New Opportunities in Fusion Power

***Science for America* White Paper**

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About Science for America

Science for America is a non-profit **"solutions incubator"** that brings together scientists and technologists, and works with partners across sectors to

- **identify potential game-changing solutions to urgent challenges**, in the US and around the world, that are not currently happening,
- **develop clear vision, strategy and execution plans**, and
- **ensure the launch and success of those solutions,** by incubating them to an appropriate stage.

Possible solutions may include the creation of projects, initiatives, shared facilities, coalitions, new companies, prizes, and advocacy efforts.

For more information, see scienceforamerica.org.

About this White Paper

This White Paper was developed under *Science for America's* **Climate & Energy Pillar**.

***SfA* Strategic Advisors and Internal Experts came together to define urgent challenges related to the climate crisis that may have the potential for game-changing solutions** that aren't already happening. The group identified several challenges on which SfA is focusing.

One of the most important of these challenges is the need for clean energy sources that are firm and on-demand (non-intermittent and can be readily ramped up and down), ubiquitous (siteable anywhere), inexpensive (much cheaper than fossil fuels), resource-light and safe. After considerable discussion, the group identified **New Opportunities for Fusion Power** as an important and promising direction.

The White Paper explores **whether recent advances suggest promising approaches to fusion that have received relatively little attention to date.**

Building on recent advances (including experimental results at the National Ignition Facility and on the Z Machine, and recent progress in pulsed magnetic power systems), **we describe two promising approaches for fusion power**. They have the potential to speed progress, decrease cost, and simplify engineering challenges and might both be tested on a single, shared "Demonstration System." **We refer to them as a Magnetic Igniter and a Sweet-Spot Burner.**

The White Paper shares the ideas with the scientific community to stimulate discussion and feedback, as well as to encourage research and commercial development of these potential solutions. SfA shares the ideas openly with the intent that anyone should be free to work on them.

The White Paper is written for a general scientific reader, although we hope that much of it will be accessible to members of the general public interested in science and technology.

This White Paper is a **DRAFT**, on which we invite input from the community. We plan to release a final version later in 2023.

Please send comments to fusion@scienceforamerica.org.

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Executive Summary

Solving the climate crisis will require the world to move rapidly from greenhouse gas-emitting fossil-fuel energy to abundant clean energy. That transition will be dramatically hastened if the clean energy alternatives are much cheaper than the fossil fuel sources.

Over the past fifteen years, there has been extraordinary progress with respect to intermittent renewable energy sources, specifically, solar and wind power. In favorable environments, they are now cheaper than fossil fuels when the sun is shining and the wind is blowing. Yet, today's technologies, though, face certain fundamental limitations: solar and wind are variable energy sources, batteries are less energy-dense than liquid fuels, and biofuels compete with food.

The world *also* needs power sources that are firm (non-intermittent), on-demand (can be ramped up and down), ubiquitous (siteable anywhere), inexpensive (much cheaper than fossil fuels), resource-light, and safe.

Fusion is, in principle, an obvious answer. Fusion is the process that powers the stars, in which light atoms (like hydrogen) are squeezed together to form heavier atoms (like helium), thereby releasing massive amounts of energy with zero CO_2 emissions. It fulfills the criteria above. And, thanks to the astronomical energy density of fusion reactions (millions of times higher energy per unit mass than in chemical reactions), fusion fuels are effectively limitless and free, with millions/billions of years of easily-accessible energy reserves.

The *idea* of fusion power is old, having been proposed more than 70 years ago. Moreover, the basic physics is well understood: a particular fuel (eg., deuterium-tritium, or D-T) confined at a pressure (P) and temperature (T) for a certain time (τ) can achieve sufficient fusion rates to release net-positive power provided that the product Pτ and the temperature T exceed certain critical thresholds. (Figure A shows the required thresholds for various values of P and τ.)

The problem has been that converting the theory into practical commercial fusion power has remained just over the horizon.

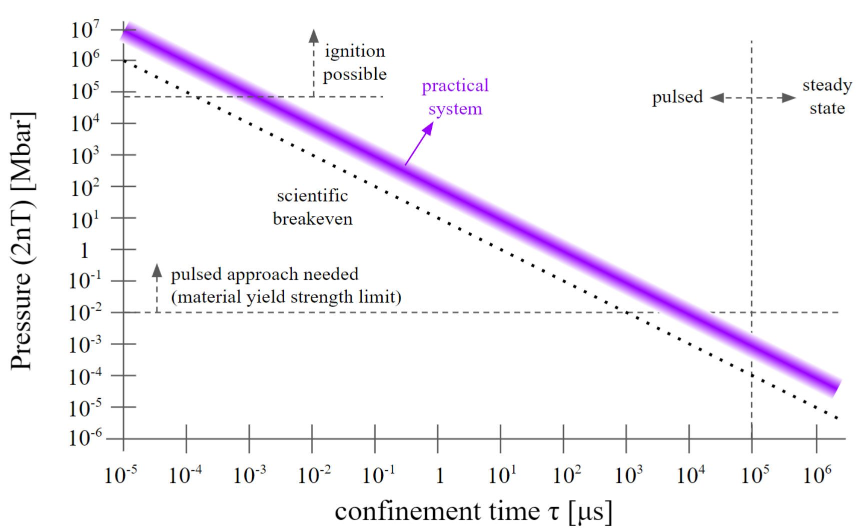


Fig A. A D-T fusion energy system must achieve a sufficiently high value of the Lawson product Pτ (at a temperature of at least ~10 keV) to release net-positive power. Scientific breakeven (power in charged fusion products exceeding plasma heating power) requires Pτ ~10 bar-s (dotted angled line), and practical energy systems require Pτ ~ 30-100 bar-s to achieve system-level net-positive power. Concepts operating at P > 10^{-2} Mbar must be pulsed, and concepts that achieve P > 10^{5} Mbar can ignite (allowing a fusion burn to propagate into cold fuel, significantly increasing attainable yield).

Recent Progress. In the past few years, there have been exciting developments that significantly raise the prospects that practical commercial fusion power can be achieved. Commercial activity has grown remarkably, with more than 30 startups worldwide, including a few with substantial funding (>$100 million). In addition, tools for designing and running fusion experiments have improved, notably recent advances in simulation and modeling tools that enable faster iteration and greater predictability.

Four approaches based on D-T fusion are currently well-supported in industry and/or government:

- **steady-state magnetic confinement.**
- **short-pulse laser-driven inertial confinement.**
- **long-pulse mass confinement.**
- **long-pulse magnetic confinement.**

Several companies are also pursuing approaches involving non-D-T fuel.

Some major recent milestones include:

- In September 2021, Commonwealth Fusion Systems showed how the high magnetic-field strength needed for compact steady-state magnetic confinement fusion could be efficiently achieved with high-temperature superconducting tape.
- In December 2022, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory provided the first demonstration of controlled ignition of fusion reactions.

Major challenges remain. Despite the exciting progress, there remain major scientific, engineering and economic challenges to creating working, inexpensive, scalable fusion energy systems that can address the world's urgent energy needs. The challenges include:

- achieving overall facility gain (that is, more energy out than in at the system level)
- avoiding rapid loss of confinement
- resilience against gradual component degradation
- systems with a wide range of rated power capacity, from small (10 MW) to large (2 GW)
- scalability and mass production of systems
- low cost of energy produced

Given the enormous transformative potential of commercial fusion power, the world should be undertaking a broad range of critical-mass efforts—including continuing to advance existing efforts *and* identifying additional approaches.

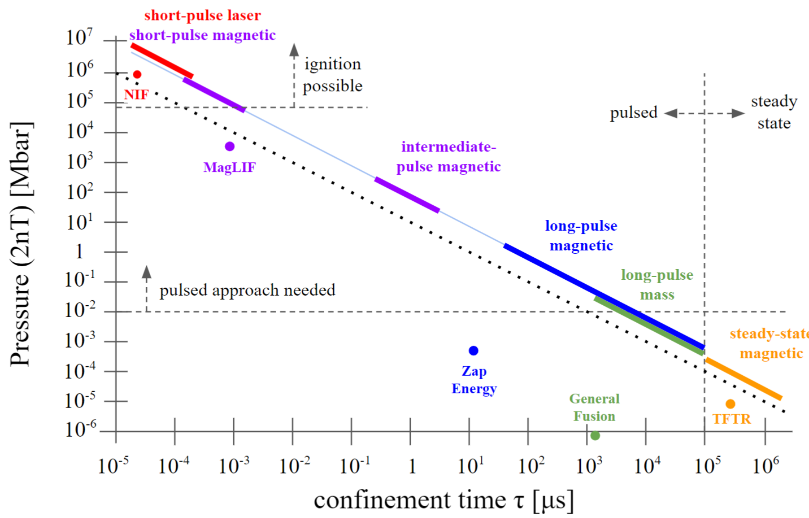
Two attractive approaches. *Science for America* therefore systematically reviewed the possible approaches to fusion to identify approaches that are currently receiving relatively little attention, but which recent evidence suggests could provide promising paths to commercial fusion.

In this White Paper, we describe two such approaches that are supported by solid scientific evidence from recent experiments and have the potential for both simpler engineering and lower cost. These approaches involve:

- **short-pulse magnetically-driven inertial confinement.**
- **intermediate-pulse magnetic confinement.**

Figure B shows a Pτ plot displaying these two approaches relative to the four currently well-supported approaches.

Fig B: This figure shows four currently well-supported fusion approaches (steady-state magnetic, short-pulse laser, long-pulse mass, and long-pulse magnetic) as well as two promising approaches currently receiving little attention: short-pulse magnetic (Magnetic Igniter) and intermediate-pulse magnetic (Sweet- Spot Burner). As discussed later, estimated peak Pτ demonstrated for different approaches in these regimes is also shown.



As a shorthand, we refer to a possible energy system using these approaches, respectively, as a **“Magnetic Igniter”** and a **“Sweet-spot Burner.”**

We briefly outline important features of each approach.

Magnetic Igniter. The concept is to use short-pulse magnetically-driven inertial confinement not just to achieve a burning fusion plasma, but to achieve ignition. Ignition is attractive because it is the point at which the system can burn additional unheated fuel, with the result that fairly small increases in energy input lead to huge increases in energy output.

The concept builds on learning from two recent experimental achievements: (i) The National Ignition Facility’s landmark demonstration in 2022 that ignition can be achieved by using *laser*-driven inertial confinement; and (ii) high-performance MagLIF experiments on Sandia’s Z Machine in 2022 using *magnetically*-driven inertial confinement to implode a cylinder of magnetized preheated fuel. Together, these two experiments demonstrated, respectively, the highest and second highest Pτ value ever achieved in the laboratory.

Our analysis indicates that short pulse magnetically-driven inertial confinement offers many potential advantages compared to laser-driven fusion. These advantages include the potential for much higher efficiency in energy delivery (>10x), much smaller scale (<1/10), much lower cost (<1/10), and simpler/cheaper targets. The minimum viable scale for the Magnetic Igniter may be in the range of ~100 MW, while also allowing much larger scales.

Sweet-Spot Burner. The concept is to use intermediate-pulse magnetic confinement (~1 μs pulses) to build a system with certain attractive properties. As described in the White Paper, the Sweet-Spot Burner design sits in the “sweet spot” that balances the minimum required energy and minimum required power for a fusion energy system, with the result that it could offer a very low minimum viable scale and cost.

For example, it should be feasible to create small energy systems (with power as low as ~10 MW, with eventual capital costs as low as tens of millions of dollars), as well as much larger systems (with power greater than or equal to 1 GW).

The possibility of small, compact, inexpensive energy systems would enable faster development cycles, expand the range of applications, broaden the customer base, allow application of mass production to drive down costs, and speed deployment around the world.

Single Demonstration Platform. Because both approaches involve pulsed magnetic fields, they involve many common components. In fact, they have enough similarities that it should be possible to demonstrate both approaches on a common pulser machine with programmable discharge timing.

With a concerted effort, it may be possible to: (i) efficiently build such a machine and demonstrate the ability to achieve net-positive facility gain and (ii) design and mass-manufacture inexpensive components with properties and costs suitable for use in commercial energy systems. (Commercial energy systems would be optimized separately for each approach and for various scales.)

Conclusion. Our examination of the fusion landscape has highlighted two promising approaches that have received comparatively little support. These two approaches — short-pulse magnetically-driven inertial confinement (Magnetic Igniter) and intermediate-pulse magnetic confinement (Sweet-Spot Burner) — are supported by recent compelling experimental evidence and offer potential engineering advantages that may facilitate development of viable commercial systems. We hope that the White Paper's discussion of these concepts – their potential advantages, challenges, and questions about how to best investigate them – will stimulate research efforts in the fusion community that complement existing fusion research efforts and accelerate fusion power as an affordable, scalable clean energy source.

Main Text

Section 1. Introduction

A. Why fusion?

Solving the climate crisis will require the world to move rapidly from greenhouse gas-emitting fossil-fuel energy to abundant clean energy. That transition will be dramatically hastened if clean energy sources are much cheaper than the fossil fuel alternatives. Over the past fifteen years, there's been extraordinary progress in intermittent renewable energy sources, specifically, solar and wind power. In favorable locations, they are now cheaper than fossil fuels when the sun is shining and the wind is blowing.

Today's technologies, though, face certain fundamental limitations: Solar and wind are variable energy sources, batteries are less energy-dense than liquid fuels, biofuels compete with food, etc. The world *also* needs power sources that are dispatchable (non-intermittent and can be ramped up and down on demand), ubiquitous (siteable anywhere), inexpensive (much cheaper than fossil fuels), resource-light (e.g., small physical footprints, low water consumption, low critical material and chemical inputs, etc.), and safe (have low risk to the environment, operators, and the general public).

Fusion is, in principle, an obvious answer. It's the process that powers the stars, in which light atoms (like hydrogen) are squeezed together to form heavier atoms (like helium), thereby releasing massive amounts of energy with zero CO_2 emissions. It fulfills the criteria above.[1,2] And, thanks to the astronomical energy density of fusion reactions (millions of times higher energy per unit mass than in chemical reactions), fusion fuels are effectively limitless and free, with millions/billions of years of easily-accessible energy reserves.

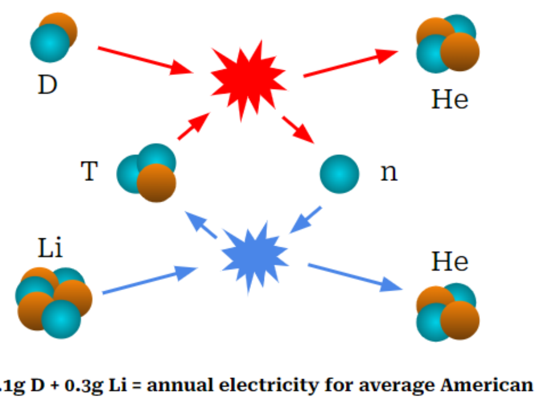


Fig 1: The easiest controlled fusion reaction merges D and T (isotopes of hydrogen) to produce a heavier He atom and a neutron, with the latter then absorbed by Li to generate more T. Thus, the fuel consumed is D and Li. It is also possible, though more difficult, to burn pure D by itself. There is enough Li on Earth for D-T energy systems to provide all of Earth's energy needs for millions of years, which would provide ample time for us to develop systems that burn D-D fuel, which could supply our energy needs for billions of years. This figure is adapted from a figure used in a CFS/MIT SPARC brochure.

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[1] Fusion has a few limits relative to fossil fuels: (i) fusion can't directly replace fossil fuels as chemical feedstocks or reductants, (ii) there is a minimum practical scale for energy-positive fusion (yields of ~1 MJ per shot or ~1-10 MWe power ratings), and (iii) fusion requires basic radiological safety practices. That said, low-cost fusion power can be used to synthesize carbon-neutral fuels and feedstocks, which can power applications where fusion isn't a direct solution.

[2] Unlike nuclear fission, fusion energy systems cannot melt down (a fusion reaction stops when you stop driving it, and there is no fission product decay heat to worry about in the event of a shutdown), do not use fissionable/fertile materials (uranium, thorium, and plutonium) that pose risks for nuclear proliferation, and do not produce radioactive waste with long half-lives. Fusion systems do require appropriate shielding and prudent, but much less onerous, regulatory safeguards.

B. Why now?

The *idea* of fusion power is old—it traces back to scientific research programs in the 1940s, if not earlier. The problem has been that converting theory into practical commercial fusion power has always remained just over the horizon. The big hurdle arises from the large barrier to squeezing atomic nuclei together, which requires getting hydrogen fuel *very* hot (10^8 ^oC) and confining it well enough and long enough to fuse. There is no *physical* barrier preventing this goal, but successful efforts must overcome substantial scientific, engineering, and commercial challenges.

In the past few years, there have been exciting developments that significantly raise the prospects that practical commercial fusion power can be achieved. Commercial activity has grown remarkably, with more than 30 startups worldwide, including a handful with significant funding (>$100 million). In September 2021, Commonwealth Fusion Systems showed how the high magnetic-field strength needed for compact steady-state fusion could be efficiently achieved using high-temperature superconducting tape. In December 2022, the National Ignition Facility at Lawrence Livermore National Laboratory provided the first demonstration of controlled ignition of fusion reactions. Over the past several years, we've also seen advances in diagnostic and simulation tools, which enable faster iteration and greater predictability in designing fusion experiments.

Whether fusion can truly deliver remains to be demonstrated. But, the transformative potential of fusion power is so enormous that the world should be undertaking a broad range of critical-mass efforts toward commercially-viable fusion.

C. Can fusion be relevant to the urgent climate crisis?

For fusion to make a major contribution to the goal of a net-zero world by 2050, it will need to quickly achieve widespread commercial deployment. This will depend on two key factors:

- **fusion being much *cheaper* than fossil energy**, to drive switching and adoption, and
- **fusion being rapidly deployable,** with a modest minimum-efficient scale, rapid innovation cycle, and mass-producible components—more similar to Tesla vehicles than to conventional large bespoke nuclear fission power plants.

D. How many ways are there to design a fusion energy system?

There are a number of fundamentally different approaches to build a fusion system based on:

- **Fuel**: Fusion involves combining light atoms to create heavier ones. The most studied reaction involves fusing two isotopes of hydrogen: deuterium (D) and tritium (T); it is the basis for most current commercial efforts. Other fuels may also be used, such as deuterium-deuterium (D-D), deuterium-helium-3 (D-^{3}He), or proton-boron-11 (p-^{11}B); they require higher energy input to achieve higher temperatures (and may require keeping ions and electrons at different temperatures, a challenging requirement) but produce fewer or less energetic neutrons, resulting in less wear on materials and waste generation.
- **Method of confinement**: There are three main approaches to confining/heating light elements (ionized in a plasma) to cause fusion reactions: magnetic confinement, laser-driven inertial confinement[3], and mass-driven confinement. These approaches may be combined in different ways.

[3] Inertial confinement typically involves imploding a small container holding fusion fuel.

- **Time of confinement**: Fusion energy systems can run in steady-state (continuously burning, like a furnace) or in pulses of different lengths (bursts of burning, like an internal combustion engine).

This White Paper focuses only on D-T-fueled fusion energy systems. (Non-D-T approaches are also being pursued, notably Helion's goal to burn D-^{3}He and TAE Technologies' goal to burn p-^{11}B.)

E. What are the essential criteria and desirable features for a commercial fusion system?

In thinking about designing a fusion energy system, it is important to keep in mind a number of essential criteria and desirable features:

(1) Positive gain. An obvious essential feature is that a commercially viable fusion system must produce more power than it consumes. The first milestone is to achieve net-positive "scientific" gain (Q_{sci}>1)—that is, the power carried by charged particles produced from fusion reactions should exceed the power required to maintain the burning plasma. The ultimate milestone is to achieve net-positive "facility" gain ($Q_{facility}$>1)—that is, the ultimate power output should substantially exceed all power inputs (including losses due to inefficiencies and parasitic losses, as well as converting the energy produced by fusion into a useful form, e.g., electricity).

(2) Avoidance of rapid loss of confinement ("fail with a bang"). Edward Teller once described fusion plasma confinement as "trying to hold a blob of jelly with rubber bands." Avoiding imperfections in confinement (such as instabilities, asymmetries, magnetic quenches) is critical because they can cause serious damage. In steady-state systems, the ever-present possibility of unplanned loss of confinement (e.g., disruptions in tokamaks) can rapidly and destructively deposit large amounts of thermal energy into the wall, necessitating shutdown[4] and wall repair or replacement. In pulsed systems, asymmetric misfires could also potentially damage the wall. Such problems could dramatically decrease a system's capacity factor (up-time) and increase its operations & maintenance costs.

(3) Resilience against steady degradation ("fail with a whimper"). Fusion energy systems will need to deal with component wear due to high plasma temperatures and high-energy fusion products.[5] To keep the operations and maintenance budget manageable, the design of shielding, coolant systems, and solid plasma-facing walls must minimize damage to components and/or enable easy, cheap, fast replacement of damaged components.

(4) Wide range of rated power capacity, from small to large. Today's conventional power plants vary in scale to address a range of needs[6] (from <1MW to >1.5GW). To similarly cover a broad range of uses and scales (e.g., baseload power, gas peaking plants, process heat for large factories), fusion energy systems would ideally be economical across a wide range of scales — from as small as 10 MW to as large as 2 GW or more.

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[4] For example, in 2016 a failure in a central magnet of the Princeton Plasma Physics Laboratory's NSTX-U tokamak resulted in significant damage that has shut the facility down to this day, with ongoing repairs likely to exceed ~$200 M.

[5] The challenges include: (i) 14 MeV D-T neutrons and 2.45 MeV D-D neutrons that can damage solid walls; (ii) high energy hydrogen and helium that will deposit in and embrittle solid walls; and (iii) X-rays and gammas that can damage wall and component materials.

[6] For a detailed description of US power plants, see the U.S. Energy Information Administration's Form EIA-860, which collects generator-level information about existing and planned generators.

(5) Modest physical footprint, without complex siting requirements. Power plants should ideally have modest physical footprints, for reasons including reduced real estate costs, faster siting approval, and decreased environmental burden. Today's nuclear fission plants require a physical footprint ~100x less than for a solar or wind farm producing comparable electricity (because their effective average power density is ~1 kW/m^2 vs. <10 W/m^2 for renewables when adjusting for capacity factor). Fusion systems should aim for similar or higher power density.

(6) Scalability and mass production. Given the enormous and urgent demand for clean power, fusion plants should be designed to be rapidly scaled, including drawing on the benefits of mass production. Some important elements are:

- **Standardized components that enable mass production, to drive down costs**.
- **Standardized designs that allow for efficient licensing by regulatory bodies**.
- **Minimal need for rare or hard-to-source materials to simplify supply chains**.
- **Small minimum scale for a working system, to speed progress down the learning curve**, by facilitating shorter, cheaper development cycles.
- **Small minimum scale to expand access**, by facilitating adoption in settings with more limited access to capital (e.g., power production in low and middle income countries).

(7) Clean and Safe. Fusion power does not suffer from the safety and proliferation issues of nuclear fission because: (i) the systems cannot meltdown (the reaction stops when you stop driving it and there is minimal decay heat upon shutdown); (ii) they do not use fissionable/fertile materials with serious consequences for nuclear proliferation (e.g., uranium, thorium, plutonium); and (iii) they do not produce radioactive waste with long half-lives (e.g., thousands of years or longer). Still, good radiological practices should be followed to shield personnel from neutrons and high energy photons, avoid tritium loss, and safely process waste (e.g., activated wall materials).

(8) Low Cost. The most important factor that will determine the ultimate success of fusion power is cost. It must be cheaper than other alternatives, at least for an important range of uses.

Costs of energy can be assessed with respect to (i) the capital cost to build a plant with a given rated power capacity (e.g., \$/W) and (ii) the cost of energy output (\$/kWh). With assumptions about plant lifetime, discount rate, and capacity factor, these costs can be translated into a Levelized Cost of Energy (LCOE) (\$/kWh). [Note: LCOE refers to the cost of capital and operations over a plant's lifetime, normalized by its output. It can be quoted in terms of either heat ($\$/kWh_{th}$) or electricity ($\$/kWh_e$).]

The LCOE today for conventional fossil-fuel generators range from $\$45/MWh_e$ to $\$100+/MWh_e$[7] (or $\$0.045 – \$0.10/kWh_e$). Under certain favorable environmental conditions (e.g., in areas with attractive wind speeds or high solar irradiance), wind and utility-scale solar are starting to reach sub-$\$30/MWh_e$ unsubsidized LCOE, though buffering this intermittent power with storage significantly increases costs, adding at least $\$85/MWh_e$ based on Lazard's current estimates. How far renewables and storage costs will fall remains an open question.

These costs help set targets for the cost of commercially viable fusion power.

[7] See Lazard's Levelized Cost of Energy Analysis.

Section 2. Fusion Basics: Lawson Criteria, Minimum Energy, Minimum Power

This section now dives into more detail about fusion systems. It describes some key basic criteria for any D-T fusion system, in terms of the required fuel pressure (P) and energy confinement time (τ):

- The Lawson criterion determines when a fusion system can produce net power.
- Related criteria provide lower bounds on a system's minimum energy, power, and cost.

A. Lawson Criterion

A fundamental requirement for a fusion energy system is that it produces net power—that is, the fusion power produced must exceed the power used to heat/confine the fuel. Because colliding hydrogen nuclei are always more likely to scatter off each other (due to Coulomb repulsion of like charges) than to fuse and release energy, a fusion system must be designed so that high-energy fuel nuclei are confined well enough and long enough to undergo thousands of collisions and finally fuse.

At the system level, this requires that the product of fuel density (n), fuel temperature (T), and energy confinement time (τ) (called the Lawson product) exceeds a certain minimum level, so that the power output from charged fusion byproducts (predominantly alpha particles, or He^{2+}) exceeds the power input required to maintain a burning plasma (i.e., the plasma's power loss rate). This allows the plasma to burn, by using the energy in charged fusion products to sustain the reaction. The **power gain** (that is, the ratio of the power output from charged particles to the power input required to maintain the burning plasma) is usually denoted by the quantity Q, and the requirement that Q>1 is known as the Lawson criterion.[8] The Lawson product is expressed in different ways, most often as nTτ or Pτ (where plasma pressure P = 2nT); nTτ is shown in Figure 2, but elsewhere we will mainly use Pτ.

Figure 2 below shows the minimum criteria to achieve Q>1 for different fuels.

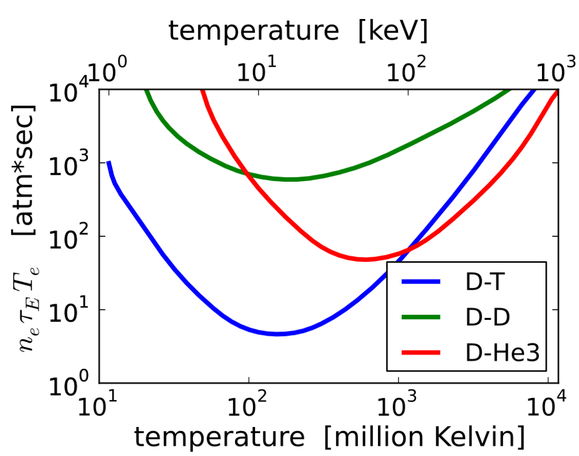

Fig 2: For a given fuel, the Lawson criterion is derived by finding the threshold L=nTτ at which the power released in charged byproducts exceeds the input power needed to sustain the plasma burn. For D-T, one must achieve Pτ ≳ 10 bar-second at $T \sim 10^8$ Kelvin. (Plot is from Wikipedia:Lawson Criterion.)

[8] The Lawson Criterion is given by $nT\tau_E > L = 12\ T^2/(<\sigma v>\ E_{ch})$, where n is the fuel density, T is the temperature (°C), τ_E = τ is the characteristic energy confinement time, <σv> is the Maxwell-averaged cross section (a measure of how often collisions lead to fusion), and is E_{ch} is the charged particle energy per reaction. The criterion can be derived by noting that Q>1 is achieved when P_{ch}, the fusion power output carried by charged particles, exceeds P_{loss}, the power required (lost) to sustain the fusion burn. For D-T fuel, $P_{ch} = n^2/4 <\sigma v> E_{ch}$, where the term $n^2/4 = n_D\ n_T$ reflects the frequency of D-T interactions ($n_D = n_T = n/2$), and $P_{loss} = E/\tau_E$ is the plasma thermal energy (E = 3nT) divided by the characteristic energy confinement time τ_E. The Lawson criterion is obtained by requiring that $P_{ch} > P_{loss}$.

In practice, a fusion energy system must significantly exceed this minimum threshold, in order to compensate for the inefficiency of plasma heating/confinement, parasitic system losses (running pumps, cryogenic systems, etc.), and the inefficiencies of converting thermal energy to electricity. Different definitions of gain (Q) are used to capture these various other requirements to break even energetically. For example:

- **"scientific" gain** ($Q = Q_{sci}$) refers to the ratio of the fusion power output carried by charged particles to the power input needed to maintain the conditions of the burning plasma. Q_{sci} = 1 is called scientific breakeven. This is the Q used for the Lawson criterion.
- **"engineering" gain** (Q_{eng}) refers to the ratio of the fusion power output to the average power needed to assemble, heat, and confine the plasma. (This accounts for practical inefficiencies in plasma heating, which can be very large in some designs—for example, lasers couple <1% of wall-plug electricity to plasma heat.)
- **"facility" gain** ($Q_{facility}$) refers to the ratio of the fusion power output to all the input power above plus the power needed to run ancillary systems (pumps, lights, etc.).

To be commercially viable, a fusion energy system must significantly exceed "facility" breakeven. For example, a reasonable requirement might be that less than one-third of gross electricity output should be reused to drive the fusion system. Assuming a heat engine with 40% efficiency, this threshold would require that $1/(Q_{facility}*0.4) < ⅓$, or $Q_{facility} > 7.5$. Depending on the approach, this might require Q_{sci}~100.

The figure below (Figure 3) illustrates the situation for D-T fuel at the minimum fusion-relevant temperature (~10 keV).

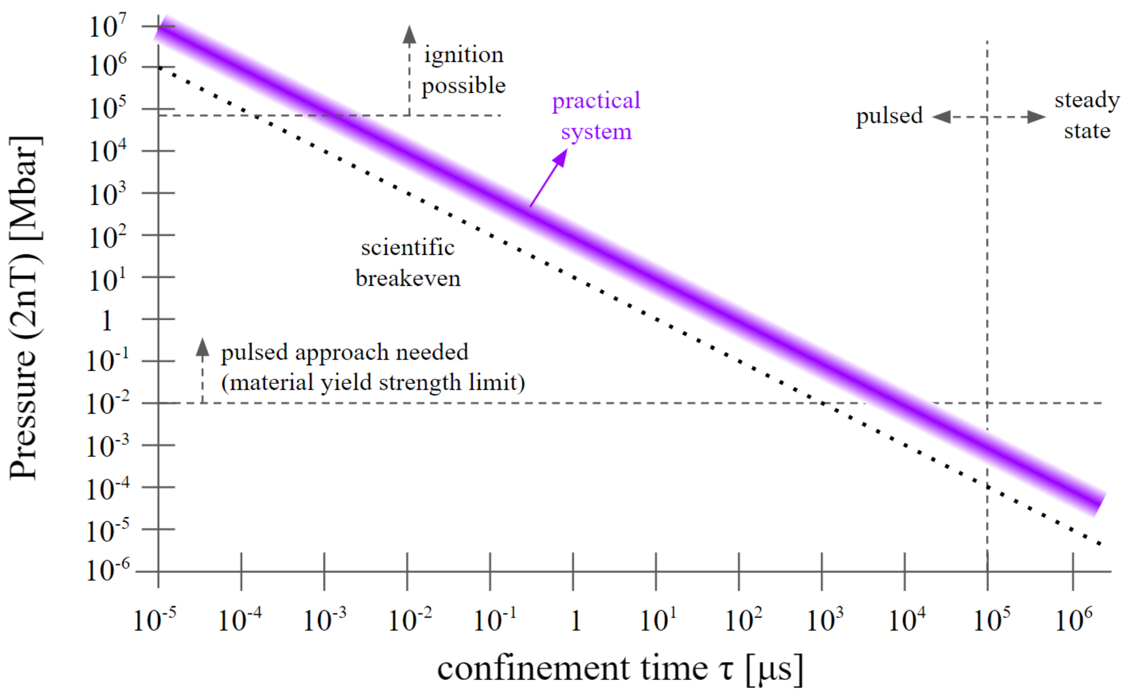

Fig 3: To achieve a good fusion burn and net-positive gain, a practical D-T fusion energy system must achieve a sufficiently high value of the Lawson product Pτ (at a temperature of at least ~10 keV). Pτ thresholds for scientific breakeven (~10 bar-s) and practical systems (30-100 bar-s) are shown above.

Figure 3 illustrates a number of key concepts:

- **Scientific breakeven (dotted line):** Achieving "scientific" gain ($Q > 1$) requires that the Lawson product $P\tau$ exceed a minimum level of 10 bar-s. This can be achieved through various combinations ranging from modest pressure for long times (as in a steady-state tokamak) to very high pressure for short pulses (as in laser-driven inertial confinement).
- **Facility breakeven (shaded region):** Achieving "facility" gain ($Q_{facility} > 1$) requires a *higher* value of the Lawson product $P\tau$ (to offset losses such as plasma heating inefficiencies, power for ancillary facility equipment, etc.). The precise value of $P\tau$ depends on the fusion approach and efficiency of heating, but it is typically in the range 30-100 bar-s — that is, 3- to 10-fold higher than for Q>1. (We discuss this below in the context of specific designs.) As the gain Q increases and fusion byproducts begin to provide a significant fraction of required plasma heating – and the plasma burns or ignites – Q increases rapidly and grows faster than $P\tau$. As a result, different fusion concepts may achieve vastly different Q with similar $P\tau$.
- **Steady-state vs. pulsed:** Steady-state confinement can only operate at pressure $P < 10^{-2}$ Mbar $= 10^4$ bar (horizontal dashed line), because no solid materials can survive greater pressures over long periods. For higher pressures, it is necessary to utilize pulsed operation (with confinement driven by mass, magnetic fields, or lasers). For pulsed approaches, the time τ can range over ten orders of magnitude, from $\tau \sim 10^5$ μs (vertical dashed line) to $\tau \sim 10^{-5}$ μs.
- **Ignition versus burn:** While plasmas that achieve the Lawson criterion can **burn** (that is, sustain fusion in a hot plasma by harnessing energy from charged byproducts), plasmas at very high pressure plasmas (>10^5 Mbar, horizontal dashed line) can also **ignite.** Ignition means that they can drive the fusion of additional *unheated* (e.g., ice-cold) fuel. As a result, a tiny marginal input of energy can translate into a huge marginal output of energy. Ignition thus allows one to vastly boost yield and gain, which can be critical to achieving facility breakeven.

B. Scaling of Minimum Energy, Power, and Cost with Confinement Time

Many different combinations of P and τ can be used to achieve the Lawson criteria, but the values of these quantities have important implications for key features of a corresponding fusion energy system — including the minimum plasma size, energy, power, and cost.

The minimum plasma size can be approximated by calculating the threshold at which the power produced by the fusion plasma exceeds the power losses, as a function of the fuel density n. The calculation shows[9] that the minimum size (r_{min}) of the plasma scales as $n^{-1/2}$ or equivalently as $\tau^{1/2}$. This lets us estimate the minimum required energy and power for the system to achieve Q>1: (i) the minimum required energy in the plasma scales with $\tau^{1/2}$ at fusion-relevant conditions, and (ii) the minimum required plasma heating power scales with $\tau^{-1/2}$, since power is energy/time. That is:

[9] To estimate the minimal size of a fusion energy system, we follow a similar scaling calculation to the one derived in Lindemuth & Siemon 2009. We consider the plasma to be a sphere (the shape that minimizes heat loss through the surface) of radius r, and we calculate the threshold r_{min} at which total fusion power (which scales as n^2r^3) just exceeds the power losses (which scale as nr, being dominated by thermal conduction). Assuming certain parameters (e.g., thermal diffusivity) remain roughly similar at different densities, minimum size r_{min} thus scales as $1/n^{1/2}$, which means minimum energy scales as $(3nT)\, r^3 \propto 1/n^{1/2}$ and minimum power scales as $n^2r^3 \propto n^{1/2}$. By using the Lawson criterion ($nT\tau = L$), one can convert the scaling from n to τ to show that minimum energy scales as $\tau^{1/2}$ and minimum power scales as $1/\tau^{1/2}$.

$$\text{Min-Energy} \propto \tau^{1/2}$$
$$\text{Min-Power} = \text{Min-Energy}/\tau \propto \tau^{-1/2}$$

The relationship between energy and power is shown in Figure 4, where the absolute value for energy and power scales are set by extrapolating from the well-studied tokamak (E_{min} ~ 200 MJ, $\tau \sim 10^6$ µs).

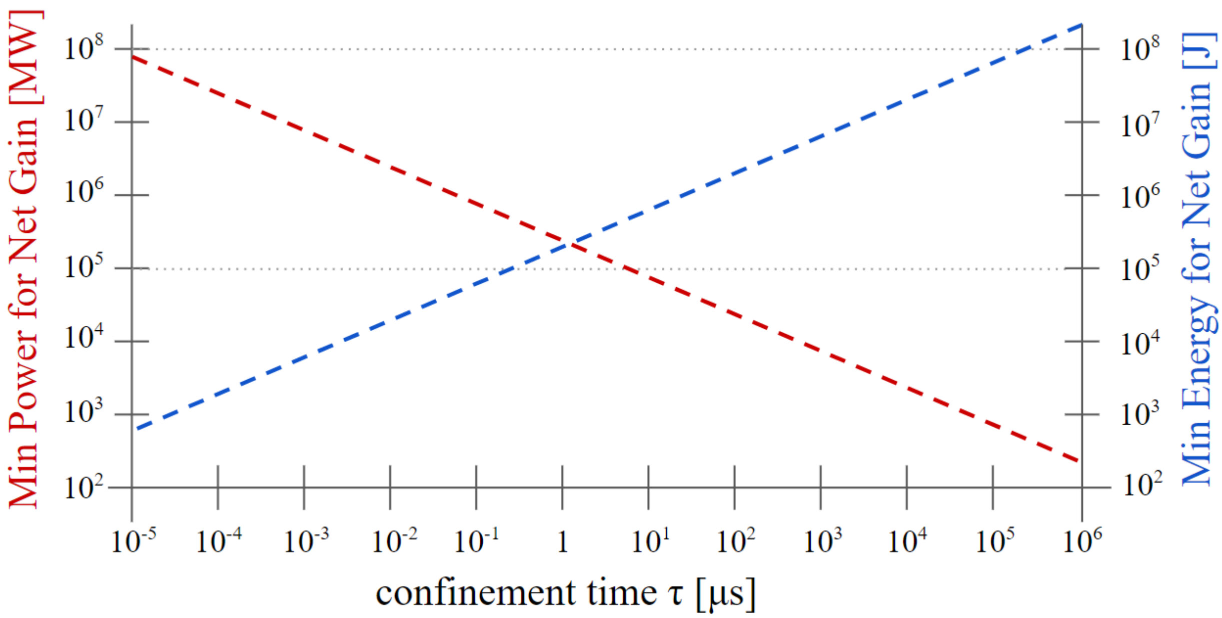

Fig 4: Estimated minimum energy and minimum power for fusion systems that can achieve net gain, scaling from a Q>1 tokamak (200 MJ plasma energy, 200 MW heating power), a rough average of ITER and CFS designs. Real concepts will depart from this curve owing to different methods of heating/confinement, but this estimate is a reasonable proxy for magnetic confinement which can be utilized (steady-state or pulsed) across the full timescale spectrum.

C. Intermediate-Pulse Length Offers a Sweet-spot for Capital Cost and Scale

The fact that the minimum required levels for plasma energy (J) and power (MW) shift in *opposite* directions by many orders of magnitude across confinement times has major implications. Considering the range of confinement times from 10^{-5} μs to 10^{+5} μs, we see that:

- **The shortest pulse times require ~100,000-fold more power** than the longest times (including steady state), and
- **The longest pulse times (including steady state) require ~100,000-fold more plasma energy** than the shortest times.

By contrast:

- **An intermediate pulse time (~1 μs) requires only ~300-fold more power and ~300-fold more plasma energy** that the minimum levels across the range.

This affects the **capital cost of an energy system,** because achieving the required energy and power levels turns out to be a major driver of capital cost. A simplified back-of-the-envelope analysis[10]

[10] The precise costs of different heating and confinement methods, which apply to concepts operating at different τ, will affect true system cost and cause departures from the estimates below.

shows how the factors interact. Letting α and β be the per-unit capital cost for energy ($/J) and power ($/MW), the capital cost attributable to these factors can be written as:

$$\textbf{capital cost} \approx \alpha\textbf{(Min-Energy)} + \beta\textbf{(Min-Power)}$$

(We choose to express α and β in terms of $/MW and $/J because, with these units, the numerical values for fusion-relevant energy systems happen to be fairly similar (that is, $\alpha \sim \beta$) based on power and energy costs from mature mainline fusion projects.)

Given the huge swings in the minimum required energy and power with confinement time τ, the total cost has a sweet spot (minimum) in the middle. As shown in Figure 5, the minimum occurs near β/α μs (that is, near 1 and 10 μs for β/α= 1 and 10, respectively).

For intermediate pulse times, the total capital cost attributable to feeding energy and power to the plasma is thus lower — by 10-100-fold — than for much longer or much shorter pulse times.

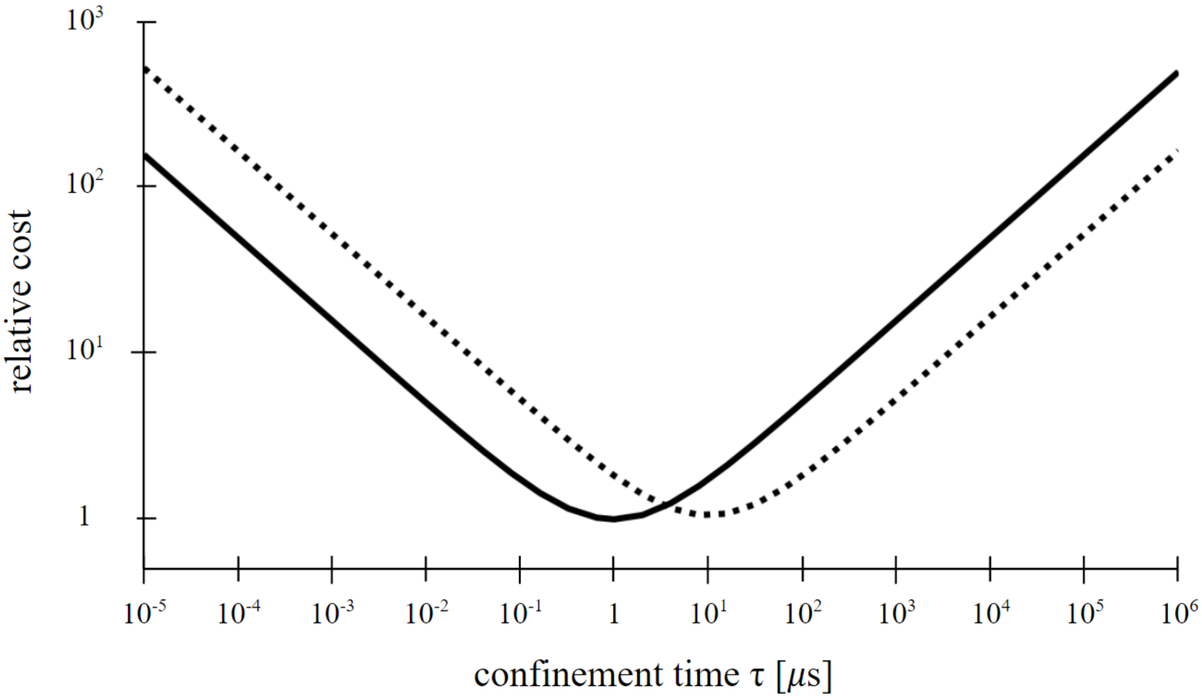

Fig 5: Effect of τ on relative cost of providing the minimum required energy and power levels, for β/α=1 (solid) and β/α =10 (dotted); see text for details.

Intermediate timescales (1-10μs) thus offer flexibility to create power plants at a wide range of scales (as low as 10 MW to over 1 GW) with affordable capital costs. This could:

- **enable faster development cycles,**[11]
- **vastly expand the potential applications and customers of fusion power,**
- **apply mass production to drive down costs**,[12]

[11] Part of the success of solar photovoltaics (relative to concentrating solar thermal power, its sibling technology) was the ability to build viable research cells at <<1 W scale and economically-viable solar PV installations down to sub-kW scale.
[12] Since learning curves depend on the number of units produced, the ability to deploy more and smaller fusion energy systems accelerates progress down the manufacturing learning curve.

- **speed deployment around the world, including in middle and low income countries.**

The fact that intermediate τ has the potential for ~100-fold lower costs is known in the literature.[13] The concept has received recent support via ARPA-E's 2015 ALPHA program and through private funding of startups, but it has historically received far less attention and support than mainline steady-state magnetic and laser-driven inertial confinement approaches.

D. Short Pulse and High Pressure Enable Ignition and Can Produce Huge Gains

The analysis above pertains to fusion energy systems that achieve a burning plasma, which for most fusion concepts can enable moderate (but limited) net gain. However, there is a second attractive approach that goes beyond burning: achieving ignition. As shown in Figure 3, ignition can be achieved by using very short pulses (<10^{-3} μs) and very high pressures (>10^{11} bar).

Ignition refers to the condition where a hot dense burning plasma is able to propagate a fusion burn into surrounding cold dense fuel. In an ignited fusion plasma, the yield is limited only by how much cold dense fuel one can place around the initial ignited "spark" – with the result that modest increases in plasma energy can lead to huge increases in yield and thus gain.

The higher minimum capital cost of ignition-capable approaches (Figure 5) cost thus may be offset by much higher energy output.

E. Two attractive time scales

The discussion above identifies two time scales with attractive features:

- **Intermediate confinement times (near the sweet spot of ~1 μs) may enable systems with the smallest minimum viable scale and capital cost, with the potential to enable rapid scaling.**
- **Short confinement times (2x10^{-4} – 2x10^{-3} μs) can enable ignition, with the potential to achieve high gain.**

In Section 4, we will discuss how certain pulsed magnetic approaches could be used for both time scales. The approaches have attractive features, but have received relatively little attention to date. We refer to them as a **Sweet-Spot Burner** and a **Magnetic Igniter**, respectively.

[13] Studies which show cost optima at intermediate τ: Lindemuth & Siemon 2009, Turchi 2008, 2002 MTF community paper.

Section 3. Four well-supported approaches for making a (D-T) fusion energy system

This section describes four well-supported approaches for fusion energy systems based on four confinement methods and confinement times, as laid out below in Table 1 and Figure 6. For each, we summarize the concept, history, advantages, challenges, and current activity.

Table 1: Four currently active approaches for making a (D-T) fusion energy system

Confinement method	Confinement time, τ (μs)
1. Steady-state Magnetic confinement	$> 10^5$
2. Short-Pulse Laser-driven inertial confinement	$2\text{x}10^{-5} – 2\text{x}10^{-4}$
3. Long-Pulse Mass confinement	$10^3 – 10^5$
4. Long-Pulse Magnetic confinement	$50 – 10^5$

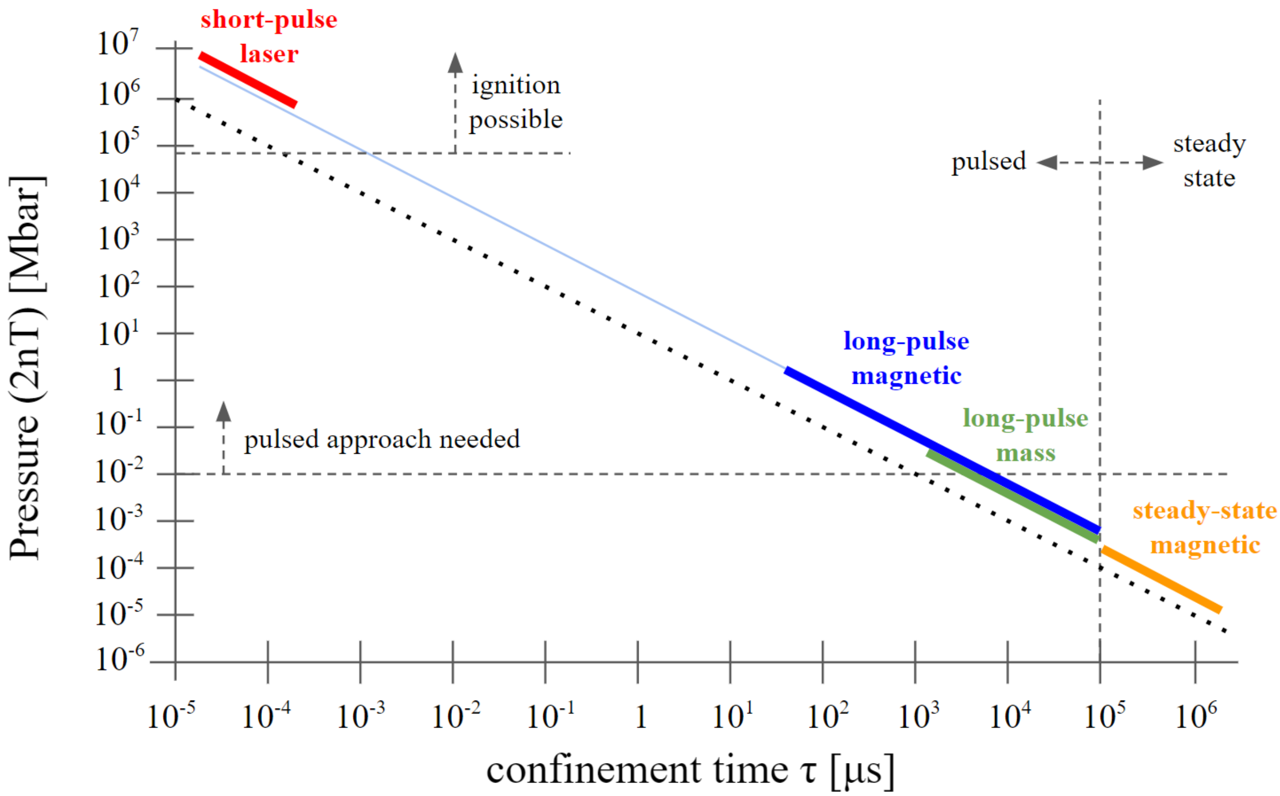

Fig 6: Practical Pτ needed to achieve system-relevant gain ($Q_{facility} > 1$) for four types of D-T systems (solid colored lines), relative to Pτ for scientific breakeven (Q > 1, dotted line).

The first three confinement approaches (Steady-state Magnetic, Laser, Mass) are applicable to specific confinement times. The fourth confinement approach (Pulsed Magnetic) can be applied over a wide range of confinement times (from $2\text{x}10^{-5} – 10^5$ μs, thin blue line), but current large commercial efforts are mainly focused on the long-pulse range ($50 – 10^5$ μs, thick blue line).

In Section 4, we will discuss two additional approaches — Short-Pulse Magnetically-driven Inertial confinement and Intermediate-Pulse Magnetic confinement — that are not currently the subject of robust commercial efforts but have attractive features.

A. Description of approaches: Concept, advantages, challenges, and current activity

1. Steady-state Magnetic ($\tau > 10^5$ μs)

Big Picture. The science of steady-state magnetic confinement has been largely derisked, but major engineering challenges remain to producing a commercially viable energy system. The minimum required heating power is low, but minimum required energy is large, with the result that the minimum viable scale is large (at least 100s of MW).

Concept. This approach uses steady-state magnetic fields – created through external magnets and by current induced in plasmas – to confine fusion plasmas indefinitely, while external heating mechanisms drive energy into the plasma. A wide range of magnetic field profiles and vacuum chamber shapes have been conceived for confining the plasma (tokamaks, stellarators, compact toroids, mirrors, etc.), with many using toroidal geometry to avoid end losses.

History. The approach dates back to the earliest major British, Russian, and American R&D programs in the 1950s. Among many steady-state variants, the tokamak has received the most funding and research support, and is the approach pursued by ITER, the world's largest fusion effort. (ITER is an international megaproject aimed at achieving a Q=10 burning plasma.)

Advantages. The advantages largely arise from the efficiency of plasma heating and confinement:

- high efficiency of plasma heating via microwaves (upwards of ~60%),
- efficient capture of charged fusion byproduct energy to sustain plasma temperature and currents, relaxing the Pτ requirement needed to achieve system-level gain ($Q_{facility}$),
- the lack of need for an energy store (which is required for pulsed approaches), and
- excellent plasma confinement refined through decades of research.

Challenges. The challenges are well known, as highlighted in Lidsky's 1983 critique, including:

- high complexity and large fuel mass (and often, large volume), which creates risks if disruptions (or other confinement loss) destabilize the plasma and dump 100s of MJ into the wall,
- continuous wear to walls and components, since steady-state operation directly exposes large fractions of solid materials to the high energy plasma and fusion byproducts,
- large in-chamber tritium needs, which increases risks of leaks and may create bottlenecks to ramping up system deployment due to the scarcity of tritium (which must be bred from lithium).

Prominent current efforts. Two prominent efforts, both tokamaks, are:

- ITER: The largest fusion project in the world, ITER was conceived in 1988 and began construction in 2013. It is projected to cost $10s of billions and take decades of effort from an international consortium, with first operations planned in the late 2020s to mid-2030s. Several research systems (e.g., General Atomics' DIII-D) support ITER's R&D mission.
- Commonwealth Fusion Systems: CFS is the best-funded fusion startup (>$2B) and has developed high-field magnets that allow it to shrink the size (and cost) of tokamaks. By using high-temperature superconducting tape to double the magnetic field (B) vs. ITER, CFS can achieve ITER-like gain at less than 1/10 the cost (because fusion power density scales as B^4.)
- There are also various major government projects (e.g., Germany's W7X stellarator) and private efforts (Tokamak Energy, Energy Singularity, and other startups).

2. Short-pulse laser-driven inertial confinement (2×10^{-5} – 2×10^{-4} μs)

Big Picture. The science of laser-driven inertial confinement has been largely derisked, as evident from the National Ignition Facility's demonstration of ignition in December 2022. But engineering hurdles make the prospect of a commercial laser-based fusion energy system uncertain. While the minimum required plasma energy is low, lasers are a fairly inefficient way to deliver stored energy. As a result, the minimum fusion energy yield to achieve net gain is high, which can lead to high minimum facility cost. A few startups have raised tens of millions of dollars, and seem poised to raise more given the NIF's recent results.

Concept. In this approach, powerful lasers are used to compress the fuel either indirectly or directly. In *indirect* drive, laser pulses mimic H-bomb physics at a tiny scale by intensely heating a cylindrical container, called a hohlraum, to create X-rays that bathe a tiny spherical fuel capsule inside, causing the capsule surface to blast outwards and the inner shell to implode inward at high speed and attain fusion-relevant conditions. In *direct* drive, laser pulses directly heat/implode the fuel capsule.

History. R&D on short-pulse confinement approaches began with the "Atoms for Peace" conference in 1957, initially as a thought exercise in exploding H-bombs for geothermal energy; it evolved into the far more feasible concept of a tiny fast implosion contained in a vessel. Beginning in the 1970s, high-power lasers provided a clear path for driving such an implosion.

Advantages. The key advantages are largely tied to the laser drive, including:

- inherent "standoff," the lack of need for a direct physical connection to the fuel since laser light can be shined across many meters onto a fuel capsule (or hohlraum holding a fuel capsule), thus minimizing catastrophic damage to nearby components,
- relatively modest vacuum requirements, since laser light can propagate through mild vacuums (or even atmosphere) with little loss, and
- small amounts of energy that must be coupled into the fusion fuel (not specific to lasers, but rather to ultra-short confinement time).

Challenges. The challenges are also largely tied to the laser driver, notably:

- inefficiency of coupling stored energy onto the target (NIF requires 400 MJ of initial stored energy to deliver 2 MJ of laser light to the hohlraum), which may lead to high requirements for fusion yield (>1 GJ) to achieve system-relevant facility gain,
- engineering challenges in rapidly cycling lasers and components (e.g., mirrors/optics), the latter of which can be damaged or dirtied by the high yield fusion output, and
- the need for high precision, expensive targets (the fuel capsule and hohlraum).

Prominent Current Efforts. The most prominent current efforts are as follows:

- NIF: The National Ignition Facility at Lawrence Livermore National Laboratory is the largest laser fusion project in the world, costing ~$10B to build and run since construction began in the 1990s. NIF lived up to its name by achieving ignition and appreciable scientific gain (with 3.15 MJ of fusion energy output for 2.05 MJ of laser energy input), as of December 2022.
- **Startups:** While several short-pulse laser-based startups exist, none have yet raised funding over $100M, though this may change in light of NIF's recent ignition event.

3. Long-pulse mass confinement ($10^3 – 10^5$ μs)

Big Picture. The science is riskier relative to mainline fusion concepts, because mass-driven confinement requires long pulses—during which instabilities may grow—and faces major challenges in undesired mixing of fuel and non-fuel impurities. The minimum required plasma energy is high but this is mitigated by a low cost of energy stored (e.g., pressurized gas). General Fusion is the only well-funded startup pursuing this approach.

Concept. In this approach, a cavity is created within a chamber containing liquid metal, either by spinning the chamber or injecting the liquid along the inner surface of the chamber wall. A magnetized fusion target – a plasma with embedded magnetic field – is formed in or injected into the cavity, and compressed gasses or other mechanical energy stores are used to implode the liquid "liner" to compress and heat the fusion plasma.

History. This approach has its origins in another 1950s-era fusion concept – a metal can ("liner") used to implode a magnetized plasma. In the 1960s, a concept was proposed that utilized a continuously-remade liquid metal liner to avoid the high cost of solid metal liners. This liquid liner concept was studied in the 1970s through a Naval Research Laboratory program called LINUS. Since the early 2000s, General Fusion has developed a new variant of this concept.

Advantages. The advantages are largely tied to the imploding liquid liner, including:

- potential for fairly efficient[14] coupling of stored energy into plasma heat,
- minimal damage to solid materials, since the liquid liner mostly encloses the plasma and absorbs the brunt of the high energy fusion byproducts, and
- lower cost of pressure-based energy storage relative to capacitive energy storage.

Challenges. The challenges are also related to the use of a liquid liner, namely:

- limited mass implosion speeds necessitating long timescales, providing more time for plasma instabilities to grow and necessitating very large minimum energy scales, and
- high potential for "**mix impurities**" – that is, injection of non-fuel impurities into the fusion plasma, which increase radiative losses and can spoil the symmetry of the implosion.

Prominent current efforts.

- General Fusion (GF) is the only well-funded effort (>$300M) in this space. GF uses an array of radial pistons to deliver a carefully-timed pulse to deliver a shock wave to the inner surface of the liquid metal, peeling off an imploding shell that compresses a magnetized fusion plasma. While shock-driven compression requires less energy than imploding the entire liquid liner (shockless), shocked compression may cause higher impurity mixing.

[14] General Fusion (2013 SOFE) suggested upwards of ~10% efficiency at coupling piston kinetic energy into plasma heat.

4. Long-pulse magnetic confinement (50 – 10^5 μs)

Concept. In pulsed magnetic confinement, high-voltage capacitors are discharged to produce large pulsed magnetic fields, either by running current directly through a linear plasma (e.g., a Z-pinch) or fuel container, or by running current through an electromagnetic coil (e.g., a θ-pinch). These pulsed magnetic fields compress and heat fusion plasmas.

History. Pulsed magnetic confinement has its origins in 1950s-era research. After early work, the field saw reduced support for decades, due to progress with tokamaks and problems with pulsed linear confinement methods—specifically, the identification of challenging plasma instabilities. In the past two decades, however, developments in novel confinement methods (e.g., shear flow pinches) and improvements in pulsed power (e.g., solid-state switches) have renewed interest in pulsed magnetic concepts.

Time-scale. In principle, pulsed magnetic confinement can be used for *any* pulse length and confinement time τ from 10^{-5} to 10^5 μs — that is, over *ten orders of magnitude*. Current large commercial efforts are mainly focused on long-pulse confinement (τ from 50 to 10^5 μs) — corresponding to roughly one-third of the logarithmic range. We discuss prospects for the remainder of the range in Section 4.

General advantages of pulsed magnetic vs. steady-state confinement.

- Pulsed magnetic confinement offers lower minimum energy and potential engineering advantages (no superconducting magnets, pulsed operation and minimal reaction chamber ports facilitating easier engineering solutions to shield sensitive components (using shutters, liquid walls, etc), potentially easier tritium breeding).
- Such systems can avoid the potential severe damage of confinement loss (a risk in steady-state).

General advantages of pulsed magnetic vs. laser-driven inertial confinement.

- Pulsed magnetic can be >10x more efficient for plasma heating.
- Only a few reaction chamber entry points (and no sensitive optics) are needed for fuel injection, vacuum pumping, and electrical connections, also allowing for easier wall shielding.

Specific advantages of long pulses. There are certain advantages relative to shorter pulsed approaches:

- Long pulses permit the use of simpler pulsed power generators and put less pressure on electrodes.

Specific challenges of long pulses. Long pulse times have certain challenges relative to shorter pulses:

- Long pulses provide much greater opportunity for instabilities to harm plasma confinement,
- Long pulses may result in movement of the electrodes that interrupts electrical continuity (e.g., an electrode subjected to 10^5 bar could be pushed several meters during a 1 ms long pulse), and
- Long pulse times can cause more wear on components (warped/destroyed electrodes, wear on switches or capacitors, etc), increasing cost and complexity.

Prominent current efforts. Zap Energy has raised ~$200M to pursue shear-flow stabilization of a linear Z-pinch. Zap has shown compelling evidence that its flow technique may keep plasmas quiescent, but must significantly increase its demonstrated Pτ to achieve system-relevant gain. To get there, it will be necessary to address challenges from increasing P (which can destroy solid electrodes or break continuity) and/or increasing τ (allowing more time for end losses and emergence of instabilities, and causing the energy scale to increase).

B. Mapping current activities onto the Pτ plot

The figure below shows the demonstrated performance of some notable efforts.

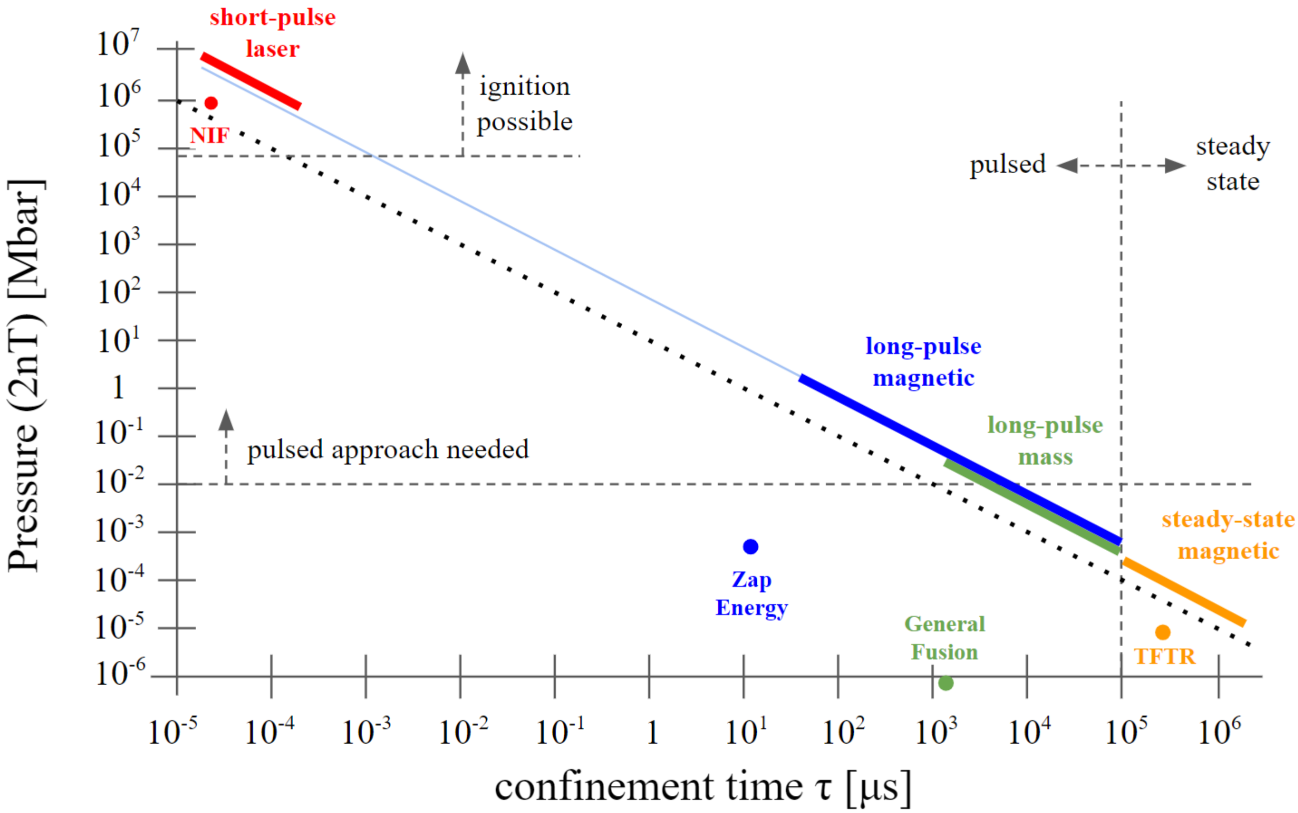

Fig 7: Estimated experimentally-demonstrated Pτ (solid dots) for various D-T approaches, relative to Pτ needed for practical systems (solid colored lines) and for Q>1 (dotted line). The TFTR tokamak achieved Pτ ~ 2.5 bar-s.

Section 4. Two additional promising approaches based on pulsed magnetic confinement

Despite the exciting progress, there remain major scientific, engineering and economic challenges to creating working, inexpensive, scalable fusion energy systems that can address the world's urgent energy needs. The challenges include:

- achieving overall facility gain ($Q_{facility}$>1)
- avoiding rapid loss of confinement
- resilience against gradual component degradation
- need for a wide range of rated power capacity, from small (10 MW) to large (2 GW)
- scalability and mass production of energy systems
- producing energy at sufficiently low cost

Given the transformative potential of commercial fusion power, the world should both continue to advance existing efforts ***and*** identify additional approaches.

We therefore reviewed the possible approaches to fusion to identify additional concepts that are currently receiving less attention, but that recent scientific evidence suggests could provide promising paths to commercial fusion.

We noted above that current well-supported efforts in pulsed magnetic fusion are largely focused on long pulses (50 – 10^5 μs) — with much less activity on shorter-pulse approaches. **We believe, however, that shorter-pulse magnetic confinement increasingly provides promising paths to commercial fusion — owing to recent advances over the past several years that provide solid scientific evidence for the approaches, and allow for the potential of both simpler engineering and lower cost**.

In this section, we describe two attractive approaches, which we refer to as a Magnetic Igniter and a Sweet-Spot Burner (Table 2, Figure 8). Briefly,

- **'Magnetic Igniter'.** This approach substitutes laser-driven inertial confinement used to drive ignition in NIF with **short-pulse magnetically-driven inertial confinement**. Stored energy is used to drive rapid, high-current discharges into fuel containers ("liners"), creating intense magnetic pressure. This would be used to implode fusion fuel to attain comparable pressure and temperature as in NIF — but at >10x higher efficiency, <1/10 the scale, <1/10 the cost, and with potential for simpler and cheaper targets. The approach could potentially lead to viable systems at scales as small as ~100 MW.
- **'Sweet-spot Burner'**. This approach uses **intermediate-pulse magnetic confinement**, with pulses in the range of 1 μs (~100x faster than for long-pulse magnetic confinement). The pulse length sits in the **sweet-spot** that balances the minimum required energy and minimum required power, thereby minimizing the minimum scale and capital cost for a viable energy system (as described in Section 2C).

We outline the common features underlying both approaches, which may allow both approaches to be developed on a single Demonstration System. We then turn to detailed consideration of the scientific foundations and advantages of each approach.

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Table 2: Six approaches for making a (D-T) fusion energy system

Confinement method	Confinement time, τ (μs)
Four well-supported active approaches	
1. Steady-state Magnetic confinement	$> 10^5$
2. Short-Pulse Laser-driven inertial confinement	$2x10^{-5} – 2x10^{-4}$
3. Long-Pulse Mass confinement	$10^3 – 10^5$
4. Long-Pulse Magnetic confinement	$50 – 10^5$
Two promising approaches with little current support	
5. Short-Pulse Magnetically-driven Inertial confinement ("Magnetic Igniter")	$2x10^{-4} – 2x10^{-3}$
6. Intermediate-Pulse Magnetic confinement ("Sweet-spot Burner")	0.2 – 2

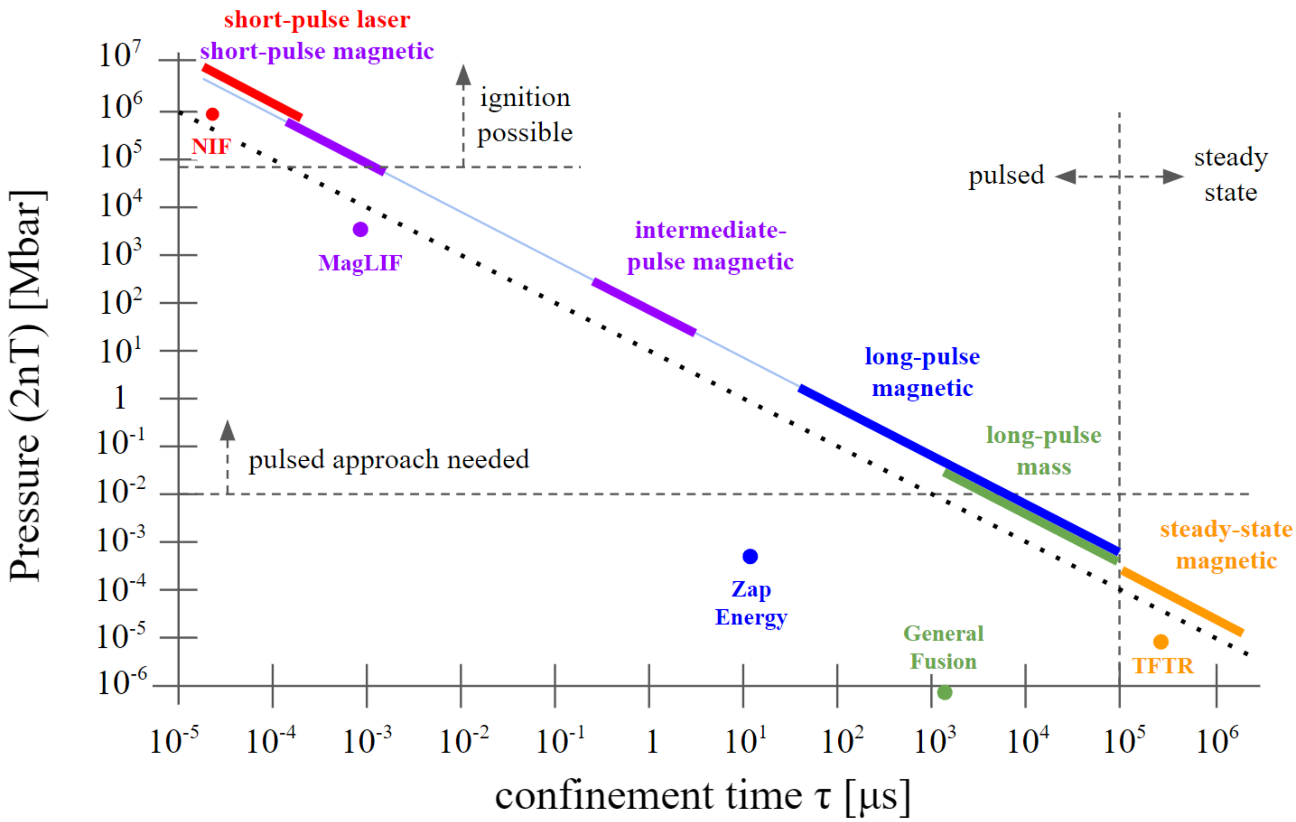

Fig 8: This Figure adds the short-pulse magnetic (Magnetic Igniter) and intermediate-pulse magnetic (Sweet-Spot Burner) regimes to Figure 7, and includes recent MagLIF performance, as discussed below.

A. Pulsed magnetic system: Essential elements

Both the Magnetic Igniter and Sweet-Spot Burner would employ a common overall architecture, with two essential elements for driving fusion reactions (Figure 9):

(1) Pulser. A pulser **provides high-power electrical pulses to the target chamber** to drive the fusion reaction. It consists of (i) **modular high-voltage pulse generators**; and (ii) **transmission lines** (consisting of two sections, the first housed in a water-filled chamber and the second in a vacuum chamber). The pulser comprises the vast majority of the system volume (>99%).

The modular high-voltage pulse generators are typically **Marx generators (MGs)**, multi-stage electrical circuits that have been widely used for many years in high-energy physics experiments. Consisting largely of capacitors and switches, they use a low-voltage DC supply to generate a high-voltage pulse. For instance, the Z Machine at Sandia National Laboratories uses a pulser with 36 Marx generators to create electrical pulses for generating X-rays.

Although Marx generators are a century old, there have been important recent advances in pulser technology over the past few years. For example, recently developed **Impedance-Matched Marx Generators** (IMGs)[15] offer performance and cost advantages — including doubling the efficiency of power delivery; doubling the power density; eliminating the need for multi-megavolt switches; and insulating switches with air rather than sulfur hexafluoride (SF_6).[16] In 2022, a team at Lawrence Livermore National Laboratory (LLNL) built a working four-stage 60 GW version of the IMG.[17] **Linear Transformer Drivers** are another innovative alternative offering advantages over conventional MGs.[18]

(2) Target Chamber. The target chamber can be thought of as an assembly of three equally-spaced concentric spheres, with the target at the center.

- The **Target** occupies a tiny region (~1 cm) at the center and consists of the fusion fuel.
- The **Reaction Chamber** is the inner sphere (~½ meter radius). It contains a vacuum (which is actively pumped) and is where the fusion reaction occurs.
- The **Blanket** surrounds the reaction chamber (or may flow inside of it) and may be ~½ meter thick. It contains a heat exchange fluid (e.g., PbLi eutectic) that captures the fusion neutrons, converting their energy to heat while also breeding more tritium for later use.
- The **Shielding** (~½ meter thick) captures remaining neutrons and high-energy photons.

The Target Chamber accounts for a small fraction of the system volume (<1%).

Fusion energy systems would be coupled to an energy conversion system. Heat is generated when energy from the fusion neutrons is deposited into the surrounding blanket material.[19] To generate electricity, heat from the blanket is transferred by a heat exchanger into a heat engine. While steam turbines have been widely used for over a century, higher efficiency designs — e.g., supercritical CO_2 Brayton cycles — are now in development and may be the best solution for future commercial fusion energy systems.

[15] W.A. Stygar, K.R. LeChien, et al., Impedance-matched Marx generators, Phys. Rev. Accel. Beams 20, 040402 (2017).
[16] SF_6 is an asphyxiant with a global warming potential that is 23,500-fold higher than that of CO_2.
[17] K. R. LeChien, W. A. Stygar, et. al., Sirius I: prototype of a prime-power source for future 1 - 10 GJ fusion-yield experiments, LLNL-TR-846570. Mar. 2023.
[18] R. D. McBride et al, A Primer on Pulsed Power and Linear Transformer Drivers for High Energy Density Physics Applications, IEEE Transactions on Plasma Science, 46, 11, 3928 (2018).
[19] The blanket, which may operate between 500 and 900 °C, serves three basic functions: (1) capturing heat by slowing down neutrons produced by the fusion, (2) capturing neutrons to breed tritium for subsequent use in the D-T fuel, and (3) serving as a radiation shield.

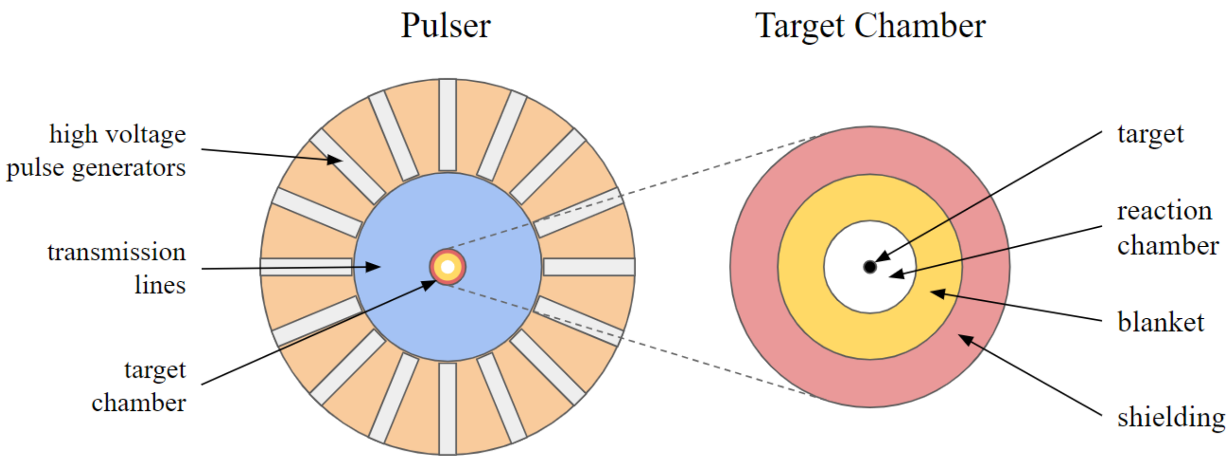

Fig 9: This top-down sketch shows elements (not to scale) of a pulsed magnetic fusion system: (1) a pulser made of high voltage pulse generators that drive energy pulses down transmission lines to the target, and (2) a target chamber with a target inside a reaction chamber, surrounded by a blanket and shielding. In a commercial system, the blanket would capture heat and transfer it to an energy conversion system to utilize the energy released.

Important implications for energy system development. The overall architecture has important implications for efforts to develop future energy systems based on the Magnetic Igniter and Sweet-Spot Burner approaches. We sketch these points here and then return to them below.

- The Pulser has **low technical and engineering risk**, as it consists of well-understood pulsed power electronic circuits.
- The Pulser would **account for the majority of the capital cost of the system**, as it comprises the vast majority of the volume (>99%).
- The Pulser **should have potential to be dramatically reduced in cost through mass-manufacturing of key components**, principally capacitors and switches.
- The Pulser for both approaches **could be built from the same building blocks, differing mostly with respect to desired pulse time and shape**.[20]
- The Target Chamber would **differ between the two approaches**.
  - For the Magnetic Igniter, the Target would consist of fuel in a container (to achieve adequate pressure through implosion).
  - For the Sweet-spot Burner, energy pulses would be directly driven into the fusion fuel.
- The small size and simple geometry of the Target Chamber could **enable rapid iteration and experimentation.**
- **In principle, it might be possible to create a single Demonstration System to test both approaches by using:**
  - A single Pulser with pulse time and shape controlled in software, and

[20] Although the confinement times for Magnetic Igniter and Sweet-Spot Burner differ by ~1,000-10,000-fold (~0.1–1 ns vs. 1 μs), the electrical pulses only need to differ by a factor of ~10-fold. Specifically, the electrical pulse for the Magnetic Igniter could have a rise time of ~0.1 μs because the fuel container/liner can amplify the pressure from this pulse and may be able to shrink the effective pulse length seen by the fuel down to < 1 ns.

- Reaction Chambers for the two approaches with compatible connections that allow them to be exchanged efficiently.

We now take a detailed look at the two approaches.

B. Magnetic Igniter (short pulse length: $2x10^{-4}$ – $2x10^{-3}$ μs)

The Magnetic Igniter concept builds on learning from two recent experimental achievements to achieve ignition and unlock a promising path to a commercial system. These major achievements are:

- **NIF's demonstration of ignition in 2022**. By using **laser-driven inertial confinement**, NIF provided the first experimental proof that ignition and net-positive fusion yield (>3 MJ) can be achieved by delivering a small amount of energy (~250 kJ of X-ray energy) over a few nanoseconds onto a small fuel capsule – to achieve the needed temperatures and pressures ($\gtrsim 10^{11}$ bar). The experiment demonstrated the **highest Pτ value** ever achieved in the laboratory (Table 3).
- **MagLIF experiments in 2014 and 2022**. The MagLIF concept uses **magnetically-driven inertial confinement** to implode a cylinder of magnetized preheated fuel, and it has been tested on Sandia's Z Machine. In spite of limited campaign time – and design limits of the Z Machine preventing achievement of ignition – MagLIF recently demonstrated the **second highest Pτ** ever achieved in the laboratory, exceeding even tokamaks (Table 3).

Together NIF and MagLIF provide strong scientific support for the Magnetic Igniter concept of using short-pulse magnetically-driven inertial confinement to achieve ignition.

Table 3: Highest Pτ values (at fusion-relevant temperatures) achieved by different concepts.

Experiment	Confinement	peak Pτ (bar-s)	Year
NIF	short-pulse laser-driven inertial (indirect)	>50	2022
MagLIF/Z Machine	short-pulse magnetically-driven inertial (direct)	3.6	2022
TFTR	steady-state magnetic (tokamak)	2.5	1995
OMEGA	short-pulse laser-driven inertial (direct)	1.6	2009
W7-X	steady-state magnetic (stellarator)	0.21	2019
Direct refers to direct heating/implosion of a fuel capsule by the primary driving mechanism (laser or magnetic), whereas indirect refers to methods that generate X-rays which subsequently heat a fuel capsule.			

However, NIF and Z are world-class research facilities — *not* prototypes for commercial fusion systems. When considering how research results on these facilities might be translated to future commercial systems, one must examine a number of key challenges that would need to be overcome.

Key challenges for future commercial systems building on NIF

- **Efficiency of energy delivery.** Lasers are a rather inefficient way to drive a target. NIF uses 400 MJ of stored energy to deliver 250 kJ of X-rays to the fuel capsule, an efficiency of <0.1%.

- **Scale required for facility gain**. Although the large energy yields enabled by ignition might "pay back" the energy investment resulting from inefficiency, this would necessitate large-scale commercial energy systems (e.g., yield of >1 GJ to offset an initial energy of 400 MJ), resulting in high capital costs and maintenance costs (due to high fusion yields and debris from the target).
- **Damage to first-wall components.** A large portion of NIF's target chamber is covered in optics that couple in laser light to drive the fusion target, and these optics must be cleaned after every shot. A future laser-driven system would need to find a way to protect such optics, other sensitive components, and the first wall from much higher yields and cycle rates than with NIF.
- **Target precision and cost**. NIF requires high-precision targets (a perfectly spherical capsule in a cylindrical hohlraum) that each cost thousands of dollars to achieve high performance. One reason that NIF requires such high precision is that its inefficiency of energy delivery puts it on the cliff-edge of ignition. A commercial energy system would require targets with higher yield *and* much lower cost (and hence lower precision), fired at roughly once a second.
- **Accuracy of energy delivery.** Optical energy must be delivered to the target with high accuracy, necessitating careful laser alignment and timing. In commercial energy systems, this accuracy would need to be maintained across repeated injections of moving targets at high speed and frequency.

NIF provides clear evidence that ignition can be achieved by rapidly delivering enough energy onto a target, but a commercial laser-driven fusion energy system would need to overcome the challenges above. Start-up companies focused on laser-based ignition have proposed different solutions to help mitigate these issues — such as higher efficiency lasers, direct drive (e.g., lasers incident on the fuel capsule rather than on a liner holding the fuel capsule), and designs to drive targets with much more energy. But, it is not certain that all of the challenges can be simultaneously addressed.

Key challenges for future commercial systems building on MagLIF

Limits on the pulser and target: MagLIF is not capable of reaching ignition and high gain on the Z-machine, which was built with older technology and optimized for different purposes. (The Z-machine can store ~20 MJ of energy and can deliver a peak current of ~27 MA, whereas MagLIF ignition would require >100 MJ initial stored energy and ~70 MA peak current.) The MagLIF target design itself was likely influenced in part by the capabilities available on the Z Machine, and a custom target optimally designed for an optimized pulser (built with modern improvements) should be able to ignite at lower energies and currents.

Despite limited campaign time and constraints of MagLIF on the Z Machine, it has rapidly provided clear evidence that short-pulsed magnetically-driven confinement can yield high $P\tau$ values.

Magnetic Igniter: Addressing Key Challenges of Laser-Driven Fusion

The Magnetic Igniter approach would build on the science and engineering achievements of NIF and MagLIF, achieving ignition conditions comparable to NIF while addressing many of the critical challenges above.

Whereas NIF uses lasers to heat a cylindrical hohlraum that bathes a spherical fuel capsule in X-rays, a Magnetic Igniter would work as follows:

- a fast pulser stores energy (e.g., 40 MJ, roughly 1/10 the stored energy of NIF) and discharges it to drive 10's of MA of peak electric current with a ~0.1 μs rise time,
- the electrical pulse is delivered via electrodes to directly and efficiently drive high currents into a small cylindrical metal liner filled with frozen and gaseous fuel,[21]
- the current pulse creates magnetic pressure that causes the liner to implode rapidly, heating the fuel, amplifying the pressure, and compressing the pulse length further (to <1 ns), thereby attaining fuel temperatures and pressures needed for ignition[22] (likely closer to NIF-like pressures of $>10^{11}$ bar than MagLIF-like pressures of $\sim10^{10}$ bar).

Fundamental features of the Magnetic Igniter concept would help mitigate some of the challenges to future commercial systems faced by laser-driven fusion (as demonstrated by NIF):

- **Efficiency of energy delivery.** In contrast to the efficiency of lasers (<0.1% on NIF), pulsed magnetic systems have much higher efficiency (~5%). Whereas NIF must store ~400 MJ of energy to achieve ignition, a fast pulser with "modest" stored energy (tens of MJ) could couple more energy into the target and fuel than NIF.
- **Scale required for facility gain**. Due to its >10x higher efficiency of energy delivery, the fusion yield required to achieve facility gain could be >10x lower than for laser-driven approaches, significantly decreasing the scale and cost of a viable system.
- **Damage to first-wall components.** A system based on the Magnetic Igniter concept may have reduced maintenance relative to a laser-based system for several reasons. First, the yield required to achieve facility gain is much lower. Second, it requires fewer sensitive components (e.g., no optics) that can get damaged. Third, by having fewer entry ports into the reaction chamber (mainly just for electrodes, fuel injection, and pumping), much more of the first wall can be shielded (e.g., by flowing liquid metal).
- **Target precision and cost**. Magnetic Igniter targets should require less precision than lased-driven targets. First, the high efficiency of energy delivery allows more energy to be coupled to the target, and this abundance of delivered energy allows for more imperfections in target fabrication. Second, in contrast to laser-driven implosions, pulsed magnetic fusion drives implosions via intense magnetic pressure. Because magnetic fields confine charged particles, this helps insulate the fuel. Both MagLIF and magnetized NIF shots have shown increased performance via fuel magnetization.
- **Accuracy of energy delivery.** Magnetic Igniter targets would only require electrical continuity between the pulser and the target (e.g., two electrical connections), which may require less accuracy than what is needed for laser-driven targets.

In summary, the Magnetic Igniter approach offers many potential advantages compared to laser-driven fusion which can help facilitate development of future energy systems, including >10x higher efficiency in energy delivery, <1/10 the scale, <1/10 the cost, and simpler/cheaper targets.

[21] In its simplest form, the liner could be a cylinder of roughly NIF or MagLIF target dimensions (1 cm long and 1 cm in diameter, with wall thickness of ~1mm).

[22] Magnetic pressure (P) = $I^2/(2\pi r^2)$, where the units are mega-bar (P), deca-mega-amp (I), and cm (r). Thus, we could achieve ignition-relevant pressures of 100 gigabars for a current of 40 mega-amps driven to a final compressed radius of 50 µm, a current and radius within factors of a few of what has been achieved in MagLIF experiments on Sandia's Z Machine.

Potential challenges. While scientific evidence for this path is strong, there are non-trivial engineering hurdles on the path to any future commercial energy systems.

- While the targets have potential to be simpler and cheaper than for laser-driven systems, precision-engineered targets (and likely bits of electrodes near the fusion event) will be consumed on every shot, and thus must be mass-manufactured (or replaced) at low cost.
- Even with highly efficient energy delivery, yields may still need to be high, necessitating careful engineering of walls and shielding to avoid frequent system maintenance.

Current efforts. While efforts at US National Laboratories (NIF at LLNL, MagLIF at SNL) have provided compelling evidence, there are no well-funded commercial efforts yet pursuing this approach. One large startup (First Light Fusion) aims to use a fast pulser to achieve ignition, but its approach – a magnetically-driven projectile that compresses a target – is different from what we discuss here.

Conclusion. Building on strong precedent and searching for the most compact, inexpensive path to ignition via short-pulse magnetic drive is analogous in some ways to how Commonwealth Fusion Systems has improved the path to commercial steady-state fusion with high-temperature superconducting magnets.

C. Sweet-Spot Burner (intermediate pulse length: 0.2 – 2 µs)

The Sweet-Spot Burner concept sits in the "sweet spot" that balances the minimum required energy and minimum required power (Figure 4). As a result, it may allow for the lowest minimum viable system scale and cost (Figure 5), perhaps as low as ~10 MW with capital costs of low tens of millions of dollars.

The system would deliver a high-voltage energy pulse of ~1 µs duration directly to the fuel — with no metal liner/container, but rather with current running directly through the fuel itself. This simplicity, along with a low minimum plasma energy, could enable a small, compact, inexpensive solution if successful.

Potential advantages. The Sweet-Spot Burner may offer a number of potential advantages:

- Relative to ignition-based approaches, the minimum required yield is lower — leading to less damage and smaller size — and there is no need for precision target fabrication.
- Relative to long-pulse magnetic confinement, the intermediate pulse length is ~100x shorter — resulting in less movement of electrodes (which can interrupt the current), less time available for instability growth and impurity mix, and potentially less electrode damage.
- As with other pulsed magnetic approaches, the wall and other sensitive components can be shielded by various approaches, such as flowing liquid walls.
- The possibility of small, compact, inexpensive energy systems would enable faster development cycles, expand the range of applications, broaden the customer base, allow application of mass production to drive down costs, and speed global deployment.

Potential challenges. The main disadvantage of the approach is the historical lack of research attention. Fortunately, experiments in this space should not require many miracles, as the technologies required to experimentally access and simulate this regime already exist, and there are clear research tasks to undertake (e.g., finding a pressure-balanced fuel profile that allows for adequate stability).

The key issue is whether it will be possible to establish a pressure-balanced fuel-density profile (such as a Kadomtsev distribution) to keep the plasma confined long enough and at the relevant pressure to achieve the desired energy confinement time. Zap Energy (which pursues long-pulse magnetic confinement) has provided one significant data point by showing that this is possible for pulsed magnetic confinement. Both in experiments and simulation, Zap has maintained quiescent long-lived plasmas and achieved $P\tau$ within 3-4 orders of magnitude of system-relevant performance. Other fuel assembly methods may also lead to pressure-balanced profiles.

Section 5. Considerations for Development and Commercialization of these Approaches

To turn the concepts into compelling clean power sources, two major milestones would need to be achieved:

(1) construction of Demonstration Systems to test the approaches and demonstrate their ability to produce net facility-level gain, and

(2) design of reliable Commercial Systems able to provide power at low cost.

In this section, we sketch some initial thoughts and questions about how this might be accomplished most effectively and efficiently. Considerable attention from dedicated efforts will be needed to flesh out these directions.

A. One Demonstration System to test both the Magnetic Igniter and Sweet-Spot Burner?

It may be possible to design a single modular Demonstration System with sufficient flexibility to test both the Magnetic Igniter and Sweet-Spot Burner approaches through the point of demonstrating net-positive facility gain ($Q_{facility} > 1$). A single Demonstration System could substantially decrease the total cost and time needed to demonstrate the two approaches.

Such a Demonstration System might:

- have a pulser incorporating modern pulsed power innovations (e.g., IMGs or LTDs), using current commercially available or easily-produced capacitors and switches.
- store ~40 MJ (1/10 the scale of NIF), which may be sufficient both to demonstrate net facility gain ($Q_{facility} > 1$) by achieving ignition for the Magnetic Igniter and driving the Sweet-Spot Burner (provided suitable pressure-balance fuel profiles can be found).
- have pulse length controlled in software, allowing one to trigger the generator modules simultaneously to produce a fast pulse (e.g., 0.1 μs rise time) for the Magnetic Igniter[23] or in a staggered way to produce a longer pulse (e.g., 1 μs) for the Sweet-Spot Burner.
- have two distinct types of reaction chamber with compatible connections designed to allow rapid replacement or servicing, to facilitate rapid experimentation and iteration. (This seems feasible since the chamber can be small: a <1 meter radius cylinder)
- have shielding and electrodes able to accommodate the different current profiles and fusion yields for both designs.

B. Design Considerations for Commercial Systems

While a Demonstration System could be built from current commercially available components, a Commercial System would require that key components be designed for high performance, high reliability, and low cost.

- The Pulser, which accounts for the majority of the cost of the system, consists largely of a few key components (e.g., capacitors and switches). Current commercial capacitor costs are ~$5/J, and current affordable switches would only last ~10^4 shots. In contrast, Commercial Systems will need capacitors and switches with much better properties — e.g., component lifetimes of ~10^9 shots (~30 years) and capacitor cost below $0.50/J.

[23] As noted above, the fuel container/liner may amplify the pressure from this pulse and shrink the effective pulse length seen by the fuel down to < 1 ns.

Fortunately, there are multiple paths to achieve these goals.[24] In addition, neither approach involves rare or hard-to-source materials, which simplifies supply chains.

- The Magnetic Igniter would contain the fuel in metal liners, which would be destroyed with each pulse. (In contrast, the Sweet-Spot Burner does not require a container for the fuel.) It will be important to minimize the cost of such targets (e.g., <$1/MWh$_{th}$).

In addition to their general applicability, the two approaches offer the possibility of Commercial Systems with distinctive features that will be difficult to achieve with current well-supported approaches: a lower-cost path to ignition with the Magnetic Igniter, and economically attractive fusion at small power scales with the Sweet-Spot Burner.

Commercial Systems would likely be optimized separately for the Magnetic Igniter and the Sweet-Spot Burner. Commercial Systems could also be developed at different scales—particularly for the Sweet-Spot Burner, allowing a wide range of scales for different settings (from 10 MW to 1 GW).

C. Economics Considerations

Finally, it is essential to focus from the outset on ensuring that Commercial Systems can deliver useful energy (heat and electricity) at a cost that is competitive with — and ideally much cheaper than — other energy sources.

We have undertaken preliminary techno-economic analyses for the Magnetic Igniter and Sweet-Spot Burner, to estimate the levelized cost of energy for both heat and electricity (including a heat engine to convert heat to electricity). For both approaches, the majority of the costs for a fusion energy system are associated with the Pulser, which involves well-understood components with low cost of materials. Initial analysis suggests that there are no inherent barriers to providing on-demand clean power at costs lower than for utility-scale firm renewable power (e.g., intermittent solar with battery storage).[25] However, achieving these cost targets will require careful design and mass manufacturing of key components, and development of strategies to keep operations and maintenance costs low.

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[24] For example, capacitor lifetime can be dramatically increased by modest reductions in the electric field strength E (specifically, reliability roughly scales with E raised to 7.5th power). Also, today's capacitors are produced with significant manual labor owing to low volume and resulting in costs that are vastly higher than the input costs.There are major opportunities for cost reduction via mass manufacturing, similar to what has happened for electric vehicle batteries.

[25] NREL provides LCOE projections for utility-scale PV as a function of resource quality and scenario type. For PV *including* storage, NREL projects an LCOE in 2035 of $0.03-0.06/kWh$_e$ in "typical" U.S. regions. For PV *without* storage, NREL projects an LCOE in 2035 of $0.01-0.02/kWh$_e$ in US regions with the highest solar irradiance and as high as $0.04/kWh in less ideal locations.

Section 6. Conclusion

There has been exciting progress in the past few years toward development of commercial fusion systems. Commonwealth Fusion Systems has recently demonstrated the critical enabling magnet technology for compact steady-state fusion. The National Ignition Facility has recently demonstrated that controlled ignition can be achieved. Various intriguing pulsed approaches are being explored by Zap Energy, General Fusion, First Light Fusion, and others. There are also startups (notably, Helion Energy and TAE Technologies) pursuing non-D-T fuel, which is harder to burn than D-T but which may offer potential engineering advantages.

By considering how known confinement mechanisms can be applied at different timescales to achieve fusion-relevant conditions, as well as the advantages and challenges of these combinations, we have highlighted two promising but underappreciated approaches to achieve both scientific viability and engineering practicality for a D-T fusion energy system. These two concepts, the **Sweet-Spot Burner** and **Magnetic Igniter**, both involve pulsed magnetic confinement with different confinement timescales.

Both approaches involve many common components, and both may potentially be demonstrated on a common pulser machine with flexible discharge timing. With a concerted effort, it may be possible to (i) efficiently and rapidly build such a machine and demonstrate the ability to achieve net-positive facility gain and (ii) design and mass-manufacture inexpensive components with properties suitable for use in commercial systems.

The goal of this White Paper is to highlight these ideas to the broader community, with the aim of inviting discussion and feedback about the approaches — including whether they may offer an additional path to cheap, reliable, scalable fusion power to meet our urgent needs for clean energy.