# Whitepaper on proposed strategic element for U.S. magnetic fusion research

## Opportunities presented by magneto-inertial fusion (MIF)

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**Executive summary of proposed strategic element:** The proposed strategic element (SE) is to advance the science and technology of magneto-inertial fusion (MIF) (aka magnetized target fusion), including but not limited to liner-driven [1–4] and Z-pinch-based approaches.[1]

**Scientific and/or engineering opportunity:** Key opportunities of this SE are to build on recent modest DOE Office of Fusion Energy Sciences (OFES) and ongoing Advanced Research Projects Agency–Energy (ARPA-E) investments to continue improving the performance of magnetized target plasmas, imploding liners, and Z-pinches in the context of fusion energy. Further development and integration of these activities into one or more devices capable of achieving fusion-relevant conditions could provide the potential to (1) significantly lower the cost of fusion-energy development (by virtue of the anticipated lower capital cost required for a breakeven-class facility in the intermediate-density regime [2,5,6], as shown in Fig. 1),[2] and (2) enable economically attractive power plant designs competitive with other sources of electricity [7], provided that the outstanding scientific and technological challenges can be overcome. Scientific proof-of-principle for MIF has essentially been achieved, e.g., multi-keV electron and ion temperatures, reactor-relevant values of the product of field times radius *BR*, and substantial neutron yield were recently demonstrated by the MagLIF project on the Z machine at Sandia [8]. S&T research to create similar plasma/fusion conditions in a manner that is compatible with low-cost, high-shot-rate operation with the potential for scale-up to a repetitively firing fusion power reactor is a primary focus of the present ARPA-E ALPHA program,[3] which ends in late 2018. Justified by the scientific results, relative engineering simplicity, and economic attractiveness of MIF, research efforts in this area should continue beyond the ALPHA program. In addition, important ancillary reasons for this SE include advancing the scientific understanding of magnetized high-energy-density plasmas, with broad relevance to scientific issues such as mix and transport, topics in plasma astrophysics, and diagnostic development, as outlined in the 2010 report on Basic Research Needs for High Energy Density Laboratory Physics (HEDLP).[4]

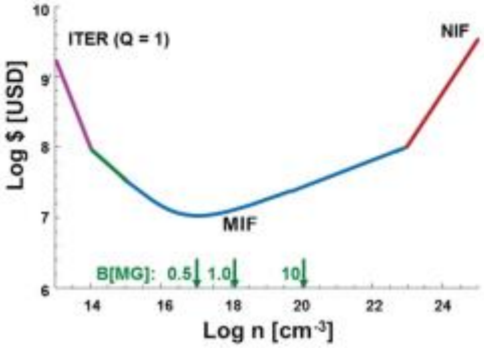

*Figure 1. Minimum in fusion-system cost vs. fuel density [5,6], based on the decrease in energy-related cost with higher density and increase of power-delivery cost with higher power density for total cost = $C_w W_p + C_p P$, where $C_w$ is cost per Joule of plasma energy $W_p$, and $C_p$ is cost per W/m$^2$ for power density $P$. Figure adapted from [6]. See also footnote 2.*

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[1] Some in our community associate the term "MIF" only with those approaches based on liner compression of a magnetized target plasma. In this white paper, we regard MIF as including any approach involving plasma compression and the use of magnetic field to enhance thermal insulation in the fusion fuel.

[2] A heuristic way to understand the low-cost minimum at intermediate density is as follows. Either increasing fuel density $n$ or increasing confinement time $\tau$ increases cost, so the cost scales as $c_1 n^a + c_2 \tau^b$, where $c_1$, $c_2$, $a$, $b$ are all positive parameters. Because the Lawson criterion requires $n\tau >$ constant, substituting $\tau =$ constant/$n$ shows that the cost scales as $c_1 n^a + d/n^b$, where $d$ is a positive parameter. It is straightforward to show that the cost becomes very large at either very small or large $n$, and thus there is clearly an intermediate $n$ at which the cost is minimized.

[3] Accelerating Low-cost Plasma Heating and Assembly (ALPHA): https://arpa-e.energy.gov/?q=arpa-e-programs/alpha.

[4] https://science.energy.gov/~/media/fes/pdf/workshop-reports/Hedlp_brn_workshop_report_oct_2010.pdf.

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## 1. Ensuring U.S. leadership in a field of plasma physics and/or fusion development

The U.S. has long been a world leader in this area, along with the former Soviet Union. There remains interest in Russia, and China is ramping up efforts in this area. General Fusion, a Canadian company, is the leading privately funded effort, and Sandia is the world leader (although its focus is on stockpile stewardship and not fusion energy). ARPA-E's sponsorship has rejuvenated this field, but the U.S. will likely fall behind if we do not continue to systematically nurture this line of research.

## 2. Impact on present and future international activities and collaborations by U.S. scientists

Further strengthening of this area would encourage worldwide efforts that would naturally lead to more international collaborations. There are already collaborations by U.S. institutions with General Fusion and Russian institutions.

## 3. Impact on the health of domestic fusion research at universities, national labs, and industry

The ARPA-E ALPHA program funded nine projects, with three each led by universities (Washington, Caltech, Swarthmore), national laboratories (LANL, Sandia, LBNL), and private companies (Helion, MIFTI, NumerEx), respectively. The ALPHA program has generated a disproportionately large amount of scientific excitement within the community, as well as significant attention from policymakers, investors, and media in light of its extremely modest budget ($30M total over 3 years). The ALPHA program has attracted many new postdocs, students, and even staff from other areas to fusion energy research, and has led to substantive engagement of fusion scientists with many non-scientist stakeholders in clean energy technology. This research will advance plasma and fusion science that can be studied in compact devices, even in devices with $Q<1$. This work is highly synergistic with many topics in the OFES discovery-plasma-science portfolio, and the ALPHA projects now represent a sizable fraction of the existing/active remnants from the earlier Innovative Confinement Concepts (ICC) and HEDLP programs. Finally, this research area was able to attract a new funding agency (ARPA-E), many private companies, and private investments to support fusion-energy research; these are all indicative of the promise of MIF.

## 4. Impact of/from unanticipated events or innovations requiring programmatic re-direction

Further and sustained success in this area could itself become an unanticipated event or innovation that could transform fusion-energy development, as it could drastically lower the cost and timeline of fusion-energy development. A breakeven-class MIF facility could potentially cost one-to-two orders of magnitude less than mainstream magnetic- and inertial-fusion breakeven-class facilities.

**Additional Considerations:** The proposed SE is the epitome of exciting, potentially high-payoff research that the fusion program needs to generate excitement among a new generation of fusion scientists and to enhance the possibility of providing an attractive product (i.e., an economically competitive fusion reactor). MIF offers a new, relatively unexplored path toward fusion energy that is based on exciting science.

## References:

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