Proposed ZEUS Project: Single Pulse Neutron Imaging of Fast-Charge Lithium-Ion Batteries

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Acknowledgments

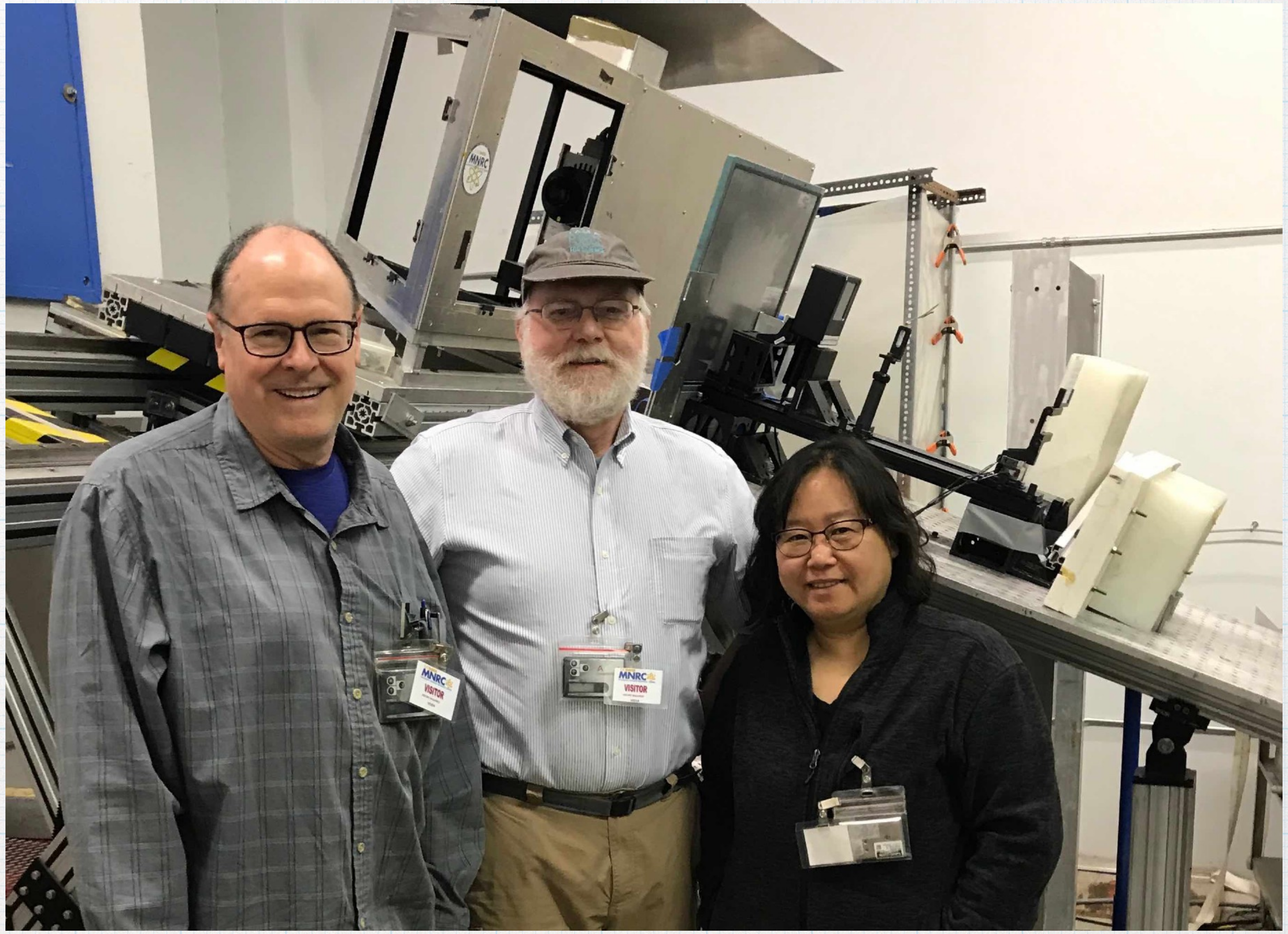
- Sven Vogel (Los Alamos) - introduced us to laser-driven neutron sources
- Ted Cremer (Adelphi Tech) - introduced us to DD-neutron generators
- Gerald Schneider (LSU) - unstoppable driver for more neutrons for science
- Markus Bleuel (Adelphi Tech/LSU) - will make DD neutron expts work
- Louis Haber (LSU) - femtosecond laser expert
- NSF Chemistry MidScale - supported June, 2022 X/N workshop
- DOE SBIR/STTR - will purchase two DD neutron generators for imaging and SANS
- Eberhard Lehman, Burkhard Schillinger, Anders Kaestner, Christian Grunzwieg, Nikolay Kardjilov, Dan Hussey, David Jacobson, Jake LaManna, Boris Khaykovich, Hassina Bilheux, Yuxaun Zhang, Michael Lerche, Adam Brooks, Kyungmin Ham - taught me neutron imaging
- Shengmin Guo and Saber Nemati - assessing the value of neutron imaging for additive manufacturing applications
- Tau Systems (Austin, TX) - bravely making a laser-driven neutron source
- "This work was supported in part by the LSU Provost's Fund for Innovation in Research - Faculty Travel Grant Program."

Overview

- Found a need for more neutron capacity in US
- Held a workshop on combined X-ray/neutron instrumentation
  - Key advice: (1) exploit all existing facilities (2) explore novel solutions
- Designed and seeking funding ($3.7M) for MIT reactor end station
- Acquiring two DD neutron generators for imaging and SANS
- Submitted beamtime proposal for our first laser-driven neutron imaging
  - Science question optimized for single-shot (or stroboscopic) imaging
- Assessed university resources: faculty, lab space, radiation, clean rooms

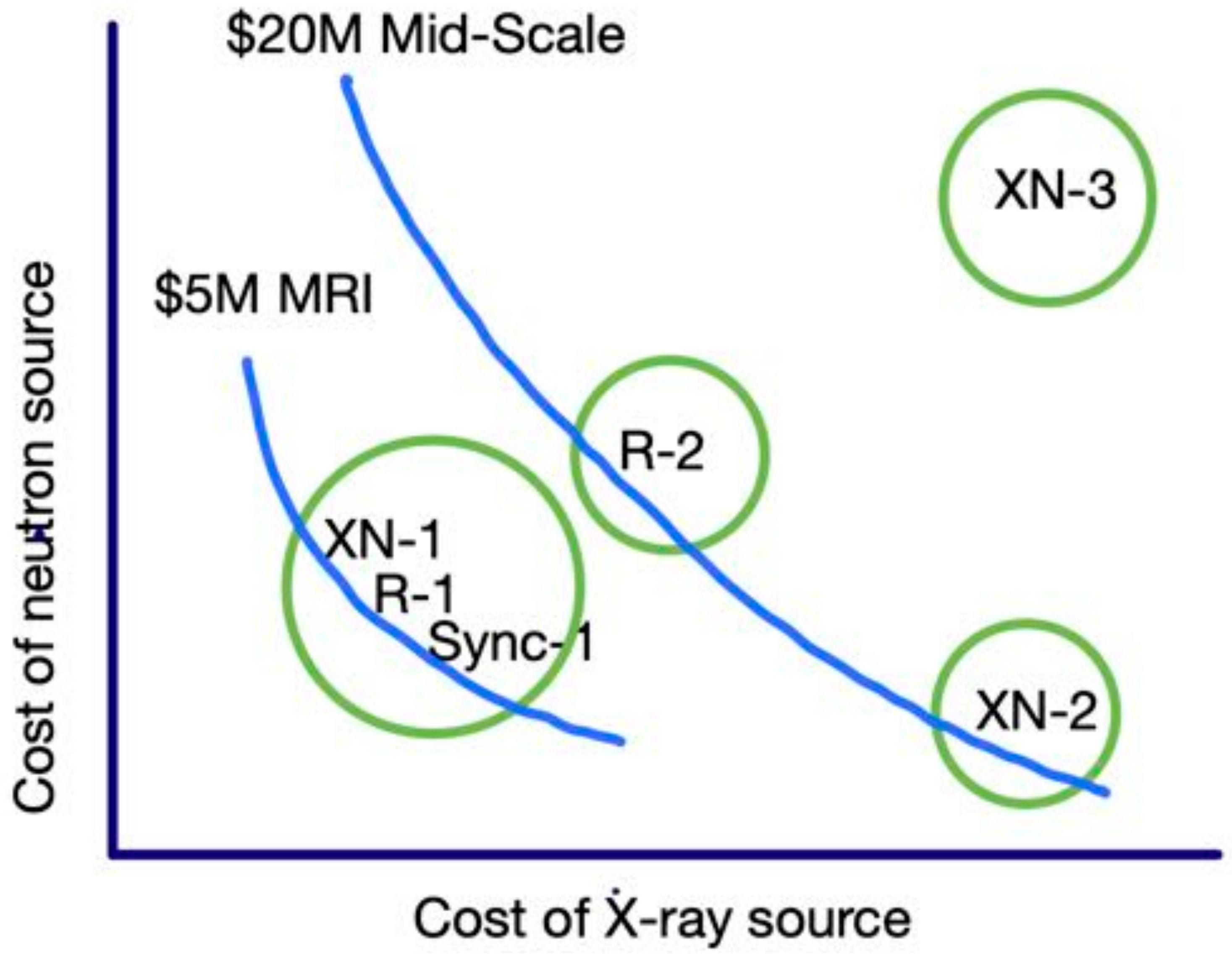
Neutron Imaging in the US (partial)

- NIST BT2 (thermal) and NIST cold
- ORNL CG-1D (thermal) and VENUS (under construction)
- McClellan/UC Davis (thermal)
- Adelphi Tech/Refined Imaging (under construction at LSU): fast/thermal from pulsed DD/poly



McClellan/UC Davis (thermal) with the 20° beamlines

Workshop on Combined X-ray/Neutron Instrumentation

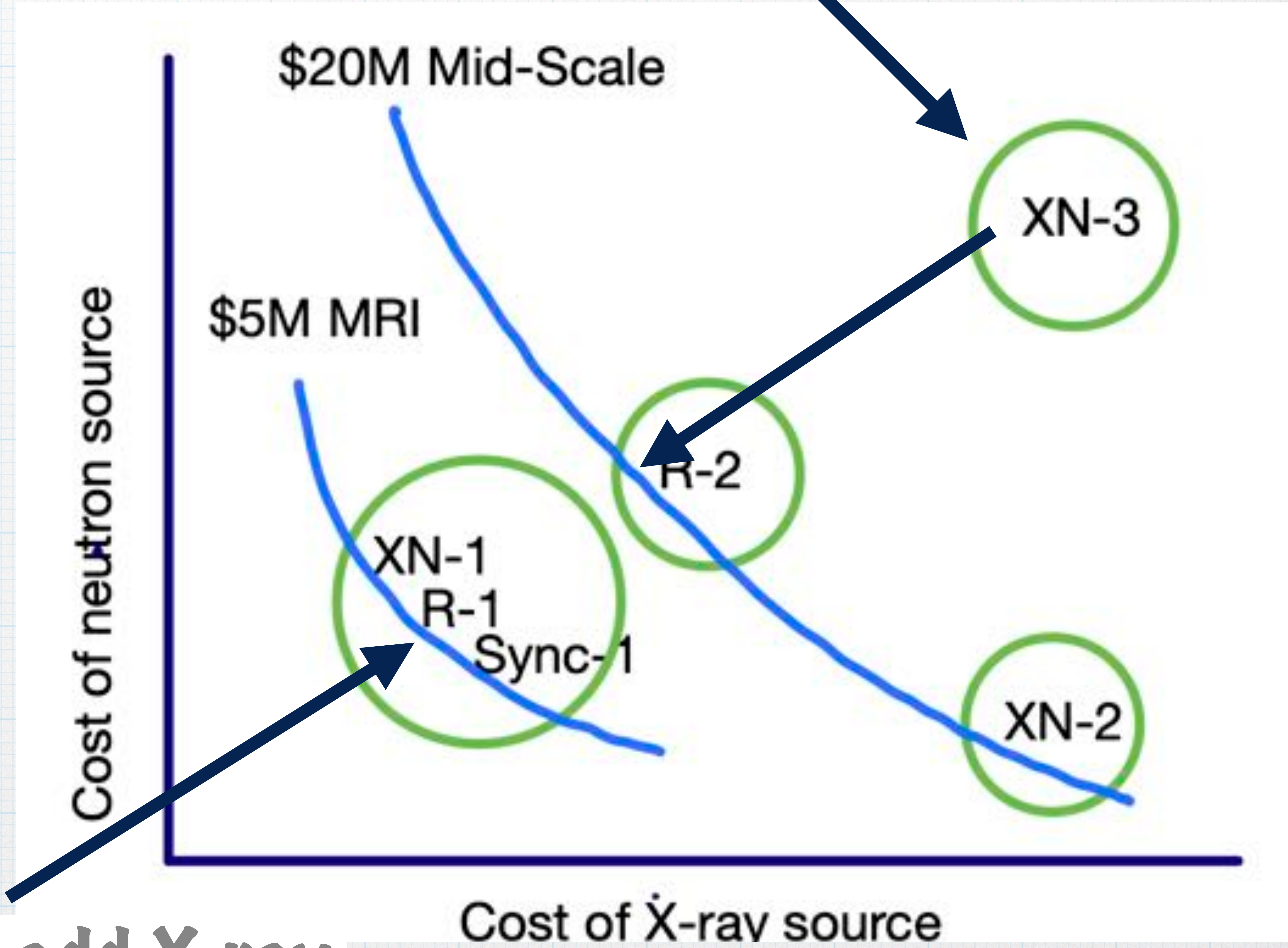


- NSF-supported workshop CHE-2219790 "MsRI-Planning Workshop: X-ray and Neutron Instrumentation", PIs Schneider and Butler, held June 2-4, 2022 at San Jose, CA.
- The workshop involved 30 in-person, and 40 by zoom participants discussing the future of neutron sources.
- Multiple "sweet stops" were identified based on technology and price.
  - The "X"s refer to advanced X-ray tubes, compact light sources, and petawatt laser accelerators.
  - The "N"s refer to DD-neutron generators and petawatt laser accelerators.
  - The "R"s refer to existing nuclear reactors. The MIT beamline is indicated as "R-1", the most cost-efficient route to combined X-ray/neutron imaging, when fitted with a corresponding X-ray system.

Money #1 of 4

US National Science Foundation

- $0.4M to $4M: Major Research Instrumentation
- $4M to $20M: Mid-Scale Design
- $20M to $1000M: Mid-Scale Implementation



LSU - Laser system

MIT reactor - add X-ray

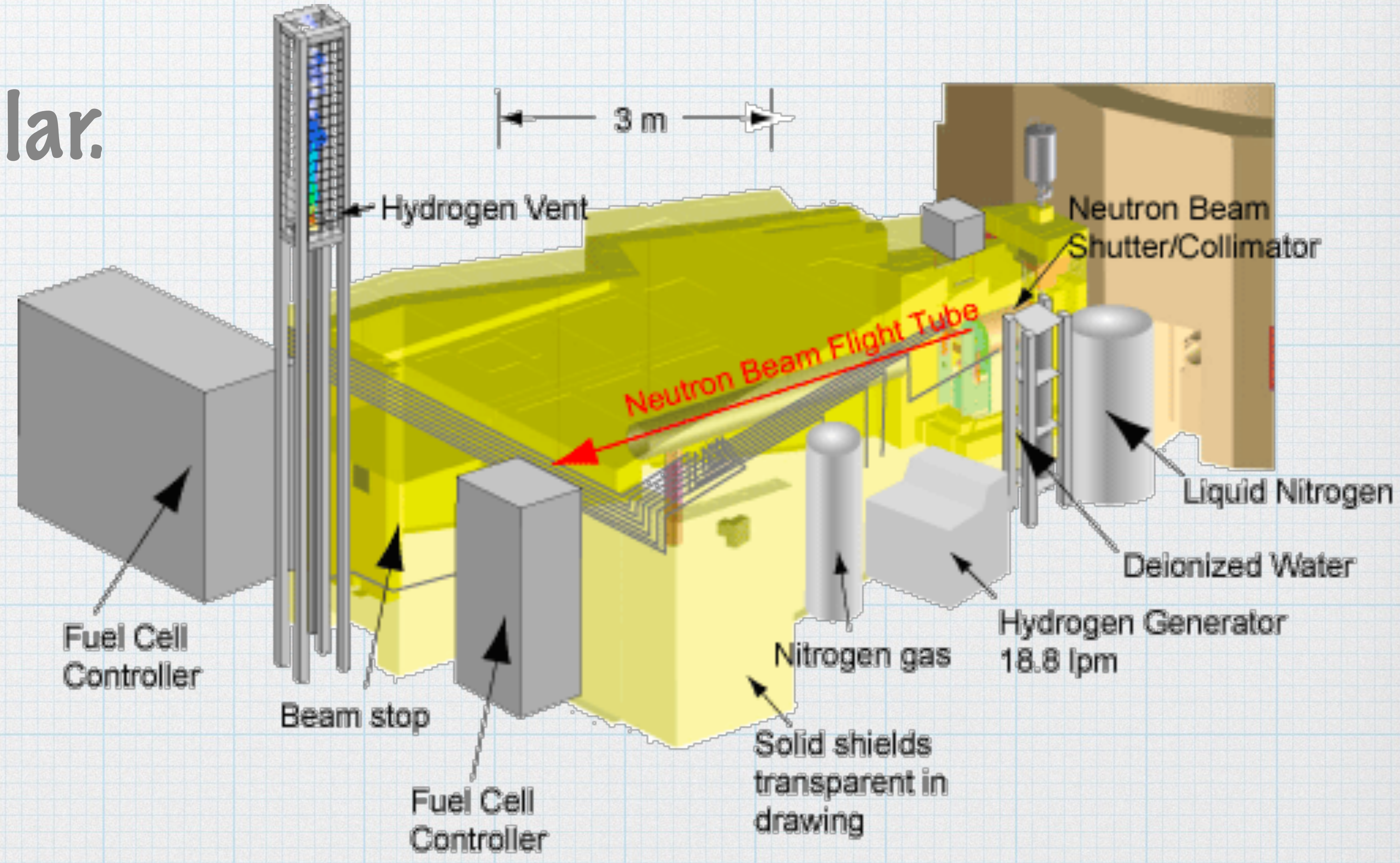
Money #2 of 4: How many neutrons can I buy for $1 USD?

NIST BT2 (thermal)

https://physics.nist.gov/MajResFac/NIF/facility.html

L (m)	Aperture d (cm)	L/d	Beam diameter (cm)	Fluence Rate (cm^{-2} s^{-1})
2	2	100	8	5.1×10^{7}
3	2	150	13	3.4×10^{7}
4	2	200	17	2.5×10^{7}
6	2	300	26	1.7×10^{7}
6	1.5	400	26	1.0×10^{7}
6	1.0	**600**	26	**4.3×10^{6}**
6	0.5	1200	26	1.0×10^{6}
6	0.1	6000	26	4.3×10^{4}

- Consider L/D = 600 for 5 days of expts and a travel cost of $3k
- 4.3×10^{6} n/second * 5 days = 1.9×10^{12} n
- = 620 million neutrons/cm^{2} per dollar
- = 620 Mn/cm^{2}-$ This is a bargain!!
  Everything else is in the US is fewer neutrons per dollar.
- We thank NIST for providing
  a billion dollar nuclear reactor for free



Money #3 of 4: DD neutron generator

Adelphi Tech DD110M

- Consider a generator equipment cost of $300k (ignoring maintenance)
- Operated in pulsed mode with time average neutron generation at target of 10^{10} n/second
- Assume 4000 hrs/year for 5 yrs
- Expts at 2 m from moderator; area of sphere with r=2 m is 502655 cm^2
- Total neutrons on sample/cm^2 after 5 yrs = 1.432 * 10^{12} n
- = 5 Mn/cm^2-$ This is pretty good for a dedicated lab system.

Our team is buying two (2) DD110M neutron generators: Imaging and SANS (both in time-of-flight modes)

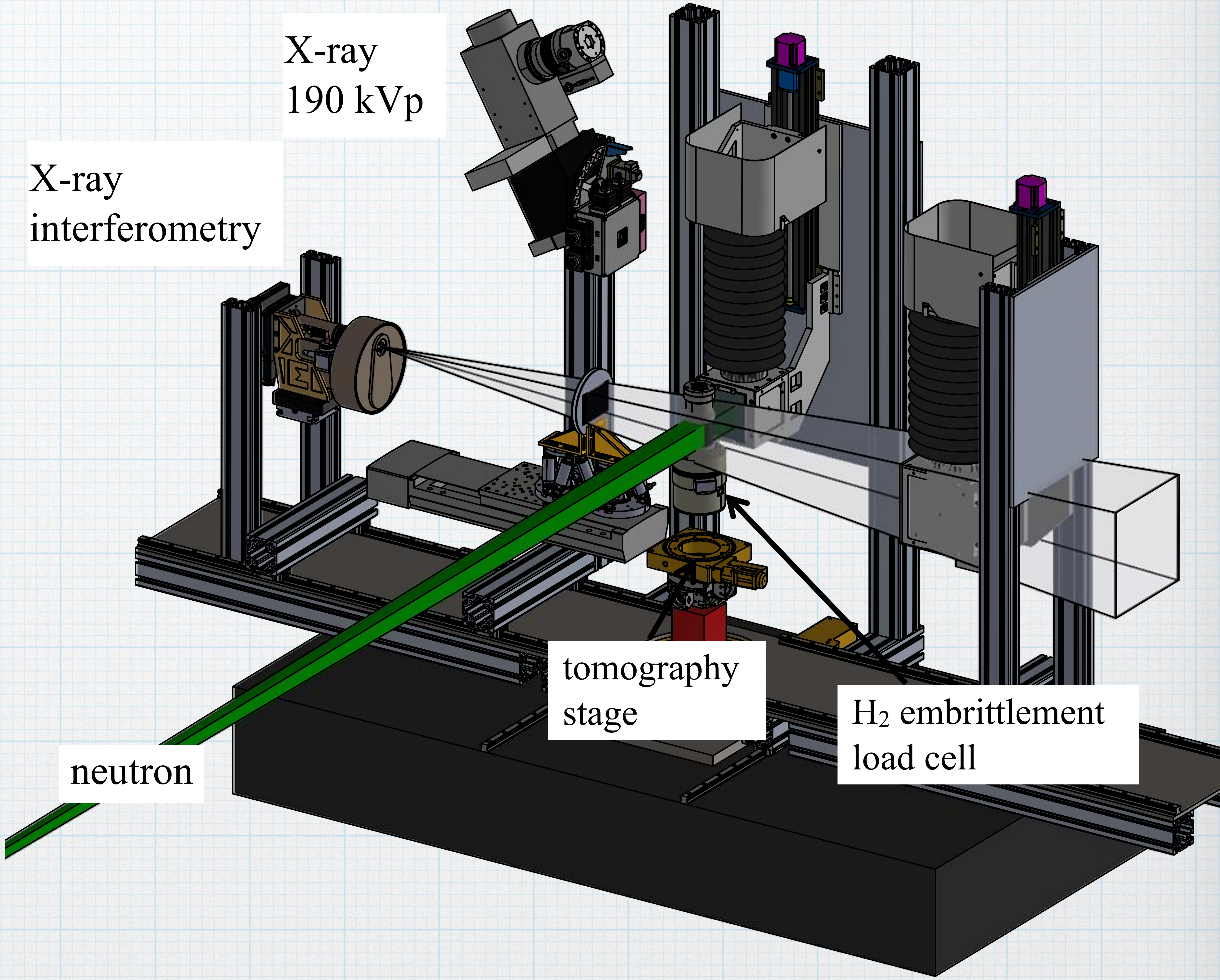
Money #4 of 4: laser-driven neutron source

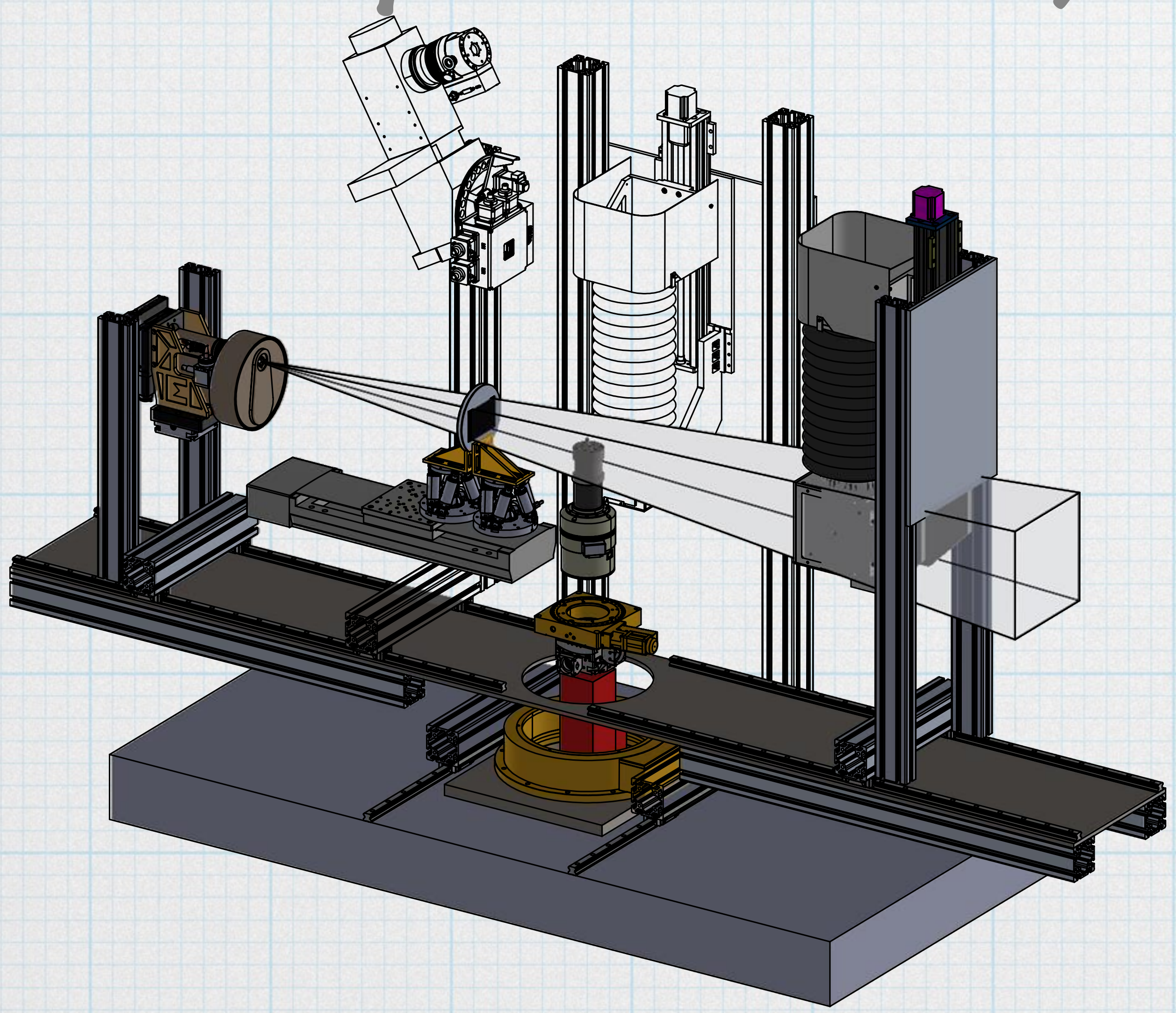
Numbers are speculative!!

- Consider a laser generator equipment cost of $10M (ignoring maintenance)
- Laser operated at 100 Hz with 1 Joule per pulse, and assume 1000 hrs/year for 5 yrs
- Assume laser to neutron conversion efficiency of 10^{10} neutrons/Joule
- Expts at 2 m from moderator; area of sphere with r=2 m is 502655 cm^2
- Total neutrons on sample/cm^2 after 5 yrs = 3.581x10 * 10^{13} n
- = 3.6 Mn/cm^2-$ A good start!!

MIT reactor - add X-ray (proposal submitted)

- Thermal neutron beam, 1/4 flux of NIST BT2
- Goal is high-resolution X-ray with "ambiguity reduction" from neutron
- Designers: Jake LaManna (NIST), Boris Khaykovich (MIT), LSU



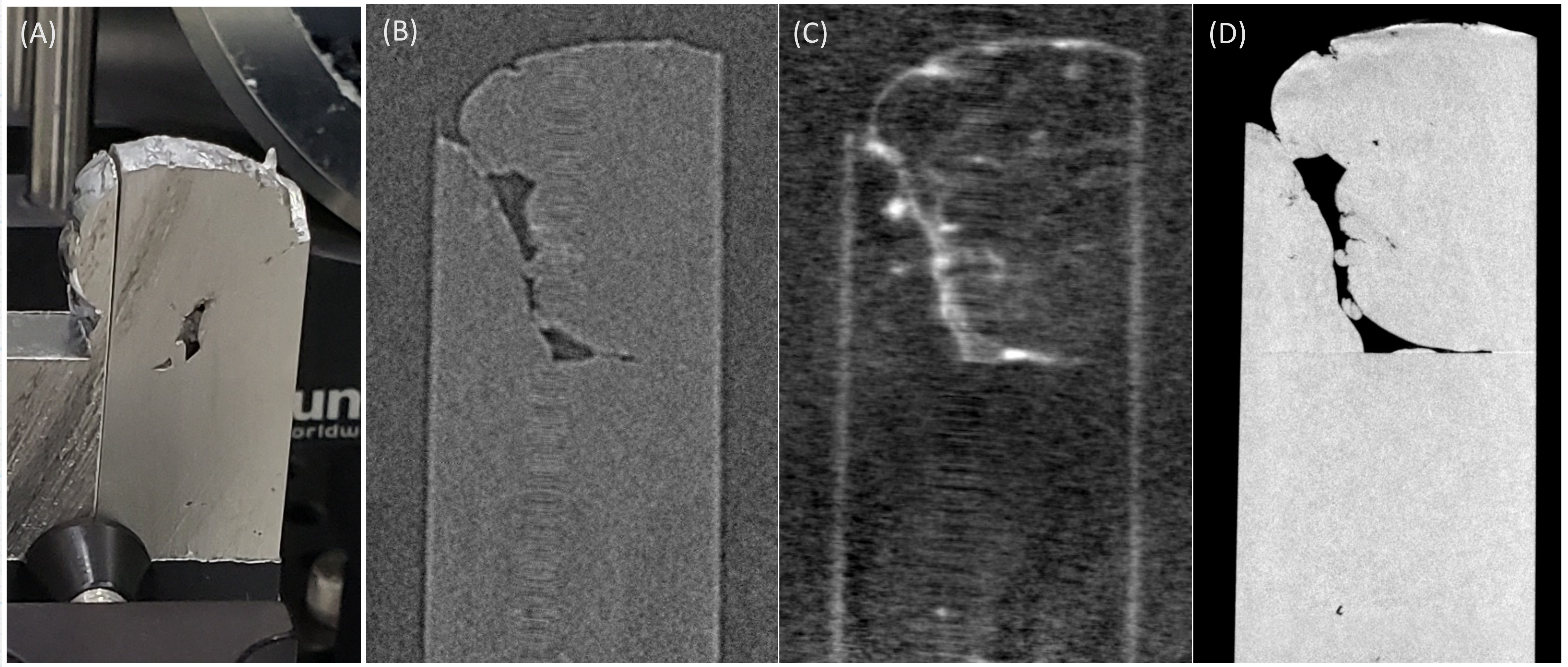


- Politics: LSU retains an X-ray only system for interferometry development

Possible Applications

- Hydrogen embrittlement in additive manufacturing
  - Load cell with 5kN, 250 °C, in-situ H_2
- Batteries
- Plant roots/soil science & coastal stabilization
- Additive manufacturing
- Cultural heritage
- Nuclear materials
- Carbon dioxide sequestration
- Quantum materials
- Cement

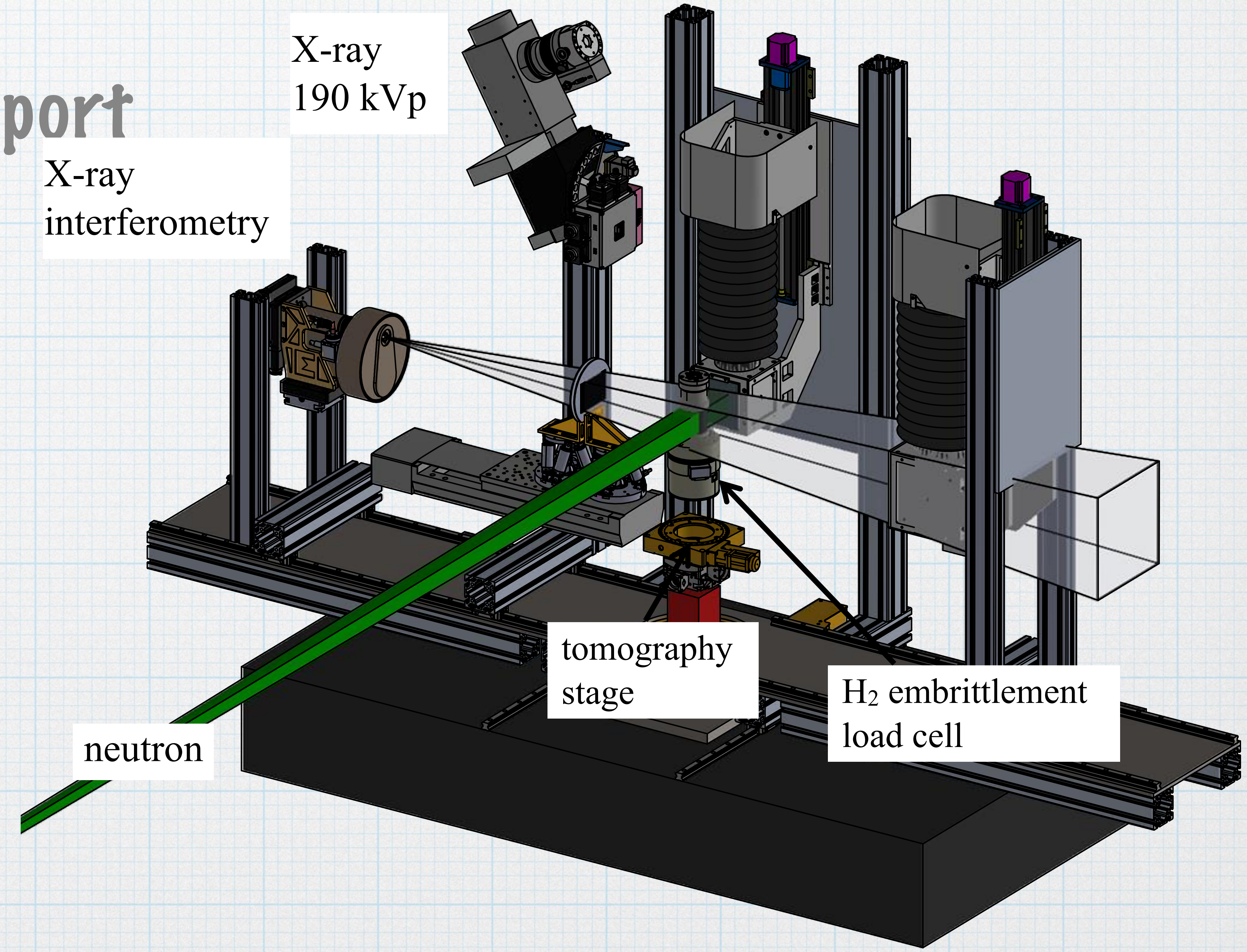
Aluminum arc-wire fabrication.
Only interferometry shows aluminum oxide impurity



Optical neutron interferometry X-ray

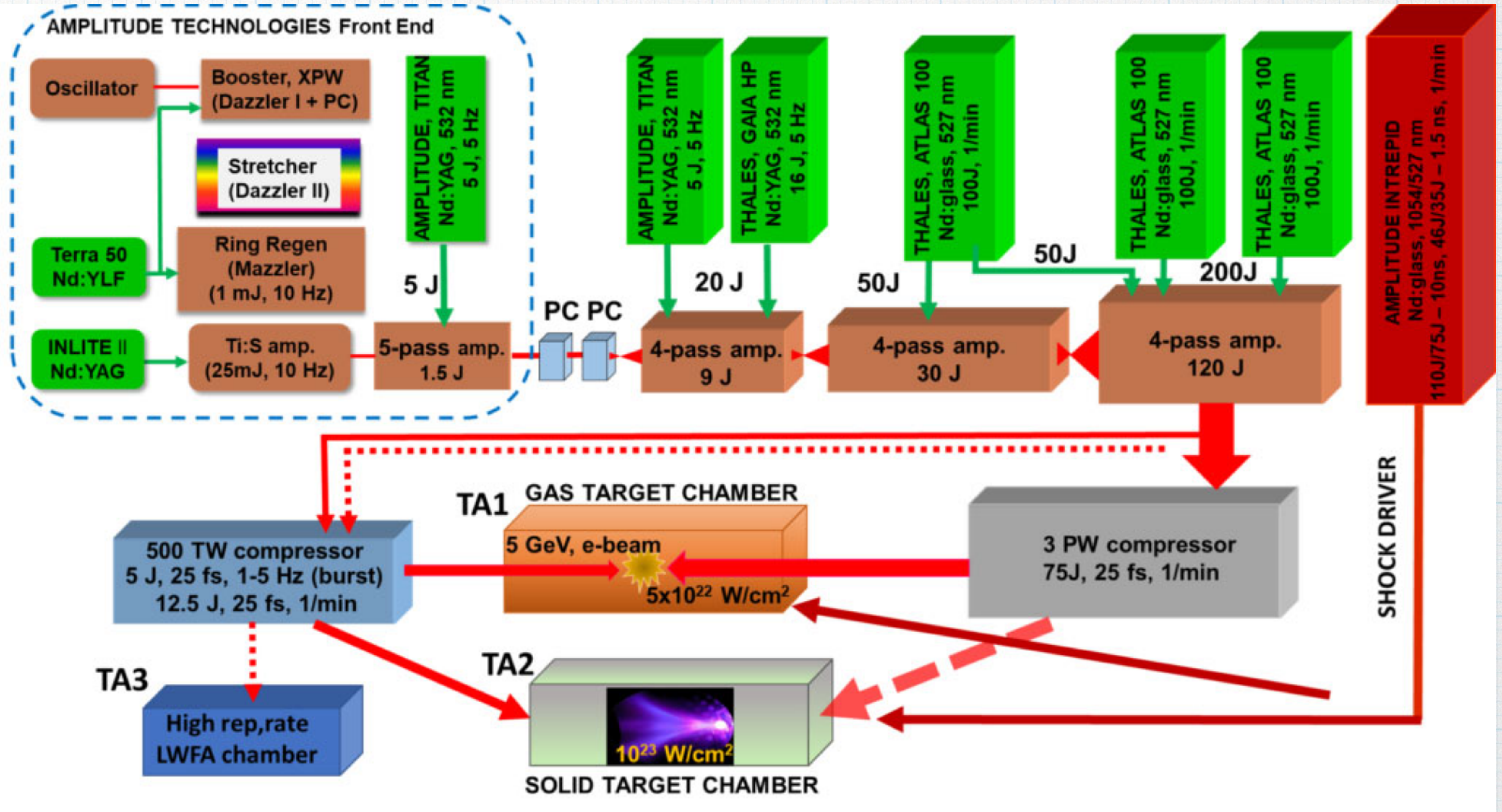
Impact of MIT X/N on LSU laser X/N

- No LSU faculty have PW laser experience
- 30 LSU faculty contributed to MIT X/N
    - Office of Research sees the groundswell of support
- Emotion: old reactor versus new laser
- Capabilities:
    - pulsed, time-of-flight
    - On-axis and perpendicular X/N
    - Have not explored muon,



First LSU experience with laser (beamtime proposal pending)

- Univ. of Michigan ZEUS: "Once completed, the ZEUS laser system will be the highest-power laser system in the US and will be among the highest-power lasers worldwide for the next decade."



(Our proposal)

5. Laser/Beam Requirements

The laser beam requirements at TA3 are meet with the specifications of 5 J, 25 fs pulses at 1 Hz burst mode. We are flexible with respect to the burst length and number of bursts per day. We will use the solid target system with thin metal foil, most likely tungsten. We will used the in-vacuum x-y-z translation stage system for metal foil mounting and rastering over 50 mm range for providing fresh metal foil to the laser beam at the 1 Hz repetition rate.

First LSU experience with laser (beamtime proposal pending)

(Our proposal)

2. Proposed Experiment and Risk Assessment

2.1 Primary Goal: Laser-Driven Thermal Neutron Generation

The procedure tested at the PHELIX laser with a 103 J, 500 fs laser pulse and metal foil target will be used at TA3 [Zimmer, 2022]. Co-investigator Sven Vogel will provide the guidance from Los Alamos to the project team operating on-site at TA3. The procedure developed at PHELIX is readily and usefully transferred to TA3. Repeating the PHELIX procedure at TA3 is technically useful as the neutron beam generation parameters are essentially for developing further applications for TA3 as a laser-driven thermal neutron generation system.

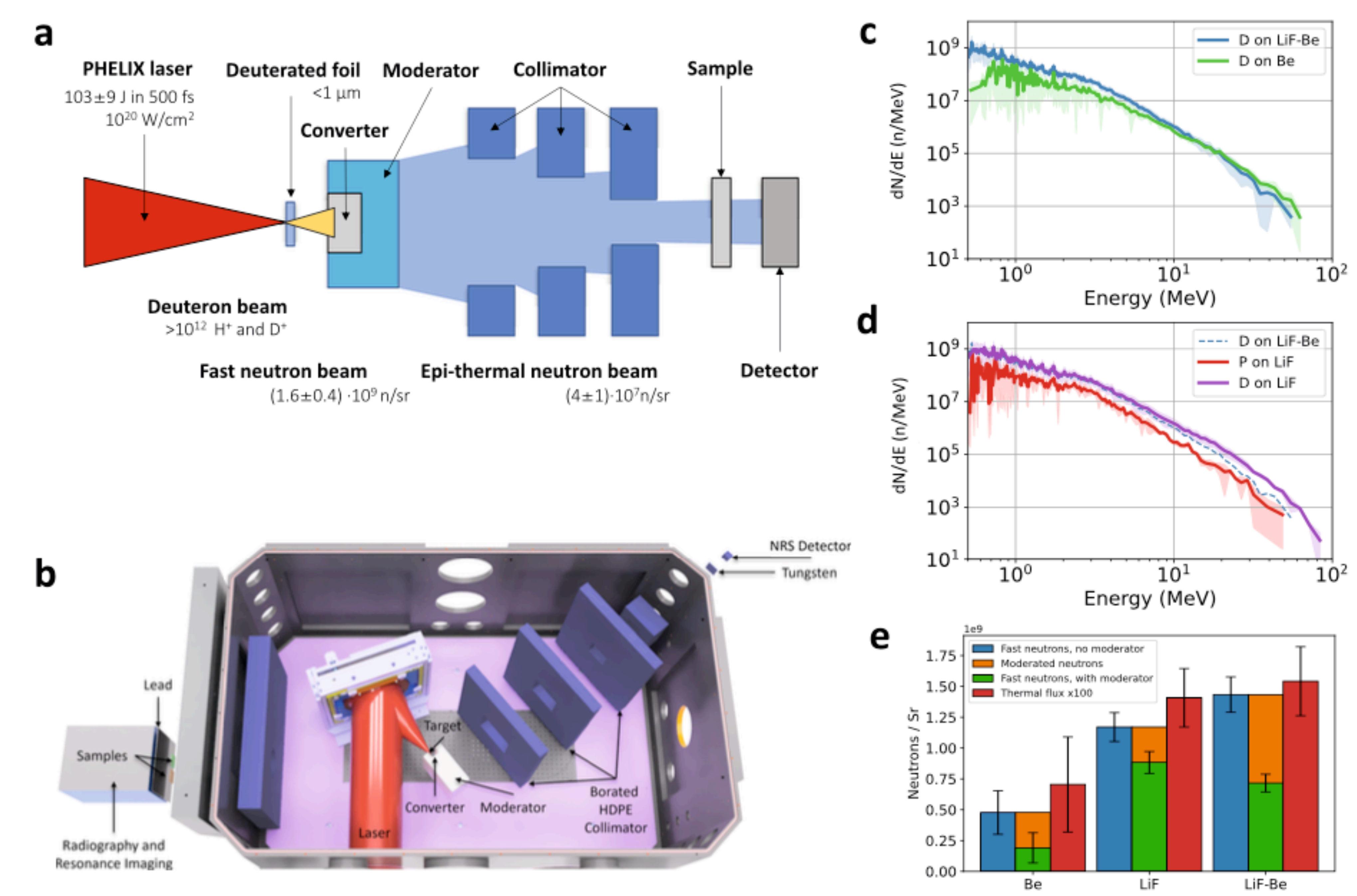
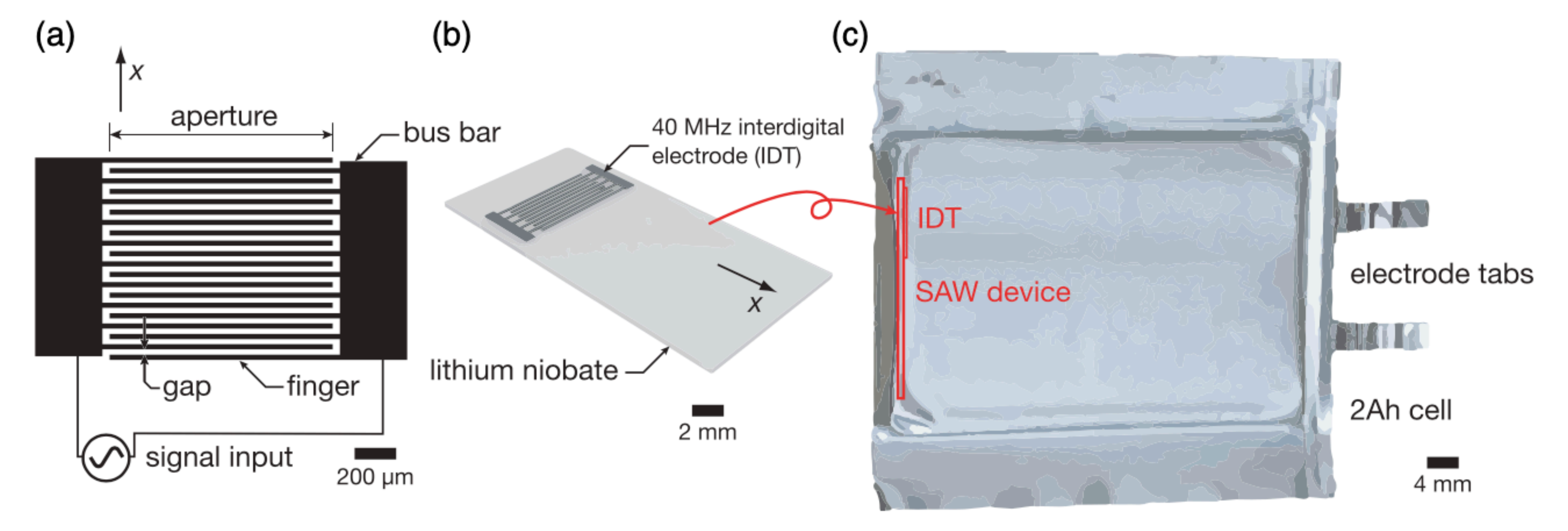


Fig 1. The laser-driven thermal neutron generation system used at PHELIX [Zimmer, 2022] operating with a laser pulse every 90 minutes. The proposed work at TA3 will used foils, most likely thin tungsten, for neutron generation and a room temperature polyethylene for moderation. Tungsten resonance imaging will be used to prove neutron imaging versus gamma ray imaging. When the thermal neutron beam is well characterized, the project will transition to the secondary goal of stroboscopic battery imaging.

First LSU experience with laser (beamtime proposal pending)

2.2 Secondary Goal: Stroboscopic Thermal Neutron Imaging of Lithium-Ion Batteries
Fast charge is the next challenge for batteries and is a problem well matched for study with intense, pulsed neutron imaging. A very recent approach to fast charging uses surface acoustical waves (SAW) [Friend, 2011] (see Fig. 3) to preserve battery lifetime at 6C charge rate (10 minutes to full charge) [Huang, 2020, 2022]. However, the mechanism of SAW electrode protection is not clear, nor is the RF cost negligible, amounting to 2% of the battery charge power. Therefore, we propose pulsed neutron imaging combined with pulsed SAW to probe strategies to reduce the SAW energy penalty, yet still retain the fast battery charge protection.

Fig 3. A (a,b) surface acoustic wave (SAW) transducer is affixed to a (c) commercial prismatic lithium-ion battery [Huang, 2022]. Operation of the SAW at power level amounting to 2% of the battery charge power has the effect of reducing localize high concentrations of lithium and thus impeding the growth of lithium metal structures that damage the battery. The SAW protection is effective up to charge rates of 6C, corresponding to a 10 minute battery charge.



Challenges for LSU laser X/N

- No lab space (unoccupied) with area, floor loading, cleanroom
    - Microfabrication facility shares lack of space problem
    - Office of Research considering new building for laser X/N and microfab cleanrooms
- Uncertain radiation issues
    - The DD neutron generator radiation approval has difficult
- Operational costs
    - Proposed X/N school for the region, like NXS
- Anything else?

25th National School on Neutron and X-Ray Scattering

August 6–18, 2023

Hosted by
Oak Ridge National Laboratory and
Argonne National Laboratory

Review

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