CHANGING WHAT'S POSSIBLE

Catalyzing Transformative Fusion-Energy R&D

Fusion Power Associates 39th Annual Meeting
"Strategies and Expectations through the 2020s"
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Scott Hsu, Program Director, ARPA-E

Acknowledgments to:
- Dr. Patrick McGrath, Deputy Director of Technology and former ALPHA Program Director
- Dr. Ryan Umstattdt, former Commercialization Advisor for the ALPHA Program
- Dr. Colleen Nehl (Booz Allen Hamilton), Technical Advisor for the ALPHA Program
- Dr. Will Regan, former Fellow who contributed significantly to the ALPHA program
- All the ALPHA teams

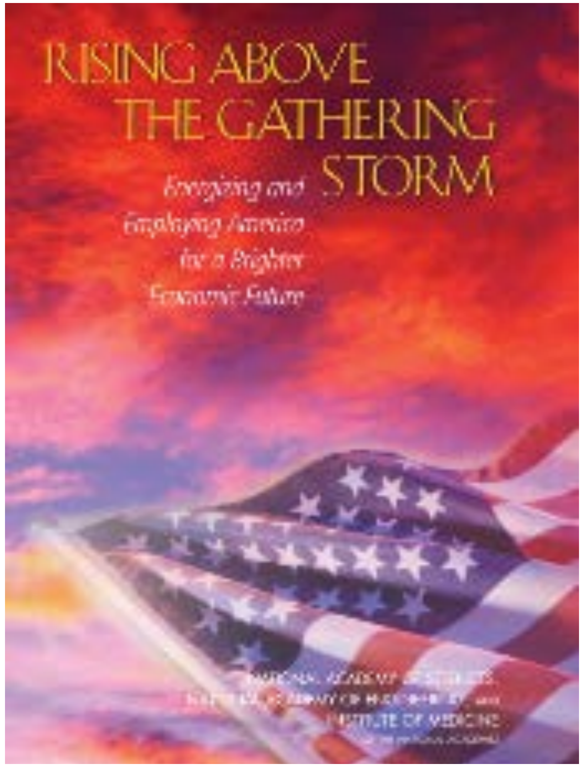
U.S. DEPARTMENT OF ENERGY

Outline

- ARPA-E and fusion
- Brief review of the ALPHA* program (2015–present)
- What's after ALPHA? (2019–?)

*Accelerating Low-Cost Plasma Heating and Assembly
https://arpa-e.energy.gov/?q=arpa-e-programs/alpha

Origin and mission of the Advanced Research Projects Agency–Energy (ARPA-E)

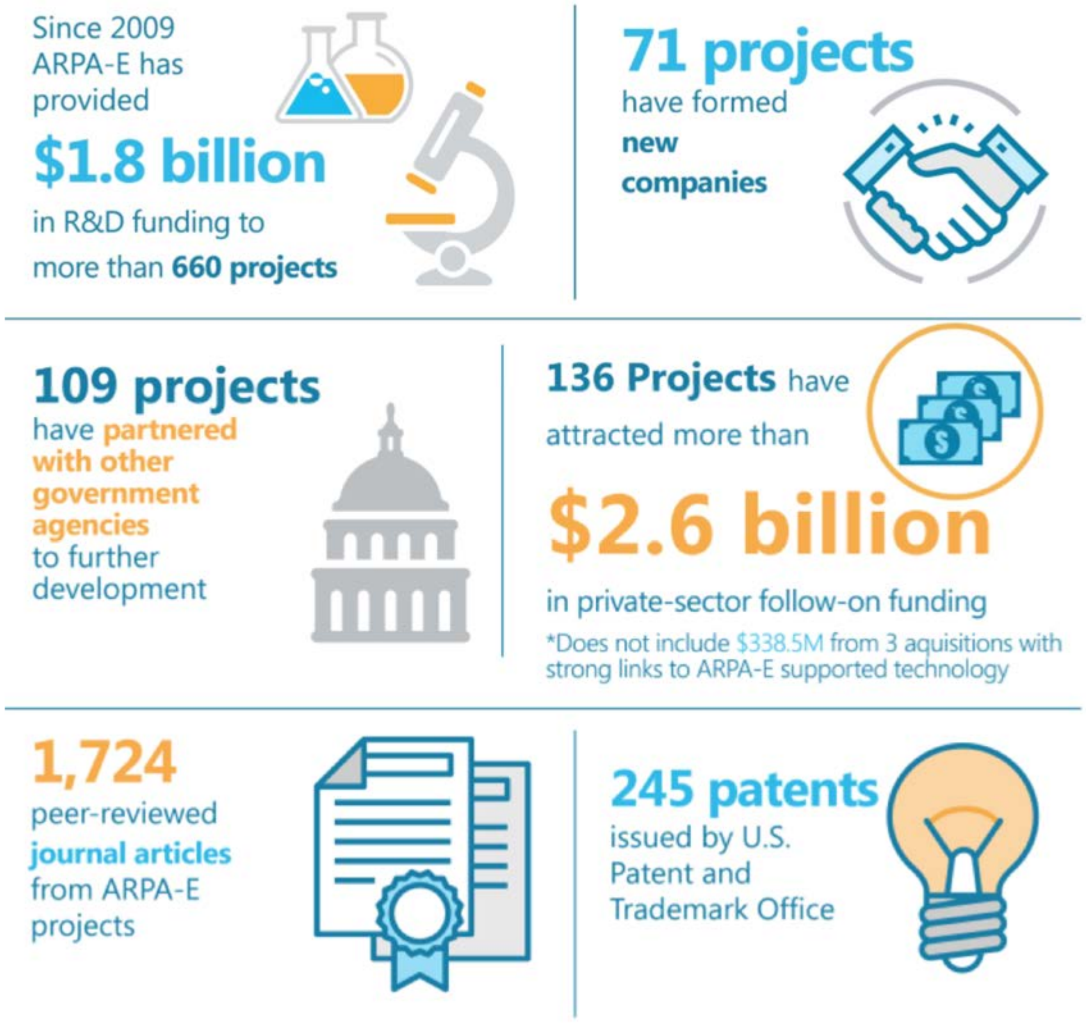


In 2007, the National Academies recommended that Congress establish an ARPA within the U.S. DOE to fund advanced energy R&D.

Mission: To overcome long-term and high-risk technological barriers in the development of energy technologies

Current Funding: **$366M** (FY19)

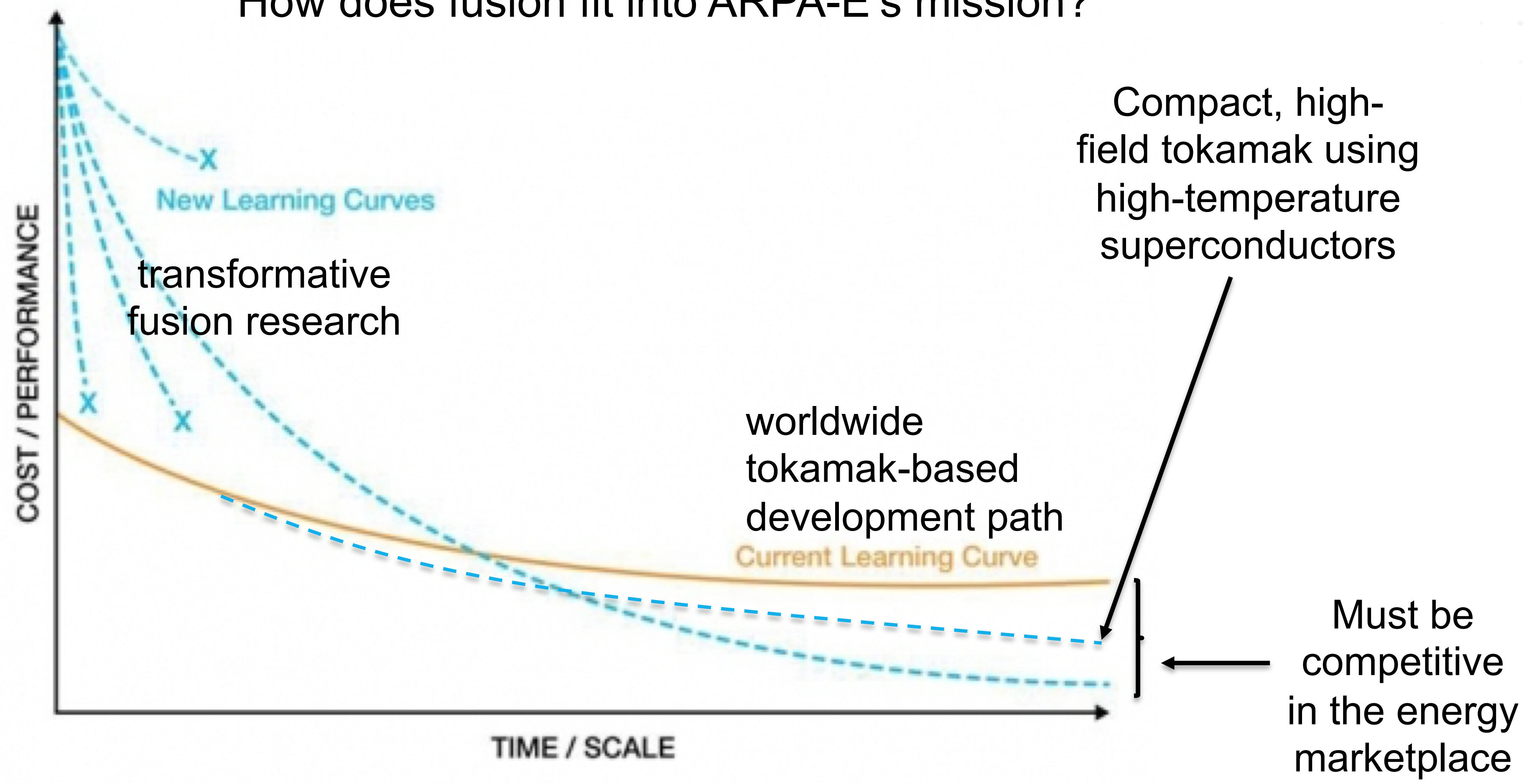
It's in ARPA-E's DNA to work with private companies and help them commercialize their energy technologies



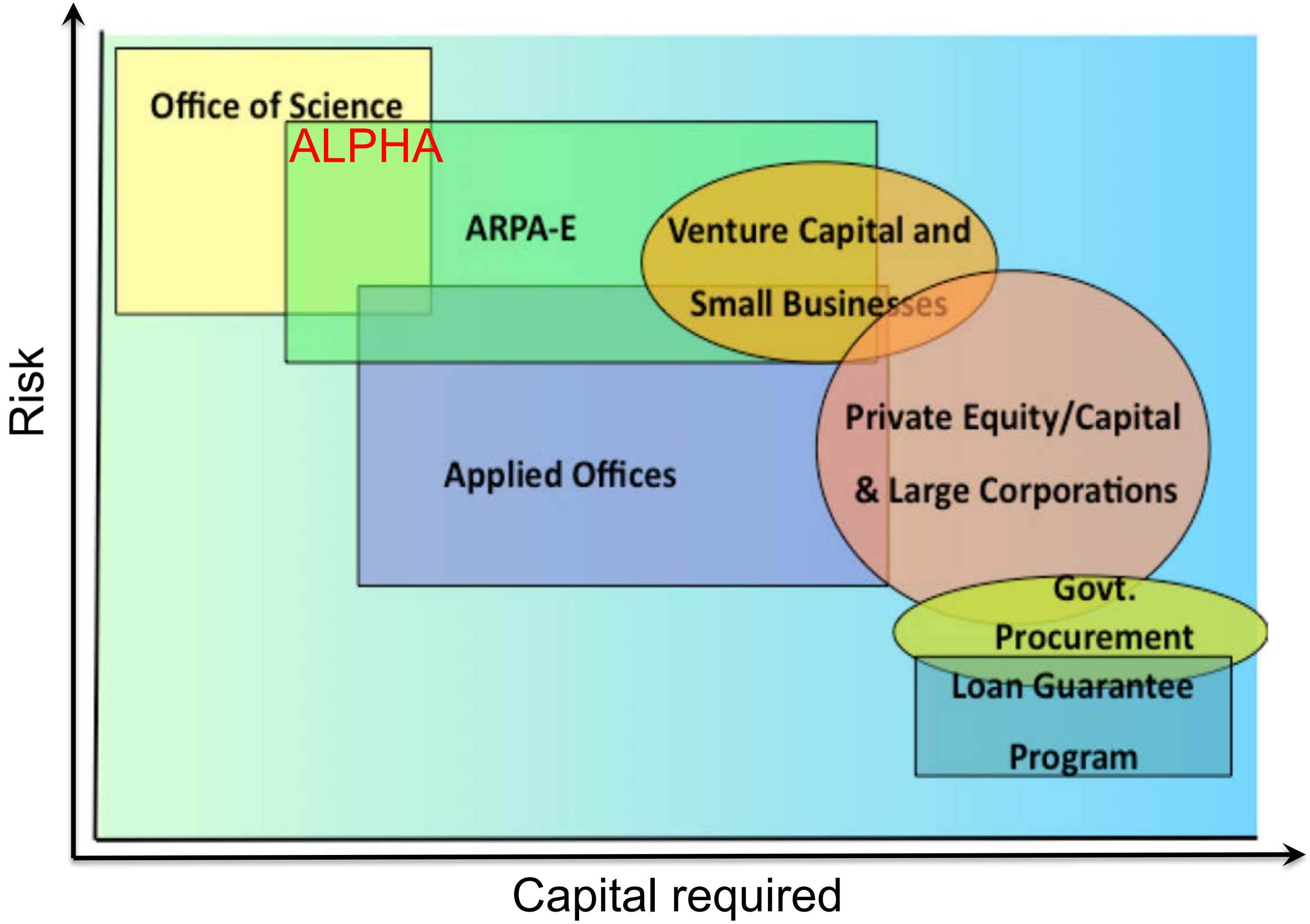
As of February 2018

ARPA-E funds potentially transformative energy R&D

How does fusion fit into ARPA-E's mission?



Can fusion energy be developed via established energy-technology commercialization path?



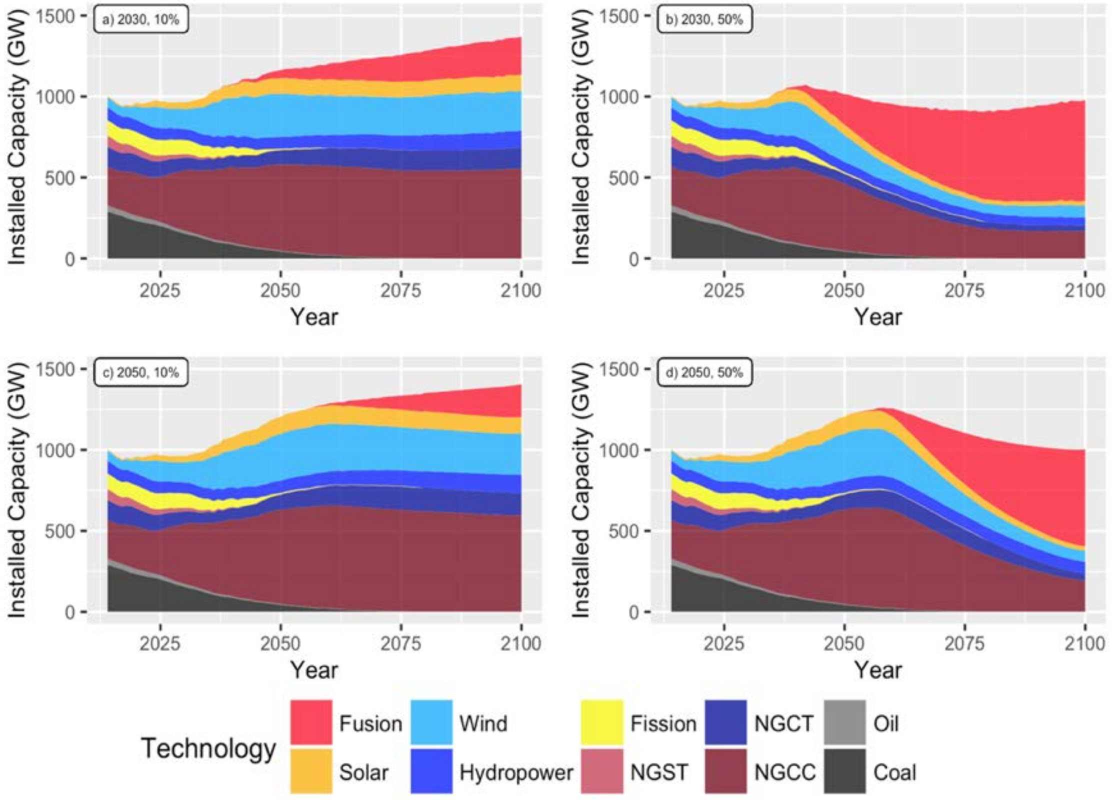
Yes, if technology is sufficiently compact and inexpensive.

Woodruff et al., J. Fusion Energy **31**, 305 (2012)

Figure adapted from former ARPA-E director A. Majumdar's testimony to the U.S. House Science Committee, 2010.

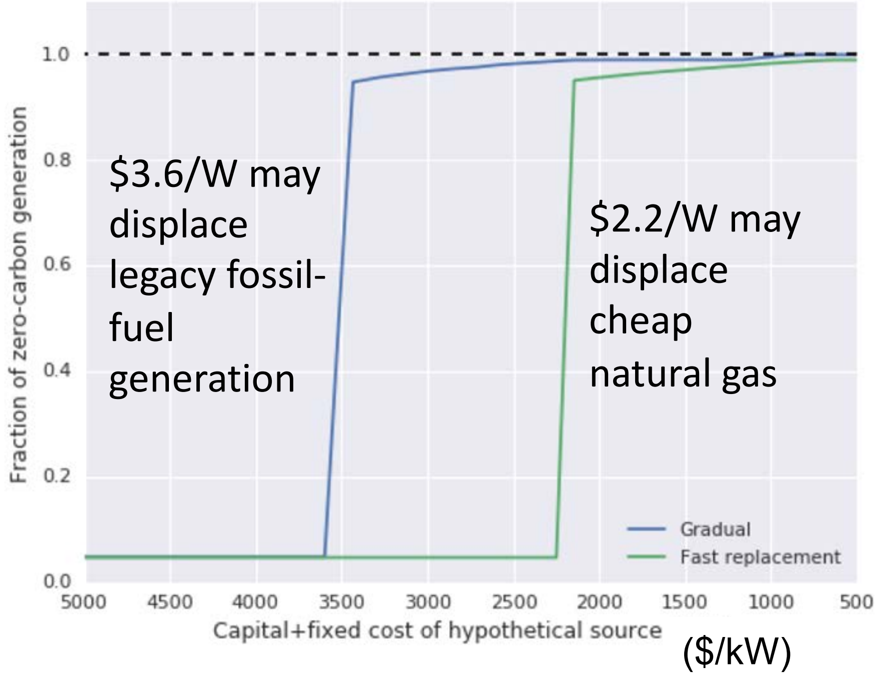
If fusion works, will it matter?

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



L. Spangher, J. S. Vitter and R. Umstattd, "Characterizing Fusion Market Entry via an Agent-based Power Plant Fleet Model," submitted for publication.

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)?



Platt, John and Pritchard, J. Orion and Bryant, Drew, Analyzing Energy Technologies and Policies Using DOSCOE (August 8, 2017). Available at http://dx.doi.org/10.2139/ssrn.3015424.

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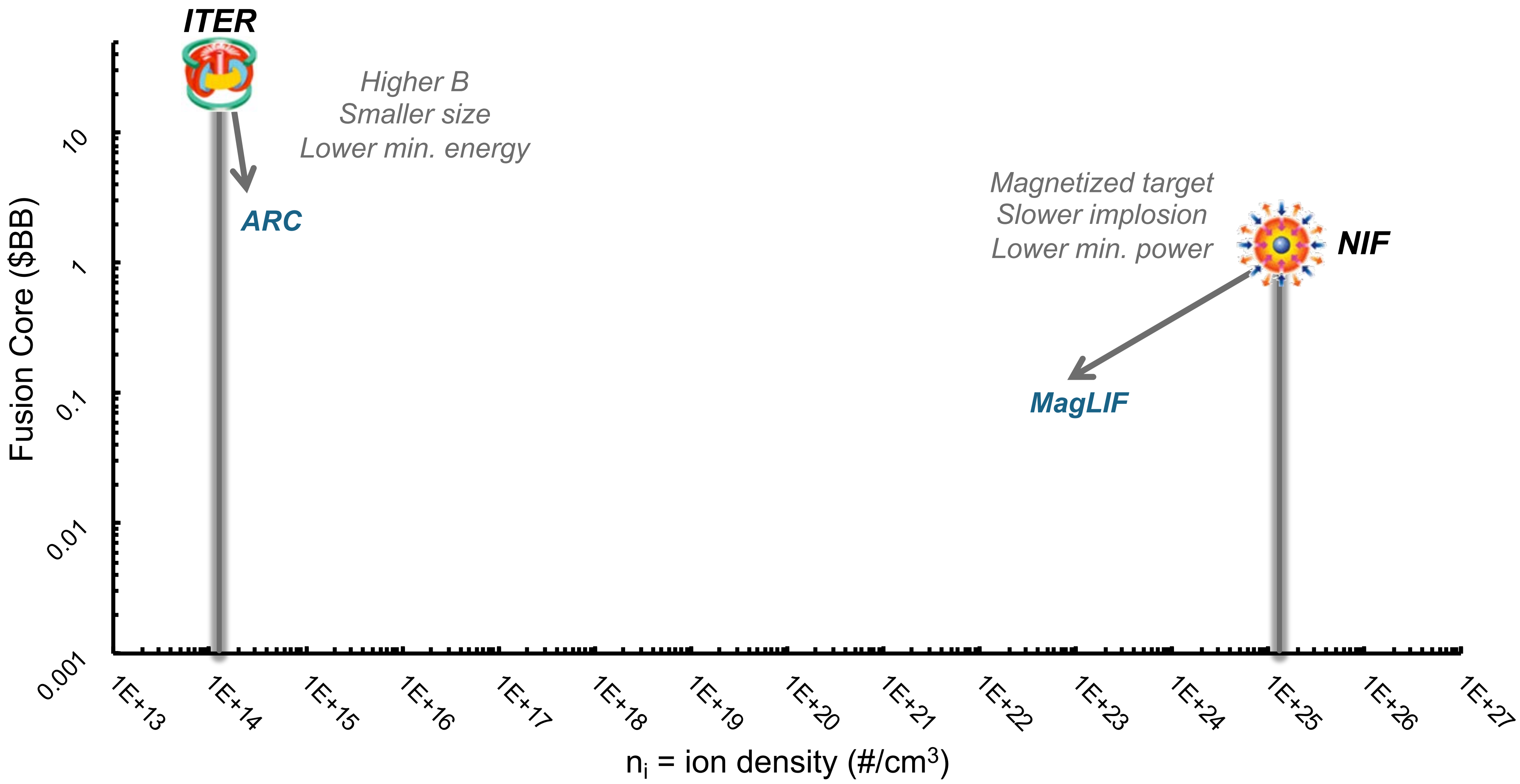
Thesis of ALPHA: to accelerate the development of commercial fusion energy, we must lower its cost



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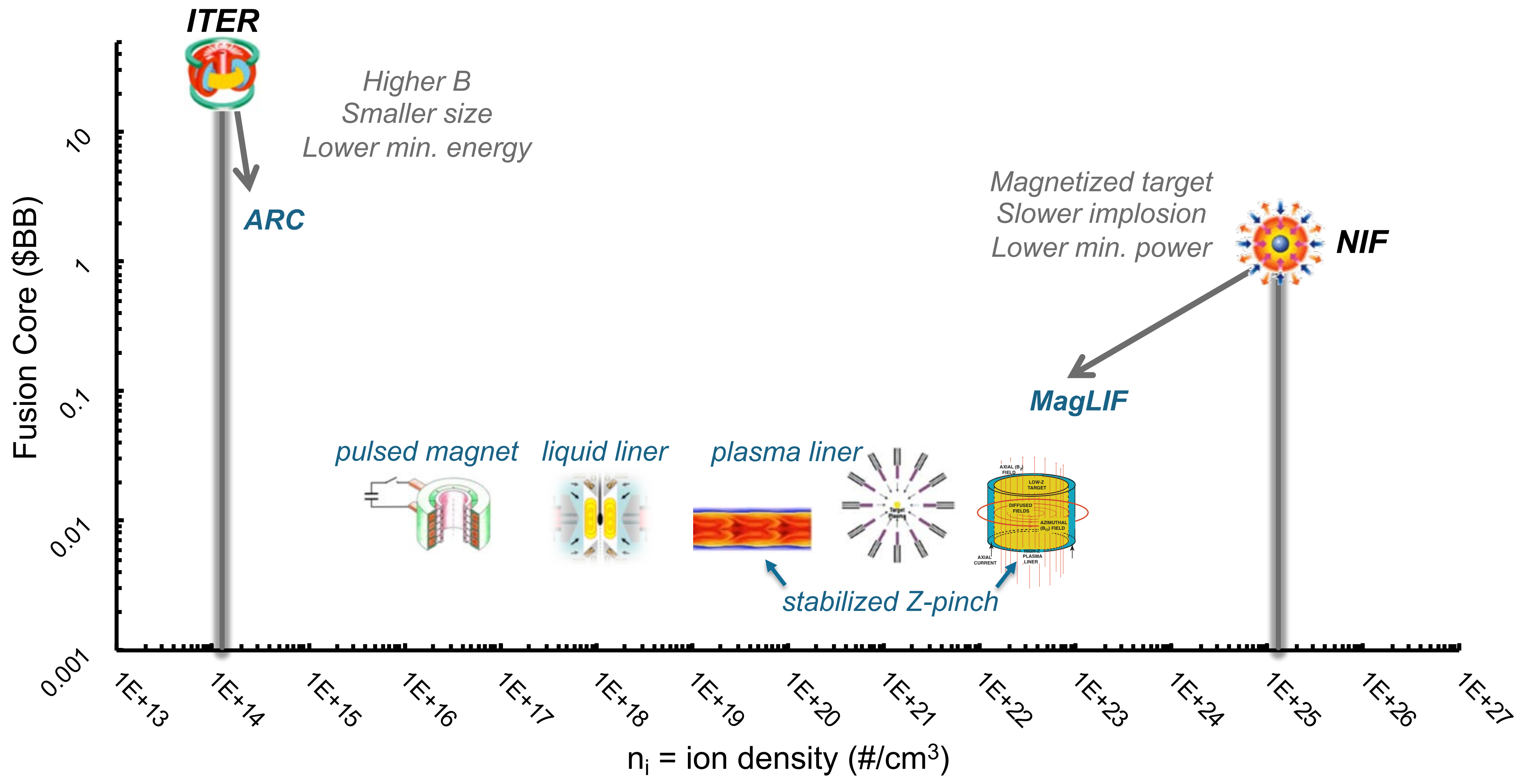
For $30M total over 3 years, ALPHA focused on developing the science and technology of intermediate-density, pulsed fusion



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ALPHA program objectives

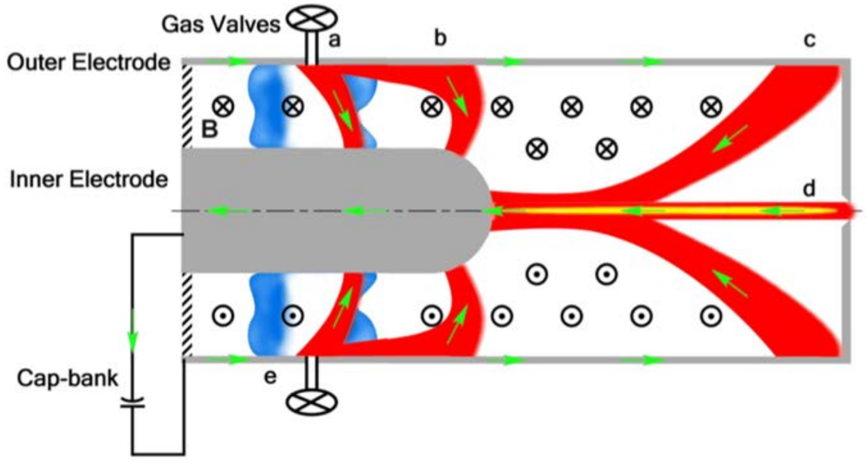
- Develop and demonstrate low-cost tools to aid in the development of fusion power with significantly reduced facilities costs
- Focus on approaches to produce thermonuclear plasmas in the final (compressed) density range of 10^{18}–10^{23} cm^{-3}
- Enable rapid learning
  - High shot rate: hundreds 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)

See archived Funding Opportunity Announcement for ALPHA, DE-FOA-0001184, at arpa-e-foa.energy.gov for rationale and references

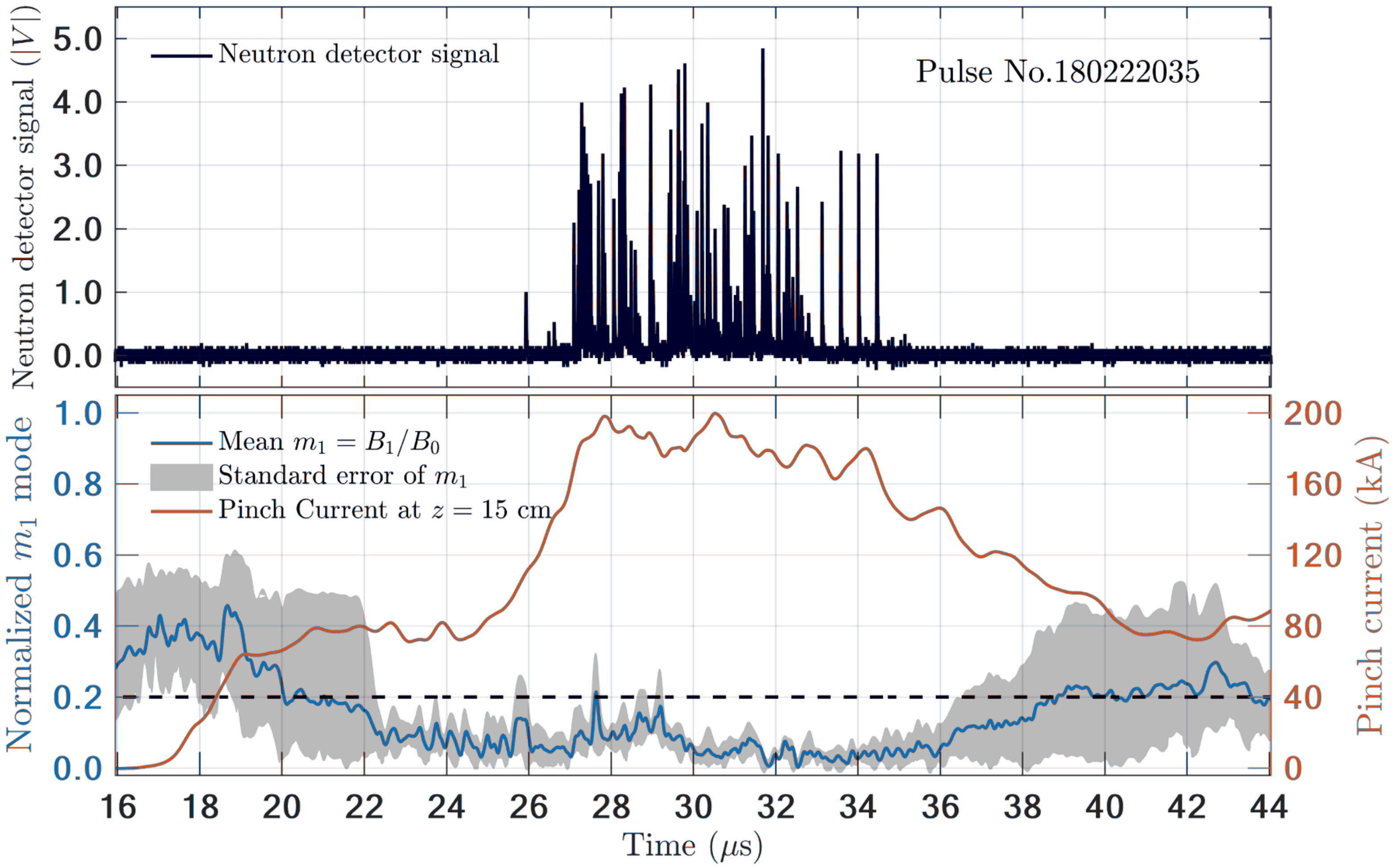
ALPHA portfolio (awards ~$400k–$5.9M)

Integrated concepts		Driver development		Applied MIF science	
Magnetic compression of an FRC	Helion Energy	Plasma guns to form high-speed plasma liners	Los Alamos National Laboratory	Underlying science of MIF at fusion conditions	Sandia National Laboratories
Shear-flow-stabilized Z-pinch (direct pulsed power)	University of Washington	Scalable MEMS-based ion accelerator	Berkeley Lab, Lawrence Berkeley National Laboratory	Helical Taylor state as stable plasma target	Swarthmore
Staged Z-pinch (direct pulsed power)	MIFTI Clean Energy	Piston-driven liquid liner	NumerEx	Physics of plasma compression	California Institute of Technology, 1891

Highlight: Sustained neutron production in a shear-flow-stabilized Z pinch, consistent with thermonuclear DD fusion



	n_i (m^{-3})	T_e=T_e (keV)	τ_E (μs)	$nT\tau_E$ (keV s/m^3)
Pre-ALPHA	3e22	0.075	5	1e16
ALPHA	1e23	1.0	5	5e17



UNIVERSITY of WASHINGTON

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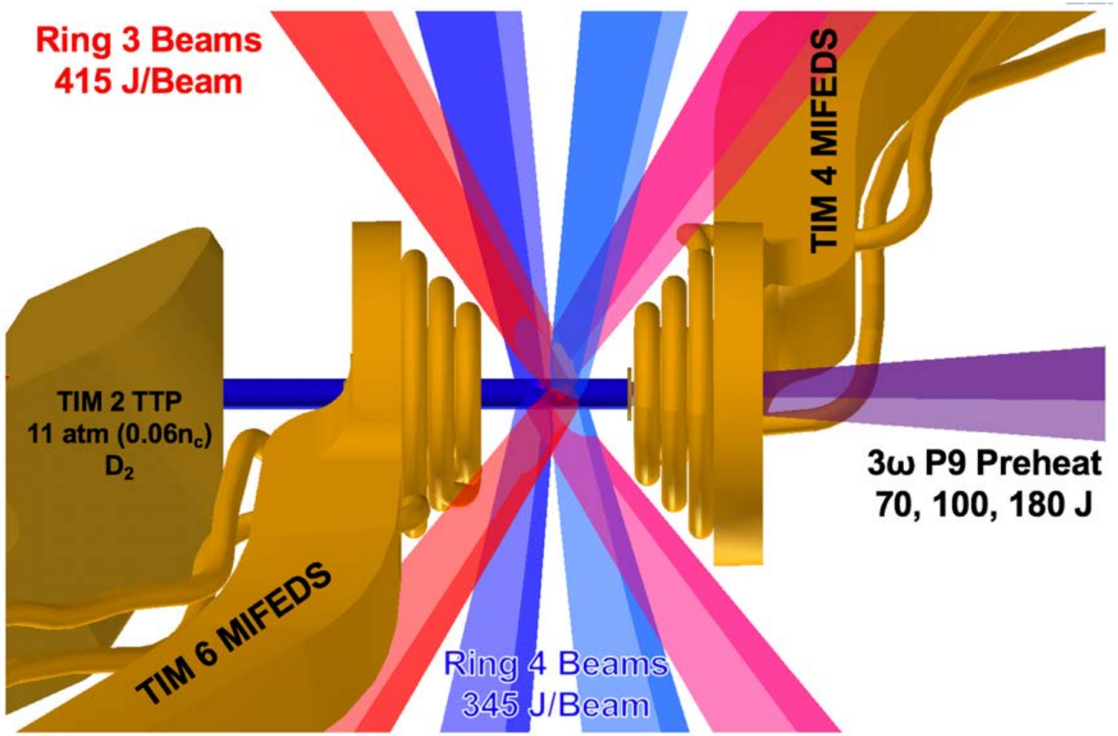
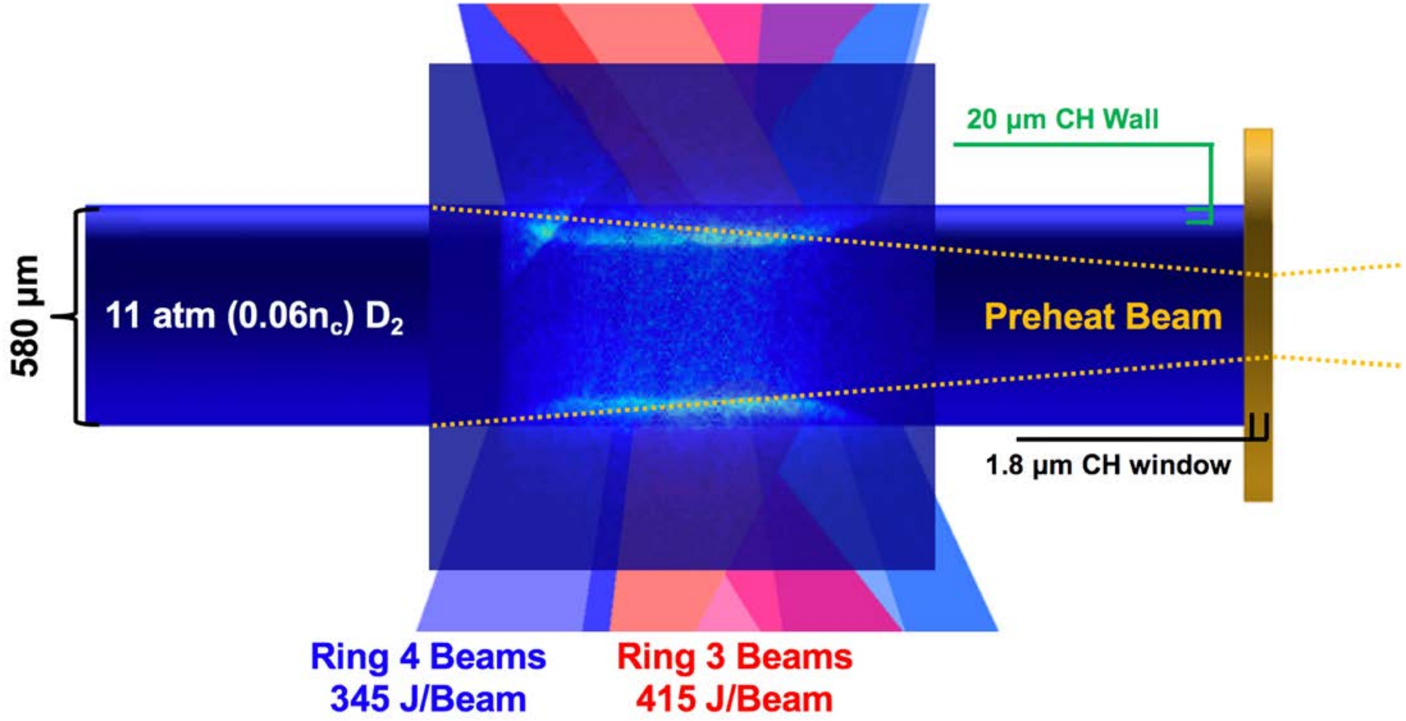
U. Shumlak et al., Phys. Plasmas **24**, 055702 (2017)
Y. Zhang et al., submitted to PRL (2018); https://arxiv.org/abs/1806.05894.

Highlight: Development of the "mini-MagLIF" platform on OMEGA to rapidly explore critical MIF scientific issues at fusion conditions





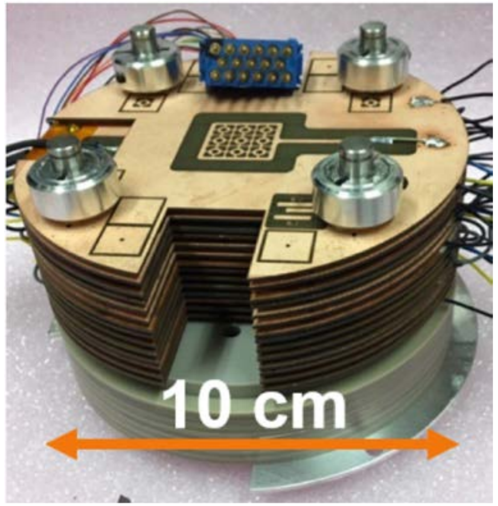
Sandia National Laboratories

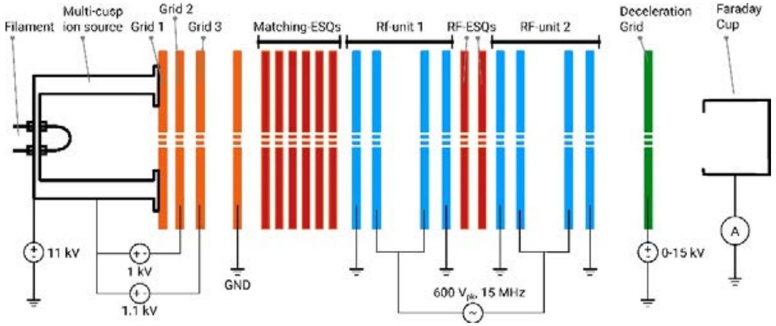
UR LLE

D. H. Barnak et al., Phys. Plasmas **24**, 056310 (2017)
J. R. Davies et al., Phys. Plasmas **24**, 062701 (2017)

Highlight: Demonstration of two new potential MIF compression-driver technologies (MEMS ion accelerator and plasma guns)

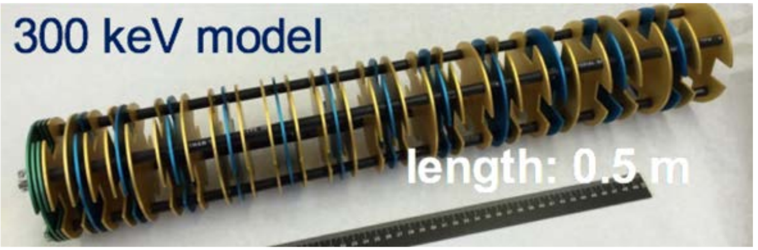
High-power ion beams at low cost





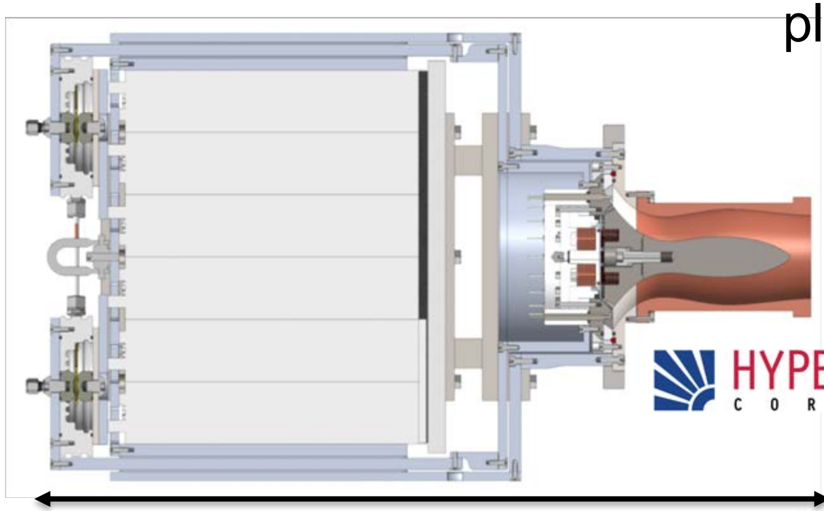
Demonstrated 2.6 kV/gap, 10.2 kV, 3×3 beam array

Next step: scale up to 1 MV/m and >100 mA



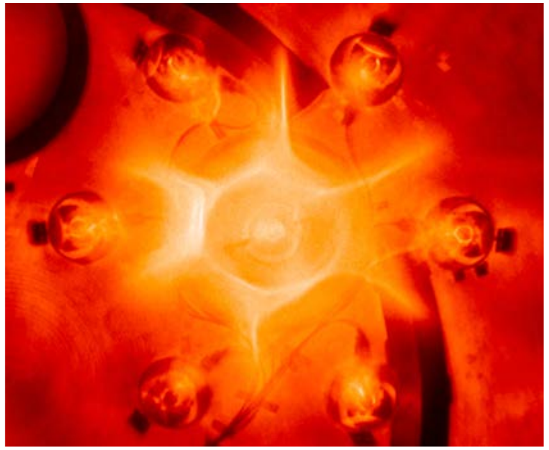
BERKELEY LAB
Lawrence Berkeley National Laboratory

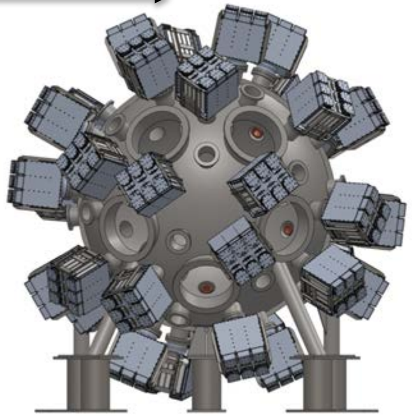
Plasma guns for high-momentum-density plasma jets



HYPERJET FUSION CORPORATION

~80 cm





Los Alamos NATIONAL LABORATORY

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LBNL: P. Seidl et al., Rev. Sci. Instrum. **89**, 053302 (2018)
LANL/HyperJet: S. C. Hsu et al., IEEE Trans. Plasma Sci. **46**, 1951 (2018)

Summary of ALPHA outcomes ($30M over 3 years)

- Technical outcomes
  - Performance improvements for integrated concepts (e.g., 50× increase in fusion triple product for SFS Z pinch)
  - Experimental demonstration of novel, scalable, MIF compression-driver technologies
  - Developed new high-shot-rate, scientific platforms to study critical MIF physics

- Tech-2-market (T2M) outcomes
  - 3 new spinoff companies and $25M private capital raised by ALPHA projects*
  - Dozens of peer-reviewed publications and 6 patent applications filed, APS-DPP mini-conference (2018)

*Since 2015, publicly disclosed private funding into worldwide fusion R&D doubled to over $1B.

JASON summer study (2018) was commissioned by ARPA-E (w/contribution from NASA) to review ALPHA

- Statement of work:
  - Survey progress of MIF teams both inside and outside of ALPHA toward their stated goals
  - Assess progress of ALPHA and non-ALPHA MIF teams toward realizing low-cost fusion
  - Assess additional time, funds, or specific technical investments necessary to realize low-cost MIF
- Abbreviated summary of findings (Final report JSR-18-Task-011-FUSION):
  - 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
  - Reaching scientific breakeven on a single MIF prototype will likely cost at least several $100M; not yet able to assess viability of MIF for commercial fusion power
  - Pursuit of MIF could lead to valuable spinoffs, especially fusion propulsion for lower-mass concepts
  - MIF could absorb significantly more funding than ALPHA
- Recommendations
  - Investment should be made to study plasma instabilities, transport, liner-fuel mix at MIF conditions
  - National Labs should contribute unclassified codes and support the training of qualified users
  - Targeted technology development should focus on developing 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; pursue system integration only insofar as needed for scientific breakeven
  - Explore pulsed neutron and propulsion spinoffs; these should supplement, not replace, basic MIF research
  - Support all promising approaches as long as possible; do not concentrate resources on early frontrunners

Executive summary publicly releasable; full report only within DOE.
Please contact ARPA-E if you want the full report.

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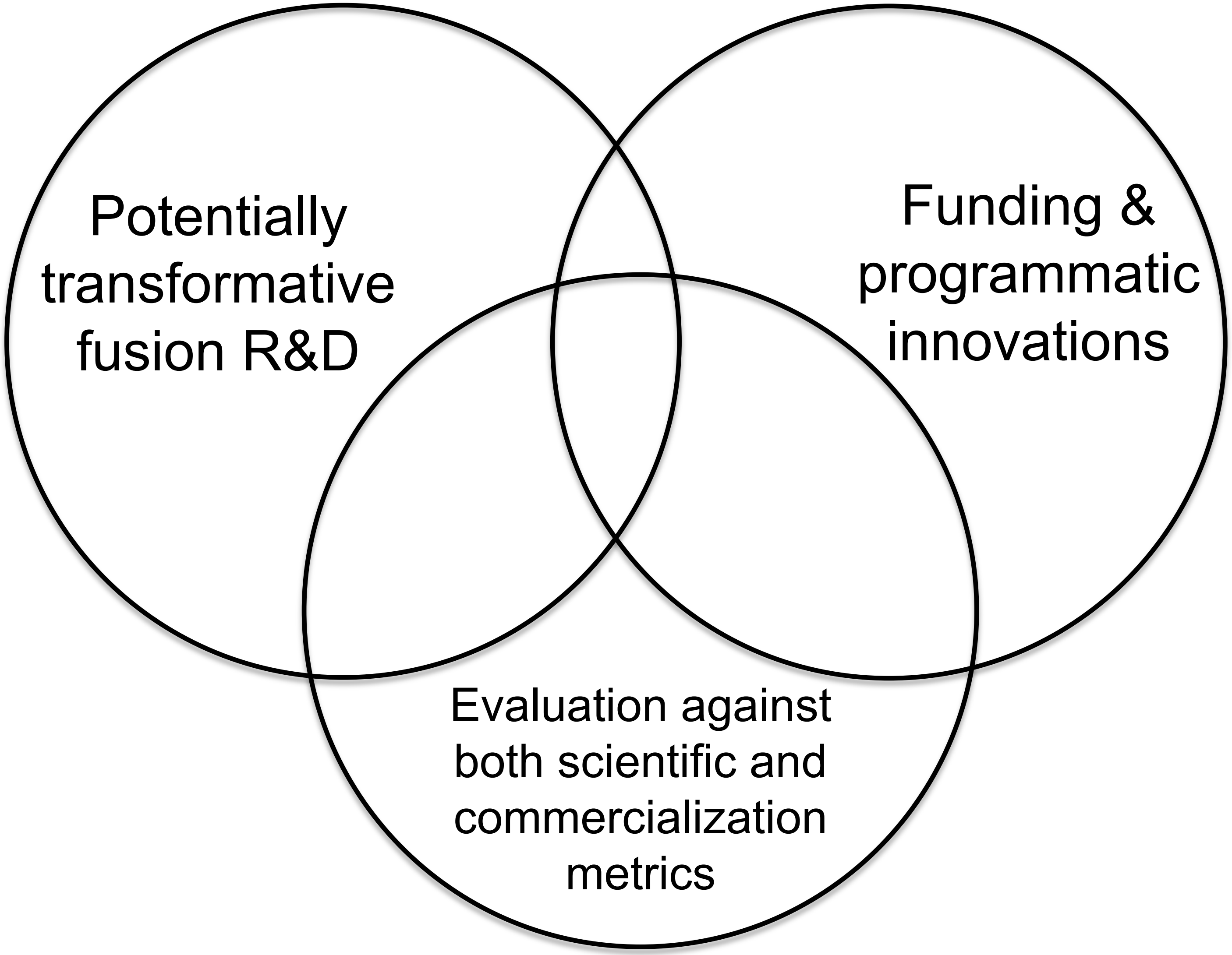
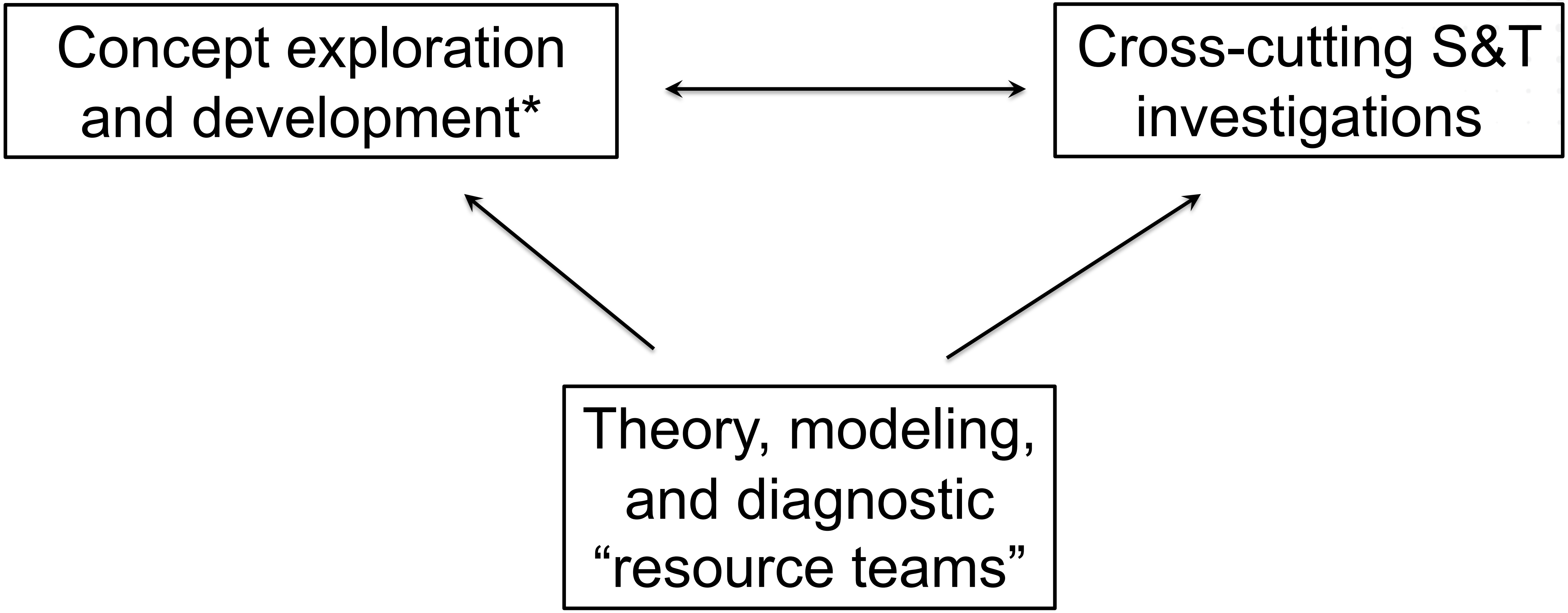
Guiding principles for a potential ARPA-E fusion program to follow ALPHA



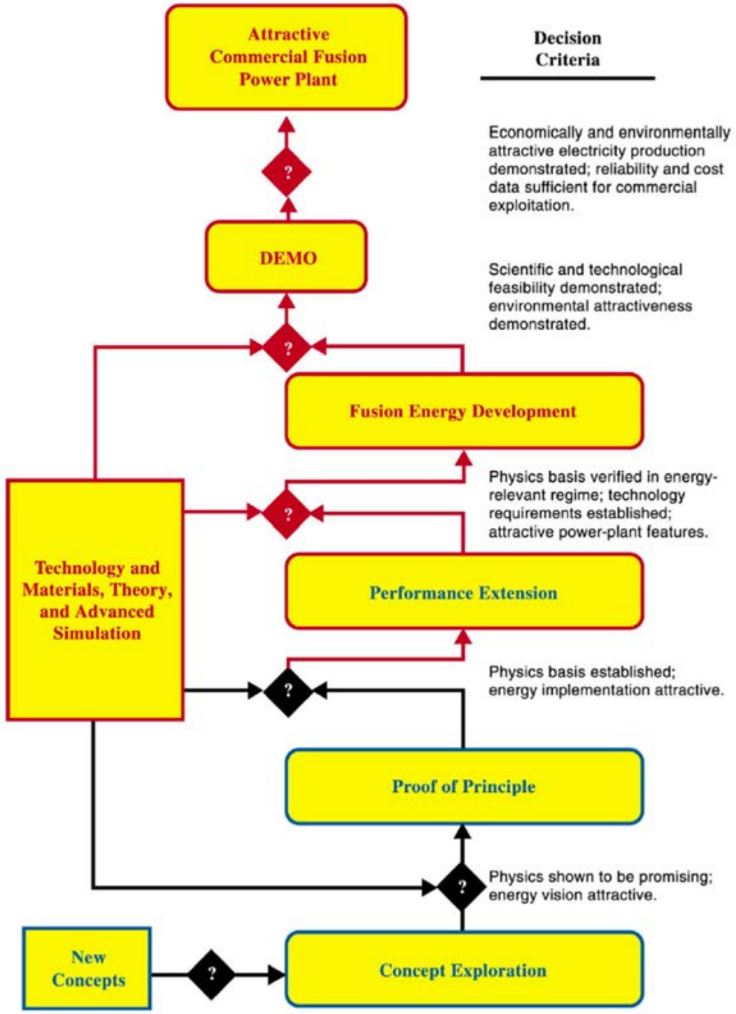
Support and further catalyze potentially transformative fusion R&D to enable timely commercial fusion power



*To include all credible fusion approaches, not just intermediate density.

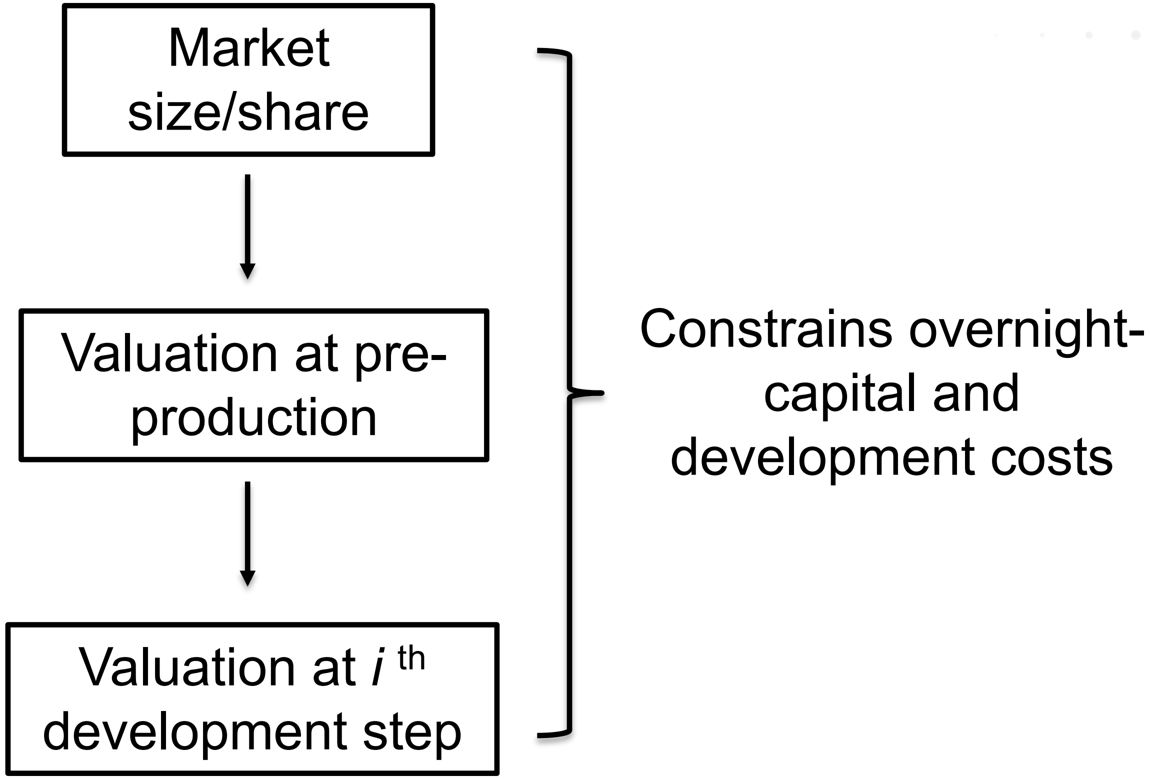
Evaluation against both scientific and commercialization metrics

Prior S&T roadmap/metrics* still applicable:



Requires appropriate $n T \tau$ metrics at each stage

Apply commercialization metrics (nothing new here,† just need to apply known corporate-finance methodologies):



*"Opportunities in the Fusion Energy Sciences Program," FESAC report (1999).
†e.g., W. Anson et al., *Fundamentals of IP Valuation*, (ABA, 2005).

Funding and programmatic innovations (in many cases inspired by models that have already been used elsewhere)

Funding

- Cost savings via shared resource teams and hardware
- Incentives to attract larger % of private $$

Programmatic

- Both scientific & commercialization metrics
- Incentivize partnerships between federally and privately funded teams
- Engage larger, growing fusion ecosystem

Summary/conclusions

- Transformative fusion-energy R&D fits into ARPA-E's mission

- ALPHA program, which aimed to create new low-cost tools for accelerating fusion development, had successful outcomes:
  - Tangible advances in fusion concept development in intermediate-density regime (e.g., 50× increase in $nT\tau$ for SFS Z pinch)
  - Demonstrated new low-cost drivers and platforms for advancing MIF S&T

- After-ALPHA planning:
  - New multi-faceted focused program in transformative fusion-energy R&D
  - Evaluation against both scientific and commercialization metrics
  - Funding and programmatic innovations

https://arpa-e.energy.gov