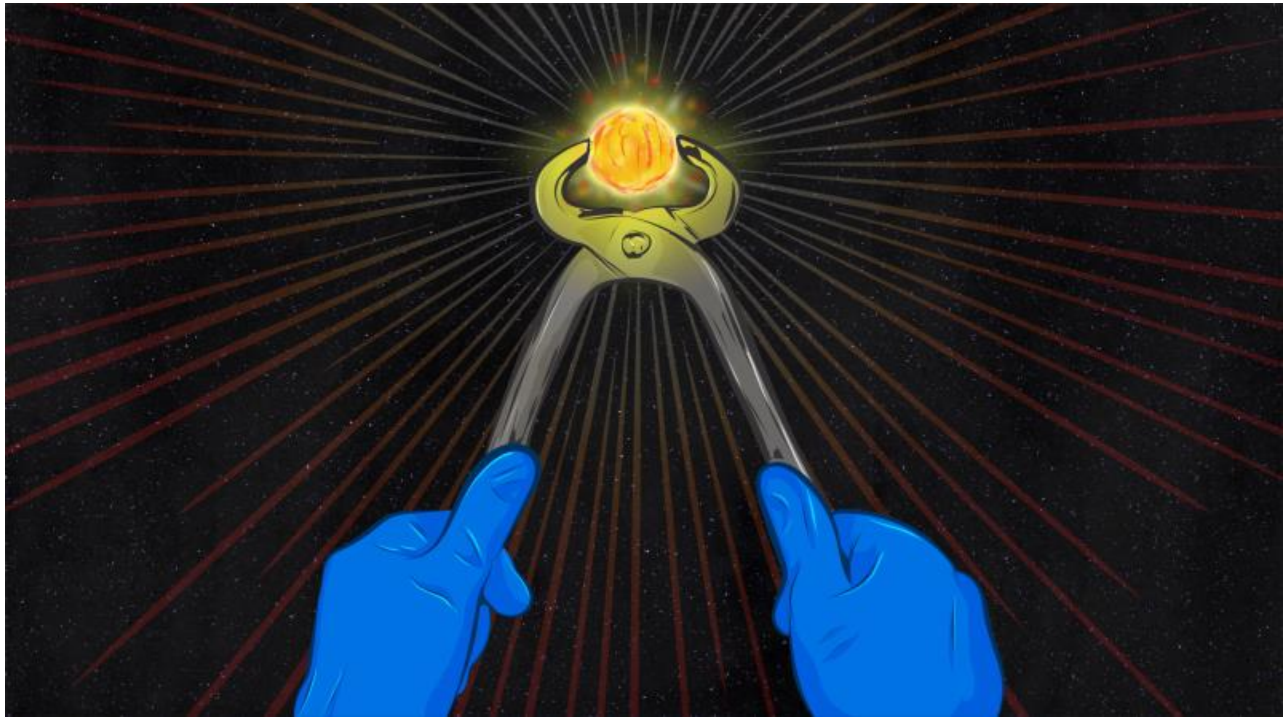
Fusion Energy and MIT's pathway to accelerated demonstration with high magnetic field tokamaks

PSFC



Art Work by Sam Woolley, thewoolley.com

Brandon Sorbom

- Nuclear Science and Engineering
- Plasma Science and Fusion Center

Many thanks

- Zach Hartwig, Dan Brunner, and Bob Mumgaard, who made many of these slides

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

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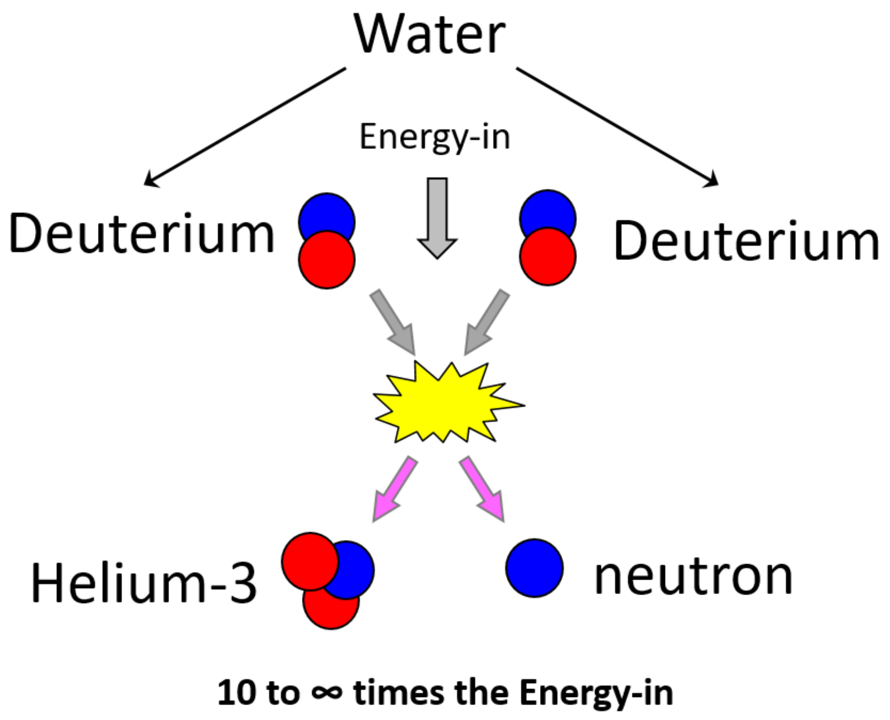
- Fusion is a fundamental process that combines two nuclei and releases energy. Its immense promise has compelled its pursuit for almost 60 years…



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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+ transport of fuels

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- 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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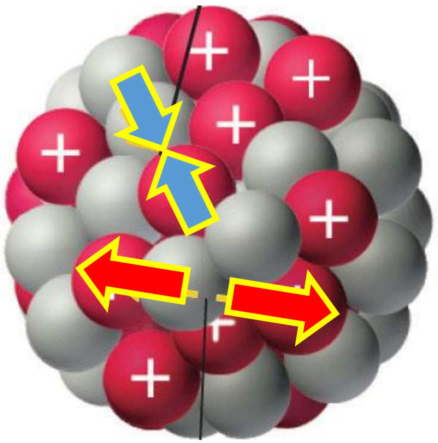
Advantages of fusion over nuclear fission energy:
- No chain reaction = no possibility of a melt down
- No long-lived nuclear waste for deep storage
  - Lower level activation of components
- Low proliferation risk
  - No need for fissile material (*e.g.* U, Pu)
  - Non-fusion clandestine use highly infeasible

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**

Strong nuclear force

n↔n n↔p p↔p



Coulomb repulsion

p↔p

Two basic physical quantities fundamentally set fusion fuel viability: (1) the reaction energetics (input, output); (2) the reaction probability

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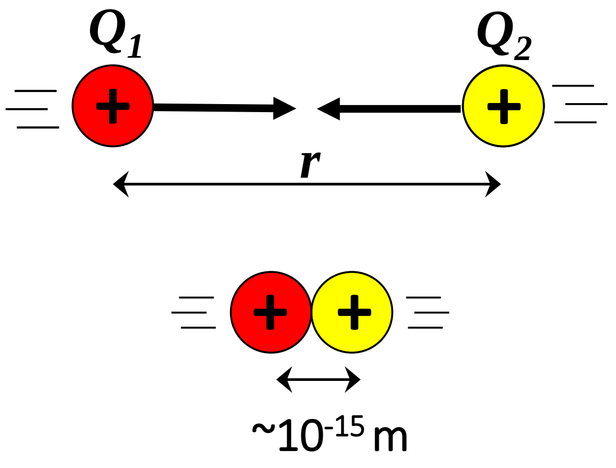
Reaction energetics

Reaction probability

Input energy:

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

$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$



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Reaction probability

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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

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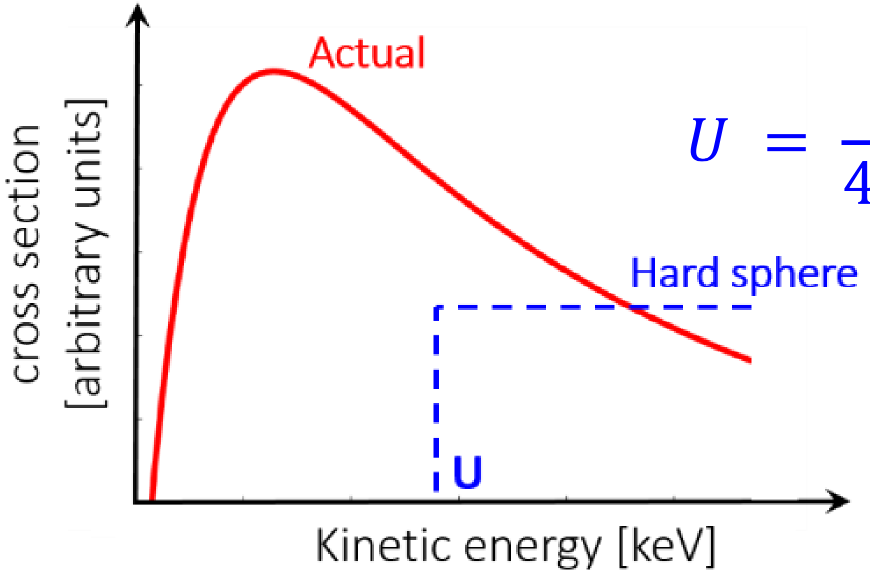
Reaction energetics

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



$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$

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

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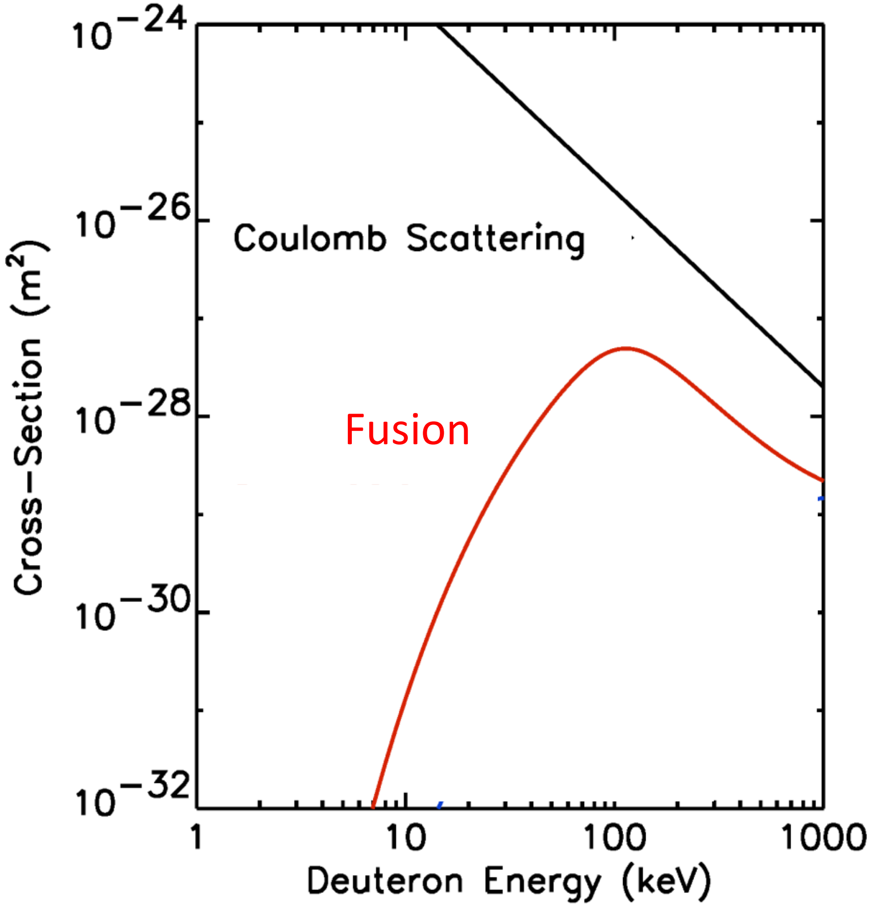
- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions

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!

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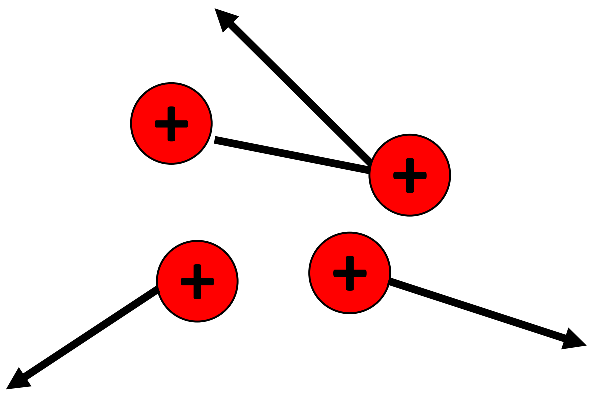
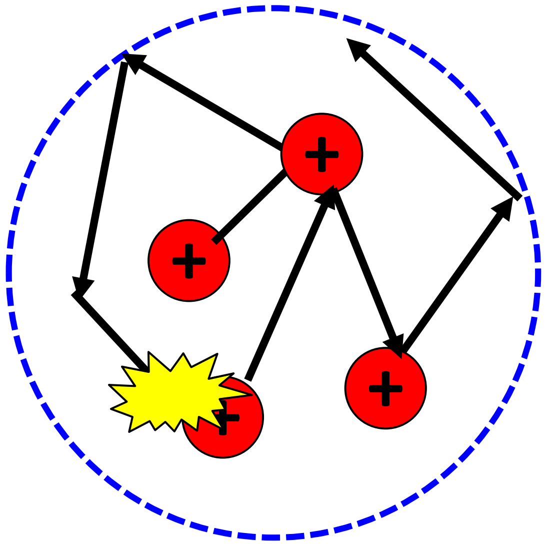
- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions

- 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!

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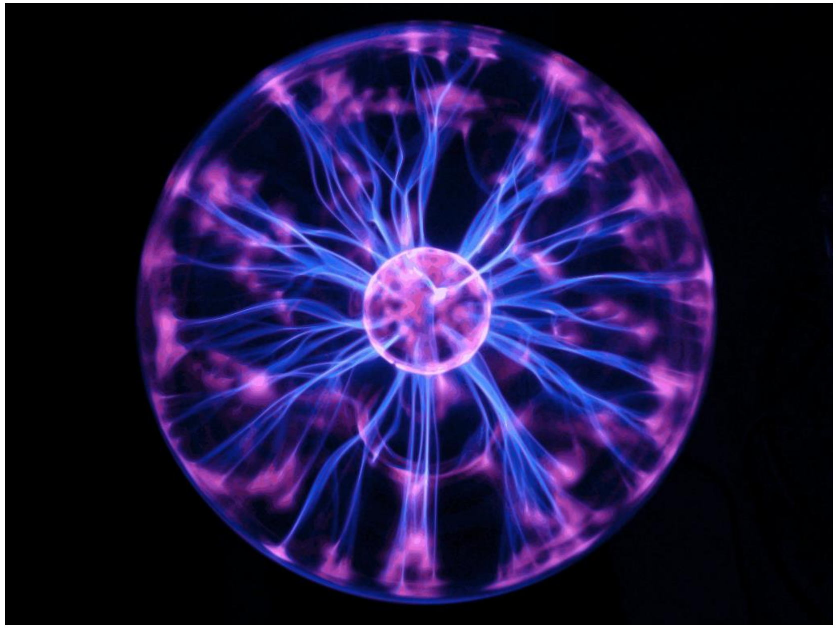
- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions

- 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



The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.

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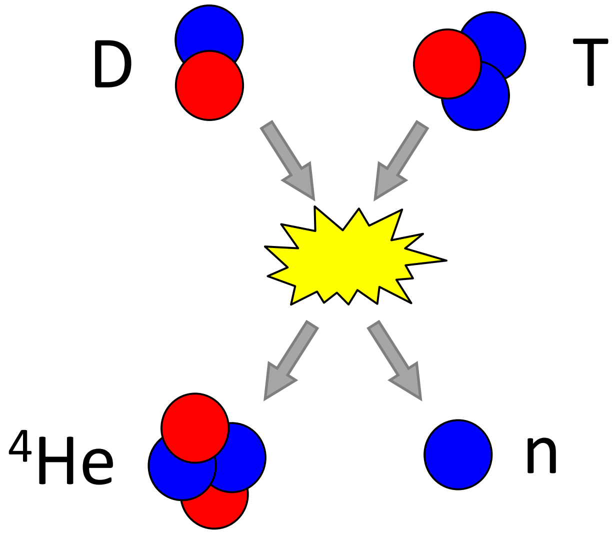
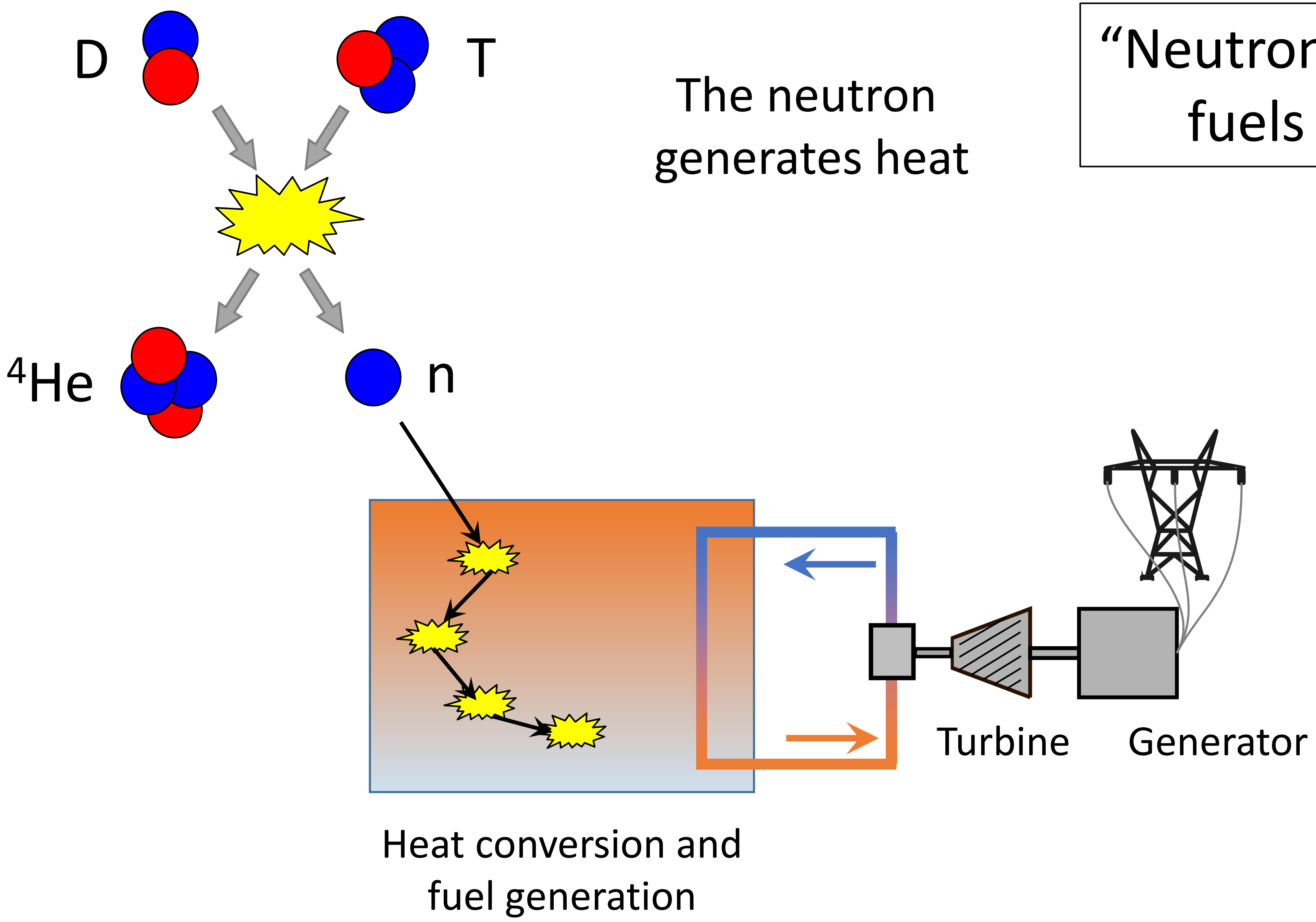


"Neutronic" fuels

The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.

"Neutronic" fuels

The neutron generates heat



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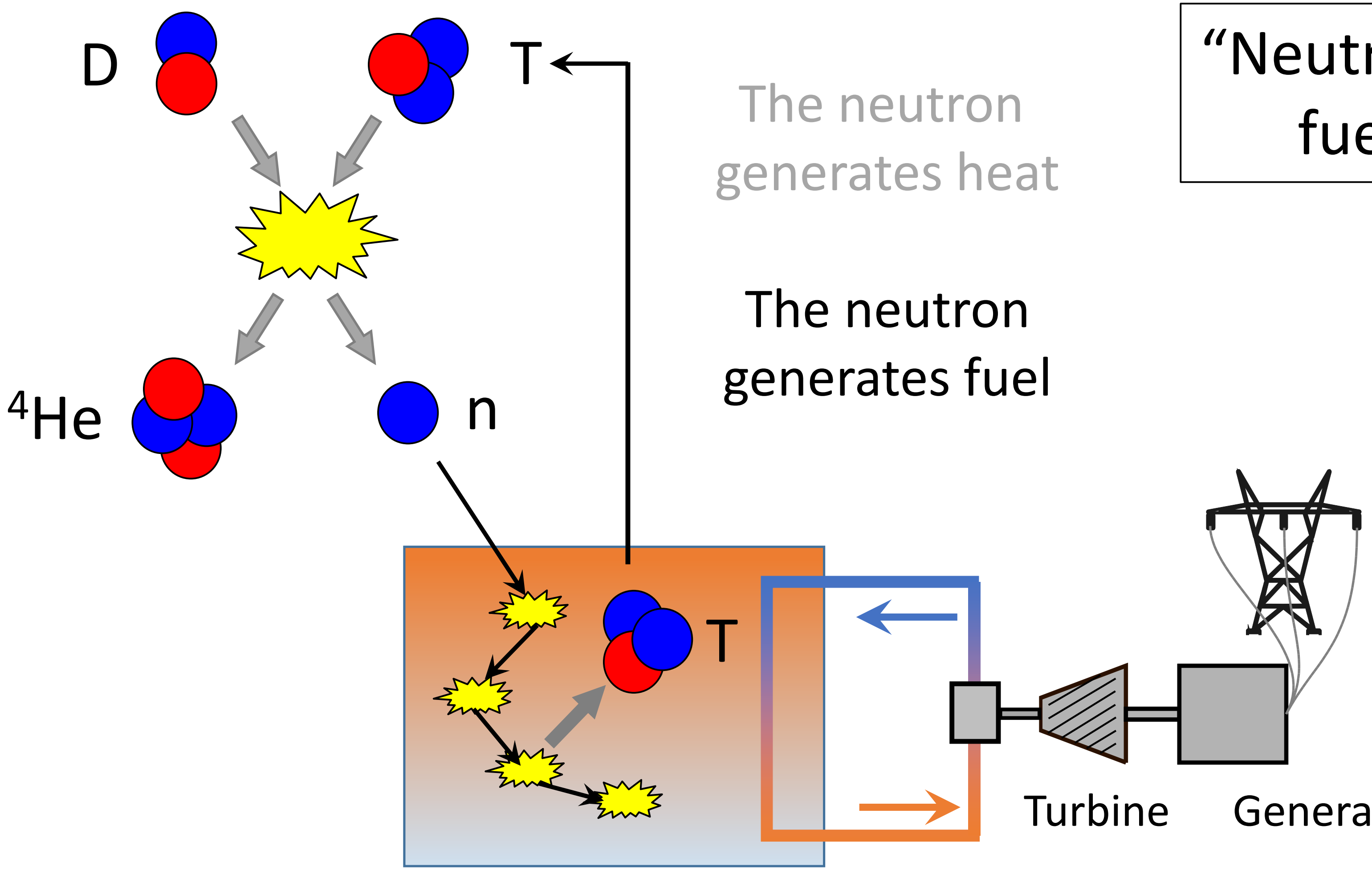
“Neutronic” fuels



The neutron generates heat

The neutron generates fuel

Heat conversion and fuel generation

The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.

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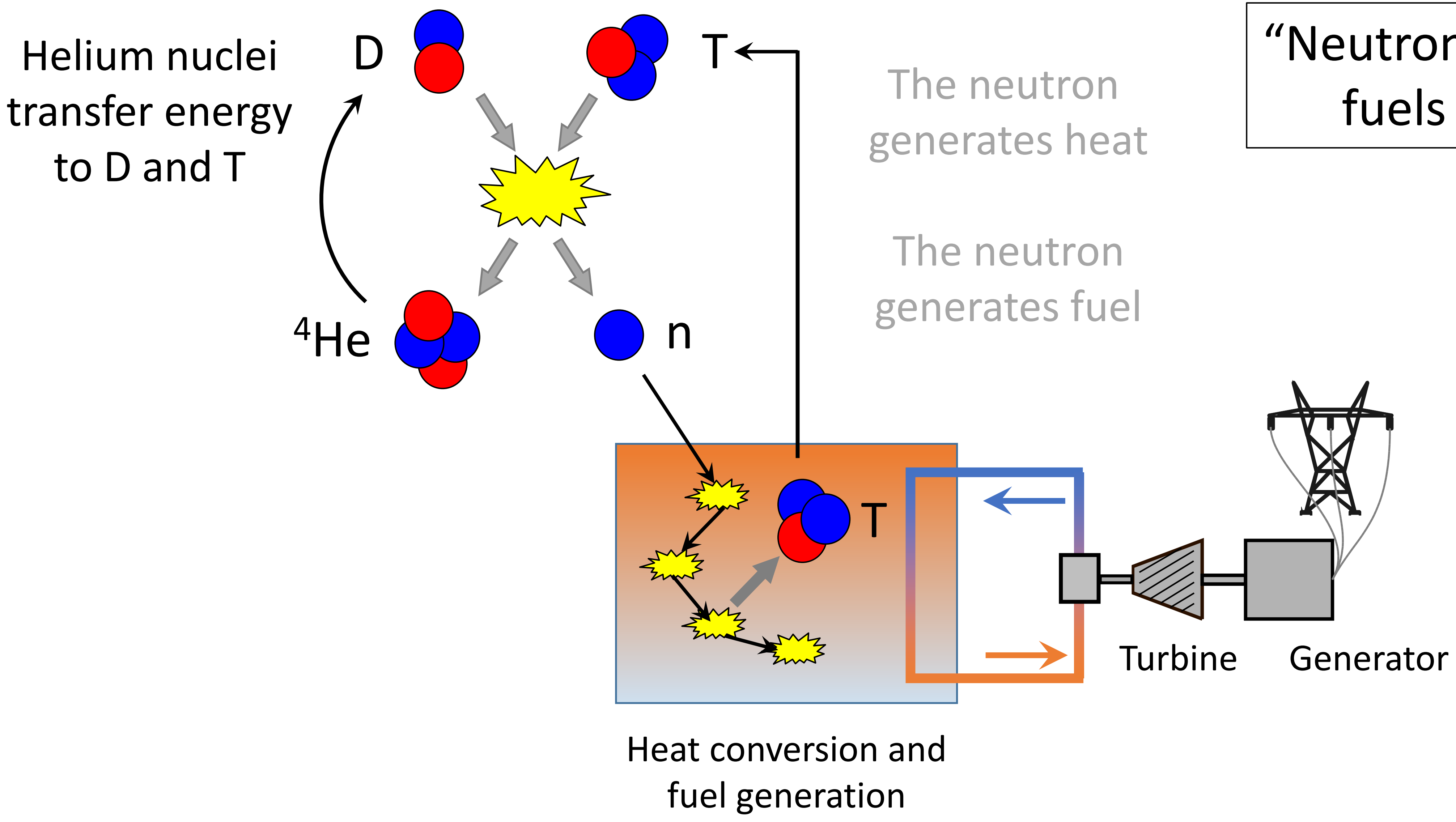

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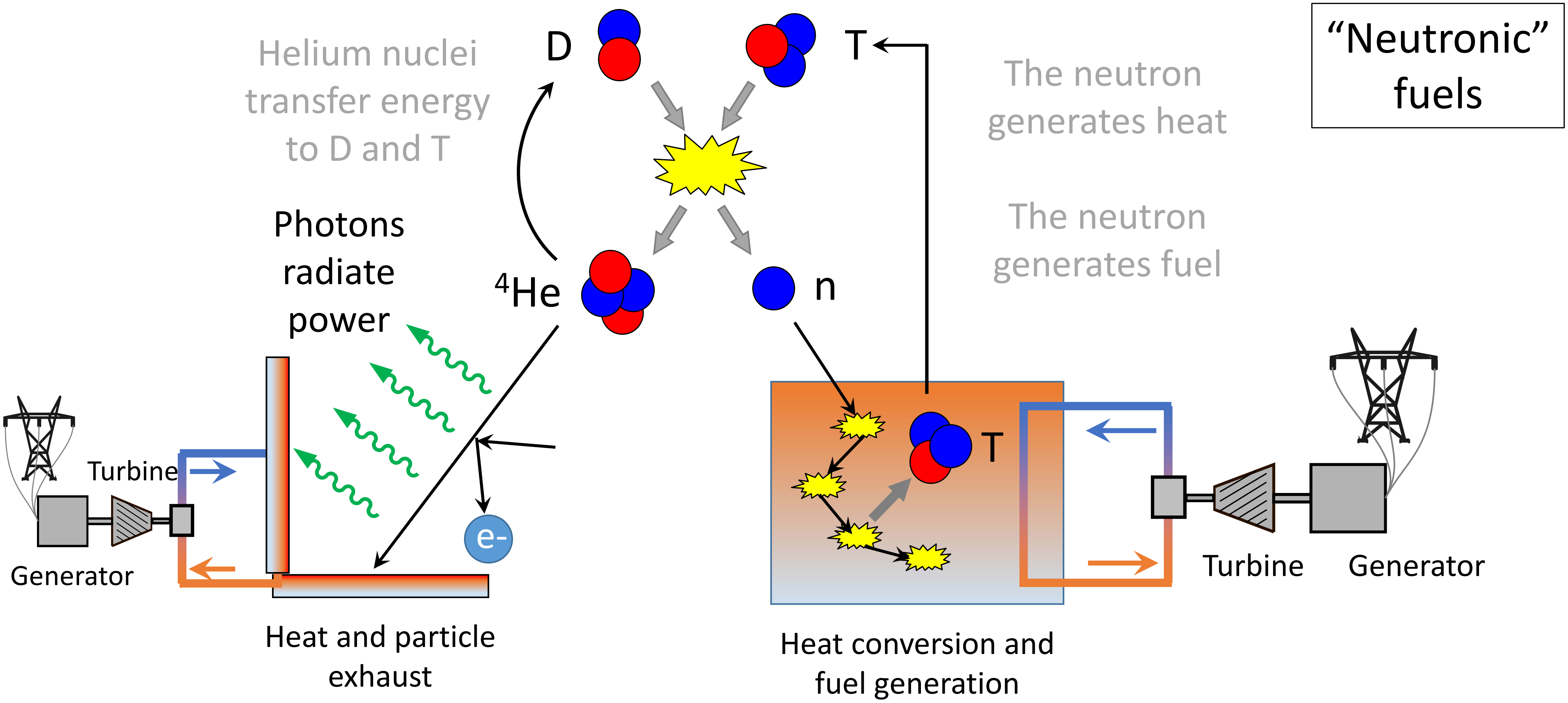


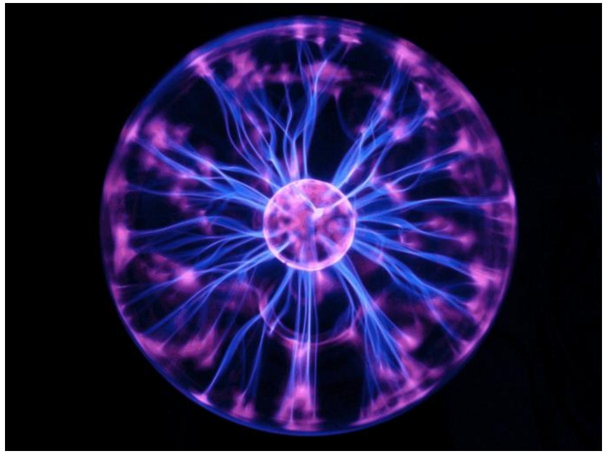
The conditions for burning wood (net chemical energy release) are roughly analogous for burning a plasma (net fusion energy release)

Wood density

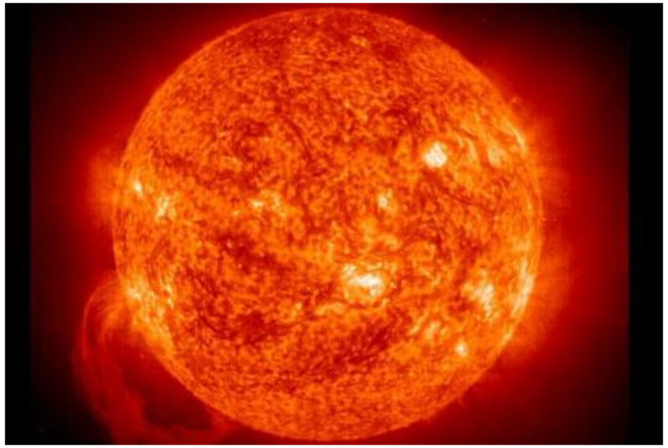
Wood temperature

Energy confinement

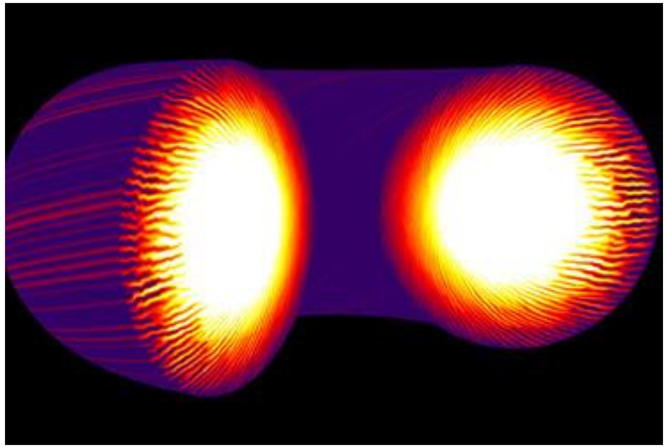
The conditions for burning wood (net chemical energy release) are roughly analogous for burning a plasma (net fusion energy release)



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

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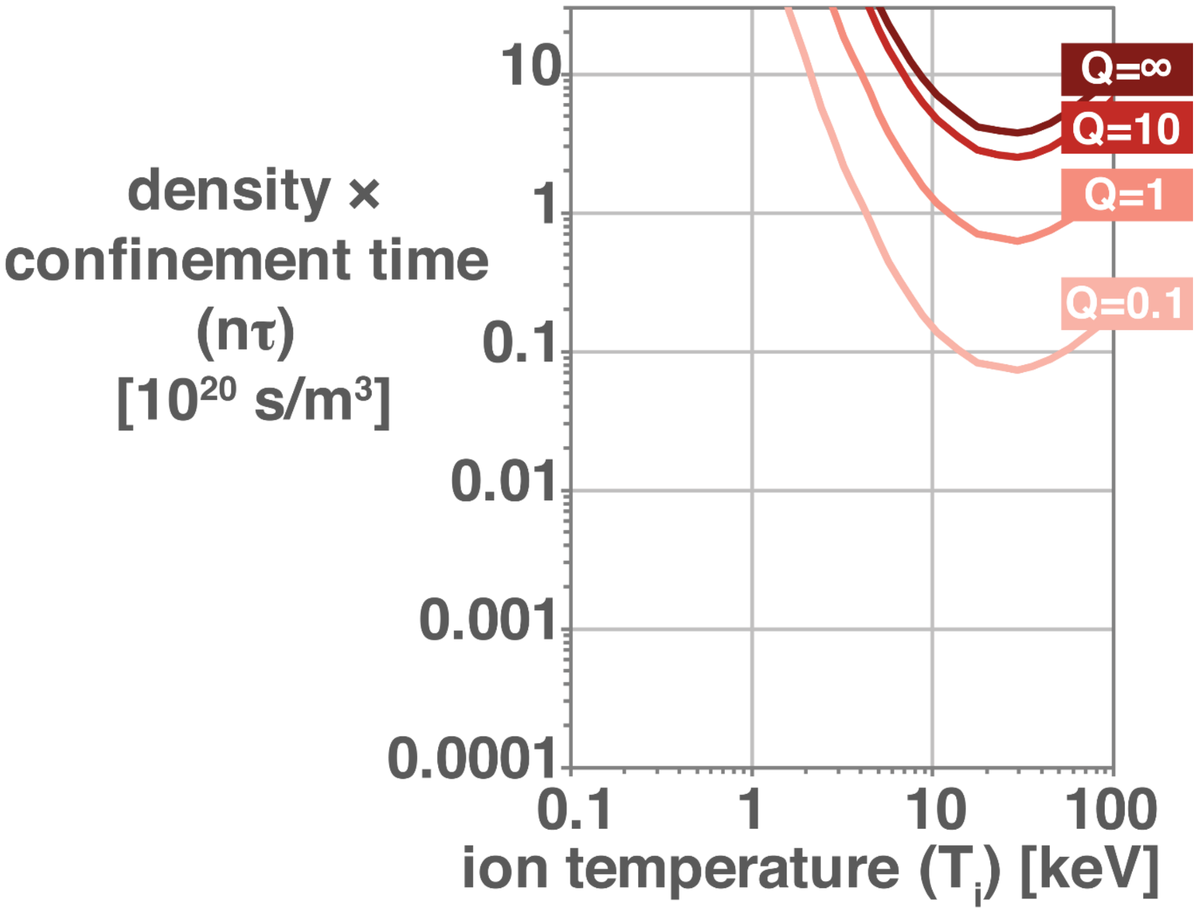

$$Q = \frac{Fusion\ energy\ output}{Energy\ input}$$

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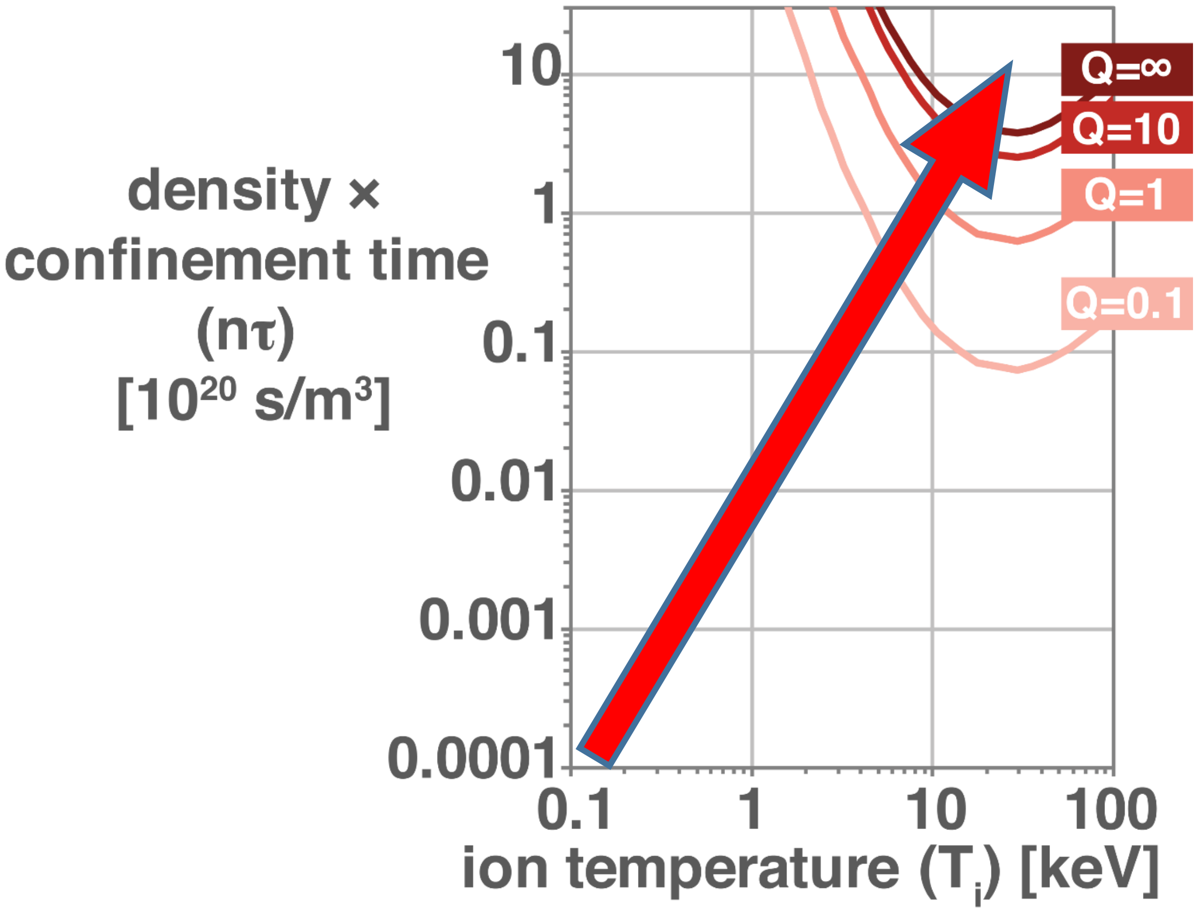
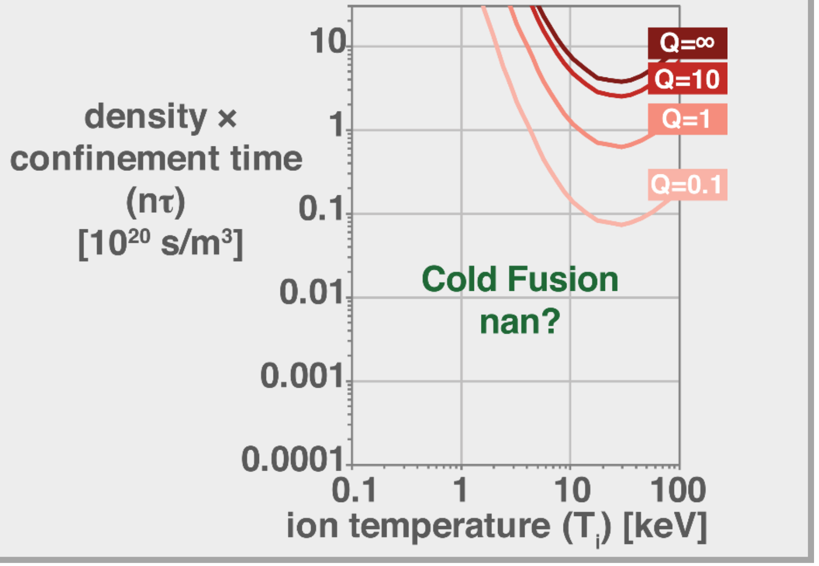


Moving into the upper-right corner has been the primary goal of fusion energy research for almost 60 years …

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


Boston Herald

MIT bombshell knocks fusion 'breakthrough' cold

Gravitational force confines plasma and create the conditions necessary for sustained generation of fusion energy in the stars

Confinement basis

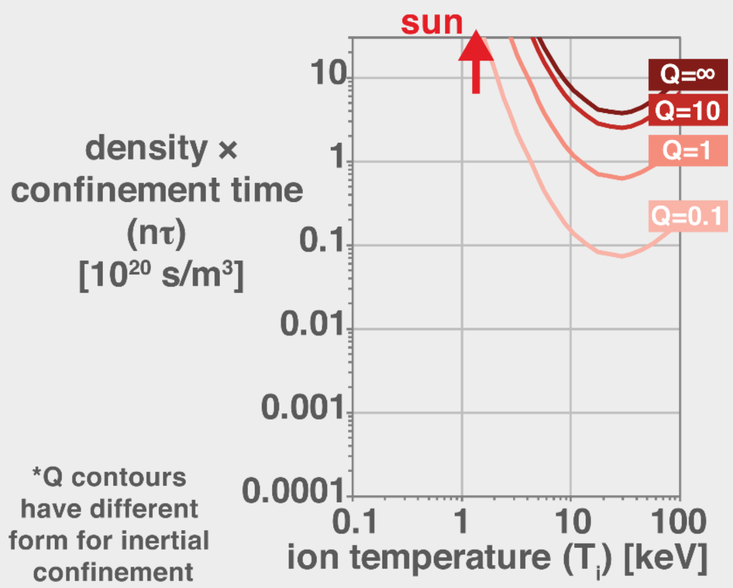
- Gravity

Active experiments

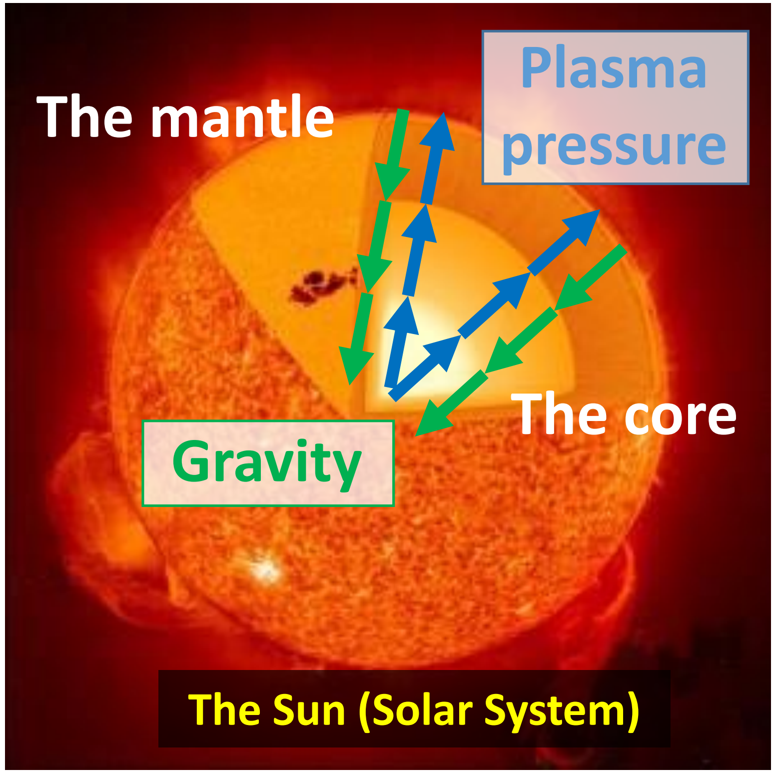
- See: The universe

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 (about your average compost pile)
  - ~10^{27} m^3 (absolute volume)
- Stars exist balance plasma pressure with gravity
  - Not likely to be replicated on Earth in the near term



H-bombs create fusion initiated by fission bombs, but resulting blast is unacceptable and infeasible for energy production.

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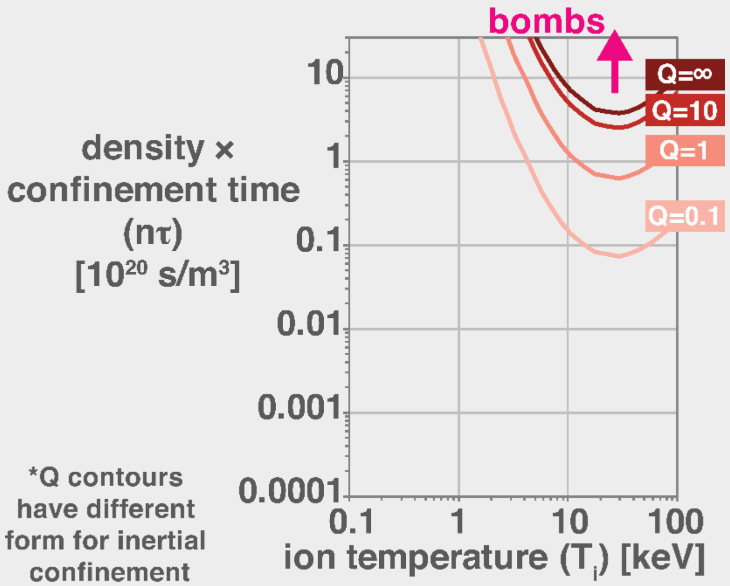
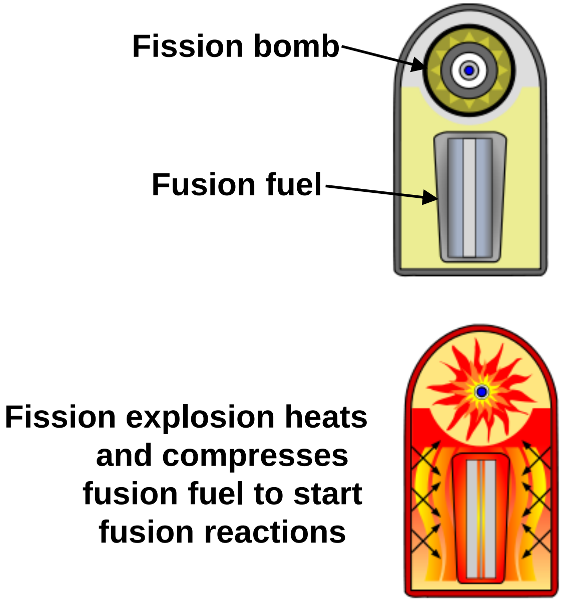
Confinement basis:
- Inertia with implosion driven by fission bomb

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.

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Confinement basis:
- Inertia with implosion driven by lasers

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

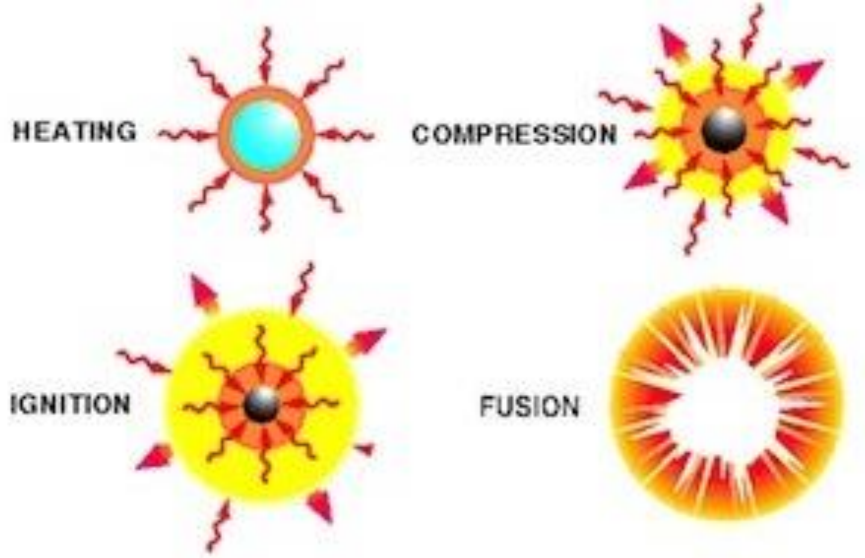
Key lessons learned:
- Capable of high performance but at very low rep rate and gain

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

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

Hurricane, O. A., et al. *Nature* 506.7488 (2014): 343-348.

- 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:

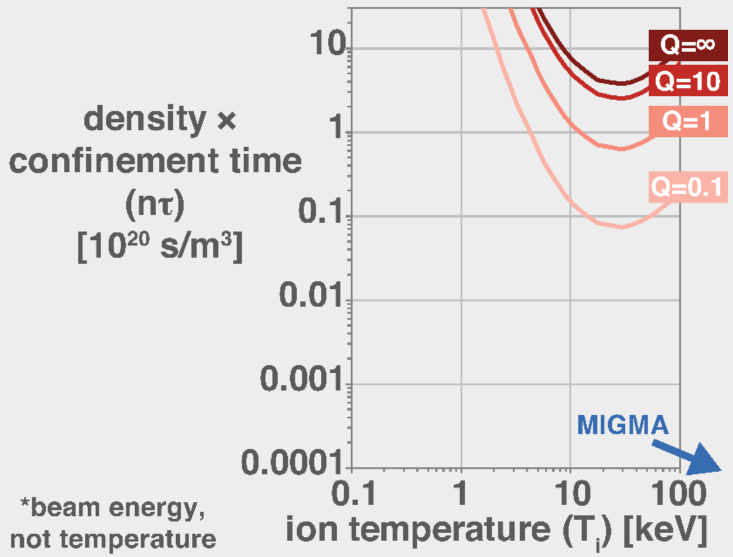
- Accelerating with electric fields

Active experiments:

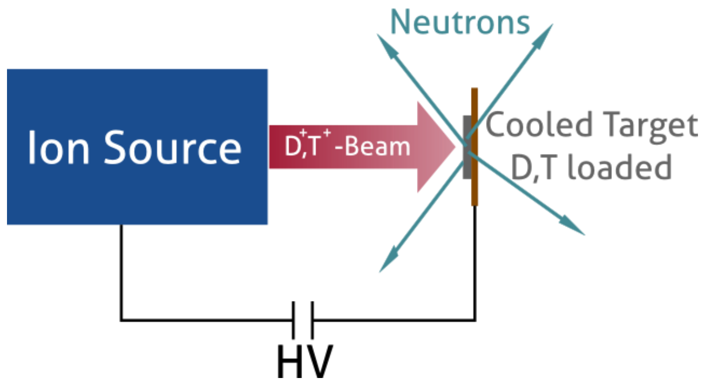
- Any accelerator with E ≥ 10 keV

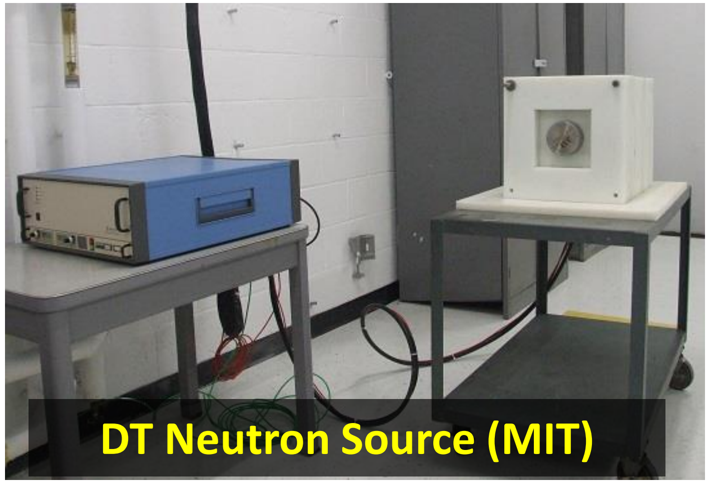
Key lessons learned:

- 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

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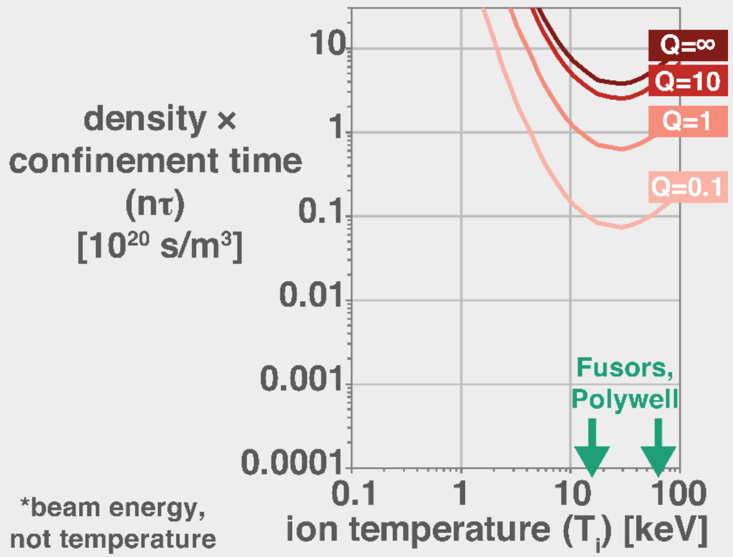
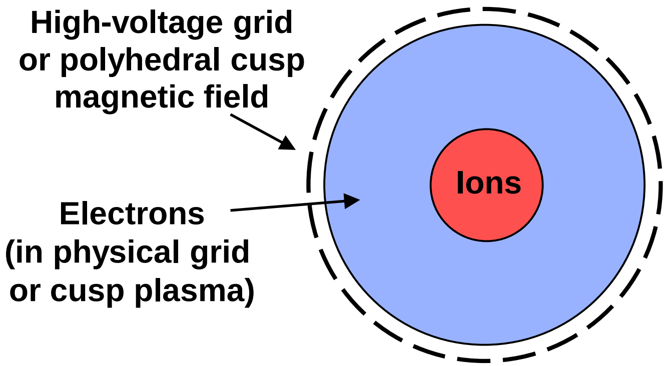
Confinement basis:
- Electric fields

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[1]
  - Coulomb collisions
  - Particle losses
  - Conduction losses
  - Bremsstrahlung
- While orders of magnitude from energy gain, can be effective simple neutron sources

Plasma in a fusor (hobbyist's garage)

[1] Rider, Todd H. "A general critique of inertial-electrostatic confinement fusion systems." *Physics of Plasmas (1994-present)* 2.6 (1995): 1853-1872.

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

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Confinement basis:

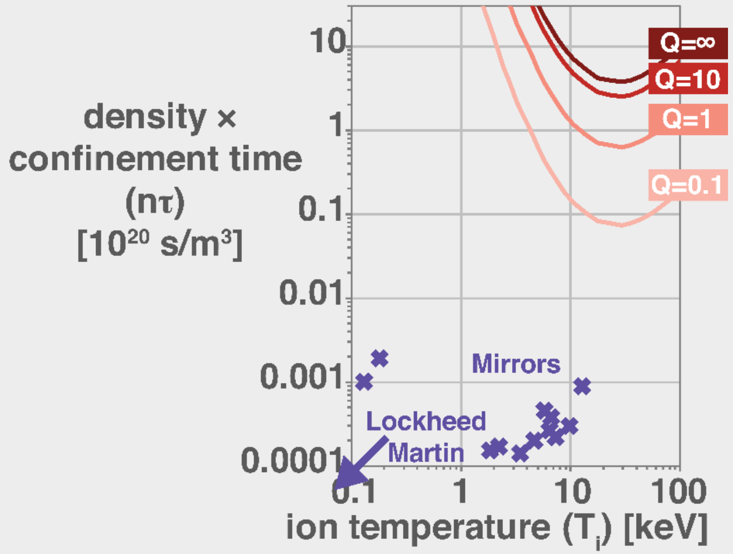
- Magnetic fields (crimped)

Active experiments:

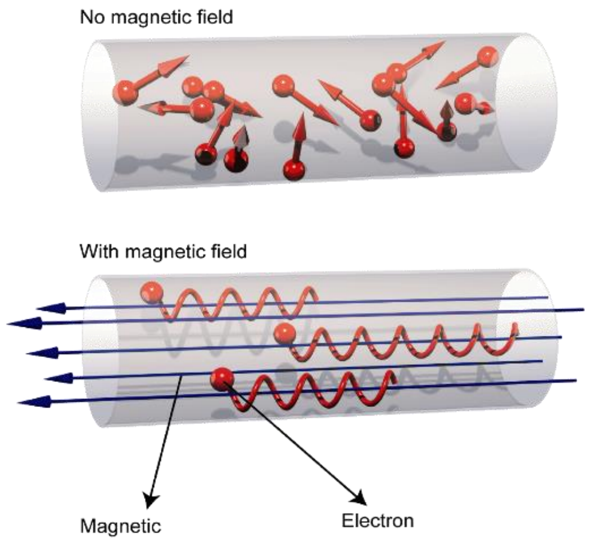
- Gamma-T (Japan), Gas Dynamic Trap (Russia), Lockheed Martin Co.

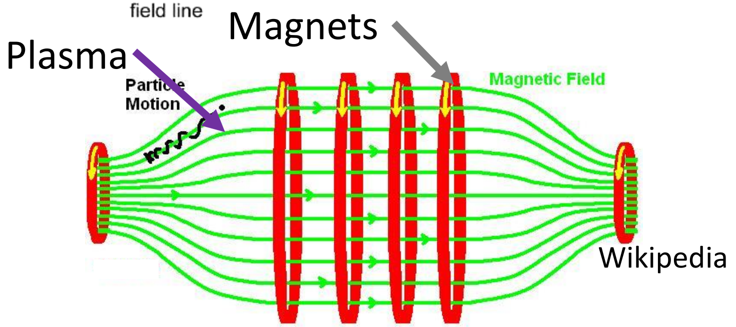
Key lessons learned:

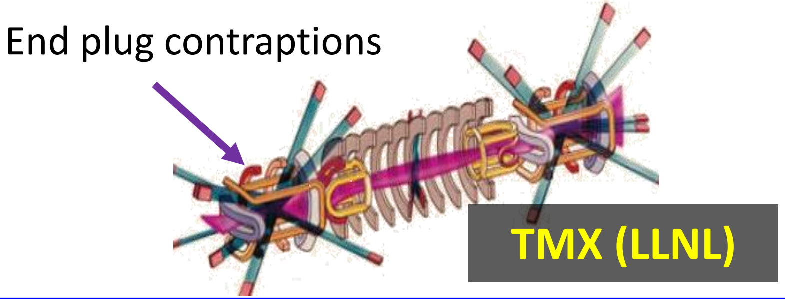
- Any open field lines lead to unacceptable losses



- 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







<u>Pinches or magnetized targets</u> use magnetic fields to rapidly compress the plasma before it leaks energy, but this creates instabilities.

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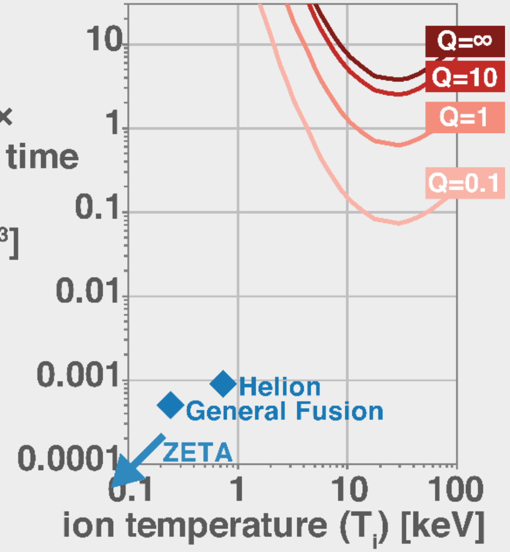
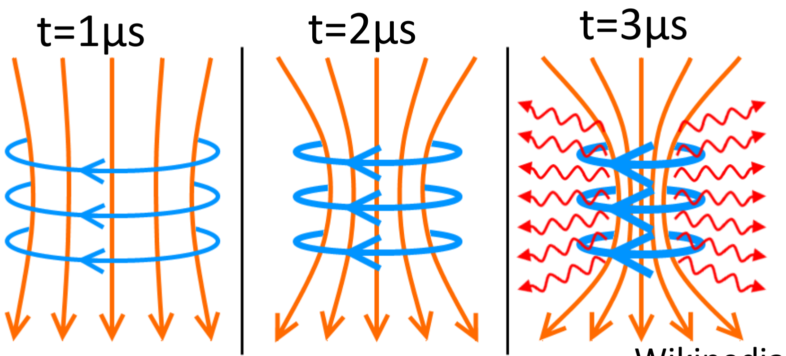
Confinement basis:
- Magnetic fields (squeezed)

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

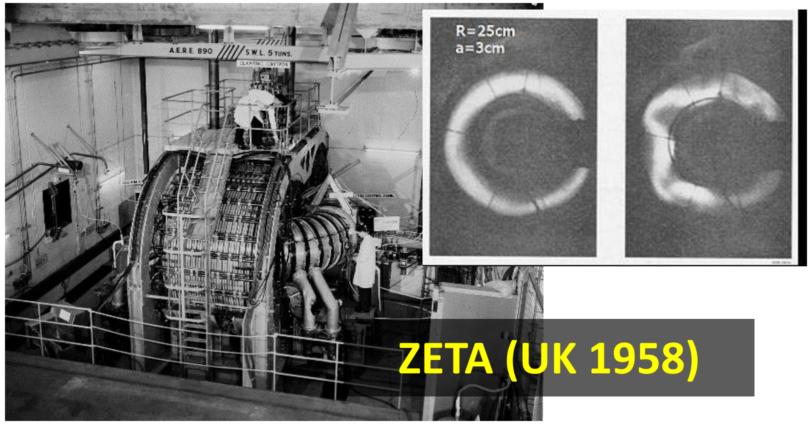
Key lessons learned:
- Instabilities are critically important

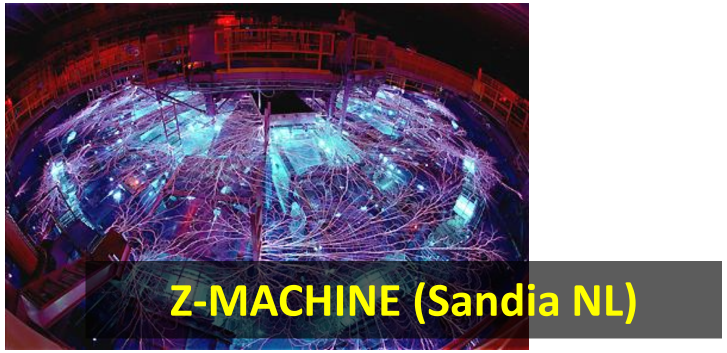


- Very quickly compress the plasma and heat it by rapidly changing magnetic field
- Many different configurations have been tried at many different scales
  - Requires large pulsed power systems
  - Often with sacrificial conductors surrounding plasma
- Large instabilities and plasma cooling occur before net-energy conditions are reached
  - Useful as a high-power X-ray or neutron source or particle accelerator



Wikipedia





Field-reverse configurations, spheromaks etc. use the plasma to create helical fields in the torus, increasing confinement at the expense of stability.

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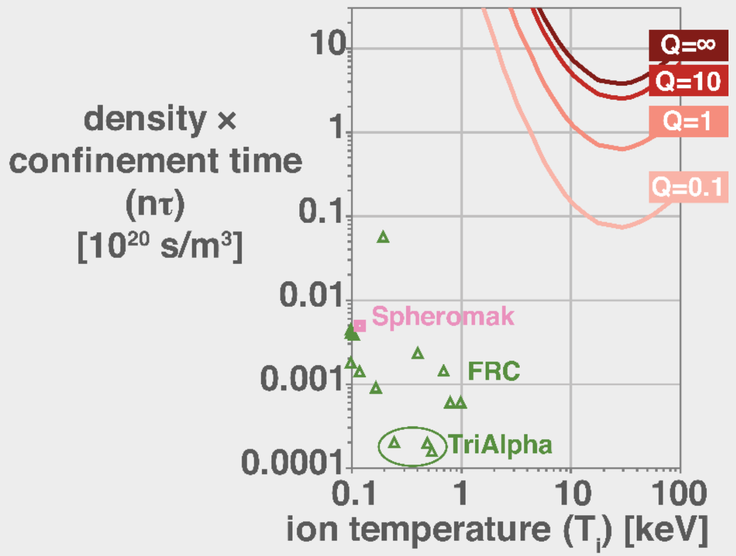
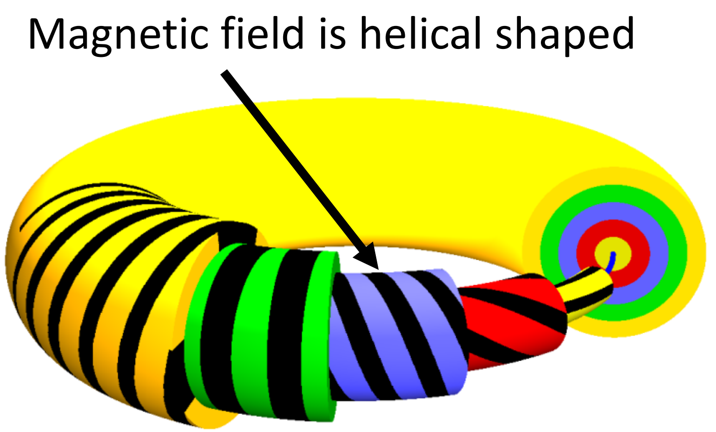
Confinement basis:
- Magnetic fields (self-twisted)

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



- 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



Reverse Field Pinch

Stellarators use external magnets to create the helical fields and are approaching fusion relevant conditions.

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Confinement basis:

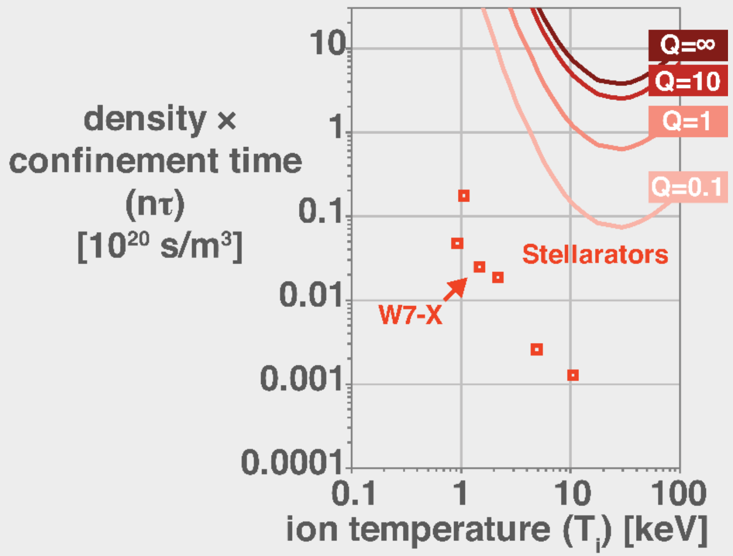
- Magnetic fields (twisted by external coils)

Active experiments:

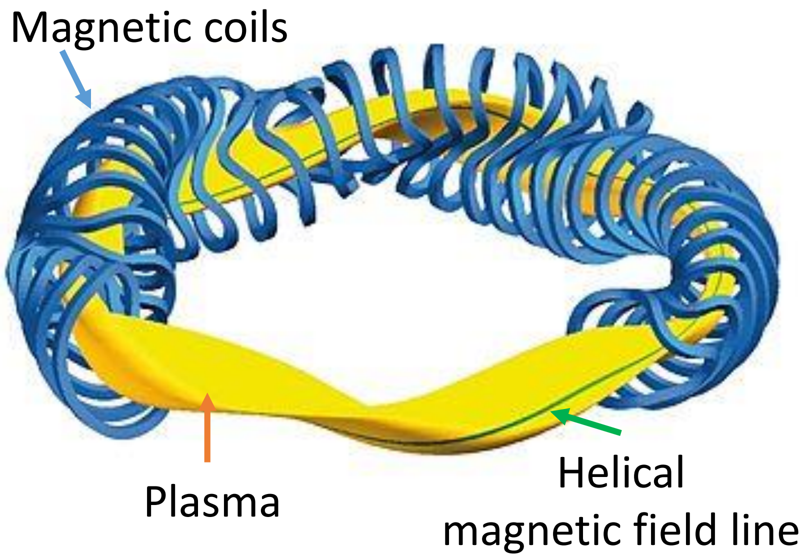
- LHD (Japan), W7-X (Germany), HSX (U. Wisc.)

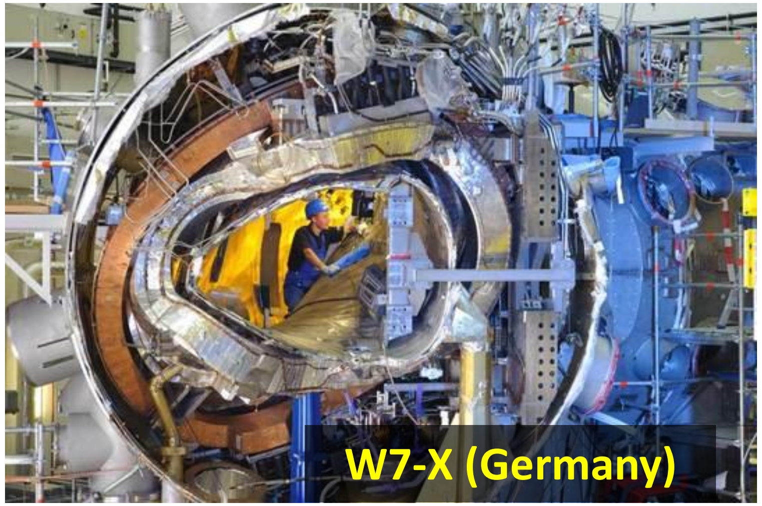
Key lessons learned:

- 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.

PSFC

Confinement basis:

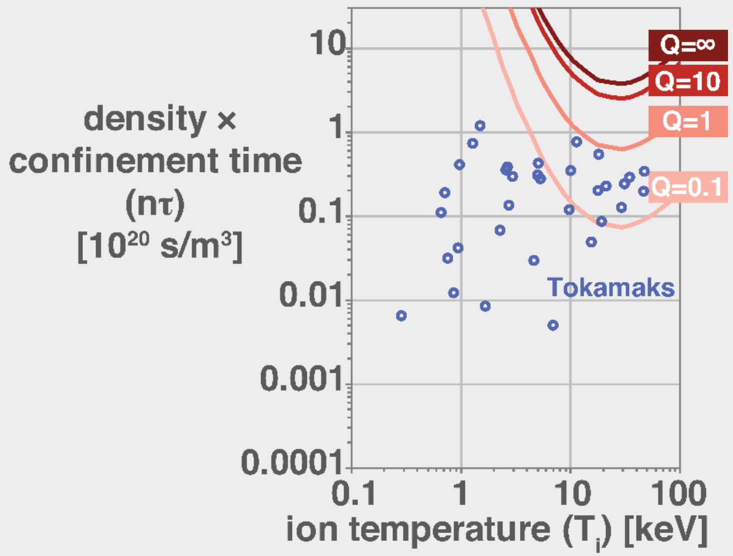
- Magnetic fields (twisted by external coils and plasma)

Active experiments:

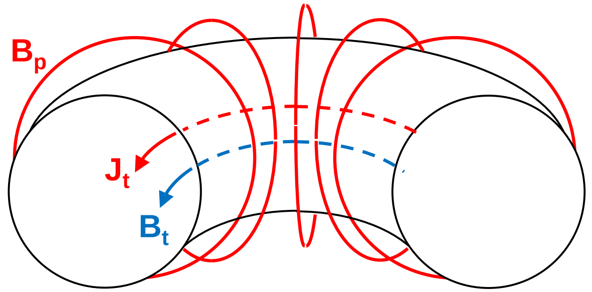
- JET, ASDEX-U, DIII-D (33 worldwide)

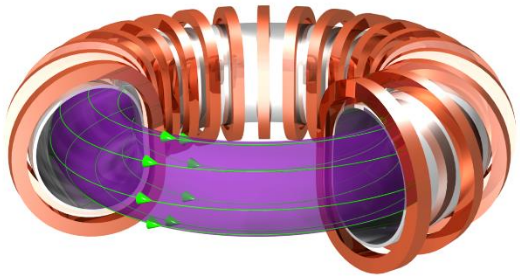
Key lessons learned:

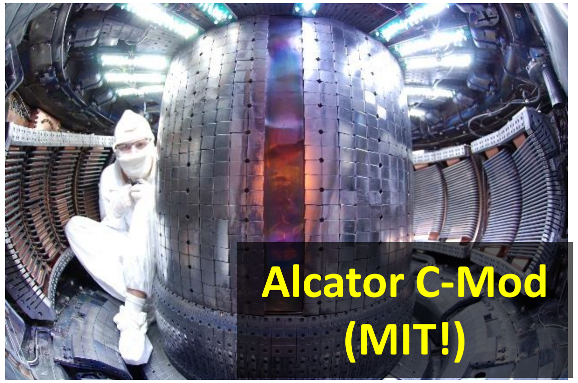
- Most promising candidate for fusion energy



- 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



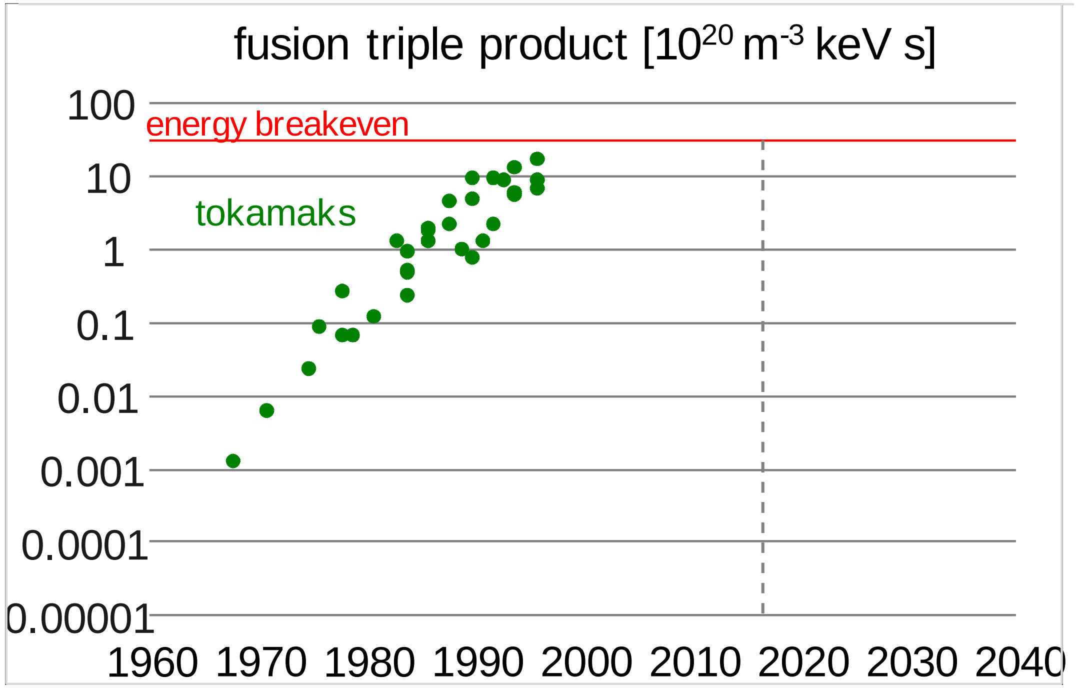




The tokamak **has** demonstrated physics performance but all is not well with the tokamak. ("Tokamaks got 99 problems but $nT\tau_E$ ain't one.")

PSFC

- Tokamaks made physics progress at a very rapid rate but that progress ceased after the late 1990
- **Key question:** What caused nTt_E performance to stop?
  - Did tokamaks hit a performance limit?
  - Encounter some insurmountable instability?
  - Unknown unknown fundamental physics issue?



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PSFC

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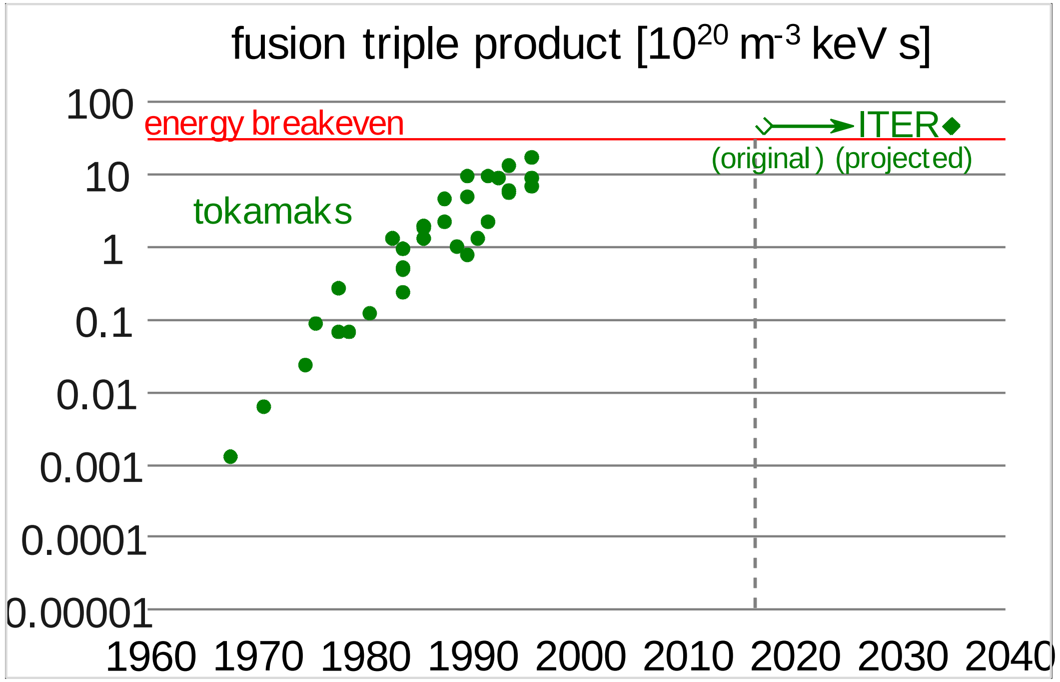
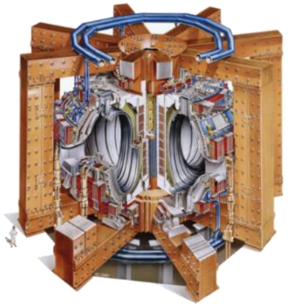
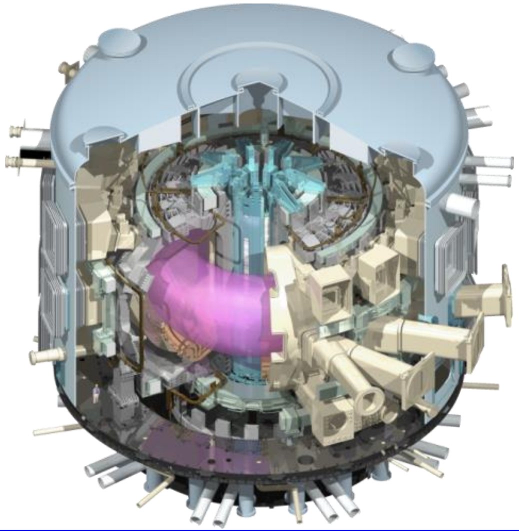
- Key question: What caused nTt_E performance to stop?
  - Did tokamaks hit a performance limit?
  - Encounter some insurmountable instability?
  - Unknown unknown fundamental physics issue?
- Answer: It stagnated due to size; it did not saturation due to any reason of physics!



JET (UK)
Peak nTt_E : 1997



This is big step

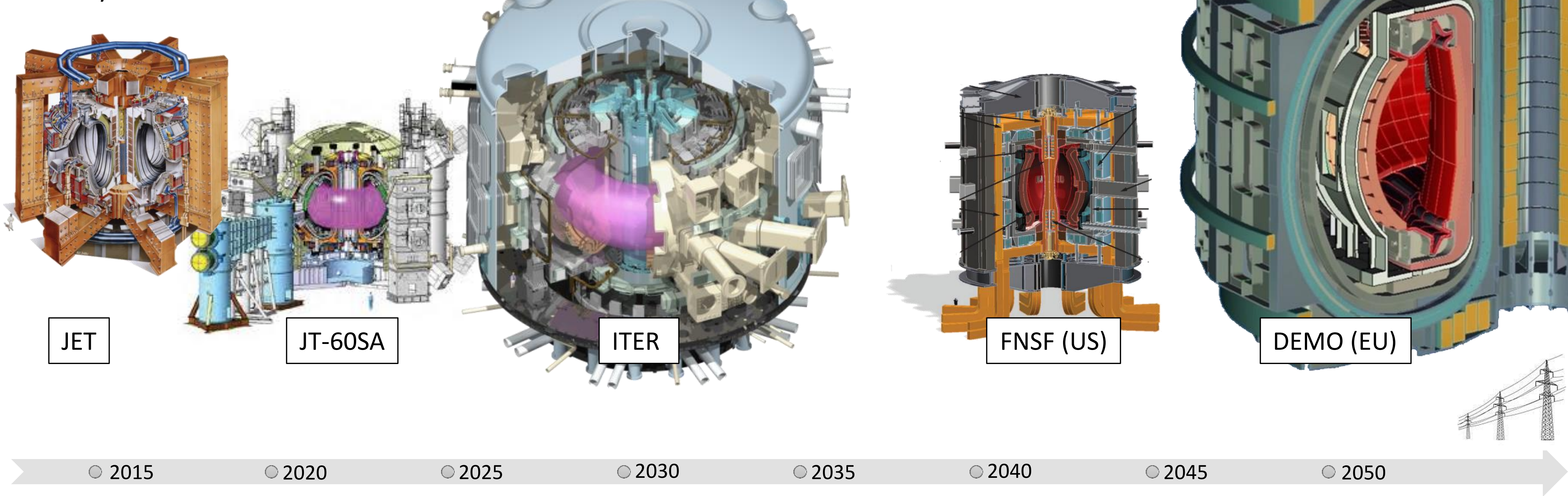


ITER (FR)
Peak nTt_E : 2040?

Human

The traditional tokamak path appears to be too big and too slow to be a credible energy source.

Approximately to scale



This graphic embodies the typical tokamak critique:

1. Tokamaks are too big
2. Tokamaks are too complex
3. Tokamaks are too slow

We completely agree and recognize that this is:

1. Caused by decisions on what tokamaks to build
2. Caused by organizational complexity at this scale
3. **Not a reason to abandon the tokamak**

Basic physics shows why increasing the magnetic field results in high fusion performance at smaller physics size

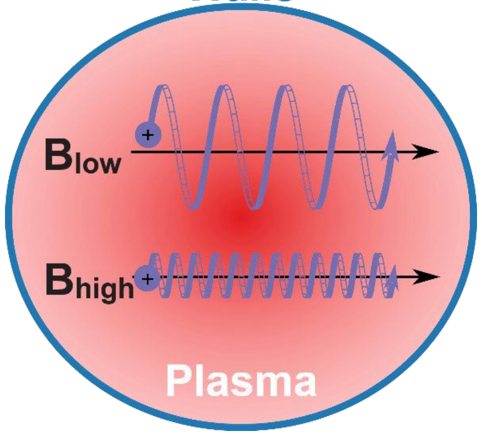
PSFC

How well a plasma is insulated via the gyro-radius:

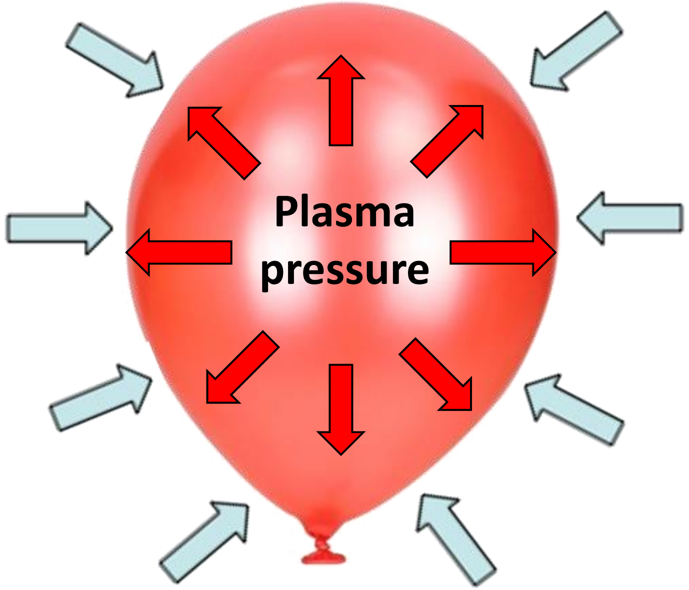
Make many of these fit inside the device → $r_{ion} \sim \frac{\sqrt{T}}{B}$

← Plasma temperature, set by fusion nuclear cross-section

← Magnetic field, set by device magnets



How stable the plasma is from MHD:



Magnetic pressure ~ B^2

How reactive the plasma is: Volumetric fusion rate ∝ (plasma pressure)^2 ∝B^4

ENERGY GAIN: (science feasibility)

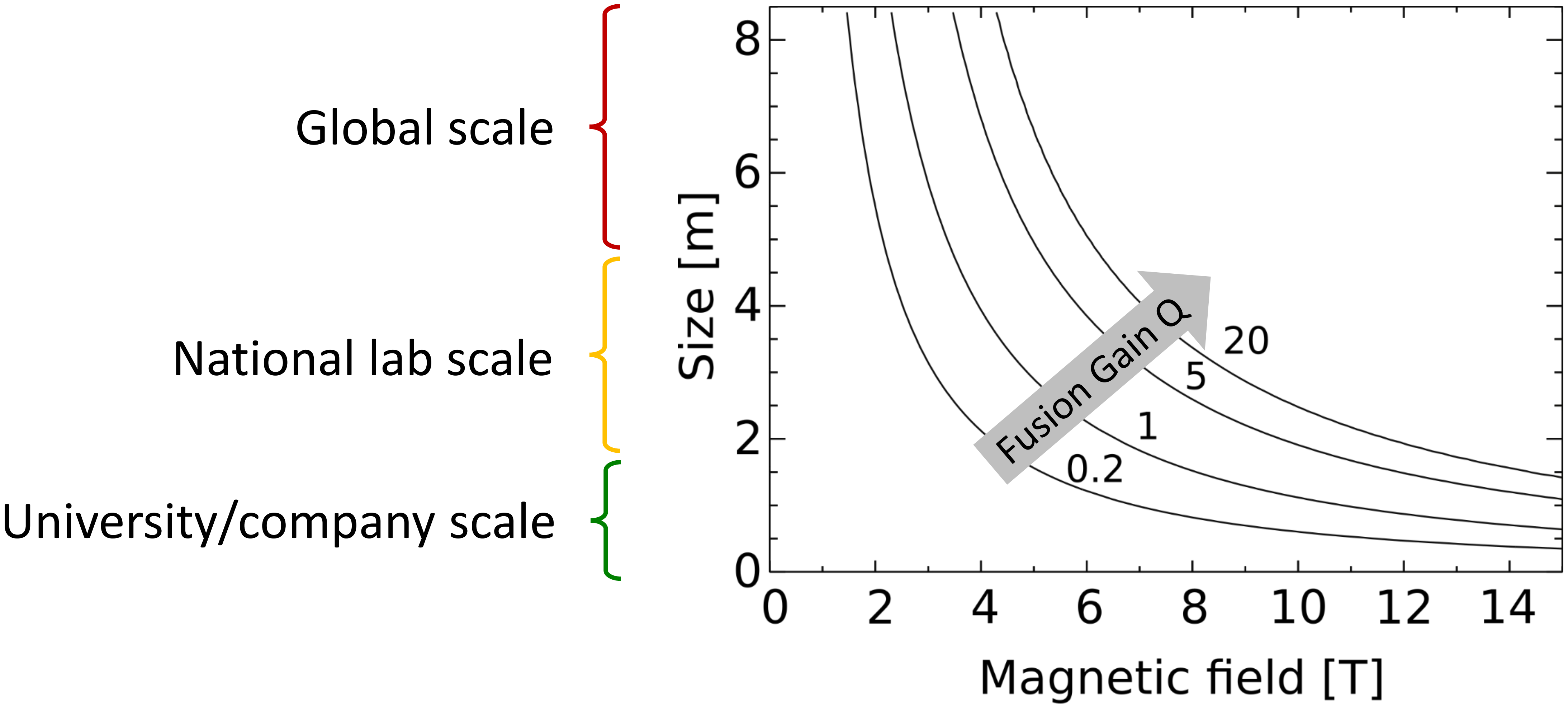
$$nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

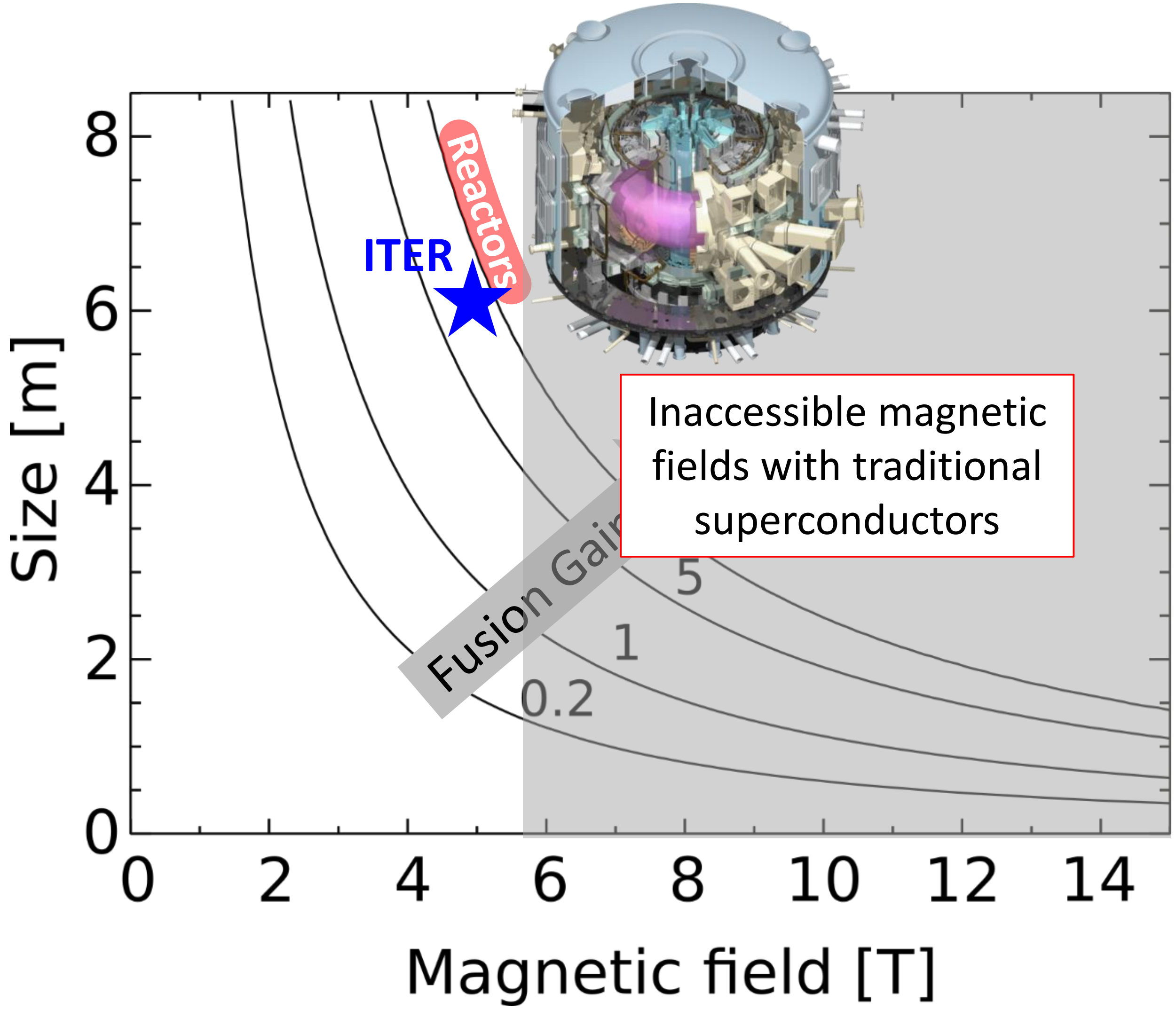
POWER DENSITY: (economics)

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

The impact of magnetic field plays a central role in determining the feasible size of a fusion device that achieves Q>1

PSFC




Size [m]
Magnetic field [T]
8
6
4
2
0
0
2
4
6
8
10
12
14
ITER
Reactors
Inaccessible magnetic fields with traditional superconductors
5
1
0.2

Recently, a completely game-changing innovation has come to industrial maturity: superconductors that enable very high field magnets

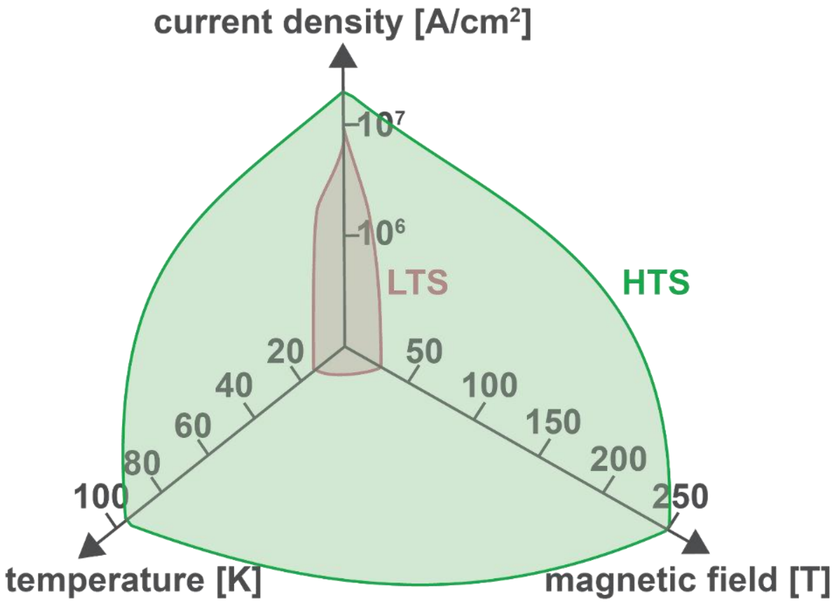
PSFC

- High-temperature superconductors (HTS) are a step-change in superconducting technology over low-temperature superconductors (LTS)
  - Construction of much higher field magnets

  ⟹ Dramatically reduce fusion size/increase performance
  - Operation at higher temperatures

  ⟹ New cryogenic options, better material properties
  - Higher current densities

  ⟹ More compact magnets with stronger structure



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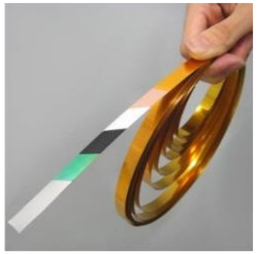
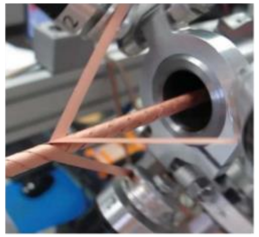
    ⇒ More compact magnets with stronger structure

- HTS has only recently become **an industrially produced** product **with sufficient performance** for use in very high-field fusion magnets

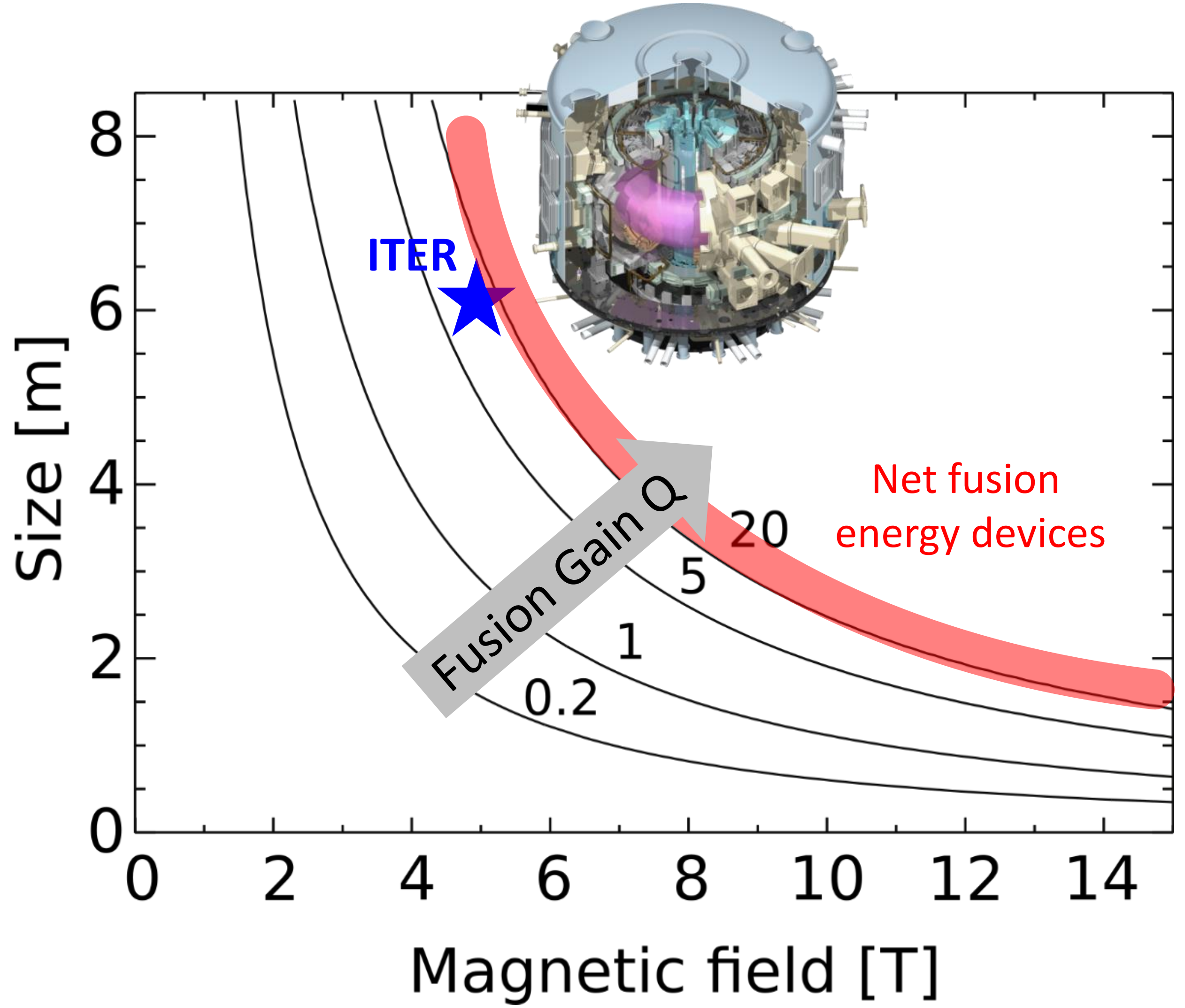

The successful construction of HTS magnets opens the path to achieving net fusion energy gain devices at significantly smaller size

PSFC

Global scale

National lab scale

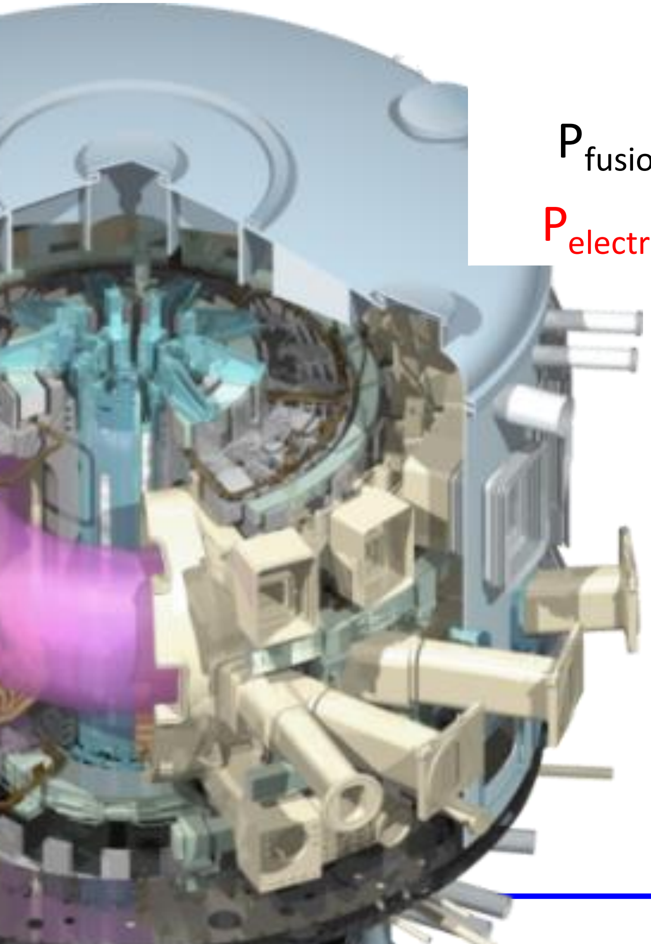
University/company scale



Higher field HTS magnets would enable ARC (a conceptual design) to produce the same fusion power as ITER in a device roughly ~10 times smaller in volume

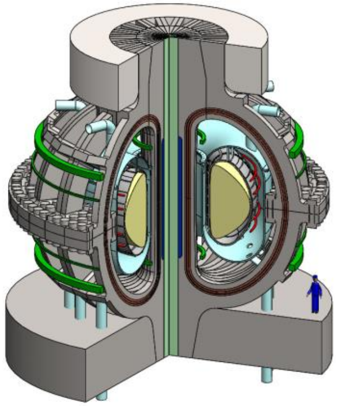
PSFC

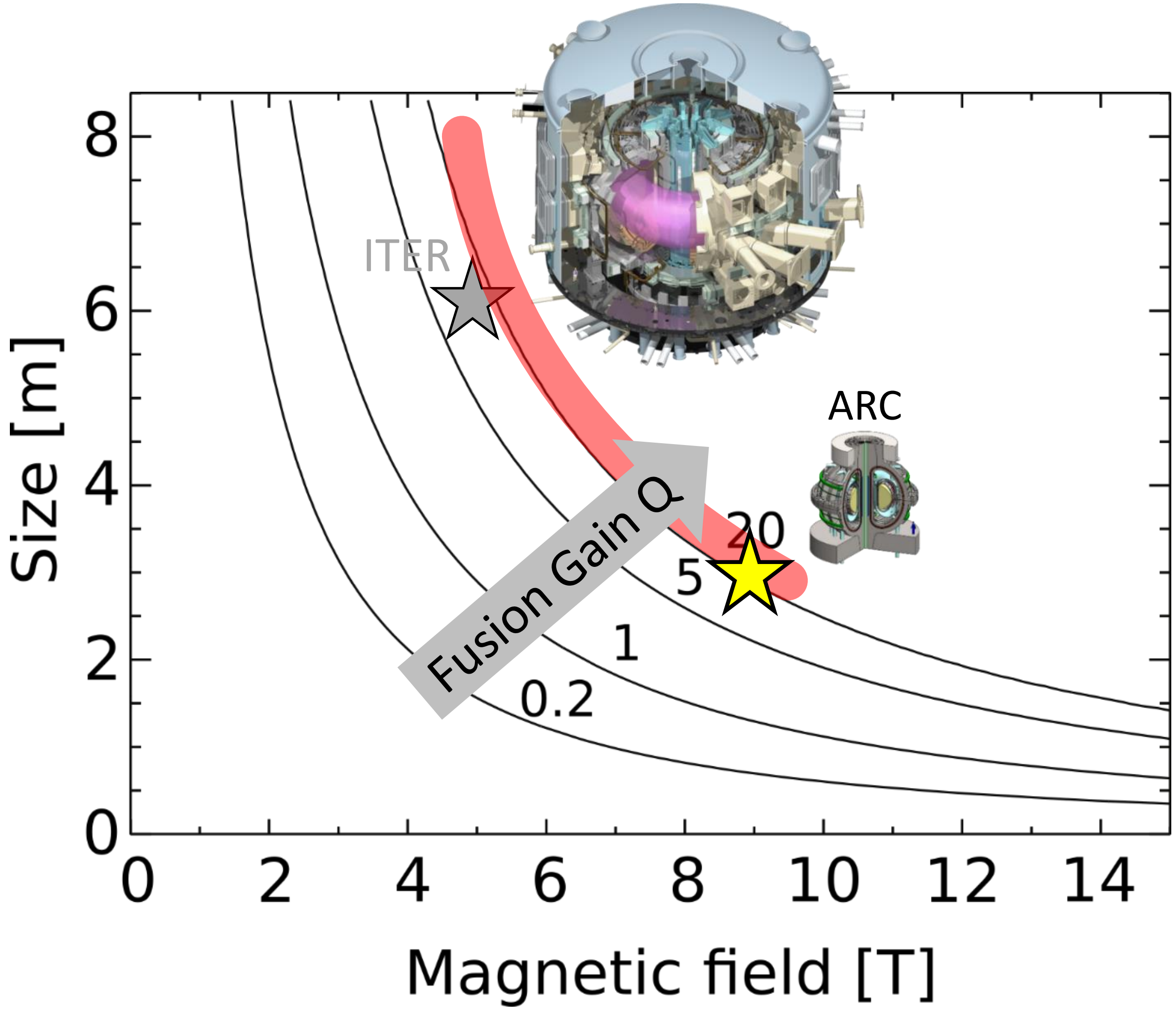
ITER



	ITER	ARC
R [m]	6.2	3.2
Magnet	LTS	HTS
B [T]	5.3	9.2
P_{fusion} [MW]	500	500
$P_{electric}$ [MW]	0	200

ARC

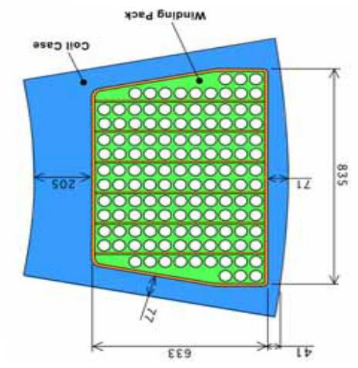




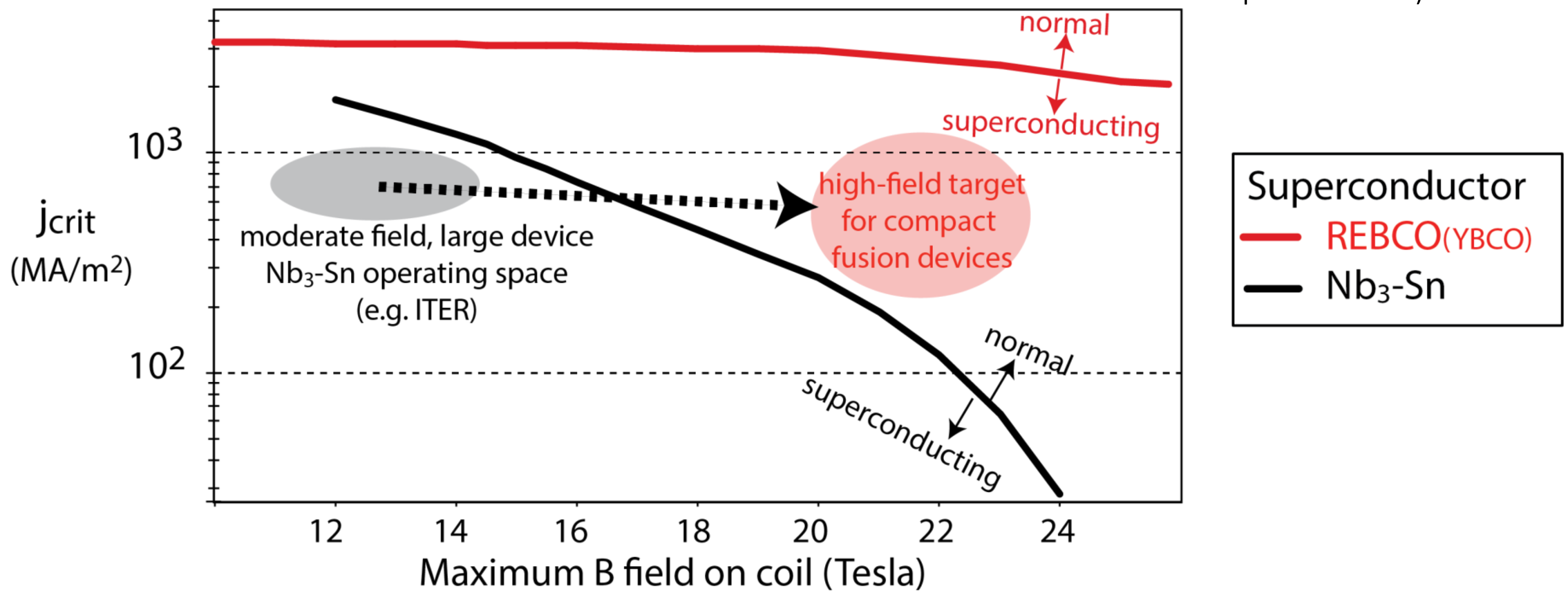
Maximum field is limited by stress limits, NOT superconducting limits

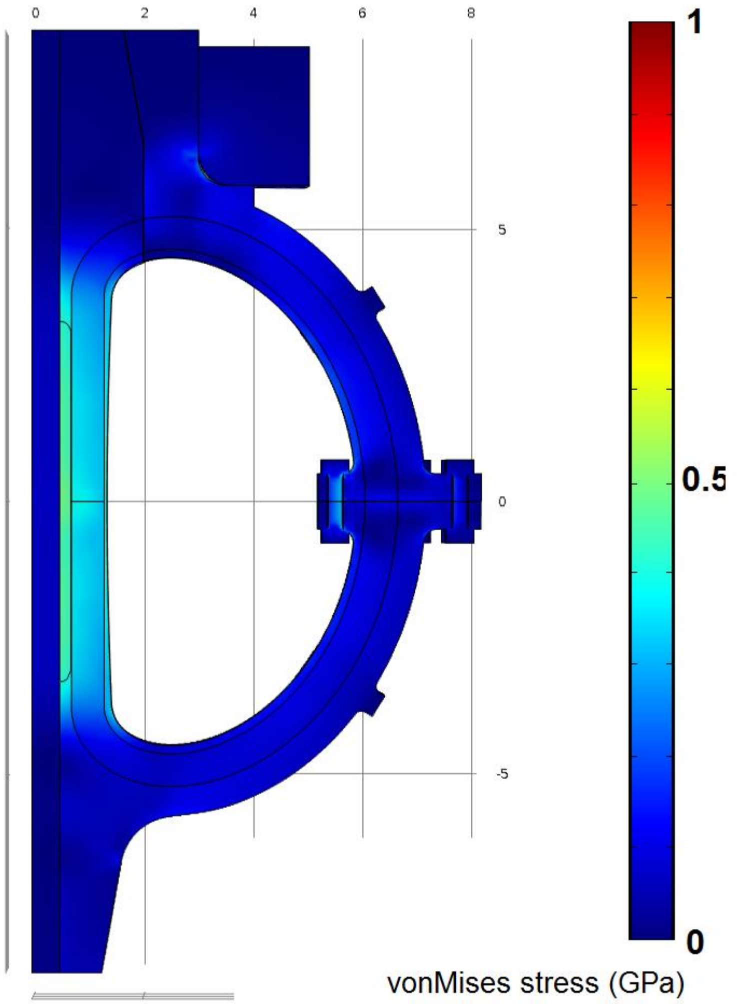
PSFC

- ARC magnet designed to operate up to ~70% of the yield stress of Inconel (1 GPa)
- HTS enables more valuable magnet real estate to be used as structure as opposed to current-carrying wire because current density is higher



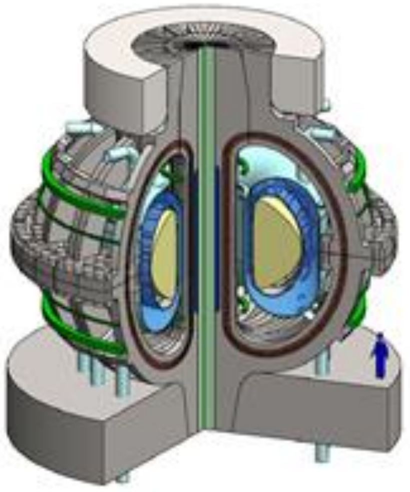
(example winding pack from ITER)

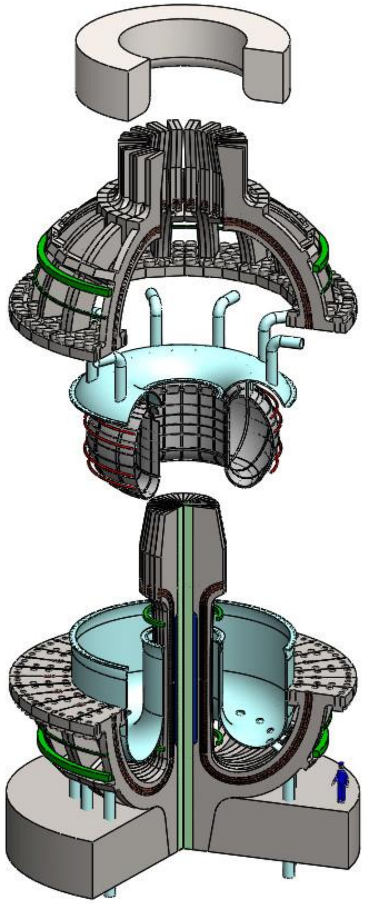




Joints allow for demountability of toroidal field magnet coils

PSFC





- Standard ITER-like reactor designs have continuous coils—maintenance is very difficult
- With joints however, reactor can be built with a nested design and be disassembled
- Demountable coils (combined with all-liquid blanket) allow ARC vacuum vessel to be a single, replaceable component
- From an experimental standpoint, many different vessel designs can be tested under reactor-relevant conditions
- Vacuum vessel will be the only activated nuclear waste produced (liquid blanket does not become activated)
- Radiation material damage limits relaxed if entire vessel can be replaced every few years

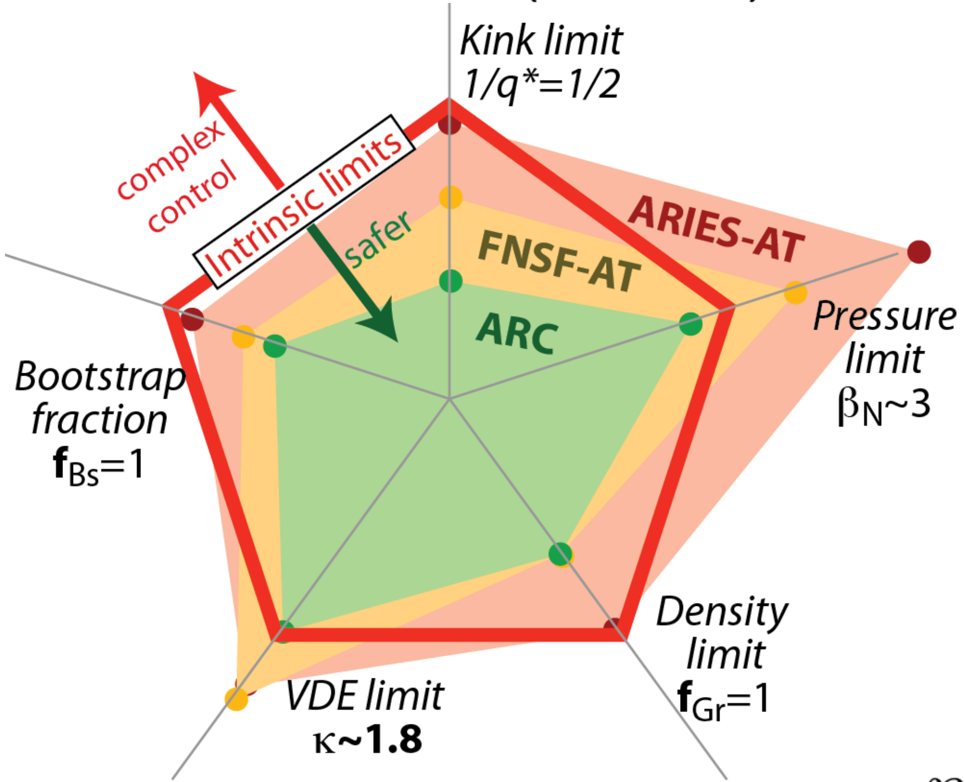
High field allows ARC to be robust to intrinsic plasma stability limits

PSFC

$$q^* = \frac{5 B_0 a \epsilon}{I_p} \left(\frac{1+\kappa^2}{2} \right) \geq 2$$

$$f_{bs} = 0.04 \frac{\beta_N q_a}{\sqrt{\epsilon}}$$

$$\beta_N \equiv \frac{a B_0}{I_p} \beta_T \leq 3$$

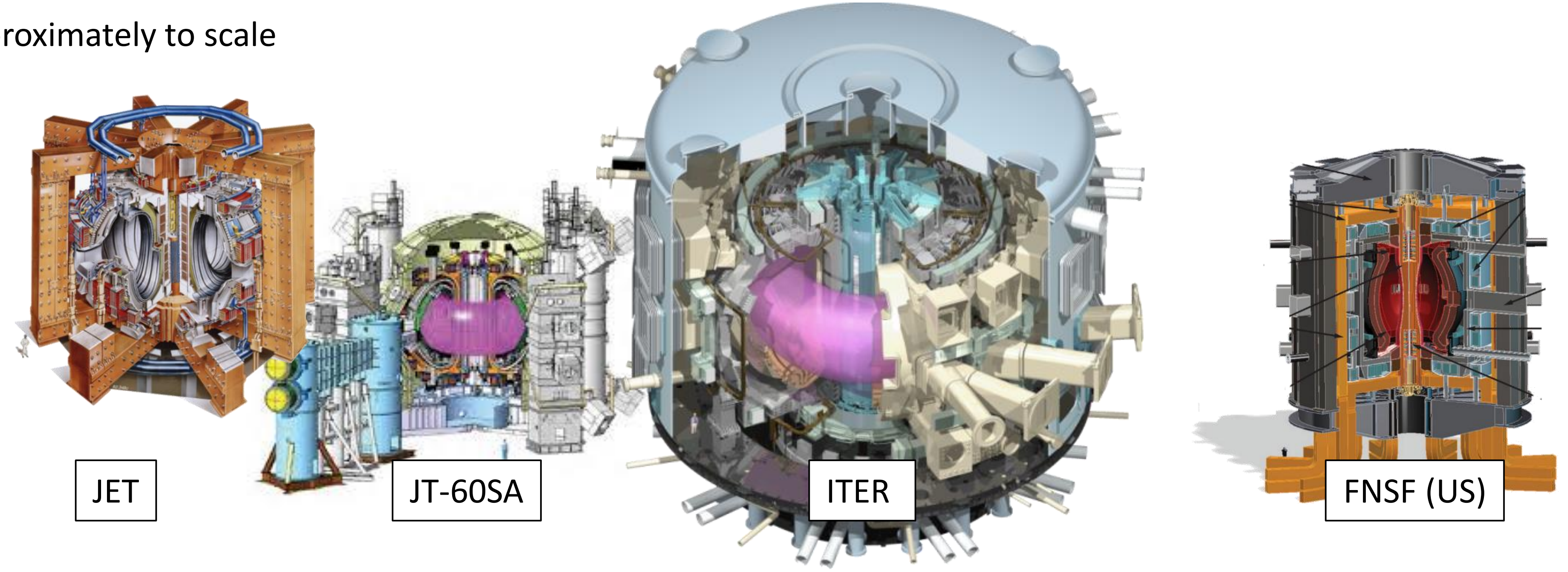


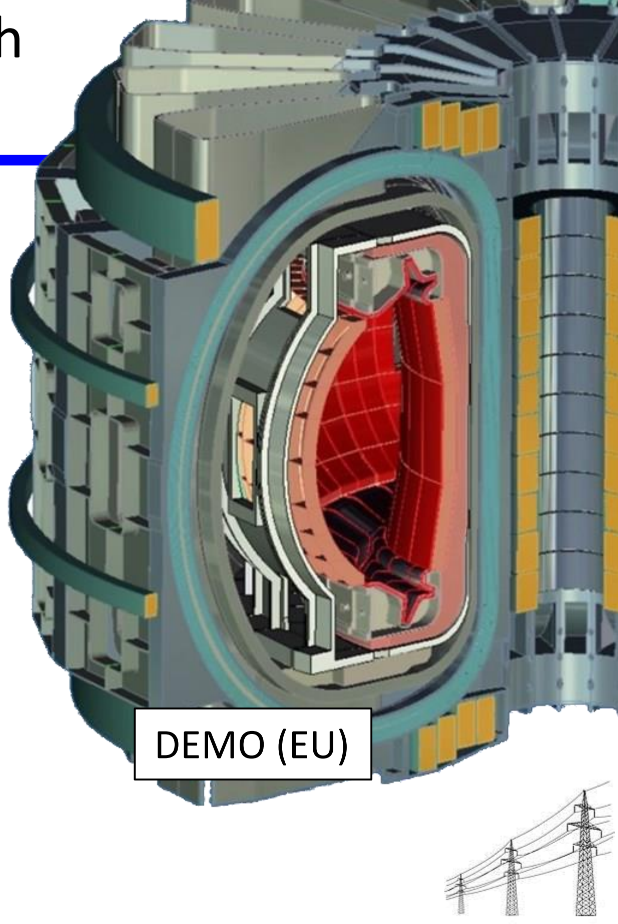
$$\kappa \lesssim 5.4\epsilon$$

$$n_{20} < \frac{I_p}{\pi a^2}$$

The PSFC is combining the superior physics performance of the tokamak with game-changing magnet technology to accelerator the path to fusion energy

Approximately to scale





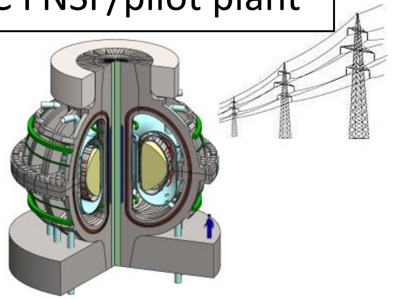
Tokamaks without HTS: Moderate field, large size

2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050

Tokamaks with HTS: High field, small size

C-Mod

ARC FNSF/pilot plant



Higher field → Smaller size → Lower cost →
Easier to try → Faster to learn →
Faster to burn → Faster to earn →
Faster to make a difference