ARPA-E Fusion-Energy Programs and Plans

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High-level ARPA-E perspective

- Fusion strategic plan should be responsive to dynamic constraints imposed by evolving energy markets through an adequately diverse portfolio
  - Very different energy landscape shaped today’s fusion program
  - The competition today: LCOE <6 ¢/kWh, unit size <<1 GWe, capital cost <$1B, <$2/W
  - Fusion should absorb fission’s lessons (i.e., reduced capex and opex)

- Increased alignment between federal and private efforts could enhance fusion’s near-term relevance and raise the tide for all boats
  - Private fusion investments represent significant market pull
  - Little federal support today in specific areas of interest to private companies
  - Federal leadership-class capabilities will help accelerate private efforts
  - Difficult for federal or private efforts alone to achieve timely, commercially viable DEMO

- ARPA-E stands ready to coordinate further with FES; we can contribute strongly to
  - Developing impactful fusion public-private partnerships
  - Providing a detailed understanding of energy markets and commercialization requirements
  - Making connections to other energy researchers solving synergistic problems
Outline

- Introduction
- Brief review of the ALPHA* program (2015–2019)
- Fusion program plans (2019–?)
- Q&A (lots of backup materials)

*Accelerating Low-Cost Plasma Heating and Assembly
ARPA-E is an agency within the U.S. Dept. of Energy modeled after DARPA

**Mission:** To overcome long-term, high-risk technological barriers in energy-technology development by providing applied R&D funding for high-risk, high-reward transformational ideas

Ensure U.S. Technological Lead & U.S. Economic and Energy Security

- REDUCE IMPORTS
- IMPROVE EFFICIENCY
- REDUCE EMISSIONS

ARPA-E supports transformative applied energy R&D, bridging the gap between basic research and energy commercialization

Adapted from former ARPA-E director A. Majumdar’s House Science testimony, 2010
ARPA-E supports transformative applied energy R&D, bridging the gap between basic research and energy commercialization.

Adapted from former ARPA-E director A. Majumdar’s House Science testimony, 2010
ARPA-E program development and execution process

- Collaborative milestone negotiation
- Active project management and feedback
- Attention to T2M

- Situational awareness
- Identification of “white space”
- Stakeholder engagement
What problem is fusion trying to solve? Risk mitigation for achieving a cost-effective zero-carbon grid by mid/late century

- Significant gap exists to achieve zero or negative carbon emissions by mid/late century
- Firm, low-carbon sources needed to keep costs reasonable


See “Heilmeier questions,” which must be answered in ARPA-E program formulation.
How much does fusion need to cost? We don’t know for sure but have an idea based on competition and financing.

Aspirational fusion-energy cost metrics that will guide fusion R&D choices at ARPA-E:

- DEMO OCC ($B)
- $/W
- LCOE (¢/kWh)
- net-gain experiment ($100M)
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*Accelerating Low-Cost Plasma Heating and Assembly
ALPHA program objectives ($30M over 3–4 years)

- Explore lower-cost path to fusion-energy development and eventual deployment

- Focus on pulsed approaches with final density of $10^{18}$–$10^{23}$ cm$^{-3}$
  - Magneto-inertial fusion (MIF) and Z-pinch variants

- Enable rapid learning
  - High shot rate: hundreds of shots during ALPHA, scalable to ≥1 Hz in a future power plant
  - Low cost per shot: “drivers” < $0.05$/MJ and “targets” < 0.05 ¢/MJ over life of plant

Sandia MagLIF provided convincing MIF proof of concept → helped justify the program


M. R. Gomez et al., PRL 113, 155003 (2014)
P. Schmit et al., PRL 113, 155004 (2014)
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<th>Integrated concepts</th>
<th>Driver development</th>
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<td>Magnetic compression of an FRC</td>
<td>Plasma guns to form high-speed plasma liners</td>
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<td>Shear-flow-stabilized Z-pinch (direct pulsed power)</td>
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<td>Staged Z-pinch (direct pulsed power)</td>
<td>Piston-driven liquid liner</td>
<td>Physics of plasma compression</td>
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ALPHA portfolio (awards ~$400k–$5.9M)

Integrated concepts
Magnetic compression of an FRC

Driver development
Plasma guns to form high-speed plasma liners

Applied MIF science
Helical Taylor state as stable plasma target

Staged Z-pinch (direct pulsed power)

Magnetic compression of an FRC

Plasma guns to form high-speed plasma liners

Piston-driven liquid liner

Physics of plasma compression

Figure 6: Top: Characteristic signal observed on the scintillator detector showing neutron production during the quiescent period. For a 20% deuterium/80% hydrogen gas mixture, the neutron signal is sustained for approximately 5 µs, which is 5000 times the m=1 mode growth time. Bottom: the normalized magnetic field fluctuation amplitude for the m=1 mode, at locations z = 5, 15, 25, and 35 cm, decreases below an empirical threshold of 0.2, which indicates a quiescent plasma from 21 to 8 µs along the assembly region. The evolution of the plasma pinch current at z = 15 cm is included for reference and shows a peak current plateau of approximately 200 kA during the sustained neutron production.

Summary
Employing the SFS Z-pinch concept, plasma parameters of $10^{17}$ cm$^{-3}$ electron particle density, $4 \times 10^4$ m/s peak plasma velocity, $10^6$ m/s radial shear, and pinch radius of approximately 0.3 cm are achieved on the FuZE device with long-lived quiescent period of approximately 20 µs. With deuterium minority mixture in hydrogen fuel (20% deuterium/80% hydrogen), the demonstration of sustained neutron production, lasting approximately 5 µs, and observed proportionality to $n_D^2$ suggest the neutron emission is the result of thermonuclear reactions. The lower limit of measured neutron yields is estimated to be $10^5$ neutrons/pulse, consistent with theoretical expectations for the measured plasma parameters. The neutron production is shown to be reproducible and insensitive to experimental variations.

References
Summary of ALPHA outcomes

- **Technical outcomes**
  - Evidence of >1-keV temperatures and DD neutron production for 3 integrated concepts
  - Demonstrated two new, potential compression-driver technologies
  - Developed three new, low-cost, high-shot-rate platforms to study MIF target physics

- **Tech-2-market (T2M) outcomes**
  - 3 new spinoff companies and $35M private capital raised by ALPHA projects*
  - Dozens of peer-reviewed publications, 6 patent applications filed, APS-DPP mini-conference (2018)
  - ALPHA teams among the founding members of the Fusion Industry Association

- **Positive (but cautious) findings from 2018 JASON report**: 
  - MIF within 10% of scientific breakeven for ~1% of total US fusion R&D funding
  - Near-term priority should be scientific breakeven in a system that scales to commercial power plant
  - Support all promising approaches; do not concentrate resources on early frontrunners

*Since 2015, publicly disclosed private funding into worldwide fusion R&D doubled to over $1.5B.
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*Accelerating Low-Cost Plasma Heating and Assembly*
ARPA-E interested in transformative fusion R&D to help enable grid-ready fusion demo in ~20 years for OCC* < “few $B”

**Cost constraint**
- Develop credible lower-cost concepts with identifiable upside potential (MIF and others)
- Develop technologies with potential to drastically reduce cost for tokamaks, stellarators, IFE

**Timeliness constraint**
- Catalyze technology/engineering development for commercially motivated fusion concepts
  - Priorities: plasma-facing/blanket, tritium-processing, and high-duty-cycle enablers
- See Request for Information (50 responses, will provide to FES/CPP PC for responses with authors’ permission)

*OCC = overnight capital cost*
Potential program A: Develop credible fusion concepts that may cost $\text{O}(\$100M)$ for net gain and $\text{O}(\$1B)$ for grid-ready demo.

Where we want to go

Objective: Deliver more concepts at or on a path to better reward/risk ratios for private development

Many low-cost concepts today
Potential program B: Catalyze enabling-technology solutions to common challenges of commercially motivated fusion concepts

- Engage outside communities
- Enable use of thick liquid blankets
- Tritium process intensification to minimize tritium inventory
- Accelerated subscale material testing

- Beyond solid divertors
- Exploit advances in modern power electronics
- Advanced fuels and power cycles

Different but synergistic challenges/requirements compared to ITER-based DEMO
ARPA-E is exploring idea of “capability teams” to support fusion concept teams

Diagnostics (8 projects funded already)
Theory, modeling, HPC
Machine learning
Engineering design/fab (mechanical+electrical)

Multiple concept teams

Leverage the best expertise
Avoid reinventing the wheel by each concept team
Stretch limited $$$
Build public-private partnership
Fusion T2M plans at ARPA-E: Smoothing the pathway to fusion commercialization

- Support studies to identify first markets for fusion at a range of unit size and cost
- Weave in programmatic structure and incentives for public-private partnering
- Build finance scaling through investor engagement
- Help establish fusion regulatory certainty and public acceptance
SC/FES legislation of interest/relevance to ARPA-E

  - SC/ARPA-E coordination on fusion energy
  - Support IFE and a portfolio of alternative and enabling fusion energy concepts

- **S. 97 “Nuclear Energy Innovation Capabilities Act of 2017”** (became public law no. 115-248 on 9/28/18)
  - Extensive language on memorandum of understanding between DOE and NRC to benefit advanced-reactor testing, development, and demonstration including fusion

- **Pending FY20 Senate appropriations language on private-public partnership:**
  - Up to $20M for INFUSE
  - Up to $20M to initiate a (NASA/COTS-like) cost-share program for integrated prototype demonstrations over the next 5 years
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In 2007, The National Academies recommended Congress establish an Advanced Research Projects Agency within the U.S. Department of Energy to fund advanced energy R&D.

**American Recovery & Reinvestment Act Signed** – Providing ARPA-E its first appropriations of $400 million, which funded ARPA-E’s first projects

**Rising Above the Gathering Storm Published** - warning policymakers that U.S. advantages in science and technology had begun to erode

**America COMPETES Act Signed** – authorizing the creation of ARPA-E

2007

2009

2019

800+ Awards
47+ Programs

Current Funding:
US$366M (FY19)
ARPA-E funds transformative, off-roadmap energy R&D with the goal of disrupting “current learning curves”
Limited-term program directors formulate, pitch, and execute “focused programs” that are each nominally 3 years, $30M total

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Complement Focused Programs
ARPA-E aims to create a “mountain of opportunity” in transformative energy technologies

![Diagram showing the investment stages: Concept, Research, Prototype, Demonstration, with corresponding investment amounts of $1M, $10M, and $100M. There is also an arrow indicating Other Investors.]
Public-private partnering is at the core of ARPA-E’s mission and program formulation/execution

Metrics:

- Private-sector follow-on funding
- New company formation
- Partnership with other government agencies
- Publications, inventions, patents

Since 2009, ARPA-E has provided $2 billion in R&D funding to more than 800 projects.

76 companies formed by ARPA-E projects.

131 projects have partnered with other government agencies for further development.

145 Projects have attracted more than $2.9 billion in private-sector follow-on funding.

2,489 peer-reviewed journal articles from ARPA-E projects.

346 patents issued by U.S. Patent and Trademark Office.

As of March 2019.
What makes a good ARPA-E proposal/project?

Idea

Transformative

Not duplicative

Compatible budget

Proposal/project

Potential to disrupt development trajectory based on present state-of-the-art projections

Impactful project result for ≤$10M (federal funds), ≤3 years that will catalyze further support/effort
Fusion must learn from fission: (1) lower the cost/complexity, (2) understand markets, (3) achieve regulatory certainty, and (4) earn public acceptance.
Markets/cost: One study suggests that, in 2030, ~465-GWe exist for fusion at >$75/MWh, and ~2.7-TWe exist at <$60/MWh.

The likely addressable market for fusion in the 2030s amounts to ~465 GW globally, with a much bigger potential of ~2,720 GW if fusion can compete with fossil fuels below $60/MWh.

Total estimated addressable market for fusion (GW) at different price levels in a high electrification scenario.

Examples:
- Alaskan village: $400/MWh
- DoD base: $200/MWh
- Singapore: $130/MWh
- Germany: $60/MWh
- Texas: $3/MWh

Source: Electrification and decarbonization: the role of fusion in achieving a zero-carbon power grid (from SYSTEMIQ, July 12, 2019)
Firm power sources (i.e., meets demand over seasons and long duration) needed for cost-effective, low-carbon grid

Fusion programs at ARPA-E are informed but not overly constrained by market awareness

To impact 21st-century markets, fusion must be solved and adopted quickly.

What capital cost is needed for a hypothetical zero-carbon, 100%-capacity-factor electricity source to be adopted quickly (i.e., to displace fossil fuels)?

$3.6/W may displace legacy fossil-fuel generation

$2.2/W may displace cheap natural gas

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Carbon tax of >$50/ton could greatly expand the market for fusion (based on modeling of fission in competitive market)

https://twitter.com/noahqk/status/1157343492332539910

Analyzing Energy Technologies and Policies Using DOSCOE
ALPHA focused on pulsed, magnetized, intermediate-density fusion (MIF and z-pinch variants) → lowers ignition requirements

Magnetic field dramatically reduces areal density (and therefore predicted facility cost) required for pulsed ignition

Fusion concepts studied within the ALPHA portfolio spanned ~6 orders of magnitude in fuel density.
ALPHA concept: Sustained neutron production in a sheared-flow stabilized Z pinch, consistent with thermonuclear DD fusion

![Diagram of Z pinch with gas valves and electrodes]

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<th>$n_i$ (m$^{-3}$)</th>
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Follow-on: scale up to 600 kA and multi-keV temperatures by spin-out Zap Energy (ARPA-E OPEN 2018 program)

ALPHA applied science: Development of the OMEGA “mini-MagLIF” platform to explore MIF science at fusion conditions

With axial field and laser pre-heat, $T_i > 2.5$ keV, $Y_{DD} > 10^{10}$ neutrons

ALPHA drivers: demonstration of two new potential MIF drivers, MEMS ion accelerator and plasma guns with preionization

Compact, low-cost, high-power ion beams

Plasma guns for plasma-liner formation via merging plasma jets

Demonstrated 2.6 kV/gap, 10.2 kV, 3x3 beam array

Follow-on: scale up to 1 MV/m and >100 mA (ARPA-E OPEN 2018 program)

ALPHA concept: Stable staged-Z-pinch implosions at $B_{z0}>1.5$ kG and DD neutron production on the 1-MA Nevada Terawatt Facility

Kr gas-puff liner gave the best results

ALPHA applied science: Acceleration and compression studies of a helically relaxed Taylor state as a potential MIF target

M. Kaur et al., J. Plasma Phys. 84, 905840614 (2018)

Equation of state during compression suggests better agreement with parallel CGL compared to MHD or perpendicular CGL

Theta-coil (not shown) pulse generated super-thermal and super-Alfvenic waves rather than effective acceleration of the plasma

Ongoing work: merging of two Taylor-state plasmas to increase density
ALPHA applied science: Fundamental studies of plasma compression and heating

Other ALPHA projects (concept and driver)

‣ Helion Energy: magnetic compression of FRCs formed by dynamic merging
  – Construction of “Fusion Engine Prototype” (FEP) device
  – Increased the magnitude of compression-magnetic-field strength and FRC flux
  – Advancing the plasma parameters of the compressed FRC
  – Generation and measurement of DD neutrons

‣ NumerEx: Design of stabilized, rotating, imploding liquid liner
  – 1-km/s implosion speed using annular pistons
  – Developed engineering design of a system using NaK with 10-cm-diameter bore
  – Did not construct the system due to challenges with high-pressure valves and triggering
ALPHA’s tech-2-market (T2M) component helped its teams with IP analysis, costing, and understanding fusion market entry.
JASON summer study (2018) was commissioned by ARPA-E to review the ALPHA program

- **Statement of work:**
  - Assess progress of ALPHA and non-ALPHA MIF teams toward realizing low-cost fusion
  - Assess future needs to realize low-cost MIF

- **Abbreviated findings:**
  - MIF is physically plausible and rapid progress has been made despite having received ~1% funding of MCF and ICF; best performing system (MagLIF) is within a factor of 10 of scientific breakeven
  - Pursuit of MIF could lead to valuable spinoffs, e.g., fusion propulsion
  - MIF could absorb significantly more funding than ALPHA

- **Main recommendations:**
  - Investments to study plasma instabilities, transport, liner-fuel mix at MIF conditions
  - National Labs should contribute unclassified codes and user training
  - Develop components, e.g., plasma guns, pulsed power, diagnostics, advanced magnets, and materials
  - Near-term goal/priority should be scientific breakeven in a system that scales plausibly to a commercial power plant
  - Support all promising approaches as long as possible; do not concentrate resources on early frontrunners

Full JASON report available to [download](#).
New fusion projects funded by ARPA-E OPEN 2018 program (represents expansion beyond MIF/Z-pinch-based concepts)

**Zap Energy/UW** ($6.8M, continuation of UW/LLNL ALPHA project)

**CTFusion/UW** ($3M, spheromak sustained by imposed dynamo current drive)

**Princeton Fusion Systems/PPPL** ($1.25M, FRC sustained/heated by odd-parity rotating magnetic field)
Diagnostic resource teams to support the validation of ARPA-E-supported fusion concepts ($7.3M, 2 yrs.)

Eight teams selected (July, 2019):

- ORNL, $1.1M, Thomson scattering (low density) and visible emission spectroscopy
- LLNL, $2M, Thomson scattering (high density)
- LLNL, $1.3M, neutron activation and nTOF detectors
- Univ. of Rochester/LLE, $1M, neutron activation and nTOF detectors
- UC, Davis, $444k, ultra-short-pulse reflectometry
- PPPL, $450k, passive charge-exchange ion energy analyzer
- LANL, $630k, filtered, time-resolved soft-x-ray imager
- Caltech, $400k, hard x-ray imaging, non-invasive B-field assessment
RFI on enabling technologies for a commercially viable fusion power plant

Recent ARPA-E Request for Information (RFI) on Enabling Technologies for a Commercially Viable Fusion Power Plant

- Fusion market entry may require reduced nameplate capacity and capital cost compared to traditional fusion reactor cost studies (typically 1 GWe and >US$5B)
- Fusion power plants at reduced scale and cost likely will have different technology requirements
- Interest in:
  - Thick, liquid blankets (e.g., molten salts or liquid metals)
  - Corrosion-resistant, high-temperature materials
  - Smaller tritium-processing systems and minimum tritium inventory
  - Repetitive pulsed-power technology (for MIF, IFE approaches)
  - Specific challenges presented by use of advanced fuels
  - Compatibility with advanced power cycles
- Reduced emphasis on
  - Developing 150-dpa solid materials
  - Solid-material divertors

Link to RFI