Nuclear Fusion:
Basic principles, current progress and ITER plans

Sources:

Mohamed Abdou – UCLA

J. Arturo Alonso – Laboratorio Nacional de Fusión (CIEMAT)

http://fusionwiki.ciemat.es/wiki/Main_Page

The ITER organization

http://www.iter.org/

OVERVIEW

- Fusion in nature → powering stars!
- Fusion reactions → nuclear fusion on earth?
- Controlled nuclear fusion
  - Inertial confinement
  - Magnetic confinement
  - ITER and Fusion technology
  - Final remarks

FUSION IN NATURE

What is Nuclear Fusion?

- Nuclear Fusion is the energy-producing process taking place in the core of the Sun and all the stars. Produce heavier matter (us!!)
- The core temperature of the Sun is about 15 million K. At these temperatures Hydrogen nuclei fuse to give Helium and Energy. The energy sustains life on Earth via sunlight.

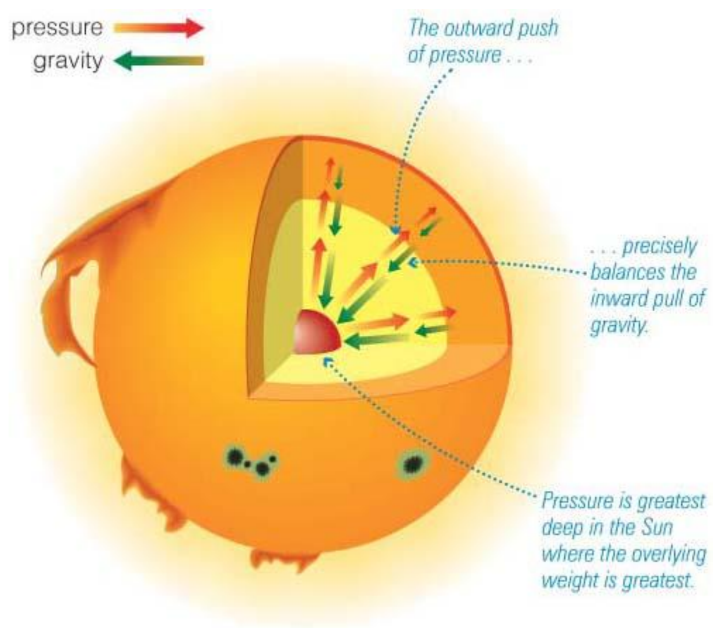
The energy of the stars

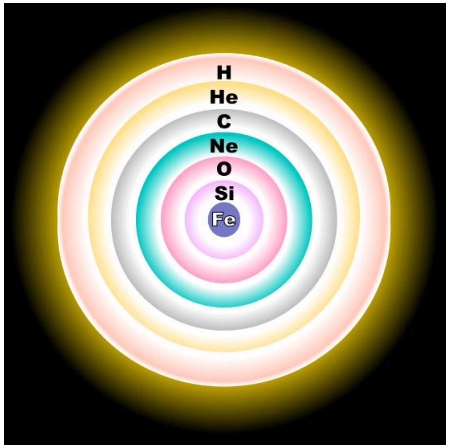
Stars are powered by the fusion of elements lighter than iron, particularly of hydrogen (^{1}H) into helium (^{4}He) $\Rightarrow$ Nucleosynthesis.

-For stars like the sun which have internal temperatures less than $15 \cdot 10^{6}$ Kelvin, the dominant fusion process is the proton-proton fusion.

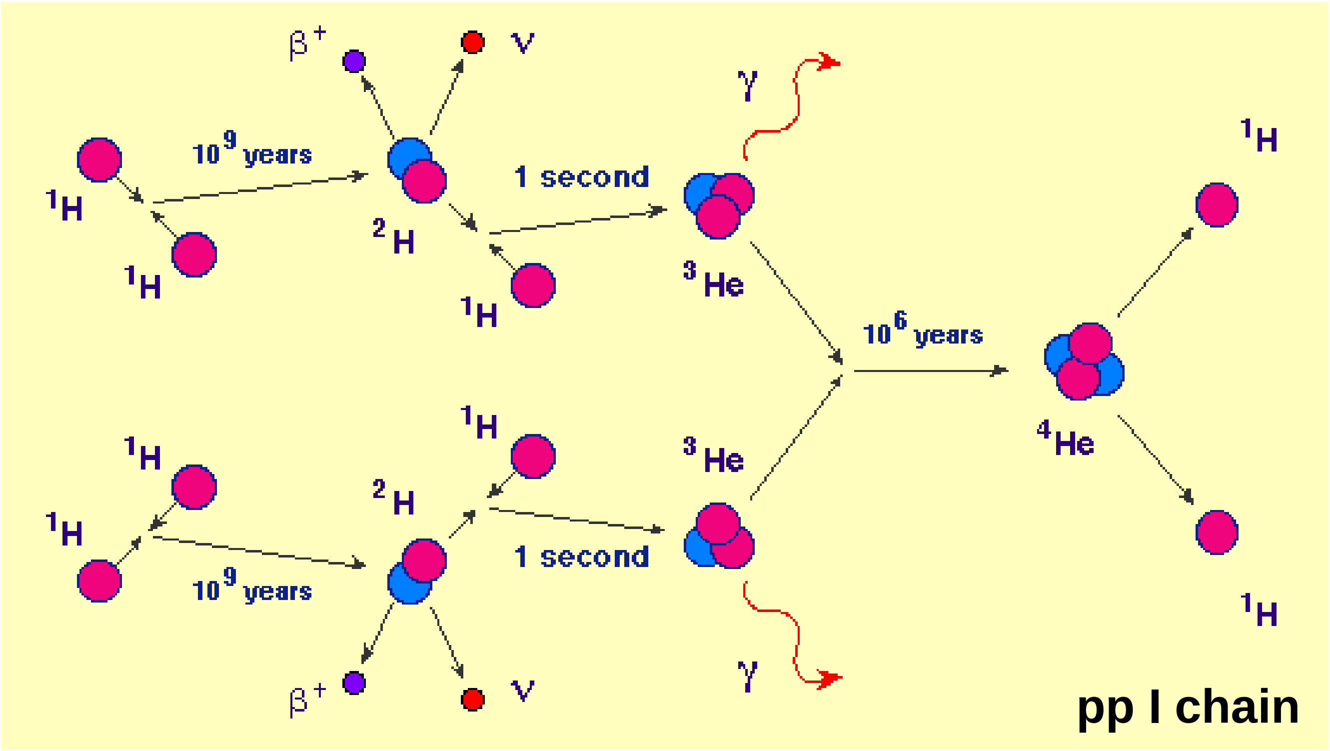
-For more massive stars which can achieve higher temperatures, the CNO cycle fusion becomes the dominant mechanism.

-For older stars which are collapsing at the center, the temperature can exceed $100 \cdot 10^{6}$ Kelvin and initiate the helium fusion process called the triple-alpha process in which three alpha particles fuse to obtain carbon.





Fusion at the sun: the pp-chain



In the sun and stars of similar mass, the dominating fusion reaction is the proton-proton (pp) chain.

It has three identified branches:

- pp I (10 < T < 14 MK)
- pp II (14 < T < 23 MK)
- pp III (T >23 MK)

pp I branch (~69% of the chain)

$$^1\mathrm{H} + {}^1\mathrm{H} \rightarrow {}^2\mathrm{H} + e^+ + \nu$$

$$^2\mathrm{H} + {}^1\mathrm{H} \rightarrow {}^3\mathrm{He} + \gamma$$

$$^3\mathrm{He} + {}^3\mathrm{He} \rightarrow \boxed{{}^4\mathrm{He}} + {}^1\mathrm{H} + {}^1\mathrm{H}$$

pp II branch (~31% of the chain)

$$^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$$

$$^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu$$

$$^7\mathrm{Li} + {}^1\mathrm{H} \rightarrow \boxed{{}^4\mathrm{He} + {}^4\mathrm{He}}$$

pp III branch (~0.3%)

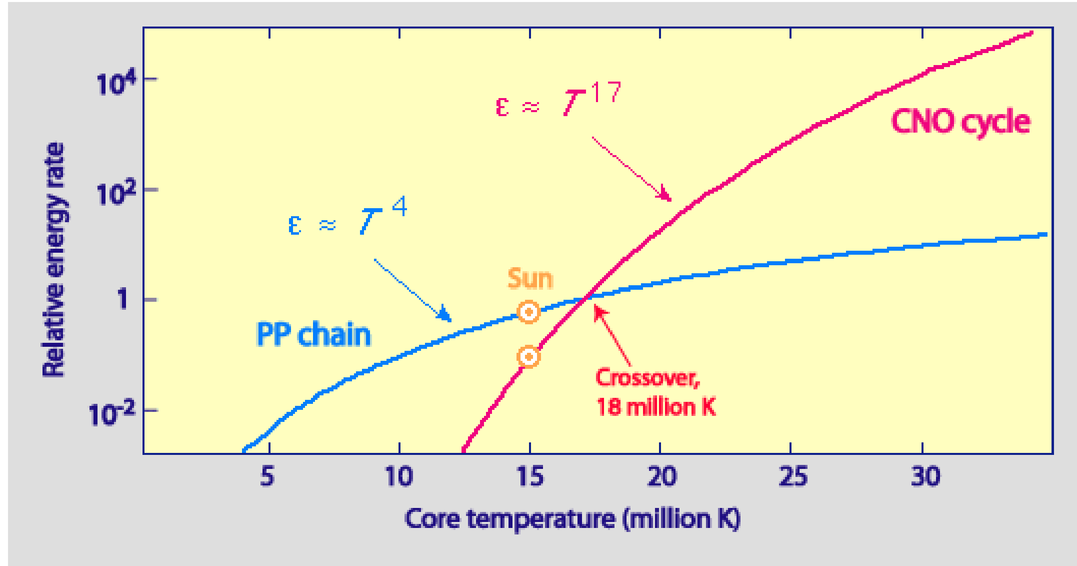
$$^7\mathrm{Be} + {}^1\mathrm{H} \rightarrow {}^8\mathrm{B} + \gamma$$

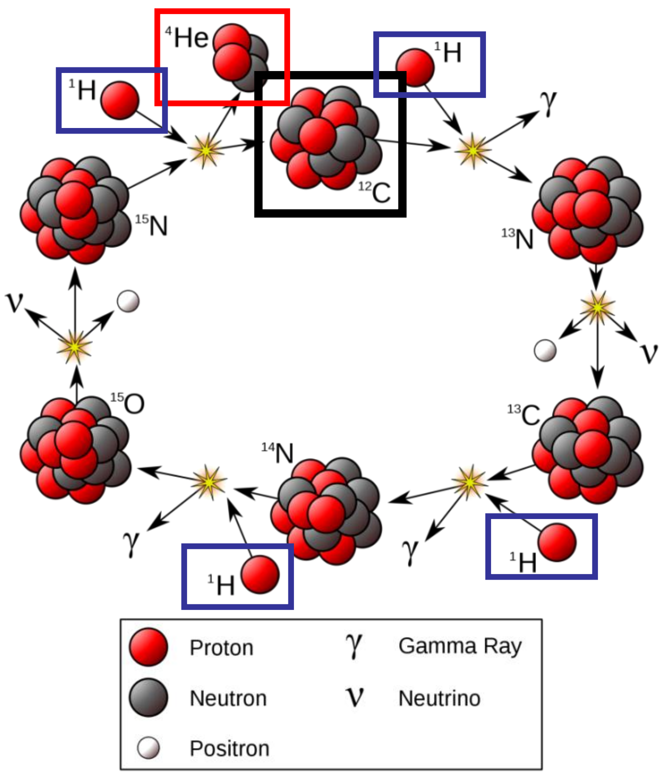
$$^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu$$

$$^8\mathrm{Be} \rightarrow \boxed{{}^4\mathrm{He} + {}^4\mathrm{He}}$$

The CNO cycle

For stars of mass greater than about two solar masses a different cycle of thermonuclear reactions (CNO catalytic cycle) involving the elements carbon, nitrogen, and oxygen dominates the total energy production.





$$^{12}C + p \rightarrow {}^{13}N + \gamma$$

$$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$$

$$^{13}C + p \rightarrow {}^{14}N + \gamma$$

$$^{14}N + p \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$$

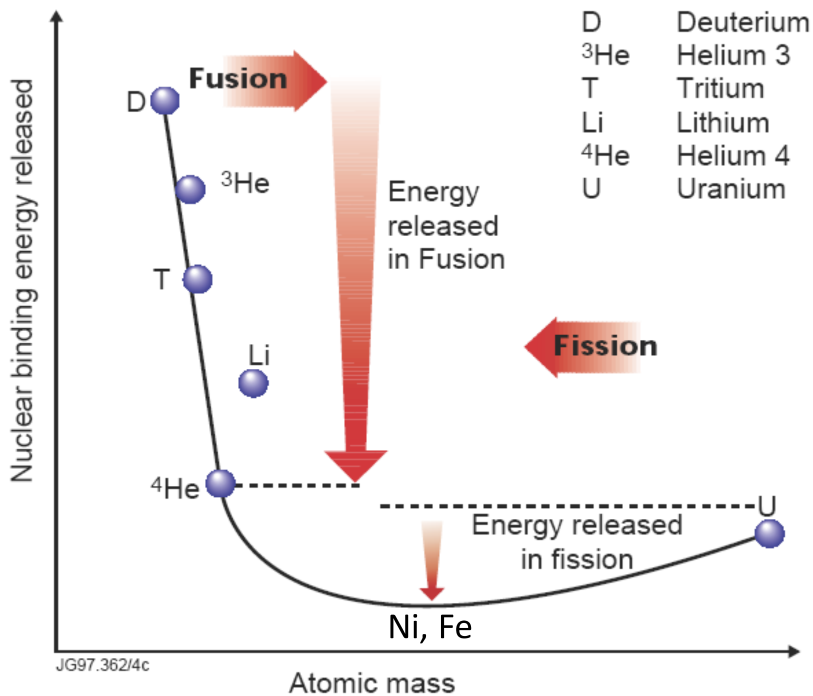
$$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$$

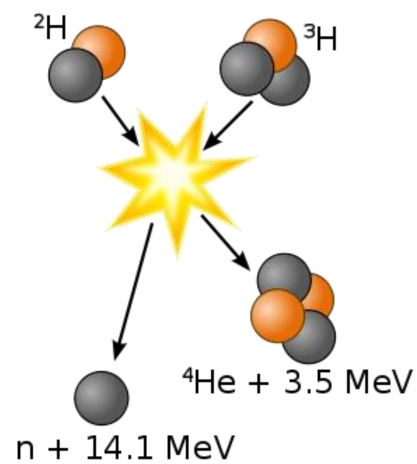
FUSION REACTIONS

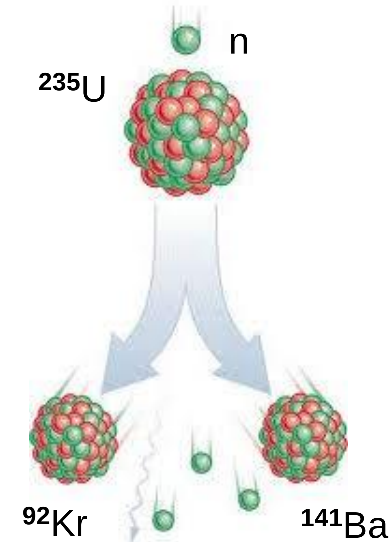
Energy released by nuclear reactions: fusion vs. fission

- **Light nuclei** (Hydrogen, Helium) release energy when they **fuse (Nuclear Fusion).**
- The **product nuclei** weigh **less** than the parent nuclei.

- **Heavy nuclei** (Uranium) release energy when they **split (Nuclear Fission).**
- The **product nuclei** weigh **less** than the original nucleus.





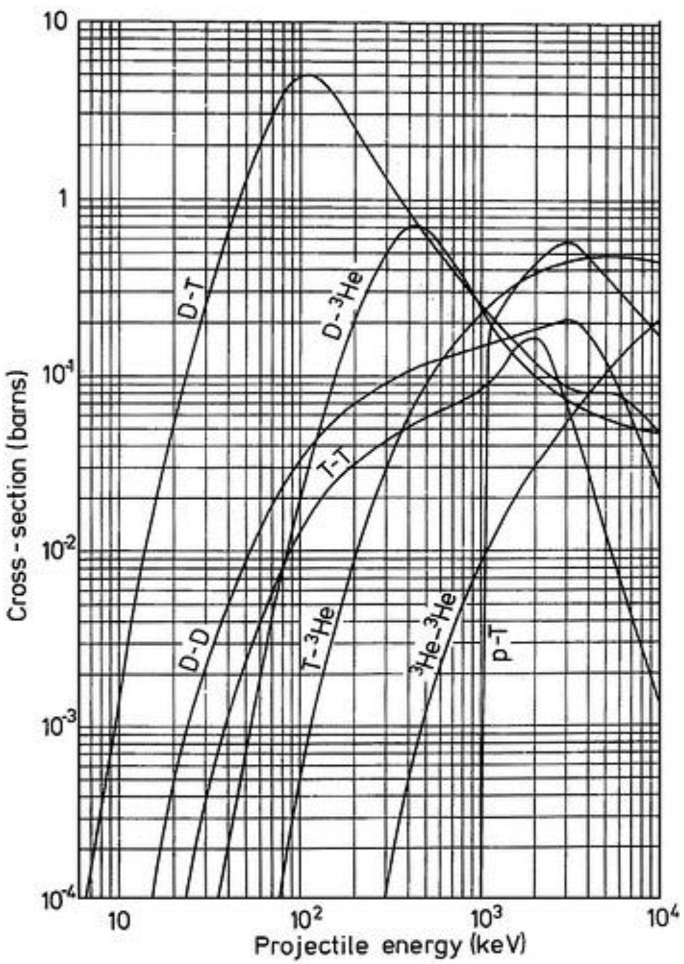


FUSION **FISSION**

- Fusion reactions release higher energies than Fission reactions

Energy released by nuclear fusion reactions

Due to the Coulomb barrier, the nuclear fusion becomes relevant at energies of keV (1 keV is approximately equivalent to $11.6 \cdot 10^6$ K).



Most promising reaction for fusion power: Q = 17.6 MeV

D[13.1 MeV]+T[15.0 MeV]$\rightarrow$^{4}He[2.4 MeV]+n[8.1 MeV]+ Q

[mass excess]

Q = 3.5 MeV/amu for Fusion

Q = 0.8 MeV/amu for Fission

Other possible fusion reactions on earth:

D + D $\rightarrow$ T + p + 4.0 MeV

D + D $\rightarrow$ ^{3}He + n + 3.3 MeV

D + ^{3}He $\rightarrow$ ^{4}He + p + 18.3 MeV

T + T $\rightarrow$ ^{4}He + 2n + 11.3 MeV

T + ^{3}He $\rightarrow$ ^{4}He + p + n + 12.1 MeV

^{3}He + ^{3}He $\rightarrow$ ^{4}He + p + p + 12.9 MeV

$$w = n_1 n_2 \langle \sigma v \rangle$$

Reaction rate.

Maxwellian averaged cross section.

Nuclear fusion and the cold war

During WW2, the USSR competed with UK and US for military superiority. The Cold War started.

- ✓1949, Sept. 23, US President (Truman) told the world about the explosion of the first USSR A-bomb in Kazakhstan.
- ✓1950, the US stepped up to develop the H-bomb.
- ✓1952, Nov. 1, US tested the first H-bomb “Mike” at Enewetak Atoll (Marshall Islands).
- ✓1953, Aug. 12, USSR tested its first H-bomb.
- ✓Britain, France, and China also have tested H-bombs.

MIKE (10 megatons):

Mushroom cloud was 13 km across, 43 km high with a 160 km wide canopy and 80 million tons of earth were vaporized.

Mar. 1, 1954 “Castle Bravo“ H-bomb exploded at Bikini Atoll yielded 15 megatons.

Oct. 30, 1961 USSR H-bomb “Tsar” yielded 50 megatons.

CONTROLLED FUSION

Incentives for developing controlled fusion

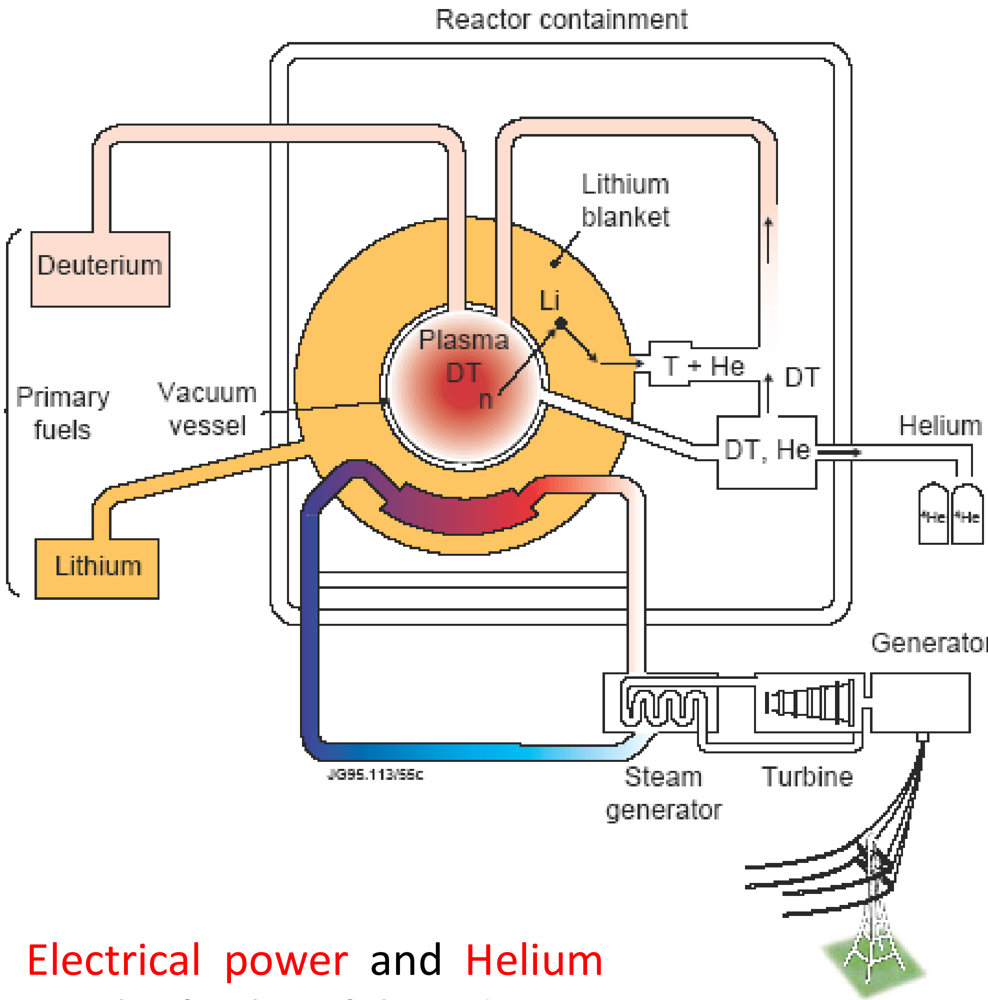
- Sustainable energy source
  - Cheap and plentiful fuel for D – T cycle; provided that lithium breeding blankets for tritium generation are successfully developed.
- No emission of greenhouse or other polluting gases
- Lower risk associated to severe accidents
  - No chain-reaction
- Less long-lived radioactive waste
  - No actinides generation
- Tritium is an “intermediate” fuel (with mature tritium breeding technology)
  - Avoids major shipment from/to off-site facilities (with the exception of initial loading)
- Moderate stored energy in plasma and fuel
- 1 Kg D – T mixture $\rightarrow$ 1 GW power station for a day

Controlled fusion energy – Disadvantages

- D - T fusion reaction is very difficult to start !!
  - High temperatures (100-200 Millions of degrees) in a pure high vacuum environment are required
  - Technically complex and high capital cost reactors are necessary
- More research and development is needed to bring concept to fruition
  - Magnetic confinement physics is well advanced but requires sustained development on a long time scale (20 to 40 years)
- Radiological risks associated to the Tritium ($^{3}T \rightarrow {}^{3}He^{1+} + e^{-} + \nu_e^{*}$; 12. 3 y)
  - Dangerous only if inhaled or ingested (tritiated water)
- Neutron induced activation of structural materials
  - Replacing structural materials during reactor life (loss of mechanical strength, heat conduction…)
  - Solid waste disposal problem
- First wall must be capable of withstanding high heat fluxes and plasma abrasion
- Tokamaks is the most advanced concept but still are:
  - Non-steady state
  - Plasma disruptions (design safety issue, may produce loss of vacuum and radioactive substances release)

D–T Fusion power plant schematic

Inertial and magnetic confinement power plants share common issues.



Electrical power and Helium are the final useful products.

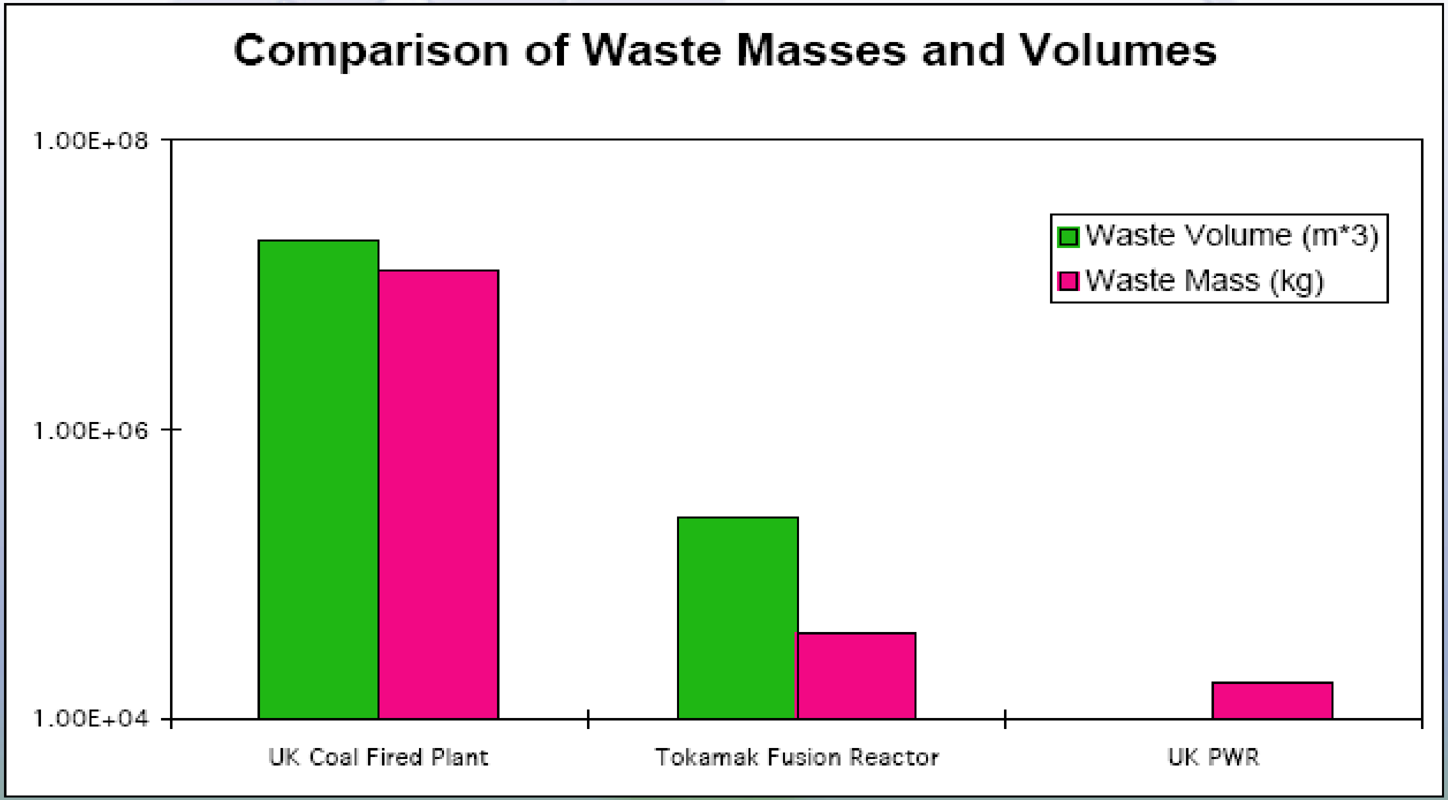
- Primary fuels: Deuterium and Lithium
- Deuterium – tritium (DT) fusion reaction:

$$\boxed{D} + T \rightarrow {}^4He + \underbrace{n} + Energy$$

$$\begin{cases} n + {}^6Li \rightarrow \boxed{T} + {}^4He \\ n + {}^7Li \rightarrow \boxed{T} + {}^4He + n \end{cases}$$

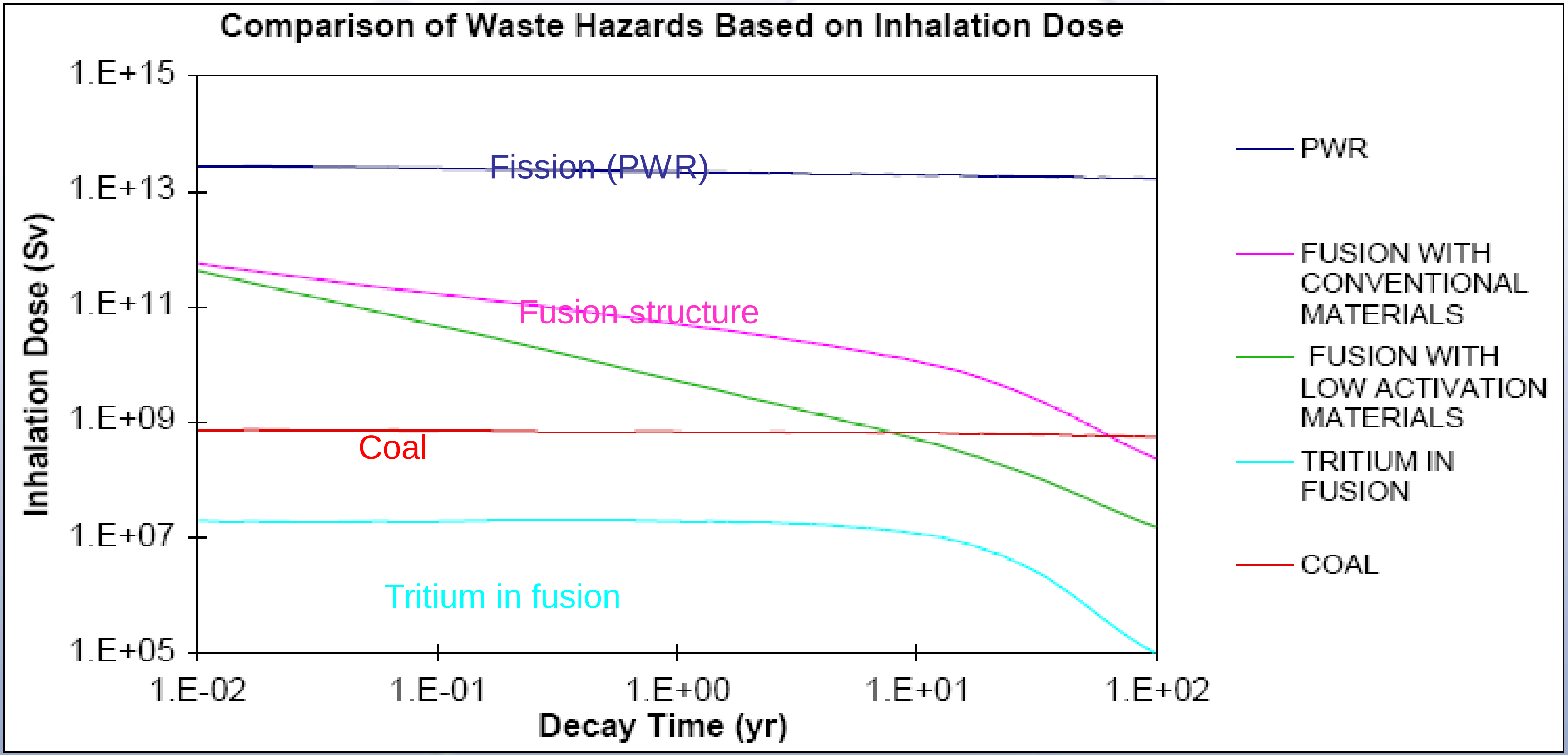
- The ^4He nuclei ('α' particles) carry about 20% of the energy and heat the plasma. The other 80% is carried away by the neutrons and can be used to generate steam and produce tritium in the blanket.
- Fusion plasmas become self-sustaining or ignited (Q=∞) when no external input power is needed (in mag. conf. fusion).

Fusion radioactive waste volumes are more than fission but much less than coal for power plants of equal size.



From "A Study of the Environmental Impact of Fusion" (AERE R 13708)

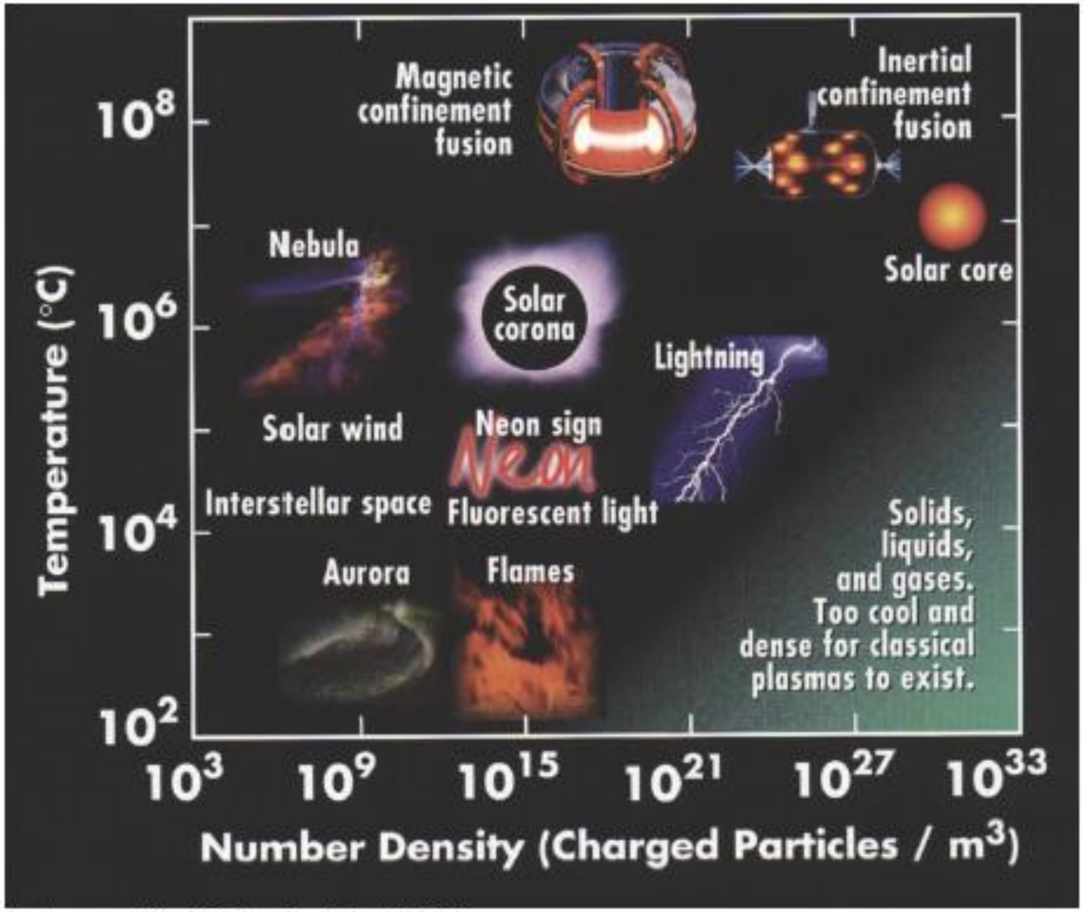
Radiotoxicity (inhalation) of waste from fusion is less than fission and similar to that from coal at 100 years.



- From "A Study of the Environmental Impact of Fusion" (AERE R 13708).
- Coal radiotoxicity is based on Radon, Uranium, Thorium, and Polonium in coal ash
- Inhalation represents major pathways for uptake of material by the human body
- Dose hazard used here is a relative measure of radiotoxicity of material

Nuclear fusion and PLASMAS

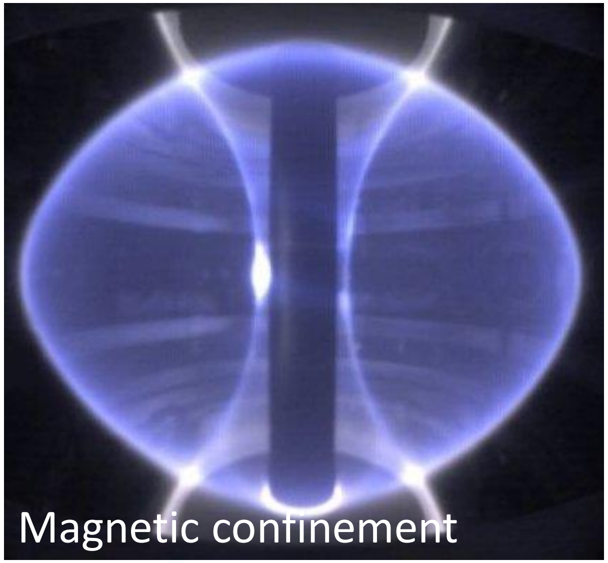
- A Plasma is an ionized gas. A mixture of ions and electrons with an overall charge neutrality and exhibiting a collective behavior.
- Plasmas constitute the 4th state of matter.
- Plasmas conduct electricity and heat.
- Plasma react strongly to electromagnetic fields.
- Plasmas with a very wide range of temperature and density occur in nature.
- Even partially ionized gases (1%) may exhibit a plasma behavior



Contemporary Physics Education Project (CPEP)

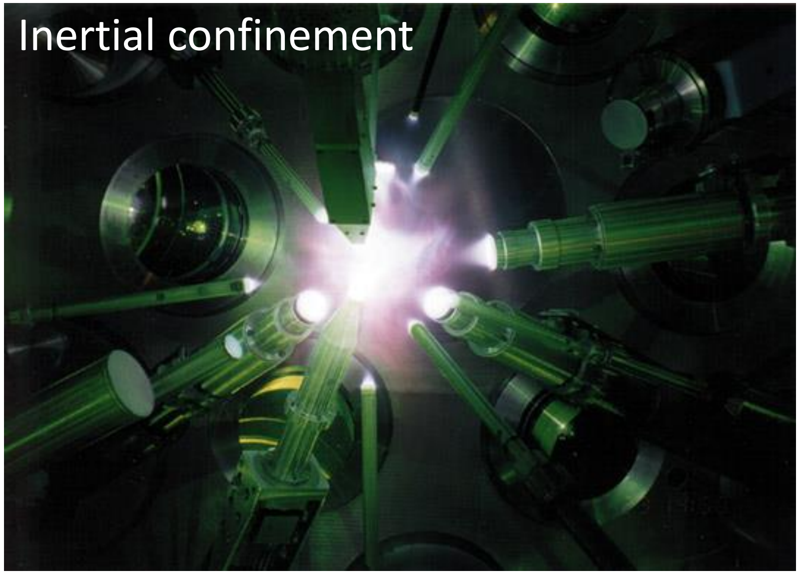
PLASMA confinement methods

•In stars plasma particles (including α's) are confined mainly by gravity and very high plasma densities are achieved ~ 10^{30} m^{-3}.



•On Earth:

- Hot dense plasmas (10^{20} m^{-3}) confined by magnetic fields (Magnetic Confinement Fusion).
- Super-dense plasmas can be obtained by imploding solid deuterium-tritium pellets (Inertial Confinement Fusion).



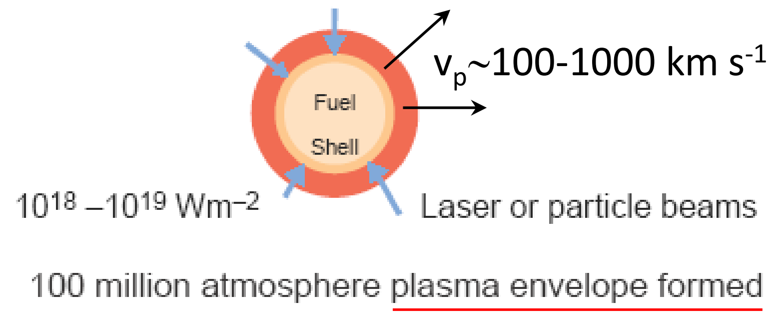
CONTROLLED FUSION

Inertial confinement

Inertial confinement

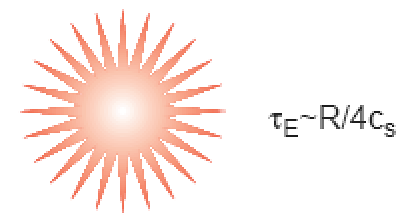
- Finite time confinement is not given by external fields but by the hot fuel inertia.

- Several laser or particle beams produce an intense heating of the small (~ 3 mm diameter) solid deuterium–tritium pellet surface



- Pressure generation by inertial reaction
  - Rocket-like blow off: v_p~100-1000 km s^{-1}
  - Implosion velocity : v_f ~ 300-500 km s^{-1}

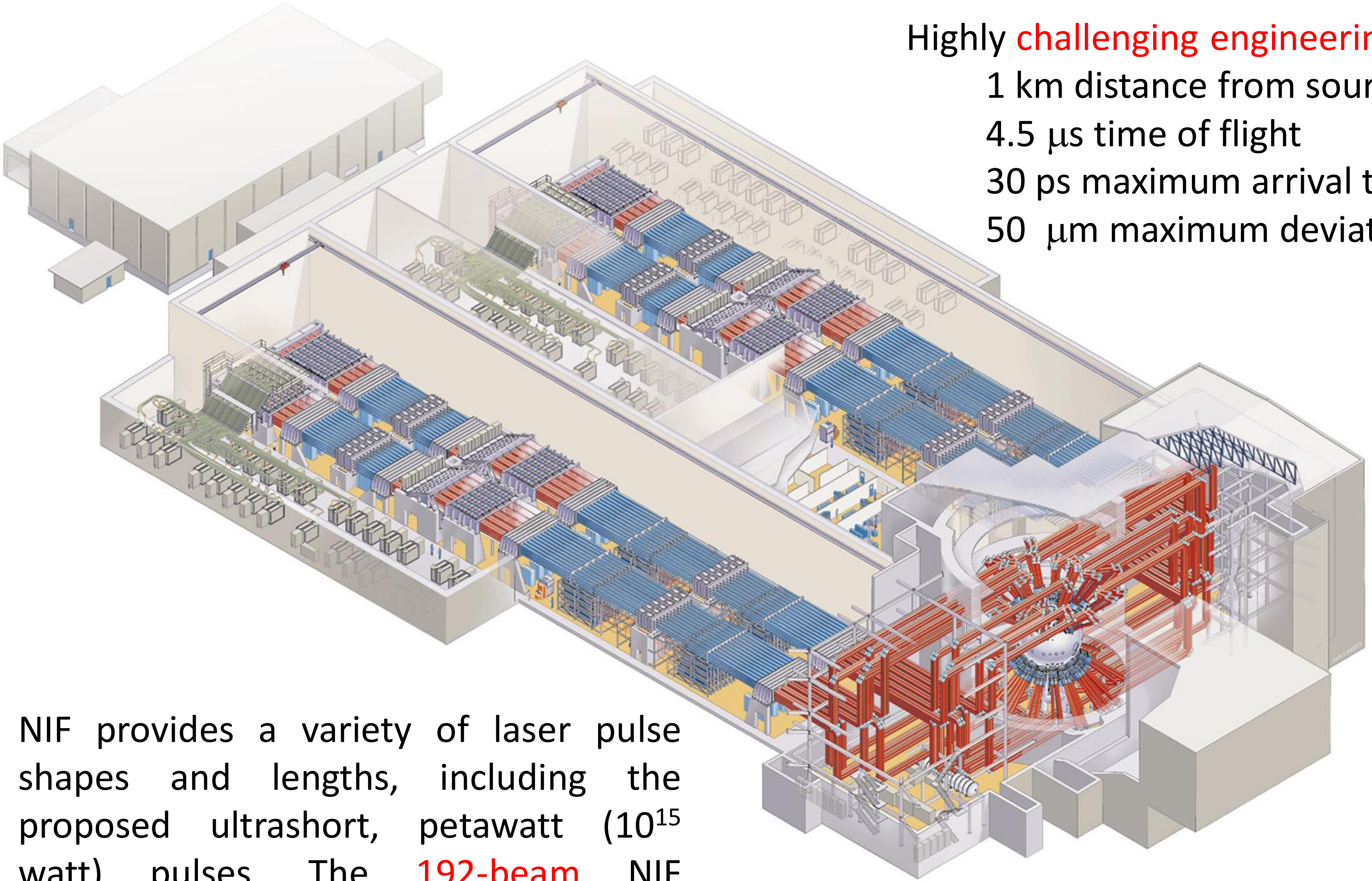
- Compression
  - Very high density of the core DT fuel (200-400 g cm^{-3}).
  - 200,000 million atmospheres.
  - 10 KeV in the core.



- Ignition and burn (30 % fractional burn required)
  - 'Spark ignition' occurs. Self heating is done predominantly by DT reaction ('α' particles) and the work of the implosion.

- Main efficiency concern: VERY high degree of circular symmetry in heating and implosion avoiding hydrodynamic instabilities.

The National Ignition Facility (NIF)



Highly challenging engineering:

1 km distance from source

4.5 μs time of flight

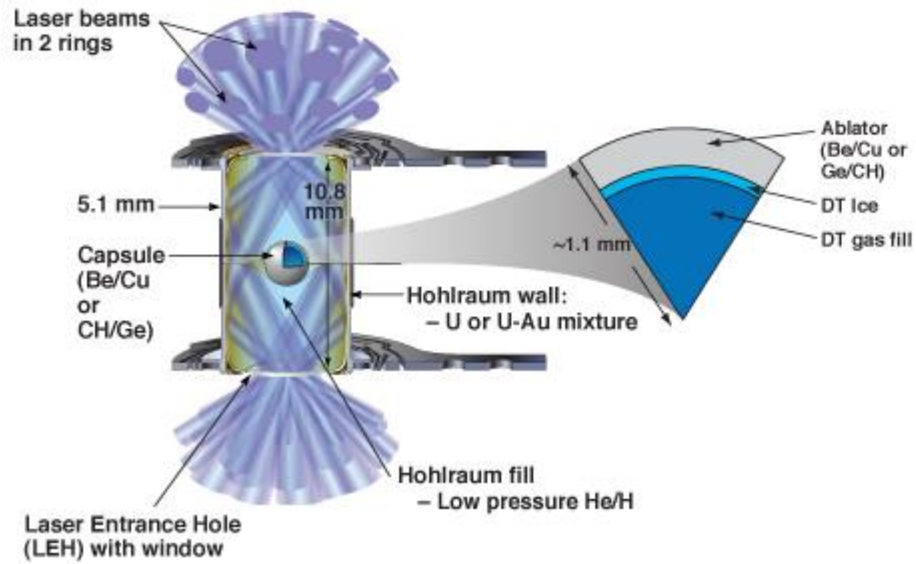
30 ps maximum arrival time shift

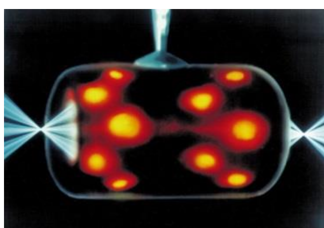
50 μm maximum deviation

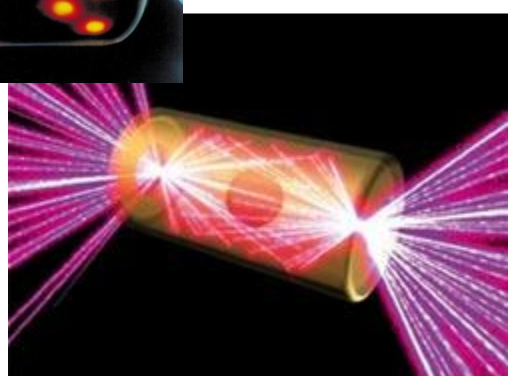
NIF provides a variety of laser pulse shapes and lengths, including the proposed ultrashort, petawatt (10^{15} watt) pulses. The 192-beam NIF generates up to 1.8 megajoules and 500 terawatts of ultraviolet laser energy.

Lawrence Livermore NL
California

The National Ignition Facility (NIF)







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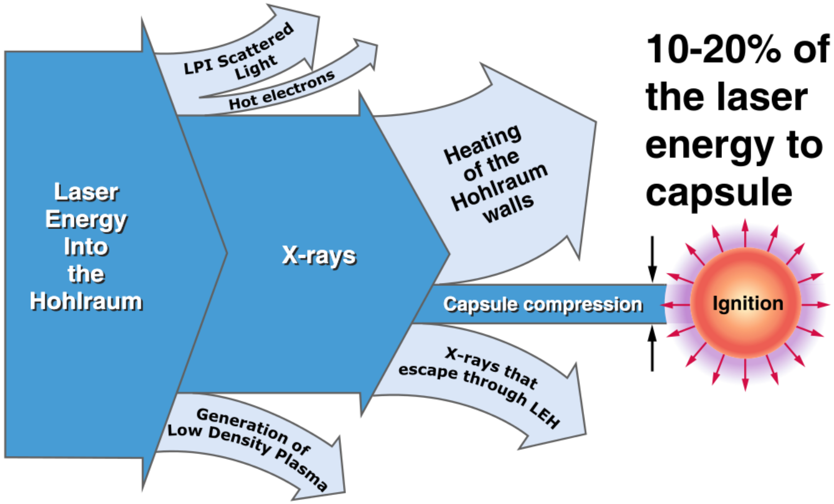
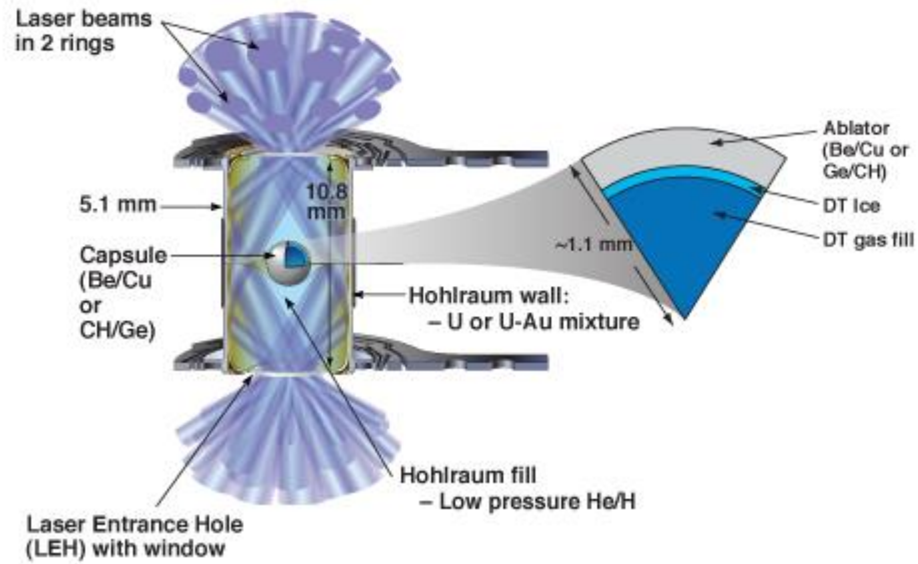
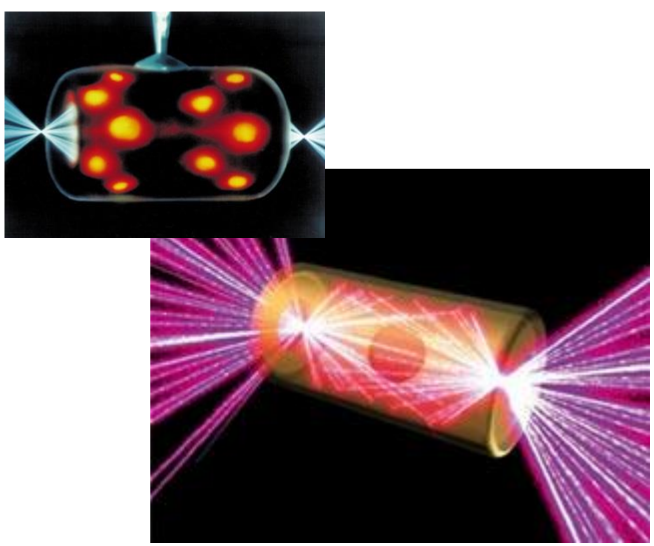






- Rayleigh-Taylor hydrodynamic instabilities cause the ablative shell to mix with the DT fuel, departing from ideal spherical symmetry, interfering with the further compression of the fuel and radiating away heat (Nature **506**, 303 (2014)). Best results are a factor of three below predictions.

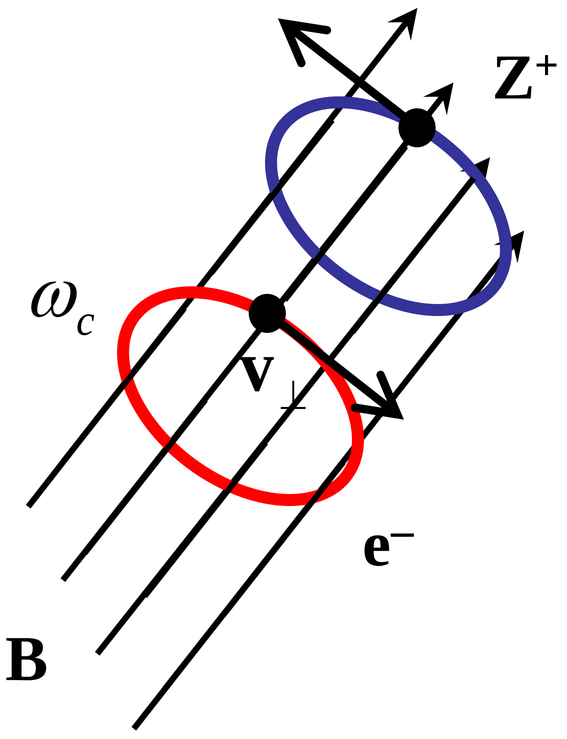
- Physics Today Jun, 2016 $\Rightarrow$ NIF may be never ignite.

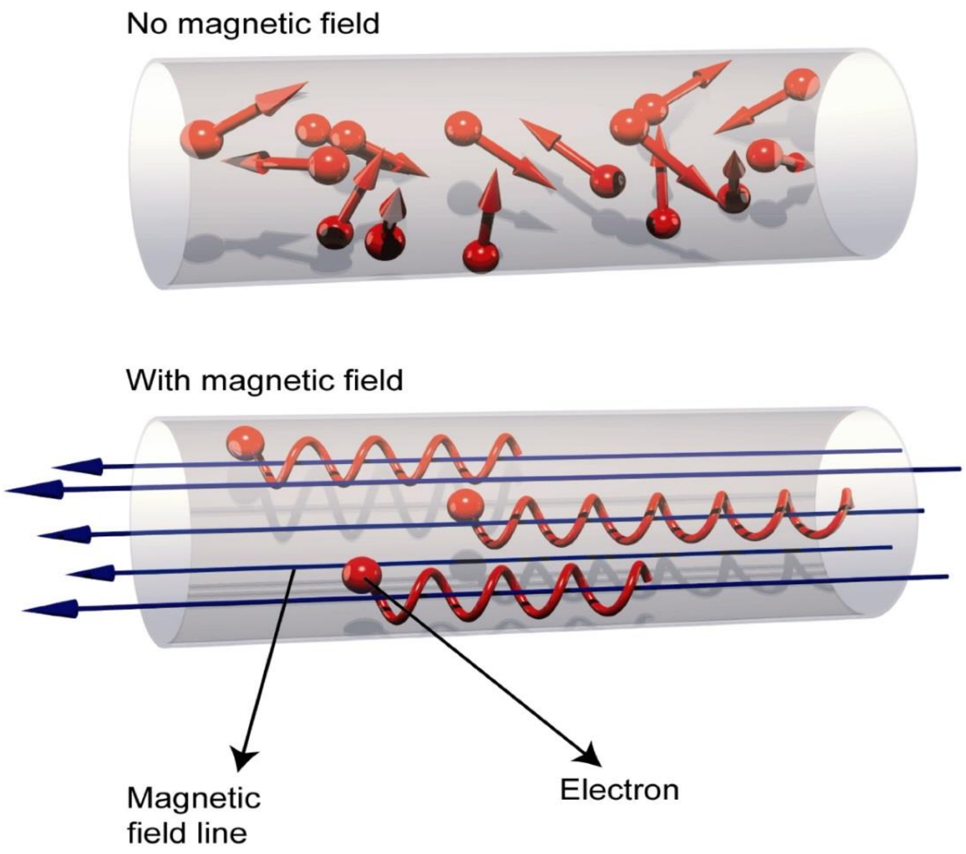
- But experiments in Jun 2018 doubled previous performance by changing capsules and hohlraum configuration improving the symmetry of the implosion (PRL 120, 2018).

CONTROLLED FUSION

Magnetic confinement

Magnetic confinement



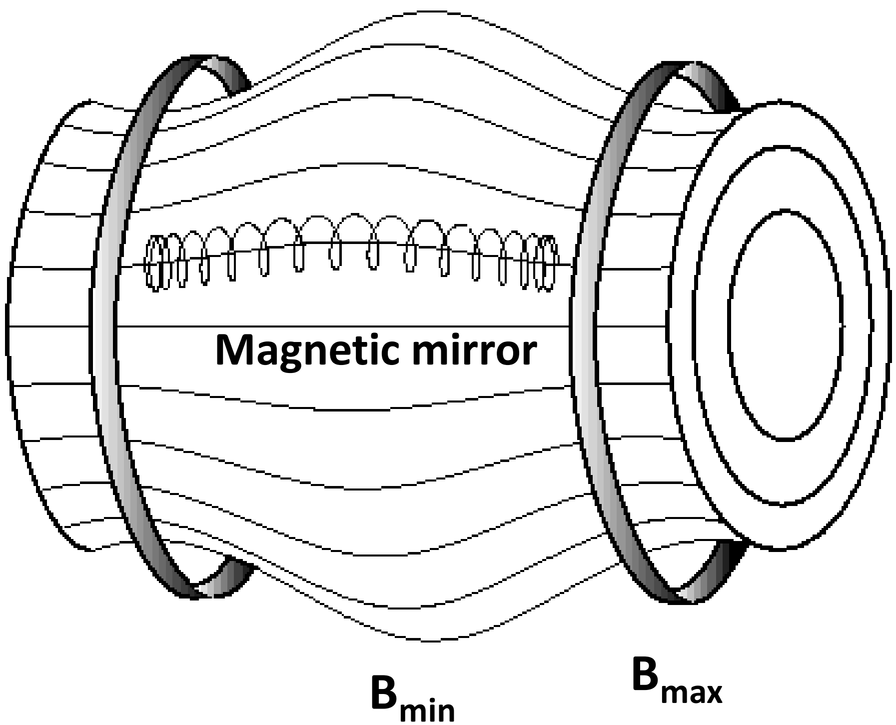


$$\omega_c = \frac{qB}{\gamma m} \qquad \rho_L = \frac{v_\perp}{\omega_c}$$

First step: open end confinement.

Magnetic confinement

Second step: “closed” end confinement



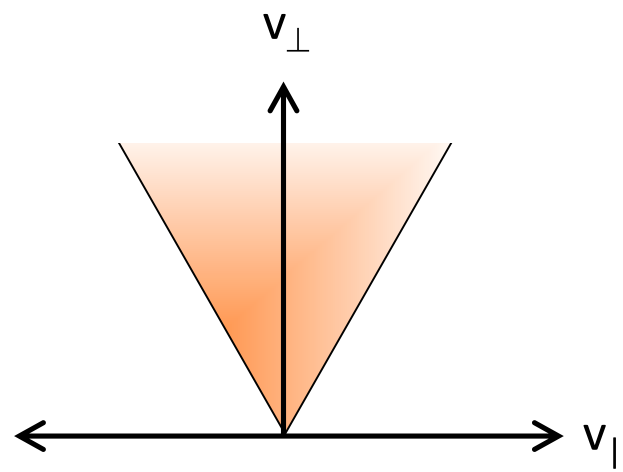
Energy conservation

$E = 1/2\ m\ (v_\perp^{\ 2} + v_{||}^{\ 2})$

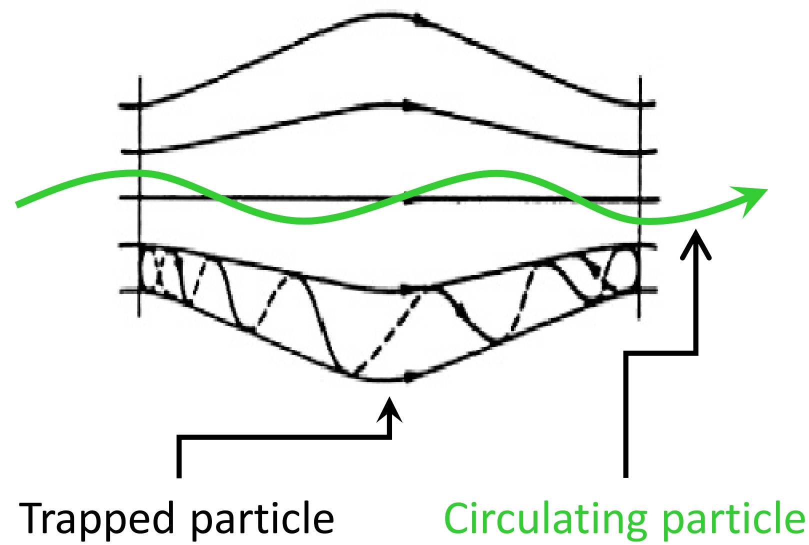
+

Adiabatic invariance of magnetic moment

$\mu = m\ v_\perp^{\ 2}/2B$

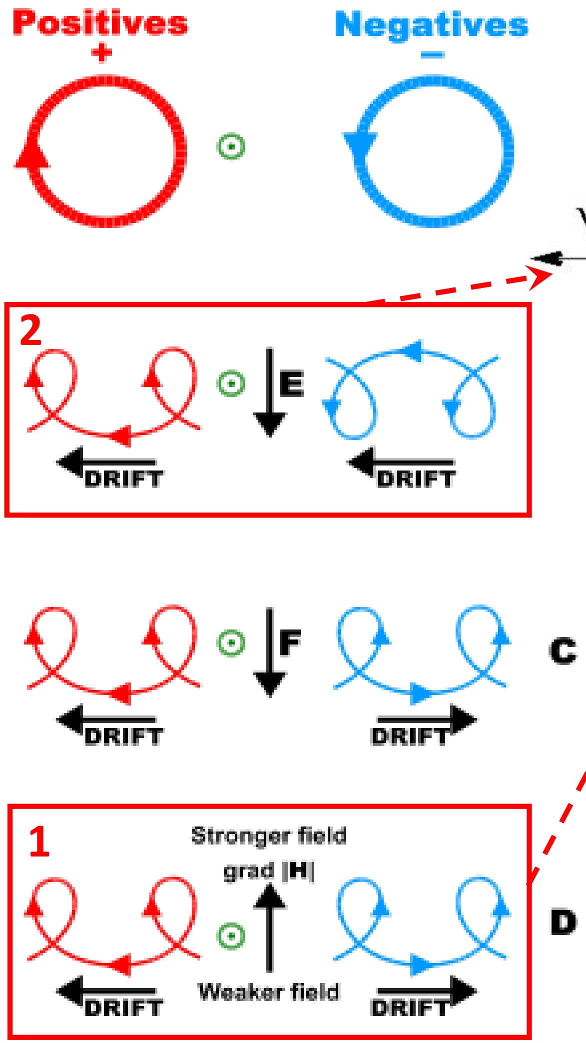


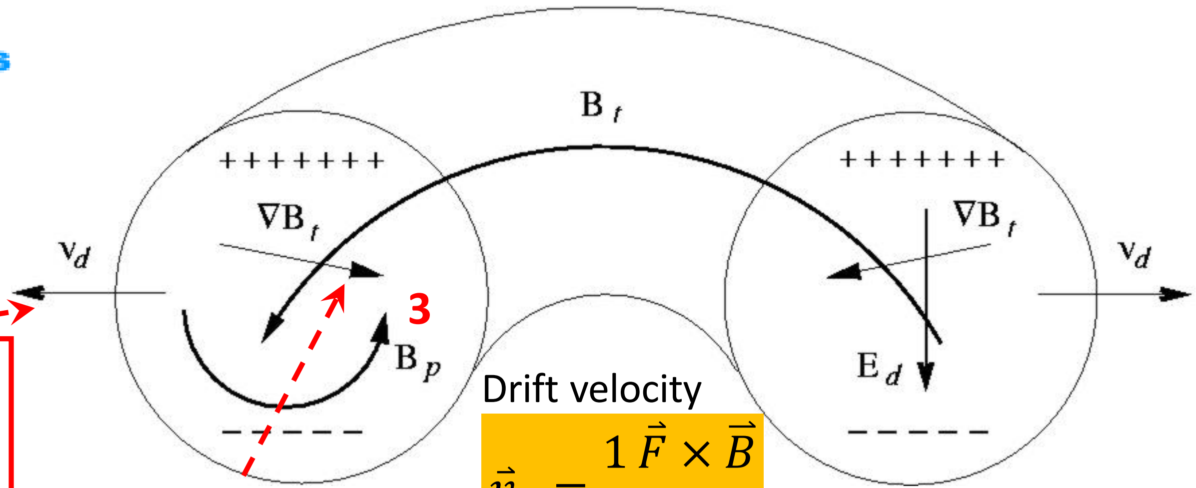
$$(v_{||}/v_\perp)_{\rm crit} = \sqrt{B_{\rm max}/B_{\rm min} - 1}$$



Magnetic confinement

Third step: closed end confinement





Drift velocity

$$\vec{v}_F = \frac{1}{q}\frac{\vec{F}\times\vec{B}}{\boldsymbol{B}^2}$$

Final step: closed end confinement with $\mathbf{B_p}$

Poloidal field $\mathbf{B_p}$ is needed (**3**) to shorcircuit particle drifts:

- Tokamak

  $\mathbf{B_p}$ is generated by plasma carrying current

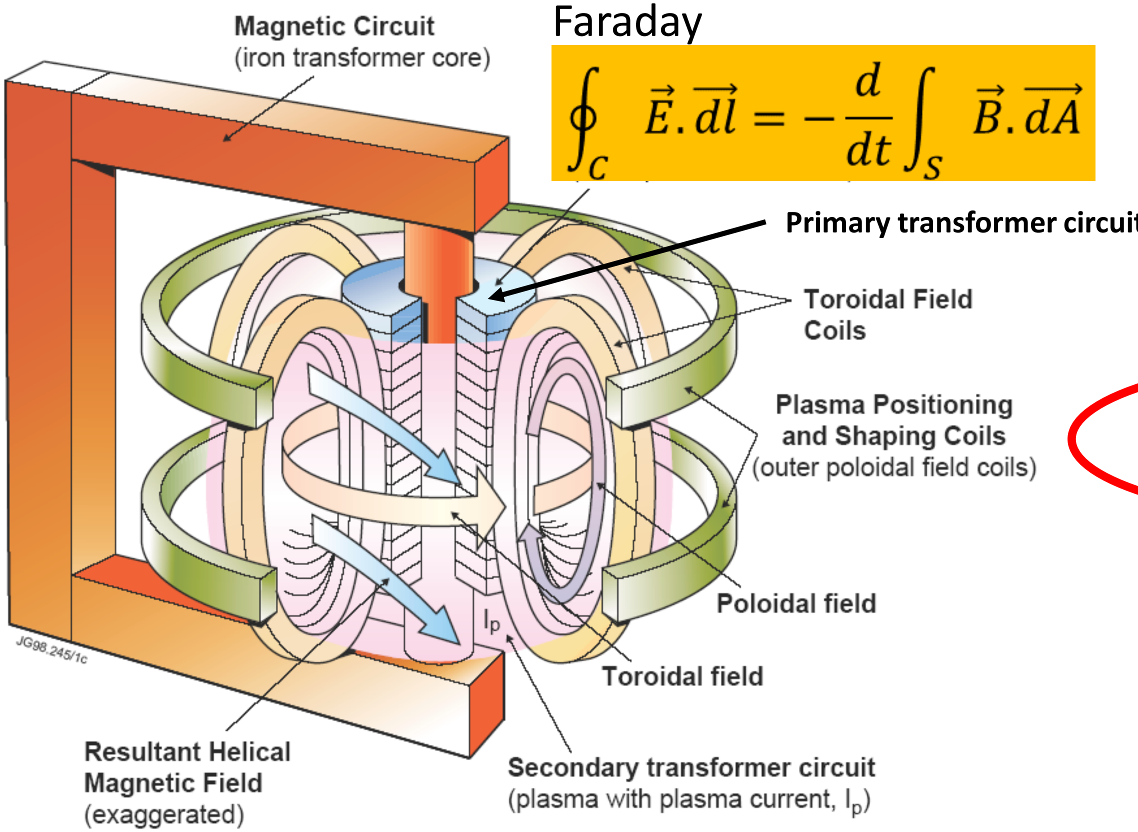
- Stellarator

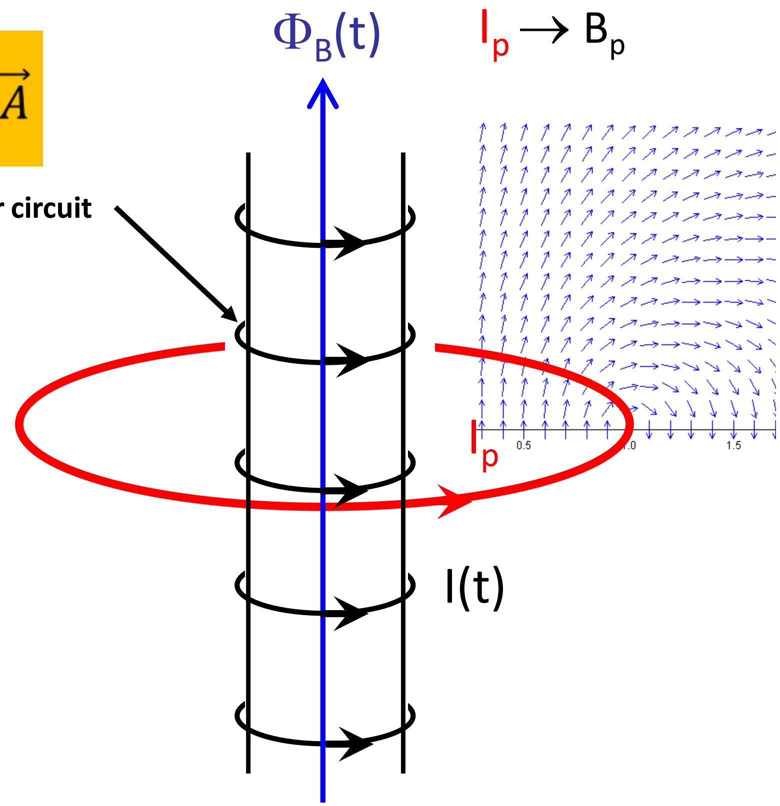
  $\mathbf{B_p}$ is generated externally with extra **B**-field coils.

Magnetic confinement: **TOKAMAK**

Faraday

$$\oint_C \vec{E}.\overrightarrow{dl} = -\frac{d}{dt}\int_S \vec{B}.\overrightarrow{dA}$$



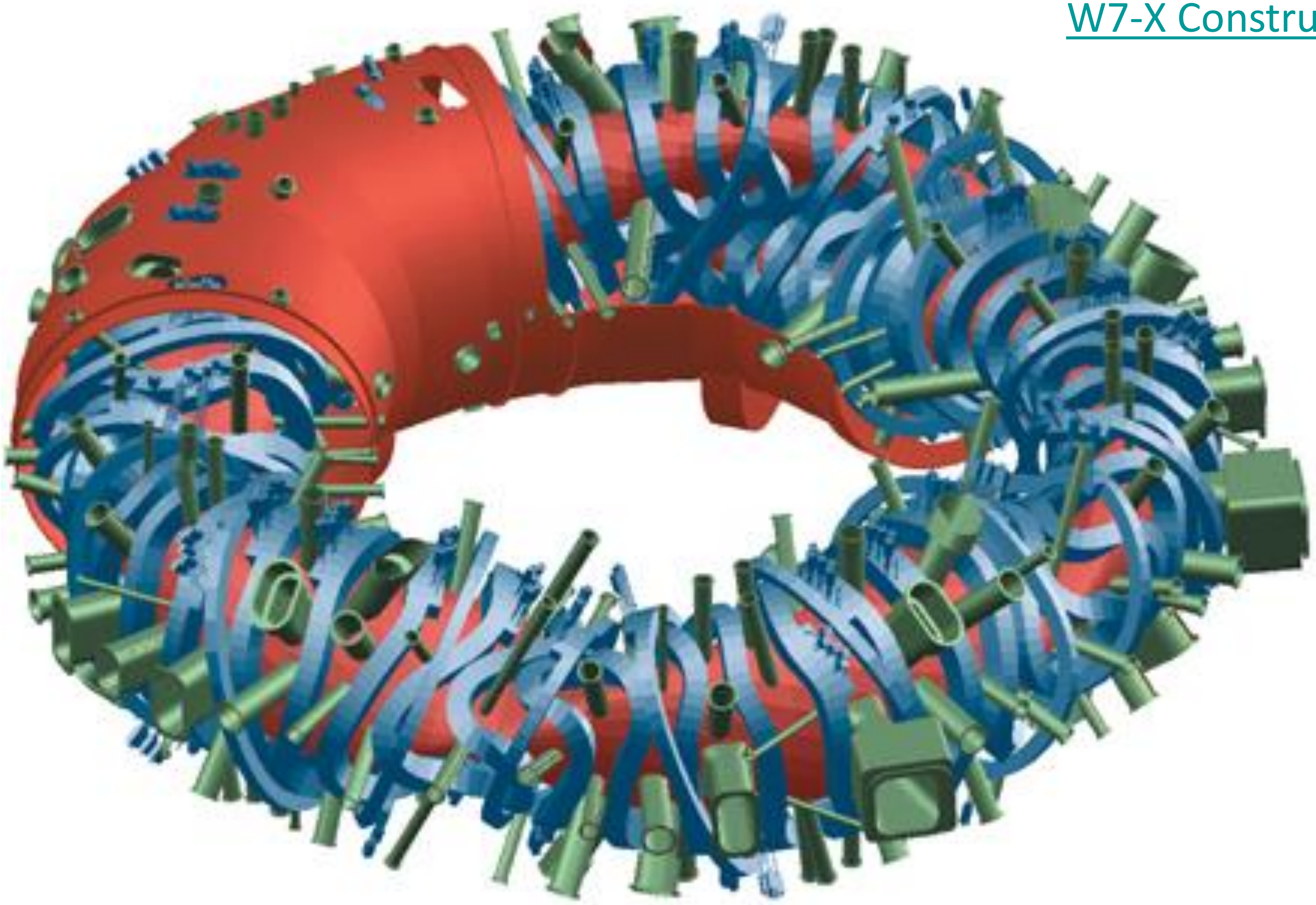


- ✓ Advantages: simpler planar coils, easier to build, basically 2-D, better confinement properties due to axisymmetric configuration.

- ✓ Drawbacks: inherently pulsed in pure ohmic regime, confinement depends on plasma itself, subjected to disruptions.

Magnetic confinement: **STELLARATOR**

W7-X Construction



Advantages: magnetic configuration is imposed externally, no plasma current, no disruptions
Drawbacks: highly 3D structure, harder to build, harder to make theoretical predictions.

Plasma heating

Initial start-up phase → Q=0; Q<1

•Ohmic Heating (Tokamaks): Transformer induced current (I_p) also heats the plasma by **Joule** effect. But limited by $\rho_p \sim T^{-3/2}$.
•Heating by electromagnetic waves (GHz – MHz):

- **E**lectron **C**yclotron **R**esonant **H**eating (**ECRH**)
- **I**on **C**yclotron **R**esonant **H**eating (**ICRH**)
- **L**ower **H**ybrid **H**eating (**LH**)

•Heating by **N**eutral **B**eam **I**njection (**NBI**): Highly energetic particle beams (several tens of keV) are injected in the plasma, which is heated by collisions with the beam particles.

Ignition phase → Q>1; Q=∞ ("ignited" plasma)

Once fusion reactions occur, α particles (3.5 MeV kinetic energy) are confined by B-fields and heat the plasma before their removal as helium ashes. They are responsible for maintain the plasma hot enough to keep the fusion reactions rate. Moreover **ECRH** and **NBI** can still be used for stability and non inductive current drive purposes, particularly in the tokamak case. Plasma heating by α particles is one of the key issues until unresolved (JET & ITER).

Power balance in a nuclear fusion device

The power balance of a fusion reactor involves different energy sources and sinks that balance in steady state (constant plasma energy W_p):

$$S_\alpha + S_H = S_B + S_K$$

S_α is the heating power coming from fusion-released particles (α particles).
S_H is the external input heating power (generaly ohmic and auxiliary as ECRH and NBI injection).
S_B Bremsstrahlung + line radiation + synchrotron radiation (no contribution at high T).
S_K diffusive heat flux through the plasma boundary

Expressions for the sources and sinks can be obtained under certain approximations [Freidberg(2008)]

$$S_\alpha = K_\alpha \frac{\langle \sigma v \rangle}{T^2} p^2 \qquad S_B = K_B \frac{p^2}{T^{3/2}} \qquad S_\kappa = K_\kappa \frac{p}{\tau_E}$$

constants (K_α, K_B, K_κ)

Plasma pressure: p
Plasma temperature: T
Energy confinement time: τ_E (measured experimentally as W_p / S_α , S_H=0)

Power balance in a nuclear fusion device

The ignition condition is reached when the α particles-heating by itself is sufficient to counterbalance the losses, i.e.

$$S_\alpha \geq S_B + S_k$$

Taking the previous definitions:

$$p\tau_E \geq \frac{K_\kappa T^2}{K_\alpha \langle \sigma v \rangle - K_B T^{1/2}}$$

Ideal ignition criterion

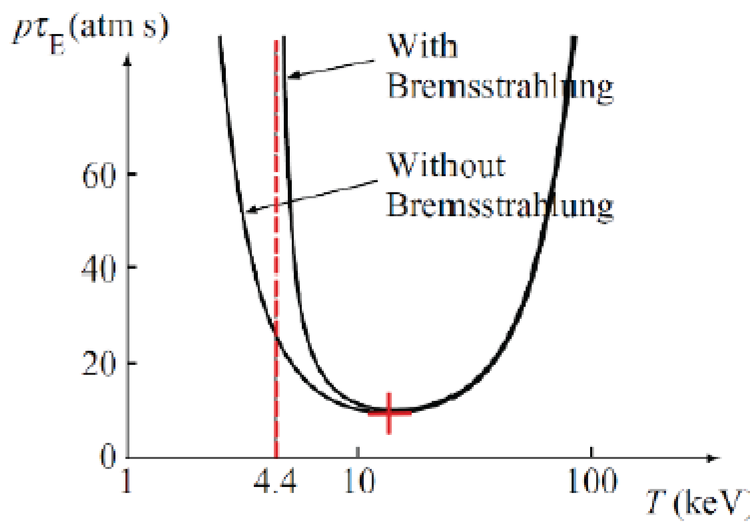
Where $p\tau_E$ is the Lawson parameter or fusion product.

Minimum T to plasma ignition:

$$K_\alpha \langle \sigma v \rangle - K_B T^{1/2} = 0$$

$T_{min} \geq 4.4$ keV

For T $\cong$ 15 keV $\rightarrow (p\tau_E) \cong 10$ atm · s



How large a device?

The above discussion is meant to illustrate the importance of several plasma parameters:

- Temperature $T=T_i=T_e$
- Density $n = n_i = n_e$ (plasma neutrality)
- Pressure $p = p_i + p_e = 2nT$ (for isothermal plasma)

• For fusion power to ignite a plasma:

- There has to be sufficient density of deuterium and tritium ions (n_i);
- The reacting ions have to be hot enough (T_i);
- The energy from the fusion α's must be confined for long enough (τ_E).
- Energy confinement time τ_E increases with the square of the device size → a large machine is needed.

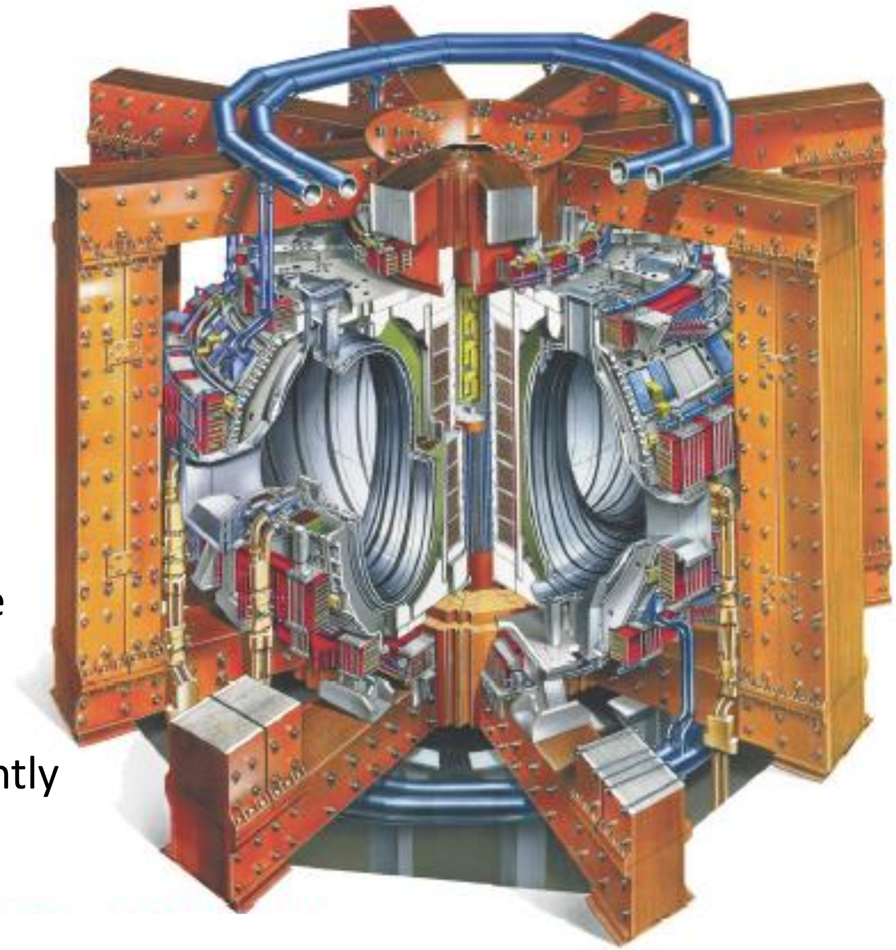
• The fusion triple product ($n_i \cdot T_i \cdot \tau_E$) and the ion temperature (T_i) must both be large enough (below a certain temperature the fusion reaction probability is too small)

pressure (ni(0)Ti(0)) ≥ 2 atmospheres; $n_i(0) \cdot T_i(0) \cdot \tau_E > 6 \cdot 10^{21}$ m^{-3} keV s
confinement time > 5 seconds
plasma ion temperature ≈ 100-200 Million °C

JET
(Joint European Torus)

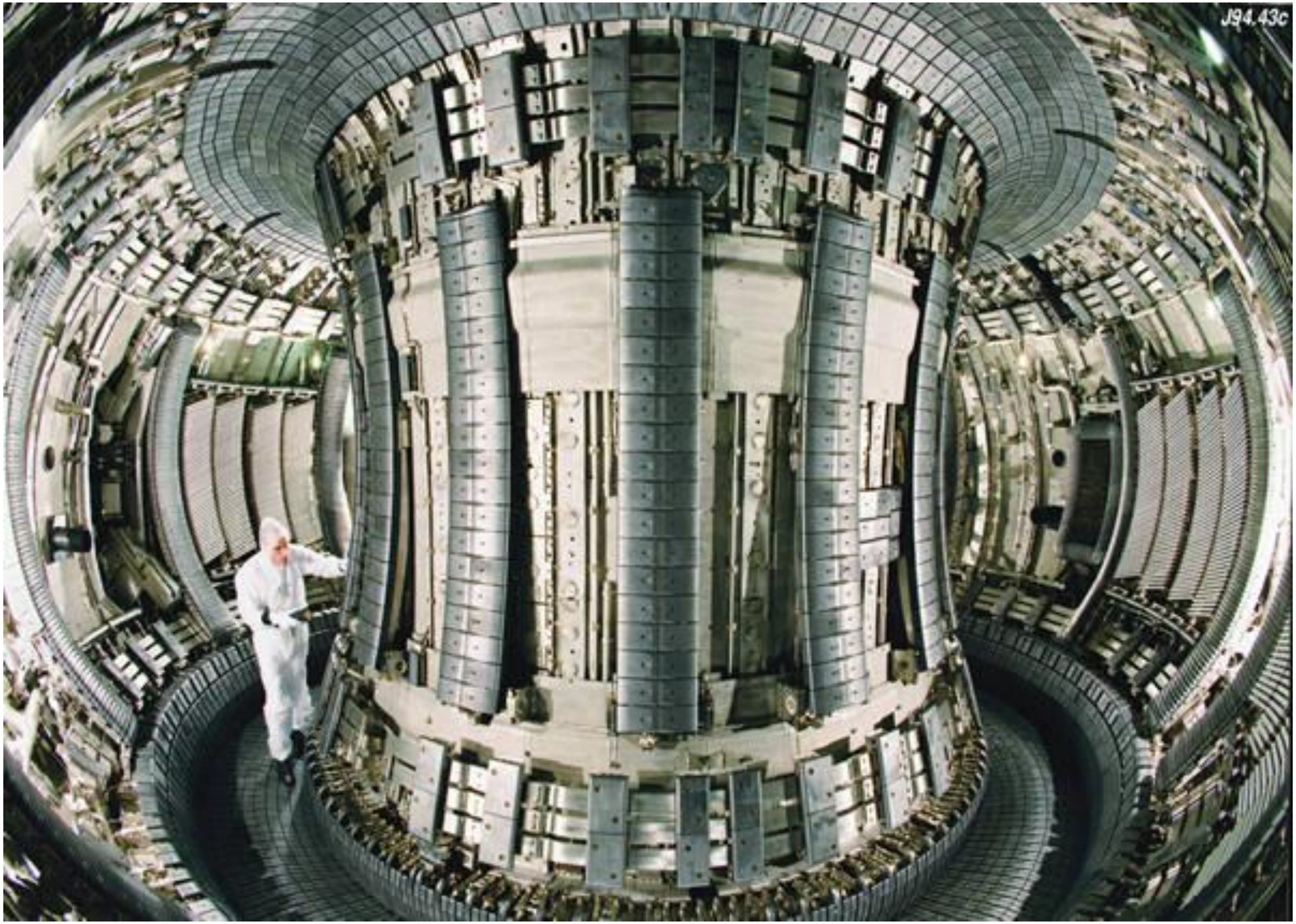
- The Joint European Torus ("JET") is the largest magnetic fusion test device in the world.
- Situated at Culham, Oxfordshire, JET:
  - was constructed between 1978 and 1983;
  - has operated from 1983 to present;
- The participating countries are the 15 EU nations + Switzerland
- The Project has a capital investment of over £500 Million and an Annual Budget of around £53 Million.

✓ Torus major radius 3.1 m
✓ Vacuum vessel 3.96 m high x 2.4m wide
✓ Plasma volume 80 m^3
✓ Plasma current up to 5 MA
✓ Main confining field up to 4 Tesla (recently upgraded from 3.4 Tesla).
✓ Pulse length 20 - 60 s
✓ 38 MW non inductive plasma heating

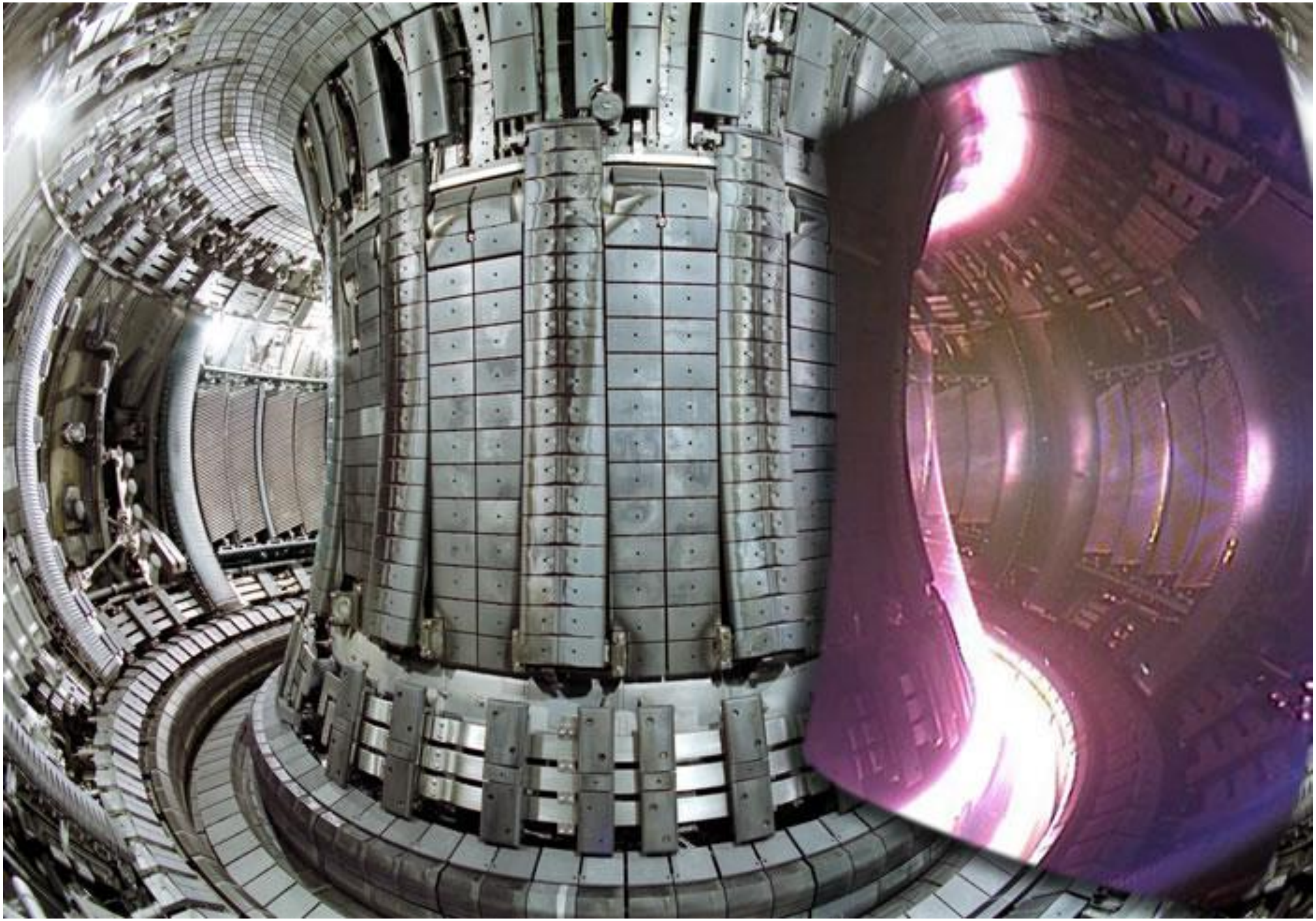


JET: 1/3 Scale model for ITER

JET
(Joint European Torus)



JET
(Joint European Torus)



Progress in magnetic confinement fusion

Large Tokamaks in the world:

- Joint European Torus (JET)
- Tokamak Fusion Test Reactor (TFTR)
- Doublet III-D Tokamak (DIII-D)
- Japanese Tokamak – 60U (JT-60U)

Have demonstrated significant progress in:

—Confinement & Transport Physics (H-Mode & Divertor);

—Fusion Technology (i.e. heating systems);

—Approaching the plasma ignition conditions (Q=0.65) ;

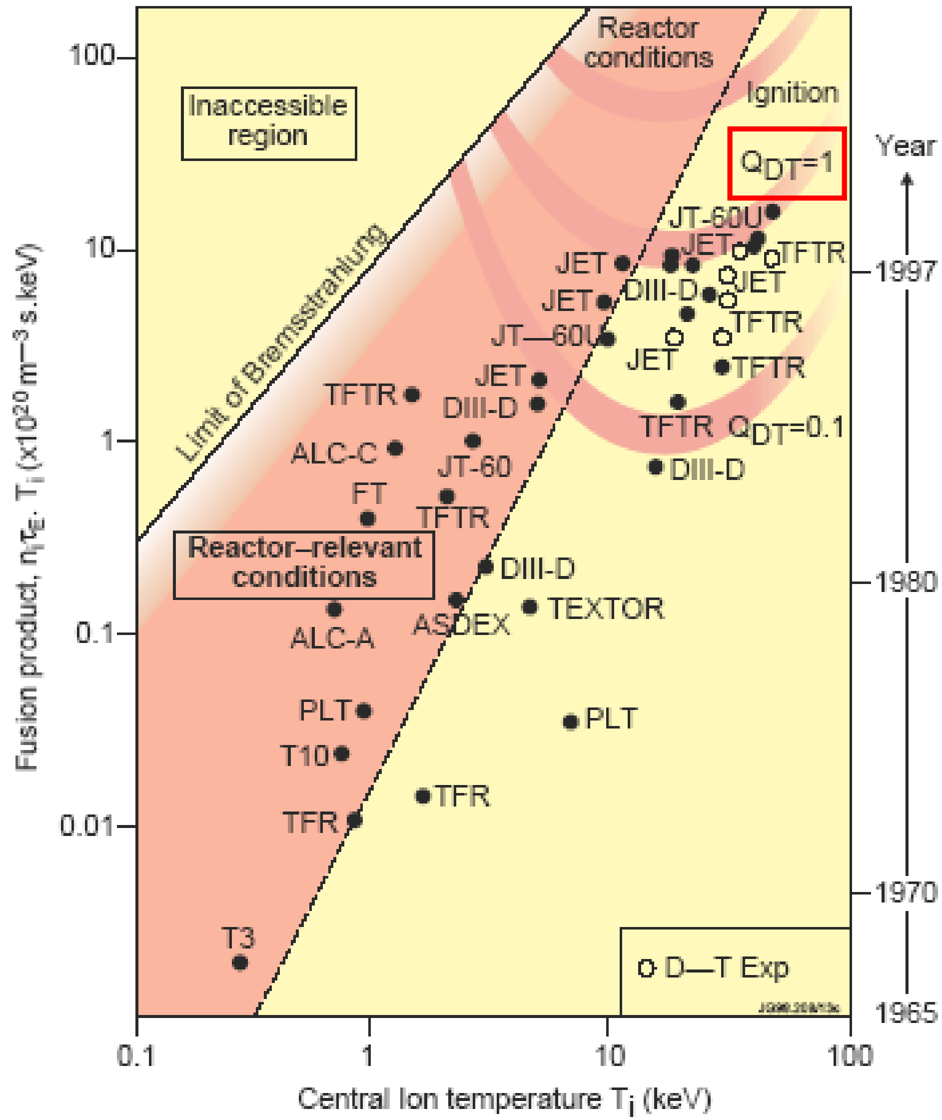
—Predicting the behaviour of a reactor plasma;

—Controlling impurities which enter the plasma;

—Operating with Tritium fuel;

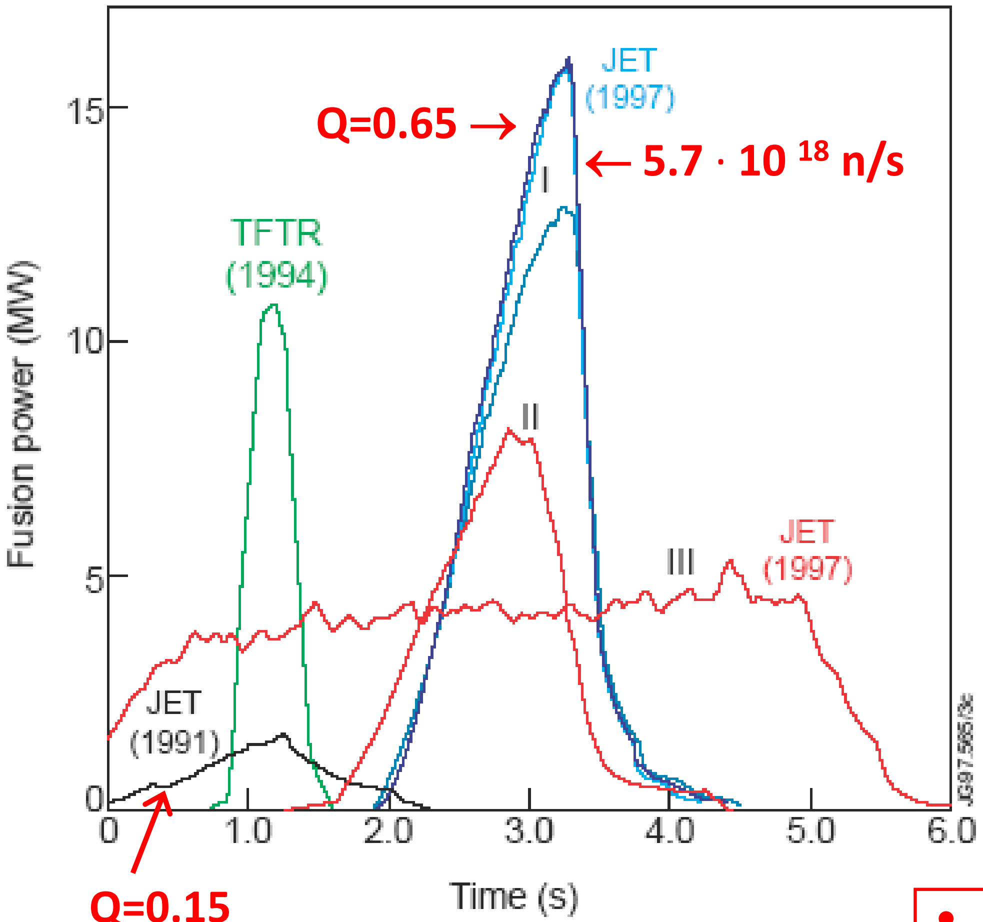
—Heating by α particles;

—$n_i(0) \cdot T_i(0) \cdot \tau_E > 1.5 \cdot 10^{21}$ m^{-3} keV s



Progress in magnetic confinement fusion

D–T experiments in JET and TFTR:
Testbed for ITER



Goal of experiments in JET:

- Attempt maximum fusion power
- Observe ‘α’ particle heating
- Demonstrate Tritium operation
- Replace divertor targets after the experiments using remote handling

The diagram encompasses:

- One pulse with 11% T in D–T mixture in JET (1991);
- A result from the D–T studies on TFTR (1993 to 1997);

High fusion power and quasi-steady-state fusion power from more than 200 pulses with >40% T in D–T plasmas during the experiments of 1997. 3 Mw of ‘α’ particle heating were achieved.

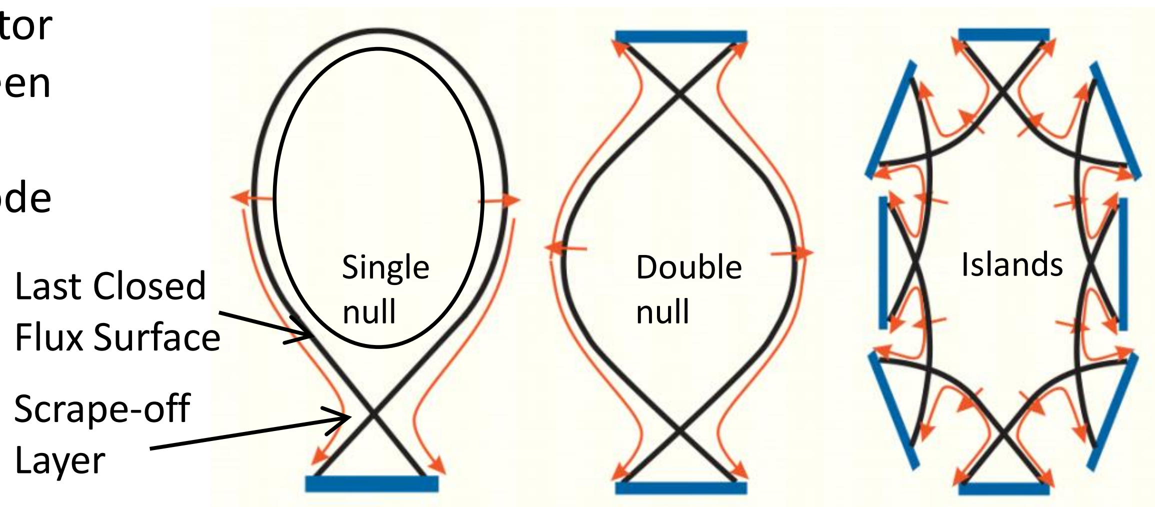
- Recent D-T experiments in Dec. 2020!!

Controlling impurities

- Impurities are a major threat to reactor success
- In an ignited plasma two primary sources of impurities exist:
  - Helium "ashes" from the fusion reaction
  - Material impurities from interactions with the high-Z Plasma Facing Components (PFC)
- Impurities must be controlled since they:
  - Radiate energy, and reduce the plasma temperature
  - Dilute the fuel, thereby preventing ignition
- The "Magnetic Divertor" is a in-vessel device for controlling impurities and remove alpha particles power. Tested successfully in JET experiments.

•Three different divertor concepts have been compared.

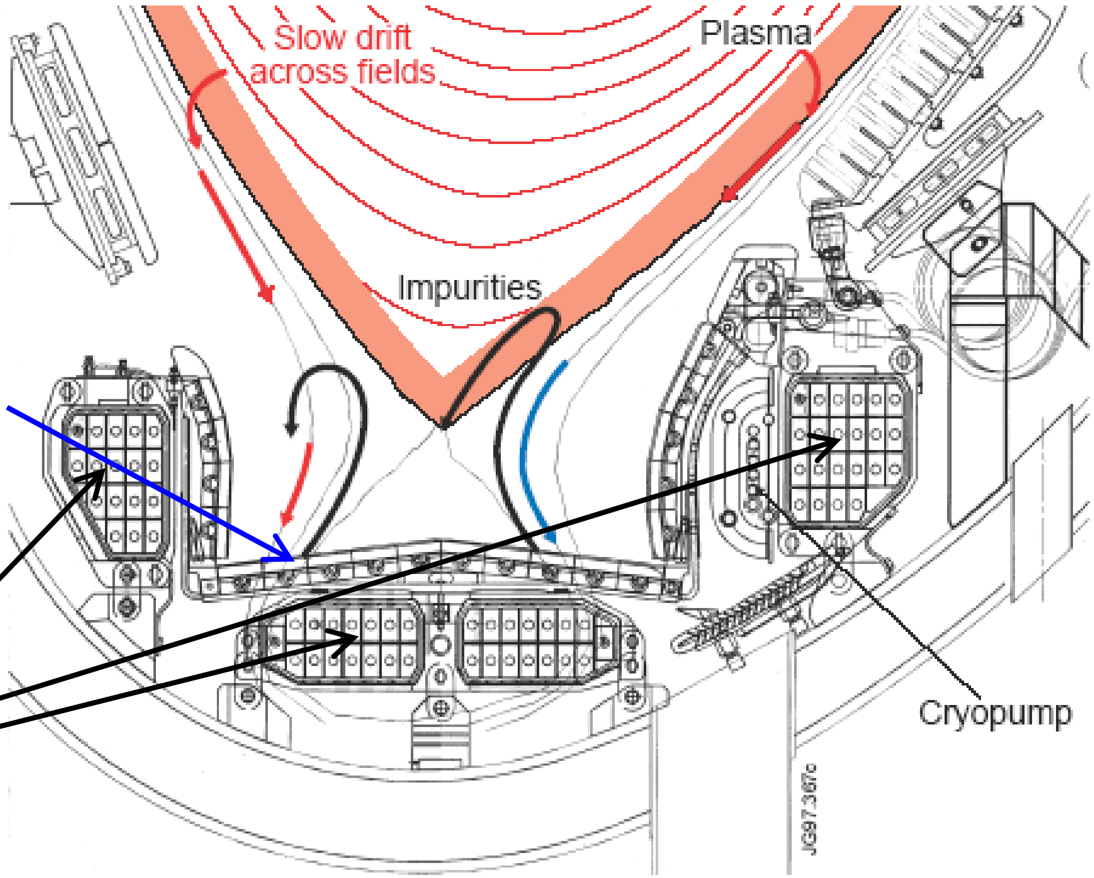
•Results agree with code predictions.



Controlling power and impurities particles exhaust

Mark I Pumped Divertor in JET

Connection length
From SOL to
Divertor CFC targets
L ~ 30 m



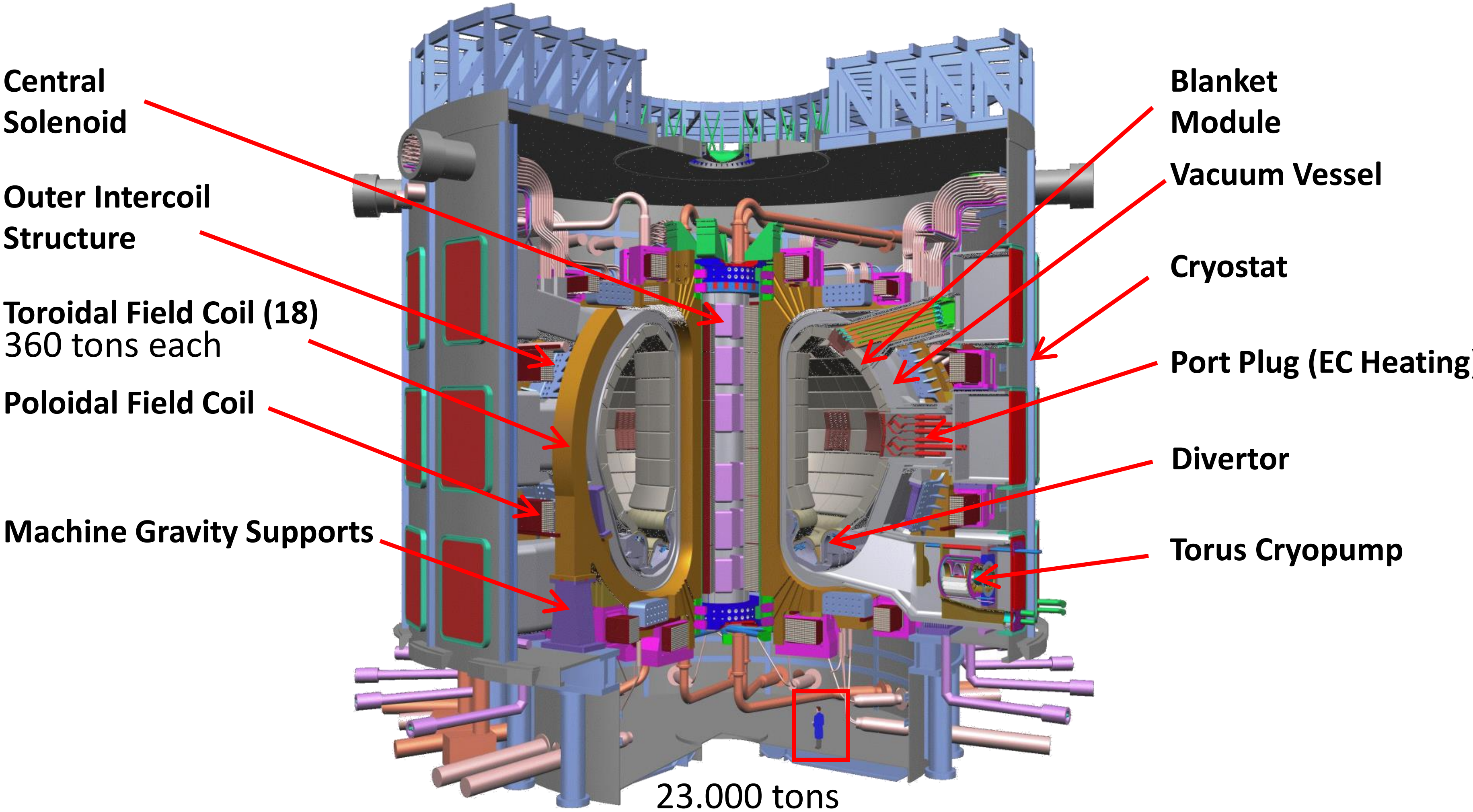
Poloidal coils

- Impurities (C, Be) are produced by ion impact on target and are ionised in the plasma and returned to target

CONTROLLED FUSION

ITER

ITER



ITER WILL BE A NUCLEAR MACHINE $\rightarrow$ $1.5 \cdot 10^{20}$ neutrons/s

ITER Location

Caradache (France)

Tokamak pit

ITER 360Tour

ITER parameters

Total fusion power	500 MW (700 MW)
Q = fusion power/auxiliary heating power	≥10 (inductive)
Average neutron wall loading	0.57 MW/m^2 (0.8 MW/m^2)
Average neutron flux	$1.5\cdot10^{20}$ neutrons/s
Plasma inductive burn time	≥ 300 s
Plasma major radius	6.2 m
Plasma minor radius	2.0 m
Plasma current (inductive, I_p)	15 MA (17.4 MA)
Vertical elongation @ 95% flux surface/separatrix	1.70/1.85
Triangularity @ 95% flux surface/separatrix	0.33/0.49
Safety factor @ 95% flux surface	3.0
Toroidal field @ 6.2 m radius	5.3 T
Plasma volume	837 m^3
Plasma surface	678 m^2
Installed auxiliary heating/current drive power	73 MW (100 MW)
Tritium	~ 1kg (from global inventory)

28.8 Ci/mmol = $4.8\cdot10^3$Ci/g = $2\cdot10^{14}$Bq/g = 0.2PBq/g -> 200 PBq

ITER Objectives

Programmatic

- Demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.

Technical

- Achieve a non steady state Q ≥ 10 for burns durations of 300-500 s.
- Demonstrate extended burn of D-T plasmas, with non-inductive steady state (~3000 s) as the ultimate goal (Q=5). Planned for beyond 2035.
- Integrate and test all essential fusion power reactor technologies and components:
  - Unprecedented size of superconducting magnets
  - First wall material (high heat and neutron fluxes)
  - Extremely high heat flux in divertor (first divertor with all-tungsten PFC)
  - Remote handling for maintenance of activated structures
- Demonstrate Tritium breeding Blankets Module concepts (TBM’ s)
- Development of a disruption management program
- Demonstrate safety and environmental acceptability of fusion

CONTROLLED FUSION

Fusion technology

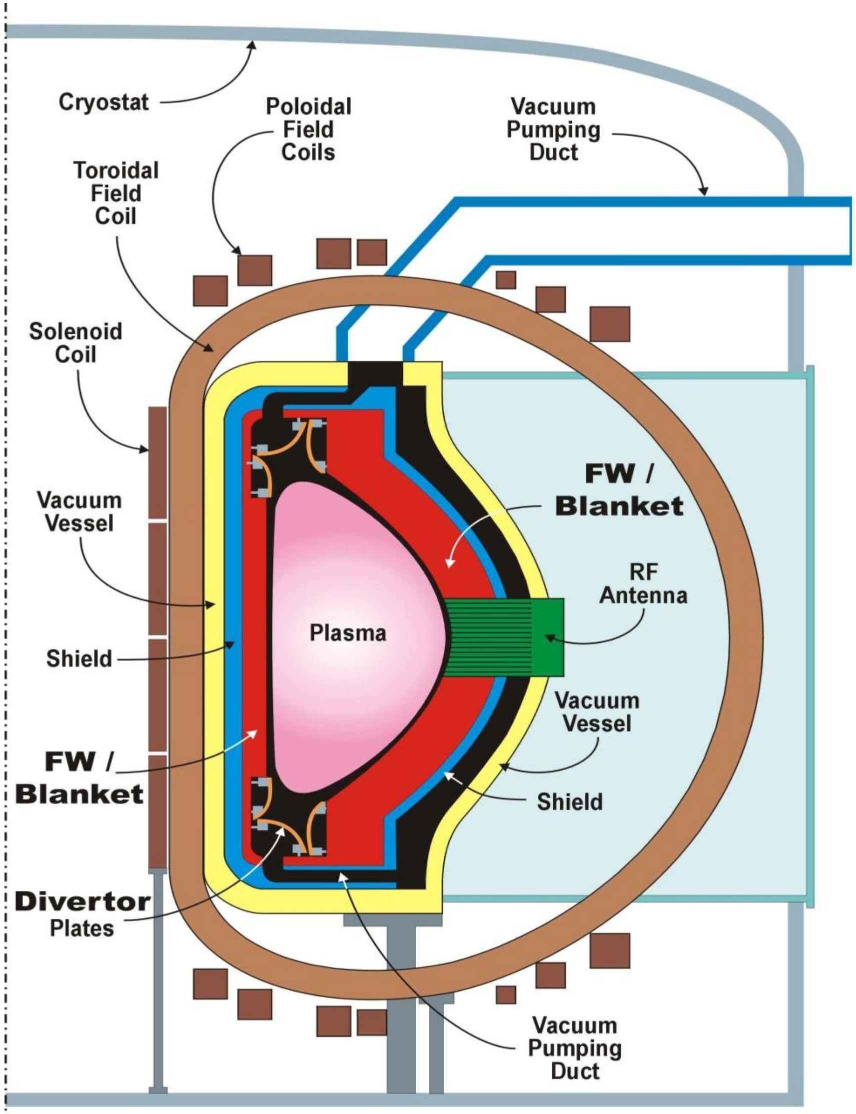
Nuclear Fusion Technology (NFT)
Fusion Power & Fuel Cycle Technology

NFT Components from the edge of the Plasma to TF Coils (Reactor "Core")

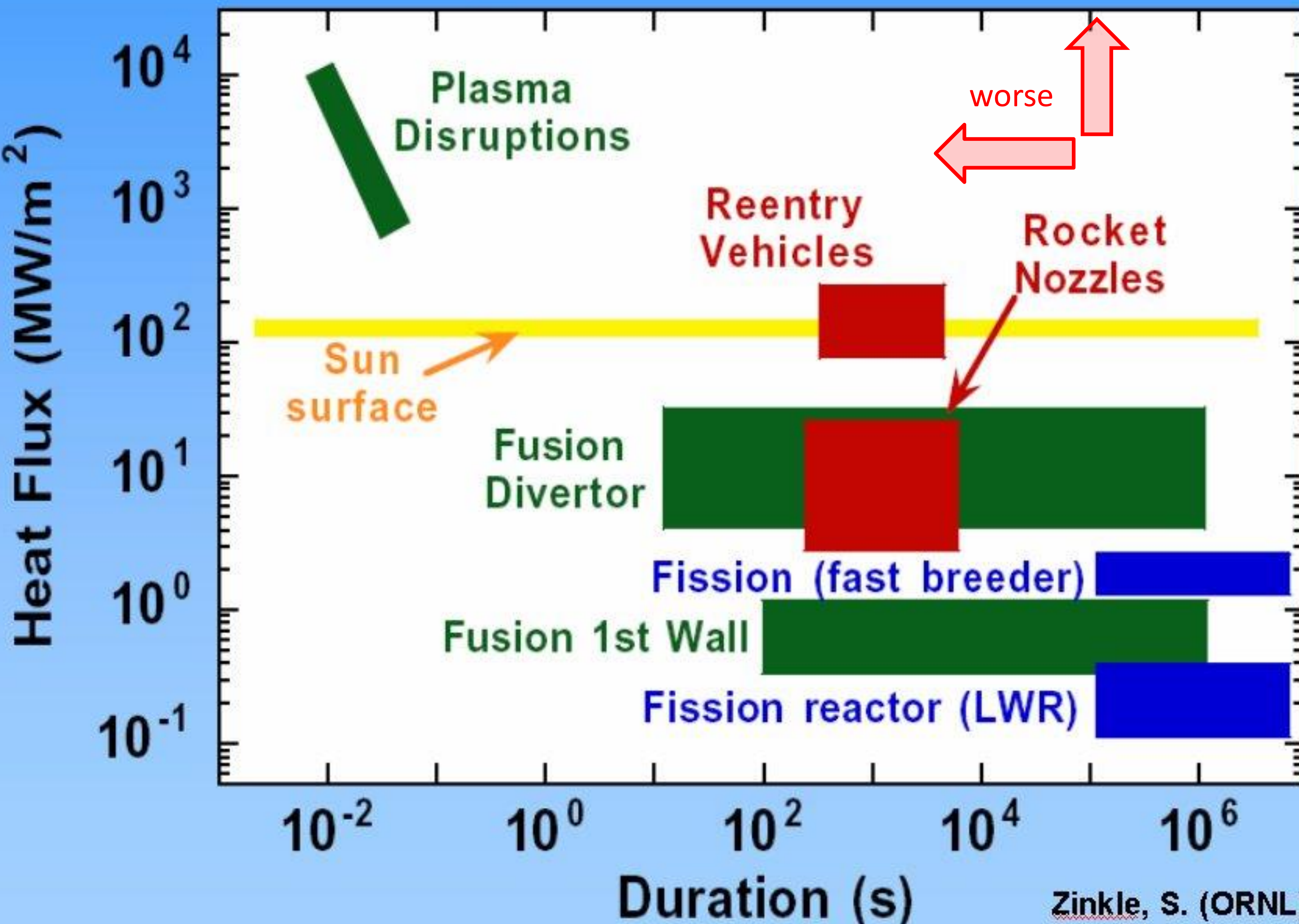
1. Blanket components
2. Plasma facing and high heat flux components
    a. Divertor, Limiter
    b. RF antennas, launchers, wave-guides, etc.
3. Vacuum Vessel & Shield Components

Other Components affected by the Nuclear Environment

4. Tritium Processing Systems
5. Instrumentation and Control Systems
6. Remote Maintenance Components
7. Heat Transport and Power Conversion Systems

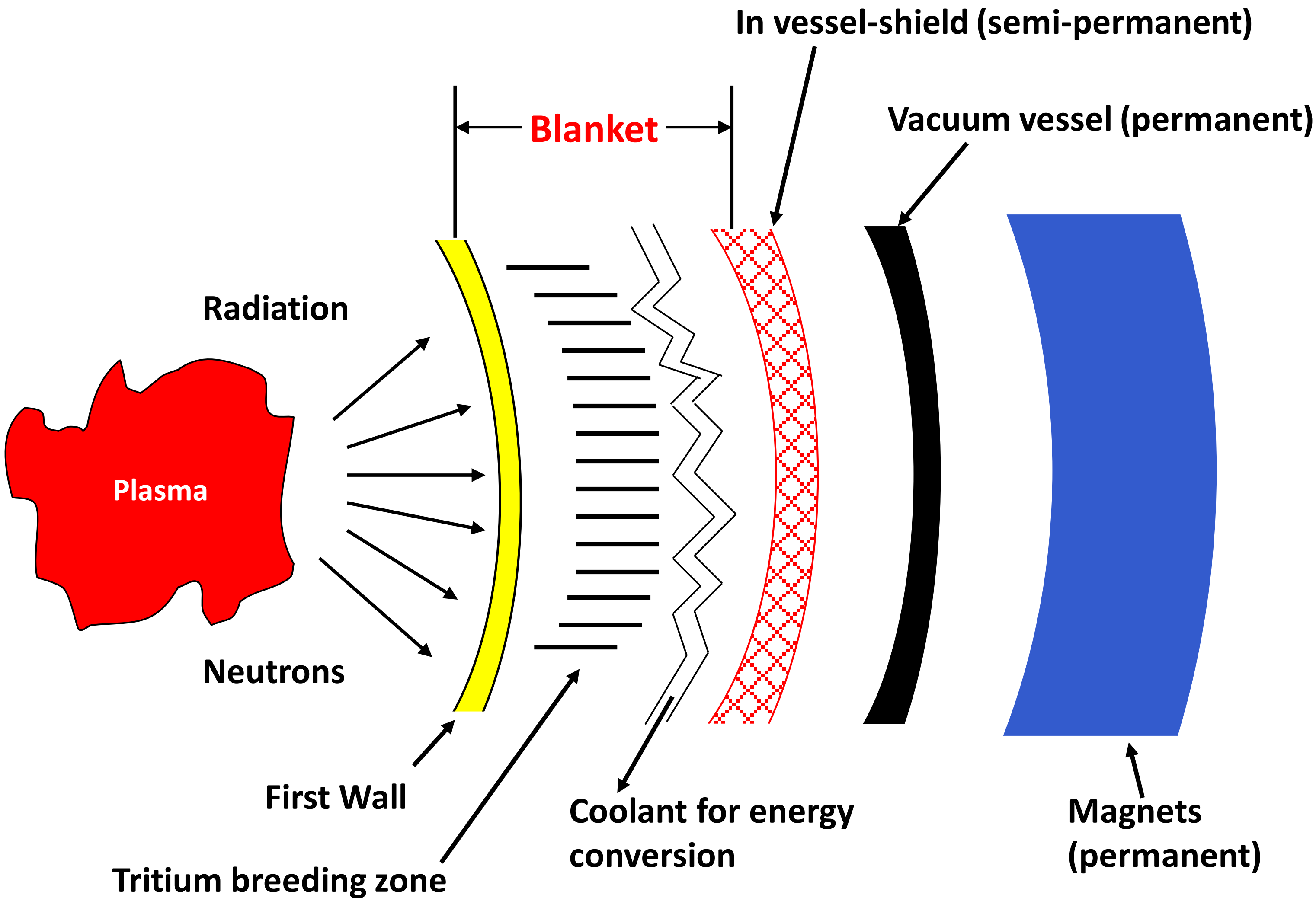


Comparison of Heat Fluxes



Zinkle, S. (ORNL)

Nuclear Fusion Technology (FNT)
Fusion Power & Fuel Cycle Technology



Blanket & First Wall Functions

1. Power Extraction
   a) Convert kinetic energy of neutrons and secondary gamma-rays into heat (collected by the coolant)
   b) Absorb plasma radiation on the first wall
   c) Extract the heat (at high temperature, for energy conversion)
2. Tritium Breeding
   a) Tritium breeding, extraction, and control
   b) Must have lithium in some form for tritium breeding
3. Physical Boundary for the Plasma
   a) Physical boundary surrounding the plasma, inside the vacuum vessel
   b) Provide access for plasma heating, fueling, diagnostics
   c) Must be compatible with plasma operation
   d) Innovative blanket concepts can improve plasma stability and confinement
4. Radiation Shielding of the Vacuum Vessel and the Magnets

Blanket Materials

1. Tritium Breeding Material (Lithium in some form)

   Liquid: Li, LiPb ($^{83}Pb\ ^{17}Li$), lithium-containing molten salts

   Solid: Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3 (high tritium release, stability)

2. Neutron Multiplier (for most blanket concepts)

   Beryllium (Be, $Be_{12}Ti$)

   Lead (in LiPb)

3. Coolant

   – Li, LiPb – Molten Salt – Helium – Water

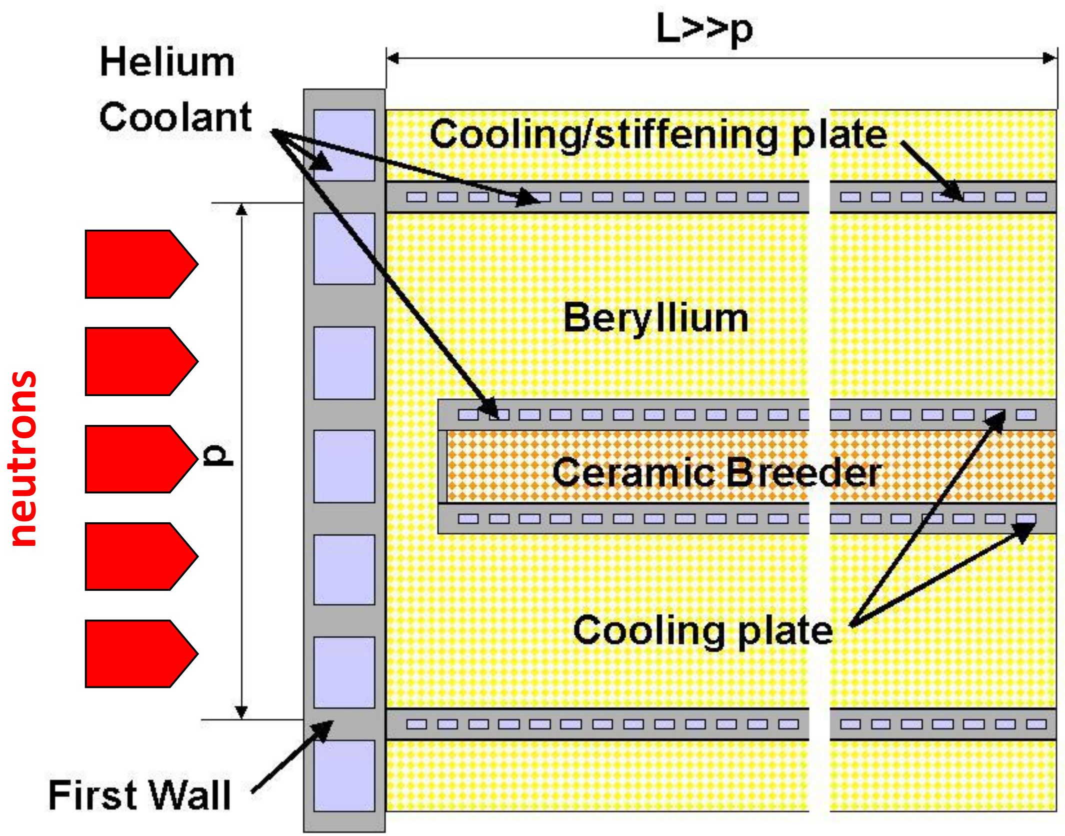
4. Structural Material

   Ferritic/Martensitic Steel (accepted worldwide as the reference for DEMO)

   Long-term: Vanadium alloy (compatible only with Li, V5Ti) and SiC/SiC

5. MHD insulators (for concepts with self-cooled liquid metals)
6. Thermal insulators (only in some concepts with dual coolants)
7. Tritium Permeation Barriers (in some concepts)
8. Neutron Attenuators and Reflectors

A Helium-cooled Li-ceramic breeder (HCPB) concept: example



Material Functions

- Beryllium (pebble bed) for neutron multiplication
- Ceramic breeder (Li_4SiO_4, Li_2TiO_3, Li_2O, etc.) for tritium breeding
- Helium purge (low pressure) to remove tritium through the "interconnected porosity" in ceramic breeder
- High pressure Helium cooling in structure (ferritic steel)
- Several configurations exist (e.g. wall parallel or "head on" breeder/Be arrangements)

$n + {}^{6}Li \rightarrow T + {}^{4}He$

$n + {}^{7}Li \rightarrow T + {}^{4}He + n$

6 different Test Blanket Systems (TBSs) will be tested in ITER.

CONTROLLED FUSION

..some final remarks

Summary on the world energy resources available

Reaction	Key element	Content in lithosphere (g/g)	Content in ocean (g/g)	Specific energy (J/g)	Earth energy resources (J)
$C + O_2 \rightarrow CO_2 + 4.2$ eV	Coal, Oil, Gas	—	—	$\sim 3\cdot 10^{4}$	$\sim 5\cdot 10^{23}$
$n + U \rightarrow$ fragments + 200 MeV	^{238}U	$4\cdot 10^{-6}$	$1.5\cdot 10^{-9}$	$0.82\cdot 10^{11}$	$\sim 3\cdot 10^{28}$
$n + Th \rightarrow$ fragments +200 MeV	^{232}Th	10^{-5}	$<5\cdot 10^{-10}$	$0.82\cdot 10^{11}$	$\sim 8\cdot 10^{28}$
$D + D \rightarrow$ $^3He + n + 3.3$ MeV $D + D \rightarrow T + p + 4.0$ MeV	D	$1.5\cdot 10^{-6}$	$1.6\cdot 10^{-5}$	$0.9\cdot 10^{11}$	$\sim 2\cdot 10^{30}$
$D + T \rightarrow$ $^4He + n + 17.6$ MeV	^6Li	$5\cdot 10^{-5}$	10^{-7}	$2.9\cdot 10^{11}$	$\sim 10^{30}$
$D + {}^3He \rightarrow$ $^4He + p + 18.3$ MeV	^3He	$7.3\cdot 10^{-19}$	—	$4.9\cdot 10^{11}$	$\sim 10^{15}$

It is accepted for estimation that the lithosphere mass up to 300 m depth is equal to 10^{23} g approx. and the ocean mass is equal to 10^{24} g approx.

Tritium availability for ITER:

- ✓ Expected total mass of tritium consumed: 14.5 kg (1kg/year during approx. 15 years)
- ✓ Maximum inventory around 2020 (considering CANDU reactors operation schedule)
- ✓ Present estimates are just sufficient for ITER DT program (achieve required neutron wall loading)
- ✓ No other major tritium consumer considered.

Fusion Roadmap (EU)

- ITER is the key facility in the roadmap:
  - ✓ Risk mitigation: ITER operation will be prepared in JET and JT-60SA.
- A solution for the heat exhaust in the fusion power plant is needed:
  - ✓ Main challenge towards NF realisation.
  - ✓ ITER baseline extrapolation to fusion power plant?
  - ✓ Divertor test facility (DDT) is necessary.
- A dedicated neutron source is needed for material development (IFMIF):
  - ✓ Irradiation studies up to 30 dpa with NF neutron spectrum are needed.
  - ✓ Risk-mitigation materials (structural, plasma-facing, breeding blanket, divertor)
- The R&D to ensure tritium self-sufficiency should be strengthened:
  - ✓ ITER Test Blanket Module (TBM) will play leading role.
- DEMO design will benefit from the ITER experience.

Fusion Roadmap (EU)

- Industry must be involved early in the DEMO definition and design:

  ✓ Industry must be able to take full responsibility for the commercial fusion power plant after successful DEMO operation.

- The EU Stellarator programme should focus on the optimised HELIAS line:

  ✓ Long-term alternative to a Tokamak fusion power plant.
  ✓ W7X is the key Stellarator facility

- Theory and modelling effort in plasma and material physics is crucial:

  ✓ Extrapolate the available physics results to ITER and DEMO.

2021 UPDATE

Tokamaks

- JT-60SA (Japan) has reached superconductivity in all its magnets
- K-STAR (South-Korea) has achieved 20 seconds pulse at T_e=100×10^6 K
- HL-2M (China) reached first plasma in December 2020.
- New devices planned ⇒ CFETR (China), STEP (UK), SPARC (US)

Stellarators

- W7-X has demonstrated that magnetic configuration optimization aiming at reducing particle and energy transport is now a reality, opening new avenues for optimized designs not achievable in tokamaks.