Magnetic Fusion Energy: Getting There Sooner*

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Fusion is the power source for the sun and all the stars, and creates the elements of the periodic table.

Average binding energy per nuclear particle (MeV)

Number of nucleons in nucleus

Yield from Nuclear Fusion

Average Mass of Fission Fragments ~118

Fusion and Fission: Complementary Forms of Nuclear Energy
Fusion has ~10 million times the energy/mass of hydrocarbon fossil fuels

Chemical Energy

- 15 kJ/g
- 20 kJ/g
- 40 kJ/g

Nuclear Energy

- FISSION
  - 50 Million kJ/g
- FUSION
  - 350 Million kJ/g
Fusion Fuels are Deuterium and Lithium
Tritium is Bred as Part of the *Fuel Cycle*

Plasma self-heating to sustain reaction energetically

\[
D + T \quad \Rightarrow \quad He + n
\]

He + T \quad \Leftarrow \quad Li + n

Energy Extraction

Breeding

Heat for Electricity Generation

Net reaction: \[ {\text{1}}D_{2} + {\text{3}}Li_{6} \quad \Rightarrow \quad {\text{2}}He_{4} + {\text{2}}He_{4} \]
Deuterium: Natural Abundance = 1/6000

Deuterium in the flow from a kitchen faucet (10 liter/minute) would fuel a 5 Gigawatt fusion reactor

Lithium:

Average World Electrical consumption (2012): 2.4 Terra-Watt; 6 TW (thermal) from fusion would require 600 tonne/year lithium (<2% of current production)

<table>
<thead>
<tr>
<th>Country</th>
<th>Production</th>
<th>Reserves [note 2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>3,200</td>
<td>850,000</td>
</tr>
<tr>
<td>Australia</td>
<td>9,260</td>
<td>970,000</td>
</tr>
<tr>
<td>Brazil</td>
<td>160</td>
<td>64,000</td>
</tr>
<tr>
<td>Canada (2010)</td>
<td>480</td>
<td>180,000</td>
</tr>
<tr>
<td>Chile</td>
<td>12,600</td>
<td>7,500,000</td>
</tr>
<tr>
<td>People’s Republic of China</td>
<td>5,200</td>
<td>3,500,000</td>
</tr>
<tr>
<td>Portugal</td>
<td>820</td>
<td>10,000</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>470</td>
<td>23,000</td>
</tr>
<tr>
<td>World total</td>
<td>34,000</td>
<td>13,000,000</td>
</tr>
</tbody>
</table>
Pros and Cons of Fusion

**Pros**
- Abundant high energy density fuel (D + Li)
- No greenhouse gases (nor NO\textsubscript{x}, SO\textsubscript{x}, particulates)
- Compared to fission
  - No chain reaction, minimal afterheat, much less residual radioactivity or waste
    - Control of fusion reaction is not a safety issue!
    - Cooling is not a safety issue!
  - Minimal nuclear proliferation risks
- Compared to renewables
  - Minimal land and water use
  - No diurnal, seasonal or regional variation – no energy storage issue

**Cons**
- We don’t quite know how to do it yet (turns out to be a really hard problem)
The Challenges Are Well Understood

- **Physics**
  - Attaining required plasma performance – thermal insulation of hot plasma (200,000,000°K = 20keV)
  - Steady State
  - Interface between “edge” plasma (1,000,000 °K) and ordinary materials (Plasma Material Interactions)

- **Engineering**
  - First Wall – PMI
  - Structural materials – in radiation environment
  - Constructability, reliability, availability, maintenance

- **Overall – cost and pace of development program**
Confine the Hot Plasma with Magnetic Fields

Magnetic fields confine charged particles in the perpendicular direction, but, there is no parallel confinement.

- At the temperatures involved, ions are moving at over 1,000 km/s
- For a practical device, the end losses must be eliminated

A torus is unique topologically: It is the only 3D shape where a non-singular vector field can be tangent to the surface everywhere.

Voila! Eliminate the ends.
Fusion Energy Progress has been Truly Remarkable

- From 1970 to 1995, fusion triple product ($n \tau T$), power and energy increased much faster than computing power (Moore’s law)
  - more than 12 orders of magnitude increase in fusion energy per pulse
Fusion Energy Development has Slowed

- From 1970 to 1995, $nT$, power and energy increased much faster than computing power (Moore’s law)

- Why the slowdown?
  - research funding decreases
  - unit size of devices being designed and built is very large

ITER 2030?
Need more urgent than ever: Greenland is Melting Away*

*New York Times, October 27, 2015
How Can Fusion Best Contribute in a Timely Way as a Carbon-Free Energy Source?
High-Field Tokamaks Long Recognized as an Expedient Approach to Study Burning Plasmas

- Compact copper-magnet designs, including Ignitor, Zephyr, CIT/BPX, FIRE
  - Demonstrate and study alpha-dominant heating regimes, in pulsed operation
  - Since the required magnetic fields were not achievable with conventional superconductors, deemed by some to be a “dead end”
A Revolution in High Temperature Superconductors (HTS) in Last Few Years

REBCO (Rare-Earth Barium Cu-Oxide) remains superconducting at VERY high B-field, and above liquid He temperatures.
Industrial Maturity of High-B Superconductors Motivates Reconsideration

Possible game-changer for fusion energy

• Devices that produce net electricity could be built at smaller scale ⇒ sooner, lower cost
  
  • Operating point would be more favorable for
    — Stability, control, sustainment, Plasma-Wall Interactions

• Higher temperature (~30 0K) operation opens new options for jointed coils
  — flexibility, maintainability
Recent Magnet Technology Advances Could Lead to Faster Development of Fusion Energy

Outline

— Superconducting Technology
— Core Confinement and Stability
— Pedestal Physics
— Power Handling and Plasma-Wall Interactions
— Sustainment
— Next steps
REBCO: coated superconductors in robust tape form, commercially available

- Strong in tension due to hastelloy steel
- Flexible
- Outer Cu coating $\rightarrow$ simple solder low-resistance joint
- Stark contrast with $\mathrm{Nb}_3\mathrm{Sn}$ superconductor strand & CIC!
Other Applications of REBCO
High-Field, High Temperature Superconductor

- Electrical Transmission
- NMR/MRI (spatial resolution)
- Possible upgrades to LHC

Field Upgrades for Large Hadron Collider*

Comparison of Mouse MRI Images using Cu and HTS Volume Resonators**


April 2015: New record of 26.4 Tesla with REBCO-only, “no-insulation” coil

S. Hahn, J.M. Kim, et al. 
NHMFL, FSU, SUNAM, MIT
What limits B in a High Temperature Superconducting Tokamak?

- Need sufficient volume for superconductor, with given $j_c$ constraints
  - thin tape geometry advantageous
- Must stay within structural stress limits
  - Understanding of mechanical stress and limits is a mature engineering discipline
  - Note that Alcator C-Mod (here at MIT) successfully operates (1000’s of cycles) at high fields (up to 17T at the coil), with demountable joints (copper)
Smaller, modular fusion devices can accelerate fusion’s development

<table>
<thead>
<tr>
<th></th>
<th>Shippingport: 1954 “Pilot” Fission Plant</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{thermal}}$ (MW)</td>
<td>230</td>
<td>500</td>
</tr>
<tr>
<td>Core volume (m$^3$)</td>
<td>60</td>
<td>~1000</td>
</tr>
<tr>
<td>Cost (2012 US B$)</td>
<td>0.6</td>
<td>~20</td>
</tr>
<tr>
<td>Cost / volume (M$/m^3$)</td>
<td>10</td>
<td>~20</td>
</tr>
<tr>
<td>Construction time (y)</td>
<td>~4</td>
<td>&gt;20</td>
</tr>
</tbody>
</table>

- Cost & time $\propto$ unit volume and mass
- ITER is an invaluable science experiment for burning plasmas but is not an optimized size for modular fusion energy “pilots”
  — ITER is a trial of just one fusion concept, fission pilot tried four different cores!
- Small size and modularity are self-reinforcing: pilots of complex engineered systems should be no larger than necessary, yet sufficiently capable
Confinement physics strongly favors high $B$ to produce fusion capable devices at smaller size.

Fusion Gain

$$nT \tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

Confinement Physics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ (m)</td>
<td>2.14</td>
</tr>
<tr>
<td>$V$ (m$^3$)</td>
<td>30</td>
</tr>
<tr>
<td>$B_0$ (T)</td>
<td>10</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>$&gt;10$</td>
</tr>
<tr>
<td>Steady-state</td>
<td>No</td>
</tr>
<tr>
<td>Tritium breeding</td>
<td>No</td>
</tr>
<tr>
<td>$Q_{electric}$</td>
<td>0</td>
</tr>
</tbody>
</table>

Power density

$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N^2 \epsilon^2}{q_*^2} R B^4$$

Copper coil pulse ~ 40 s

Can this be made steady-state with High-B Superconductors?
Known physics scaling + Superconductor $B_{\text{peak}} > 20$ T → High-gain burning plasma: Compact Size & Steady-State

$$nT \tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

$$V, \mu R^3$$

$$P_{\text{fusion}} \sim \frac{\beta_N^2 \rho_e^2}{q_*^2} R B^4$$

**ARC**

REBCO superconductor

<table>
<thead>
<tr>
<th></th>
<th>FIRE*</th>
<th>ARC</th>
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</thead>
<tbody>
<tr>
<td>$R$ (m)</td>
<td>2.14</td>
<td>3.2</td>
</tr>
<tr>
<td>$B_0$ (T)</td>
<td>10</td>
<td>9.2</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>$&gt;10$</td>
<td>$&gt;10$</td>
</tr>
<tr>
<td>Steady-state</td>
<td>No</td>
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<tr>
<td>Tritium breeding</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>$Q_{\text{electric}}$</td>
<td>0</td>
<td>$\sim 4$</td>
</tr>
</tbody>
</table>


Marmar IAP January 11, 2016
High B field permits a plasma edge with required pressure for fusion performance, well within stability limits

- Edge sets the boundary condition, determines pressure in the center of the plasma
- Reactor edge conditions are constrained: Pressure $\sim 0.15$ MPa (1.5 atmosphere) at $T\sim 5\text{keV}$ ($6\times 10^7 \text{oK}$)
- But the normalized pressure limit must not be violated, otherwise suffer surface damage from bursts of lost plasma, due to edge instabilities (ELMs).

Stability limits determined by normalized pressure:

$$\beta \equiv \frac{\text{Pressure}}{(B^2/2\mu_0)}$$

- This greatly favors high $B^2$ to push the required edge pressure away from the stability limit
Doesn’t Compact, High Field Make the Surface Power Handling Problem Harder?

- Actually, the answer is no!
- Empirically, the width of $q_{||}$, the power channel along $B$ at the plasma edge, is independent of device size
  - $q_{||} \propto 1/(\text{poloidal field strength})$
- Taking geometry into account, this means that $q_{||} \propto P_{\text{SOL}}B/R$
- Fixing power/(plasma area), and the fact that fusion performance relates size to field ($R \propto 1/B^{2.3}$)
  - $q_{||} \propto 1/B^{1.3}$
Surface Power Handling is a Significant Challenge in all Pilot and Reactor Concepts

- Comparing conventional reactors with ARC:
  - no significant difference in expected edge power density flowing along B ($q_{||}$)
- But in all cases, challenge is about 10X that faced by most currently operating tokamaks
High-Field Divertor Test Tokamak Proposed to Solve the Power Handling Challenge

in-depth understanding of the science for projection to reactors needs a flexible facility that allows innovative divertor and plasma facing component options with rapid evaluation cycles*

Advanced Divertor eXperiment

R=0.73 m, B₀=8 T
Plasma Current =2 MA

Modularity and small size should be enabling to solving critical issues of divertor heat exhaust

- Advanced divertor coils built into modular core as replaceable components
  - Exploit physics advances from expanded volume divertors


Compact, High-Field, Divertor Test Tokamak (DTT)*

Also test liquid metals

Must Sustain Plasma Current in Steady-State

- A fraction (~30%) of the plasma current ($I_p$) must be driven by external power
- Must keep recirculating power to a minimum
- Microwave current drive has the highest efficiency: works best at high magnetic field
  - compact, high-field wins on both counts

![Graph showing current drive efficiency as a function of local magnetic field strength](image)

$$\eta = \frac{I_{CD}}{P_{CD}} \times \frac{n}{10^{20}} \times R$$

Electron density = $2 \times 10^{20}$ m$^{-3}$
HTS could also be revolutionary for Stellarators

- High current density
  - reduced coil pack size
- Strong, flexible
  - simpler coil design
  - does not require reacting after winding
- Slowly varying fields can simplify engineering requirements

Modular HTS Option for FFHR-d1*

Conventional Designs for Pilot Plants/Reactors Assume Aggressive Confinement Physics

- Previous $B$ limit for conventional, low-temperature superconductors led to aggressive advanced tokamak designs
  - Very high normalized pressure, strong shaping, operating close to (or above) stability and density limits
- Lack of jointed coils also implies very challenging through-port sector maintenance (“ship in a bottle”)
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ARC conceptual design example of “smaller, sooner” modular fusion devices using new superconductors

- Demountable magnetic field coils
  - Enabled by jointed conductor
- Employ liquid blanket
- Single-unit vertical lift

Small, modular design features generically attractive for any Magnetic Fusion Energy choice: ST, stellarator, liquid wall, etc.

Peak stress ~ 0.67 Gpa
~65% of limit for 316SS LN
ARC* conceptual design example of “smaller, sooner” fusion device using new superconductors

Copper, $B_0 = 3.5$ T

$P_{\text{fusion}} \sim 10$ MW

$\sim 4$ years construction

$JET: \ R \sim 3$ m

$\text{REBCO superconductor, } B_0 = 9.2$ T

$I_p = 7.8$ MA

$P_{\text{fusion}} \sim 500$ MW

$R = 3.2$ m

Near-term, *small-scale* research can pursue this exciting path for fusion energy.

High-Field, High Power Density Plasma Science Experiments

- Alcator C-Mod
- Cable
- DTT
- Magnet Assembly
- ARC

High-Field Superconducting Magnet Development
Where are we now?

- Superconducting technology advance opens a new window for a faster path
  - HTS coils are a reality; not yet at scale needed for fusion
  - Jointed construction would yield significant improvement in flexibility, maintainability
    - R&D required
- Physics basis already largely demonstrated
  - Need improved surface power handling and current drive efficiency
What can/should we do moving forward?

Fusion is needed, and soon: We need to be continually looking for technology and science innovations to accelerate fusion’s development.

- HTS High Field Magnet R&D for fusion:
  - Full scale models; Joint development
- Aggressive research to solve the power handling and sustainment challenges:
  - New, purpose-built facilities required to develop the solutions
- Combine in a net-electricity producing Pilot
IAP Plasma Science and Fusion Center Talks and Tours this Week and Next

- **Tuesday, 1/12, 6-120**
  - 11:00 am *Turbulence in Fusion Plasmas*, Anne White (MIT)

- **Thursday, 1/14, NW17-218**
  - 11:00 am *SPARC: A Small Tokamak for Changing Climates*, R. Mumgaard, D. Brunner, Z. Hartwig, B. Sorbom (MIT)
  - 12:45 pm *Alcator C-Mod Tour*, T. Golfinopoulos, A. Kuang (MIT)

- **Tuesday, 1/19, NW17-218**
  - 11:00 am *Surfaces, Interfaces, Spins - Control it All, From Exchange Interaction to Quantum Transport to Molecular Spintronics*, Jagedeesh Moodera (MIT)

- **Thursday, 1/21, NW17-218**
  - 2:00 pm *Structural Biology at the Francis Bitter Magnet Lab.*, Mei Hong (MIT)

- **Friday, 1/22, NW17-218**
  - 11:00 am *Creating, Diagnosing and Controlling High-Energy-Density Matter with the National Ignition Facility*, Mark Herman (LLNL)
  - 2:00 pm *Exploring High-Energy-Density Science at NIF, OMEGA and Z using MIT-developed Nuclear Diagnostics*, Maria Gatu Johnson (MIT)
  - 3:00 pm *Inertial Confinement Fusion Tour*, Andrew Birkel (MIT)