

Advanced Energy Conversion (AEC) Project NASA Glenn Research Center

Lattice Confinement Fusion (LCF) Overview

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L. Dudzinski (NASA HQ)

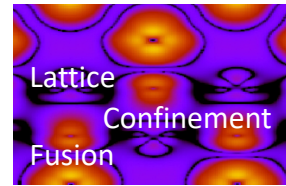
Contributing Panelists

M. Forsbacka (NASA HQ) and R. Litchford (NASA HQ)

August 19, 2020

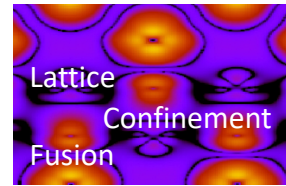


Overview



- **AEC Project**
 - Project Charter
 - Project Objectives Met
 - Bremsstrahlung Initiated Nuclear Reactions in Deuterated Metals, *Animation*
- **LCF Virtual Workshop Executive Summary**
 - Workshop Objectives Met
 - Process and Theory
 - Bremsstrahlung Irradiation Team On-Site, *Animation*
 - *Physical Review C* Papers
 - Past and Present Partners
 - Publications and Patents
- **Workshop Feedback**
 - Panelists
 - Attendees
- **Path Forward**
 - Mechanisms and Modeling
 - Development Approaches
- **Conclusion**
- **Acknowledgments**

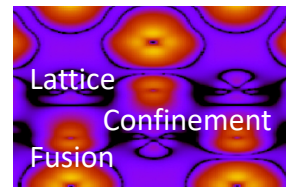
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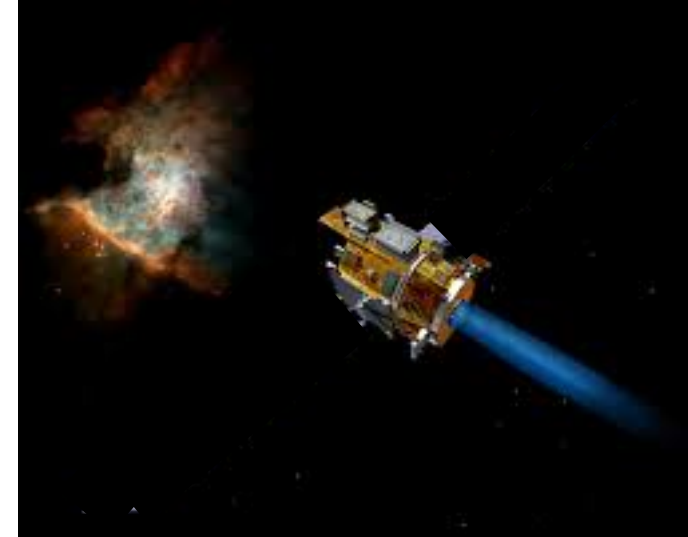
Advanced Energy Conversion (AEC) Project



AEC Project Charter



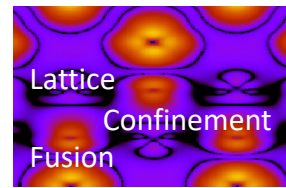
- **Overall Goal:**
 - Power/energy sources for long-duration deep space mission
- **Initial Research Objectives:**
 - No solar energy
 - Non-radioactive starting materials
 - No actinide fission/decay-based solution
 - Benign operations
 - >10 yr lifetime
 - Power < kW_e level
 - Space rated systems: weight/watt
- **SMD requirement:**
 - Understand, demonstrate and publish bremsstrahlung-initiated sub-barrier nuclear reactions to validate approach.



**NO CONVENTIONAL
ENERGY SOURCE EXISTS
TODAY TO MATCH THESE
REQUIREMENTS**



AEC Project: Objectives Met

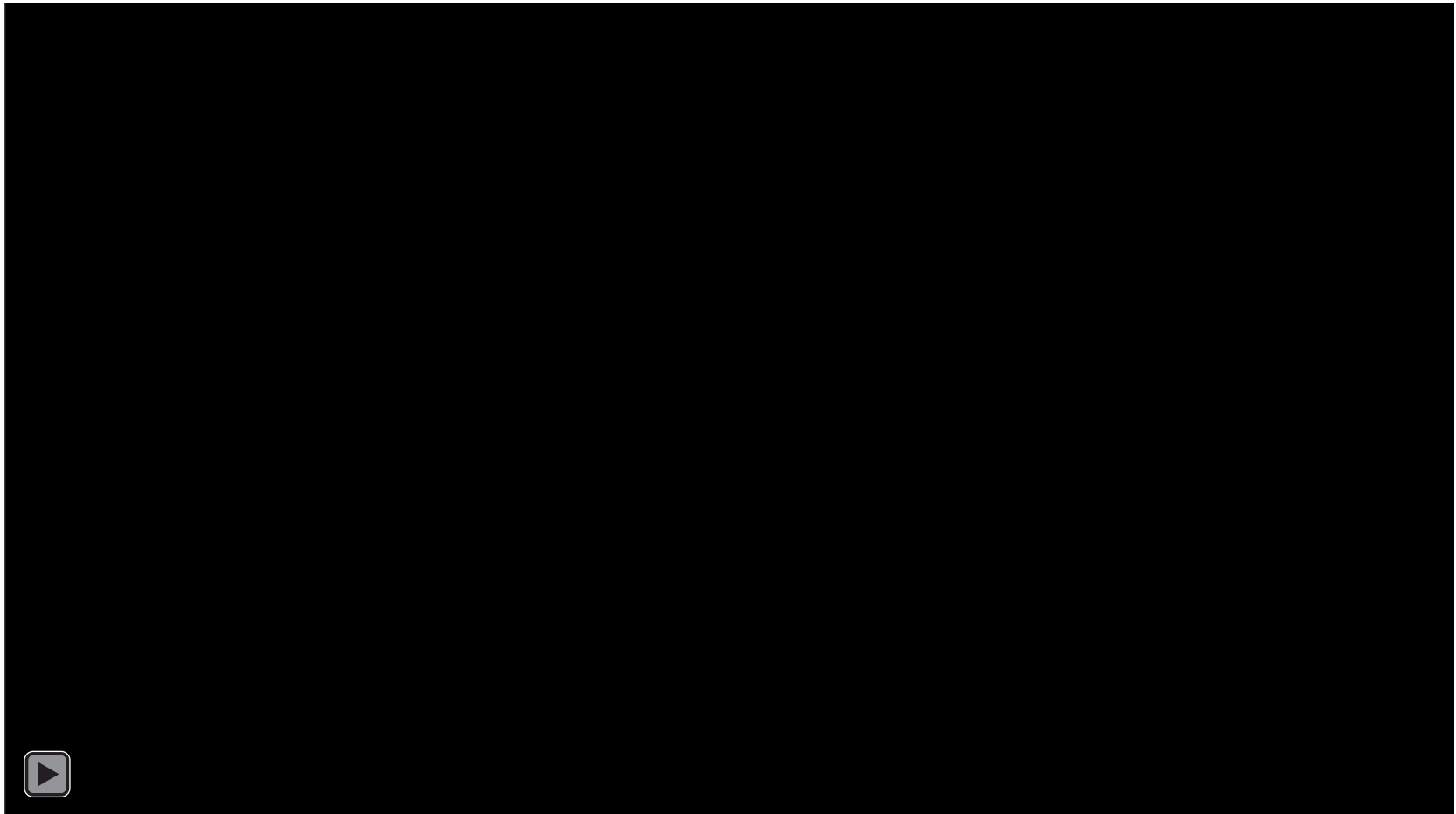
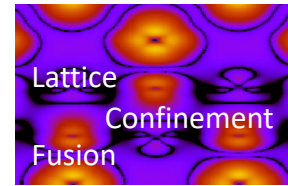


- **Demonstrated Sub-barrier Fusion**
 - ✓ Lattice Electron-screened, bremsstrahlung-photoneutron initiated nuclear reactions
 - ✓ Lattice Confinement Fusion, boosted fusion, stripping reactions
- **Results Published in *Physical Review C***
 - ✓ Theoretical: electron screening enhancement, neutron heating
 - ✓ Experimental: bremsstrahlung photo-neutron initiated, repeatable LCF
- **Demonstrated Non-actinide Fission**
 - ✓ Transmutation of Pd and Ag
 - ✓ ICP-AES, TOF-SIMS, SEM/EDX, **observed non-actinide fission products**
- **Demonstrated Excess Power in Metal Deuterides**
 - ✓ US Navy Dahlgren/NASA AEC Partner using JWK Co-dep patent
 - ✓ Comparison of thermal power/gram:

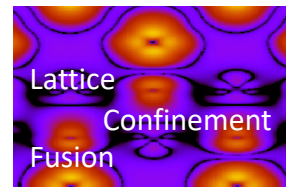
• ^{238}Pu thermal decay	0.54	W_t/gm	(continuous)
• Pd/Rh/Li deuteride	15.0 - 90.0	W_t/gm	(continuous but unoptimized)
• ^{235}U thermal fission	1.0	MW_t/gm	(if all fissioned)
 - ✓ ICP-AES, XPS, TOF-SIMS, SEM/EDX, **observed non-actinide fission products**
- **Also Demonstrated Depleted Uranium (^{238}U) Activation and Fission**
 - *Bremsstrahlung-initiated, hybrid fusion-fast-fission*
 - *Modeled fission and activation with MCNP-6*



Bremsstrahlung-Initiated Nuclear Reactions in Deuterated Metals



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LCF Virtual Workshop *Executive Summary*

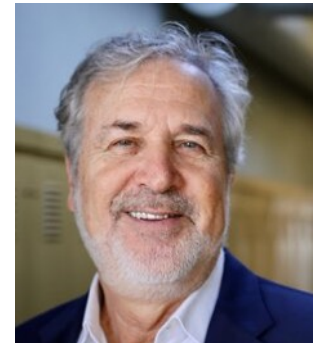
Dr. Bruce Steinetz, Senior Technologist
Dr. Arnon Chait, Dr. Vlad Pines and Dr. Marianna Pines
Senior Scientists
NASA GRC



Dr. Bruce Steinetz
Principal Investigator



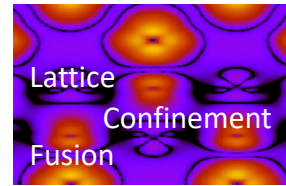
Dr. Vlad Pines and Dr. Marianna Pines
Theory



Dr. Arnon Chait
Theory



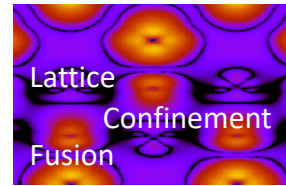
LCF Workshop: Objectives Met



- ✓ **Objective 1: Disseminate AEC Project Findings**
 - NASA Glenn Research Center (GRC) disseminated key findings in the *Phys Rev C* journal papers through a virtual Workshop
 - 70+ attendees including four NASA panelists
 - Emphasized electron screening enhanced nuclear fusion in a confined deuterated lattice initiated by photo-neutron heating
- ✓ **Objective 2: Challenge the Findings**
 - *Panelists concluded theory and experiment were sound*
 - Panelists suggested paths forward from science to technology to engineering
 - Feedback from other attendees



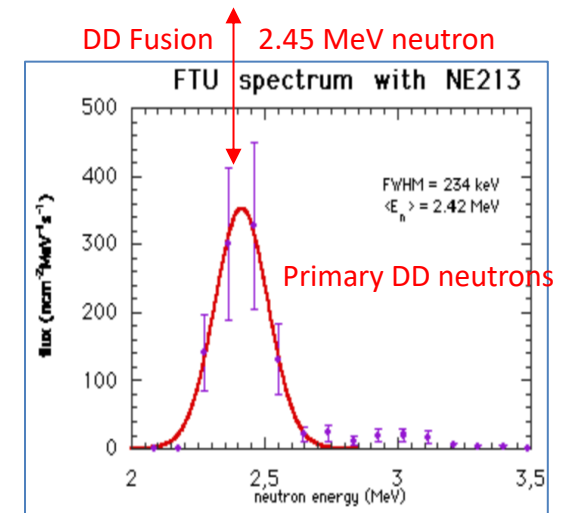
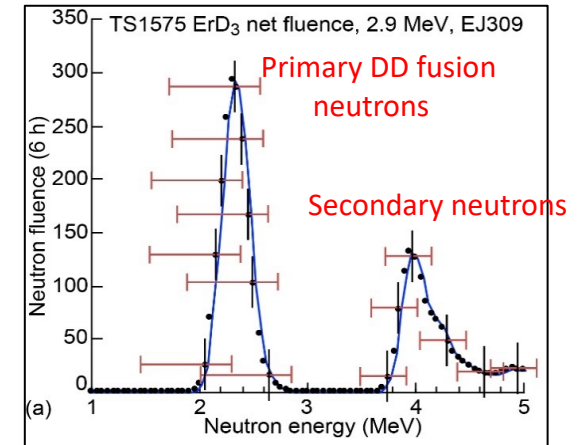
Executive Summary



- **Successfully induced nuclear reactions by novel methods**
 - High Energy Drivers
 - Bremsstrahlung: x-ray and gamma (70 keV – 15 MeV)
 - Ebeam: SEM, eGun, accelerator (5 kV – 6 MV)
 - Low Energy Drivers
 - Electrolytic loading (< 30 V)
 - Glow/Plasma Discharge (500 eV – 7 keV)
 - Johnson-Mathey deuterium cycling (< 2 eV)
- **Nuclear emissions observed: neutrons, protons, tritons, alphas, ^3He**
 - Transmutations including tritium
 - Actinide and non-actinide particle capture and fission demonstrated
 - Excess power observed (with US Navy, 15 – 90 W_t/gm)
- **AEC Project**
 - Developed critical expertise in experiment and theory
 - Experiment: *Co-deposition and photon stimulation highly reproducible.*
 - Theory: *driven by astrophysics and accelerator electron screening experiments*
- **Related Work**
 - US Navy partners and US Army participating with Navy
 - DoE LBNL reproduced related work with glow/plasma discharge
- **Compact, low power, space-rated accelerators make bremsstrahlung-boosted sub-critical reactors possible combined with other methods**

Demonstrated “hot” d-D fusion in “cold” fuel (deuterated metal) under bremsstrahlung radiation

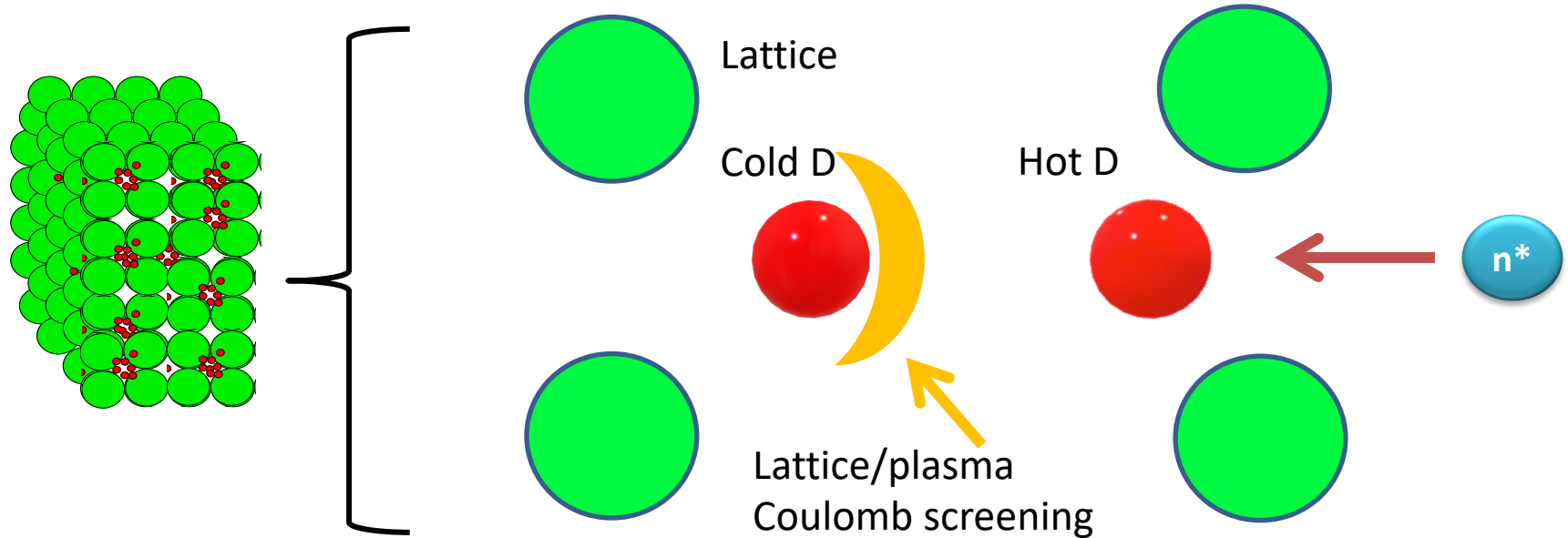
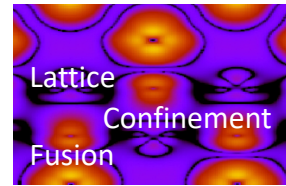
Theoretical model predictive of observed reactions



Italian ENEA-Fusion Tokamak¹

¹“Neutron spectrum in FTU ohmic discharges” Fig 10,
<https://www.afs.enea.it/basilio/neutronica/Neutroni.htm>

Lattice Confinement Fusion: Process Description

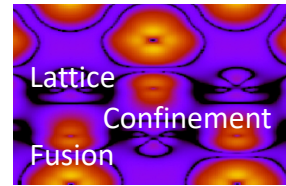


- Reactions are highly localized: majority of the fuel is **cold**
- D-D interactions are highly screened: **most favorable large/small angle scattering probability** → highest nuclear tunneling probability
- Most efficient means to heat fuel – **neutrons** – for high tunneling probability
- **Only use energy to heat the projectile D via n^* , not the entire fuel D**
- **Process control** is possible through:
 - Rate and energy of neutron source; fusion process controllable via removing n^* source
 - Customizing fuel and lattice elements



Theory At a Glance

Neutron Heating and Electron Screening



- Large/small angle scattering
- Nuclear tunneling

- Essential role of electron screening in nuclear fusion: Seemingly negligible – but critical
- Unified formulation of all screening types: shell, conduction, plasma channels created by gamma and Compton electrons
- Increase in astrophysical factor $S(E)$ due to screening independently of its effect on tunneling
- Large/small angle scattering with screening for light/heavy charged particles and for neutrons
- Kinematic equations for calculations of all reaction product energies including subsequent events

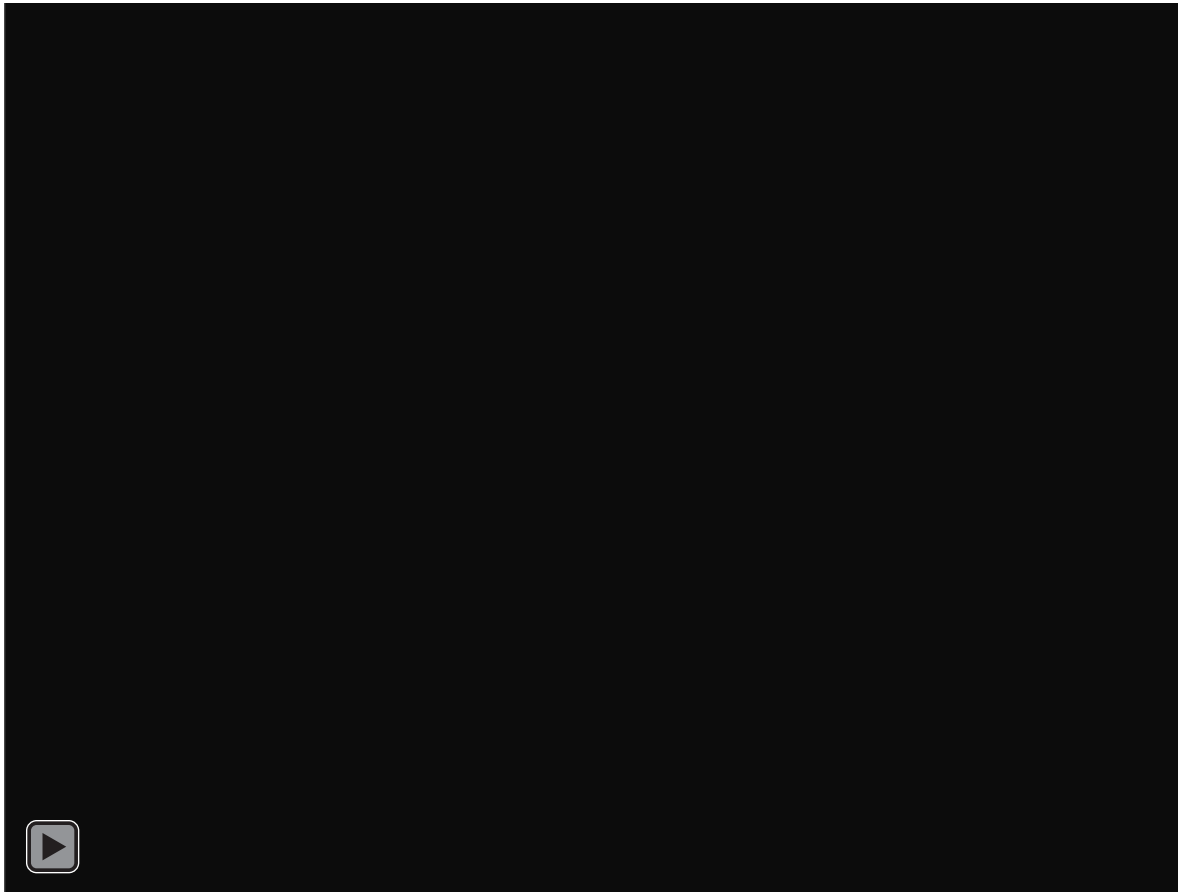
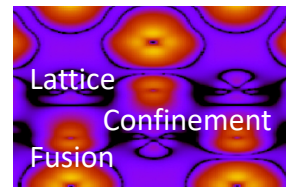
- Large/small angle scattering
- Lattice poisoning
- O-P reactions with hot D
- Multiplication events

Future Directions:

- Choice, source, and energy of neutral particles for mediating fusion
- Choice of lattice and fuel elements
- Scaling/multiplication processes



Bremsstrahlung Irradiation Team On-site

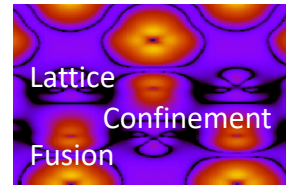


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Physical Review C Papers

Bremsstrahlung-induced Nuclear Reactions in Electron Screened, Deuterated Metal Lattices



Theoretical

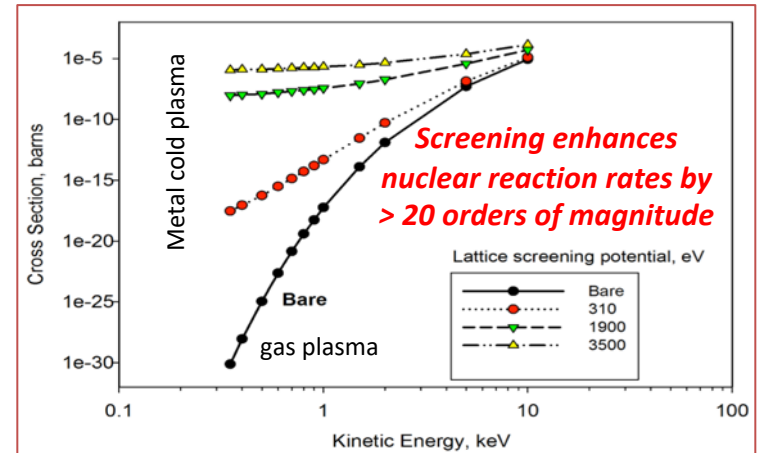
PHYSICAL REVIEW C
covering nuclear physics

Accepted Paper

Nuclear fusion reactions in deuterated metals
Phys. Rev. C

Vladimir Pines, Marianna Pines, Arnon Chait, Bruce M. Steinetz, Lawrence Forsley, Robert C. Hendricks, Theresa L. Benyo, Gustave C. Fralick, Bayarbadakh Baramsai, Philip B. Ugorowski, Michael D. Becks, Richard E. Martin, Nicholas Penney, and Carl E. Sandifer II

Accepted 10 December 2019



Electron Screened Enhanced Cross Sections



Experimental

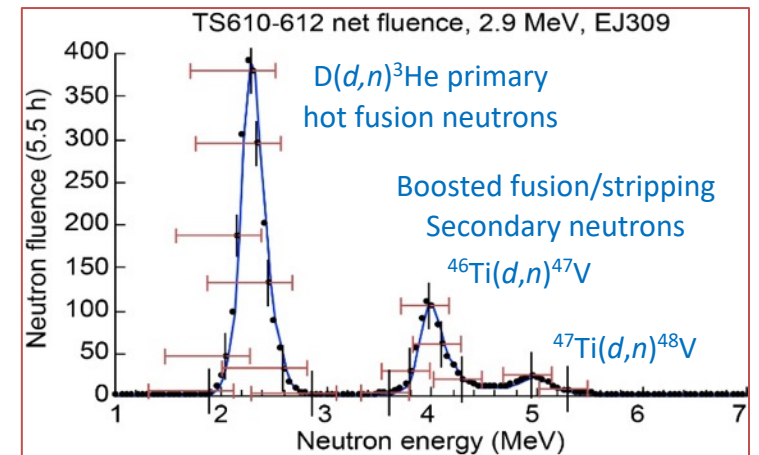
PHYSICAL REVIEW C
covering nuclear physics

Accepted Paper

Novel nuclear reactions observed in bremsstrahlung-irradiated deuterated metals
Phys. Rev. C

Bruce M. Steinetz, Theresa L. Benyo, Arnon Chait, Robert C. Hendricks, Lawrence Forsley, Bayarbadakh Baramsai, Philip B. Ugorowski, Michael D. Becks, Vladimir Pines, Marianna Pines, Richard E. Martin, Nicholas Penney, Gustave C. Fralick, and Carl E. Sandifer II

Accepted 6 December 2019



Fast Neutrons Observed

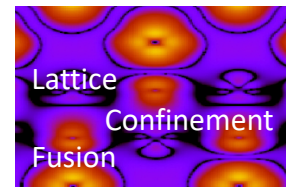
Lattice Confinement Fusion

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PRC Papers as NASA Technical Papers

Tables of Contents



Experimental Paper

Theory Paper

Summary	1
1.0 Introduction.....	1
2.0 Experimental Setup, Data Acquisition, and Analysis	2
2.1 Electron Accelerator and General Layout	2
2.2 Cave Description.....	3
2.3 Beam Characteristics.....	3
2.3.1 Photon Flux	3
2.3.2 Photodissociation Neutrons	4
2.4 Neutron Detection	4
2.4.1 Prompt Neutron Detection.....	4
2.4.2 Prompt Neutron Signal Postprocessing	4
2.4.3 Energy Calibration.....	5
2.4.4 Signal Filtering and Hybrid PSD Approach	5
2.4.5 Neutron Energy Determination.....	6
2.5 Sample Materials and Methodology.....	6
2.5.1 Sample Materials	6
2.5.2 Case-Control Methodology	6
3.0 Experimental Results.....	7
3.1 Pulse Shape Discrimination Spectra.....	7
3.2 Comparison of Fueled and Unfueled Results	7
3.3 Neutron Spectra and Process Reproducibility	8
3.4 Alternate Material Exposure: Titanium Deuteride	8
3.5 Comparison of TiD ₂ and ErD ₃ Neutron Production	9
3.6 Measurement Uncertainty	9
4.0 Discussion.....	10
4.1 Evidence of Fusion and Fast Neutrons	10
4.1.1 Fusion Neutrons.....	10
4.1.2 Efficiency of Detecting Fusion Neutrons.....	10
4.1.3 Other Enhanced Nuclear Reactions	10
4.2 Comparison of Current Deuteron Heating to Published Work	12
4.3 Comparison of Measured and Theoretical Calculations	12
4.3.1 <i>d</i> -D Fusion Rates, Calculation	12
4.3.2 <i>d</i> -D Reaction Rates, Experimental.....	12
5.0 Summary of Results.....	13
6.0 Future Work.....	13
References	13

Summary.....	1
1.0 Introduction	2
2.0 Nuclear Fusion Cross Section of Bare Nucleus Ions	2
3.0 Nuclear Fusion with Electron Screening	3
3.1 Coulomb Barrier Screening by Lattice Electrons.....	3
3.2 Coulomb Barrier Screening by Plasma Particles	5
3.3 Coulomb Barrier Screening by Conduction Electrons in Metal Lattice.....	8
3.4 Screening of Reacting Hydrogen Isotope Nuclei by Atomic Shell (Bound) Electrons in Deuterated Metals	8
4.0 General Screening Case For Reacting Hydrogen Isotope Nuclei	9
5.0 Coulomb Scattering on Target Nuclei	9
5.1 Light Particles Elastic Coulomb Scattering (e^- , e^+).....	9
5.2 Heavy Particle Elastic Coulomb Scattering (p , d , α)	11
5.3 Compton Scattering on Free Deuteron.....	12
6.0 Neutron Elastic Scattering on Deuteron Nuclei.....	14
7.0 Neutron Energy Loss in Elastic Collisions With Deuteron Nuclei.....	15
8.0 Summary of Results	16
References	16

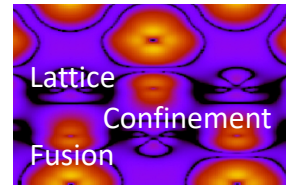
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NASA-TP-20205001616

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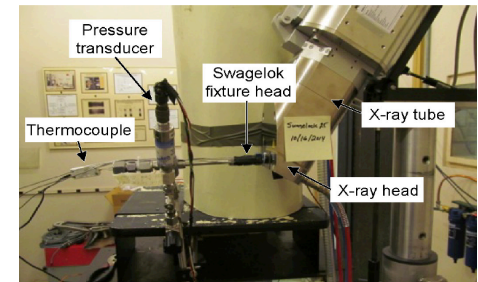
Past and Present Partners



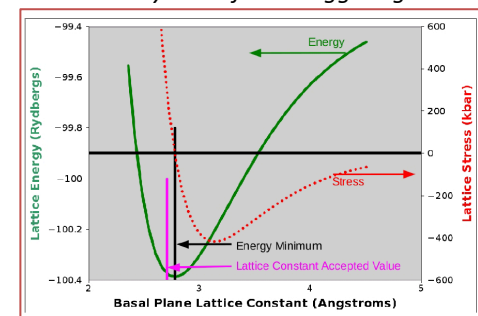
- **NASA Glenn Research Center (GRC)** Pre-AEC: (1989-2014)
AEC: (2014 -)
 - “Advanced Energy Conversion (AEC) Project”
 - Develop a non-actinide space power system
 - Understand Condensed Matter Nuclear Reactions
- **US Navy (SPAWAR)** (1989-2012)
 - NASA GRC and SPAWAR different processes, similar nuclear results
 - Additional funding provided by DTRA, ONR, DoE and NNSA
- **JWK/NAVY NCRADA (SPAWAR)** (2008-2012)
 - “Study of Low Energy Nuclear Reactions I & II”
- **JWK/NAVY NCRADA (China Lake)** (2010-2012)
 - “Metal Interactions with Low Z Gasses”
- **JWK/NAVY NCRADA (NSWC Dahlgren)** (2015-)
 - “LENR Materials Design and Characterization”
 - DFT Model of LENR Active Materials
 - Correlate Co-deposition and B Field effects
- **Univ of Maryland (Tim Koeth, PhD)** (2015-2016)
 - < 3 MeV LINAC unstable for our needs
- **DoE Jefferson National Lab** (2016-2017)
 - AEC Project schedule and JLAB schedule did not match up
- **DoE Argonne National Lab** (2017)
 - Van de Graaff generator unstable and did not meet our needs.
- **IBA Industrial** (2017-2018)
 - Hosted most recent AEC experimental activity with 3 MeV Dynamitron
- **JWK/NAVY NCRADA (NSWC Indian Head)** (2020-)
 - “Advanced Energy and Propulsion Research and Development”



US Navy SPAWAR
Pd/D Co-deposition and Patents



NASA GRC
X-Ray Microfocus Triggering

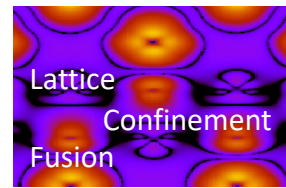


US Navy NSWC Dahlgren Division
Lattice Strain Modeling

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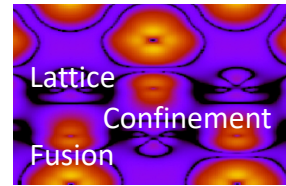
Conference Papers, NASA TM & TP Presentations, Patents and Patent Applications



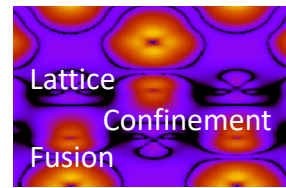
- US Patent 8,419,919, “System and Method for Generating Particles”, (2013)
- Benyo, T.L. *et al.*, “Investigation of Deuterium Loaded Materials Subject to X-ray Exposure”, NASA TM-2015-218491/REV1, (2015).
- Pines, V., *et al.*, “METHODS AND APPARATUS FOR ENHANCED NUCLEAR REACTIONS”, USPTO Application 20170263337 (2016).
- Steinetz, B., *et al.*, “Experimental Observations of Nuclear Activity in Deuterated Materials Subjected to a Low-Energy Photon Beam”, NASA TM-2017- 218963, (2017).
- Forsley, L., “Space Power: The Genie Fast-Fission Sub-Critical Core”, ANS, Nuclear and Emerging Tech. for Space, Las Vegas, NV (2018).
- Benyo, T.L., *et al.*, “Evidence of Electron-screened Oppenheimer-Phillips Reactions $^{162}\text{Er}(d,n)^{163}\text{Tm}$ or $^{162}\text{Er}(p,\gamma)^{163}\text{Tm}$ in Deuterated Materials Subjected to a Low-energy Photon Beam”, 9th Int. Particle Accelerator Conference, Vancouver, Canada, (2018).
- Benyo, T.L. *et al.*, “Gamma Energy Evaluation for Creation of $^{111\text{m}}\text{Cd}$, $^{113\text{m}}\text{In}$, and $^{115\text{m}}\text{In}$ Isotopes”, European Nuclear Physics Conference, Bologna, Italy, (2018). (refereed publication)
- Smith, P., “Permeation Rate Equations for Hydrogen and Deuterium in a Palladium-Silver Alloy”, NASA TM-2019-220189. (2019).
- Forsley, L., *et al.*, “Cryogenically Stable Propellant”, NASA Patent Disclosure 1568407350. (2019).
- Steinetz, B., *et al.*, “ Novel Nuclear Reactions Observed in Bremsstrahlung Irradiated Deuterated Metals”, *Phys. Rev. C* **101**, 044610 (2020) <https://journals.aps.org/prc/abstract/10.1103/PhysRevC.101.044610> NASA-TP-20205001616
- Pines, V, *et al.*, “Nuclear Fusion Reactions in Deuterated Metals”, *Phys. Rev. C* **101**, 044609 (2020) <https://journals.aps.org/prc/abstract/10.1103/PhysRevC.101.044609> NASA-TP-20205001617



Papers and Patents in Process



- Fralick, G., *et al.*, “Transmutations Observed from Pressure Cycling Palladium Silver Metals with Deuterium Gas”, *Journal submission*.
- Baramsai, B., *et al.*, “Fast Neutron Spectroscopy with Organic Scintillation Detectors in High Radiation Environments”, *In revision*.
- Ugorowski, P., *et al.*, “Fast Neutron Spectroscopy with a Volumetrically-Sensitive, Moderating-Type Neutron Spectrometer in a High Radiation Environment”, *In revision*.
- Smith, P., *et al.*, “Bubble Detector Neutron Dosimeter Measurements During Electrolytic Co-Deposition”, *In review*.
- DeChiaro, L.F. and Forsley, L.P., “A Summary of Density Functional Theory Calculations in Selected Binary and Ternary Metal Alloys and Hydrides”, *Joint Navy/NASA Technical Report in review*.
- DeChiaro, L.F., *et al.*, “A Multi-Laboratory Study of Anomalous Elements and Magnetic Field Orientation Effects in LENR Codeposition Experiments”, *Joint NAVY/NASA Technical Report in review*.
- DeChiaro, L. F., *et al.*, “Method for Improving Nuclear Reactions by Modified Magnetic Fields”, *Disclosed and patent to be filed*



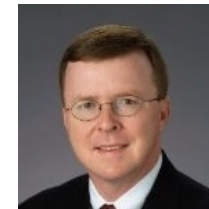
Panel and Attendee Feedback



Theresa Benyo, PhD; Panel Moderator
Analytical Physicist, Materials & Structures Division
NASA GRC



NASA Glenn Research Center
May 21, 2020

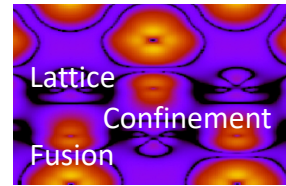


Panel Members:

Matt Forsbacka NASA HQ, Michael Houts NASA MSFC,
Ron Litchford NASA HQ, John Scott NASA- JSC



Panelist on Experiment – Phys Rev C 101, 044610 (2020)



- **Meticulous Execution & Attention to Details**
 - Configuration & Set-up
 - Material Characterization
 - Measurements (methods, accuracy, calibration, statistics, etc.)
 - Signal Discrimination & Potential Spoofing Effects
- **Interpretation**
 - Well Characterized Neutron Production Rates & Energy Spectrum
 - Demonstrated Reproducibility (multiple ErD_3 & bare Er experiments)
 - Theoretically Framed Analysis & Interpretation of Results
 - Neutron Production: Screening enhanced fusion & other enhanced nuclear reactions
 - Comparison of Theory & Experiment: Reasonable agreement & discrepancy rationale
 - Compelling Evidence for Electron Screening Enhanced LCF Hypothesis

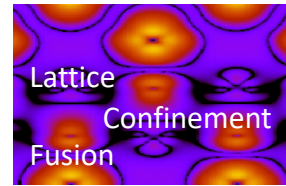


*Ron Litchford, PhD, Aerospace Engineering, Univ. of Tenn. Space Institute
Principal Technologist NASA STMD, HQ*

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Panelist on Theory – **Phys Rev C 101, 044609 (2020)**



- **Novel Physical Mechanisms & Methodically Crafted Theory**
 - Rooted in Well Established Foundational Physics – ***No Magic Required!***
 - Solid Physical Rationale for Simplified Parameterization
 - Electron Screening Parameters: U_e & λ_{sc}
 - Coulomb Barrier Tunneling Probability Enhancement Factor: $f(E)$
 - Exhaustive Evaluation of Contributing Mechanisms & Non-Ideal Effects
 - Enhanced Coulomb Barrier Screening Mechanisms
 - Enhanced Probability of Large-Angle Coulomb Scattering
 - Enhanced Secondary Nuclear Reactions
 - Rigorous Deductive Formulation – Technical Physics Tour de Force
 - No Unexplained Leaps in Logic
 - Careful Examination of Assumptions & Implications
 - Enables “a priori” Predictions Based on Known or Estimable Parameters
 - Testable & Verifiable!

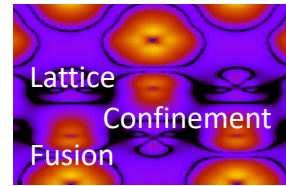


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Panelist on Tidying Up - Future Work



- **Tidying Up**

- Resolve Masking Effects from Competing LCF Processes
 - Fine Grain Quantification of Primary/Secondary Contributing Mechanisms
- Resolve Lattice Structure Effects – Potential Tuning Knobs
 - Fuel Loading Optimization – Super Packed Fuel Density
 - Screening Dependencies – Lattice Scales, Void Fraction, Defects, Dislocations, Grains
 - Engineered Lattice Assemblies – Atomic Layer Deposition & Epitaxial Growth Methods
- Resolve Fusion Reaction Energetics & Overall Fusion Power Yield
 - Multiple Fusion Reaction Branches

- **Future Work**

- Gain & Power Scaling
- Assembly Configurations & Process Optimization
- Evaluation of Technical Application Scenarios
- Reduce to Engineering Practice

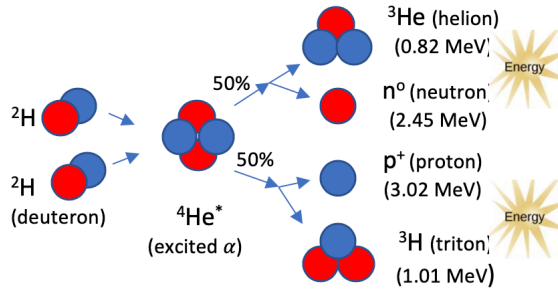
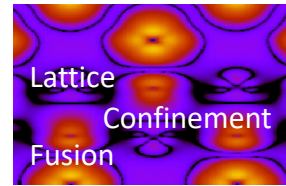


Ron Litchford

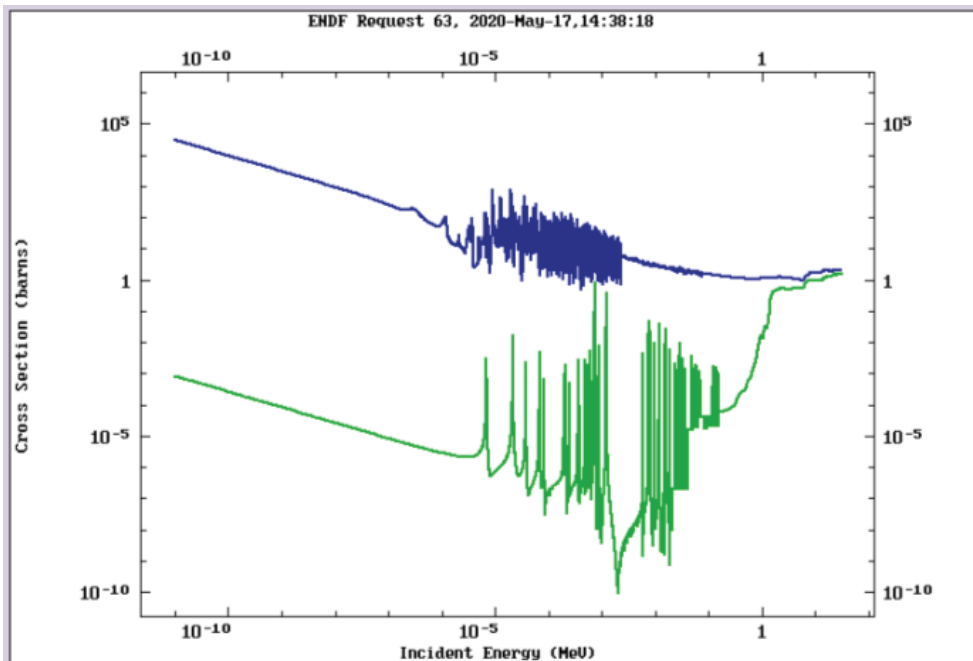
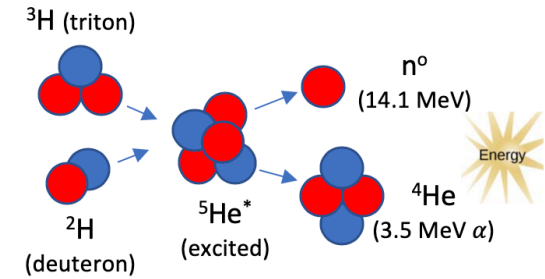
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Panelist on Fusion-Fission-Fusion: A Symbiotic Relationship?

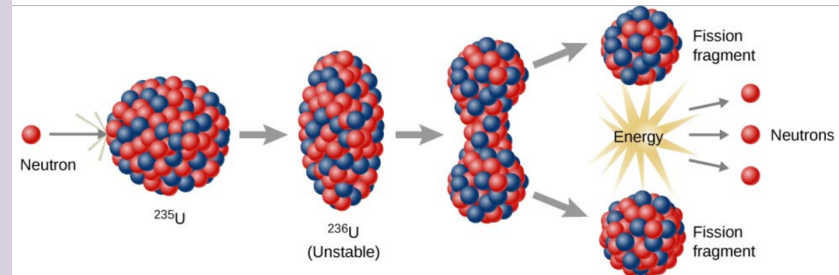


And/Or?



Select data for plotting [all] [none]
☒ 1) ENDF/B-VIII.0: U-235(N,F)
☒ 2) ENDF/B-VII.1: U-238(N,F)
☐ 3) Use my data [example][2]
☒ Use my control file [init] [help]
See: plotted data (1972Kb) out: e6 json+

+prompt and delayed gammas



<https://opentextbc.ca/universityphysicsv3openstax/chapter/fission/>

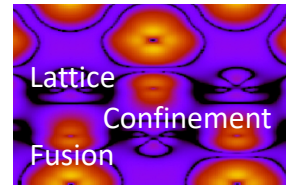
Matt Forsbacka, Ph.D. Nuclear Engineering, Univ. of Virginia
NASA Director, Safety and Assurance Requirements Division (SARD), HQ

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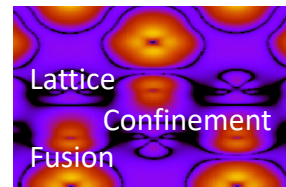


Attendees' Comments



- “I wish to thank you and all of the panelists yesterday for the superb and compelling presentations. As a former advisor to the director of NASA Glenn (Larry Ross) and the NASA Administrator (Dan Goldin), I feel some of the pride that must permeate the Glenn experimental / theory teams. The work is outstanding.”
- [Arden Bement](#), Ph.D.
(former NSF, NIST Directors, DoD Deputy Undersecretary for Research and Advanced Technology)
- “The powerful impact comes from having both experiment and theory in 2 separate papers that should always be read together: the sum of both (together) of the two is greater than the individual sum of the parts since they compliment each other.”
- [Michael R. Staker](#), Ph.D., P.E.,
(Professor, Dept. of Engineering, College of Arts and Science, Loyola University, MD)
- “Thank you for inviting me to attend yesterday’s briefing. The team has made remarkable progress during these last few years in the conduct and findings of the experimental work along with its theoretical underpinnings. Congratulations to you all for your impressive advances!”
- [Michael Salamon](#), Ph.D. (former Program Scientist, NASA HQ)
- “Fun event, very nice presentations and discussions. Will be great to see follow ups to this work (e. g. ideas for next experiments, cross checks, etc). Also an interesting example of a targeted workshop in the "new normal" of no or hardly any travel, which we might be stuck in for a while.”
- [Thomas Schenkel](#), Ph.D. (Senior Scientist, Physicist, Accelerator Technology and Applied Physics, DoE LBNL)
Observed electron screened LCF, published in [Nature](#) and [Journal of Applied Physics](#)
- “Really terrific session, thank you! I congratulate you and your team, and look forward to your further successes!!”
- [Curt Brown](#), CEO, (PointSource Energy)
- “Thanks for including me in the virtual workshop today. I was glad to hear that other labs are working in the area of LCF. Verification by independent sources was mentioned by a nuclear scientist friend as an important step in gaining acceptance of LCF.”
- [Frank Lynch](#), CEO (Hydrogen Components, Inc.)

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Lattice Confinement Fusion (LCF) Workshop

The Path Forward

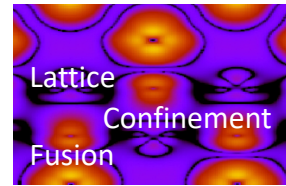
Lawrence Forsley
Senior Lead Experimental Physicist
Global Energy Corporation

NASA Glenn Research Center
Advanced Energy Conversion Team
May 21, 2020



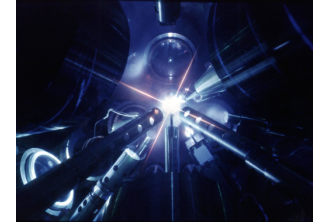
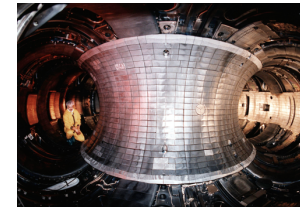


Comparing Fusion Methods



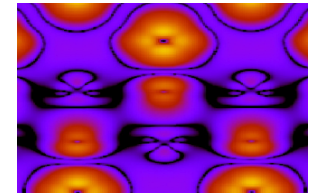
- **ICF: Inertial Confinement Fusion** (e.g. laser fusion)
 - Laser ablation compression “match”
 - “Alpha Heating”: $d(d,n)^3\text{He}(d,p)\alpha(d,\alpha')d^*(d,n)^3\text{He}$
 - *Inefficient small-angle scatter alpha heating.*
- **MCF: Magnetic Confinement Fusion** (e.g. tokamaks)
 - RF, Ohmic heating, neutral beam “match”
 - “Alpha Heating”: $d(d,n)^3\text{He}(d,p)\alpha(d,\alpha')d^*(d,n)^3\text{He}$
 - *Inefficient small-angle scatter alpha heating.*
- **LCF: Lattice Confinement Fusion** (e.g. $\gamma\text{:TiD}_2$ and $\gamma\text{:ErD}_3$)
 - Bremsstrahlung γ photoneutron “match”
 - “LCF Cascade”: $d(\gamma,p)n(d,n')d^*(d,n^*)^3\text{He} \rightarrow d(n^*,n')d^{**}(d,n^{**})^3\text{He}^*$ and so on
 - *Efficient large angle scatter with momentum transfer* from fast neutrons and screened quasi-neutral charged particles.

TFTR (MCF)¹



Omega (ICF)²

AEC (LCF)³



Type	Density ions/cm ³	Ion _T (keV)	n mean free path	radius active region	Confinement Time
ICF	10 ²⁶	3 - 10	<40 μm	< 100 μm (core)	nanoseconds
MCF	10 ¹⁴	1 - 10	10 km	meters	seconds
LCF	10 ²³	64	1 cm	> 1 cm	indefinite

No fusion without electrons!

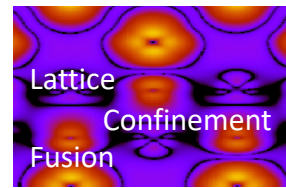
¹ [https://commons.wikimedia.org/wiki/Category:Tokamak_Fusion_Test_Reactor#/media/File:U.S._Department_of_Energy_-_Science_-_114_035_002_\(14281232230\).jpg](https://commons.wikimedia.org/wiki/Category:Tokamak_Fusion_Test_Reactor#/media/File:U.S._Department_of_Energy_-_Science_-_114_035_002_(14281232230).jpg)

² https://upload.wikimedia.org/wikipedia/commons/8/86/U.S._Department_of_Energy_-_Science_-_282_022_002_%2816502292185%29.jpg

³ Dechiaro, L.F. et al., “Strained Layer Ferromagnetism in Transition Metals and its Impact upon Low Energy Nuclear Reactions”, *JCMNS*, **17** (2015) p. 10.

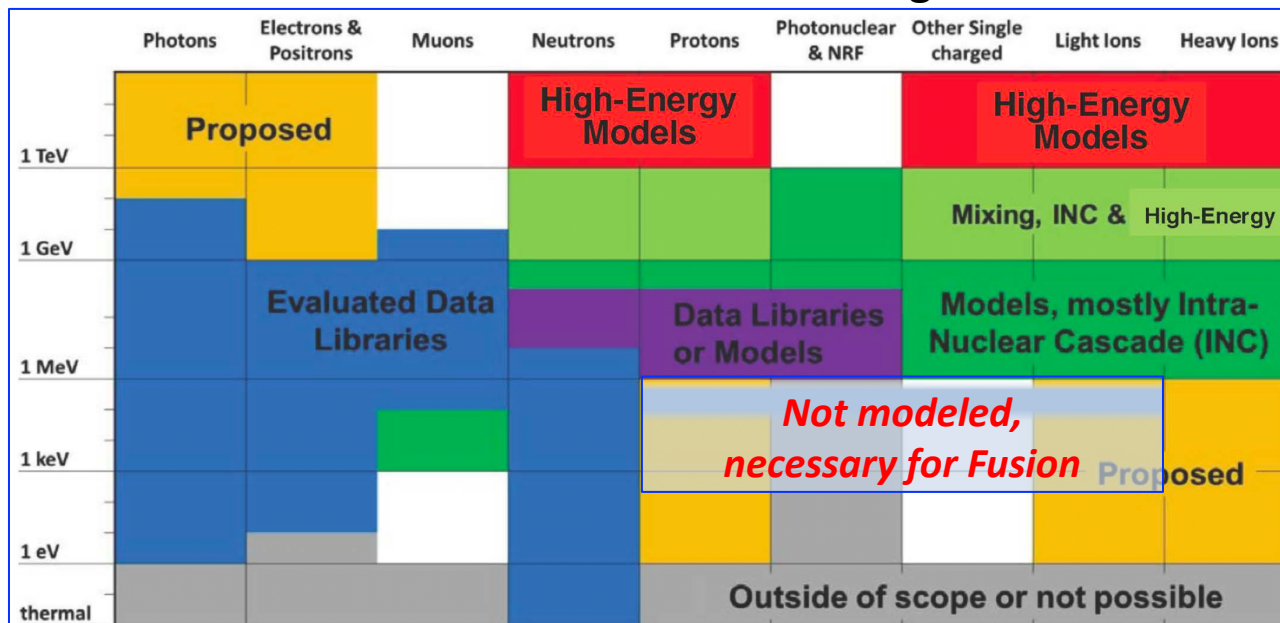


Nuclear Reaction Modeling



- Model charged, neutral and lattice element interactions.

MCNP Particle Interaction Modeling Domains¹



Neither LANL MCNP-6.x nor CERN GEANT-4 Monte Carlo nuclear codes handle heavy charged particles < 1 MeV nor electron screening effects.

- Acquired MCNP subroutines designed for ITER gas plasma to handle DD, DT and D³He fusion from 10 keV- 50 keV with charged particle scattering using SRIM/TRIM tables.
- Then modify for lattice scattering.
- Add PRC Theory Paper enhancement factor, $f(E)$, electron screening to equivalent 1 keV deuteron KE.
- With DFT and DMFT modeling to calculate electron screening < 1 keV.
- Test against LBNL plasma/glow discharge 1.2 keV c.m. Ion_7 fusion results.

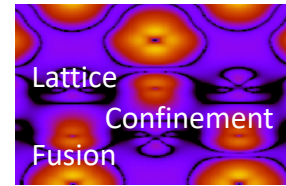
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¹Hughes, H. Grady III and James, Michael R." MCNP6 Class", LANL, LA-UR-14-21281 (2014)

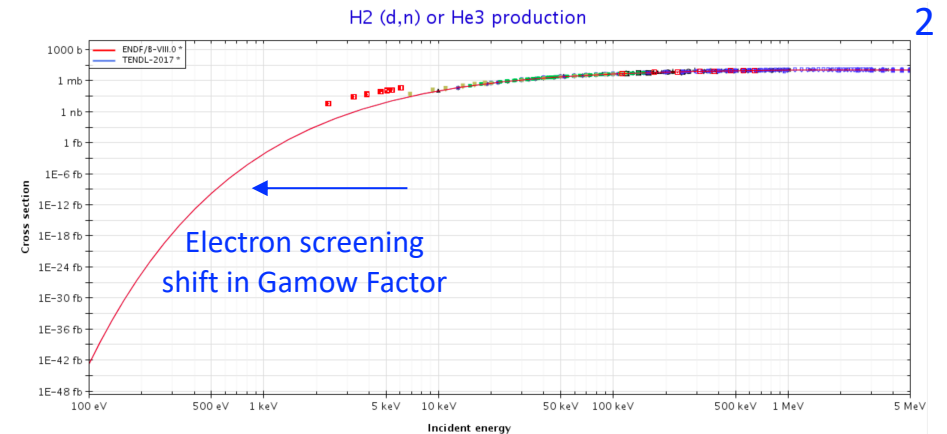
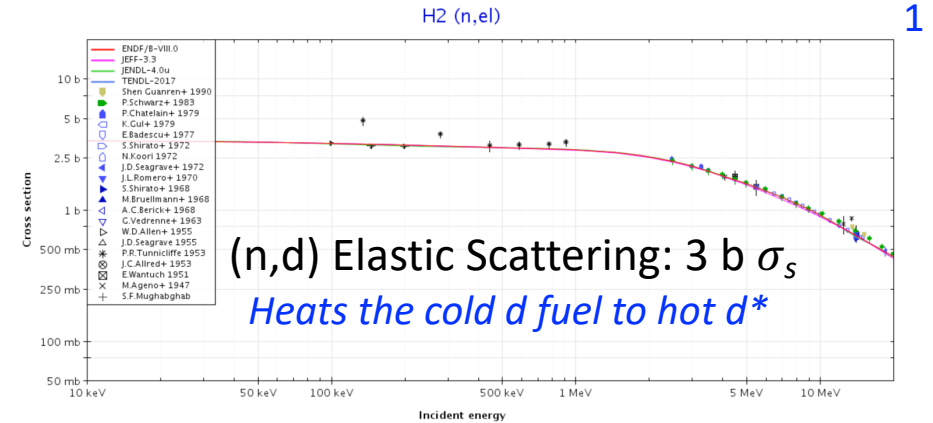


Neutron Cross-Sections

Deuteron Heating (σ_s) & Fusion (σ_f)



- The neutron mean-free path at various energies defines the size of the prospective reactor.
- The lattice materials influence neutron:
 - Mean-free path via density and scattering cross-sections
 - Energy by the same
 - Capture cross-sections
- Both MCNP and GEANT-4 codes handle neutron energies from thermal (.025 eV) to > 1 GeV
- Modeling predicts the neutron economy: *losses vs production*
 - Not unlike conventional reactors*



d*d Fusion: << fb to < 1 b σ_f

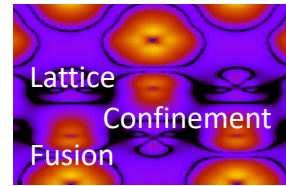
But, electron screening increases probability!

¹<http://www.oecd-neo.org/janisweb/book/neutrons/H2/MT2/renderer/452>
 Retrieved May 20, 2020.

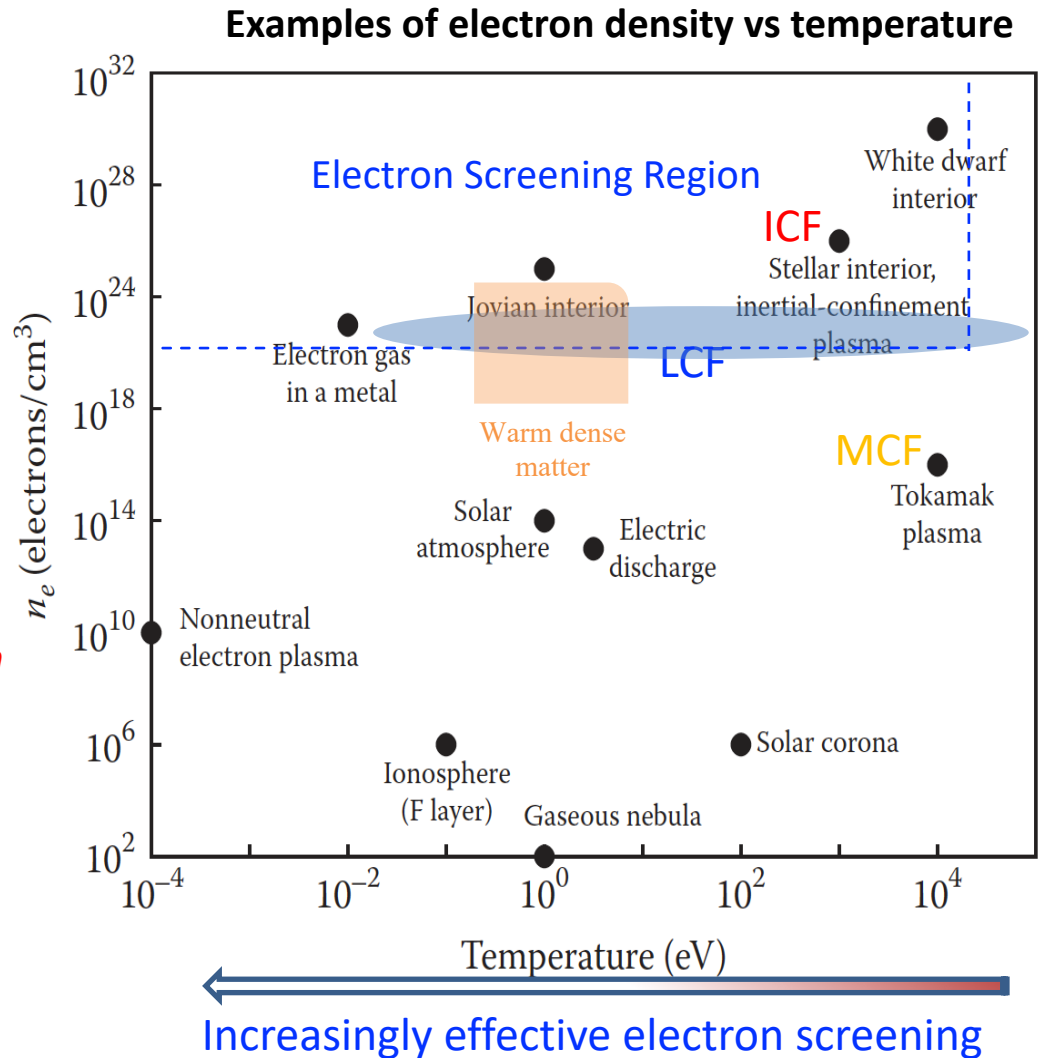
²<http://www.oecd-neo.org/janisweb/book/deuterons/H2/MT4/renderer/532>
 Retrieved August 17, 2020.



Electron Screening: Metals, Jovian-like Planets and Stars

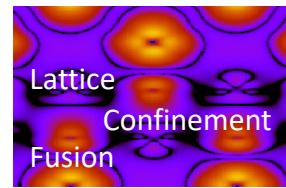


- Fermi Degeneracy occurs with $\approx 10^{23}$ electrons/cm³:
 - White Dwarf stars
 - Gas giant planets
 - Metals
 - LCF deuterated lattices
- Fermi Degeneracy is relatively temperature insensitive.
- LBNL results published in *Nature* and the *Journal of Applied Physics* attribute a **100-fold increase in fusion rates due to electron screening at only 1.2 keV c.m.**
- Screening is most effective < 10 keV.
- LCF straddles hot fusion and electron screened regimes.
- LCF is laboratory astrophysics.**



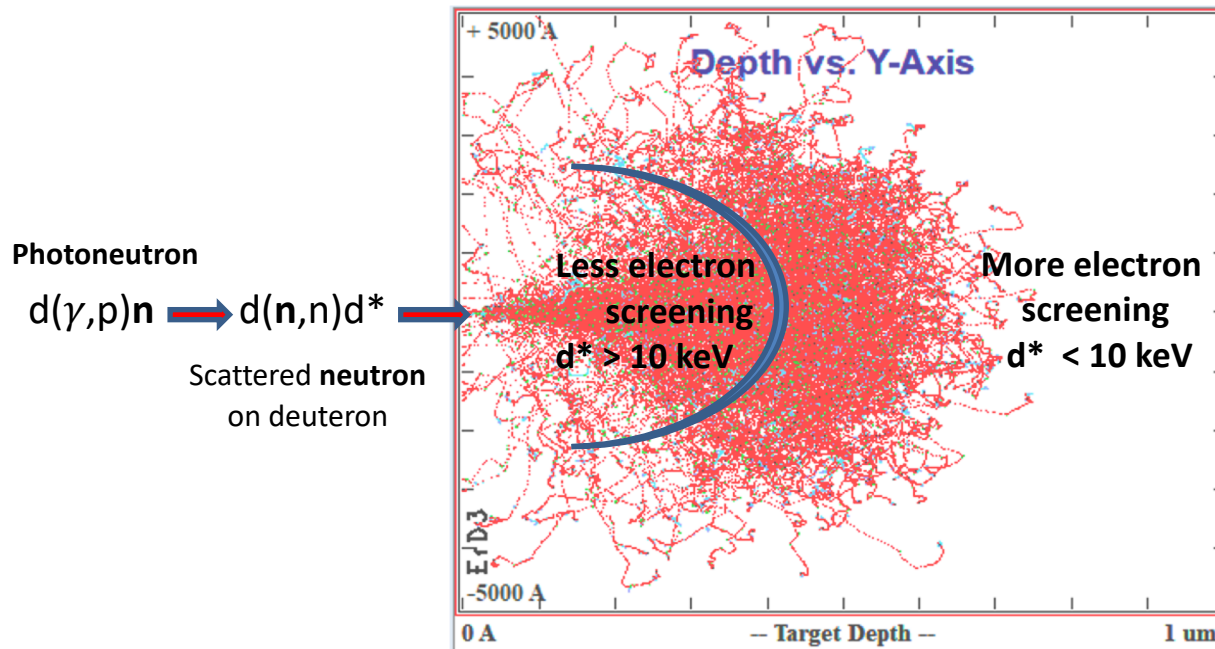


Electron Screening: LCF Deuteron Slowing in Deuterated Lattice



SRIM/TRIM¹ Ion Transport in Matter Model of 64 keV d* Ions slowing in ErD₃ Lattice

10³ particles tracked



Calculation Parameters		
Backscattered Ions		22
Transmitted Ions		0
Vacancies/Ion		29.9
ION STATS		
	Range	Straggle
Longitudinal	4358 Å	1315 Å
Lateral Proj.	1392 Å	1707 Å
Radial	2197 Å	1061 Å

Runs of 10³ and 10⁴ particles have similar spatial trajectories and energy distributions.

Induced metal vacancies provide additional deuteron interaction sites.

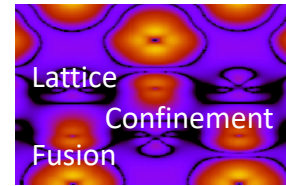
1. 2.9 MeV bremsstrahlung deuteron photo-neutrons on average transfer 64 keV to cold deuterons.
2. d* ion loses energy by ionizing lattice atoms producing free electrons and *plasma screening*.
3. When d* energy drops below 10 keV electron screening predominates.
4. Eventually *all 64 keV d* slow down by Linear Energy Transfer (LET) to below 10 keV.*
5. *Except when nuclear interactions occur resulting in MeV reaction products.*

¹Ziegler, James F. ; Ziegler, M. D. ; Biersack, J. P., "SRIM - The stopping and range of ions in matter", *Nuclear Instruments and Methods in Physics Research Section B*, **268**, (11-12), p. 1818-1823. (2010)

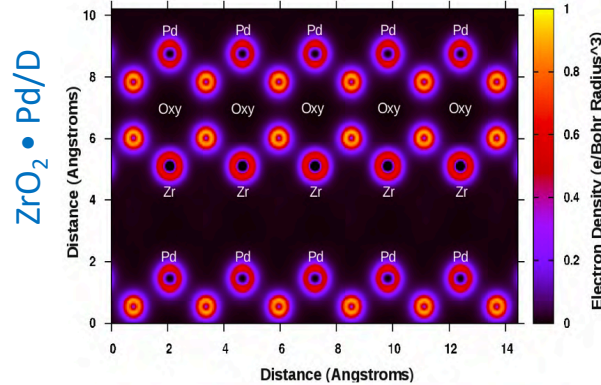


Alternative Electron Screened LCF Driver

Lattice Effects via Density Functional Theory

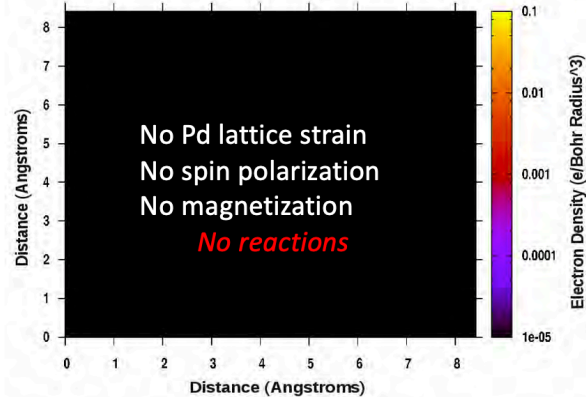
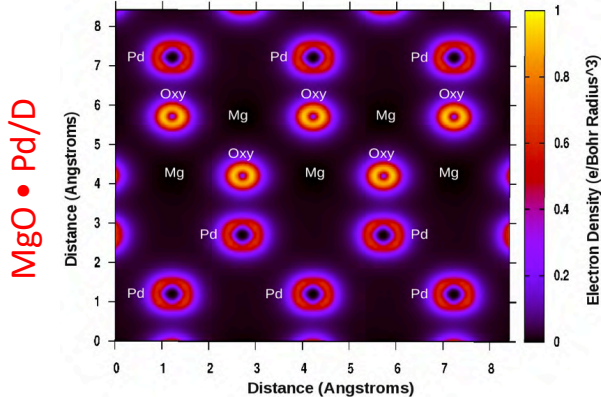
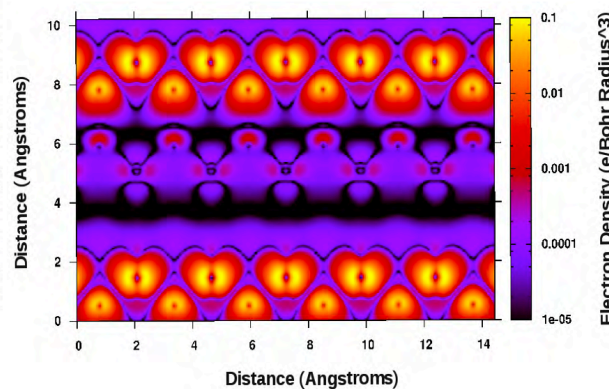


Electron charge density



Electron Spin Polarization

Magnetization



DFT modeling summary

Strained Pd lattice

ZrO₂ and PdD electron charge density with *spin polarization* and *significant magnetization*.

Iwamura observed⁴ *nuclear reactions*.

*Strained lattices also exhibit electron screening.*³

Unstrained Pd lattice

MgO and PdD electron charge density but *No spin polarization* and *No magnetization*.

Iwamura observed *No reactions*.

Strain-Induced Ferromagnetic LCF Driver

¹ DFT modeling conducted by L.F. DeChiaro, Naval Surface Warfare Center, Dahlgren Division, using Quantum Espresso.

² L.F. DeChiaro, L.P. Forsley, and P.A. Mosier-Boss, "Strained Layer Ferromagnetism in Transition Metals and its Impact Upon Low Energy Nuclear Reactions", *JCMNS*, **17**, (2015) 1 – 27.

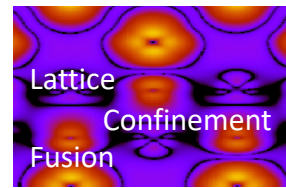
³ M. Lipoglavšek and U. Mikac, "Electron Screening in Metals", *AIP Conf. Proc.* **1377**, 383 (2011)

⁴ Y. Iwamura, et al., "Transmutation reactions induced by deuterium permeation through nano-structured palladium multilayer thin film", *Current Science*, **108**, 4, (25Feb2015).



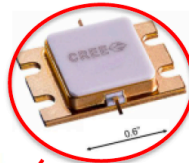
Bremsstrahlung/electron source for sub-critical reactor

Space-rated, 1.25 m relativistic e^- accelerator



We Believe 5-GHz Cavities Driven By Solid-State HEMTs Are A Practical Accelerator Technology For Space

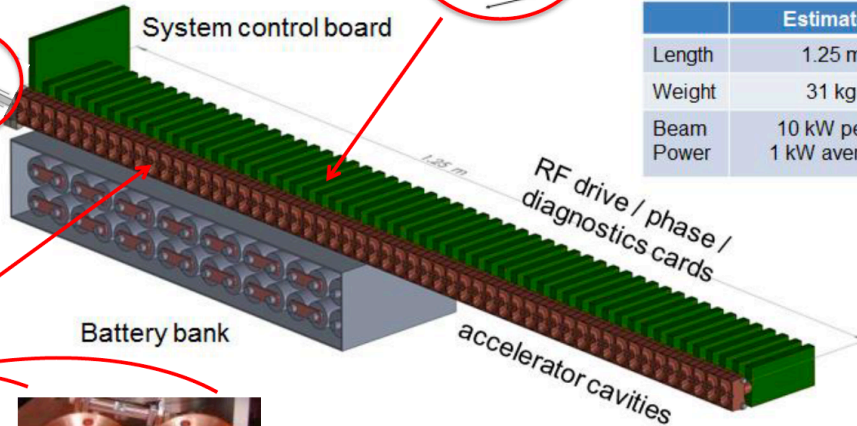
SLAC/LANL partnership developing accelerator-in-space technology (leads: Nguyen, Lewellen, Neilson)



50-V, 500-W, 50%-efficient HEMTs currently under radiation testing by LANL/Goddard

	Estimates
Length	1.25 m
Weight	31 kg
Beam Power	10 kW peak 1 kW average

Standard space-qualified technology for 10-kV DC electron gun



Battery bank



Stanford built and LANL characterized **10 stage, 190 keV accelerator 25 cm long. Operates from 50 V DC bus.**

AEC Sub-critical neutron driven hybrid reactor becomes realistic at 2.5 MeV, or ≈ 3 meters of HEMT accelerator cavity stages.

HEMT/cavity improvements may double the acceleration/stage cutting length in half: ≈ 1.5 m.

Accelerator enhanced electron screening¹ without neutron driver may be effective at 190 keV: Only 10 stages, 25 cm long!

UNCLASSIFIED

May 4, 2018 28



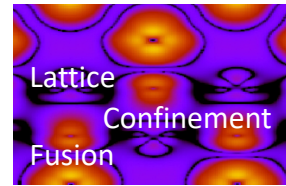
Joint NASA BeamPIE and CONNEX Missions with Stanford University and Michigan University,. Tested by NASA Goddard and Los Alamos National Laboratory. BeamPie sounding rocket Wallops launch scheduled for 4/21. (Blue Book 2020)

¹ Benyo, T.L. et al., "Investigation of Deuterium Loaded Materials Subject to X-ray Exposure", NASA TM-2015-218491/REV1, (2015)



The Path Forward:

Possible Development Approaches

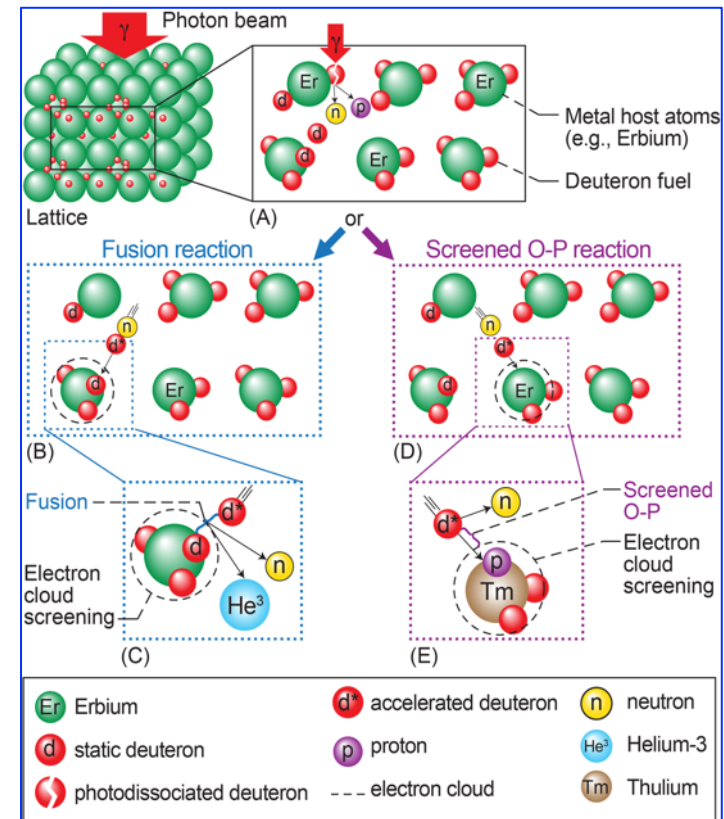


- **Use Existing NASA Infrastructure**
 - Thermoelectric and dynamic power conversion
 - Heat dissipation systems
 - Fit within mass/volume/power/radiation budgets
 - Test with existing 6 MV GRC Plum Brook LINAC
 - Degrade beam energy endpoint from 6 MV to < 1 MV with water table
 - Use Be photo-neutron source or AmBe/ ^{252}Cf for efficiency testing
 - Compare LCF Initiation
 - Photo-neutrons [e.g. $^9\text{Be}(\gamma, n)^8\text{Be} > 2 \alpha$]
 - Isotopic neutrons [^{252}Cf and AmBe]
 - < 1 MV electron screening [glow/plasma discharge, JM cycling, electrolytic]
- **Replace 93% ^{235}U with LEU ($< 20\%$ ^{235}U), DU ($< .2\%$ ^{235}U) or ^{232}Th**
 - Follow US Navy nuclear fleet recommendations¹
 - Provide alternative sub-critical reactor technology
 - *Bremsstrahlung-boosted, sub-critical reactor.*
 - AEC project demonstrated bremsstrahlung fission of DU
 - *Builds on success described in Phys Rev C papers.*

¹. “Low-Enriched Uranium for Potential Naval Nuclear Propulsion Applications”, JASON, JSR-16-Task-013, (November, 2016)

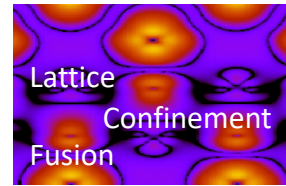
- **Demonstrated:**
 - Bremsstrahlung photoneutron initiated fusion in a “Globally Cold - Locally Hot” environment.
 - Process is repeatable and works with different lattice materials holding the deuterium fuel.
 - Observed boosted fusion or nuclear stripping reactions indicate a path to scaling.
- **Calculated:**
 - Electron screening increases localized fusion rates in dense fuel.
 - Neutrons and screened charged particles most efficiently heat the dense fuel.
 - Electron screening increases large angle scattering between charged particles enhancing quantum tunneling and increased fusion rates.
- **Predicted:**
 - Fusion rates consistent with observed neutron flux.
- **Published:**
 - Two papers in *Physical Review C* indicating acceptance of theory and results by the physics community.

Bremsstrahlung-initiated nuclear reactions





Acknowledgement of Senior Management and Review Panel

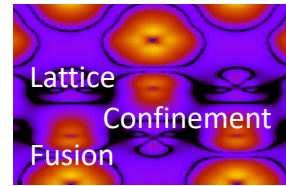


- **NASA HQ Management**
 - Dr. Thomas Zurbuchen, Dr. Lori Glaze, Mr. Eric Ianson, Mr. Len Dudzinski
 - Mr. Tom Cremins, Dr. John Grunsfeld, Mr. David Schurr, Mr. Paul Westmeyer
- **NASA Glenn Center Management**
 - Dr. Marla Perez-Davis, Dr. Rickey Shyne, Mr. Bryan Smith, Mr. David Stringer, Mr. John Hamley, Dr. Tibor Kremic
 - Mr. Jim Free, Dr. Janet Kavandi
 - Mr. Ray Lugo, Dr. Jih Fen Lei
- **NASA Review Panel**
 - Dr. Michael Houts, Dr. Ron Litchford, Mr. John Scott, Dr. Matthew Forsbacka



AEC Project Team

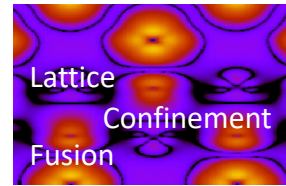
Bremsstrahlung Irradiation Campaign



- **AEC Leads**
 - Bruce Steinetz, Principal Investigator (PI) and Rich Martin, Deputy Principal Investigator
 - Arnon Chait, Senior Science Lead
 - Carl Sandifer II Project Manager
- **AEC Physicists**
 - Vladimir Pines, Senior Theoretical Physicist
 - Marianna Pines, Scientist and Mathematica Programming
 - Robert Hendricks, Senior Scientist
 - Gus Fralick, Senior Physicist
 - Theresa Benyo, Analytical/Theoretical Physicist (*Transitioning to PI)
 - Larry Forsley, Senior Lead Experimental Physicist
 - Bayar Baramsai/Phil Ugorowski, Senior Experimental Physicists: Data Acquisition
 - Fred VanKeuls/Wayne Jennings/Frank Lynch, Materials Loading
- **AEC Engineers and Testing Support**
 - Mike Becks, MCNP Simulations/Test Coordination
 - Nicholas Penney and Tracy Kamm, Test Equipment Engineer / Test Sample Coordination
 - Chris Blasio, Radiation Safety Officer
- **IBA Team**
 - Rick Galloway, IBA Test Engineer/Dynamitron Lead
 - Jim Scheid, IBA Dynamitron Technician
- **AEC Support Staff**
 - Laura Becker/Lorie Passe, Editor / Manuscript Lead
 - Megan Sigetic, LCF Animation
 - Vadim Lvovich, Workshop Preparation/Feedback



For More Information



<https://www1.grc.nasa.gov/space/science/lattice-confinement-fusion>

<https://spectrum.ieee.org/energywise/energy/nuclear/nuclear-fusion-tokamak-not-included>

<https://www.ans.org/news/article-447/nasa-work-on-lattice-confinement-fusion-grabs-attention/>