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What are the fastest routes to fusion energy?

Special Collection: Private Fusion Research: Opportunities and Challenges in Plasma Science

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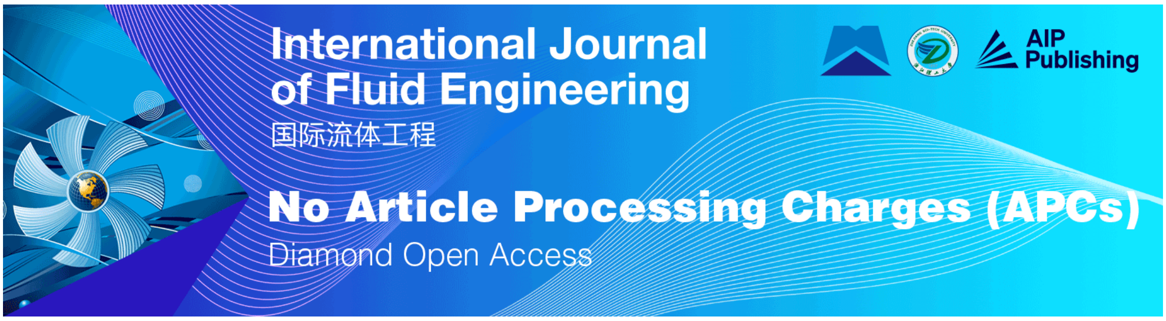

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ABSTRACT

In recent years, the effort to develop practical fusion energy has rapidly evolved from a focus on only tokamak and laser inertial devices to include a wide array of approaches. We survey this increasingly diverse set of routes to fusion to assess what approaches are likely to lead to practical fusion with the least outlay of resources and thus are potentially the fastest routes. While a conclusive answer can only be determined once some approach actually succeeds in producing a practical fusion-energy generator, and the speed of advance depends on the allocation of resources, it is possible to arrive at tentative conclusions now. We find that basic, long-standing obstacles make the path to practical fusion more difficult, and more resource-intensive, for all approaches using deuterium fuels (DT, DHe3) as well as for approaches with low-density plasma. The approaches that combine hydrogen–boron (pB11) fuel with high-density plasma have an easier, less resource-intensive path. At present, only a few private companies have joined the government projects in actually publishing fusion yield results. However, so far these results reflect the basic advantages of high-plasma-density approaches.

I. INTRODUCTION

The announcement[1] in December 2022 that the National Ignition Facility had achieved, in a single shot, more fusion yield than the energy focused on the fuel pellet has increased public discussion of fusion energy as a possible alternative to fossil fuels. The possibility that a substantial fusion contribution can occur in the first half of the century has been raised by predictions from many private fusion companies, including our own, that practical fusion generators could be developed in the coming decade.

These new predictions have occurred in the context of a major evolution of the field over the past decade, from an effort almost entirely focused on large-scale government projects involving either tokamaks or lasers, to a much more diverse endeavor involving over two dozen private fusion companies using a wide variety of approaches. Given this situation, it's an appropriate time to assess these approaches and their prospects for developing fusion generation on a scale that actually affects a transition away from fossil fuels.

We here make an interim assessment by answering two questions. First, which approaches can achieve a transition to a fusion-based economy the fastest? By fastest, we mean here with the least expenditure of resources as measured by person-years of effort or money expended, since of course the actual time any goal takes depends on the rate of resources invested. Second, which approaches are, at this time (mid-2023), the furthest advanced toward the initial goal of net energy—more energy out of an entire device than is put into it?

We choose to address these questions in particular because they potentially can be answered in an objective, observationally based manner. In contrast, the question of which approach is most likely to succeed, a question often posed by government funding agencies, is inherently unanswerable in the present research phase of the fusion energy effort. Unless an approach can be demonstrated to be physically impossible, the probability of success is an objectively unmeasurable quantity until success actually occurs.

While there are a large number of projects aiming at practical fusion energy, the most significant distinctions among them can be made on the basis of the fuel used—either deuterium-based or boron-based, and on the density of the fuel—either high density with $n > 10^{15}/\text{cm}^3$ or low density with $n < 10^{15}/\text{cm}^3$. This groups all projects into four categories that broadly share key characteristics relevant to their speed or cost of development.

II. COMPARISON OF DEUTERIUM AND BORON FUELS

Fusion research long emphasized deuterium–tritium (DT) fuel, as this fuel achieved significant fusion reaction rates at lower ion temperatures (T_i) than any other fuel. However, the DT reaction releases most of its energy in the form of a 14 MeV neutron. Since the early days of fusion energy work, researchers have been aware that this situation generates barriers to rapid deployment of any DT-based fusion generators and, conversely, puts a floor on the capital cost of such generators.

This is because there is no known way to convert neutron kinetic energy into electricity except by a conventional thermal generation system, as has been used in electric systems for well over a century. In existing fossil fuel generation plants, the energy conversion system, such as a steam turbine and generator, constitutes 80% or more of the capital cost. The conversion technology is by now extremely mature, and capital costs for these systems alone are in the area of \$1–1.5/W of installed capacity.[2]

These two considerations mean that it is practically impossible for any DT system to have capital costs less than existing fossil fuel plants. This, of course, does not mean that the delivered cost of electricity, which includes the fuel price, could not be less for DT fusion plants. However, it sets a floor on the minimum capital cost of a transition from fossil fuels to DT fusion generation.

Since about 50% of all energy use is for heating and would not necessarily require conversion to electricity, a complete conversion to DT fusion would require, at 2023 levels of energy consumption of 20 TW, a minimum of \$10 trillion for energy conversion equipment alone. In itself, this is not a prohibitive amount over a 15-year transition period, as compared with fossil fuel costs in the area of \$75 trillion over the same period at present prices. However, it is a useful benchmark for comparison with other routes.

Fuel cycles based on pure deuterium, such as that proposed by Helion Corp. to produce He3 for the DHe3 reaction, have many of the same considerations as DT approaches, as neutron-producing reactions cannot be entirely avoided. For a broad range of T_i, DD reactions that produce T and subsequent DT reactions will produce about 25% of fusion energy in the form of neutrons.

In contrast, pB11-fueled generator would produce energy almost entirely in the form of either charged particle kinetic energy or x-rays. In both cases, several direct conversion schemes have been proposed or developed for other applications. These include photoelectric conversion for x-rays[3] and both electrostatic and electromagnetic deceleration for charged particle beams.[3–5] In the case of many of these technologies, no secure cost estimates can be obtained. However, an idea of the cost advantage over thermal conversion can be obtained by looking at one-of-a-kind or low-unit costs of direct energy conversion technologies such as gyrotrons, which convert electron beam energy into microwaves. One-of-a-kind or small numbers, <20, of 1 MW gyrotrons typically have prices of around \$1/W.[6] With reasonable scaling for mass production in thousands or millions of units that would be needed for a full transition to fusion, cost reductions to the area of \$0.1/W are to be expected, reducing the minimum energy conversion costs for such a transition to the region of \$1 trillion.

Other inherent aspects of DT devices also will increase cost and slow rollout. Neutron damage to structures, not present with pB11, will shorten generator lifetime and produce radioactive materials that will need to be disposed of. The essential tritium-breeding blanket is an additional cost not needed in pB11 devices. Thus, exclusive of the actual design of the fusion generators, a transition to DT fusion energy will require considerably more resources than one to pB11 fusion, or equivalently will take longer for a given level of investment.

Despite the clear economic advantages of pB11, little or no government funding has been provided for approaches using this fuel. This decision was justified on the basis of studies in the 1970s that claimed that increased bremsstrahlung radiation due to boron's five atomic charges would prevent any pB11 generator from reaching ignition with more fusion power than x-ray power.[7] However, subsequent research showed that this analysis was faulty for several reasons. First, it rested on reaction cross sections and reaction rates that were more than a factor of 2 too low.[8] Second, it assumed that there was no way to maintain, for the duration of a fusion burn, a large gap between electron and ion temperatures, which would decrease bremsstrahlung emission. This also turned out not to be valid.

LPPFusion's own research[9] demonstrated that at high magnetic fields, the quantum magnetic field effect would produce $T_i > 25\,T_e$. This effect, first pointed out in the 1970s[10] and studied in the case of neutron stars,[11] involves the reduction of energy transfer from ions to electrons in the presence of a strong magnetic field. In most fusion plasmas, the plasma is strongly magnetized, meaning that the ions and electrons circle around the magnetic field lines many times before they undergo a collision. For the ions, this results in their velocity vector being closely aligned with the local direction of the magnetic field.[12]

In collisions between charged particles, momentum transfer can only occur in the direction perpendicular to the direction of motion. (Somewhat the same way pedestrians move sideways to avoid each other on a busy sidewalk.) So, for an ion moving along a magnetic field line (in the direction of the magnetic field) to transfer energy to an electron, the electron must move away from the magnetic field direction, acquiring more angular momentum as it moves in a wider circle around the field direction.

In a strong magnetic field, since angular momentum is quantized in units of ħ, electrons can have only discrete energy levels, termed Landau levels (ignoring motion parallel to the magnetic field),

$$E_b = \left(n + \frac{1}{2}\right)\frac{e\hbar B}{mc} = \left(n + \frac{1}{2}\right)\cdot 11.6\,\mathrm{eV}\cdot B(GG). \tag{1}$$

Since maximum momentum transfer is mv, where v is the relative velocity, for $mv^2/2 < E_b$ almost no excitation of electrons to the next Landau level can occur, so very little energy can be transferred to the electrons in such collisions. Again, ignoring the electron's own motion along the field lines, such a condition will occur when ion energy

$$E_i < \left(\frac{M}{m}\right)E_b. \tag{2}$$

For $E_i = 300\,\mathrm{keV}$, this implies $B > 14\mathrm{GG}$ for p, $B > 3.5\mathrm{GG}$ for α, and $B > 1.3\mathrm{GG}$ for $^{11}\mathrm{B}$. Such field strengths should be attainable with the dense plasma focus (DPF) device, z-pinch and with laser-driven devices. In fact, detailed analysis shows that the effect starts to become important at considerably weaker fields.

As calculated,[12] for $T = T_i/E_b(M/m) < 1$, the energy transfer rate can be reduced by a factor as large as 25 for the heating of electrons by ions, which can only heat electrons that are moving slower than the ions. For the heating of the ions by the much faster thermal electrons, with $T_e/E_b \gg 1$, quantum effects can be ignored and the coulomb logarithm in the collision rate formula is simply ln $(2T_e/E_b)$ with no reduction from the classical result. As a result, the ratio of these two heating rates can be as high as 25, which results in a similar value for

T_i/T_e. This results in a reduction of x-ray emission by as much as a factor of five.

In addition, other work by TAE, a private fusion company, showed in simulations that ion beams in field-reversed configuration (FRC) devices[13] could reach net energy conditions without substantial heating of electrons. HB11 and Marvel Fusion, additional fusion companies, have shown the same for side-on laser irradiation[14] approaches. These calculations demonstrated that net energy production with pB11 was physically possible. Among other effects, they noted that heating of ions by fusion-produced alpha particles could be faster than the heating of electrons. There is now preliminary experimental verification of these effects (see Sec. IV).

A significant challenge of boron fuels is that they require a much higher T_i than DT to achieve a comparable burn rate. While the DT reaction rate peaks at 9×10^{22} m^3/s at a T_i of 60 keV, the Pb11 reaction rate peaks at a somewhat lower level of 6×10^{22} m^3/s at a T_i of around 900 keV. Significant pB11 burn requires $T_i > 150$ keV.

However, LPPFusion already demonstrated[15] in 2017 confined ion energy in excess of 200 keV. At the high densities expected with optimized performance of the FF-2B device, fusion burn of pB11 fuel will increase T_i to >600 keV, according to simulations.[16]

III. COMPARISON OF HIGH AND LOW-DENSITY APPROACHES

A second primary distinction is between low-density plasma and high-density plasma approaches. As we will show, a useful criterion separates high and low density at $n_i = 10^{15}$/cm^3. Since $n\tau > 10^{14}$ s/cm^3 for minimum fusion burn in a practical generator, this criterion also separates short pulse systems $\tau < 0.1$ s from long pulse and steady-state systems. At the present time, all systems using external magnetic fields primarily to confine plasmas are low-density approaches, while high-density approaches use internally generated magnetic fields as in dense plasma focus devices and z-pinches, or inertial confinement as in laser and impact systems. High-density approaches may use external magnetic fields in addition to other confinement, but not by themselves.

In devices that use external magnets alone to confine the plasma, the maximum theoretical n is limited by the strength of the magnetic field, as $\beta < 1$, where β is the ratio of thermal energy density to magnetic field energy density $\beta = 4 \times 10^{-11}$ nT/B^2, where B is the magnetic field strength in G, T ion temperature in eV, and n ion number density in cm^{-3}. Until around 2010, limitations on superconducting materials limited practical magnetic fields in plasma vessels to about 5×10^4 G or 5 T, which limits $n < 3 \times 10^{15}$ even with $\beta = 1$.

However, fundamental stability considerations limit density considerably more, even with the recent development of REBCO superconducting tapes that can increase central B to around 10 T. As Alfvén and Falthammar first pointed out 50 years ago,[17] high-energy plasmas in nature are metastable, rather than absolutely stable, with lifetimes short relative to energy circulation times. We here define "energy circulation time," τ_{ec}, as the time for the total energy (magnetic and thermal) to circulate once around the plasma at the velocities of the ions. Quantitatively, natural plasma formations, such as in solar flares, do not exist for longer than about 10^3 times the energy circulation time. For natural plasmas with the thermal/magnetic energy ratio, $\beta \sim 1$, this limit is equivalent to a limit on ion confinement to about 1000 orbits.

Thus, for example, large solar flares have durations, d, linearly proportional to flare ribbon separation lengths,[18] L, with $d = L/(3 \times 10^6$ cm/s). Such solar flares have Alfvén velocities[19] around 1.7–2 $\times 10^8$ cm/s and thus survive typically for only about 20 τ_{ec} but can have durations up to 200 τ_{ec}. At much larger scales, galaxies have typical τ_{ec} of the order of 200 My and typical dynamical decay times of the order of 10 Gy, or 50 τ_{ec}. Essentially, no natural plasma endure > 10^3 τ_{ec}.

For fusion plasma with external magnets, lower β leads to longer confinement times with the same limit on energy circulation.

We can write this limit on confinement time, τ, of 1000 times the energy circulation time as

$$6 \times 10^{-3} R\, \mu^{1/2}/T^{1/2}\beta > \tau, \tag{3}$$

or 10^3 times the ion orbit time divided by β.

Since $\beta = 4 \times 10^{-11}$ nT/B^2, we can rewrite (3) as

$$1.5 \times 10^8 > n\tau T^{3/2}/B^2 R\mu^{1/2}, \tag{4}$$

where R is the radius of the plasma, and μ is the ion mass in units of the proton mass. Significantly, no controlled fusion experiments have exceeded this limit. Relatively long confinement times have been achieved only by reducing β to 1%–2% or less and reducing n to the region of 10^{14}/cm^3. Since practical fusion reactors with DT must have $n\tau > 2 \times 10^{14}$ s/cm^3 and $T > 30$ keV, for $B < 10$ T, Eq. (4) implies $R > 4.9$ m. While not so large as ITER's 6.2 m major radius, such large devices necessarily imply cost and resources needs relative to power that are far above those of existing energy sources.

For example, Commonwealth Fusion Systems' (CFS) ARC design[20] with $B = 9.2$ T, $R = 3.3$ m, $T = 27$ keV, $n = 1.8 \times 10^{14}$, and energy confinement time τ of 0.64 s conforms to limit in Eq. (4) with the right hand side $= 1.2 \times 10^8$. CFS expects ARC to generate 190 MW net power with a device whose fusion-generating core has a mass of 7200 tons and a cost of \$5.6 billion, or \$30/W, far in excess of the minimum \$1/W capital costs for steam generators and also far above capital costs for existing energy sources. These considerations apply to devices based on pB11 as well, if confinement is supplied by external magnets and the same limits on B then apply. For example, TAE estimates[21] that its planned generator will have a capital cost of \$4/W.

Given the n^2 power density scaling, a reduction in fusion core costs to below the \$1/W characteristic of the most economical energy sources today will require $n > 10^{15}$/cm^3.

In contrast, dense plasma approaches are not limited by external magnetic strengths. Typical densities already achieved[22–24] in DPFs $>10^{22}$/cm^3, in z-pinches $>10^{20}$/cm^3 and in laser fusion $>10^{24}$/cm^3. Similarly, magnetic fields in pinch devices have already exceeded 10^3 T and are projected[23] to reach $>5 \times 10^5$ T. Even at conditions typical for pB11 fusion, $n\tau \sim 2 \times 10^{15}$, $T > 600$ keV, plasma radii are in the range of micrometers to mm and are not significant factors in determining device size. Instead, the main costs involved in dense plasma devices are the energy drive systems, which include capacitor banks for all approaches. Laser-driven systems, of course, need the lasers as well as the capacitor banks to supply them, so must be more capital intensive, especially considering lasers' relatively low efficiency.

For all these drivers, there is no physically unavoidable scaling relationship between driver mass or cost and net power output. Since these are pulsed systems, planned power output depends on the duty cycle, which in turn is determined by cooling and other considerations not directly connected to the driver technology. However, the engineering cost estimates done by some of the companies show that potentially far lower costs are possible. For example, LPPFusion[25] calculated that a DPF-based pB11 generator with a pulse rate of 200 Hz could generate 5 MW net electric output from a 120 kJ capacitor bank with an overall capital cost of \$0.1/W and a per-unit capital cost of <\$500 000. Similarly, the generator is planned for a far more compact size, with a mass of ∼0.6 ton/MW as compared with, for example, ARC's 35 ton/MW.

Even with far more expensive PW laser drivers, with typical costs of \$300–500 million dollars, HB11 calculates[18] that 1 GJ pulses at a few Hz could generate 1 GW net electricity, implying a capital cost in the area of \$0.3/W. Thus, there is a capital cost ratio of approximately 50–1 between, on the one hand, low-density approaches of any fuel with costs of \$4–25/W and, on the other hand, high-density approaches with pB11 with costs of \$0.1–0.3/W. High-density approaches with DT, which would still have capital costs dominated by energy conversion, are at an intermediate level in the region of \$1–2/W.

At the present time, as noted above, external magnetic field confinement approaches are all low-density approaches. However, that situation could change in the future. First, an increase in the magnetic field strength by a factor of 3–4 could allow the increase in n to $>10^{15}$. Such an increase is certainly conceivable with progress in high-T superconducting commercial materials, but would not likely occur in the next few years.

Second, new magnetic confinement designs, including for tokamaks, could reorient to shorter pulses. For any approach, the stability limit [Eq. (4)] limits minimum R, but power output increases as n^2 so the use of pulse length $< \sim 0.2$ s with $n > 10^{15}$ could increase power output by a factor of 25 with a concomitant reduction in capital cost per W. While CFS does not specify a pulsed design for ARC, the short 0.64 s energy confinement time indicates a step in that direction.

In addition, scaling laws observed specifically in tokamaks indicate better confinement with shorter pulses. Recently, Song *et al.*[26] complied data showing a strong negative correlation of the best $n\tau T$ performance with pulse length with an empirical limit of

$$n\tau T < 10^{18}/\tau, \tag{5}$$

which again indicates the benefits of shorter pulses <0.2 s.

However, for DT external magnet confinement schemes, either path would involve large increases in wall loading of neutron flux, which may make such approaches infeasible.

Examples of companies pursuing each approach outline here are shown in Table I.

IV. COMPARISON OF CURRENT FUSION YIELD RESULTS

The comparison outlined in Secs. II and III leads to the expectation that high plasma density approaches can make more progress with smaller expenditure of resources. Indeed, looking at the present state of the fusion energy effort at the time of this writing (October 2023), we find that this is the case. At the present time, no approach has yet reached the goal of net device energy—more energy out of an entire device than is put into it. The ratio of fusion yield to device energy, termed Q total or wall plug efficiency, is, thus, a good measure of the present state of various approaches. Ideally, the comparison should be made with the same fuel, but we here consider all fuels.

TABLE I. Summary of the organization of fusion efforts into the four categories outlined here. At least, one company is listed for each approach, but this is not a comprehensive list (which in any case is growing rapidly).

Fuel	Low plasma density	High plasma density
DT/DD	Helion	MIFTI
pB11	TAE	LPPFusion, HB11, Marvel Fusion

For deuterium, which is still the most widely used experimental fuel, LPPFusion's own results[25] for Q total are substantially in the lead of all private fusion efforts (Fig. 1) Our results are only 30% lower than the best achieved by government-funded efforts with orders of magnitude less resources expended. Only two other private fusion efforts, MIFTI[27] and TAE,[28] have reported fusion yields, and only LPPFusion and TAE have done so with their own equipment. The MIFTI results were obtained on the publicly funded Zebra z-pinch at the University of Nevada.

TAE's deuterium results were obtained on their own "Norman" device. The device, ∼100 m in length, operates in a pulsed mode by first generating two toruses of plasma, which are projected toward each other by external magnetic fields. These merge into a single "field-reversed configuration" with its own toroidal and poloidal magnetic fields. Ion beams are then accelerated into the FRC, heating it to around 1 keV.

For pB11, both HB11 (Ref. 29) and TAE[30] have reported fusion yields although neither have done so on their own equipment. So, as is the case with MIFTI, the resources expended by HB11 understates the overall cost of the experiment. Despite pB11's greater reactivity, these results do not yet match those for pure deuterium. However, the

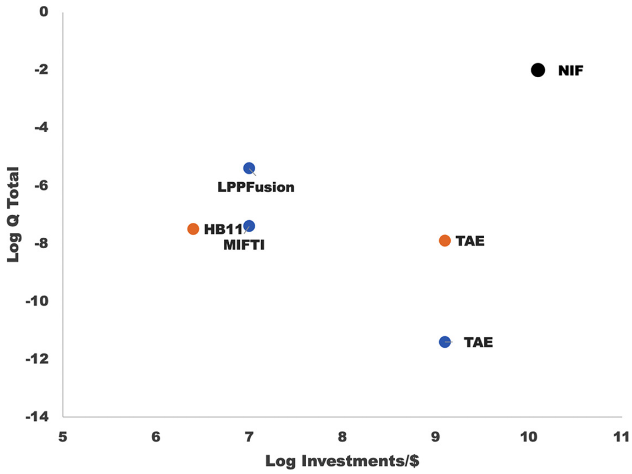

FIG. 1. Log Q total is plotted against log of total investments in the company to date. Blue dots are results with deuterium, and orange with pB11. The three companies with low investments and high Q total all use high-density plasma approaches. NIF results with DT are added for comparison.

increase in the pB11 yield has been rapid, with yields increasing by a factor of a thousand in the past decade.

HB11's results are based on a side-on laser beam aimed at a solid pellet. The beam does not produce fusion conditions directly. Rather, the picosecond pulse accelerates electrons rapidly out of the focus area into the bulk of the target, creating an extremely high electric field. This field, over a longer period of time, accelerates a beam of protons to MeV energies, and this beam produces fusion reaction by colliding with target boron nuclei. Additional reactions are produced as the alpha particle generated in the reactions heat the target protons directly. HB11's calculations indicate that the measured yields of about 4×10^9 reactions per J of laser energy on the pellet greatly exceed theoretical expectations of beam-particle reactions and can only be explained by taking into account alpha-particle heating. This direct heating helps to maintain a higher T_i than T_e.

The progress made by private efforts has inspired publicly funded institutions such as ENN in China to further advance this work. In August, 2023, while this paper was under review, a team from several institutions reported[31] comparably high yield from a laser-produced proton beam on a foam target, which led to enhanced electric fields.

At the present time, the largest Q total of any fusion experiments, around 0.01, in the NIF results, is for DT, in which no private fusion effort is yet using. This is a factor of 2400 more than the Q total achieved by LPPFusion with pure D fuel. The maximum Q total for the JET tokamak, also using DT, is very close to the same quantity.

A rough measure of speed of progress can be made by dividing Q total by total money expended (Fig. 2). Again, it is clear that the approaches that are progressing the fastest use dense plasmas. LPPFusion's results are expressed in these units.

V. CONCLUSIONS

Fusion approaches using high-density plasma and those using pB11 fuel have clear advantages both in terms of the speed of development and the cost of the eventual technology, if successfully developed. At present, only those approaches that use both dense plasma and pB11 fuel have any feasible path to capital costs less than those of existing energy sources and thus to a reduced overall cost of a transition away from fossil fuels. This is due to the fact that only dense plasma approaches with aneutronic fuel can achieve compact generators with direct energy conversion.

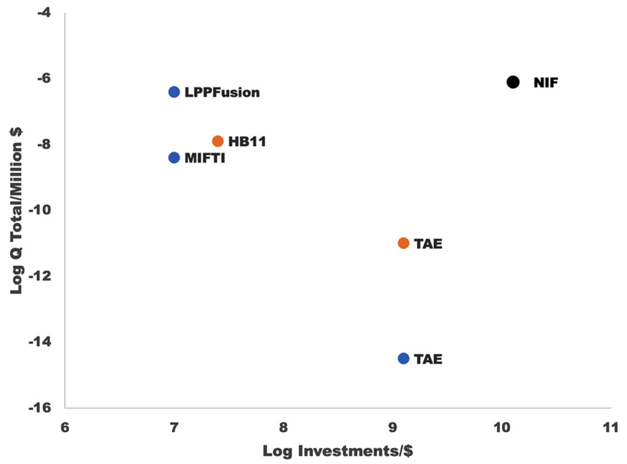

FIG. 2. The ratio of Q total to investments in millions of dollars is plotted as a rough measure of speed of advance against total money invested. Again, the current advantage of high-density plasma approaches is evident. By this measure, LPPFusion's rate of advance is comparable with NIF's.

Yet the dense-plasma, pB11 approaches have received a wholly insignificant fraction of governmental funding and less than 1% of the total private funding. Of course, any or all of the high-density pB11 approaches may encounter in the future currently unforeseen but insurmountable scientific or engineering obstacles. Thus, it is wise to continue funding deuterium-based and low-density fusion approaches. However, clearly an optimal funding allocation that maximizes the chance of a rapid development of economical fusion energy should provide as much funding for the high-density, pB11 approaches as they can usefully absorb, certainly more than double current funding. This will initially involve the reallocation of only a few percent of total fusion funding, but will ensure that we are indeed on the fastest route to fusion energy.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Eric J. Lerner: Conceptualization (equal); Investigation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Syed Hassan:** Investigation (equal); Writing – review & editing (equal). **Ivana Karamitsos-Zivkovic:** Writing – review & editing (equal). **Rudolph Fritsch:** Investigation (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] See https://www.llnl.gov/news/lawrence-livermore-national-laboratory-achieves-fusion-ignition for "Lawrence Livermore National Laboratory achieves fusion ignition (2022)."
[2] See https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capital_cost_AEO2020.pdf for "Capital cost and performance characteristic estimates for utility scale electric power generating technologies (2020)."
[3] E. J. Lerner and A. Blake, "Method and apparatus for producing x-rays, ion beams and nuclear fusion energy," U.S. Patent 7,482,607 (27 January 2009).
[4] M. Matsuoka, M. Araki, and M. Mizuno, Fusion Technol. **26**(4), 1296 (1994).
[5] K. Yoshikawa, Y. Nimura, Y. Yamamoto, and H. Watanabe, Fusion Technol. **17**, 527 (1990).
[6] J. T. Kare and K. L. G. Parkin, AIP Conf. Proc. **830**, 388 (2006).
[7] T. H. Rider, Phys. Plasmas **2**, 1853 (1995).
[8] T. A. Mehlhorn, L. Labun, B. M. Hegelich, D. Margarone, M. F. Gu, D. Batani, E. M. Campbell, and S. X. Hu, Laser Part. Beams **2022**, 2355629.
[9] E. J. Lerner, M. Krupakar, and A. Haboub, J. Fusion Energy **30**, 367 (2011).

[10] J. R. McNally, Nucl. Fusion **15**, 344 (1975).
[11] G. S. Miller, E. E. Salpeter, and I. Wasserman, Astrophys. J. **314**, 215 (1987).
[12] E. J. Lerner, in *Current Trends in International Fusion Research—Proceedings of the Fifth Symposium (2003)*, edited by E. Panarella (NRC Research Press, National Research Council of Canada, Ottawa, ON, Canada, 2007).
[13] J. W. Reep and S. Toriumi, Astrophys. J. **851**, 4 (2017).
[14] E. J. Lerner, S. M. Hassan, I. Karamitsos, and F. Von Roessel, Phys. Plasmas **24**, 102708 (2017).
[15] E. J. Lerner and R. E. Terry, in *Current Trends in International Fusion Research—Proceedings of the Sixth Symposium (2007)*, edited by E. Panarella (NRC Research Press, 2009).
[16] M. J. Aschwanden, Astrophys. J. **895**, 134 (2020).
[17] S. V. Putvinski, D. D. Ryutov, and P. N. Yushmanov, Nucl. Fusion **59**, 076018 (2019).
[18] H. Hora, S. Eliezer, G. J. Kirchhoff, N. Nissim, J. X. Wang, P. Lalousis, Y. X. Xu, G. H. Miley, J. M. Martinez-Val, W. Mckenzie, and J. Kirchhoff, Laser Part. Beams **35**, 730 (2017).
[19] H. Alfven and C.-G. Falthammar, *Cosmic Electrodynamics* (Clarendon Press, 1963).
[20] B. N. Sorbom, J. Ball, T. R. Palmer, F. J. Mangiarotti, J. M. Sierchio, P. Bonoli, C. Kasten, D. A. Sutherland, H. S. Barnard, C. B. Haakonsen, J. Goh, C. Sung, and D. G. Whyte, Fusion Eng. Des. **100**, 378 (2015).
[21] See https://lynceans.org/wp-content/uploads/2021/02/TAE-Technologies_US-converted.pdf for "The fork in the road to electric power from fusion" (2015).
[22] A. Sakurai, K. Shimoda, and K. Hirano, Jpn. J. Appl. Phys., Part 1 **17**, 1687 (1978).
[23] D. Klir, J. Kravarik, P. Kubes, K. Rezac, S. S. Anan'ev, Y. L. Bakshaev, P. I. Blinov, A. S. Chernenko, E. D. Kazakov, V. D. Korolev *et al.*, Phys. Plasmas **15**, 032701 (2008).
[24] D. J. Schlossberg, G. P. Grim, D. T. Casey, A. S. Moore, R. Nora, B. Bachmann, L. R. Benedetti, R. M. Bionta, M. J. Eckart, J. E. Field *et al.*, Phys. Rev. Lett. **127**, 125001 (2021).
[25] E. J. Lerner, S. M. Hassan, I. Karamitsos-Zivkovic, and R. Fritsch, J. Fusion Energy **42**, 7 (2023).
[26] Y. Song, X. Zou, X. Gong, A. Becoulet, R. Buttery, P. Bonoli, T. Hoang, R. Maingi, J. Qian, X. Zhong *et al.*, Sci. Adv. **9**, eabq5273 (2023).
[27] H. U. Rahman, E. Ruskov, P. Ney, F. Conti, J. C. Valenzuela, N. Aybar, J. Narkis, F. N. Beg, E. Dutra, and A. Covington, Phys. Plasmas **26**, 052706 (2019).
[28] M. W. Binderbauer, T. Tajima, M. Tuszewski, L. Schmitz, A. Smirnov, H. Gota, E. Garate, D. Barnes, B. H. Deng, E. Trask *et al.*, AIP Conf. Proc. **1721**, 030003 (2016).
[29] D. Margarone, J. Bonvalet, L. Giuffrida, A. Morace, V. Kantarelou, M. Tosca, D. Raffestin, P. Nicolai, A. Picciotto, Y. Abe *et al.*, Appl. Sci. **12**, 1444 (2022).
[30] R. M. Magee, K. Ogawa, T. Tajima, I. Allfrey, H. Gota, P. McCarroll, S. Ohdachi, M. Isobe, S. Kamio, V. Klumper *et al.*, Nat. Commun. **4**, 955 (2023).
[31] W.-Q. Wei, S.-Z. Zhang, Z.-G. Deng, W. Qi, H. Xu, L.-R. Liu, J.-L. Zhang, F.-F. Li, X. Xu, Z.-M. Hu *et al.*, arXiv:2308.10878v1 (2023).