ARPA-E Fusion Overview and Perspectives

Scott C. Hsu, Program Director, ARPA-E

Acknowledgments: Sam Wurzel (T2M Advisor) and Colleen Nehl (Tech. SETA)

Fusion Power Associates 42nd Annual Meeting

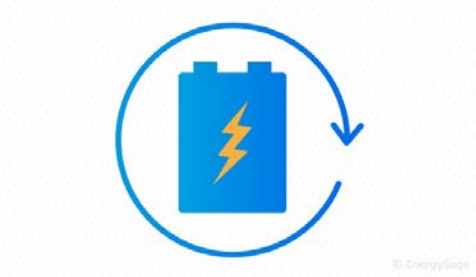
Pathways to Fusion Power

December 15, 2021

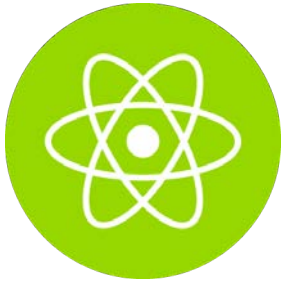
OVERVIEW OF ARPA-E FUSION PROGRAMS

Framing of fusion energy within ARPA-E's portfolio

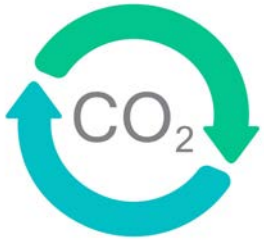
- World needs >500 EJ/year of sustainable, carbon-neutral primary energy



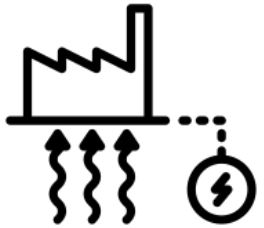
Renewables + long-duration storage



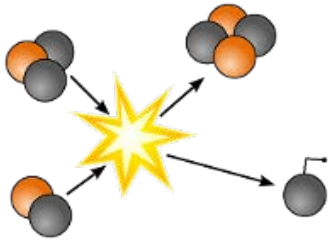
Advanced nuclear fission



Fossil fuels with carbon capture, utilization, sequestration (CCUS)



Enhanced geothermal



+ fusion?

Fusion is needed risk mitigation $\lesssim$2050 and Plan A $\gtrsim$2050.

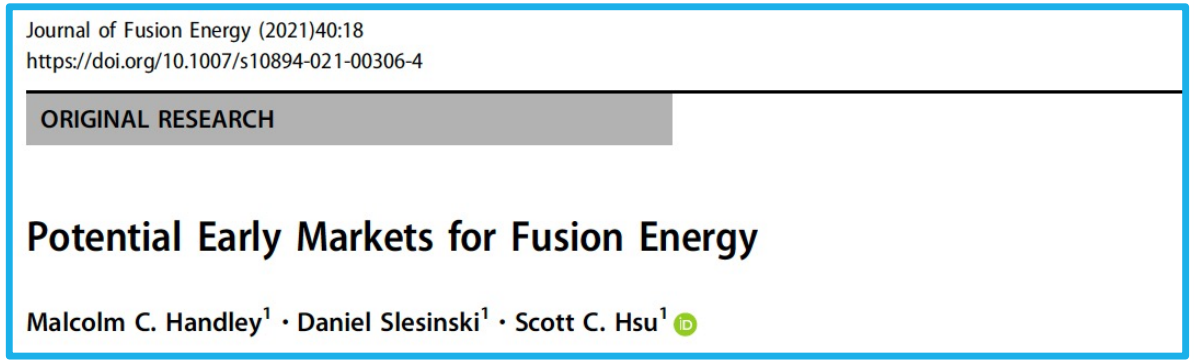
As with all ARPA-E programs, our fusion programs are guided by market-aware, techno-economic metrics

Aspirational economic targets

Item	Cost target
Overnight capital cost (~tenth-of-a-kind)	~$2B, <$5/W
LCOE	Initially < $75/MWh Longer-term < $50/MWh
“wall-plug gain” experiment	<$1B, <<$1B even better

Capex based on reports examining economics of nuclear advanced reactors.

LCOE based on ARPA-E tech-to-market (T2M) study:

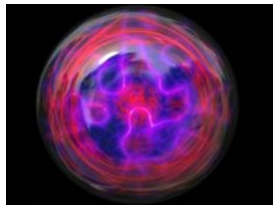


https://doi.org/10.1007/s10894-021-00306-4

ARPA-E fusion timeline/programs (total of ~$120M†)

Dr. Patrick McGrath decides to pursue a fusion program

ALPHA*



Dr. Scott Hsu joins ARPA-E (Nov. 2018)

Breakthroughs Enabling THermonuclear-fusion Energy

Stay tuned!

2013 — 2015 — 2018 — 2019 — 2020 — 2021

Included 3 fusion projects

Diagnostic "capability teams"

joint with SC/FES

Galvanizing Advances in Market-aligned fusion for an Overabundance of Watts

*Accelerating Low-Cost Plasma Heating and Assembly Retrospective: https://doi.org/10.1007/s10894-019-00226-4

†includes $20M from FES on jointly funded projects

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Philosophy/vision of the BETHE (2020–2023) and GAMOW (2021–2024) programs

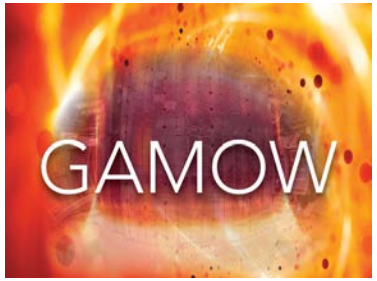
Objective: catalyze R&D trajectory toward timely commercial fusion energy.

Technical drivers

More low-cost approaches at higher levels of fusion performance

+ “capability teams”

Shorten the time from ”wall-plug gain” to commercial pilot



joint with SC/FES

Programmatic drivers

Engage larger portion of the fusion R&D community

Leverage SotA expertise/capabilities

Incentivize publicly and privately funded teams to work together

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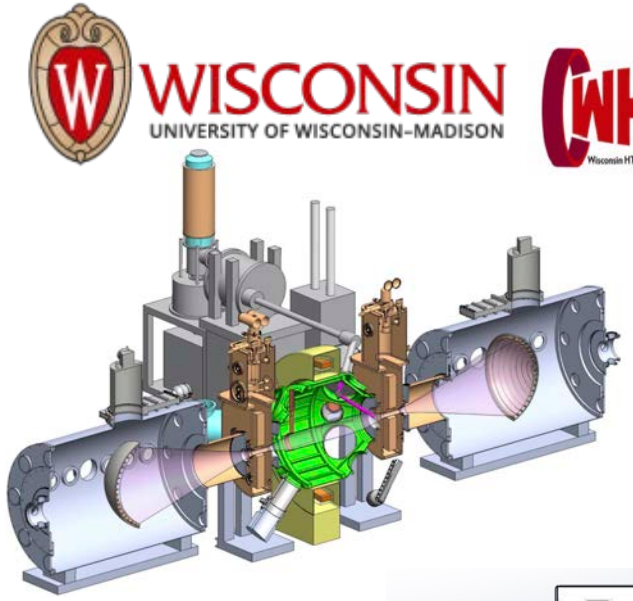
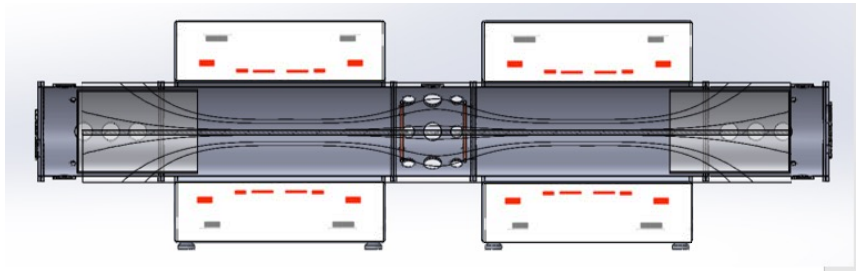
https://arpa-e.energy.gov/news-and-media/energy-briefs (episode 7)

Subset of BETHE category A: advance the performance of lower-cost concepts

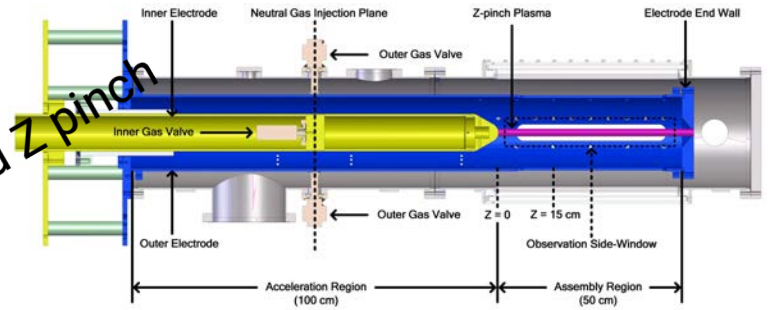
- Enable 2–3 lower-cost concepts to reach $T_e, T_i \geq 1$ keV for first time
- Bring one concept to $nT\tau_E \geq 10^{18}$ keV·s/m^3



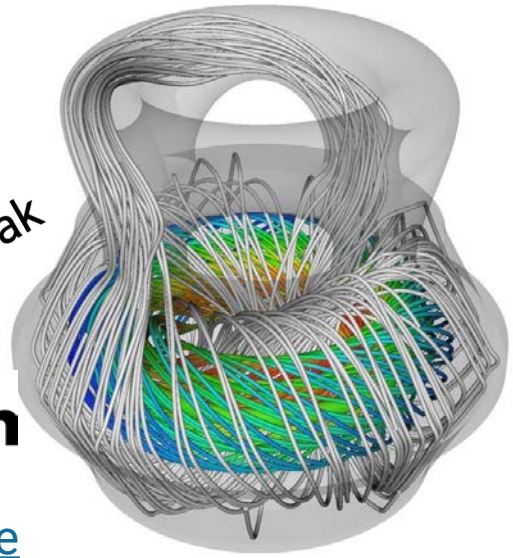
"Return of the mirror"



Stabilized Z pinch



Sustained spheromak



https://arpa-e.energy.gov/technologies/programs/bethe

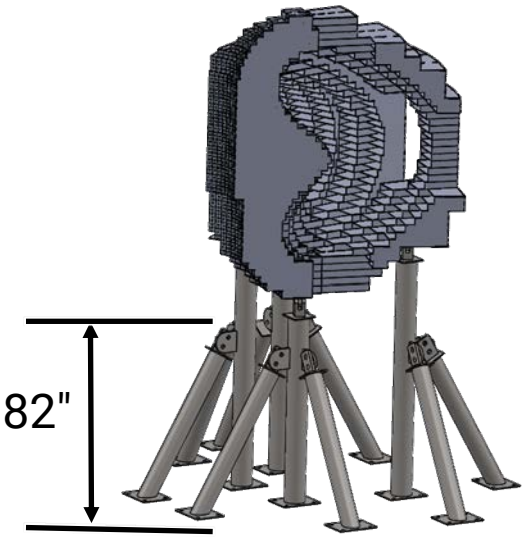
Subset of BETHE category B: lower the cost of more-mature concepts

- Exploit new enabling technologies
- Enable eventual overnight capital cost <$2B, <$5/W

Stellarator

TYPE ONE ENERGY

PPPL



Inertial fusion energy (IFE) “subprogram”

LABORATORY FOR LASER ENERGETICS UNIVERSITY OF ROCHESTER

U.S. NAVAL RESEARCH LABORATORY

Next-gen laser development (high-efficiency & bandwidth)

IFE-relevant high-gain target designs

jointly funded with SC/FES

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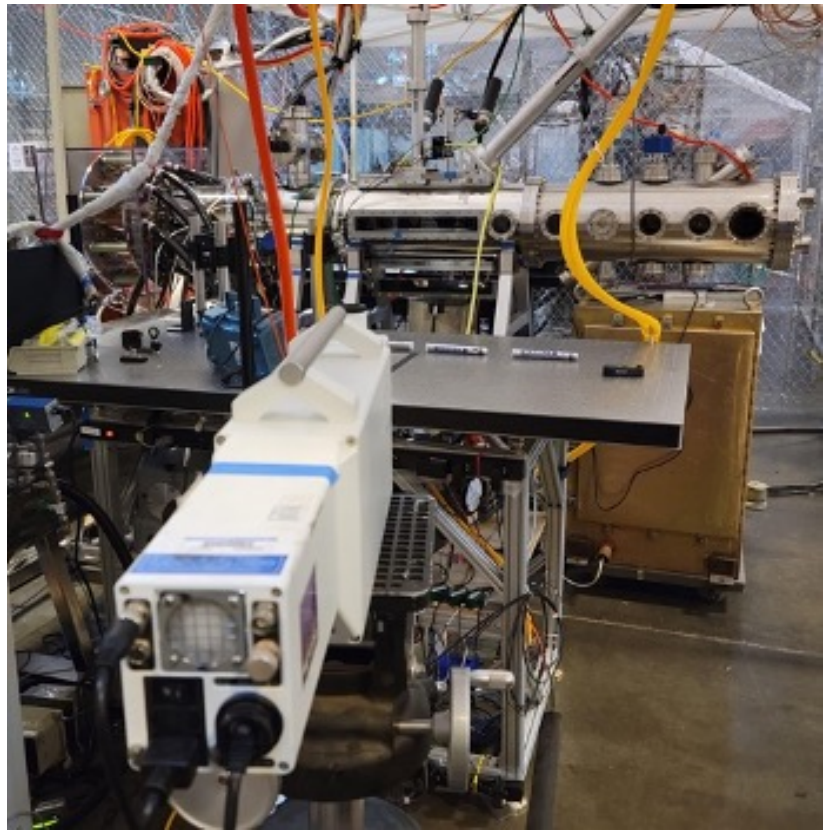
https://arpa-e.energy.gov/technologies/programs/bethe

Diagnostic “capability teams” (mini-program: 2019–2022) have deployed to experiments around the country

BETHE category C included computational capability teams

ORNL team bringing their diagnostic to the Princeton FRC (Princeton Fusion Systems and PPPL).



LANL and LLNL diagnostics installed on the FuZE device (Zap Energy).

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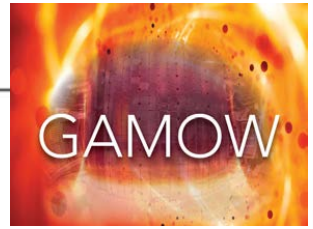
https://www.arpa-e.energy.gov/news-and-media/blog-posts/fusing-further-advancement-introducing-arpa-e-fusion-capability-teams

GAMOW program: Accelerate R&D in fusion materials and enabling technologies to support commercially viable fusion concepts



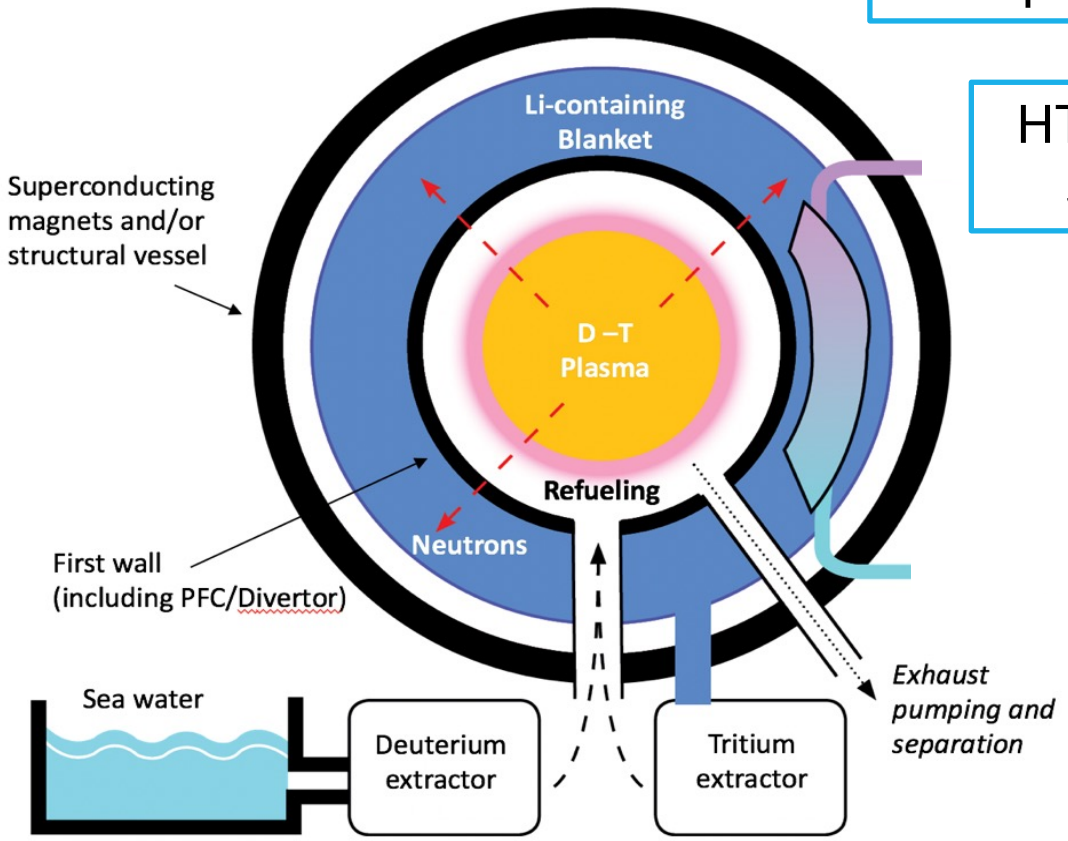
Deployable in experiments well within a decade

Device simplification or elimination of entire subsystems

Significant cost reduction

Improvements in RAMI, safety, sustainability

Joint program with SC/FES



>900-K blanket operation

HTS tape <$10/kA-m, substrate >3 GPa

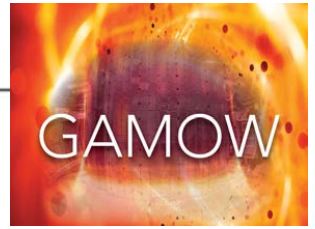
<1000-Ci (100-mg) T annual release

>10-MW/m^2 continuous power handling at 1st wall

<0.75-kG T inventory for 500-MW$_{th}$ system

Click here for program overview.

GAMOW portfolio: 14 projects across 7 technical categories



Joint program with SC/FES

Goals: Reduce fusion energy system cost by enabling device simplification or elimination of entire subsystems; improve development time and cost; improve safety and sustainability of fusion energy systems and reduce the need for specialized testing/qualification facilities.

Integrated first-wall and blanket modeling (ORNL)

Advanced HTS (Univ. of Houston)

Innovative PFC/divertor solutions (ORNL, UCLA)

Novel fusion materials, advanced manufacturing, testing (ORNLx2, Phoenix/Shine, Stony Brook Univ., PNNL)

Tritium extraction, pumping (SRNLx2, Colorado School of Mines)

High-efficiency electrical-driver systems (Princeton Fusion Systems, Bridge 12)

Prime recipients: 5 universities, 3 private companies, 6 national labs; click here for full list of project teams. GAMOW kickoff meeting (virtual), Jan. 21-22, 2021.

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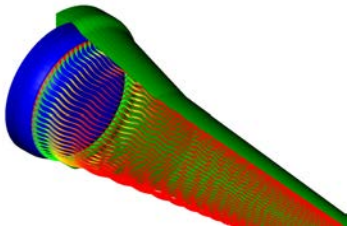
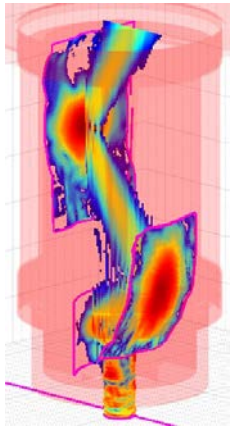
Fusion Energy Sciences (FES)

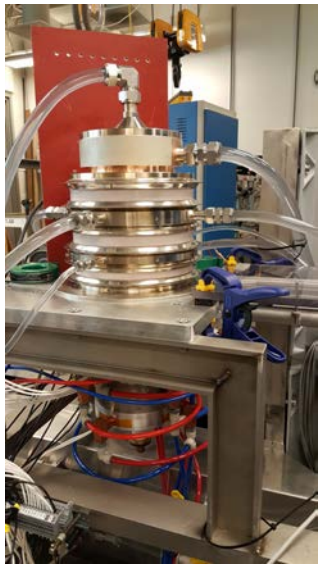
GAMOW theme: enabling technologies (subset of projects)

Bridge12 Technologies, Inc.

1-MW, 230-GHz gyrotron for plasma heating and instability control

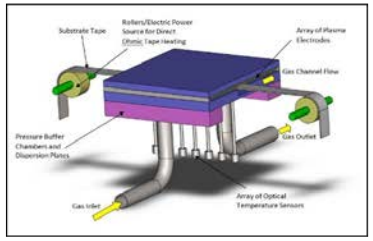




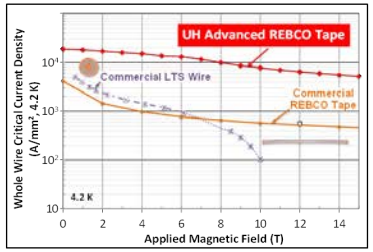


University of Houston

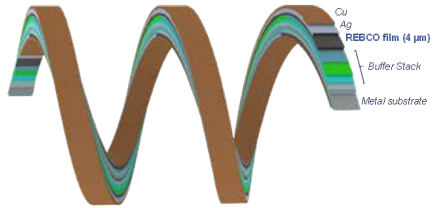
Advanced HTS Conductors Customized for Fusion



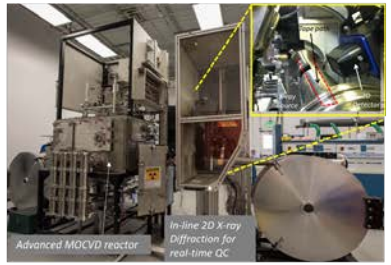
Advanced Metal Organic Chemical Vapor Deposition for 5 µm thick films



UH REBCO tapes with 5x critical current (I_c) of commercial tapes



Double-sided 5 µm thick films with 10x I_c and 7x precursor-to-film conversion efficiency



In-line Quality Control in Advanced MOCVD for high-yield manufacturing

REBCO tapes @ 30x lower cost: $10/kA-m at 20 K, 20 T

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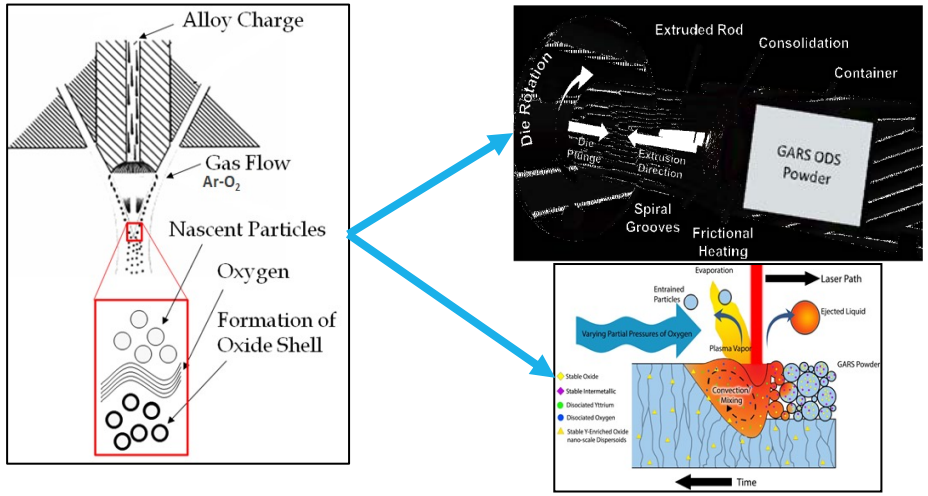
Example GAMOW theme: cross-cutting materials R&D (subset of projects)

Phoenix, LLC,
a division of SHINE

Pacific Northwest
National Laboratory

Application of Plasma-Window Technology to Enable an Ultra High-Flux DT Neutron Source

Microstructure Optimization and Novel Processing Development of Oxide-Dispersion-Strengthened Steels for Fusion



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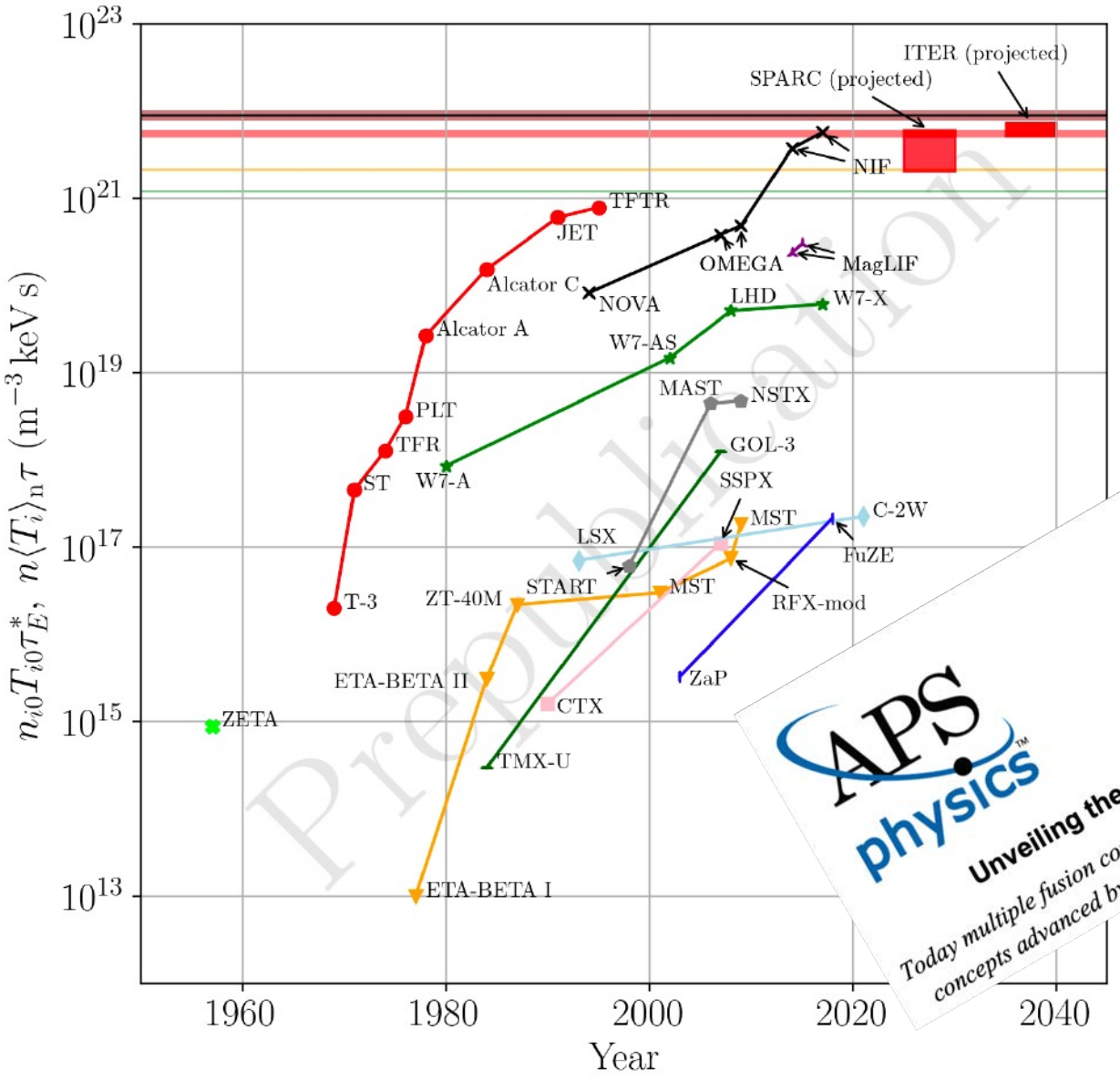
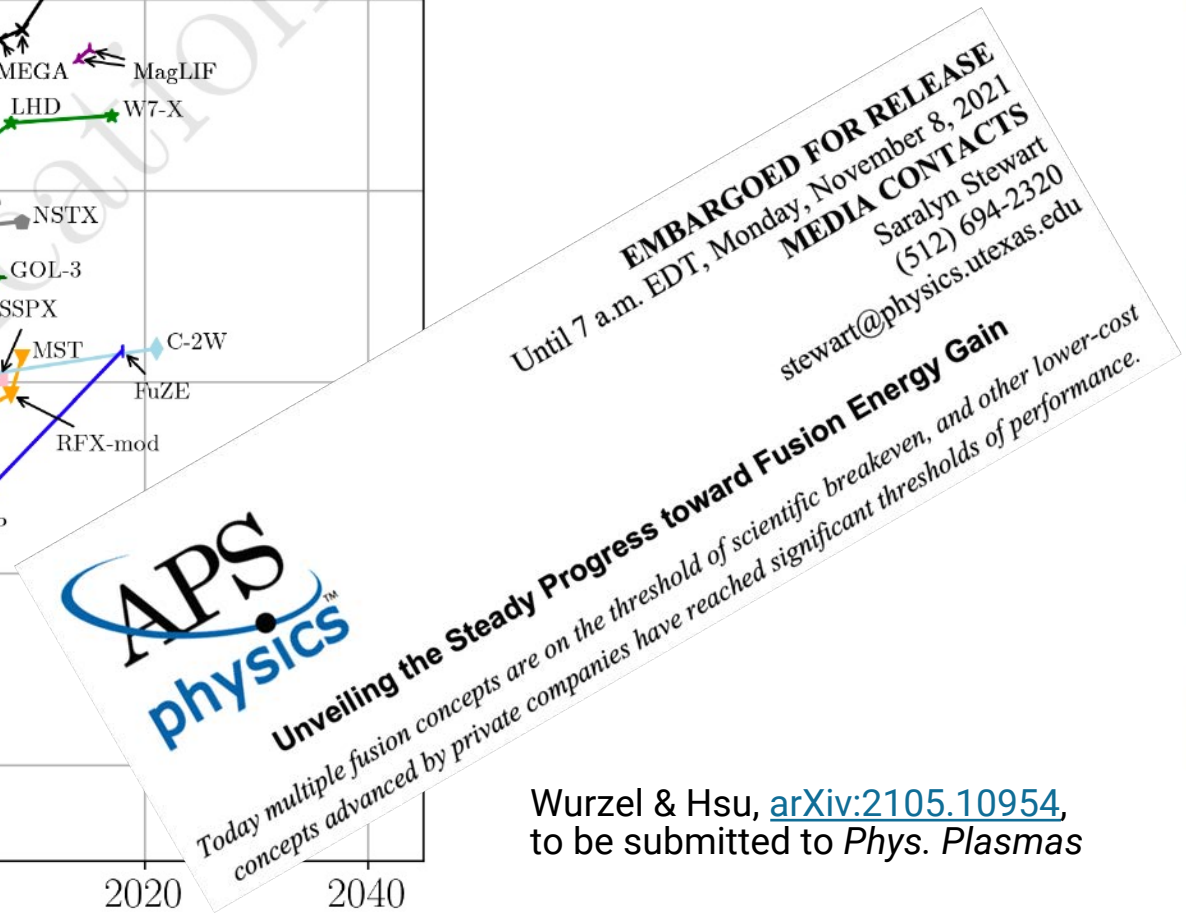
Tech-to-Market (T2M): investor engagement





EMBARGOED FOR RELEASE
Until 7 a.m. EDT, Monday, November 8, 2021
MEDIA CONTACTS
Saralyn Stewart
(512) 694-2320
stewart@physics.utexas.edu

Unveiling the Steady Progress toward Fusion Energy Gain

Today multiple fusion concepts are on the threshold of scientific breakeven, and other lower-cost concepts advanced by private companies have reached significant thresholds of performance.

APS physics

Wurzel & Hsu, arXiv:2105.10954,
to be submitted to *Phys. Plasmas*

Tech-to-Market (T2M): anticipating the importance of social acceptance

Response to request-for-information (2019):

Post Road Foundation

1999 Harrison St., Suite 1800, Oakland, CA 94612 | 510-859-8575 | www.postroadfoundation.org

June 4, 2019

RE: Response for Enabling Technologies for a Commercially Viable Fusion Power Plant, DE-FOA-0002131

To Whom It May Concern:

Thank you for the opportunity to provide input on ARPA-E's fusion R&D program.

I am the Chief Operating & Science Officer of a small non-profit, The Post Roa
to help communities build sustainable infrastructure. I am trained as both
physicist (Princeton Ph.D., 2003) and an environmental law attorney (Harv
specialization in energy law and policy. In addition to running Post Road, I
focused research on nuclear-related issues, such as the means by which new nu
secure a social license. Note that the views expressed herein are my own and are
the Post Road Foundation.

My response pertains to question 6, "Other ideas and suggestions"

Upcoming meetings

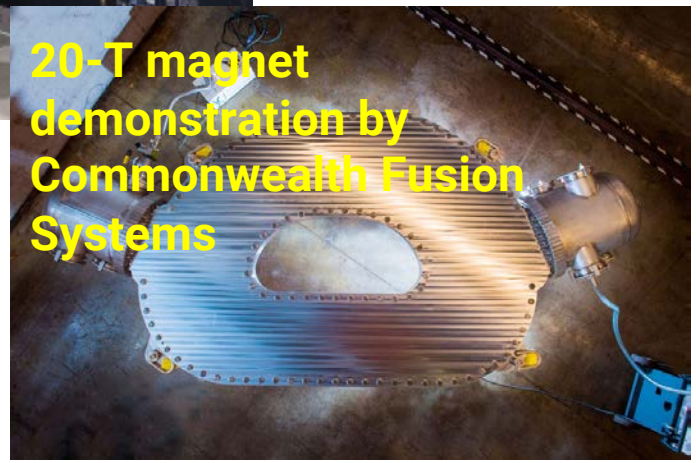
- ARPA-E fusion portfolio-wide annual meeting
  - Aiming for in-person/hybrid, **Apr. 26–28, 2022**, near San Francisco, CA
  - Technical updates from 40+ projects (OPEN 2018, Diagnostic capability teams, BETHE, GAMOW)
  - T2M topics/mini-sessions on PPPs and social license

- ARPA-E Energy Innovation Summit
  - In-person, **Mar. 14–16, 2022**, Denver, CO

PERSPECTIVES

Fusion R&D landscape is changing rapidly

S&T advances in the FES program



Growth of private-sector fusion investment

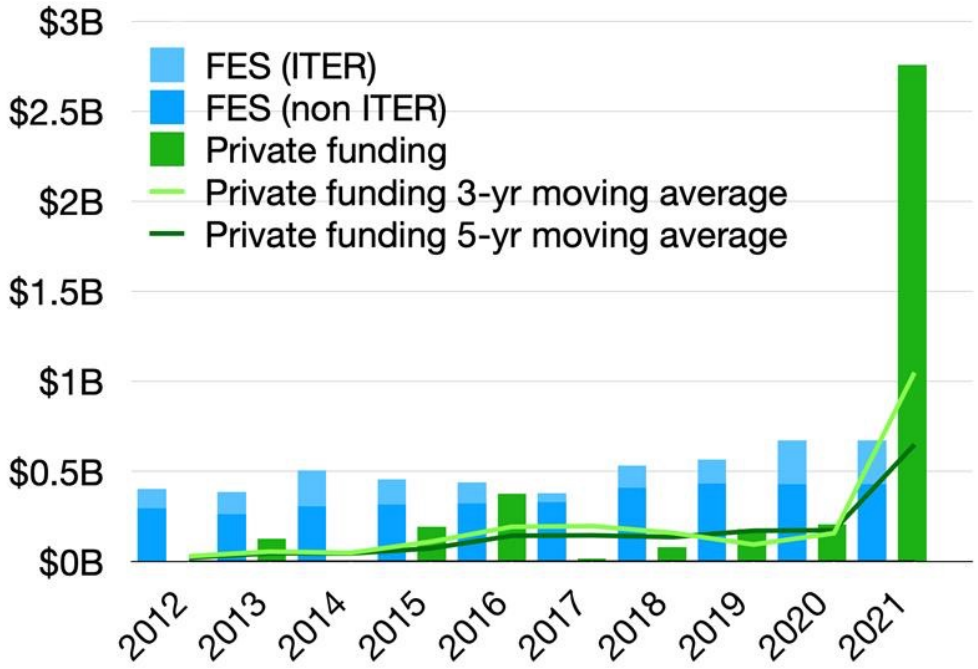


Figure credit: Sam Wurzel, ARPA-E fusion T2M Advisor, compiled from public sources

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We know what we need to do

- Fusion development including PPPs* as recommended by NASEM Bringing Fusion to the U.S. Grid
  - Needs further definition and broad stakeholder engagement (public and private sectors)
- Fusion R&D activities authorized in Energy Act of 2020 (enacted 12/28/20)
  - Augmented in pending Build Back Better Act HR 5376
- FESAC LRP unconstrained scenario
  - based on Community Planning Process report (also multiple reports over the past decade, and upcoming IFE workshop)

*Public-private partnerships

Different public-private-partnership models can potentially accelerate R&D and ensure commercial alignment up to FOAK

Development stage	Objectives	Possible program mechanisms
Foundational R&D (broad in scope)	Build underpinning science and tools; advance fusion concepts to threshold level of performance	Largely federal grants and cooperative agreements
Earlier-stage R&D needs driven by industry	Provide access to federally funded expertise, capabilities, and/or facilities	Voucher program, e.g., INFUSE and industry FOAs, e.g., the one from NE, ARPA-E-like "capability teams," NE NRIC-like
Proof of concept through net gain	Increase plasma performance toward achieving net energy gain in concepts with commercial interest/backing	Cost-share programs, e.g., NE ARDP & NRIC-like, ARPA-E SCALEUP-like
Reactor materials, subsystems, and engineering	Develop, test, and qualify high-duty-cycle driver systems, reactor materials/components, and fuel-cycle technologies	Industrial partnerships, e.g., recent Eni/ENEA partnership to build a Divertor Test Tokamak, NASA/COTS-like, NE ARDP & VTR-like, ARPA-E SCALEUP-like
Pre-commercial pilot plant	Fully test and qualify integrated operation of all subcomponents and close all remaining technical and licensing gaps (i.e., the first grid-ready prototype)	Major industrial partnerships, e.g., NASA/COTS-like, DOE/NE ARDP & VTR-like, DOE Clean Energy Demonstrations, LPO
First-of-a-kind commercial demonstration (FOAK)	First commercial system selling electricity on the grid	Financed by combination of industrial companies, utilities, private investments, and/or federal loans (LPO)

Many resources light the path forward, e.g., (1) DOE/NE Advanced Demonstration and Test Reactor Options Study (2017), (2) NGO studies such as Rozansky & Hart, *More and better: Building and Managing a Federal Energy Demonstration Portfolio*, ITIF (2020) and *Where Good Technologies Come From*, Breakthrough Institute (2010), (3) academic studies such as D. Hart, *Energy Policy* **119**, 367 (2018).

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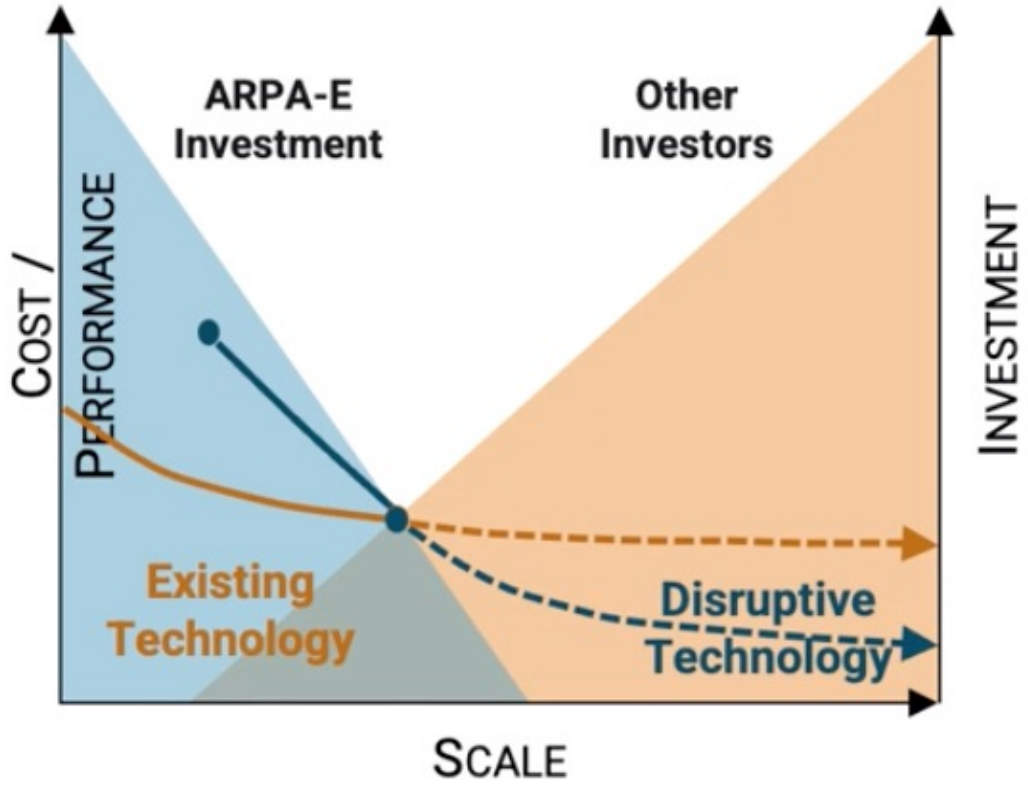
ARPA-E SCALEUP program contains relevant elements that could be applicable for new fusion PPPs

Overcoming scale-up valley of death



- Includes development ("scale-up and pre-pilot") and demonstration activities
- Applicant IP-ownership requirements
- Commercialization partnerships and private cost share *required*
- Oral interviews (team assessment)

Acknowledgment: Dr. James Zahler and ARPA-E T2M team

Tri-agency (ARPA-E, DOD, NASA) workshop on compact fusion (April 28, 2021) reveals grassroot interest in multi-agency collaboration

https://aerospace.org/article/sizing-compact-fusions-potential

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Many potential future ARPA-E fusion R&D programs waiting to be pitched by YOU!

- Enabling fusion with advanced fuels (i.e., aneutronic)
- Accelerating laser and target-manufacturing R&D for IFE
- Everything other than Q_{plasma} in the equation for engineering gain (e.g., energy recovery, input/conversion efficiencies, etc.)
- Revolutionary materials for fusion
- Novel blanket and first-wall concepts
- Enabling co-generation applications of fusion (and coal retrofits)
- …

https://arpa-e.energy.gov/career/job-opportunities

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