Introduction to Fusion (Energy)

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MIT Plasma Science and Fusion Center

13 Jun 22
First, let me introduce myself. Nothing like an embarrassing photo to kick things off...

MIT PSFC
How did I get here? Some snapshots.
Note: Not an entirely linear path!

- Highest precision measurement of the muon lifetime (2005)
- Much needed time away from science: bike racing, traveling, reading (2005-2007)
- New in-situ ion beam diagnostic for fusion facing materials (2013)
- PI and Project Head of the SPARC Toroidal Field Model Coil Project (2019-21)
- Co-founded Commonwealth Fusion Systems and the SPARC Project (2018)
- Nuclear security: Cargo screening and weapons treaty verification (2014-15)
It’s an exciting time to talk about fusion energy!
It’s an exciting time to talk about fusion energy:
The National Ignition Facility at LLNL produced a 1.3 MJ shot

This NIF “shot” produced 10 quadrillion watts (1e16 W) for 100 trillionths of a second (1e-10 s) ... don’t blink! (August 2021)

~1.3 MJ of fusion output puts NIF just shy of ignition!
(And a gain factor of ~0.7 depending how you count)
It’s an exciting time to talk about fusion energy:
The ITER tokamak is well on its way to construction

ITER will produce 500 MW of fusion power with gain factor of ~ 10 (i.e. 10x more power produced by the plasma than it takes to heat the plasma)

The plasma physics will be impressive.

For now, the fusion engineering dominates the project is simply breathtaking.
It’s an exciting time to talk about fusion energy:
The SPARC Toroidal Field Model Coil achieved 20 tesla at MIT

The TFMC, weighing ~10,000 kg and using almost 300 km of high temperature superconductor, achieved ~20.5 tesla peak field-on-coil in Sep 2021, opening up a new path to fusion energy that seeks to be smaller, sooner, and lower cost.
It’s an exciting time to talk about fusion energy:
Construction of the SPARC site in Devens MA by CFS has begun

SPARC is racing to be the first net-energy (gain > 1.0) fusion energy experiment. It could produce a gain factor up to 11x and >100 MW of fusion power in a device that is ~70x smaller than the ITER tokamak if successful.
It’s an exciting time to talk about fusion energy: A private fusion industry has emerged and is growing

The total private capital in fusion energy start ups is now on the order of $5 billion.

This represents a new private approach (launching off of national government funded foundations in fusion) that didn’t exist 10 years ago.

Work is underway around the world with massive promises made publicly. Succeed or fail, it will certainly be an exciting next few years!
It's an exciting time to talk about fusion energy: The world is increasingly desperate for new solutions to climate change

- Historically, energy technologies experience exponential early growth (~1% total energy) and then slow linear growth

- Precedents of new energy sources in 20th century provide insight into potential for fusion energy to contribute

- Fusion scale-up required is compatible with mitigating worst effects of climate change and contributing to mid-century CO2 goals...

  ... but first demonstration must happen by the mid-2030’s at the latest if fusion is to help mitigate the worst effects of climate change!
What is fusion?
“Fusion” typically denotes the process of combining two light (i.e. low-Z) nuclei into a heavier nucleus.

Fusion is a fundamental process that combines two nuclei, often releasing enormous energy. Its immense potential has driven research for almost 60 years...

Water

Deuterium → Deuterium

Helium-3 → neutron

10 to ∞ times the Energy-in
There are many different uses of fusion in science and engineering...

**Stockpile stewardship**
The National Ignition Facility (LLNL) and Z-Machine (SNL) replicate conditions of nuclear weapons (and stellar and planetary cores)

**Planetary / Space science**
The levitated dipole experiment (MIT) created planetary like magnetic fields

**Nuclear security**
The dense plasma focus (LLNL) is an ultrafast high-fluence DD and DT neutron source

**Cosmology**
RHIC (BNL) creates the conditions of the early universe (quark gluon plasma)

**Space propulsion (maybe...)**
Fusion rockets and nuclear weapons propulsion!
... but I want to talk about fusion energy today.

Looks like any other power system, except the source of heat is fusion.
You should be able to speak knowledgeably about fusion energy!

There are so many topics that we could cover today; however, I’d like to focus this introductory lecture on two objectives:

• **Primary:** Understand the basic technical foundation of fusion energy

• **Secondary:** Ensure that you can answer questions such as:
  • “Why do we spend so much money on fusion energy research?”
  • “Where does the energy come from in fusion?”
  • “What is the fuel in a fusion energy power plant?”
  • “We can’t we just use cold fusion? That’s a thing, right?”
  • “I read about this fusion company in Time ... are they for real?”
  • “Isn’t most fusion research focused on nuclear weapons?”
  • “What’s the most realistic approach to achieving fusion energy?”
Why fusion energy?
Advantages of fusion over fossil fuels:

- No carbon, SOx/NOx, particulate emissions
- Inexhaustible fuel supply
  - Thousands to millions of years
- Fuels equally accessible to all
- No large scale extraction or transport of fuels

1. Filter the 20 gal of deuterium from 1/600th of the water displaced by the tanker*
2. Fuse it
3. Produce as much energy as in the tanker’s oil**
4. Do not emit 200,000 tons of CO₂

*Or buy it for $200k  ** $750M value
Fusion has some key advantages over other energy sources

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Advantages of fusion over other renewables:
• High power density land use
• High power density materials use
• On when it is wanted
• Site where it is needed
• Plugs into established grids
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Advantages of fusion over nuclear fission energy:
- No chain reaction = no possibility of a melt down
- No long-lived nuclear waste for deep storage
  - Lower level activation of components
- Low proliferation risk
  - No need for fissile material (e.g. U, Pu)
  - Non-fusion clandestine use highly infeasible

Fusion fuel cycle:
- Helium is the waste

Fission fuel cycle:
- Transuranics are the waste

Release to environment

Actively cool for 5 years
Store for 10,000 years
The advantages of fusion energy are compelling ...

- Low carbon
- Inexhaustible fuel
- Deployable
- Highly complementary

- Load-following energy
- Intrinsically safe
- Zero fissile materials
- Civilization-scale energy

“Unlimited energy for everyone forever”
... the disadvantages are obvious.

(It doesn’t work ... yet!)
How can I evaluate fusion energy?
Fusion is a fundamental process that combines two nuclei and releases energy. Its immense potential has driven research for 60 years...

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The term “fusion energy” describes a basic physical process for producing energy; the complications come from the approach!

• Fusion is a fundamental process that combines two nuclei and releases energy. Its immense potential has driven research for 60 years...

• ...but there are so many approaches to fusion energy that it can be extremely difficult to distinguish “winners” from “long-shots” from “losers”.
  • This is true of the layperson, interested reader, investor, students, and even fusion scientist themselves!
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- ...but there are so many approaches to fusion energy that it can be extremely difficult to distinguish “winners” from “long-shots” from “losers”.
  - This is true of the layperson, interested reader, investor, students, and even fusion scientist themselves!

- The primary purpose of this talk is to give you tools to think critically about fusion energy, it’s opportunities and challenges
Developing “The Rules” for assessing fusion energy concepts:

• Q1: What are the viable fusion fuels and how do they affect the approach?
• Q2: What are the physical conditions required to achieve net fusion energy?
• Q3: What fusion energy approaches exist and how should they be evaluated?
Part 1: Developing “The Rules” for assessing fusion energy concepts

- Q1: What are the viable fusion fuels and how do they affect the approach?
- Q2: What are the physical conditions required to achieve net fusion energy?
- Q3: What fusion energy approaches exist and how should they be evaluated?
Rearranging the neutrons and protons that form the building blocks of atomic nuclei can release enormous amounts of energy.

- Protons and neutrons are held together in the nucleus by the **strong nuclear force**, which overcomes **Coulomb repulsion**.
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Nuclear physics makes configurations of protons and neutrons different:

- Some nuclei “like” to be together and require less “binding energy.”
- Some nuclei “dislike” being together and require more “binding energy.”

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- Changing the configuration can make unneeded binding energy available
  - **Fission**: splitting a single weakly bound nuclei (e.g. uranium)

![Diagram showing binding energy per nucleon with examples of light and heavy atomic masses, including the example of fission with 238U.]
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- Protons and neutrons are held together in the nucleus by the strong nuclear force, which overcomes Coulomb repulsion.
- Nuclear physics makes configurations of protons and neutrons different:
  - Some nuclei “like” to be together and require less “binding energy”
  - Some nuclei “dislike” being together and require more “binding energy”
- Changing the configuration can make unneeded binding energy available
  - Fission: splitting a single weakly bound nuclei (e.g. uranium)
  - Fusion: combining two weakly bound nuclei (e.g. hydrogen into helium)

Binding energy released per nucleon ($H \rightarrow He$):

\[ \sim 7 \text{ MeV} \sim 10^{-14} \text{ J} \]
Two basic physical quantities fundamentally set fusion fuel viability:
(1) the reaction energetics (input, output); (2) the reaction probability

**Reaction energetics**

**Input energy:**
The energy provided to ions to overcome the Coulomb barrier must be reasonably achievable

\[ U = \frac{1}{4\pi \varepsilon_0} \frac{Q_1 Q_2}{r} \]

\( r \approx 10^{-15} \text{ m} \)
Two basic physical quantities fundamentally set fusion fuel viability: (1) the reaction energetics (input, output); (2) the reaction probability

**Reaction energetics**

**Input energy:**
The energy provided to ions to overcome the Coulomb barrier must be reasonably achievable

\[ U = \frac{1}{4\pi \varepsilon_0} \frac{Q_1 Q_2}{r} \]

**Output energy:**
Energy released from reaction must not only be net positive but sufficiently large enough
Two basic physical quantities fundamentally set fusion fuel viability: (1) the reaction energetics (input, output); (2) the reaction probability

**Reaction probability**

**Fusion reaction cross section**

The probability that two nuclei will fuse must be sufficiently high. Probability is not simple but governed by quantum and nuclear physics.

\[ U = \frac{1}{4\pi \varepsilon_0} \frac{Q_1 Q_2}{r} \]
Two basic physical quantities fundamentally set fusion fuel viability: (1) the reaction energetics (input, output); (2) the reaction probability

Reaction energetics

The ideal fusion fuel will have:

1. Low input energy to induce a fusion reaction
   - Technologically easier to achieve
   - Economically requires less input energy

2. A high probability of fusion

3. High output energy for converting to electricity

Reaction probability

$$ U = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{r} $$
Let’s take a closer look at combining nuclides and assess what combinations might be attractive for fusion fuels.

### Input nucleus 1

<table>
<thead>
<tr>
<th>1H</th>
<th>2H</th>
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<th>3He</th>
<th>4He</th>
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### Input nucleus 2

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**Theoretically feasible**

**Borderline**

**Not feasible**

Neglect:
- Nuclei with $\tau_{1/2} < 1$ min
- 3-body fusion

Let’s take a closer look at combining nuclides and assess what combinations might be attractive for fusion fuels.
The fusion reaction energy and probability dramatically restrict viable fusion fuels

<table>
<thead>
<tr>
<th>Input nucleus 1</th>
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<td>$^1\text{H}$</td>
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**Reason**
- Coulomb barrier too high

- $Q_1 + Q_2 \approx 10^{-15}$ m

**Neglect:**
- Nuclei with $\tau_{1/2} < 1$ min
- 3-body fusion

---

**Theoretically feasible**

**Borderline**

**Not feasible**

- $Z_1 Z_2 \geq 8$
- Coulomb barrier is too high

- $Z_1 Z_2 \geq 7$
- Coulomb barrier is too high
The fusion reaction energy and probability dramatically restrict viable fusion fuels.

<table>
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<tbody>
<tr>
<td>¹H H</td>
<td>²H D</td>
<td>Negligible</td>
<td>1.9 MeV</td>
<td>&gt;10⁻²² b at &gt;1 MeV</td>
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<tr>
<td>²H D</td>
<td>³H T</td>
<td>Negligible</td>
<td>5.5 MeV</td>
<td>10⁻⁶ b at 1 MeV</td>
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<tr>
<td>³H T</td>
<td>³He He</td>
<td>Negligible</td>
<td>-0.76 MeV</td>
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<td>⁴He He</td>
<td>Negligible</td>
<td>19.8 MeV</td>
<td>1.5 MeV</td>
<td>10⁻²⁵ b at &gt;1 MeV</td>
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<tr>
<td>Negligible</td>
<td>⁶Li Li</td>
<td>Negligible</td>
<td>16.9 MeV</td>
<td>&gt;0.03 b at &gt;1 MeV</td>
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<tr>
<td>Negligible</td>
<td>⁷Li Li</td>
<td>Negligible</td>
<td>17.3 MeV</td>
<td>0.006 b at 400 keV</td>
</tr>
<tr>
<td>Negligible</td>
<td>⁷Be Be</td>
<td>Negligible</td>
<td>0.14 MeV</td>
<td>2x10⁻⁶ b at 600 keV</td>
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<td>Negligible</td>
<td>⁹Be Be</td>
<td>Negligible</td>
<td>1.1 MeV</td>
<td>0.2 b at 1 MeV</td>
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<td>Negligible</td>
<td>¹⁰Be Be</td>
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<td>Negligible</td>
<td>7.6 MeV</td>
<td>0.001 b at 500 keV</td>
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<tr>
<td>Negligible</td>
<td>¹⁴C C</td>
<td>Negligible</td>
<td>5.5 MeV</td>
<td>10⁻⁶ b at 700 keV</td>
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Neglect:
- Nuclei with $\tau_{1/2} < 1$ min
- 3-body fusion

**Reason**
Cross section too low

Theoretically feasible: $Z_1 Z_2 ≥ 8$

Borderline: $Z_1 Z_2 ≥ 7$

Not feasible: Coulomb barrier is too high

The graph shows the cross section of fusion reactions as a function of kinetic energy, with a hard sphere and actual cross section comparison.
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<tr>
<td>$^1H$ 1.4 MeV $&gt;\times 10^{20}$ b at $&gt;1$ MeV</td>
<td>$^2H$</td>
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<tr>
<td>$^2H$ 5.5 MeV $\times 10^4$ b at 1 MeV</td>
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<tr>
<td>$^3H$ -0.76 MeV</td>
<td>11.3 MeV 0.16 b at 1 MeV</td>
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<tr>
<td>$^3He$ 19.8 MeV Negligible</td>
<td>13 MeV $&gt;0.2$ b at $&gt;450$ keV</td>
<td>12.9 MeV $&gt;0.15$ b at $&gt;3$ MeV</td>
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<tr>
<td>$^4He$ Negligible</td>
<td>1.5 MeV $\times 10^7$ b at 700 keV</td>
<td>2.5 MeV</td>
<td>1.6 MeV</td>
<td>Negligible except stellar $3\alpha$ fusion</td>
</tr>
<tr>
<td>$^6Li$ 4.0 MeV 0.2 b at 2 MeV</td>
<td>5.0 MeV 0.1 b at 1 MeV</td>
<td>16.1 MeV</td>
<td>16.9 MeV $&gt;0.03$ b at $&gt;1$ MeV</td>
<td>-2.1 MeV</td>
</tr>
<tr>
<td>$^7Li$ 17.3 MeV 0.006 b at 400 keV</td>
<td>15.1 MeV $&gt;0.5$ b at $&gt;1$ MeV</td>
<td>8.9 MeV $&gt;0.2$ b at $&gt;4$ MeV</td>
<td>11-18 MeV</td>
<td>8.7 MeV 0.4 b at 500 keV</td>
</tr>
<tr>
<td>$^7Be$ 0.14 MeV 2$\times 10^4$ b at 600 keV</td>
<td>16.8 MeV</td>
<td>10.5 MeV</td>
<td>11.3 MeV</td>
<td>7.5 MeV 0.3 b at 900 keV</td>
</tr>
<tr>
<td>$^9Be$ 2.1 MeV 0.4 b at 300 keV</td>
<td>7.2 MeV $&gt;0.1$ b at $&gt;1$ MeV</td>
<td>9.6 MeV $&gt;0.1$ b at $&gt;2$ MeV</td>
<td></td>
<td>5.7 MeV 0.3 b at 1.3 MeV</td>
</tr>
<tr>
<td>$^{10}Be$</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$^{10}B$ 1.1 MeV 0.2 b at 1 MeV</td>
<td>9.2 MeV $&gt;0.2$ b at $&gt;1$ MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{11}B$ 8.7 MeV 0.8 b at 600 keV</td>
<td>13.8 MeV</td>
<td>8.6 MeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{11}C$</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$^{12}C$ 1.9 MeV $\times 10^4$ b at 400 keV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{13}C$ 7.6 MeV 0.001 b at 500 keV</td>
<td></td>
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</tr>
</tbody>
</table>

#### Energy out + cross section are weak

- The fusion reaction energy and probability dramatically restrict viable fusion fuels

#### Reason

- Energy out + cross section are weak

#### Actual

- Cross-section [arbitrary units]
- Kinetic energy [keV]

#### Hard sphere

- Coulomb barrier is too high
  - $Z_1Z_2 \geq 8$
  - $Z_1Z_2 \geq 7$
The fusion reaction energy and probability dramatically restrict viable fusion fuels: only ~0.2% of all known isotopes even approach viability!

<table>
<thead>
<tr>
<th>Input nucleus 1</th>
<th>Input nucleus 2</th>
<th>Theoretically feasible</th>
<th>Borderline</th>
<th>Not feasible</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1H</strong></td>
<td>1.4 MeV</td>
<td>3.65 MeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;10&lt;sup&gt;-20&lt;/sup&gt; b at &gt;1 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2H</strong></td>
<td>5.5 MeV</td>
<td>17.6 MeV</td>
<td>11.3 MeV</td>
<td>16.9 MeV</td>
</tr>
<tr>
<td>10&lt;sup&gt;4&lt;/sup&gt; b at 1 MeV</td>
<td>5 b at 80 keV</td>
<td>0.16 b at 1 MeV</td>
<td>&gt;0.03 b at &gt;1 MeV</td>
<td>-2.1 MeV</td>
</tr>
<tr>
<td><strong>3H</strong></td>
<td>-0.76 MeV</td>
<td>19.8 MeV</td>
<td>13 MeV</td>
<td>&gt;0.15 b at &gt;3 MeV</td>
</tr>
<tr>
<td>0.8 b at 300 keV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3He</strong></td>
<td>19.8 MeV</td>
<td>18.3 MeV</td>
<td>13 MeV</td>
<td>&gt;0.2 b at &gt;450 keV</td>
</tr>
<tr>
<td>Negligible</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>4He</strong></td>
<td>10&lt;sup&gt;-7&lt;/sup&gt; b at 700 keV</td>
<td>2.5 MeV</td>
<td>1.6 MeV</td>
<td>Negligible except stellar 3α fusion</td>
</tr>
<tr>
<td><strong>6Li</strong></td>
<td>4.0 MeV</td>
<td>5.0 MeV</td>
<td>16.1 MeV</td>
<td>16.9 MeV</td>
</tr>
<tr>
<td>0.2 b at 2 MeV</td>
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<td></td>
<td>&gt;0.03 b at &gt;1 MeV</td>
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<tr>
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</tr>
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<td>11.3 MeV</td>
</tr>
<tr>
<td>2x10&lt;sup&gt;-6&lt;/sup&gt; b at 600 keV</td>
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<td><strong>9Be</strong></td>
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<td>0.4 b at 300 keV</td>
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<tr>
<td><strong>10Be</strong></td>
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</tr>
<tr>
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<td>1.1 MeV</td>
<td>9.2 MeV</td>
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</tr>
<tr>
<td>0.2 b at 1 MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>11B</strong></td>
<td>8.7 MeV</td>
<td>13.8 MeV</td>
<td>8.6 MeV</td>
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</tr>
<tr>
<td>0.8 b at 600 keV</td>
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<td></td>
</tr>
<tr>
<td><strong>11C</strong></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td><strong>12C</strong></td>
<td>1.9 MeV</td>
<td></td>
<td>9.2 MeV</td>
<td></td>
</tr>
<tr>
<td>1x10&lt;sup&gt;4&lt;/sup&gt; b at 400 keV</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td><strong>13C</strong></td>
<td>7.6 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.001 b at 500 keV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>14C</strong></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Neglect:
- Nuclei with τ<sub>1/2</sub> < 1 min
- 3-body fusion

**Z,Z<sub>2</sub>≥8** Coulomb barrier is too high

**Z,Z<sub>2</sub>≥7** Coulomb barrier is too high

---

The MIT and PSFC logos are visible in the image as well.
Only 4 fusion fuels are considered practical for energy production. Their feasibility rank depends most strongly on required input energy.

<table>
<thead>
<tr>
<th>Fuel (Input)</th>
<th>Exhaust (output)</th>
<th>Energy gain (MeV)</th>
<th>Cross section (barn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D + T</td>
<td>$^4$He + n</td>
<td>17.6</td>
<td>5.0 @ 80 keV</td>
</tr>
<tr>
<td>D + D</td>
<td>T + p (50%) $^3$He + n (50%)</td>
<td>3.7</td>
<td>0.1 @ 150 keV</td>
</tr>
<tr>
<td>D + $^3$He</td>
<td>$^4$He + p</td>
<td>18.3</td>
<td>0.8 @ 300 keV</td>
</tr>
<tr>
<td>p + $^{11}$B</td>
<td>3 $^4$He</td>
<td>8.7</td>
<td>0.8 @ 600 keV</td>
</tr>
</tbody>
</table>
Because the probability of scattering dominates fusion for all fuels, the fuel must be arranged to allow many fusion attempts with fuel loss!

- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions.

The bane of fusion energy
Because the probability of scattering dominates fusion for all fuels, the fuel must be arranged to allow many fusion attempts with fuel loss!

- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions.

- Overcoming Coulomb scattering requires keeping fuel around long enough to get many chances. We call this “confinement”.

**No confinement:**
- Particles scatter and are lost
- No fusion occurs

**Ideal confinement**
- Who cares if particles scatter?
- Fusion occurs eventually
Because the probability of scattering dominates fusion for all fuels, the fuel must be arranged to allow many fusion attempts with fuel loss!

• Coulomb scattering provides a fundamental challenge to getting enough fusion reactions

• Overcoming Coulomb scattering requires keeping fuel around long enough to get many chances. We call this “confinement”.

• Confinement of particles at these energies creates the conditions of a plasma
  • Ionized gas (“fluids” of electrons and ions)
  • Dominated by collective behavior
  • Energy of the system is best described as a temperature
Only 4 fusion fuels are considered practical for energy production. Their feasibility rank depends most strongly on required temperature.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Fuel (Input)</th>
<th>Exhaust (output)</th>
<th>Energy gain (MeV)</th>
<th>Peak reactivity ([\text{m}^{-3} \text{s}^{-1}])</th>
<th>Temperature ([\text{K} / \text{C} / \text{F}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D + T</td>
<td>(^4\text{He} + \text{n})</td>
<td>17.6</td>
<td>1x10^{-18} @ 15 keV</td>
<td>175,000,000</td>
</tr>
<tr>
<td>2</td>
<td>D + D</td>
<td>(\text{T} + \text{p} \ (50%)) (^3\text{He} + \text{n} \ (50%))</td>
<td>3.7</td>
<td>1x10^{-20} @ 20 keV</td>
<td>232,000,000</td>
</tr>
<tr>
<td>3</td>
<td>D + (^3\text{He})</td>
<td>(^4\text{He} + \text{p})</td>
<td>18.3</td>
<td>2x10^{-20} @ 50 keV</td>
<td>580,000,000</td>
</tr>
<tr>
<td>4</td>
<td>p + (^{11}\text{B})</td>
<td>(^3, ^4\text{He})</td>
<td>8.7</td>
<td>3x10^{-21} @ 150 keV</td>
<td>1,740,000,000</td>
</tr>
</tbody>
</table>

**Primary condition:** the required temperature must be practically achievable
- This turns out to be so important as to determine the ranking
Only 4 fusion fuels are considered practical for energy production. Their feasibility rank depends most strongly on required input energy.

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<td>D + T</td>
<td>$^4$He + n</td>
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**Primary condition:** the required temperature must be practically achievable
  - This turns out to be so important as to determine the ranking

**Secondary condition:** the reactivity and energy gain must be large
  - These conditions are necessary but not sufficient
Q1: What are the viable fusion fuels and how do they affect the approach?

Rule 1

Fuel choice fundamentally sets the difficulty of any approach to fusion energy

*D-T fuel is the easiest by far.*

*D-D and D-³He increasingly difficulty.*

*p-¹¹B possibly infeasible; other fuels are not viable.*

Questions you should ask:

“What fusion fuel are they using? Do they acknowledge difficulties?”

“How do they propose conversion to electricity?”

“How mature and demonstrated is this technology?”
Part 1: Developing “The Rules” for assessing fusion energy concepts
• Q1: What are the viable fusion fuels and how do they affect the approach?
• Q2: What are the physical conditions required to achieve net fusion energy?
• Q3: What fusion energy approaches exist and how should they be evaluated?

Part 2: MIT’s accelerated pathway to demonstrate net fusion energy
The conditions for burning wood (net chemical energy release) are roughly analogous for burning a plasma (net fusion energy release).

Wood density

Wood temperature

Energy confinement
The conditions for burning wood (net chemical energy release) are roughly analogous for burning a plasma (net fusion energy release).

Plasma density

Plasma temperature

Energy confinement

\[ n \times T \times \tau_E \]

The three things required for fusion energy ... known since 1955!
Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions.

$$Q = \frac{\text{Fusion energy output}}{\text{Energy input}}$$

density × confinement time
($n\tau$)  [10^{20} s/m^3]

ion temperature ($T_i$) [keV]
Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions.

Moving into the upper-right corner has been the primary goal of fusion energy research for almost 60 years ...
Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions.

Moving into the upper-right corner has been the primary goal of fusion energy research for almost 60 years...

This turns out to be enormously difficult:
- Moving orders of magnitude in dimensional, absolute parameters
- Unknown unknowns (plasma instabilities) wait to destroy your fusion energy dreams

Be *very* wary of extrapolation in this space...

List of plasma instabilities from Wikipedia

- Alfvén instability
- Fast electron inertia
- Ion acoustic instability
- Betatron instability
- Ion gyroradius instability
- Ion hybrid instability
- Ion kinetic instability
- Ion acoustic wave instability
- Ion cyclotron instability
- Ion Bernstein mode instability
- Ion Bernstein mode instability (Type II)
- Ion kinetic instability
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Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions.

What does this mean for fusion energy concepts?

Let’s make a simple analogy...
Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions.

Fusion Energy: The Ride!
Q2: What are the physical conditions required to achieve net fusion energy?

**Rule 2**
Proximity to burning plasma conditions is the ultimate arbiter of the viability of any fusion energy approach.

\[ T \text{ and } n\tau_E \text{ giving } \sim Q \geq 0.1 \text{ is ready for fusion energy.} \]
\[ T \text{ and } n\tau_E \text{ giving } \sim Q \leq 0.1 \text{ is a physics experiment.} \]

Questions you should ask:
“What is the plasma pressure? The ion temperature? The confinement time?”
“What Q values (energy gain) are achieved on present machines?”
“Is the plasma magnetohydrodynamically (MHD) stable?”
“What problems with turbulence are they encountering?”
Part 1 : Developing “The Rules” for assessing fusion energy concepts
• Q1: What are the viable fusion fuels and how do they affect the approach?
• Q2: What are the physical conditions required to achieve net fusion energy?
• Q3: What fusion energy approaches exist and how should they be evaluated?

Part 2 : MIT’s accelerated pathway to demonstrate net fusion energy
There are a surprisingly large number of ways to attempt fusion energy. In short: we’ve tried just about everything to get \( n, T, \) and \( \tau_E \) up!

---

(There are 12 slides in the posted deck going into 12 different concepts in more detail)

The tokamak outperforms by far all other fusion energy concepts in nTtE, justifying its claim as the leading contender for fusion energy

Only the tokamak has demonstrated the proximity to Q > 1
- Maximum achieved nTτE gave Q ~ 0.7 (JET, UK, 1997)
- Not quite there yet (still requires adult supervision to ride...)

![Density x confinement time (nT) vs. ion temperature (T_i)](image-url)

![Ride supervision sign](image-url)
Q3: What fusion energy approaches exist and how should they be evaluated?

Rule 3

Many approaches to fusion energy have been/are being tried; only the tokamak has demonstrated energy-ready performance.

The tokamak ($n T \tau_E$ giving $Q \sim 0.65$) leads by a lot.
Stellarators come next and will be interesting to watch.
All others a very distant (factor of $10^4$ – $10^6$) third.

Questions to ask:
“Has this approach been tried before? Why was it previously abandoned?”
“How far in $n T \tau_E$ are they extrapolating to show energy-relevance?”
“How do they propose achieving a $10^4$ to $10^6$ needed $n T \tau_E$ improvement?”
“What cost and time were historically required to make $n T \tau_E$ improvement?”
The Rules for assessing fusion energy approaches

**Rule 1**
Fuel choice fundamentally sets the difficulty of any approach to fusion energy.

**Rule 2**
Proximity to burning plasma conditions is the ultimate arbiter of the viability of any fusion energy approach.

**Rule 3**
Many approaches to fusion energy have been/are being tried; only the tokamak has demonstrated energy-ready performance.
Backup
Cold fusion (alias: Low energy nuclear reactions or “LENR”) can be described by no known physical model and has never achieved verified power production.

**Confinement basis**
- Cold Fusion / LENR

**Active experiments:**
- Surprisingly numerous, “eCAT”

**Key lessons learned:**
- If it’s too good to be true, then it almost certainly is.

- Cold fusion purports to use some process to create fusion energy conditions at room temperature
  - First “discovered” by Pons and Fleischmann in 1989

- Proposed processes cannot be rectified with any known model of physics
  - Rapidly and continually debunked
  - Zero independent validation by critics
  - Initial Pons and Fleischmann debunking done by MIT

- Considered a pathological science: research that continues in an enthusiastic minority long after scientific consensus establishes it as false
Gravitational force confines plasma and create the conditions necessary for sustained generation of fusion energy in the stars.

**Confinement basis**
- Gravity

**Active experiments**
- See: The universe

**Key lessons learned**
- Conditions required for net energy fusion are allowed by this universe, but need different confinement mechanism

- Stars initially fuse hydrogen but progress to fusing heavier elements
- Energy release from fusion reactions generates tiny power densities but over massive volume:
  - 0.27 W/m$^3$ average power density
  - \( \sim 10^{27} \) m$^3$ (absolute volume)
- Stars exist balance plasma pressure with gravity
  - Not likely to be replicated on Earth in the near term
Hydrogen bombs create fusion initiated by fission bombs, but resulting blast is unacceptable and infeasible for energy production.

**Confinement basis:**
- Inertia with implosion driven by fission bomb

**Active experiments:**
- Weapon-industrial complex

**Key lessons learned:**
- To date, only successful fusion net gain on Earth but not great for energy...
- Fission bomb is ignited next to fusion fuel
  - Resulting X-rays rapidly heat and compress fuel to fusion conditions prior to destruction
  - Fusion boosts the fission explosion energy by 1000x
- Important to note: that fusion explosion *requires* fission explosion first
- Not a good power source!
Inertial confinement fusion (mini-bombs) has demonstrated impressive physics performance but has very unfavorable technological scaling to fusion energy.

Confinement basis:
- Inertia with implosion driven by lasers

Active experiments:
- NIF, Omega (US), Laser Mégajoule (FR)

Key lessons learned:
- Capable of high performance but at very low rep rate and gain

Lawson criterion has different form for inertial confinement. Apples-to-apples comparison to magnetic confinement through $Q$ for NIF:

\[
Q = \frac{E_{\text{fusion}}}{E_{\text{driver-on-target}}} = \frac{17 \text{ kJ}}{150 \text{ kJ}} \approx 0.1
\]


- Instead of using a bomb, use something else that is powerful and fast
  - Lasers: NIF, achieved near-breakeven

- Gives insight into how bombs work which is the primary purpose of the R&D

- Impressive performance but scaling to reactor looks difficult:
  - Maintenance: Significant machine components destroyed each implosion
  - Rep rate: present ~1/day (max); need ~1/s (need 100 000 scale-up)
  - Efficiency: 0.7% of NIF wall plug power makes it to the fusion fuel target

National Ignition Facility (LLNL)
Particle accelerators can easily achieve necessary conditions for fusion, but high Coulomb cross section compared to fusion cross section leads to tiny gain.

**Confinement basis:**
- Accelerating with electric fields

**Active experiments:**
- Any accelerator with \( E \geq 10 \text{ keV} \)

**Key lessons learned:**
- Coulomb collisions and instabilities reduce gain to unacceptable levels

- Fire beam of high energy particles into other particles
  - Easy to build a compact 100 keV beam
  - Can fuse anything from standard DT fuel (neutron source) to heavy ions (RHIC) depending on beam energy

- But...Coulomb cross section is \(~100,000x\) too large
  - Beam ions slows down before fusion dominates
  - Beam requires more energy than it makes from fusion

- Good for neutron source, but low gain precludes energy generation
Electrostatic potential wells (fusors) can be used to accelerate and confine ions, but several loss mechanisms limit plasma performance.

Confinement basis:
- Electric fields

Active experiments:
- Hobbyists, university students

Key lessons learned:
- Simple devices, good for teaching tools but too many loss mechanisms for net power production

A spherical ion accelerator with a potential well to collide ions against each other in the center:
- Physical high-voltage grid or a “virtual cathode” made of electrons

Multiple mechanisms slow or eject the ions before enough fusion happens for net gain:
- Coulomb collisions
- Particle losses
- Conduction losses
- Bremsstrahlung

While orders of magnitude from energy gain, can be effective simple neutron sources

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Magnetic mirrors use a magnetic field to confine plasma in 2 dimensions and then unsuccessfully try to plug the losses along the magnetic field.

**Confinement basis:**
- Magnetic fields (crimped)

**Active experiments:**
- Gamma-T (Japan), Gas Dynamic Trap (Russia), Lockheed Martin Co.

**Key lessons learned:**
- Any open field lines lead to unacceptable losses

- Charged particles spiral around magnetic field lines
  - But confinement is only in 2D
  - Some particles always leak out the ends

- Many different configurations tried to plug the ends of the “mirror”
  - Large $1B$-class experiments
  - Losses always dominate fusion unless the mirror is very long

- Conclusion: A net-energy device is unrealizably long (~km) still a good fusion neutron source
Pinches or magnetized targets use magnetic fields to rapidly compress the plasma before it leaks energy, but this creates instabilities.

**Confinement basis:**
- Magnetic fields (squeezed)

**Active experiments:**
- Z-machine (SNL), Dense Plasma Focus (LLNL), ZaP (U. Wash), LPP co., General Fusion Co., Helion Co.

**Key lessons learned:**
- Instabilities are critically important
  - Very quickly compress the plasma and heat it by rapidly changing magnetic field
  - Many different configurations have been tried at many different scales
    - Requires large pulsed power systems
    - Often with sacrificial conductors surrounding plasma
  - Large instabilities and plasma cooling occur before net-energy conditions are reached
    - Useful as a high-power X-ray or neutron source or particle accelerator
A torus of mirrors or cusps eliminates end losses by turning the system onto itself but with the toroidal shape come new instabilities.

### Confinement basis:
- Magnetic fields (bumpy)

### Active experiments:
- None anymore

### Key lessons learned:
- Symmetries are important

- Instead of plugging the mirror end losses, feed them into another mirror
  - Ad infinitum = A torus

- Tried with many geometry variations in the 1970s and 1980s in large programs
  - ORNL: ELMO bumpy torus
  - UC California: TORMAC
  - NASA: Bumpy torus

- But breaking the symmetry created additional instabilities in the plasma
  - Limited the temperatures and ruined confinement
  - Interesting plasma physics!
Field-reverse configurations, spheromaks etc. use the plasma to create helical fields in the torus, increasing confinement at the expense of stability.

**Confinement basis:**
- Magnetic fields (self-twisted)

**Active experiments:**
- Tri-alpha Energy Co., RFX (EU), MST (U. Wisc.), Dynomak Co.

**Key lessons learned:**
- A helical magnetic field gives good confinement and sometimes stability, but relying on the plasma alone is difficult
  - Magnetic field is helical shaped
  - Reverse Field Pinch

- Instead of torus of many mirrors, make a torus with the magnetic field spiraling in a helix
  - Increases the stability

- Plasma can create these field shapes though “self-organization”
  - Transient effects limited to milliseconds
  - Studied widely over a long period

- Very rich plasma physics but very difficult to control and confinement still lacking
  - Have not yet reach energy-relevant confinement or temperatures
Stellarators use external magnets to create the helical fields and are approaching fusion relevant conditions.

**Confinement basis:**
- Magnetic fields (twisted by external coils)

**Active experiments:**
- LHD (Japan), W7-X (Germany), HSX (U. Wisc.)

**Key lessons learned:**
- Good plasma performance but tough engineering

- Use many external magnetic coils to create precisely the desired magnetic field shape
  - Stable and steady-state

- Requires highly optimized field shapes and magnets to obtain best performance
  - One of the original fusion concepts
  - Ongoing work world-wide

- Higher performance but with complex engineering to create the exact right 3D shapes
  - Makes an expensive reactor
Tokamaks use the plasma and simple external coils to generate the helical magnetic field. They have performed the best.

**Confinement basis:**
- Magnetic fields (twisted by external coils and plasma)

**Active experiments:**
- JET, ASDEX-U, DIII-D (33 worldwide)

**Key lessons learned:**
- Most promising candidate for fusion energy

- Simplify the magnets by carrying toroidal current in the plasma to create a slightly helical field
  - Good stability and can be made steady-state
  - Symmetry provides good confinement

- High initial performance led to lots of research for the past 50 years,
  - ~170 devices built (6 at MIT)
  - Extensive physics understanding
  - Technologies well developed
  - Only devices to make significant fusion energy (17MW Q~0.65)

- Consensus among world plasma physics community is that tokamaks will be able to generate net energy