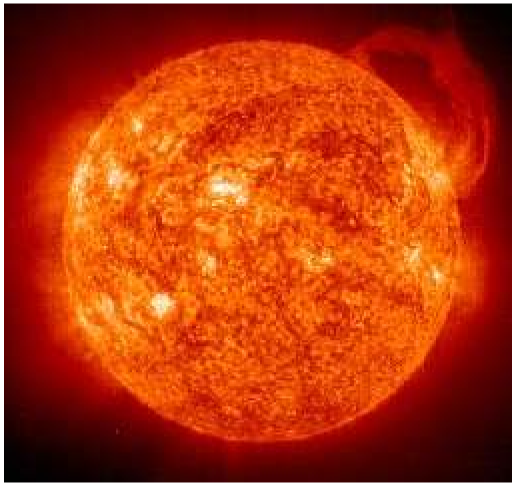
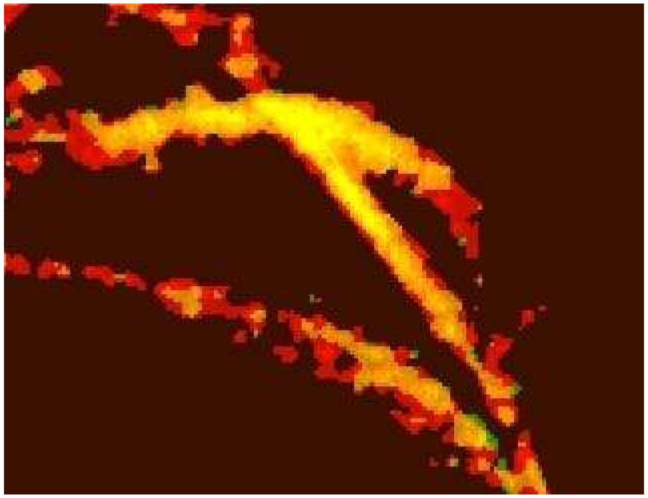
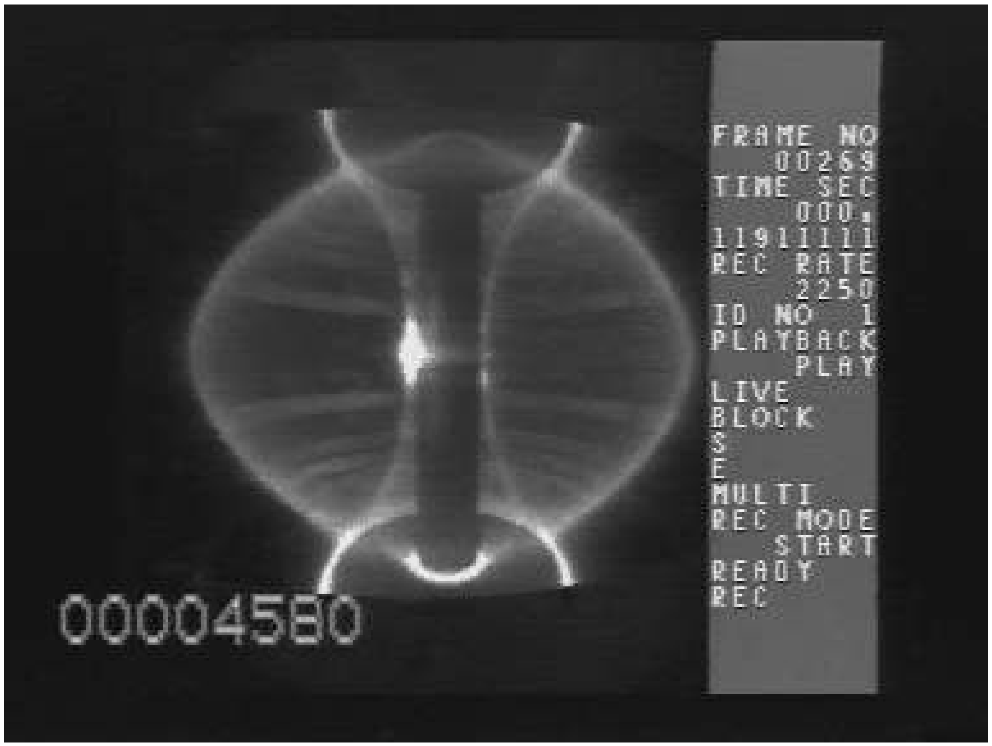
Nuclear Fusion:
on earth as it is in the heavens?

Presented by Andrew Kirk
UKAEA Fusion

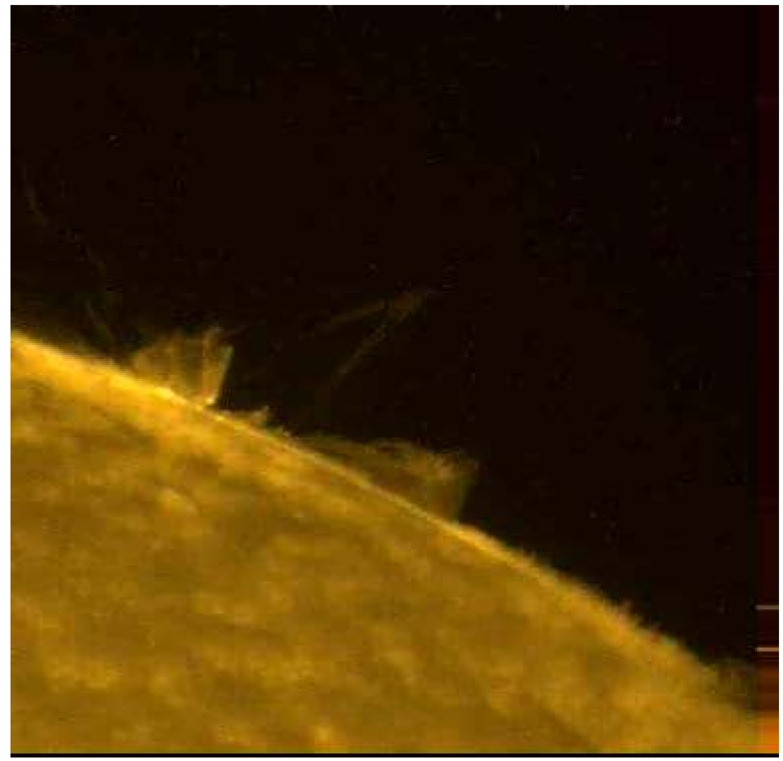




What may these two processes have in common?



ELMs on MAST τ~100 μs



Solar flares τ >10 000 s

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Outline

- The need for new energy resources

- What is nuclear fusion and how can it help

- Magnetically confined nuclear fusion

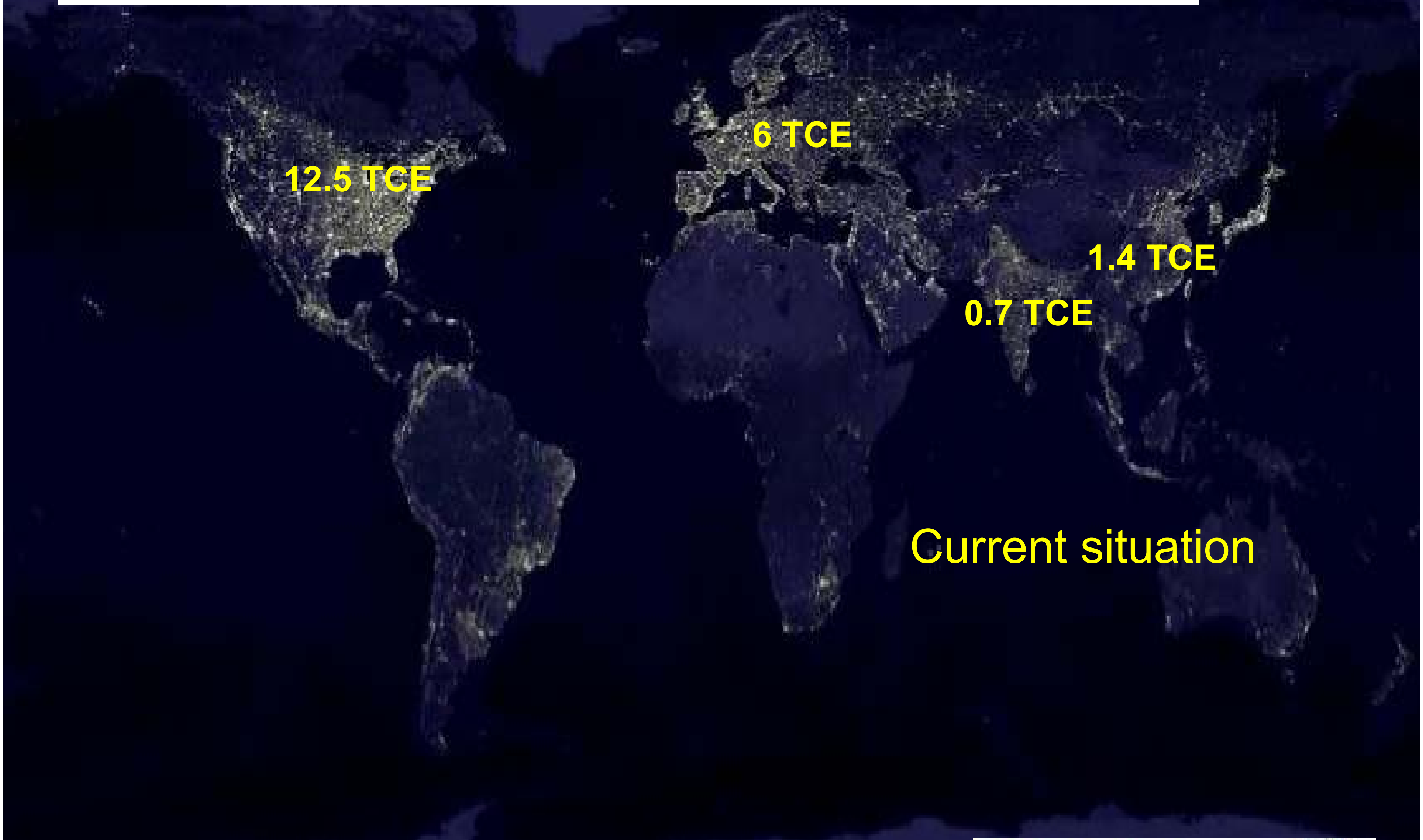
    - How does a Tokamak work?

- Some of the challenges - Plasma instabilities

- Next step devices and future power plants

The need for new energy sources

The rapid growth in global energy demand



Present annual consumption / person

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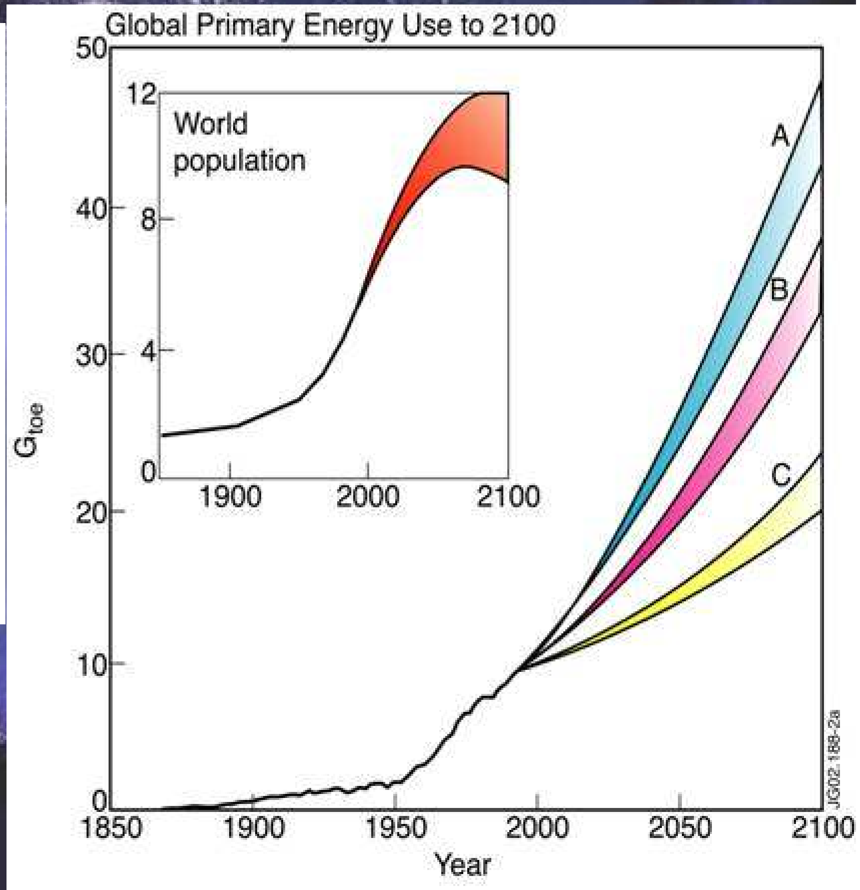
The rapid growth in global energy demand

- Population increase
- Growing industrialisation
  - China, India
- 2-5 fold rise in energy demand predicted in 2100



Energy production has to increase!

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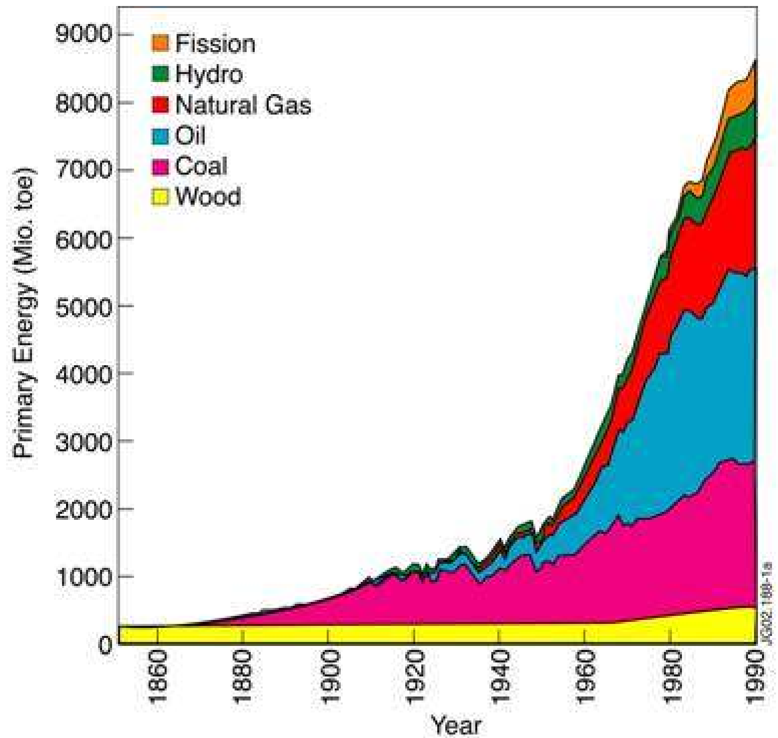
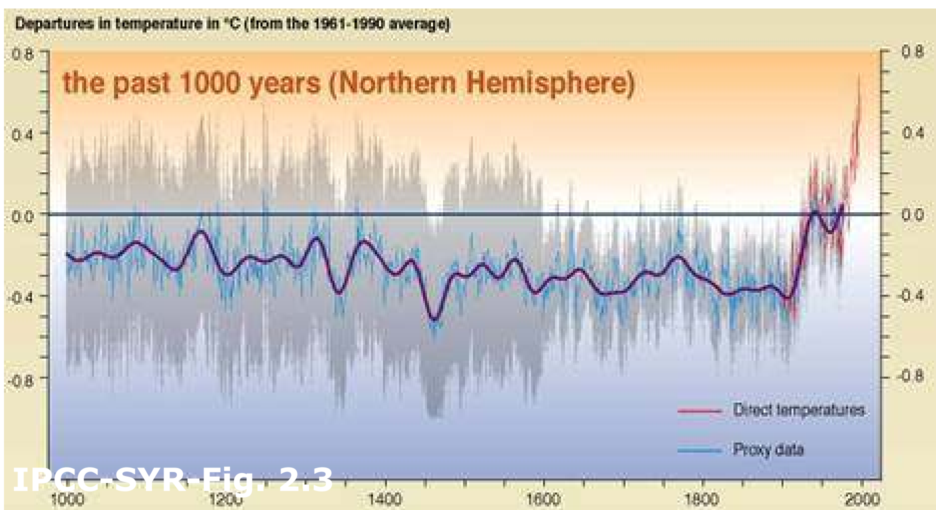
We can't rely on fossil fuels

- Fossil fuels are formed over million of years.
- Conventional oil and gas production will peak in about 15 years.
- World total hydrocarbon shortage perhaps as early as 2010
- CO_2 emission contributes to global warming





New clean sources are needed

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Renewable sources are attractive but…

- Low energy density.
- Fluctuations require storage system or back-up production.

- Photovoltaic, wind, and water power offer
  - Long term solution
  - Clean production

Nuclear fission produces no CO_2 but…

- Long lived radioactive waste
  - Public concern about safety.

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Nuclear fusion would help to solve the problem

- High energy density.
  - Of the order of 1GW
- Clean
  - No CO_2 production
  - No long lived radioactive waste.
- Constant power source.
- Virtually unlimited resources
  - More than 10000 years on earth.

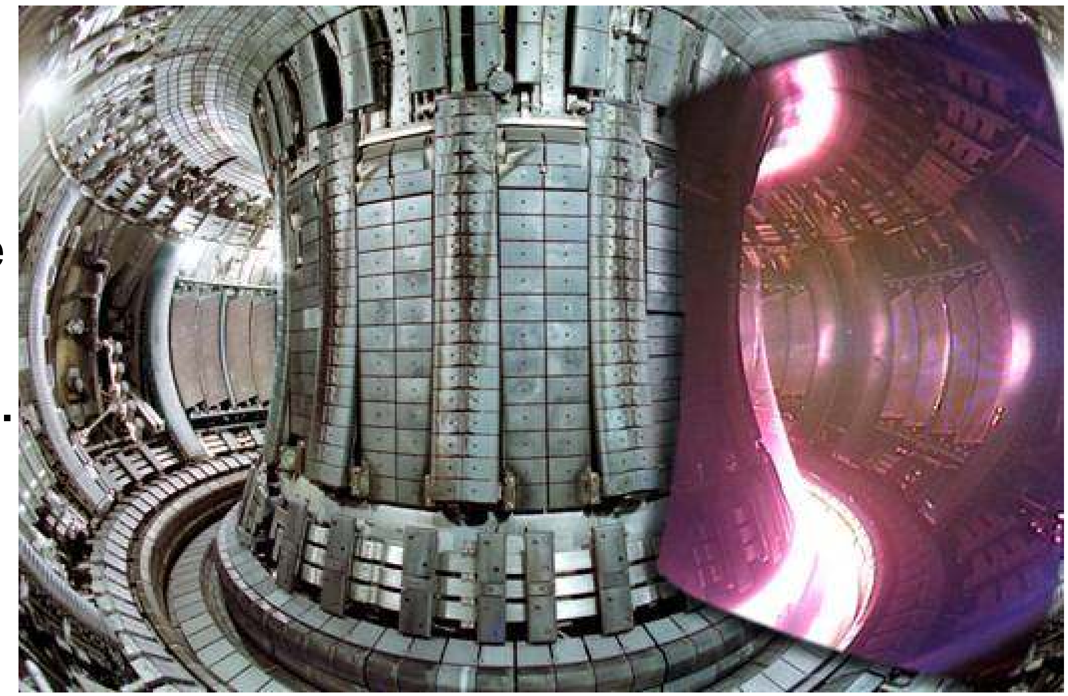
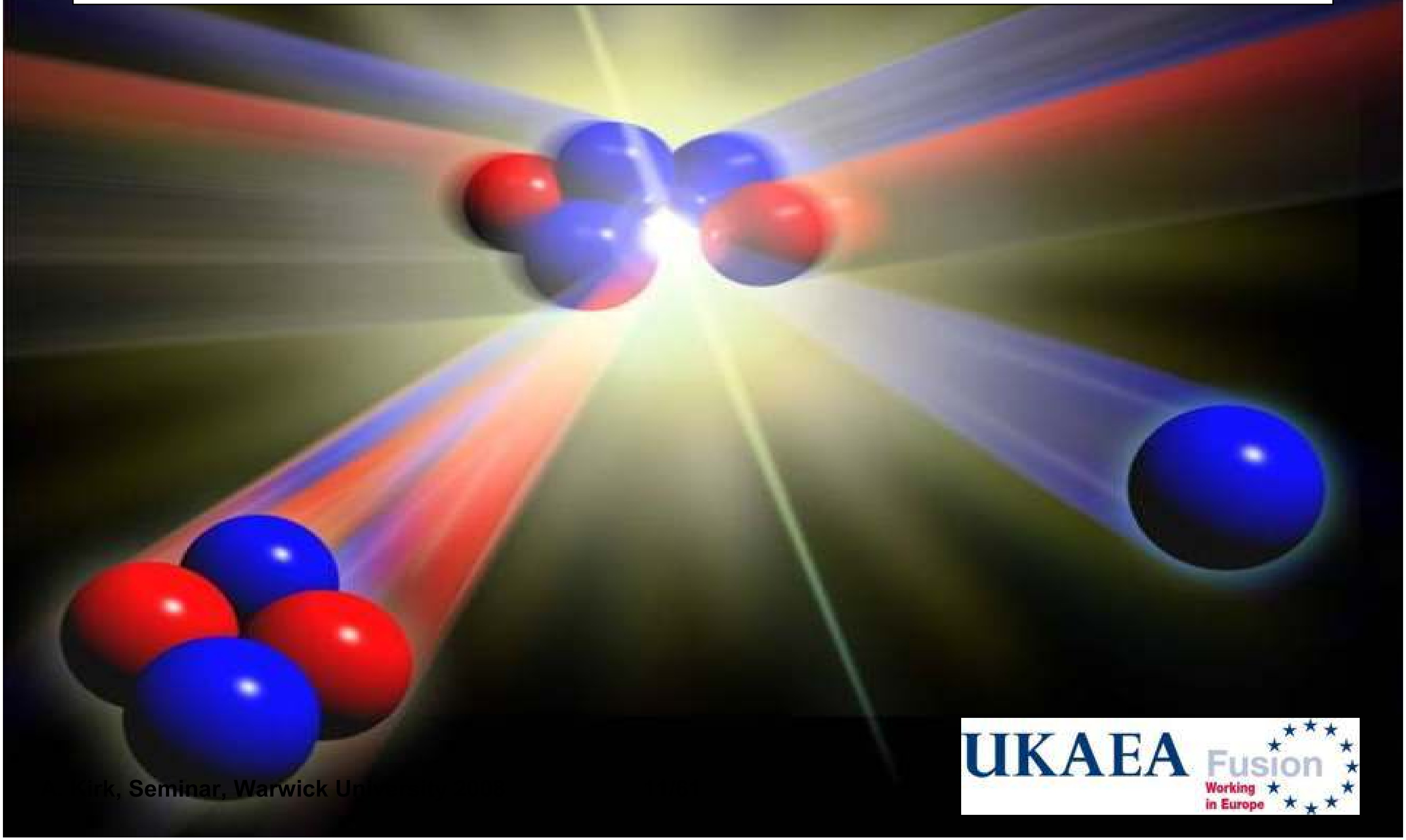
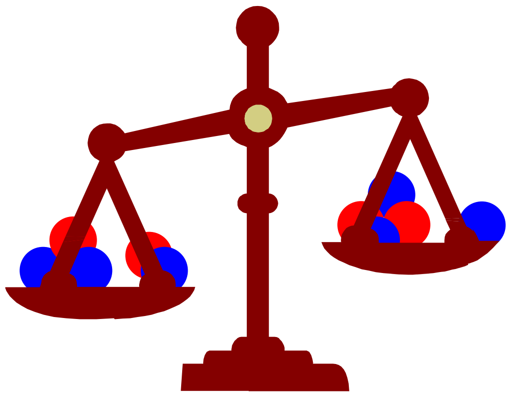


Photo: EFDA-JET

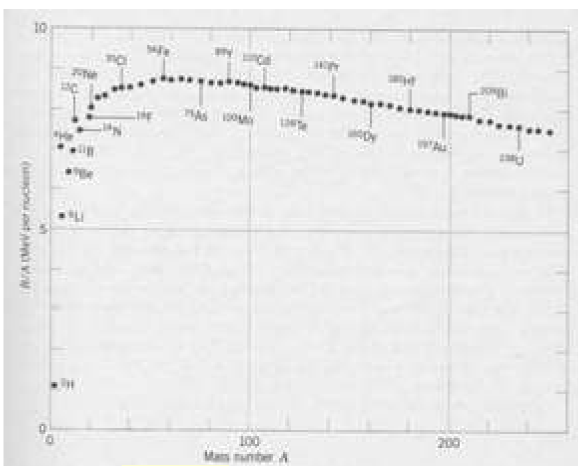
How does fusion work?



$E=mc^2$



- Two Light nuclei fuse and form a new nuclei
- The new nuclei has less mass than the initial two nuclei – the missing mass is released as energy



The binding energy per nucleon.

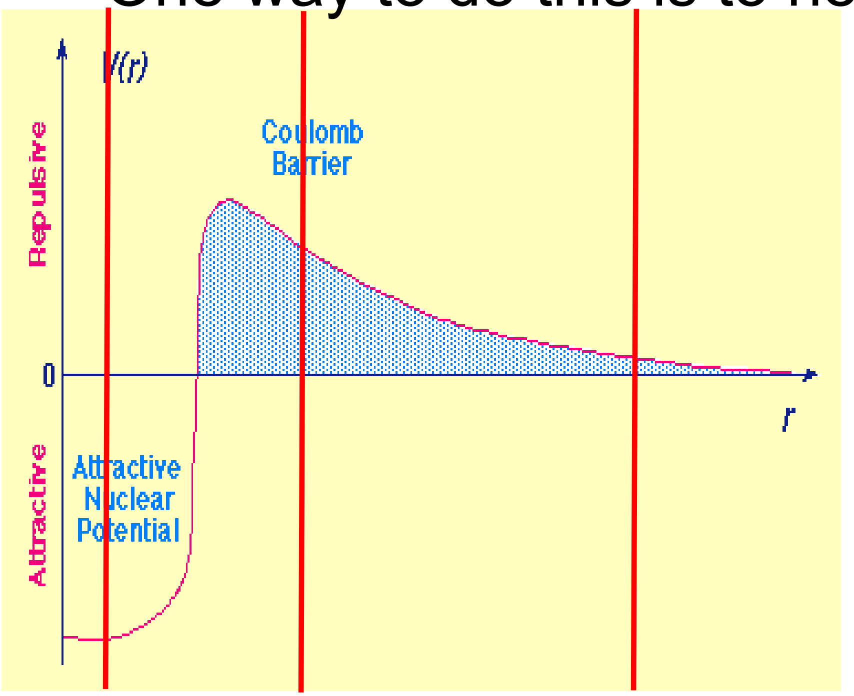
This process fuels the stars

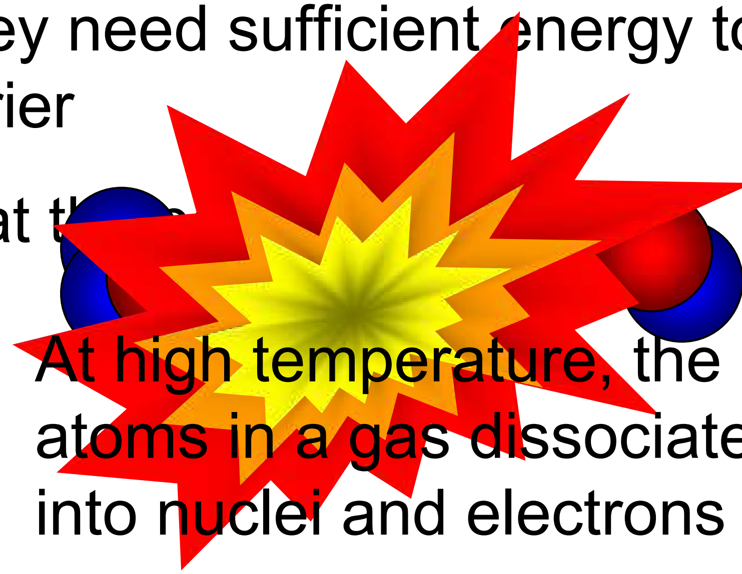
And in principle is possible with nuclei up to Iron

Overcoming particles natural repulsion

In order to make the nuclei fuse we need to bring them close enough together – they need sufficient energy to overcome the coulomb barrier

One way to do this is to heat t





At high temperature, the atoms in a gas dissociate into nuclei and electrons

As the temperature is increased the nuclei fuse

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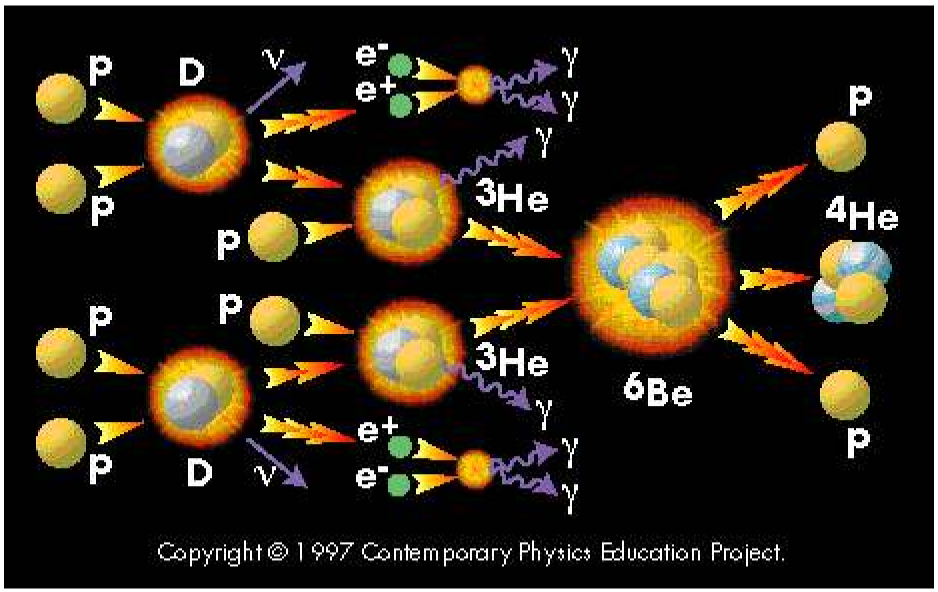
The process in the sun is too slow

The sun:

$$4p + 2e^- \rightarrow {}^4He + 2\nu_e + 6\gamma$$



This process is governed by the weak force
– is slow and inefficient

1m^3 of the sun produces 30 W

The sun works because it is big

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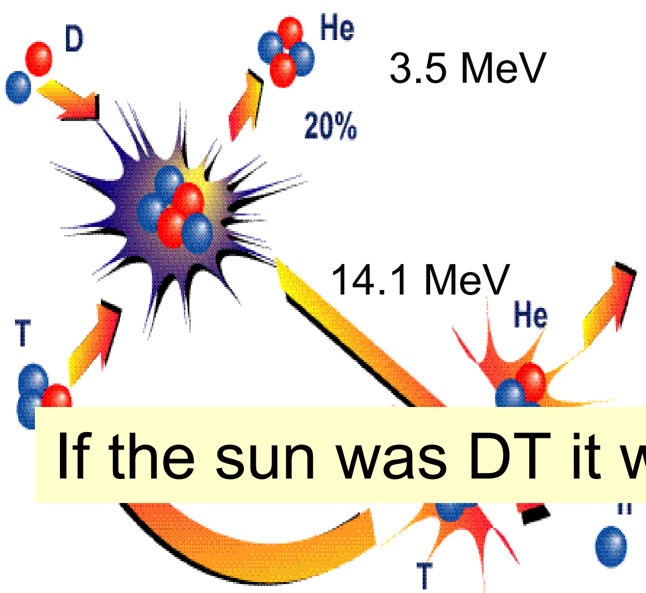
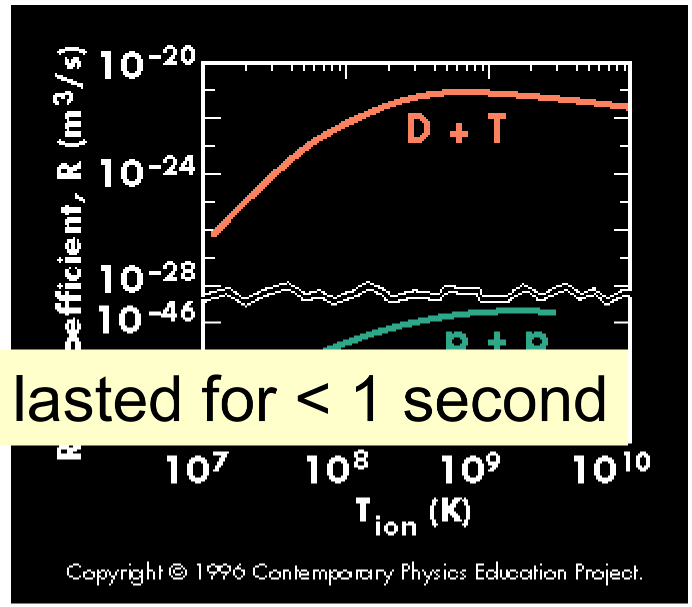
The DT reaction is much more efficient





If the sun was DT it would have lasted for < 1 second

Strong reaction-> faster rate

d + t $\rightarrow$ 4He + n
Need to breed tritium from Li.
α-particles (4He+) heat the plasma

Need higher temperatures
To work ~ 100 million degrees

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How much fuel is needed?

- A power plant is expected to generate 3GW of fusion power for 1 GW electrical power.
- Uses 1 kg of fuel per day (cf. 10 000 tons of coal)
- Total fuel content at any time approximately 0.1 g

The D from half a *tub full of water* (250 l) and the T (15g) produced from the *Li contained in a laptop battery* (30g) accounts for the fuel needed to supply the *life-time electricity needs of an average person* in an industrialised country!

How much fuel is needed?

 + 

Deuterium in ½ bath of water + Tritium obtainable from Li in a lap-top battery

The D from half a *tub full of water* (250 l) and the T (15g) produced from the *Li contained in a laptop battery* (30g) accounts for the fuel needed to supply the *life-time electricity needs of an average person* in an industrialised country!

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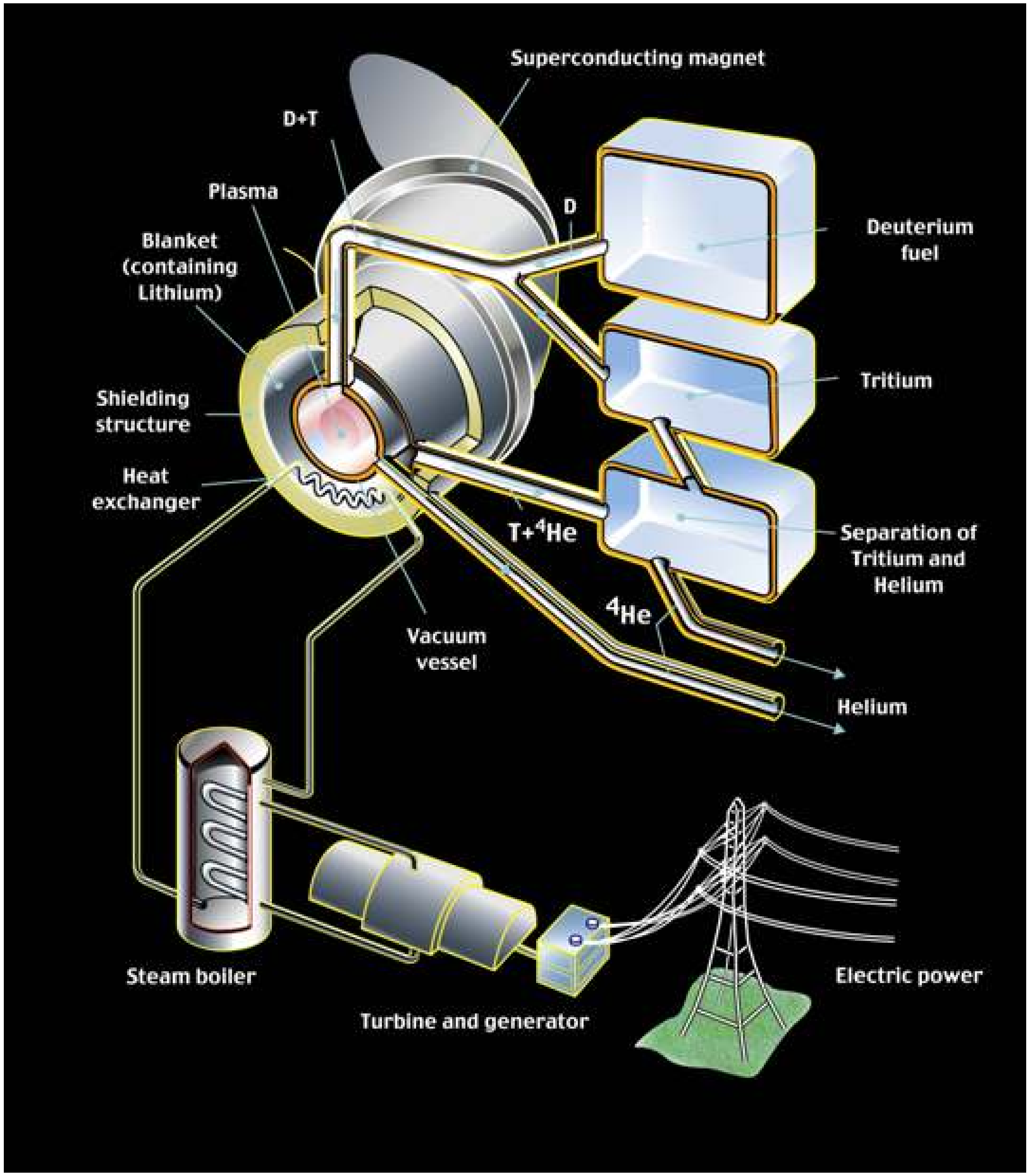
What would a DT power station look like?



Lithium blanket captures energetic neutrons from the fusion process and serves two purposes.

Boils water in a heat exchanger to produce steam to drive a generator.

The Lithium and neutron react to produce Tritium, one of the primary fuels in the fusion process.

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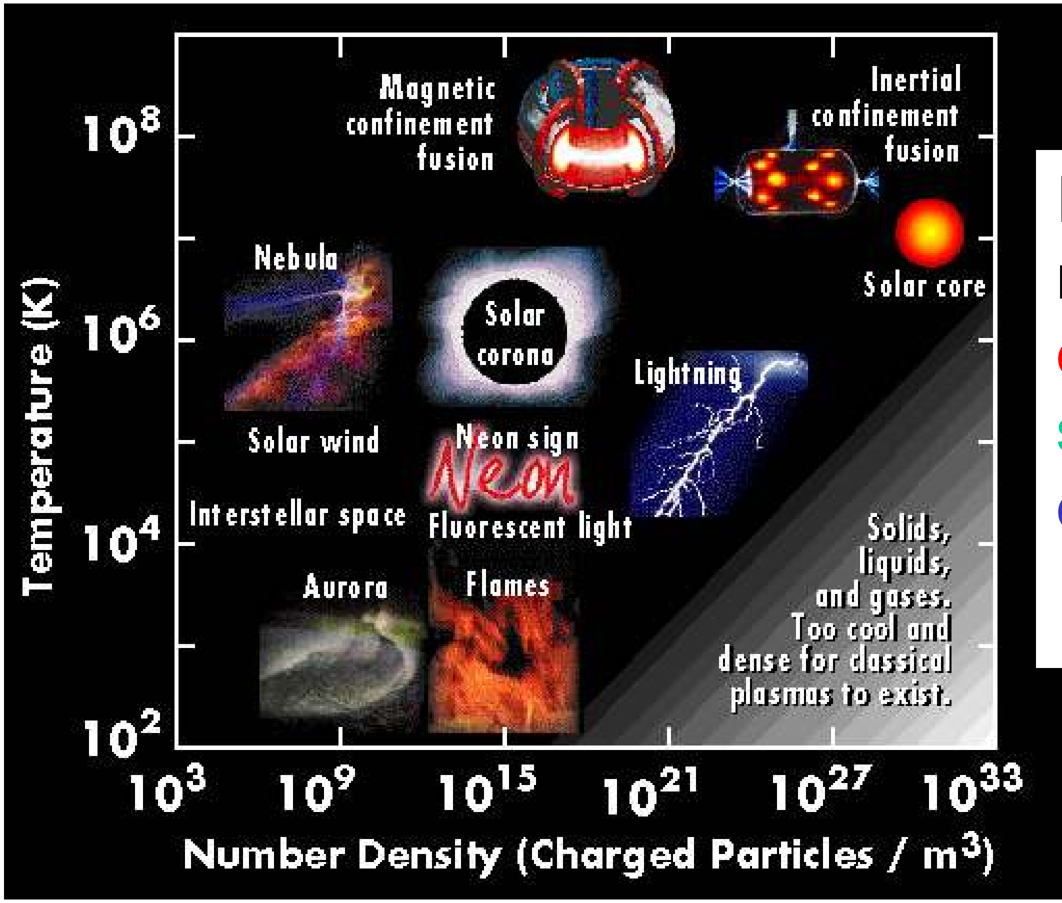
Making Fusion a reality



In order to make fusion a reality you need to confine enough particles with sufficient energy for a long enough period

The Lawson criteria

$$n \cdot T \cdot \tau_E > 3 \cdot 10^{21} \frac{\text{keVs}}{\text{m}^3}$$

10 keV < T_i < 100 keV (1 keV = 11600 K)

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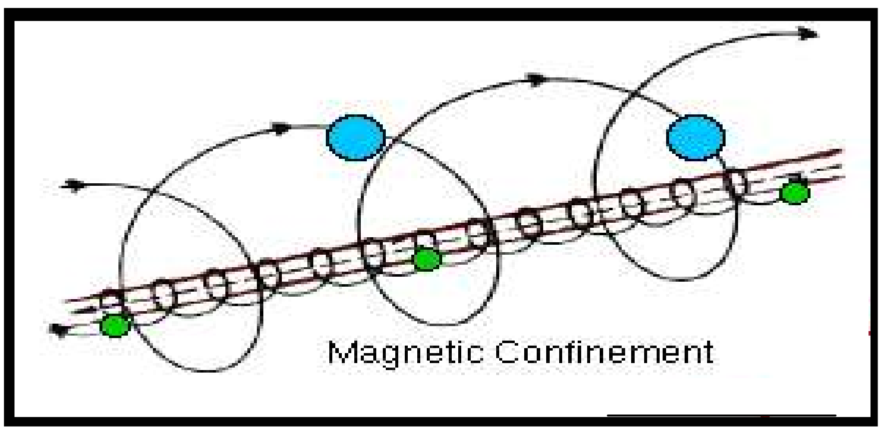
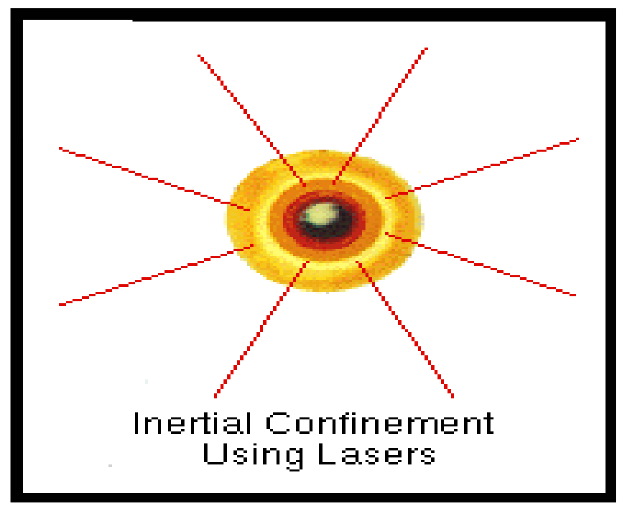
Confining the plasma

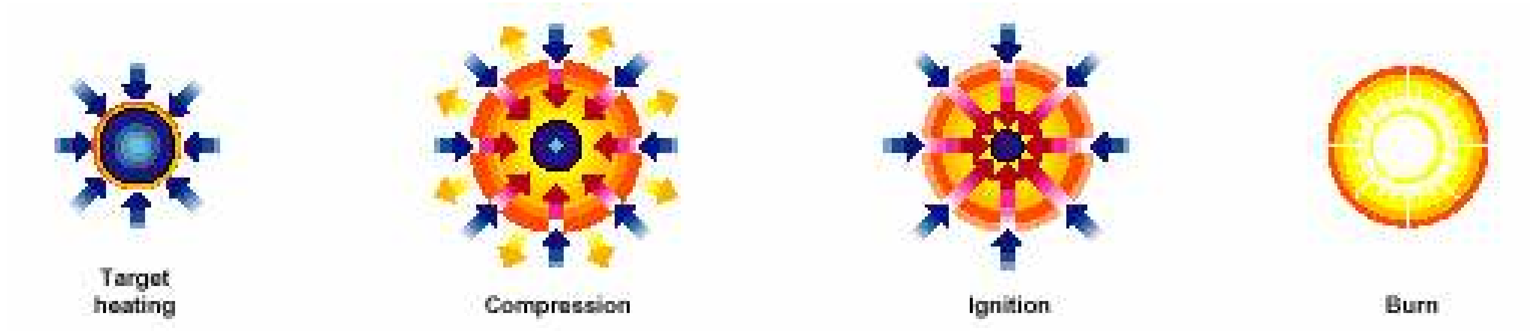
- Stars use gravity – not an option.
- Negative *and* positive charges can be confined by a magnetic field.
- If compressed fast enough the plasma can be confine by its own inertia.





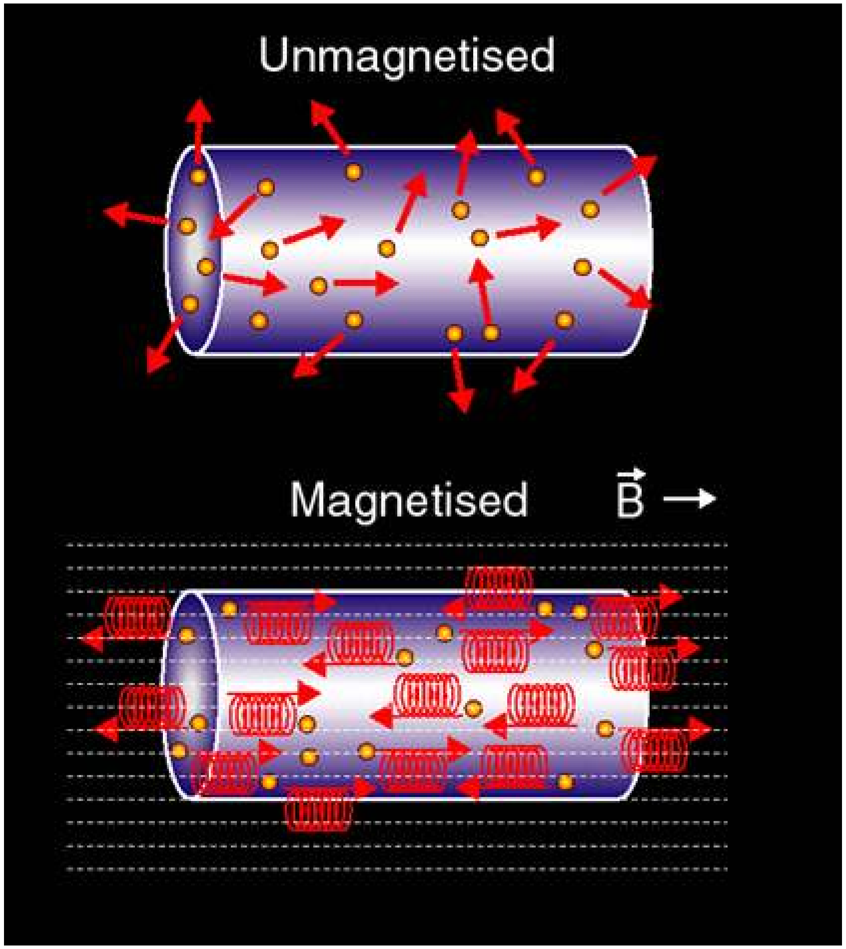
Inertial confinement – Laser fusion

- Small pellet of fuel is targeted by lasers or heavy ions.
- Heating ablates material, which compresses the target.
- The compression heats the fuel until fusion occurs.
- Economic power production needs a repetition rate of 5-10 Hz
- Main UK research done at RAL.



Magnetic confinement – the principle

- Charged particles gyrate around a field line.
  - Fast movement along the field line.
  - Slow diffusion across the field
- In a cylindrical system particles can escape at the ends
  $\Rightarrow$ toroidal symmetry.



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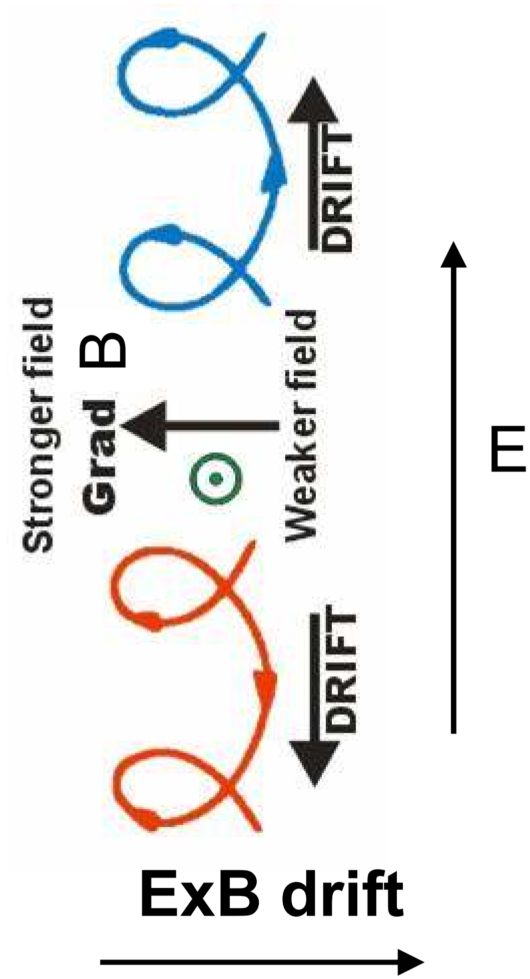
How to build a magnetic confinement device

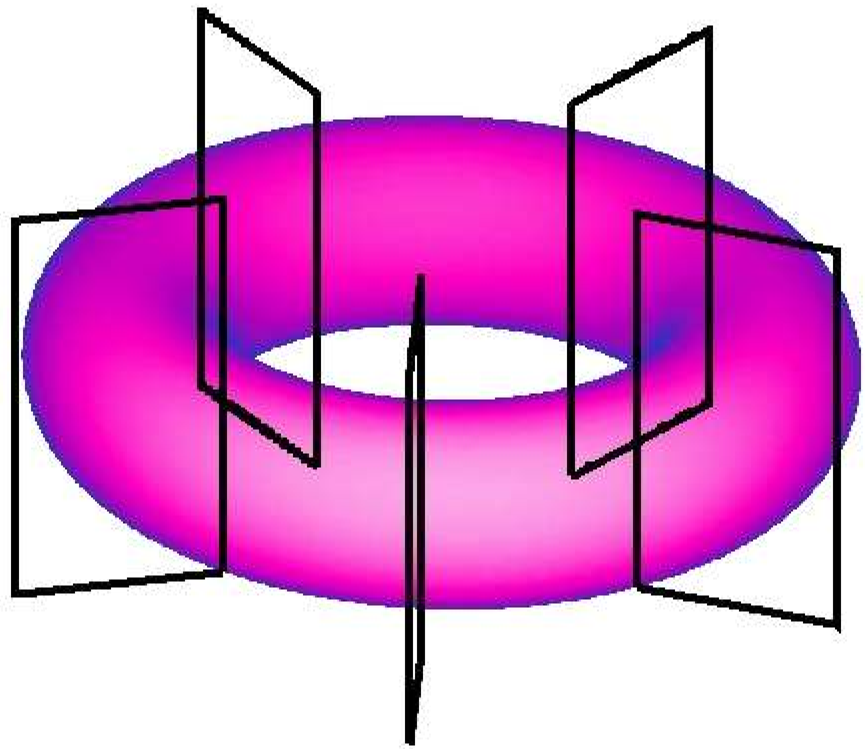
A magnetic bottle is not sufficient

Need a toroidal field to avoid end losses

A toroidal field is not enough

- Just toroidal B field





Other fields are needed

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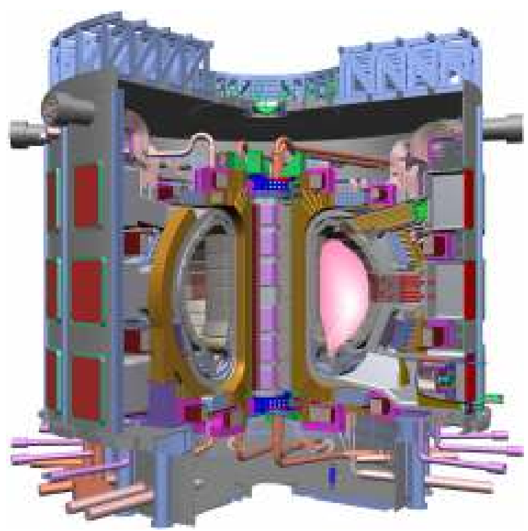
Two main concepts exist

TOKAMAK

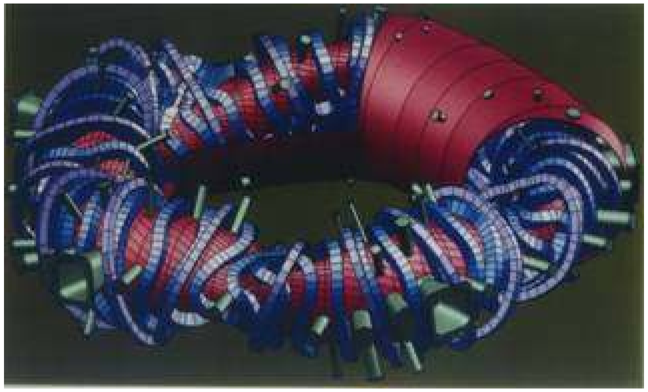
- Axisymmetric toroidal field.
- Current flowing in the plasma creates poloidal field.

ITER



Stellarator

- Field structure is produced by external coils only.
- No axisymmetry possible.



W7-X

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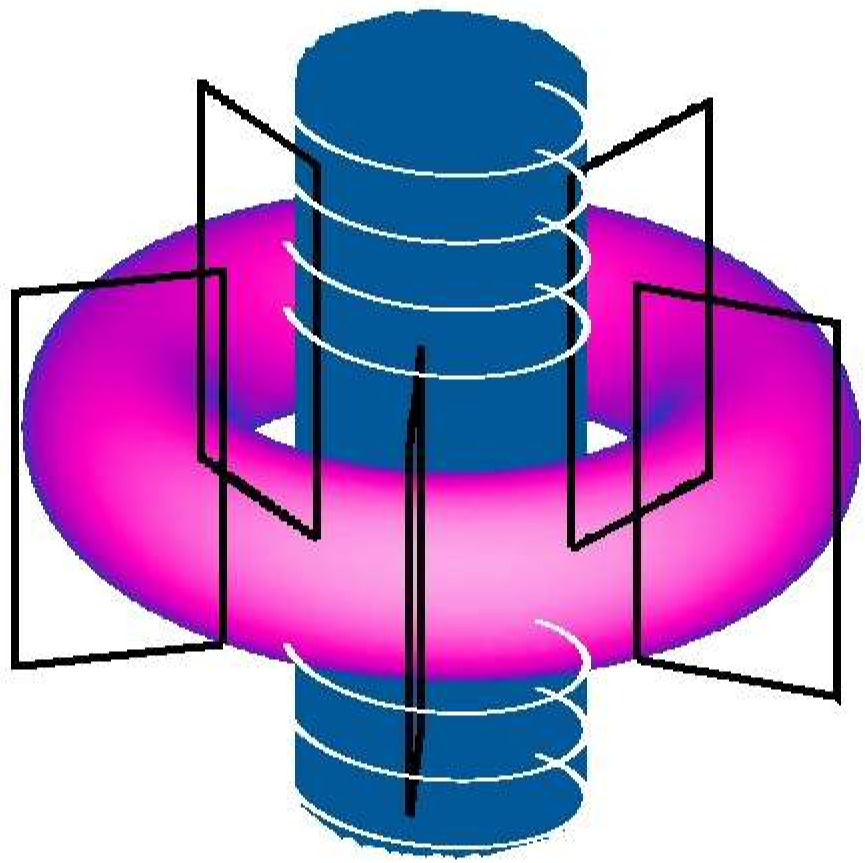
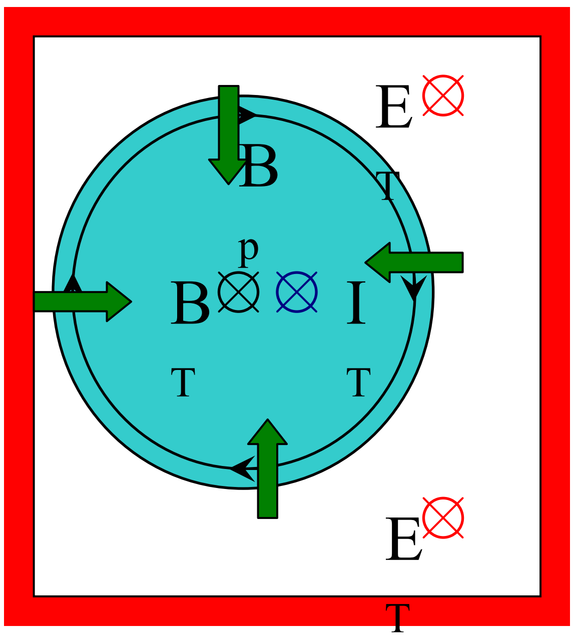
How a Tokamak works

- Initially just toroidal B field
- Induce toroidal E field

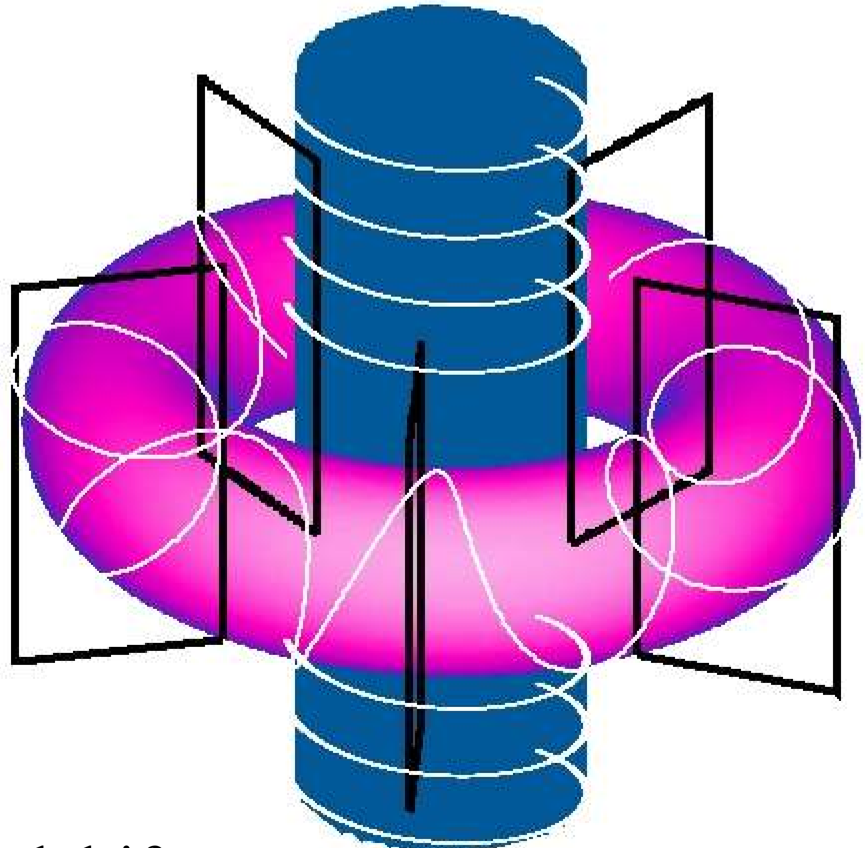


How a Tokamak works

- Initially just toroidal B field
- Induce toroidal E field
- Produces toroidal current
- Which results in a poloidal B field

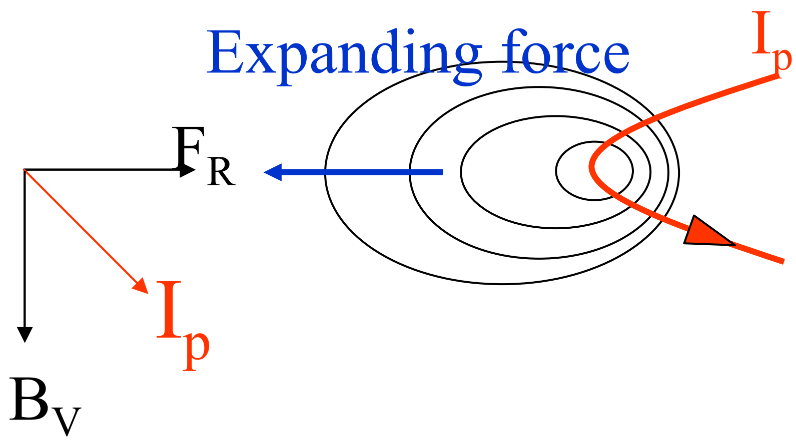


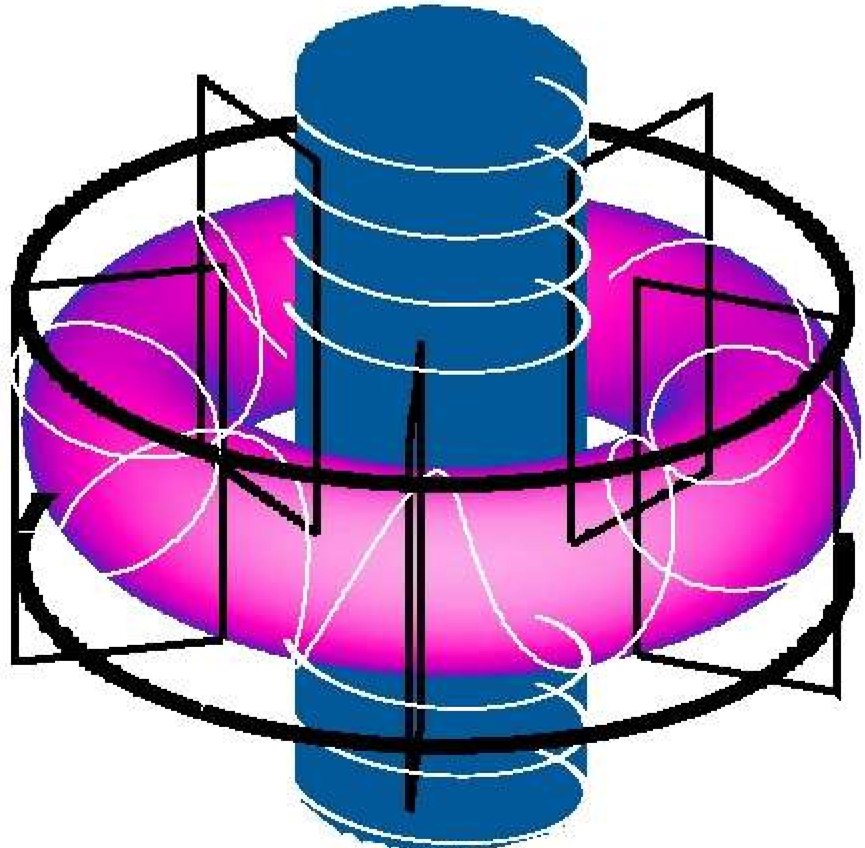
•ExB inward drift



How a Tokamak works

Plasma pressure





Need vertical field coils to control and shape the plasma

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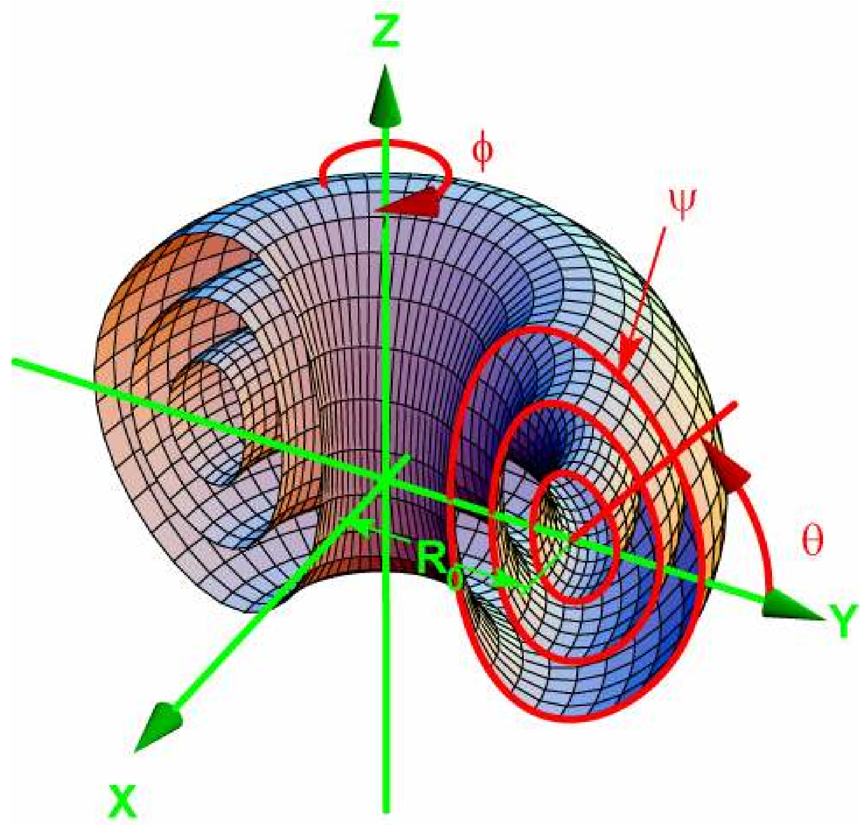
How a Tokamak works

- Magnetic field lines lie on closed flux surfaces.
- Equilibrium

$$\mathbf{j}\times\mathbf{B} = \nabla p$$

$$\mathbf{B}\cdot\nabla p = 0$$

The last closed flux surface defines the edge of the plasma where the plasma comes into contact with parts of the vacuum vessel



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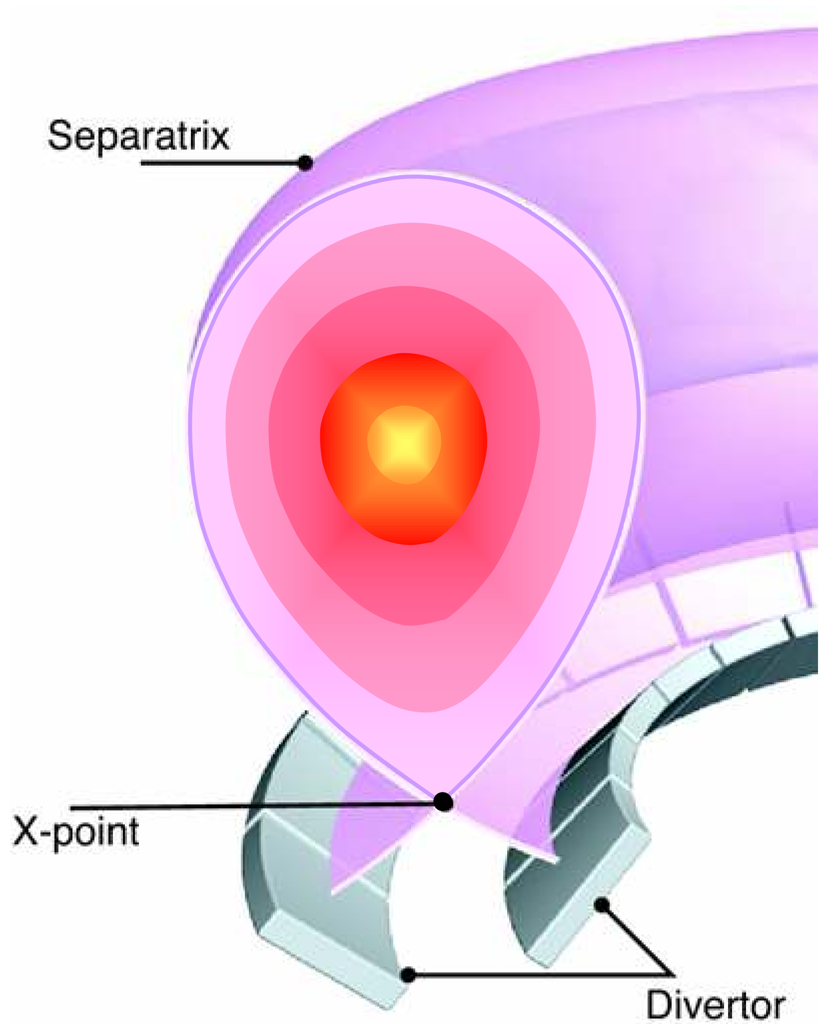
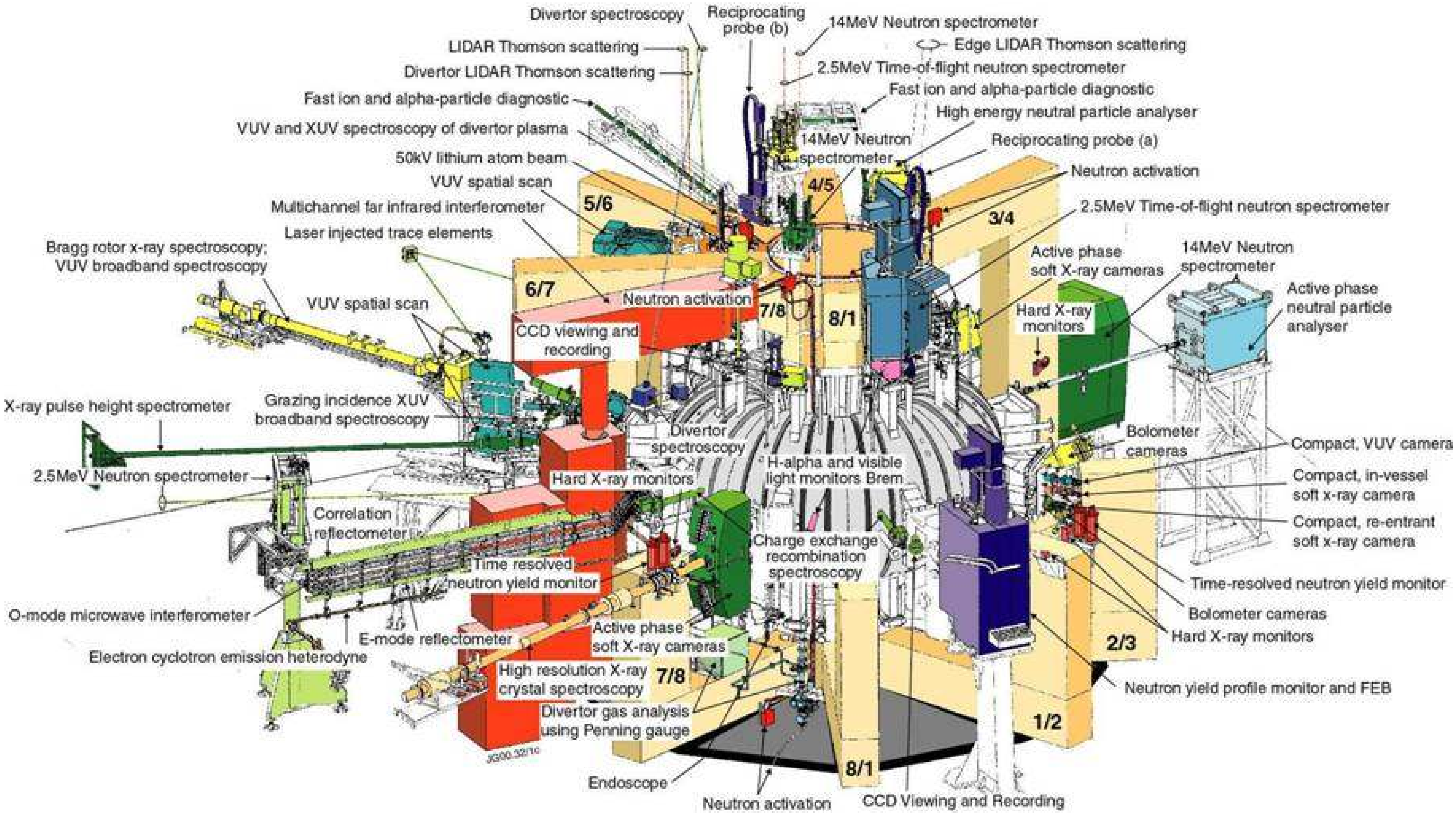
How a Tokamak works

Additional coils can be added to modify the flux surface and to divert the plasma that leaves the edge of the confined region towards "divertor" targets which are designed to take the heat load



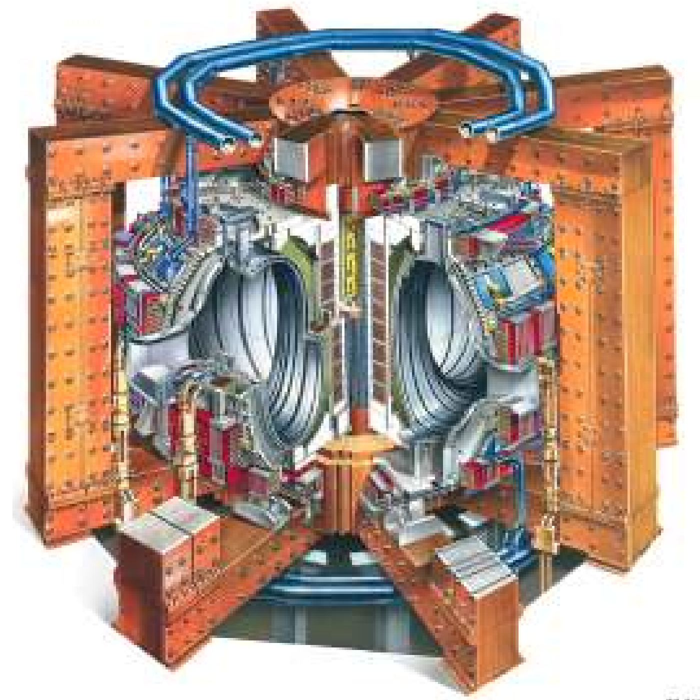
How to diagnose the plasma



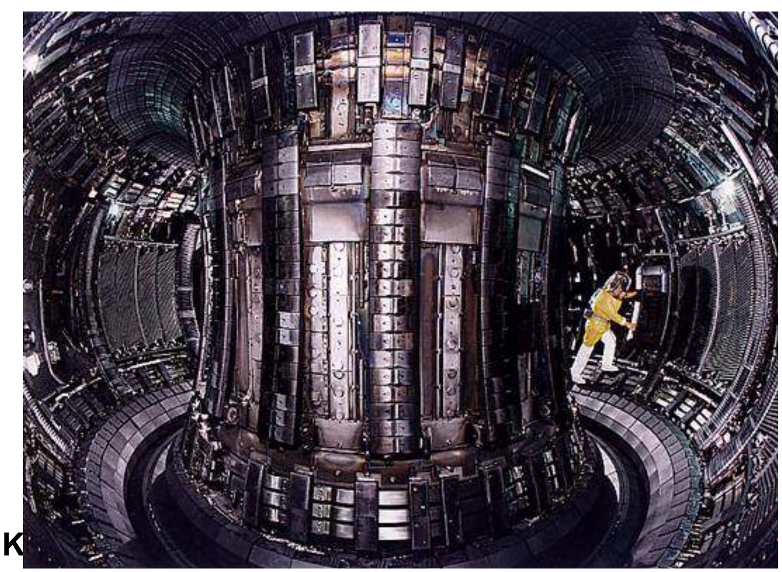
Measure effectively the whole E.M spectrum
from Radio waves to Gamma rays + neutrons and neutrals

The Joint European Torus (JET)

Torus radius	3.1 m
Vacuum vessel	3.96 m high 2.40 m wide
Plasma volume	$80\ m^3$ - $100\ m^3$
Plasma current	up to 7 MA
Main confining field	up to 4 Tesla



Height
13 m

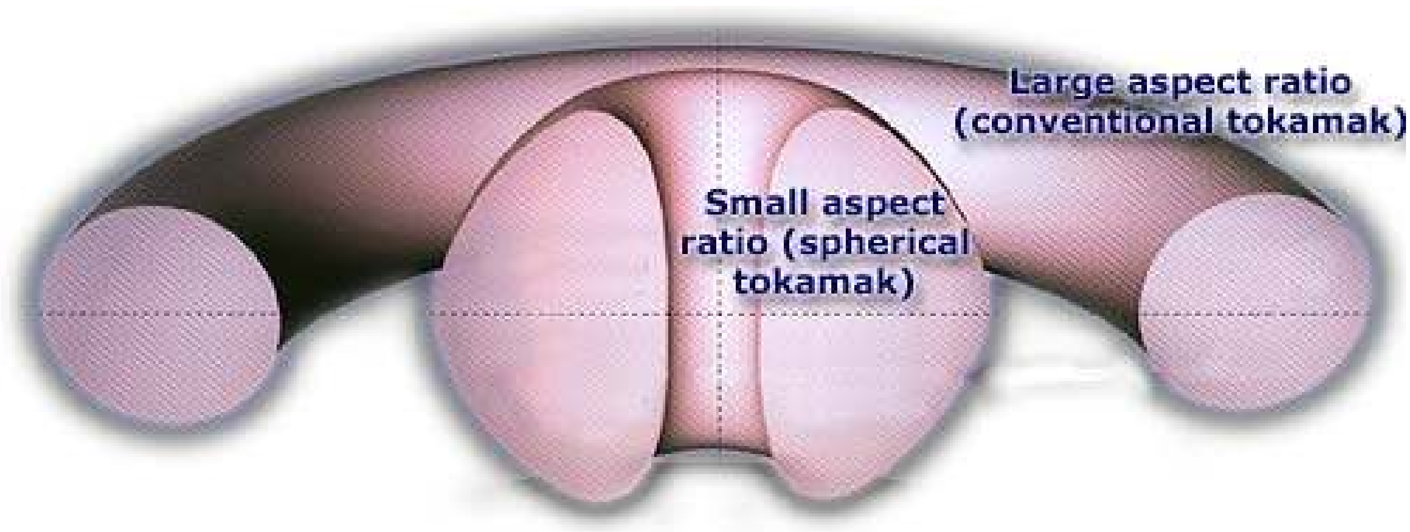


- Largest TOKAMAK in the world
- Built in 1983
- Since 2000 it has been operated by UKAEA on behalf of EFDA.

UKAEA Fusion
Working in Europe

MAST – a spherical tokamak

A concept evaluation device



This shape has improved stability leading to higher plasma pressures being possible

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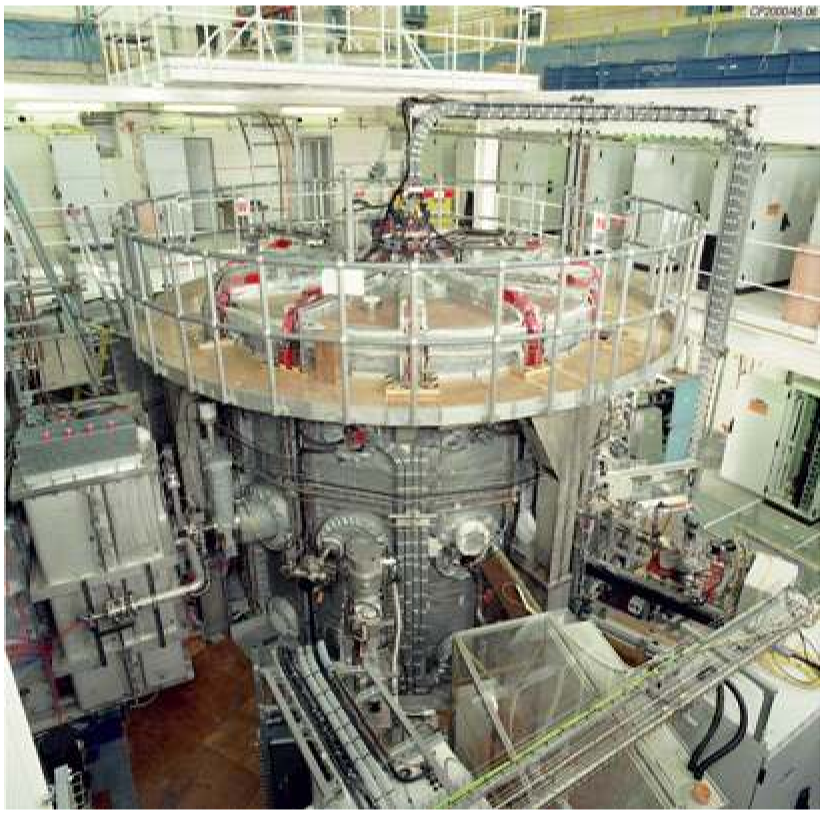
MAST – a spherical tokamak

- Operational since 2000
- The worlds biggest ST

	Design	*Achieved*
Major radius	0.85 m	0.85 m
Minor radius	0.65 m	0.65 m
Elongation	>2	2.6
Triangularity	0.5	0.6
Plasma current	2 MA	1.2 MA
Toroidal field	0.52 T	0.52 T
NBI heating	5 MW	3.5 MW
RF heating	1.5 MW	0.9 MW
Pulse length	5 s	0.7 s



Goals

- to advance key tokamak physics issues for ITER
- to explore the long-term potential of the spherical tokamak (ST).

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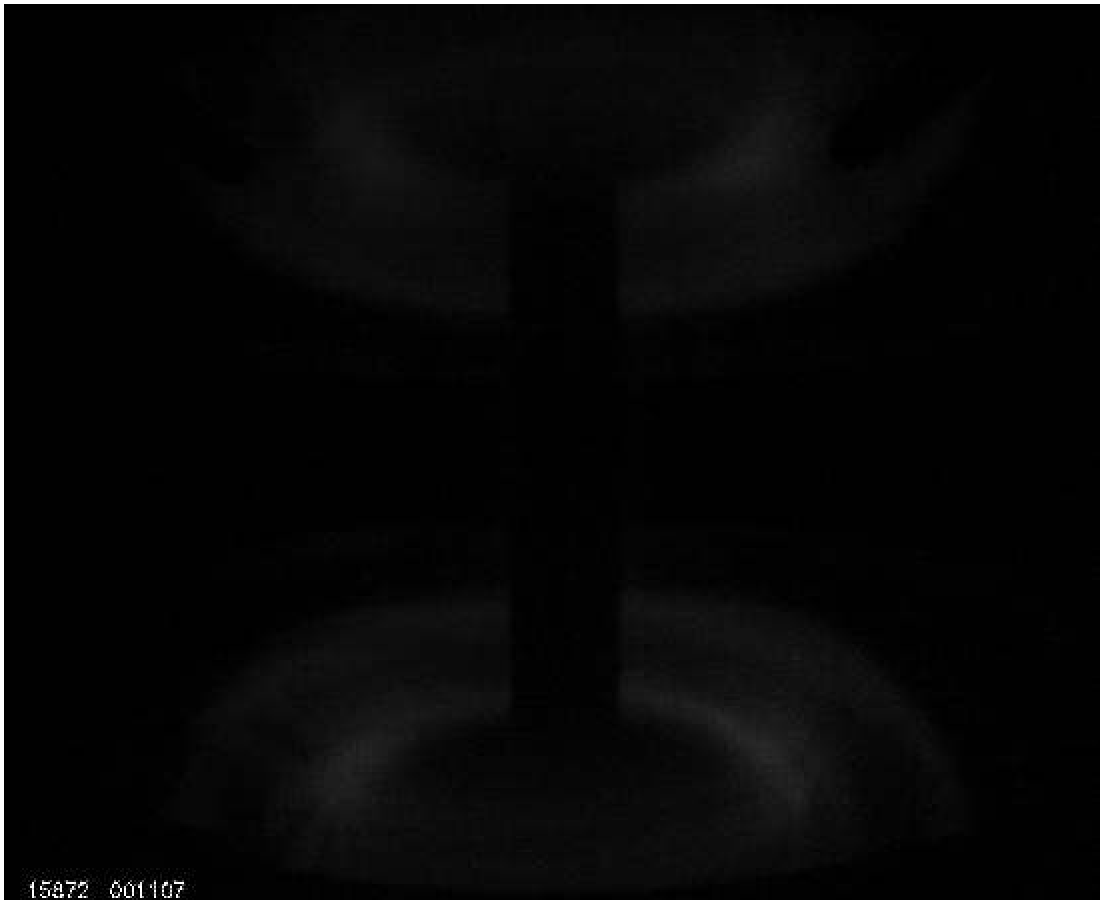
How to make a fusion plasma

Making a plasma

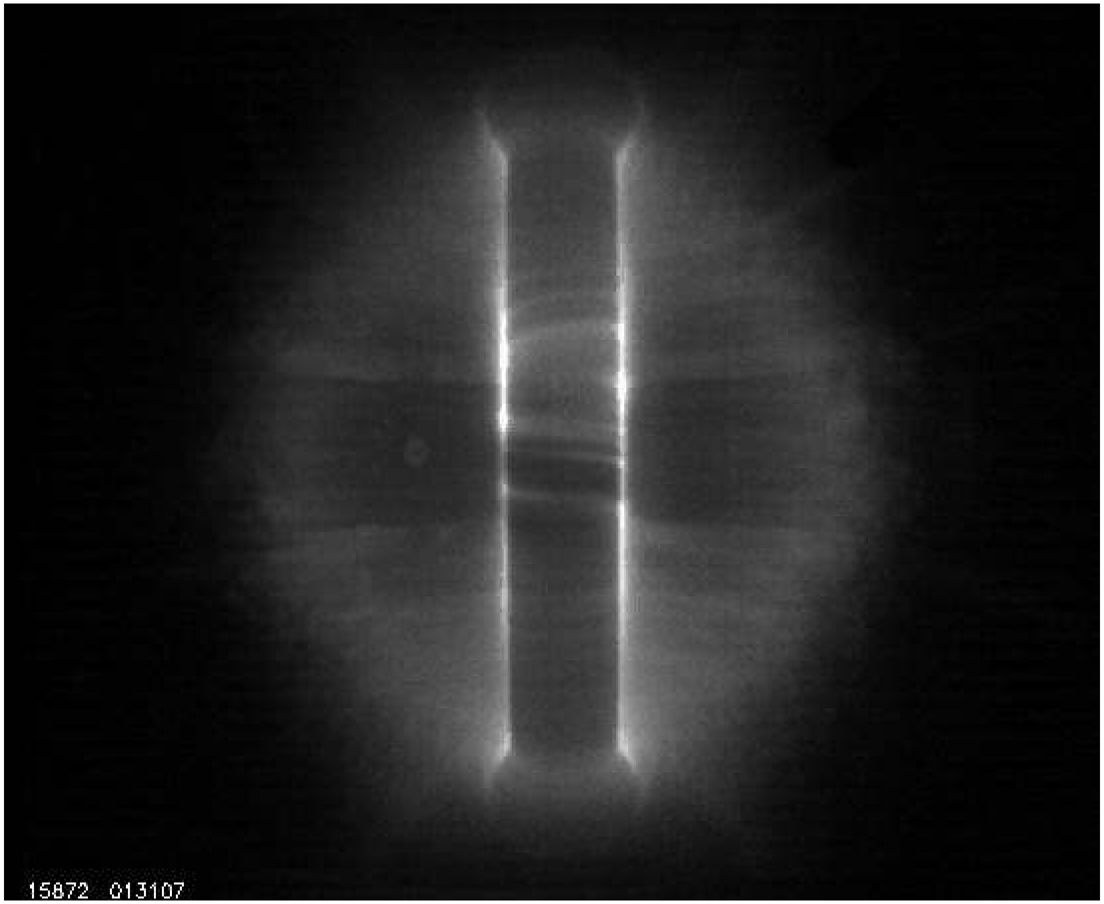


Inject neutral Deuterium gas

Strip the electrons from the atoms by inducing an electric field

Plasma forms in Magnetic configuration ~ 10 ms

Shaping the plasma

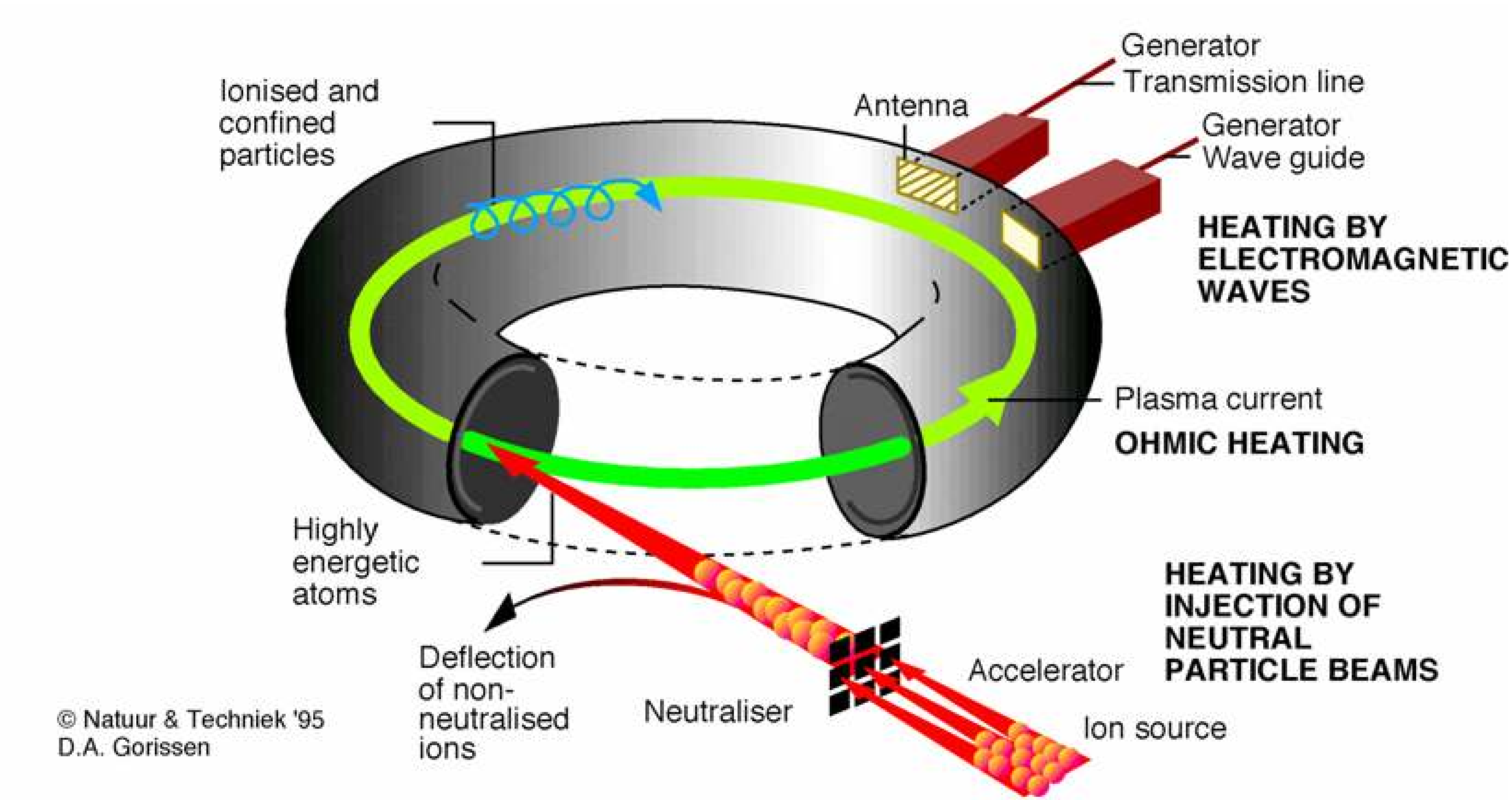


Modify the magnetic fields to shape the plasma and pull it away from in vessel components

Arrange that it only interacts with the divertor targets ~ 100 ms

Start to heat the plasma

Heating the plasma



Ohmic, RF and NBI

Turbulence – Low Confinement Mode

Turbulent structures at the edge of the plasma limit the confinement

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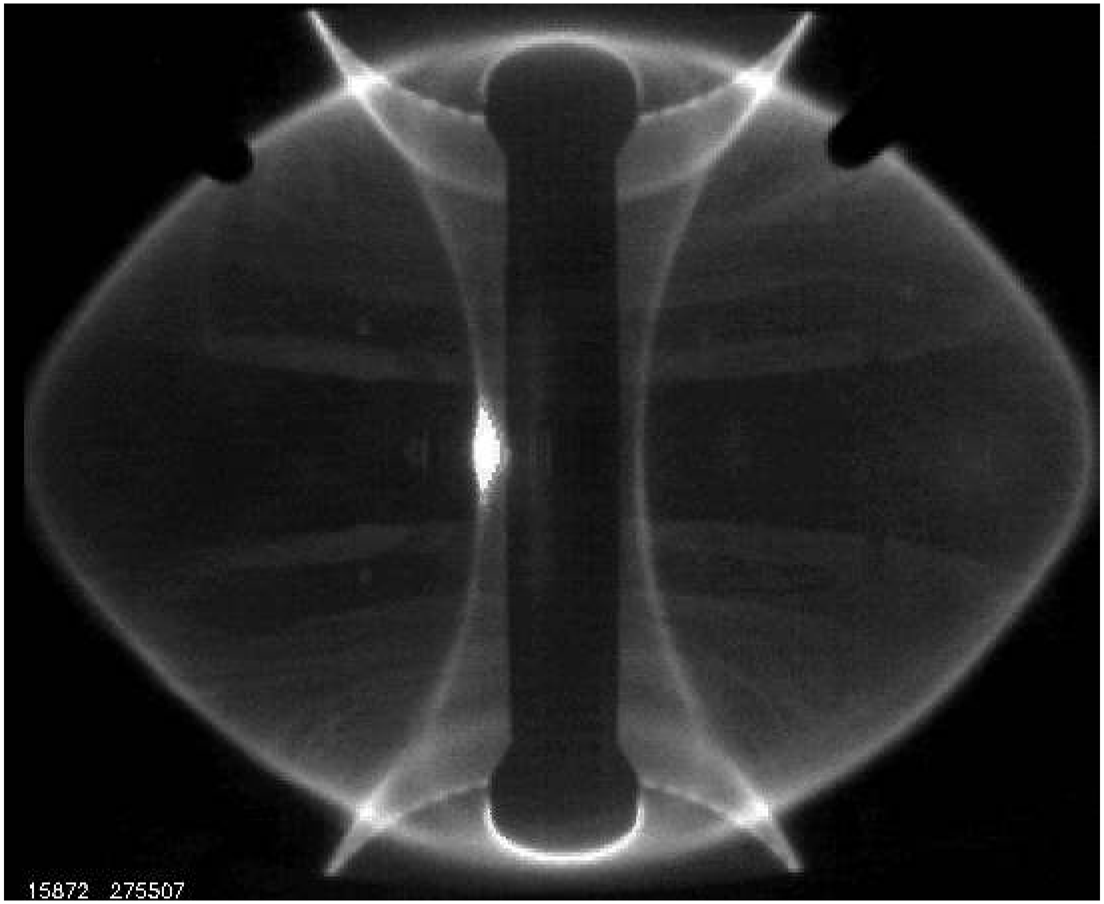
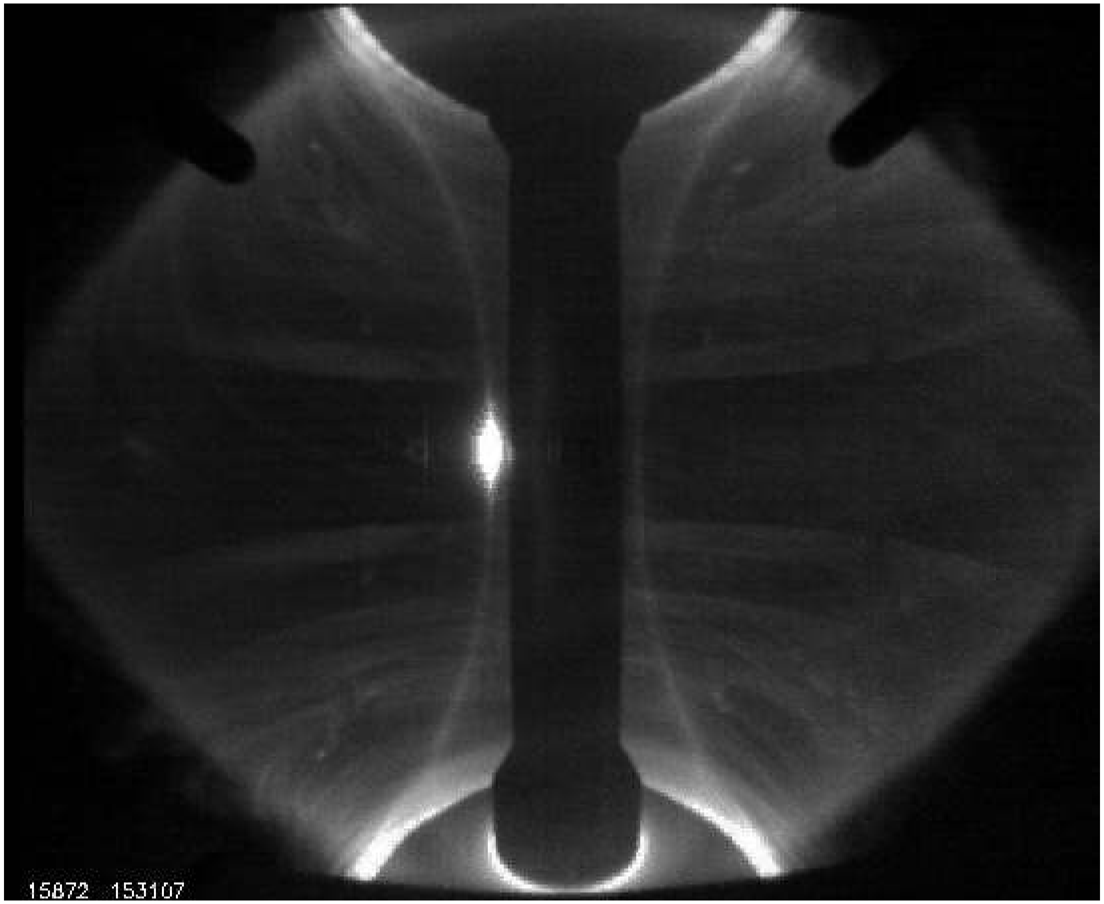
Turbulence suppression – High confinement mode



However when the input power is above a critical level the plasma spontaneously organises itself into an improve confinement (H-mode) regime.

L-H transition movie



Edge turbulence removed

An insulating barrier forms at the edge of the plasma

The plasma confinement increases by a factor of 2

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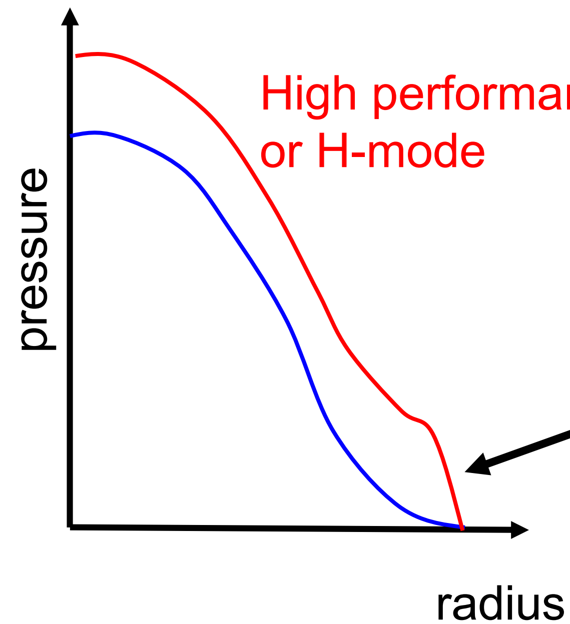
L-H transition

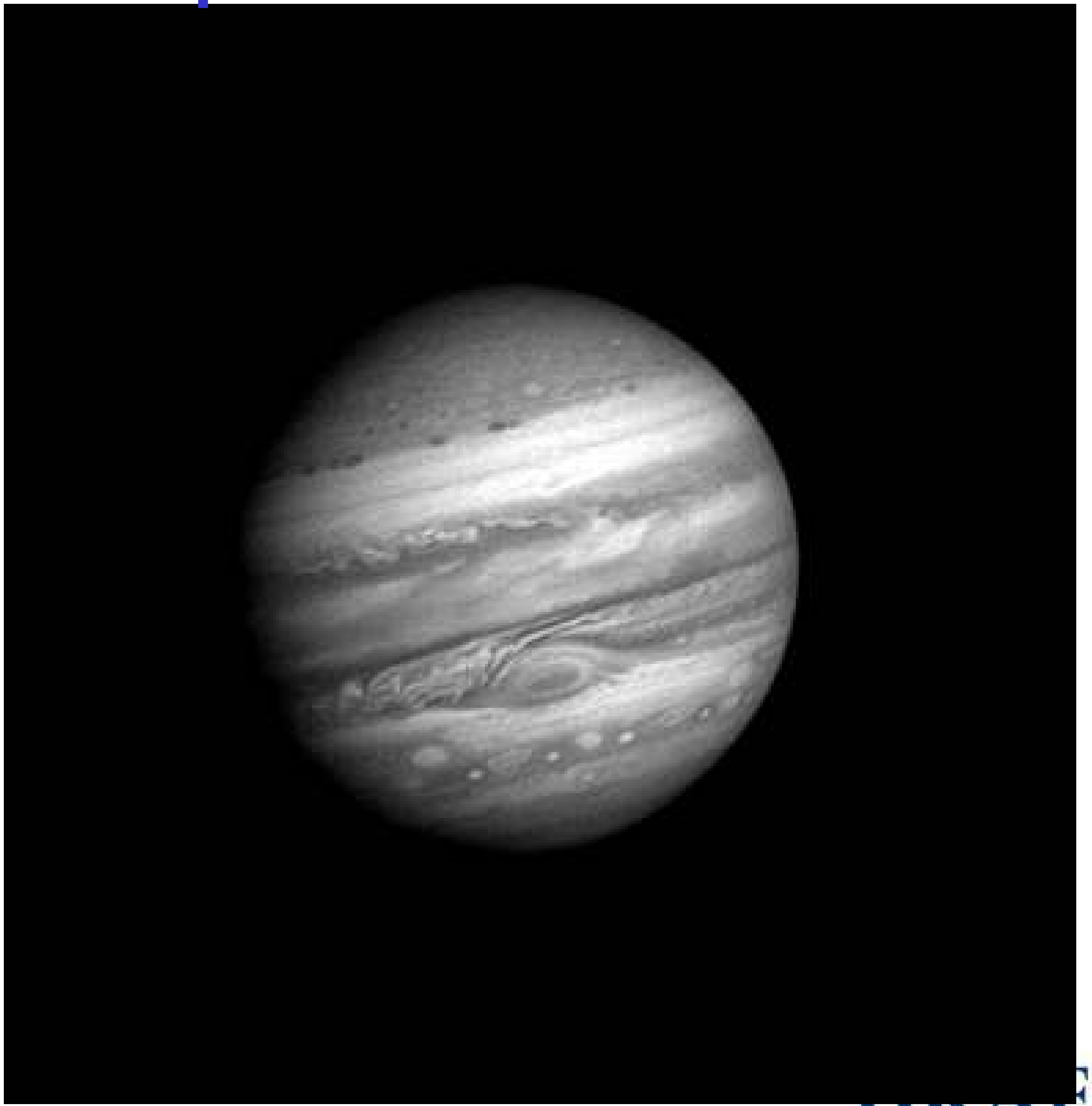


A transport barrier is formed

Steep pressure gradient at plasma edge

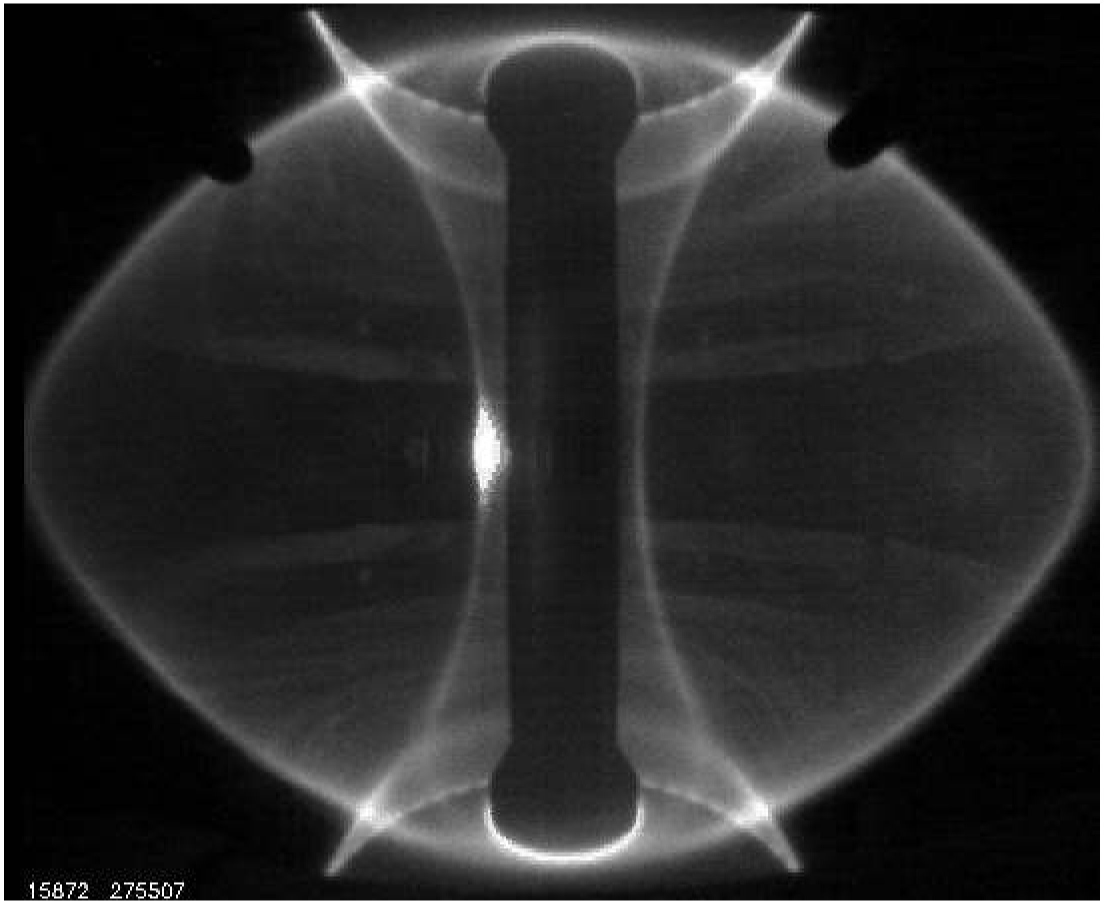
Produced by strong flow shear at edge which destroys turbulent eddies

Illustration of “zonal flows” on Jupiter: May be a related phenomenon



Voyager images

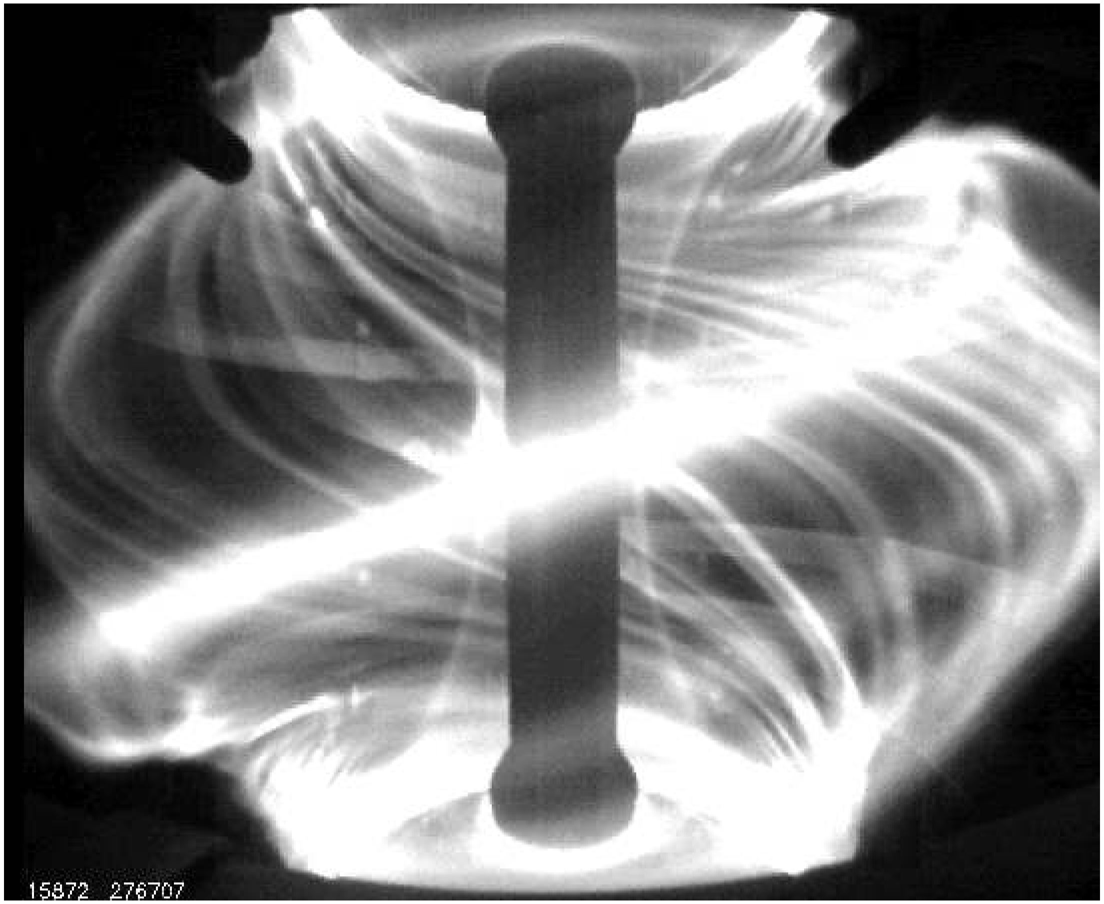
The price of H-mode - ELMs



The steep pressure and current gradients at the edge of the plasma produce instabilities called Edge Localised Modes (ELMs)

Can release several % of the plasma energy in < 1ms
On ITER: 20 MJ in 500μs

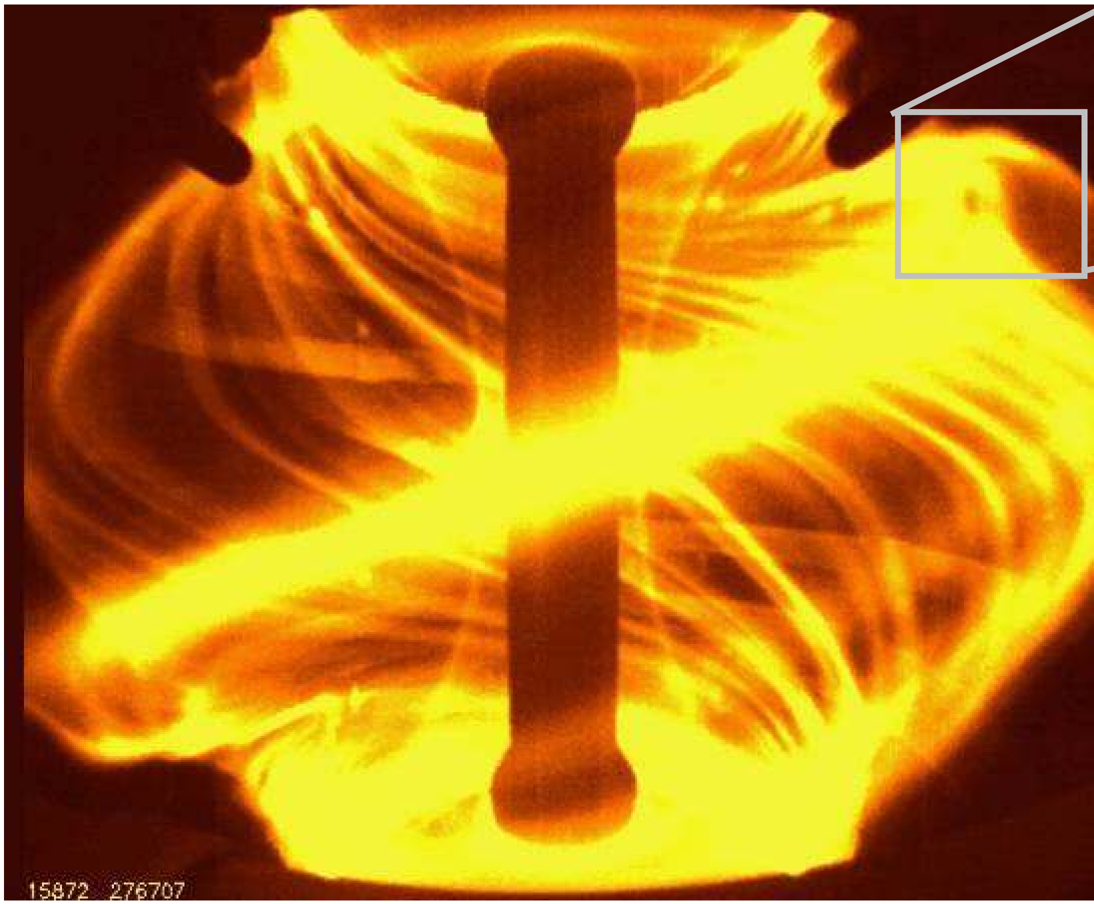
The price of H-mode - ELMs

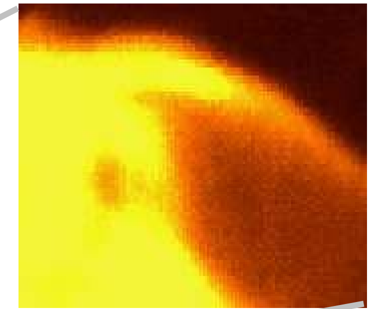


In order to avoid expensive damaged that could be caused by ELMs in future devices we need to understand them and learn how to control them

They have many similarities with Solar eruptions

ELMs and Solar eruptions



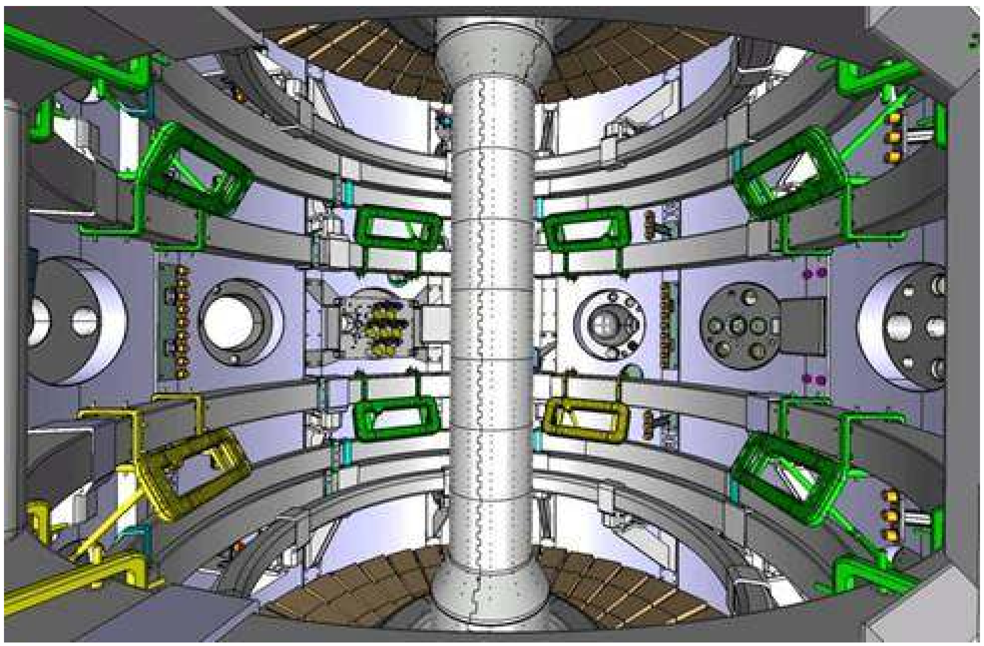


Both visually and theoretically

Observation of these filamentary structures has increased our knowledge of ELMs and allowed us to find mechanisms that can mitigate them

How to mitigate ELMs

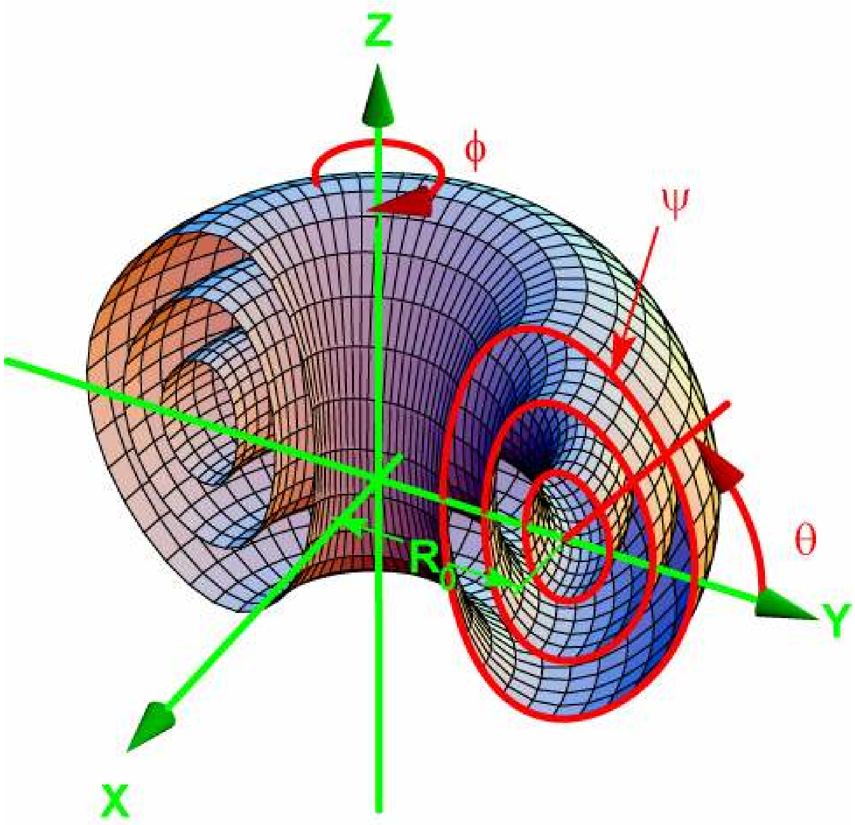
Want to keep the good confinement due to H-mode but need to stop the instability growing
– modify the flux surfaces near the plasma edge using a non-axisymmetric perturbation to the magnetic field

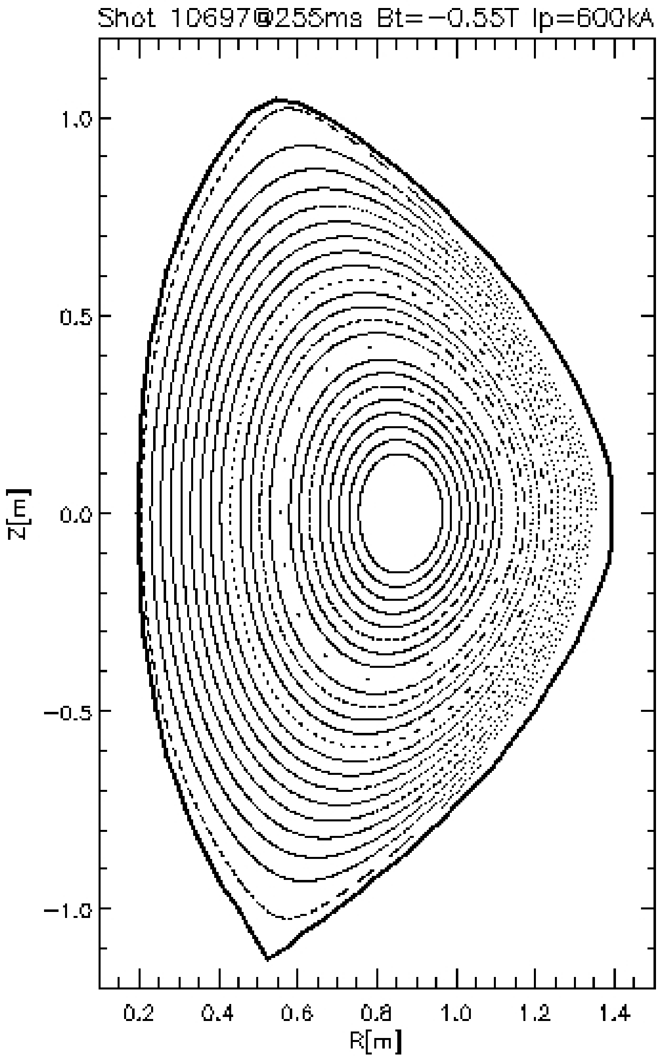


Perturbation supplied using toroidally discrete coils

How to mitigate ELMs

Without perturbation

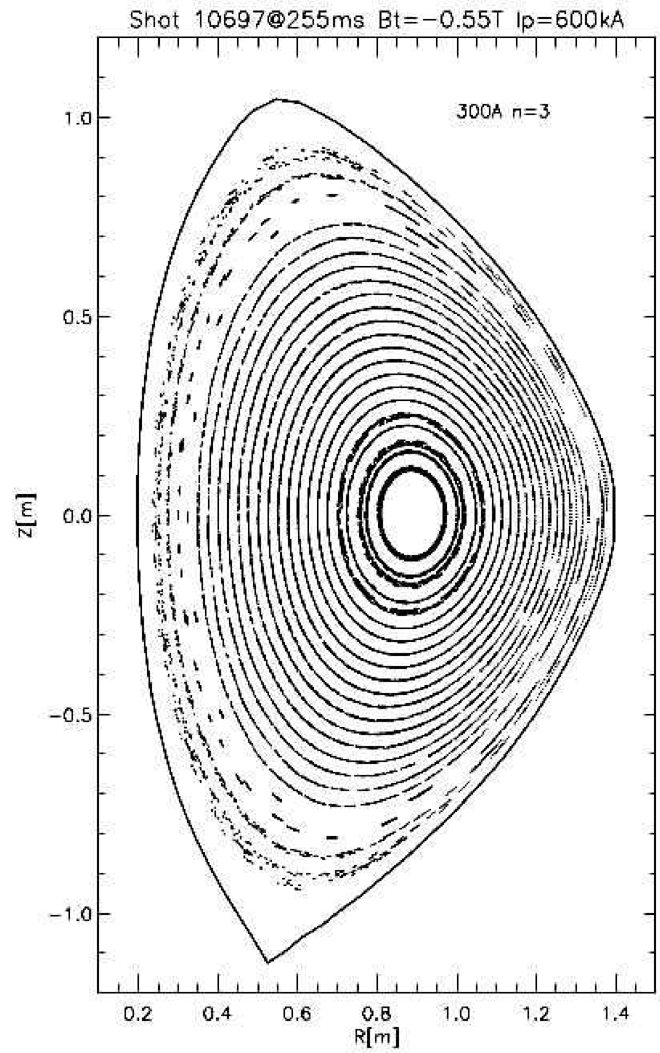




How to mitigate ELMs

With perturbation

Flux surfaces near the edge are perturbed



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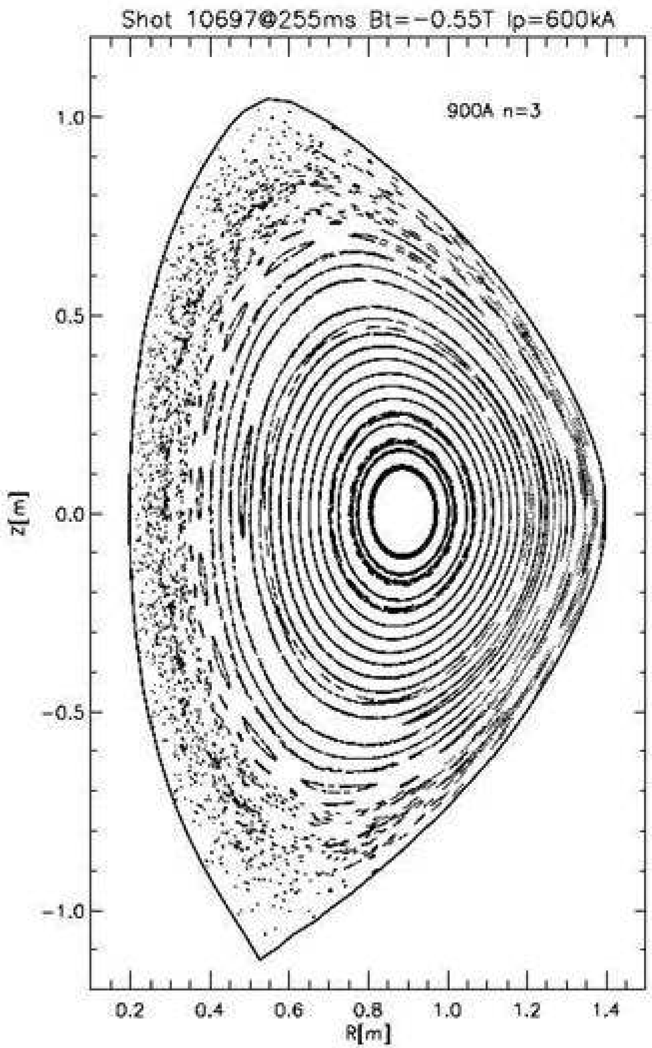
How to mitigate ELMs

The disturbance of the flux surfaces reduces the edge pressure and stops the filaments growing

By changing the current in the coils the disturbance can be tuned to effect just the correct area



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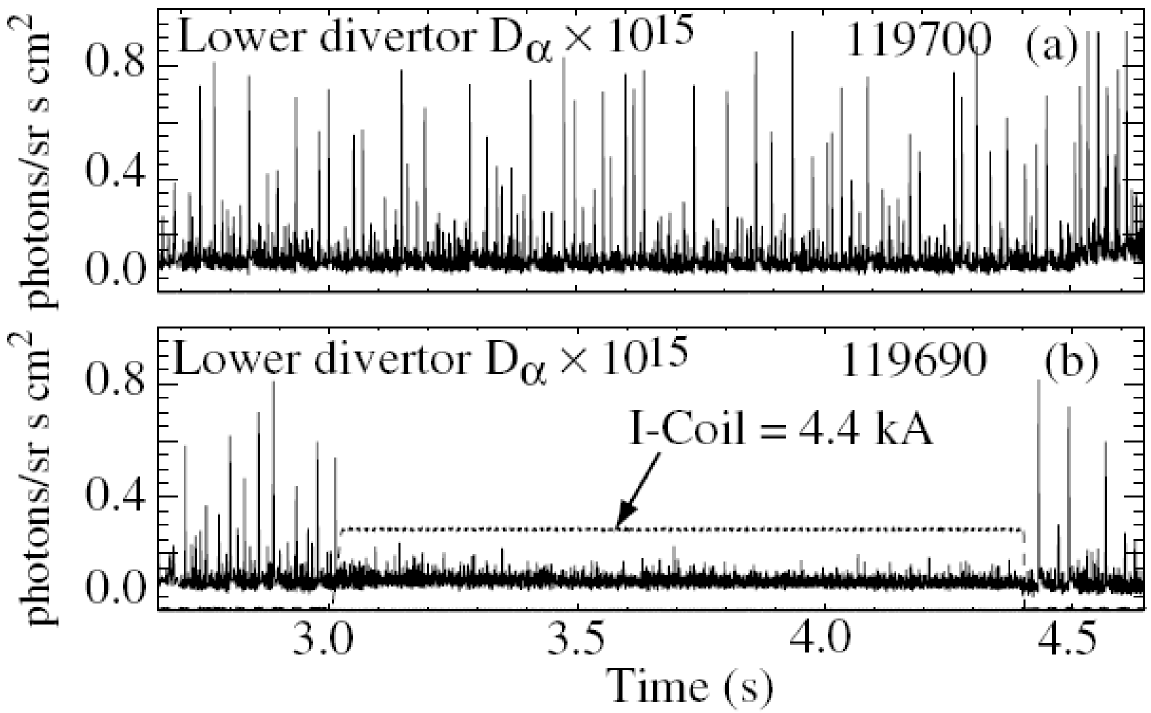
ELM mitigation achieved

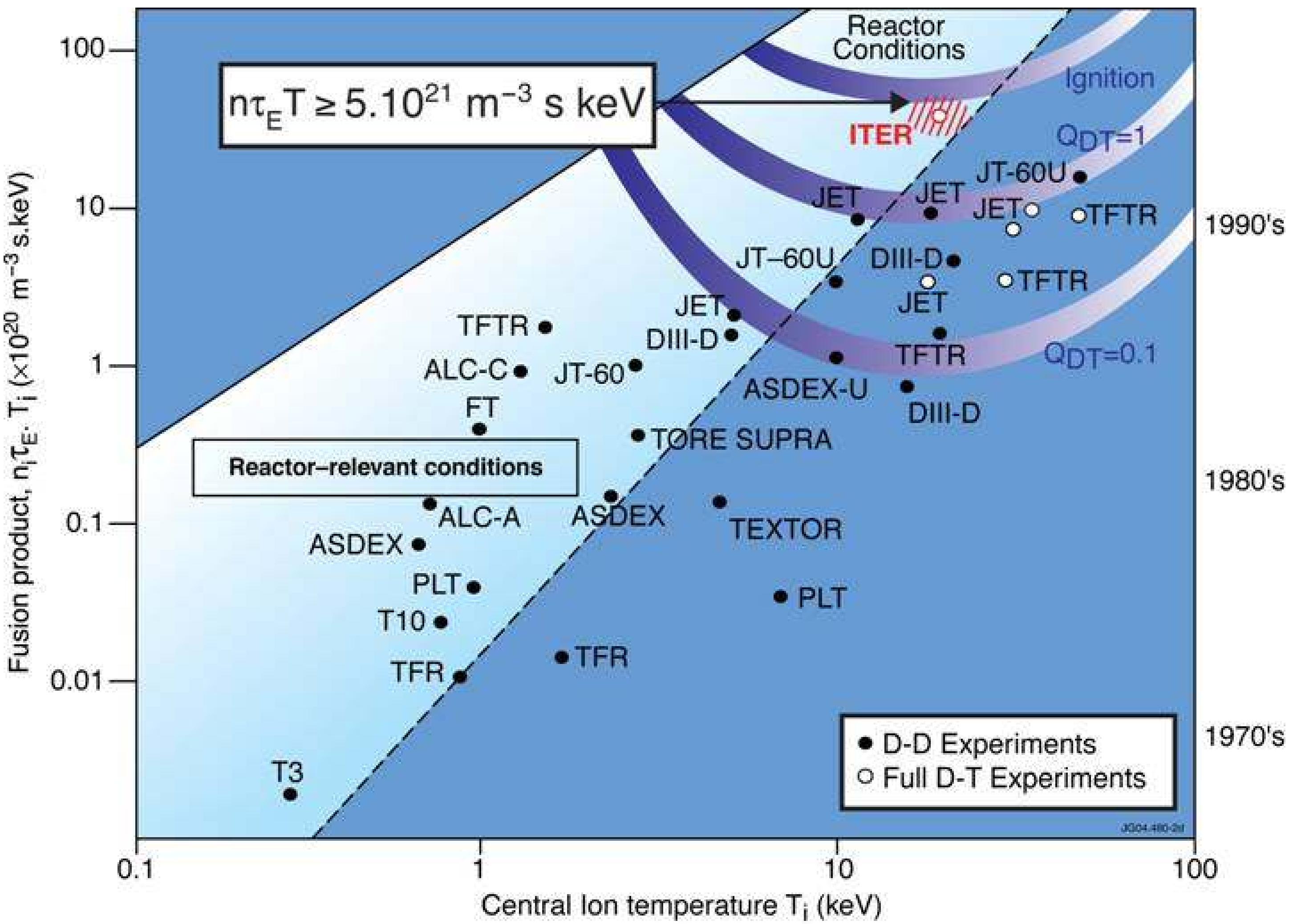


Complete suppression has been achieved while maintaining the good confinement

Current status and future plans

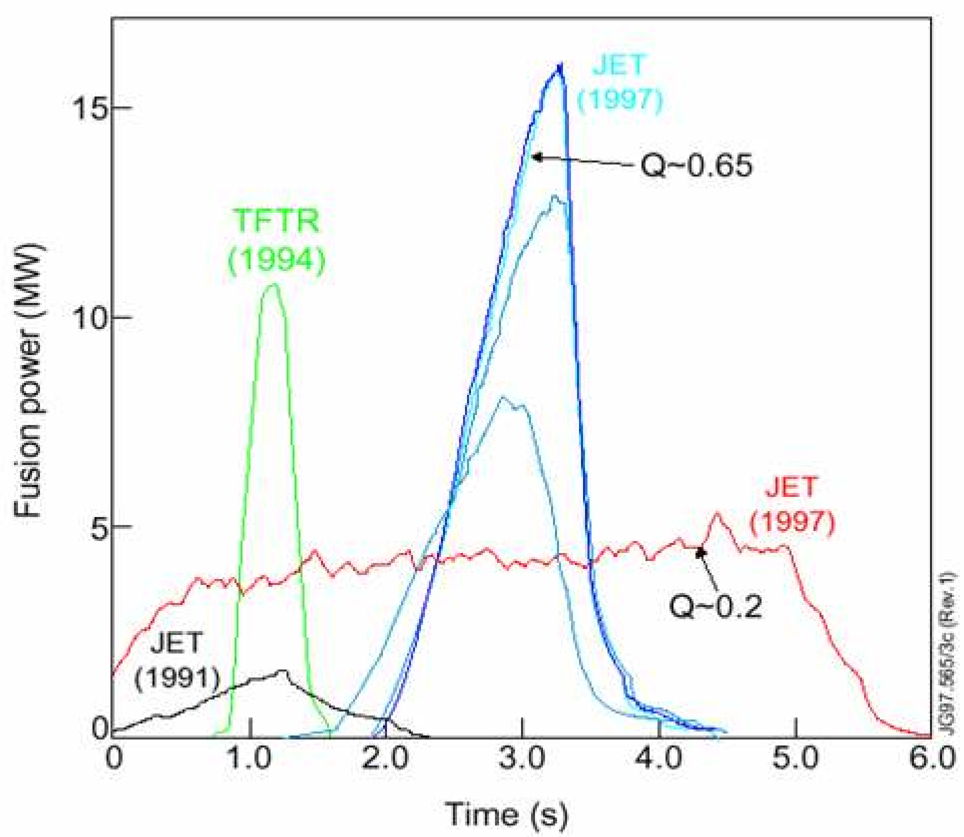
Current status – plasma performance

Progress towards reactor relevant conditions



Current status – fusion power

- Existing tokamaks do not usually operate with tritium (increases costs and complexity) and so have negligible fusion
- JET and TFTR (USA, now closed) are exceptions



Almost reached breakeven

To achieve Q>>1 will require a bigger device

So why can't we build a power station now?

We could – but it would not be economically viable

To built a power plant that is commercially competitive we need

To improve the design i.e.:

- how big should we build it?
- how much heat will material components need to withstand?

To do this we need research in key areas:

- Plasma physics: Confinement, exhaust and stabilty
- Engineering: Continuous operation
- Materials (heat loading and tritium retention)

ITER: The next step

To address these remaining questions, the multi-national ITER experiment will be constructed in the South of France

- about twice the size of JET (in linear dimensions)

One objective is for ITER to study "burning plasma" physics i.e. achieve Q=10

With plasma up to 30 minutes long

Fusion Power: ~500 MW

Pulse Length: ~500 secs

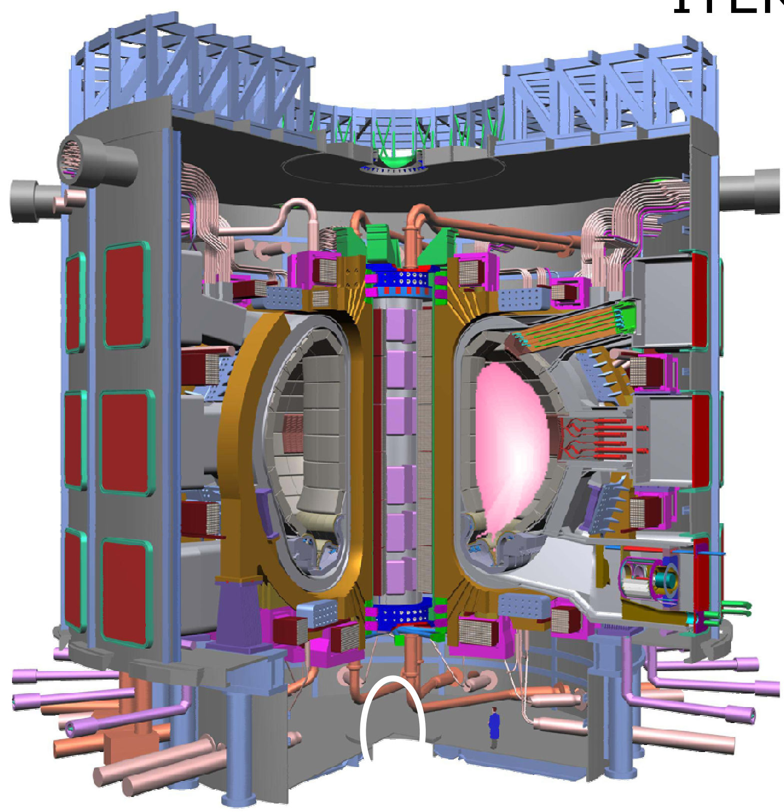
Plasma Current: ~14 MA

Plasma Volume: 840 m^3

Typical Density: 10^{20} m^{-3}

Typical Temperature: 20 keV

ITER



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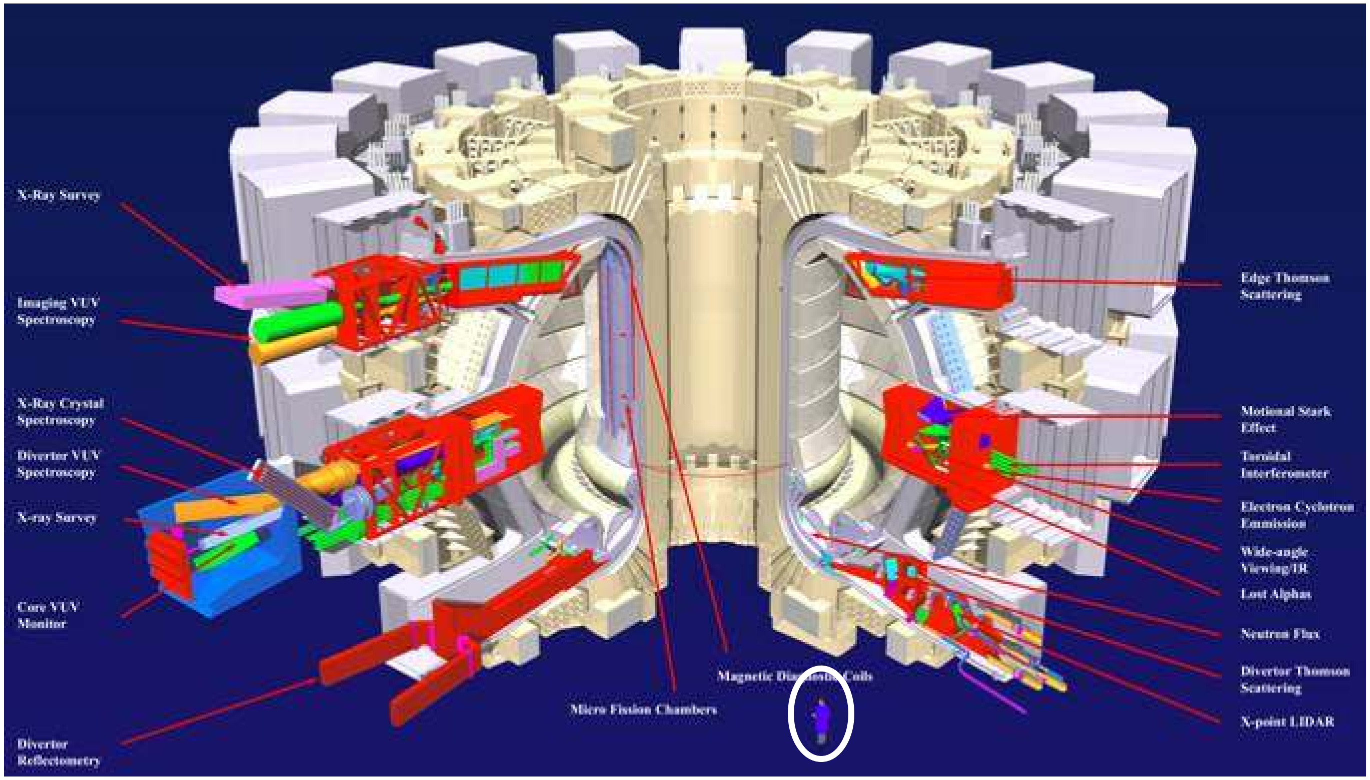
ITER hosted by the EU



Construction has started in Cadarache (France).

The ITER construction costs £3 billion over 10 years

First plasma 2016

The strategy: A "fast track" to fusion

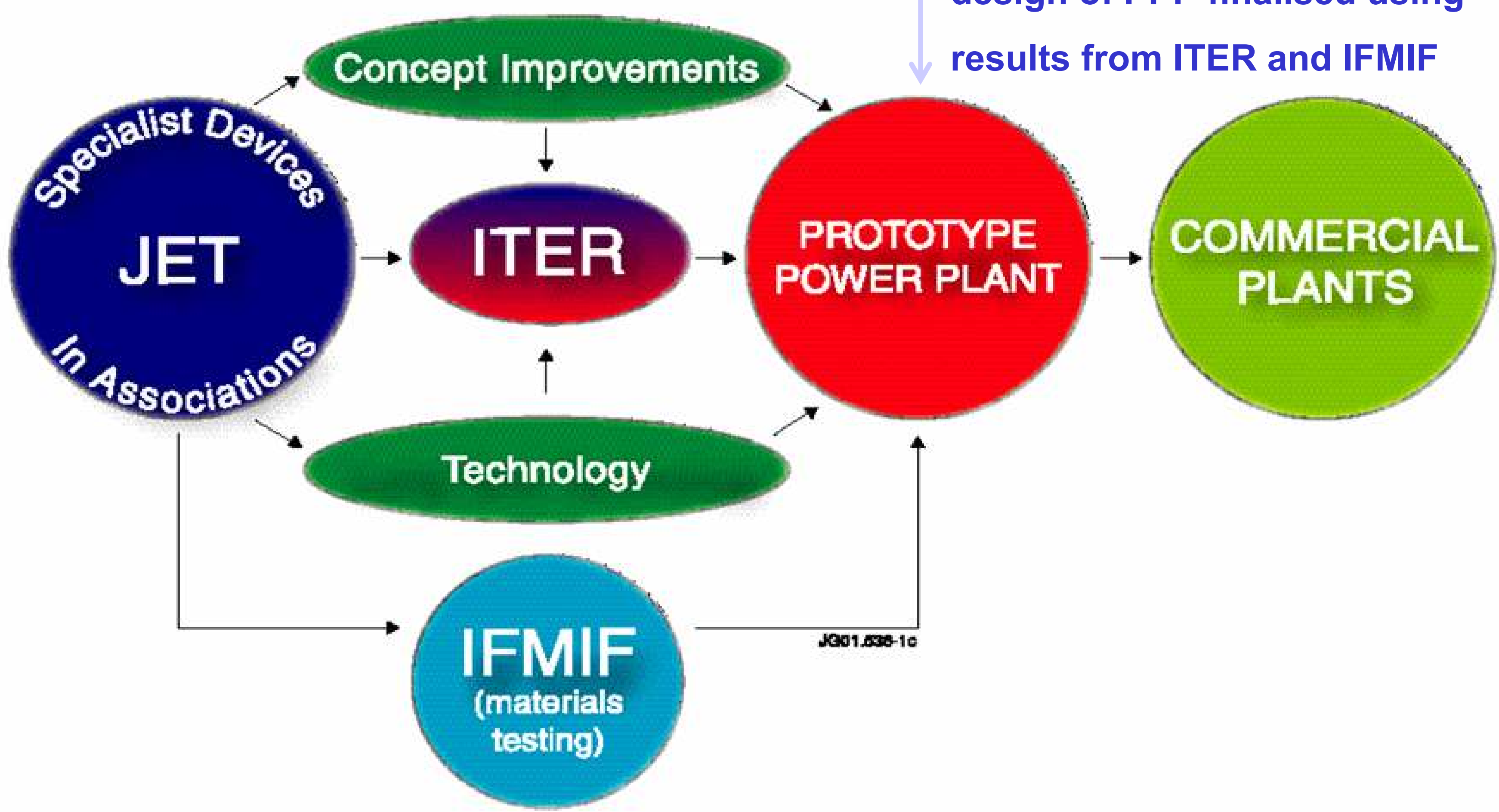
- In parallel with ITER, a materials development facility is needed (IFMIF)

- One could then move on to a proto-type power plant, followed by commercial fusion power production

25 years from now -

design of PPP finalised using

results from ITER and IFMIF



A. Kirl

The future of fusion power

	When?	Fusion Power	Typical Pulse duration	Q
	1997	16MW	10 second	0.65
	2016-2020	500-700MW	30 minutes	10
	2030/40	1.5-2GW	steady state	30

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Summary

- Magnetic confinement fusion energy has many attractive features: safe, clean and economically competitive
- There remain a number of basic plasma physics issues to address
  - these will be addressed by ITER
- Materials development is another important area; need to identify materials which:
  - have appropriate structural properties
  - can tolerate high heat loads (eg in the exhaust region)
  - can withstand the hostile neutron environment
  - do not retain large amounts of tritium
  - do not produce long-lived radio-active isotopes when exposed to fusion neutrons
- Fusion has a very good chance of success
  - ITER will, we hope, pave the way for the World's first fusion power plant