Introduction to fusion plasma physics

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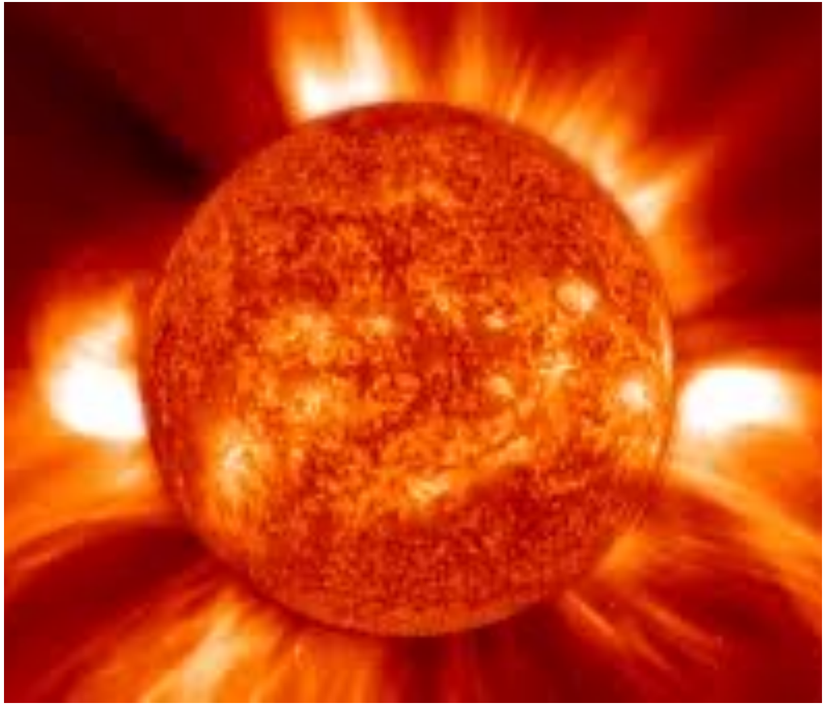
In the 1920-30's it was realized that the sun and stars make their energy by fusing hydrogen, thus creating all elements

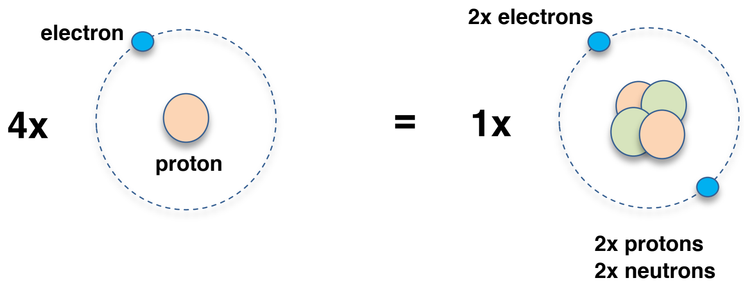


Mother Nature knows how to make fusion work

- F. W. Aston measurements
  - $m_{hydrogen}$ = 1.00794 atomic mass units (amu)
  - m_{helium} = 4.0026 amu
- Arthur Eddington conjecture (1920)
  - Aston experiments imply all elements are constituted out of hydrogen atoms bound together
- George Gamow (1928)
  - Derived probability formula for nuclear reaction, the "Gamow Factor"
- Hans Bethe (1939)
  - Stellar Nucleosynthesis
    - proton-proton chain
    - carbon-nitrogen-oxygen cycle

The relationship of Einstein's $E=mc^2$ formula to fusion

Eddington idea: Helium is made in the sun/stars by combining 4 hydrogen atoms



But the masses don't add up ...
There's a difference ("mass deficit"): $4 \times 1.00794 - 4.0026 = 0.029$ amu $= 4.87 \times 10^{-29}$ kg

"Binding Energy" $E = 4.4 \times 10^{-12}$ Joules

1 kg then gives 7×10^{14} Joules of energy

18,000 × average US household yearly energy use

Instead of doing fusion atom-by-atom, we utilize an ionized ”gas” of atoms – a state of matter called a plasma

Four states of matter

Solid

e.g. ice

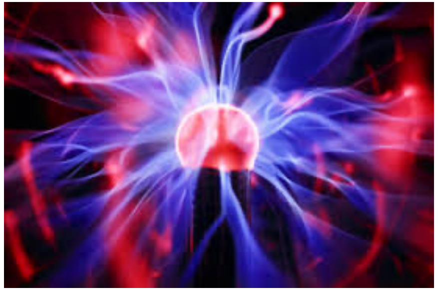
Liquid

e.g. water

Gas

e.g. steam

Plasma

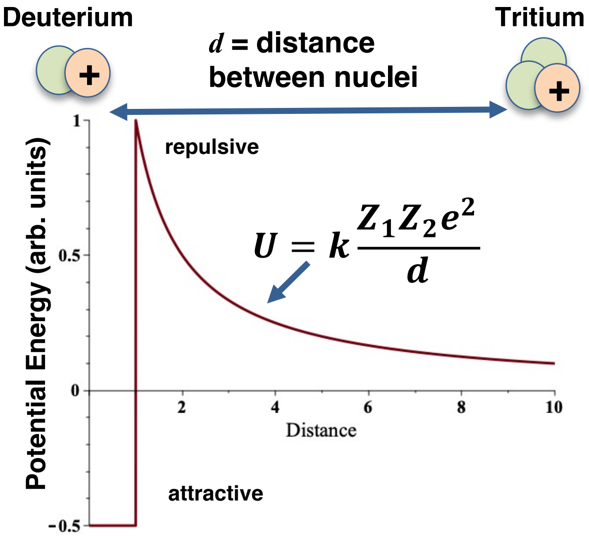


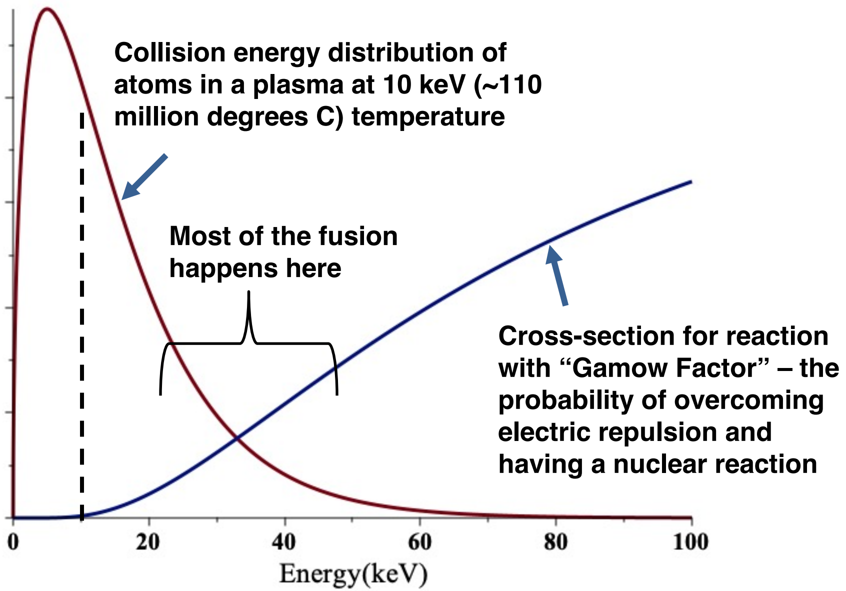
e.g. electrical discharge into a gas

Increasing energy and temperature
Increasing disorder of atoms

All hot fusion schemes involve a plasma at some stage because a high inter-atom kinetic energy is needed to overcome repulsion

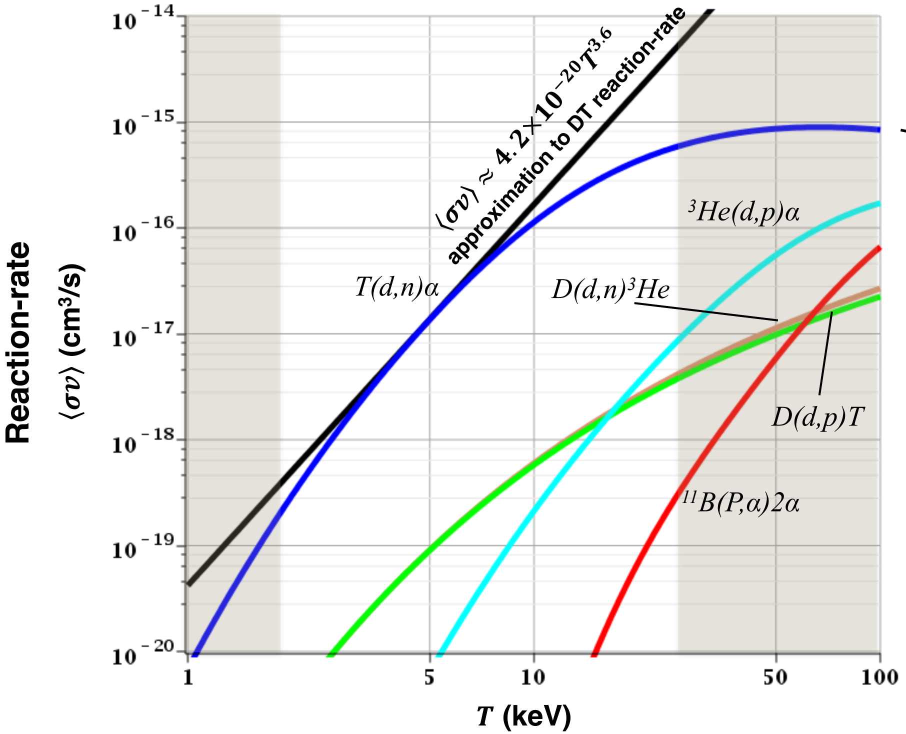
The electron repulsion of positively charged nuclei needs to be overcome for fusion to occur



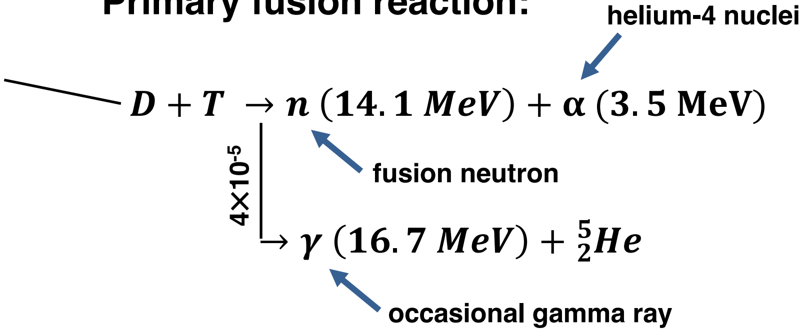


The energy "cost" of electric repulsion is why fusion favors isotopes of hydrogen, rather than atoms higher up on the periodic table (higher atomic number, Z)

Solar fusion reactions using H too slow for terrestrial use, so most efforts on Earth concentrate on hydrogen isotopes deuterium (D) & tritium (T)



Primary fusion reaction:



$$D + T \rightarrow n\,(14.1\,MeV) + \alpha\,(3.5\,\mathrm{MeV})$$

$$\rightarrow \gamma\,(16.7\,MeV) + {}^{5}_{2}He$$

Advantages:

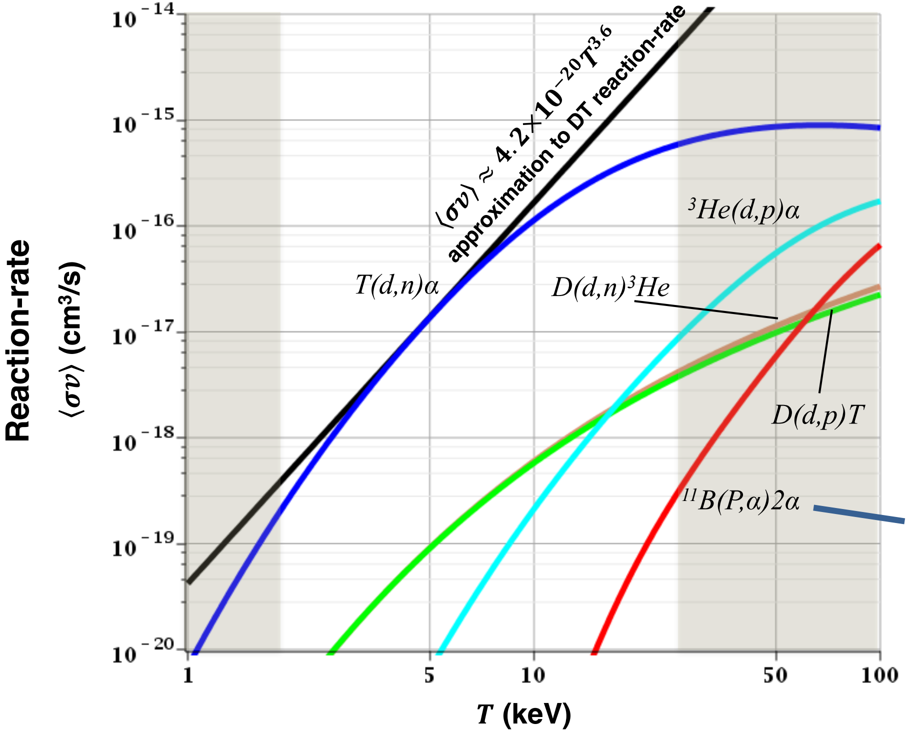
- Peak in reaction-rate at lowest temperature
- *D* plentiful in sea-water

Disadvantages:

- *T* radioactive (12-year half-life)
- *T* must be made from $n + {}^{6}_{3}Li$ reaction
- neutron causes problems

1 eV = 11,600 Kelvin = 11,327 C = 20,420 F

Other known fusion reactions require significantly higher temperatures (and therefore energy input) to work

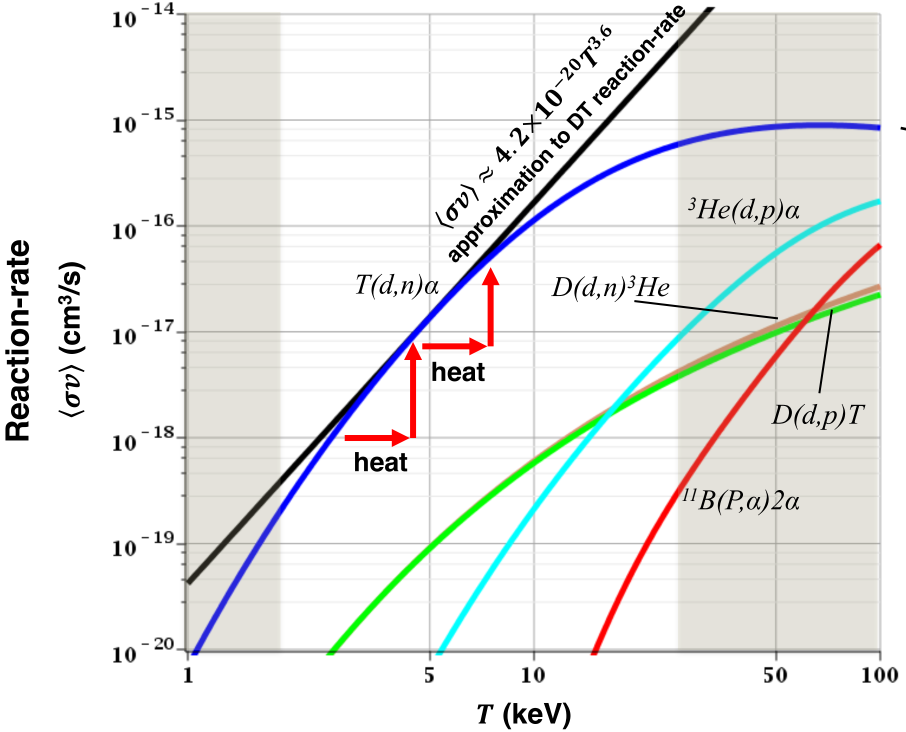


These are interesting for experimental science, but they don't make sense (presently) for fusion energy purposes

"p-Boron" aka "HB11" – is an a-neutronic reaction, but it's far less reactive than DT and generates less fusion energy per reaction

1 eV = 11,600 Kelvin = 11,327 C = 20,420 F

The neutron leaves the fusion plasma and is how we get the heat out to generate electricity, but if we can stop the alpha-particle from leaving things get interesting



Primary fusion reaction:

helium-4 nuclei

$$D + T \rightarrow n\,(14.1\,MeV) + \alpha\,(3.5\,\text{MeV})$$

fusion neutron

If we can stop the alpha-particle inside the fusion region, we can get "self-heating" a.k.a. "alpha-heating"

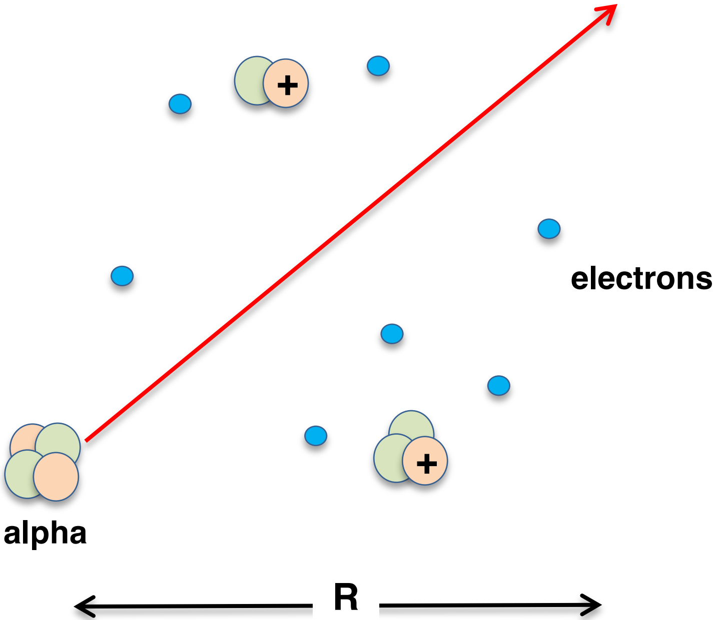
Lawson "ignition" criterion:

- a condition on plasma pressure, temperature, and time
- means fusion heating power > cooling

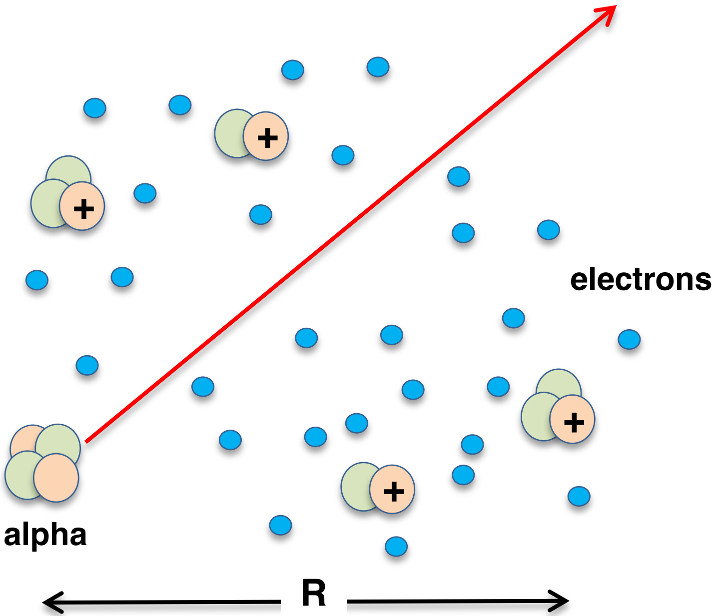
1 eV = 11,600 Kelvin = 11,327 C = 20,420 F

There are two ways to increase the probability of an alpha particle leaving its energy inside the plasma: size (R) and/or density (ρ)

Low ρR
(low chance of interaction)



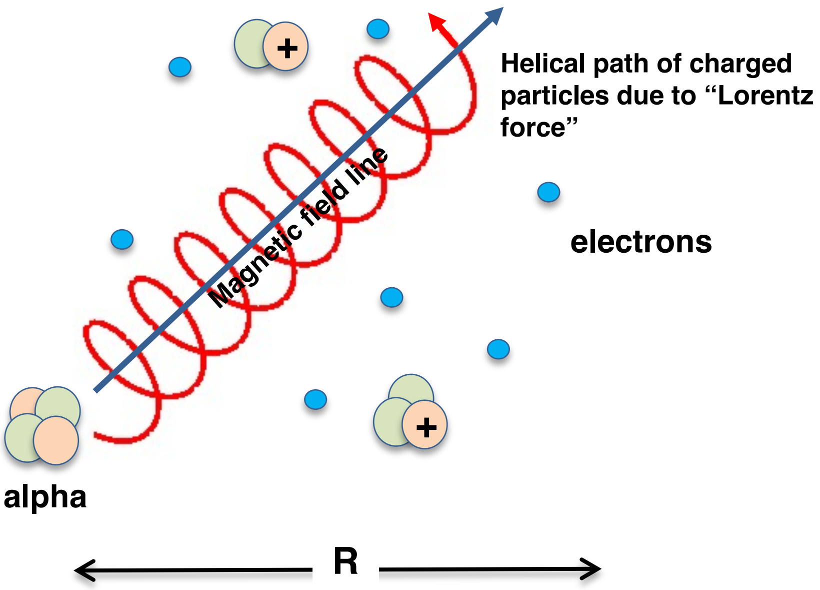
High ρR
(high chance of interaction)



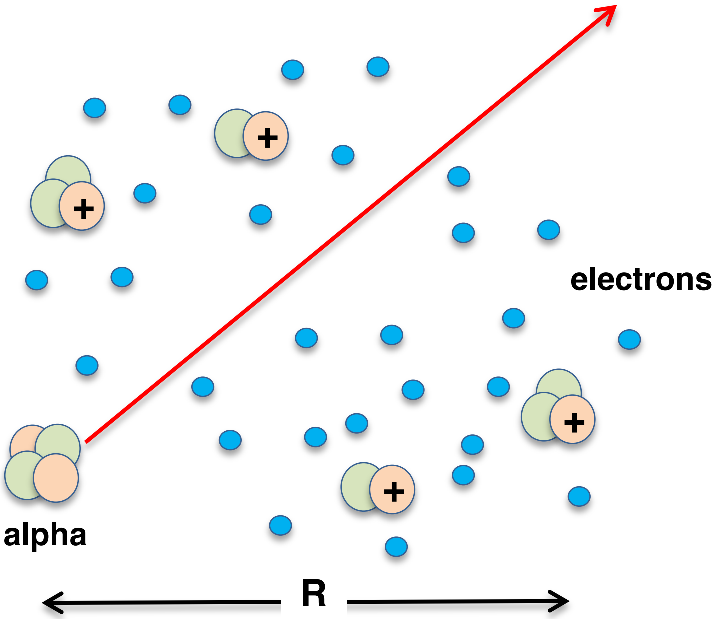
But density has a consequence on pressure

There are two ways to increase the probability of an alpha particle leaving its energy inside the plasma: size (R) and/or density (ρ)

Longer path length with magnetic field (higher chance of interaction)



High ρR (high chance of interaction)



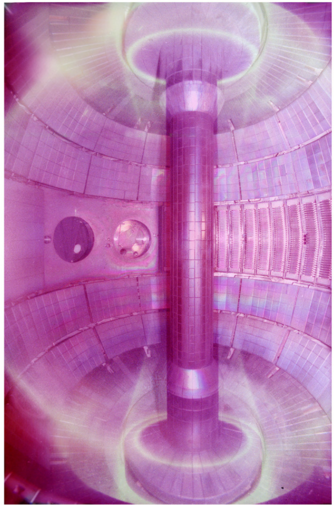
But density has a consequence on pressure

DT plasma at fusion temperatures have significant pressure, so some confinement scheme is needed to hold onto them

Ideal gas law applies to hot DT plasma:

$$p(Mbar) = 770\rho(g/cm^3)T(keV)$$

Plasma @ 0.001 g/cc & 10 keV	~ 7.7 Mbar!
Pressure at sea level	~1 bar ~ 1 atm
Yield strength of 6061 Al	55 MPa ~ 550 bar
Yield strength of 304 stainless	205 MPa ~ 2 kbar
High explosive pressure	100's kbar



NSTX device at Princeton Plasma Physics Lab

Faced with a choice:

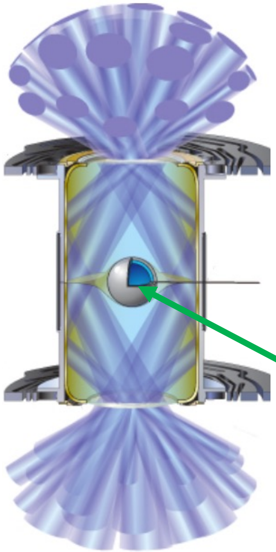
- **Work with a very low-density plasma that can be confined in a pressure vessel (magnetic fusion)**
- **Or work with a high-density plasma that explodes (inertial confinement fusion)**

The choice of confinement method leads to much different looking configurations that function differently, but the Lawson parameter goal is about the same

Inertial Confinement Fusion (impulsive)

Target that is "shot" and destroyed in the process

1 cm

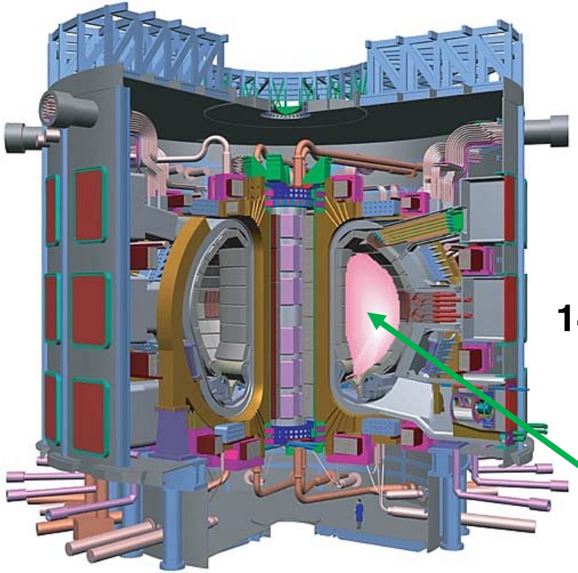


Tiny volume, of cryogenic DT fuel that forms ultra-high-density plasma during shot

P ~ 4 x 10^{11} atmospheres
T ~ 10 keV
$\tau \sim 10^{-10}$ seconds

Magnetic Confinement Fusion (quasi-steady state)

Vessel that operates in a quasi-steady state



14 m

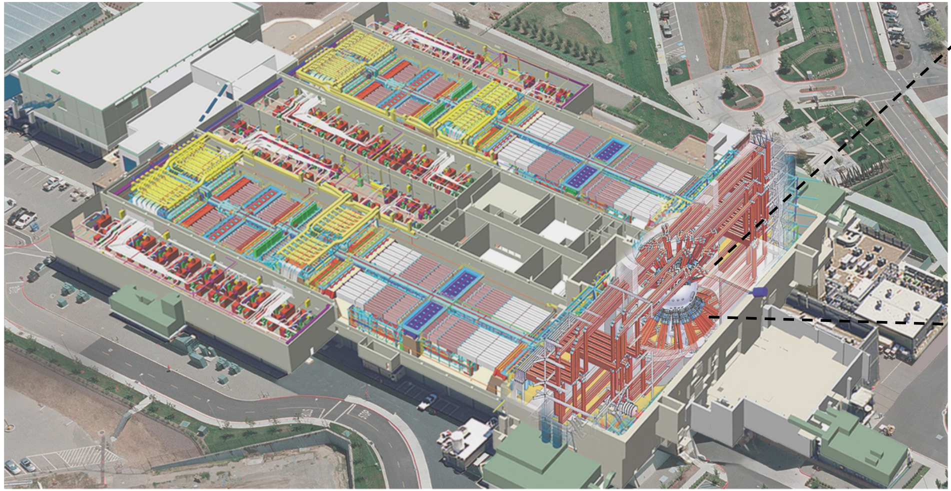
Large volume, low density plasma

P ~ 7 atmospheres
T ~ 20 keV
τ ~ many seconds

1 eV = 11,600 Kelvin = 11,327 C = 20,420 F

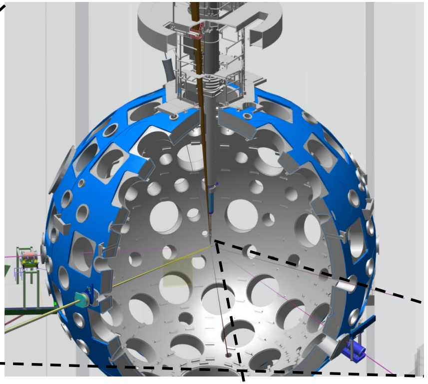
While ICF targets are small, the machines that drive them to fusion conditions are large

National Ignition Facility (NIF)



300-400 MJ of electrical energy in capacitor banks in a facility the size of 3 football fields

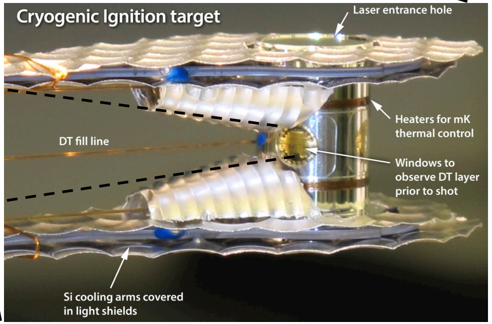
Target chamber cut-away



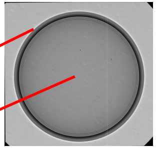
1-2 MJ of laser energy to target

scale ~ 10 m (diameter)

scale ~ 1 cm



Capsule with fusion fuel inside



scale ~ 2mm

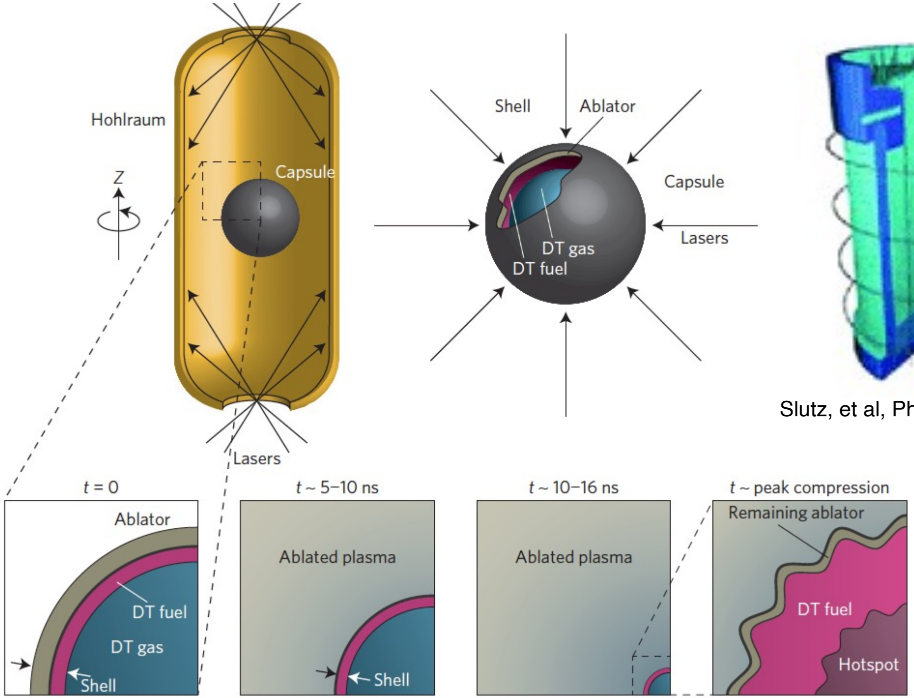
200 kJ of energy absorbed by capsule surface

20 kJ of energy absorbed by DT fuel inside

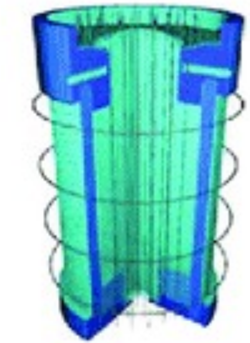
Energy is “traded” for energy-density (pressure)

ICF schemes use an implosion in a small target to obtain the needed fusion conditions in fusion fuel

Indirect Drive | **Direct Drive** | **Magnetic Drive** | **"Fast" ignition**

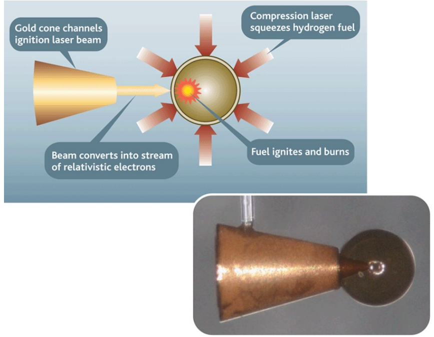


Betti & Hurricane, Nature Phys. (2016)



Slutz, et al, Phys. Plasmas (2018)

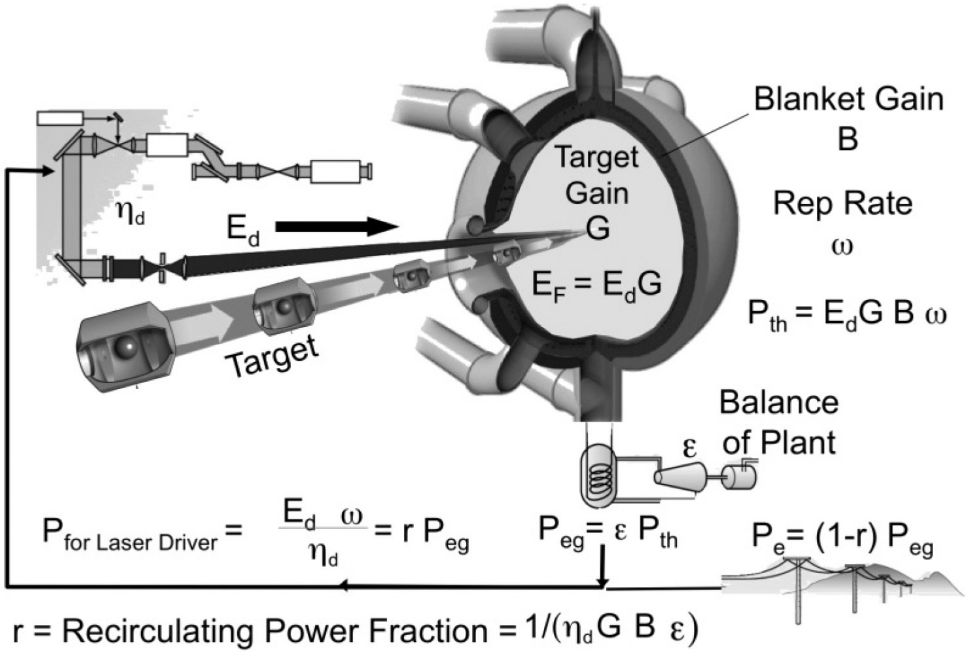
Science, Vol. 310 (5754), pp. 1610-11 (2005)



Compression & heating are separated

All result in a "micro-explosion" of fusion energy

The NIF facility is a national security research facility, so *hypothetical* inertial fusion energy (IFE) reactors would have additional complications



Storm and Lindl, Chapter 4 in "Energy in the nucleus," 2015

Needs, yet solved:

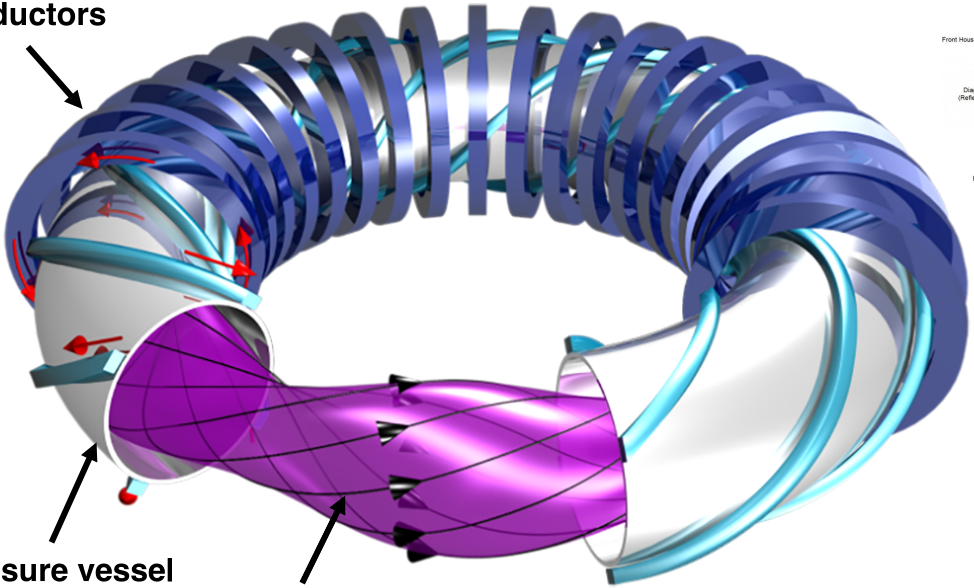
- Demonstration of target with high enough energy gain (G) for this to make sense (G ~ 0.7 demonstrated, >40 needed)
- High rep-rate (many times per second) target injector system
- Targets that could survive the injector system
- Target that are economical to build
- A target factory that turns out the targets
- A high power and energy laser (or pulsed power system) that could be fired at high rep-rate without destroying itself

Advantage is that targets are independent of facility

Magnetic fusion confinement devices have different complications

“Tokamak”

Current carrying conductors



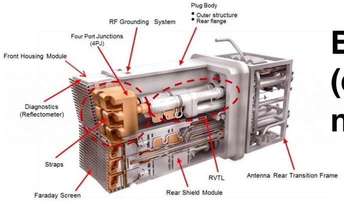
Pressure vessel wall made with refractory metal

Plasma “held” in equilibrium with magnetic field

$$\nabla P = -\frac{\nabla B^2}{2} + \vec{B} \cdot \nabla \vec{B}$$

magnetic pressure force

magnetic curvature force

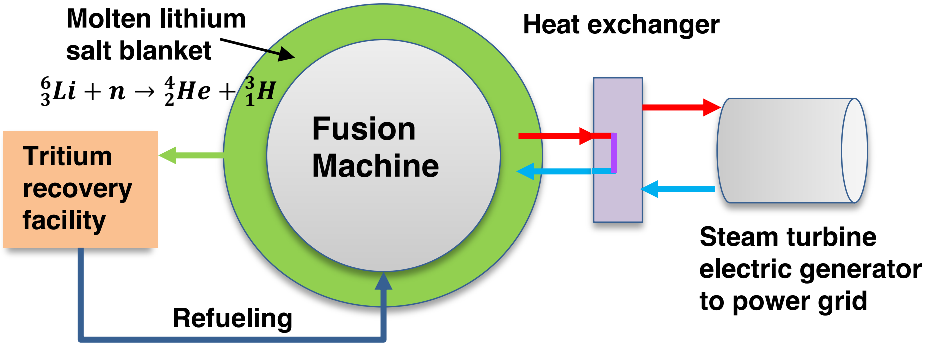


External heating scheme (e.g. radio-frequency, neutral beam, etc.)

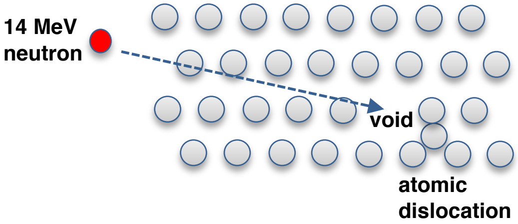
- Q (fusion power out/power input to plasma) ~ 0.7 demonstrated, Q > 10 needed
- Ability to maintain plasma equilibrium determined by β (beta=plasma pressure/magnetic pressure) stability limit
- Fusion power limited by β
- High electro-magnetic mechanical stresses on device → disruption can break device
- Very high heat load on wall of device

Challenges common to all DT fusion approaches

- At present, we have fusion experiments, not "reactors"
- Creating the necessary conditions of pressure, temperature, and confinement time is difficult
- For energy production, fusion energy out not only needs to be greater than fusion energy into the plasma, but considerably greater than that used to run the machine (usually 10-100 x more)
- Tritium breeding in lithium blanket needs to be an integrated part of the device
- Neutron damage to metals of device eventually destroys the device and creates low-level radioactive waste
- Tritium and neutrons are an ES&H (environment, safety, & health) as well as regulatory issue

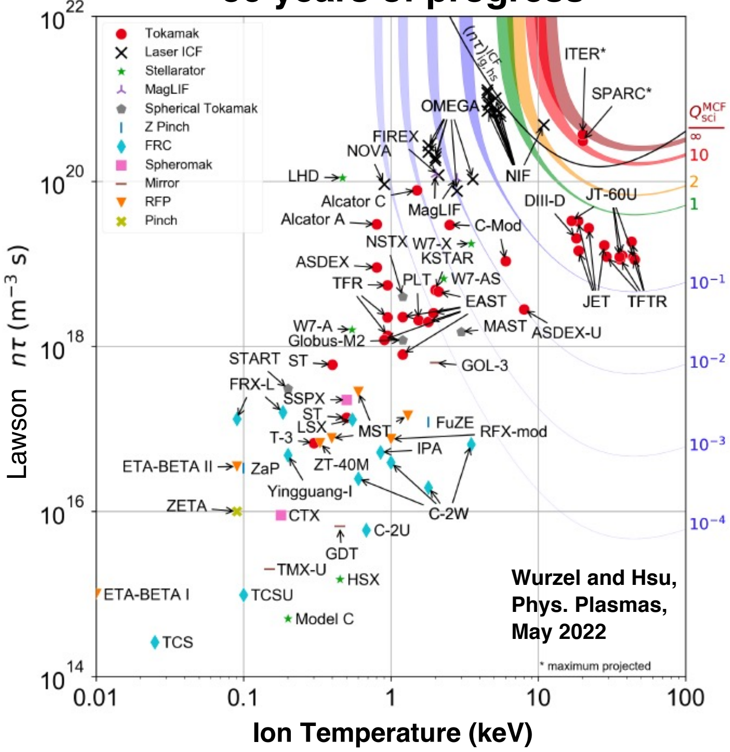


Neutron damage turns crystal lattice to "swiss cheese"



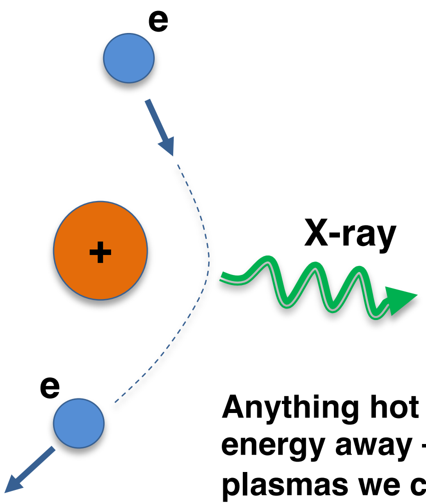
Despite challenges, there has been steady progress towards in fusion research over many decades

~50 years of progress

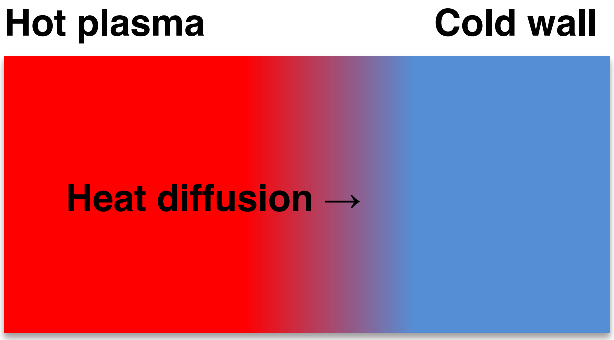


- There are many ways to make fusion and today there are a plethora of concepts that have been tried
- Each concept has its own pro's and con's (no magic bullet)
- Fusion is still in a research phase, but the engineering needed for "useful" fusion energy is coming into focus
- This past year, an existence proof of laboratory ignition has been demonstrated and record levels of fusion energy have been reported (still < input energy)
- Many challenges remain ... are all the problems solvable?

Mother Nature tries to cool off any plasma we try and make hot via the processes of x-ray emission and thermal conduction



Anything hot radiates energy away – in plasmas we call this "Bremsstrahlung" emission



Usually in the form of electron conduction in plasmas

These processes set limits on minimum operating temperature, plasma impurity concentration, plasma surface to volume ratio, materials used, etc.