Fusion : a sustainable energy source

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EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

Outline

- Introduction: What is fusion?
- Fusion as a sustainable energy source
- Physics of magnetically confined plasma
- Technology of a fusion reactor
- Roadmap towards fusion

Fusion reaction

- Light nuclei can fuse and release energy:

D + T ---> He^4 (3.5 MeV) + n (14.1 MeV)

Li^6 + n ---> T + He^4 +4.8 MeV

The total energy liberated is 100×10^6 kWh/kg

D + D ---> He^3 +n + 3.2 MeV

D + D ---> T + H + 4.03 MeV

D + He^3 ---> He^4 + H + 18.3 MeV

He^4 is also called α particle

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Fusion as a sustainable energy source

- Issue of the fuel: Li reserve and resource
- Issue of environmental impacts:
  - CO_2 emission
  - Radioactive waste
  - Safety

Fuel

- Reserve of D: 1 D for 6700 of H

(88 kg/a for a 1000 MW_e power plant (PP))

- T: short lived radio isotope (13 years) but is generated in the reactor from reaction $Li^6 + n \dashrightarrow T + He^4$

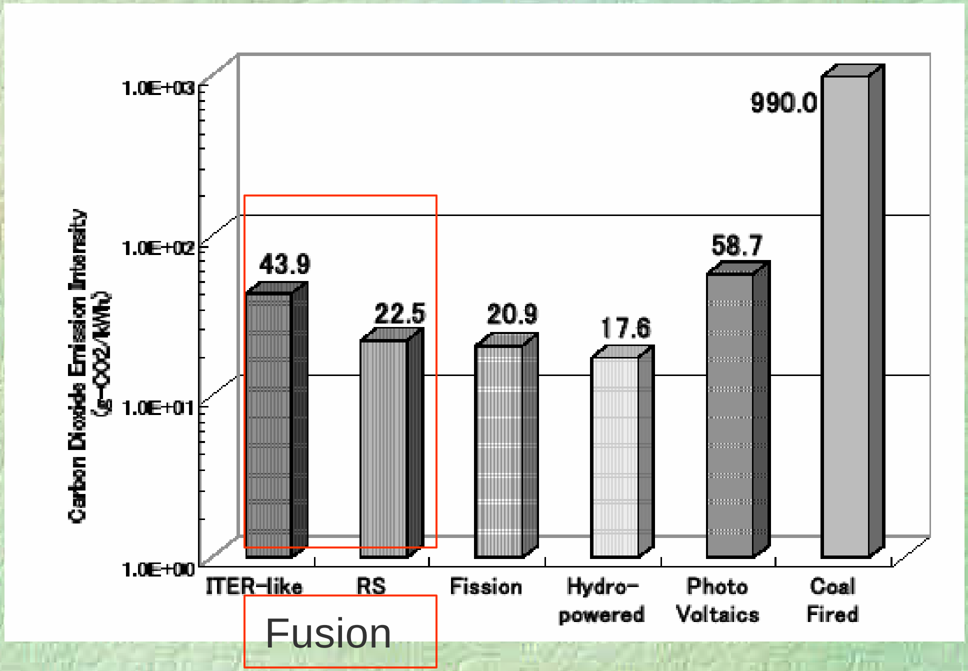
(236 kg of Li^6 / year for a 1000 MW_e PP)

- Li reserve and resource:
  - Earth: 9 Mt reserve; >12 Mt resource
  - Sea water: 170/billion; 2×10^{11} tons

Fuels are practically inhexaustible

CO_2 emission

- The production of energy from fusion does not generate any green house gas
- Life cycle study

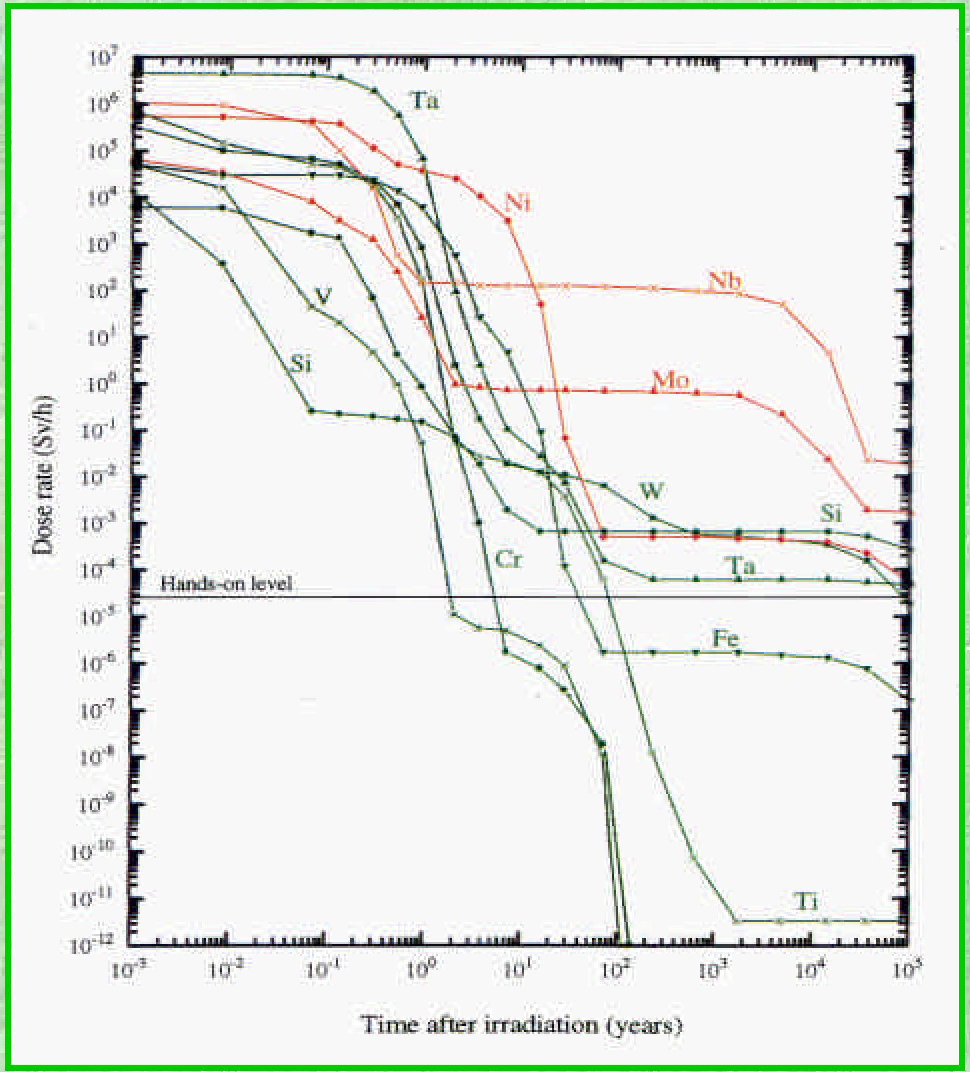


Ref. Tokimatsu et al 17th IAEA FEC

Waste (1)

- The fusion reaction D+T does not yield any radioactive daughter product (only a n and a He nucleus)
- The interaction of the energetic neutron (14 MeV) with nuclei will produce transmutation and hence yield radioactive daughter products
- But these products does not have extremely long life (Cf following viewgraphs and Discussion on materials for a fusion power plant)

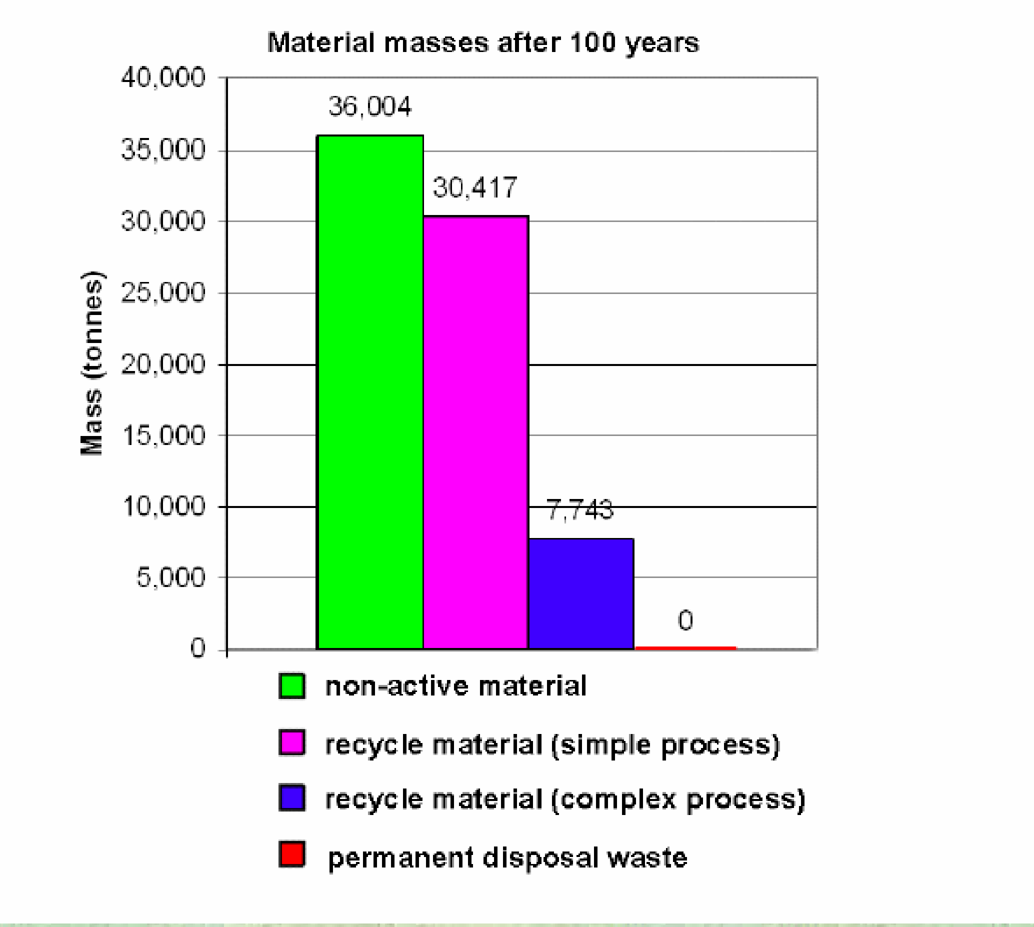
Waste (2)



Dose rate (Sv/h)
Time after irradiation (years)
Hands-on level
Ta
Ni
Nb
Mo
V
Si
W
Cr
Fe
Ti

Waste (3)

- Calculation of radioactive life time and recycling limit of a fusion power plant



Ref. EU Fusion Power Plant Conceptual Study (PPCS) , EFDA

Waste (4)

Activated material classifications	*Contact dose rate after 50 y (mSvh^{-1})*	*Decay heat per unit volume after 50 y (Wm^{-3})*	*Clearance index after 50 y*
PDW, Permanent Disposal Waste (Not recyclable)	> 20	>10	> 1
CRM, Complex Recycle Material (Recyclable with complex RH procedures)	2 - 20	1 - 10	> 1
SRM, Simple Recycle Material (Recyclable with simple RH procedures), Hands On Recycling for D < 10 µSvh^{-1}	< 2	< 1	> 1
NAW, Non Active Waste (to be cleared)	< 0.001	< 1	< 1

According to ICRP and IAEA recommendation

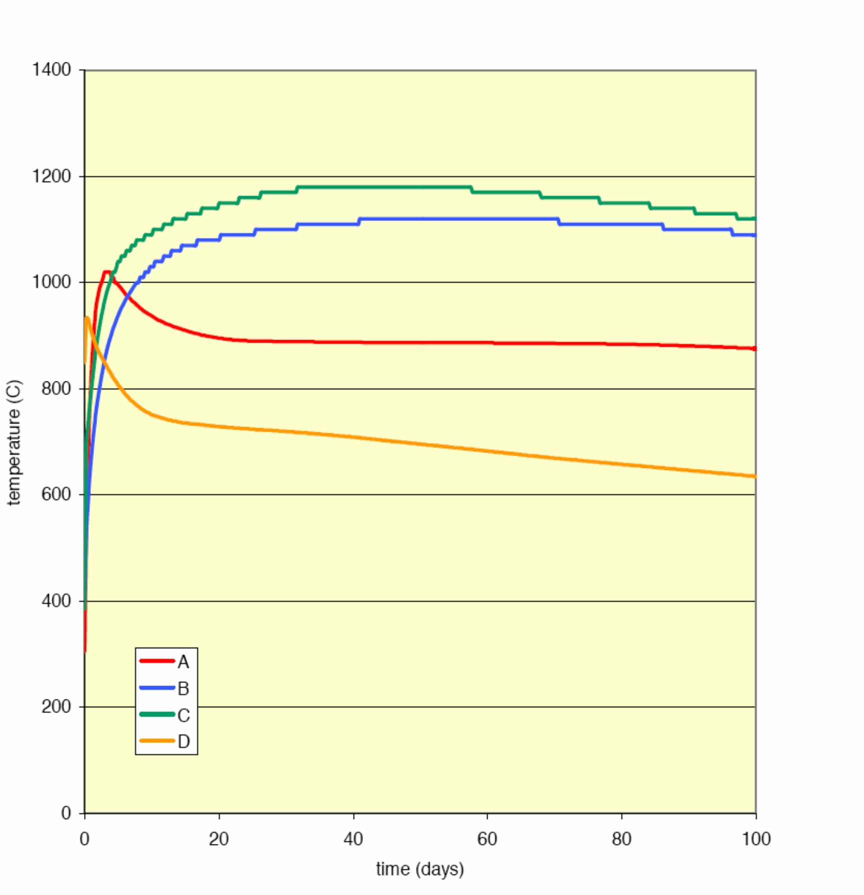
Ref.: PPCS study , EFDA

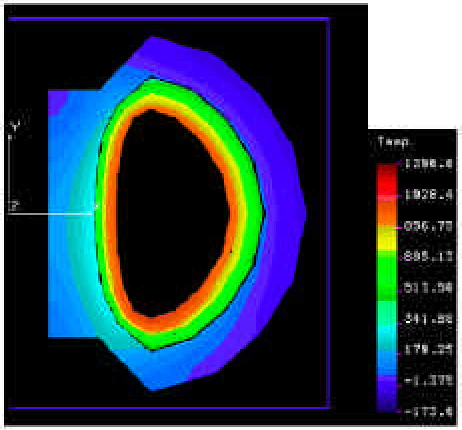
Accident (1)

- Accident sequences were assessed during the design phase of ITER and during the power plant conceptual study.
- No evacuation of the population: most severe conceivable accident driven by in plant energies lead to a dose of 18 mSv, below the threshold of 50 mSv for evacuation

Accident (2)

- Beneficial aspects in case of loss of coolant accident (LOCA): delicate balance of conditions for fusion reactions, fuel inventory sufficient only for a few minutes of burn





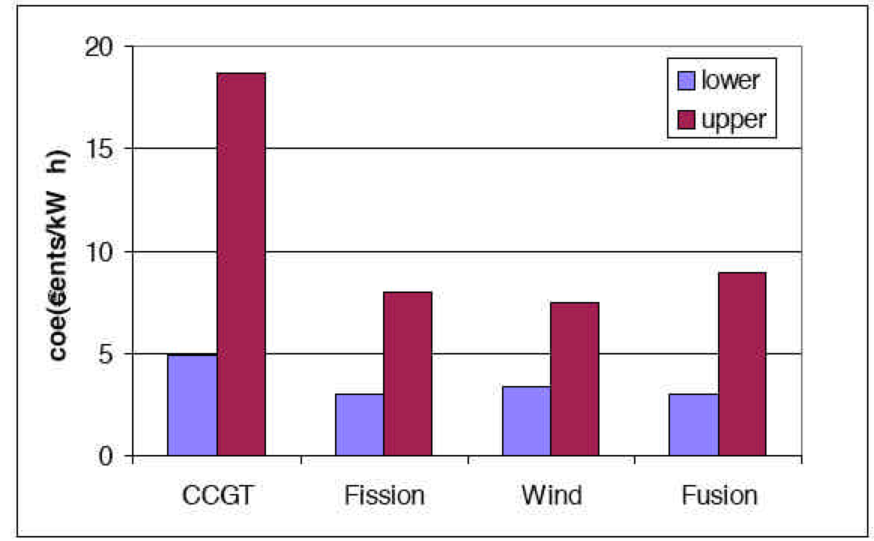
Temperature below melting point

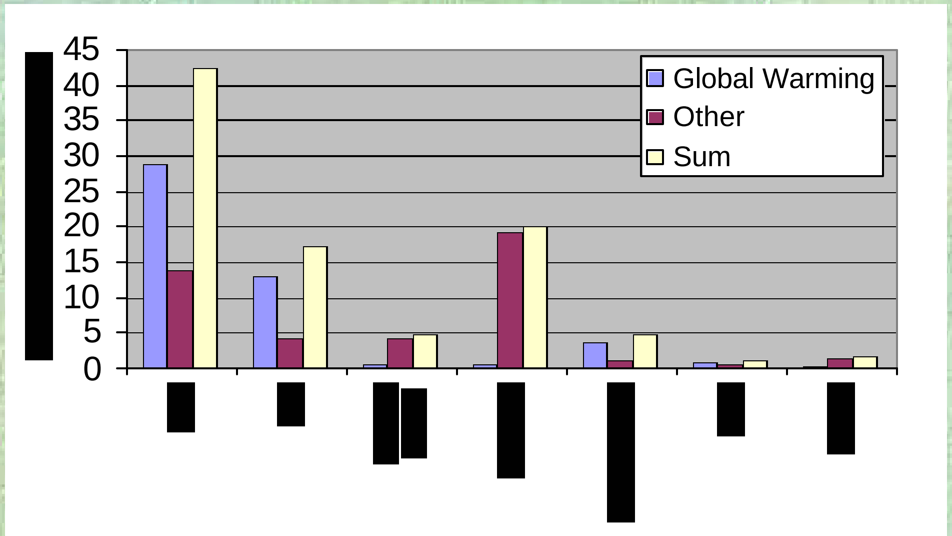
Ref.: PPCS study , EFDA

Economic studies for fusion (1)

- Cost of electricity

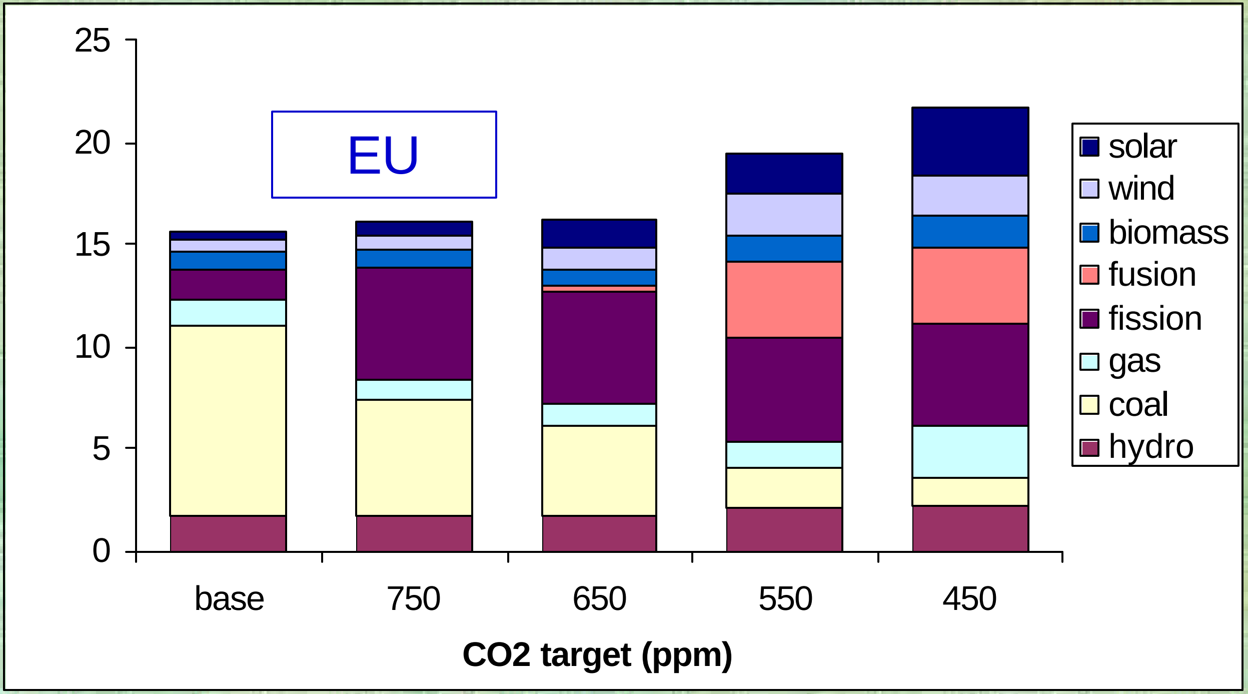
External cost, based on EU EXTERN E methodology

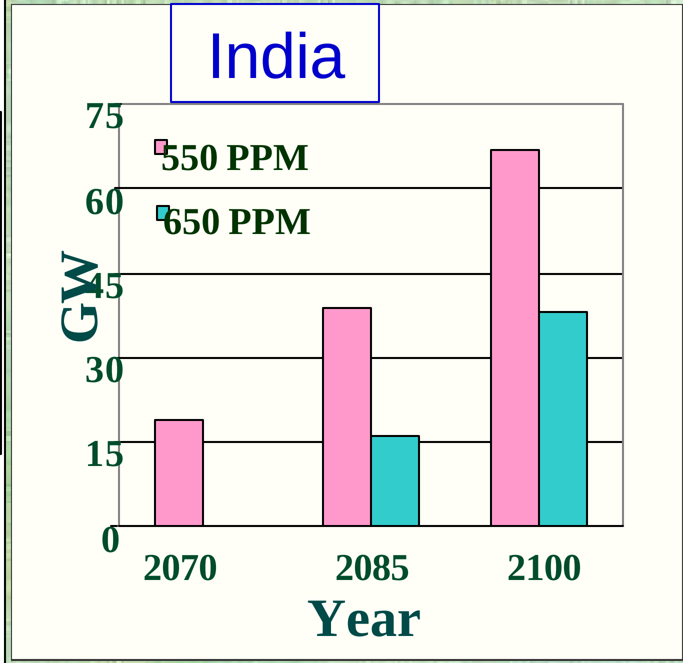




Ref. SERF studies, EFDA

Economic studies for fusion (2)





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Cross sections

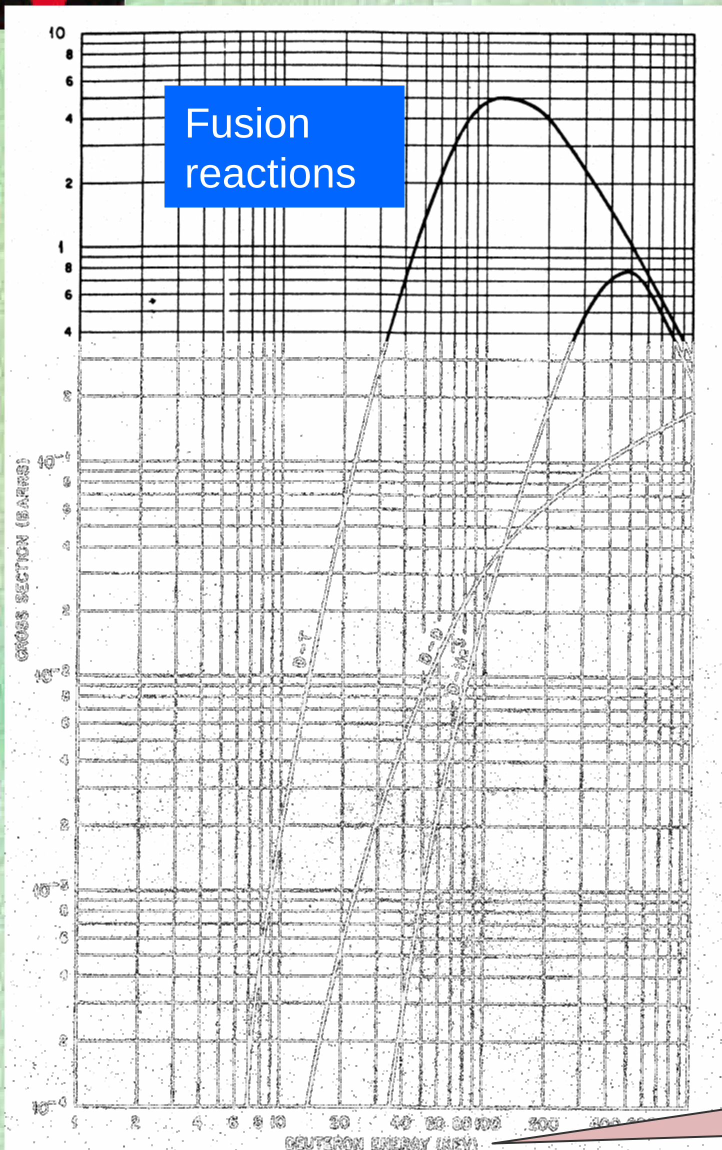
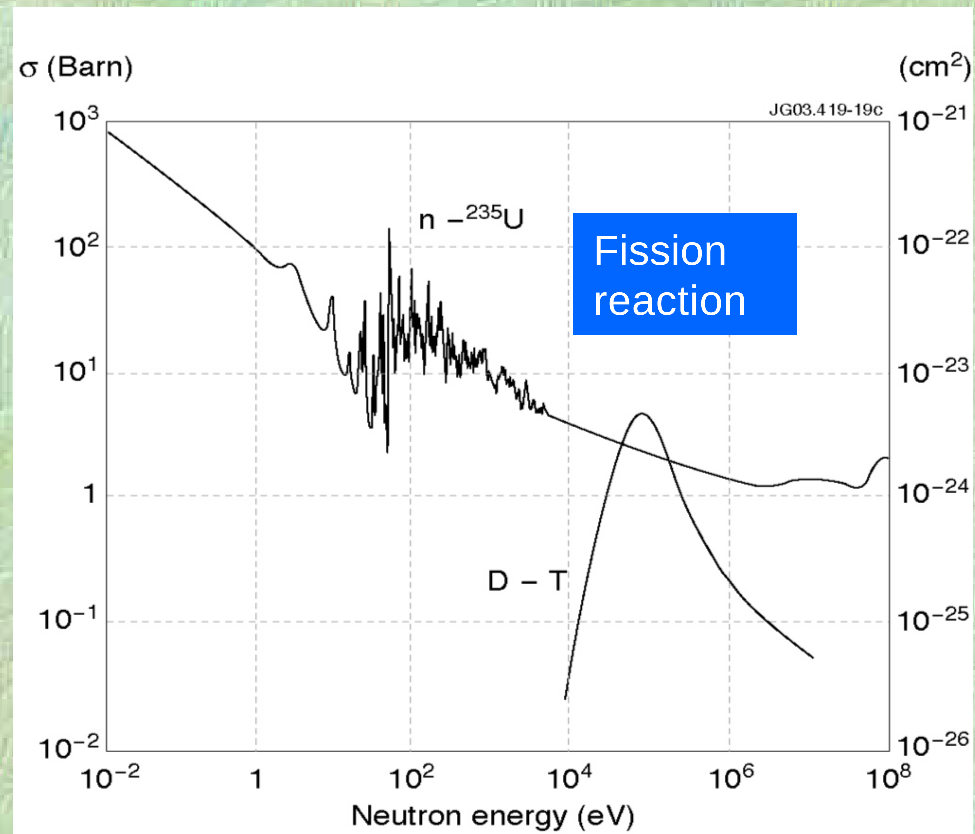


Fig 2.3. Cross sections for D-T, D-D (total), and D-He³ reactions.



1 keV is equivalent to 10^7 °K

Mean free path of fusion reaction

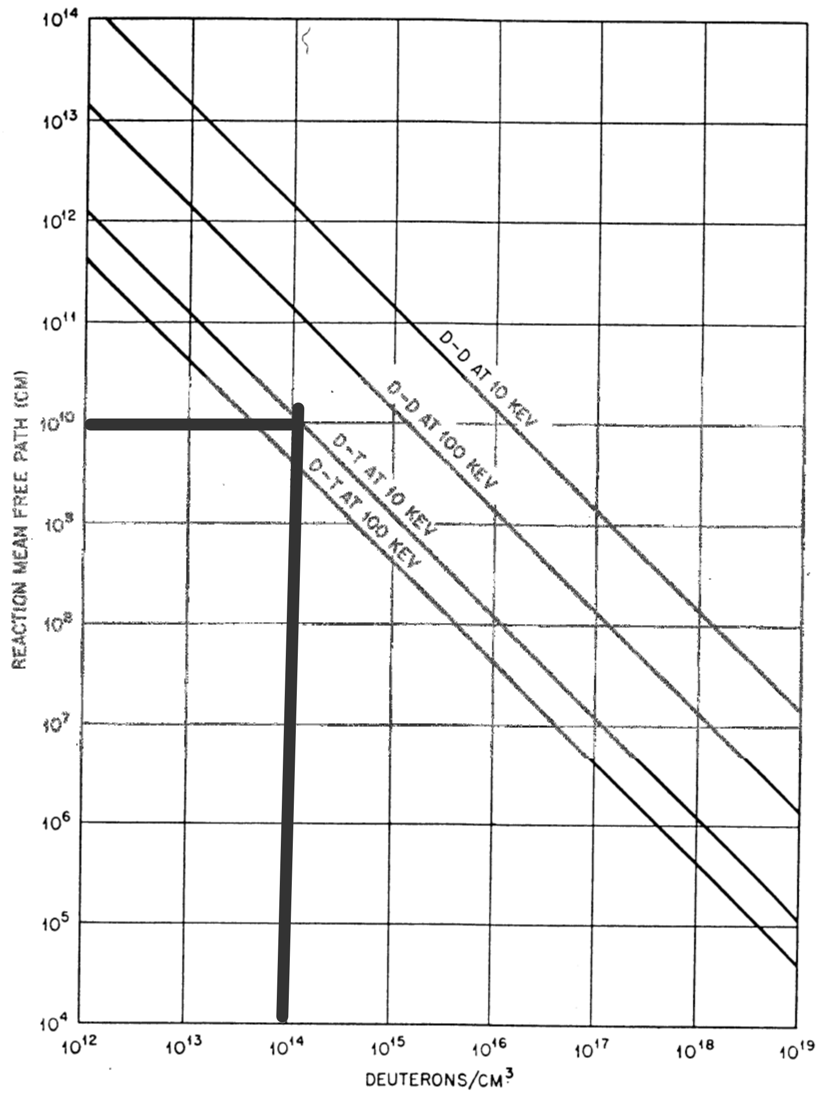


FIG. 2.5. Mean free paths for D-T and D-D (total) thermonuclear reactions.

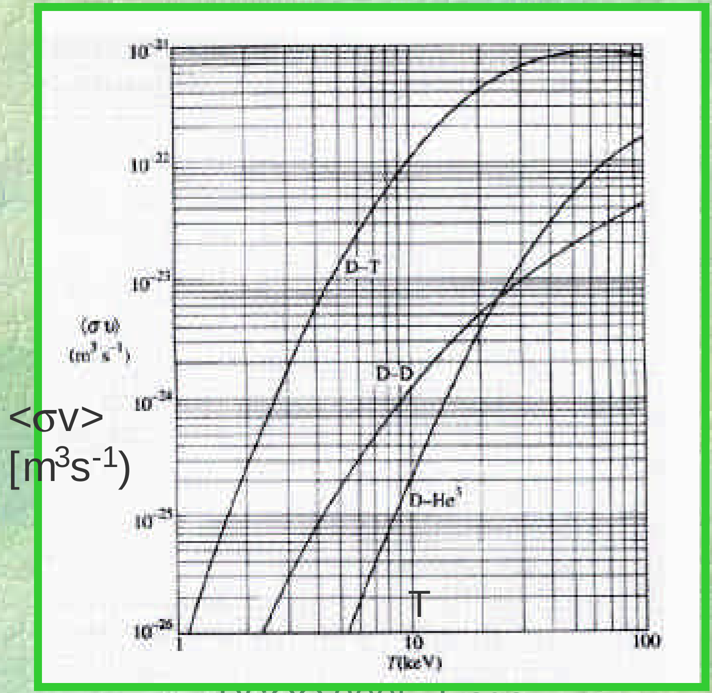
Power balance (1)

- Power produced by fusion reaction

$$P_{fusion} = \frac{1}{4} n^2 \langle \sigma v \rangle E_{fusion} \quad V$$

n = Particle density of D or T

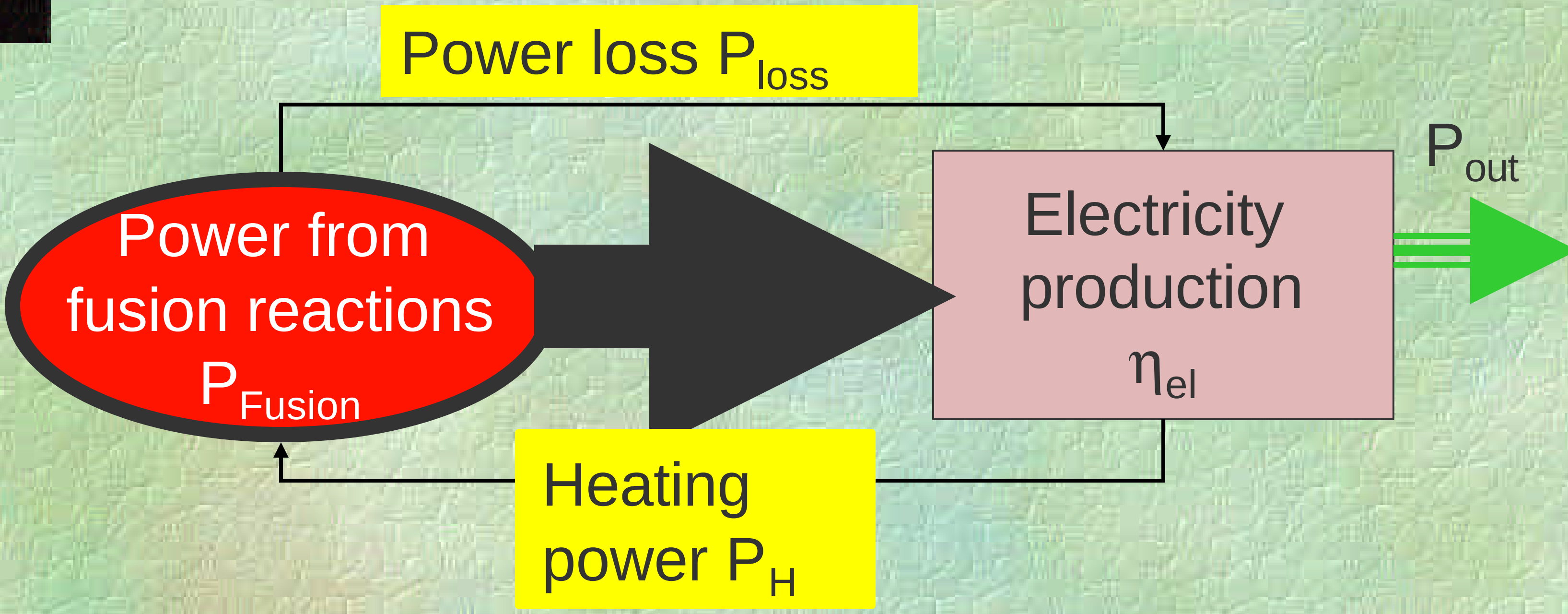
$\langle \sigma v \rangle$ is function of the temperature T



T is expressed in keV

1 keV=10 millions degrees

Power balance (2)



$$P_\alpha = P_{loss} \quad \text{(Ignition)}$$

$$n\tau_E > 1.5 \times 10^{20}\ \text{m}^{-3}\text{s at } T = 10\ \text{keV}\ (10^{8\,o})$$

$$n\tau_E T > 5 \times 10^{21}\ \text{m}^{-3}\text{skeV}$$

$$n\tau_E T = \text{Fusion triple product}$$

Condition for a positive power balance

- Triple product $n\tau_E T > 5x10^{21}$. Typically: $n = 10^{20}$ m^{-3}. $T = 10$ keV, $\tau_E = 5$ s
- Another important quantity:

$$Q = \frac{P_{Fusion}}{P_{External \quad heating}}$$

Q is infinite at "ignition", where the power loss P_{loss} is compensated by the P_α

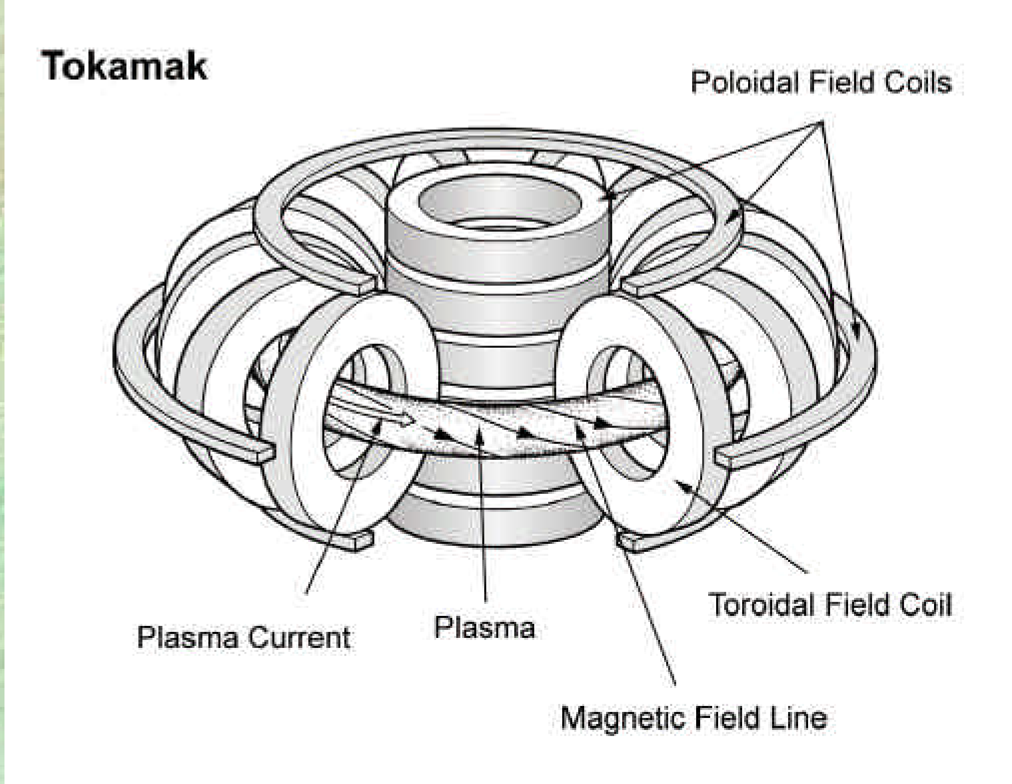
For the operation of a reactor, Q is of the order of 40

Confinement of the plasma

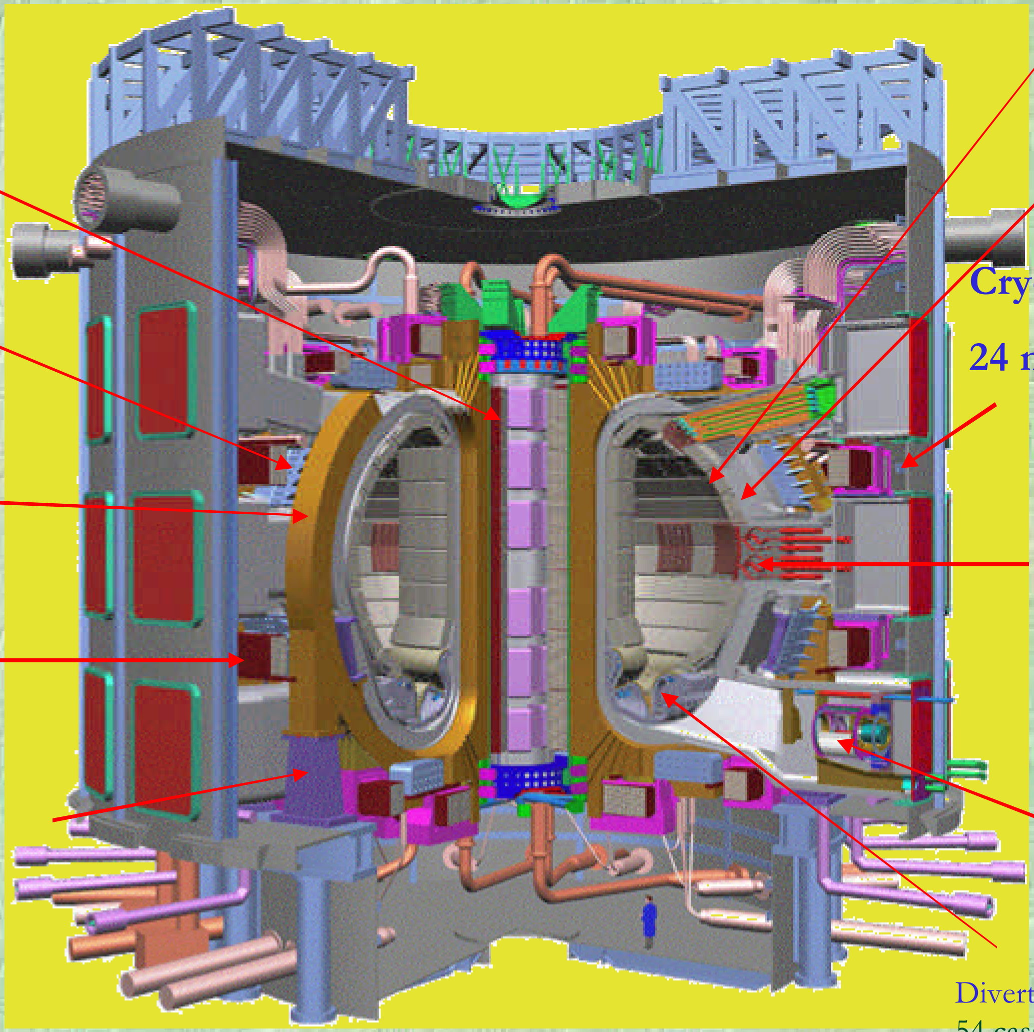
- A gas at temperature above about 10^4 ^oK is ionized and formed a plasma.
- Definition of a plasmas: ionized gas with global charge neutrality and where collective effect dominates
- How to confine a plasma? Use of magnetic field
- Two concepts. Tokamak (such as ITER) and stellarator

Tokamak plasma confinement

- The plasma in a tokamak is confined by magnetic fields: toroidal field created by coils and poloidal field created by a current carried by the plasma of toroidal shape



ITER tokamak



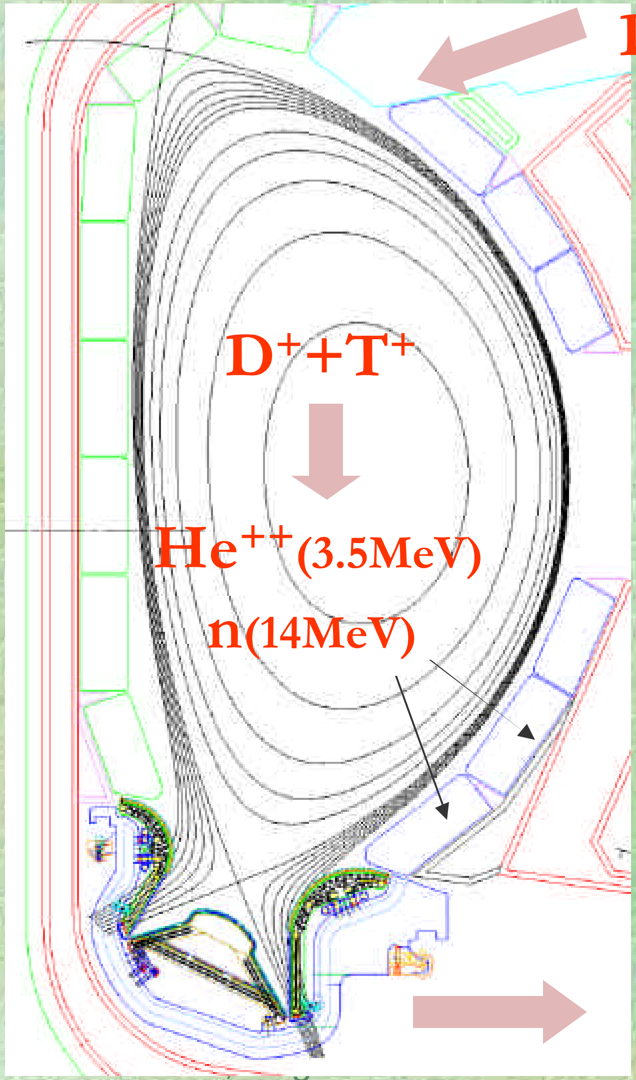
ITER plasma

Plasma

- V: 840m³
  R/a: 6.2m /2m
  Vertical elongation: 1.85
  Triangularity: 0.45

- Density: $10^{20}m^{-3}$
- Temperature: 17keV
- Fusion power : 500MW

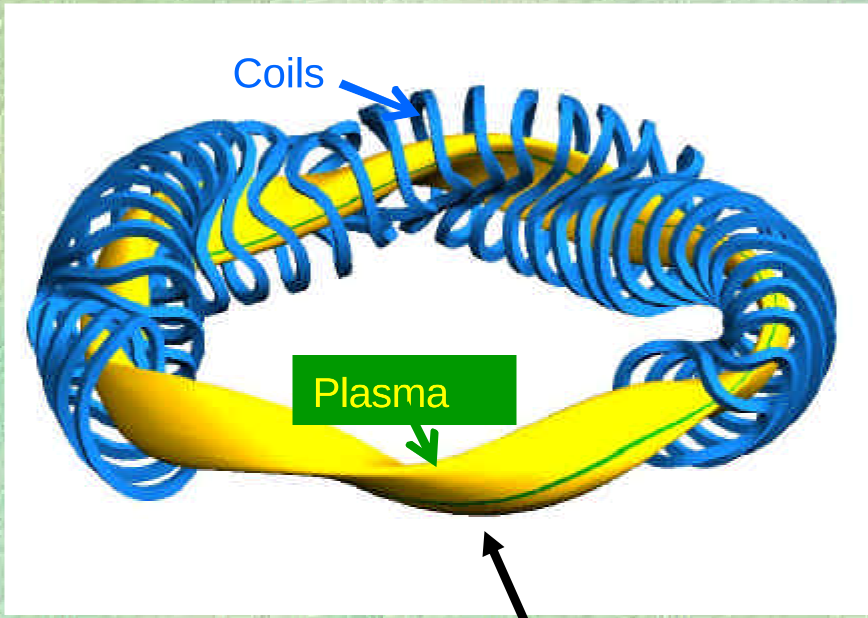
- Plasma current : 15MA
- Toroidal magnetic field: 5.4 T

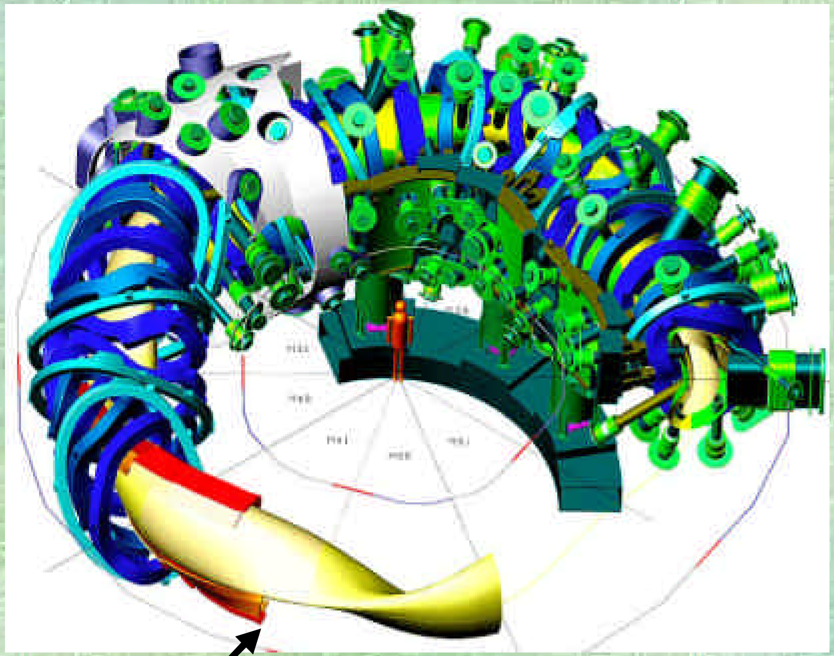


Courtesy : ITER IT

Stellarator plasma confinemennt

- The plasma is confined by magnetic field created only by external coils

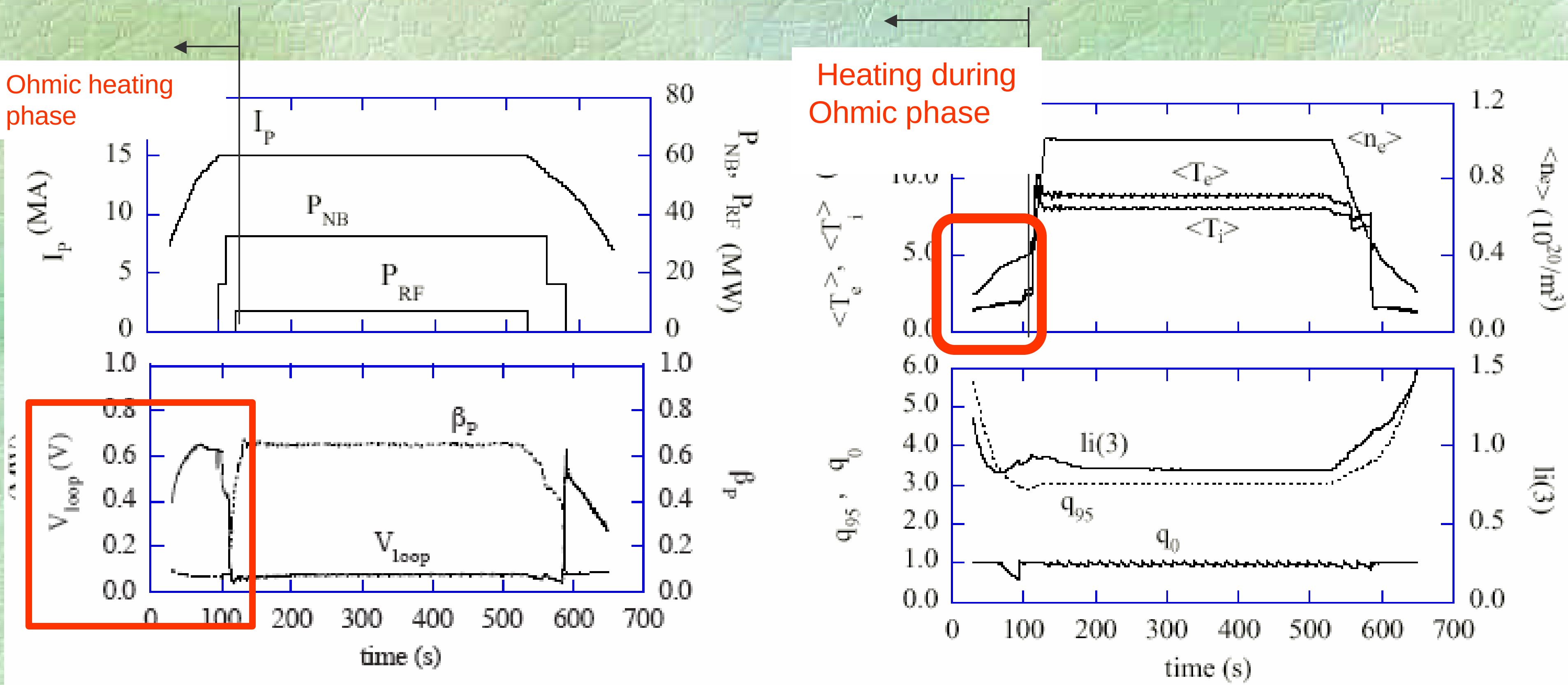




Physicist view - W7X - Engineer view

Plasma heating (1)

- In a tokamak, heating is performed by Joule heating due to the plasma current(Example from simulation of ITER)

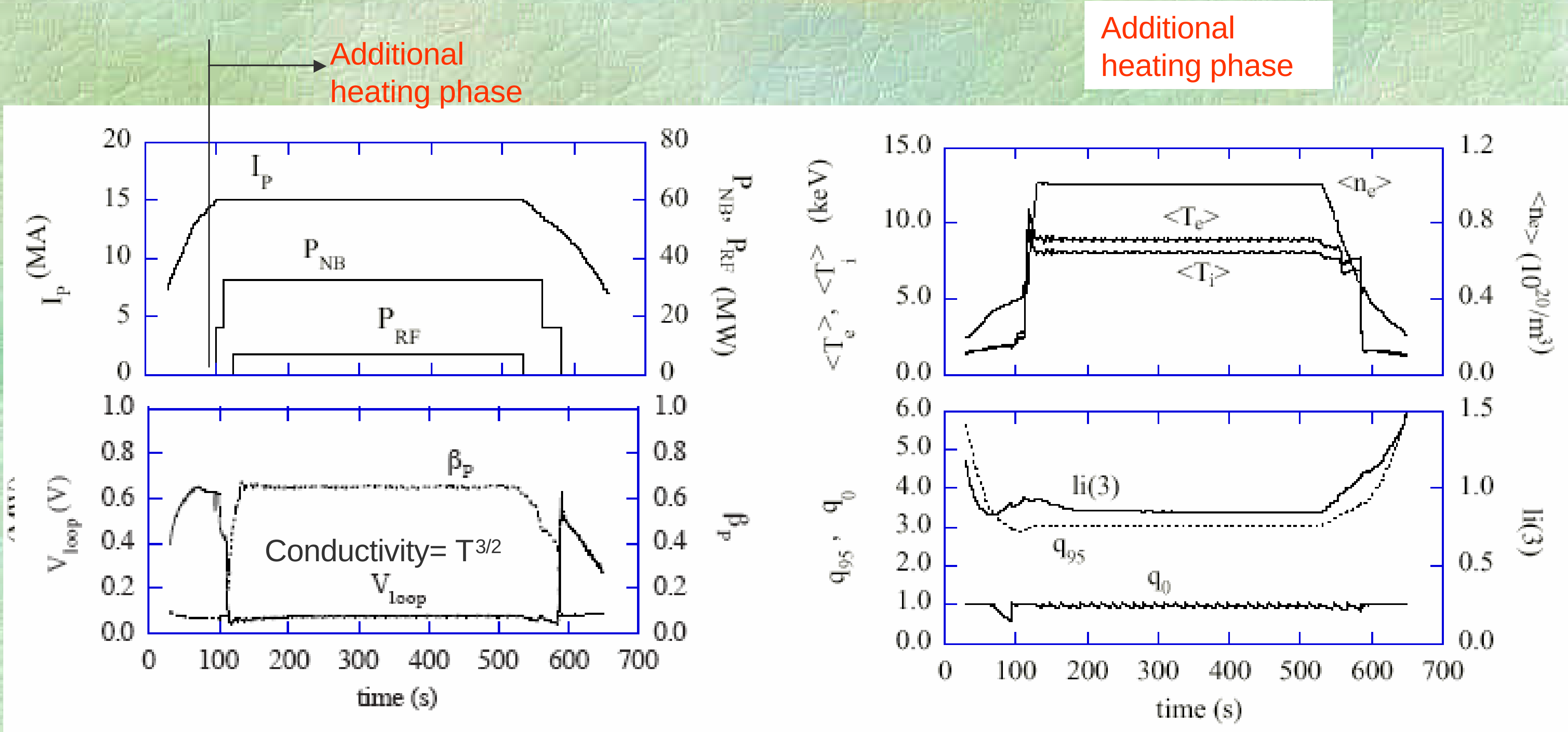


Heating (2)

- Ohmic heating decreases with temperature since the plasma electrical conductivity increases as $T^{3/2}$
- Additional heating by RF waves at
  - Ion cyclotron frequency (50-100 MHz for ITER)
  - Electron cyclotron frequency (170 GHz for ITER)
  - Lower hybrid frequency, a magnetized plasma resonance (5 GHz for ITER)

Heating (3)

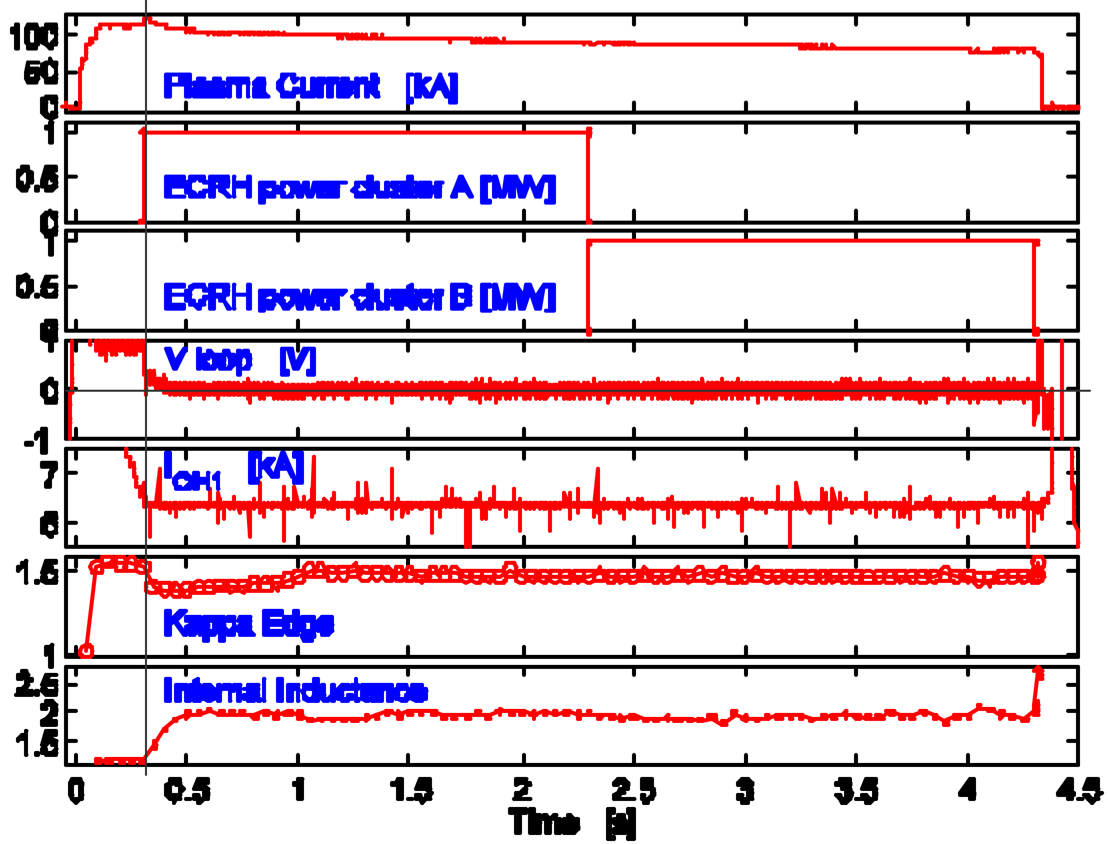
- Heating by injection of energetic neutral beam (1MV, 40 A for ITER)

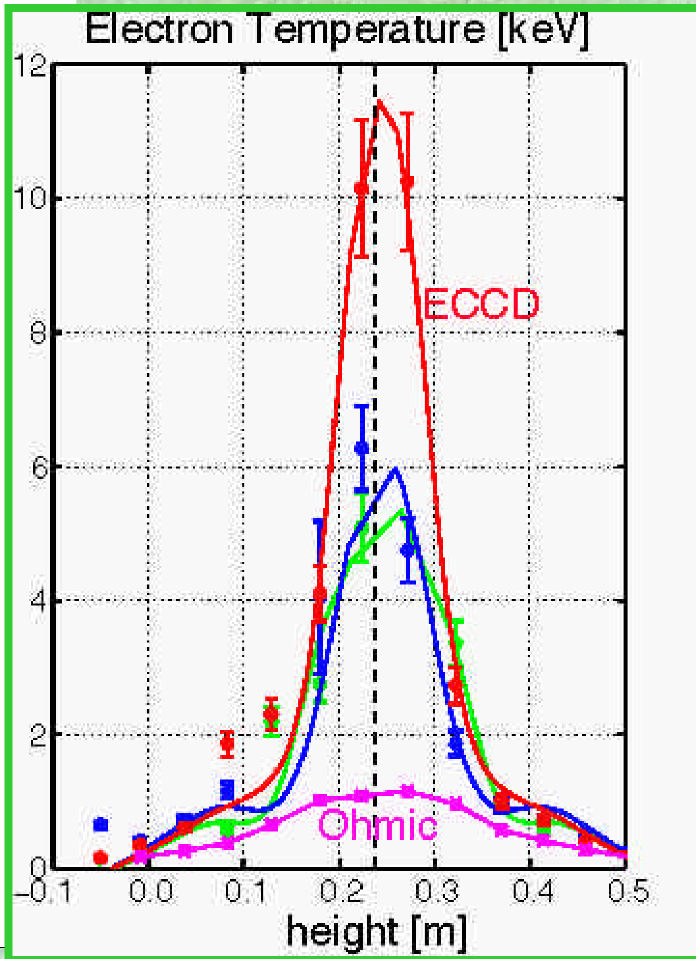


Heating (4)

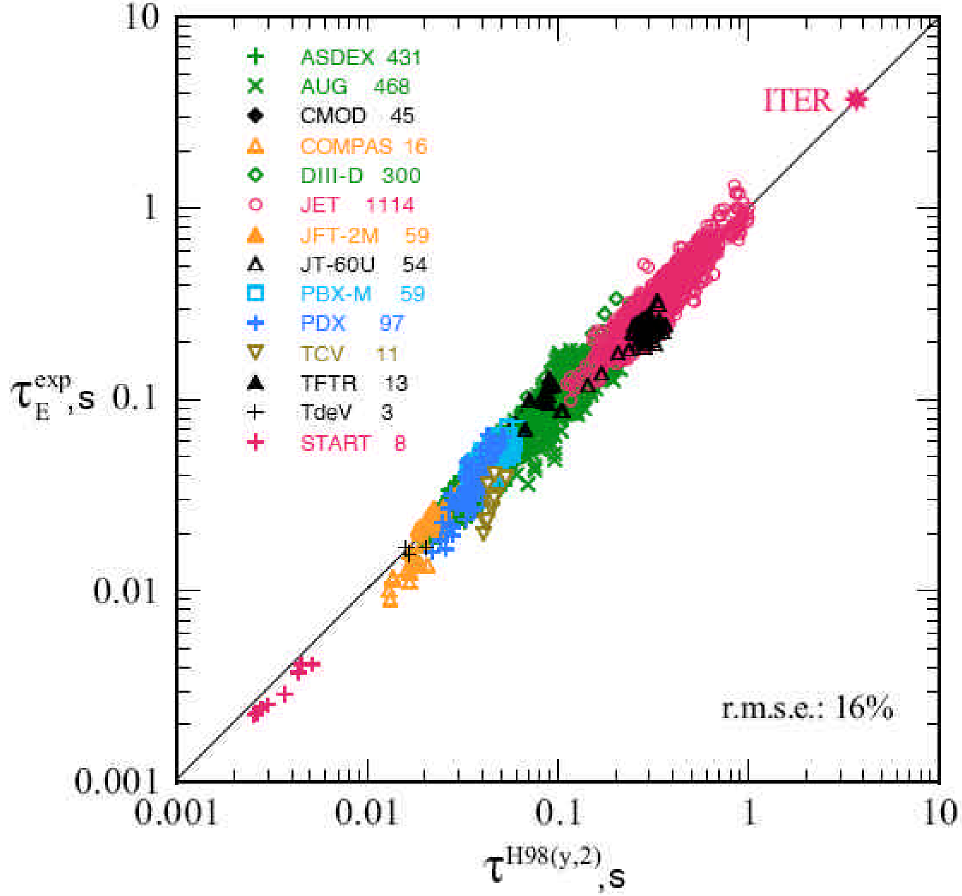
- Example from the Lausanne tokamak: Additional heating by electron cyclotron wave

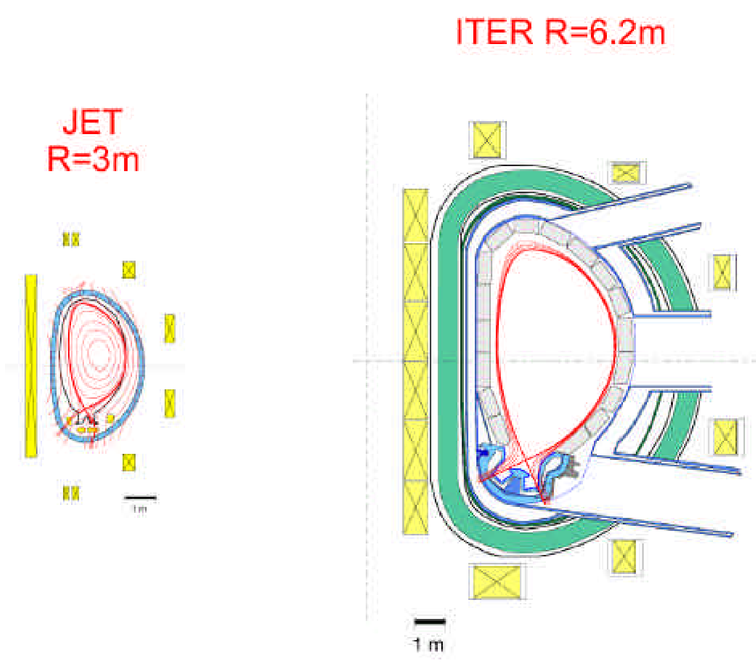
P_{ohmic}= Plasma current * V_{loop}





Energy confinement

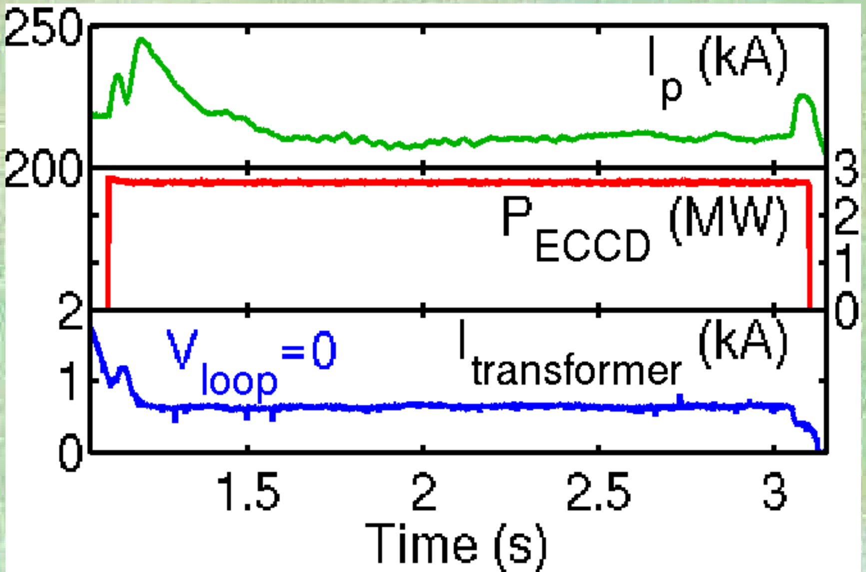




$$\tau_E^{H98(y,2)} = 0.0562 I^{0.93} B^{0.15} \bar{n}_{19}^{0.41} P^{-0.69} R^{1.97} \kappa_a^{0.78} \varepsilon^{0.58} M^{0.19}$$

Current drive (1)

- Issue:in a tokamak how do you maintain the plasma current which is induced through a transformer?
- Injection of RF wave of neutral beam can supply the plasma current without the transformer
- Example of the sustainment of the plasma current by injection of waves at the electron cyclotorn frequency in the Lausanne tokamak TCV



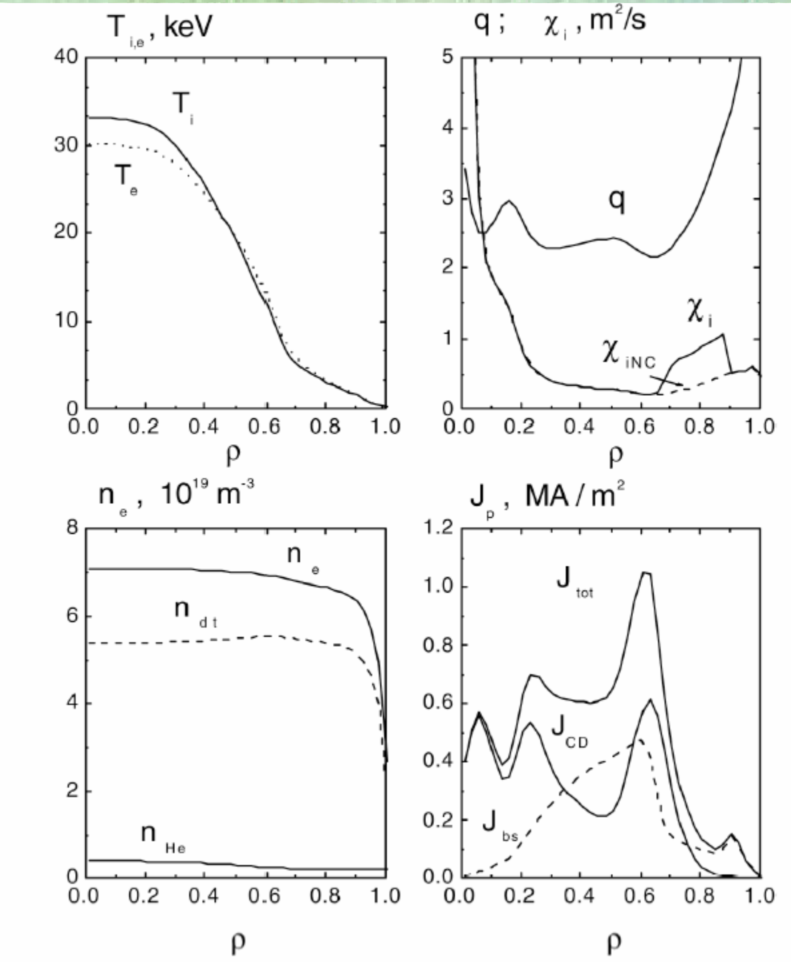
Plasma current I_P is maintained by P_{ECCD}

$I_{transformer}$= Constant-->

No induced plasma current

Current drive (2)

- Example of plasma current sustainment simulation for ITER



Q= 6

P_{fusion}= 360 MW

I_P = 9 MA

P_{LH}= 29 MW

P_{NB} = 30 MW

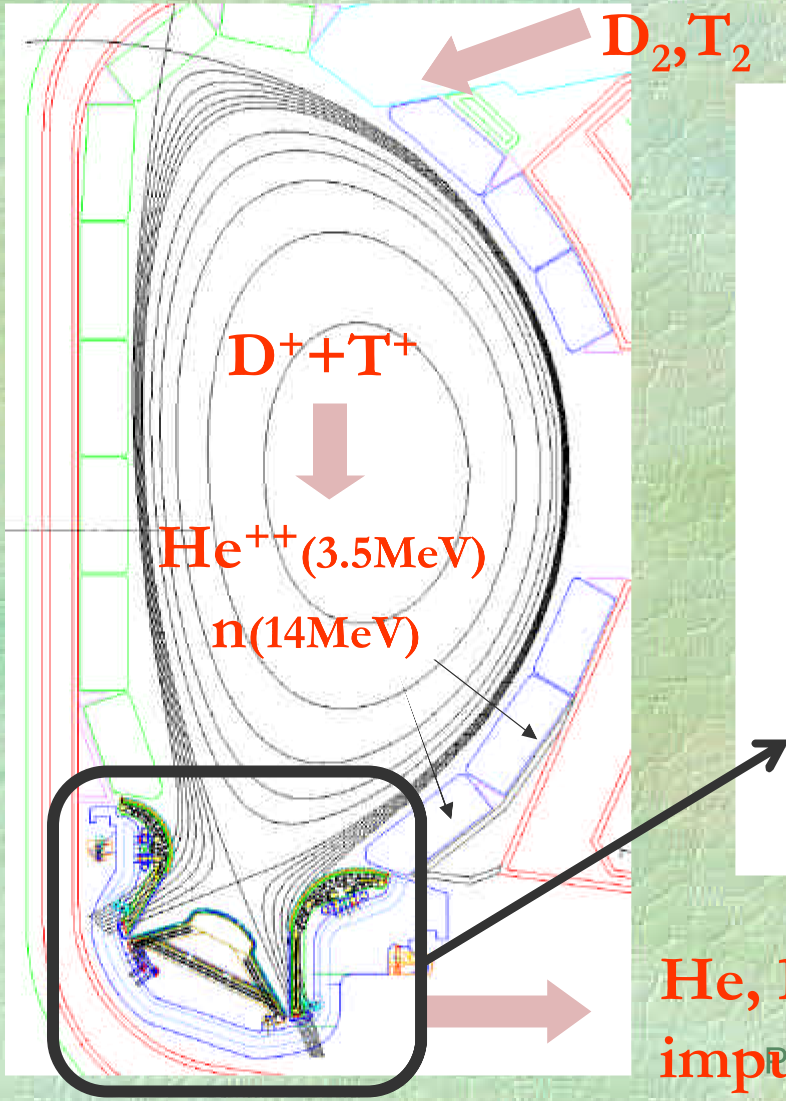
I_{CD}/I_P= 52%

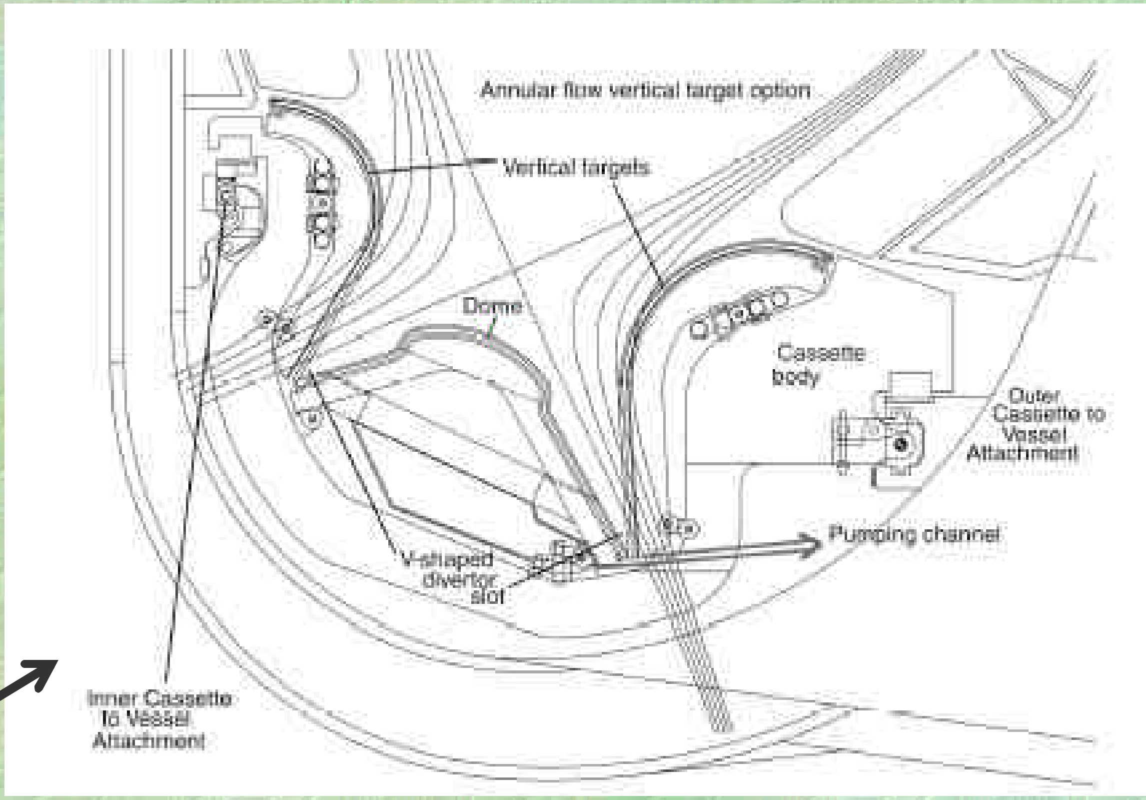
I_{BS}/I_P = 48%

Plasma power exhaust: Divertor

- Divertor function: remove the major part of the energy of the He particles, the He ashes and impurities
- Issues : High heat load on the divertor components. In ITER, heat flux of 10 MWm^{-2} in steady state with transient (10 s)up to 20 MWm^{-2} .

Divertor



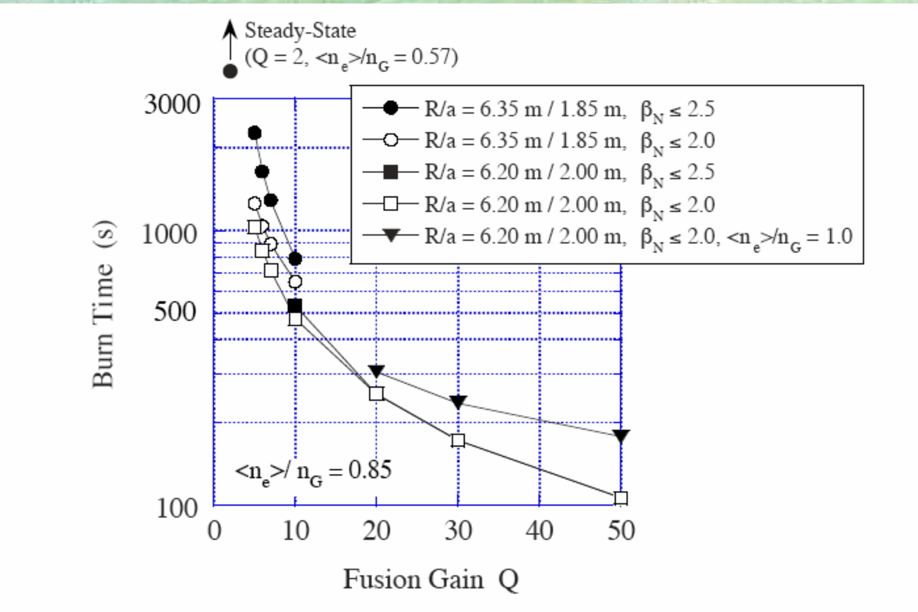


He, D_2, T_2, impurities

ITER

- ITER is the next international (Partners:China, EU, Japan, Korea, Russia, USA, India has requested to be member) fusion device , which is designed to produce significant fusion power during long pulse

Major radius R	6.2m
Minor radius a	2.0 m
Plasma current I_P	15 MA
Elongation	1.7
Plasma volume	837 m^3
Heating power	73 MW
B_T	5.3 T
Neutron flux	0.57 MW/m^2
Fusion power (thermal)	500-700 MW during 400s
Electrical power required	500MW-400 MVAr



ITER physics goals

ITER is designed to

- produce a plasma dominated by α-particle heating
- produce a significant fusion power amplification factor (Q = 10) in long-pulse operation
- aim to achieve steady-state operation of a tokamak (Q = 5)
- retain the possibility of exploring ‘controlled ignition’ (Q = 30

ITER technical objectives

- From a technological point , ITER goals are:
  - demonstrate integrated operation of technologies for a fusion power plant (inclusive heating systems
  - test components required for a fusion power plant
  - test concepts for a tritium breeding module
  - demonstrate the safety characteristic of a fusion power plant

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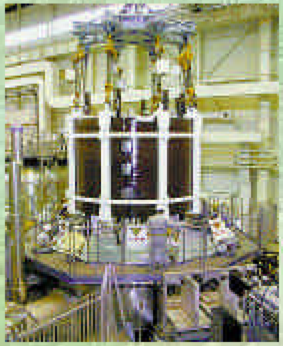
Technology

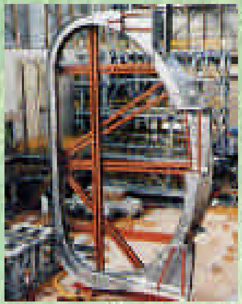
Many technologies have been developed in view of ITER

CENTRAL SOLENOID MODEL COIL

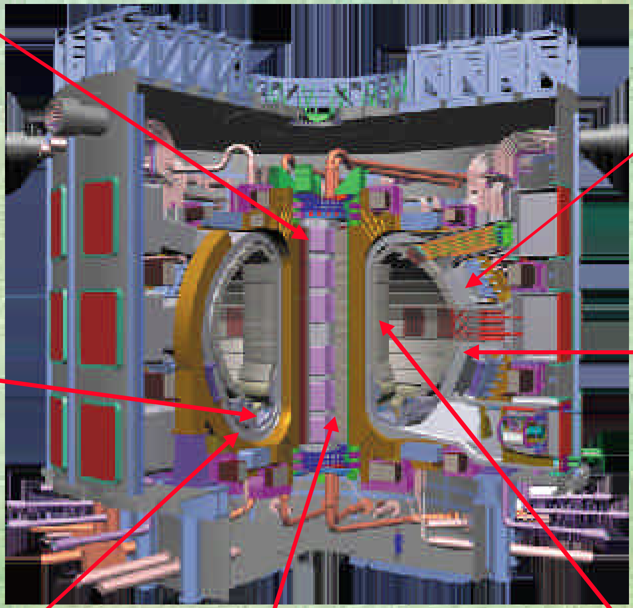


Radius 3.5 m
Height 2.8m
B_{max}=13 T
W = 640 MJ
0.6 T/sec

VACUUM VESSEL SECTOR



Double-Wall, Tolerance ±5 mm



REMOTE MAINTENANCE OF DIVERTOR CASSETTE

Attachment Tolerance ± 2 mm

BLANKET MODULE

HIP Joining Tech
Size : 1.6 m x 0.93 m x 0.35 m

DIVERTOR CASSETTE

Heat Flux >15 MW/m^2, CFC/W

TOROIDAL FIELD MODEL COIL

Height 4 m
Width 3 m
B_{max}=7.8 T
I_{max} = 80kA

4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

Material science

- Material in a fusion reactor should have low activation (Cf. Viewgraphs Waste 2) and retain their mechanical properties under irradiation by the 14 MeV neutrons

Effect on the microstructure (1)

- Transmutation nuclear reactions yield the formation of impurities (e.g. H, He atoms).
- Atomic displacement cascades produce point structure defects (vacancies, interstitials).

Nuclear reactions	Cascades	Diffusion processes
Production of impurities (He, H)	Production of vacancies and interstitials	Formation of the final microstructure
10^{-16}	10^{-13} - 10^{-8}	10^{-6}

Time [s]

Effect on the microstructure (2)

- The final microstructure of the irradiated material results from interactions between the various irradiation-induced defects. It can be formed of:

Small defect clusters
Dislocation loops
Stacking fault tetrahedra
Precipitates
Voids
He bubbles

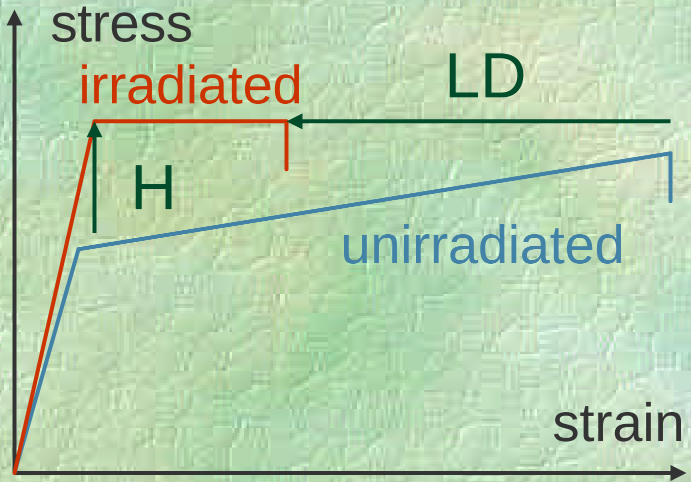
Effect on the material properties

- Physical properties:

Decrease of electrical conductivity (low temperatures)
Decrease of thermal conductivity (ceramic materials)

- Mechanical properties:

Hardening (H)
Loss of ductility (LD)
Loss of fracture toughness
Loss of creep strength



- Dimensional stability:

Swelling

Characterisation of irradiation damage

- Dpa= displacement per atom

MWy/ m^2	$n.m^{-2}$	dpa (Fe)
1	$1.4 \cdot 10^{25}$	9.5
0.3 –1 (ITER)	$0.4 – 1.4 \cdot 10^{25}$	2.8 –9.5
3 –4 (DEMO reactor)	$4 – 5.6 \cdot 10^{25}$	28 -76
10 – 15 (REACTOR)	$14 – 21 \cdot 10^{25}$	95 -143

- He production : 10 appm/ dpa
- H production : 40 appm/ dpa

The main difficulty is the non availabiliy of suitable neutron sources : energy = 14 MeV and high fluence

Material for fusion reactor

- Criteria:

  Specific radioactivity
  Radioactive decay heat
  Half-life radio nuclides
  Waste disposal (Cf Viewgraph Waste 3)

Candidate materials presently under developement have a chemical composition based on low activation elements (Cf. Viewgraph Waste 3):

Fe, Cr, V, Ti, W, Ta, Si, C

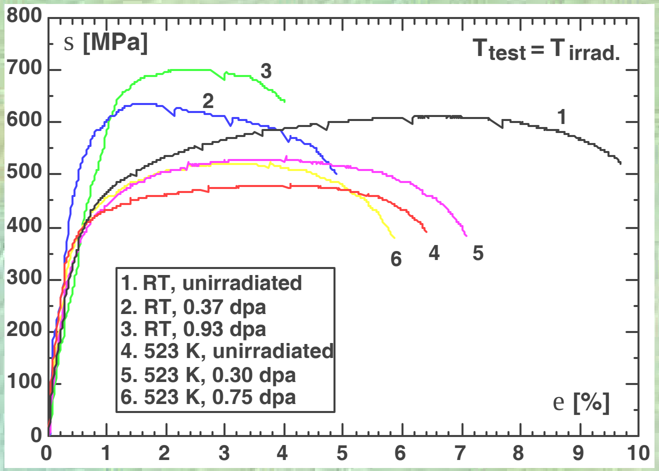
Steel of the 9Cr type such as EUROFER 97: 8.9 wt.% Cr, 1.1 wt.% W, 0.47 wt.% Mn, 0.2 wt.% V, 0.14 wt.% Ta, 0.11 wt.% C, Fe for the balance.

SiC_f in a matrix of SiC

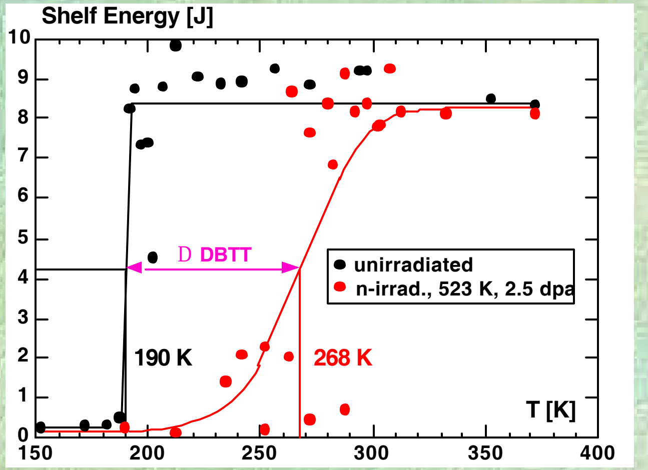
Va alloys

Change in mechanical properties (1)

- Hardening and loss of ductility

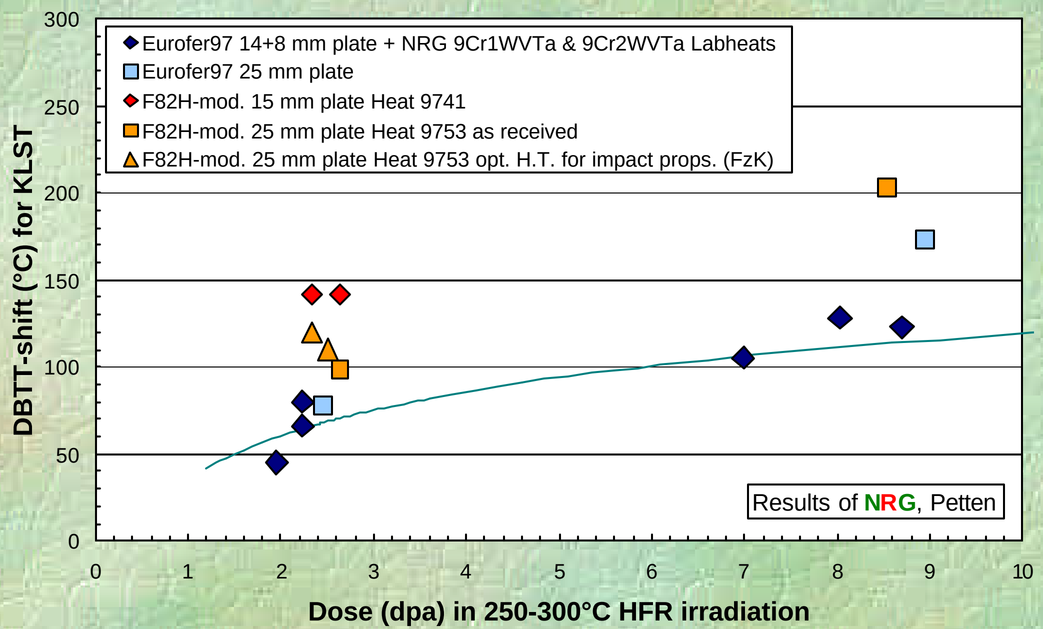


- Change in ductile to brittle transition temperature, ΔDBTT



OPTIMAX 9Cr steel

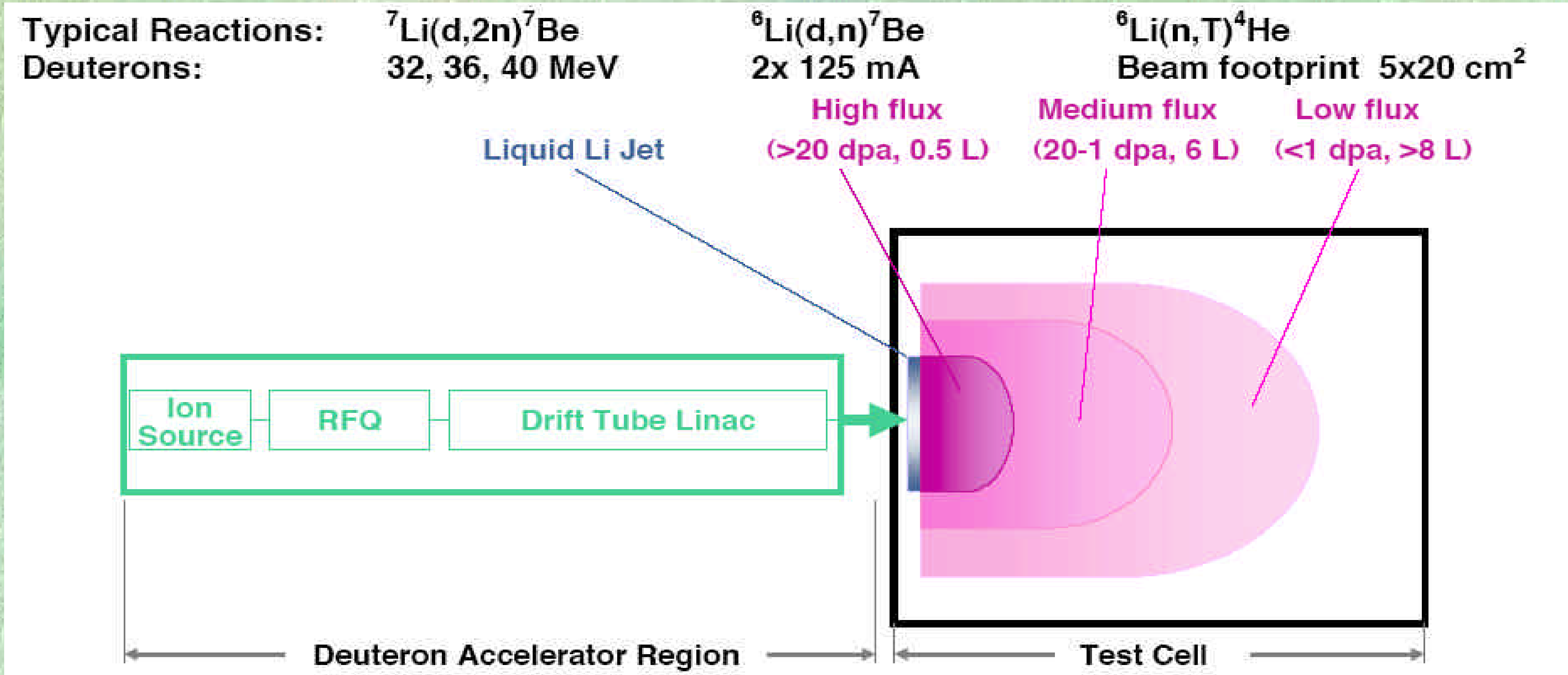
Change in mechanical properties (2)



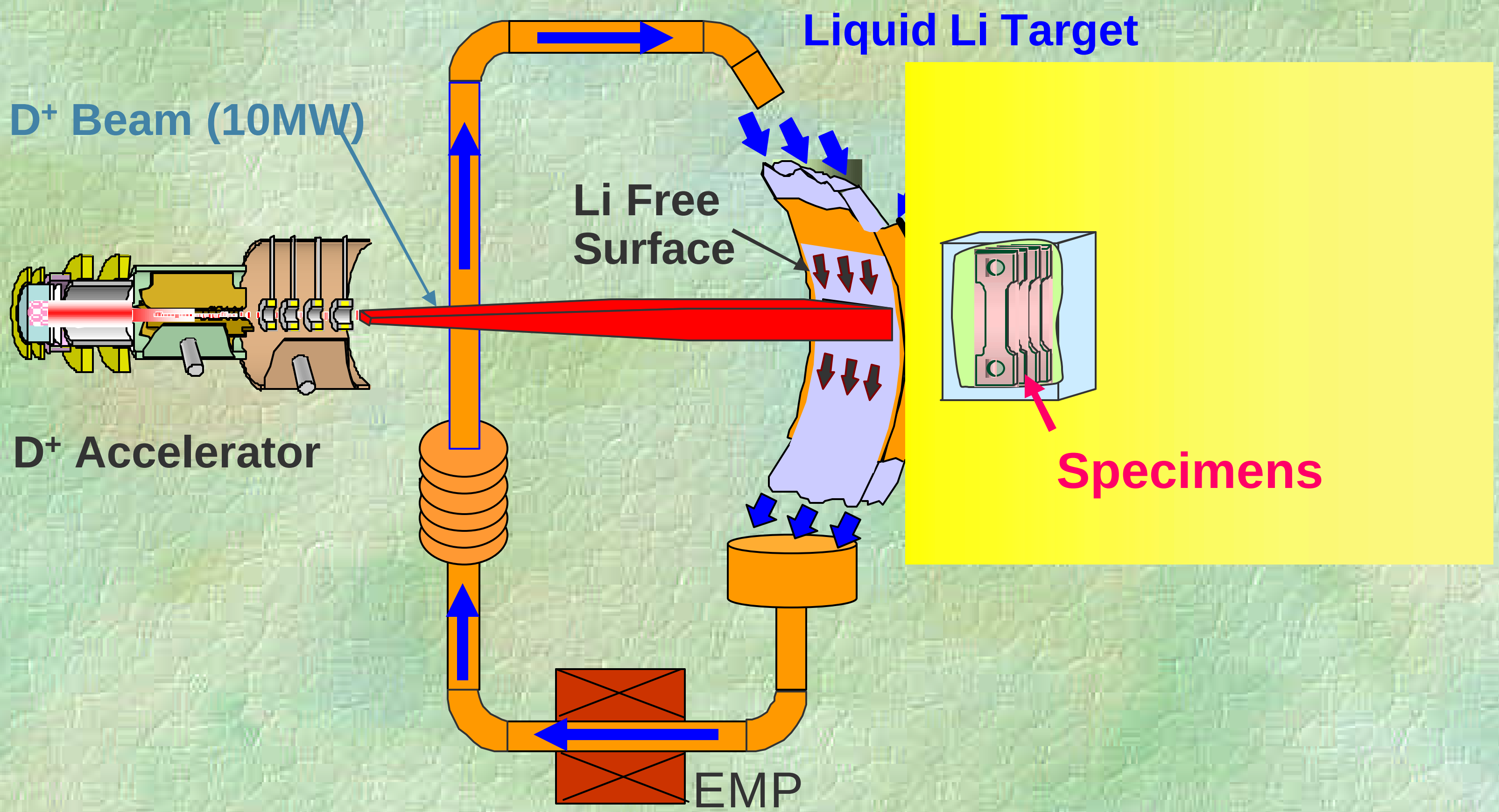
J. Rensman, E. Lucon, J. Boskeljon, J. van Hoepen, F.P. van den Broek, R. den Boef, M. Jong, P. ten Pierick, *Irradiation Resistance of Eurofer97 at 300°C up to 10 dpa*, ICFRM-11

IFMIF (1)

- International fusion material irradiation facility IFMIF: a neutron source capable of simulating the fusion neutron with high flux

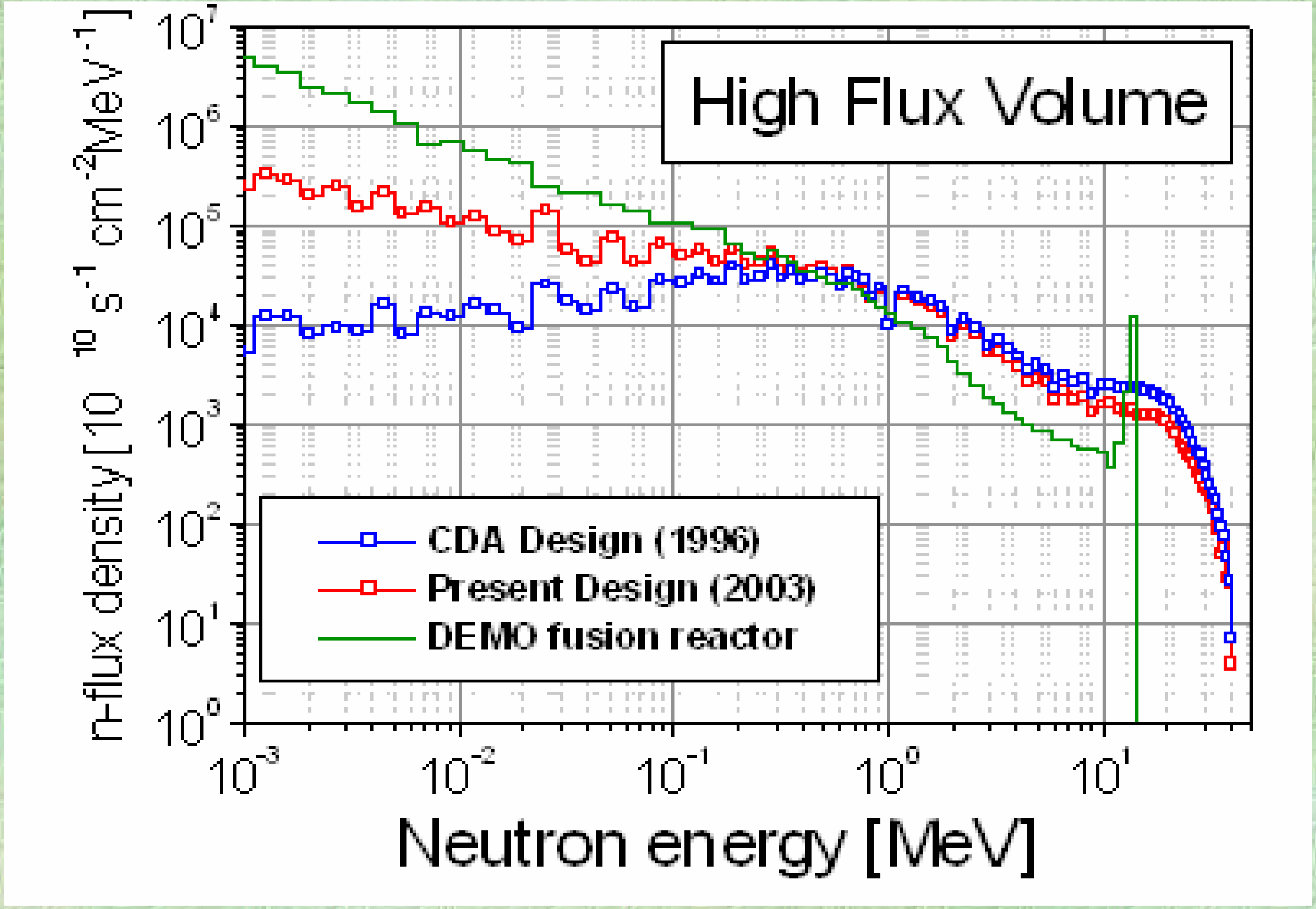


IFMIF (2)



Liquid Li Target
D+ Beam (10MW)
Li Free
Surface
D+ Accelerator
Specimens
EMP

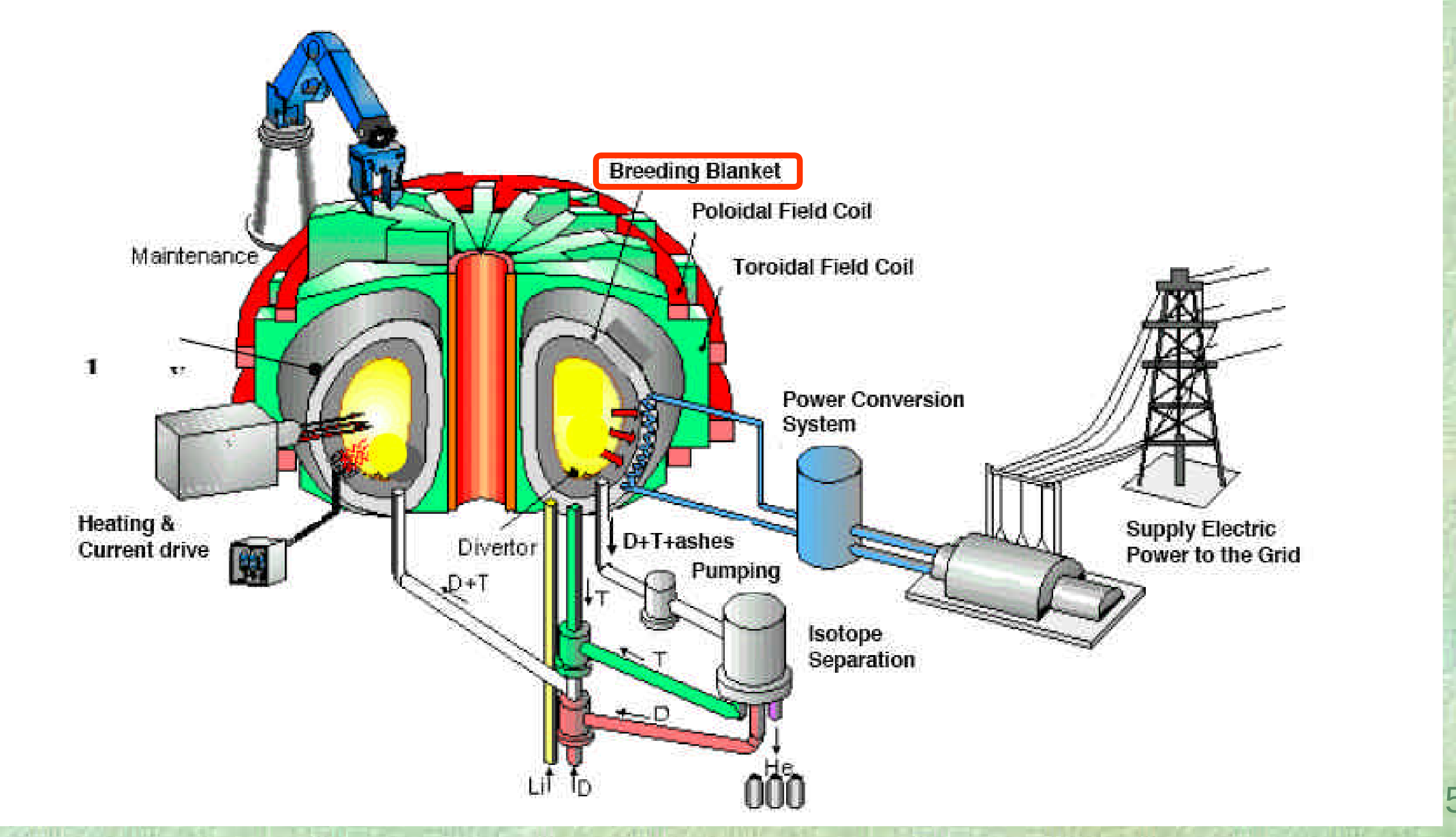
IFMIF (3)



High Flux Volume
CDA Design (1996)
Present Design (2003)
DEMO fusion reactor
n-flux density [10^10 s^-1 cm^-2 MeV^-1]
Neutron energy [MeV]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-3
10^-2
10^-1
10^0
10^1

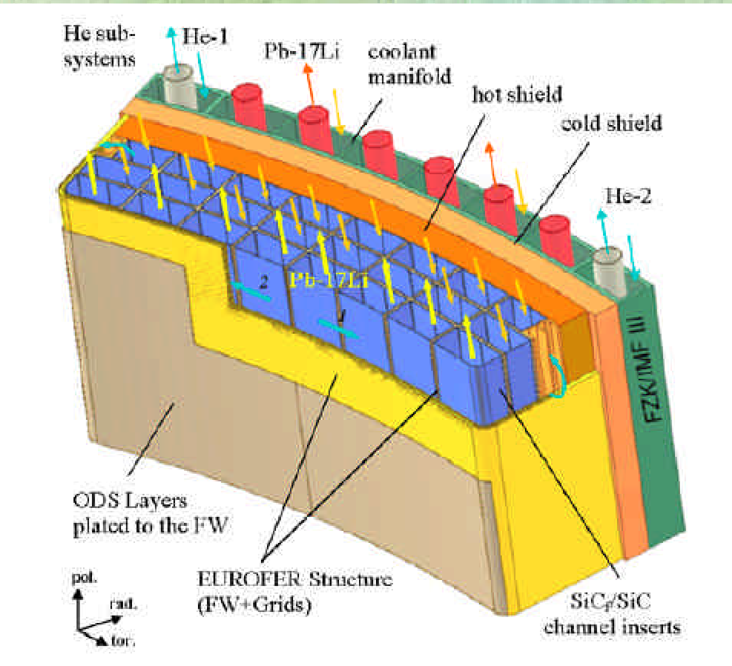
Breeding blanket (1)

- The role breeding blanket is to recover the kinetic energy of the neutron and to “breed “ the T from Li^6



Breeding blanket (2)

- Tritium breeding materials: Li, Pb-Li alloy, Li_2O, $LiAlO_2$, Li_2ZrO_3, Li_4SiO_4, Li_2TiO_3 ($^6Li + n \rightarrow {}^4He + T + 4.8$ MeV)
- Neutron multiplier materials: Be, Pb to have a breeding ratio slightly larger than 1 (about 1.1)
- Coolants: water, He, liquid Pb-Li alloy



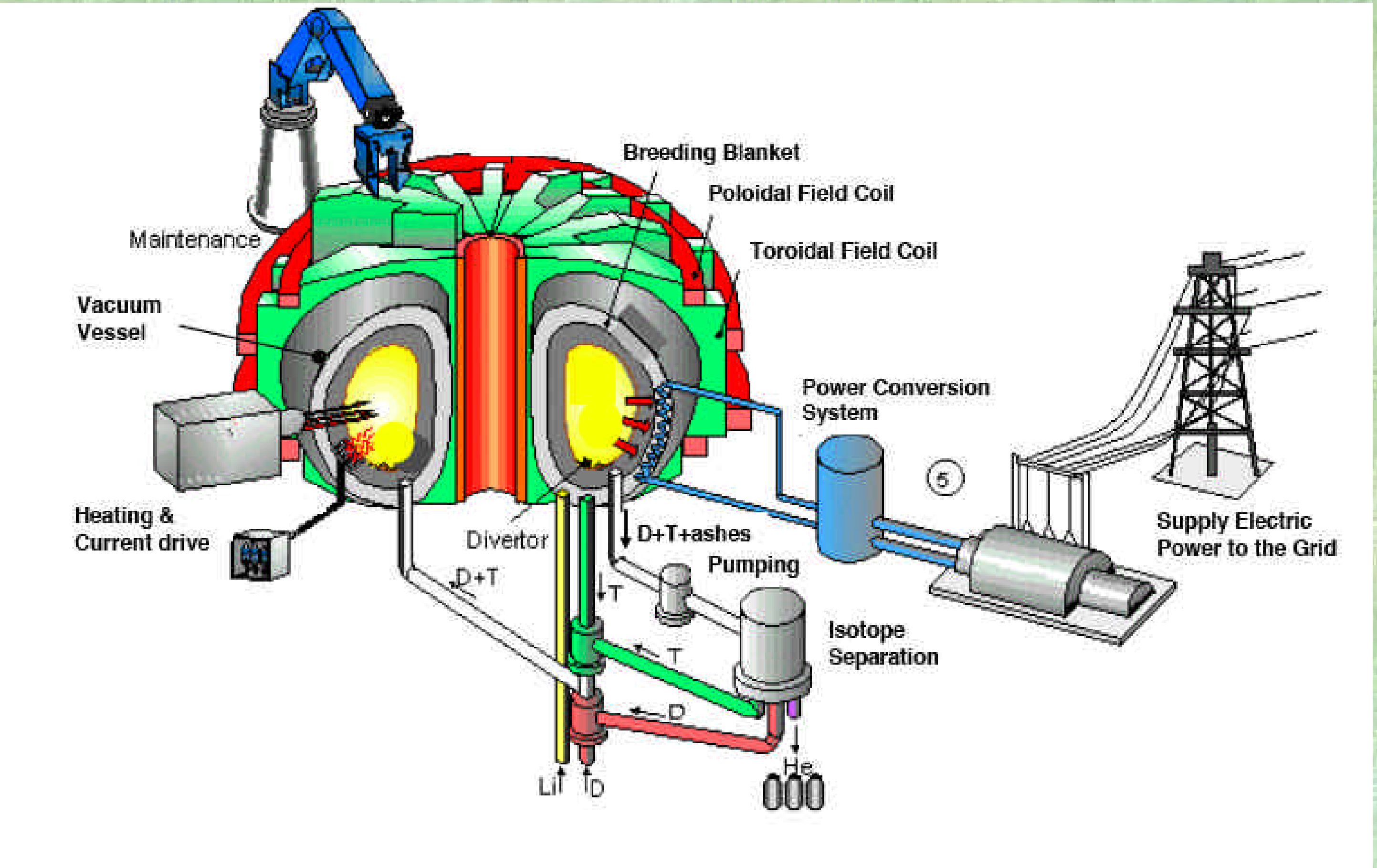
Outline

- Introduction: What is fusion?
- Fusion as a sustainable energy source
- Physics of magnetically confined plasma
- Technology for a fusion reactor
- Roadmap towards fusion

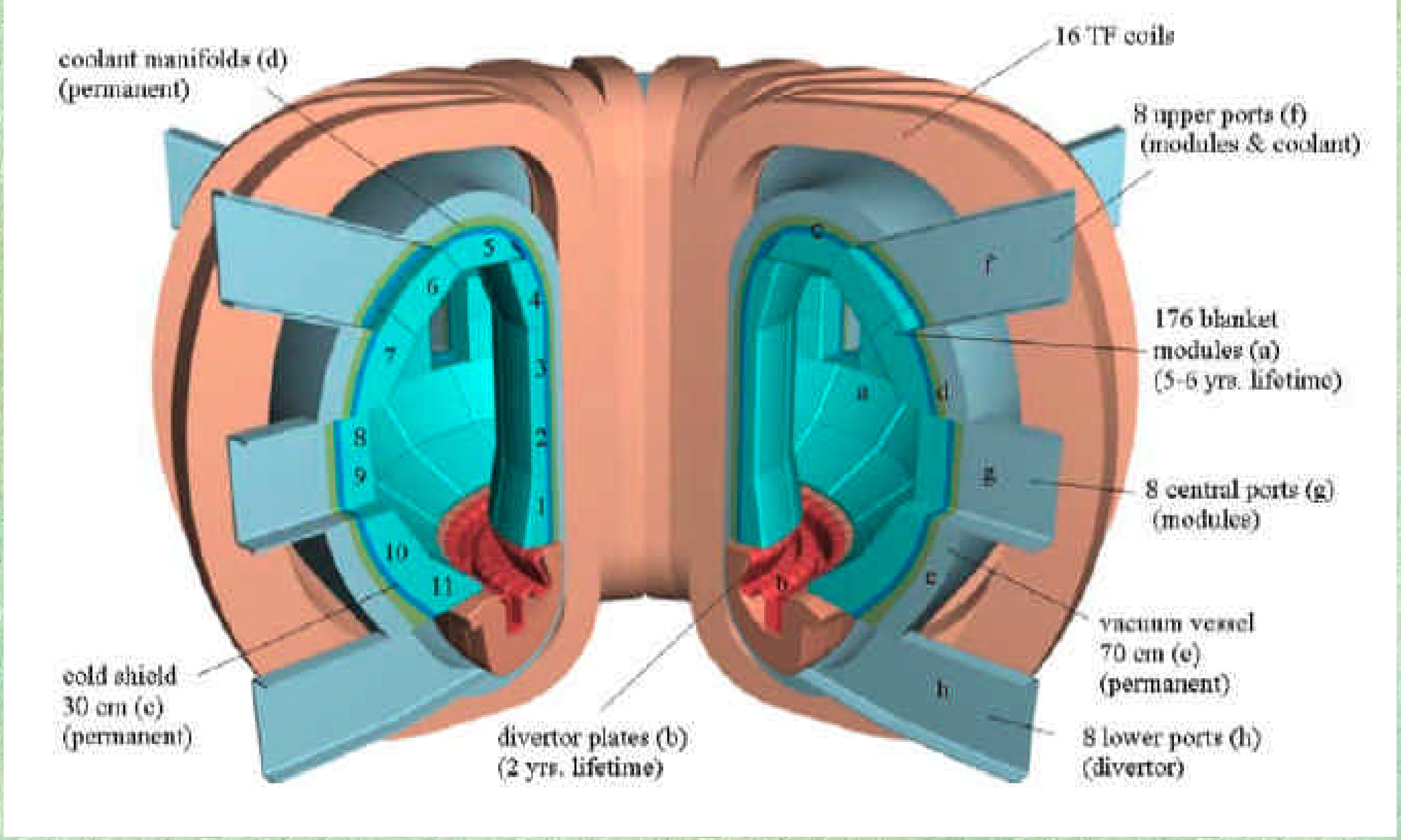
Road map towards fusion

- The two key elements of the road map are ITER and IFMIF, which lead to the construction of a DEMO fusion reactor producing electricity.
- The decision to build ITER at the European site of Cadarache was taken by the six Parties (China, EU, Japan, Korea, Russia)
- After this decision, India has formally expressed its wish to become a Party of ITER
- Under finalisation: the final agreement regarding ITER
- Also under negotiation with Japan, an agreement on the different components of a “broader approach” towards the realisation of fusion as an energy source

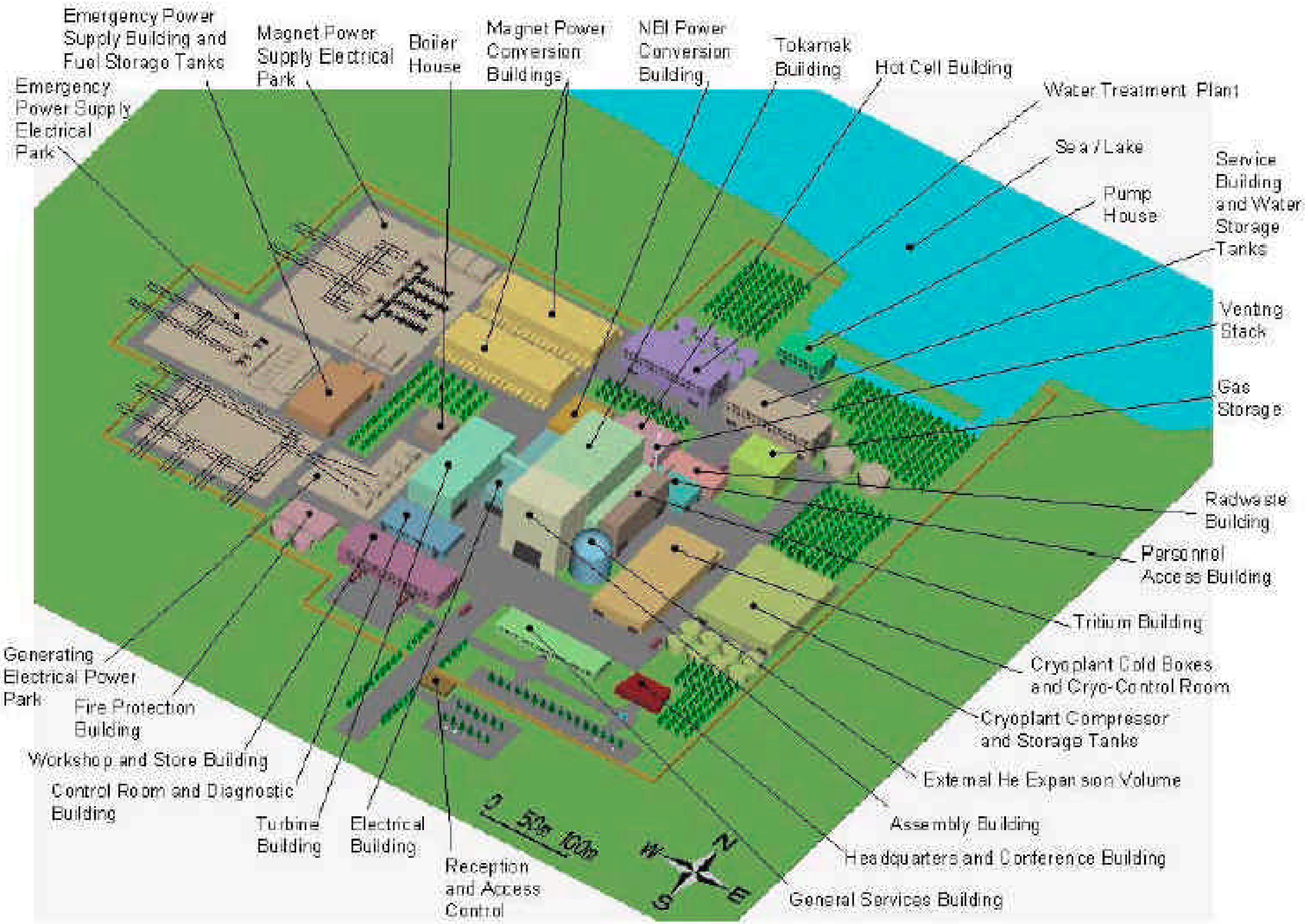
Fusion power plant (1)



Fusion power plant (2)



Fusion power plant (3)

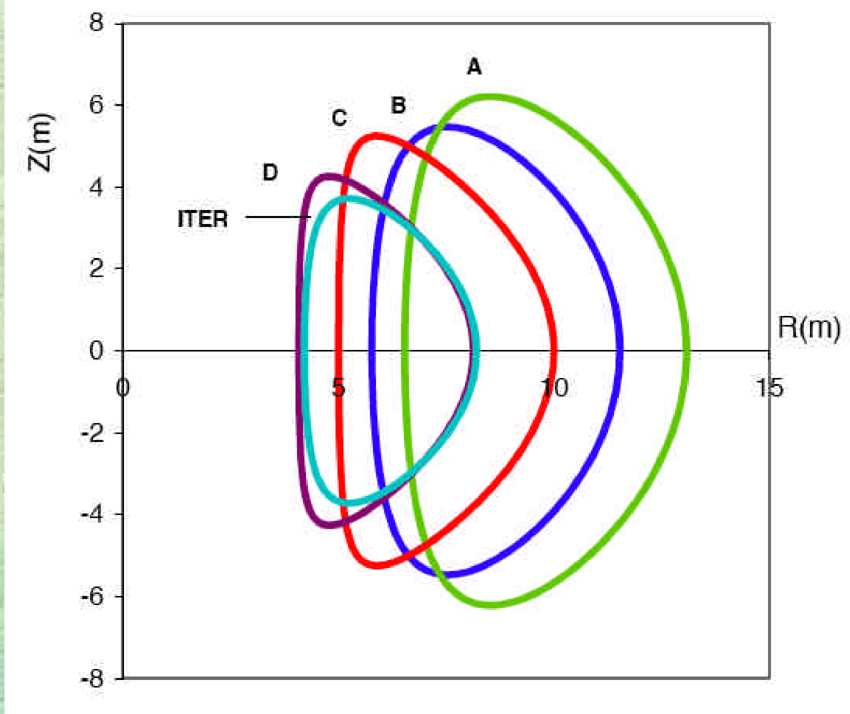


Fusion power plant (4)

Parameter	Model A	Model B	Model C	Model D	ITER
Unit Size (GW_e)	1.55	1.33	1.45	1.53	
Blanket Gain	1.18	1.39	1.17	1.17	
Fusion Power (GW)	5.00	3.60	3.41	2.53	0.5
Plant efficiency *	0.31	0.36	0.42	0.60	
Aspect Ratio	3.0	3.0	3.0	3.0	
Elongation (95% flux)	1.7	1.7	1.9	1.9	
Triangularity (95% flux)	0.25	0.25	0.47	0.47	
Major Radius (m)	9.55	8.6	7.5	6.1	6
TF on axis (T)	7.0	6.9	6.0	5.6	5.3
TF on the TF coil conductor (T)	13.1	13.2	13.6	13.4	
Plasma Current (MA)	30.5	28.0	20.1	14.1	15-17
β_N(thermal, total)	2.8, 3.5	2.7, 3.4	3.4, 4.0	3.7, 4.5	
Average Temperature (keV)	22	20	16	12	
Temperature peaking factor	1.5	1.5	1.5	1.5	
Average Density ($10^{20}m^{-3}$)	1.1	1.2	1.2	1.4	
Density peaking factor	0.3	0.3	0.5	0.5	
H_H (IPB98y2)	1.2	1.2	1.3	1.2	
Bootstrap Fraction	0.45	0.43	0.63	0.76	
P_{add} (MW)	246	270	112	71	73
n/n_G	1.2	1.2	1.5	1.5	
Q	20	13.5	30	35	10
Average neutron wall load	2.2	2.0	2.2	2.4	
Divertor Peak load (MWm^{-2})	15	10	10	5	
Z_{eff}	2.5	2.7	2.2	1.6	

Ref. : PPCS, EFDA

Fusion power plant (5)



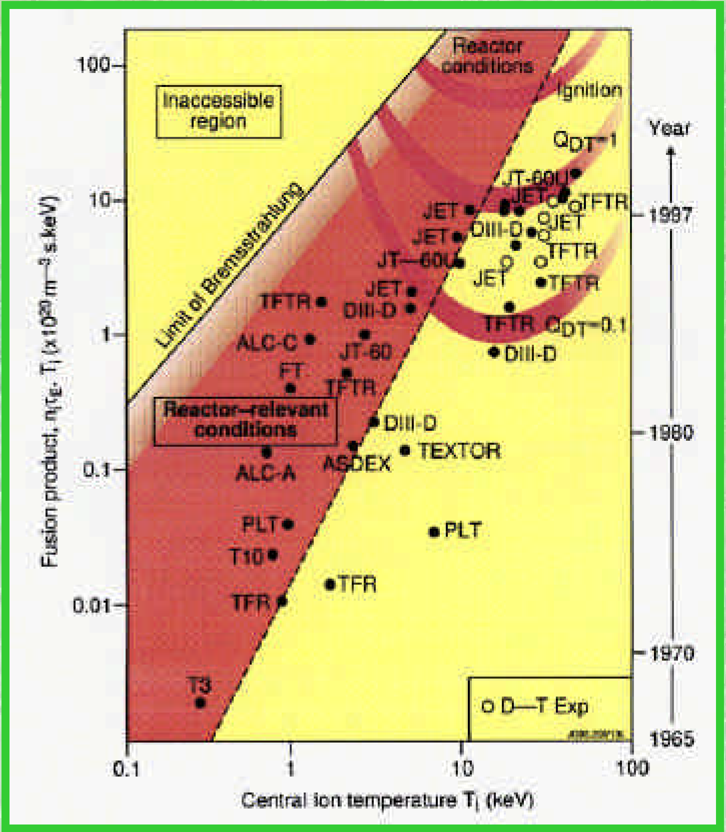
Relative size of ITER and possible model of power plant

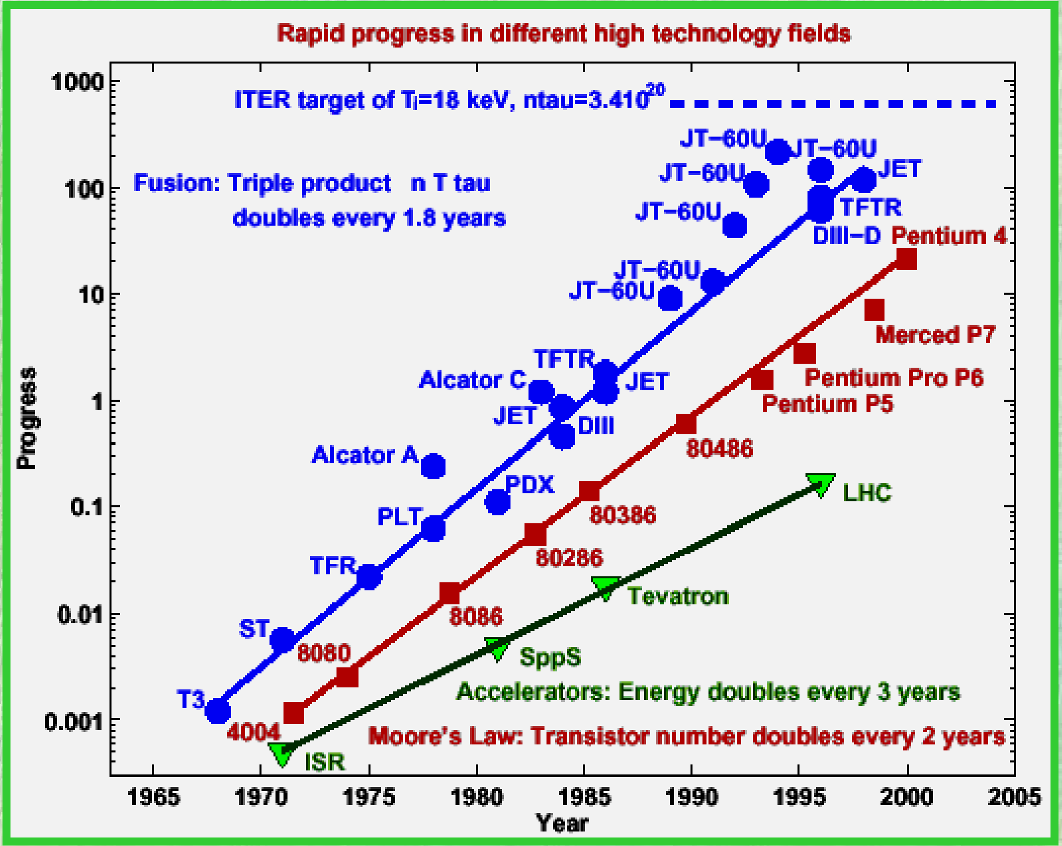
The European programme

- Physics R&D in preparation of ITER exploitation and for the DEMO physics basis
- Plasma engineering in support of ITER construction and later enhancements
- Technology (including Socio-Economic studies) and Materials science and technology in view of ITER and DEMO, with IFMIF as a key element
- Training of physicists and engineers: a vigourous effort is being performed to train the new generation
- Enhancement of relations with universities, research institutes and industry to broaden the the scientific basis and to enhance technology transfer with industry

Conclusion (1)

- Fusion could be a component of a sustainable energy portfolio
- Fusion research has made significant progress in the last decades





Conclusion (2)

- ITER physics and technology were fully assess by the international community
- The decision to build ITER at the European site Cadarache opens a new era for fusion research and will be beneficial for the European scientific community and industry