Courses at the Alfvén Laboratory

ED2200 ENERGY AND FUSION RESEARCH, 6 hp, period 4

Learning outcomes:

The student should be able to

- give an overview of the national and global energy production within a sustainable perspective
- discuss the need for fusion energy for future production of electricity
- describe the principles for magnetic confinement, both at particle- and at macroscopic level
- give an account of the most important plasma models
- solve simpler problems within the fusion plasma physics fields of equilibrium, stability and transport
- describe the basic plasma parameters and corresponding diagnostic techniques for fusion plasmas
- explain the function of different plasma heating techniques
- describe the components of a fusion reactor, and their functions
- give an account of alternative confinement schemes and the planned route to a reactor

Teaching and learning:

- Lectures (2 x each week)
- Exercise sessions (1 x each week))
- Mini group work (1 x each week)

Examination is continual. No final exam:

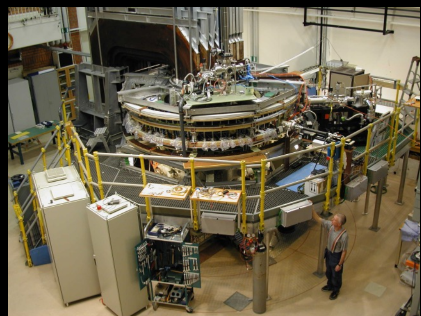
- Home assignments (weekly)
- Last course week – extended Home assignment
- Mini group works (weekly)

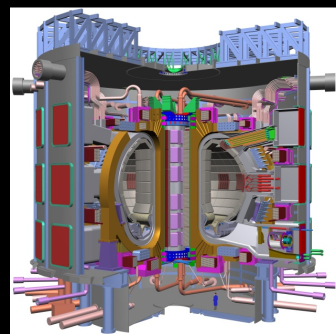
CDIO:

- Mini group work 45 min, three students randomly selected in each group, secretary hands in answers

Relation to other courses:

- Plasma Physics course desired, not needed
- Some TET and Vector Analysis needed
- Certain skills such as linearization introduced



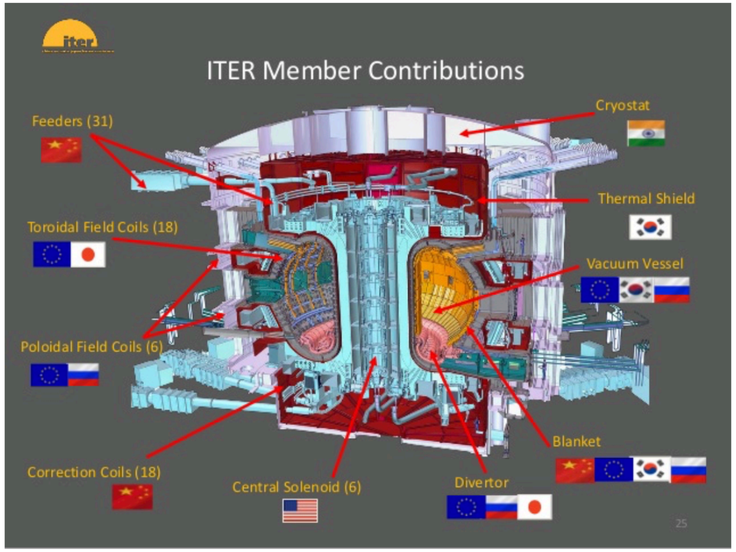


ED2200 VT17-1 Energy and Fusion Research

ENERGY AND FUSION RESEARCH

This introductory course will present the state of today's fusion research and provide insight into the physics and technology of fusion.

More about the history, design, evaluation and analysis of the course you find in Kursutveckling.



The development of fusion has now reached a state when it may be said that fusion power will indeed be realized. **ITER**, in the picture above, is the world's largest scientific experiment, now under construction in Cadarache, France. It will produce some 500 MW of fusion power.

In this course, different solutions to "the greatest technological challenge ever pursued" will be presented.

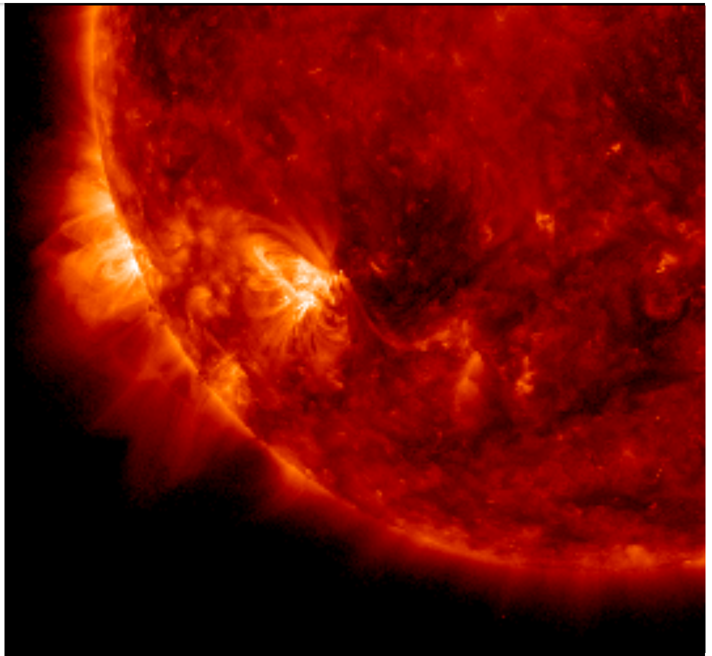
As a background, we will discuss the energy and environmental problems that threat to become critical towards the mid-century unless new energy sources are developed. Comparisons with the non-fossil energy sources that are known today will be made.

For a taste of fusion, you may take a look at these video lectures.
Or check out the latest on European fusion research at EURO*fusion*.

Below you will find some important information about the course.
Here also the Home assignments can be downloaded.

But first - **download the course-PM**, which contains important information for this year's course offering, including schedule.

The **learning outcomes** of this course require the student to be able to



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More details about course contents, prerequisites etc can be found in the course plan .

Home assignments are found here.
Each home assignment should be handed in no later than at the first lecture in the course week just after.

For the interested:
- Take a look at the KTH Fusion plasma physics homepage
- Run your own "fusion experiment "
- Do your Master Thesis at KTH Fusion plasma physics

FUSION PLASMA PHYSICS
School of Electrical Engineering
KTH
Jan Scheffel and Per Brunsell

ENERGY AND FUSION RESEARCH

Spring 2017

Course teachers: Jan Scheffel (jan.scheffel@ee.kth.se, phone: 790 8939)
Per Brunsell (per.brunsell@ee.kth.se, phone: 790 6246)
Visiting address: Alfvén Laboratory, Teknikringen 31
Course home page: **https://kth.instructure.com/courses/1911**
(see also **www.kth.se/social/course/ED2200**)

COURSE SUBJECT

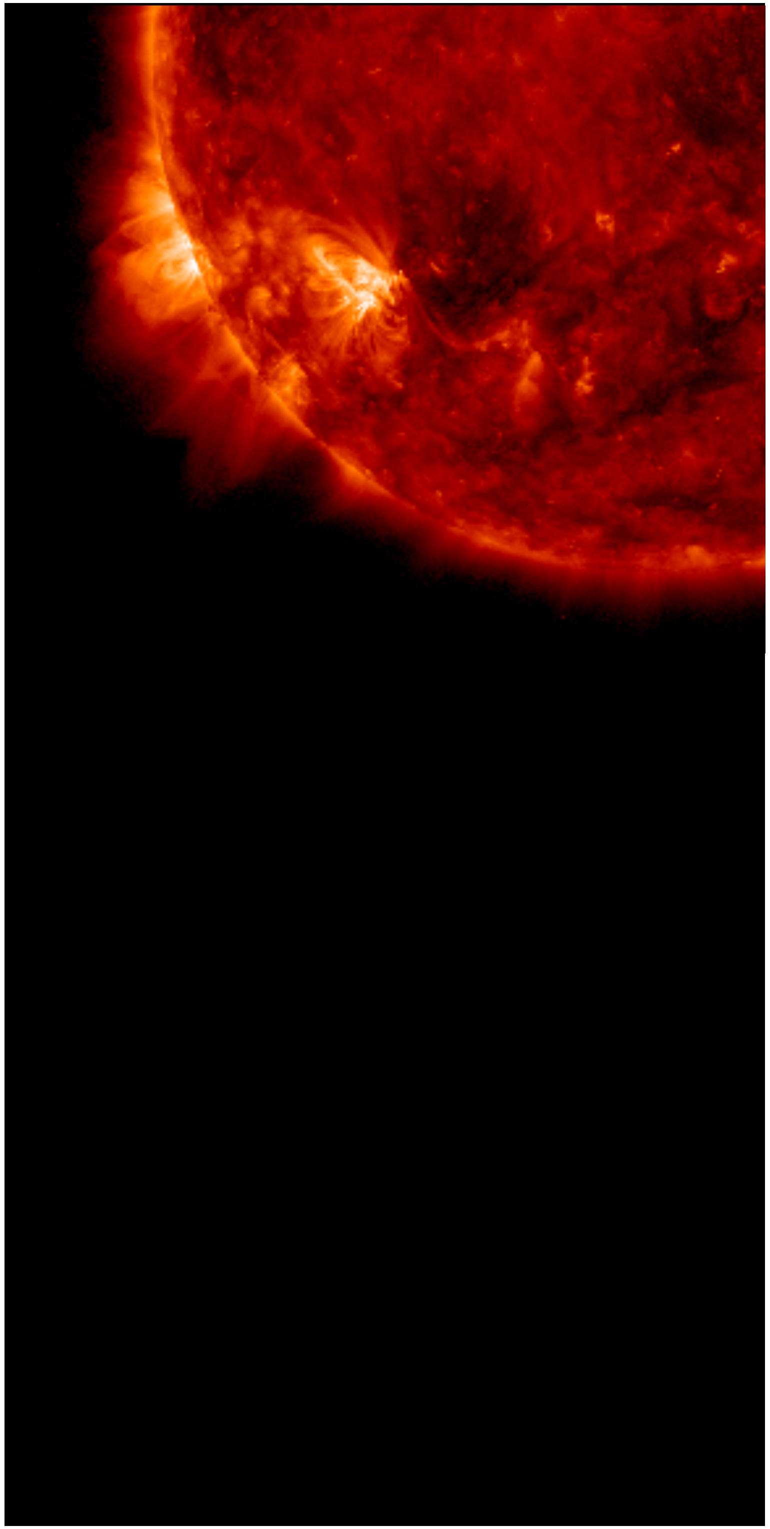
In earlier days, the question ”For how long will the fossil fuels last?” was often raised, but experiences during the last decades have given us reasons to instead ask the question ”When can we free ourselves from the dependence on fossil fuels?”. In this course, a background is given to the problems concerning future energy provision that we are realizing today and that will become critical towards the mid-century unless new energy sources are developed. We will also discuss the alternative energy sources that are known today. Within fusion research, the goal is to produce an energy source for large scale generation of electricity. By using the surplus energy that is released when light atomic nuclei merge (fusion), the final benefit comes from an endurable and environmentally friendly ”Sun on earth”. The Alfvén Laboratory at KTH is part of the international collaboration in this field. This introductory course will provide the physical and technological basics and give a picture of the state of present day fusion research. The development has now reached a state where we may say, with some confidence, that fusion power will indeed be realized. In the course, different solutions to this ”the greatest technological challenge ever pursued by man” will be presented.

COURSE LITERATURE

Fusion Physics – introduction to the physics behind fusion energy, J. Scheffel and P. Brunsell
Exercises with solutions, J. Scheffel and P. Brunsell
Course literature cost: 250 kr.

ABOUT TEACHING AND LEARNING IN THIS COURSE

The lectures (Le) provide an overview of the energy provision problem and the development of fusion research, as well as an understanding for important problems in fusion research. Some course book material will be taught as home assignments, being distributed at each lecture. **The home assignments** provide credits for the course examination.
The class exercises (Ex) develop skills to solve formal problems within fusion research and an opportunity to discuss questions encountered during the studies. Normally a few problems are solved on the blackboard, where after the students solve a given problem as a group exercise. Protocols from each group are handed in at the end of the session, as part of the examination.



EXAMINATION

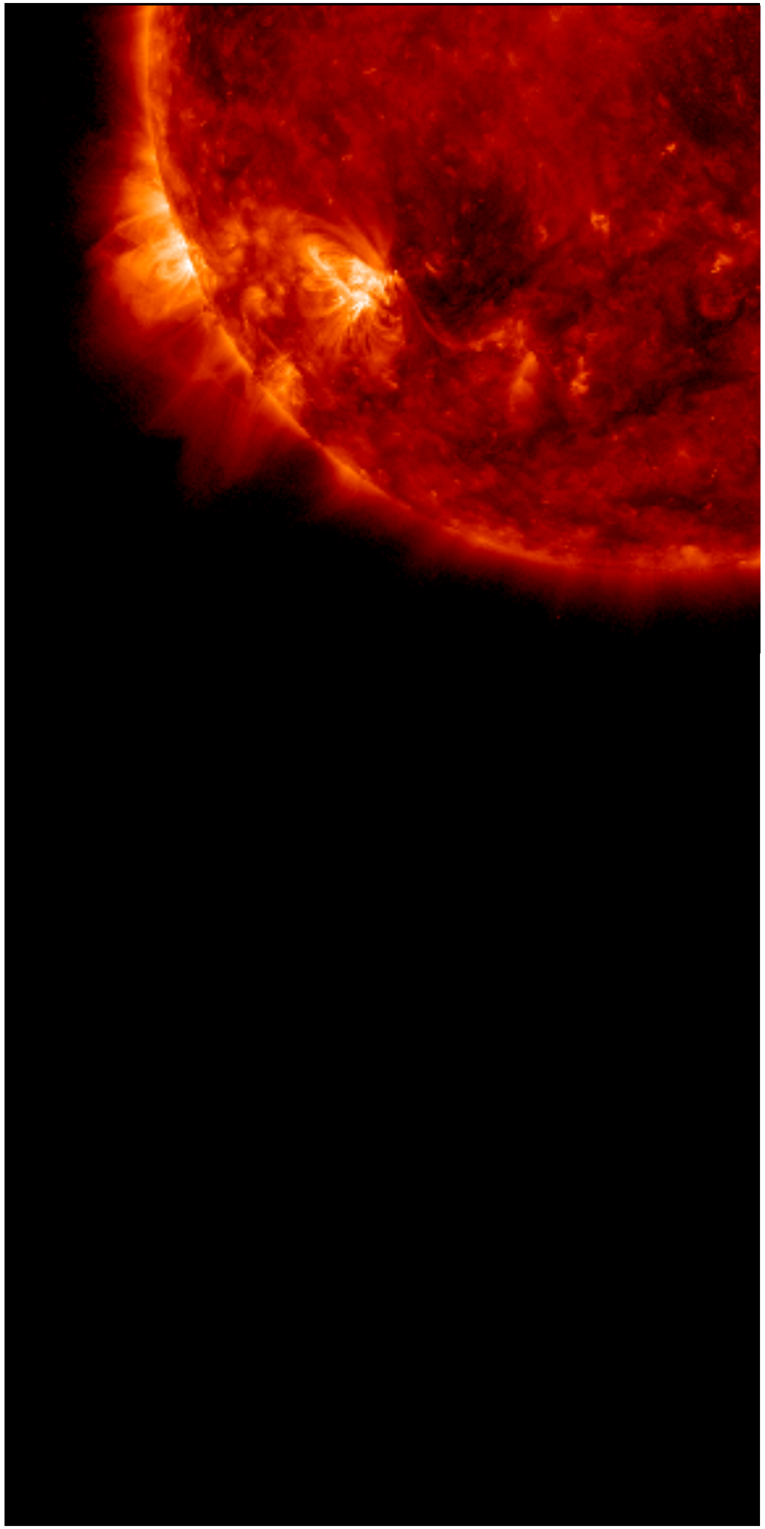
Continuous examination, based on a credit point system is used. The grades "pass" (P) or "fail" (F) are determined by the total number of credit points accumulated during the course. A maximum of 42 credit points are available. A minimum of 30 credit points is required for grade "pass". Students achieving 26-29.5 credit points, may be awarded the grade "pass" after completing an additional oral exam within 6 weeks after the course.

The two course activities required for **examination** are as follows:

- ***Home assignments*** are six in total and provide a total maximum of 30 credit points. They are handed out each week, and should be handed in at the first lecture the week after. *The first five assignments* cover the subjects presented in the lectures the same week and each assignment give maximally 4 credit points. The first part of the *sixth assignment* covers the last week's lectures and can give 4 credit points while the second part of the sixth assignment covers the whole course and can give maximally 6 credit points. Note that your individual understanding is in focus – you are free to cooperate with other students during the solution of the problems, but your answers *must be formulated from your personal understanding*. *Measures will be taken in cases of plagiarism*!
- ***Group work sessions*** at the class exercises may provide 12 credit points in total. Handed in protocols for each session are graded "pass" or "fail". Constructive participation is a minimum requirement for the "pass" grade. Protocols graded "pass" in 4-6 sessions give 12 credit points while protocols graded "pass" in 2-3 sessions give 6 credit points.

COURSE PROGRAM

Week	Day	Date	Time	Place	Le/Ex	Topic
12	Mon	20 Mar	10-12	E32	Le 1	Fusion in nature, future energy needs, energy alternatives (Ch 1.1).
	Wed	22 Mar	15-17	E32	Le 2	Energy alternatives, cont'd., fusion reactions, brief fusion history (Ch 1.2).
	Thu	23 Mar	10-12	E32	Ex 1	Le 1, 2
13	Mon	27 Mar	10-12	L21	Le 3	Lawson criterion, quality parameters of the fusion plasma (Ch 1.2, 2).
	Wed	29 Mar	15-18	E36	Le 4	Plasma models; particle, kinetic and fluid models (Ch 2).
	Thu	30 Mar	10-12	E32	Ex 2	Le 3, 4
14	Mon	3 Apr	10-12	E35	Le 5	Equilibrium, plasma waves (Ch 3, 4).
	Wed	5 Apr	15-18	E32	Le 6	Stability (Ch 4).
	Thu	6 Apr	10-12	E36	Ex 3	Le 5, 6
16	Tue	18 Apr	10-12	E32	Le 7	Transport (Ch 5).
	Wed	19 Apr	15-17	E32	Le 8	Transport cont'd (Ch 5).
17	Wed	26 Apr	15-17	E32	Ex 4	Le 7, 8
	Thu	27 Apr	10-12	E32	Le 9	Radiation, boundary, heating (Ch 6).
18	Wed	3 May	15-17	E32	Le 10	Diagnostics (Ch 7). Visit to the Alfvén laboratory.
	Thu	4 May	10-12	E32	Ex 5	Le 9, 10
19	Mon	08 May	10-12	E33	Le 11	Alternative concepts, inertial confinement fusion (Ch 8).
	Wed	10 May	15-17	E32	Le 12	Reactor, safety, environment (Ch 9).
	Thu	11 May	10-12	E32	Ex 6	Le 11, 12



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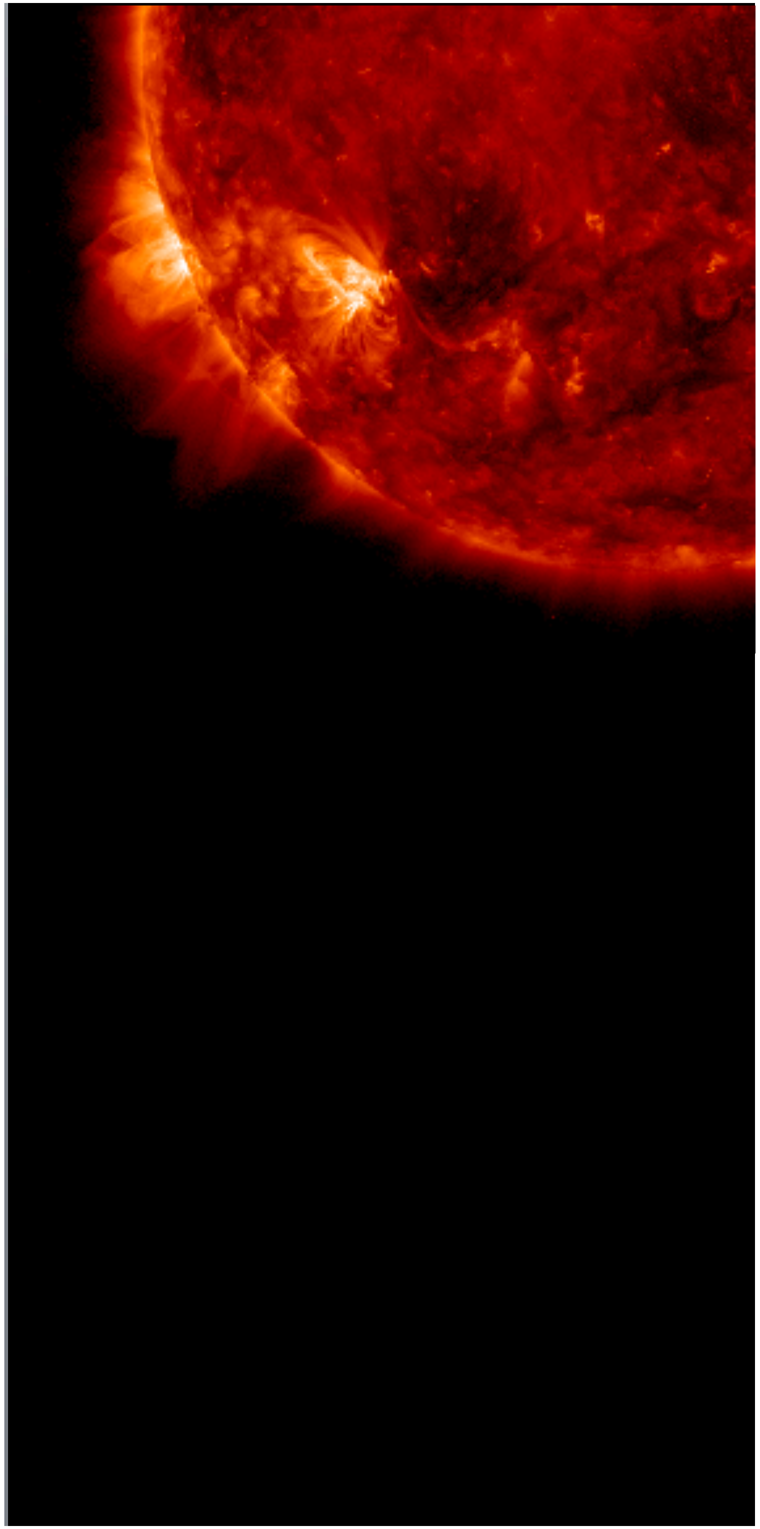
  First five assignments
  cover subjects presented in the lectures the same week; each assignment give maximally 4 credit points.

  Sixth assignment
  first part covers same week's lectures - can give 4 credit points
  second part covers whole course - can give 6 credit points.

- ***Group work sessions*** may provide
  12 credit points for ***constructive*** participation in ≥ 4 sessions
  or
  6 credit points for ***constructive*** participation in 2-3 sessions.



FUSION PLASMA PHYSICS
Alfvén Laboratory, KTH
Jan Scheffel, Per Brunsell

HOME ASSIGNMENT 1
(pages 1-30)
ENERGY AND FUSION RESEARCH
ED2200, Spring 2017

Answer the following questions <u>in detail</u> *on this sheet* (+ back side if needed).
Use proper English!
Hand in no later than at the following week's first lecture *with your name*!
Each home assignment may provide 4 credits to the examination.

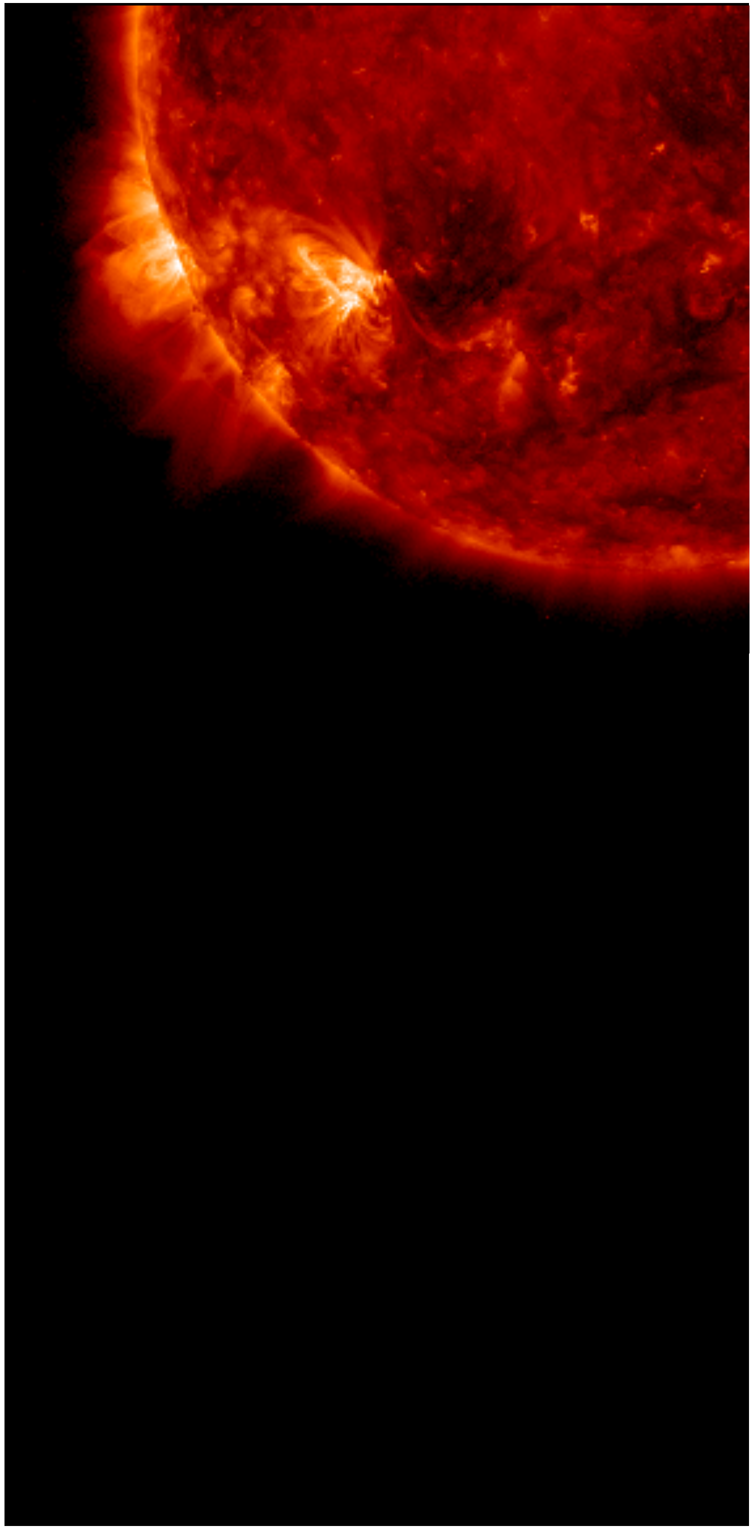
NAME, in block letters:____

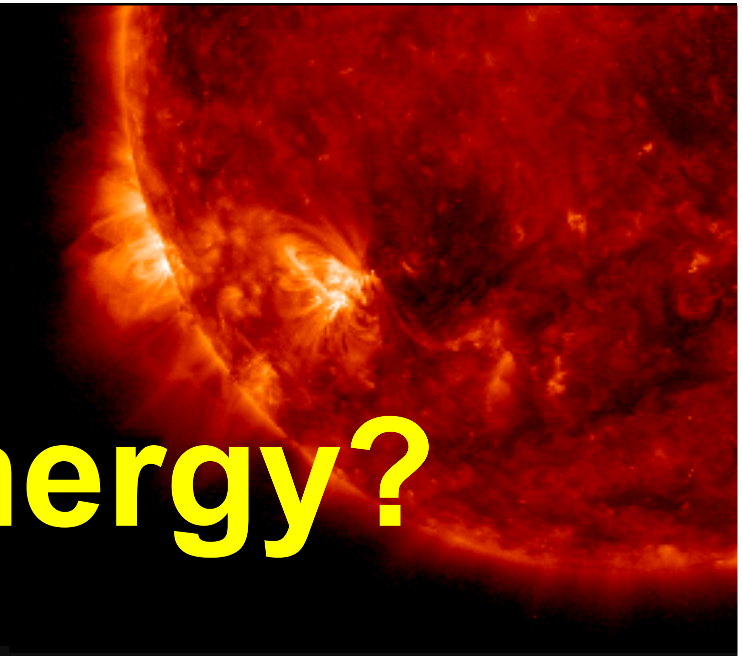
1) What do you consider most important in this part of the course? Answer with two topics and *motivate* why.

2) What are the main problems with today's global electricity production?

3) What energy sources do you think can replace the fossil fuels in the future? Motivate (including an environmental point of view)!

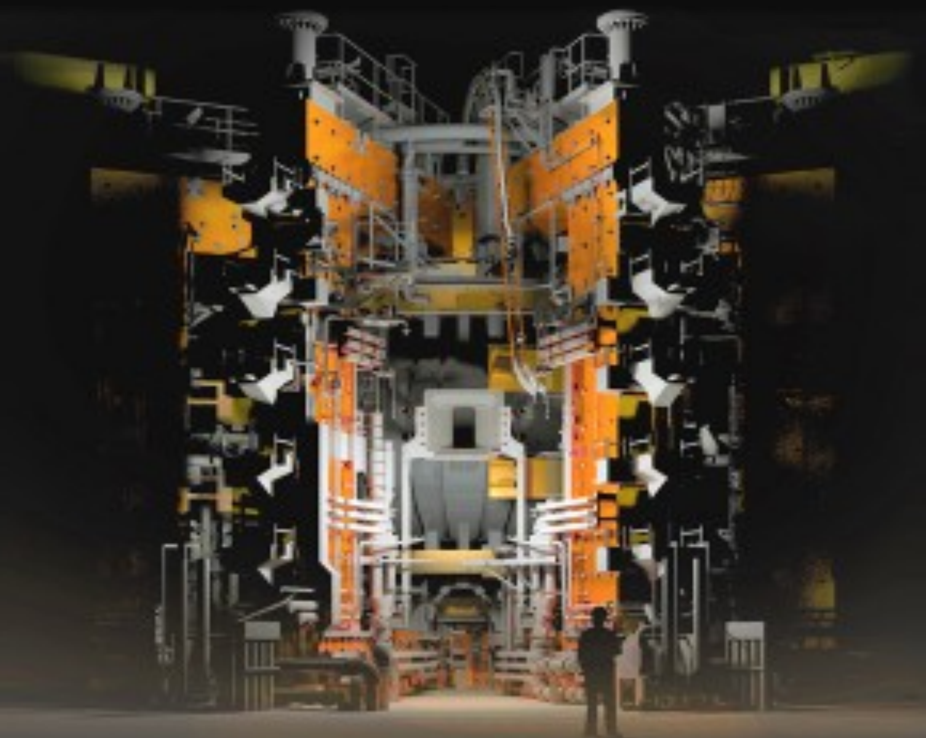
4) *Derive* an expression for the reactivity <σv> from *first principles*, using Fig. 1.19, for fusion reactions in a two species Maxwellian plasma. Give units and explain, in your own words, what <σv> measures.



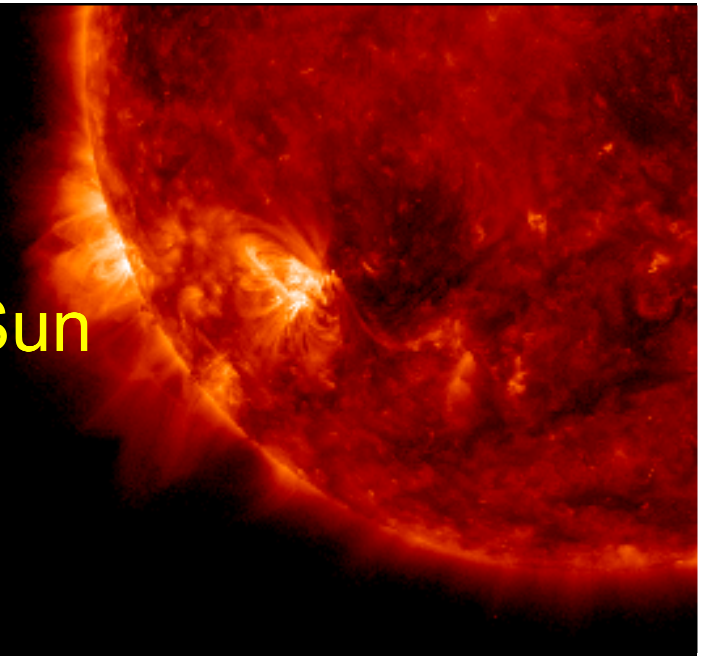


What is fusion energy?

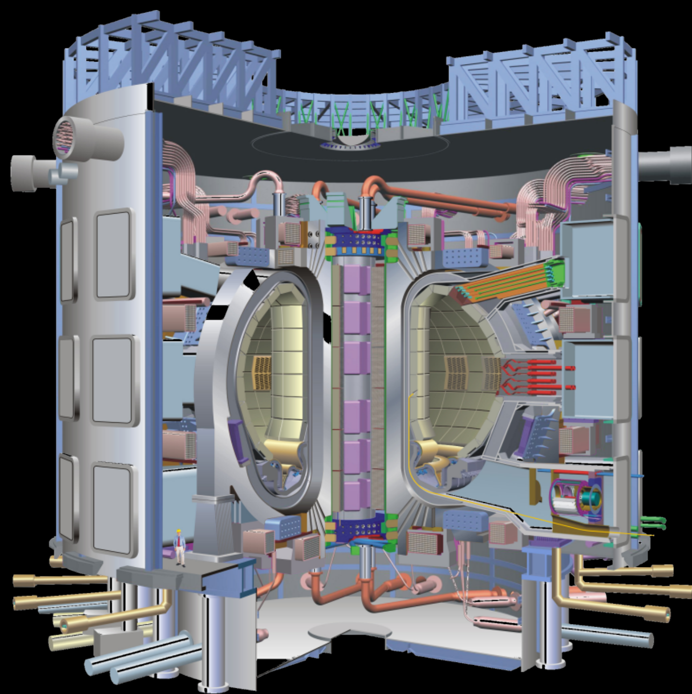
Jan Scheffel, professor
Fusion Plasma Physics
KTH



Background

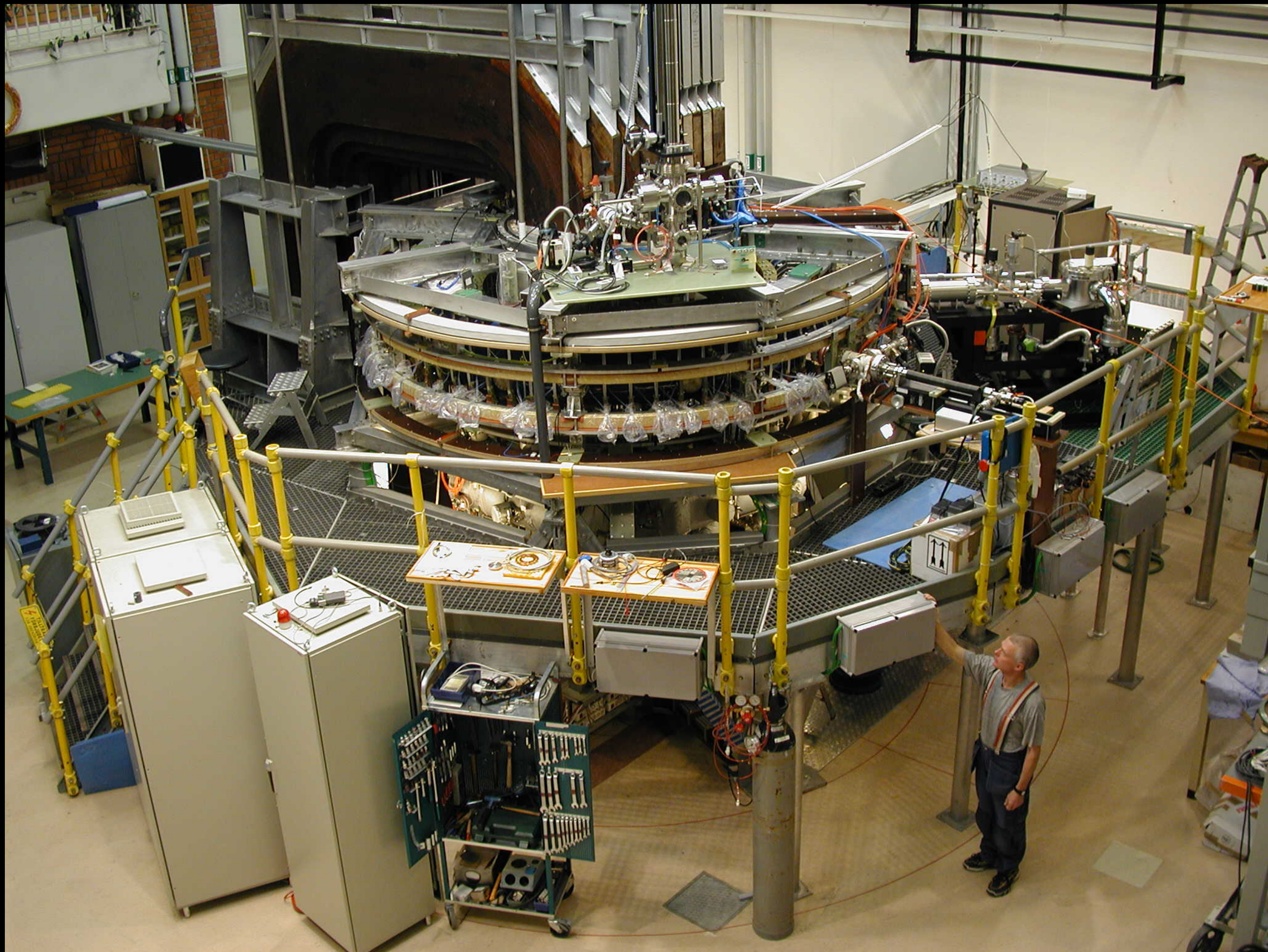


- Fusion is the energy source of the Sun
  - On earth – a potentially sustainable, clean energy source
  - But – a great technical challenge!
- Today we build ITER – the first reactor to produce more energy than it consumes
- How do we move from ITER to commercial power stations?

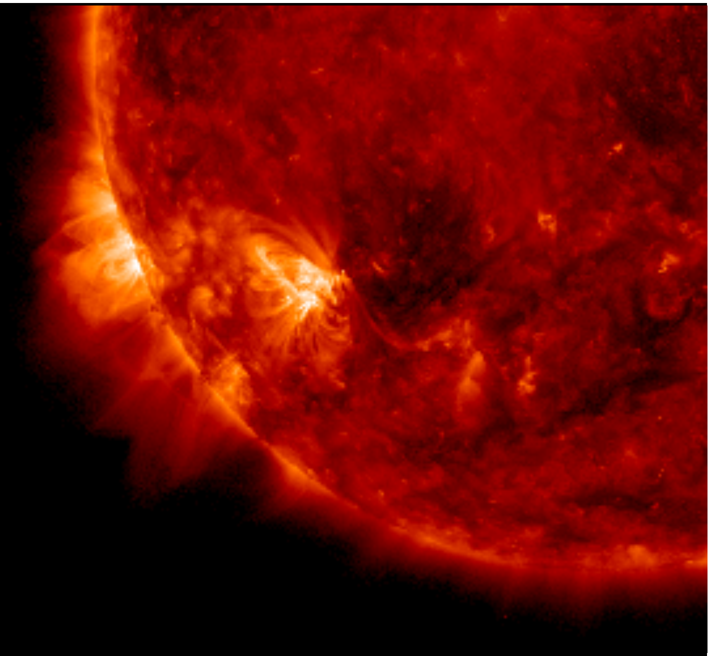


EXTRAP T2R, Alfvén Laboratory, KTH

Scandinavia’s only fusion experiment – a reversed-field pinch



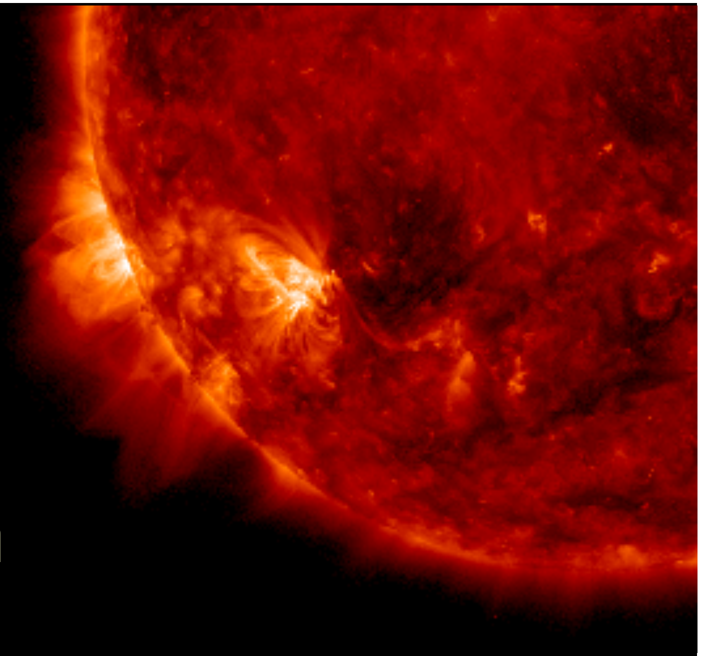
Question



ITER will be built in

- Spain
- Canada
- Japan
- France

Question



ITER will produce 500 MW from

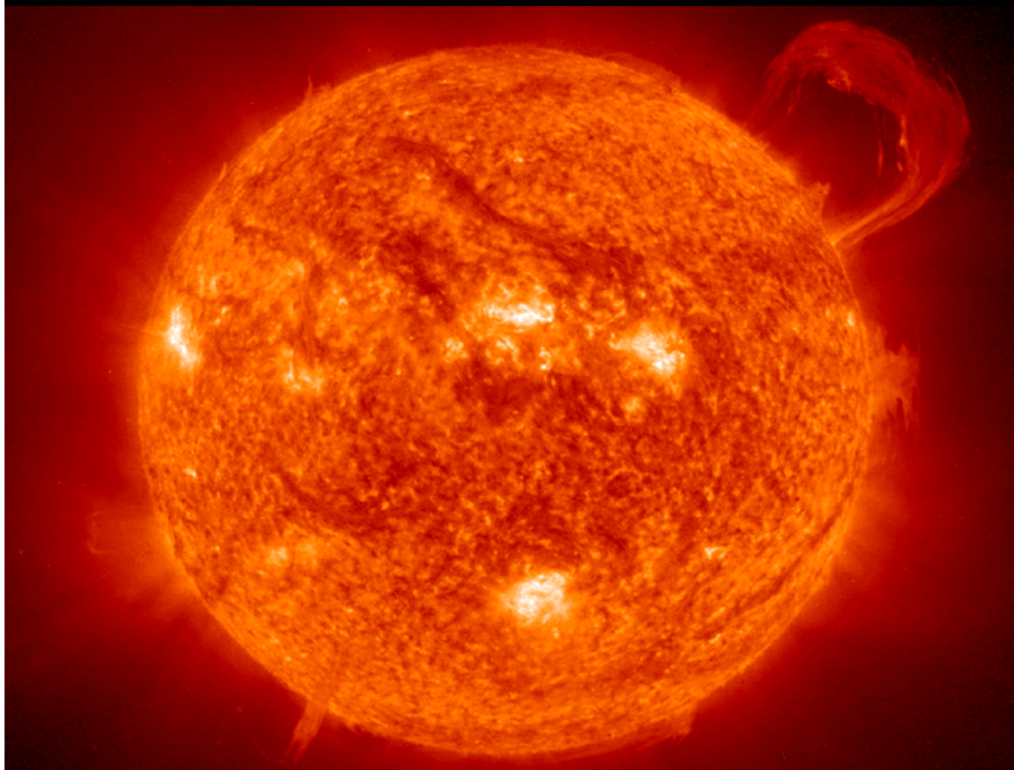
- **D-T reactions**
- **D-D reactions**
- **p-p reactions**
- **p-B reactions**

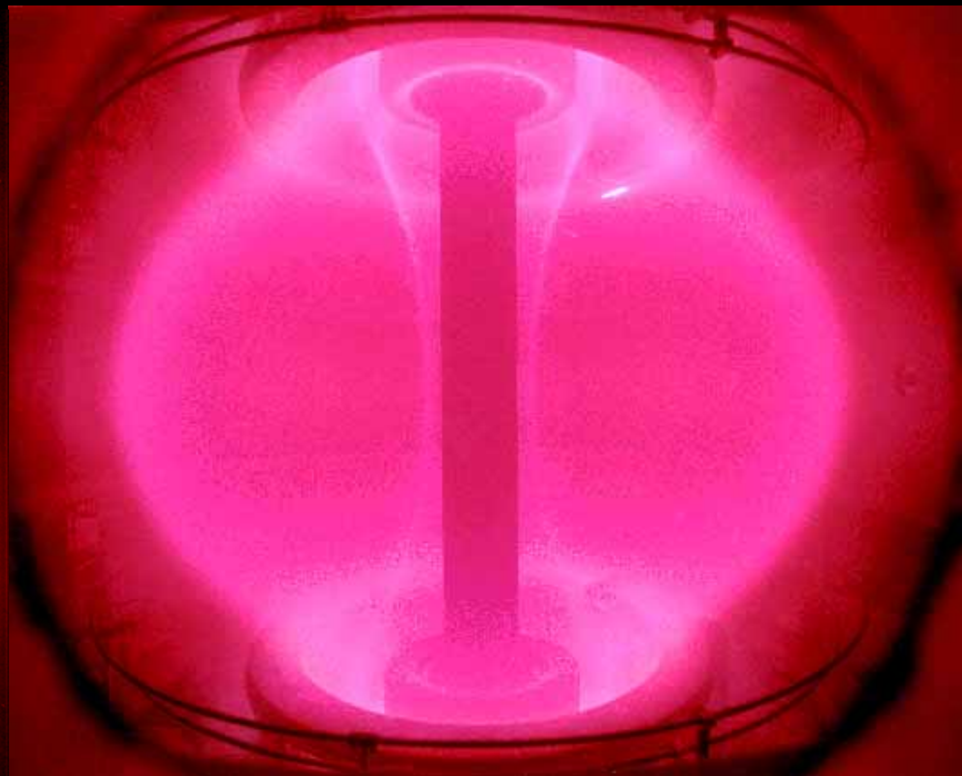
Question

Which criterion determines breakeven?

- **Double product criterion**
- **Triple product criterion**
- **Shafranov's criterion**
- **Alfvén limit**

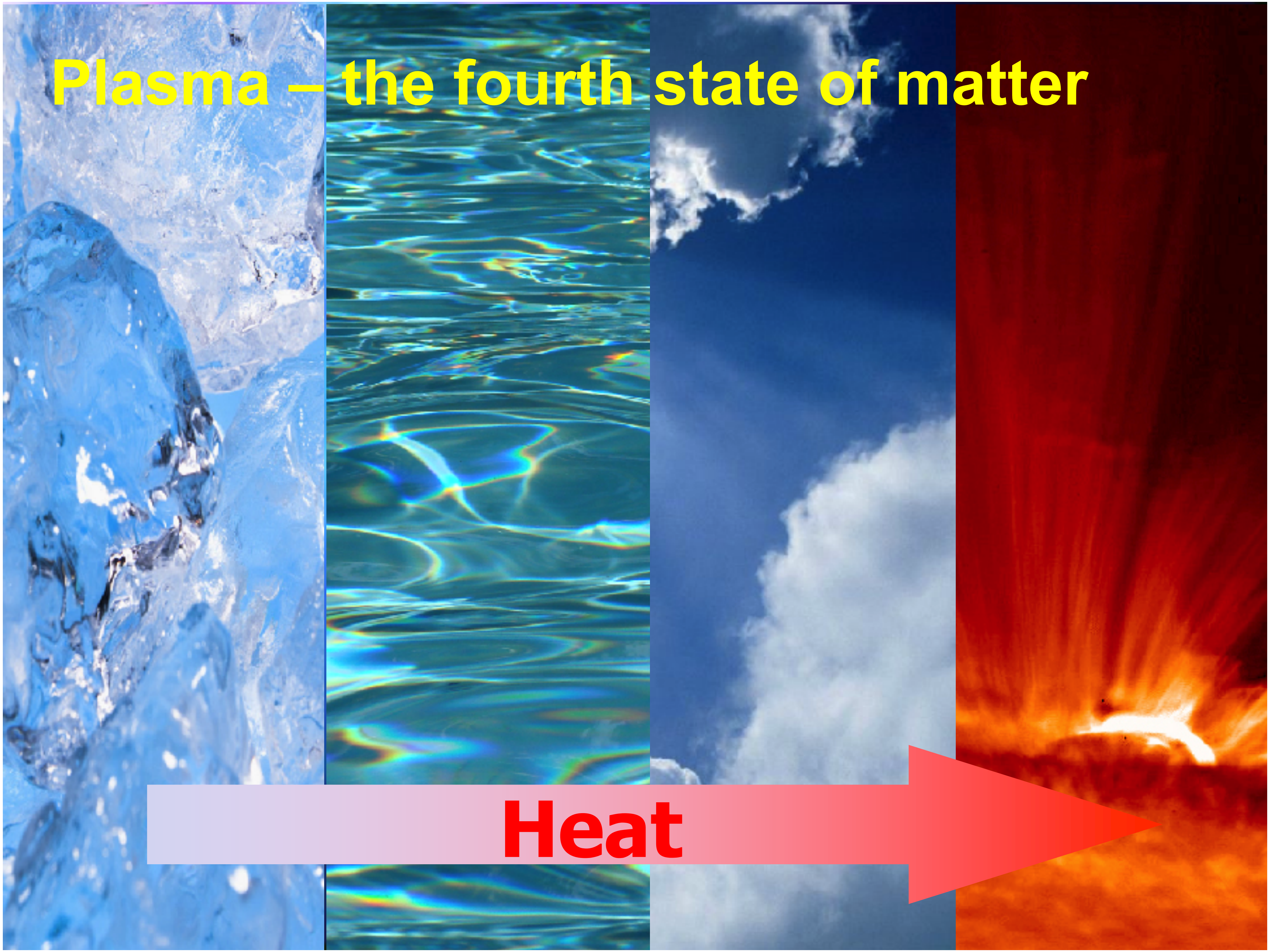
What is fusion energi?



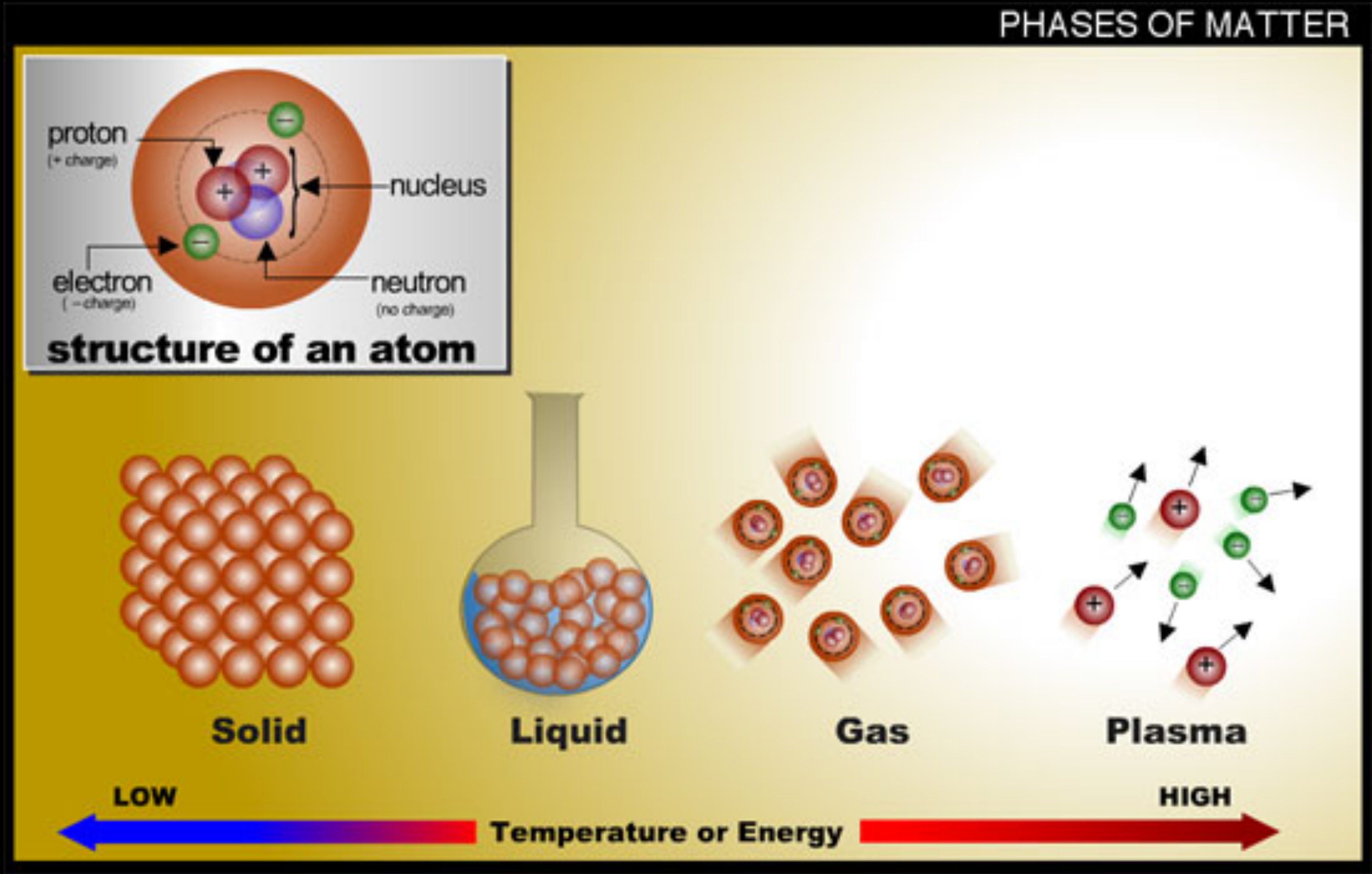


Picture courtesy of the
SOHO/EIT collaboration

Plasma – the fourth state of matter



Plasma



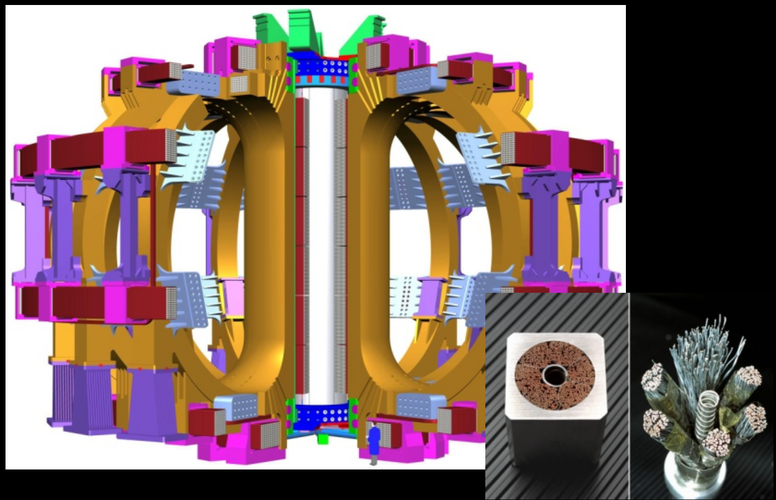
PHASES OF MATTER
proton
(+ charge)
nucleus
electron
(– charge)
neutron
(no charge)
structure of an atom
Solid
Liquid
Gas
Plasma
LOW
HIGH
Temperature or Energy

Plasma – needed for today's technology!

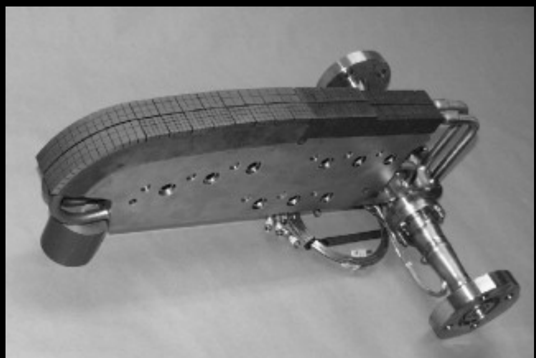
01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

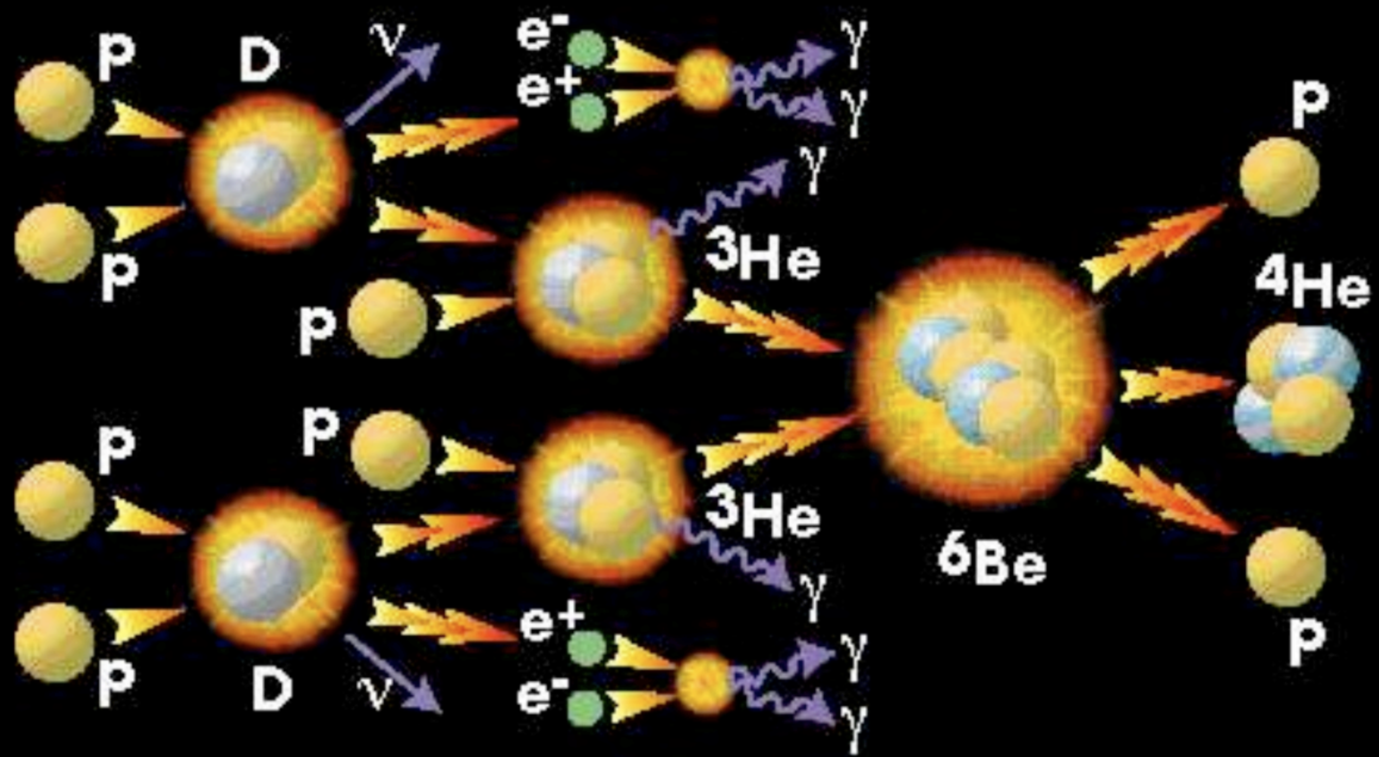
Fusion Technology - Spin Off Examples

Superconducting Magnets for medical use



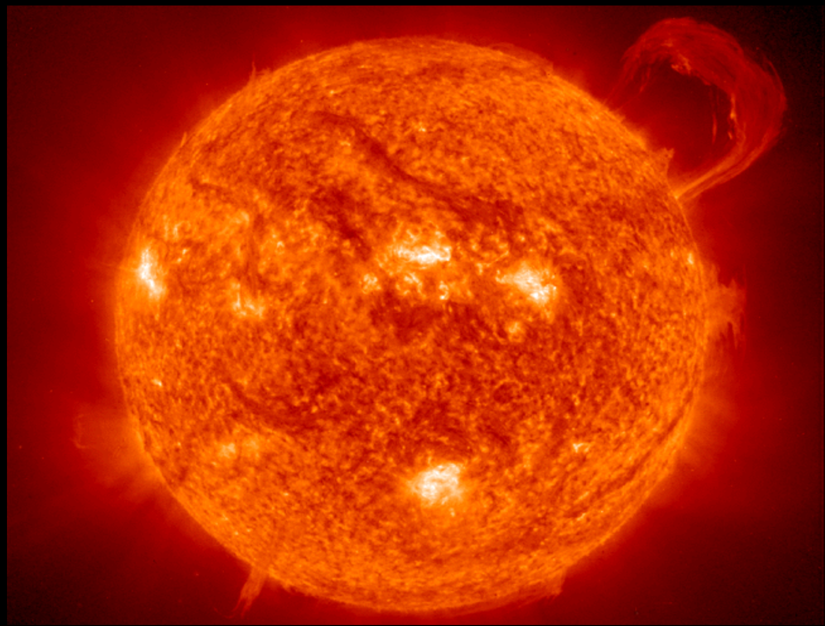
New materials: CFC for Airplane breaks





Fusion reactions in the sun

The energy we use on earth started as fusion energy



Renewables (direct energy):

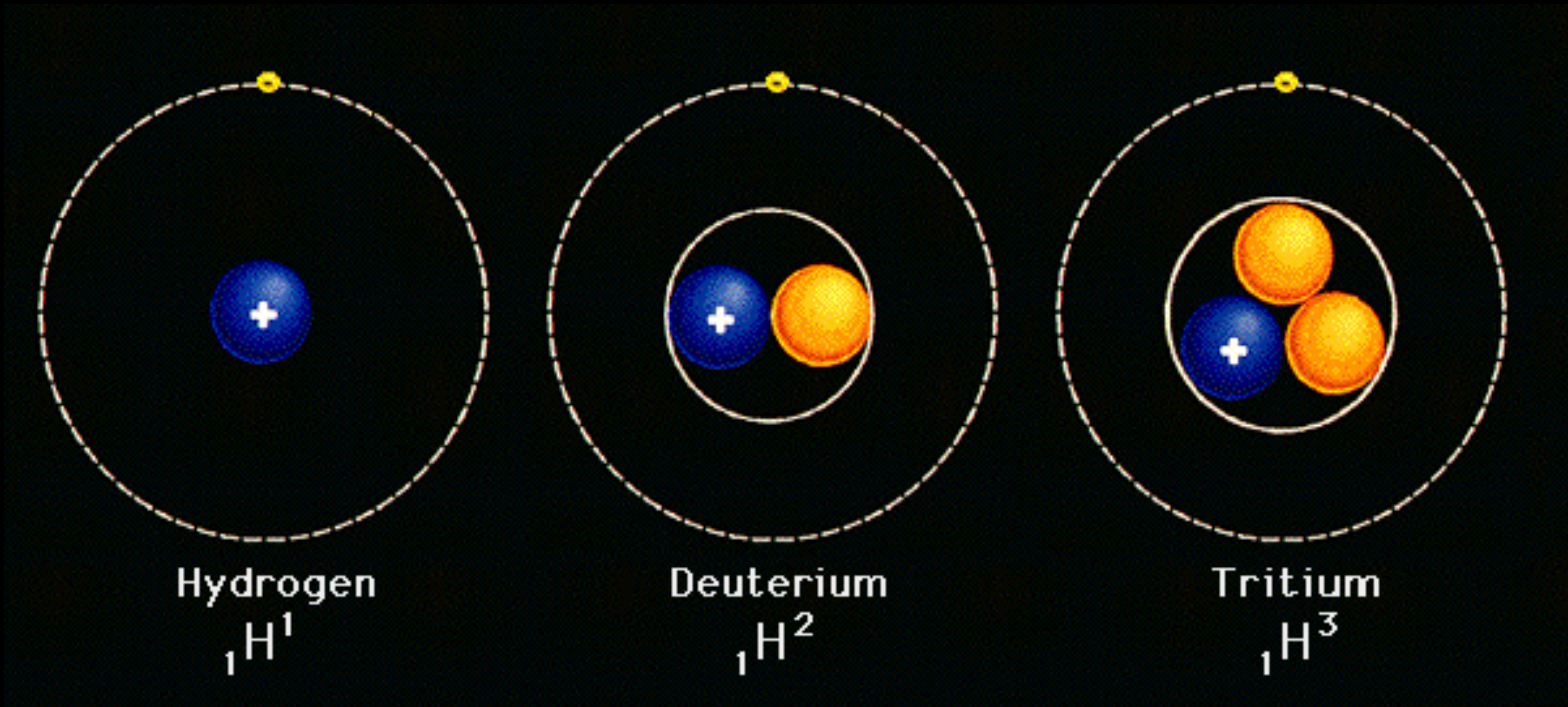
* solar, wind, hydro

Fossil (stored solar energy in organic material):

* coal, oil, gas

Fission (uranium is formed during super nova explosions)

HYDROGEN ISOTOPES



Radioactive
Half life
12.6 years

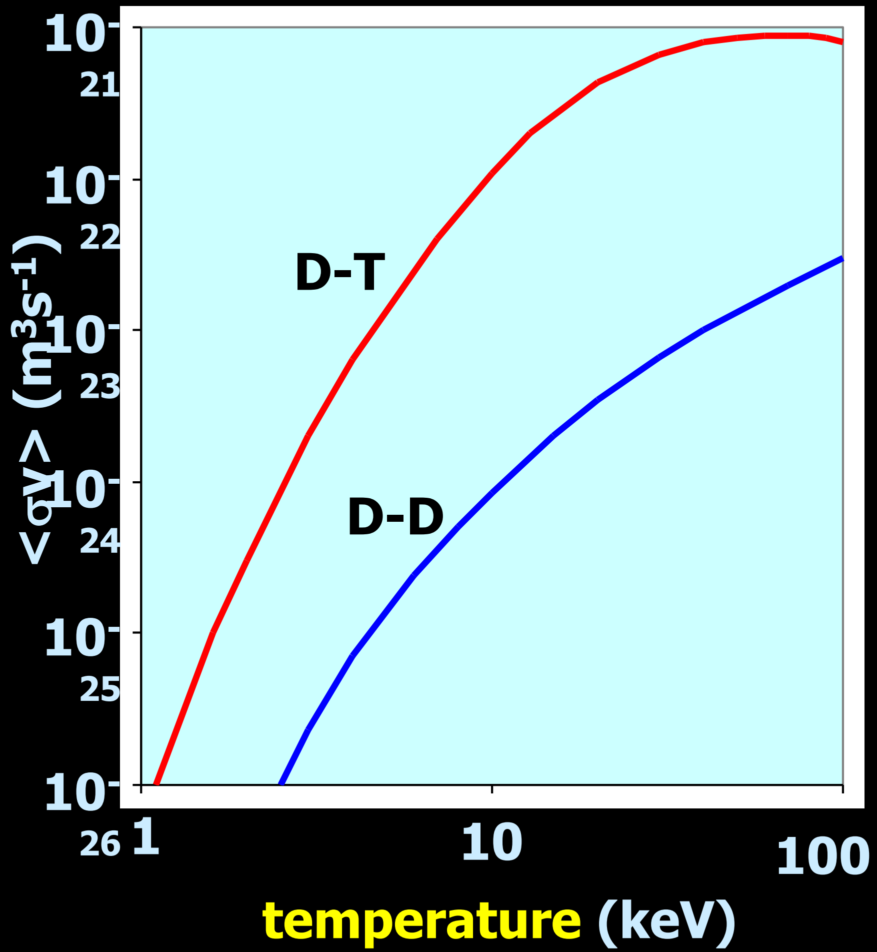
Fusion reactions

$$D + T \rightarrow {}^4He(3.5\,MeV) + n(14.1\,MeV)$$

- **Fusion power per unit volume:** $p_{fusion} = n_D n_T \langle \sigma v \rangle E$

Where
n is the fuel ion density
E is the fusion energy per reaction

REACTIVITY

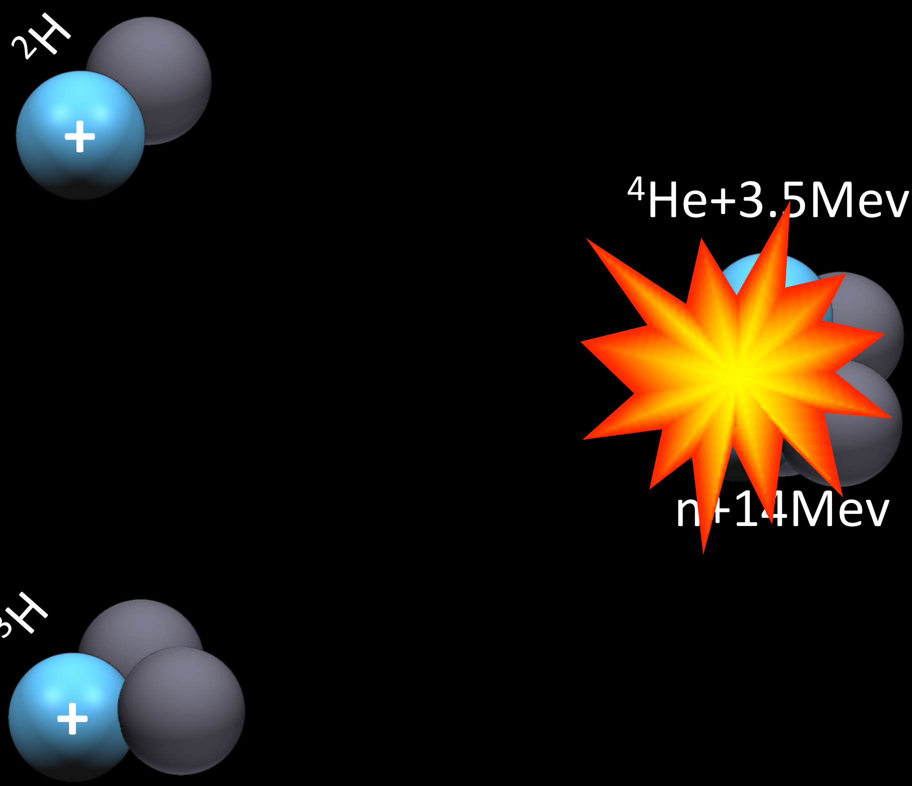


Fusion reactions on Earth

(deuterium) *(tritium)* *(helium)* *(neutron)*

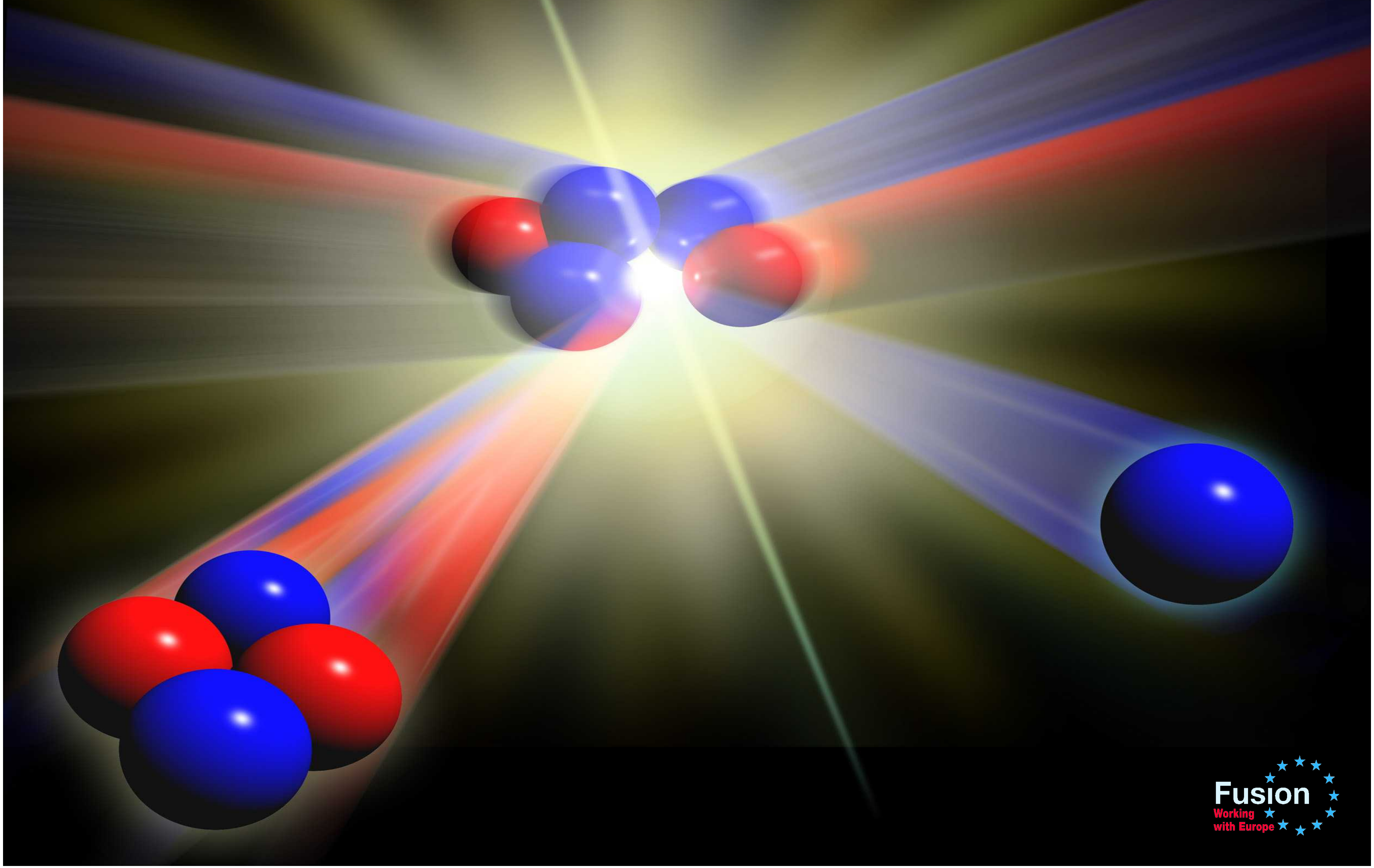
$^{2}H + {}^{3}H \;\; \text{->} \;\; {}^{4}He + n$

Weight: 5.03 u -> 5.01 u



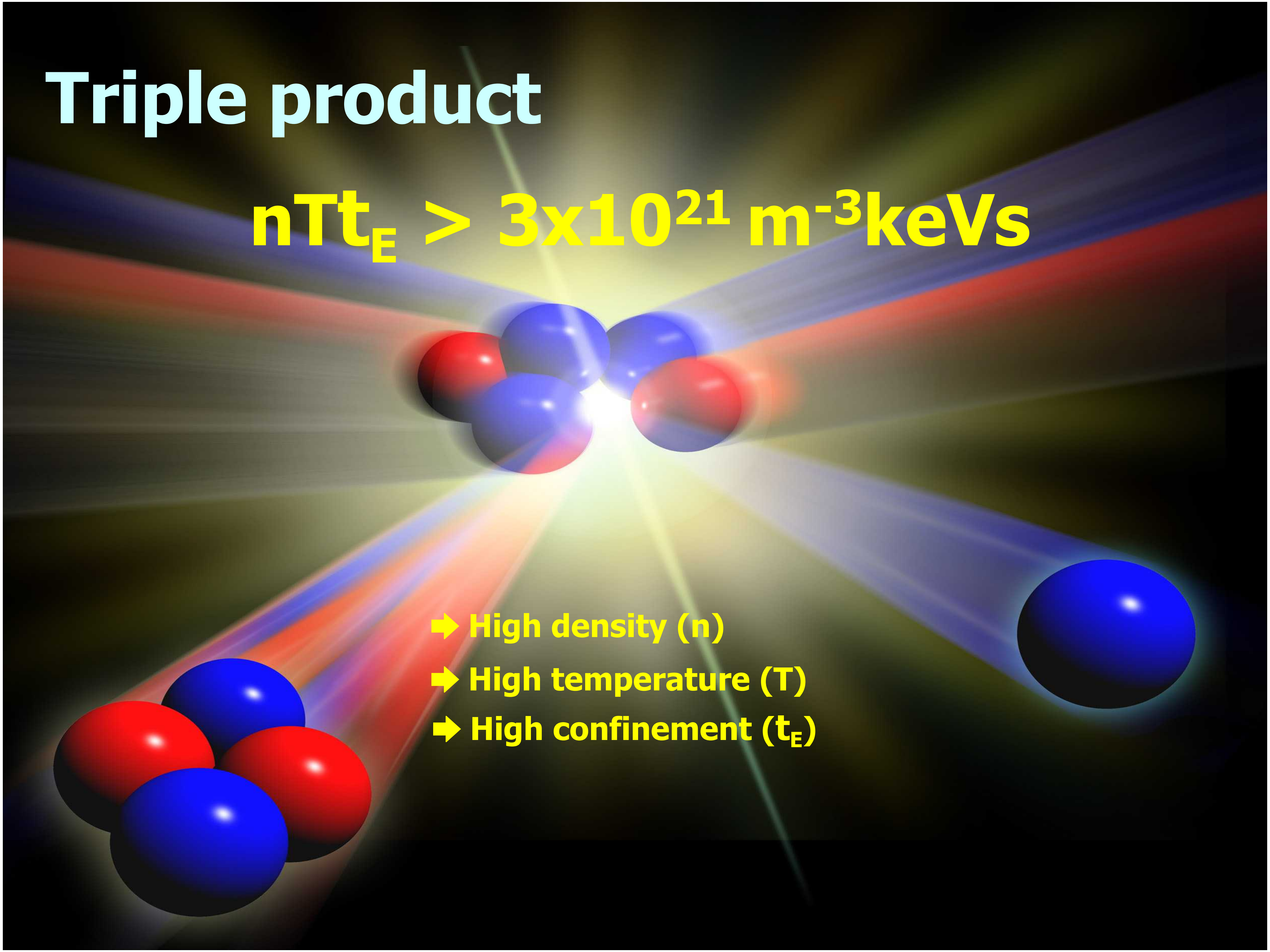
$1eV=1.6\ 10^{-19}J$

1 kg fusion fuel provides as much energy as 1 000 000 kg coal!



Triple product

$$nTt_E > 3\text{x}10^{21}\ \text{m}^{-3}\text{keVs}$$



- ➨ **High density (n)**
- ➨ **High temperature (T)**
- ➨ **High confinement (t_E)**

Energy confinement

How long is the energy in the system (home or plasma) ?

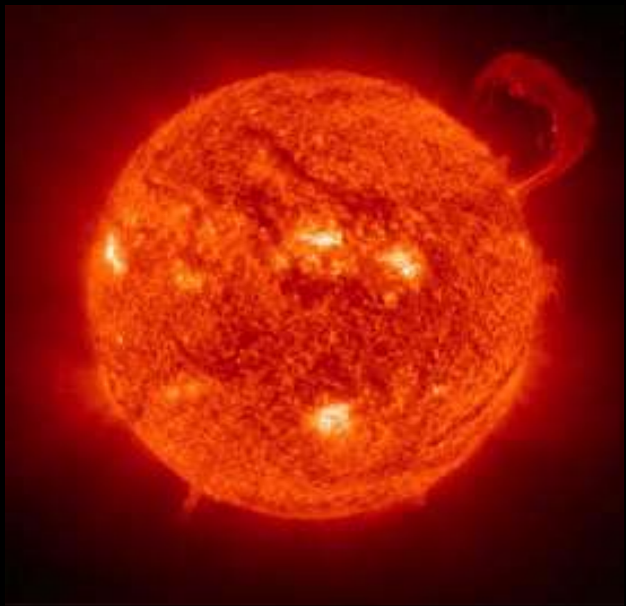
Energy confinement time $\tau_E = \dfrac{W}{P_{\text{loss}}}$ **W ~ energy density**

Home:
τ_E ~ 0.5-1 day
Winter ~ 90-120 days

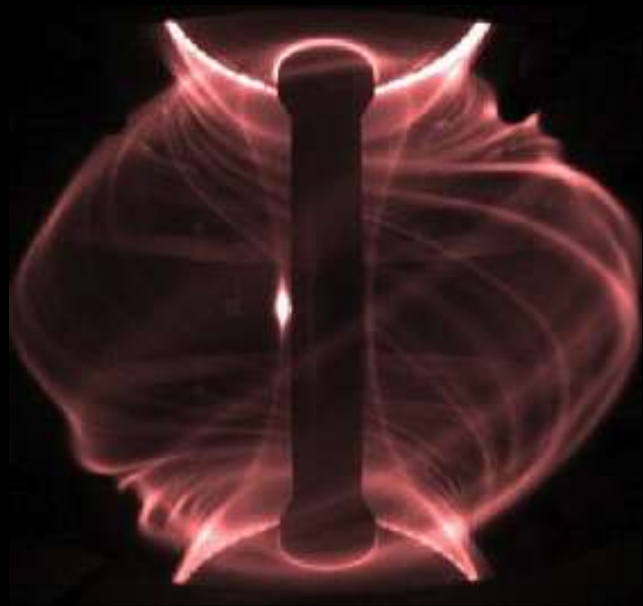
Plasma in tokamak:
τ_E ~ 0.2-1 seconds (JET)
Plasma duration ~ 30 s

The heat must be kept!

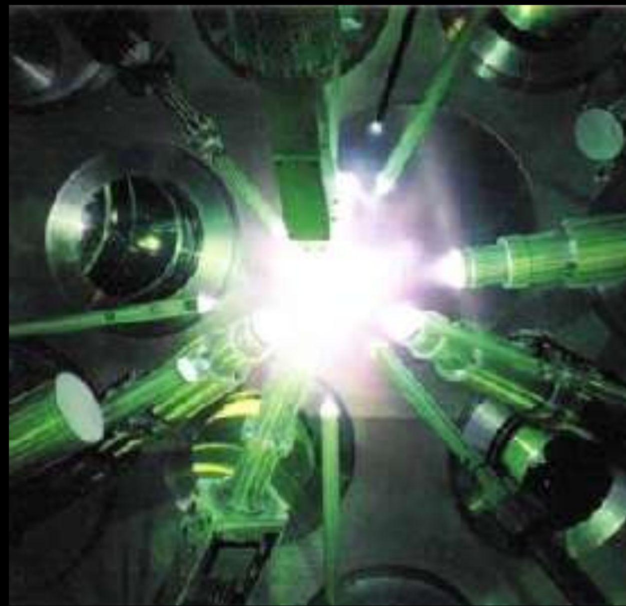
Confinement



gravitational



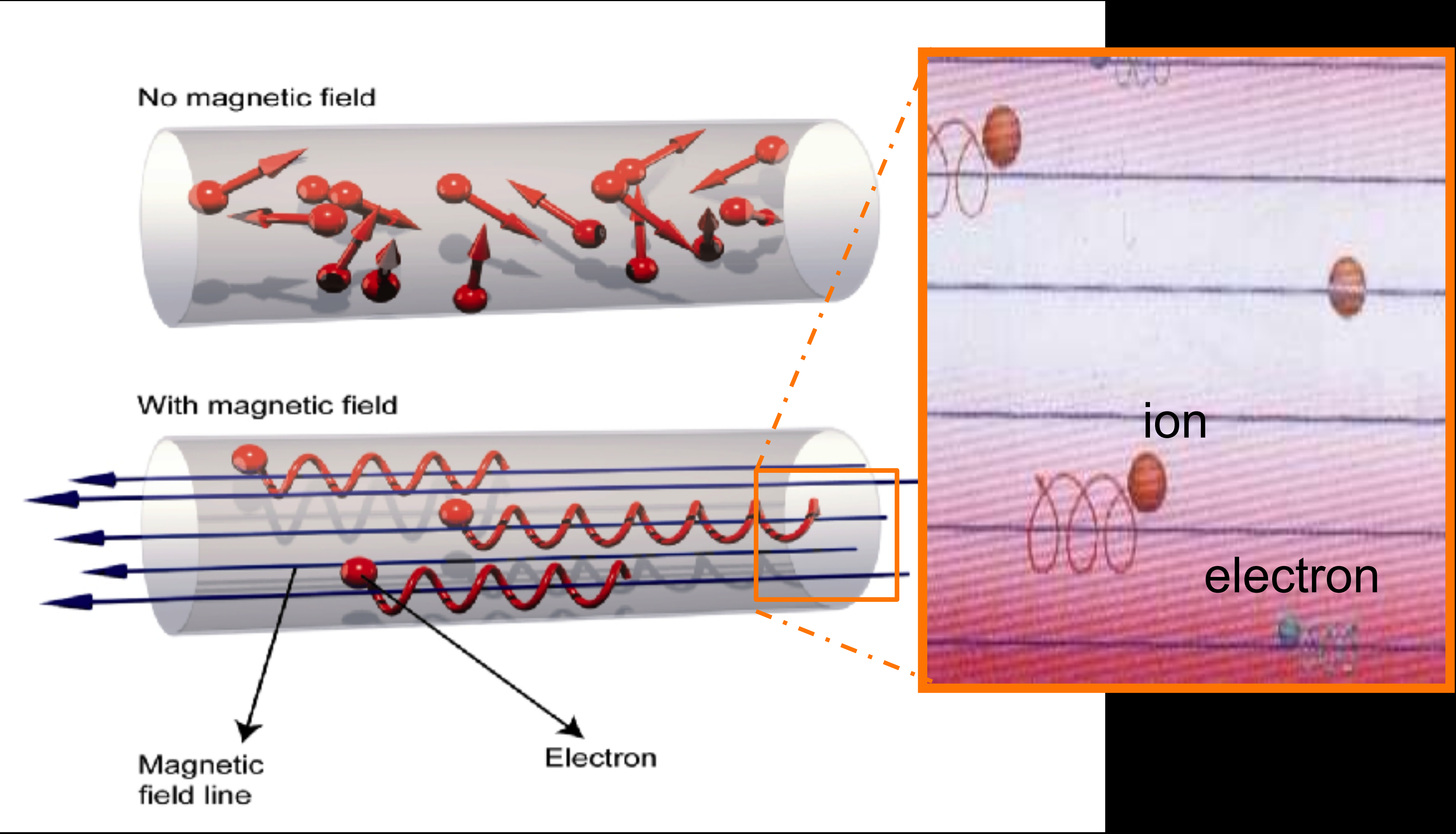
magnetic



inertial

Magnetic confinement appears most favourable for energy production on earth

Particle orbits in a magnetic field - 1



Particle orbits in a magnetic field - 2

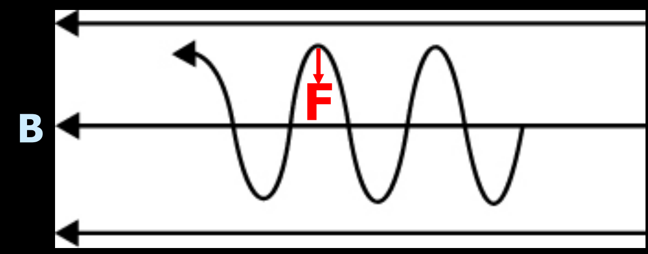
Charged particles moving in a magnetic field feel a force:

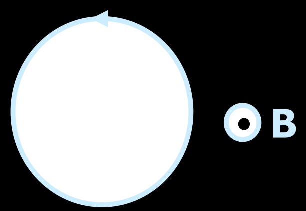
$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

Ions and electrons then move round the tokamak, orbiting around magnetic field lines

$$\frac{mv_\perp^2}{r_g} = qv_\perp B$$

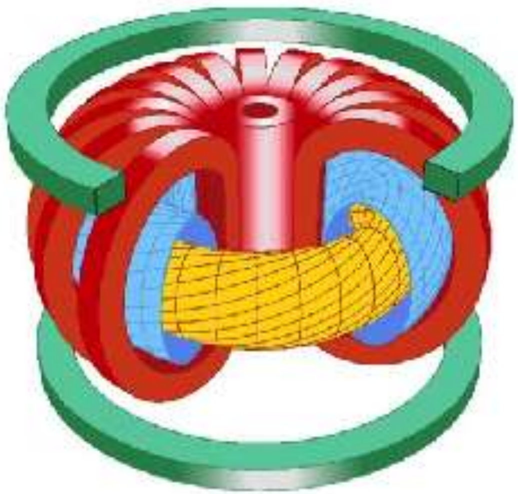
$$\text{radius} = r_g = \frac{\mathrm{m}v_\perp}{qB}$$





Different magnetic confinement schemes

Tokamak



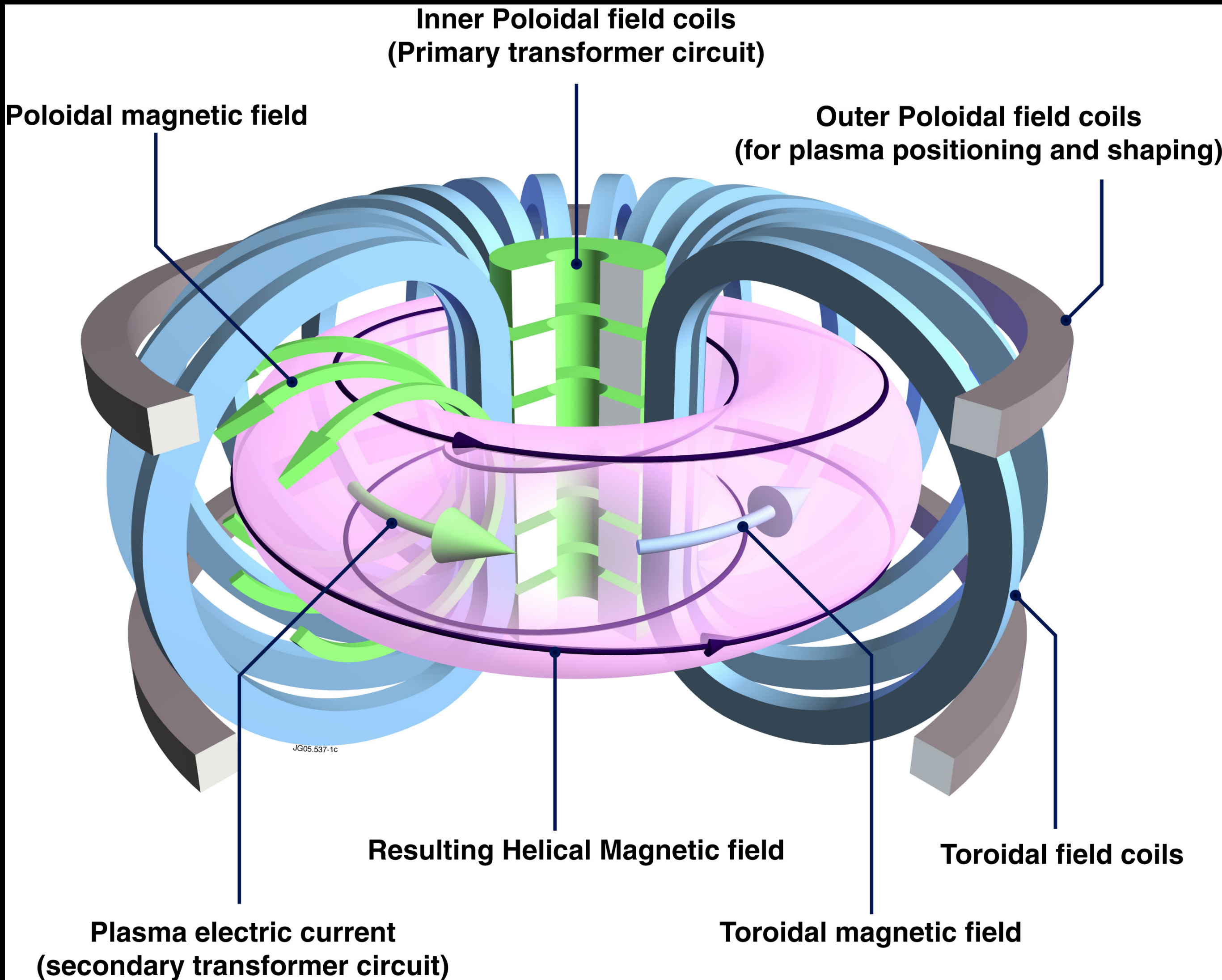
Stellarator

Reversed-field Pinch

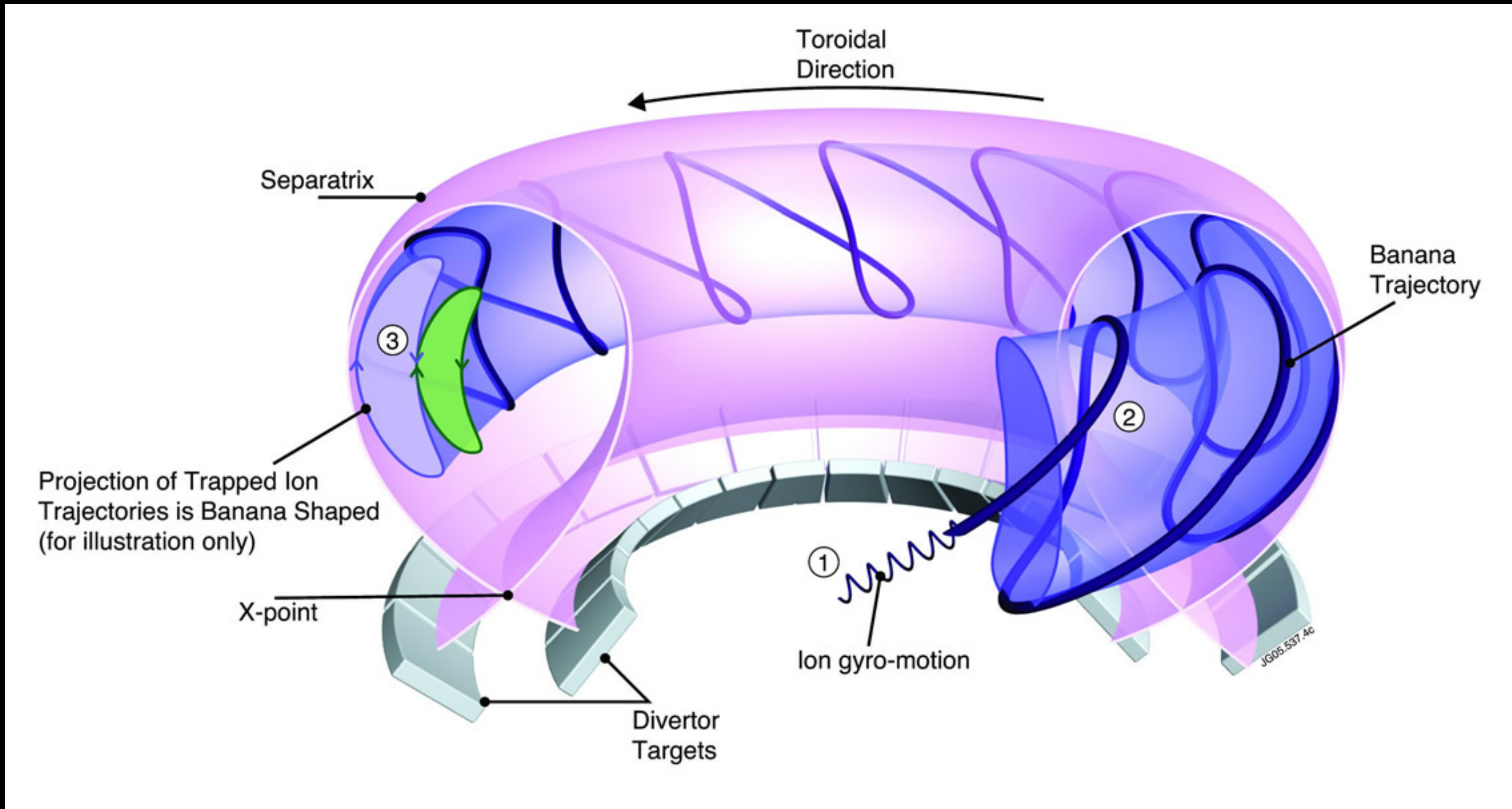
EU world leading

The tokamak is presently the main line

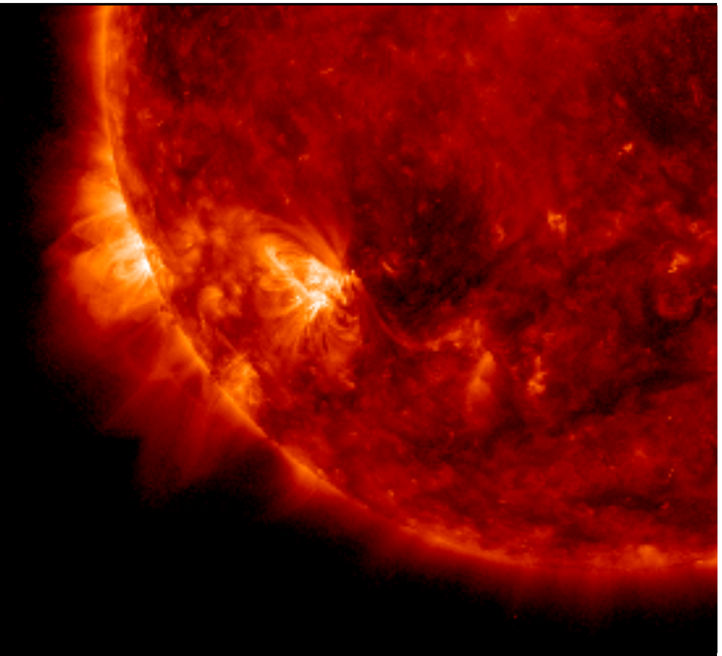
Magnetic confinement



Magnetic confinement



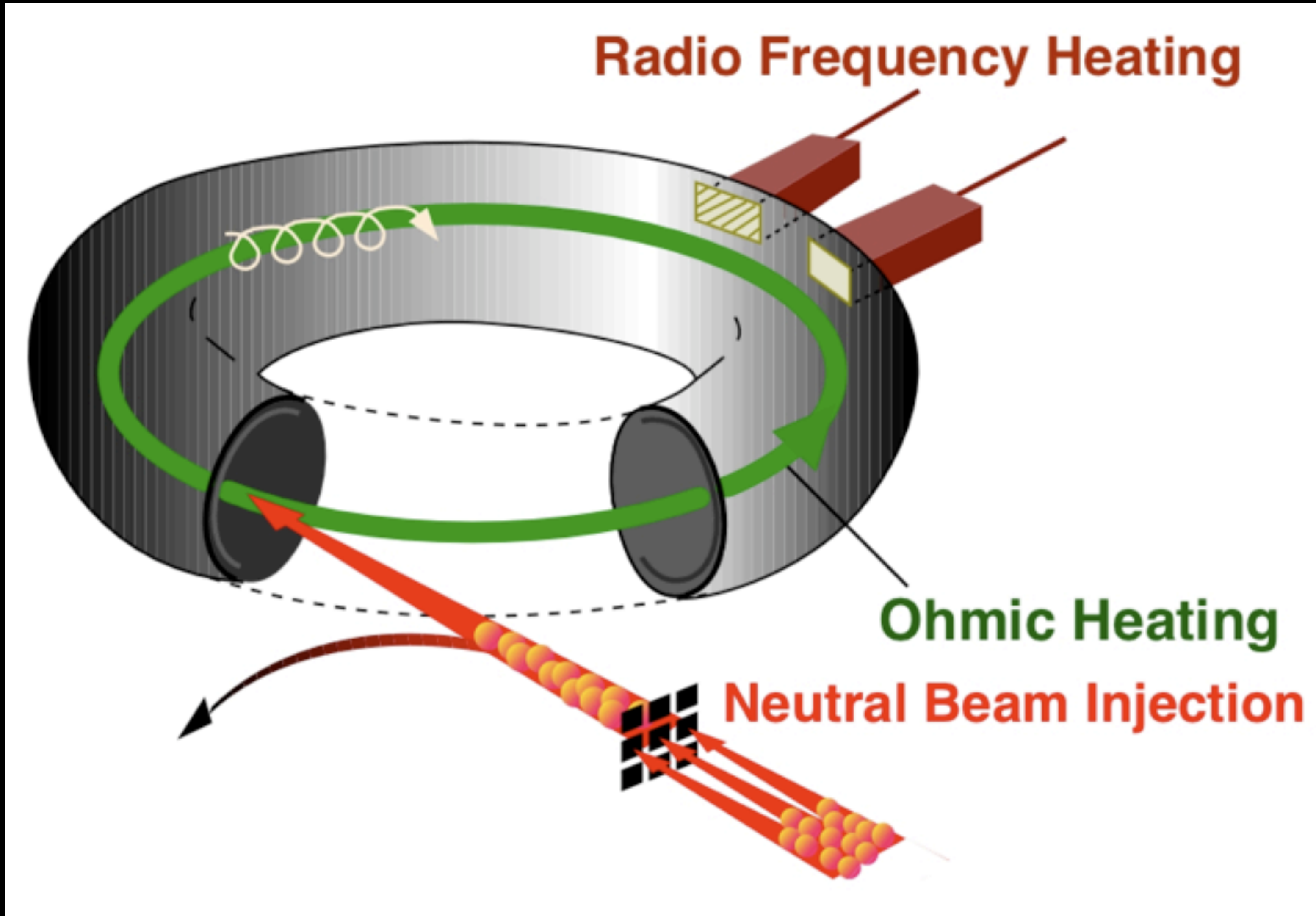
Question



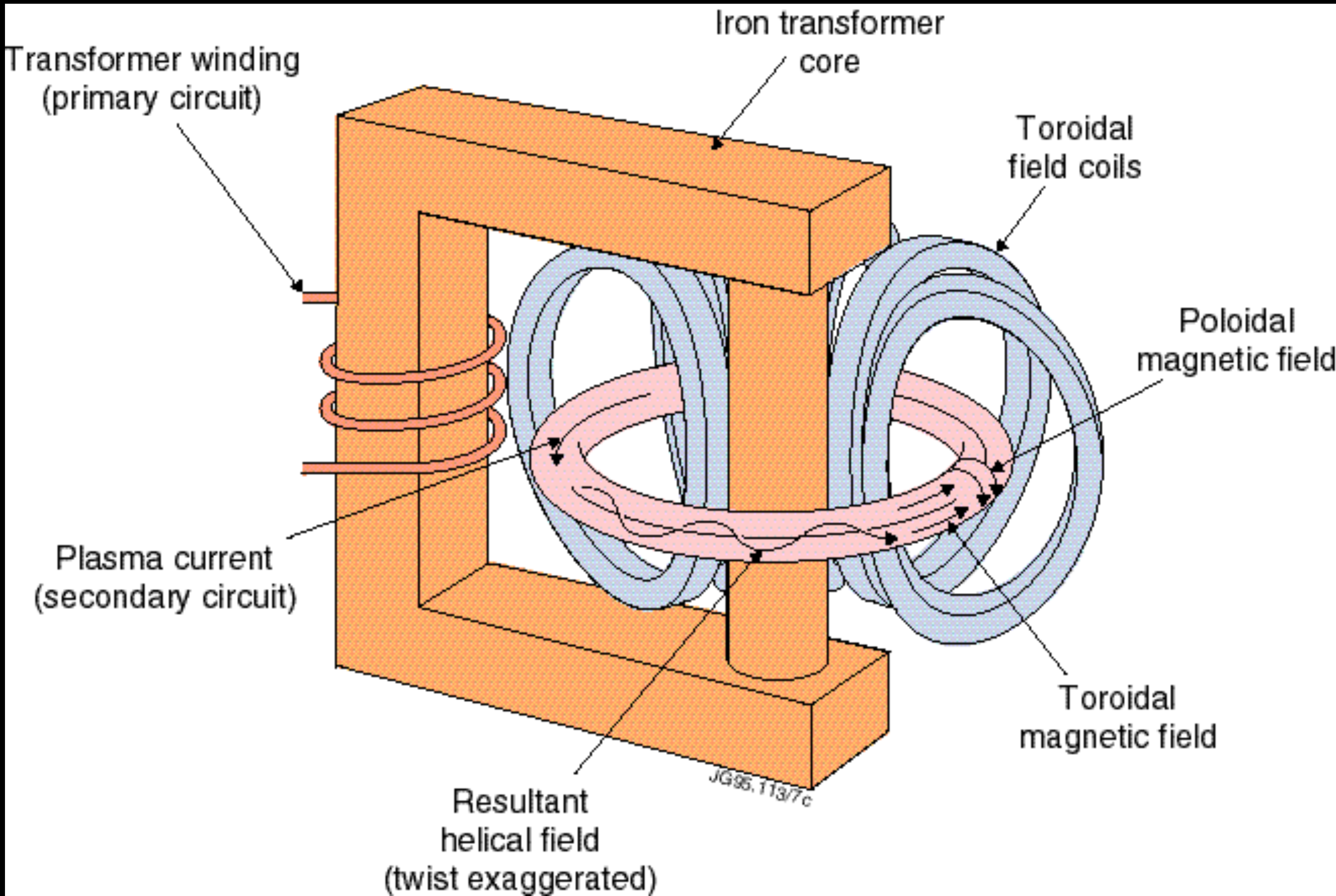
Which is <u>not</u> a way to heat a fusion plasma?

- **Radio frequency waves**
- **Neutral beam injection**
- **Adiabatic compression**
- **Ohmic heating**

Plasma heating



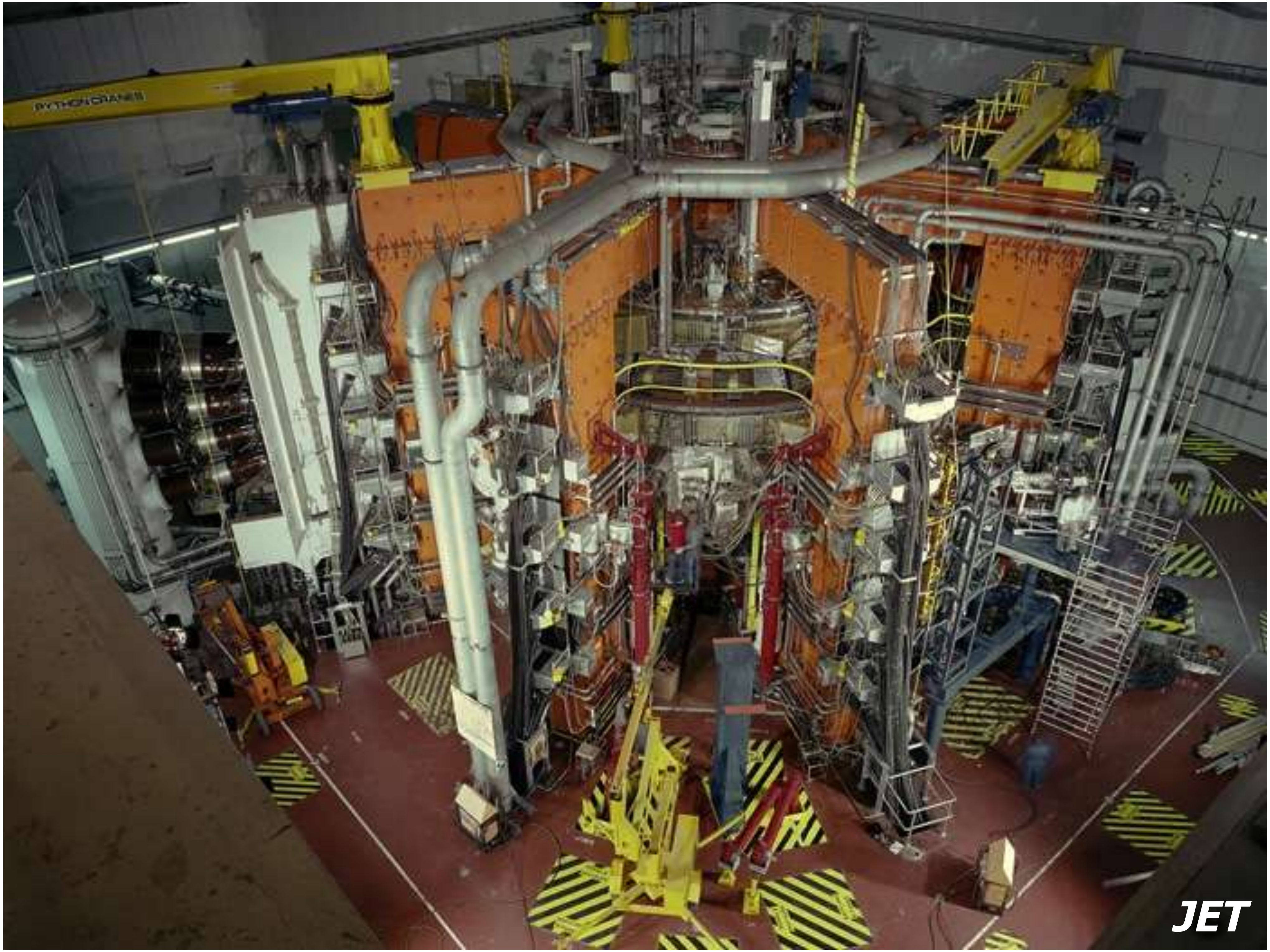
The Tokamak – successful magnetic bottle



Magnetic field coils

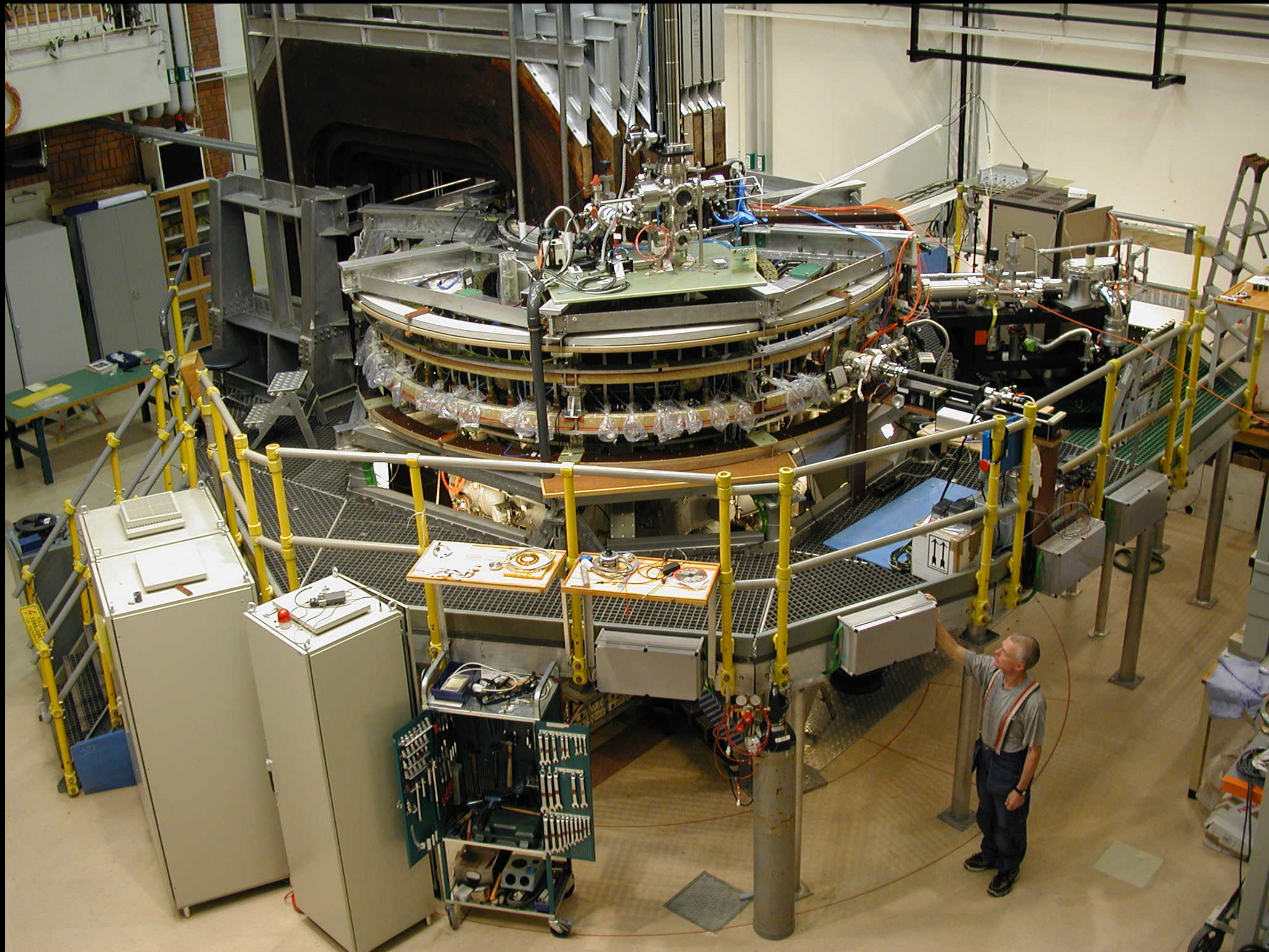
An octant section of JET's torus, held in a C-frame, being transported in 1982

Final octant section being installed in 1982

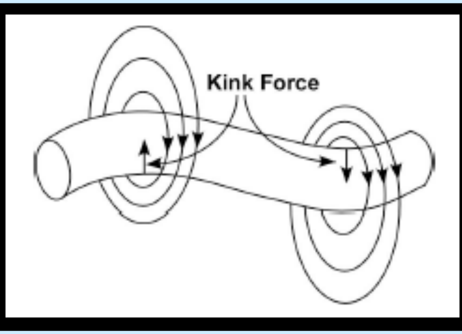

PYTHON CRANES
JET

EXTRAP T2R, Alfvén laboratory, KTH

Only fusion experiment in Scandinavia – a Reversed-field Pinch (RFP)

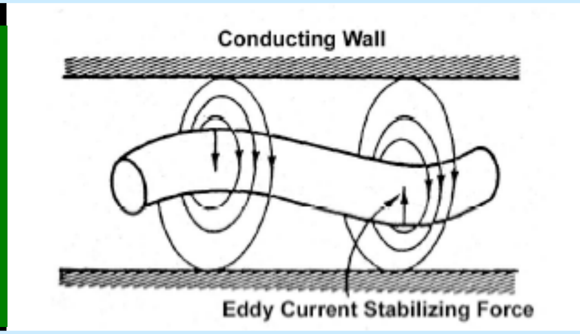


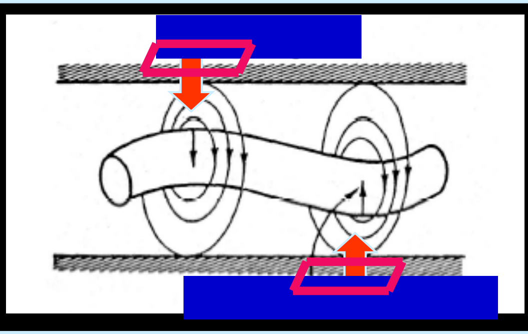
Plasma instabilities - and stabilisation



1. Plasma instability: small perturbations lead to growing deformations

2. Passive stabilisation: an electrically conducting shell confines the magnetic field and provides damping of the perturbation by the magnetic pressure at the wall

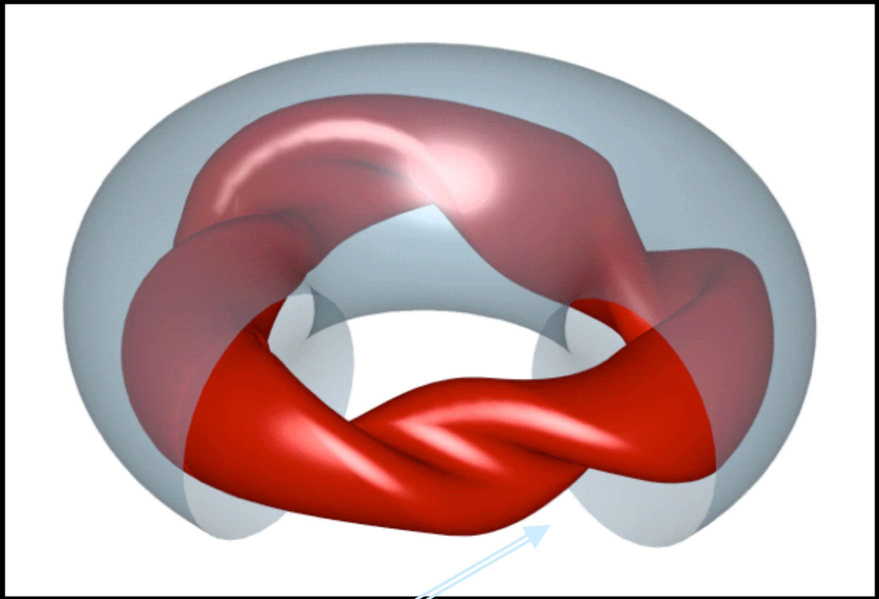




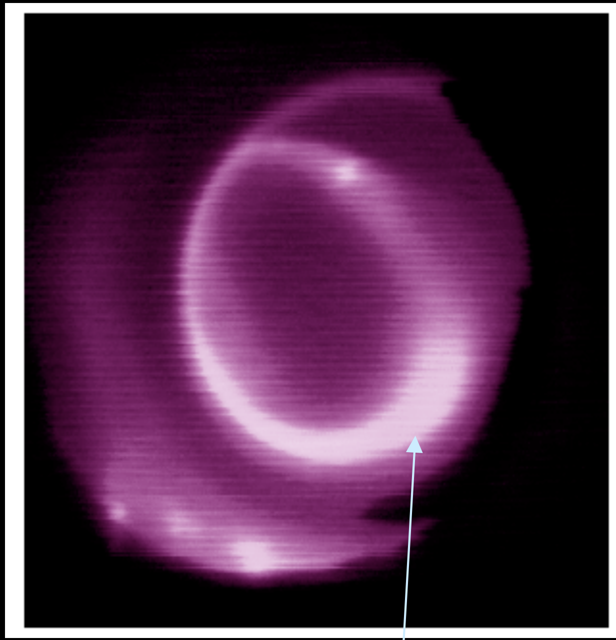
3. Active stabilisation: The perturbation can be completely damped when the shell is combined with outer magnetic coils that provide magnetic return forces on the plasma

Plasma perturbation in EXTRAP T2R

The plasma deformation grows in time (exaggerated here)

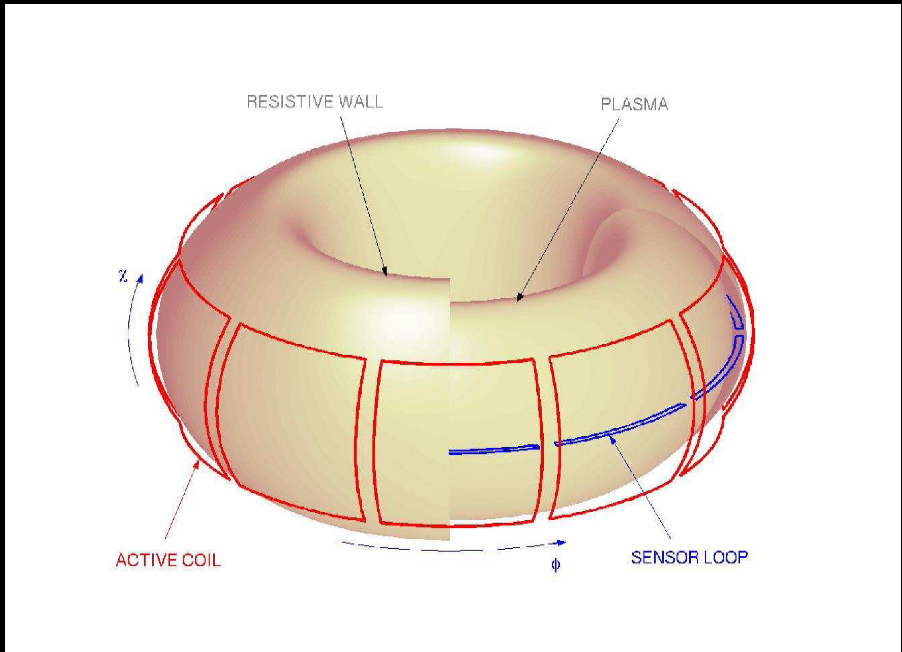


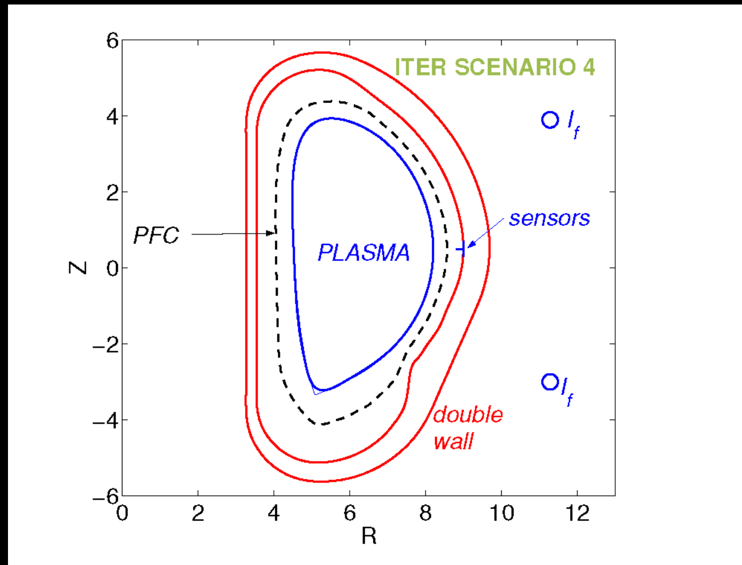
Camera view for picture at the right



Experiment, showing light from parts of wall that are in contact with the plasma

Potential for ITER





- **Active plasma control in ITER can improve plasma stability**
- **Higher plasma pressure can be confined and more fusion reactions per second results.**