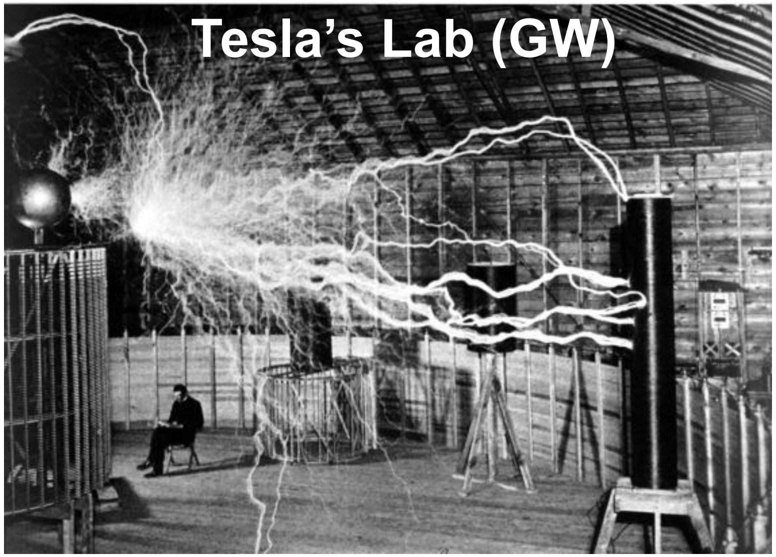

Pulsed power technology in early 1900s

Pulsed power today

SAND2016-7529PE

Overview of progress and plans for developing a national Pulsed Power Science and Technology strategy

Dan Sinars

Sandia National Laboratories

August 2, 2016

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

The labs were tasked by the NNSA to develop a strategic plan for pulsed power science & technology (PPS&T) to address high energy density physics applications for the Stockpile Stewardship Program

Sandia National Laboratories
Lawrence Livermore National Laboratory
Los Alamos NATIONAL LABORATORY

Department of Energy
National Nuclear Security Administration
Washington, DC 20585

NNSA National Nuclear Security Administration

May 13, 2016

TO: J. STEPHEN ROTTLER
DEPUTY LABORATORIES DIRECTOR AND EXECUTIVE VICE PRESIDENT
SANDIA NATIONAL LABORATORIES (SNL)

CHARLES P. VERDON
PRINCIPAL ASSOCIATE DIRECTOR FOR WEAPONS & COMPLEX INTEGRATION
LAWRENCE LIVERMORE NATIONAL LABORATORY (LLNL)

ROBERT B. WEBSTER
PRINCIPAL ASSOCIATE DIRECTOR OF WEAPONS PROGRAM
LOS ALAMOS NATIONAL LABORATORY (LANL)

FROM: KEITH R. LECHIEN
DIRECTOR, INERTIAL CONFINEMENT FUSION (ICF)
NATIONAL NUCLEAR SECURITY ADMINISTRATION (NNSA)

RALPH F. SCHNEIDER
DIRECTOR, RESEARCH AND DEVELOPMENT (R&D)
NATIONAL NUCLEAR SECURITY ADMINISTRATION (NNSA)

SUBJECT: Developing a strategic plan for pulsed power science and technology capabilities for high energy density physics applications for the Stockpile Stewardship Program (SSP)

- Letter addressed to three weapons laboratories
- Expectation is that they define a tri-laboratory plan
- Each laboratory appointed a single POC to work with Bryan Sims at NNSA
  - Dan Sinars
  - John Edwards
  - Kim Scott
- Requests that the plan be submitted to NNSA by Aug. 18

The NNSA request covers a broad swath of areas, the time scale to provide a response is short, and not all of the mission area needs can be discussed in an open setting

- The memo identifies five key elements
  - Dynamic Material Properties
  - Nuclear Survivability & Radiation Effects Science
  - Thermonuclear Burn Physics and ICF
  - Next-generation Codes for PPS&T Design
  - Academic & Industry engagement in PPS&T

- The first three are major mission areas in the Stockpile Stewardship Program
- The last two are areas supporting pulsed power contributions to the first three areas. An implicit area is pulsed power technology itself.
- Activities at the labs in response to the memo didn't begin in earnest until early June—leaving us with ~2.5 months to collect input (working around people's summer vacation plans too!)
- This is an opportunity to have open and frank discussions at the national labs about the role of pulsed power, and build a community around these roles

Many are contributing to the activities this summer, but we began by appointing POCs along the lines of the memo

Role	SNL	LLNL	LANL
Overall POC	Dan Sinars 505-284-4809 dbsinar@sandia.gov	John Edwards 925-321-0104 edwards39@llnl.gov	Kim Scott 505-665-8534 kscott@lanl.gov
Dynamic Materials POC	Dawn Flicker 505-845-7398 dgflick@sandia.gov	Dennis McNabb 925-423-0749 mcnabb3@llnl.gov	Russ Olson 505-667-6667 rtolson@lanl.gov
Survivability POC	Bryan Oliver 505-284-7868 bvolive@sandia.gov	Ted Vidnovic 925-422-6456 vidnovic@llnl.gov	Dave Hollowell 505-665-4223 daveh@lanl.gov
TN/ICF POC	Joel Lash 505-284-4518 jslash@sandia.gov	Jim Hammer 925-423-9709 hammer2@llnl.gov	Brian Albright 505-665-0497 balbright@lanl.gov
Next-gen Codes POC	Scott Collis 505-294-1123 sscoll@sandia.gov	Chris Clouse 925-422-4576 clouse1@llnl.gov	Chris Rousculp 505-665-3678 rousculp@lanl.gov
Academic & Industry POC	Michael Cuneo 505-844-8767 mecuneo@sandia.gov	Alan Wan 925-423-3342 wan1@llnl.gov	Bob Reinovsky 505-667-8214 bobr@lanl.gov

HQ POC: Bryan Sims 202-586-3781 bryan.sims@nnsa.doe.gov

The NNSA labs are trying to understand the present and future environment (“situation”), our requirements and needs (“targets”), in order to frame possible proposals

SITUTATION How things are now “Environmental scan”	TARGET How you’d like them to be “Requirements & needs”	PROPOSAL How to get there
• Starting point • Facts and opinions about current conditions • Predictions about efforts to change • Environment as the group perceives it • Norms • Current reality	• Goals, aims, ends, values, purposes, and objectives • Outcomes desired by the group • Termination point • Wishes • Ideal State	• Path from S to T • Means, plan, strategy, implementation, procedure • Solution or suggestion • Actions

This is not a linear process. Achievable targets are often constrained by the feasibility of proposals and can imply or reveal things about the situation.

What do we want to accomplish by August 18?

- **End product will be a classified report to the NNSA**
  - Needs to capture any consensus views amongst the three laboratories
  - Should capture the key elements that we believe the NNSA needs to know to make informed decisions
  - Expect that it will be formally signed by the recipients of the NNSA memo (Rottler, Verdon, Webster) to ensure it is a consensus view
- **Content of the report will contain the following**
  - Environmental scan (“Situation”)
  - Requirements and needs (“Targets”)
  - A clear picture of what pulsed power technology investment would have the highest impact
  - A discussion of potential investments in today’s capabilities or future capabilities that would have impact
  - Some discussion of the tradeoffs or existing constraints for implementing multiple proposals
  - Would be great to include some discussion of prioritization across proposals if we can come to a consensus, but this is not essential

Most of our activities this summer are centered around trying to collect and discuss content for the report

- We are holding three workshops, loosely focused on Situation (June 24), Target (July 15), and Proposal (August 8).
- Today's meeting is well timed for giving you all a picture of where we are today, where the labs would like to be in the future, and have you help us figure out proposals for how to get there.
- Inputs into the report include
  - Written laboratory position papers
  - Workshop discussions and outbriefs
  - Edits to the master document (1st draft completed Friday, July 29 with placeholders for "proposal" sections of document)
  - Today's academic workshop and subsequent discussions
  - Weekly laboratory POC discussions
- Dan Sinars is serving as lead editor of the document and helping the POCs to pull this all together. He is working full time on this through Aug. 18.
- Ideally, sometime after Aug. 18 we will produce an unclassified excerpt to help keep the conversation going, but too hard to do in such a short time.

NNSA HQ insists that the report must be 50 pages or less, which means that it must be concise and to the point

- Header/Forward (Cover page, Author/abstract, copy of memo, TOC, acronyms)
- (2 pages) Introduction to pulsed power science & technology for non-technicals
- (11 pages) Dynamic Material Properties Mission
  - (3) Brief mission overview and Environmental scan
    - Who cares & why? Present applications of PPS&T. Expected changes in next 20 years
  - (5) Desired outcomes
    - New physical conditions that would support the stockpile. Program elements that allow us to respond to unanticipated threats. Deterrence value.
  - (3) Overview of potential proposals
- (11 pages) Nuclear Survivability and Radiation Effects Mission [Same sections as above]
- (11 pages) Thermonuclear Burn & Inertial Confinement Fusion [Same sections as above]
- Supporting the Missions
  - (4 pages) Next-generation codes
    - Environmental scan (existing capabilities, how are they supported?)
    - Desired outcomes (new capabilities that would support PPS&T)
  - (4 pages) Pulsed Power Technology
    - Environmental scan (existing capabilities, how are they supported?)
    - Desired outcomes (Capability investments implied by mission proposals)
  - **(3 pages) Industry Partnerships**
    - **Environmental scan & Recommendations**
  - **(3 pages) International Partnerships**
    - **Environmental scan & Recommendations**
  - **(3 pages) Academic Partnerships**
    - **Environmental scan & Recommendations**
- May be value in capturing a Volume 2 with supplemental material for many of these

1st draft of report completed last Friday looks pretty close to this

There are some compelling broad themes emerging from this activity that will guide our strategy going forward

- **We want to amplify pulsed power value for near-term stockpile stewardship program decisions, particularly in materials science and nuclear survivability**
  - Building upon major advances in pulsed power for materials science, we want to increase the capacity for such research in the U.S. in the near future (~5 years) to affect decisions ~2024-2025 impacting the nuclear explosive package
  - Sustain and refurbish existing NS/RES capabilities to ensure a second ~25-30 years of contributions (e.g., refurbish 28-year-old SATURN facility in ~5 years)
  - Both mission areas could also benefit from higher-pressure capabilities in the future (>10 year horizon), particularly those enabled by large fusion yields
- **We want to position pulsed power and magnetic direct drive as a viable options for high-yield laboratory fusion in the future (we reaffirm value of high yield for NNSA)**
  - Increase the vitality of present target physics program (e.g., increased shot rate on Z) over next 5 years to try and meet national 2020 ICF goal
  - Invest in supporting capability maturation (e.g., demonstration LTD module, code capabilities for modeling power flow) over next 5 years
  - Assess technical risks (we fail) vs. technological surprise risks (others succeed)
- **We want to create a sustained development and maturation strategy for pulsed power technology, in partnership with academia and industry**
  - Achieved through near-term NNSA and Academic Program investments

We want to amplify pulsed power value for near-term stockpile stewardship program decisions, particularly in materials science and nuclear survivability

- **Historical perspective:**
  - Pulsed power for materials science was not envisioned twenty years ago—today it is a routine and vital contributor to dynamic materials science
  - Pulsed power for radiation sources has a long history going back decades!
  - Z's shot distribution today reflects the growing utility of pulsed power for various stockpile stewardship applications (materials, opacity, radiation flow)
- **Pulsed power could address near-term needs in Dynamic Materials**
  - The SSP (out of NA-10) is facing critical production decisions in mid-2020s that better DMP science and capabilities can address
  - Other NNSA programs also have needs on top of NA-10
  - Possible "high-capacity facility" proposal may be able to address both needs
- **Pulsed power for radiation effects needs a shot in the arm**
  - Existing facilities meet the needs, but are almost 30 years old
  - Also suffer from "feast or famine" issues with ebbs and flows in LEP/ALTs
  - Interested in revitalizing the facilities and the people (allow for R&D too, not just weapon qualification activities)
  - Long term interest in high yield sources, but tension with short-term needs

The recently published ICF Framework document sets the 2020 goal and lays out the program of work to achieve it

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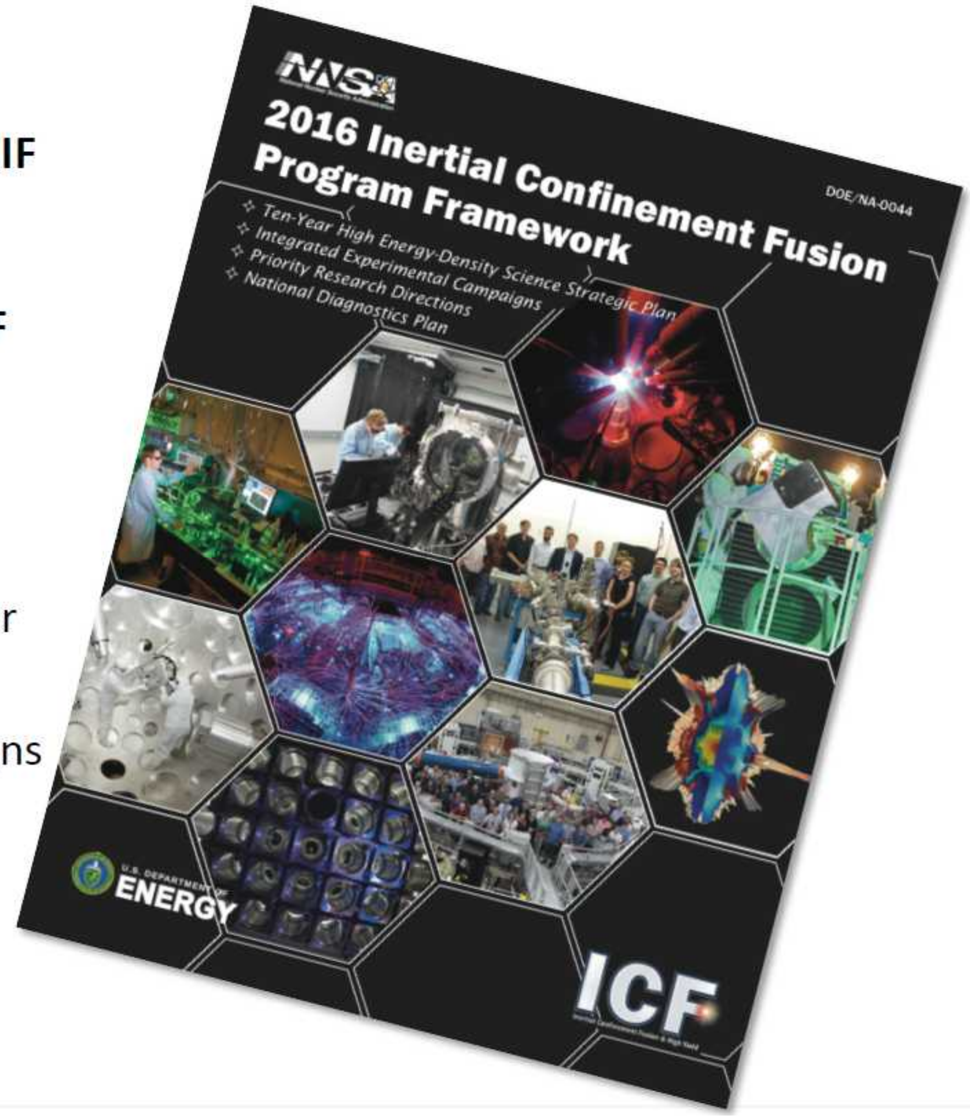
- We will, by 2020, **determine the efficacy of reaching ignition on the NIF and of achieving credible physics scaling to multi-megajoule fusion yields for each of the three major ICF approaches**
- Organized around four framework elements:
  - 10-year scientific strategic Plan for HED Science for SSP
  - Integrated Experimental Campaigns
  - Priority Research Directions (Science/Diagnostics)
  - Transformative Diagnostics



After demonstrating the fundamental concept of MagLIF, we are now focusing on understanding the science and developing the requirements for ignition and high yield.

~85% of total effort (Z,Ω,NIF)

- **Study the underlying science of MDDs, emphasizing MagLIF**
  - Primarily accomplished by the Priority Research Direction teams
  - Teams have dedicated experiments on multiple facilities (e.g., Z, Z-Beamlet, Omega, Omega-EP, universities, NIF)

~10% of effort

- **Demonstrate target performance over available range of conditions**
  - Primarily accomplished through integration experiments on Z
  - **100 kJ DT yields; P-tau > 5 Gbar-ns; BR > 0.5 MG-cm**

~5% of effort

- **Develop a path to ignition and beyond, and assess its credibility**
  - Define credible gas (~5 MJ) and ice burning (~ 1GJ) ignition designs
  - Demonstrate "at-scale" fuel heating on NIF relevant to MagLIF
- **Update the mission needs for ignition and high yield**
  - Why does the nation need a facility capable of ~1 GJ/shot?

We need to make rapid progress in the next 5 years to evaluate the science and general efficacy of MagLIF and establish credible requirements for ignition and high yield.

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Proposed ICF milestones consistent with the national ICF framework

FY17
- Develop a methodology for inferring B-r and P-τ as quantitative performance metrics from integrated MagLIF experiments.

FY17
- Demonstrate >1 kJ of laser energy coupled to the MagLIF fuel

FY18
- Develop and characterize a MagLIF baseline at 15-20 T, 20-22 MA, and 1-2 kJ

FY19
- Quantify the amount and relative origins of Mix

FY20
- Develop and characterize an enhanced MagLIF baseline at 20-30 T, 22-24 MA, and 2-4 kJ

FY20
- Provide credible physics extrapolation to ignition
  - Demonstrate 30 kJ heating on NIF

Integration Goals

We want to position pulsed power and magnetic direct drive as a viable options for high-yield laboratory fusion in the future (we reaffirm value of high yield for NNSA)

- **What does it mean to achieve a credible physics scaling to multi-MJ fusion yields for magnetic direct drive (e.g., MagLIF)?**
  - Achieve some level of performance on the existing Z facility (~100 kJ??)
  - Demonstrate that changes in the target configuration (Current, Bfield, preheat energy) result in understandable changes in the overall performance
  - Implied that we are measuring observables than just yield (shape, BR, temperatures, etc.)
  - Large interest from ICF program to increase MDD shot rate—working on proposals for how to achieve this in practice on Z
- **Actually achieving multi-MJ fusion yields requires more than target physics**
  - Proposal to build an LTD module to address technology integration challenges
  - Need a robust program in power-flow physics—we don't want to fail to deliver current to a target! Implies both experiments and computational code capability development.
  - Need some experience with tritium handling on pulsed power (which will increase the diagnostic options for target physics)
- **Draft document reaffirms the long-term SSP mission need for high yield**

We want to create a sustained development and maturation strategy for pulsed power technology, in partnership with academia and industry

- **Pulsed power technology development**
  - Different mission needs imply several different types of pulsed power machines and technology (high-current, high-voltage, highly flexible current pulse shapes, etc.)
  - These in turn set requirements on the various pulsed power elements
  - No sustained investment today from NNSA in either the science or the technology development
- **Pulsed power industry**
  - Used to be multiple companies providing pulsed power systems, today mostly companies delivering components (except maybe L3)
  - Opportunities for engagement in software development, not just hardware
- **Academia**
  - Pulsed power mentioned in SSAP calls, but without emphasis
  - Main interest is in target physics, but what about technology?
  - What are best ways for NNSA and the labs to engage? To ensure pipelines of students in target physics and pulsed power technology? Need your input!

One broad theme for academic engagement is access to facilities—how could this be improved?

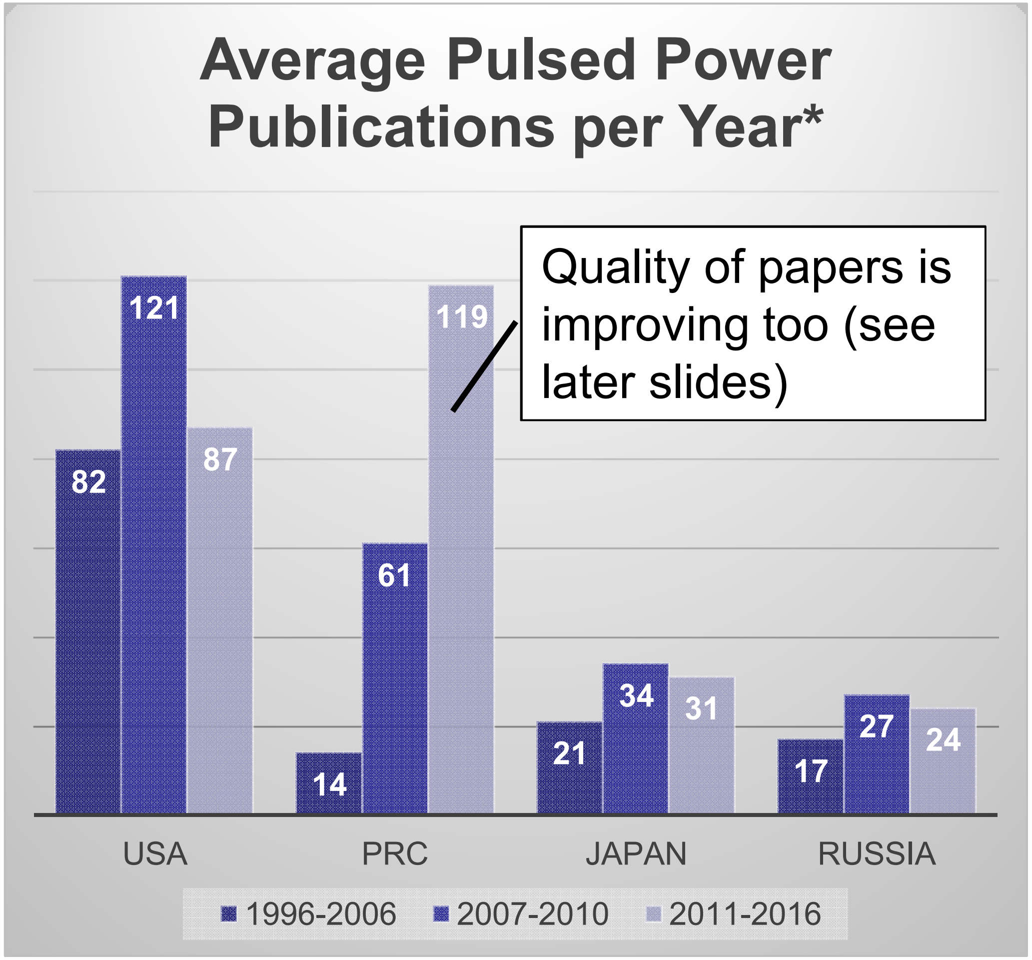
- Lack of intermediate-scale facilities an issue for scaling to Z
  - Biggest university facilities ~100 kJ, ~1 MA (vs. Z at ~20 MJ, ~26 MA)
  - Bigger (~200x) gap than Omega to NIF (30 kJ to 1.8 MJ). Some physics such as imploding liners hard to study at smaller scale.
  - If nation builds a bigger Z someday, the discrepancy will worsen
  - Pertinent to past ZFSP proposals that attempted to scale work from smaller facilities to Z

- Bringing pulsed power to diagnostic is another theme of strategy
  - Many capabilities exist today that are critical for good science that can't easily be moved to the pulsed power driver (e.g., LCLS, APS-DCS, MaRIE). Interest in bringing the driver to the diagnostic?
  - What is interest of this community in such ideas?
    (e.g., a ~0.5 Mbar materials driver at the MEC station at LCLS?)

There could be several ways to get academic access to intermediate-scale facilities—we need your help to think through the pros and cons

- Draft proposal is to build a materials-centric “capacity” facility at labs. Could make academic access and shot time a priority
- Draft proposal to refurbish the 5-6 MA SATURN facility at Sandia. Could make improving its capabilities for academic users and giving them access a priority
- LLE has proposed building an intermediate scale capability coupled to the Omega-EP laser.
- Others?

The changing international landscape in pulsed power could play a role in our strategic planning thoughts



* English language or English-indexed journals only

<u>Top 5 Institutions (1996-2006)</u>

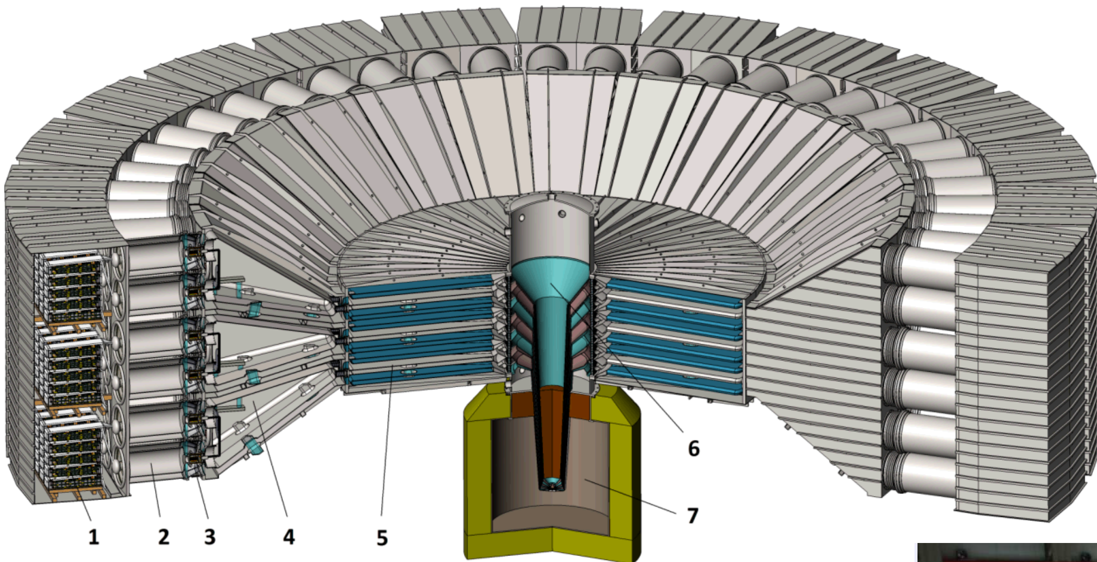
Sandia Natl. Labs: 135
Russian Acad. Sci.: 71
USN: 63
LANL: 46
Univ. Cal. LANL: 44

<u>Top 5 Institutions (2011-2016)</u>

Hauzhong Univ. Sci. & Tech.: 78
Sandia Natl. Labs: 56
Xi An Jiao Tong Univ.: 56
Chinese Acad. Sci.: 55
Tsinghua Univ.: 54

We engaged with Russia in 1996-2006 on LTD technology and joint research. Should we be engaging with China going forward???

Both China & Russia have communicated plans for large-scale pulsed power for multi-MJ fusion yields



Russian Facility (Baikal)

- 50 MA, 150 ns, 100 MJ (4 x Z)
- Stated goal: 25 MJ fusion yield
- Original completion by 2019…
- …but with collapse of oil prices activity in Russia has slowed for past two years!

Operating Chinese Facility (PTS)

- 8 MA, 100 ns, 8 MJ (1/3 x Z)
- Successfully duplicating previously published work
- Built a 1 ns, 1 kJ laser facility like Z-Beamlet
- Evaluating LTD and Marx-based architectures. CAEP told visitors in May that they are requesting a 50 MA facility to be built ~10 years from now

Recent Chinese review articles suggest they have had an active effort in pulsed power at CAEP since early 1960s for radiography, EM launch, high-power microwaves, free electron lasers, materials science, and environmental/medical science (i.e., not just fusion research!)

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2760 IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 43, NO. 8, AUGUST 2015

Overview of Pulsed Power Research at CAEP

Jianjun Deng, Jinshui Shi, Weiping Xie, Linwen Zhang, Suping Feng, Jin Li, Meng Wang, Lianshen Xia, Zhiyong Dai, Hongtao Li, Qin Li, Long Wen, Sifu Chen, Xin Li, Ziping Huang, Qingui Lai, Kaizhi Zhang, Minghe Xia, Yongchao Guan, Songyi Song, Lin Chen, Ce Ji, Liangji Zhou, An He, Wenkang Zou, Xianbin Huang, Shaotong Zhou, Zhaohui Zhang, Siqun Zhang, Xiaobing Ren, Bing Wei, Qing Tian, Anming Yang, Hong Li, Min Xie, Jinfeng Liu, Chenggang Ma, Xun Ma, Wei Wang, Guiji Wang, Libing Yang, Yuanchao Gu, Yi He, Chenggang Li, Yiwei Zhou, Zhanji Zhang, Guangshen Dai, Huacen Wang, Nianan Chen, Chengjun Liu, Chengwei Sun, Zhou Xu, Fanbao Meng, and Hongke Ma

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MATTER AND RADIATION AT EXTREMES
Matter and Radiation at Extremes 1 (2016) 48–58
www.journals.elsevier.com/matter-and-radiation-at-extremes

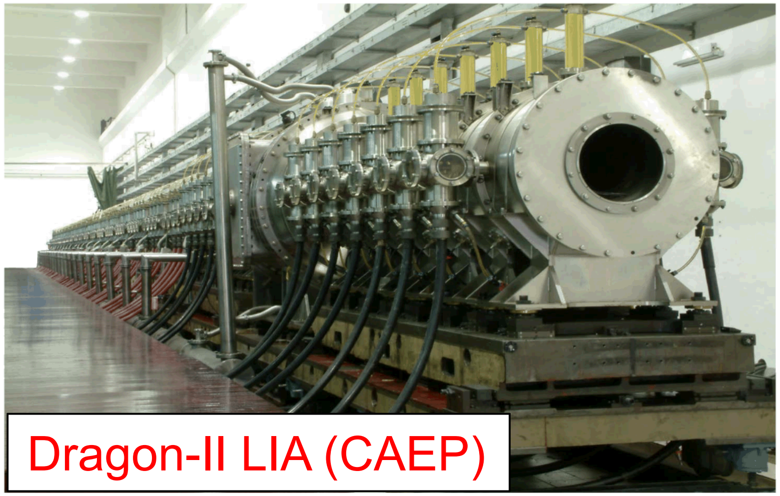
From concept to reality — A review to the primary test stand and its preliminary application in high energy density physics

Jianjun Deng*, Weiping Xie, Shuping Feng, Meng Wang, Hongtao Li, Shengyi Song, Minghe Xia, Ji Ce, An He, Qing Tian, Yuanchao Gu, Yongchao Guan, Bin Wei, Xianbin Huang, Xiaodong Ren, Jiakun Dan, Jing Li, Shaotong Zhou, Hongchun Cai, Siqun Zhang, Kunlun Wang, Qiang Xu, Yujuan Wang, Zhaohui Zhang, Guilin Wang, Shuai Guo, Yi He, Yiwei Zhou, Zhanji Zhang, Libing Yang, Wenkang Zou**

Key Laboratory of Pulsed Power, Institute of Fluid Physics, China Academy of Engineering Physics, Mianyang 621999, China

Available online 27 January 2016

The CAEP has developed a radiographic capability that on paper exceeds the capabilities of DAHRT-II in the U.S.



J.J. Deng *et al.*, presentation at ICMRE (2016).

S. Nath, LINAC2010 Proceedings

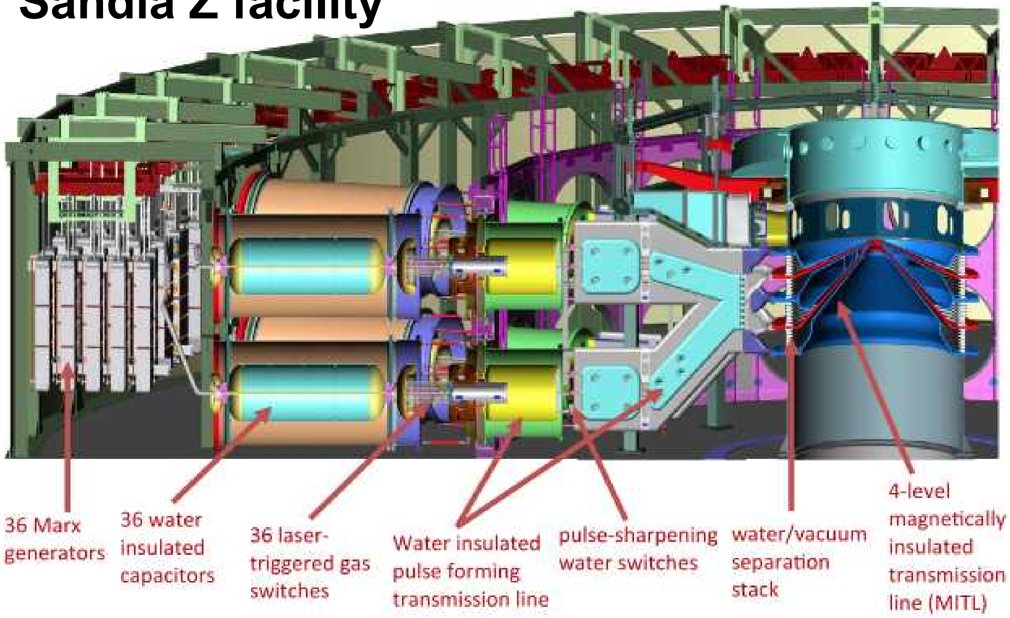
Dragon II	DARHT II (LINAC 2010)
Three electron-beam pulses	One long electron-beam pulse
80 LIA cavities	74 LIA cavities
900 kg/cavity	7300 kg/cavity
0.724-m-diameter cavity	1.85-m-diameter cavity
19 MeV, 19 MeV, 19 MeV	16.5 MeV
2.1 kA, 2.1 kA, 2.1 kA	2.0 kA
1.3-, 1.4-, 1.6-mm spot sizes	1.55-, 1.75-, 1.78-, 1.6-mm spot sizes
65-, 75-, 75-ns pulses	

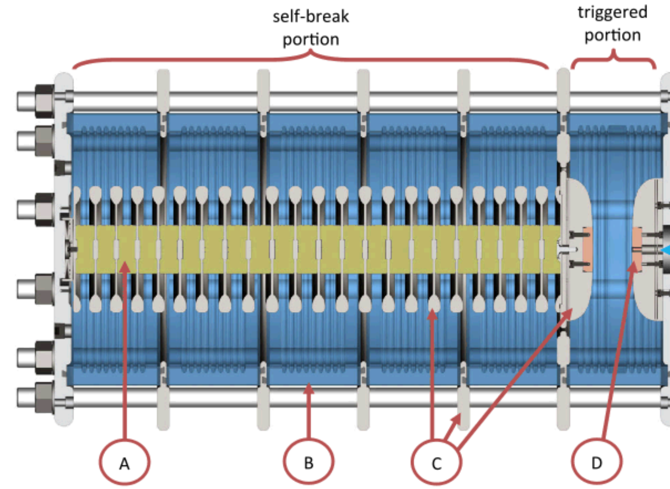
Summary courtesy of W.A. Stygar, who attended the ICMRE.

Deng stated that a Dragon-II publication was in preparation.

The CAEP's Primary Test Stand (PTS) facility shows remarkable similarity in design to Z/ZR

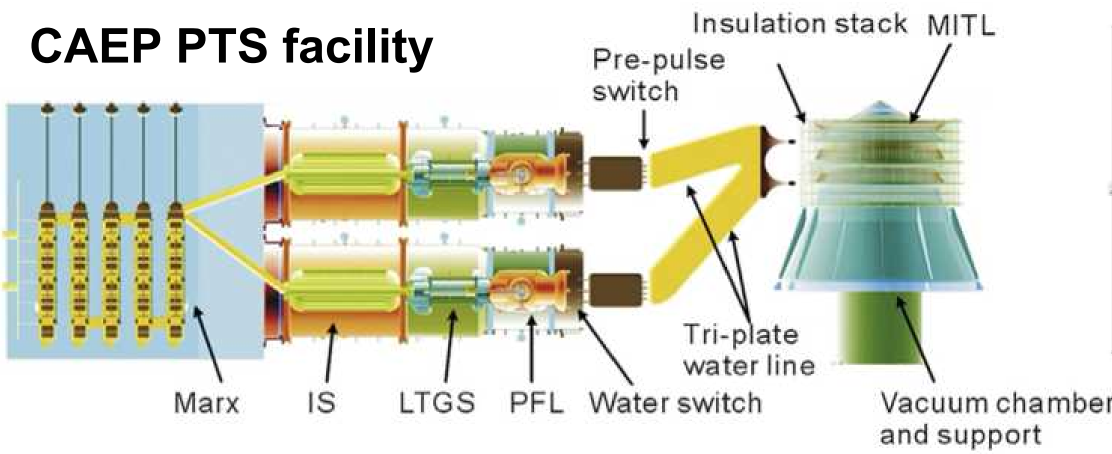
Sandia Z facility

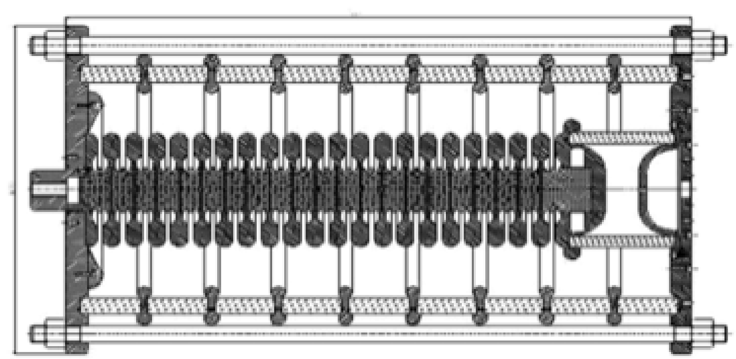




6.1-MV, 0.79-MA Laser-triggered gas switch
K.R. LeChien *et al.*, PRSTAB (2010).

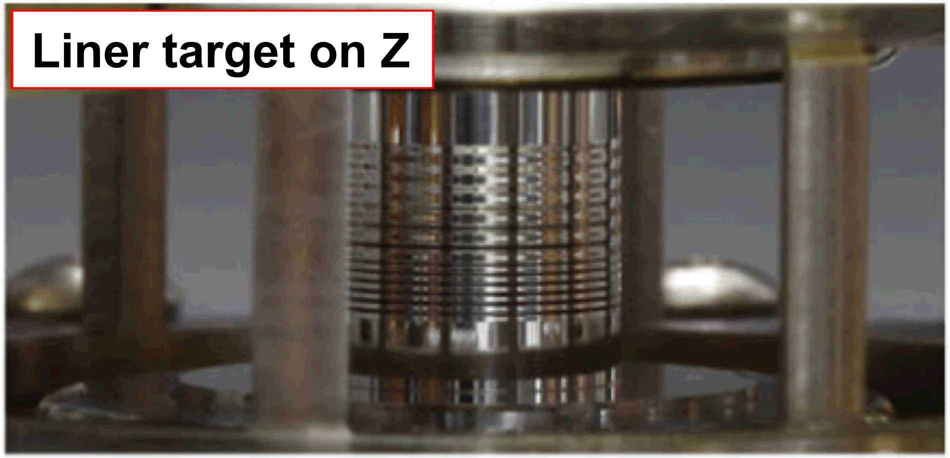
CAEP PTS facility



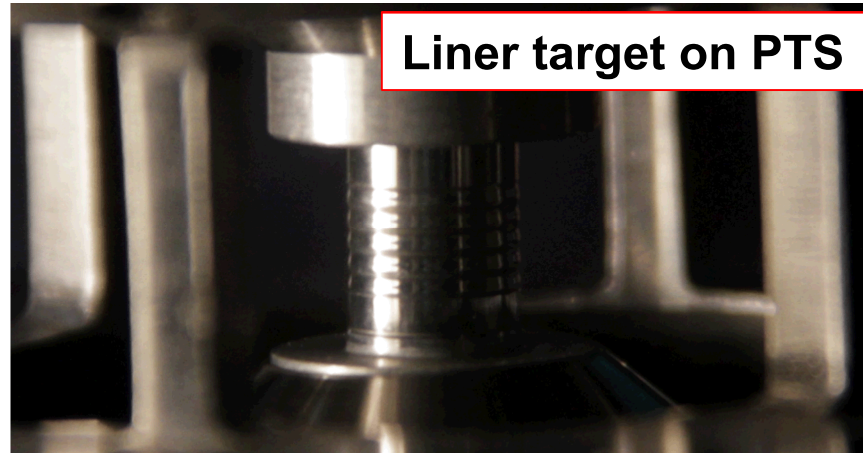


5.0-MV, 0.5-MA Laser-triggered gas switch
J.J. Deng *et al.*, MRE (2016).

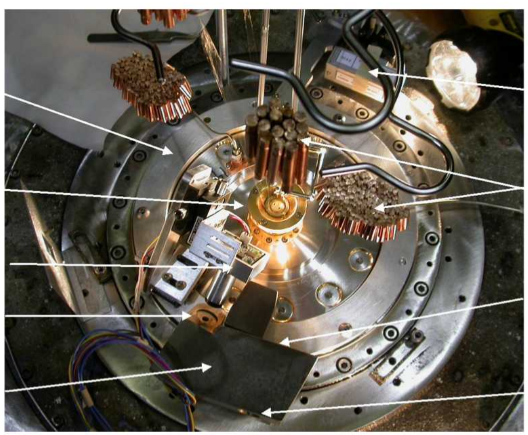
The CAEP is duplicating Sandia's facilities, diagnostics, and experiments (e.g., built 1 kJ, 1-TW, Nd:glass laser for PTS)



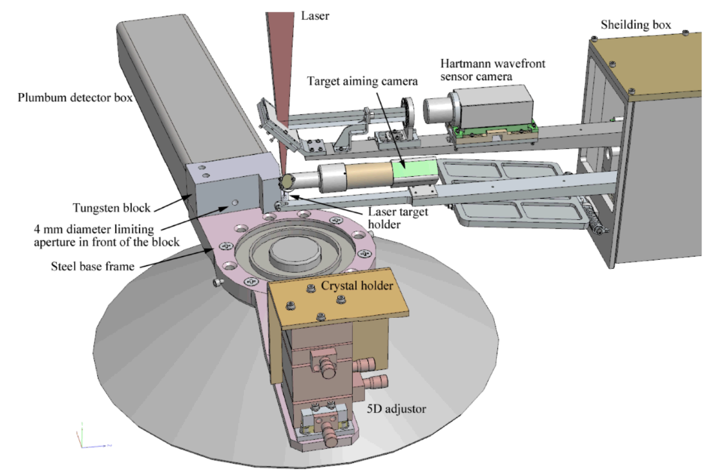
D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).



Q. Yang *et al.*, Rev. Sci. Instrum. (2016).



D.B. Sinars *et al.*, Rev. Sci. Instrum. (2004).
1.865 & 6.151 keV Spherical Crystal Imager
Supported by Z-Beamlet: 1-2 kJ, 1-TW Nd:glass laser



Q. Yang *et al.*, Rev. Sci. Instrum. (2016).
1.865 keV Spherical crystal imager
Supported by KLS: 1 kJ, 1-TW Nd:glass laser

What role can academia play in helping to ensure that our country remains a strong player in pulsed power?

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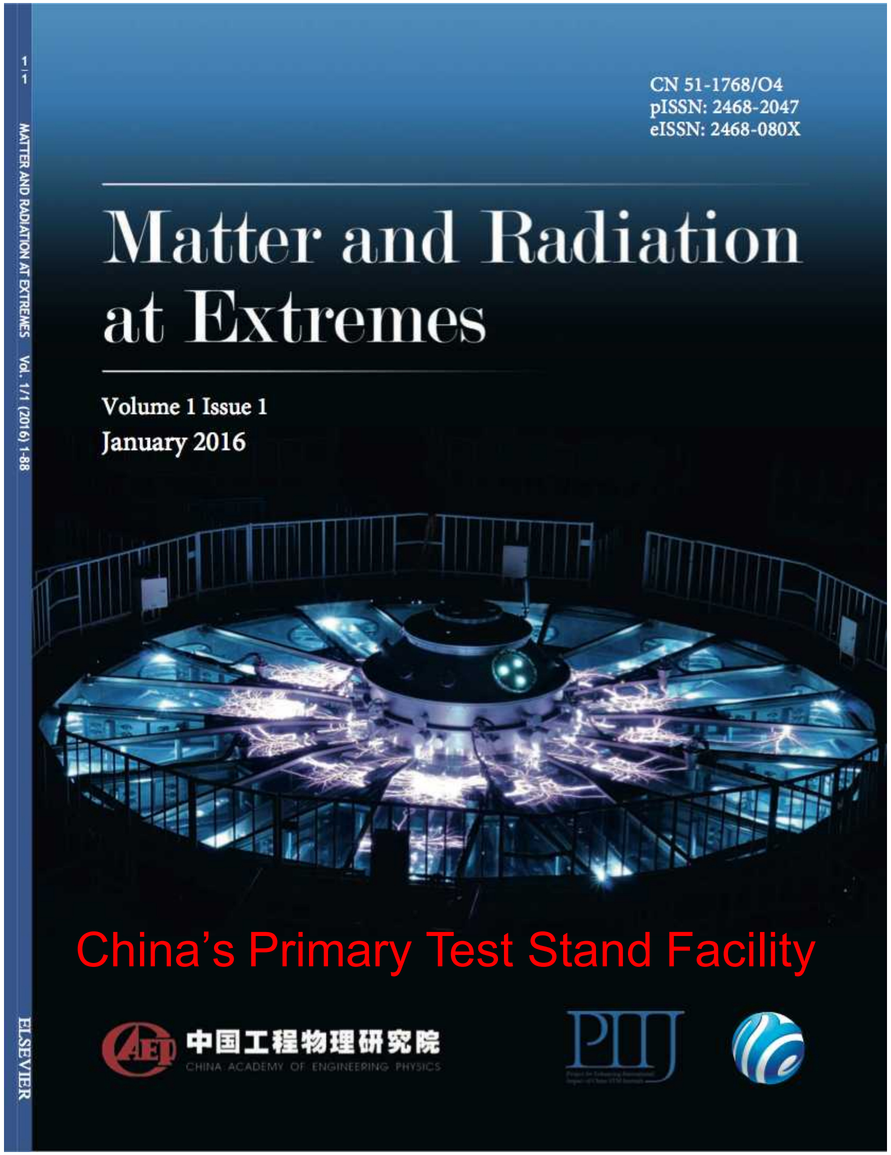
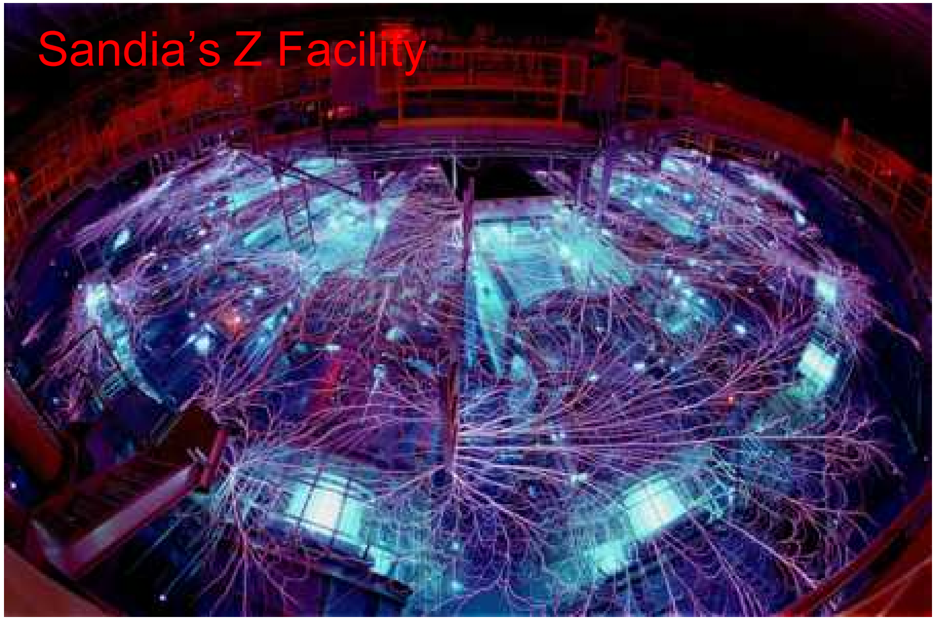


Sandia Z facility:
26 MA, 110 ns rise time, 36 modules
Z conversion 1996, Z refurbished 2007

CAEP PTS facility:
10 MA, 90 ns rise time, 24 modules
China's first multi-module PP facility
Project started in 2002, 1^{st} shot in 2013



We want your thoughts and input!

- Goal of today is to capture initial debates and discussion from those who were able to participate in today's workshop
- We are open to further comments and thoughts, especially from your colleagues and friends that could not make it today
- While a report is due to the NNSA by August 18, it will mainly be focused on "needs". Proposals, solutions, and other ideas will still be welcome after that.
- Feel free to contact me to express your thoughts: dbsinar@sandia.gov; (505) 284-4809