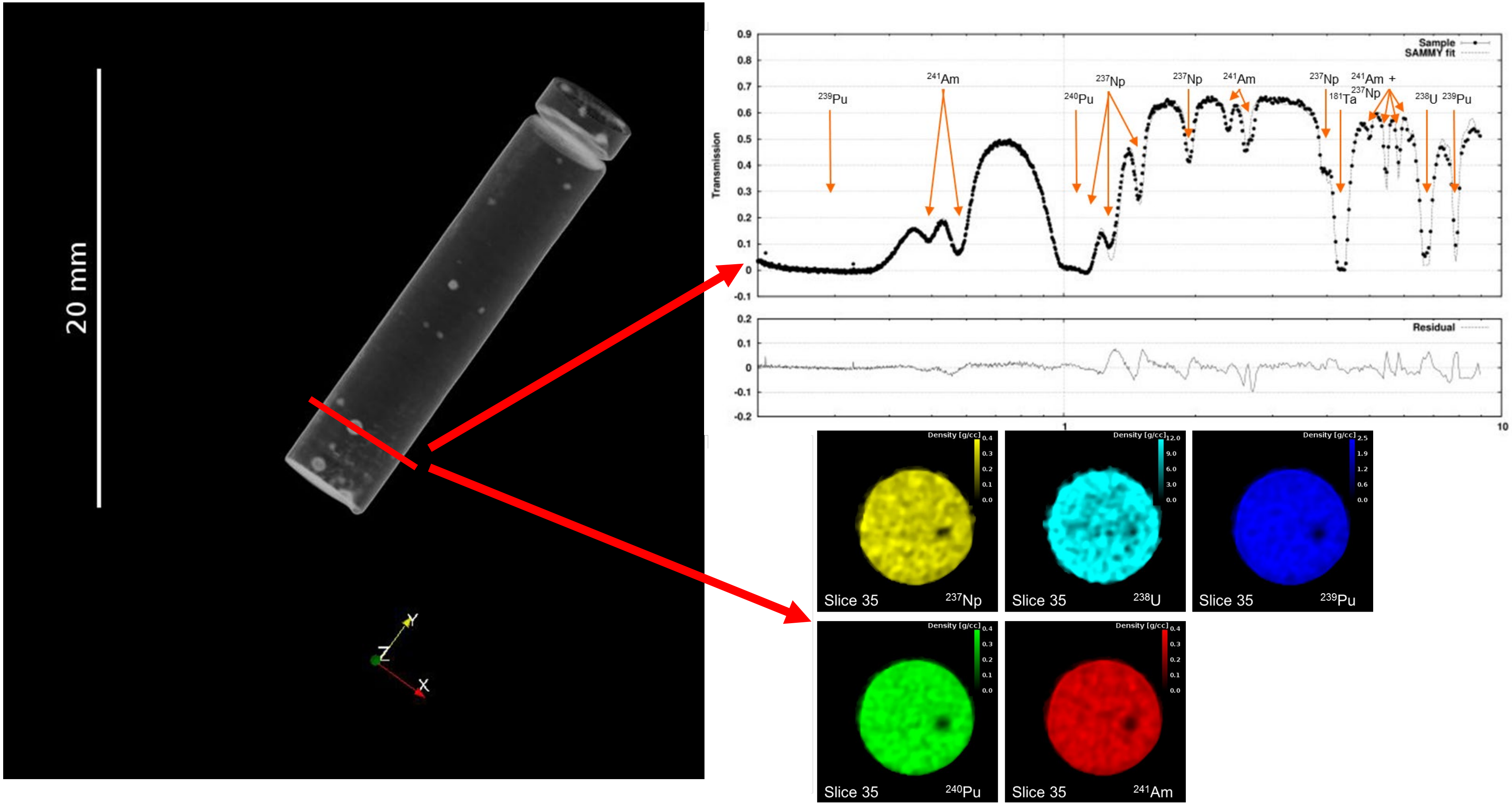
[1]Los Alamos National Laboratory, Los Alamos, NM, U.S.A.

[2]TU Darmstadt, Darmstadt, Germany
[3]Colorado State University, Fort Collins, CO, U.S.A.

[4]FRM-2, TU München, München, Germany
[5]University of California at Berkeley, Berkeley, CA, U.S.A.

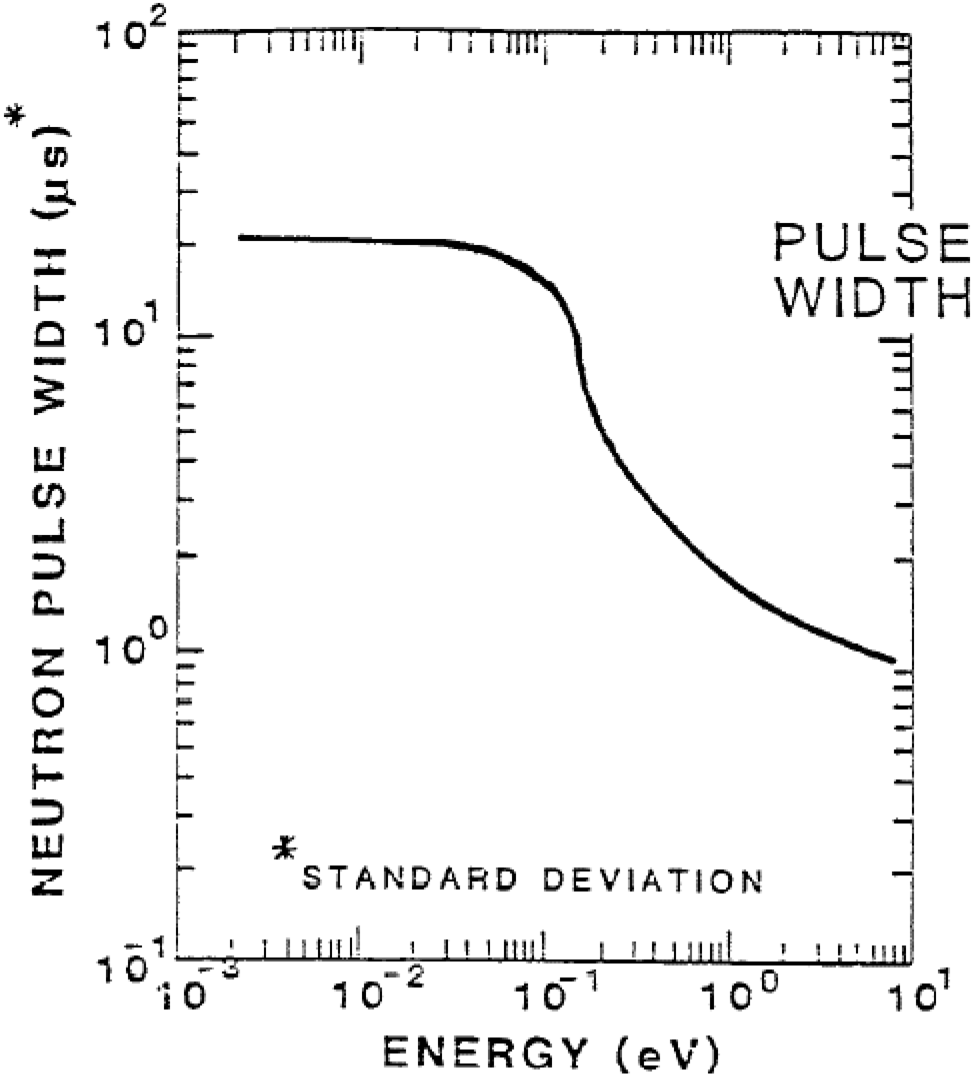
LA-UR 16-24633, 16-23796, 18-24935, 18-28584, 18-28739

3D Reconstruction of isotope densities in dU-20Pu-10Zr-3Np-2Am (Transmutation fuel) using energy-resolved neutron imaging (ERNI)



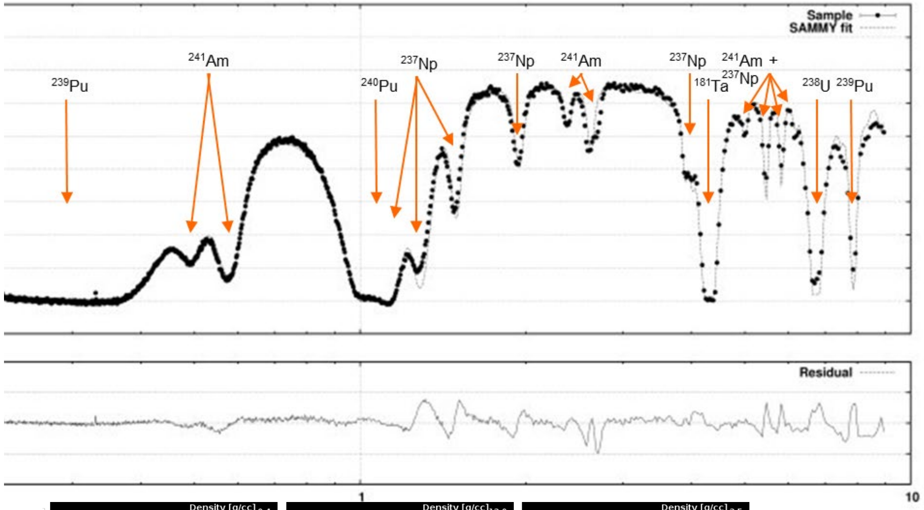
- **Pixel-wise reconstruction of areal densities followed by tomographic reconstruction creates 3D isotope density maps**
- **Requires short-pulsed neutrons**

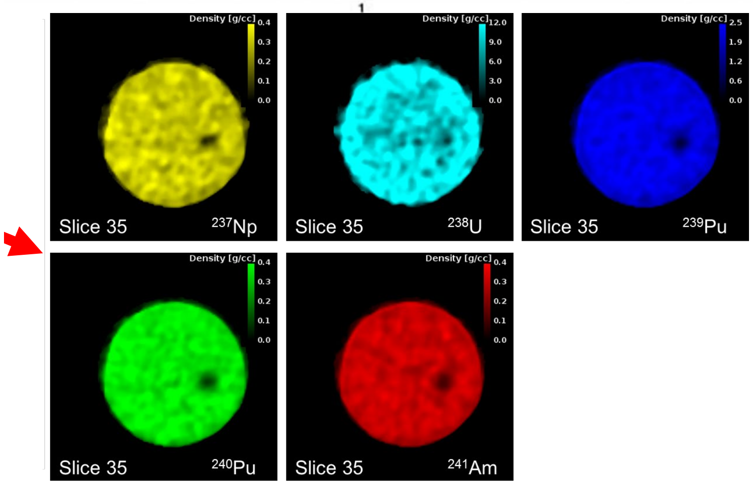
3D Reconstruction of isotope densities in dU-20Pu-10Zr-3Np-2Am (Transmutation fuel) using energy-resolved neutron imaging (ERNI)



Allowable initial p/d pulse width should be less than required neutron pulse width for desired energy (~1μs for 10 eV epithermal neutrons)

From: Gary Russell et al. ICANS-VIII Proceedings (1985)





al densities followed by
ates 3D isotope density maps

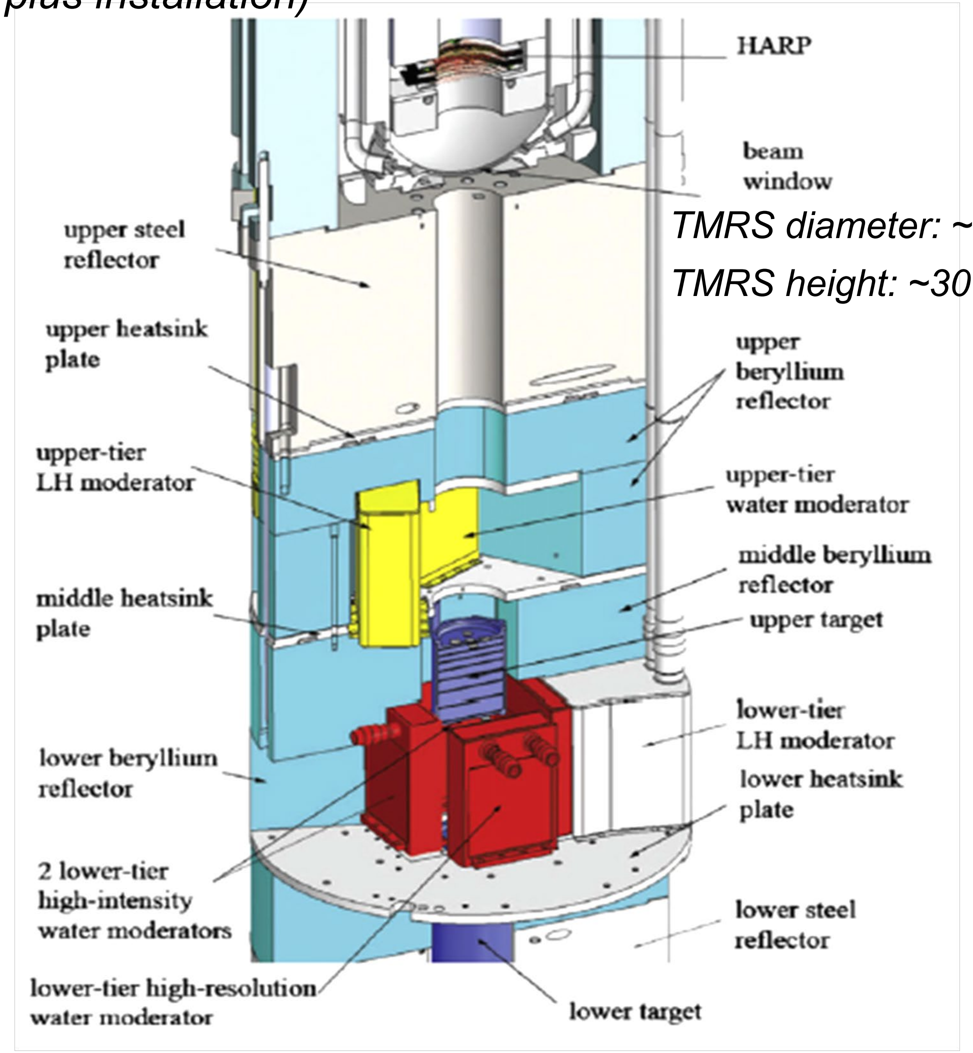
Conventional Pulsed Neutron Source

LANSCE – 800 MeV linear proton accelerator, ½ mile long, 100 μA on target, 20 Hz, spallation

⇒ >$1B investment, ~$10M for new target (plus installation)

⇒ ~100 people to operate just the source

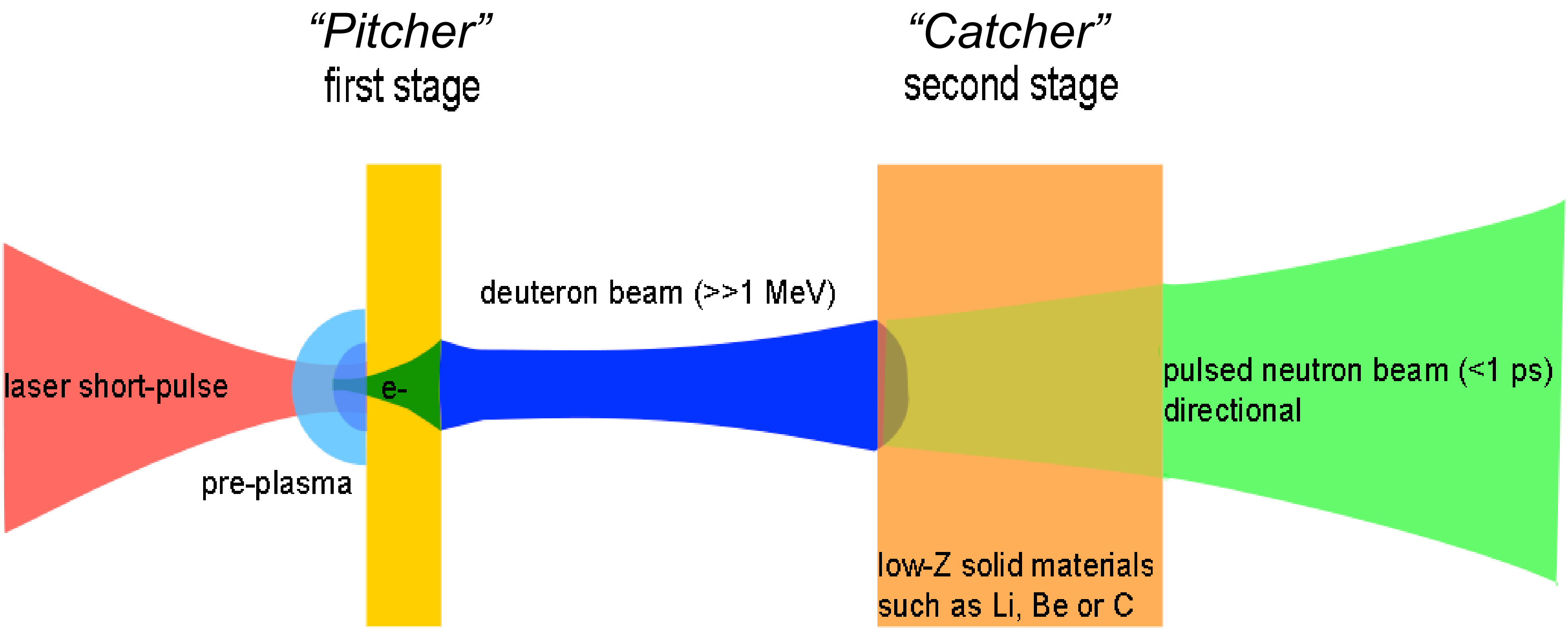
⇒ ~$1M/month electricity bill



TMRS diameter: ~60 cm

TMRS height: ~300 cm

Principle of Laser-driven Neutron Sources



Accelerator shrinks from half mile to half micron

Target/moderator shrinks from 3m to 3 cm

Cost shrinks from ~1B$ to ~10M$

Flux shrinks from… Stay tuned!

Roth et al., PRL 110, 044802 (2013)

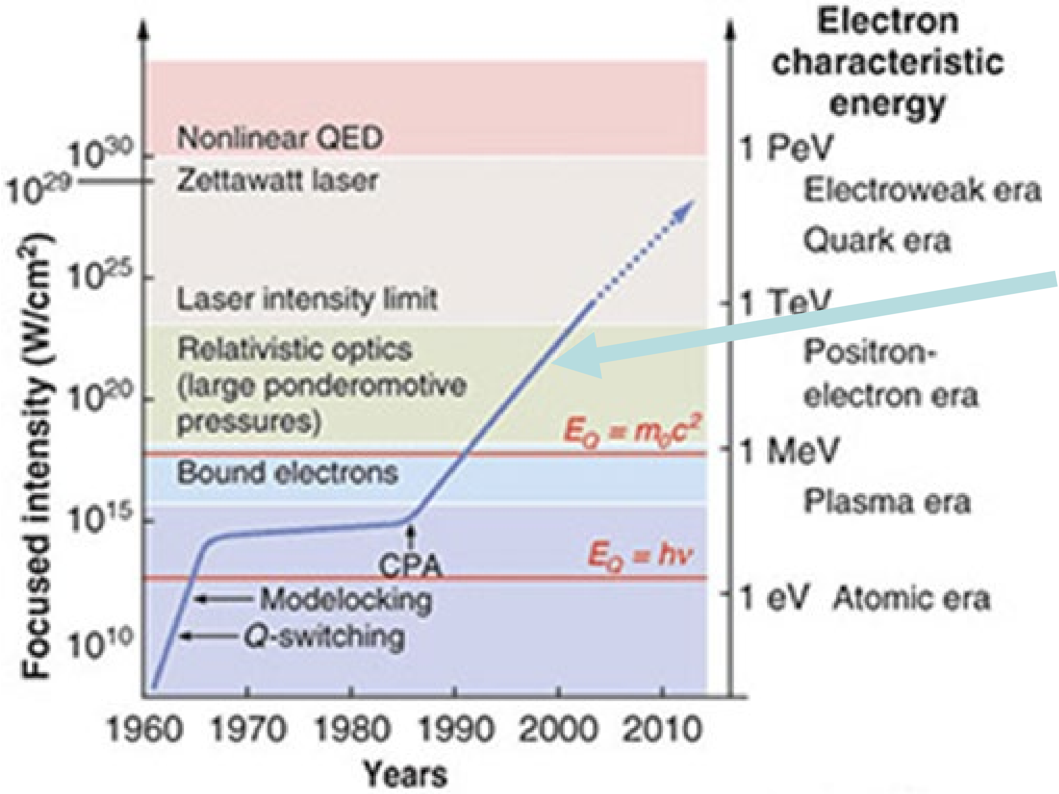
Enabling technology: Laser power is increasing by orders of magnitude per decade

Number of produced neutrons is >linear with laser energy

Neutron energy scales with laser intensity (& power)

Useful sources possible today

⇒ Now is the time to explore laser-driven neutron sources!

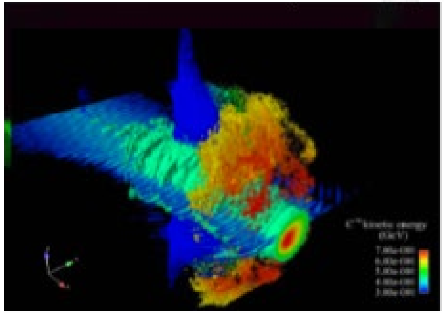


TRIDENT@LANL: 1.2×10²¹ W/cm²

http://physics.anu.edu.au/ampl/research/theoretical/theoreticalpage2.php

Los Alamos made significant contributions

Ion acceleration with lasers: Break out Afterburner (BOA) effect



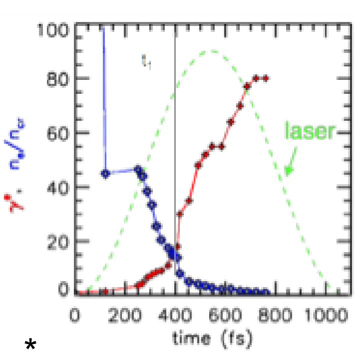
t_1: relativistic transparent

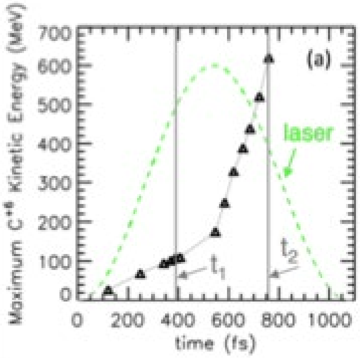
$n' > 1 \geq n'/\gamma$

t_2: classically underdense

$n' < 1$

$$\eta = \sqrt{1 - \omega_p^2/\omega_L^2}, \qquad \omega_p^2 = \frac{e^2 n_e}{\varepsilon_0 \bar{\gamma} m_e}$$





*

Yin, et al., Laser and Particle Beams 24 (2006), 1-8

Yin, et al., Phys. Plasmas 14, 056706, (2007)

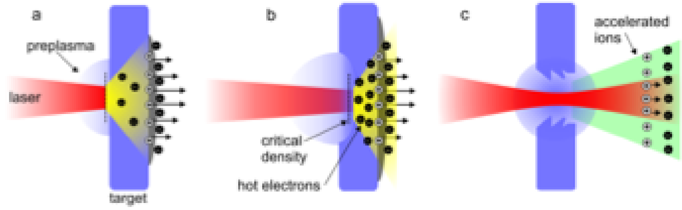
Yin, et al., Phys. Plasmas 18, 063103 (2011)

Albright, et al., Phys. Plasmas 14, 094502 (2007)

Yin, et al., Phys. Rev. Lett. 107, 045003 (20011)

Simulations on Roadrunner @ LANL

First Experimental Proof on TRIDENT @LANL



a) Target Normal Sheath Acceleration (TNSA) phase
b) Intermediate phase
c) Laser Breakout Afterburner (BOA) phase

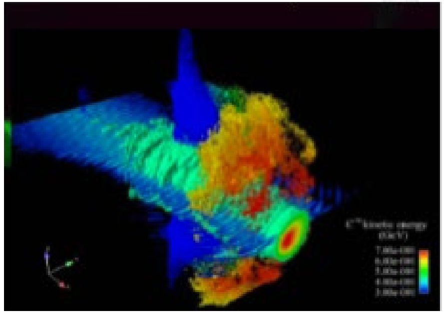
BOA mechanism:*

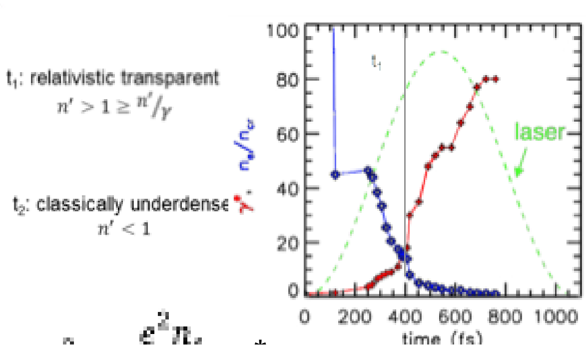
1. *Laser heats all the electrons within the spot to relativistic temperatures & drives an electron drift ~ c*
2. *Relativistic mass of electrons increases-> relativistic transparency*
3. *Volumetric laser-plasma interactions further drives electrons & electrostatic waves*
4. *Electrostatic waves drive ions, keep quasineutrality*
5. *Requires in practice nanofoil targets (& therefore high-contrast laser pulse)*

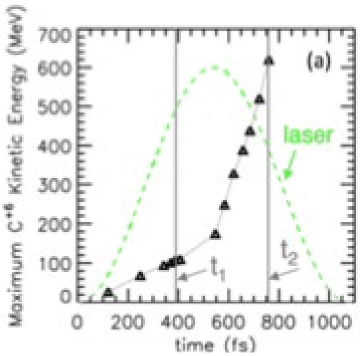
Fernandez et al., Phys. Plasmas, **24** 056702 (2017), *Vogel et al., Neutron News **29** (2018)*

Los Alamos made significant contributions

Ion acceleration with lasers: Break out Afterburner (BOA) effect







Novel physics predicted and experimentally demonstrated:

- *Chirped Pulse Amplification (CPA): ~1985*
  (Nobel Price 2018: Gérard Mourou/École Polytechnique & Donna Strickland/Univ. of Waterloo)
- *Target-sheath normal acceleration (TNSA): ~2000*
- *Break-out Afterburner (BOA): ~2010*
- *Laser diodes, plasma mirrors etc. improve lasers in general*
- *Sandwiched multi-nanolayer targets, coated targets etc. to be explored*

⇒ Field of lasers and laser-matter interactions still young!

5. *Requires in practice nanofoil targets (& therefore high-contrast laser pulse)*

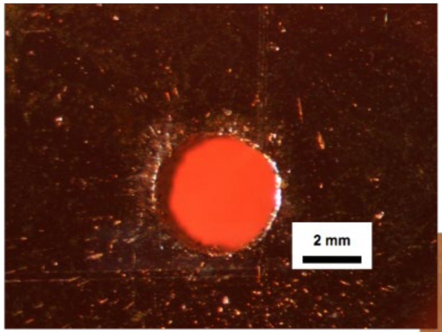
Fernandez et al., Phys. Plasmas, **24** 056702 (2017), *Vogel et al., Neutron News* ***29*** *(2018)*

Targets

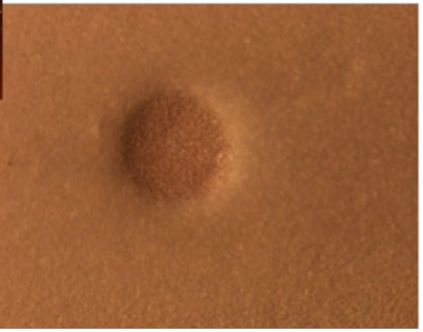
CH_2 Targets

- Poly(4-methyl-1-pentene), trade name TPX (Mitsui, Inc.)
- Soluble in cyclohexane
- Full density films (800 mg/mL) dip- or spin-cast (<200 nm – 1 um)
- Low density foams (5 – 50 mg/mL) produced by freeze-dip-casting, freeze drying (~50 um)

Full-density film

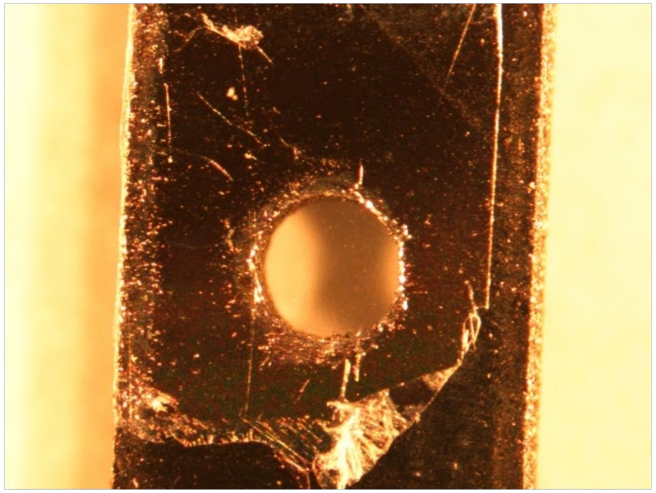


Low-density film



CD_2 Targets

- Deuteropolyethylene(85% D content)
- Soluble in hot toluene/ xylenes
- Full density films (940 mg/mL) drop-cast onto warm Si wafers (300 nm- 1um)



Roth et al., PRL 110, 044802 (2013)

Roth, Vogel et al. "Assessment of Laser-Driven Pulsed Neutron Sources for Poolside Neutron-based Advanced NDE – A Pathway to LANSCE-like Characterization at INL." LA-UR-17-23190. LANL (2017).

Targets

CH_2 Targets

- Poly(4-methyl-1-pentene), trade name TPX (Mitsui, Inc.)
- Soluble in cyclohexane
- Full density films (800 mg/mL) dip- or spin-cast (<200 nm – 1 um)
- Low density foams (5 – 50 mg/mL) produced by freeze-dip-casting, freeze drying (~50 um)

CD_2 Targets

- Deuteropolyethylene(85% D content)
- Soluble in hot toluene/ xylenes
- Full density films (940 mg/mL) drop-cast onto warm Si wafers (300 nm- 1um)

Beam spot <10 micron

Providing deuterated thin-film targets at e.g. 10 Hz is active research area:

- *Thin films/free-standing targets (TU Darmstadt, Tel Aviv University…)*
- *Deuterated liquid crystals (Ohio State Univ., Lawrence Livermore NL)*
- *Deuterated cryo-jets (Stanford)*

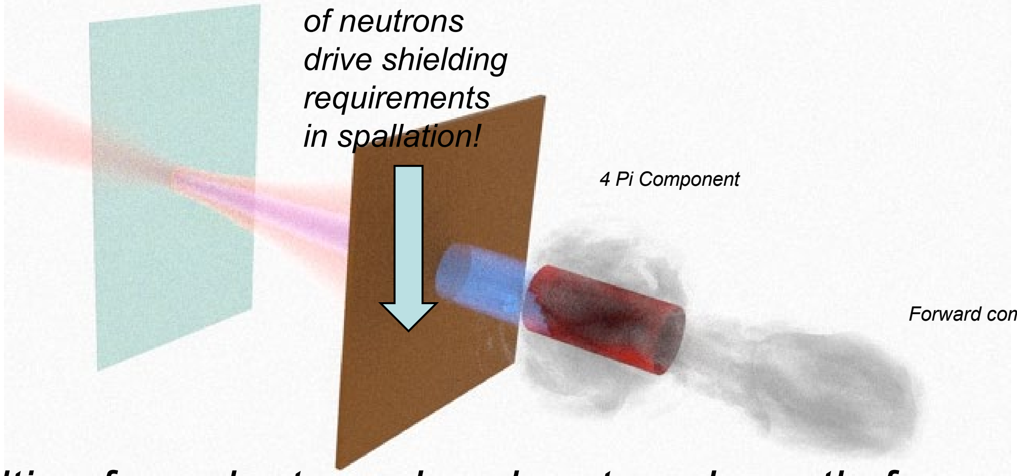
The same lasers are used to mechanically shock materials
$\Rightarrow$ not a trivial problem…

Roth et al., PRL 110, 044802 (2013)

Roth, Vogel et al. "Assessment of Laser-Driven Pulsed Neutron Sources for Poolside Neutron-based Advanced NDE – A Pathway to LANSCE-like Characterization at INL." LA-UR-17-23190. LANL (2017).

Neutron Production in Beryllium target

Several production reactions: ^{9}Be(d,n), ^{9}Be(p,n), and deuteron breakup reaction*



Few percent of neutrons drive shielding requirements in spallation!

Neutrons resulting from deuteron breakup travel mostly forward

⇒ Easier to capture majority of produced neutrons in moderator

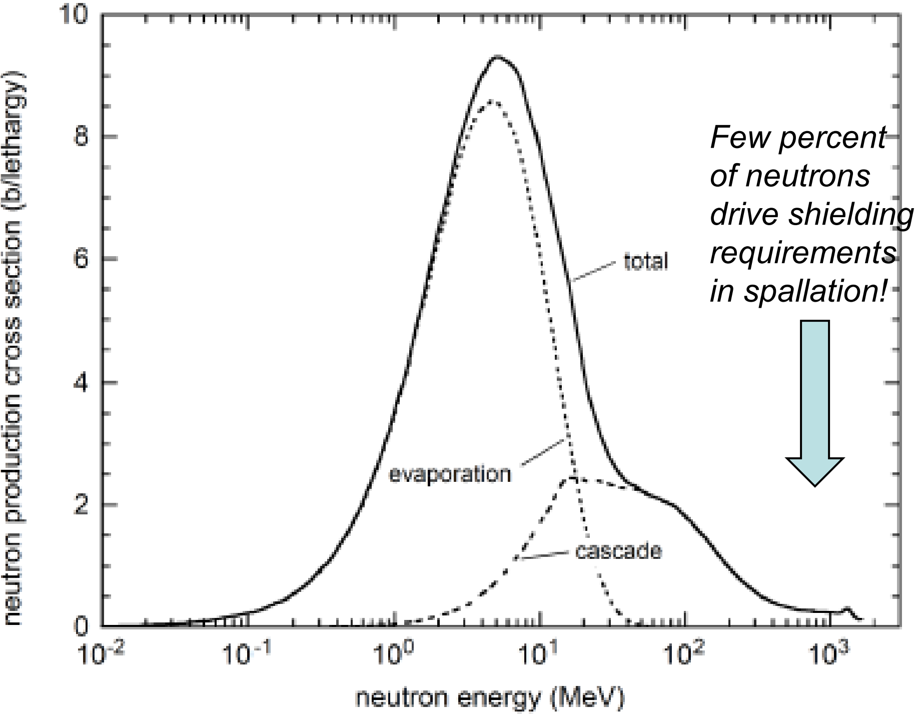
⇒ Much less complex radioactive target inventory than spallation or reactor

⇒ No shielding for 100 MeV neutrons

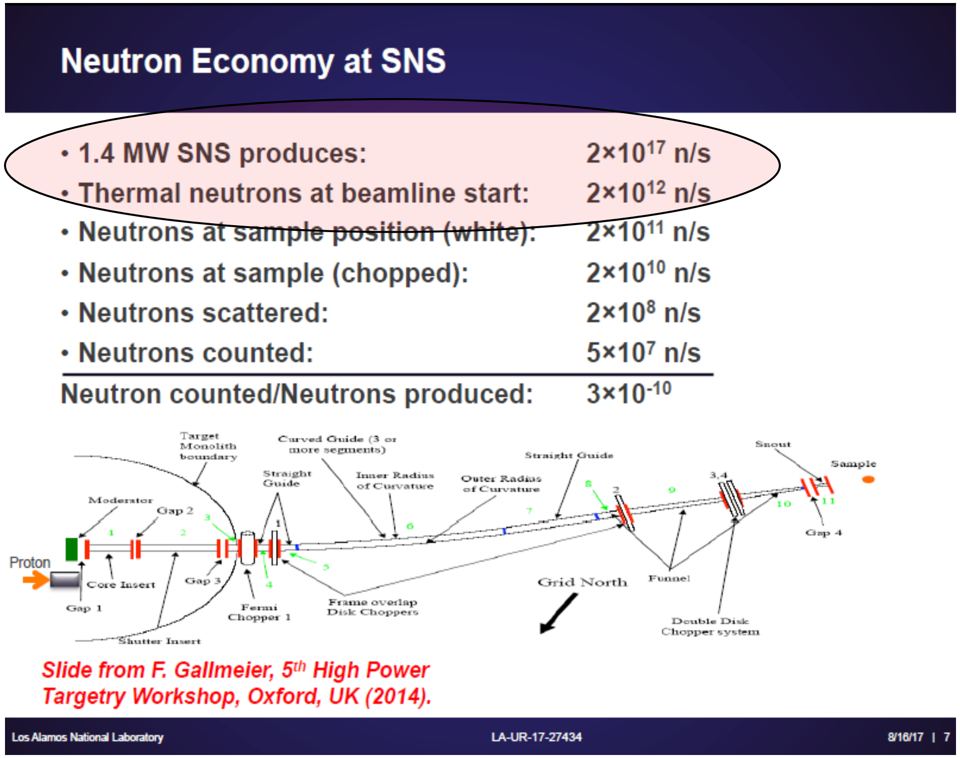
* *J. R. Oppenheimer, Phys. Rev. 47, 845 (1935), R. Serber, Phys. Rev. 72, 1008 (1947)*

Neutron Production LDNS vs. SNS

Neutron production cross section for 1.7-GeV protons on tungsten



Few percent of neutrons drive shielding requirements in spallation!



Neutron Economy at SNS

• 1.4 MW SNS produces:	2×10^{17} n/s
• Thermal neutrons at beamline start:	2×10^{12} n/s
• Neutrons at sample position (white):	2×10^{11} n/s
• Neutrons at sample (chopped):	2×10^{10} n/s
• Neutrons scattered:	2×10^{8} n/s
• Neutrons counted:	5×10^{7} n/s
Neutron counted/Neutrons produced:	3×10^{-10}

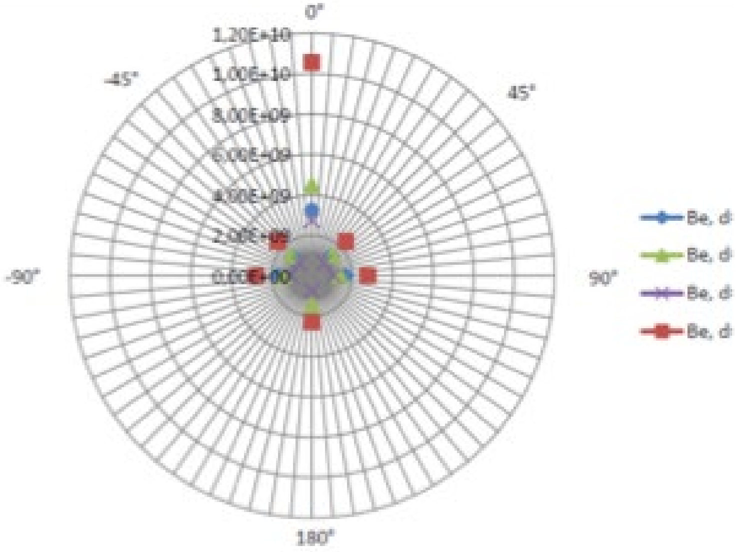
Slide from F. Gallmeier, 5th High Power Targetry Workshop, Oxford, UK (2014).

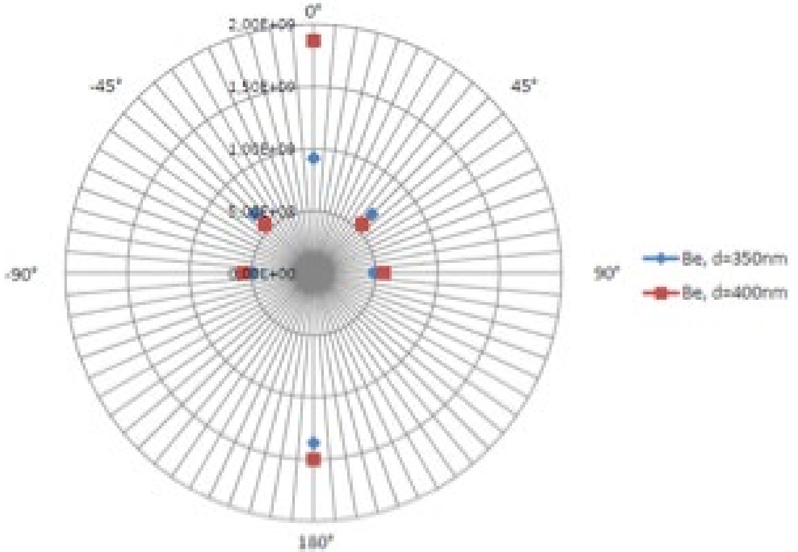
Los Alamos National Laboratory LA-UR-17-27434 8/16/17 | 7

- *LDNS utilizing deuteron breakup (or photoneutrons) requires much less shielding than spallation neutron source*
- *Neutrons produced with directionality provide ~orders of magnitude better source-to-moderator coupling*

U.S. DEPARTMENT OF
ENERGY
Nuclear Energy

How many neutrons can we get? And where?

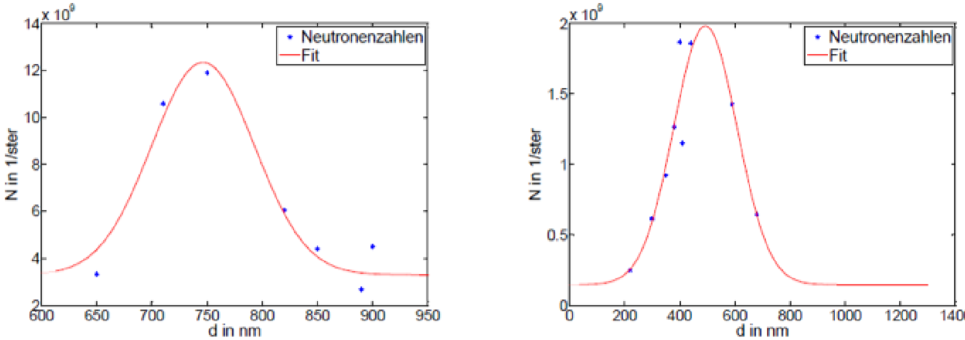




Results for different laser powers:
500 J and 500 fs VULCAN (sub-optimal contrast): 10^9 n/s
80 J and 600 fs TRIDENT (high contrast): >10^{10} n/
60 J and 450 fs PHELIX (high contrast): >10^{10} n/

Contrast is more crucial than laser power, as suggested b
and BOA!

(…and 10^{-10} pre-pulse on a PW laser is still enough energ
destroy the target before anything happens!)



Target thickness is crucial, as suggested by BOA

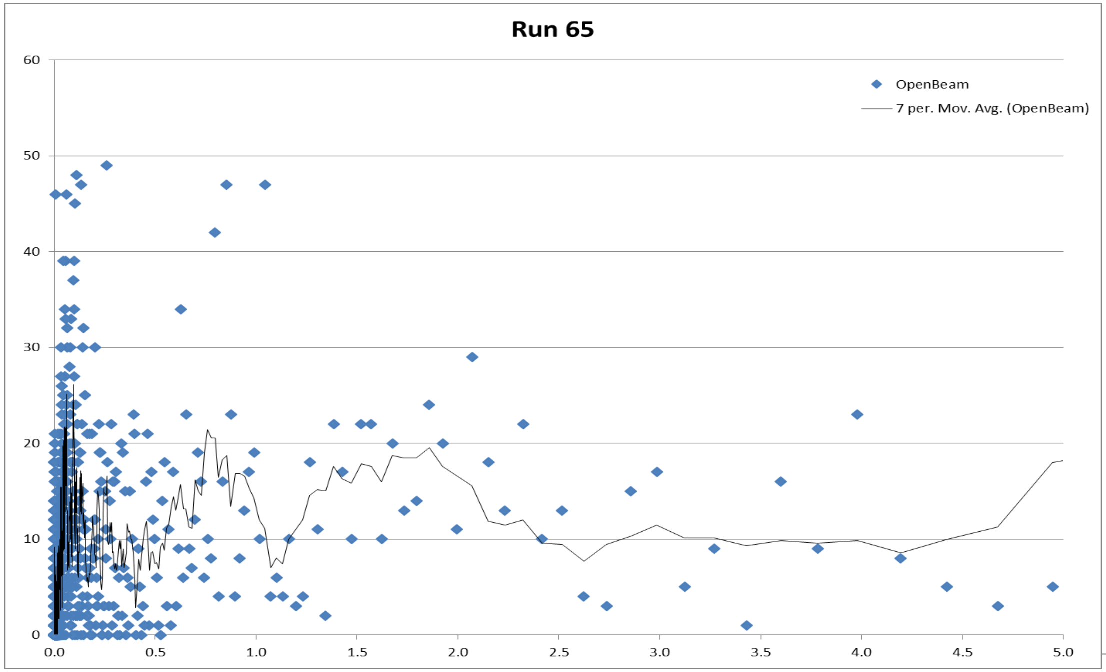
Contrast is of paramount importance!
Thickness must match laser energy and pulse duration to obtain optimal yield ⇒ need to know what we are doing!
TRIDENT had "older" glass optics ⇒ needed to cool down lenses for 90 minutes between shots

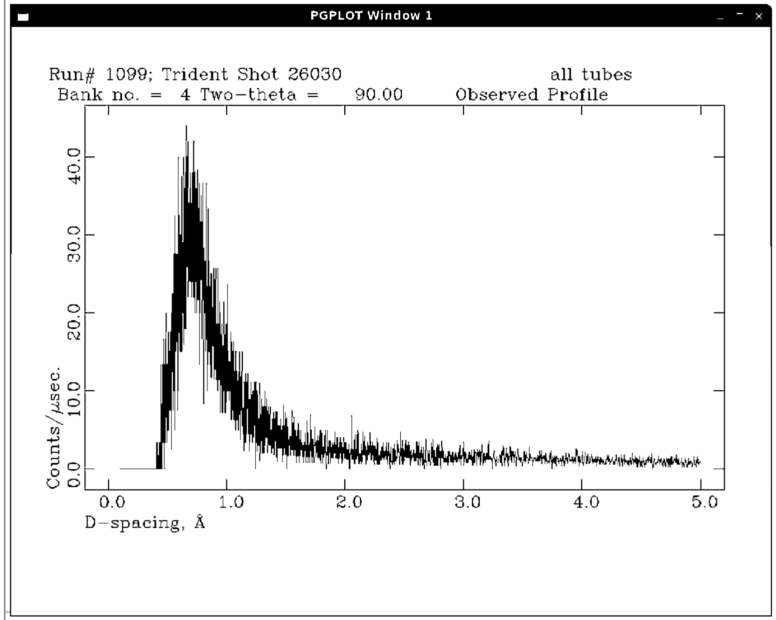
Roth et al., PRL 110, 044802 (2013), Fernandez et al., Physics of Plasmas, **24** 056702 (2017)

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Results from last TRIDENT Campaign 2016

- *Installed 3 HIPPO panels (24 ^{3}He tubes each) and Tremsin TOF imaging detector at TRIDENT*
- *TOF imaging detector: $(1.23 \pm 0.09)\times10^{5}$ epithermal and thermal events (detector shut off during γ-flash) on 28x28 mm^{2} (7.84 cm^{2}) at 1.7m from source (perpendicular to laser pulse) $\Rightarrow (5.51\pm0.5)\times10^{9}$ n/pulse at source (without much optimization…)*
- *Observed indium resonance with single pulse*
- *Detected thermal spectrum with ^{3}He diffraction setup*
- *Need a high rep-rate (1Hz…) source to optimize, calibrate etc.*

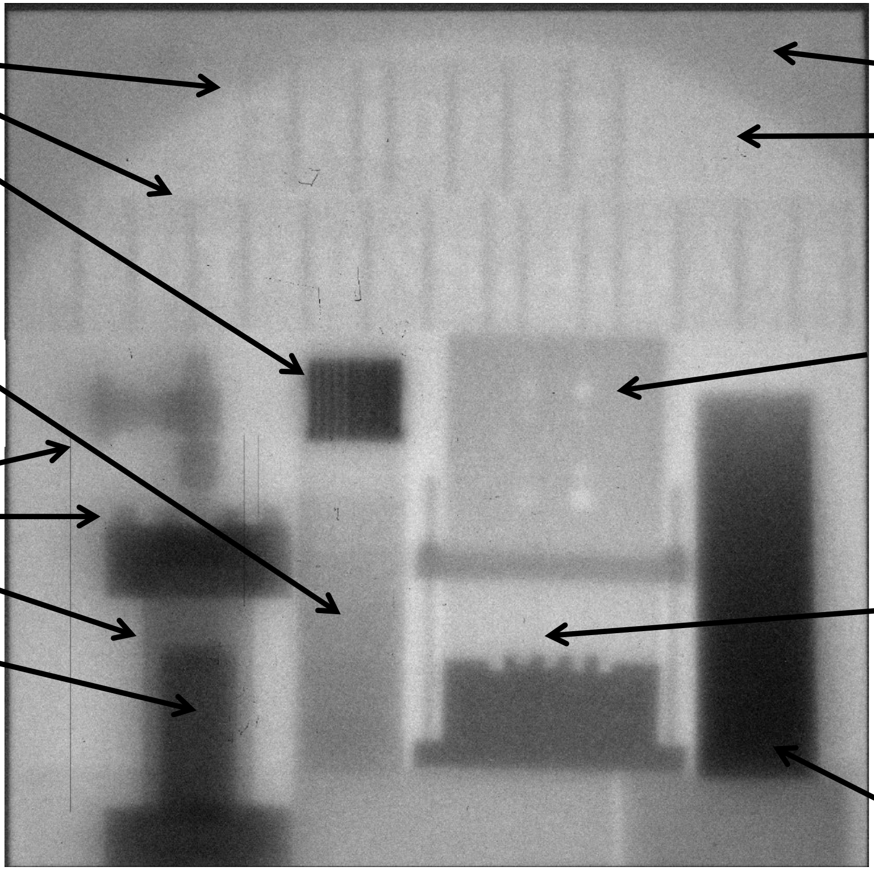




Results from last TRIDENT Campaign

Fast Neutron & Hard X-ray imaging

TRIDENT n-radiograph using a-Si Flat Panel with poly+ZnS(Cu) converter, single pulse, July 6th 2016



Thin brass stencils – "TRIDENT" & "NEUTRONS4SALE"

Ta + poly line pair gauge 0.1" & smaller

Polyethylene step wedge – 6 steps

Brass valve, bolt heads, stainless steel cylinder containing nylon and W parts.

6.25 cm Al plate

2.5 cm Al plate

Polyethylene penetrameter with holes and partial holes

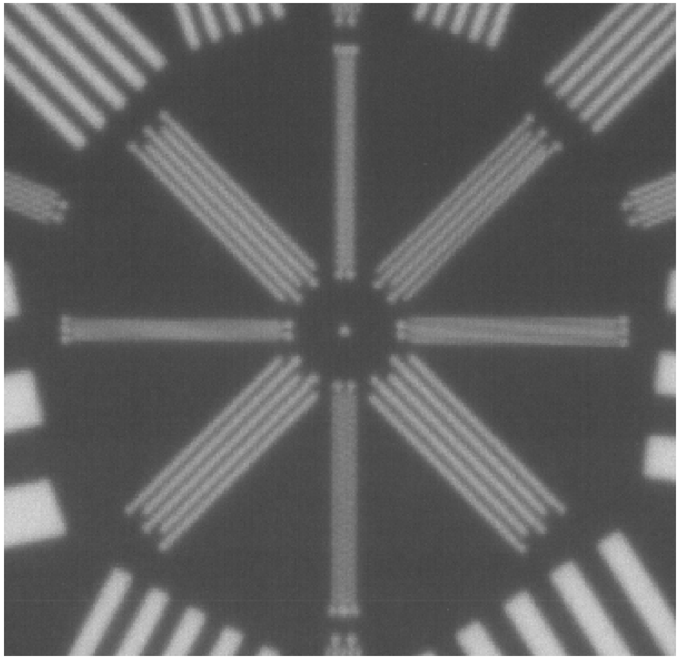
Steel and polyethylene phantom with "teeth"

W wedge 5 cm at base

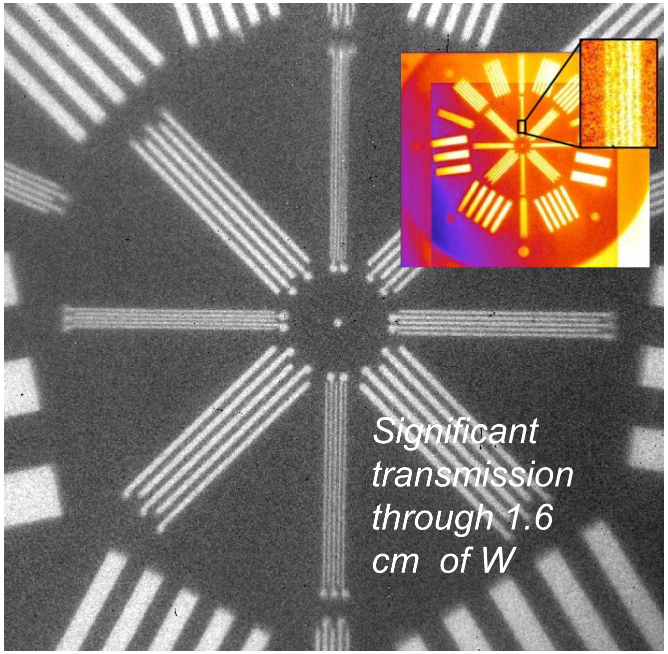
Results from last TRIDENT Campaign

Hard X-ray imaging (protons on W instead of deuterons on Be)

Kaleidoscope Target Comparison: DARHT vs. Trident
(DARHT: Dual-Axis Radiographic Hydrodynamic Test Facility)



DARHT Axis 1, 19mm Cathode,
~750μm source size



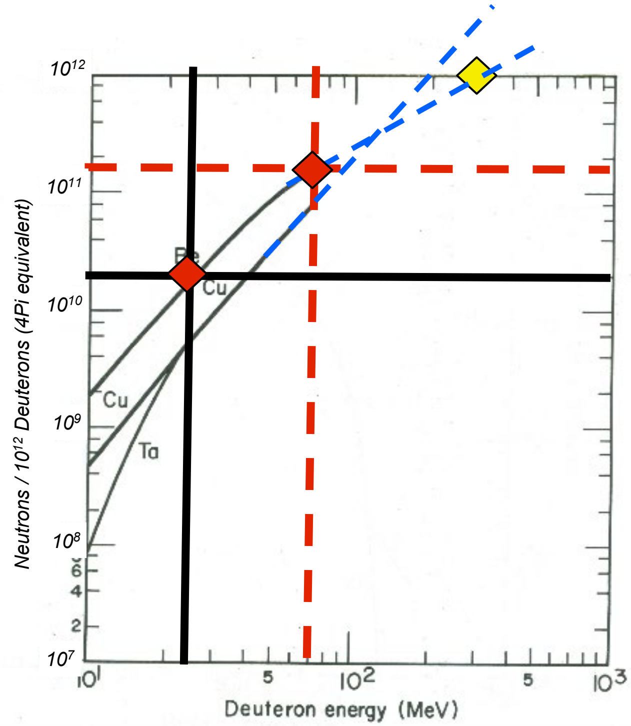
Significant transmission through 1.6 cm of W

TRIDENT (raw image)
<125μm source size (determination limited by detector pixel size)

Order of magnitude smaller source size for the laser (magnification) compared to optimized X-ray radiography facility with ultra-short pulse (no motion blur)!

Then TRIDENT was shutdown…

What are the prospects if deuteron energy increases?



Using BOA:
10^{12} deuterons @ 20 MeV
yield is consistent with data from 1975

Second campaign: Higher energies and higher D_2 resulted in more than 10^{11} neutrons (4Pi equivalent)
@ 70 MeV and up to energies of 200 MeV

The forward D_2 breakup is already comparable to 2×10^{11} n/pulse (in 4Pi)

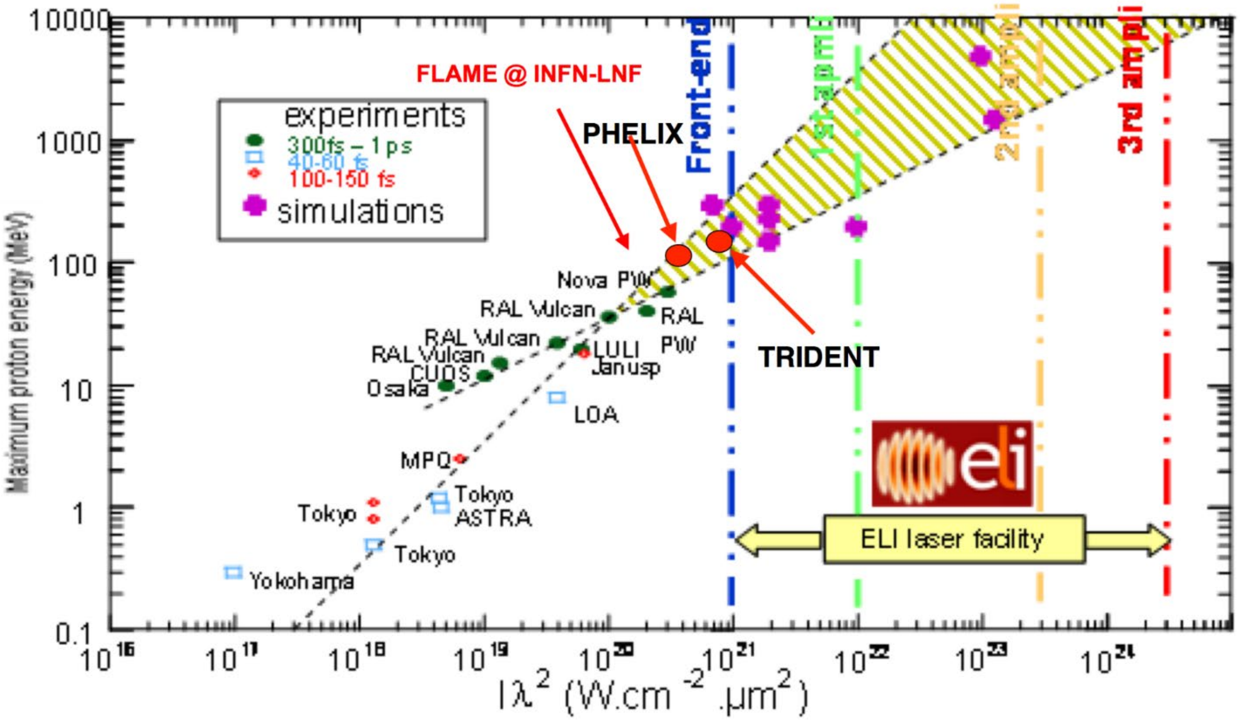
Using BOA and novel Targets (cryo) VPIC indicate 200 MeV/u ...

Changing to Ta or Cu converter reduces safety hazards on the converter

@ 10 Hz: 1 kW HESP laser, diode pumped,
20 kW electrical input > 10^{13} n/s possible (majority reaches moderator)

Cross-section for neutron production increases better than linear with deuteron energy
⇒ next generation lasers will produce more neutrons!

What about state-of-the-art lasers?



Once proton energies sufficient for spallation are reached, one could choose to produce ~20 n/p (but isotropic and with radioactive target inventory)

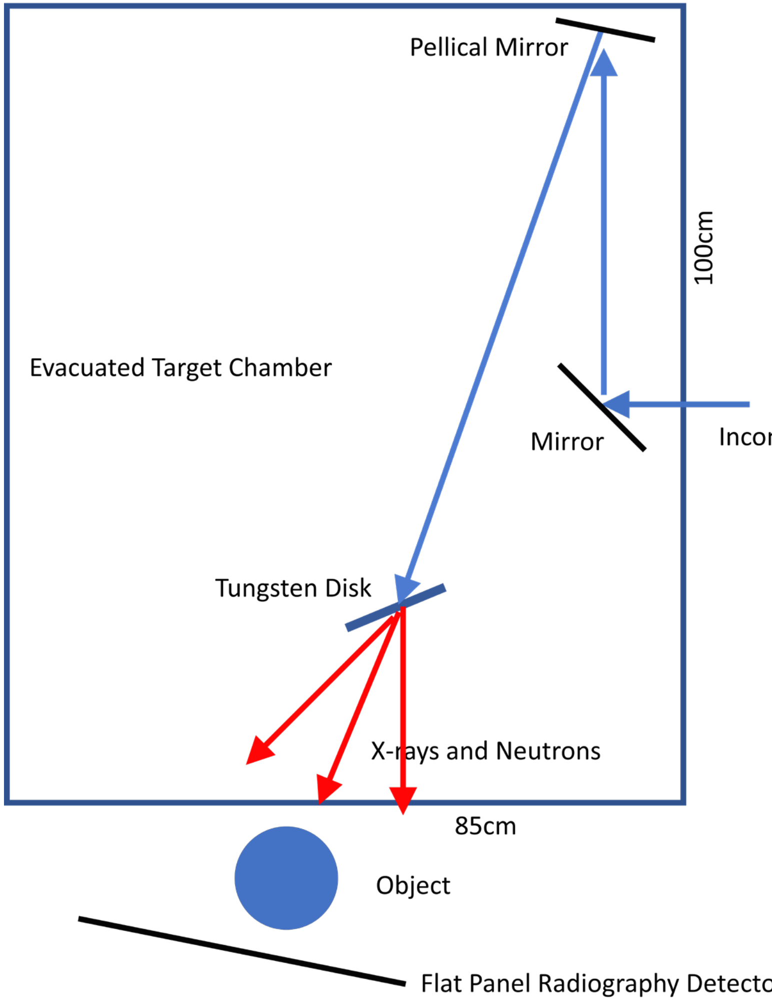
Or do pRAD…

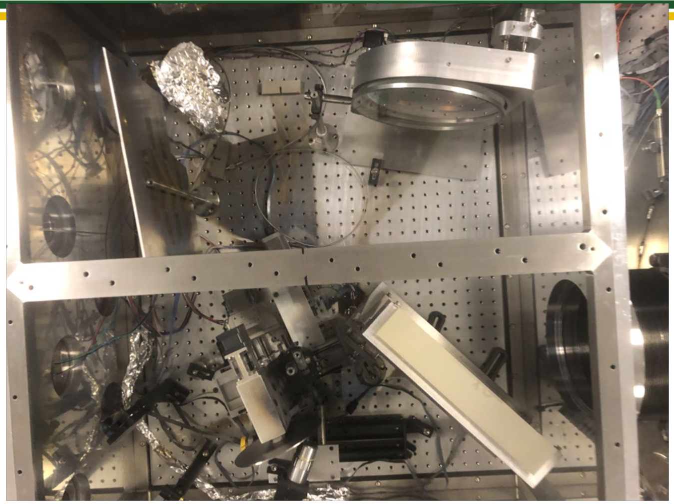
European Extreme Light Infrastructure (ELI) will allow pulsed proton acceleration comparable to current linacs used for large-scale neutron production
(ELI Prague total budget: € 278 million for several lasers, buildings, labs etc.)

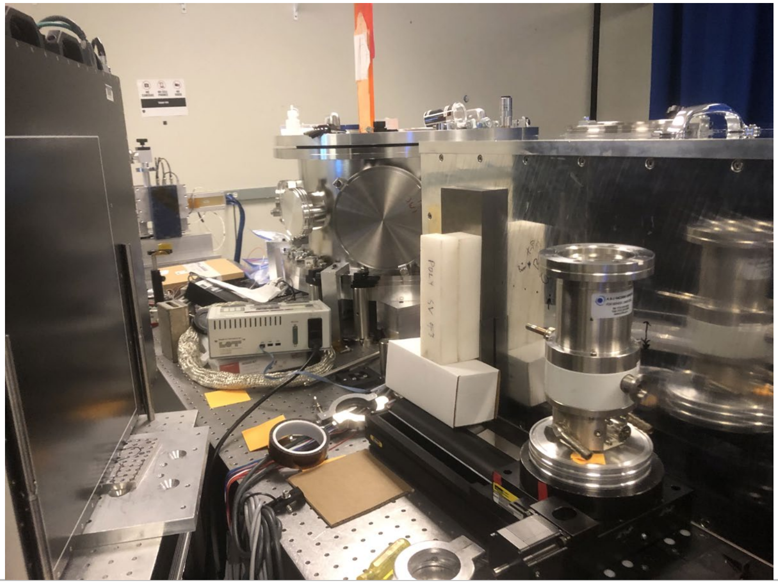
Recent results from Fort Collins

- 25J laser pulses at up to 3.3 Hz (burst mode, short time) or 1 Hz or less for hours
- Limiting factor for laser repetition rate is cooling of optics
- Goal of the beam time: Explore X-ray source size smaller than conventional X-ray sources for radiography applications
- X-rays produced by sending laser pulses on 1 to 3 mm thick tungsten disks ⇒ Bremsstrahlung
- Some Bremsstrahlung X-rays are enough high in energy to produce photo-neutrons
- Brought neutron detectors to characterize source
- Uneven surface of tungsten disks (micrometers) requires pre-scan to adjust laser focus to maximize yield
- Home-made motion control (alignment, rotation etc.)

Setup at Colorado State University

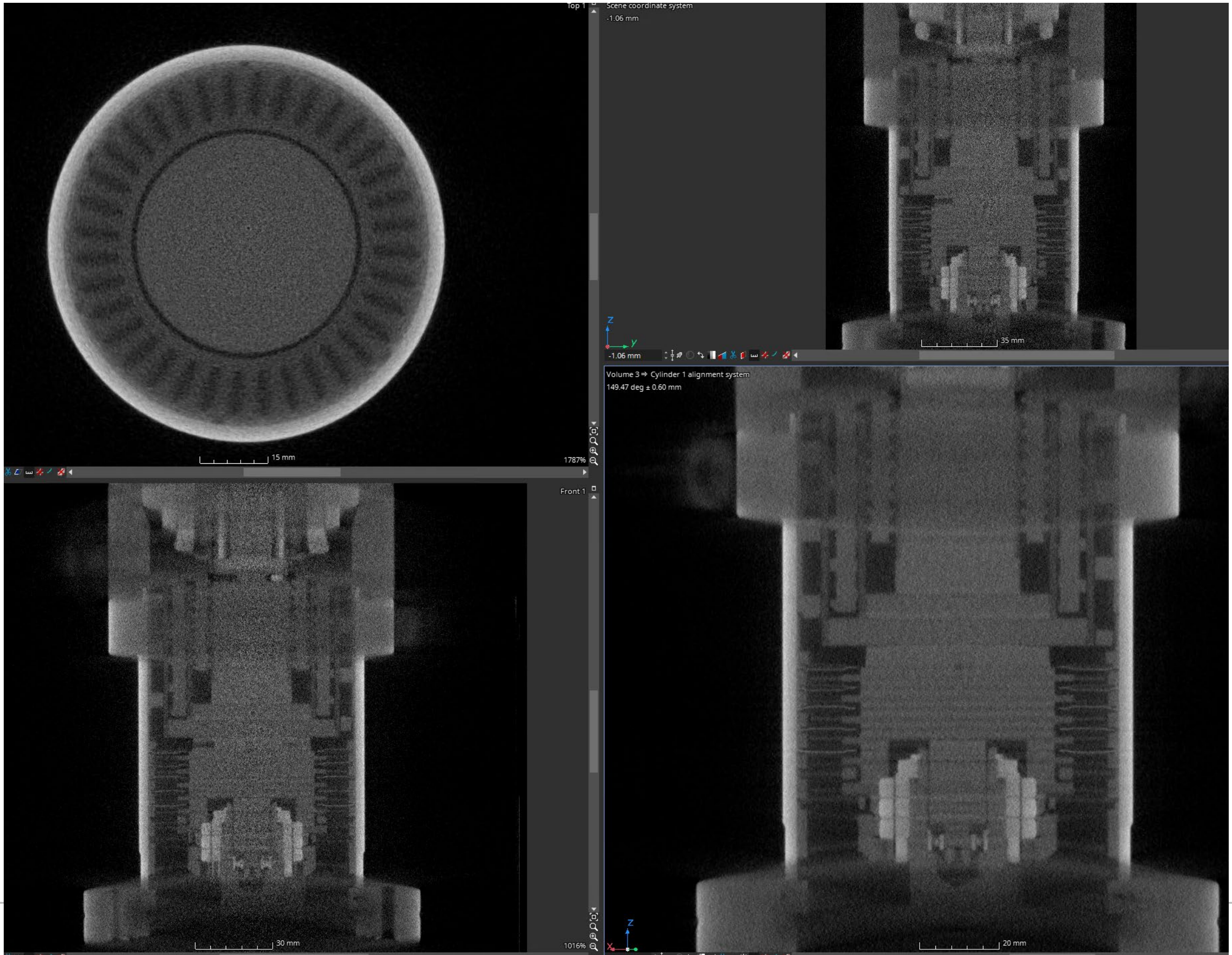






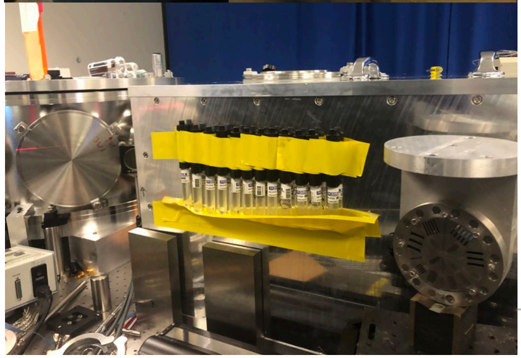
X-ray radiography

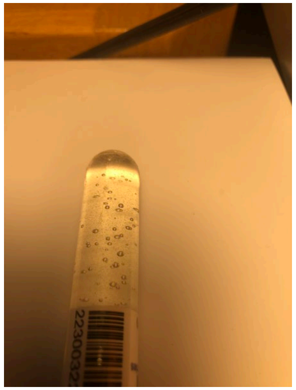
- X-ray CT reconstruction of turbo pump
- ~1000 single shots
- Small source size provides great magnification



Bubble Chamber Characterization

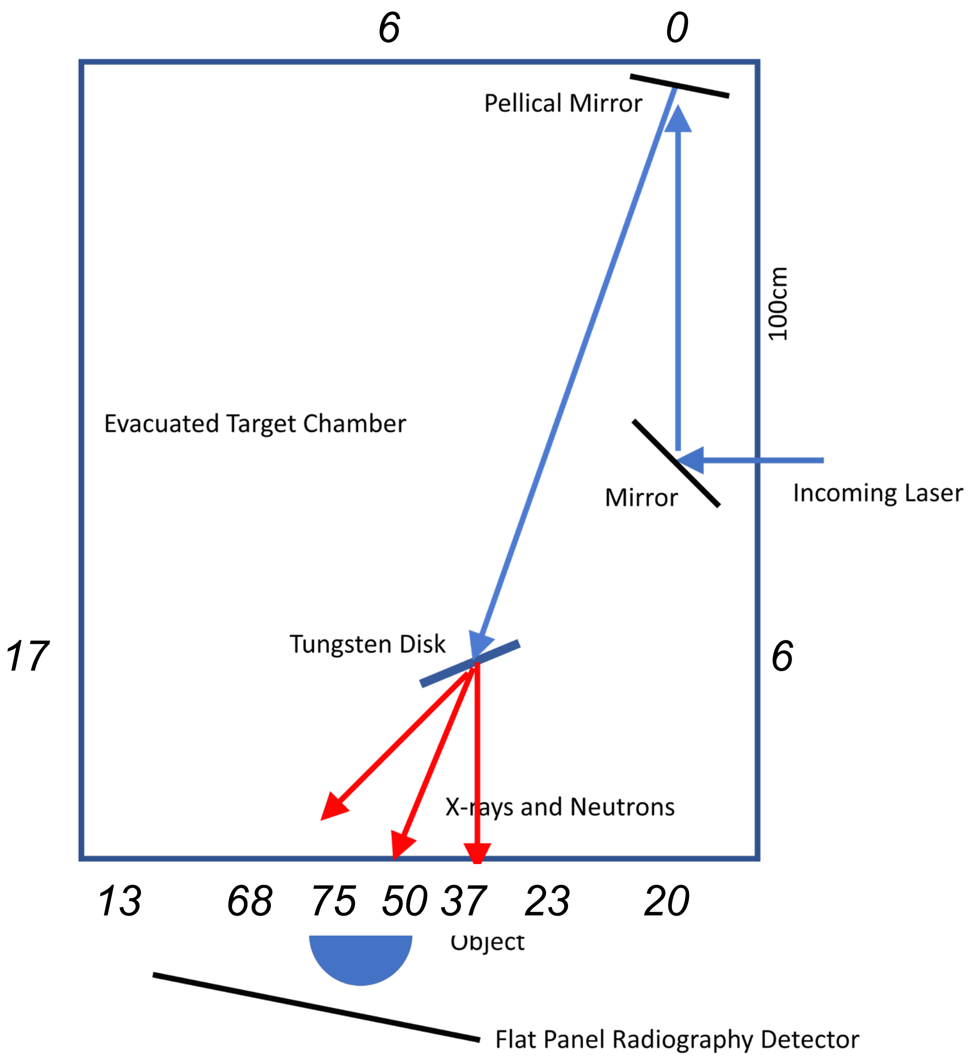
- Bubble chambers ~uniform sensitivity for neutrons between 0.3 and 35 MeV ⇒ neutrons as produced, not thermal neutrons
- Number of bubbles proportional to dose
- Dose ~proportional to number of neutrons
- Normalize by solid angle (distance, chamber dimensions)

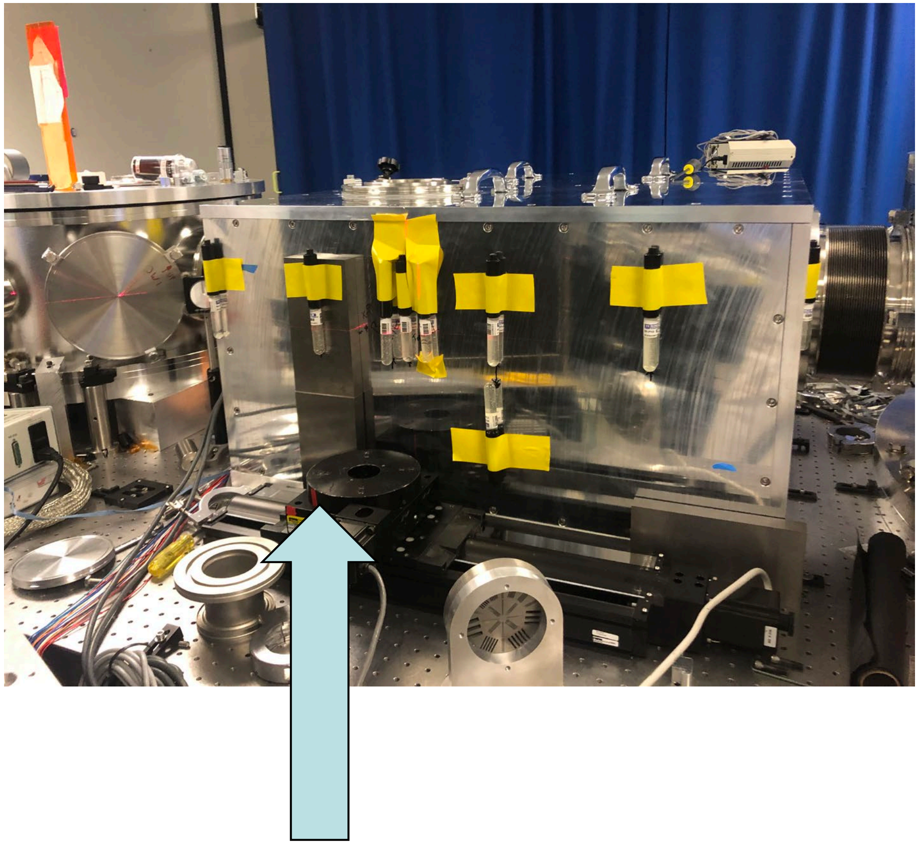




Bubble Chambers Results #1

Bubbles after 10 laser pulses on 3mm W disk

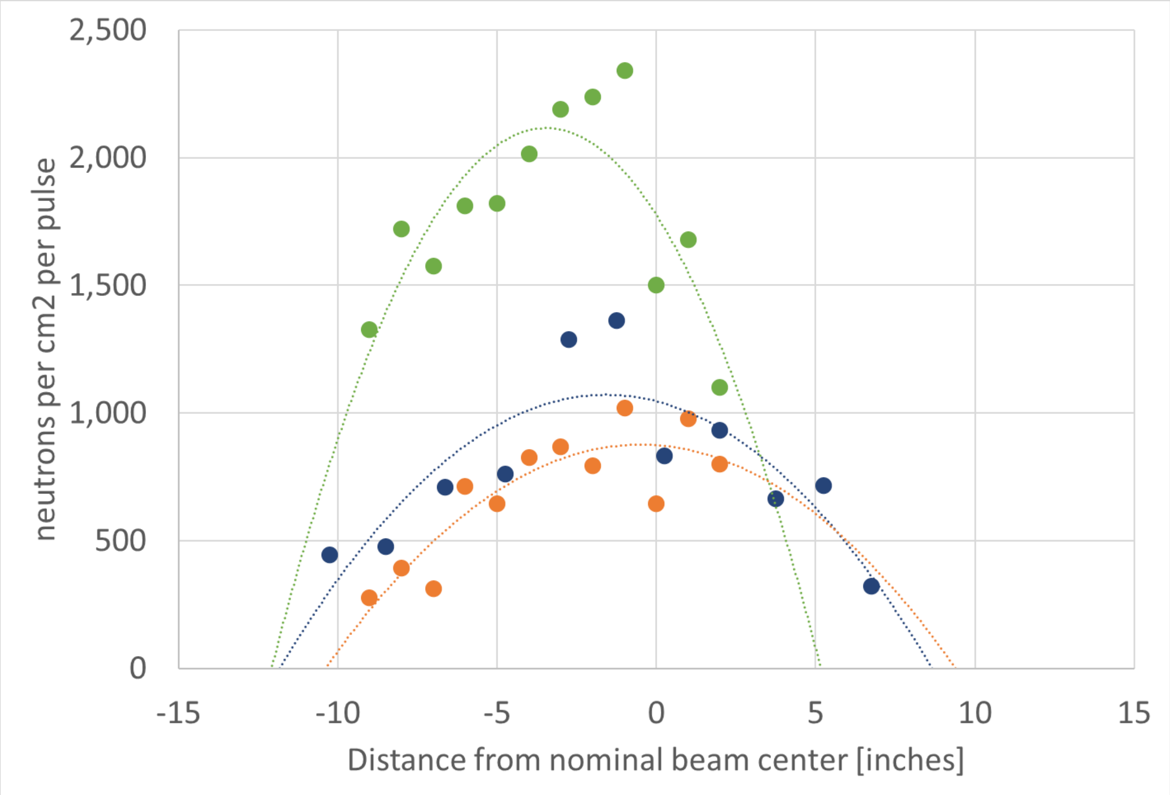


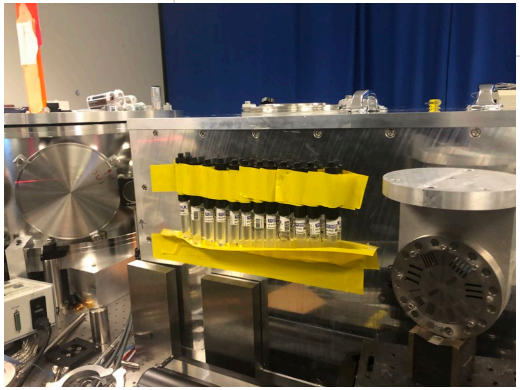


1" thick tungsten to shield X-ray radiography flat panel
⇒ secondary target?

Bubble Chambers Results #2

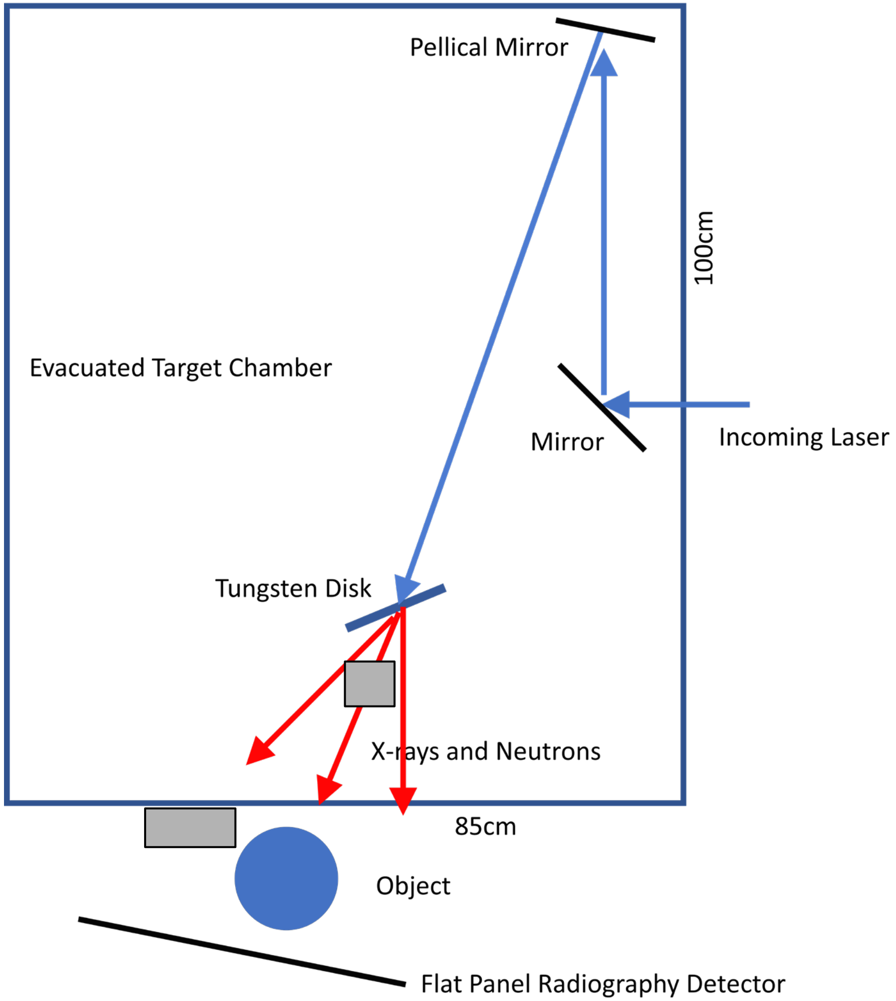
- **1mm tungsten target produces ~twice as many neutrons as 2mm and 3mm**
- **Off-center shift observed (no W block)**
- **Total number consistent with ~1 million neutrons per pulse**

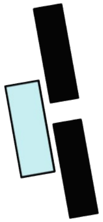




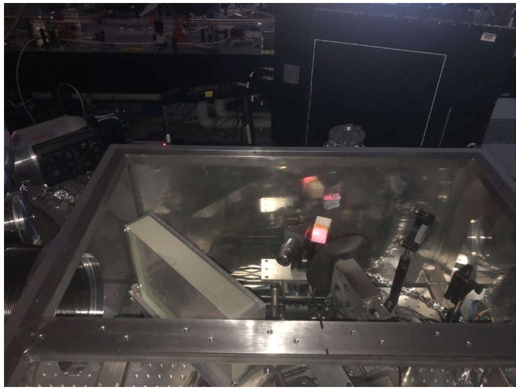
TOF Imaging Detector

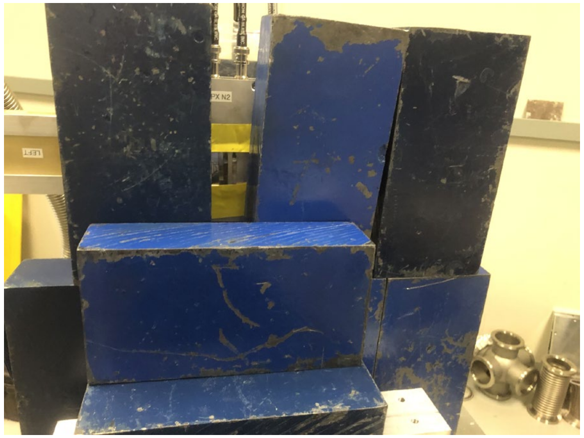
- MCP & TimePix chip
- 512x512 pixels, 28x28mm^2
- Positioned ~70° off from direct beam, viewing moderator
- Moderator either 1x1x2” poly piece inside or 1x8x2” poly piece outside the chamber
- Distance moderator to detector 2.15m or 1.87m (EMP, gammas)
- Detector shielded by Pb bricks
- FOV fully covered with 0.1mm Au foil (stops gammas, potential resonance)
- FOV partially covered with Indium (absorber)
- Detected ~10 events per pulse with TOF consistent with moderated neutrons
- No moderator ⇒ no events
- Total events also consistent with ~1M neutrons produced per pulse

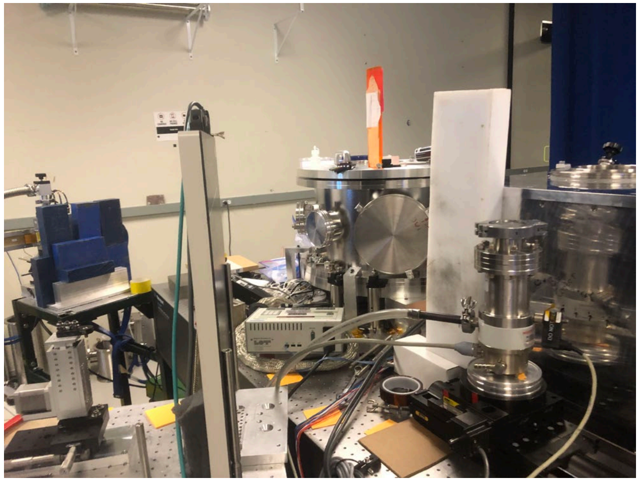


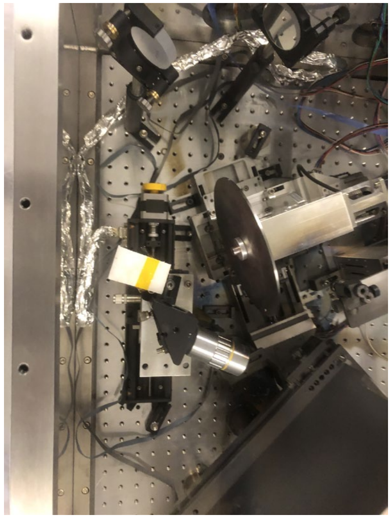


Moderated Neutrons



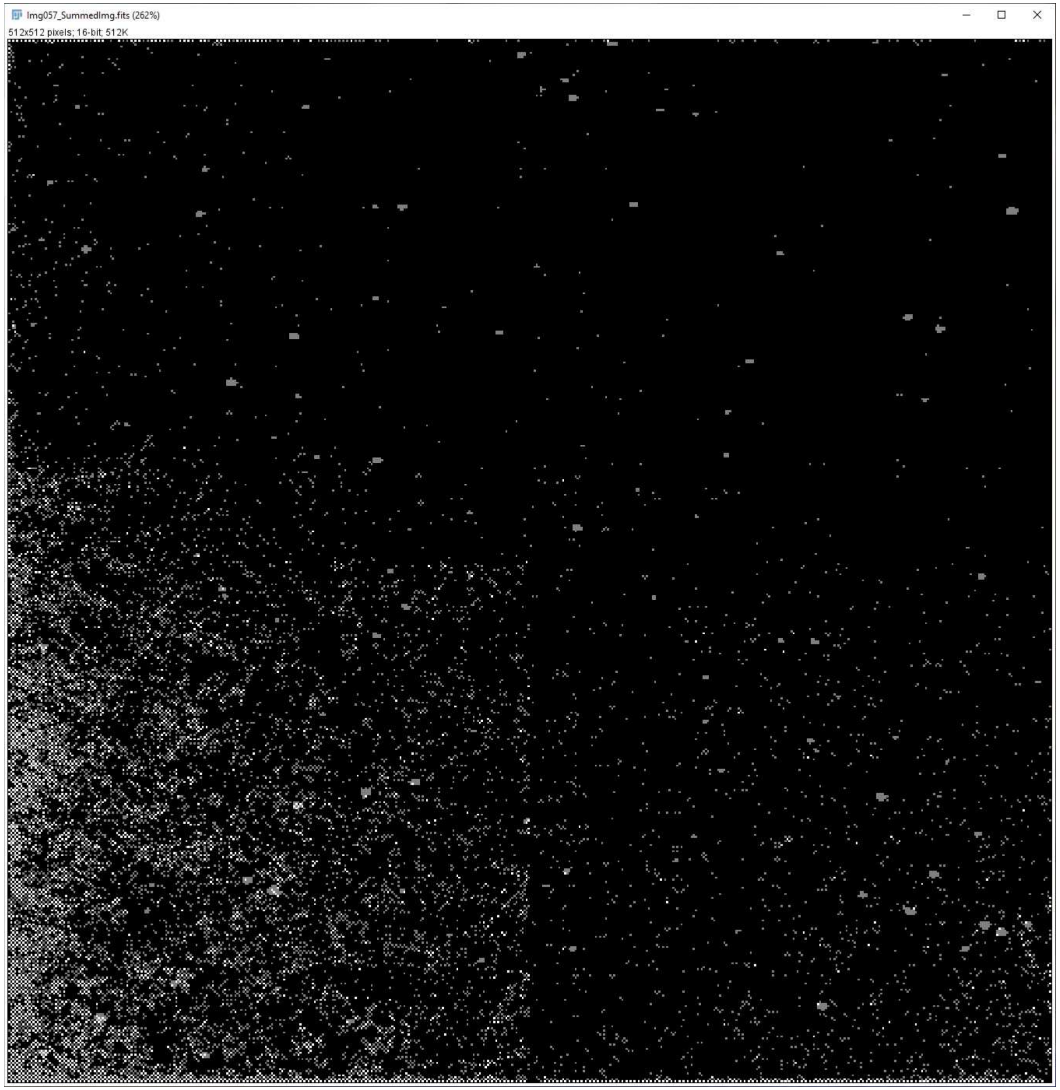






TOF Results

- **Few events recorded (small solid angle, only 100 shots possible) show attenuation where Indium was located (right side)**



Next step: D_2O microjet

- D_2O microjets provide deuterons for pitcher/catcher
  ⇒ Deuteron break-up
  ⇒ Should be higher yield than photoneutrons
- Entire March at CSU planned for SLAC team
- If bubble chamber results are promising, LANL, UC Berkeley, and TUM folks may flock to Fort Collins last week of March
- Try to get 3×24 10” He-3 tubes, MCP TimePix and Losko camera running if one or two orders of magnitude more neutrons are available

High-repetition-rate, multi-MeV deuteron acceleration from converging heavy water microjets at laser intensities of 10^{21} W/cm^2

Cite as: Appl. Phys. Lett. **121**, 074104 (2022); doi: 10.1063/5.0098973
Submitted: 13 May 2022 · Accepted: 27 July 2022 ·
Published Online: 16 August 2022

F. Treffert,[1,2,a)] C. B. Curry,[1,3] H.-G. J. Chou,[1,4] C. J. Crissman,[1,5] D. P. DePonte,[1] F. Fiuza,[1] G. D. Glenn,[1,6] R. C. Hollinger,[7] R. Nedbailo,[7] J. Park,[7] C. Schoenwaelder,[1,8] H. Song,[7,b)] S. Wang,[7] J. J. Rocca,[7,9] M. Roth,[2] S. H. Glenzer,[1] and M. Gauthier[1,a)]

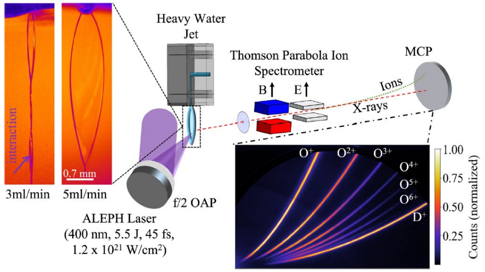
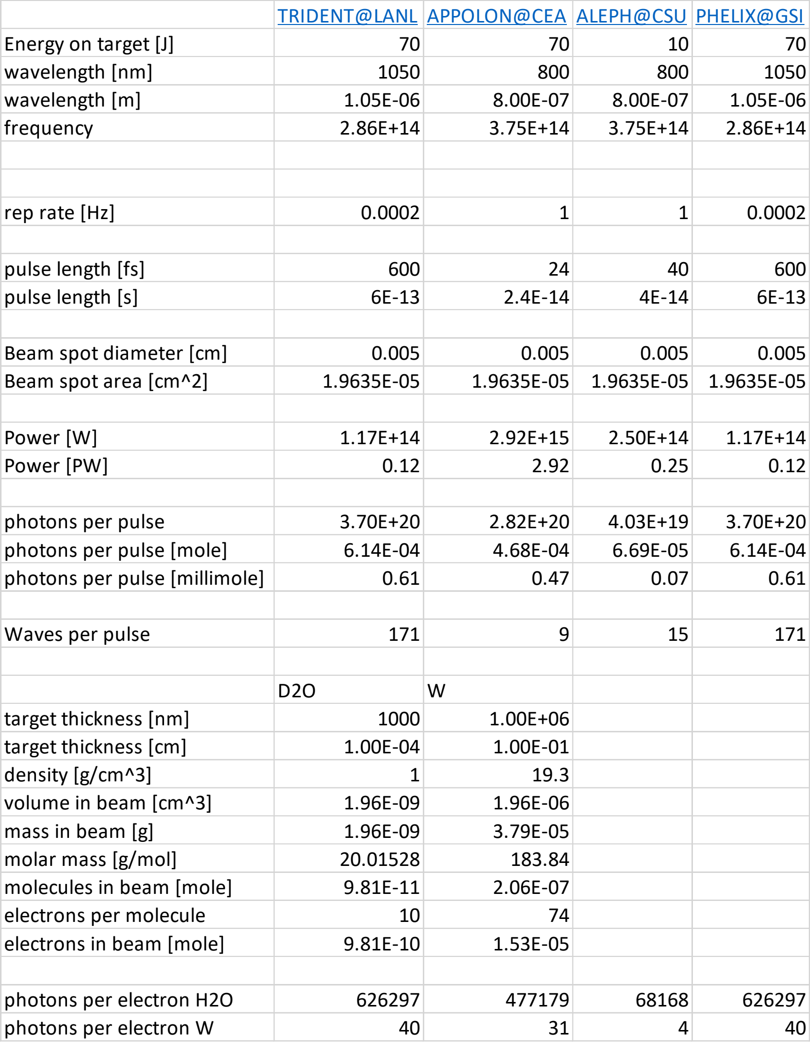


FIG. 1. Simplified schematic of the experimental setup for 0.5 Hz deuteron acceleration from a heavy water jet. A Thomson parabola equipped with a high repetition-rate compatible microchannel plate (MCP) detector was positioned in the laser forward direction. The sum of 60 consecutively recorded raw MCP images for a laser energy of 5.5 J (120 TW) is shown in the bottom right corner with the individual traces identified for different isotopes and the counts normalized to the maximum detected value.

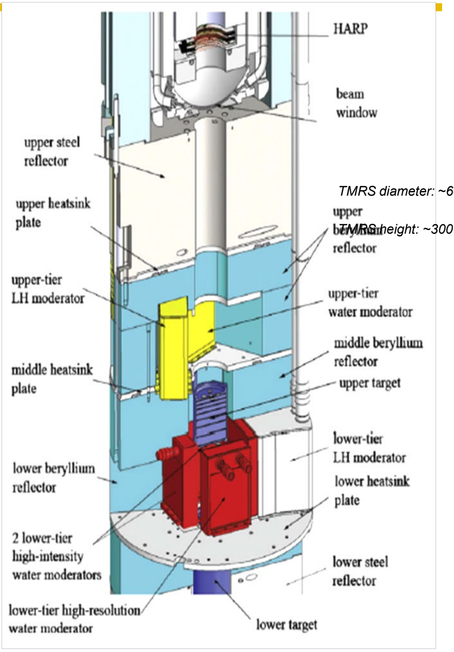
Comparison of laser facilities

- **Key parameters for lasers used for particle acceleration:**
  - Laser energy ⇒ number of photons
  - Wavelength
  - Pulse duration
  - Repetition rate
  - ??
- **What are optimal parameter for a laser-driven neutron source?**
- **How do these parameters depend on the target & reaction used for neutron generation?**



	TRIDENT@LANL	APPOLON@CEA	ALEPH@CSU	PHELIX@GSI
Energy on target [J]	70	70	10	70
wavelength [nm]	1050	800	800	1050
wavelength [m]	1.05E-06	8.00E-07	8.00E-07	1.05E-06
frequency	2.86E+14	3.75E+14	3.75E+14	2.86E+14
rep rate [Hz]	0.0002	1	1	0.0002
pulse length [fs]	600	24	40	600
pulse length [s]	6E-13	2.4E-14	4E-14	6E-13
Beam spot diameter [cm]	0.005	0.005	0.005	0.005
Beam spot area [cm^2]	1.9635E-05	1.9635E-05	1.9635E-05	1.9635E-05
Power [W]	1.17E+14	2.92E+15	2.50E+14	1.17E+14
Power [PW]	0.12	2.92	0.25	0.12
photons per pulse	3.70E+20	2.82E+20	4.03E+19	3.70E+20
photons per pulse [mole]	6.14E-04	4.68E-04	6.69E-05	6.14E-04
photons per pulse [millimole]	0.61	0.47	0.07	0.61
Waves per pulse	171	9	15	171
	D2O	W		
target thickness [nm]	1000	1.00E+06		
target thickness [cm]	1.00E-04	1.00E-01		
density [g/cm^3]	1	19.3		
volume in beam [cm^3]	1.96E-09	1.96E-06		
mass in beam [g]	1.96E-09	3.79E-05		
molar mass [g/mol]	20.01528	183.84		
molecules in beam [mole]	9.81E-11	2.06E-07		
electrons per molecule	10	74		
electrons in beam [mole]	9.81E-10	1.53E-05		
photons per electron H2O	626297	477179	68168	626297
photons per electron W	40	31	4	40

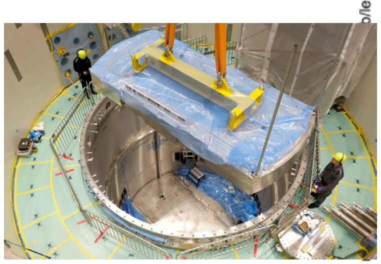
How far away are we from Laser-LANSCE?

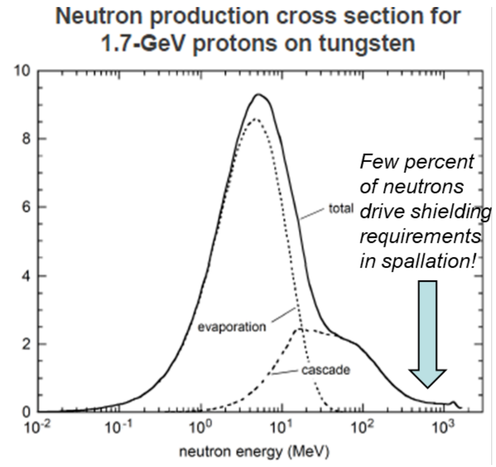


- ~10^{10} n/pulse achieved @ TRIDENT
  (March & July 2016, 70J output energy ⇒ 20 MeV deuterons
  70J/600 fs=0.1 PW)
- Neutrons pre-dominantly forward
  ⇒ majority reaches moderator
  ⇒ ~10^{10} moderated n/pulse (~1 ns pre-moderation pulse width)
- LANSCE:
  ⇒ 100 μA proton current @ 20 Hz, 800 MeV
  ⇒ ~3×10^{13} p/pulse
  ⇒ ~20 n/spallation process
  ⇒ ~6×10^{14} n/pulse, but isotropic, out of a 10cm ∅, 20cm target)
  ⇒ ~1×10^{13} moderated n/pulse (~270 ns pre-moderation pulse width,
  ~2% of neutrons cross moderator surface)
- TRIDENT – LANSCE: $10^{10} : 1\times10^{13}$
- Laser system, deuteron & neutron target optimizations: Factor 10 ⇒ 10^{11}
- kJ laser: Breakup cross-section predicts factor ~20 ⇒ 2×10^{12}
- 0.2×10^{13} moderated n/pulse feasible (have 5 lasers?)
- Smallest source-to-sample distance at LANSCE: ~6 m
- Source-to-sample distance for laser-driven source: <2 m ($1/L^2$ ~factor 10)
  ⇒ setup for e.g. resonance imaging/NRTA/mini-HIPPO possible!

Cost Drivers for Spallation Sources

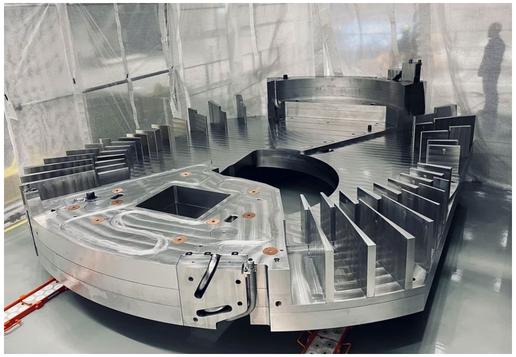
- **Linear accelerator**
  - Lots of energy used to keep protons together over ~km distance
  - Proton storage ring needed to compress
- **Target system**
  - Isotope inventory needs to be monitored
  - Complex, heavy & expensive system in itself
- **Target building**
  - Shielding must be designed for neutrons of energy close to proton energy
  - Expensive, heavy, drives closest sample position to >15m from source (1/L^2 bites…)
  - Significant amounts of funding to manage sagging of floor in the building to keep beamlines aligned
  - Huge chunk of cost of source
- **LDNS would not need any of that**

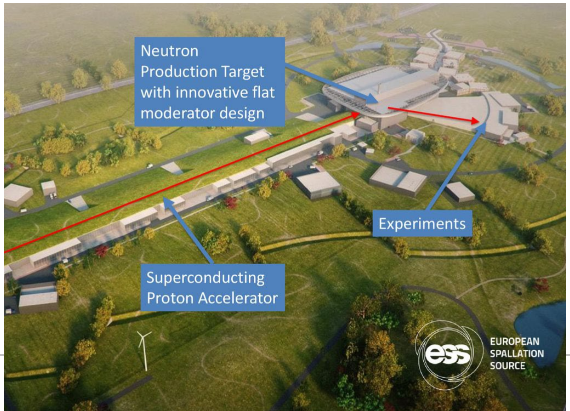


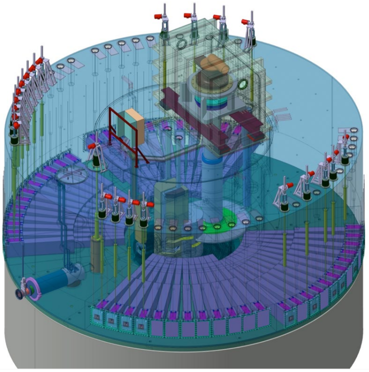


Neutron production cross section for 1.7-GeV protons on tungsten

Few percent of neutrons drive shielding requirements in spallation!

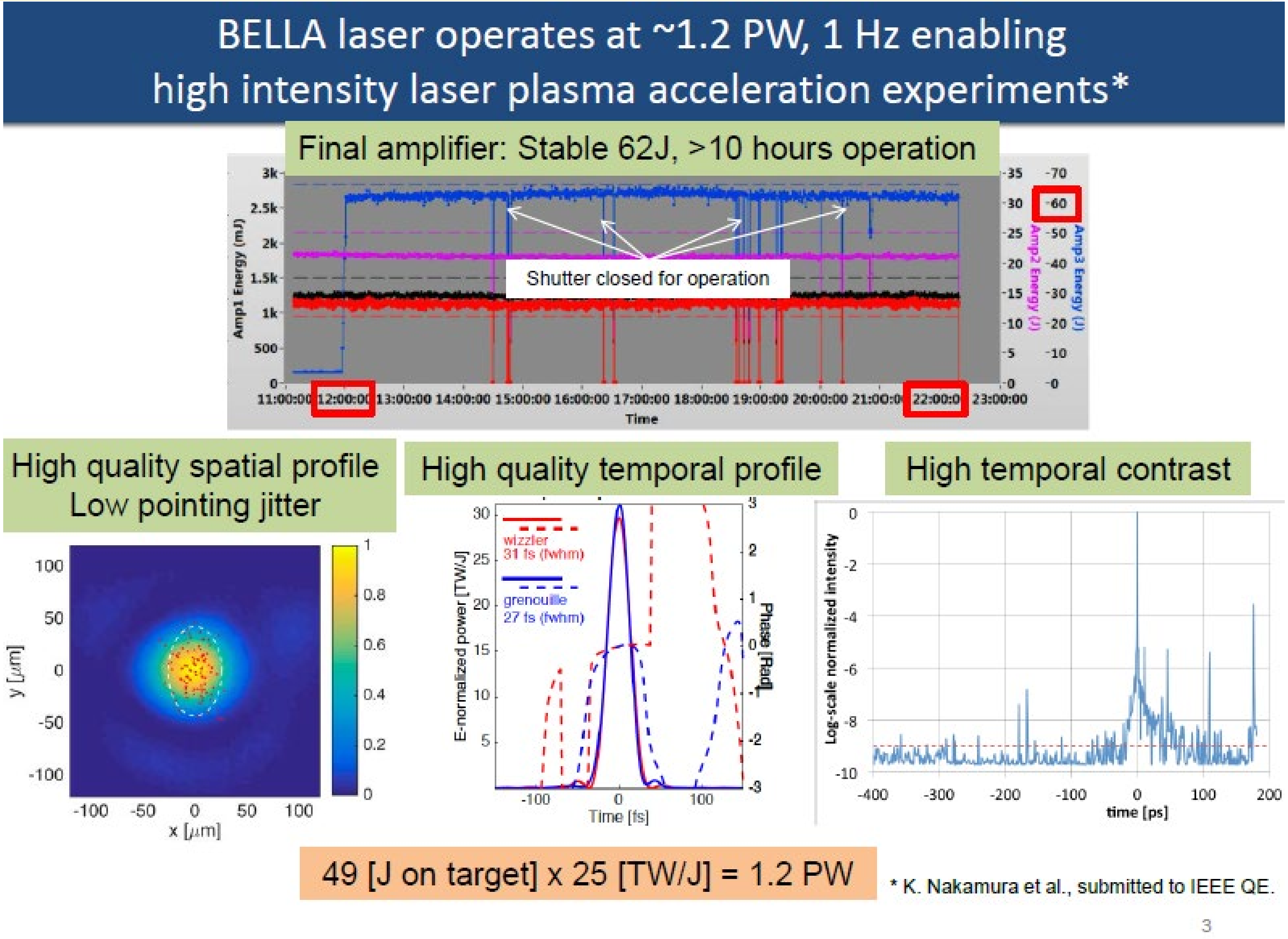






Picture credit: J. Womersley ESS slides, August 2018 & ESS website "How it works

Lasers for useful neutron sources exist today!



BELLA laser operates at ~1.2 PW, 1 Hz enabling high intensity laser plasma acceleration experiments*

Final amplifier: Stable 62J, >10 hours operation

Shutter closed for operation

High quality spatial profile
Low pointing jitter

High quality temporal profile

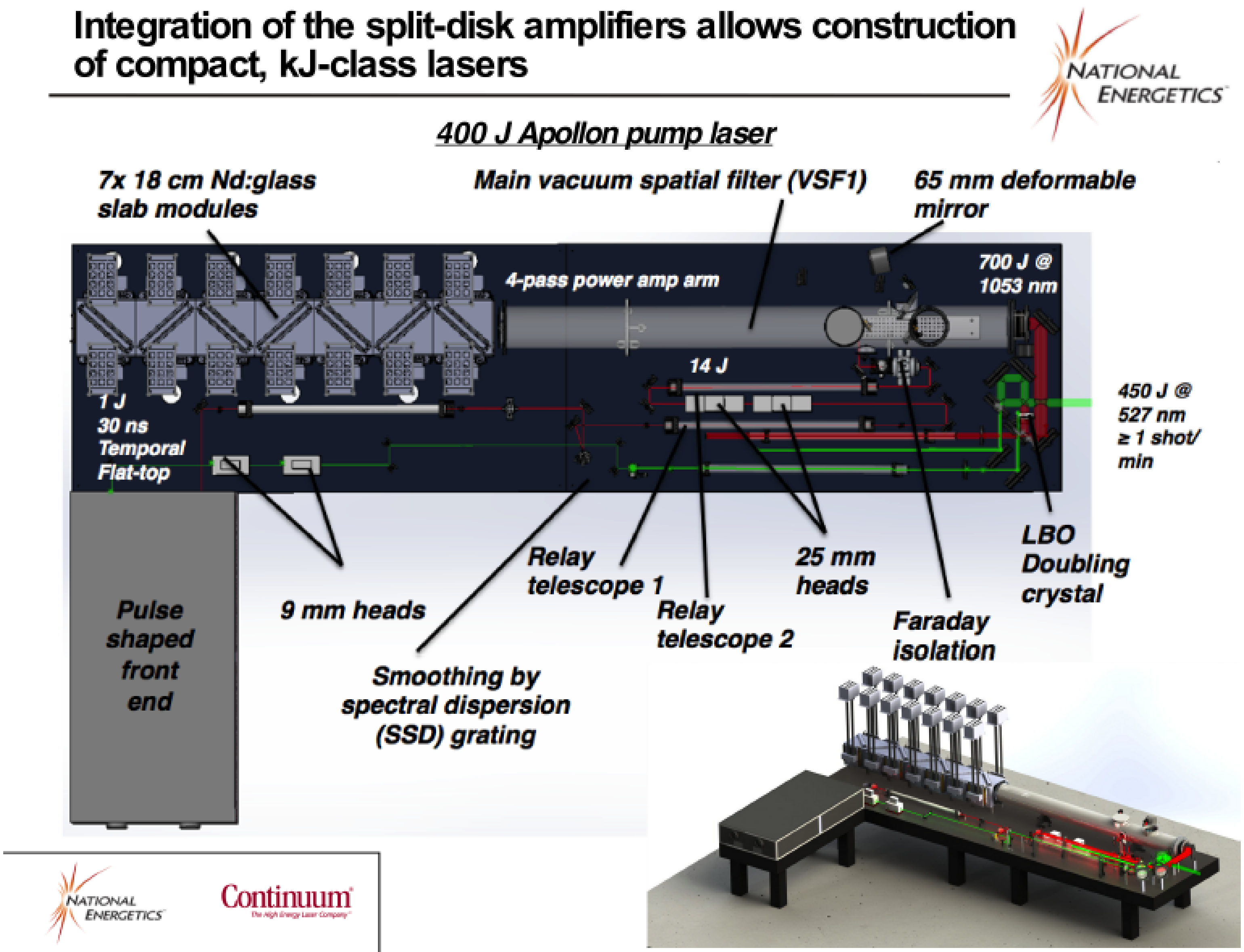
High temporal contrast

49 [J on target] x 25 [TW/J] = 1.2 PW

* K. Nakamura et al., submitted to IEEE QE.

Slide courtesy of T. Schenkel/LBL from
“Workshop on laser-driven neutron sources”, Vogel et al., Neutron News ***29*** *(2018)*

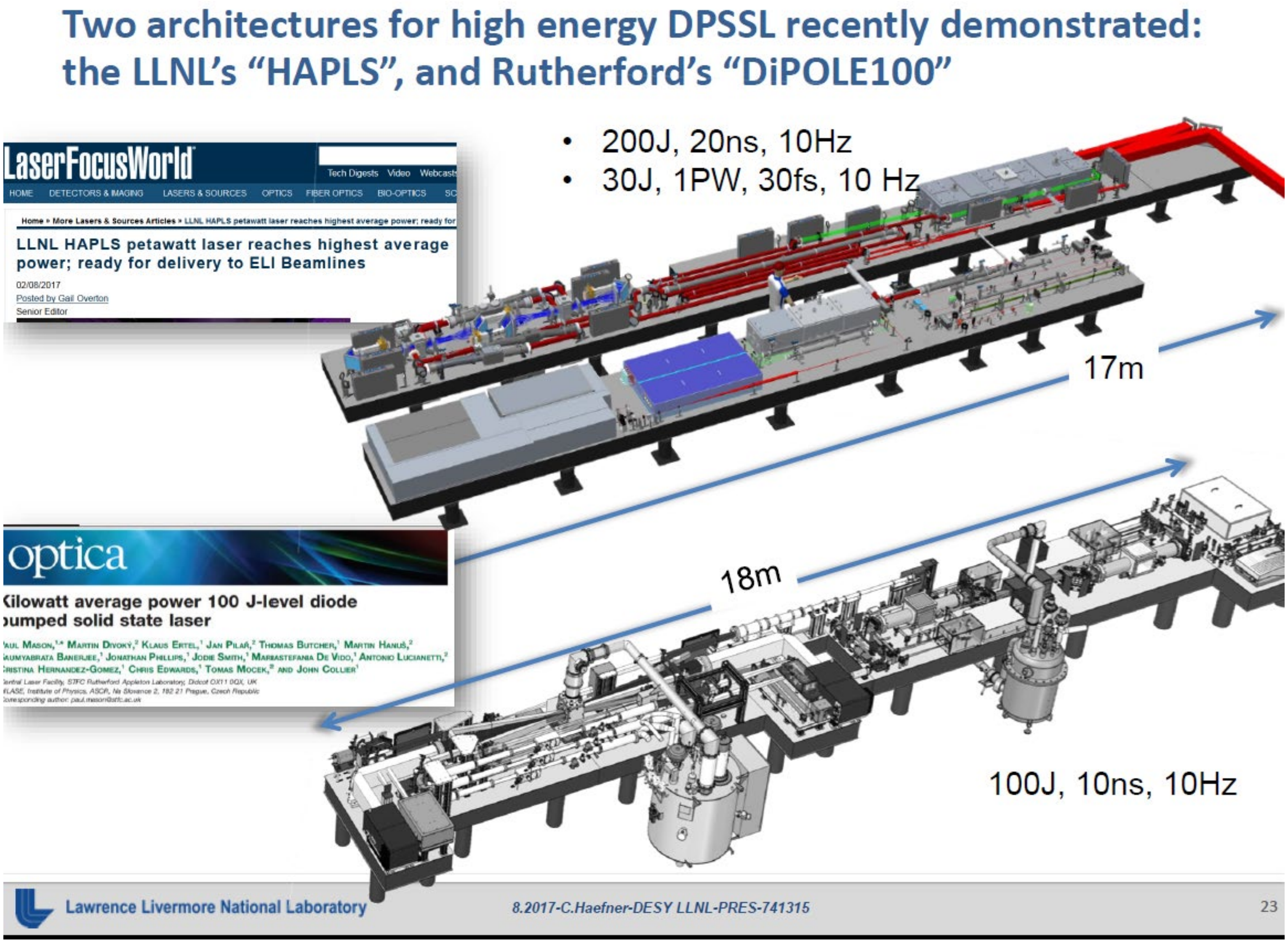
Lasers for useful neutron sources exist today!



Integration of the split-disk amplifiers allows construction of compact, kJ-class lasers

Slide courtesy of T. Dittmire/National Energetics, from “Workshop on laser-driven neutron sources”, Vogel et al., Neutron News **29** (2018)

Lasers for useful neutron sources exist today!



Two architectures for high energy DPSSL recently demonstrated: the LLNL's "HAPLS", and Rutherford's "DiPOLE100"

- 200J, 20ns, 10Hz
- 30J, 1PW, 30fs, 10 Hz

Home » More Lasers & Sources Articles » LLNL HAPLS petawatt laser reaches highest average power; ready for

LLNL HAPLS petawatt laser reaches highest average power; ready for delivery to ELI Beamlines

02/08/2017
Posted by Gail Overton
Senior Editor

Kilowatt average power 100 J-level diode pumped solid state laser

Paul Mason,[1,*] Martin Divoký,[2] Klaus Ertel,[1] Jan Pilař,[2] Thomas Butcher,[1] Martin Hanuš,[2] Saumyabrata Banerjee,[1] Jonathan Phillips,[1] Jodie Smith,[1] Mariastefania De Vido,[1] Antonio Lucianetti,[2] Cristina Hernandez-Gomez,[1] Chris Edwards,[1] Tomas Mocek,[2] and John Collier[1]

Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot OX11 0QX, UK
HiLASE, Institute of Physics, ASCR, Na Slovance 2, 182 21 Prague, Czech Republic
Corresponding author: paul.mason@stfc.ac.uk

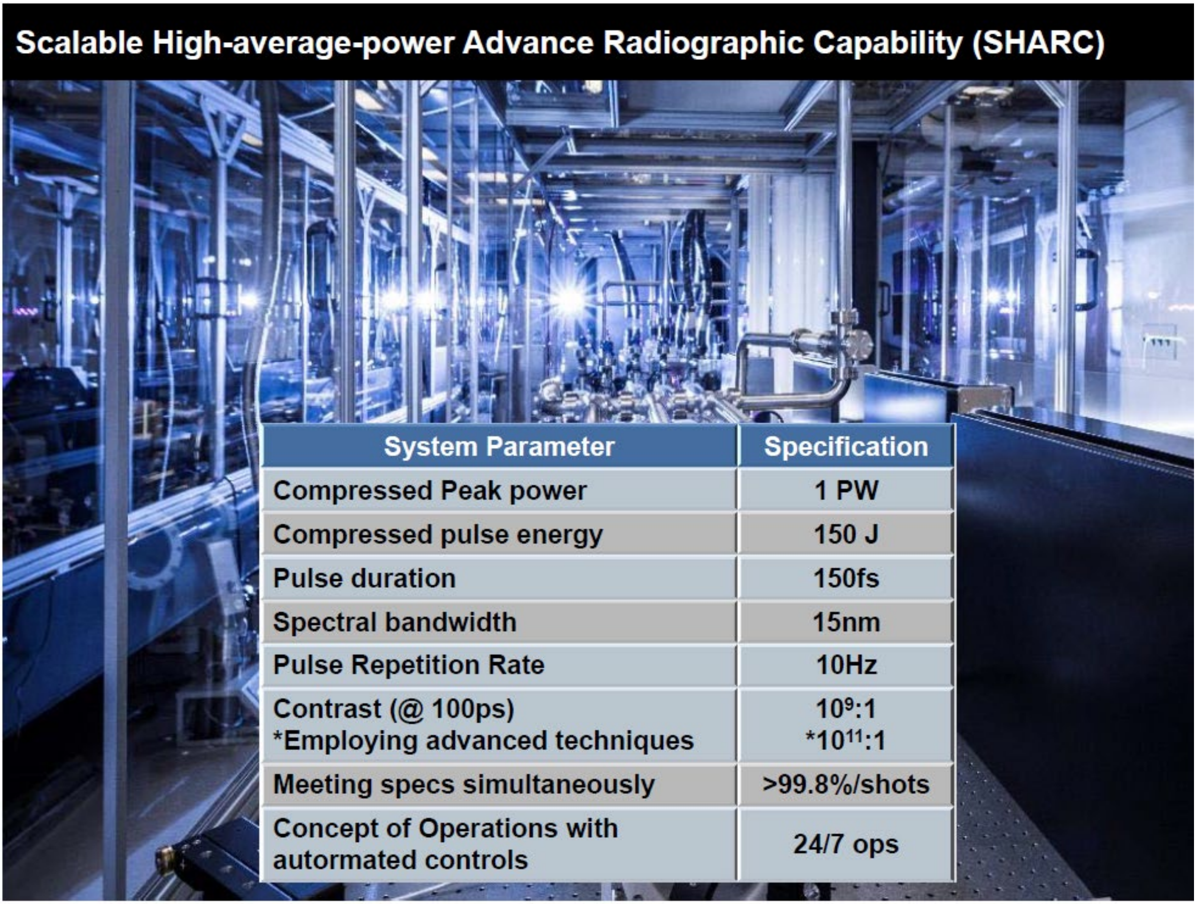
100J, 10ns, 10Hz

Lawrence Livermore National Laboratory 8.2017-C.Haefner-DESY LLNL-PRES-741315 23

Slide courtesy of C. Haefner/LLNL from
"Workshop on laser-driven neutron sources", Vogel et al., Neutron News ***29*** *(2018)*

Lasers for useful neutron sources exist today!

- LLNL's SHARC could be a workhorse to drive Laser-LANSCE
- Laser industry (Trumpf et al.) provides industrial (e.g. welding) and military lasers
  ⇒ reliability even in rugged environments proven
  ⇒ mobile pulsed neutron sources for characterization are conceivable ("LANSCE-on-a-truck")
  ⇒ Cost for laser diodes follows a Moore's Law, cost will continue to go down

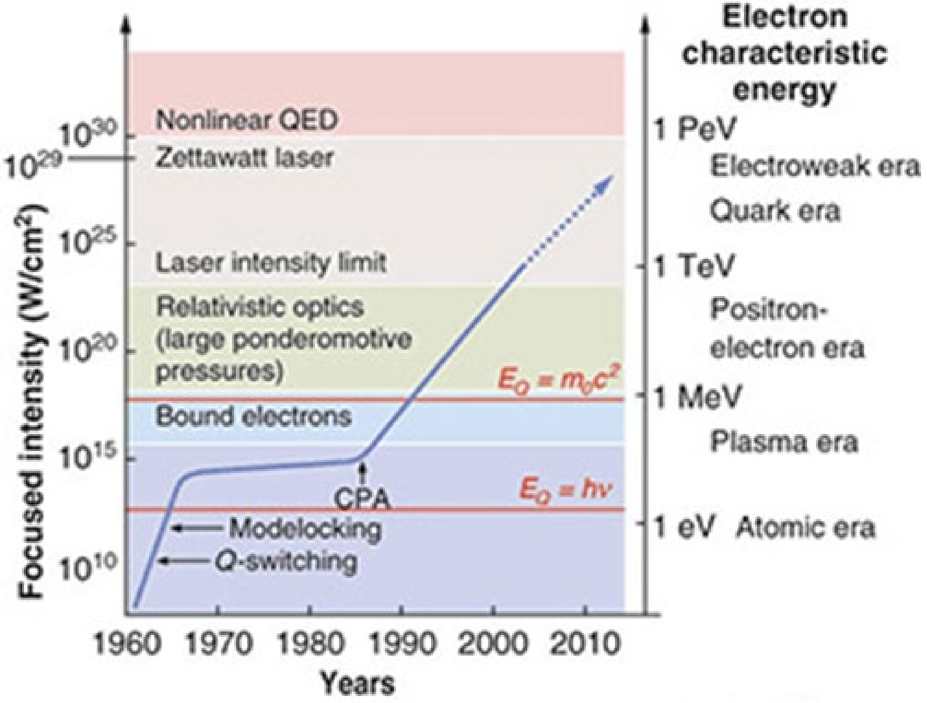


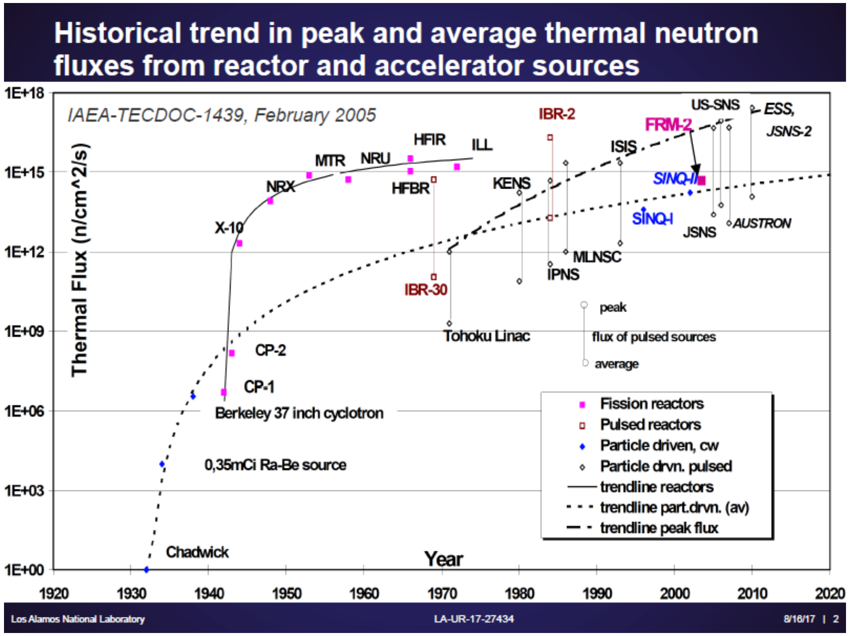
Scalable High-average-power Advance Radiographic Capability (SHARC)

System Parameter	Specification
Compressed Peak power	1 PW
Compressed pulse energy	150 J
Pulse duration	150fs
Spectral bandwidth	15nm
Pulse Repetition Rate	10Hz
Contrast (@ 100ps) *Employing advanced techniques	10^9:1 *10^{11}:1
Meeting specs simultaneously	>99.8%/shots
Concept of Operations with autormated controls	24/7 ops

Slide courtesy of C. Haefner/LLNL from
"Workshop on laser-driven neutron sources", Vogel et al., Neutron News ***29*** *(2018)*

Can lasers improve peak neutron flux?





Historical trend in peak and average thermal neutron fluxes from reactor and accelerator sources

Los Alamos National Laboratory LA-UR-17-27434 8/16/17 | 2

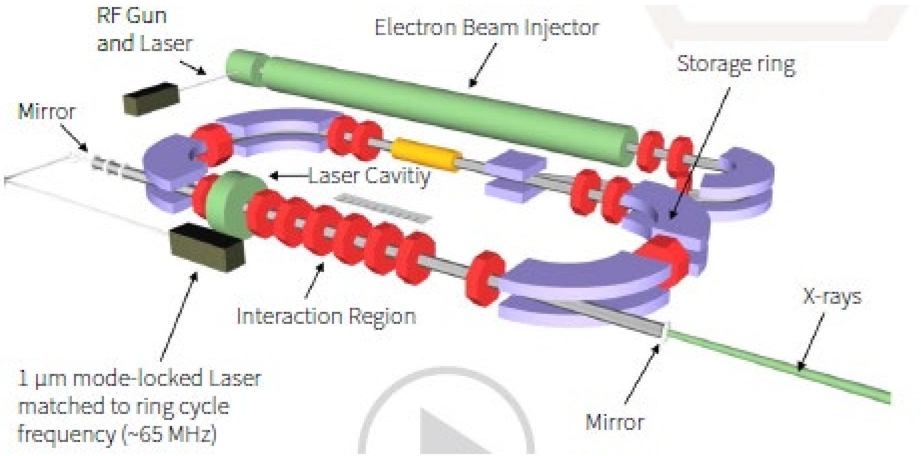
Cross-section for neutron production increases with deuteron energy
⇒ next generation lasers will produce more neutrons!

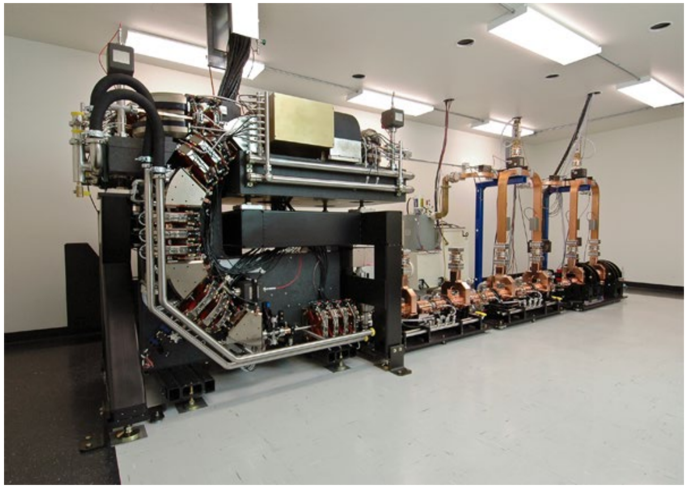
$1B user facility allows installation of multiple laser/target systems providing neutrons to the same moderator within a fraction of the ~1 μs moderation time (<1 ns initial pulse width)

Synchrotron Community is ahead (as usually): The Lyncean Compact Light Source

- ”A breakthrough in local, on-demand X-ray synchrotron light”
- Commercial provider: Lyncean Tech, Fremont, CA
- Undulator/wiggler replaced by laser ⇒ much smaller ring
- Energy 20 to 80 keV (similar to APS, DESY etc.)
- Total Flux (~4% BW) – 4mrad cone: up to 10^{11} ph/s
- Price: ~$11M, plus 5%/year for service/operation

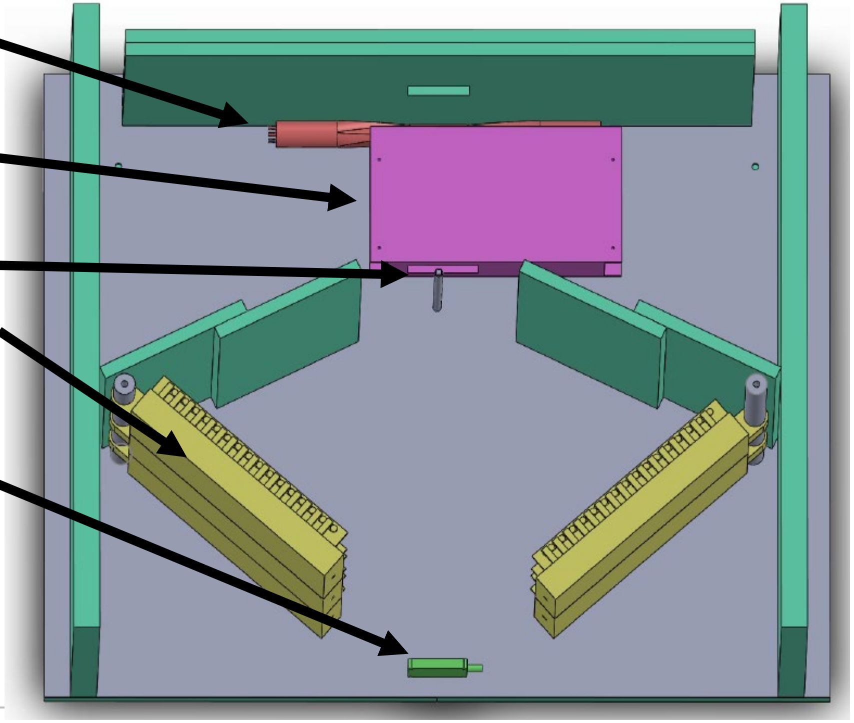
- CAN THERE BE A NEUTRON SOURCE NEXT?





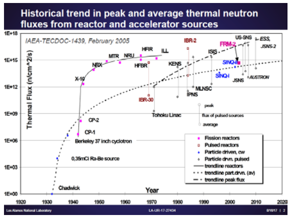
LANSCE-in-a-box

- ~1Hz pulsed laser beamtimes scheduled for LDNS
- Targets (films, D_2 cryo jets, liquid crystals) are developed
- Need suitable neutron diagnostics to characterize source and produce right demonstration data for potential funding agencies
- LANSCE-in-a-box combines
  - Dual PMT ^{6}Li scintillator (resonance spectroscopy)
  - MCP TOF imaging detector (energy resolved neutron imaging)
  - Scintillator screen, mirror, CCD camera (radiography)
  - Calibrated sample position
  - ^{3}He tubes (diffraction, 5 panels of 24 each)
  - Beam monitor (fission chamber)
- Also prototype for multi-probe beamline
- Under construction, to be calibrated on FP5@LANSCE this summer

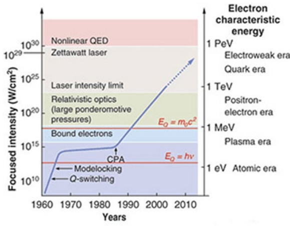


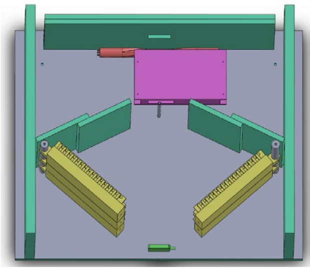
Summary

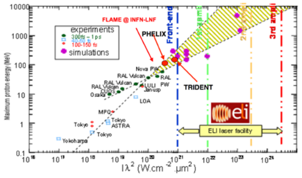
- **Few 1,000 (at best…) laser driven neutron pulses produced so far in history of humankind ⇒ early stages!**
- **Applications of laser-driven neutron sources:**
  - Neutron resonance imaging and NRTA need neutron pulses <1µs
  - CT and flash-radiography with neutrons and hard X-rays
  - Potentially replace conventional larger accelerator sources
- **Now is the time to develop laser-driven neutron sources!**
  - Avoid charge density problems of conventional accelerators
  - Current available technology at the verge of being useful
  - Much lower investment and operation cost than spallation sources
  - Technology developing fast ⇒ neutron part needs to be ready!
  - Optimization potential from unknown physics in laser/matter interactions (sandwiched nano-layer targets, conduction layer on opposite side etc.)
- **Parameters for LDNS (need Joules & contrast) differ from state of the art in laser facilities (ultra- short pulses, high power)**

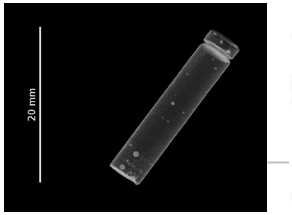


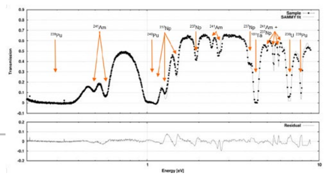
Historical trend in peak and average thermal neutron fluxes from reactor and accelerator sources

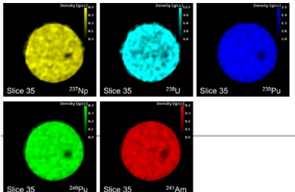


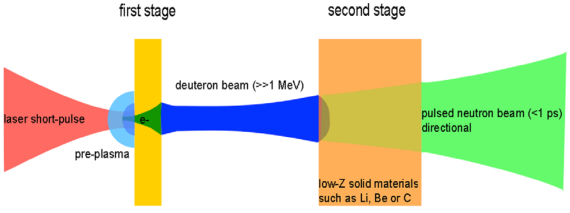












first stage

second stage

laser short-pulse

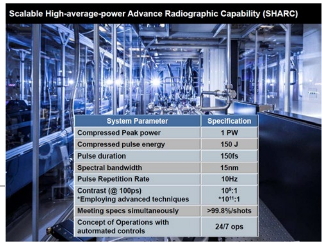
pre-plasma

e-

deuteron beam (>>1 MeV)

pulsed neutron beam (<1 ps) directional

low-Z solid materials such as Li, Be or C



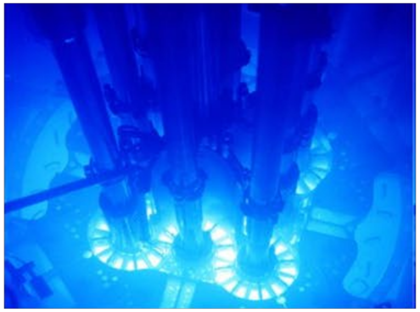
Scalable High-average-power Advance Radiographic Capability (SHARC)

System Parameter	Specification
Compressed Peak power	1 PW
Compressed pulse energy	150 J
Pulse duration	150fs
Spectral bandwidth	15nm
Pulse Repetition Rate	10Hz
Contrast (@ 100ps) *Employing advanced techniques	10^9:1 *10^{11}:1
Meeting specs simultaneously	>99.8%/shots
Concept of Operations with automated controls	24/7 ops

Los Alamos, Oak Ridge, and Idaho National Laboratories: Fuel Development & Accelerate Licensing

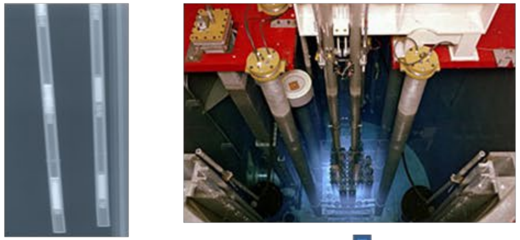
ATR: Advanced Test Reactor
DE: Destructive Evaulatuon
HFEF: Hot Fuel Examination Facility
IMCL: Irradiated Material Characterization Lab
NDE: Non-destructive Evaluation
ROI: Region of Interest

Irradiation in ATR at INL



Ship from ATR to HFEF at INL

Neutron radiography and typical NDE at INL



Define reference points with fiducials

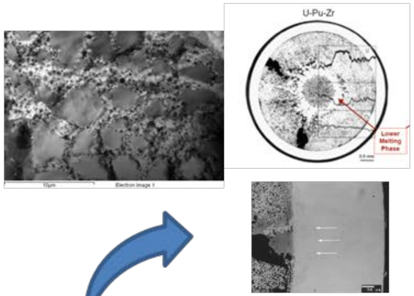
Ship from INL to LANL

NDE at LANSCE: Identify ROIs

Ship from LANL to INL

Section ROIs identified at LANSCE in HFEF

DE at INL at IMCL, etc.



Complete, 3D, A-NDE Characterization to Optimize DE Characterization of Irradiated Fuels

Vogel et al., "Assessment of advanced NDE techniques and the path forward to evaluating an AFC-2 irradiated fuel pin", LA-UR 13-2167

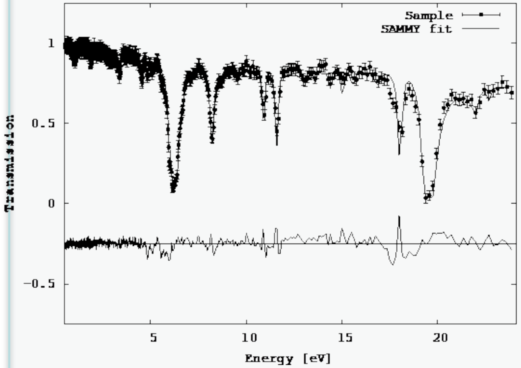
U.S. DEPARTMENT OF
ENERGY
Nuclear Energy

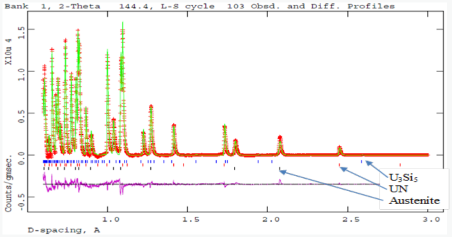
Pillars of Advanced Post-Irradiation Examination at LANL

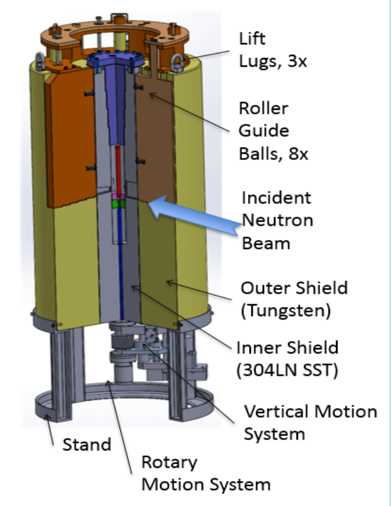
Los Alamos NATIONAL LABORATORY EST.1943

NNSA

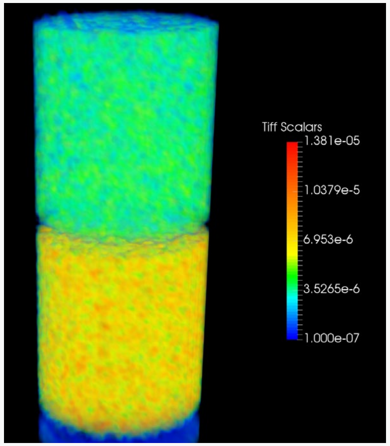
Method Development

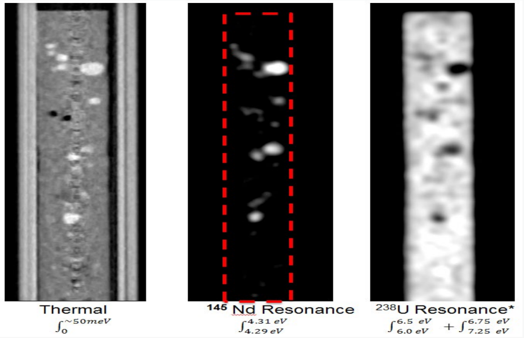


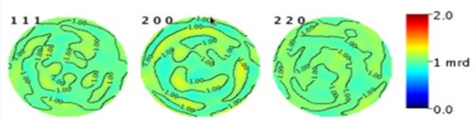


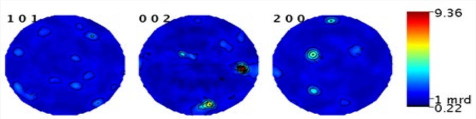


Demonstration & Application









Develop Pool-side Capability