Nuclear Fusion

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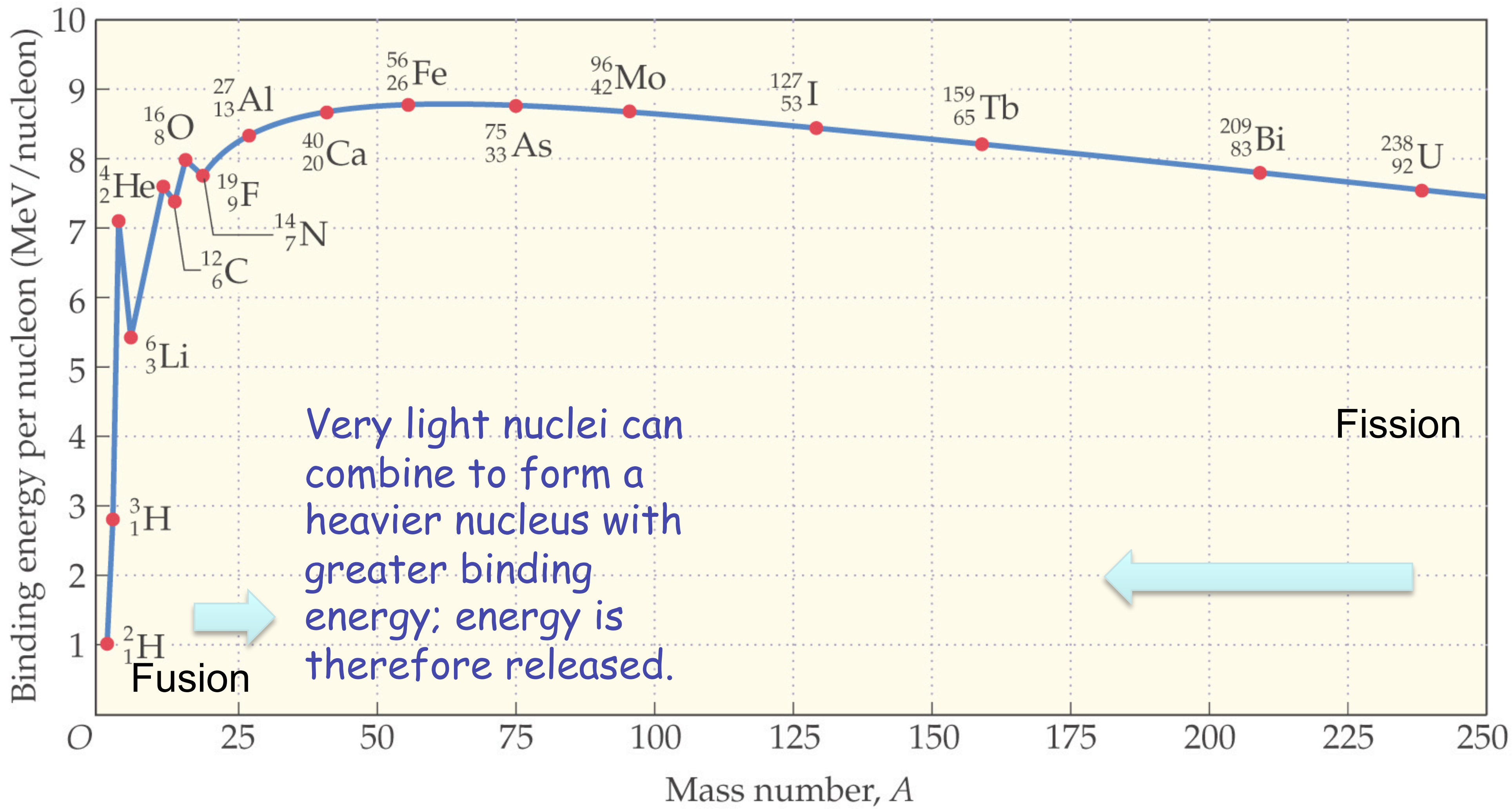


MeV is a unit of energy: 1 MeV = 1.6×10^{-13} J

Energy released in fission is ~ 1 MeV per nucleon (neutron or proton)

Energy released in fusion is ~ 3 MeV per nucleon

Fusion provides more energy per mass

Nuclear Fusion: Energy source of choice for the stars (and the universe)

The nuclear fusion process in the Sun begins with two protons fusing to form deuterium, and then fusing with a third proton to form helium-3.

$$
\begin{aligned}
{}^1_1\mathrm{H} + {}^1_1\mathrm{H} &\longrightarrow {}^2_1\mathrm{H} + \mathrm{e}^+ + \nu_\mathrm{e} \\
{}^1_1\mathrm{H} + {}^2_1\mathrm{H} &\longrightarrow {}^3_2\mathrm{He} + \gamma
\end{aligned}
$$

After that, a helium-4 nucleus is formed in one of the following two ways:

$$
\begin{aligned}
{}^1_1\mathrm{H} + {}^3_2\mathrm{He} &\longrightarrow {}^4_2\mathrm{He} + \mathrm{e}^+ + \nu_\mathrm{e} \\
{}^3_2\mathrm{He} + {}^3_2\mathrm{He} &\longrightarrow {}^4_2\mathrm{He} + {}^1_1\mathrm{H} + {}^1_1\mathrm{H}
\end{aligned}
$$

This is called the proton proton cycle: the net result is four protons getting together to produce a Helium nucleus (an alpha particle), two positrons, two neutrinos and lots of energy (26.7 MeV)

Nuclear Fusion

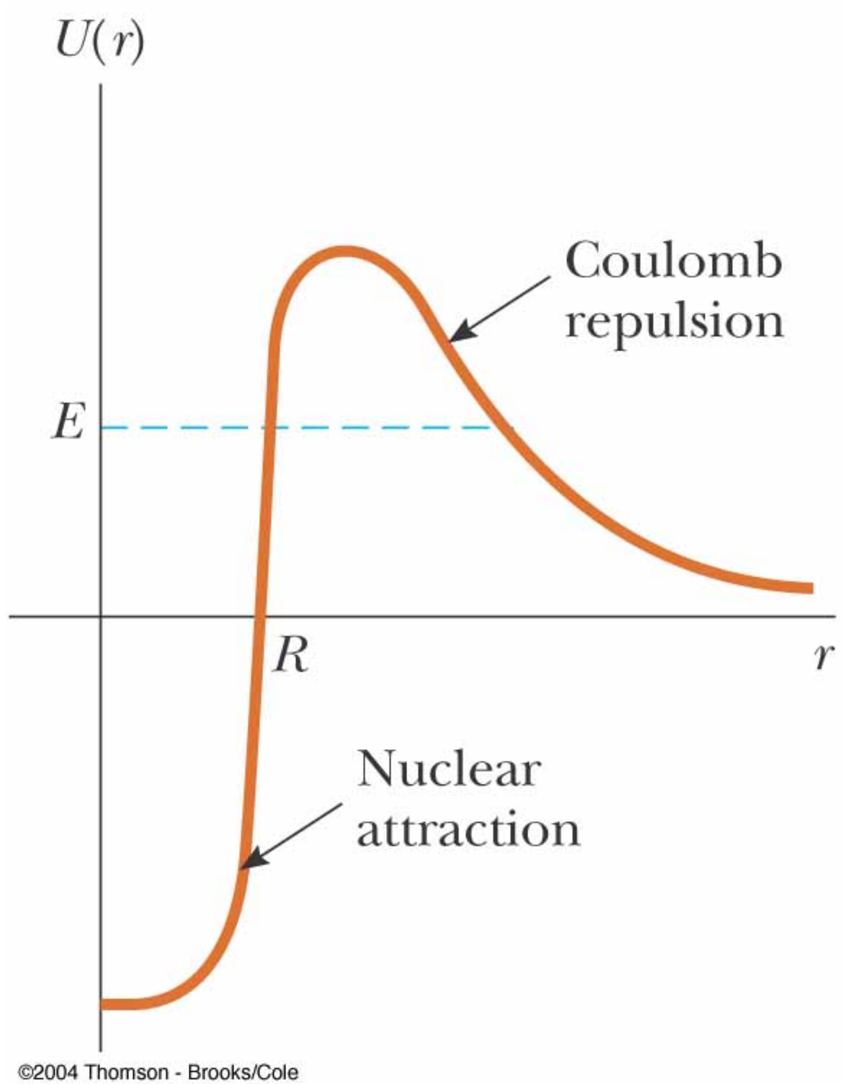
- Higher energy output compared to fission
- Fuel readily available
- Runaway accidents are not possible
- Fewer radio-active waste

So what is the problem ?

Electro-static repulsion between protons: requires very high temperature and pressure to overcome this :

No problem for the sun and stars: interior T ~ 15 MK, and extremely high proton densities.

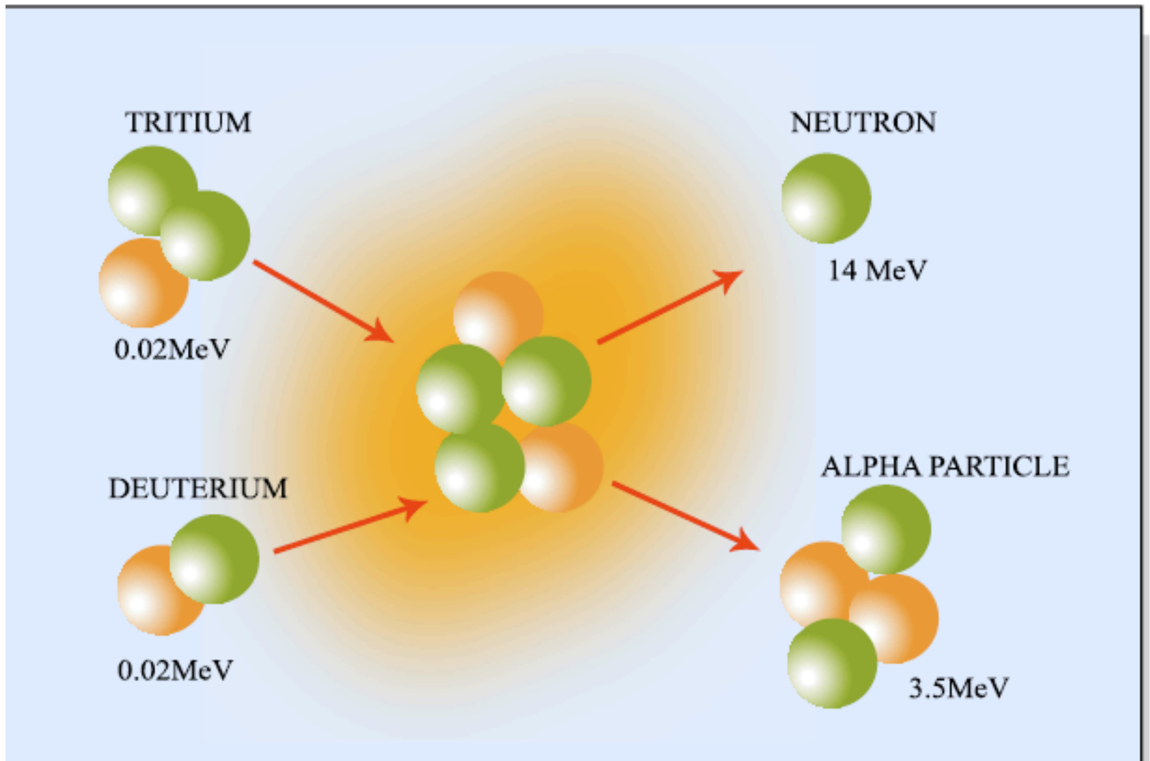
At these temperatures, electrons are ripped out of atoms; a hot plasma of positive and negative charges floating around.



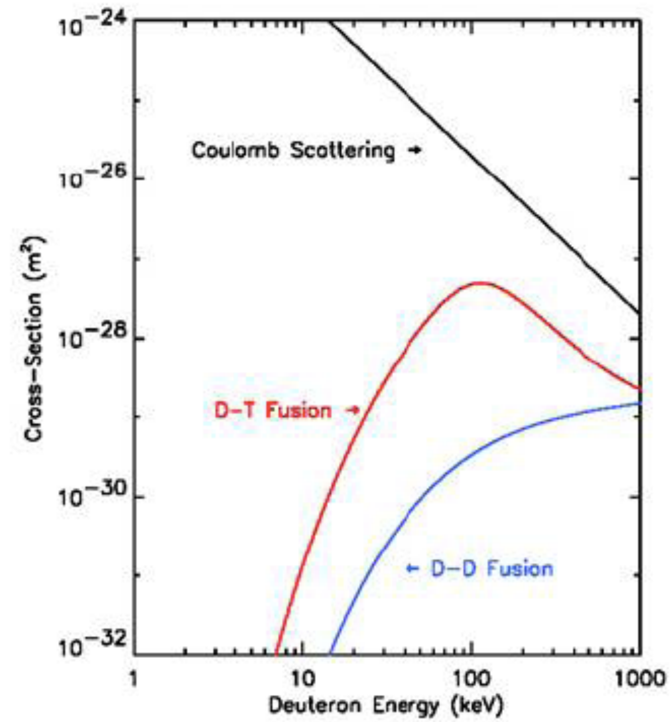
The strongly attractive nuclear force between nucleons has a very short range (~ 10^{-15} m.) , where the electric (Colomb) repulsion between protons is a long range force. The the nuclei need to have enough energy to overcome the repulsion to come close enough for the nuclear force to come into effect for fusion

Nuclear Fusion Reactors

Very light nuclei can combine to form a heavier nucleus with greater binding energy; energy is therefore released. This can only occur at extremely high temperatures, as the nuclei must be moving fast enough to overcome the electrical repulsion.



- If D and T ions manage to touch then the nuclear force takes over and turns $D + T \Rightarrow He(3.5MeV) + n(14.1MeV)$



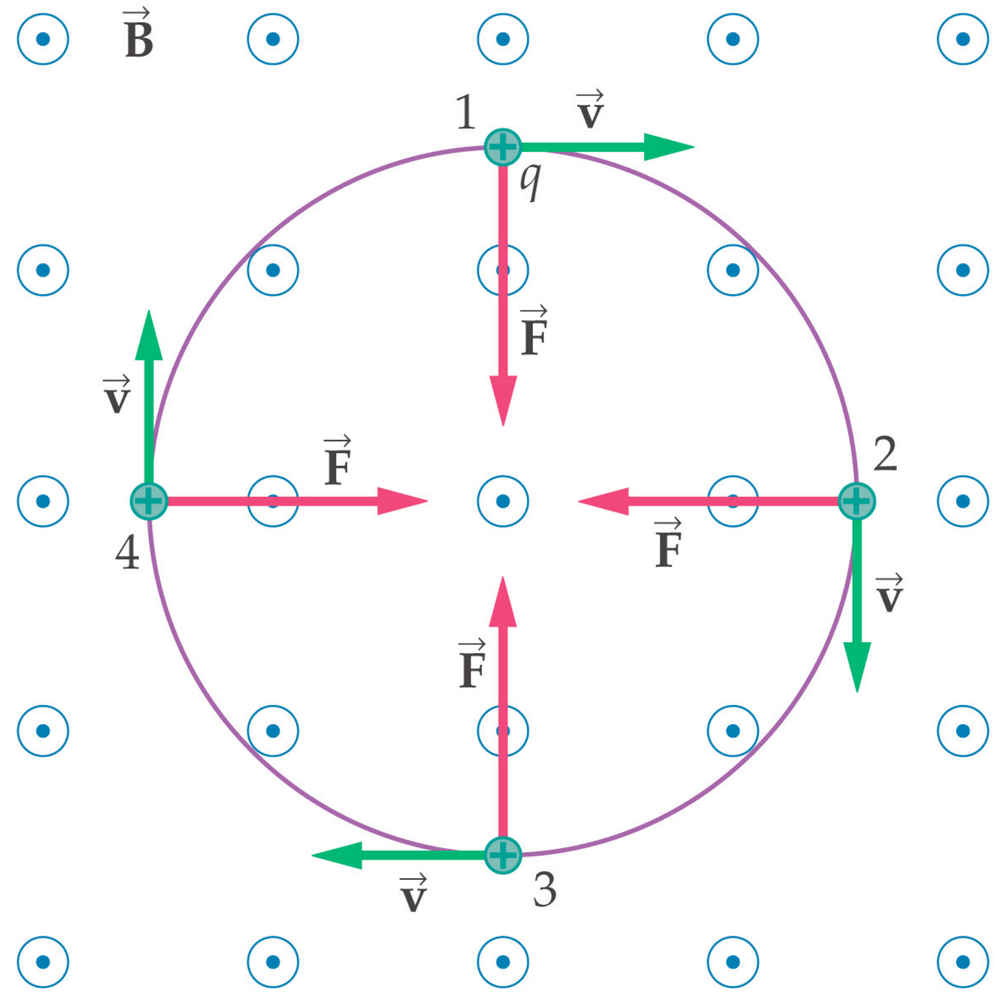
Optimum T_i ~ 20 keV ~ 230 million K

Gases fully ionized: PLASMA

But how do we confine a 230 Million K plasma?

Charge particles are susceptible to E&M fields...Magnetic Confinement..

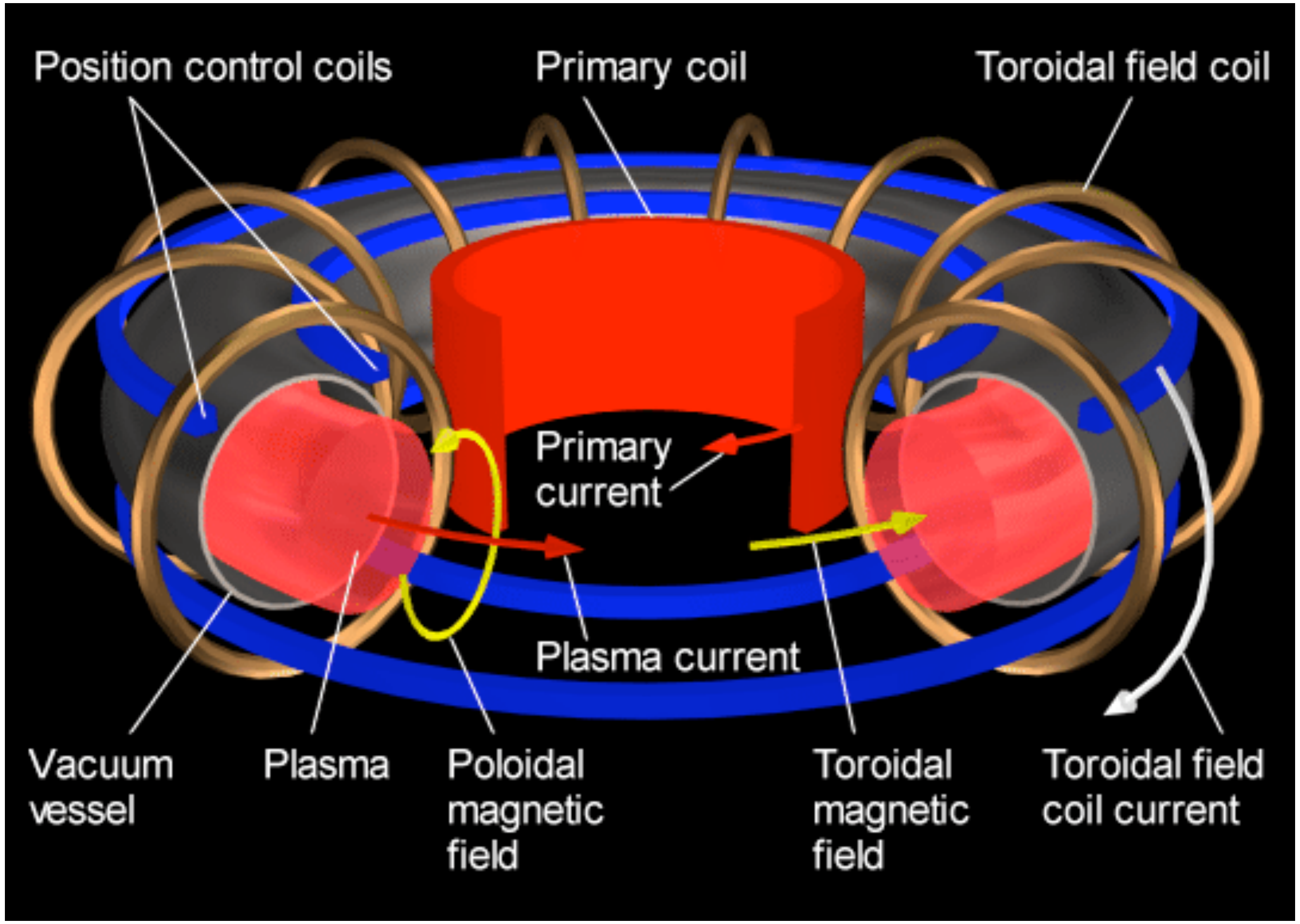
A charged particle moving in a magnetic field perpendicular to its velocity, experiences a force which perpendicular to both velocity and the magnetic field (in the figure the magnetic field is coming out of the page).



Since the force is always perpendicular to the velocity, the particle will travel in a circular path

This principal is used to create a "magnetic bottle" to contain the hot plasma.

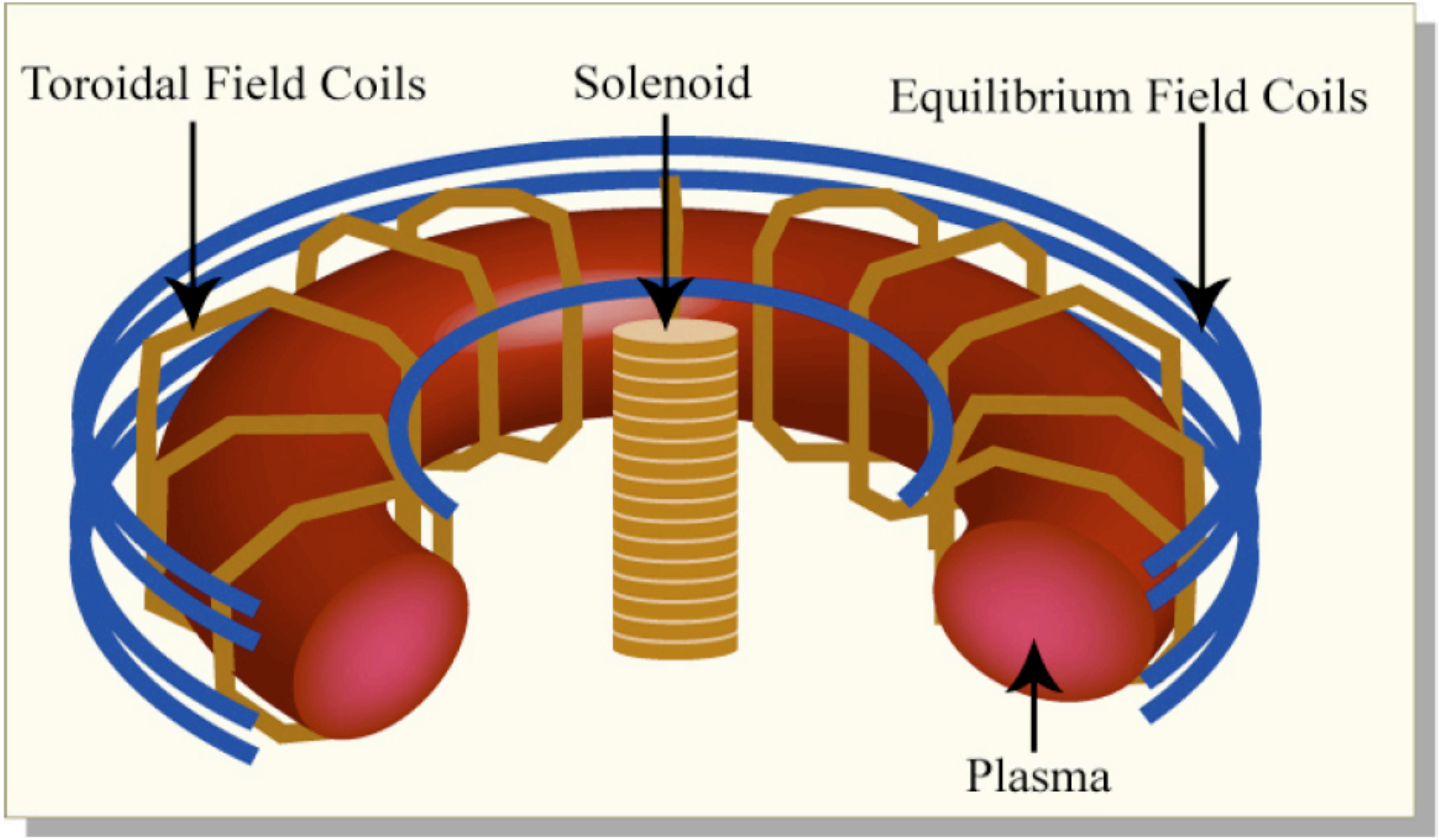
Magnetic Confinement of Hot Plasma



In addition to the very high T required, high plasma densities and long enough confinement times are requires: currently achieved times ~ 1 s.

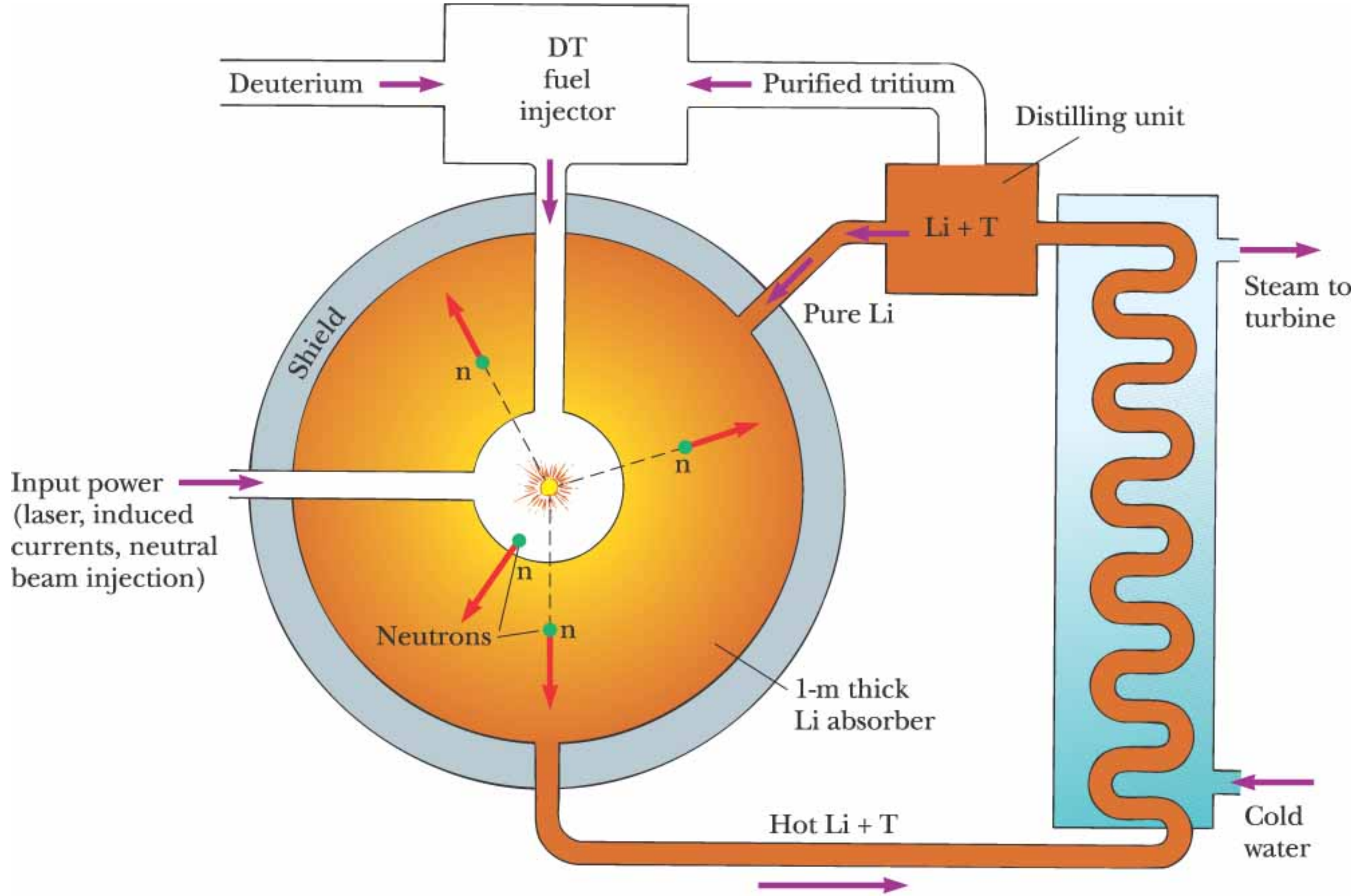
Magnetic Confinement of Hot Plasma

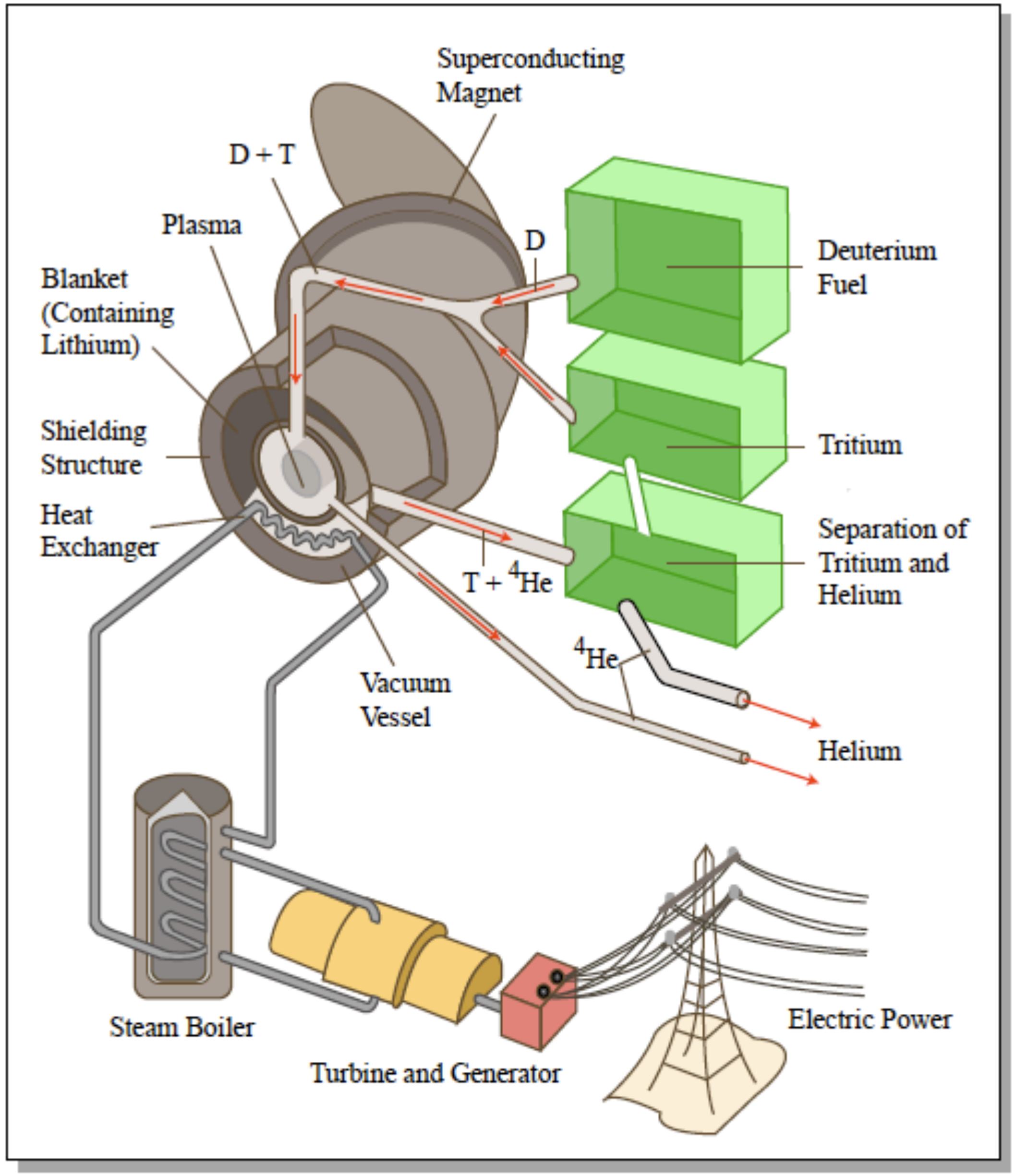
Tokamak Coils



Problem #2: How to take the thermal energy out?

- When the fusion reaction starts going, the alpha particles stop in the core and contribute to maintain the core temperature
- But the neutron, carrying most of the energy, come out
- Question is: how to stop these neutrons before they escape taking the energy with them and creating a radiation hazard ?
- two birds with one stone: Li blanket for heat absorption and breeding of T.


DT
fuel
injector
Deuterium
Purified tritium
Distilling unit
Li + T
Pure Li
Steam to
turbine
Shield
n
n
Input power
(laser, induced
currents, neutral
beam injection)
n
Neutrons
n
1-m thick
Li absorber
Hot Li + T
Cold
water



•In steady-state, the energy from the fusion reactions are radiated to the first wall and blanket.

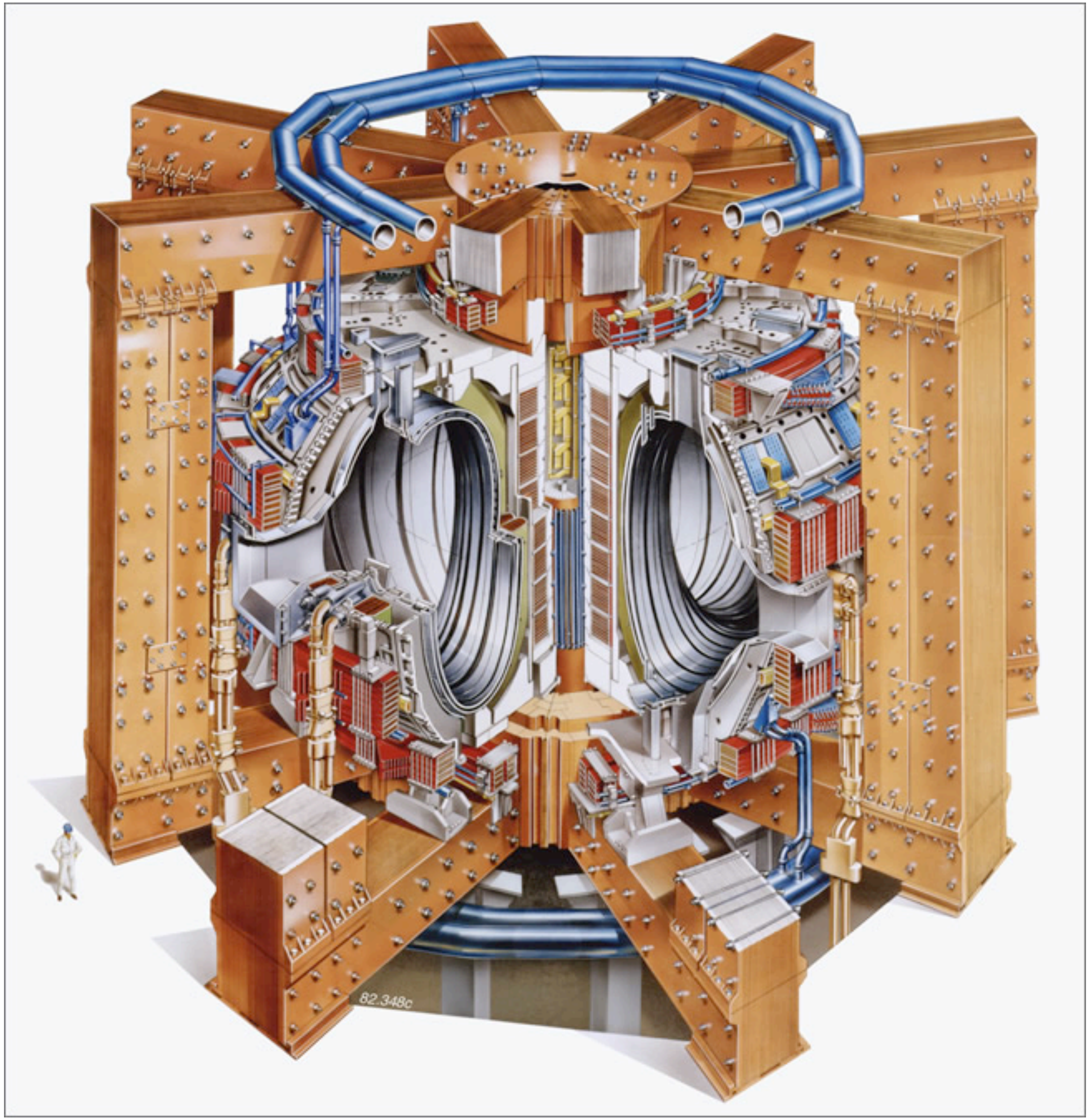
•Tritium is not available naturally but can be readily bred with lithium.

•The 14.1MeV neutron is absorbed into a blanket containing lithium in order to breed tritium.

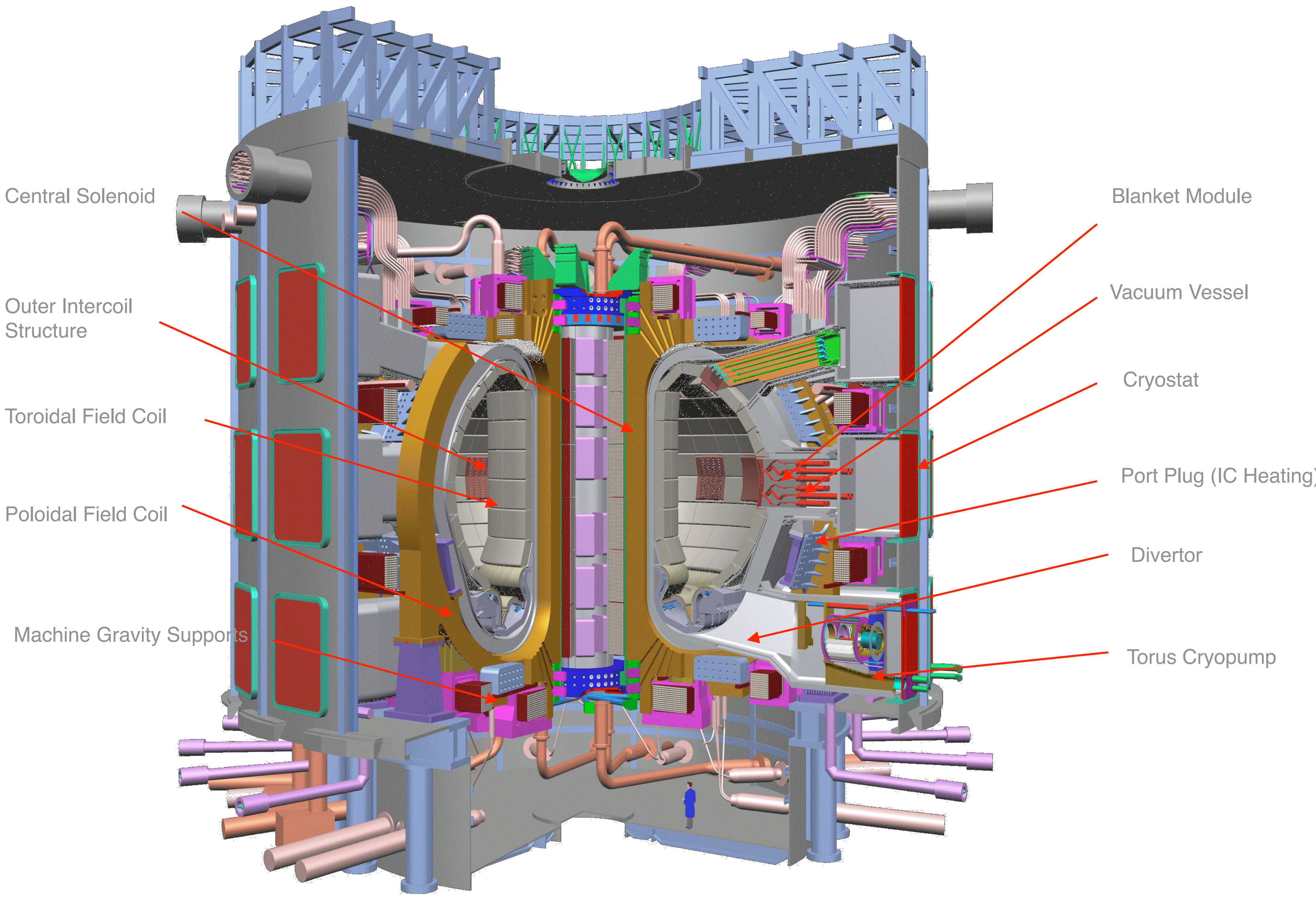
•The hot blanket and first wall is cooled; the thermal energy Is extracted from the coolant for power generation.

Nuclear Fusion

- Thermonuclear Fusion is currently realized in labs around the world; but more energy is needed to keep it going than can be produced.
- ITER – International Thermonuclear Experimental Reactors is designed to address the technical challenges: but there are many challenges to overcome before fusion can be used as a source of energy.
- Economically viable fusion reactors may be in 50 – 100 years
- Deuterium readily available from sea water: about 1.5 gr. From 1 gallon: cost is about 4 cents: sufficient to generate 100 times more energy compared to a gallon of gasoline
- Tritium can be extracted from the Lithium blanket.


82.348c

ITER



Central Solenoid
Outer Intercoil
Structure
Toroidal Field Coil
Poloidal Field Coil
Machine Gravity Supports
Blanket Module
Vacuum Vessel
Cryostat
Port Plug (IC Heating)
Divertor
Torus Cryopump

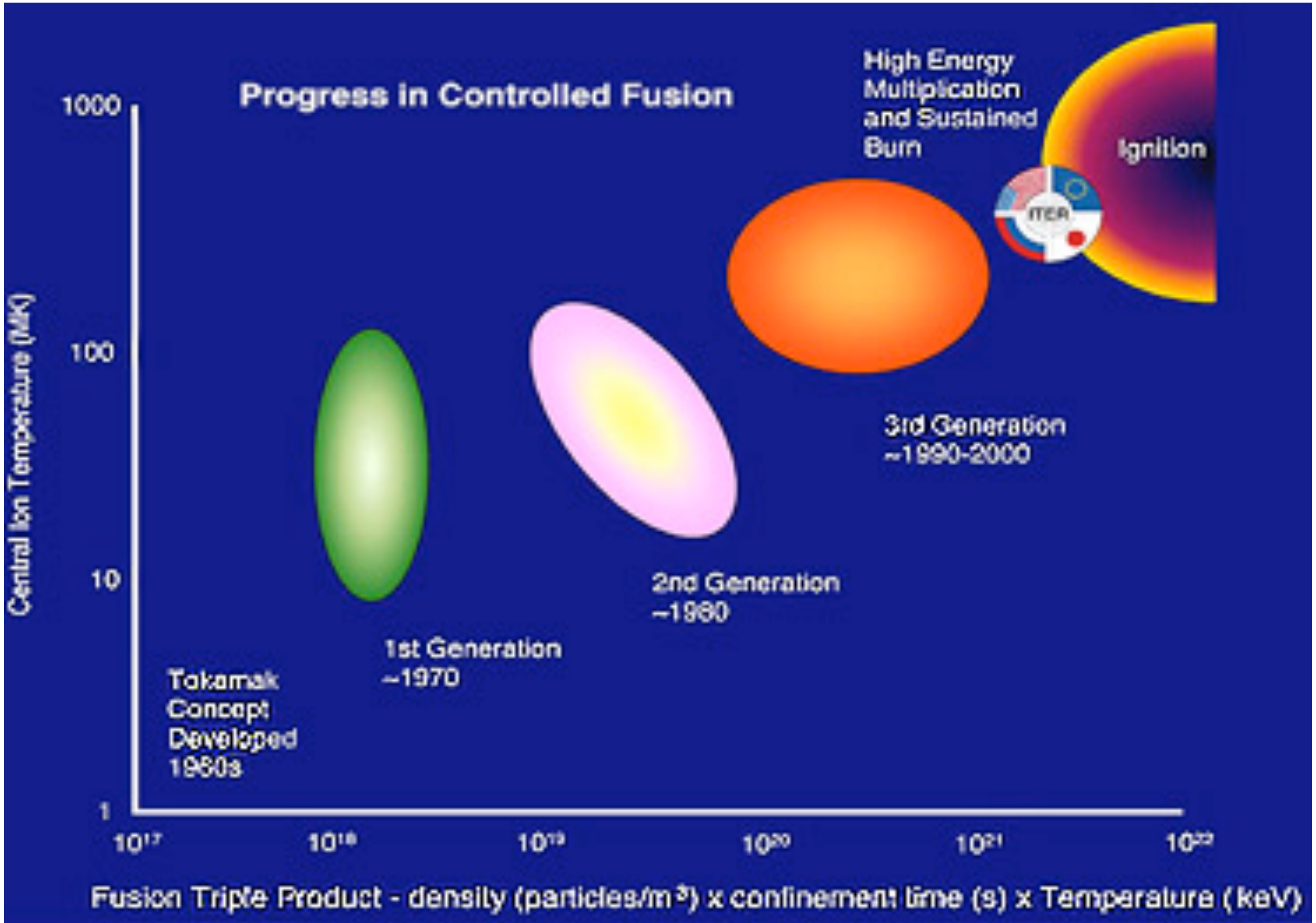
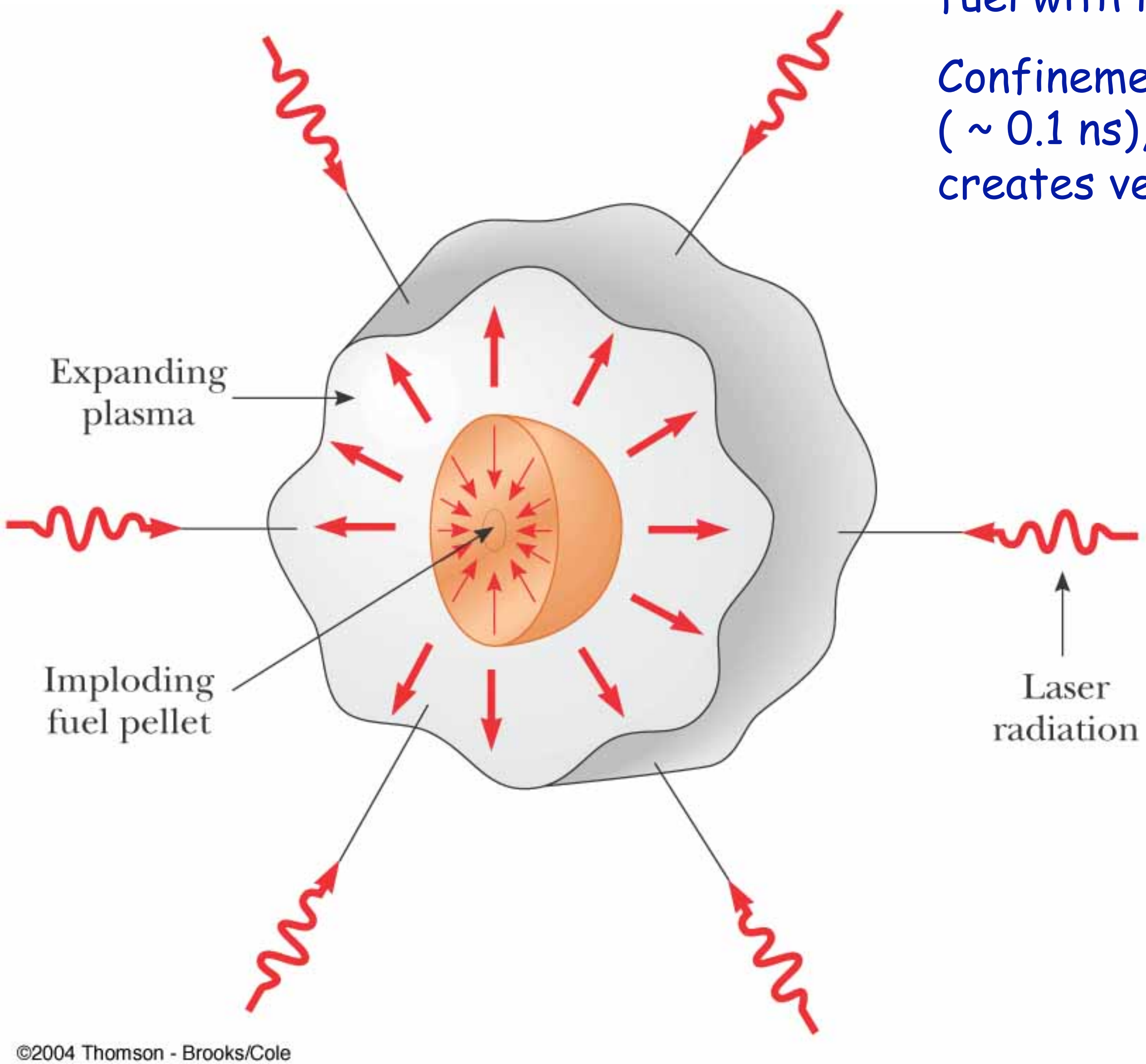


Figure 1 : Progress of fusion research over the last few decades leading to ITER.

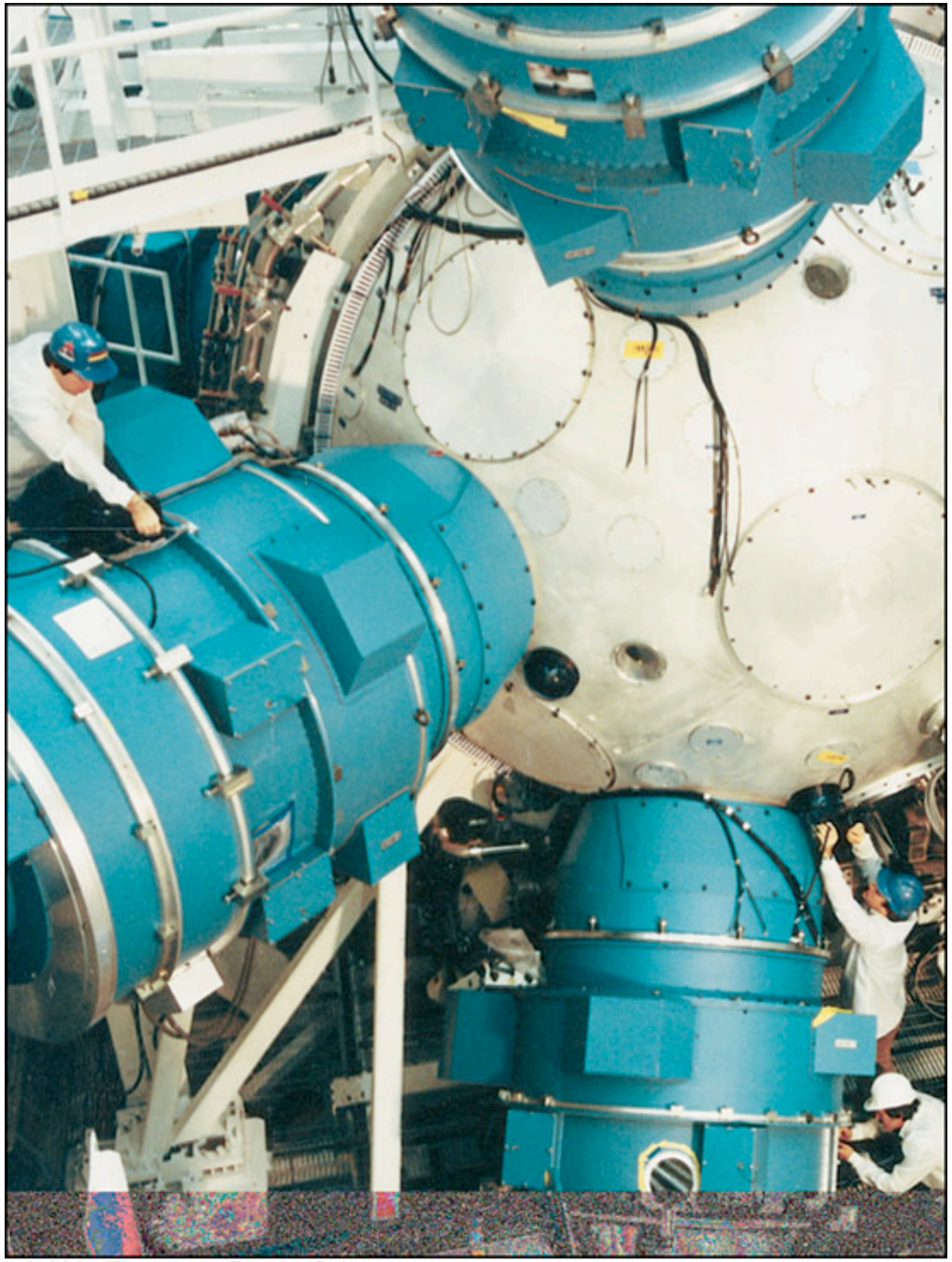

North Atlantic Ocean
North Sea
Baltic Sea
UNITED KINGDOM
IRELAND
DENMARK
NETH.
POLAND
GERMANY
BEL.
LUX.
CZECH REPUBLIC
SLOVAKIA
AUSTRIA
HUNGARY
LIECH.
SWITZ.
SLOVENIA
CROATIA
BOSNIA AND HERZEGOVINA
Celtic Sea
English Channel
Guernsey (U.K.)
Jersey (U.K.)
Bay of Biscay
FRANCE
MONACO
SAN MARINO
Ligurian Sea
ITALY
Adriatic Sea
ANDORRA
Cadarache
VATICAN CITY
PORTUGAL
SPAIN
Balearic Sea
Tyrrhenian Sea
Mediterranean Sea
Gibraltar (U.K.)
Ceuta
Alboran Sea

Another approach: inertial confinement



Zap tiny (~ 1mm) pellets of D-T fuel with lots of high power lasers.

Confinement times are very short (~ 0.1 ns), but the imploding core creates very high densities.



D-T pellets about 0.5 mm in size; confined in plastic shells with walls about 100 nm thick

Stellar nuclear synthesis

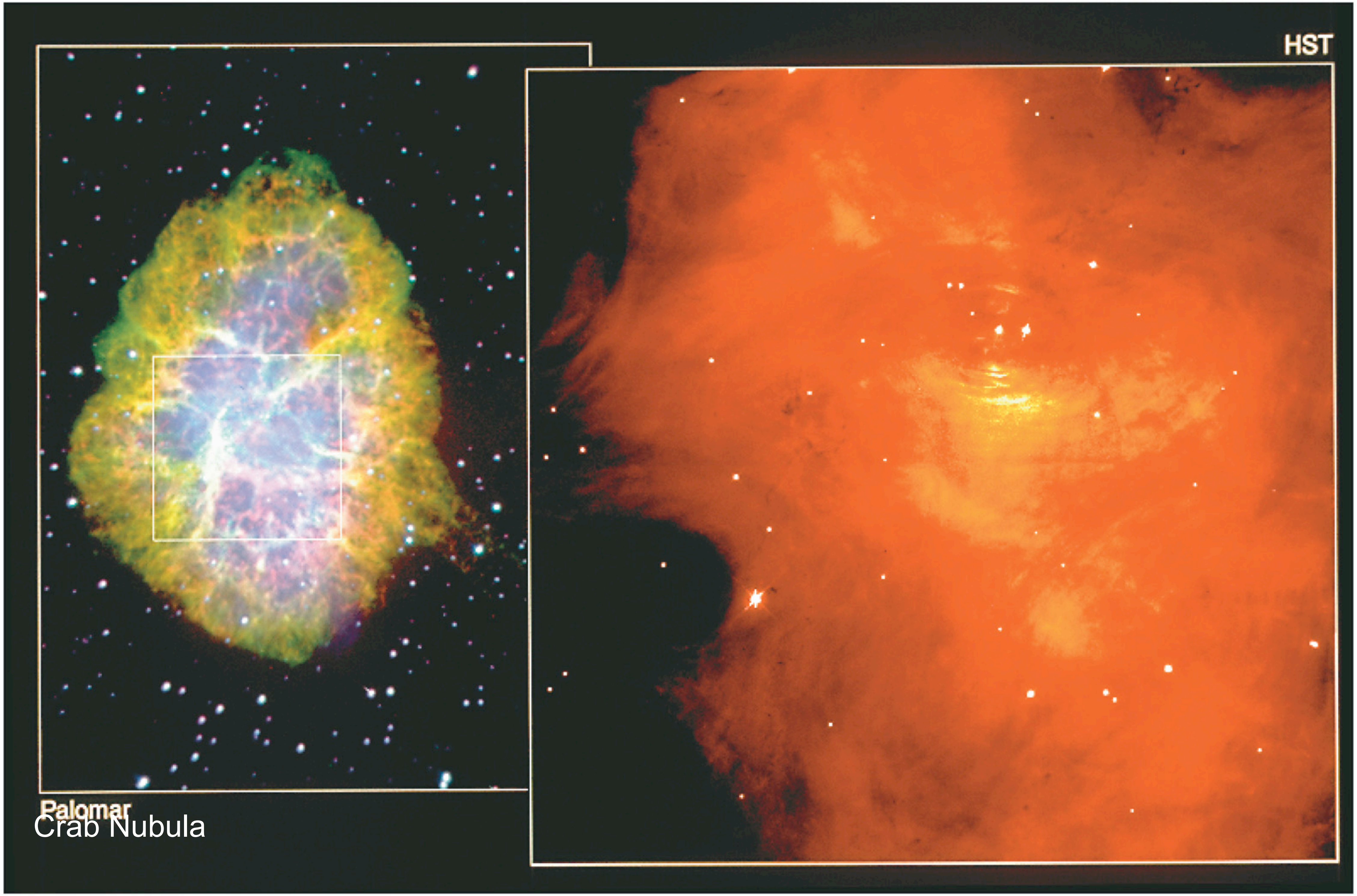
When stars are formed from the gravitational collapse of inter-stellar gas clouds, KE and T go up as the radius goes down; the fate of the star depends on its mass

- $M < 0.1.M_{sun}$: Collapse stops when gravity balance out by electron degeneracy pressure: T is not high enough for fusion. Becomes a cold ball of gas
- $M \sim M_{sun}$ $(0.1 < M < 4M_{sun})$
  - "well behaved, respectable star": T becomes high enough for fusion before electron degeneracy pressure kicks in: core temp (T_c) ~ 10 MK. H burning chains for 10 to hundreds of billions of years.
  - When H runs out, further collapse till $T_c \sim 100$ MK; high enough to over come Coloumb barrier in He; He burning starts, outer layers evaporates: red giant
  - mostly to C, but some O and Ne too
  - When all He runs out, contracts till electron degeneracy pressure kicks in: white-dwarf.

- ($4 < M < 10\ M_{sun}$):
    - Due to larger mass T during is H burning is much higher hundreds of MK; H burns out faster; lifetime ~ 1 GY: after that He burning.
    - When He runs out further collapse till T_c ~ 600 MK; and then later to T_c ~ 2 GK: high enough to over come Coloumb barrier in C and O respectively; C and O burning start.
    - Then at T_c ~ 3 GK Si burning with alpha particles: larger and larger Z all the way to Fe.
    - At this state the star stays in layers; like an onion; Iron in the middle, Si burning in the next one, etc.
    - When everything turned to iron; no more fusion: violent collapse of the star; when the outer layers hit the core, a super-nova explosion; brightest event in night sky; like a billion stars put together for a few days.
    - very large Ts and large neutron fluxes: creation of heavier nuclei up to Uranium; all these nuclei thrown in to space: seed material for next generation stars
    - The pressure wave can stimulate birth of new starts from inter-stellar gas: large regions of new-born stars.

- ($4 < M < 10\ M_{sun}$):
    - core continues to contract (only about 1.4 Msun left now) T so high reverse beta decay of electrons and protons into neutrons; only neutrons now. Collapse stops when neutron degeneracy pressure and short range nuclear repulsion.
    - size is ~ 10 km; angular momentum conservation: spins very fast.

- $M > 10\ M_{sun}$: Nothing can withstand gravitational pressure: contracts to a point: a black-hole is born.


HST
Palomar
Crab Nubula

http://www.nasa.gov/centers/marshall/news/background/facts/CrabNebulaFactSheet.html
http://chandra.harvard.edu/photo/2002/0052/