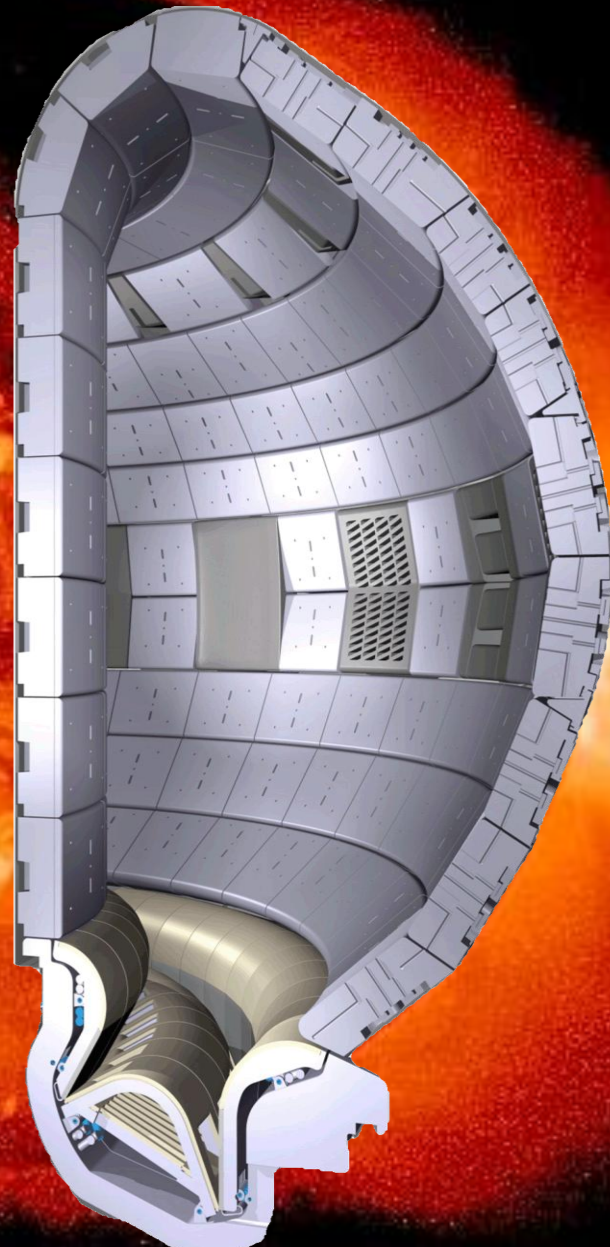
Nuclear fusion energy



Professor Odd Erik Garcia
Department of Physics and Technology
University of Tromsø

Overview

The plasma state

Nuclear fusion reactions

Resources, waste and safety

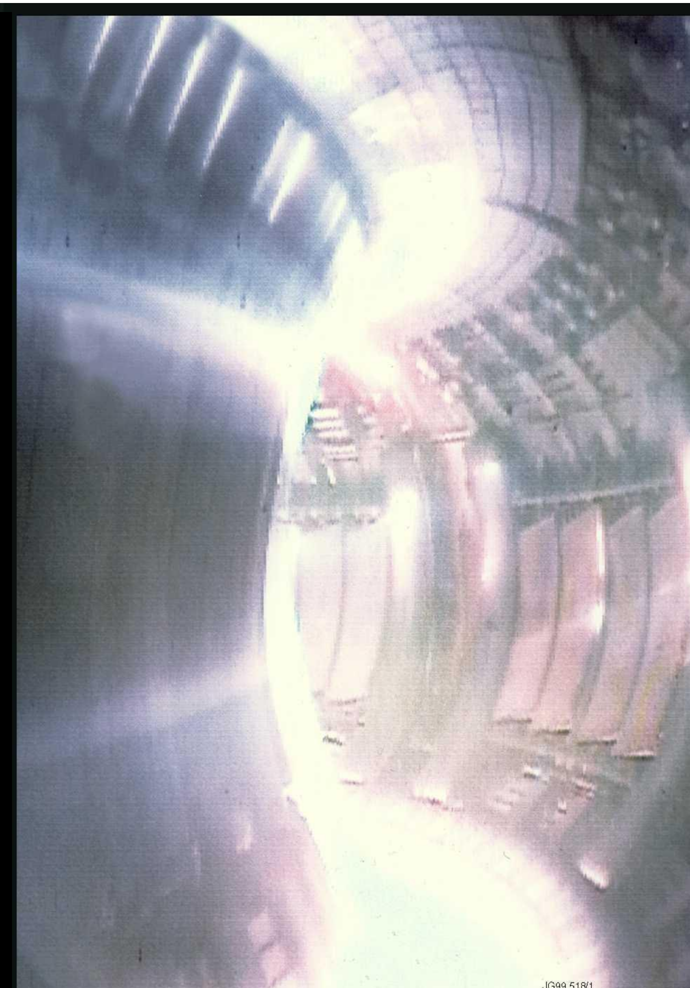
Magnetic confinement

Heating and fast ion dynamics

Plasma-wall interactions

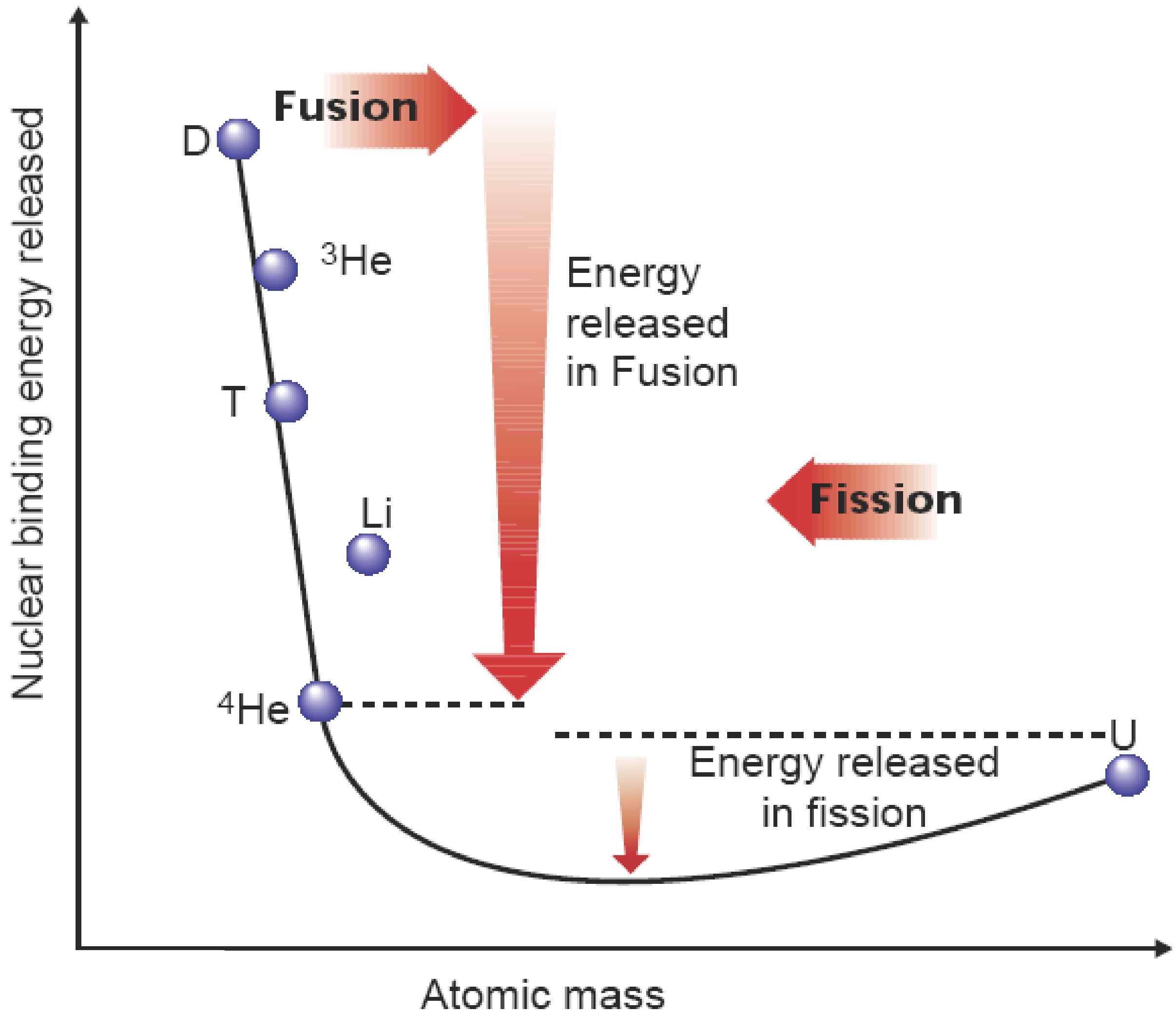
Future reactors and ITER

Research at UiT



Fusion reactions, resources and waste

Kinetic energy from nuclear reactions



Fusion reactions release much more energy than fission reactions

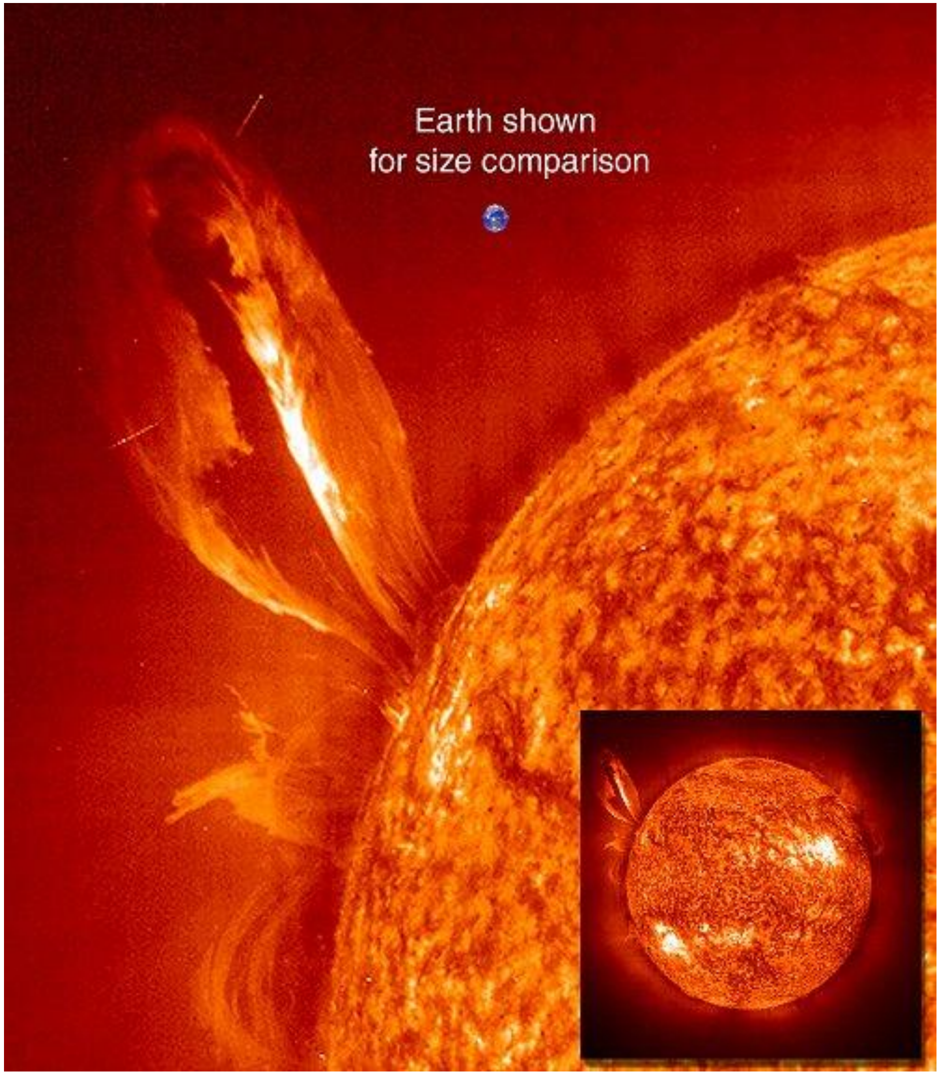
Fusion in stars

Fusion reactions power the sun and other stars

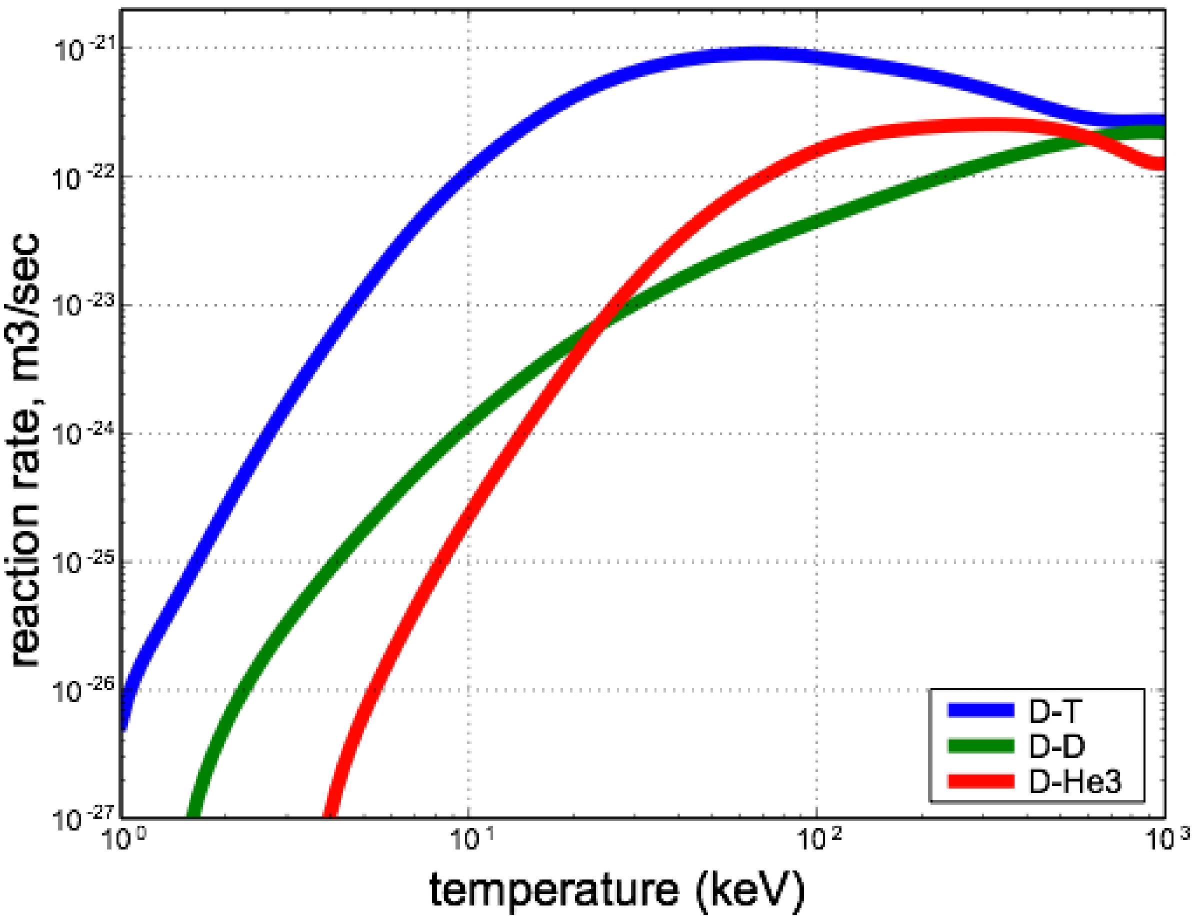
High density fuel is compressed by gravitation

Temperature in the centre is 15 000 000 K

Hydrogen is burned to form helium



Reaction rates for fusion processes



D-T reactions have the highest probability for fusion at the lowest temperature

The D-T fusion reaction

Plasma

$\downarrow$

$\mathbf{D + T \rightarrow He + n}$

$\uparrow \quad \uparrow$

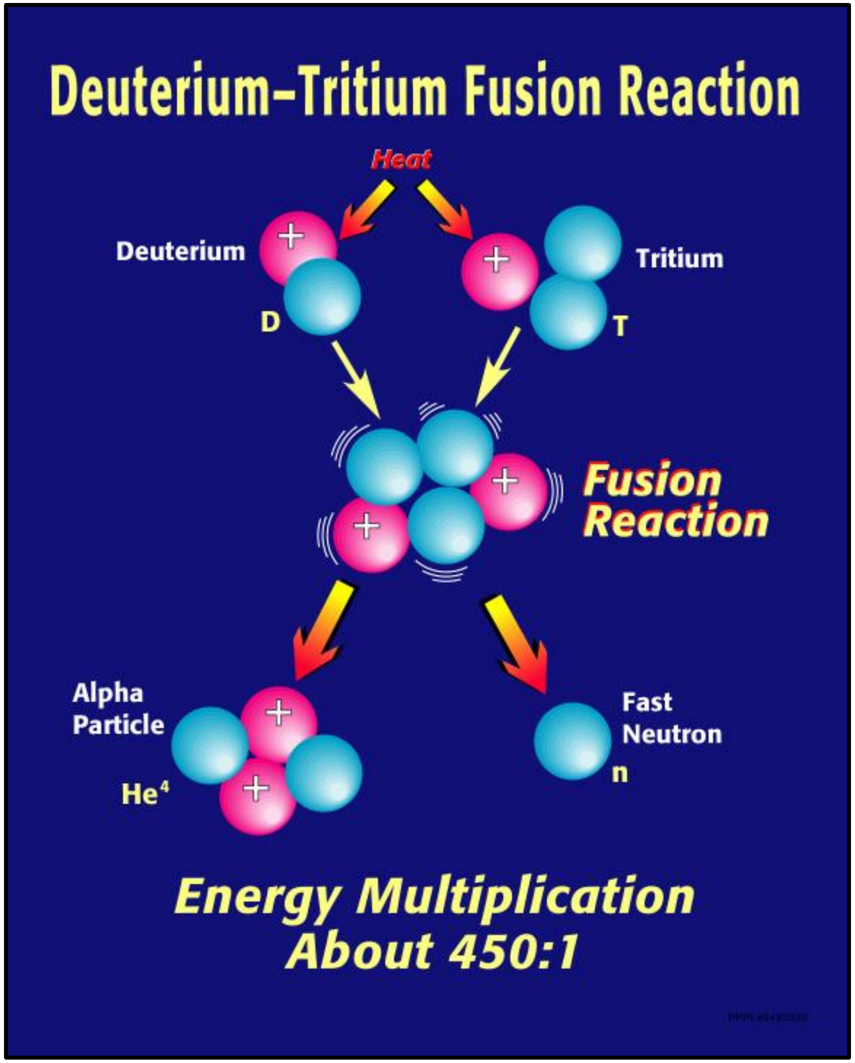
3.5 MeV   14 MeV

Process requires T=10^8 K

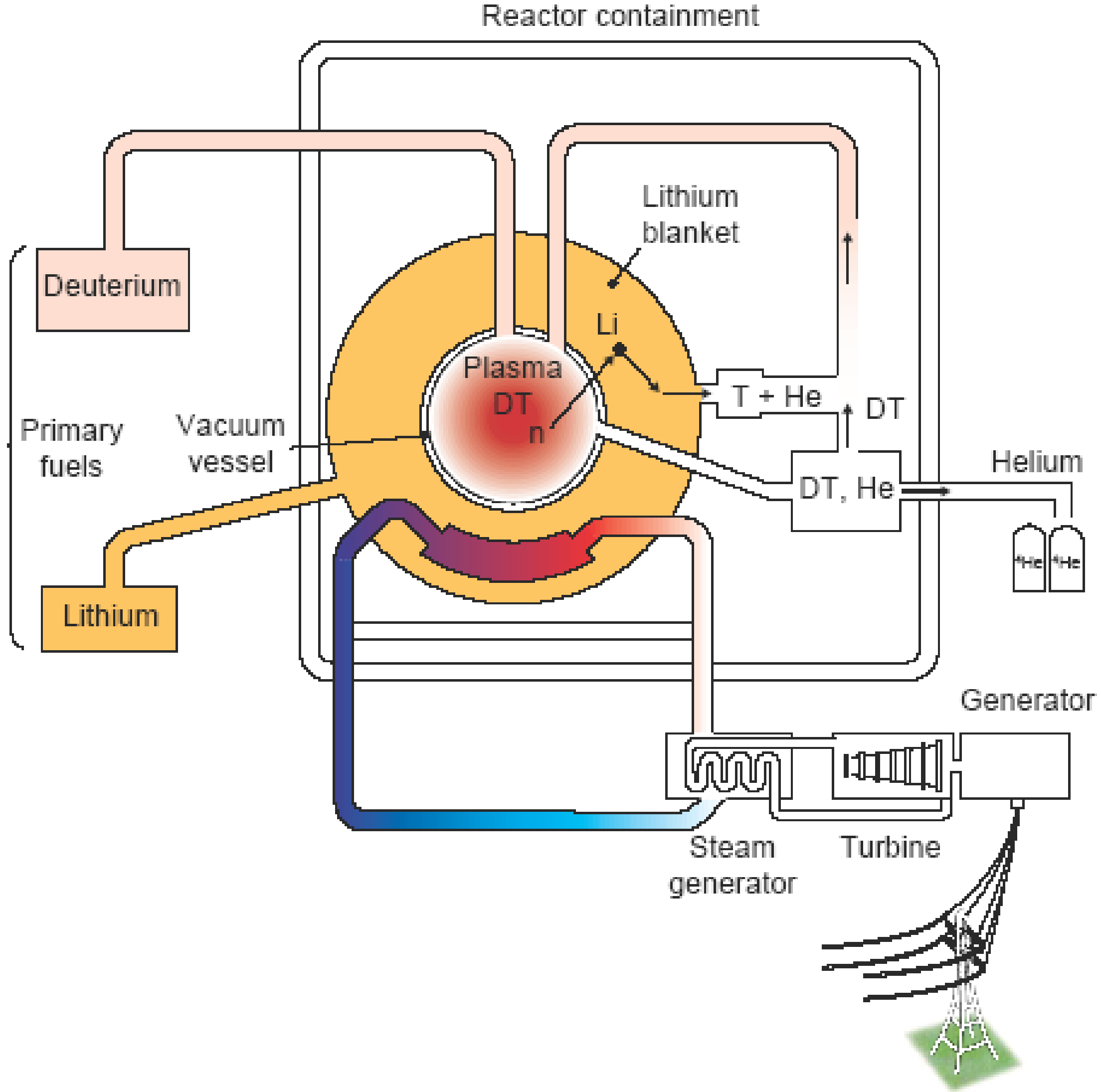
D extracted from water

T breeded from lithium

$\mathbf{Li + n \rightarrow He + T}$



A fusion power reactor



Waste management

- High-energy neutrons in a reactor will make the structural materials radioactive
- The radioactive inventory at shut-down may be comparable to that of a fission reactor
- But shorter half-life, fewer unique species, non-volatile and biologically less active
- Short half-life makes the process attractive, as waste management is fairly straightforward
- By 50 to 300 years the material would have the same radioactivity as coal ash

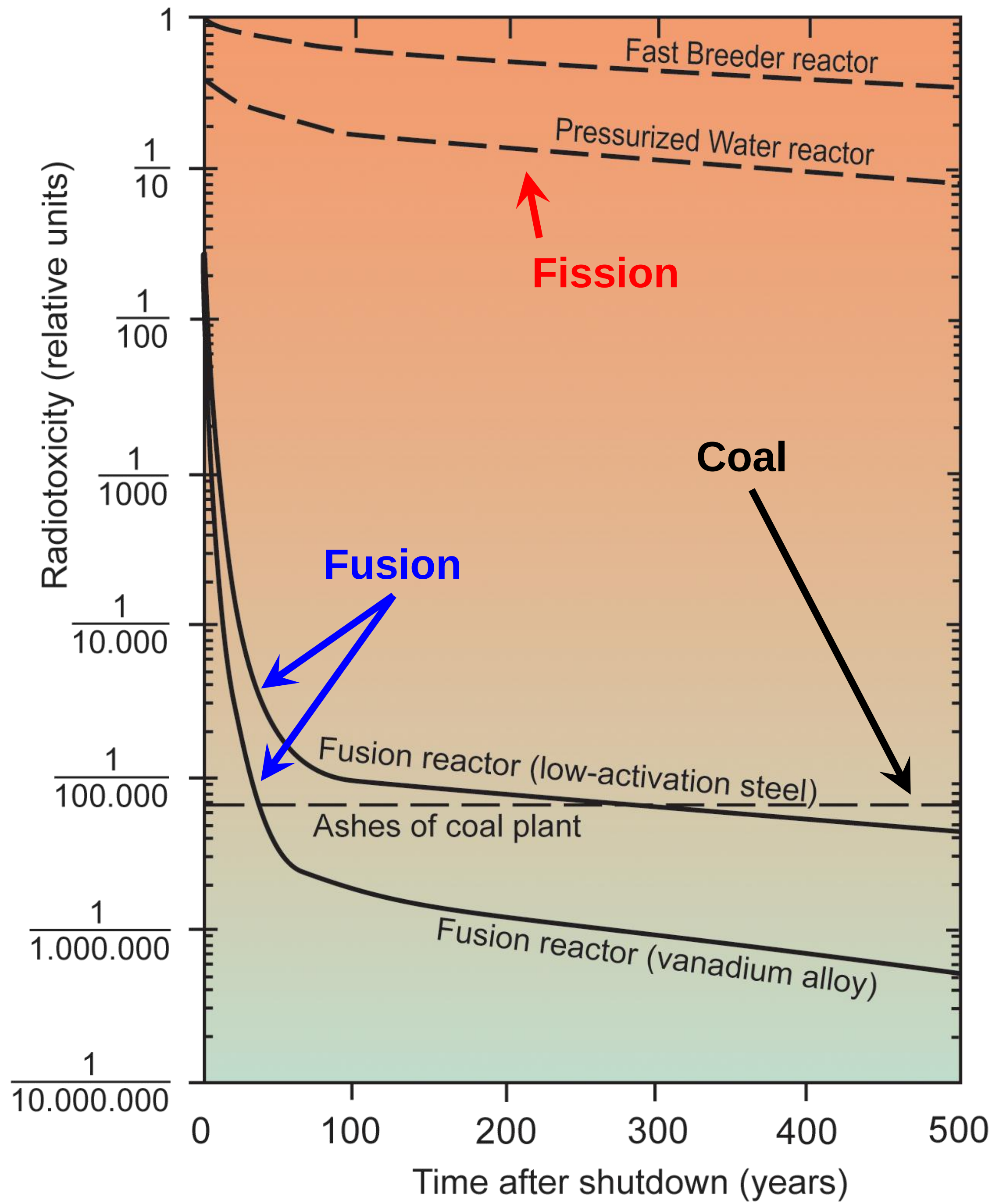
Radiotoxity

Neutrons result in induced radioactivity within the reactor structure

Radiotoxity from fusion waste decays within 50 years

Waste from fusion is less radiotoxic than that from coal plants

Reactors may be periodically upgraded and reused



Deuterium, Tritium and Lithium

- Deuterium is a stable isotope of hydrogen
- Natural abundance in the oceans with 154 ppm
- Tritium has half life of 12 yr and must be breeded
- Lithium is a stable soft alkali metal found in the crust
- Widely distributed and 33rd most abundant element
- Difficult to contain and may leak from reactors
- Flammable and explosive if exposed to air and water
- Can be used to breed tritium by neutron irradiation

  $^{6}Li + n \rightarrow {}^{4}He + T$ (exothermic, absorbs n)

  $^{7}Li + n \rightarrow {}^{4}He + T + n$ (endothermic, releases n)

Resources for fusion energy

Resources are abundant and widely distributed:

Deuterium:	30 mg/litre water
Lithium:	65 g/tonnes in the Earth's crust

Practical example:

280 litres of crust	(50 grams lithium, two laptop batteries)
400 litres of water	(12 grams deuterium, a full bathtub)

The energy gain corresponds to approximately 300 tonnes of oil, or the energy consumption for the life time of an European

Resources for fusion are available for thousands of years

Accident potential

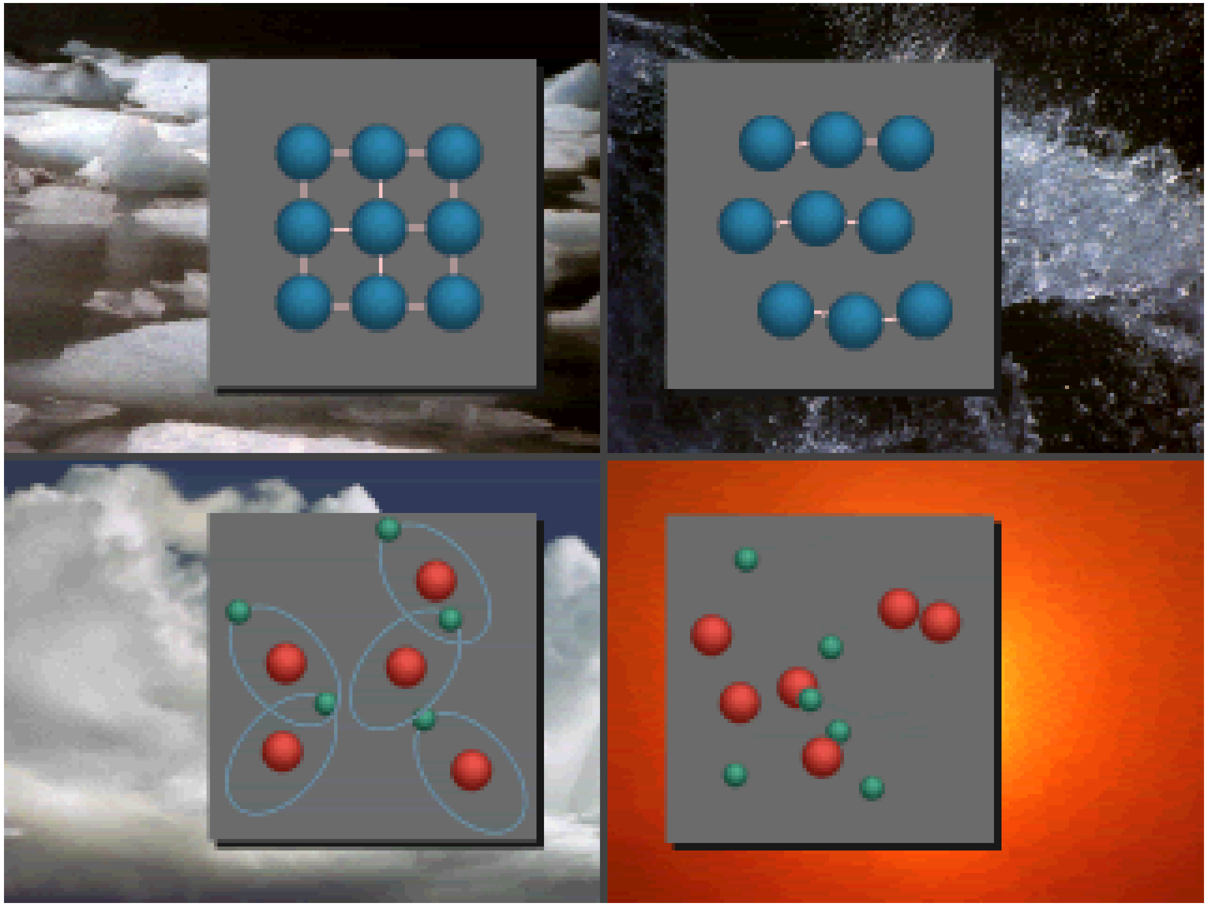
- Likelihood of a catastrophic accident in a fusion reactor is much smaller than in a fission reactor
- Fusion requires precisely controlled conditions of temperature, pressure and magnetic field
- No risk of a runaway reaction since the plasma is normally burnt at optimal conditions
- Total amount of fusion fuel in the vessel is very small, typically a few grams

Open questions for fusion energy

- How to confine D and T in the reactor core?
- How to control interactions with material walls?
- Can the fuel be heated to the required 10^8 K?
- Any problems due to high energy neutrons?

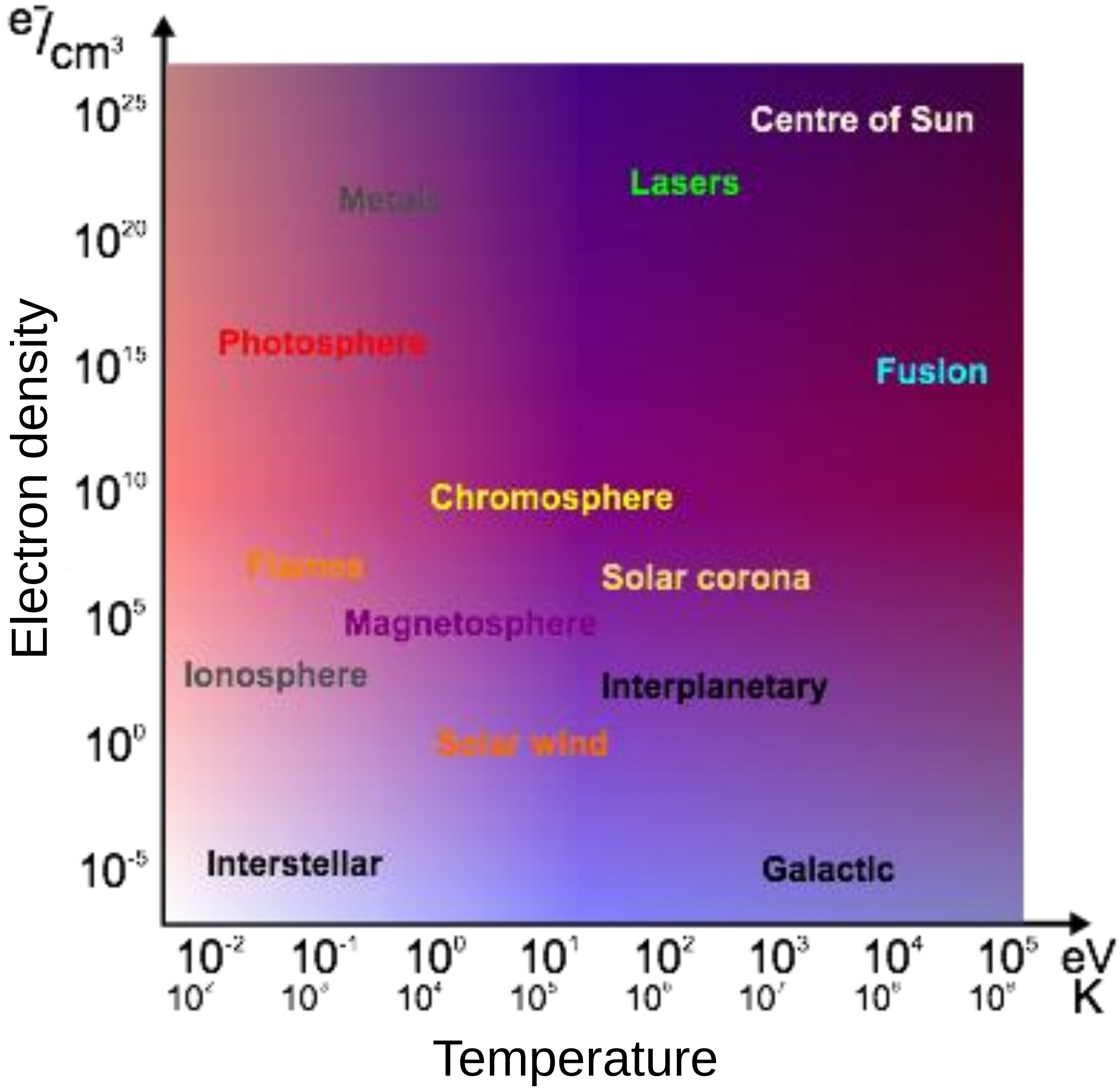
Plasma, confinement and heating

Plasma: the fourth state of matter

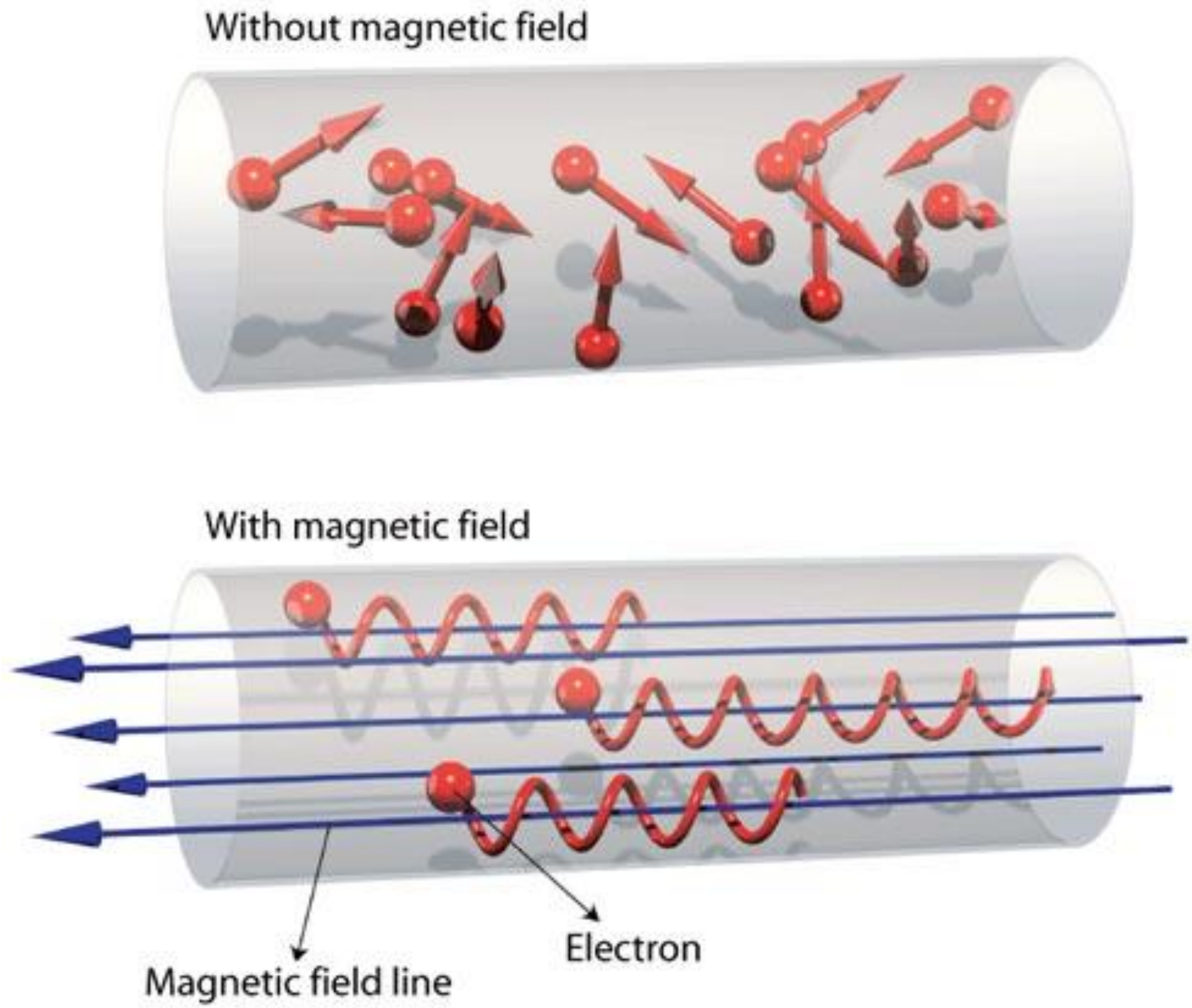


Plasma consists of free electrons and ions resulting in long-range interactions

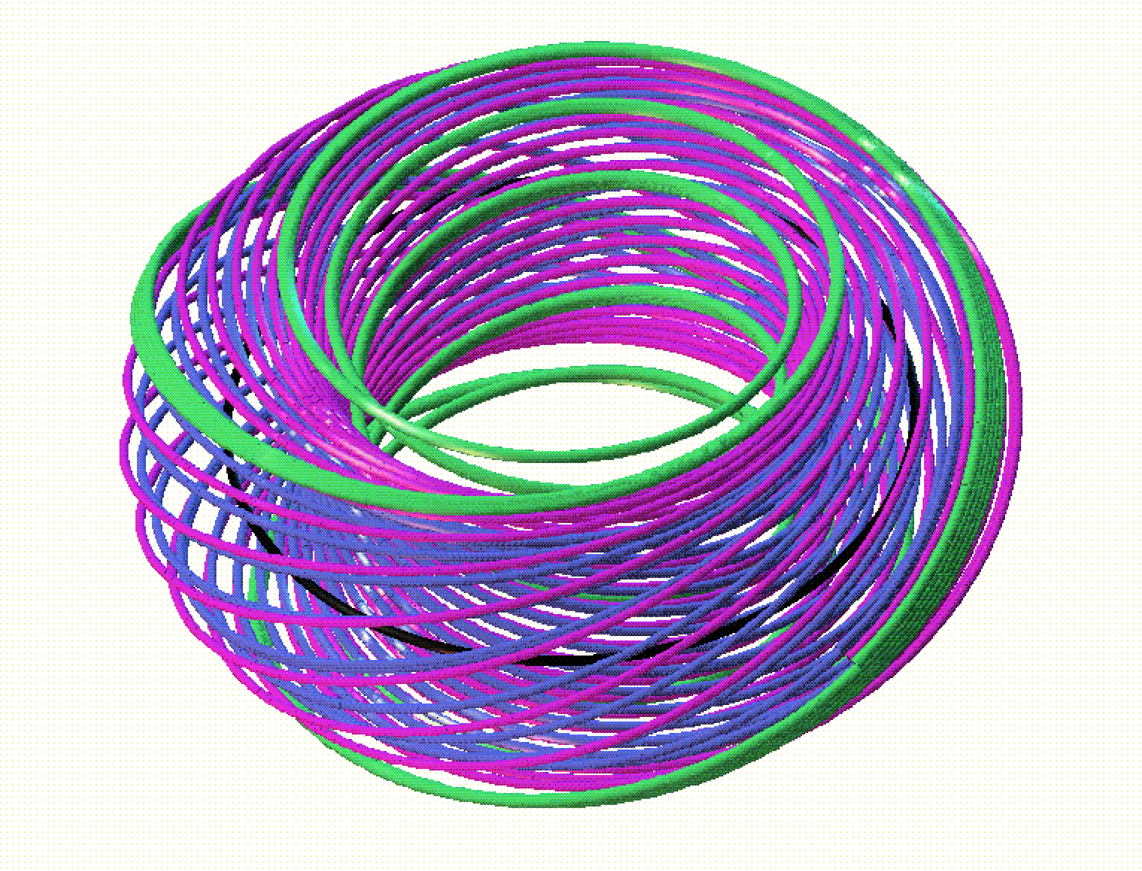
The range of plasmas



Single particle confinement



Magnetic bottle



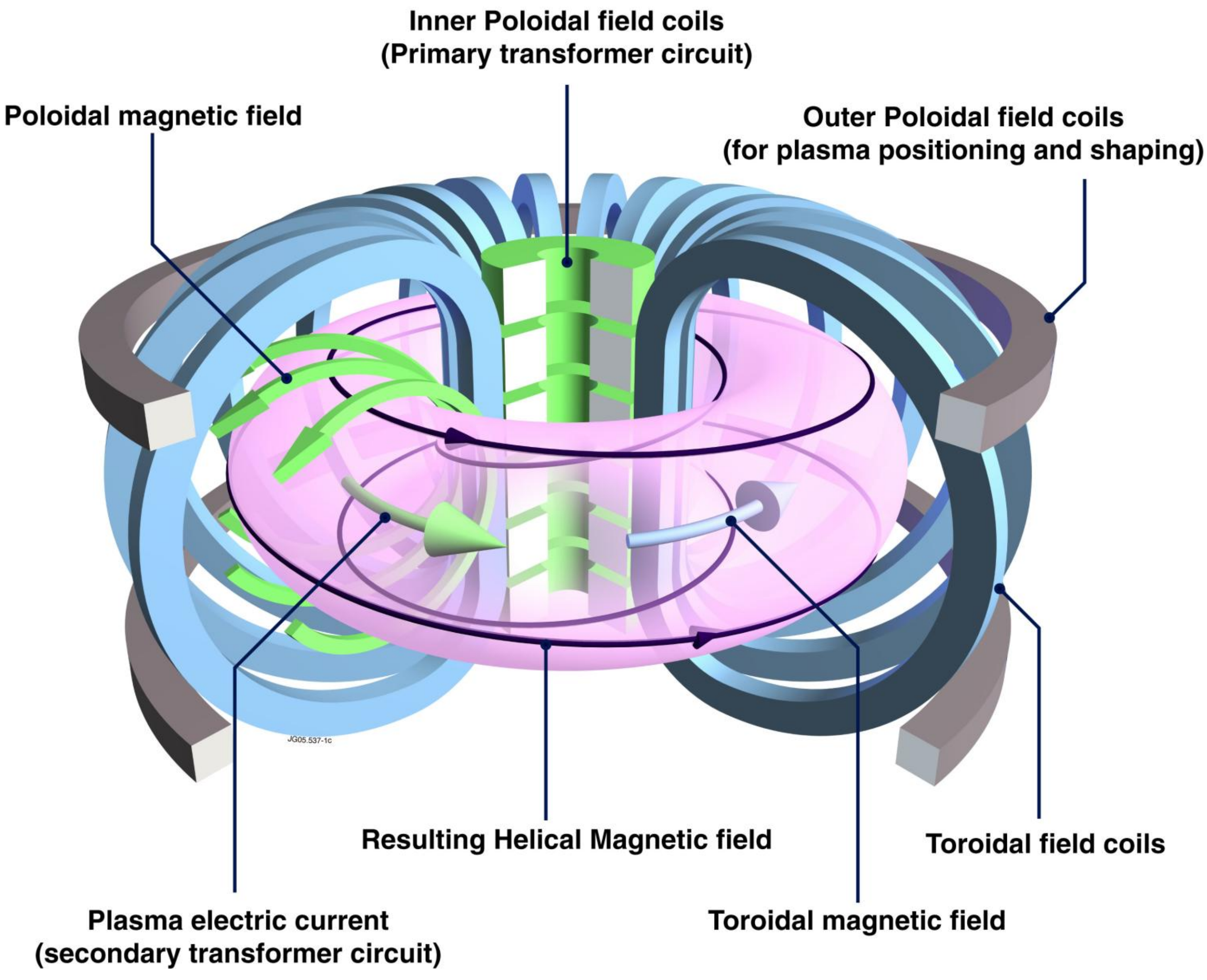
Electric currents create a magnetic field that confines the plasma

Charged particles move along magnetic field lines on toroidal surfaces

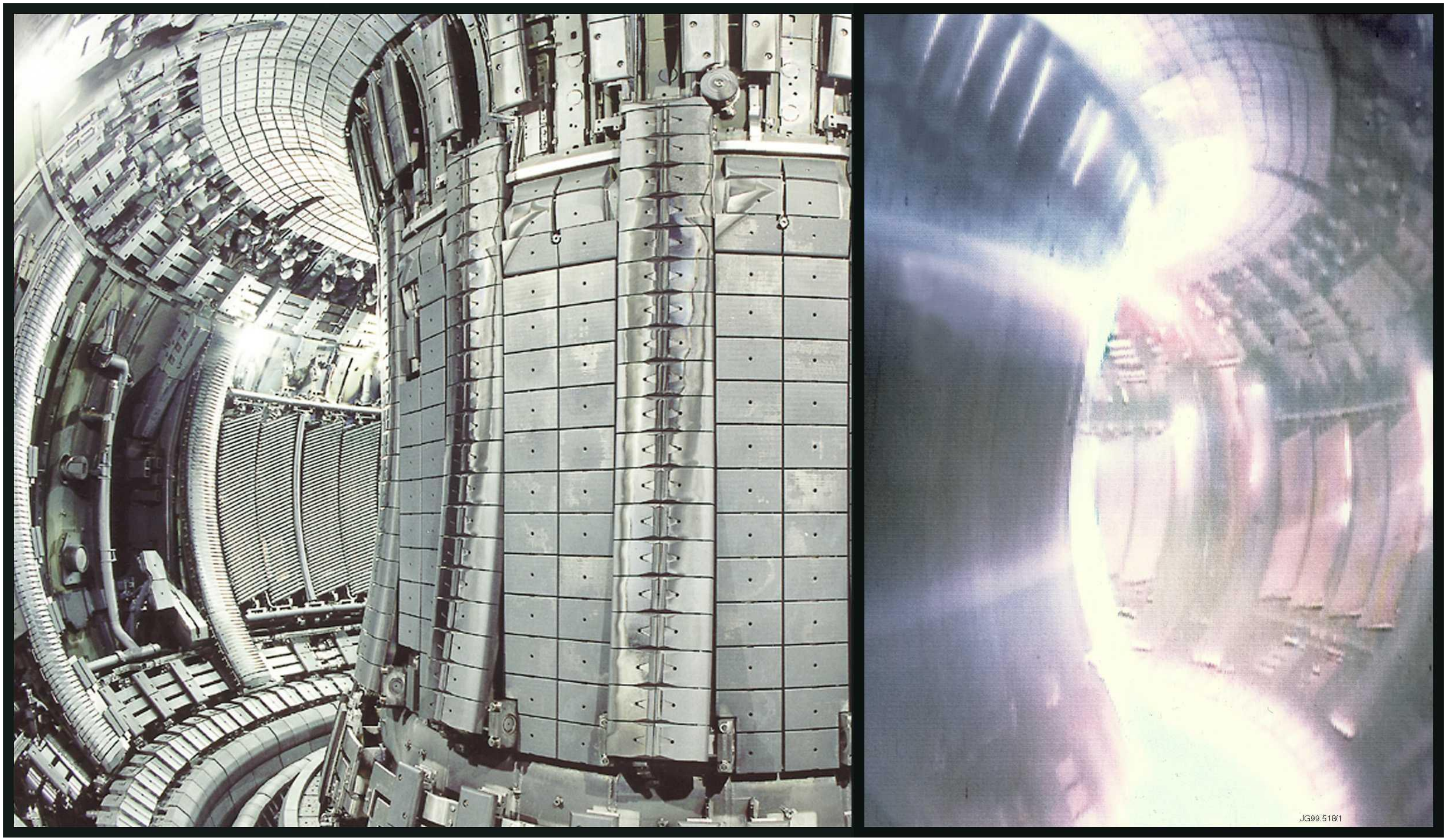
The tokamak configuration

- Acronym for ‘toroidal chamber with magnetic field’
- Transformer action induces toroidal plasma current
- The poloidal magnetic field gives closed **B**-surfaces
- This provides magnetic confinement of the plasma
- Current also leads to Ohmic heating of the plasma
- Resistivity decrease as plasma temperature increase
- Inductive drive prevents steady state operation
- New current drive schemes are now developed

The tokamak


Inner Poloidal field coils
(Primary transformer circuit)
Poloidal magnetic field
Outer Poloidal field coils
(for plasma positioning and shaping)
JG05.537-1c
Resulting Helical Magnetic field
Toroidal field coils
Plasma electric current
(secondary transformer circuit)
Toroidal magnetic field

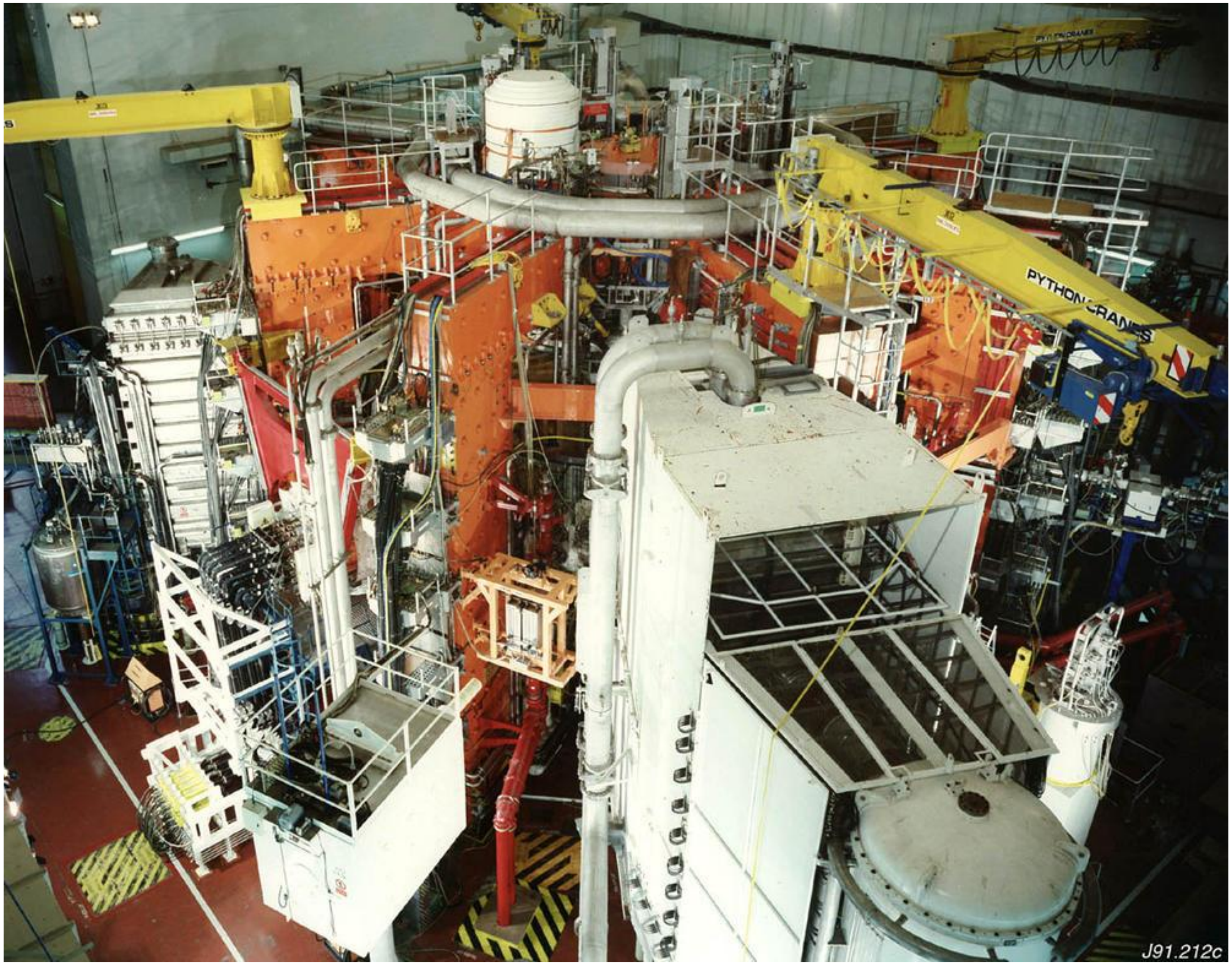
Joint European Torus



Joint European Torus

- Constructed in 1983 at Culham, Oxfordshire, UK
- The worlds largest tokamak experiment to date
- Minor radius 1.25m, major radius 3m, current 5MA
- Fully equipped with remote handling facilities
- Experiments made with 50-50 DT fuel mix
- World record peak fusion power 16 MW in 1997
- Total available heating power is now over 40 MW
- Run by European Fusion Development Agreement

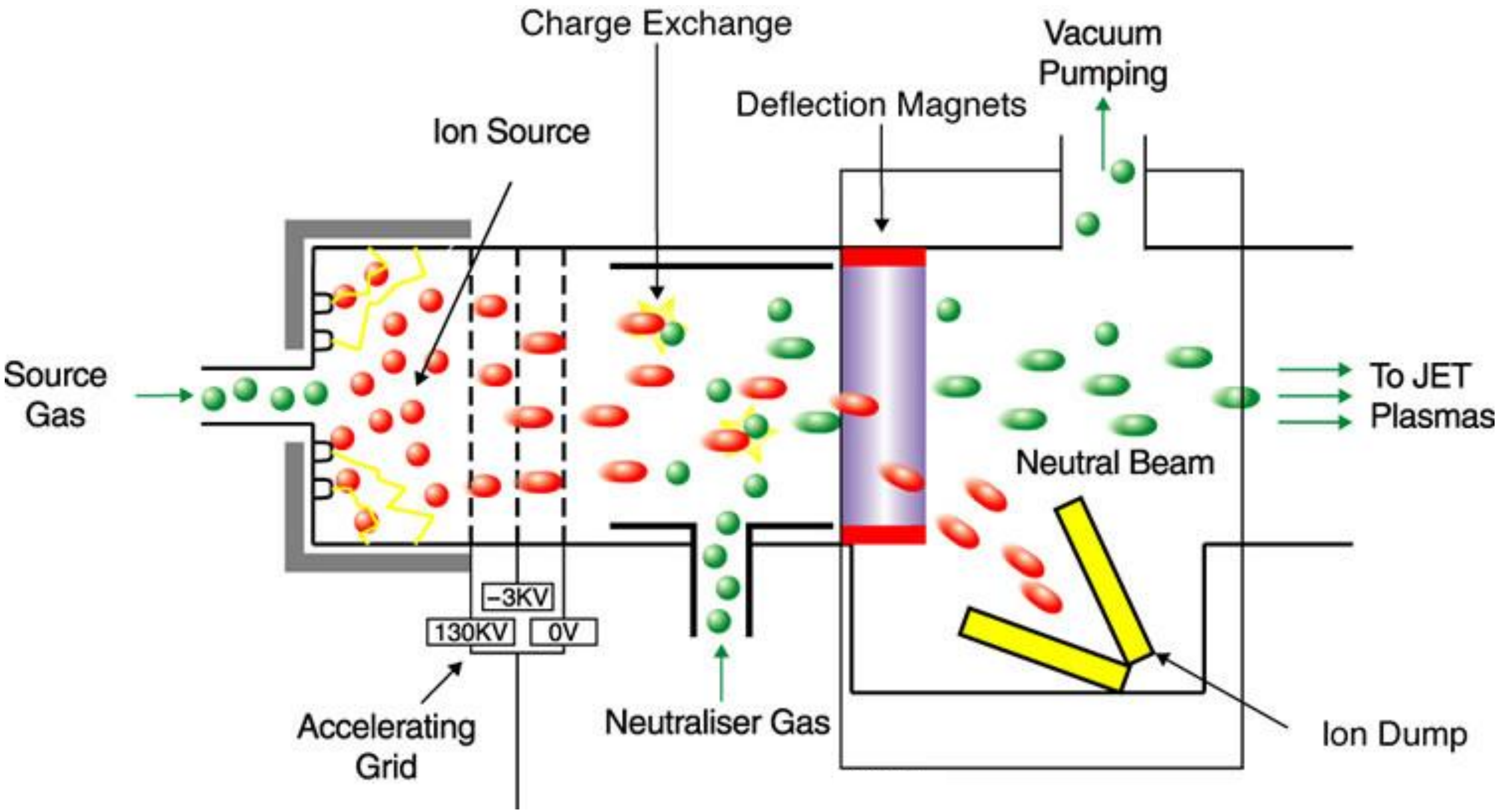
External view of JET



Ohmic and auxiliary plasma heating

- Ohmic heating from inductive plasma current
- Auxiliary heating schemes
  - Neutral beam injection
  - Electromagnetic waves
- Localized heating can additionally be used to
  - control profile and drive plasma current and rotation
- Alpha particle from fusion reactions heat plasma
  - At 3.5 MeV they are much more energetic than bulk
  - Bulk plasma heating through collisions with alphas

Neutral beam injection mechanism



JET neutral beam injection

High energy particle beams

Neutral atoms for deep penetration

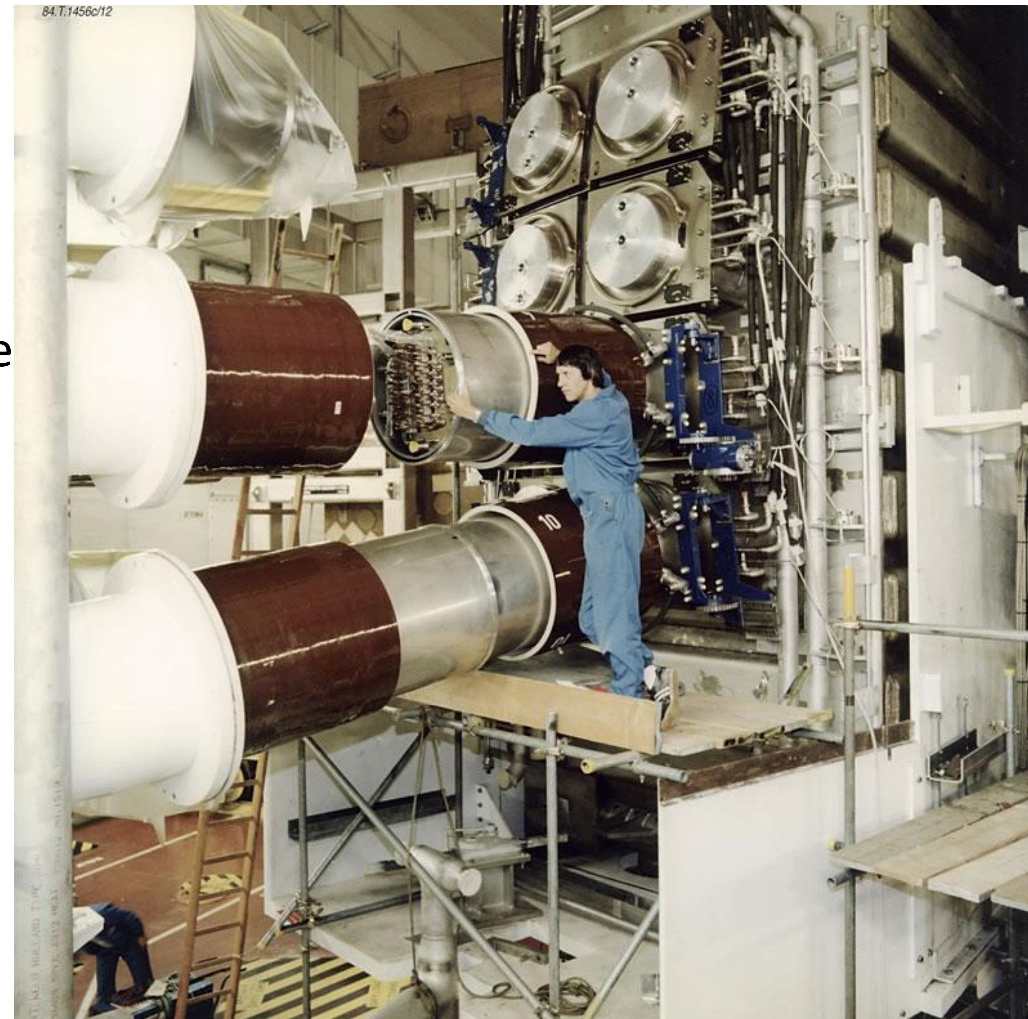
Electrons are stripped off in the core

Charged particles are then confined

Bulk plasma is heated by collisions

The beam energy is 80 or 140 keV

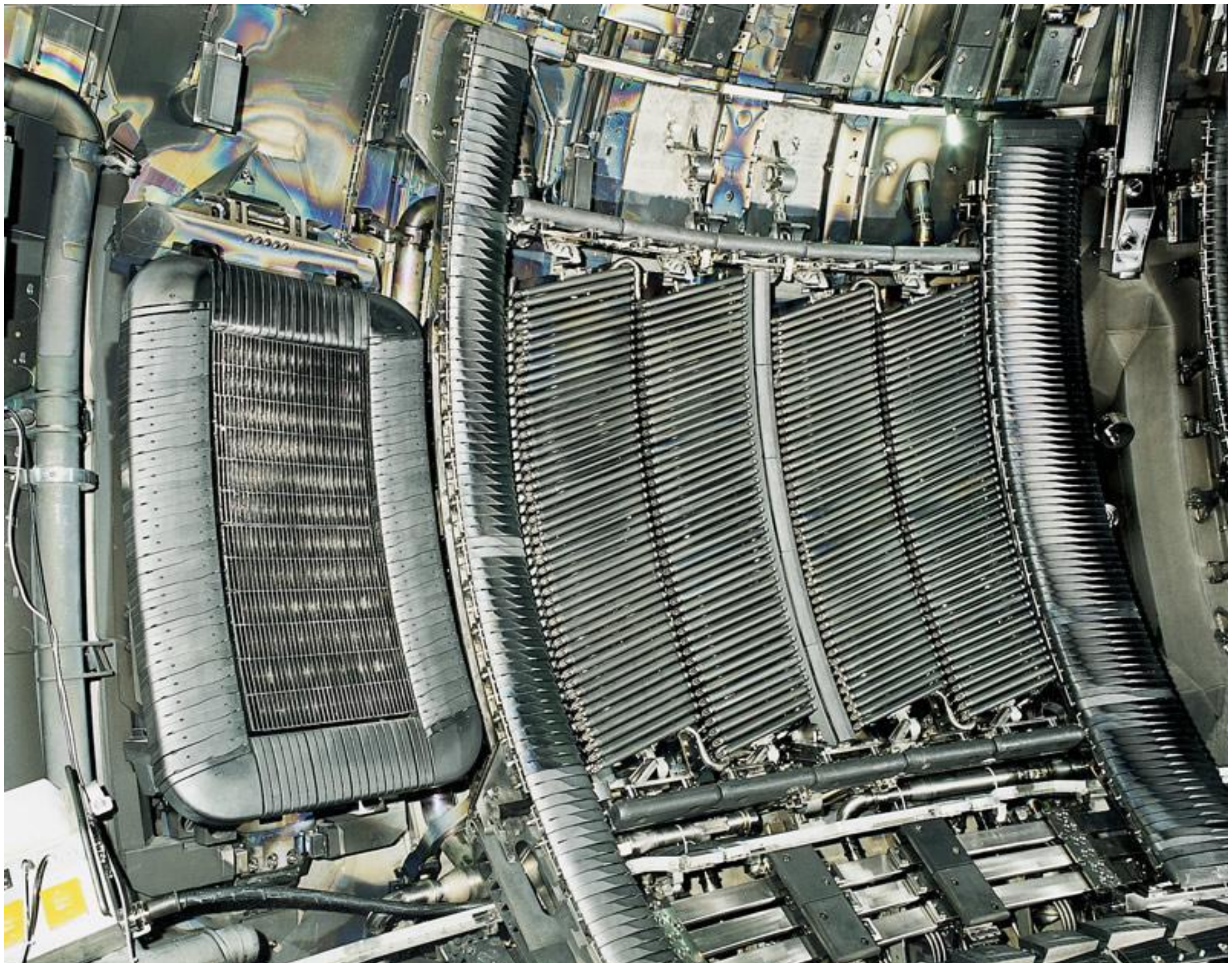
Heating power is up to 23 MW



Radiofrequency wave heating

- Electromagnetic waves launched into the plasma
- Resonant energy transfer from wave to particles
- Increases the thermal energy of the plasma
- Resonance position is given by the magnetic field
- Plasma heating power is of the order 10 MW
- Vacuum electromagnetic wavelength 10m
- Waves can also be used to drive plasma currents

LHCD and ICRH antennas in JET



Heating by alpha particles

Plasma

↓

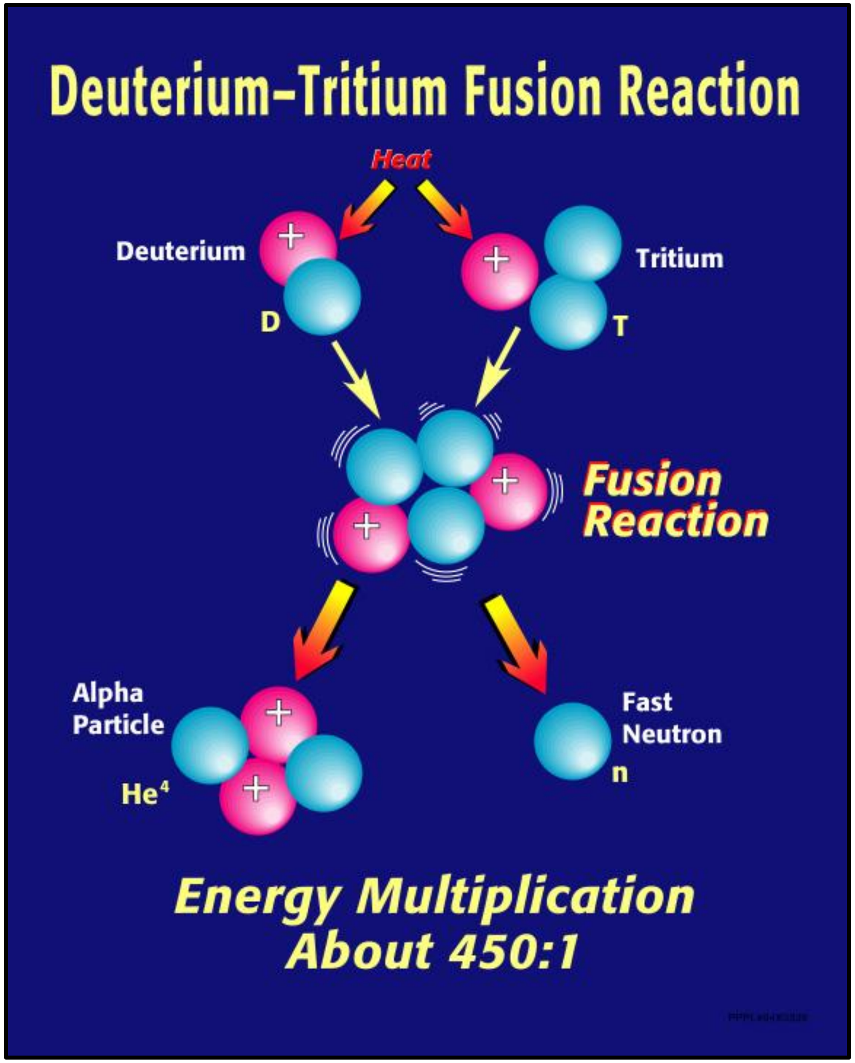
D + T → He + n

↑ ↑

3.5 MeV 14 MeV

He from fusion processes will heat the bulk plasma

May resonate with waves



Plasma turbulence simulations

Code: **GYRO**

Authors: Jeff Candy and Ron Waltz

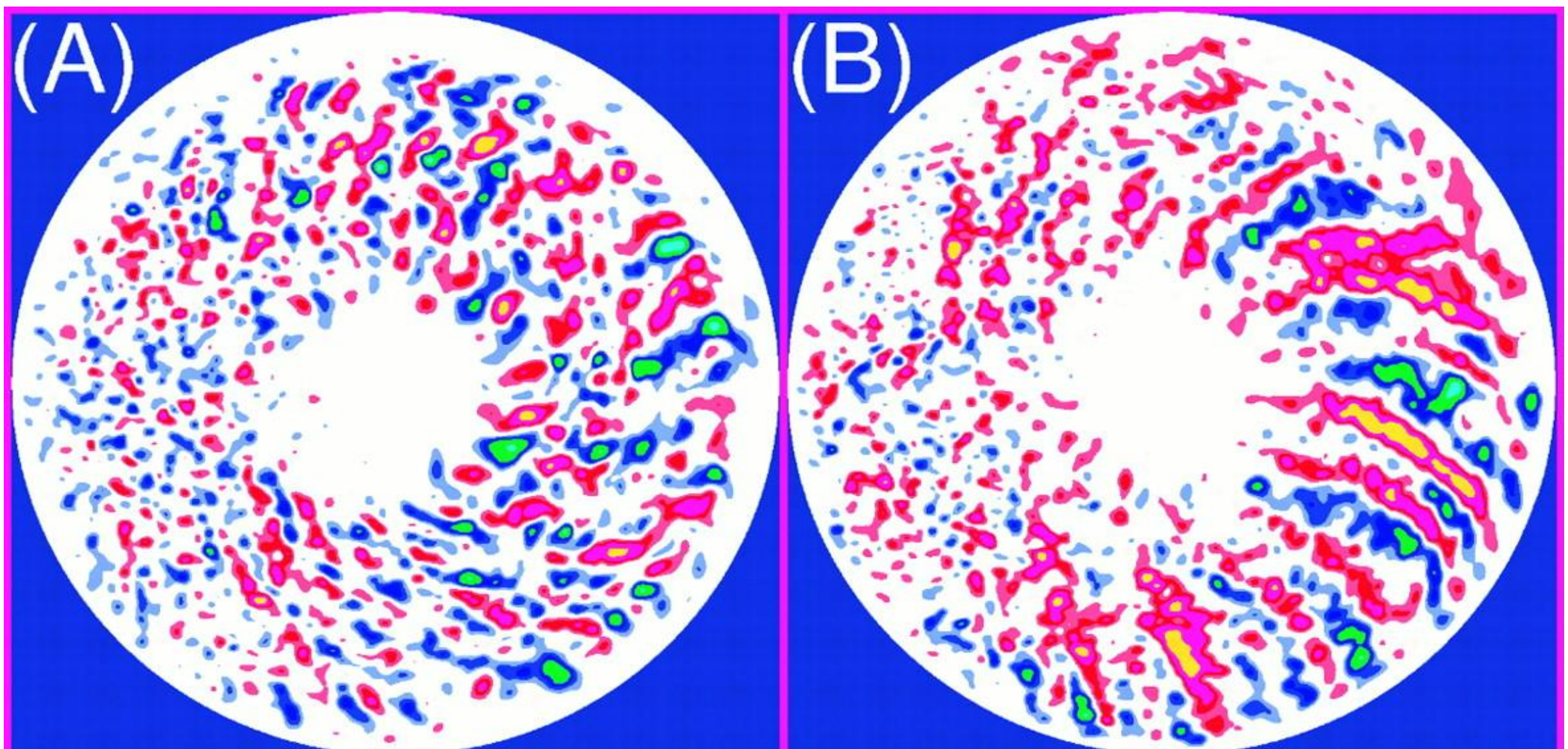
Plasma turbulence simulations

With differential rotation:

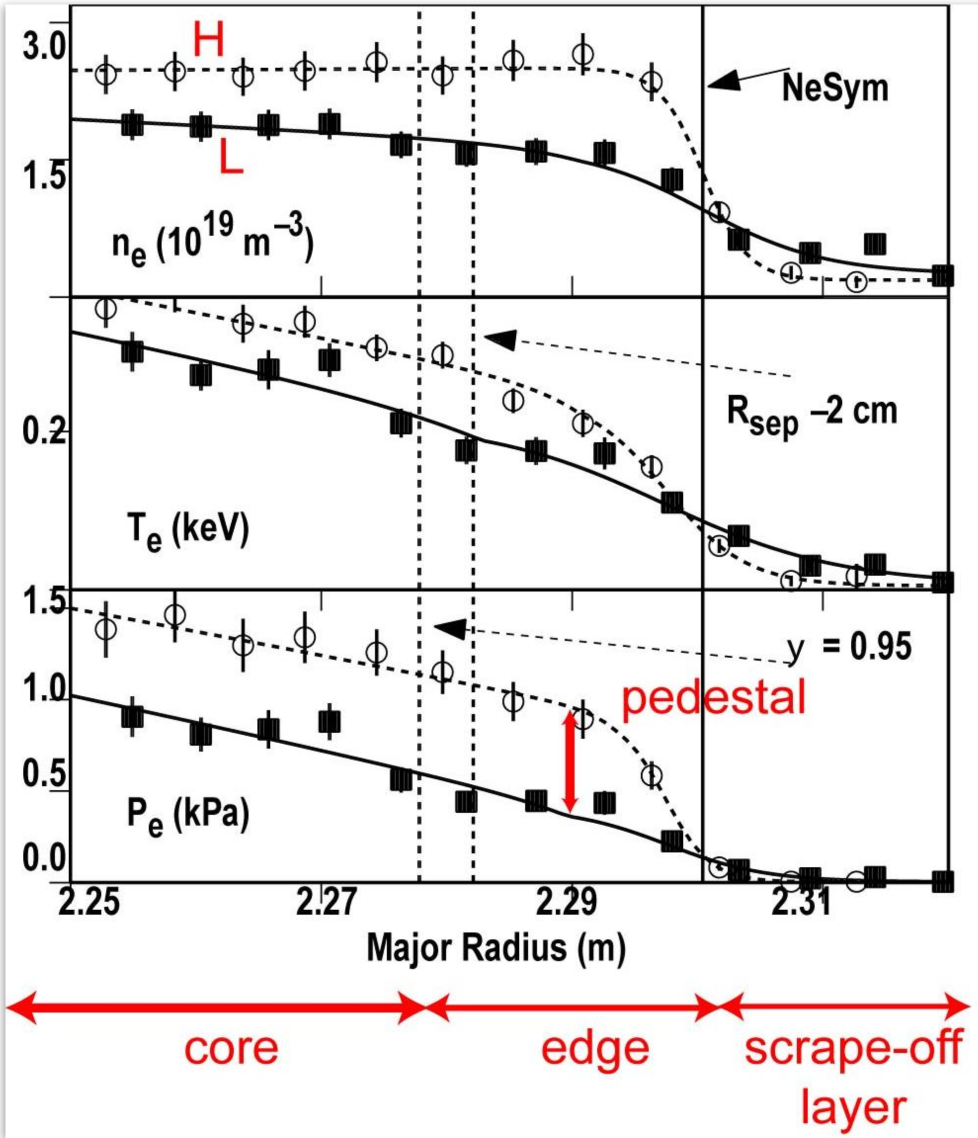
break-up of turbulent eddies

Without differential rotation:

radially elongated structures



Improved confinement state



Transition at critical heating level:

L: low confinement level

H: high confinement level

Self-organizaton of the plasma:

Increased free energy reduces the fluctuation level

Spontaneous differential rotation:

Turbulent transport suppressed

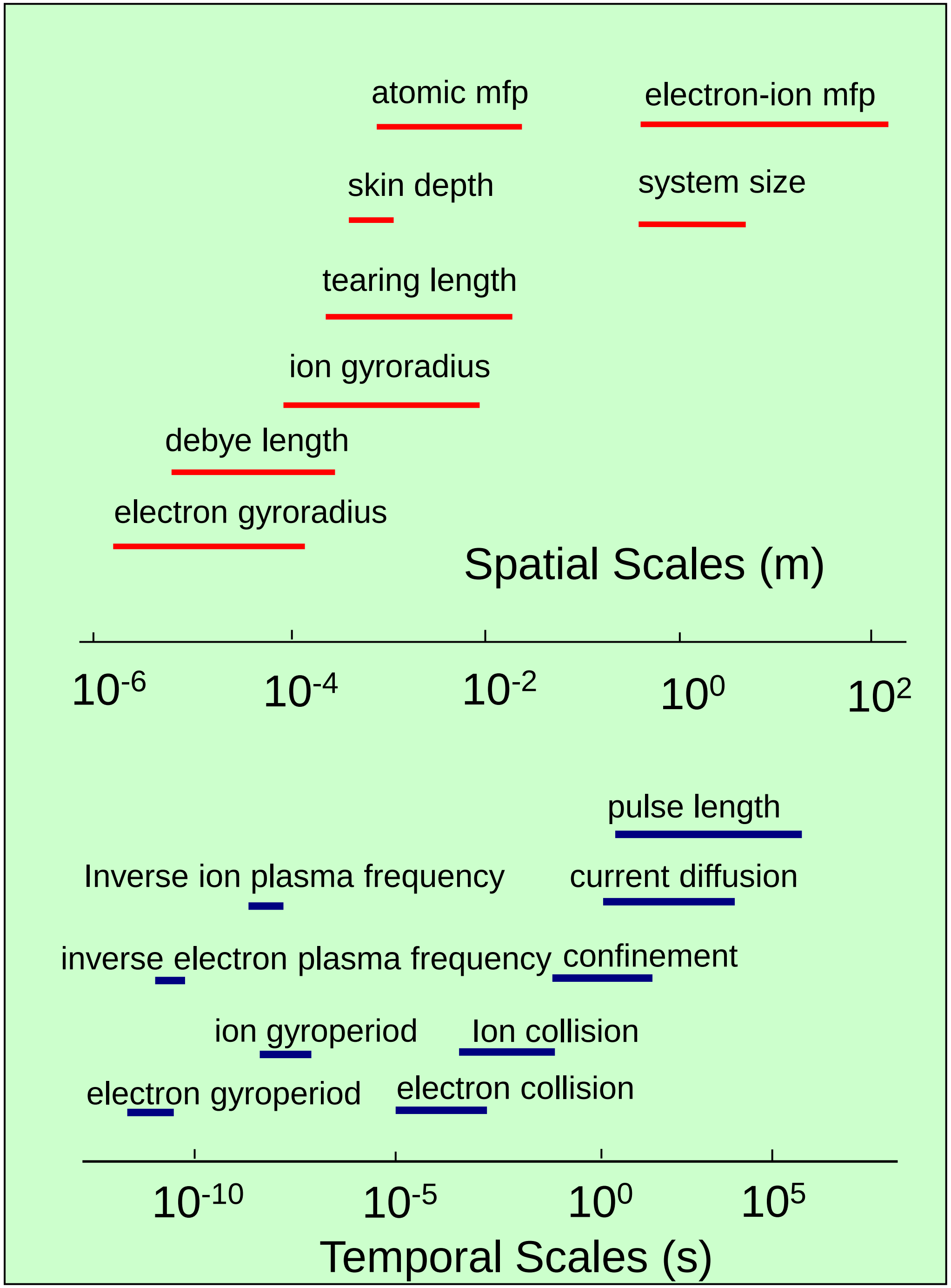
Boundary conditions are crucial:

Choise of material and treatment

Challenges for theory

Vast range of spatial and temporal scales

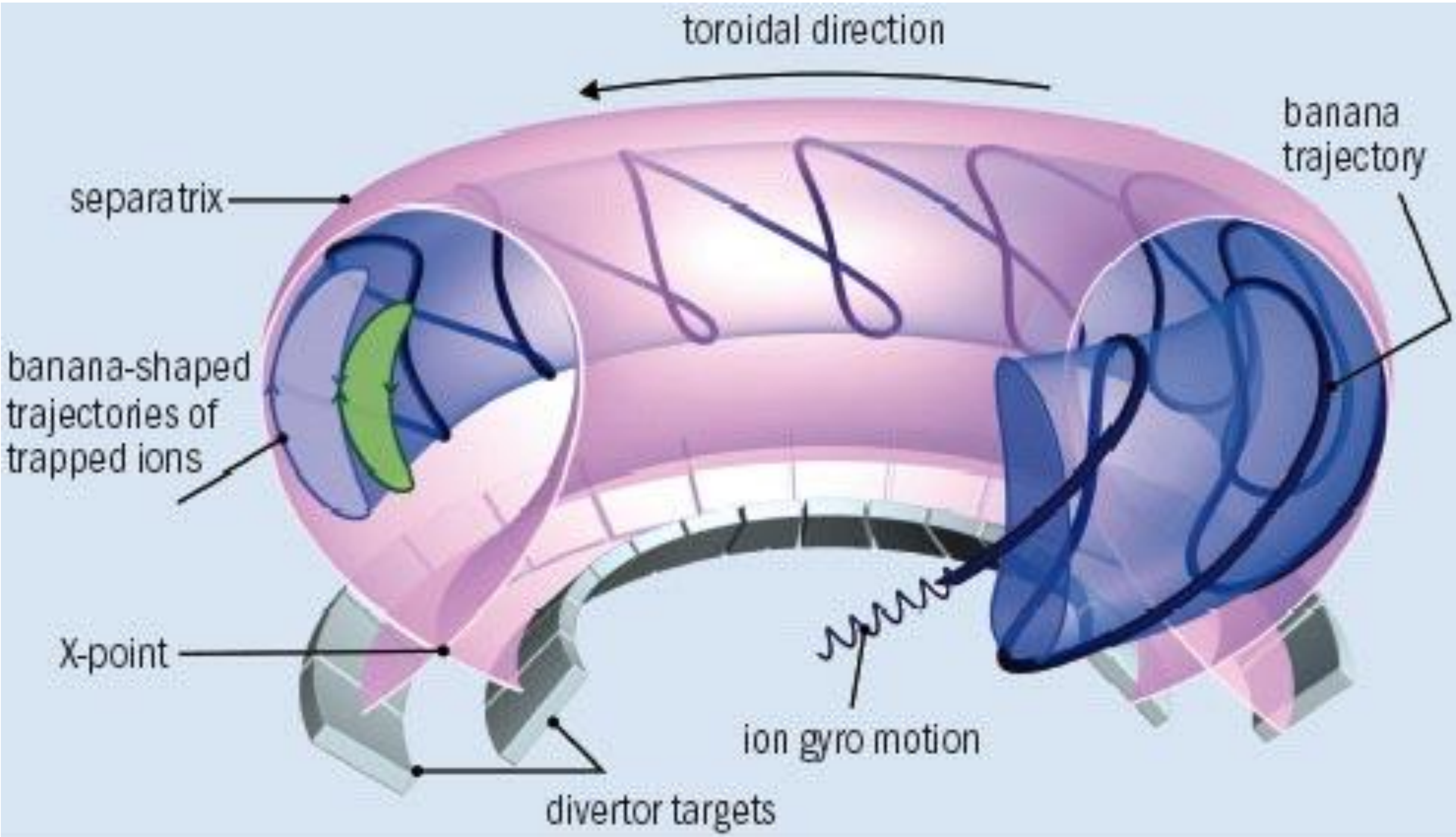
Overlap of scales prevents simplifications



The role of fast ions

- Energetic alpha particles are produced by fusion
- Energy of 3.5 MeV is far more than the bulk plasma
- Alphas should heat the plasma to maintain fusion
- Fast ions can resonate with waves in the plasma
- They may thus be quickly lost from the core plasma
- Diagnostic must be developed for their investigation
- No experiments with large alpha population to date
- The fast ions carry 1/3 of the plasma kinetic energy

Fast ion motions in a tokamak



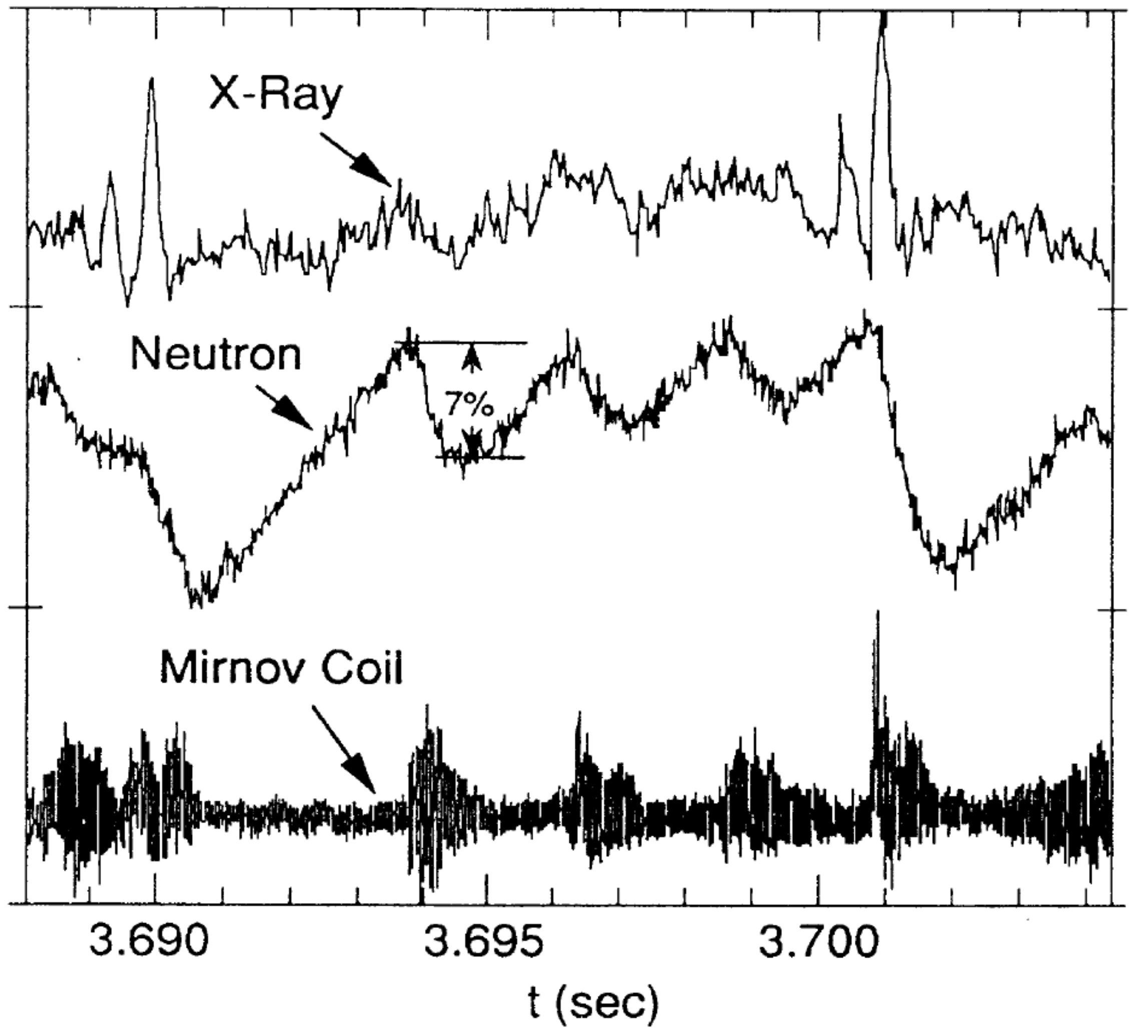
One of the most pressing problems for fusion energy is related to fast ions dynamics

Loss of fast ions due to collective motions

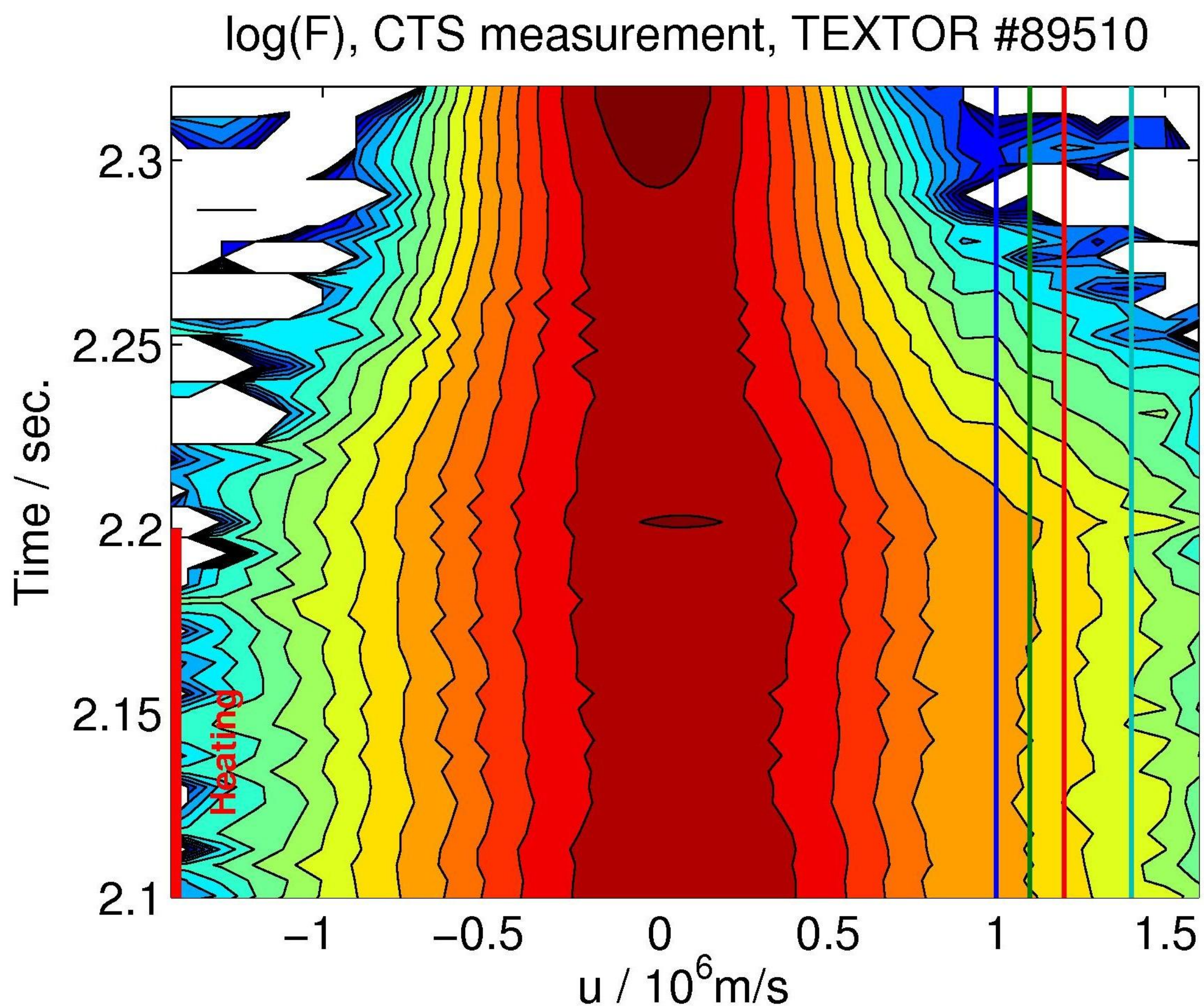
X-Ray:
No electron losses

Neutron:
Fusion processes

Mirnov coil:
Fluctuations of **B**

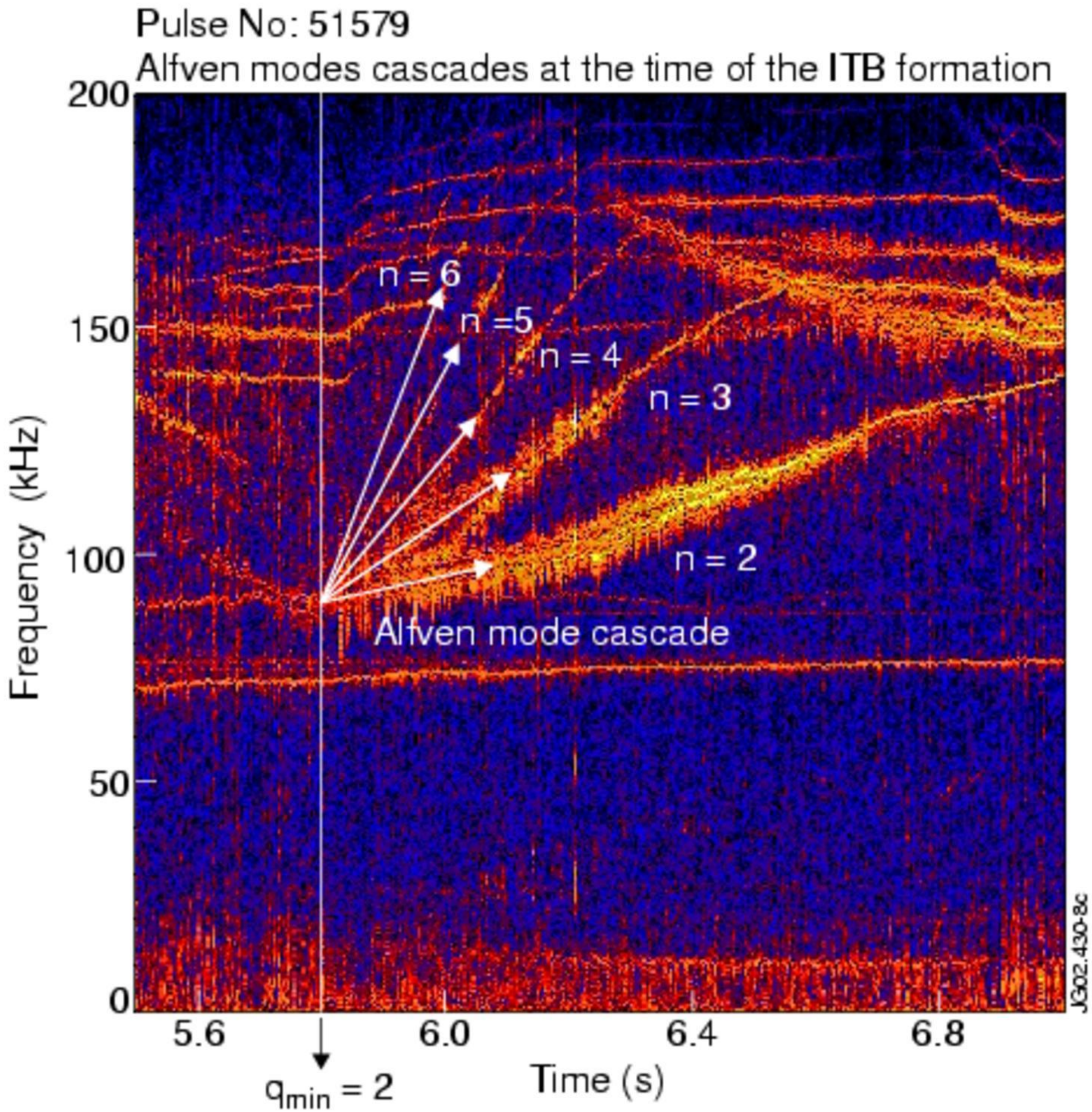


Velocity distribution of fast ions



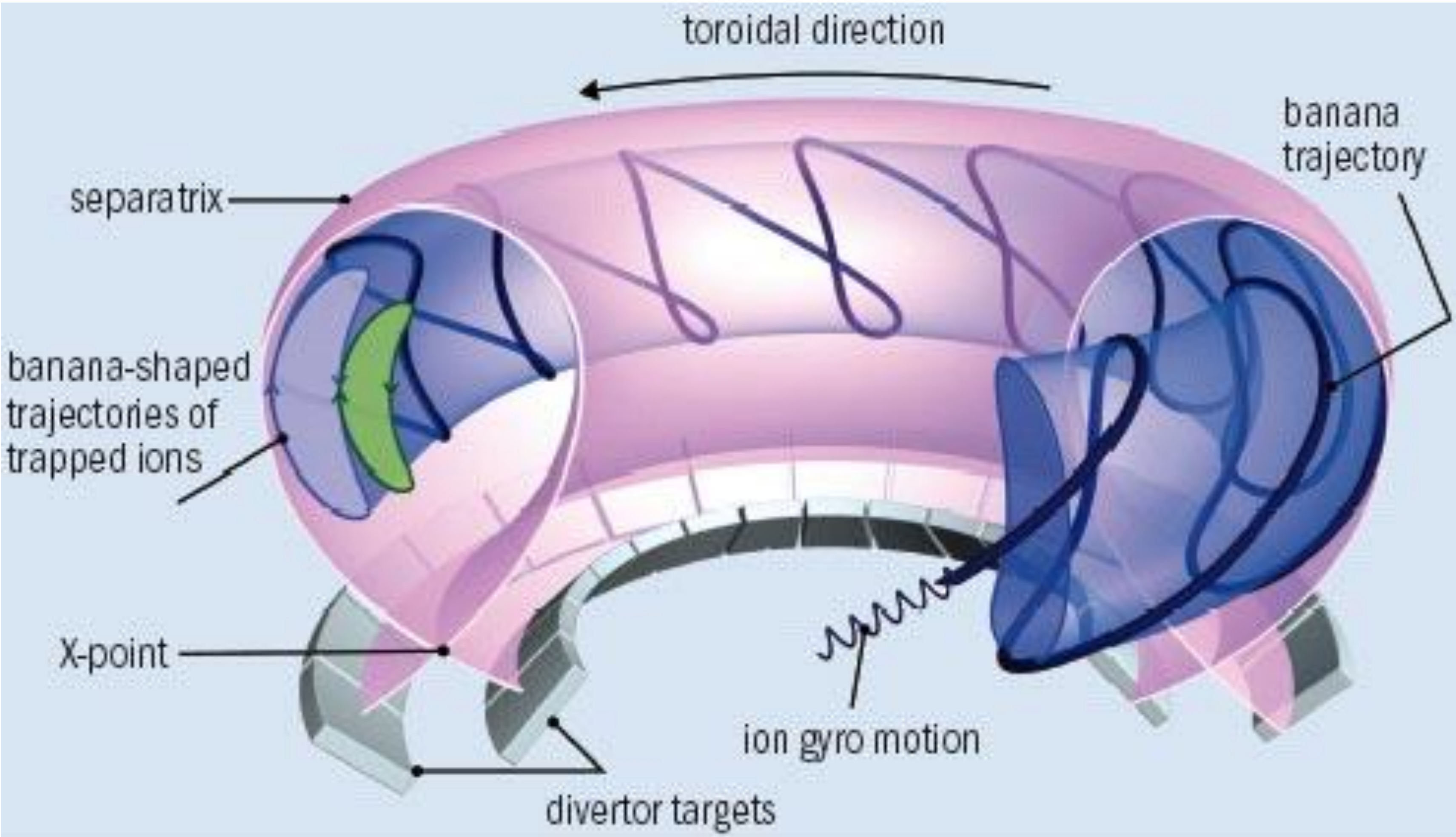
When auxiliary heating is turned off at t=2.2 s the fast ions slow down due to collisions

Fast ion dynamics in JET



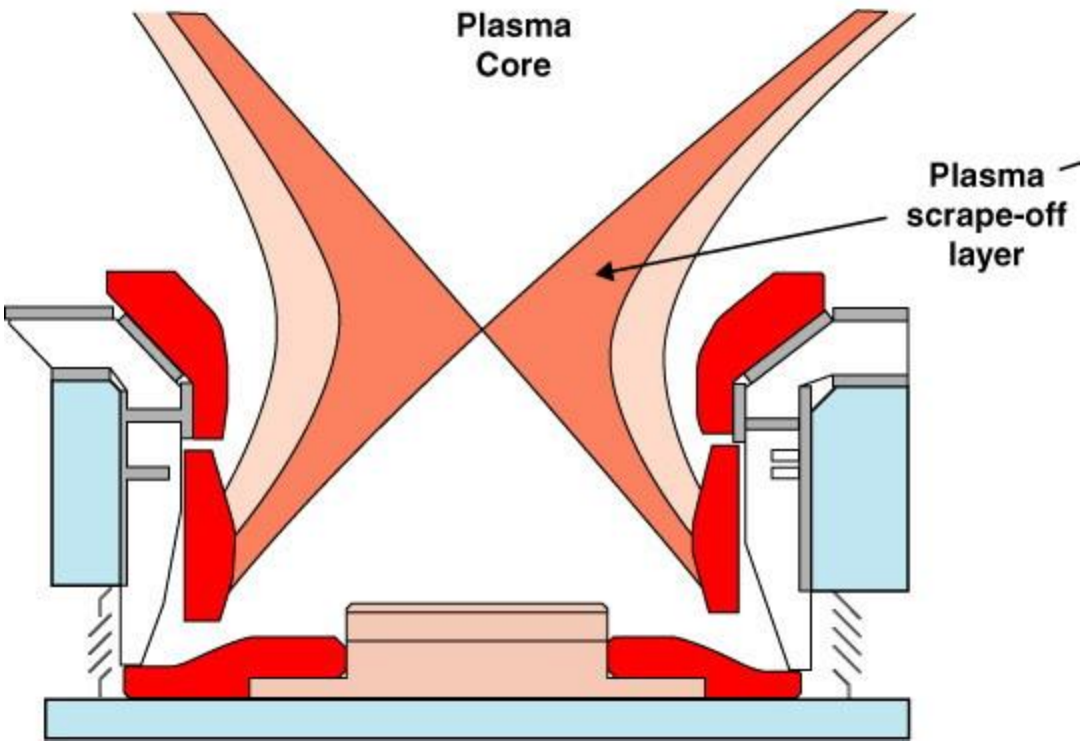
Plasma-wall interactions

Tokamak with magnetic X-point



One of the most pressing problems for fusion energy is plasma-wall interactions

Magnetic X-point and divertor



Surfaces of C, W or Be?

Heat fluxes up to 10 MW / m^2

X-point in magnetic field

• external current coils

Plasma is scraped off

• relatively cold edge plasma

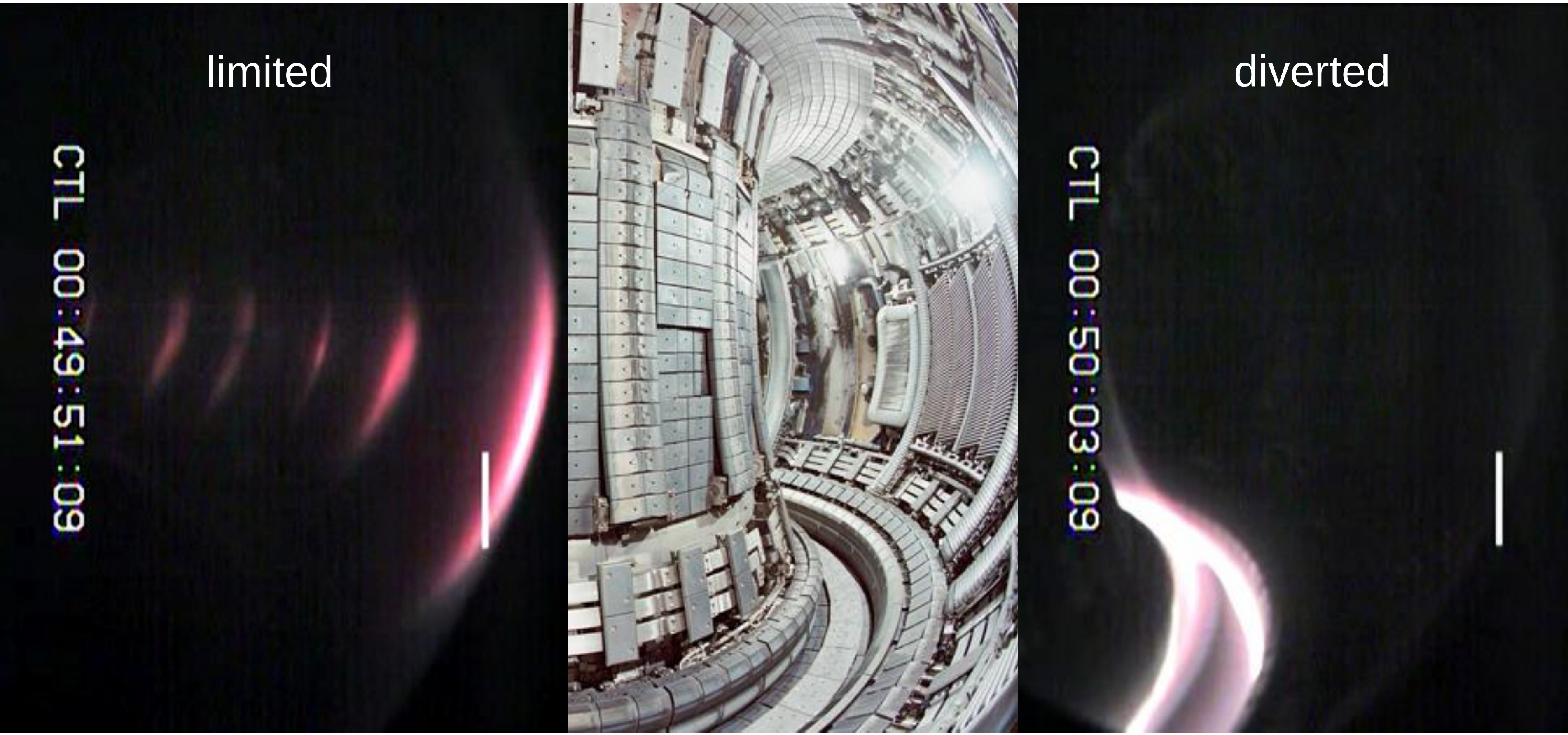
Localized wall contact

• heat, erosion, impurity

Removeal of He-ash

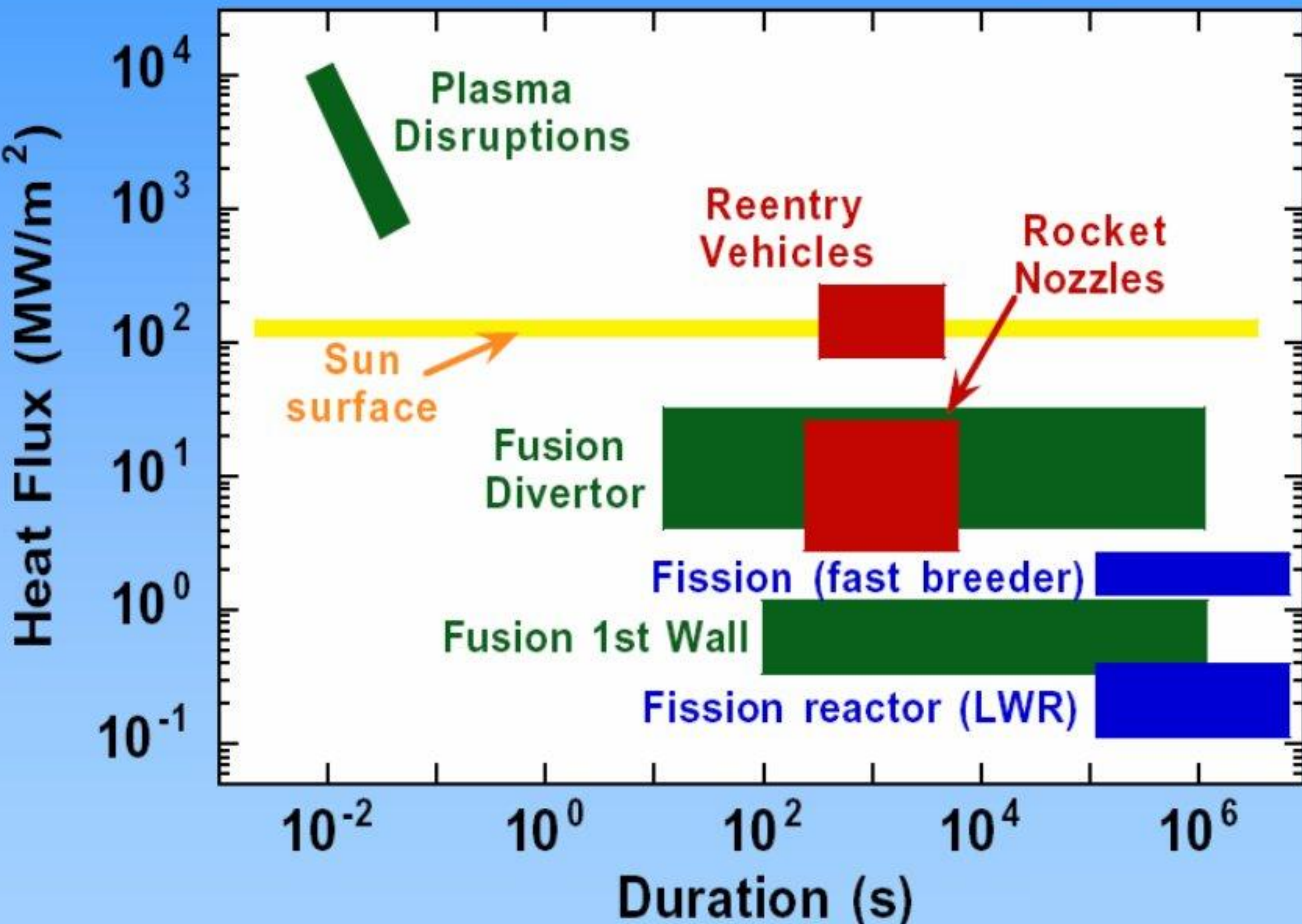
• neutral gas pumping

Limited and diverted plasmas

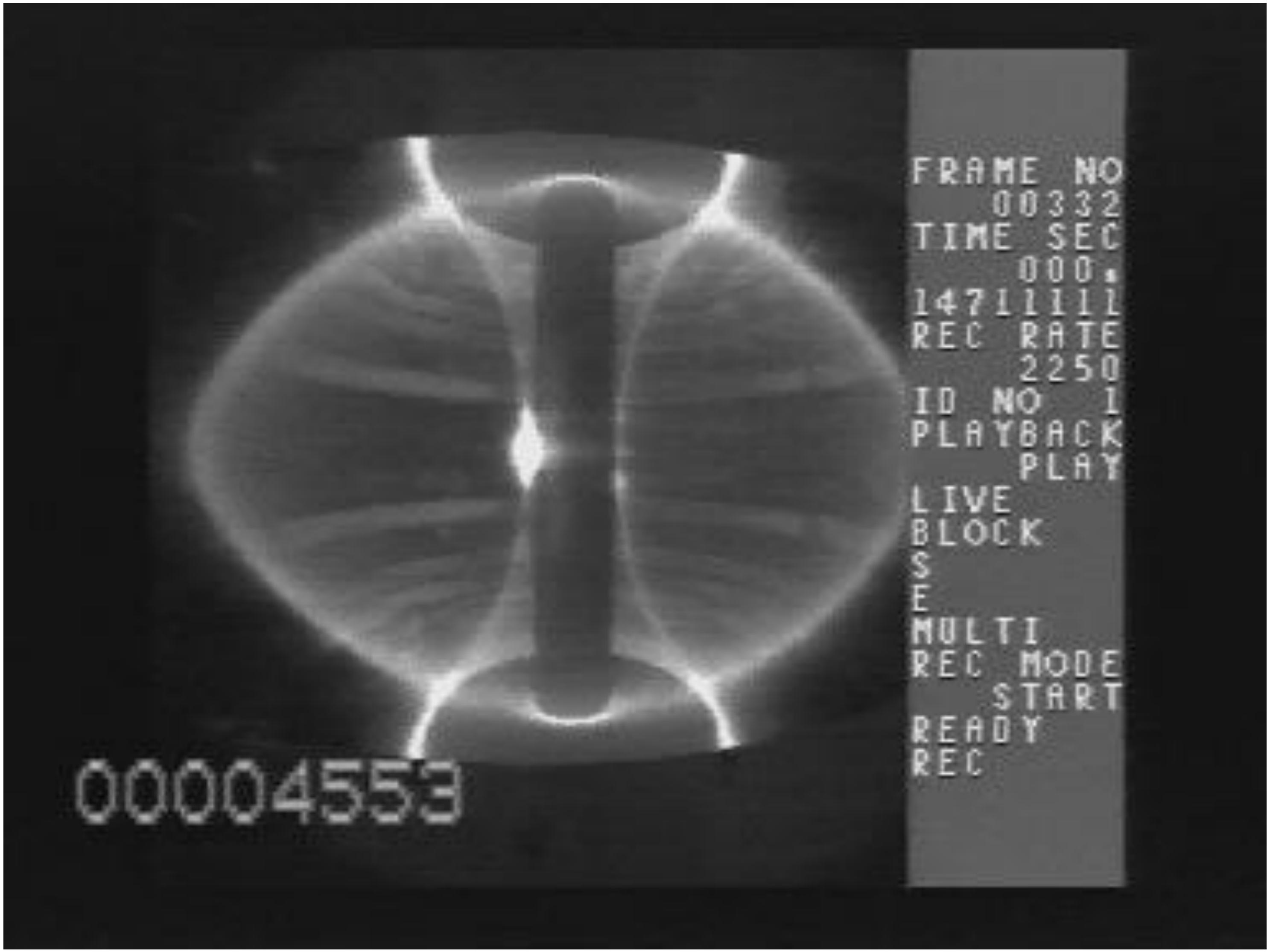


Special structures are built to localize and control interactions with the walls

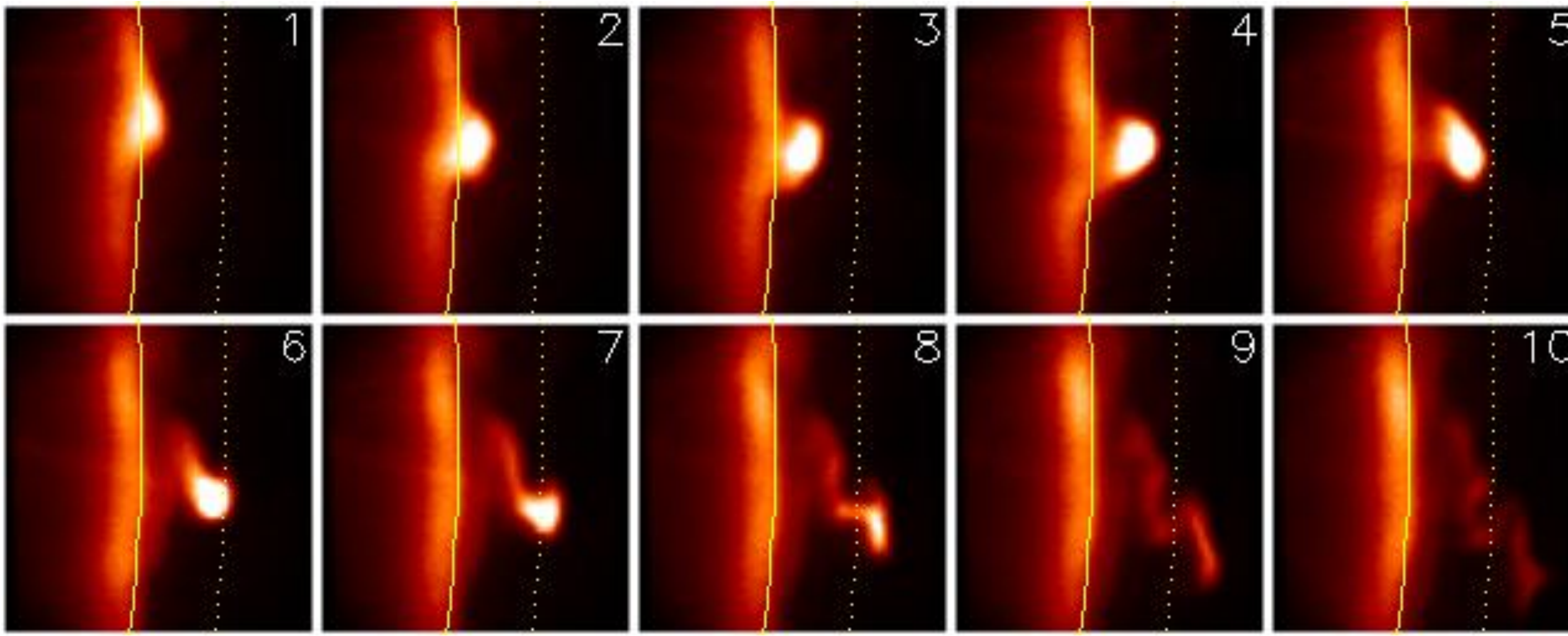
Comparison of Heat Fluxes



Unstable tokamak plasma edge



Structure motion in the scrape-off layer

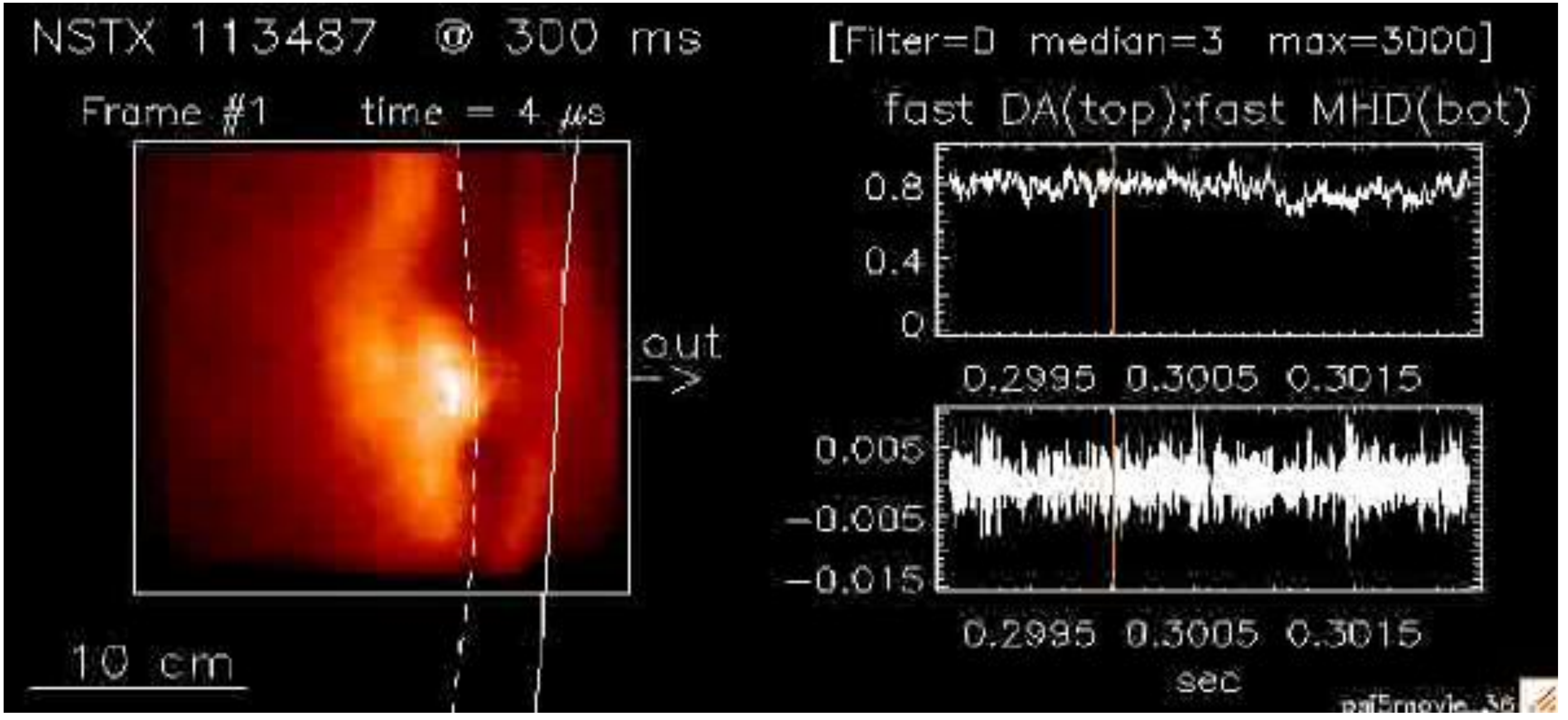


Localized puff of neutral deuterium gas into the edge plasma region

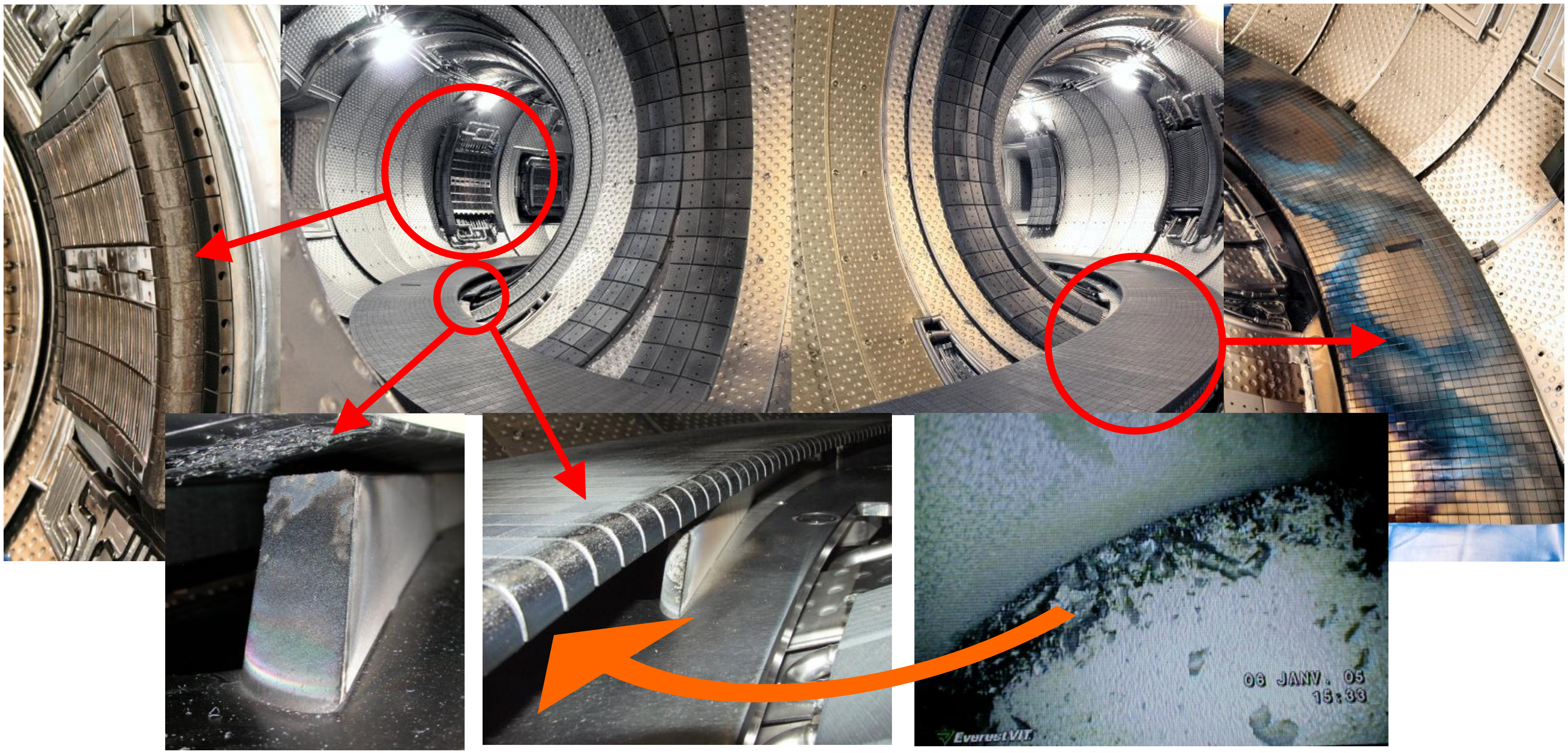
Camera records an area of 23x23 cm^2 with 100 000 frames per second

Plasma-wall interactions results in erosion and release of impurities

Fast camera imaging of turbulence



Migration of radioactive tritium



Migration of dust and tritium all over the machine with remote depositions

Every pulse is fueled by 50 g T but machine cannot contain more than 350 g

Status of fusion research

Ignition and energy gain factor Q

A fusion plasma is said to have reached ignition when the heating of the plasma by the products of the fusion reactions is sufficient to maintain the temperature of the plasma against all losses without external power input

The fusion energy gain factor Q is the ratio of fusion power produced in a nuclear fusion reactor to the heating power required to maintain the plasma in steady state

Confinement time and triple product

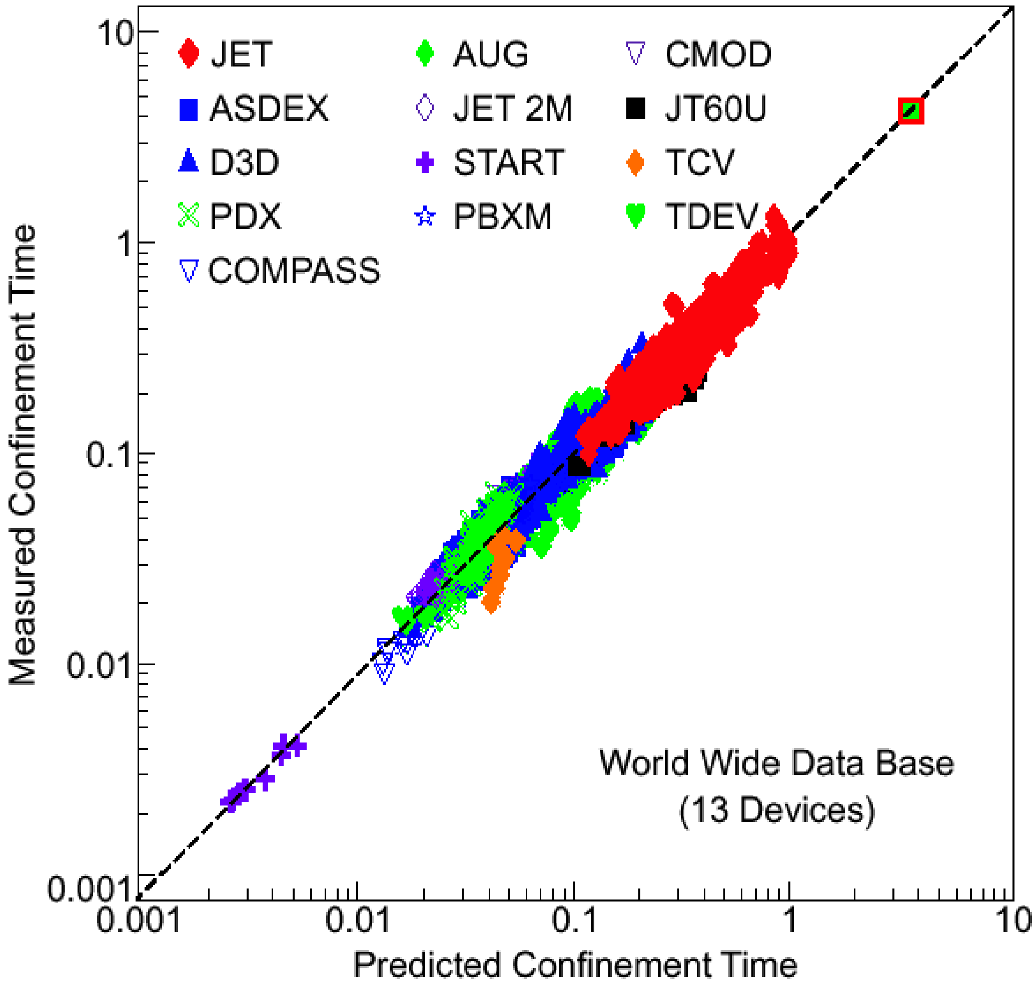
- Confinement time is the characteristic cooling time

  τ = Stored thermal energy / Heating power
- Depends on plasma current and radius as $\tau = c I_p R^2$
- Required condition for ignition is the triple product

  $n\, T\, \tau \geq 10^{21}$ keV s / m^3
- Not reached in any experiment so far
- Experimental confinement time scaling

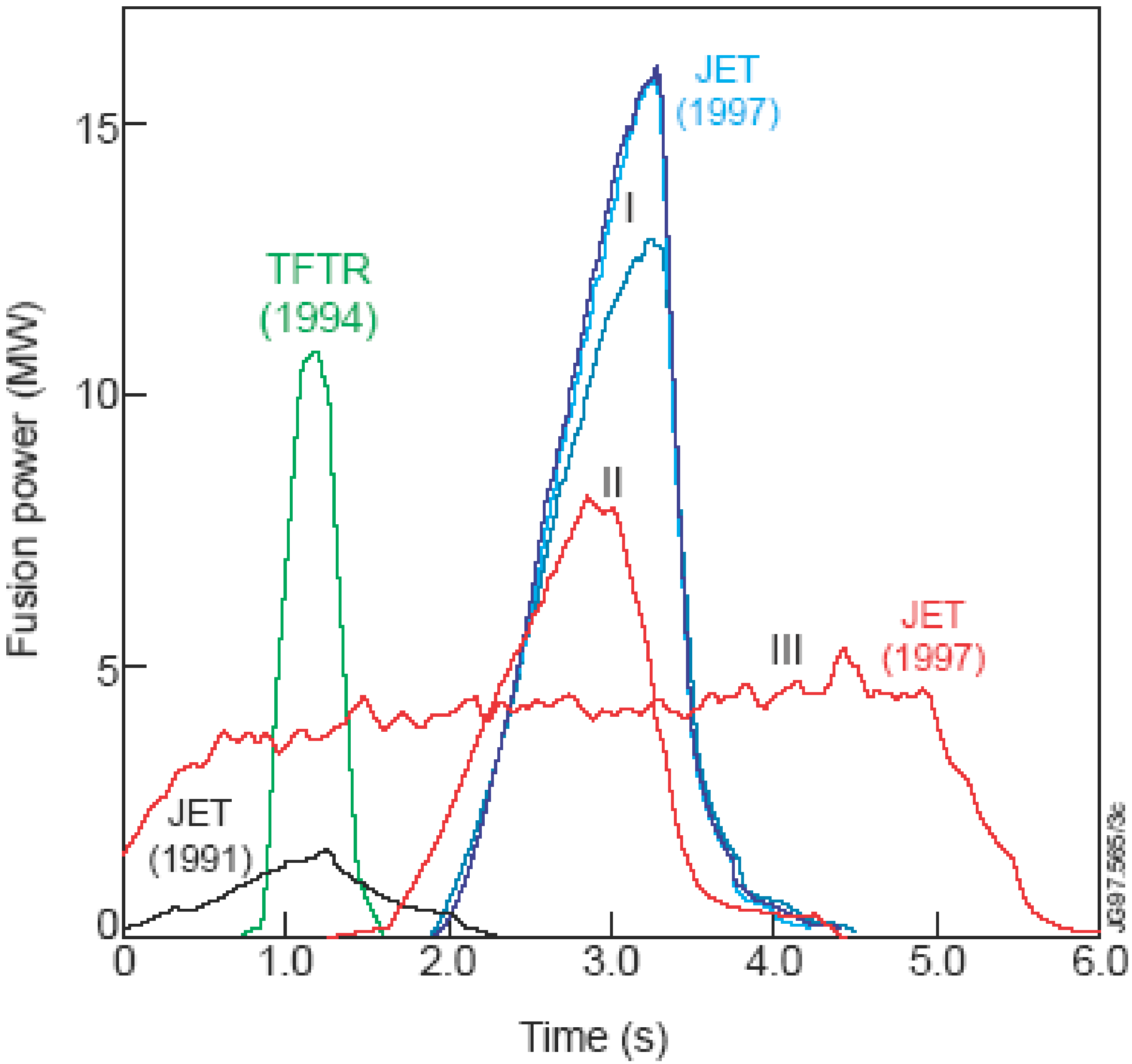
$$\tau_{exp} = 0.0562\, H\, I_p^{0.93}\, B_T^{0.15}\, P^{-0.69}\, n_e^{0.41}\, M^{0.19}\, R^{1.97}\, \varepsilon^{0.58}\, K_a^{0.78}$$

Plasma confinement scaling



The ITER design is based upon extrapolation from earlier experiments

Fusion power generation



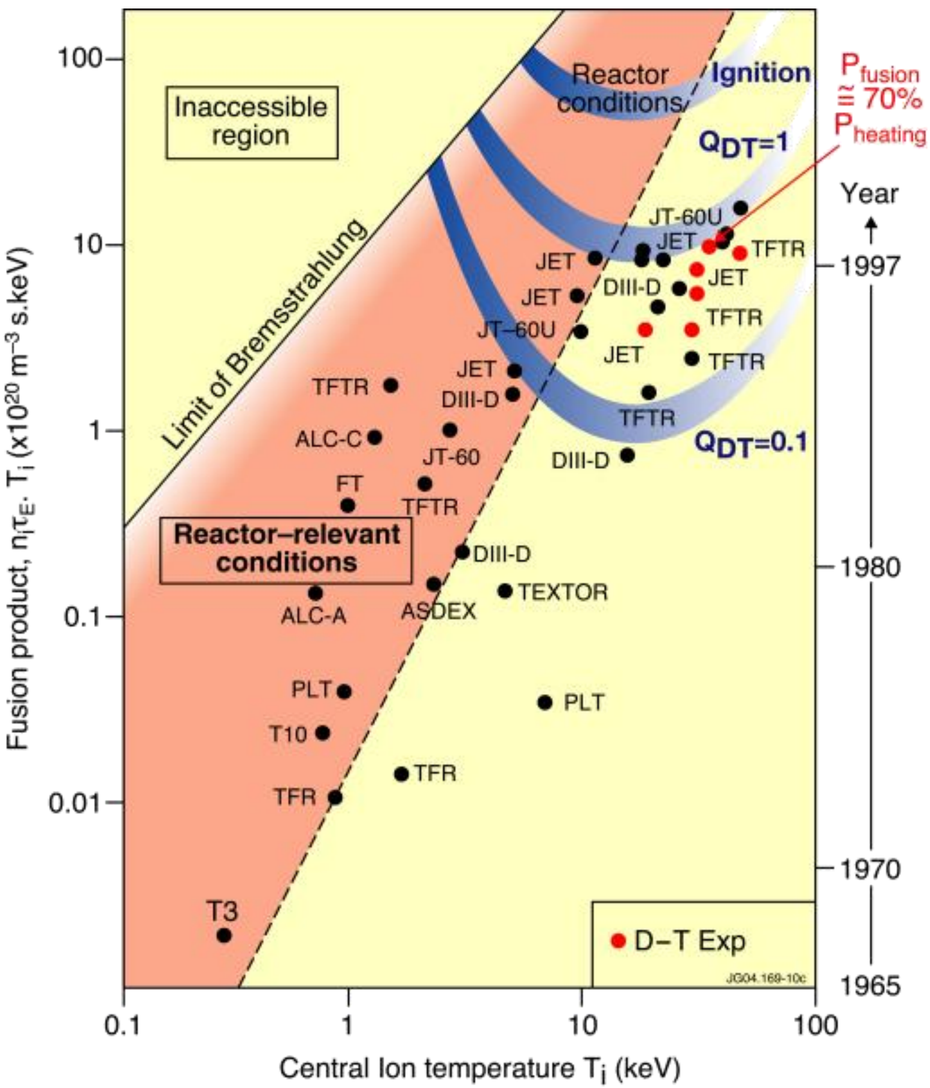
JET 1991: first controlled DT fusion experiments on Earth producing 1.7 MW of fusion power

TFTR 1994: produced a new record of 11.5 MW fusion power

JET 1997: standing record of 16 MW with Q=0.65, significant alpha heating was observed

JET 1997: sustained fusion power production in ITER scenario

Fusion triple products in experiments



- Highest triple product reached in D-T experiments
- Foreseen parameter domain has been covered
- Dominant heating by fusion alphas has been observed

Future fusion research

Nuclear fusion reactor technology

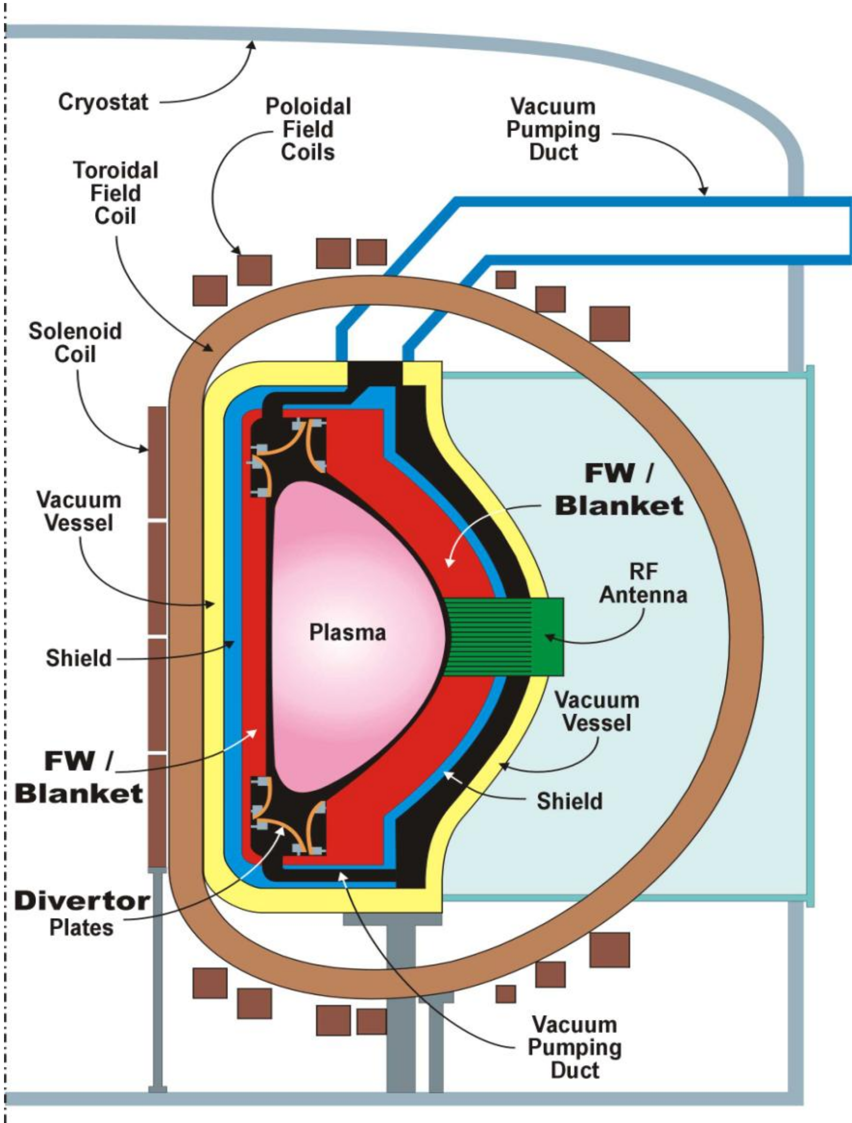
Superconducting magnetic field coils

Entire reactor embedded in a cryostat

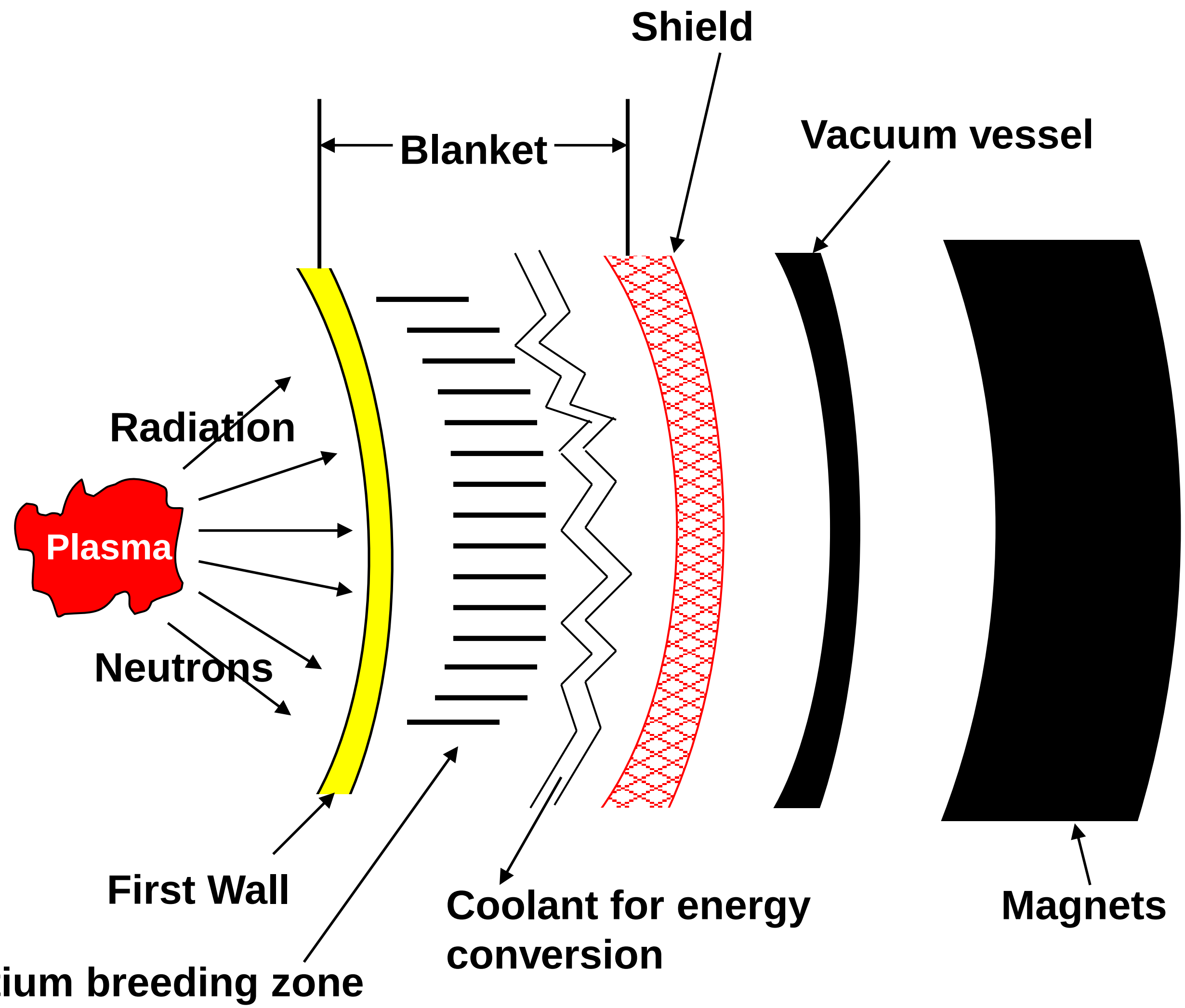
Electromagnetic wave heating

Divertor and limiter surfaces

Lithium blanket for tritium breeding



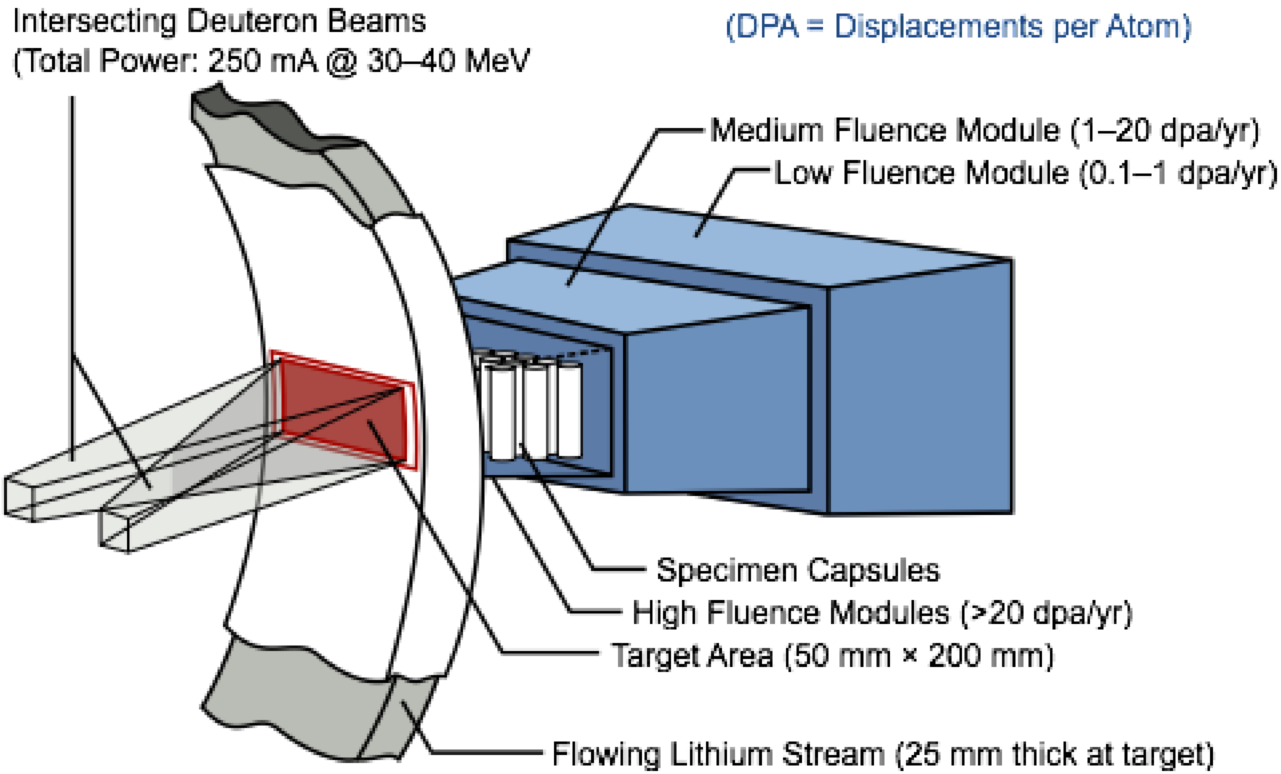
Components from plasma to coils



IFMIF

- International Fusion Materials Irradiation Facility
- Research program designed to test materials for suitability for use in a fusion reactor
- Will use a particle accelerator-based neutron source to produce a large neutron flux
- Test the long-term behavior of materials under conditions similar to those expected at the inner wall of a fusion reactor
- This will help the development of radiation resistant and low activation materials for use in reactors
- Expected costs of will be about €800 million

International Fusion Materials Irradiation Facility



€800M

The IFMIF will consist of two parallel 50m long accelerators producing beams of D. On contact with a lithium target, these will be converted into high-energy neutrons and used to irradiate material test components.

ITER — the way

Design completed in 2001

Decided on June 28, 2005

- EU host, localized in France

Contract signed Nov 21, 2006

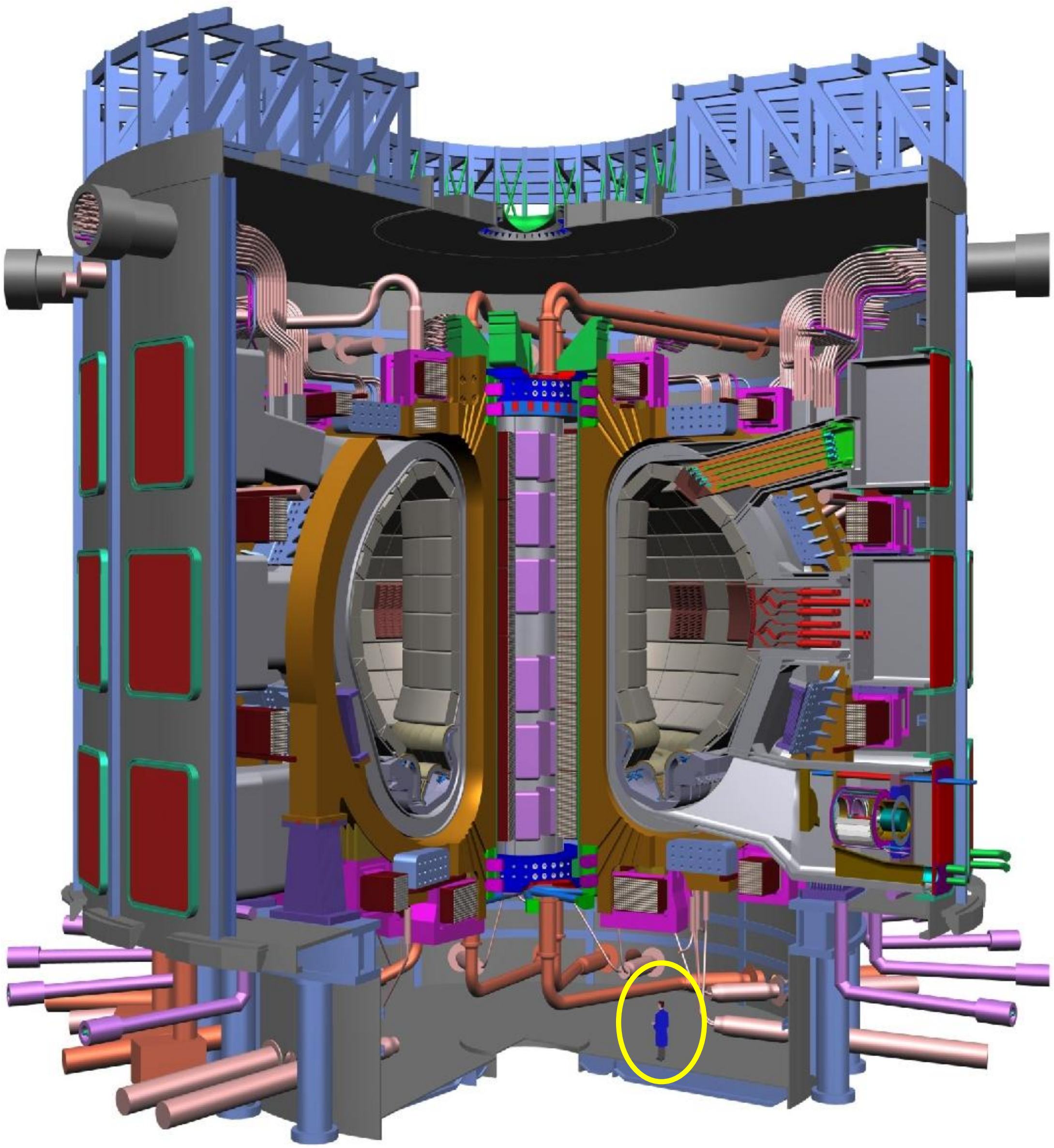
- 7 parties

Construction

- 10 years
- First contracts 2007
- Operation by 20~~16~~ ~~18~~ 20 …

Estimated total cost

- USD 10 billion = 50 IWD

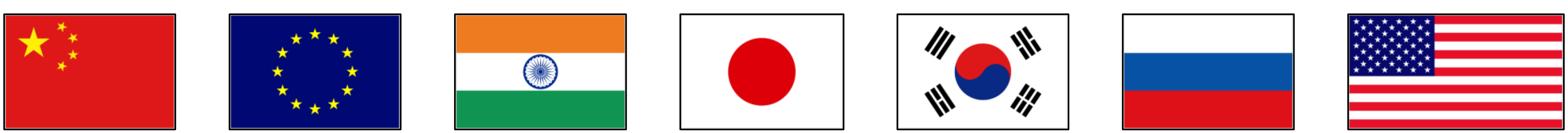


The 7 ITER parties

ITER is a scientific and technological endeavor by

- European Union
- Japan
- People's Republic of China
- India
- Republic of Korea
- Russian Federation
- United States of America

Representing more than half the world's population



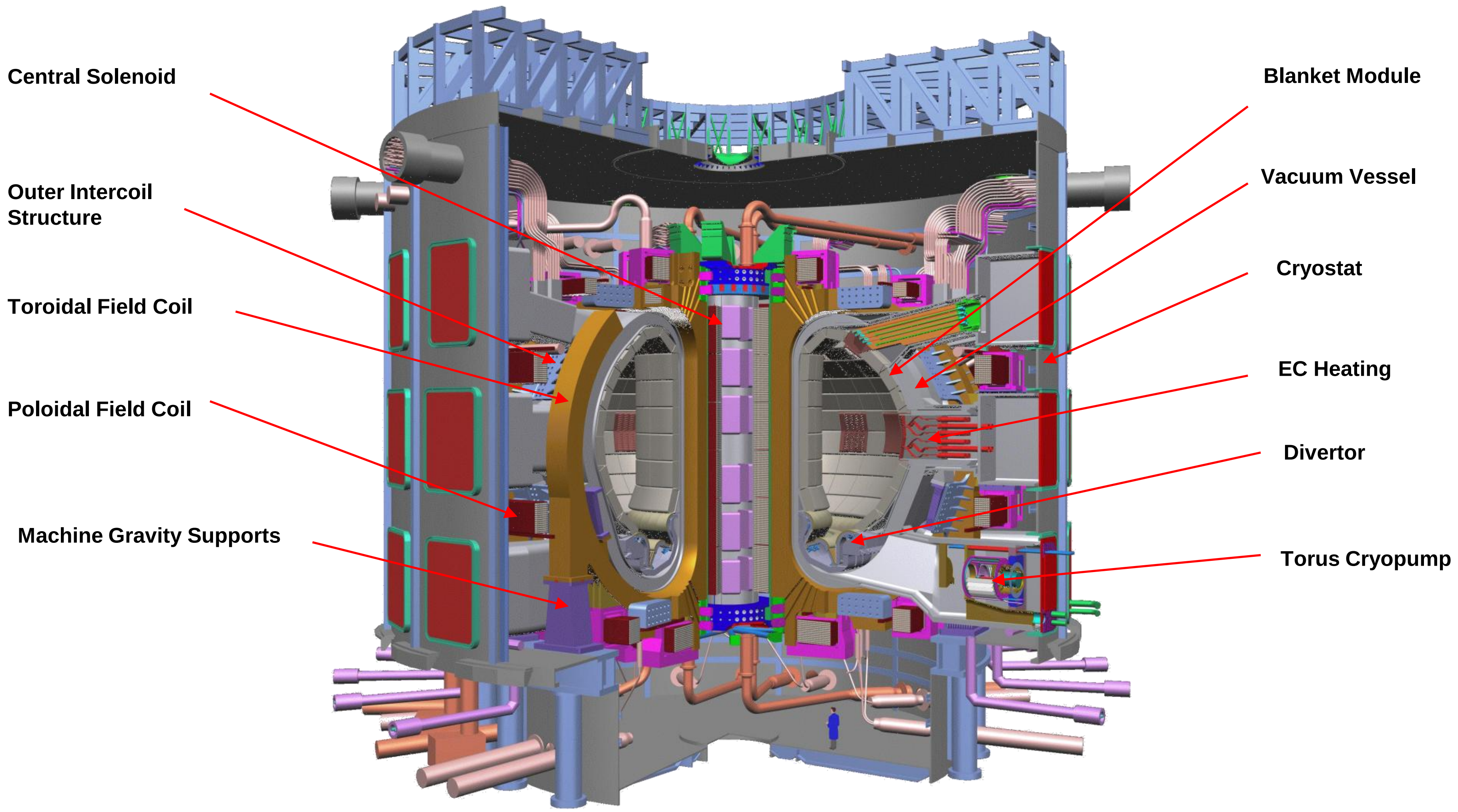
ITER location at Cadarache, France

Construction of the first building…

ITER parameters

• Plasma minor radius	2 m
• Plasma major radius	6.2 m
• Plasma surface	678 m^2
• Plasma volume	837 m^3
• Inductive plasma current	15 MA
• Toroidal magnetic field	5.3 T
• Auxiliary heating	73 MW

ITER parts


Central Solenoid
Outer Intercoil Structure
Toroidal Field Coil
Poloidal Field Coil
Machine Gravity Supports
Blanket Module
Vacuum Vessel
Cryostat
EC Heating
Divertor
Torus Cryopump

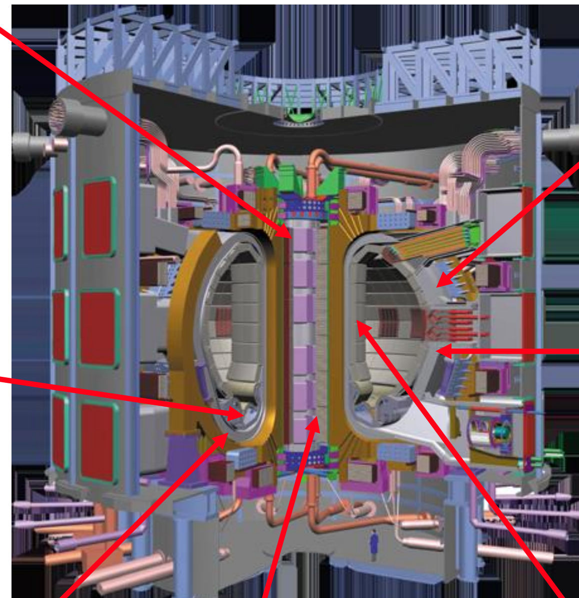
Technology for ITER

CENTRAL SOLENOID MODEL COIL

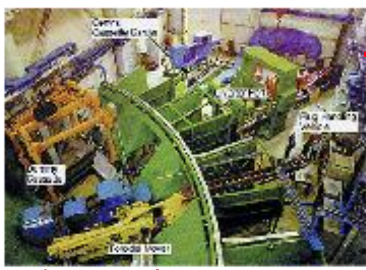
Radius 3.5 m
Height 2.8m
B_{max}=13 T
W = 640 MJ
0.6 T/sec

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/m², CFC/W

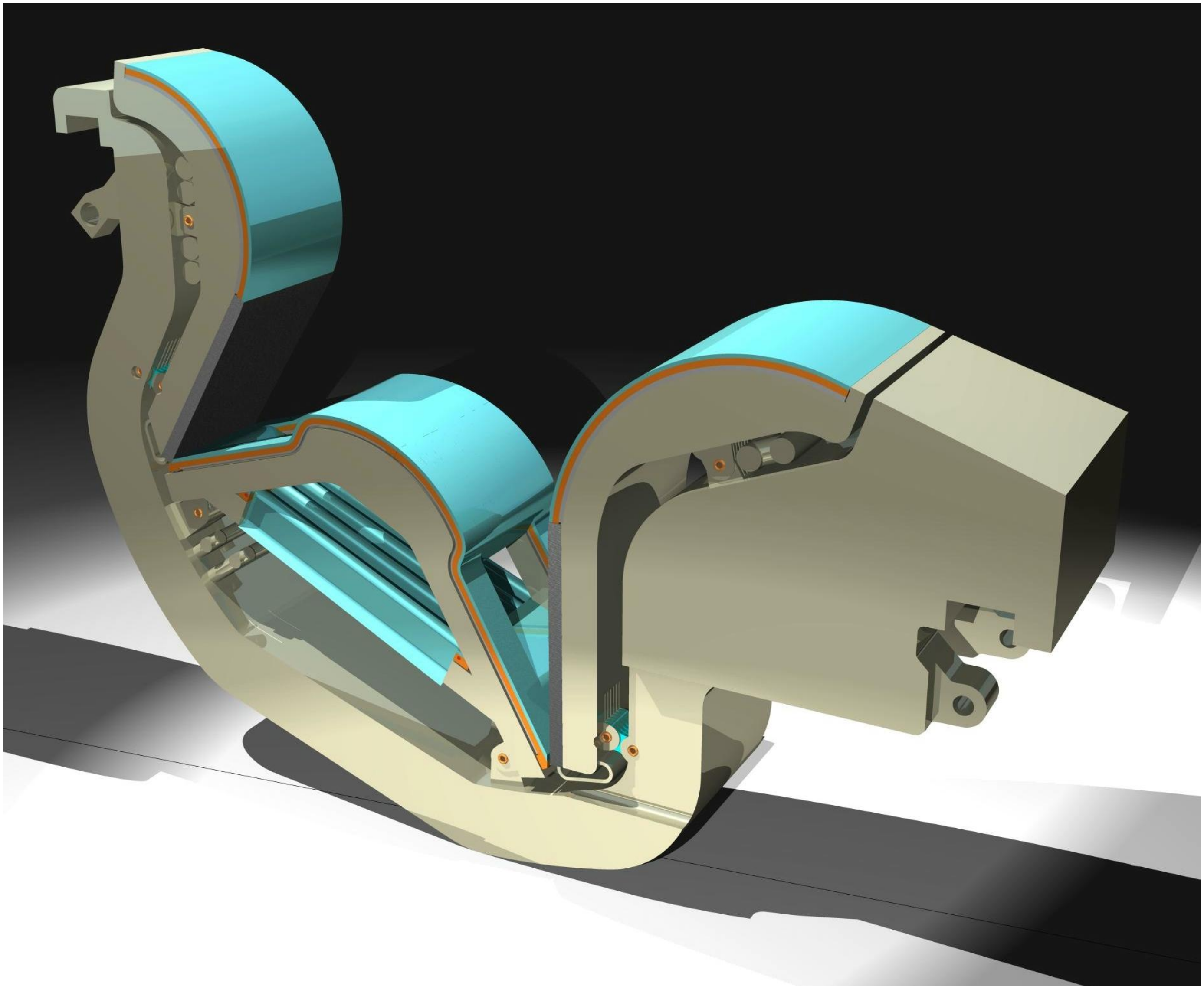
TOROIDAL FIELD MODEL COIL

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

REMOTE MAINTENANCE OF BLANKET

4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

ITER divertor cassette



ITER technical objectives

- Inductive plasma burn with $Q \geq 10$
- Steady-state operation with $Q > 5$
- Integrate technologies essential for fusion reactors
  - e.g., superconducting magnets, remote maintenance
- Test components for a future reactor
  - e.g., divertor and torus vacuum pumps
- Test tritium breeding module concepts
- Inductive flat top capability of 300-500 sec
- Plasma heating dominated by alpha particles
- Average neutron flux > 0.5 MW/m^2

Summary for nuclear fusion power

Fusion of D og T in magnetically confined plasmas

- Abundant resources
- No atmospheric pollution
- Low radioactive burden

Tremendeous progress in physics and technology achieved

- Control of plasma-wall interactions
- Auxiliary heating and real time control

Next generation experiment will demonstrate fesability

- Power of 500 MW with puls duration up to 400 sec
- Power amplification factor Q = 10, lithium breeding, …

Alternative fusion concepts are also under development

Fusion research at UiT

- Three research groups from 2011/01/01
  - Electrical engineering
  - Space physics
  - Energy and climate
- Fusion plasma physics
  - At present one permanent position
  - Nominated for 2010 Nuclear Fusion Award
  - Specialized on turbulent transport of particles and heat
  - Strong connection to space plasma physics

More information

- www.iter.org
- www.efda.org
- en.wikipedia.org/wiki/Fusion_power