Prospects for Low Cost Fusion Development
Executive Summary

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In 2014 ARPA-E initiated the three-year $30M ALPHA program to explore magneto-inertial fusion (MIF) concepts in a span of 10^5 in plasma density (10^{18} – 10^{23} ions/cm^3), lying between the mainline tokamak (10^{14}/cm^3) and inertial (NIF at 10^{26}/cm^3) approaches. ALPHA's goal was to identify ways to accelerate progress toward fusion power.

With the ALPHA program nearing completion, ARPA-E asked JASON to assess its accomplishments and the potential of further investments in this field. JASON members listened to two days of briefings that included participants in ARPA-E's ALPHA program, MIF teams not supported by ALPHA-E, and teams working on pure magnetic confinement fusion. JASON also surveyed nine teams for quantitative metrics of past, present, and projected progress along critical physical parameters.

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EXECUTIVE SUMMARY

Controlled thermonuclear fusion has been pursued for more than 60 years. In recent decades, US funding has focused on laser-driven inertial confinement (ICF) for national security purposes and on magnetic confinement (MCF), primarily in tokamaks, for energy production. The major component of the latter international program is the $25B ITER project, expected to begin DT operation in 2035.

In 2014 ARPA-E initiated the three-year $30M ALPHA program to explore magneto-inertial fusion (MIF) concepts in a span of 10^5 in plasma density (10^{18} – 10^{23} ions/cm^3), lying between the mainline tokamak (10^{14}/cm^3) and inertial (NIF at 10^{26}/cm^3) approaches. ALPHA's goal was to identify ways to accelerate progress toward fusion power.

With the ALPHA program nearing completion, ARPA-E asked JASON to assess its accomplishments and the potential of further investments in this field. JASON members listened to two days of briefings that included participants in ARPA-E's ALPHA program, MIF teams not supported by ALPHA-E, and teams working on pure magnetic confinement fusion. JASON also surveyed nine teams for quantitative metrics of past, present, and projected progress along critical physical parameters.

The findings of this study are summarized as follows:

1. Magneto-Inertial Fusion (MIF) is a physically plausible approach to studying controlled thermonuclear fusion in a region of parameter space that is less explored than Inertial Confinement Fusion (ICF) or Magnetic Confinement Fusion (MCF).
2. MIF research is immature. Despite having received ~1% the funding of MCF and ICF, MIF experiments have made rapid progress in recent years toward break-even conditions, and some (e.g. MagLIF) are within a factor of 10 of 'scientific break-even'.
3. There are many plausible and distinct approaches to MIF. Some early projects supported by the ALPHA program are showing rapid progress in critical physical parameters and have not *yet* reached insurmountable obstacles. As in ICF and MCF, instabilities may make scientific break-even MIF more challenging than simple scaling estimates suggest.
4. ALPHA program support for development of broadly applicable technologies has accelerated progress of multiple efforts. All MIF approaches would benefit from improved understanding of plasma instabilities and liner-plasma interactions, better computational tools, and improved diagnostics.
5. While scaling from current experiments is uncertain, it is likely that reaching scientific break-even with a single MIF prototype will cost at least several $100M and possibly much more. Considerably larger expenditures would be required to go from scientific breakeven to a demonstration power plant; and even more from a demo to a production capability.

6. Given the immaturity of the technologies, the future ability of fusion-generated electricity to meet commercial constraints cannot be usefully assessed. Rapidly developing infrastructures for natural gas and renewable energy sources and storage will compete with any future commercial fusion efforts. Nevertheless, there is a small but growing private-sector community investing in and pursuing commercial fusion projects.
7. The pursuit of MIF could lead to valuable spinoff technologies, and to non-power fusion applications, with broad civilian and military import. Some approaches have low enough mass to be candidates for space propulsion, but it is too early to impose the relevant design constraints (low weight, low thermal dissipation) on ongoing research.
8. MIF research could productively absorb a significantly higher level of funding than the $10M/yr of the ALPHA program.

These findings lead to the following recommendations:

1. MIF activities should be supported by an investment in basic research to:
    - study plasma instabilities and transport under MIF conditions, and
    - study plasma-liner interactions.
2. The National Laboratories should contribute their unclassified state-of-the-art simulation codes to collaborations with academic and commercial efforts, and support training of qualified users.
3. Targeted technology development programs should focus on development of components, including plasma guns (high Z and low Z), pulsed power and electronics, diagnostics, and advanced magnets and materials.
4. The near-term goal should be scientific break-even (thermonuclear energy out > mechanical + electromagnetic energy into the fuel) in a system that plausibly scales to a commercial plant. Until that goal is achieved, set aside questions of neutron economy (tritium breeding) or balance of plant. Pursue system integration only insofar as it is needed to demonstrate scientific break-even.
5. Explore pulsed neutron sources and space propulsion as motivating applications with different constraints than grid electricity. Efforts in these speculative directions should supplement, not replace, basic MIF research.
6. Support all promising approaches for as long as possible. Do not concentrate all resources on early front-runners.