جمعية المهندسين المصرية

جمعية المهندسين الكيميائيين

دعوة عامة

تتشرف

جمعية المهندسين المصرية وجمعية المهندسين الكيميائيين

بالمشاركة مع جمعية رواد الهندسة والتكنولوجيا

بدعوة سيادتكم لحضور ندوة بعنوان :

مفاعلات الاندماج النووي بين الحلم والحقيقة
الهيدروجين وقود المستقبل نحو طاقة نظيفة

يحاضر فيها

السيد الأستاذ الدكتور / شريف خليل

أستاذ البلازما والاندماج النووي بمركز البحوث النووية – هيئة الطاقة الذرية

السيد الدكتور مهندس / محمد الصاوي

خبير استراتيجيات الطاقة

وذلك يوم الأحد الموافق ٢٠١٨/١/١٤ في الساعة السادسة والنصف مساءاً

بمقر جمعية المهندسين المصرية ٢٨ ش رمسيس – القاهرة

والدعوة عامة لمن يهمه الأمر

أمين عام جمعية المهندسين الكيميائيين	أمين عام جمعية رواد الهندسة والتكنولوجيا	أمين عام جمعية المهندسين المصرية
مهندس / حسين أحمد النحاس	مهندس / شريف الصيرفي	مهندس إستشاري / حسب النبي أحمد عسل

FUSION ENERGY for the THE NEXT MILLENNIA

Dream & Reality

EGYPT

هيئة الطاقة الذرية
مركز البحوث النووية
قسم البلازما والأندماج النووى

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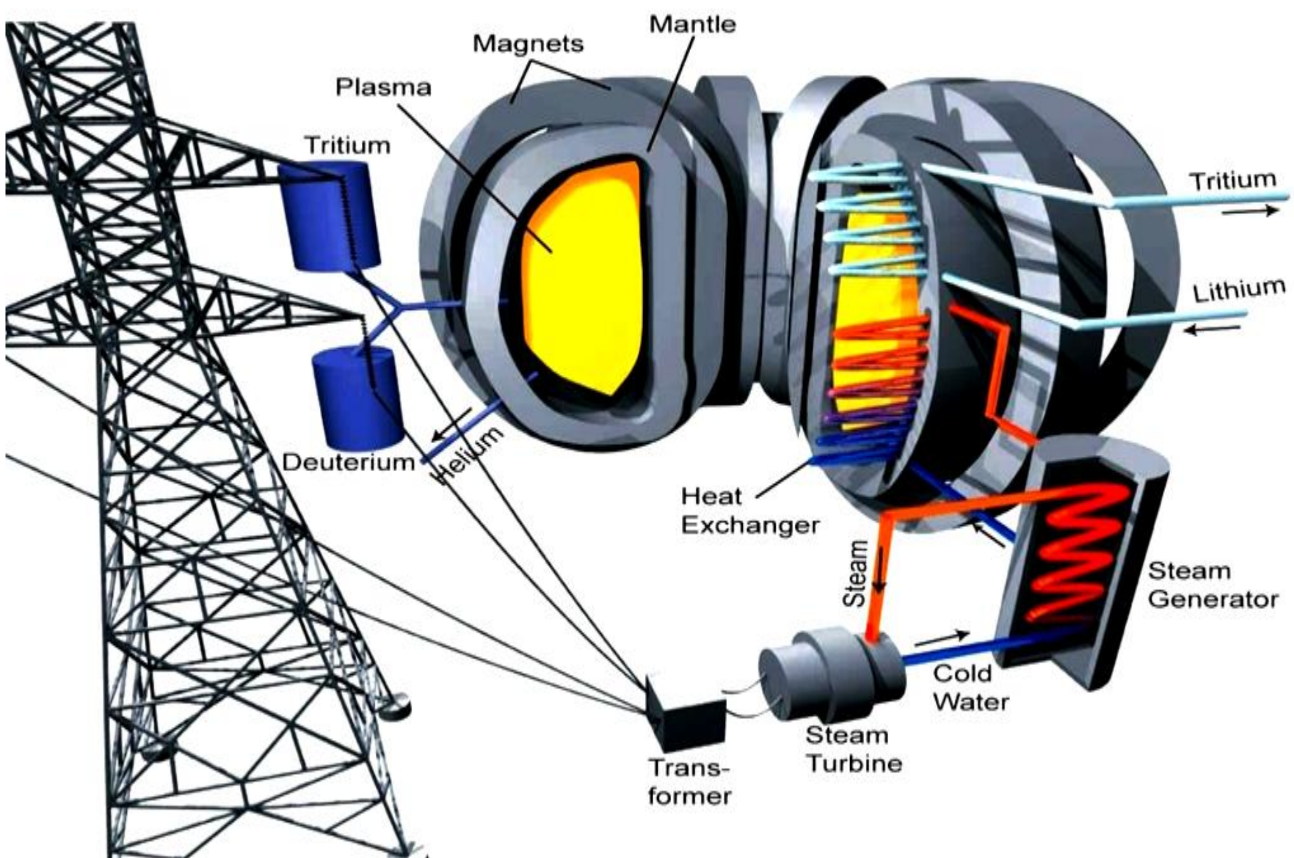


قسم البلازما والأندماج النووى
مركز البحوث النووية
هيئة الطاقة الذرية

a day without

NUCLEAR FUSION

is a day without sunshine!


ITER
For New Generation,
Micro-Sun on Earth

CREATING A STAR ON EARTH

Fusion

The Ultimate Energy Source for Humanity

ENERGY SOURCES and POLLUTION

(*)

Modern industries uses fuels that damage our lifes due to sulpher and nitrogen oxides comes from burning coal and oil

(*)

5.5 billion tons of carbon added each year to the atmosphere more than a ton for each person on the planet.

(*)

Since the beginning of the industrilization the content of carbon dioxide has increased by more than 25% due to the burning of fossil fuels

(*)

span methane has more than doubled and nitrous oxide gone up by 10%

(*)

Increasingly, it seems neither oil, nor coal, nor nuclear fission power can be counted on to meet future energy needs

ENERGY CONSUMTION

At present

Western European on the average uses 136 GJ energy/day
for an Indian is 13 GJ
for an Egyptian is 24 GJ

especially energy used in the form of electricity is a measure of the stage of development

Western European uses	**5,700 Kwh electricity/year**
in India it is	**356 Kwh**
in Egypt	**754 Kwh**

Accordingly

developing countries with 3/4 of the world's population
use 1/3 of the energy and 1/4 of the electricity produced in the world

It is clear that there is a strong need to move towards more industrialization and, consequently, more energy use in the developing world.

RECENT REPORTS
Inrenational Atomic Energy Authority (IAEA)
World Energy Council (WEC)

pessimistic about solar, wind and other new renewable energy resources

The IAEA estimates

only 1% of electricity will be generated from such sources in 2010

The WEC gives

1.5-2% of the total energy supply in 2020

NUCLEAR FISSION ENERGY

provides about 6% of the world's energy supply

17% of the electricity

(only slightly less than we get from hydro power)

NUCLEAR POWER from FISSION REACTORS

is facing concern regarding

safety, accidental radioactive releases , waste disposal and proliferation of nuclear material .

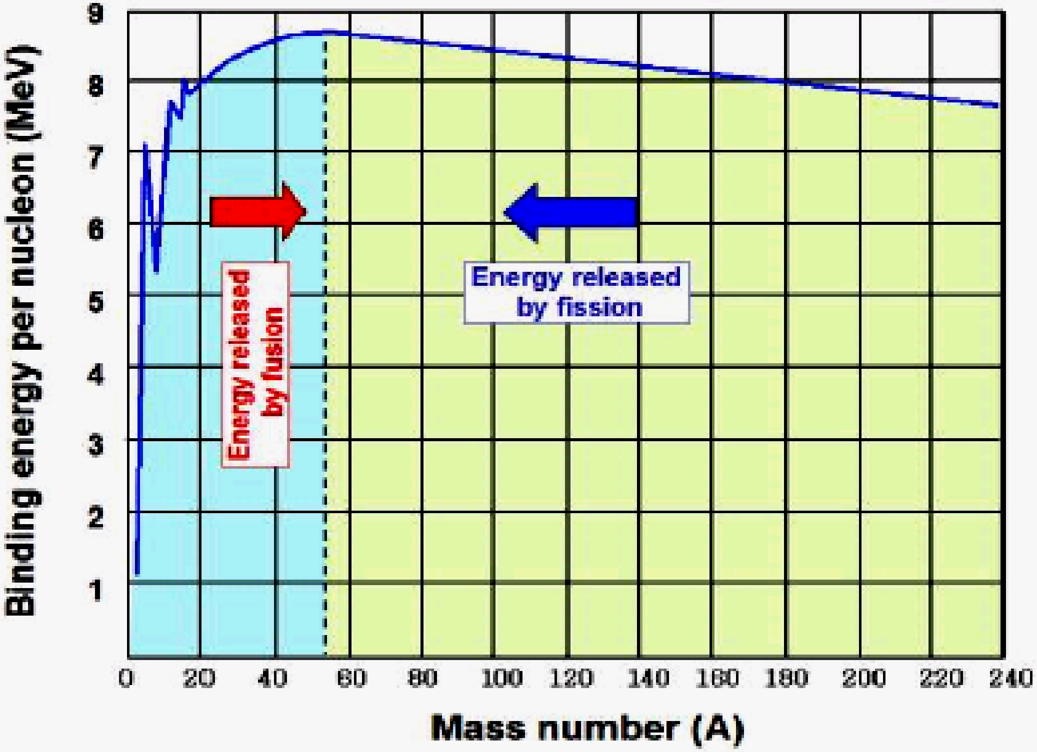
What is nuclear fusion?

- Two light nuclei combining to form a heavier nuclei, converting mass to energy
  - the opposite of nuclear fission where heavy nuclei are split apart

- In nuclear (fission and fusion), mass is converted to energy , Einstein's famous Eq.

  $E = mC^2$

  Small mass → Huge energy



- In contrast to fossil fuels (oil, gas, coal) where chemical energy is stored, and huge mass needed to "store" energy

The question that comes up among policymakers again and again is

if not fossil fuels, renewable energy sources , and if not nuclear fission, then what?

ONCE AGAIN THE ANSWER MAY BE

The Thermonuclear Fusion Energy

FUSION - What is it?

Magnetic Confinement Fusion (MCF)
Inertial Confinement Fusion (ICF)

PHENOMENA

fuse of the two heavy isotopes of hydrogen (D + T reaction)

CONDITIONS

(1)

the fuele (D+T) must be heated to temperatures in excess of 100 MoC (> 10 Kev)

(2)

energy confinement for a time 1-10 sec (MCF) or 3x10-11sec (ICF)

(3)

the amount of fuel (plasma density) must be
> 1014 cm-3 (for MCF) and > 3x1025cm-3 (for ICF)

THERMONUCLEAR FUSION ADVANTAGES

- Huge potential for meeting our energy needs: 1 g of H_2 produces energy from burning 1 ton of coal
- Deuterium is naturally occurring and is available at 0.015% abundance. $^{2}_{1}H$ in water could meet energy needs for millions of years.
- Tritium is radioactive and must be produced via fission of Li (abundant in earth's crust).
- $^{6}_{3}Li + ^{1}n_{0} \rightarrow ^{4}_{2}He + ^{3}_{1}H$

Continued .....

* For example, 10 grams of Deuterium which can be extracted from 500 L (or 0.5 Mg) of water and 15g of Tritium produced from 30g of Lithium would produce enough fuel for the lifetime electricity needs of an average person in an industrialized country.

* Produces minimal radioactive waste, but risks exist with β emitting tritium.

* Produces no greenhouse gases or acid rain.

* But requirements to carry out a controlled fusion reaction and convert the energy produced to industrial and household uses is very difficult technologically and financially.

Continued .....

- No carbon emissions are generated by fusion.
- The raw fuels are abundant around the globe (no geopolitical issues) and will last for millions of years. They are a type (isotope) of hydrogen – deuterium (found in seawater) – and lithium (a light metal which is found in the Earth's crust and in seawater). The lithium in the fusion reactor wall produces tritium (another isotope of hydrogen). In the plasma the deuterium and tritium fuse to produce energy.
- Fusion is a very efficient form of energy production. 1 kg of deuterium and tritium would supply the same amount of energy as 10 million kg of coal. The lithium in one laptop battery plus the deuterium from half a bathtub of water would provide the UK's per capita electricity production for 30 years.
- Fusion is environmentally responsible and it has intrinsic safety features. There is no possibility of a run-away reaction or explosion, no greenhouse gas emissions, and although radioactive materials will be generated in the walls of a fusion power plant they would decay with half-lives of about 10 years and the whole plant could be re-cycled within 100 years. In principle this gives fusion significant advantages over nuclear fission (the splitting of heavy nuclei) on which conventional nuclear power stations are based.
- Tritium is a hazardous radioactive substance (with a half life ~12 years) but the amount that is present in the reacting plasma at any time is tiny (only a fraction of a gram). Even if 1 kg were released (and nobody has been able to imagine how this could happen) it would probably not be necessary to evacuate anyone outside the site.
- The estimated cost of electricity generated by fusion is similar to the cost of electricity produced in other environmentally responsible ways.

Continued .....

ADVANTAGES OF THERMONUCLEAR FUSION

- Fusion is an inexhaustible, non-polluted energy source
- Its basic fuel, deuterium is found in water, and lithium widely distributed throughout earth crust
- The fusion process is clean; it leaves no polluting by-products or radioactive "ashes" behind and is inherently safe
- Fusion does relay on a nuclear process but there is no possibility of a "runaway" or "meltdown" accident
- Limited radioactive hazards can be further substantially reduced by use of improved and/or new "low activation" materials and by eventual use of fuels that will produce a minimum number of neutrons, thereby minimizing the amount of radioactivity produced in the reactor structure
- Fusion power plants could also compete economically with fission and coal-fired plants

Abudant Supply of Fusion Fuel

- Deuterium isotope ≈ 1/ 6000 of hydrogen atoms in water
  and can be extracted at a negligible cost (≈ $1/gr)
- Deuterium in 1 gallon of water has the same energy as 300
  gallons of gasoline, if burned in a fusion D-T reactor
- Tritium is not present in Nature (13 year half-life), but slightly more than 1
- Tritium atom can be created for each DT neutron in a lithium "breeding
  blanket"

  Li6 + n -> T + He4 (7% natural Li)

  Li7 + n -> T + He 4 + n (93% natural Li)

Reactor accidents

A fission reactor can experience a meltdown if its cooling system fails, and it can experience a runaway chain reaction if its controls fail. A meltdown followed by hydrogen explosions occurred at several of the reactors at Fukushima Daiichi in Japan after an earthquake and tsunami in March 2011. A runaway reaction occurred at Ukraine's Chernobyl plant in 1986 when its controls were improperly used. In both cases, radioactivity was widely dispersed, leading to extensive contamination of food, soils, buildings, and the displacement of entire communities.

At fusion reactors, a runaway chain reaction cannot happen because a malfunction leads fusion to stop. However, accidents that could release tritium and radioactive structural material beyond the walls of the facility are still possible.

Limited risk of proliferation: Fusion doesn't employ fissile materials like uranium and plutonium. (Radioactive tritium is neither a fissile nor a fissionable material.) There are no enriched materials in a fusion reactor like ITER that could be exploited to make nuclear weapons

No risk of meltdown: A Fukushima-type nuclear accident is not possible in a tokamak fusion device. It is difficult enough to reach and maintain the precise conditions necessary for fusion—if any disturbance occurs, the plasma cools within seconds and the reaction stops. The quantity of fuel present in the vessel at any one time is enough for a few seconds only and there is no risk of a chain reaction.

FUSION ECONOMICS

- the cost of fusion electricity will be dominated by the capital cost of the plant.

- the costs of deuterium extraction and of the recycling of tritium do not. contribute appreciably to the electricity costs

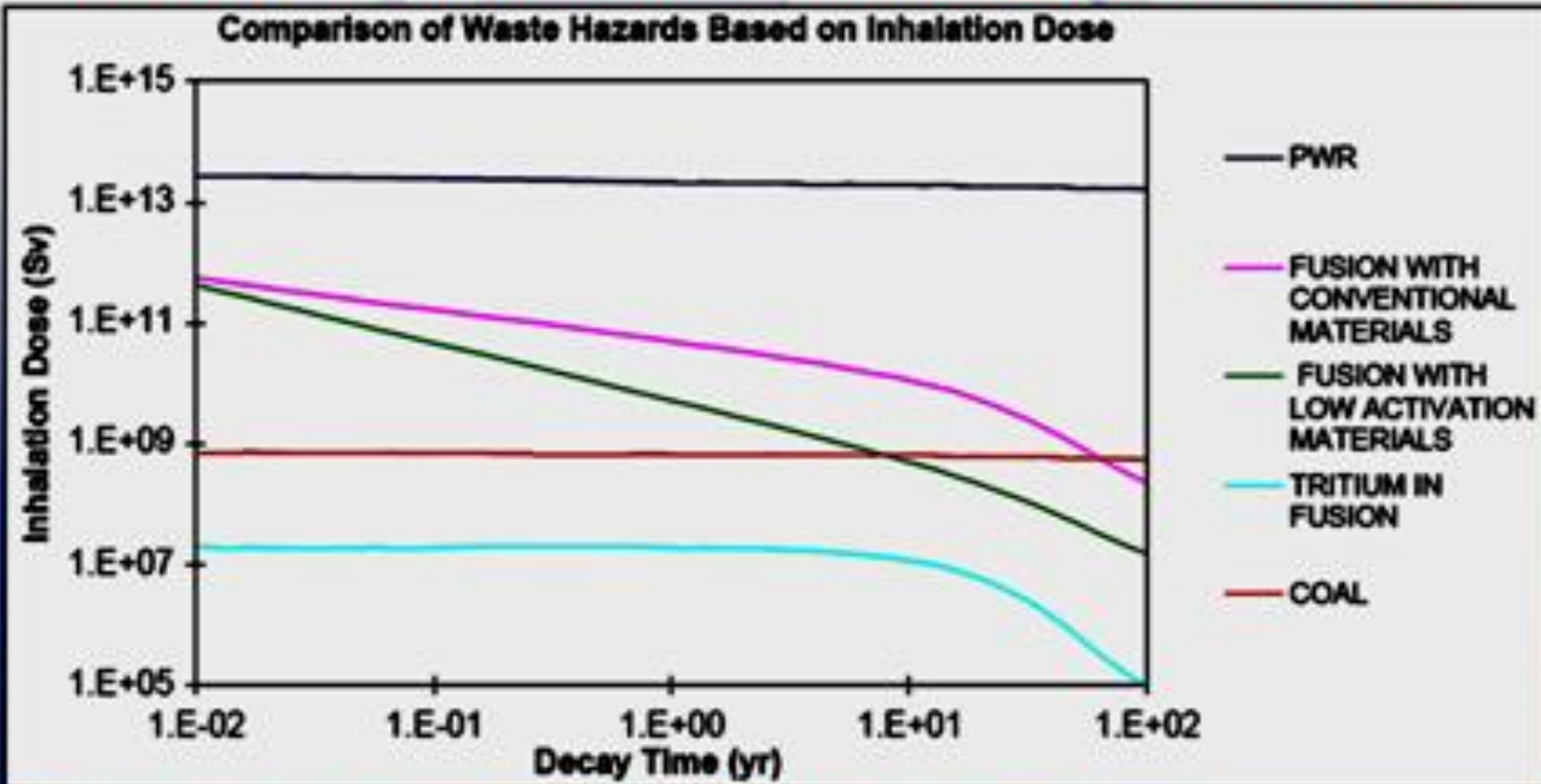
- the need to replace the first wall and the blanket at regular intervals; this will contribute significantly to the operating cost.

- It has been estimated that, if a fusion device is to be competitive with the PWR, i.e., if the kilowatt-hour cost of both systems are the same, the capital cost of a series ordered fusion plant can constitute up to about 3/4 of the total unit cost of electricity.

under the assumption that in real terms
the cost of electricity will be about the same

Energy source	Advantages	Disadvantages and research needs
Coal	• Plentiful • Technology exists today • Safe	• Near-term environmental implications require development of "clean coal technologies" or fuel substitutions that may increase the cost of energy • CO_2 buildup may make increased dependence on fossil fuels undesirable
Oil and gas	• Technology exists today • Fewer combustion byproducts emitted than coal • Less CO_2 emitted per unit energy than coal	• Questionable long-term resource base • Does not avoid CO_2 emission
Fission	• Plentiful • No emission of CO_2 • No emission of combustion byproducts • Technology exists today	• Unfavorable economics and safety concerns suggest development of advanced reactor designs that are smaller and passively safe • Nuclear waste disposal not yet resolved • Public confidence must be improved and may or may not result from technical improvements
Renewable	• Unlimited fuel supply • No net CO_2 emission • Technologically simple • Modular design	• Uncertain economics and technical problems require more R&D • Intermittence and diffuseness may make renewable inadequate substitute for central-station power generation in arbitrary locations
Fusion	• Unlimited fuel supply • Potential for higher degree of safety assurance than fission • No CO_2 production or combustion byproduct emission • Substantially less hazardous nuclear waste than fission*	• Significant R&D effort required to establish technical feasibility • Environmental and safety potential highly dependent on design, especially on materials choice • Economic potential unknown

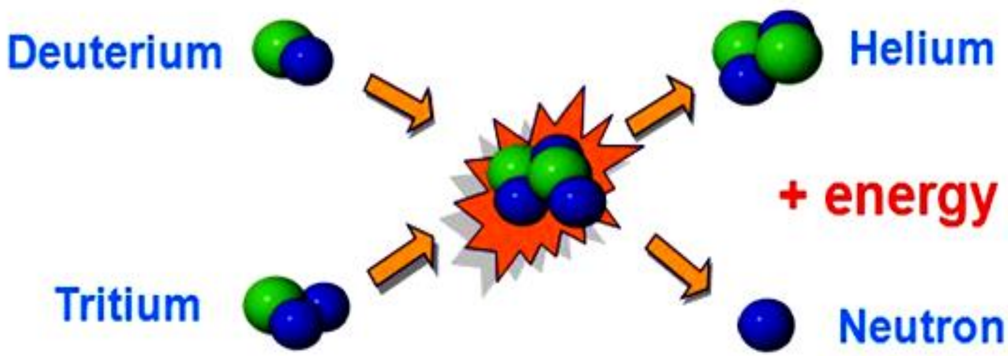
Radiotoxicity (inhalation) of waste from fusion is less than fission and similar to that from coal at 100 years.



- 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

WHAT IS FUSION ?

Most effective fusion process involves deuterium (heavy hydrogen) **and tritium** (super heavy hydrogen) **heated to above 100 million °C :**

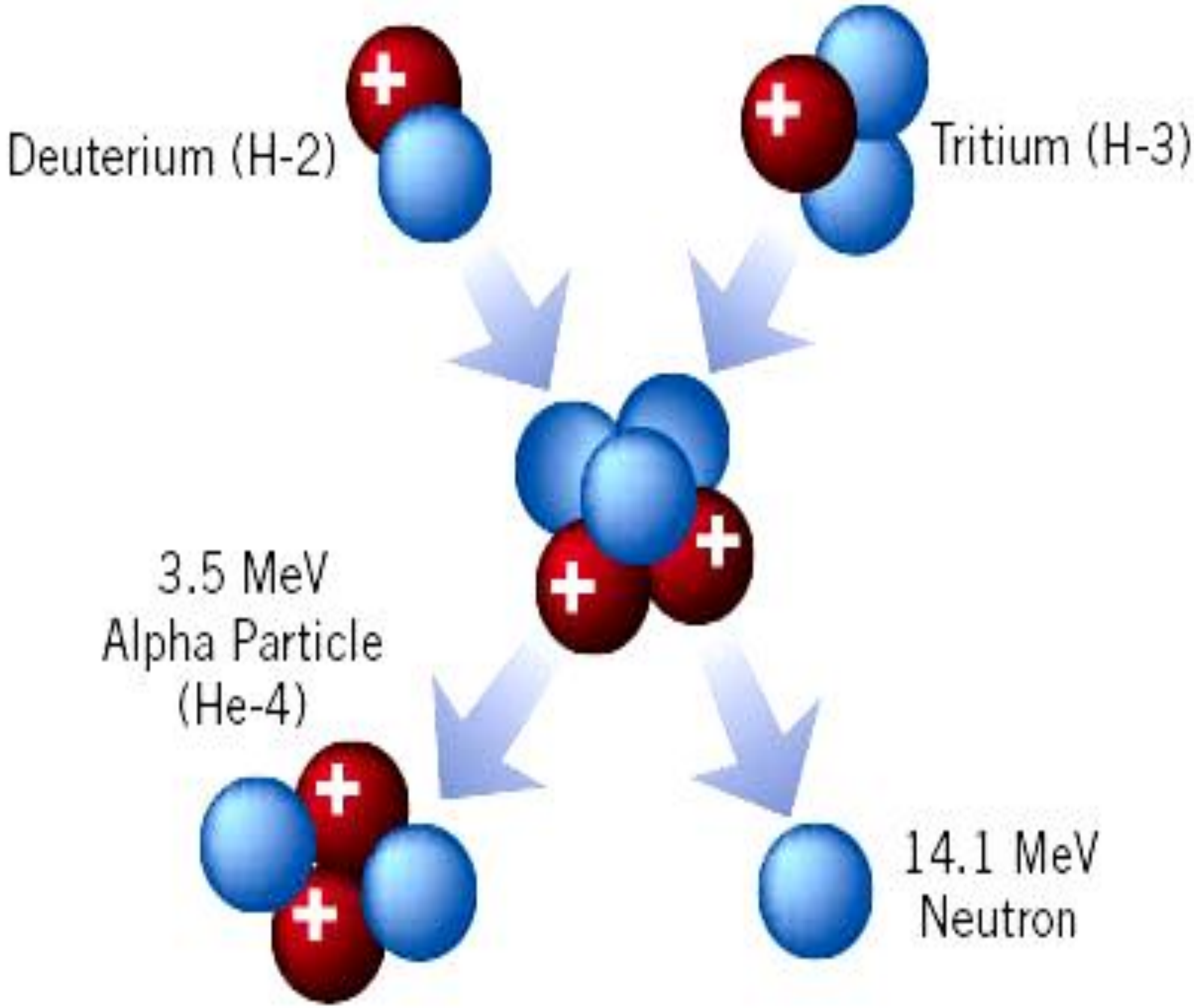


A "magnetic bottle" **called a** tokamak **keeps the hot gas away from the wall**

Challenges: make an effective "magnetic bottle" (now done ?) a robust container, and a reliable system

* ten million times more than in chemical reactions, e.g. in burning fossil fuels

⇒ **while a 1 GW coal power station would use 10,000 tonnes of coal a day, a fusion power station would only use 1 Kg of D + T**


Deuterium (H-2)
Tritium (H-3)
3.5 MeV
Alpha Particle
(He-4)
14.1 MeV
Neutron

Fusion Reactions

Deuterium – from water
(0.02% of all hydrogen is *heavy hydrogen* or *deuterium*)

Tritium – from *lithium*
(a light metal common in the Earth's crust)

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

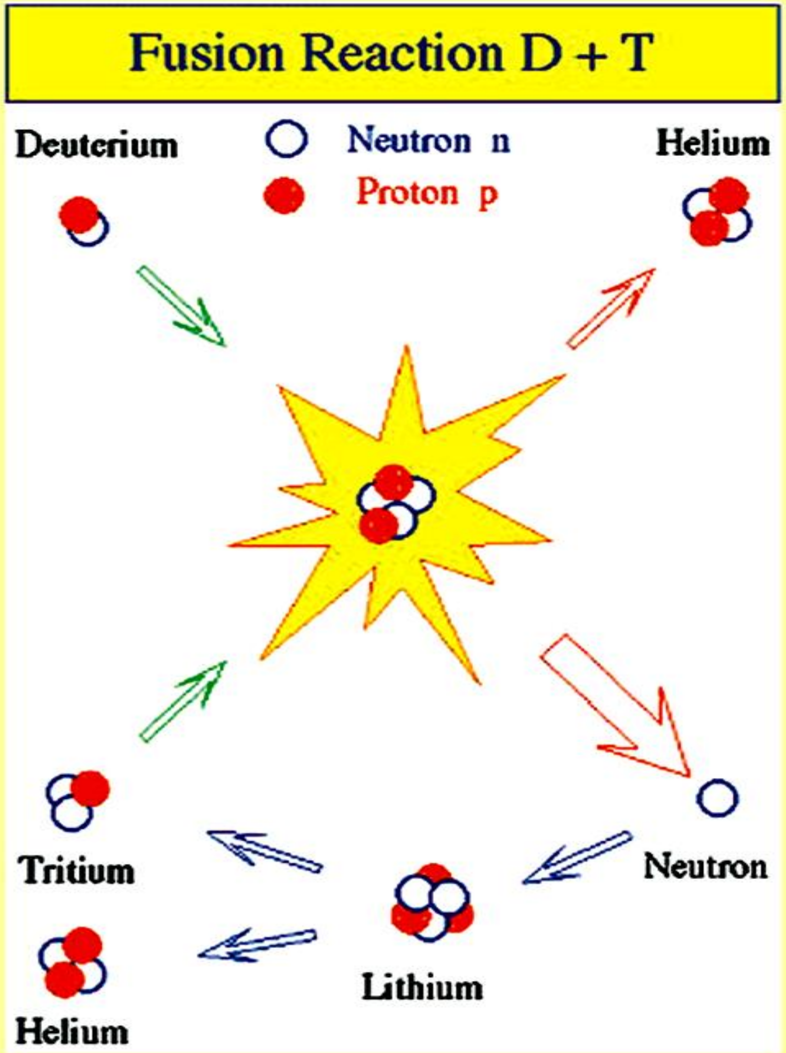
Tritium production

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

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

Deuterium + Lithium ⟶ Helium + Energy

- 1/6500 atoms of H in sea water is deuterium
  - 1.03×10^{22} D atoms in 1 L of sea water
  - 1 km^3 has energy potential of 1360 billion barrels of crude oil
- Tritium is radioactive
  - t1/2=12.4 yr
  - generated from Li via neutron capture



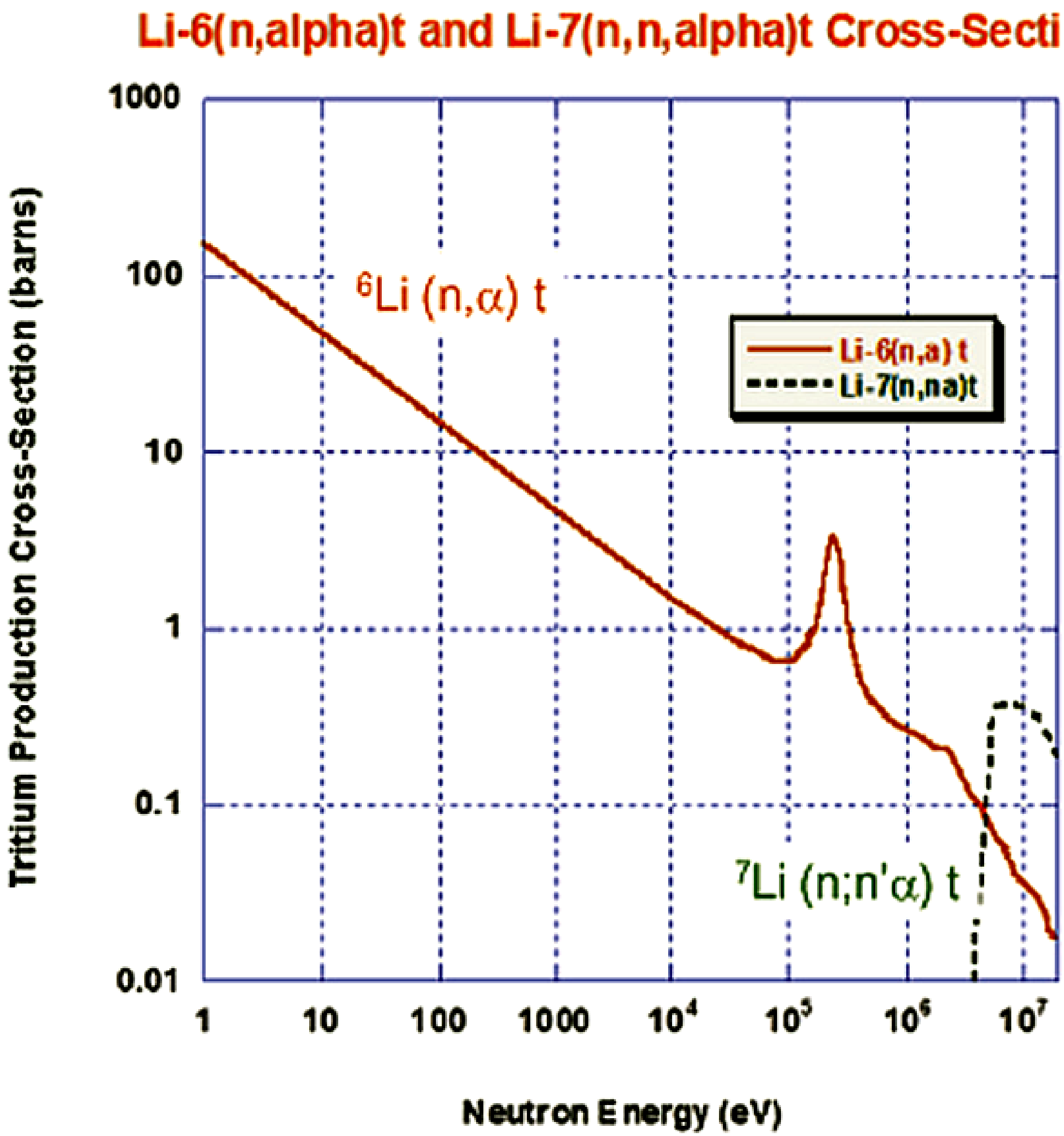
$$_1H^2 + {}_1H^2 \longrightarrow {}_1H^3 + {}_1H^1 + 4Mev$$
$$_1H^2 + {}_1H^2 \longrightarrow {}_1H^3 + {}_0n^1 + 3.25Mev$$
$$_1H^2 + {}_1H^3 \longrightarrow {}_2He^4 + {}_0n^1 + 17.6Mev$$
$$_1H^2 + {}_2He^3 \longrightarrow {}_2He^4 + {}_1H^1 + 18.3Mev$$

Thermonuclear Fusion Conditions

Lawson's Criterion for Fusion

$$nT\tau_E > 3 \times 10^{21} m^{-3} keVs$$

Tritium Breeding

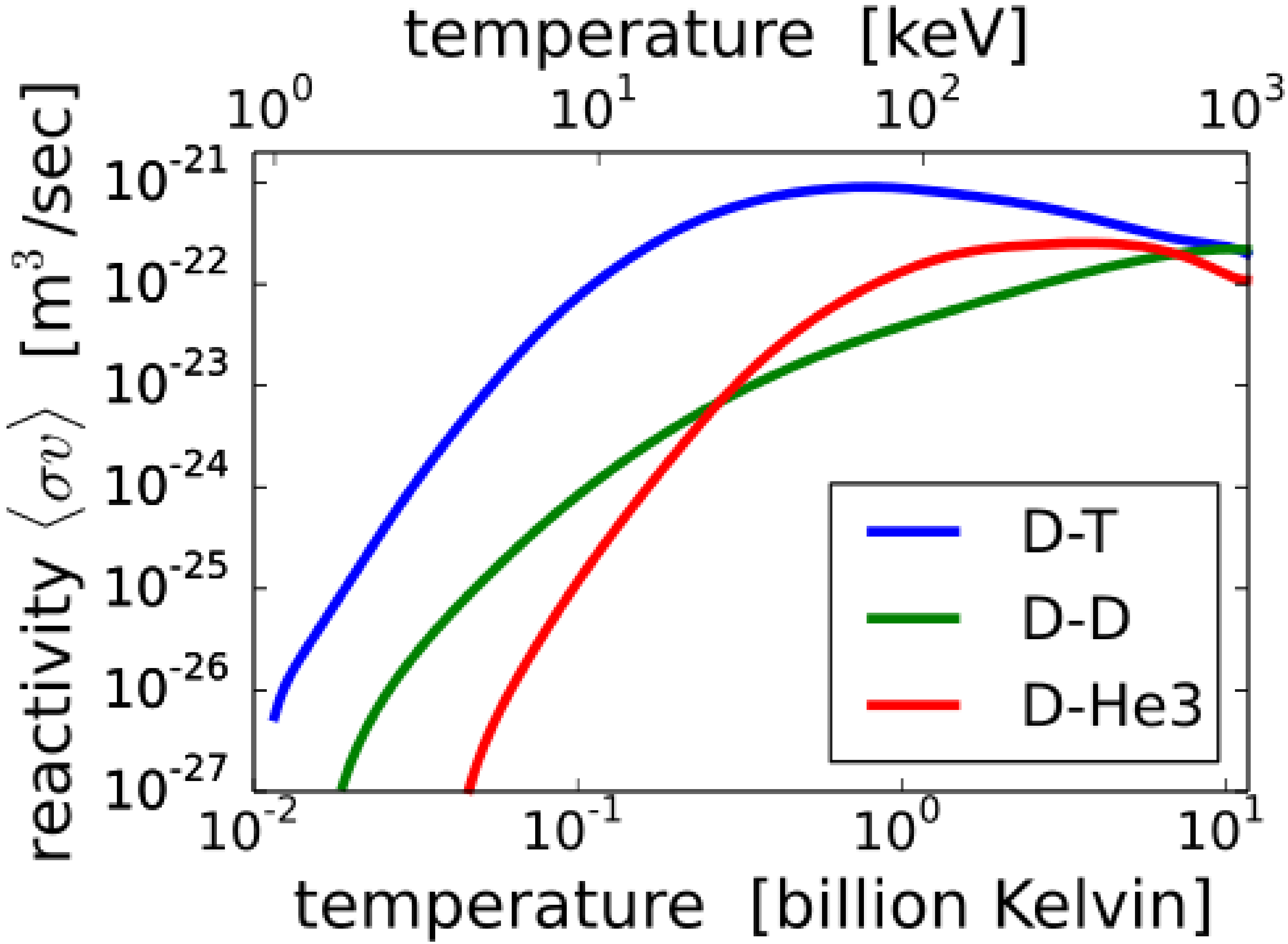


Natural lithium contains 7.42% ^{6}Li and 92.58% ^{7}Li.

$$^6Li + n \rightarrow t + \alpha + 4.78MeV$$

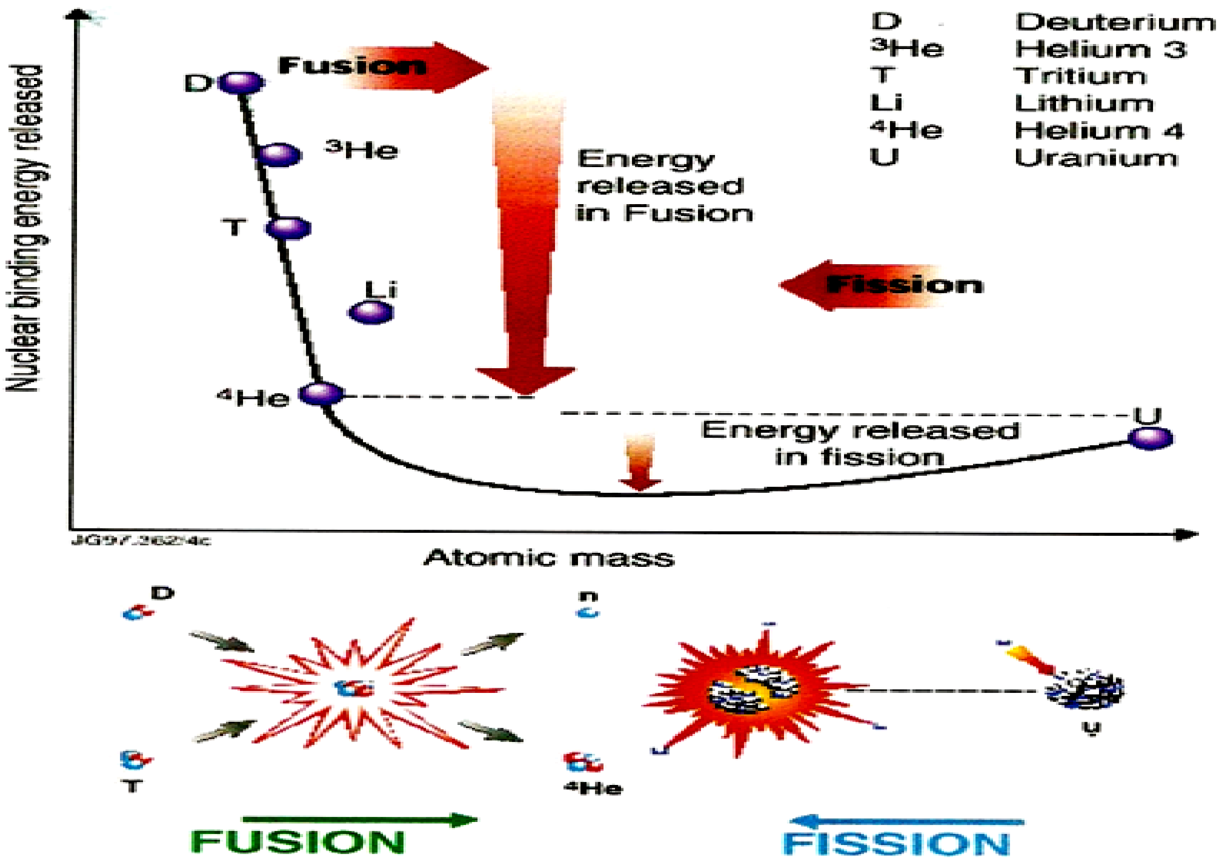
$$^7Li + n \rightarrow t + \alpha + n - 2.47MeV$$

The ^{7}Li(n;n′α)t reaction is a threshold reaction and requires an incident neutron energy in excess of 2.8 MeV.

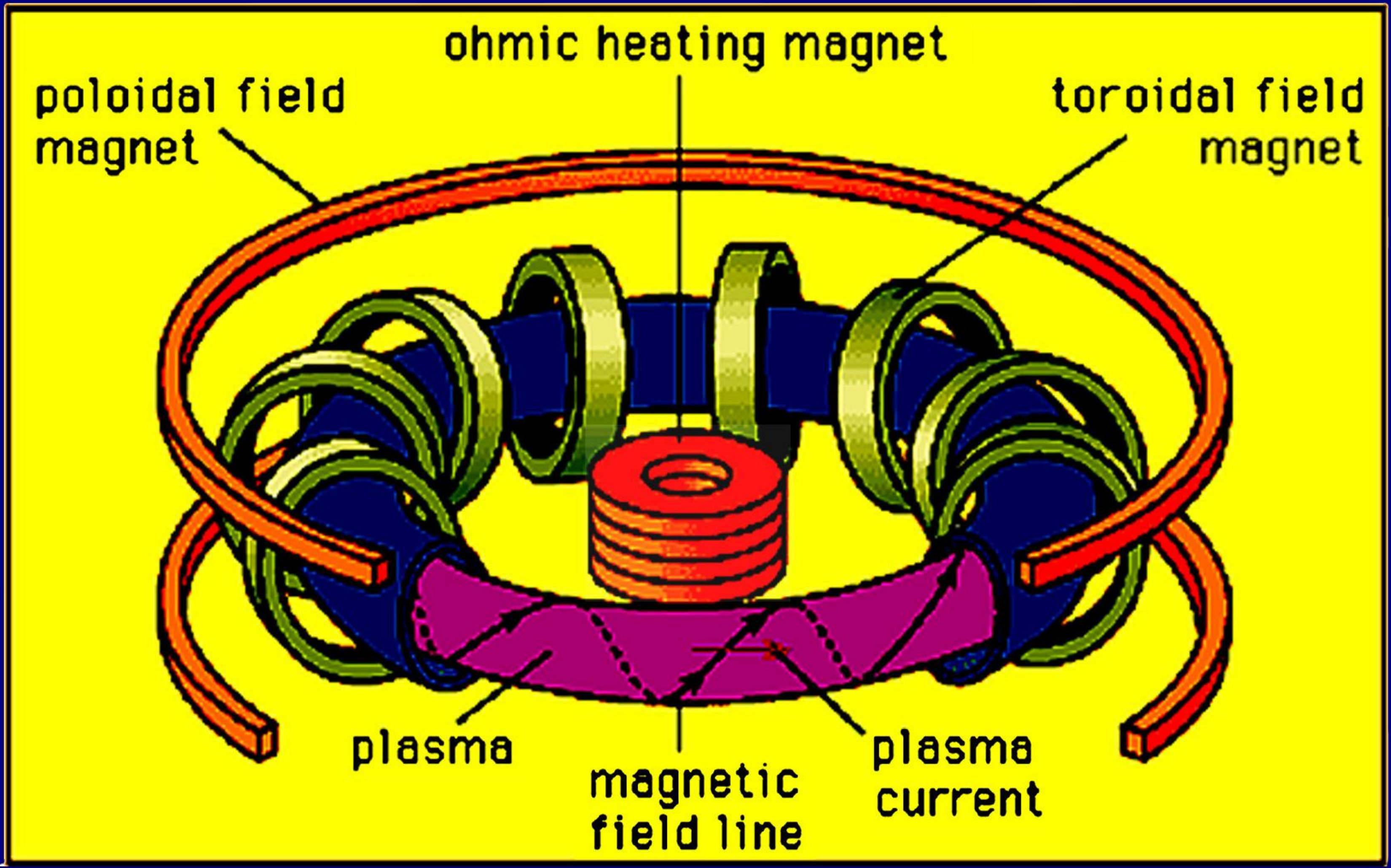

temperature [keV]
10^0
10^1
10^2
10^3
10^-21
10^-22
10^-23
10^-24
10^-25
10^-26
10^-27
reactivity ⟨σv⟩ [m^3 /sec]
D-T
D-D
D-He3
10^-2
10^-1
10^0
10^1
temperature [billion Kelvin]

Energy Released by Nuclear Fusion and Fission

Fusion reactions
__release much higher energies than__
Fission reactions

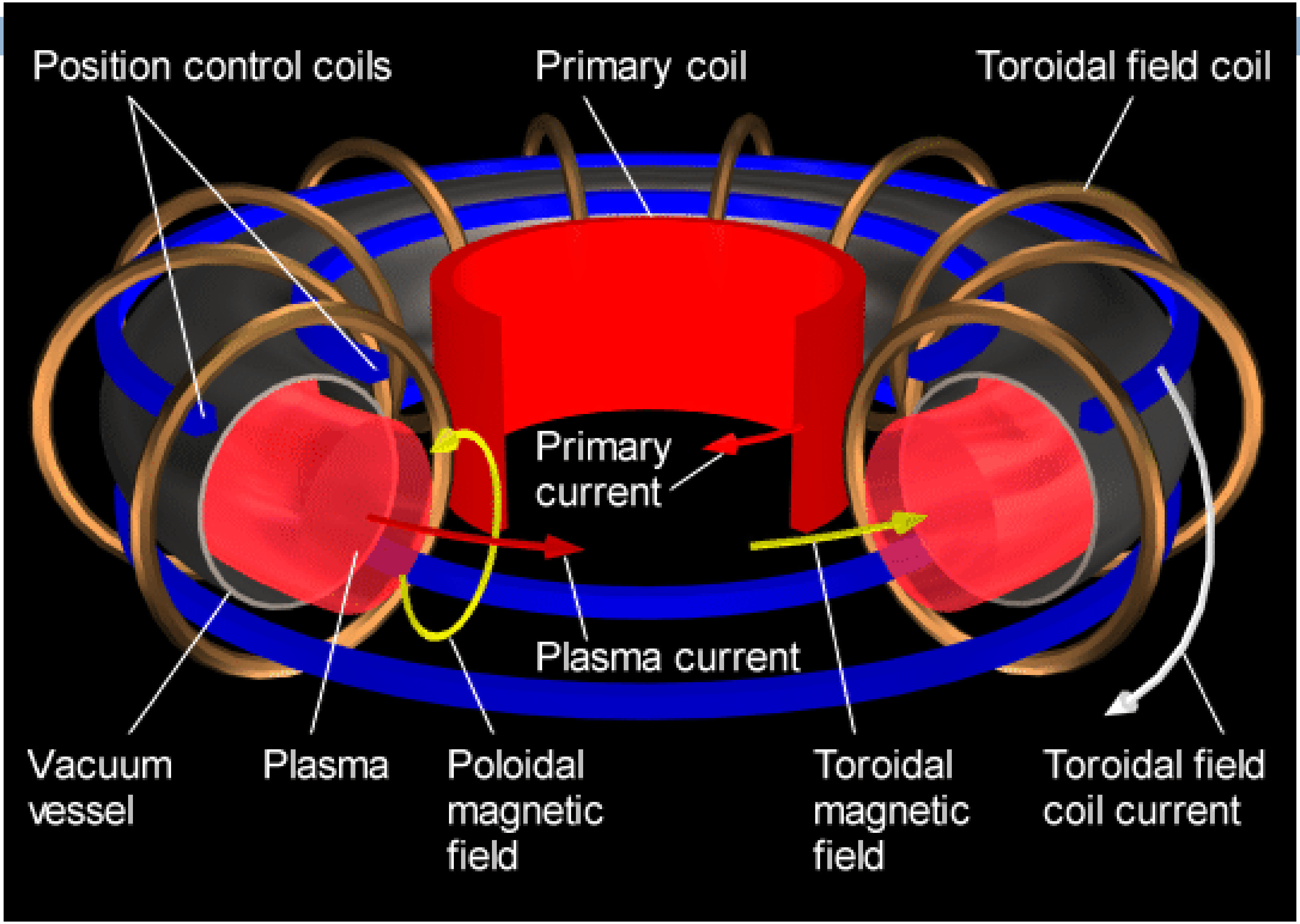


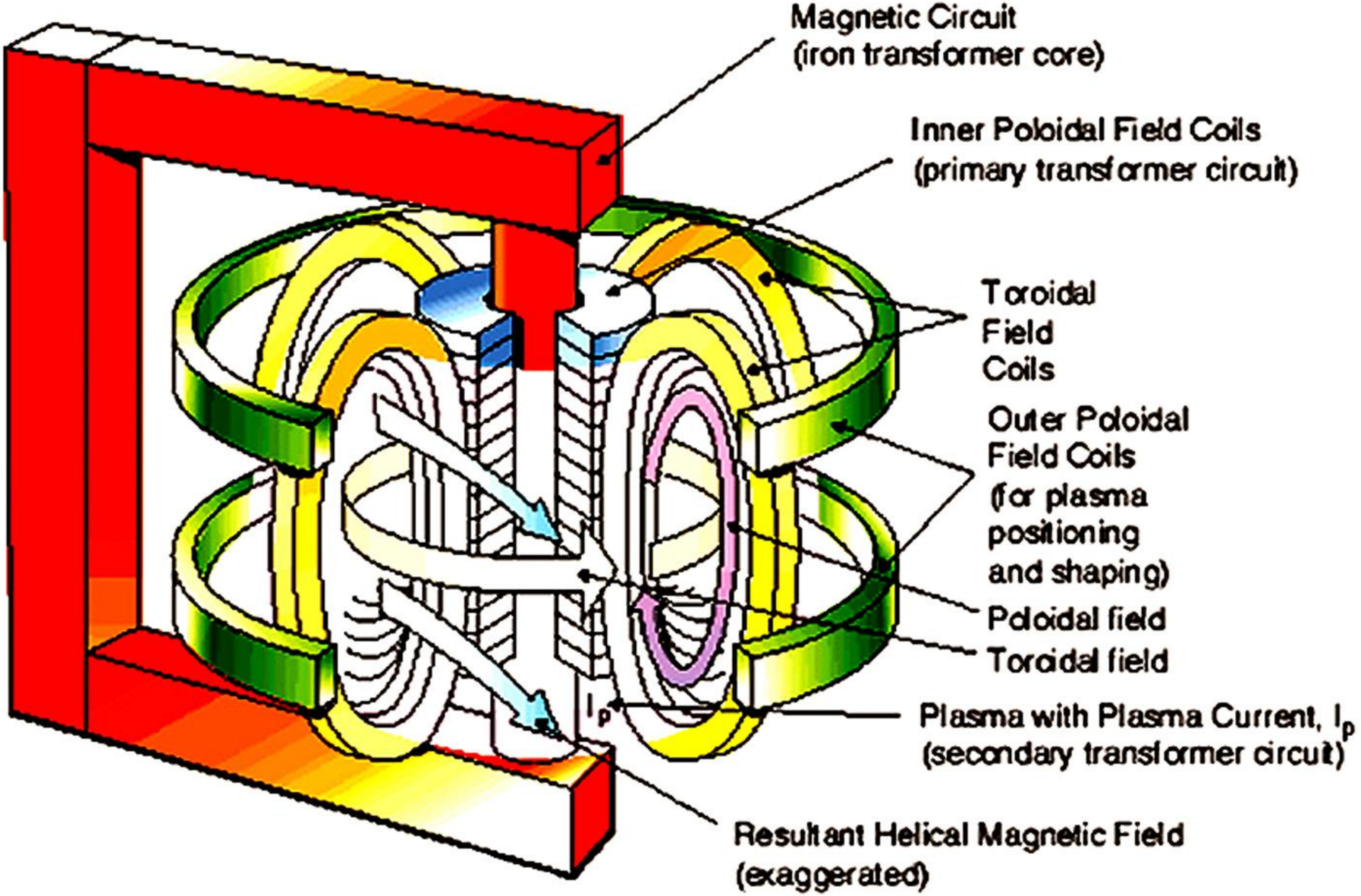
Fusion reactor, also called fusion power plant or thermonuclear reactor a device to produce electrical power from the energy released in a nuclear fusion reaction



Tokamak Magnetic Confinement

Plasma Confinement

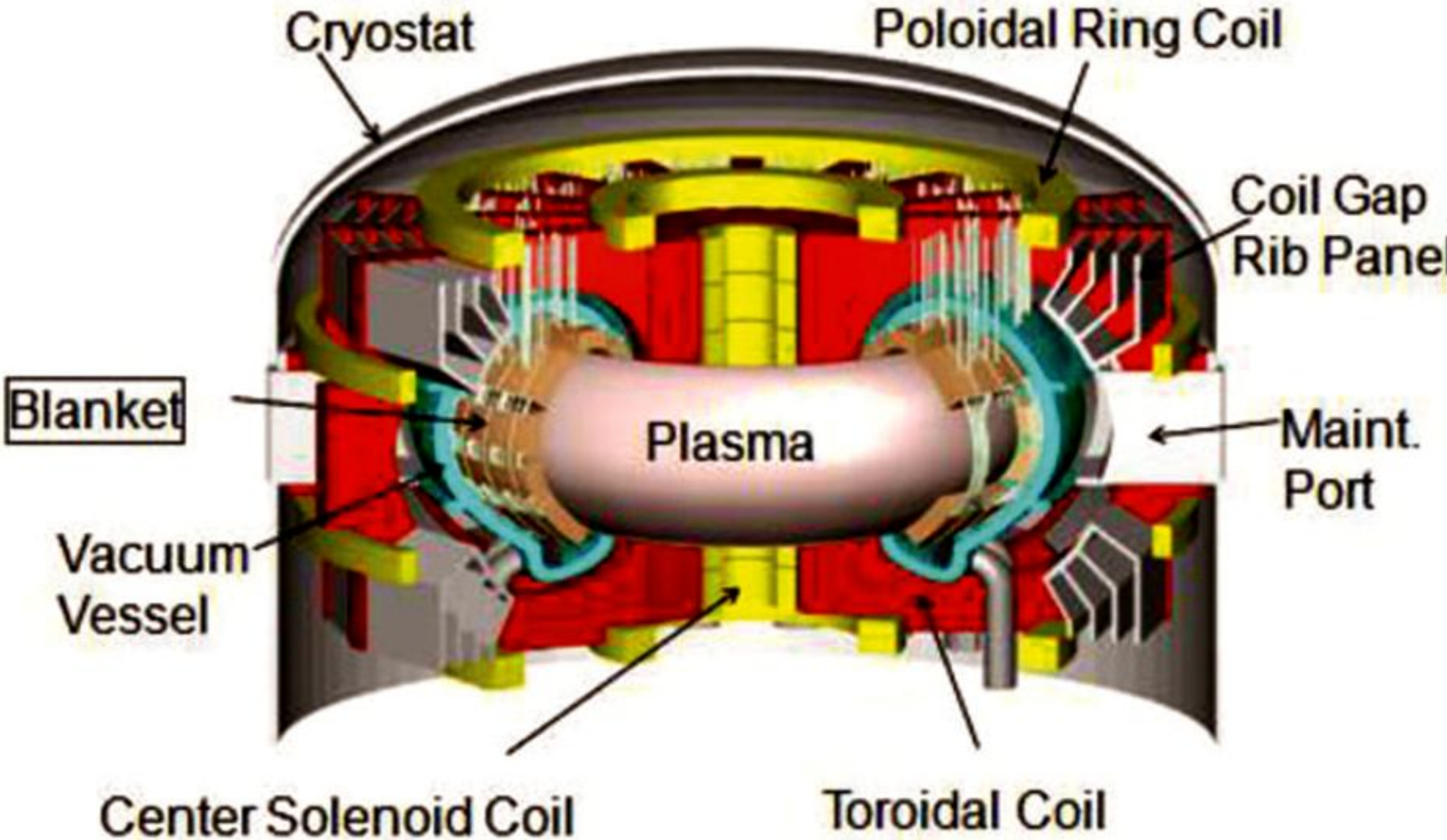




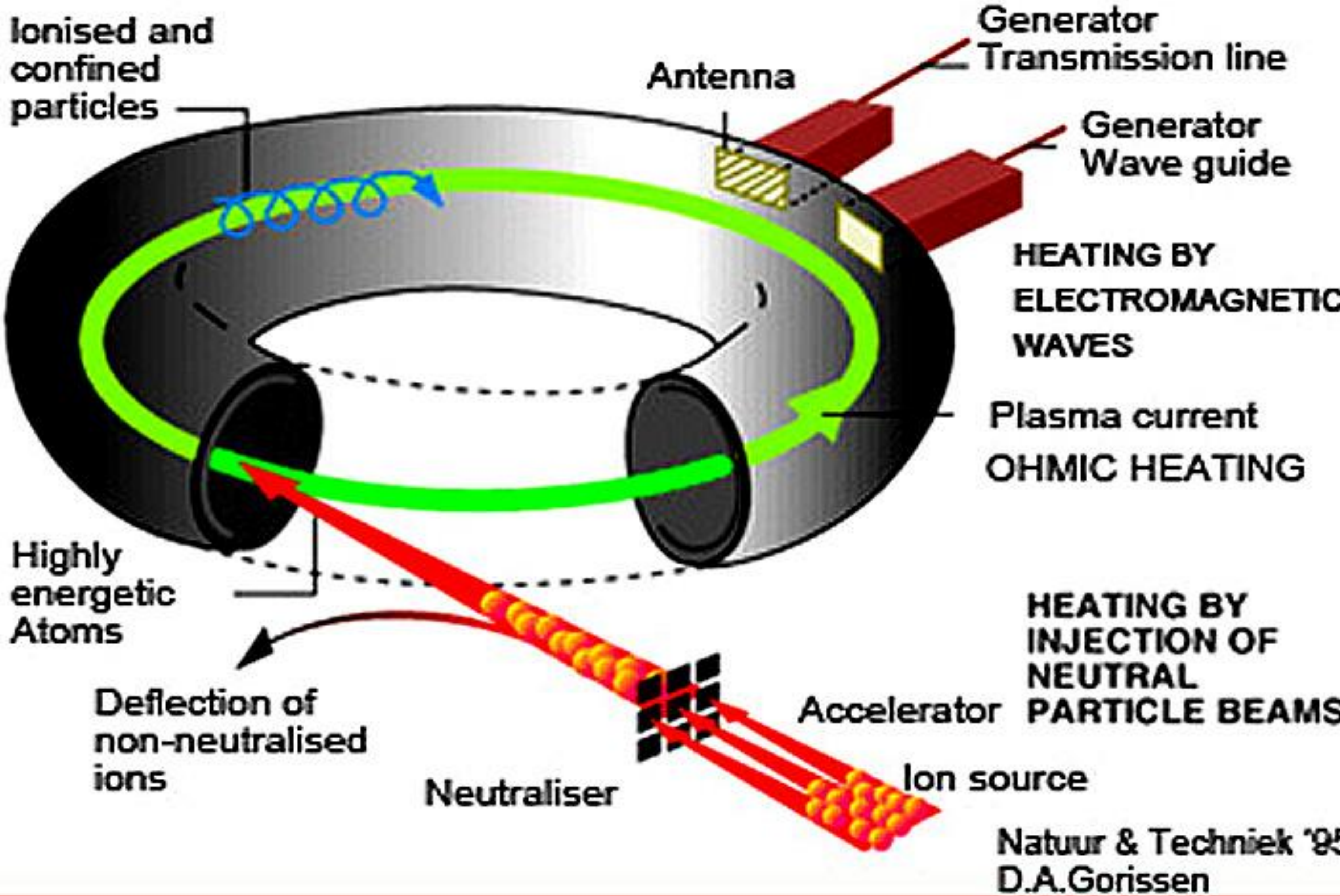
Magnetic fields for confining Tokamak Plasmas.

FNT: Components from Edge of Plasma to TFC

Blanket / Divertor immediately circumscribe the plasma



JAEA DEMO Design



Various tokamak plasma heating techniques

$$nT\tau_E > 3 \times 10^{21} m^{-3} keVs$$

How Large a Device?

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).

τ_E increases with the square of the device size (a large machine is needed).

The fusion triple product ($n_i T_i \tau_E$)
and
The ion temperature (T_i)
must both be large enough

below a certain temperature the fusion reaction probability is too small

* pressure ($n_i T_i$) $\geq$ 2 atmospheres
* confinement time > 5 seconds
* plasma ion temperature $\approx$ 100-200 Million °C

Worldwide Fusion Devices

The Big Three

- TFTR (tokamak fusion test reactor located at Princeton University)
- JET (joint European torus, located in Culham, UK as part of a European collaboration)
- JT-60 (located in Japan)

Joint European Torus
(JET)

- The largest magnetic fusion test device in the world

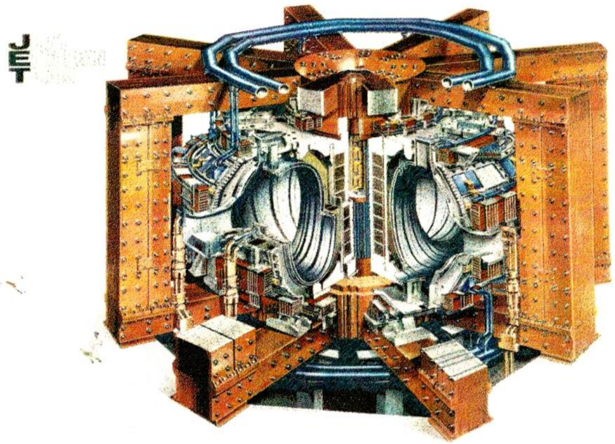
- Situated at Culham, Oxfordshire
- constructed between 1978-1983
- has operated 1983 - present

- is the largest Project in the European Union's Fusion programme

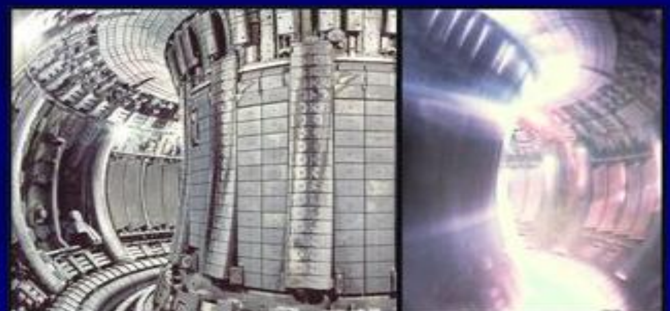
- The participating countries are the 15 EU nations + Switzerland

- The Project has a capital investment of over £500 Million and Annual Budget of around £53 Million

JET is a Tokamak with
* Torus radius 3.1m
* Vacuum vessel 3.96m high x 2.4m wide
* Plasma volume 80m^3
* Plasma current up to 5MA
* Main confining field up to 4 Tesla



JET – Joint European Torus



- JET begins operation in the United Kingdom in 1978, it is the largest operational Tokamak
- As the largest Tokamak, it is the technology demonstrator for the ITER, the future
- It has also set many world records
  - 22 megawatts from a single pulse
  - 16 megawatts of power output (surpassing TFTR)

Fusion Production at JET

- **World's first production of controlled fusion, about 2MW for one second.**
- **50:50 deuterium / tritium fuel used.**
- **Three world records established:**

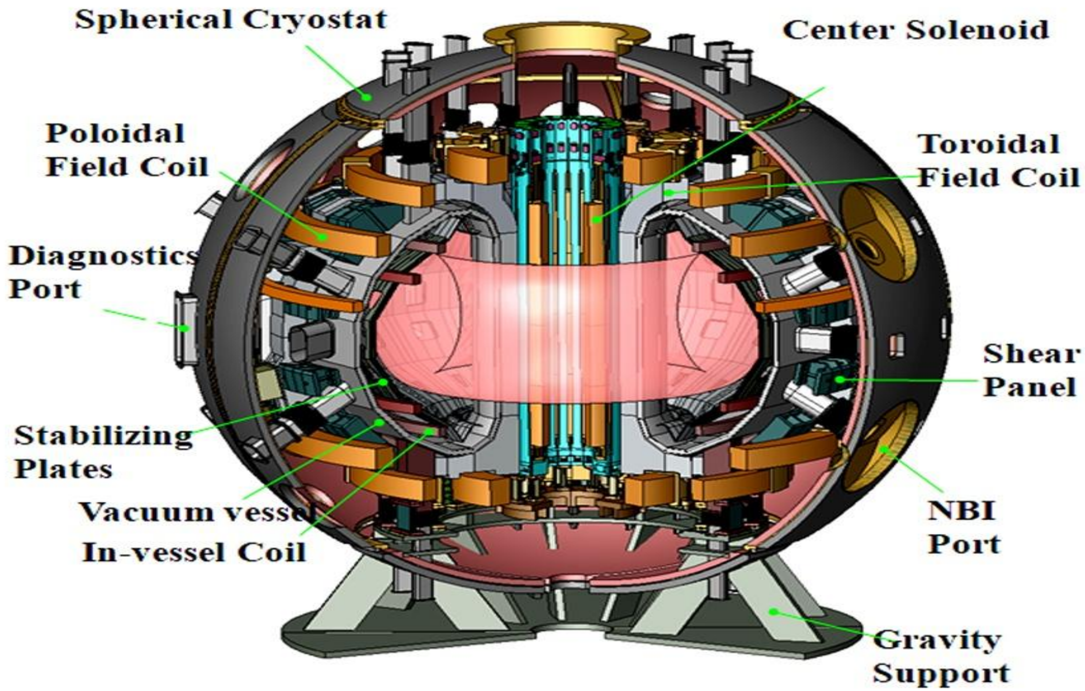
**** Fusion Power 16MW***

**** Fusion Energy 22MJ***

**** Q-factor: Ratio of Fusion Power to Input Power 0.64***

JT-60 (Japan Torus-60)

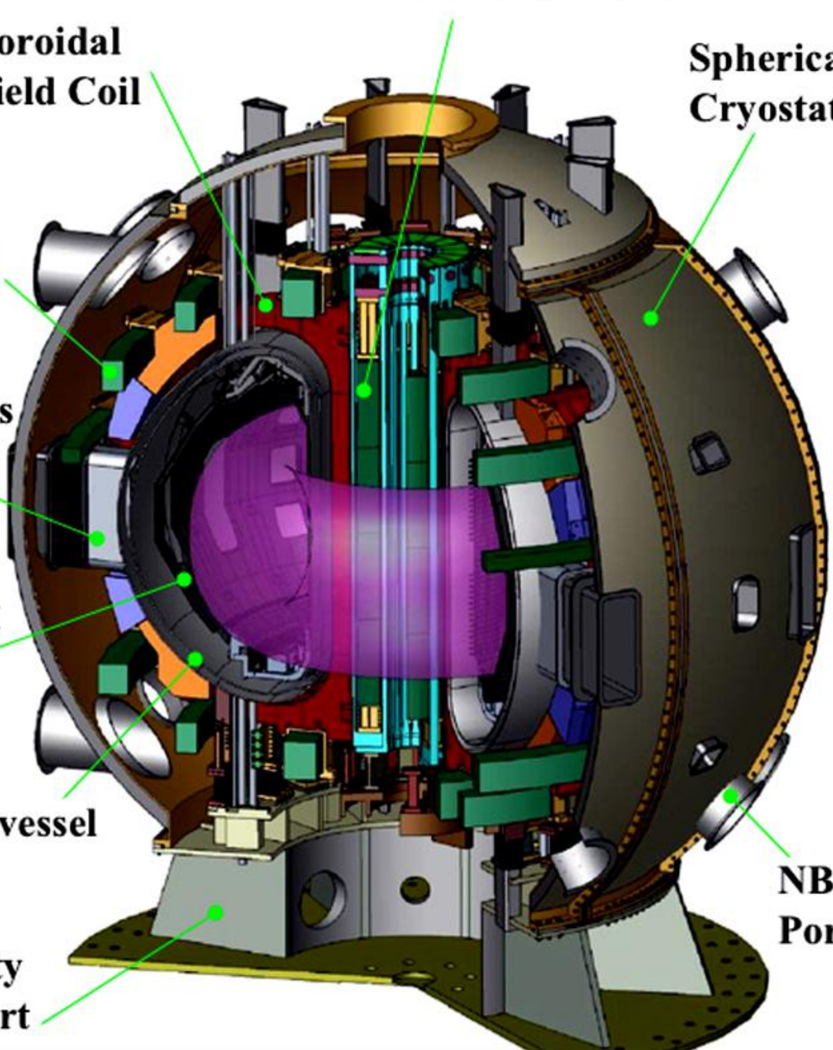
Type	Tokamak
Operation date	1985–2010
Size (Major radius/Minor Radius	3.4 meters (11 ft)/1.0 meter (3 ft 3 in)
Plasma volume	90 m^3 (3,200 cu ft)
Magnetic field	4 T (toroidal)
Location	Ibaraki Prefecture, Japan



JT 60 of Japan

Basic Machine Parameter of JT-60SA

JT-60SA Euratom

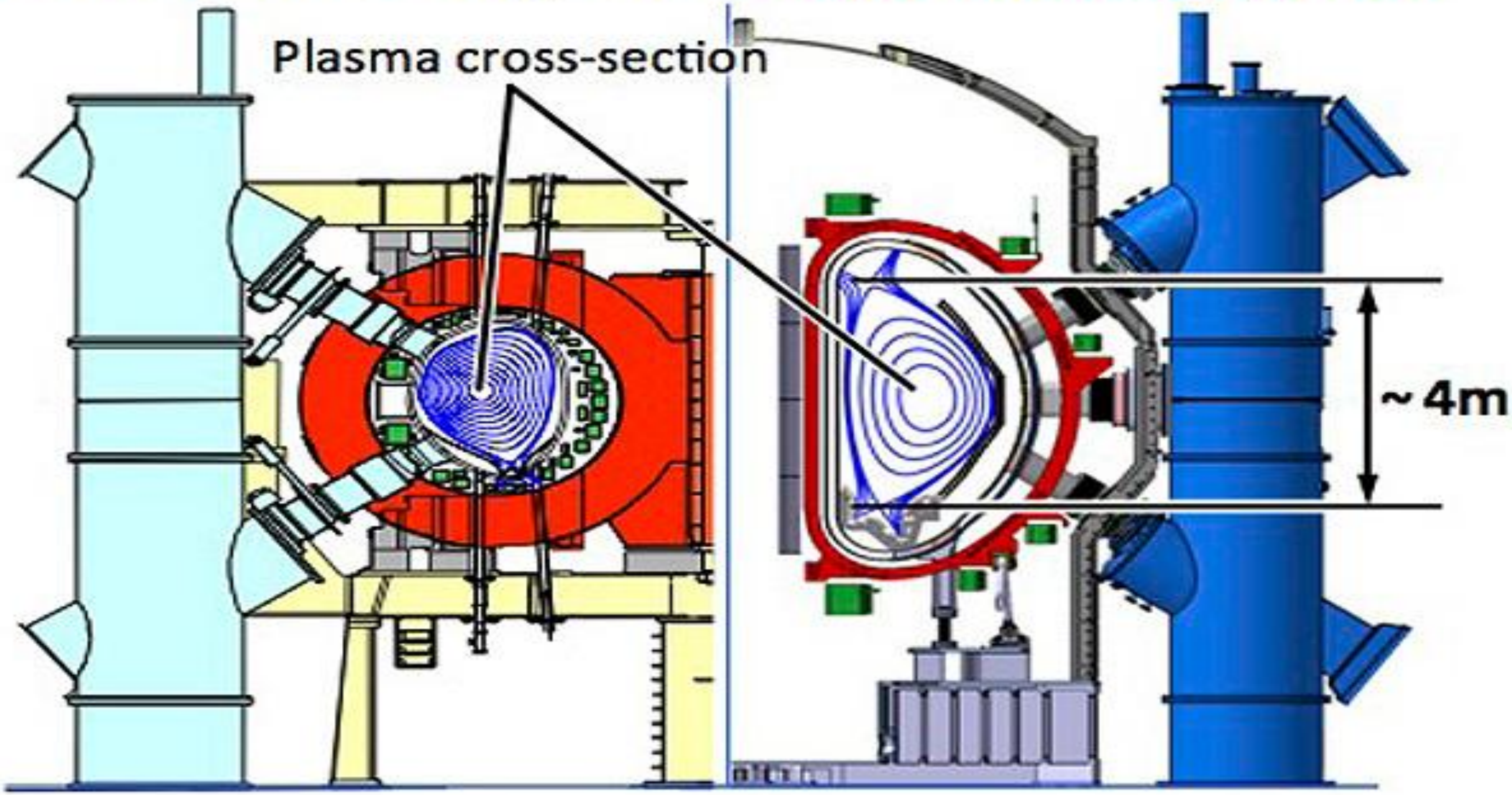


Plasma Current I_p	5.5MA
Toroidal Field B_t	2.68T
Major Radius R_p	3.06m
Minor Radius a_p	1.15m
Elongation κ_{95}	1.76
Triangularity δ_{95}	0.45
Safety Factor q_{95}	3.11
Volume V_p	$127 m^3$
Flattop Duration	100 s (8Hr)
Heating & CD power	41MWx100 s
Perpendicular NBI	16 MW
Tangential Co NBI	4 MW
Tangential CTR NBI	4 MW
N-NBI	10 MW
ECRH	7 MW
PFC wall load	$15 MW/m^2$
Annual Neutron	4×10^{21}

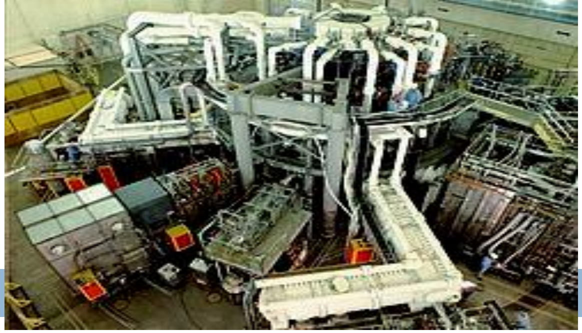
D_2 main plasma + D_2 beam injection
Remote handling is required.

JT-60 ⇨ JT-60SA

Normal conducting coils **Superconducting coils**



- **Modification from a tokamak with normal conducting coils to one with superconducting coils**
- **Plasma cross-sectional shape suitable for sustaining a high-pressure plasma**

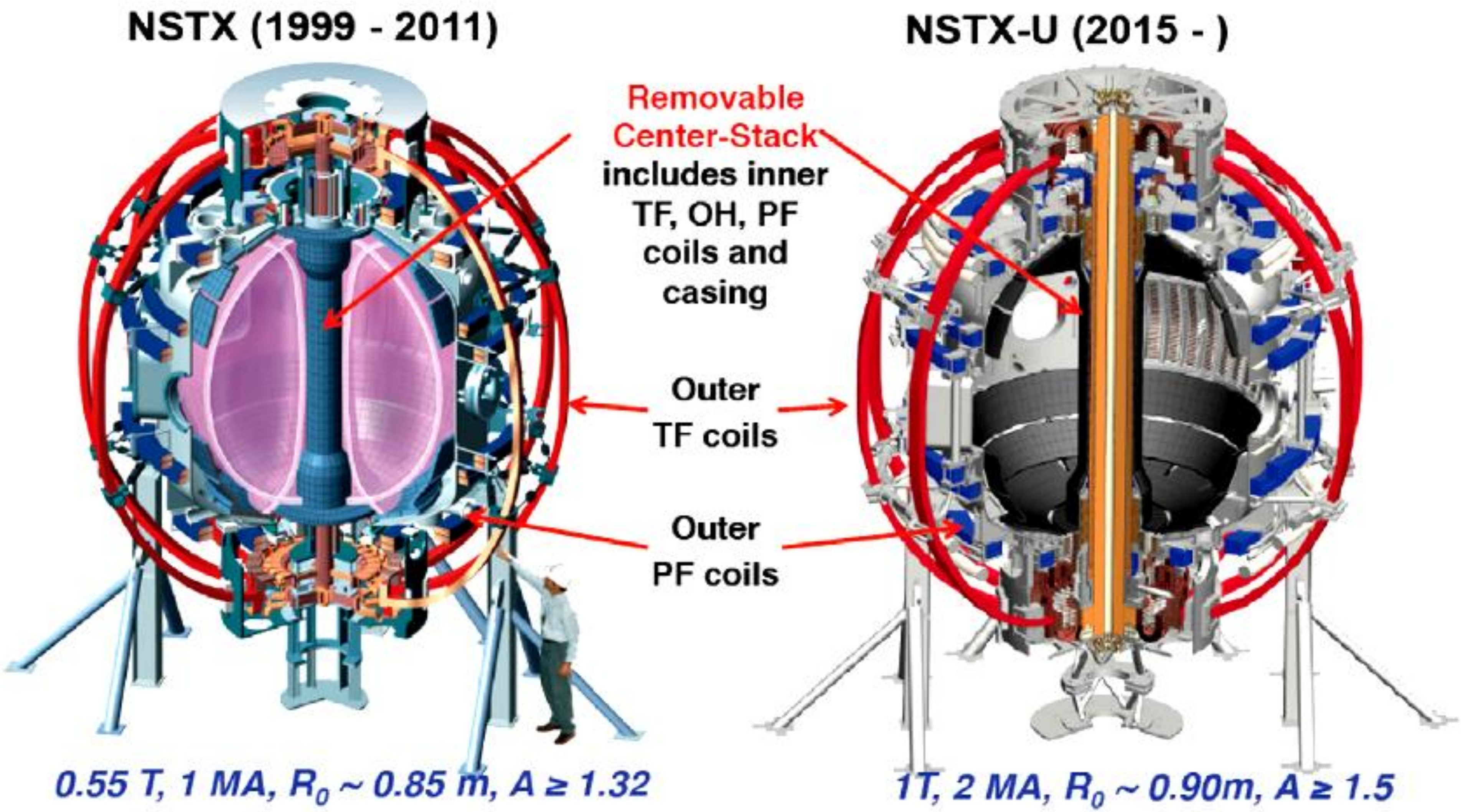


Tokamak Fusion Test Reactor (TFTR)

Type	Tokamak
Operation date	1982–1997
Major radius	2.1–3.1 m
Minor Radius	0.4–0.96 m
Magnetic field	6.0 T (toroidal)
Heating	51 MW
Plasma current	3.0 MA
Location	Princeton, New Jersey, USA

TFTR remained in use until 1997. It was dismantled in September 2002, after 15 years of operation.
It was followed by the NSTX spherical tokamak.

National Spherical Torus Experiment - NSTX



Performance goals:

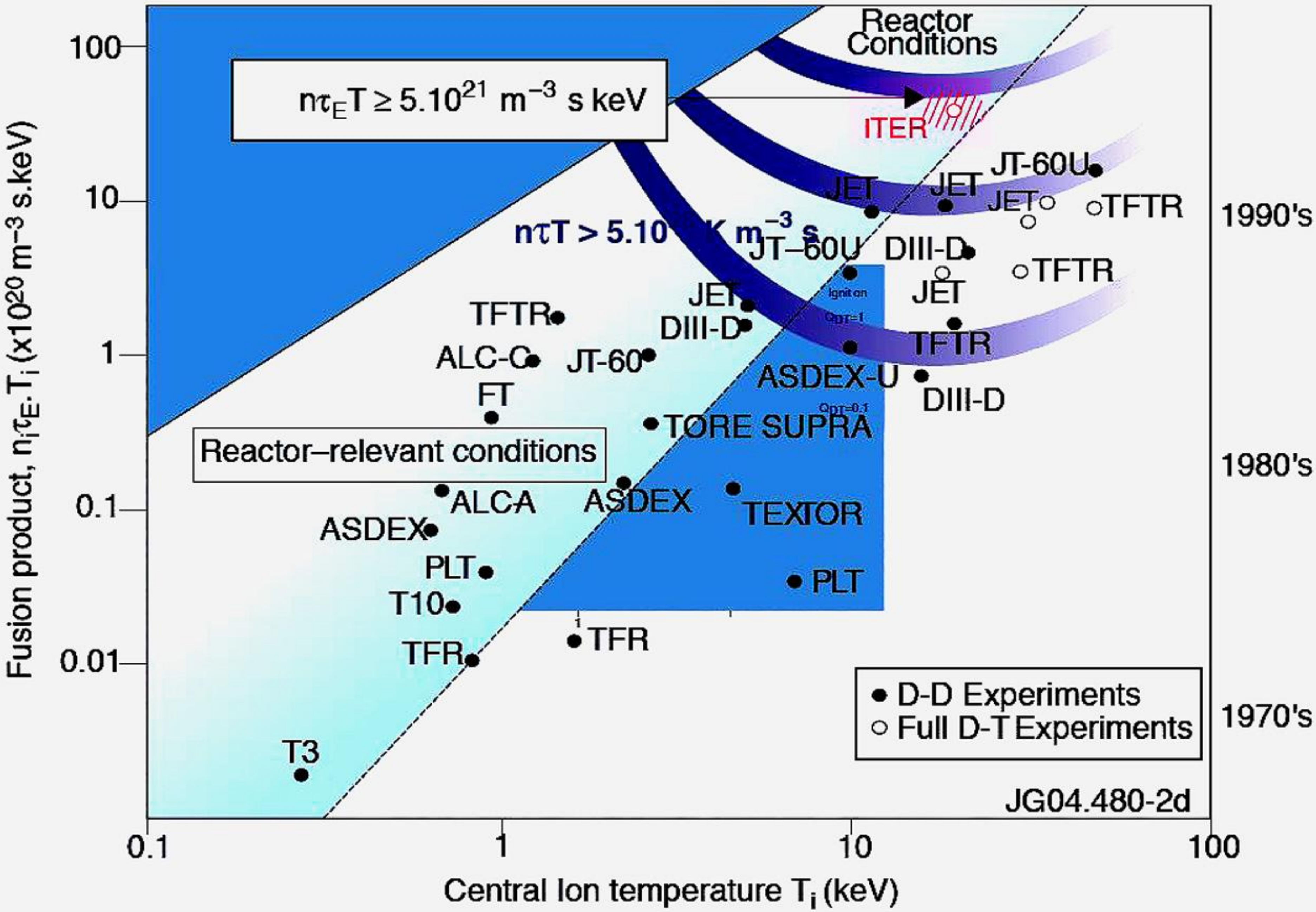
➢2× toroidal field (0.5 → 1T)
➢2× plasma current (1 → 2MA)
➢5× longer pulse (1 → 5s)

➢2× heating power (5 → 10MW)
- Tangential NBI → 2× current drive efficiency

➢4× divertor heat flux (→ ITER levels)
➢Up to 10× higher $nT\tau_E$ (~MJ plasmas)

Goals for future NSTX-U operation

- Increase field to 0.8-1T, current to 1.6-2MA, extend flat-top duration (H-mode) to 2-5s
- Assess global stability, energy confinement, pedestal height/structure, edge heat-flux width
- Characterize 2nd beam: heating, current drive, torque / rotation profiles, fast-ion instabilities
- Push toward full non-inductive current drive
- Test advanced divertor heat flux mitigation



Triple Product Achieved On Different Fusion Facilities

Comparison table of significant 'Conventional' Tokamaks

Name	Country	Location	Operating	Config.	Major radius (m)	Minor radius (m)	TF (tesla)	IP (MA)	ECH (MW)	ICH (MW)	NBI (MW)	LH (MW)
Full deuterium-tritium operation												
JET (Joint European Torus) (divertor configuration)	EU	Culham	1992	D-shape Divertor	2.96	0.96	4	6	-	12	24	7
JET (Joint European Torus) (original limiter configuration)	EU	Culham	1983 - 1992	D-shape Limiter	3.00	1.25-2.1	3.45	7	-	18	21	7
TFTR (Tokamak Fusion Test Reactor)	USA	Princeton	1982 - 1997	Circular Divertor	2.40	0.80	6	3	-	11.4	39.5	-
ITER	International	Cadarache, France	2018	D-shape Divertor	6.20	2.00	5.3 SC	17	20	20 (40)	33 (50)	0 (40)
Non-tritium operation												
ADITYA	India	Gandhinagar	1989	Circular Limiter	0.75	0.25	1.5	0.25	0.2	0.2	-	-
ALCATOR C (ALto CAmpo TORus)	USA	MIT, Cambridge, MA	1978	Circular Limiter	0.64	0.16	12	0.9	-	-	-	4
ALCATOR C-Mod (ALto CAmpo TORus)	USA	MIT, Cambridge, MA	1993	D-shape Divertor	0.67	0.22	8	2	- -	6	DNB only	1.5 (2.5)
ASDEX (Axially Symmetric Divertor EXperiment)	Germany	Garching	1980 - 1990	Circular Divertor (double null)	1.54	0.40	2.6	0.5	-	3	4.5	2
ASDEX upgrade	Germany	Garching	1991	D-shape Divertor	1.65	0.5-0.8	3.9	1.4	4	6	20	
CASTOR	Czech Rep.	Prague	1985 - 2007	Circular Limiter	0.40	0.09	1.5	0.025	-	-	-	0.02
CLEO (Closed Line Electron Orbit)	UK	Culham	1972 - 1987	Limiter tokamak and stellarator	0.90	0.13	2	0.12	0.2	-	0.04	
COMPASS	Czech Republic	Prague	2009	D-shape Divertor	0.56	0.21	2.1	0.32				

ITER

A big next step

Produce a **burning plasma**

Plasma kept hot by fusion energy itself ,

"self-heating"

- The world has started construction of the next step in fusion development, a device called ITER.
- ITER will demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.
- ITER will produce 500 MW of fusion power.
- Cost, including R&D, is ~15 billion dollars.
- **ITER is a collaborative effort among Europe, Japan, US, Russia, China, South Korea and India. ITER construction site is Cadarache, France.**
- ITER will begin operation in hydrogen in ~2020. **First D-T Burning Plasma in ITER in ~ 2027.**

ITER is a reactor-grade tokamak plasma physics experiment – a huge step toward fusion energy

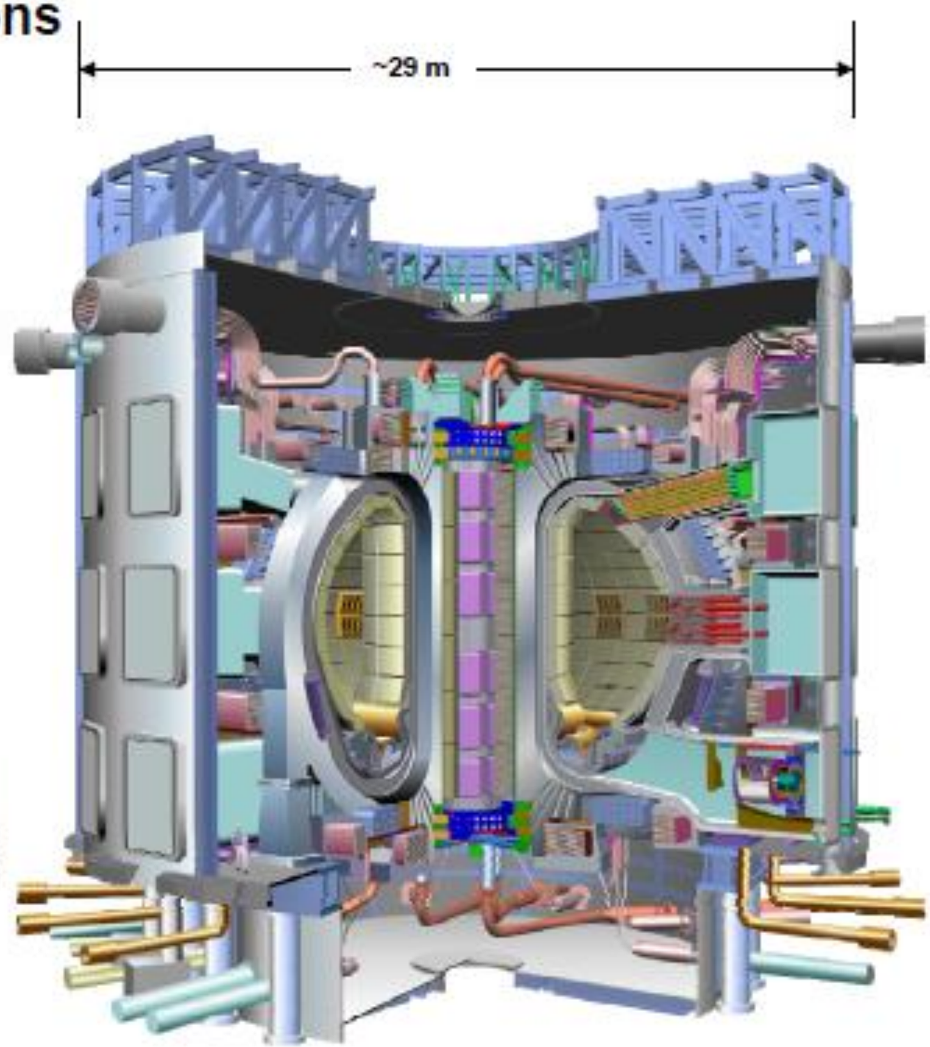
- Will use D-T and produce neutrons
- 500MW fusion power, Q=10
- Burn times of 400s
- Reactor scale dimensions
- Actively cooled PFCs
- Superconducting magnets

<u>By Comparison</u>

JET

- ~10 MW
- ~1 sec
- Passively Cooled

JET



ITER

New Long-Pulse Confinement and Other Facilities Worldwide will Complement ITER

China

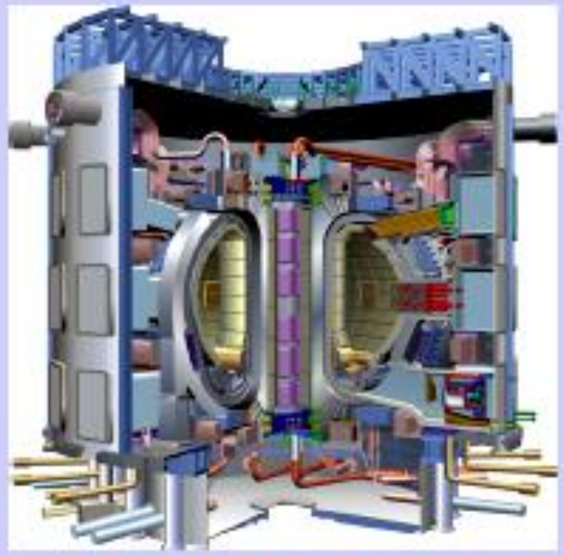
EAST

Europe

W7-X
(also
JT-60SA)

India

SST-1



ITER Operations:

34%	Europe
13%	Japan
13%	U.S.
10%	China
10%	India
10%	Russia
10%	S. Korea

Japan (w/EU)

JT-60SA
(also LHD)

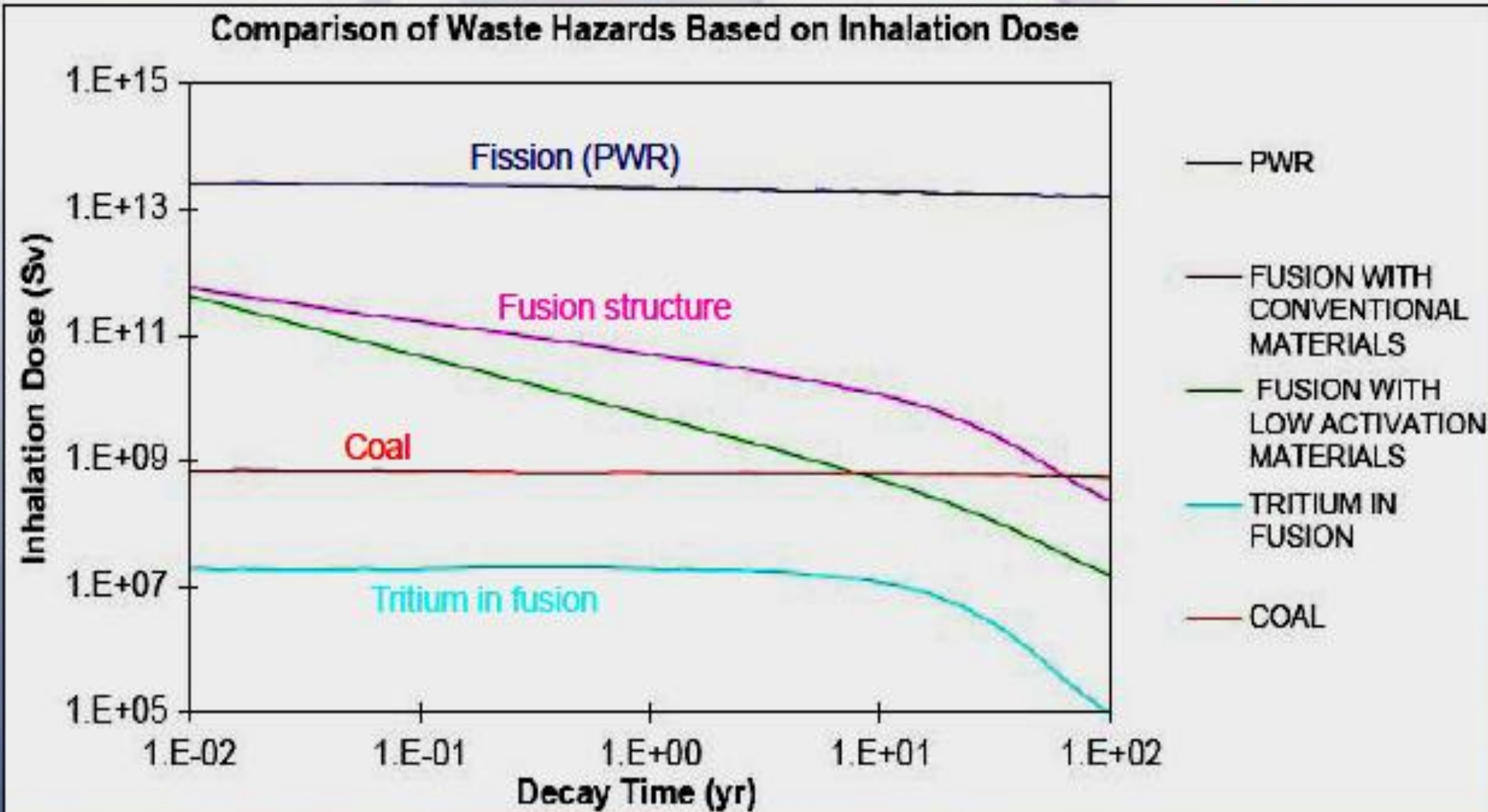
South Korea

KSTAR

U.S.

Being planned
Fusion Nuclear Science &Technology Testing Facility (FNSF/CTF/VNS)

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

The Deuterium-Tritium (D-T) Cycle

- World Program is focused on the D-T cycle:

$$D + T \rightarrow n + \alpha + 17.58 \text{ MeV}$$

- The fusion energy (17.58 MeV per reaction) appears as kinetic energy of neutrons (14.06 MeV) and alphas (3.52 MeV)

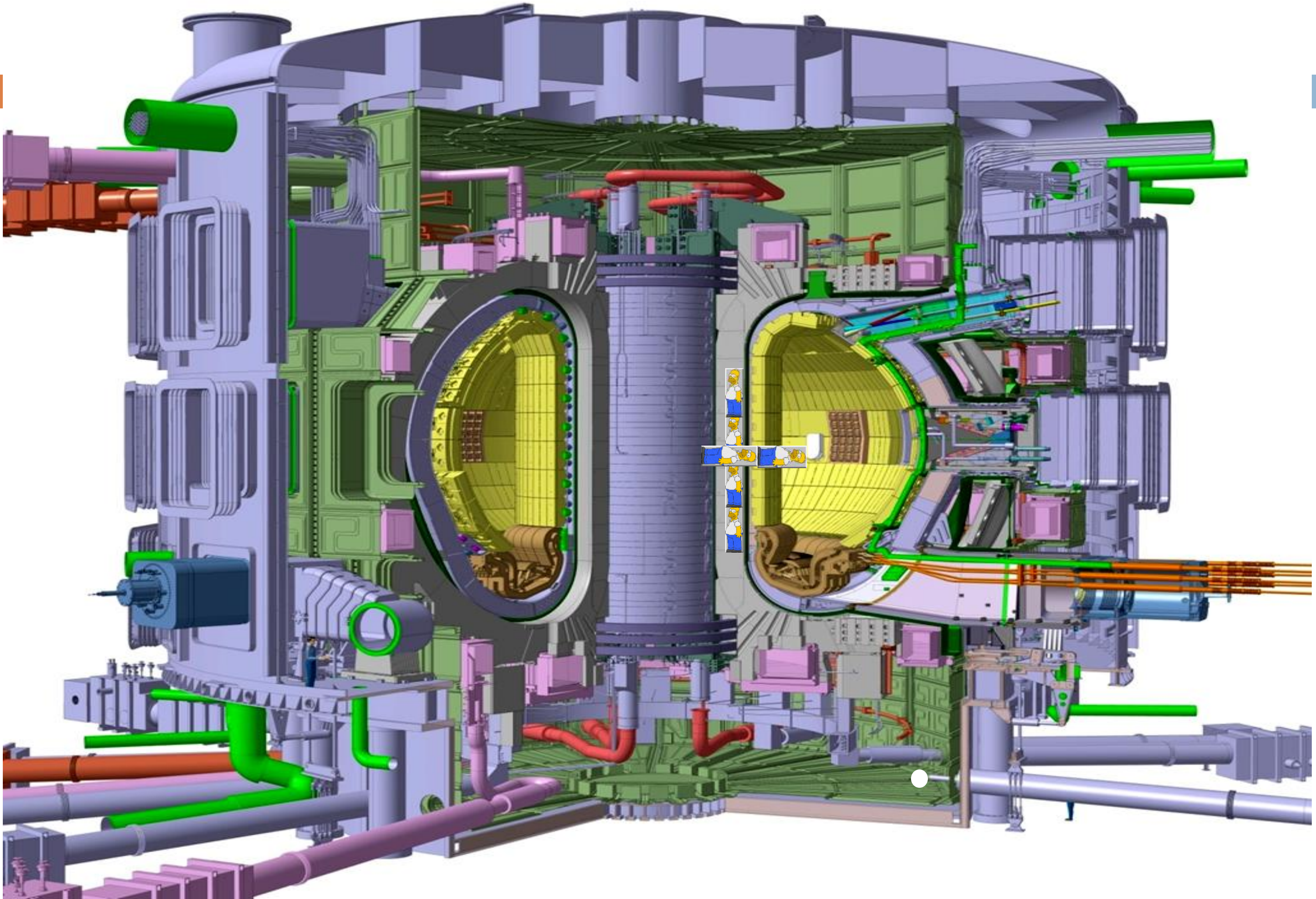
- Tritium does not exist in nature! Decay half-life is 12.3 years
  - Tritium must be generated inside the fusion system to have a sustainable fuel cycle
  - The only possibility to adequately breed tritium is through neutron interactions with lithium. Lithium, in some form, must be used in the fusion system.

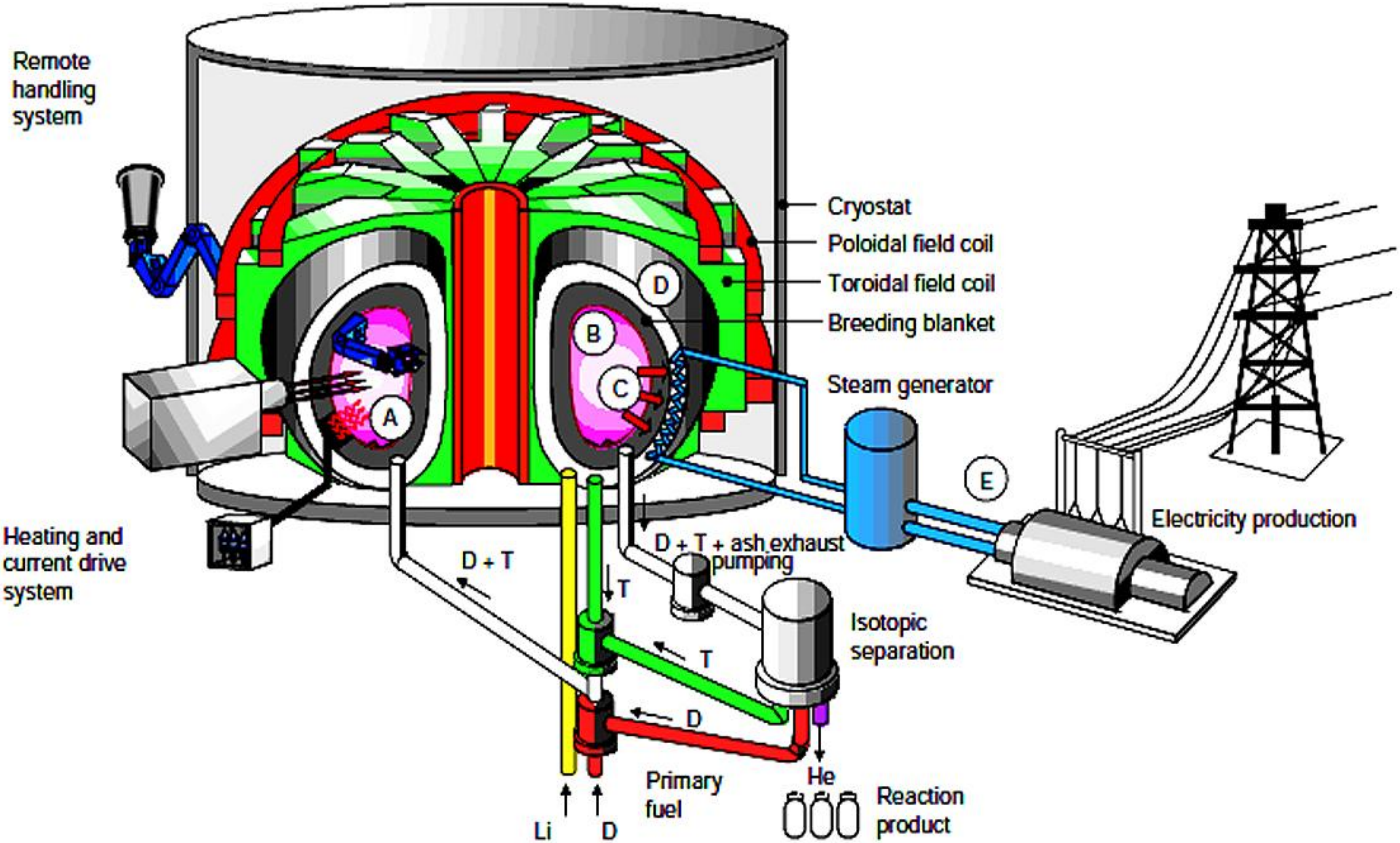
- α particles will slow down in the plasma imparting their energy to D and T and keep the plasma heated.
  - *But this "He ash" must be removed from the plasma, eg. via "Divertor"*

ITER Parameters

major radius	6.2 m
minor radius	2.0 m
fusion power	500 MW
power amplification	>10
plasma volume	840 m^3
toroidal field on axis	5.3 T
plasma current	15.0 MA
burn flat top	>400s

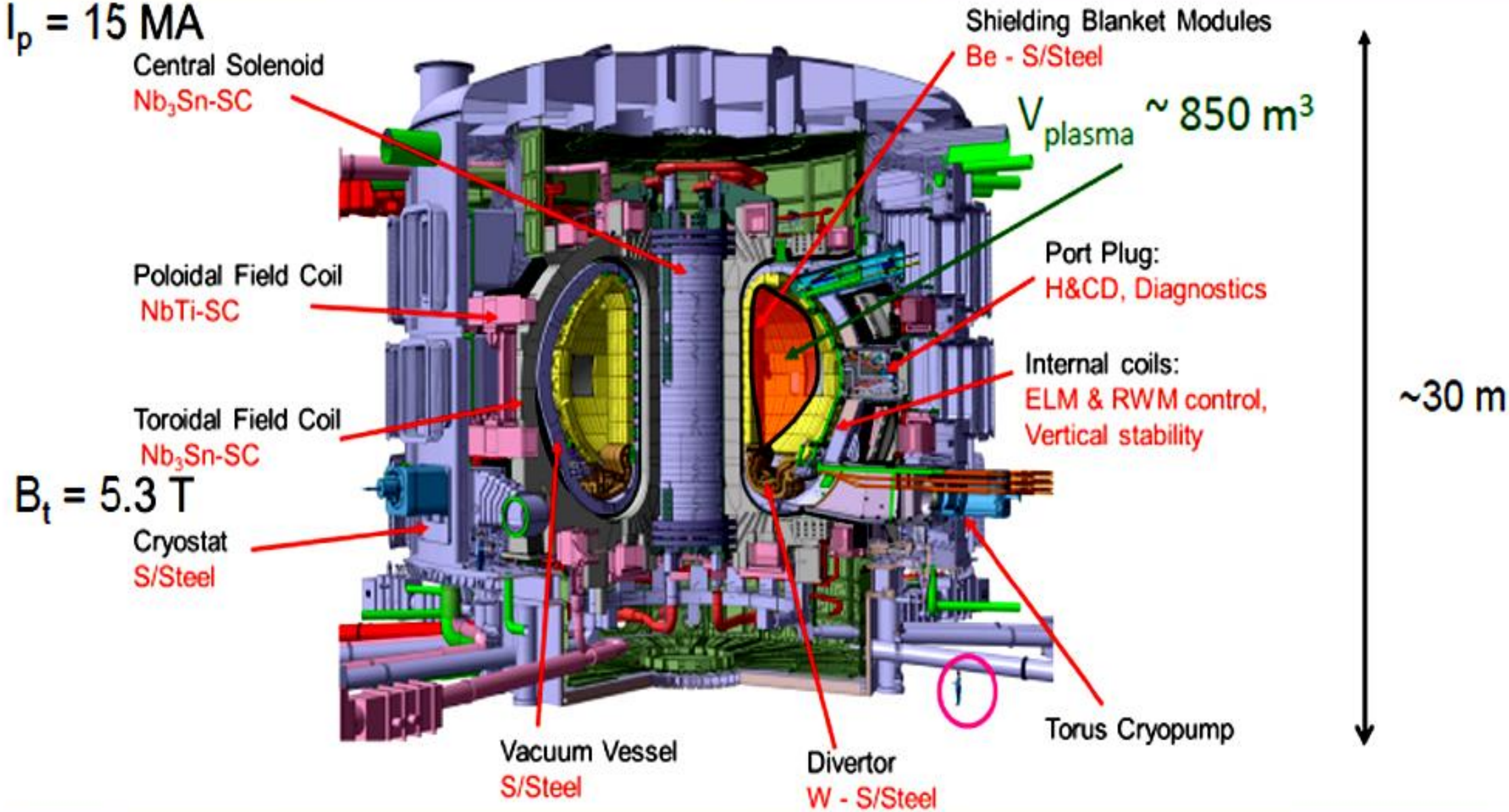
ITER – Cadarache, France





Schematic view of a fusion reactor based on a magnetic confinement: (A) vacuum chamber; (B) plasma; (C) plasma radiation; (D) blanket; (E) electricity production.

ITER - Main Features



NBI (1 MeV)	ECH (170 GHz)	ICH (40-55 MHz)	LH (5 GHz)	Total
33 MW (+16.5 MW)	20 MW (20 MW)	20 MW (20 MW)	0 MW (20 MW)	73 MW (130 MW-110 MW simultaneous)

Controlling Impurities

Fuel Impurities are a major threat to *FUSION* reactor success

Two primary sources of impurities

Helium "ash" from ***the fusion reaction***

Material impurities from ***plasma-wall interactions***

Impurities must be controlled

since they

Radiate energy, and reduce the plasma temperature

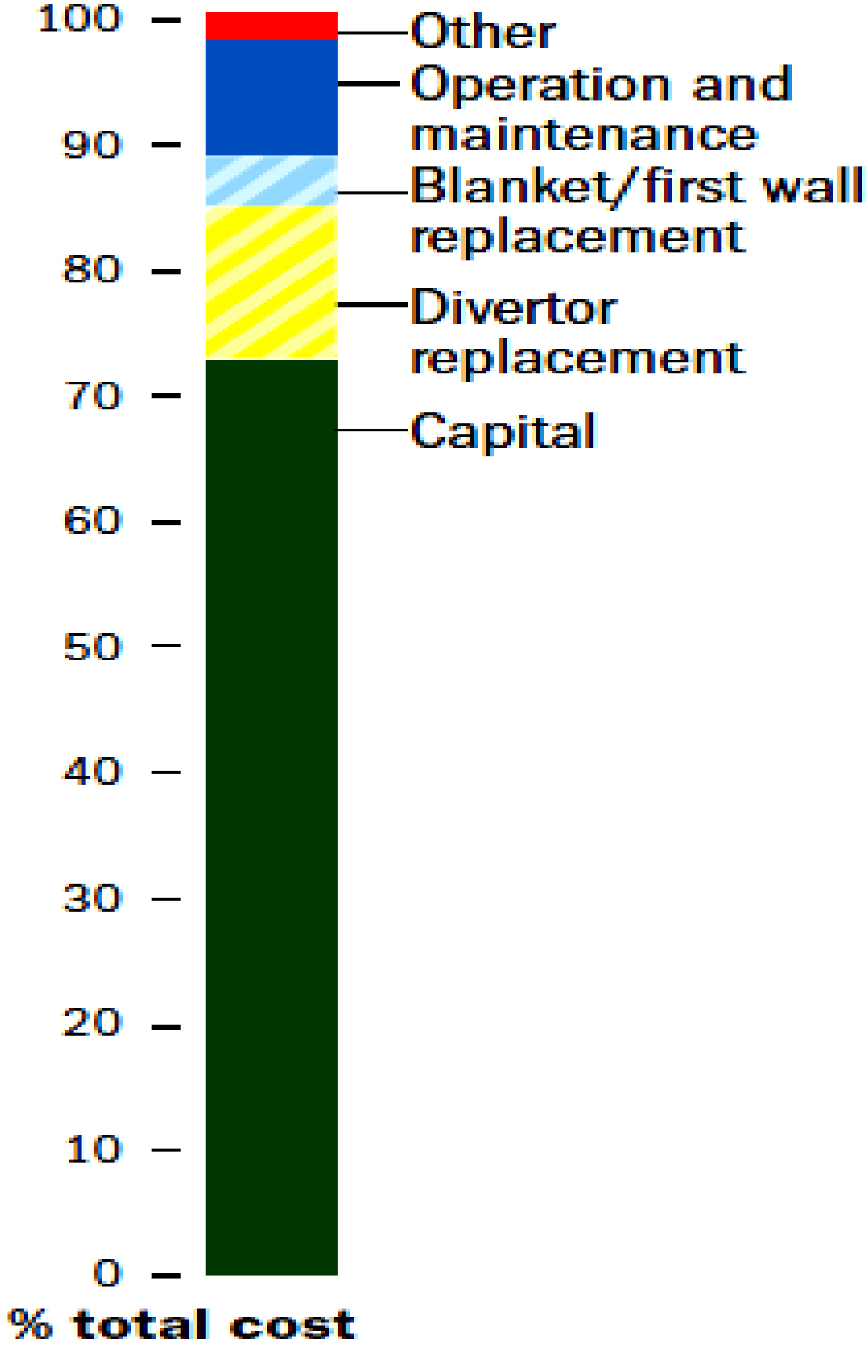
Dilute the fuel, thereby preventing ignition

How to Controll Helium "ash"and Material impurities?

- The **"Magnetic Divertor"** is a device for controlling impurities.
- This has been tested successfully in **JET , TFTR, JT-60**.
- Three different concepts have been compared.
- Results agree with code predictions.

ITER Timeline

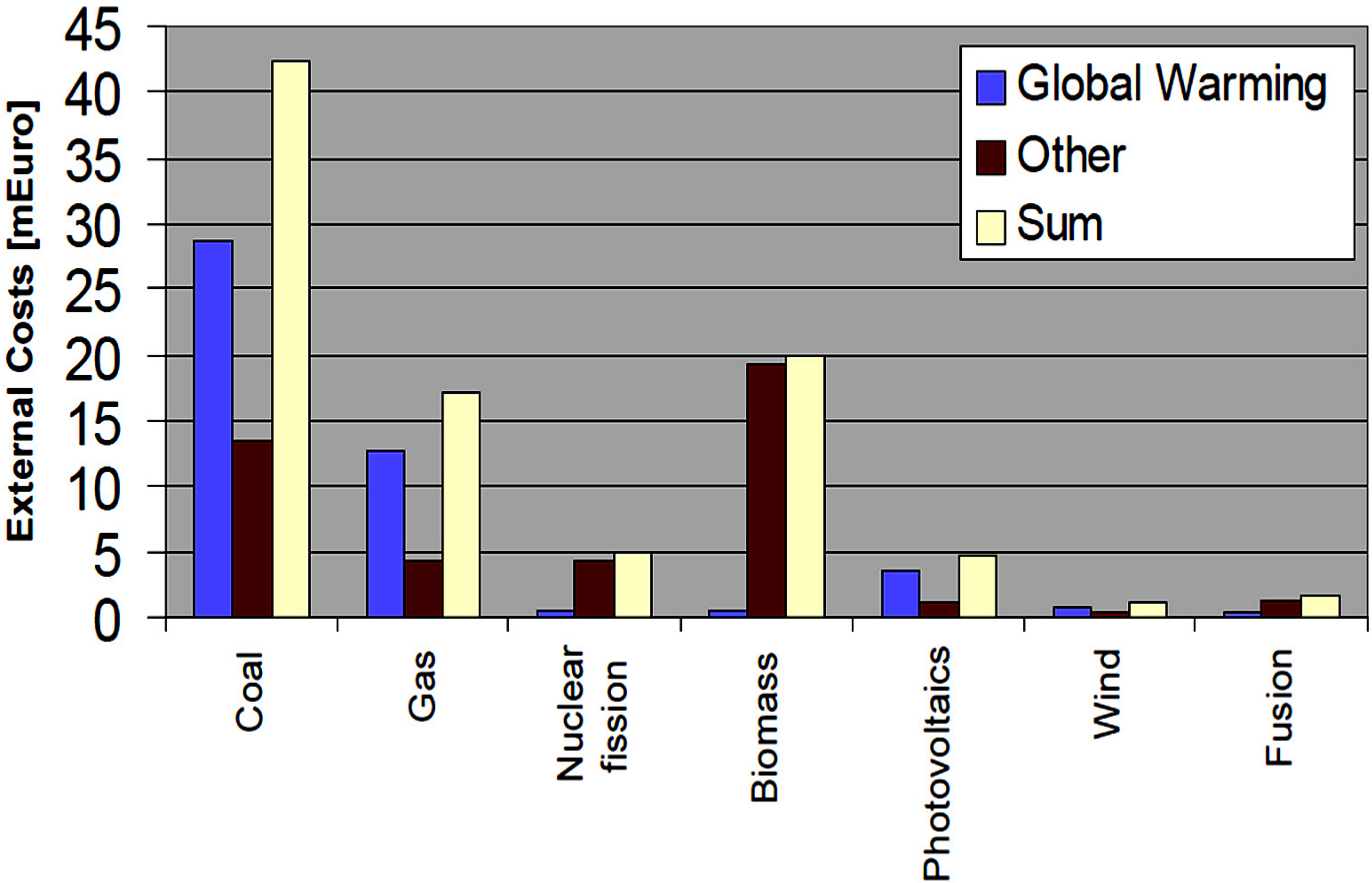
2005	Decision to site the project in France
2006	Signature of the ITER Agreement
2007	Formal creation of the ITER Organization
2007-2009	Land clearing and levelling
2010-2014	Ground support structure and seismic foundations for the Tokamak
2012	Nuclear licensing milestone: ITER becomes a Basic Nuclear Installation under French law
2014-2021*	Construction of the Tokamak Building (access for assembly activities in 2019)
2010-2021*	Construction of the ITER plant and auxiliary buildings for First Plasma
2008-2021*	Manufacturing of principal First Plasma components
2015-2021*	Largest components are transported along the ITER Itinerary
2018-2025*	Assembly phase I
2024-2025*	Integrated commissioning phase (commissioning by system starts several years earlier)
Dec 2025*	First Plasma
2035*	Deuterium-Tritium Operation begins



Components of the total cost of electricity produced by a magnetic confinement fusion reactor, shown as a percent of total cost. The two components shown with stripes are costs for replacement of critical elements of the reactor whose lifetime, due to neutron bombardment, could be much shorter than the rest of the reactor.

Energy source	Fuel needed for a 1000 MW plant, during one year	For comparison
Biomass	2,000 km^2 of energy crop	3 times surface lake of Geneva
Wind	2,700 windmills of 1.5 MW (25% capacity factor)	486 km^2
Solar PV	23 km^2 of solar panel on the equator	2555 soccer fields
Biogas	20 million pigs	
Gas	1,2 km^3	47 Cheops pyramids
Oil	1,400,000 tons	10,000,000 oil barrels or 100 super tankers
Coal	2,500,000 tons	26,260 train waggon loads
Nuclear fission	35 tons of UO2	210 tons of Uranium ore
Fusion	100 kg D and 150 kg T	2850 m^3 of sea water and 10 tons of lithium ore

Table. Fuel requirements for different energy sources. In the table, the fuel use is shown for a 1000 MW power plant for one year (total output about 7000 million kWh). Clearly, wind, solar and biomass need a lot of space. Fission and fusion stand out as they require only very modest amounts of fuel.



External costs (in Western Europe) of electricity generation from various sources.

Summary

- Fusion is the most promising long-term energy option
  - renewable fuel
  - no emission of greenhouse gases
  - inherent safety
- 7 nations started construction of **ITER** to demonstrate the scientific and technological feasibility of fusion energy
  - ITER will have first DT plasma in ~2026
  - ITER is the largest scientific/engineering project in the world
- **Fusion research has made considerable progress**
  - **But significant challenges remain ahead for fusion energy development and demonstration**
  - **Fusion research offers exciting opportunities for the next generation of bright young scientists and engineers**

COUNTRY	PER CAPITA CONSUMPTION
Canada	13600 W
Norway	13200 W
USA	10900 W
Europe (West & West)	5100 W
Japan	4900 W
Former Soviet Union	6600 W
Chuina	830 W
India	320 W
Developing Countries	100-1000 W
World	2200 W

Table 1.

Per capita total primary power consumption for selected countries
average annual total primary power consumption
per country divided by the number of its inhabitants

FUEL	PROVED RECOVERABLE RESERVES	YEARS OF USE AT THE CURRENT RATE OF CONSUMPTIOM
Coal	1.0×10^{12} tons	270
Crude Oil	950×10^{9} barrels	40 - 50
Natural Gas	120×10^{12} m^3	60 - 70
Uranium	2.0×10^{6} tons	40 - 50
		2400 - 3000 (*)

Table 2

Years of use of different fuels at the current rate of consumption
(*) if breeder technology is employed.

ENERGY SOURCE	CONTRIBUTION TO PRIMARY ENERGY PRODUCTION
Oil	40 %
Coal	27 %
Gas	21 %
Fission	6 %
Hydro - electricity	6 %

Table 3

Contribution of different energy sources to the primary energy production in the world

METHOD	INVESTMENT NEEDED FOR 1000 MW(e)
Photovoltatic panels	about 100 K m^2 in Middle Europe (10% efficiency assumed)
Windmills	6660 mils of 150 K W (with rotor blades of 20 m and at the average wind speed prevailing at the North Sea Coast)
Biogas	60 million pigs or 800 million chickens
Bioalcohol	6200 K m^2 of sugar beet 7000 K m^2 of potatoes 16100 K m^2 of corn 27200 K m^2 of wheat
Bio - Oil	24000 K m^2 of rapeseed
Biomass	30000 K m^2 of wood

Table 4

<u>Limitations of renewable energy sources</u>

assumed to be used for electricity generation ; where necessary an overall efficiency of 40 % for the thermal cycle is included ; no compensation for losses due to storage is included for solar or wind power

Fusion Reaction	Energy Generated/gm of Reactants (jouls)	Ignition temp. (^oC)
$D + T \rightarrow {}^4He + n$	34×10^{10}	45×10^6
$D + D \rightarrow T + P$	10×10^{10}	650×10^6
$D + D \rightarrow {}^3He + n$	8×10^{10}	900×10^6
$D + {}^3He \rightarrow {}^4He + p$	36×10^{10}	220×10^6

Table 5

Fusion Reactions

Fusion Fuel	Equivalent To
D	5×10^{11} TW yr
Li (known reserves)	9×10^3 TW yr
Li (in sea water)	1.7×10^8 TW yr

Table 6

Estimated reserves of fusion fuels

	COAL PLANT	D - T FUSION PLANT
FUEL	9,000 T. COAL	1.0 L B D_2 3.0 L B Li^6 (1.5 L B T_2)
WASTE	30,000 T. CO_2 600 T. SO_2 80 T. NO_2	4.0 L B He^4

Table 7

Daily Fuel Consumption
Daily Waste Production
for 1,000 Megawatts

DEMO

FURTHER STEP VIA FUSION REACTOR

DEMO (DEMOnstration Power Station) is a proposed nuclear fusion power station that is intended to build upon the ITER experimental nuclear fusion reactor. The objectives of DEMO are usually understood to lie somewhere between those of ITER and a "first of a kind" commercial station. While there is no clear international consensus on exact parameters or scope, the following parameters are often used as a baseline for design studies: DEMO should produce at least 2 gigawatts of fusion power on a continuous basis, and it should produce 25 times as much power as required for breakeven. DEMO's design of 2 to 4 gigawatts of thermal output will be on the scale of a modern electric power station.

To achieve its goals, DEMO must have linear dimensions about 15% larger than ITER, and a plasma density about 30% greater than ITER. As a prototype commercial fusion reactor, DEMO could make fusion energy available by 2033. It is estimated that subsequent commercial fusion reactors could be built for about a quarter of the cost of DEMO.

Last Step via nuclear fusion power station

DEMOnstration Power Station (DEMO)

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What is ?

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Timeline

In 2004 The following timetable was presented at the IAEA Fusion Energy Conference:

- Conceptual design is to be complete by 2017
- Engineering design is to be complete by 2024 (after input from ITER D-T tests, and data from IFMIF - both delayed as of 2016)
- The first construction phase is to last from 2024 to 2033
- The first phase of operation is to last from 2033 to 2038
- The station is then to be expanded and updated (e.g. with phase 2 blanket design)
- The second phase of operation is to start in 2040.

Updated

In 2012 European Fusion Development Agreement (EFDA) presented a roadmap to fusion power with a plan showing the dependencies of DEMO activities on ITER and IFMIF.

- Conceptual design to be complete in 2020
- Engineering design complete, and decision to build, in 2030
- Construction from 2031 to 2043
- Operation from 2044, Electricity generation demonstration 2048

IFMIF (International Fusion Materials Irradiation Facility)

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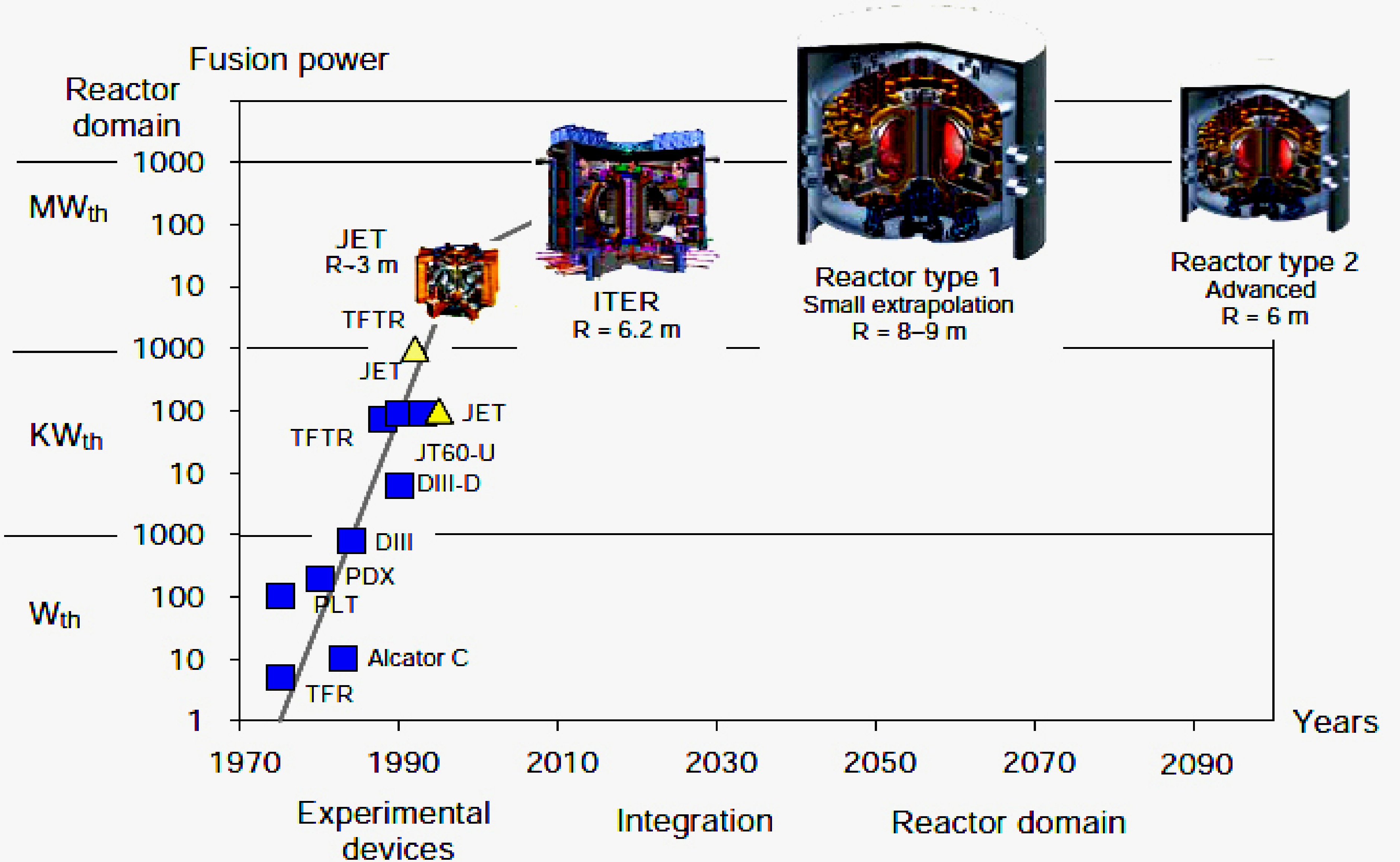
IFMIF (International Fusion Materials Irradiation Facility)

CONCLUSIONS

- Path to Fusion Reactor



- In the current state of rapid use of natural resources and depletion of easily available ones, there is a high demand for alternative sources of energy. Importance of this is also increasing in the light of need for ecology protection.
- Fusion power would be the best answer to the problem, as the fuel it requires is virtually unlimited and the waste it produces will not impose a negative impact on the environment.
- There are multiple other advantages in developing and transitioning to fusion as a source of energy, among which are intrinsic safety of stations' operation, relative ease of resources acquisition and waste handling, and minimal costs associated with operation.
- The research in the field is rapidly growing and commercial use of fusion energy is not too far off.
- Fusion energy features numerous qualities. It is a nearly unlimited energy source that does not generate any greenhouse gas effect or environmental pollution, and it features undeniable advantages in terms of safety. With adequate design, radioactive wastes from the operation of a fusion plant should not constitute a burden for future generations.

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Thank you!

Em. Prof. Sherif Khalil

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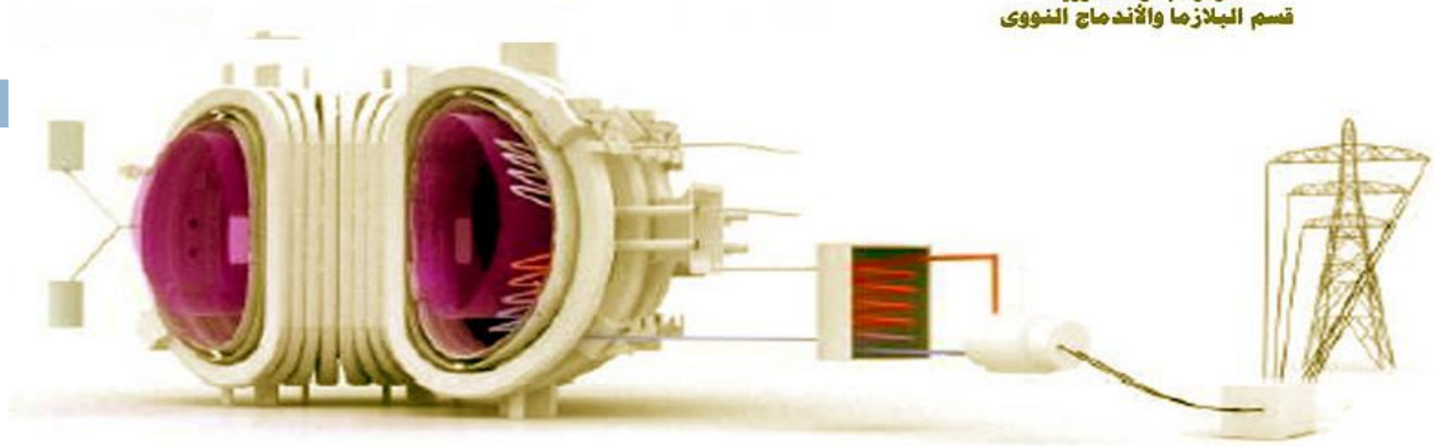
قسم البلازما والأندماج النووى



Thank You for Kind Attention

OPEN FOR DISCUSSION & QUESTIONS

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EAEA

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