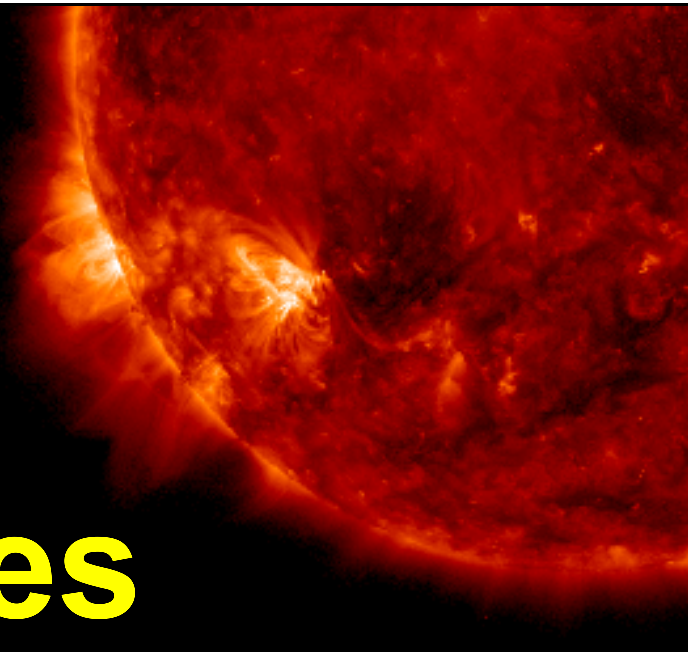
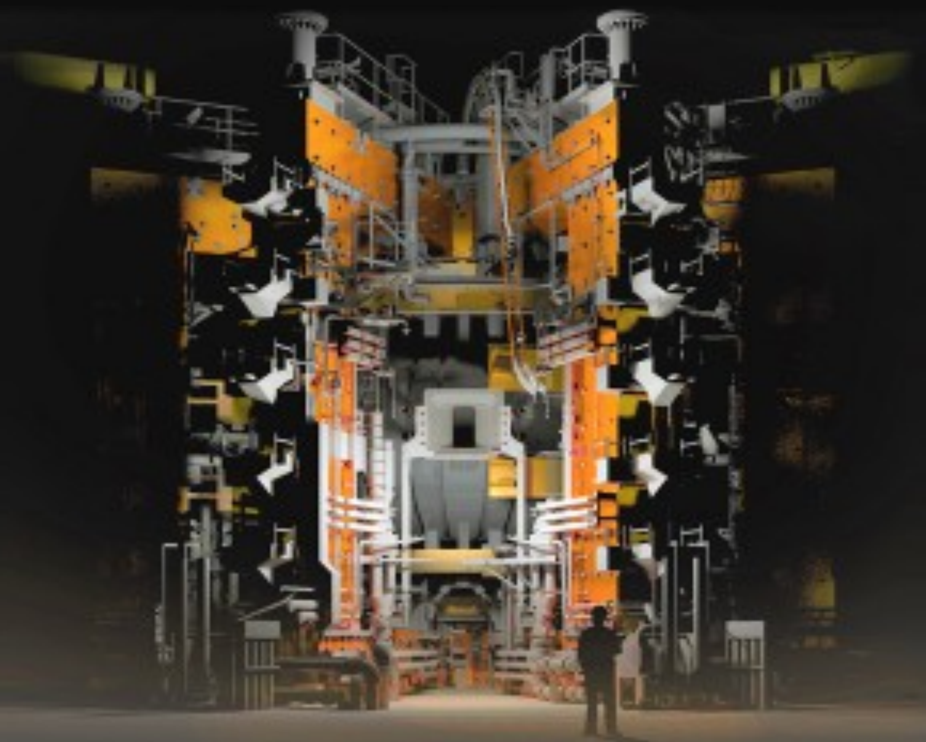
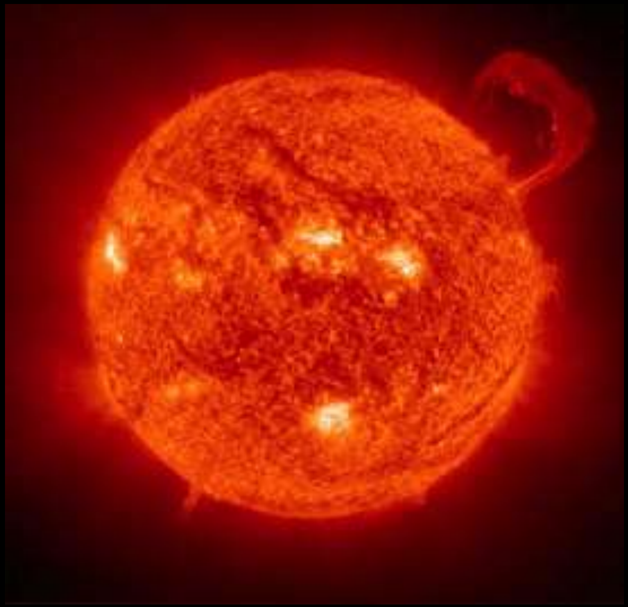
The tokamak and the alternatives



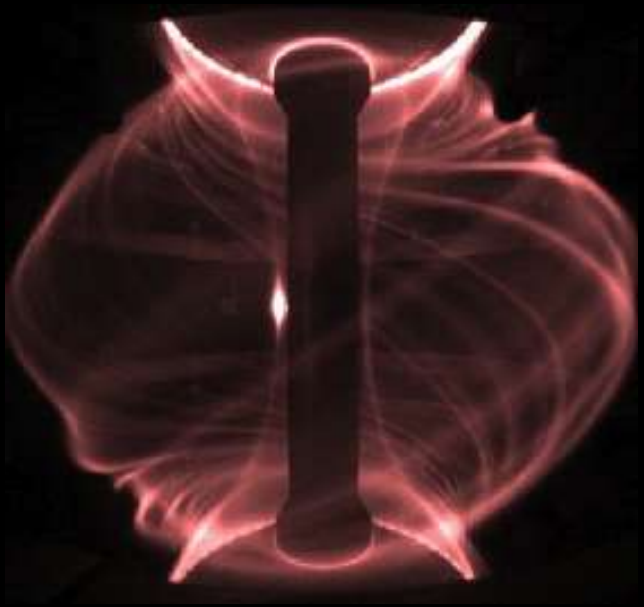
Jan Scheffel, professor
Fusion Plasma Physics
KTH



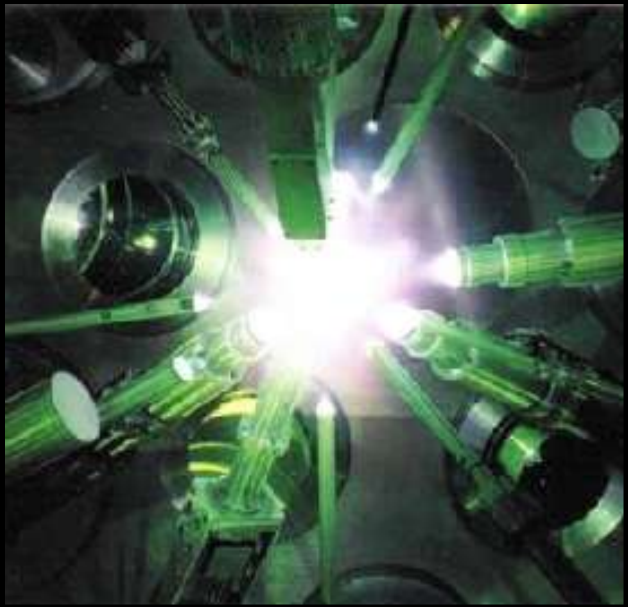
Confinement



gravitational



magnetic

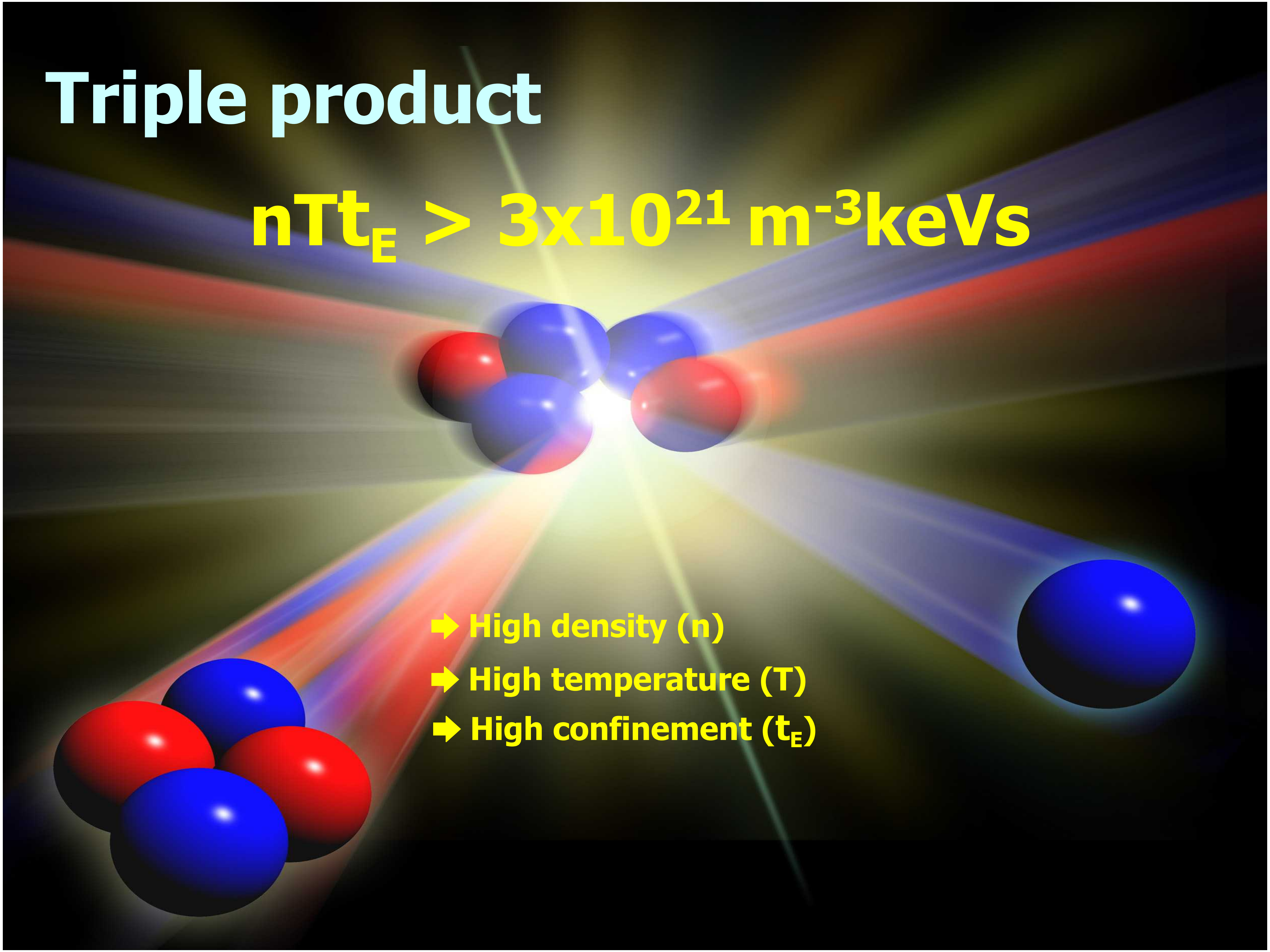


inertial

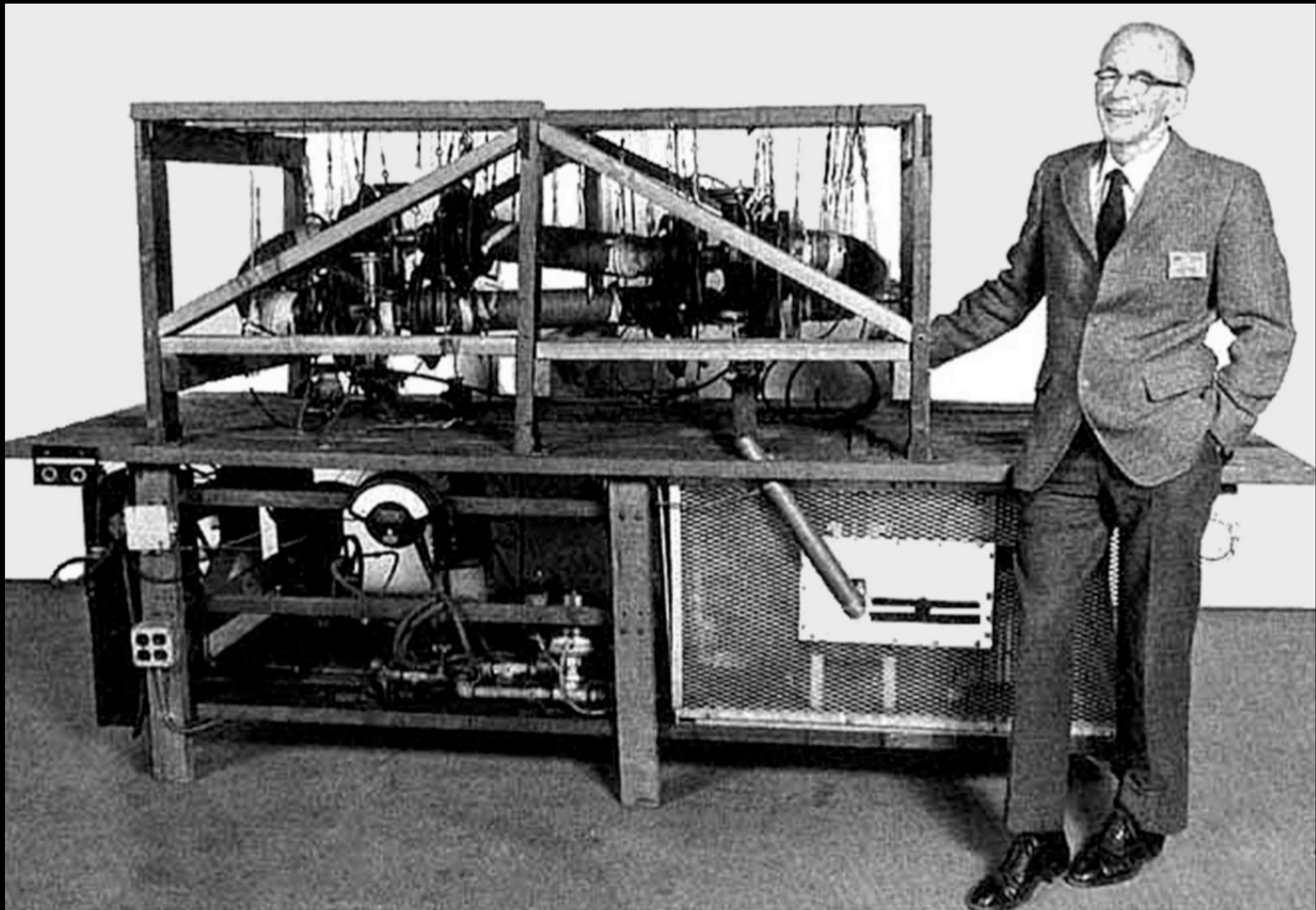
Magnetic confinement appears most favourable
for energy production on earth

Triple product

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



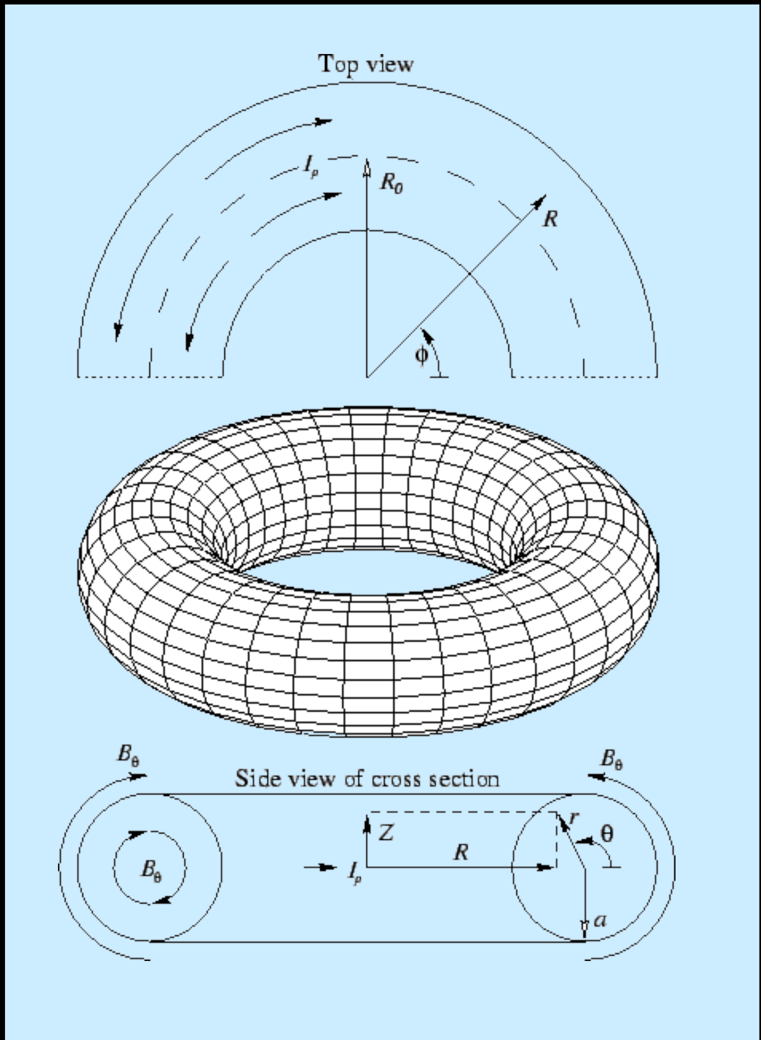
- High density (n)
- High temperature (T)
- High confinement (t_E)



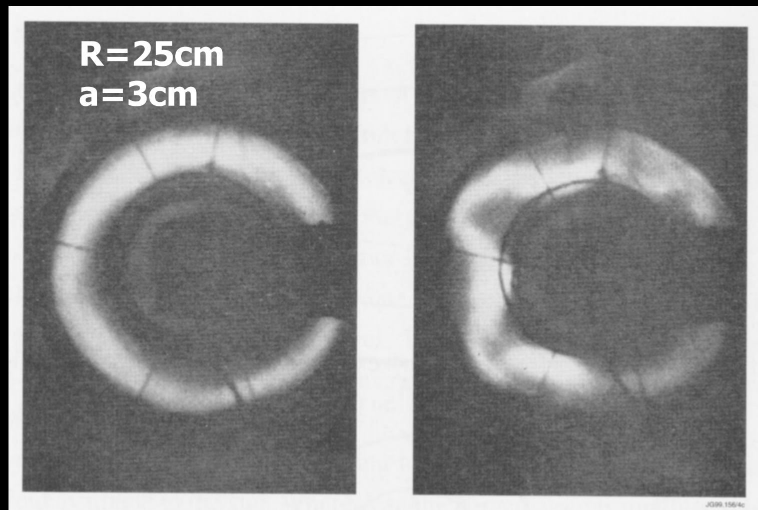
Stellarator – early 1950's

The Pinch Effect - 1940's

Peter Thonemann and Sir George Thomson's idea

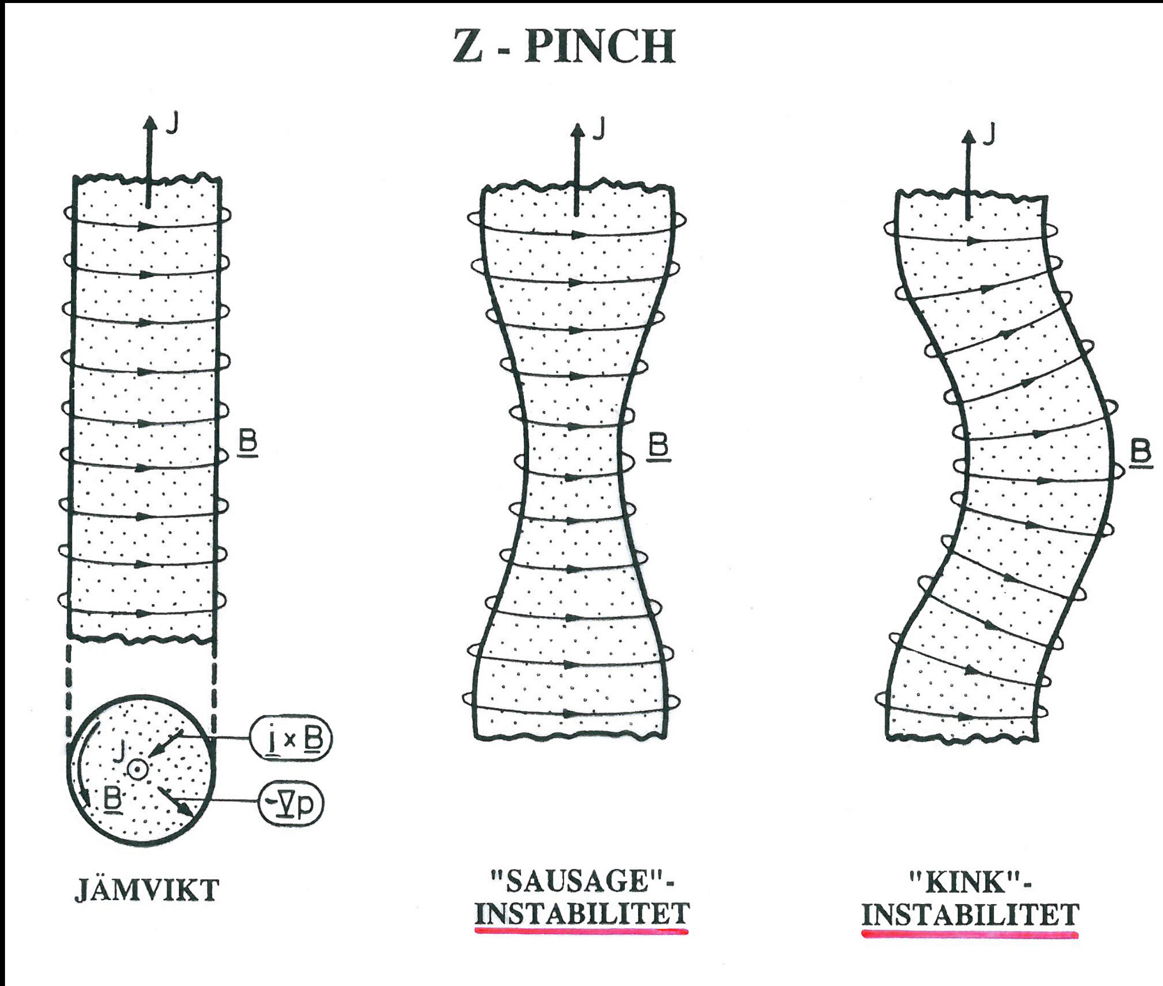


Alan Ware, Thomson Imperial College.

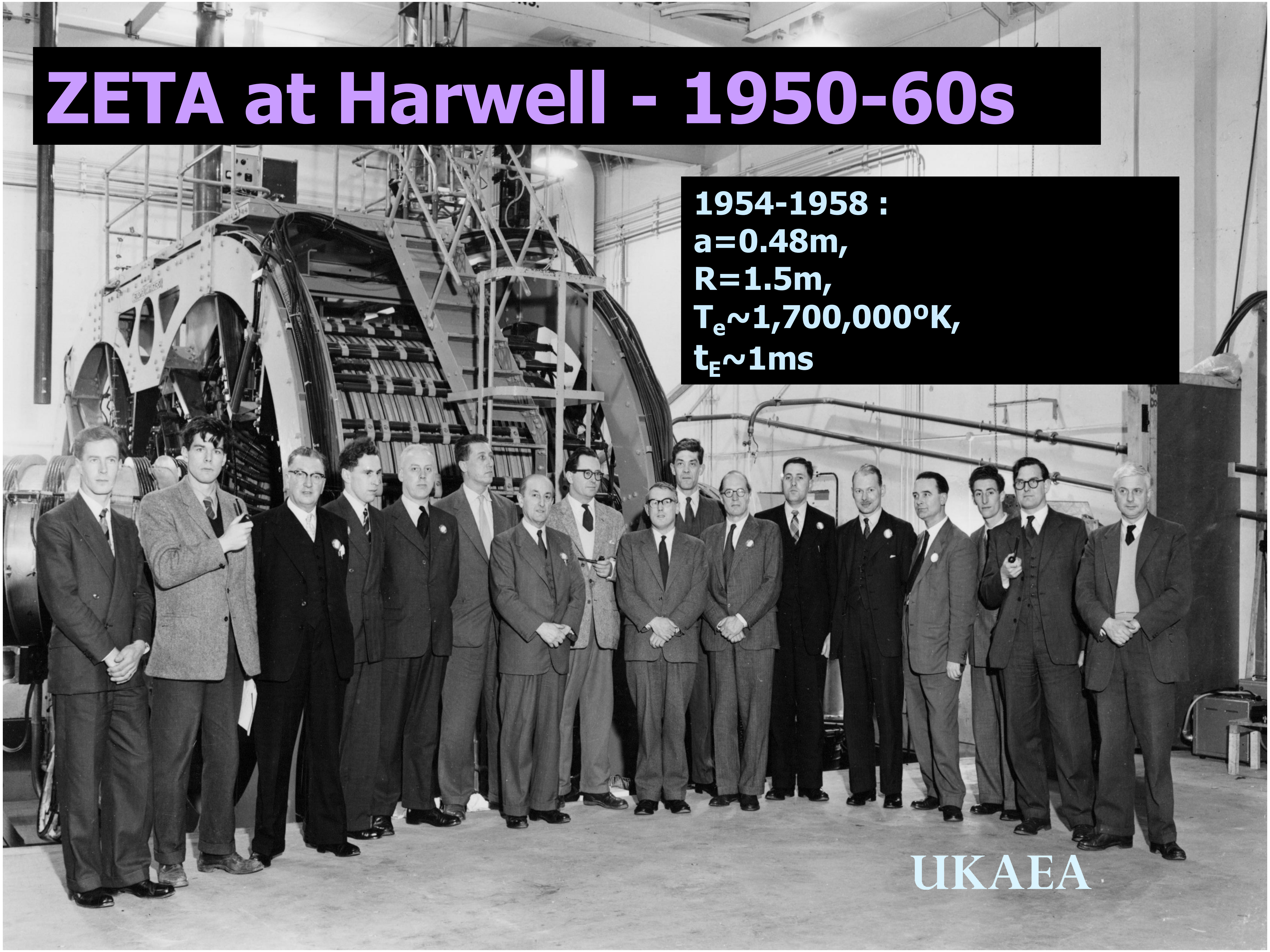


UKAEA

z-pinch instabilities

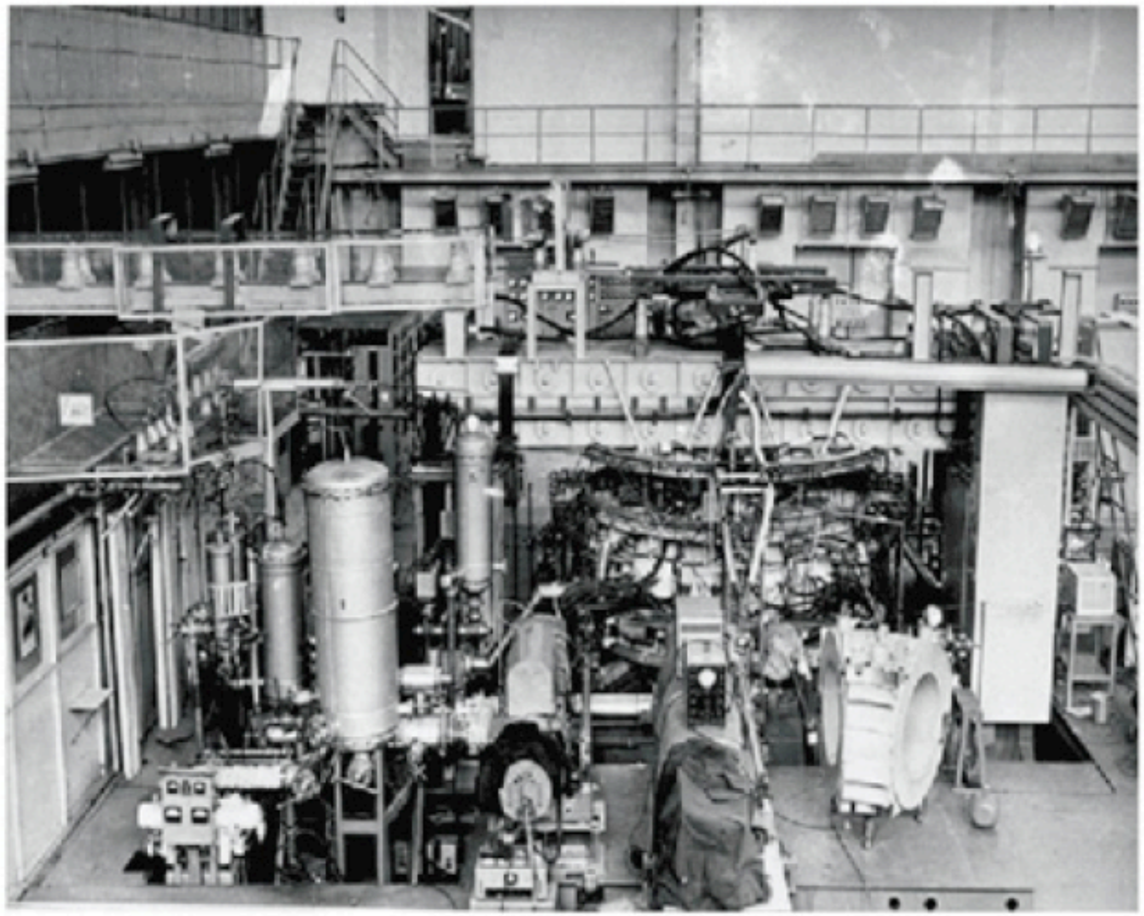


ZETA at Harwell - 1950-60s



1954-1958 :
a=0.48m,
R=1.5m,
T_e~1,700,000ºK,
t_E~1ms

The Tokamak- a Soviet invention



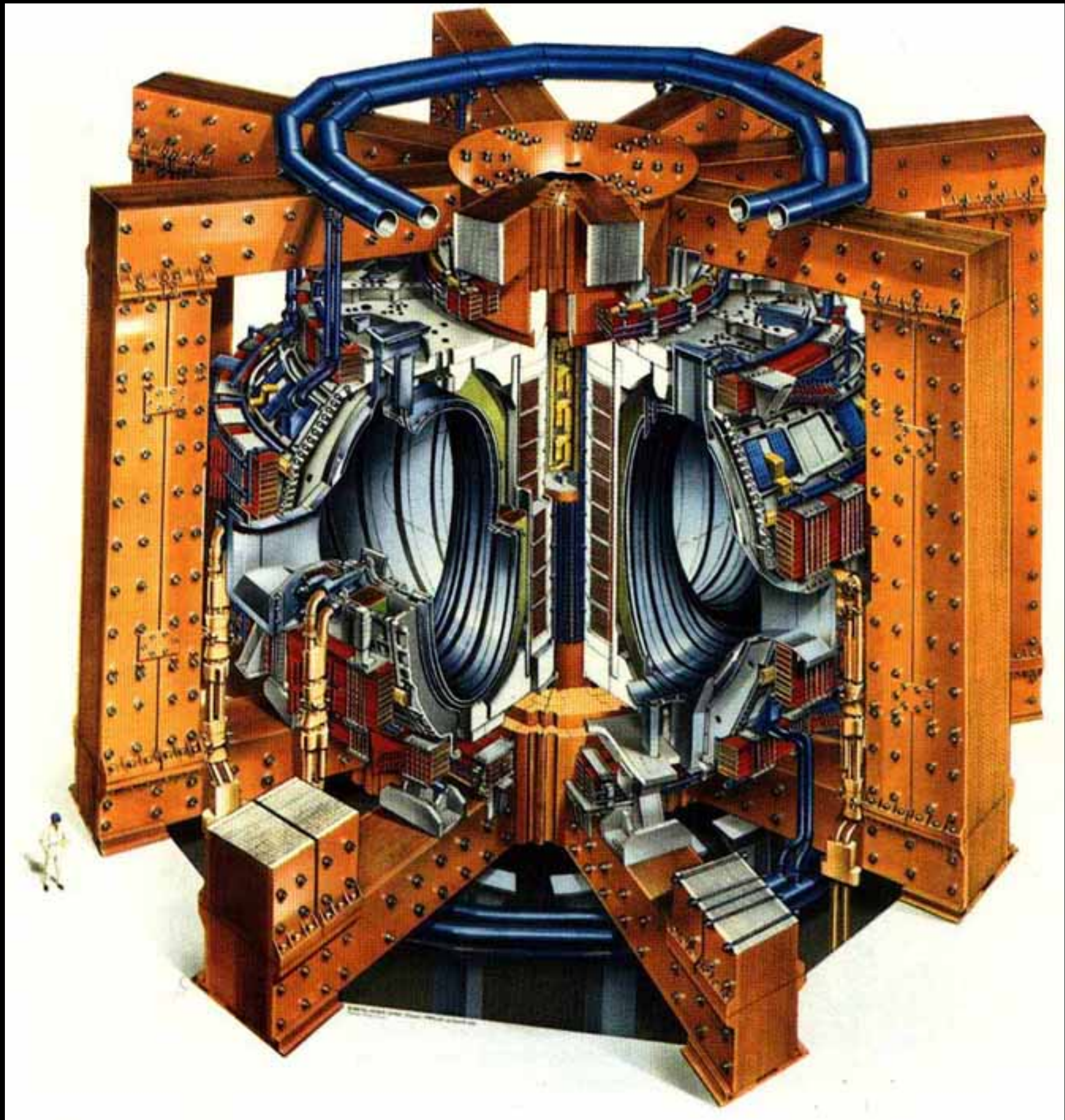
Tokamak T-3 (1962)
R = 1 m, a = 0,15 m, B = 3,8 T, I = 150 kA

Time:
1950-60

Place:
Moscow

Characteristic:
Strong magnetic field

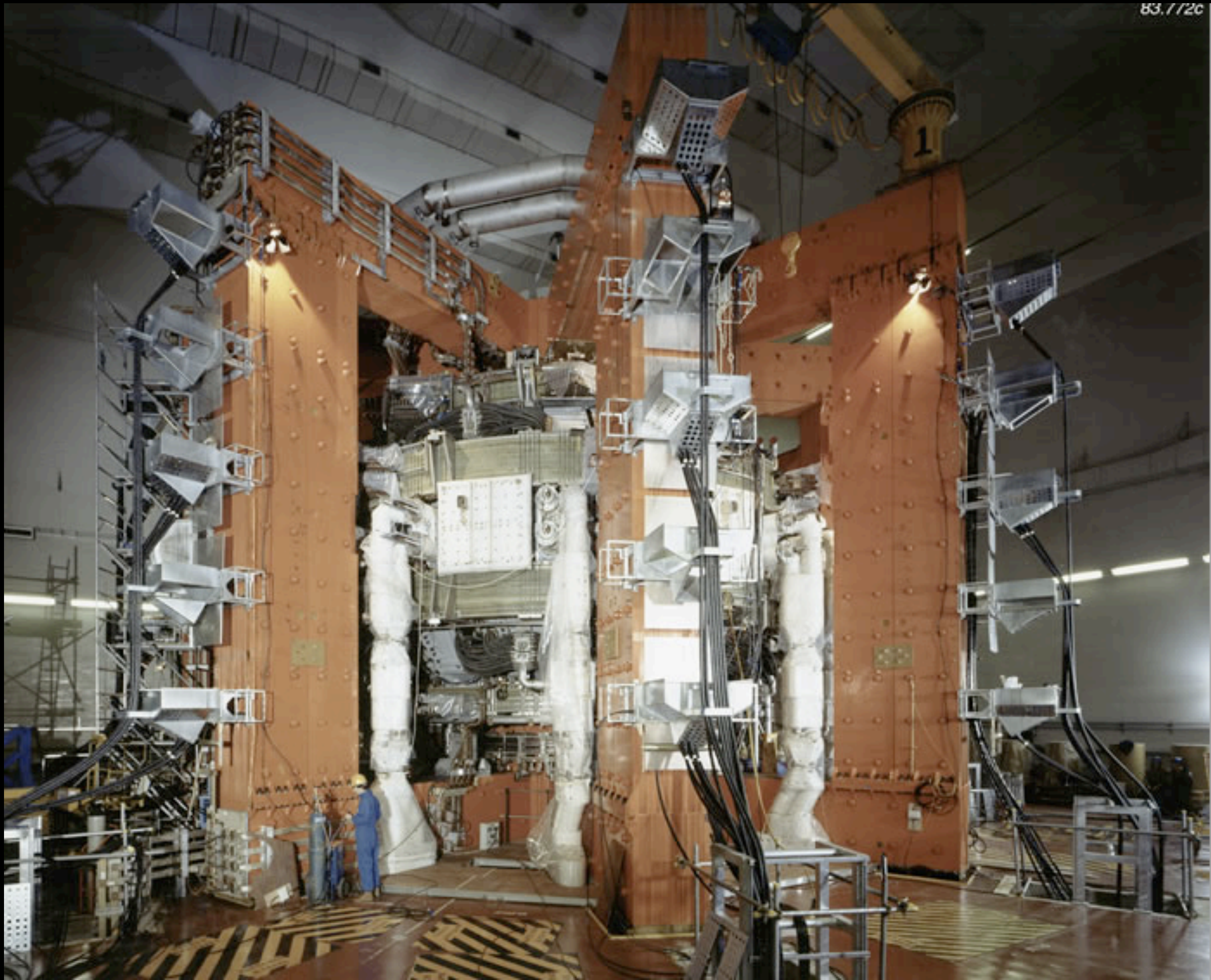
JET – the world's largest fusion experiment



Location:
Culham, England

European project

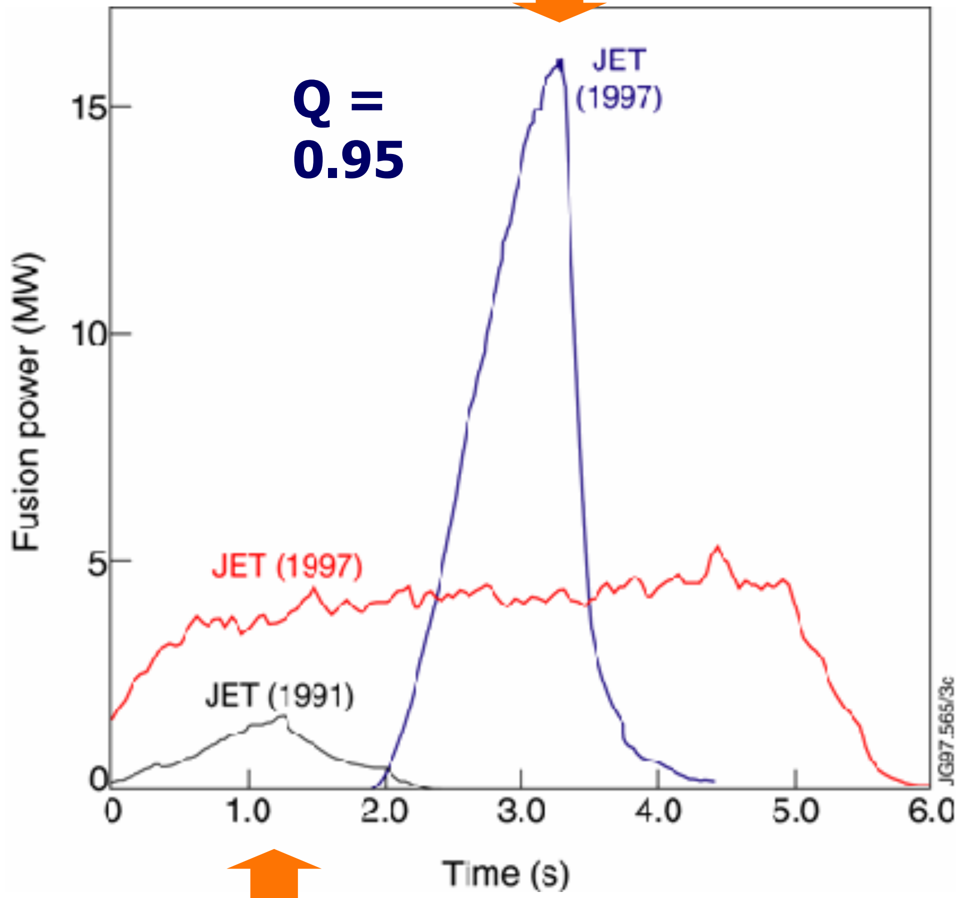
JET – the world's largest fusion experiment



JET
Tokamak

Demonstration in JET: production of fusion energy

16.2 MW
(World Record)



1.7 MW
(World First)

Heating

25 MW

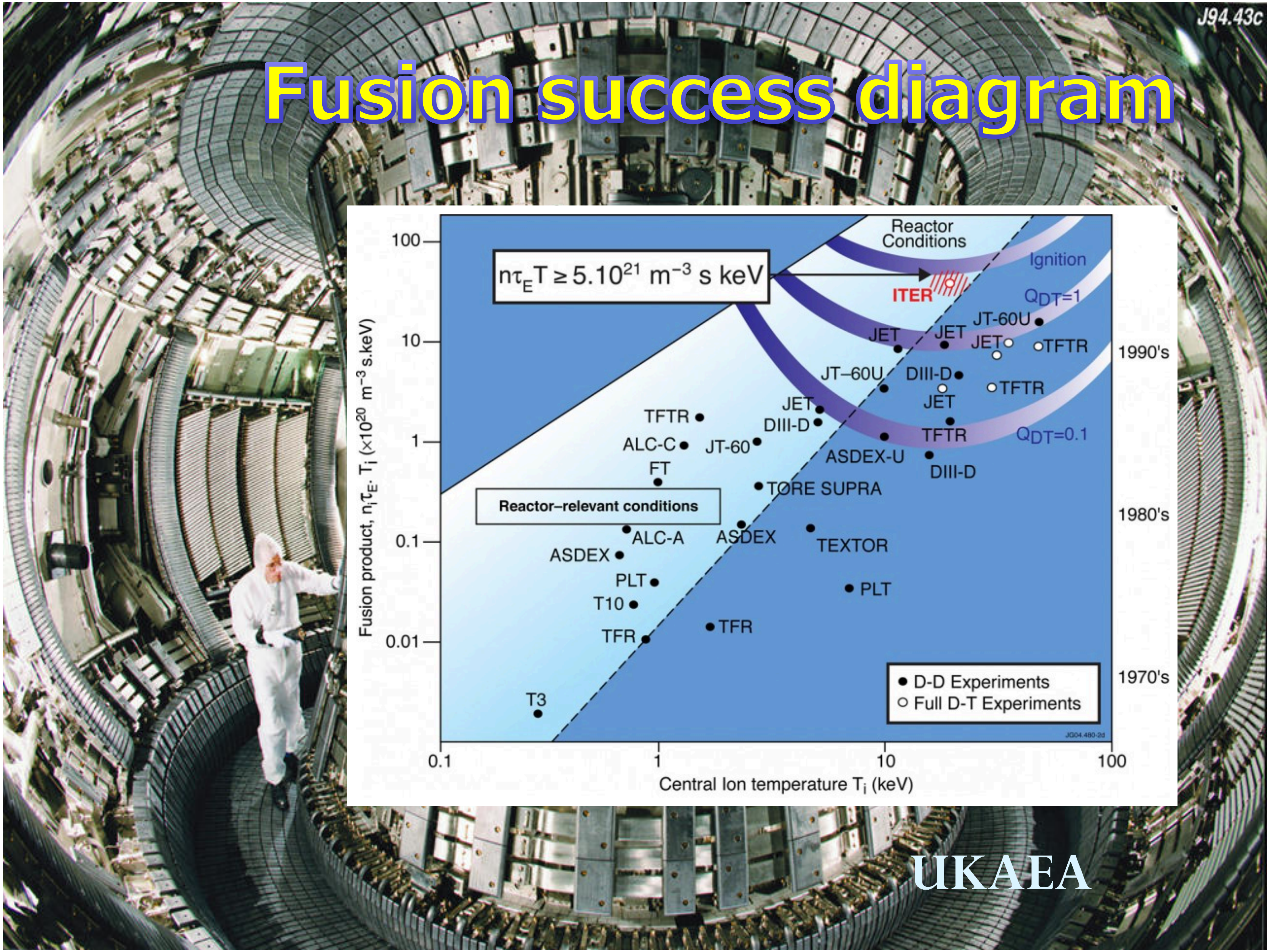
2 s,

Q=0.6

16 MW

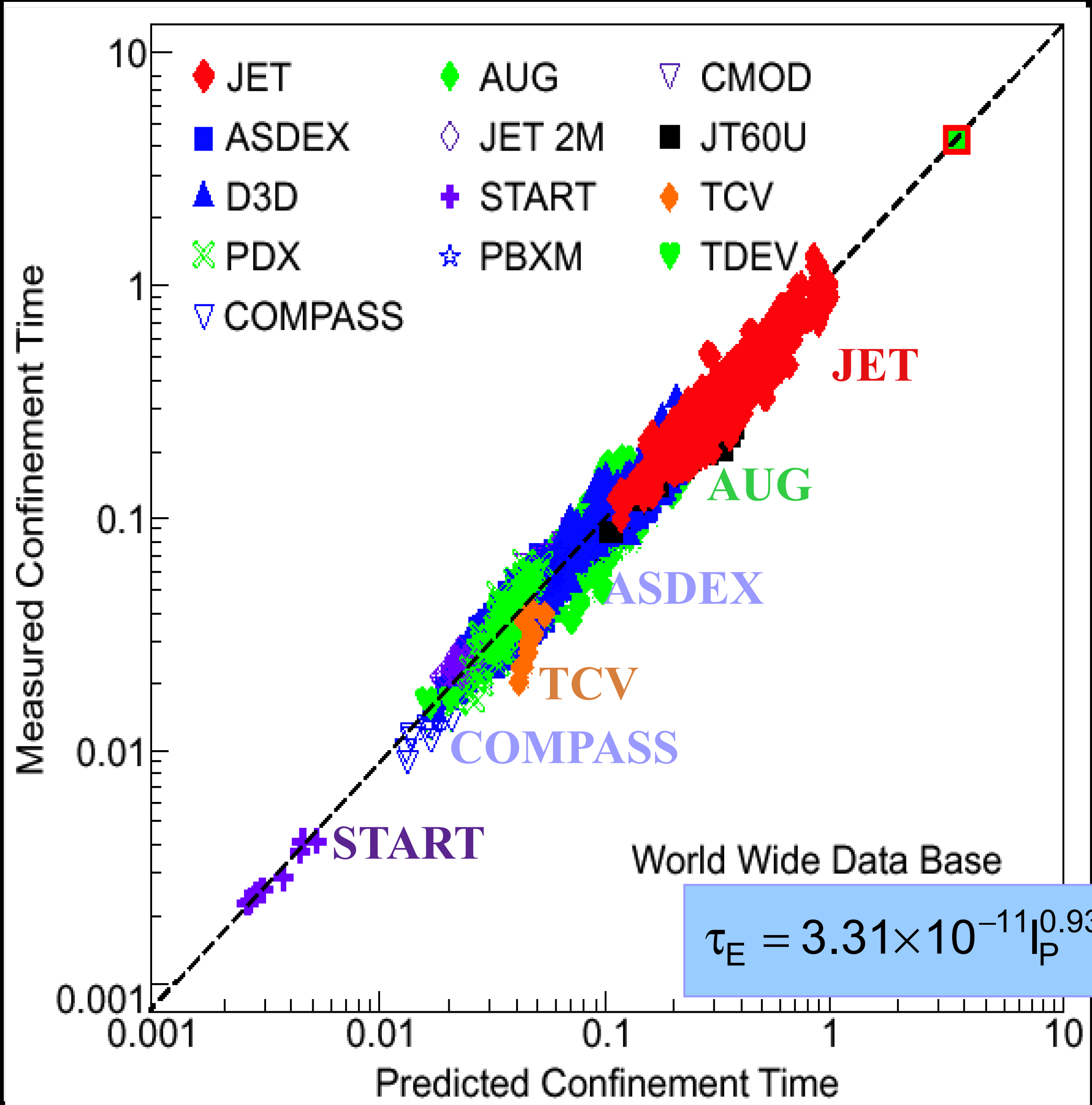
Fusion Energy

Fusion success diagram



EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

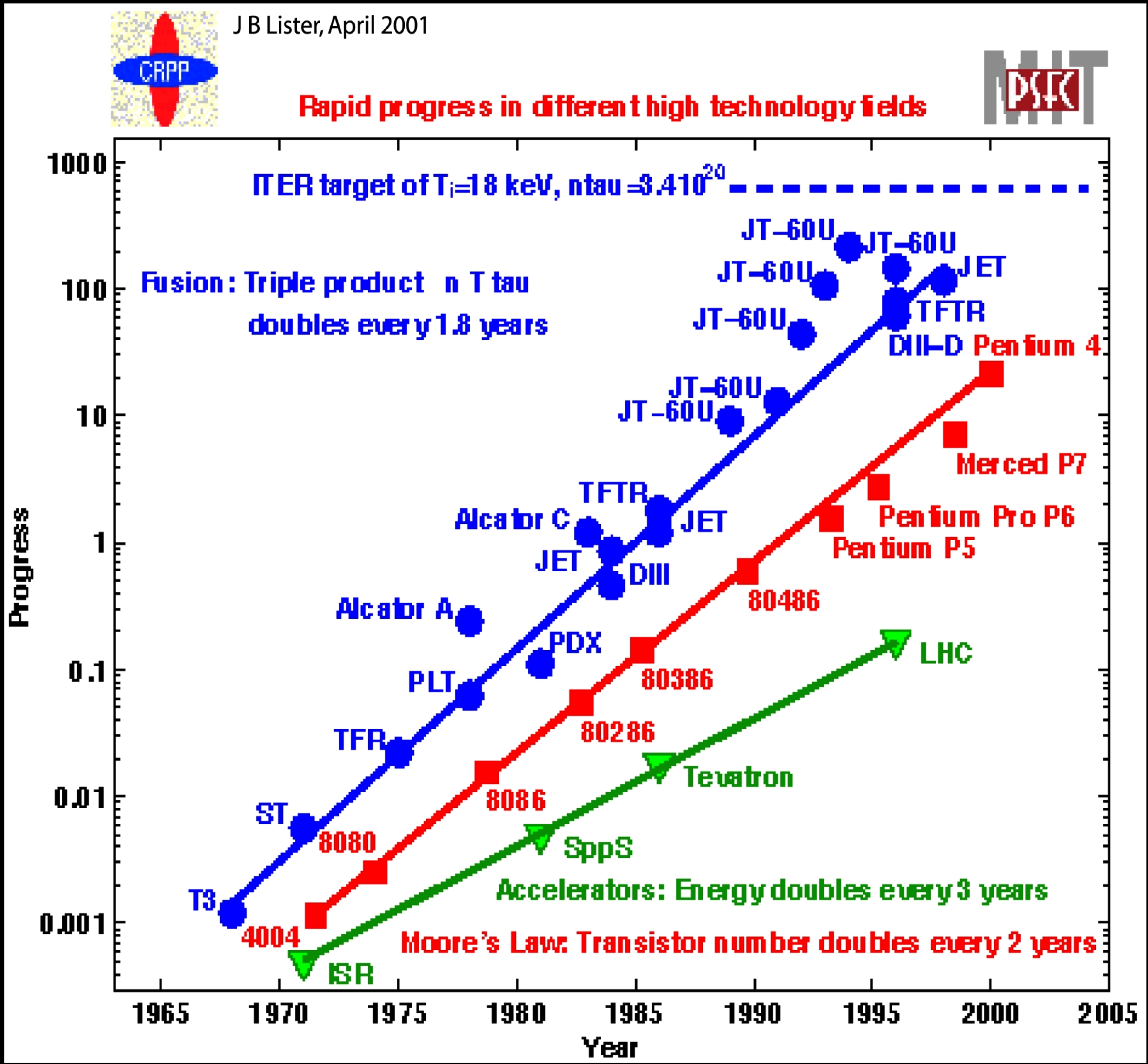
Progress in ITER like Scenario



$$\tau_E = 3.31\times10^{-11} I_P^{0.93} B^{0.15} P^{-0.69} R^{1.97} n^{0.41} M^{0.19} \varepsilon^{0.58} \kappa^{0.78}$$

Fusion devices in the EU make a major contribution to the databases for ITER

Fusion progress is comparable with other fields

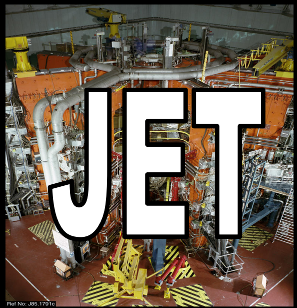
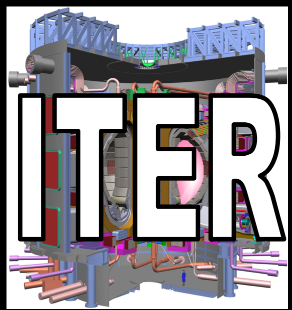
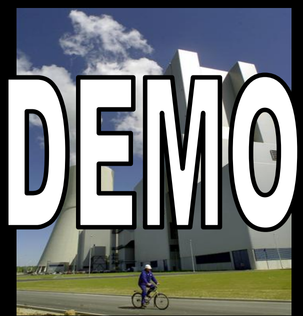


n = Density
a measure of the number of reactions we can have

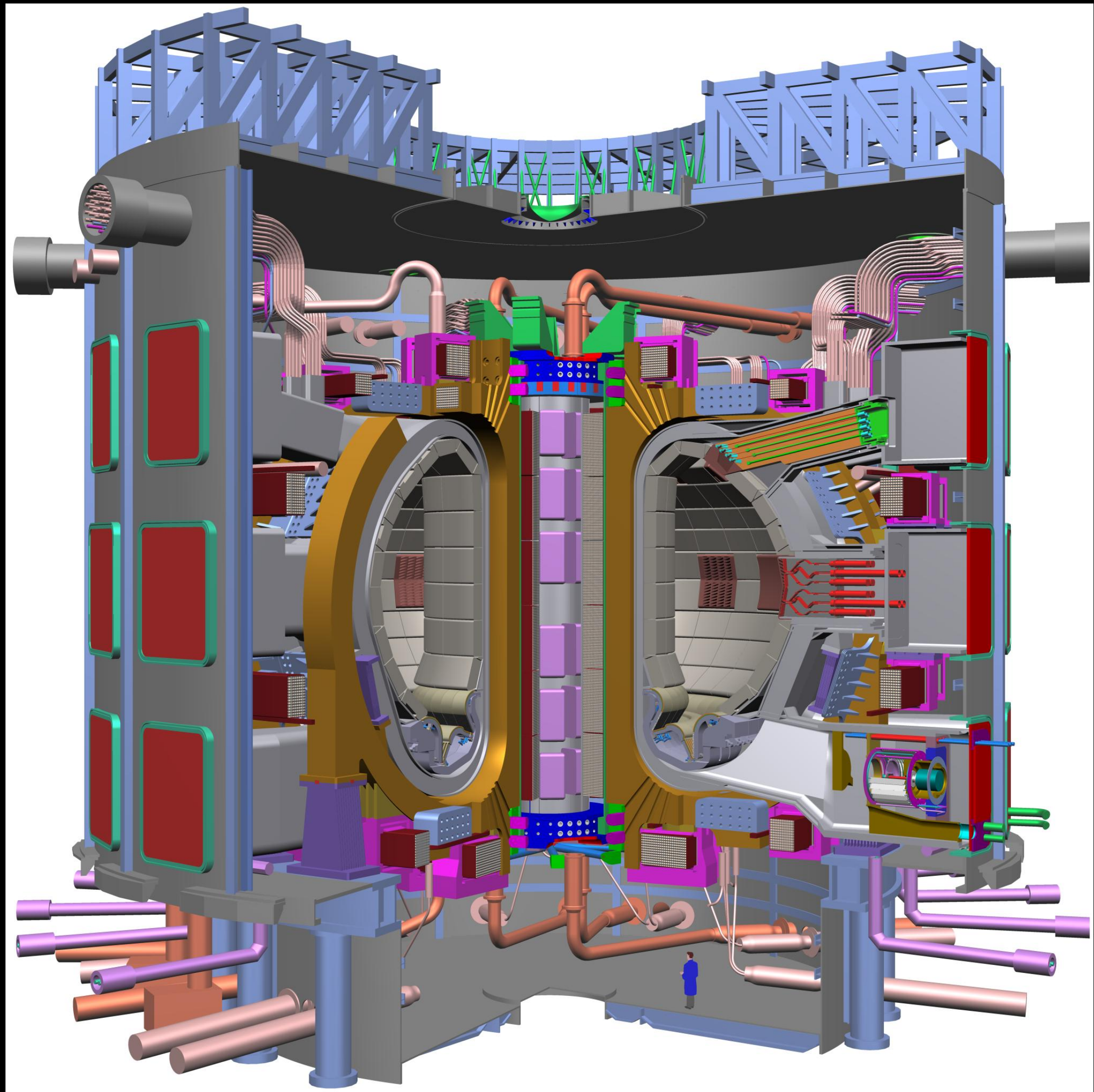
T = Temperature
a measure of the energy given to the fuel particles

τ = Confinement time
a measure of the thermal insulation of the fuel

Development of fusion energy

	When?	Fusion power	Pulse length	Q
	1997	16MW	10 seconds	0.65
	2025 -	500-700MW	5 minutes	10
	2035/40	1.5-2GW	days/stationary	30

ITER – next step towards fusion



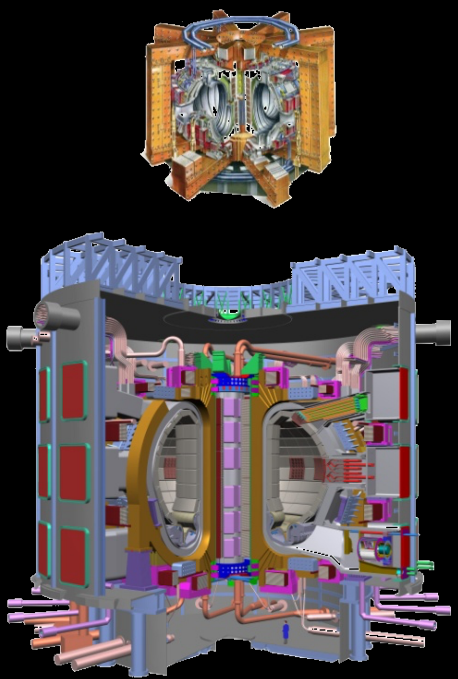
Location:
Cadarache, France

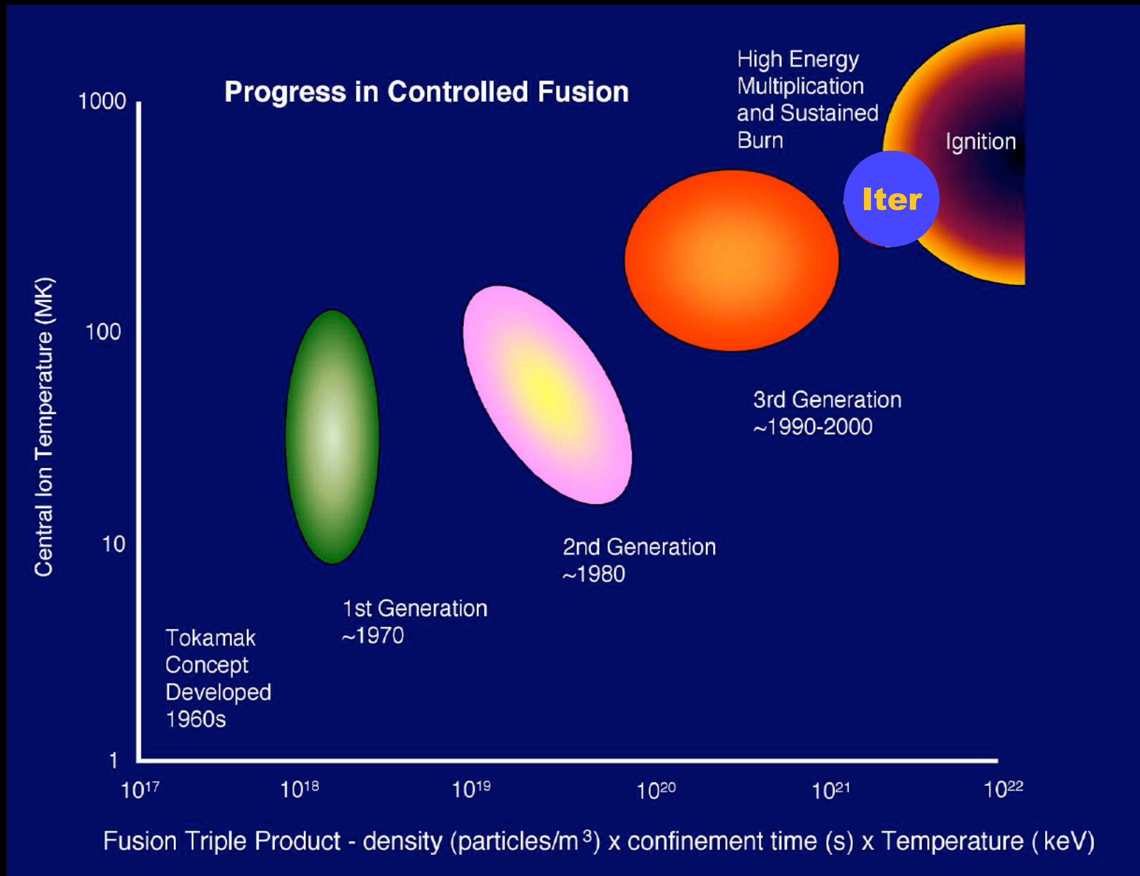
Collaboration:
EU
China
Japan
Russia
South Korea
India
USA

ITER progress

ITER represents a big step in fusion research but is in line with the continuous progress over the years

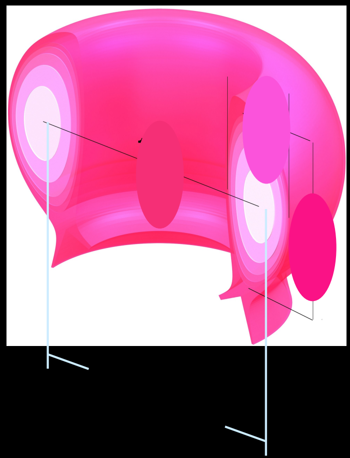
More than double the size of JET



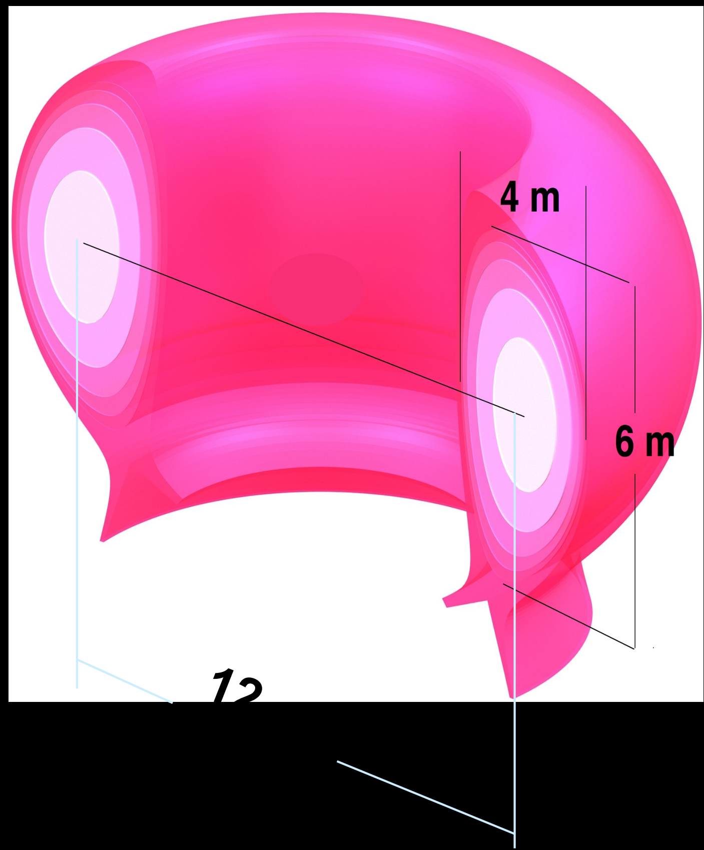


Comparison JET - ITER

JET



ITER



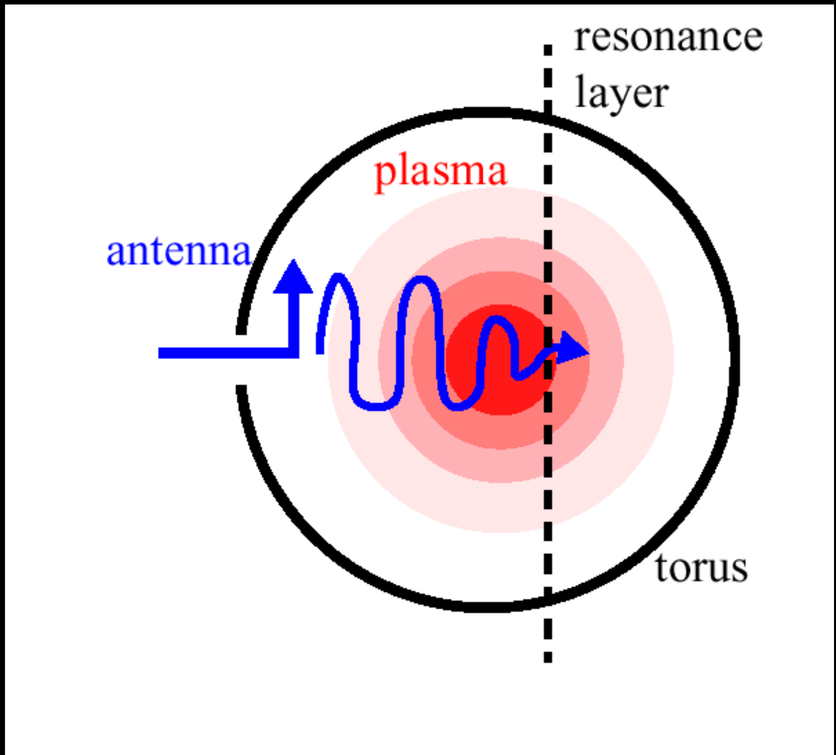
ITER - Goals

- Produce 500 MW fusion power.
(10 times more power than what is needed to run the experiment).
- Smaller than a power station but big enough to prove principle.
- Optimize plasma physics.
- Test technology that is needed for a power station (*exception: materials*).
- In operation: for 20 years.

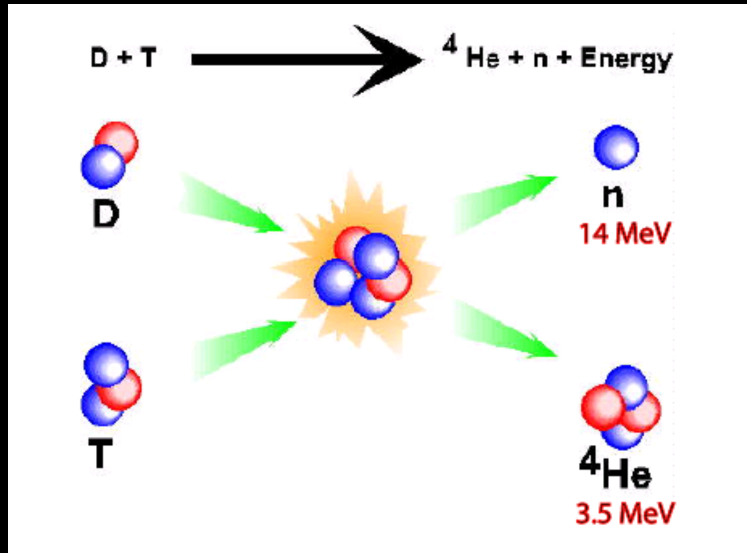
ITER´s mission: physics of burning (self-heating) plasma

Tokamak operation so far: external heating

For example wave heating:



ITER: $nT\tau$ sufficient for dominant self-heating

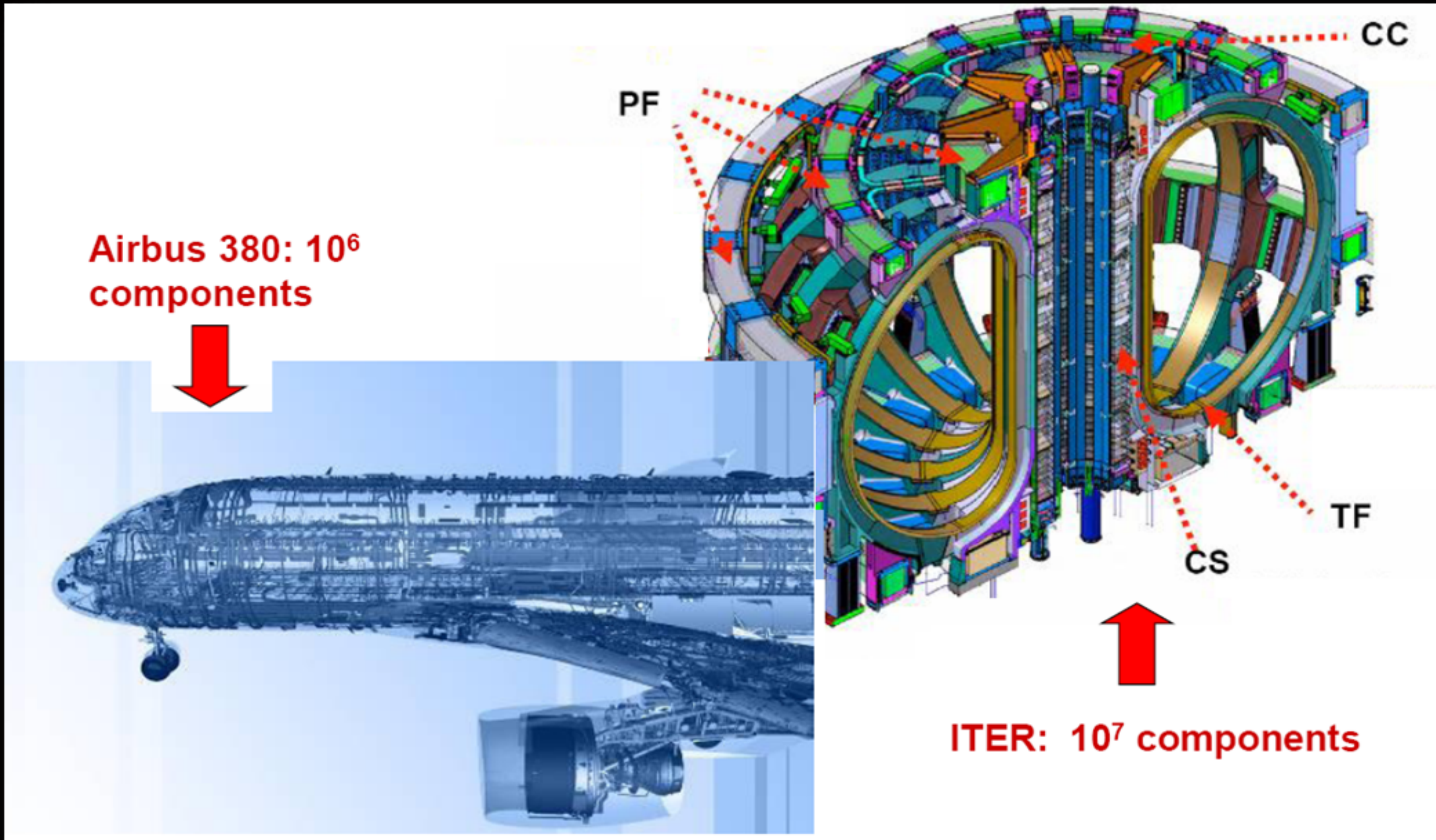


$$Q = \frac{\text{fusion produced power}}{\text{externally applied heating power to plasma}} \rightarrow 10$$

α - heating of plasma

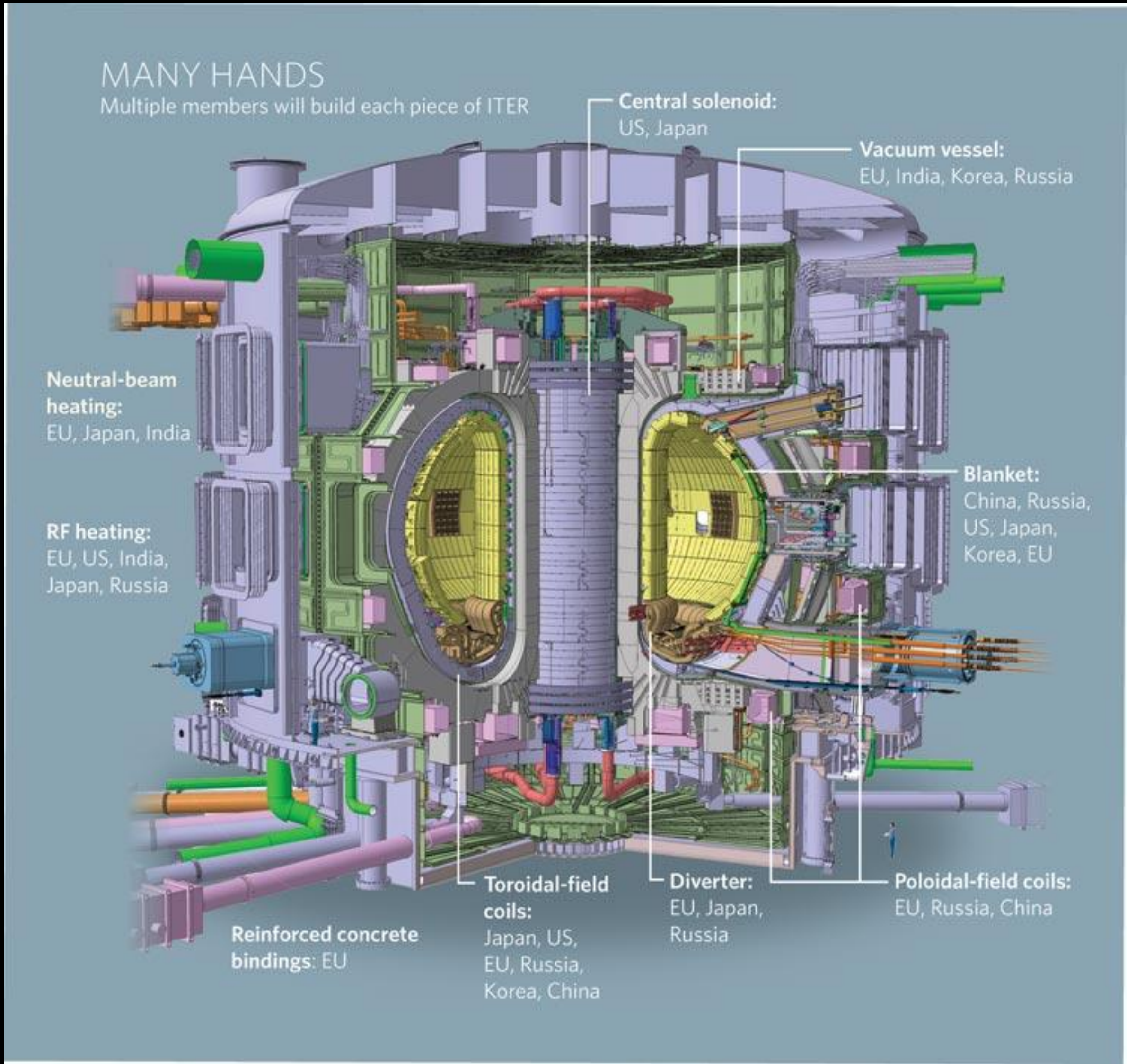
$\rightarrow 2 \times$ externally applied heating power to plasma

Integration - Engineering



Courtesy CIEMAT

ITER – next step towards fusion



Location:
Cadarache, France

Collaboration:
EU
China
Japan
Russia
South Korea
India
USA

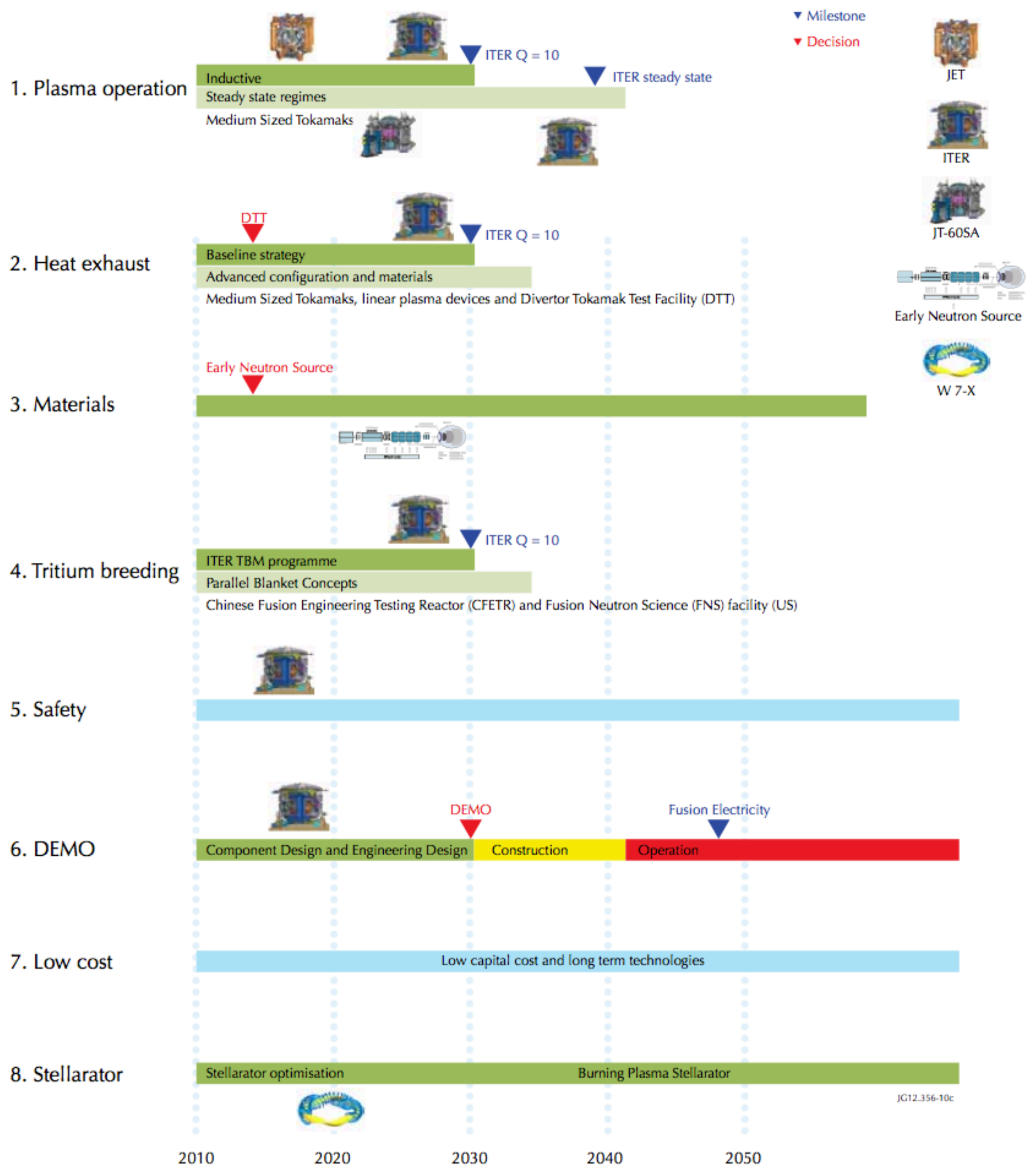
Europe provides through
Fusion For Energy (http://fusionforenergy.europa.eu)

45 % of ITER construction costs

34 % of operation, deactivation, decommissioning

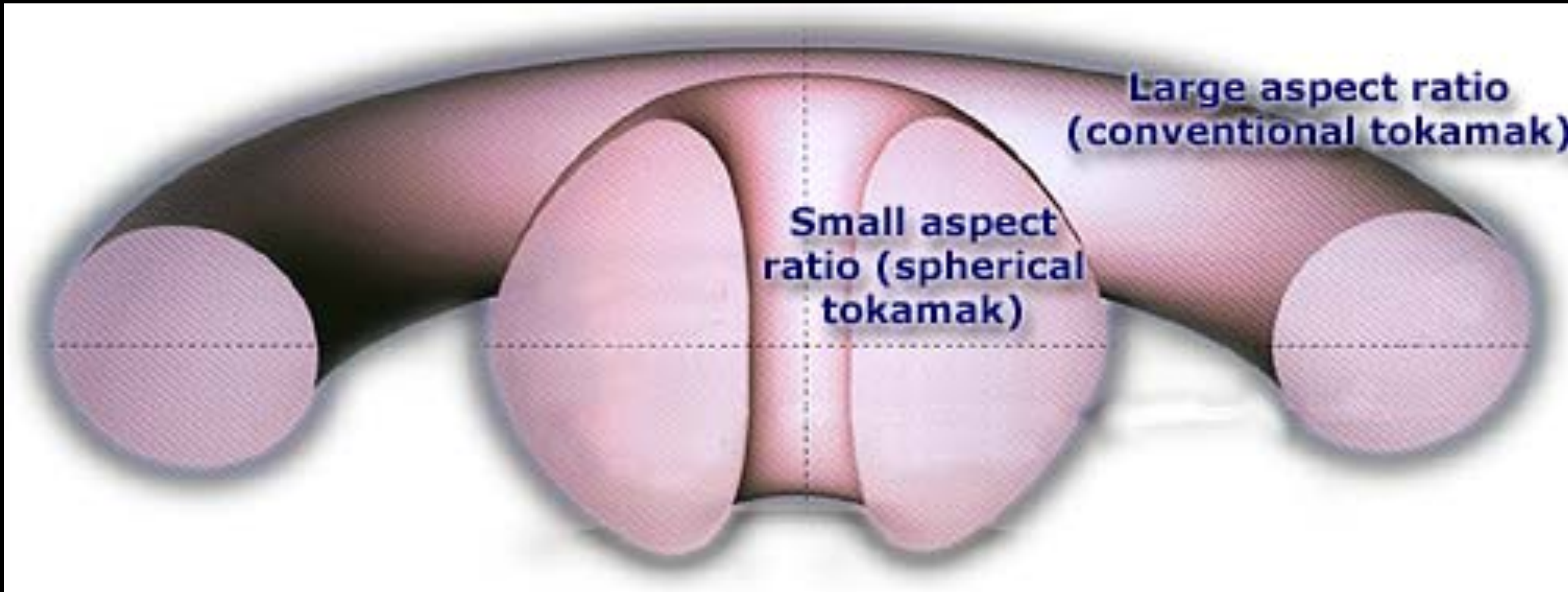
ITER
Wall sector

Fusion Roadmap

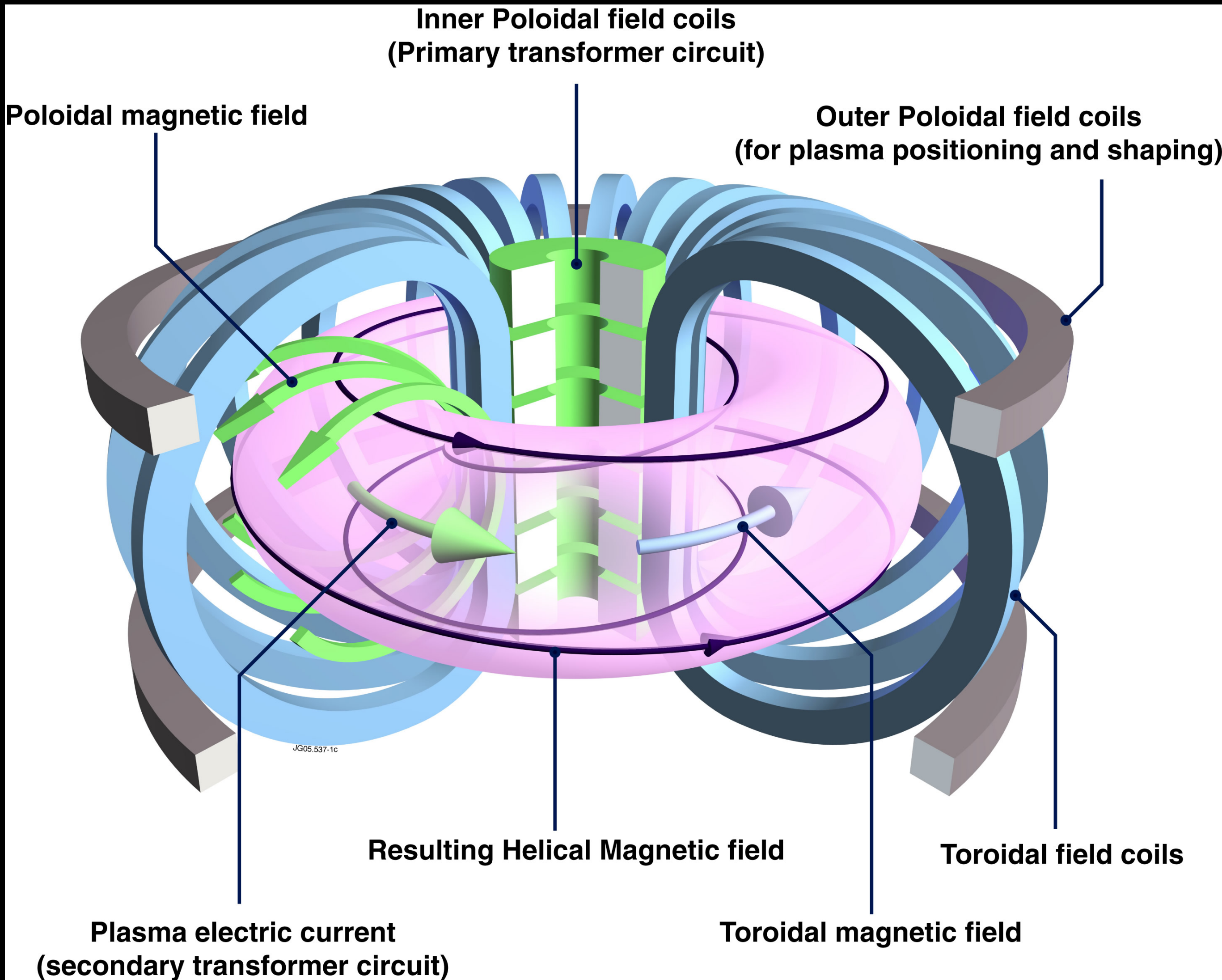


The missions to the realisation of fusion electricity

Can we improve the tokamak?

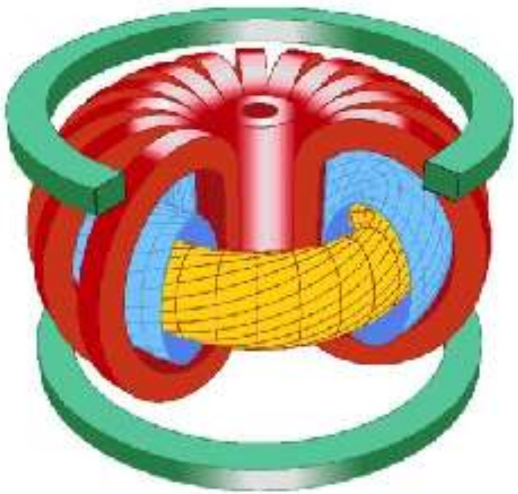


Magnetic confinement



Different magnetic confinement schemes

Tokamak	Stellarator	Reversed-field Pinch



EU world leading

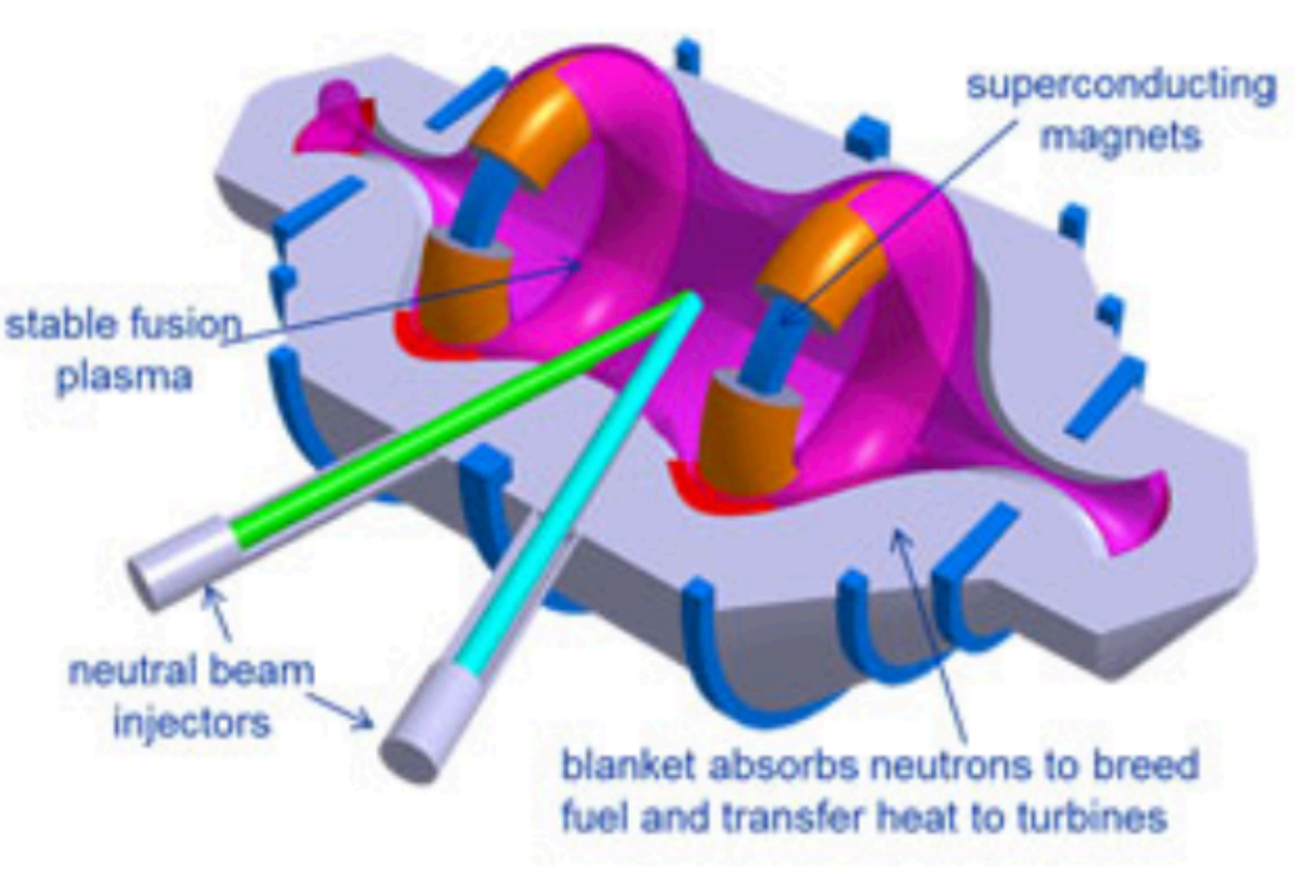
The tokamak is presently the main line

Alternative configurations

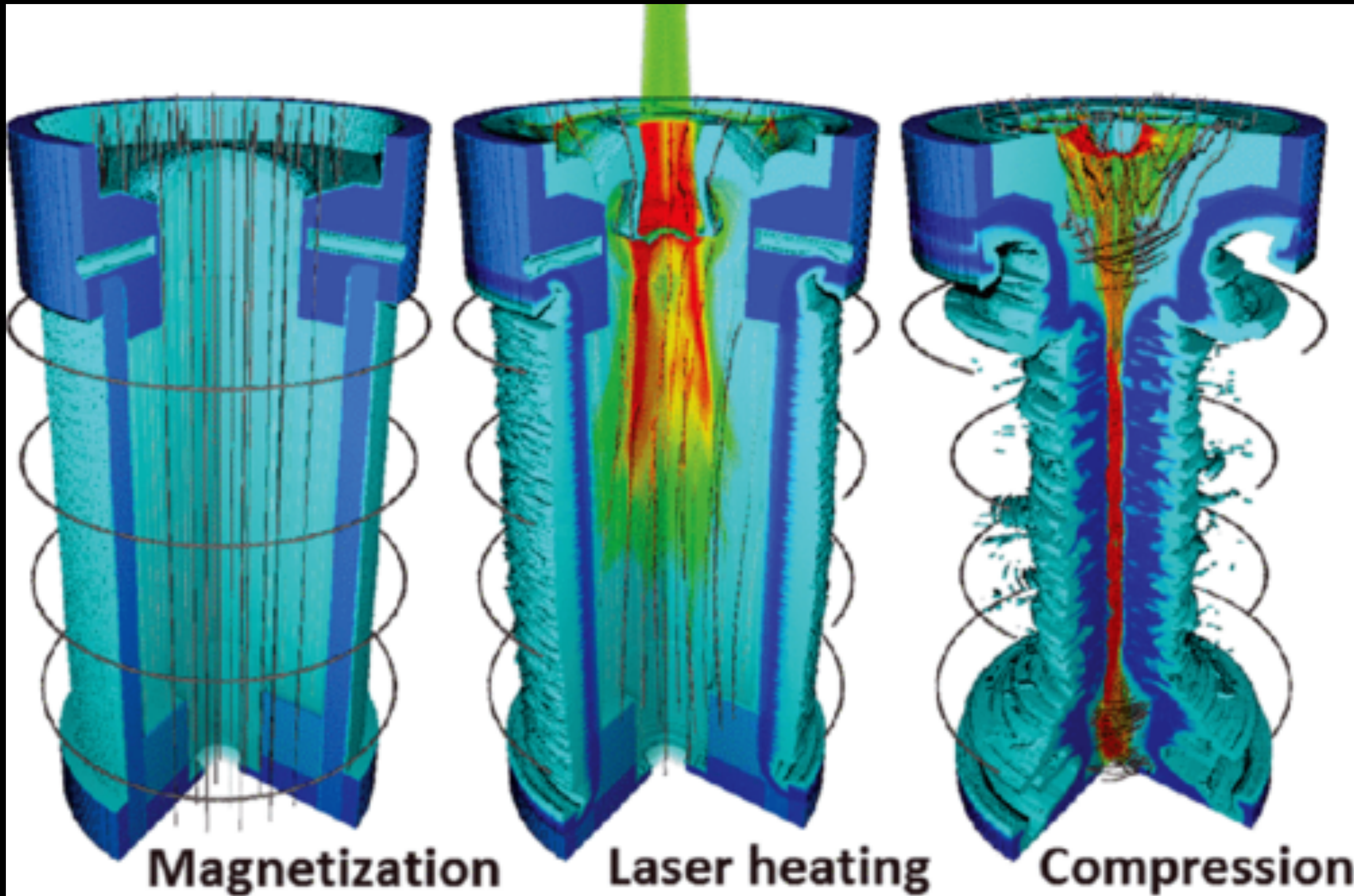
PROPERTY	CONVENTIONAL TOKAMAK
Compact size	NO
High beta value	NO
Burning plasma	YES
Continuous operation	?
Low recirculating power	?
Possibility - advanced fuels	NO
Possibility - direct conv. to electricity	NO
Environmentally superior	YES
COE lower than for fossils or fission	NO

Dense plasma focus (DPF)

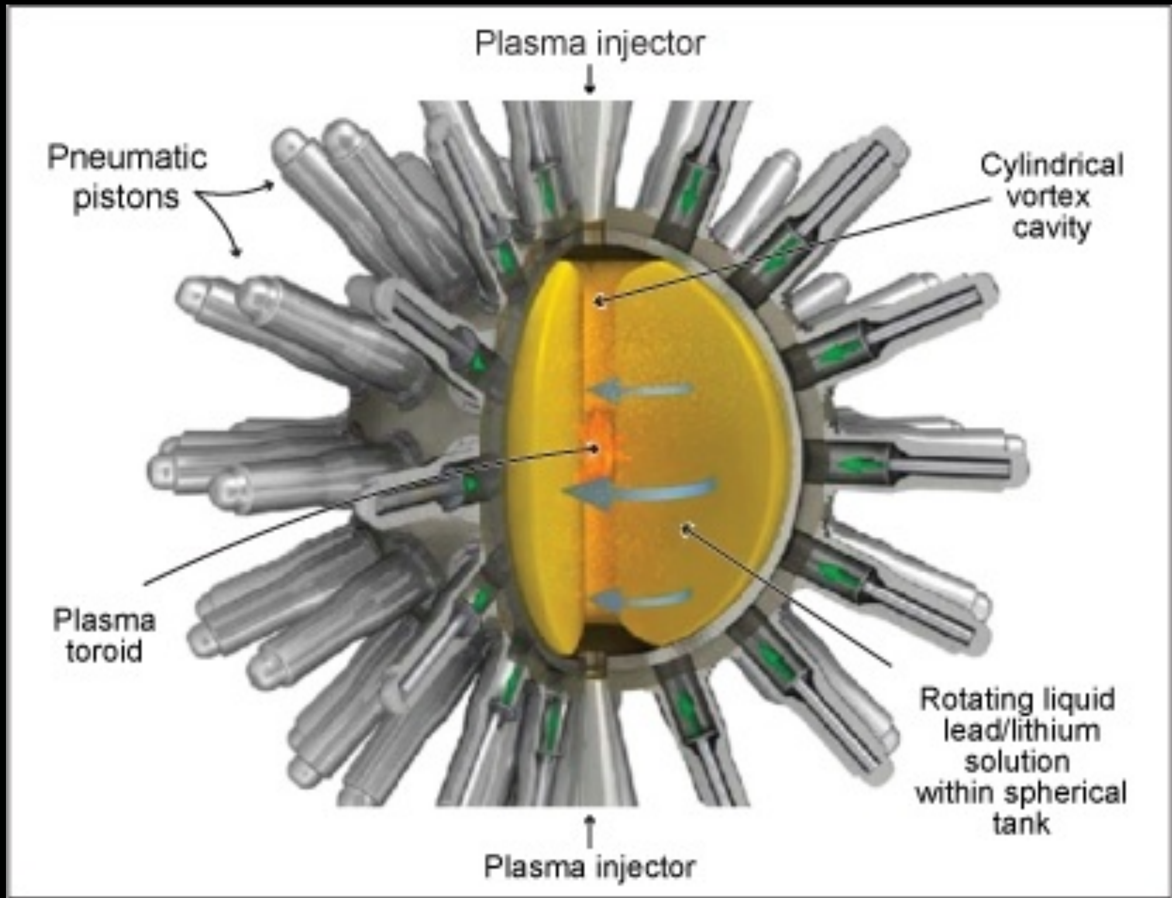
Lockheed Martin – compact fusion



Magnetized target fusion (MTF)

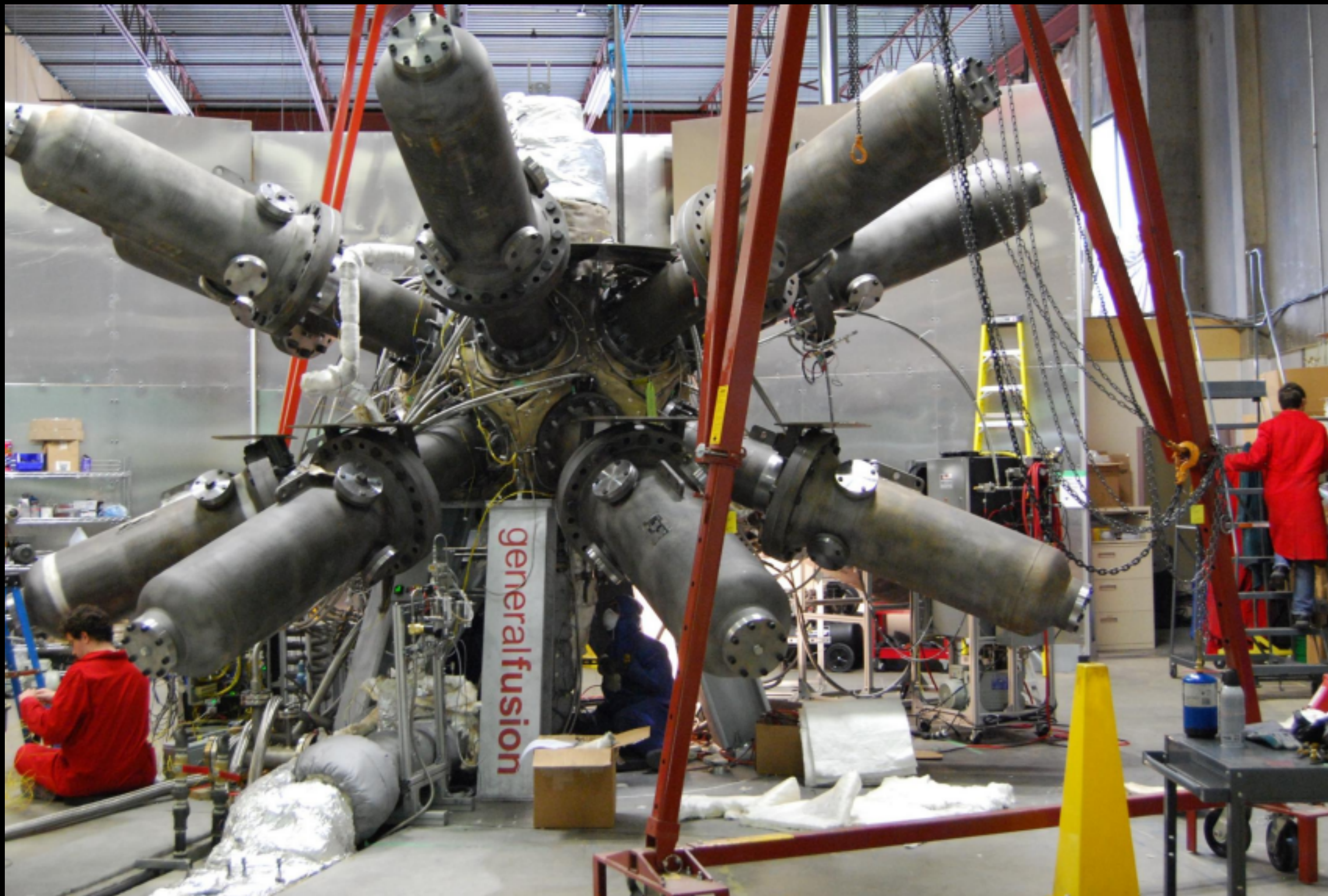


General fusion



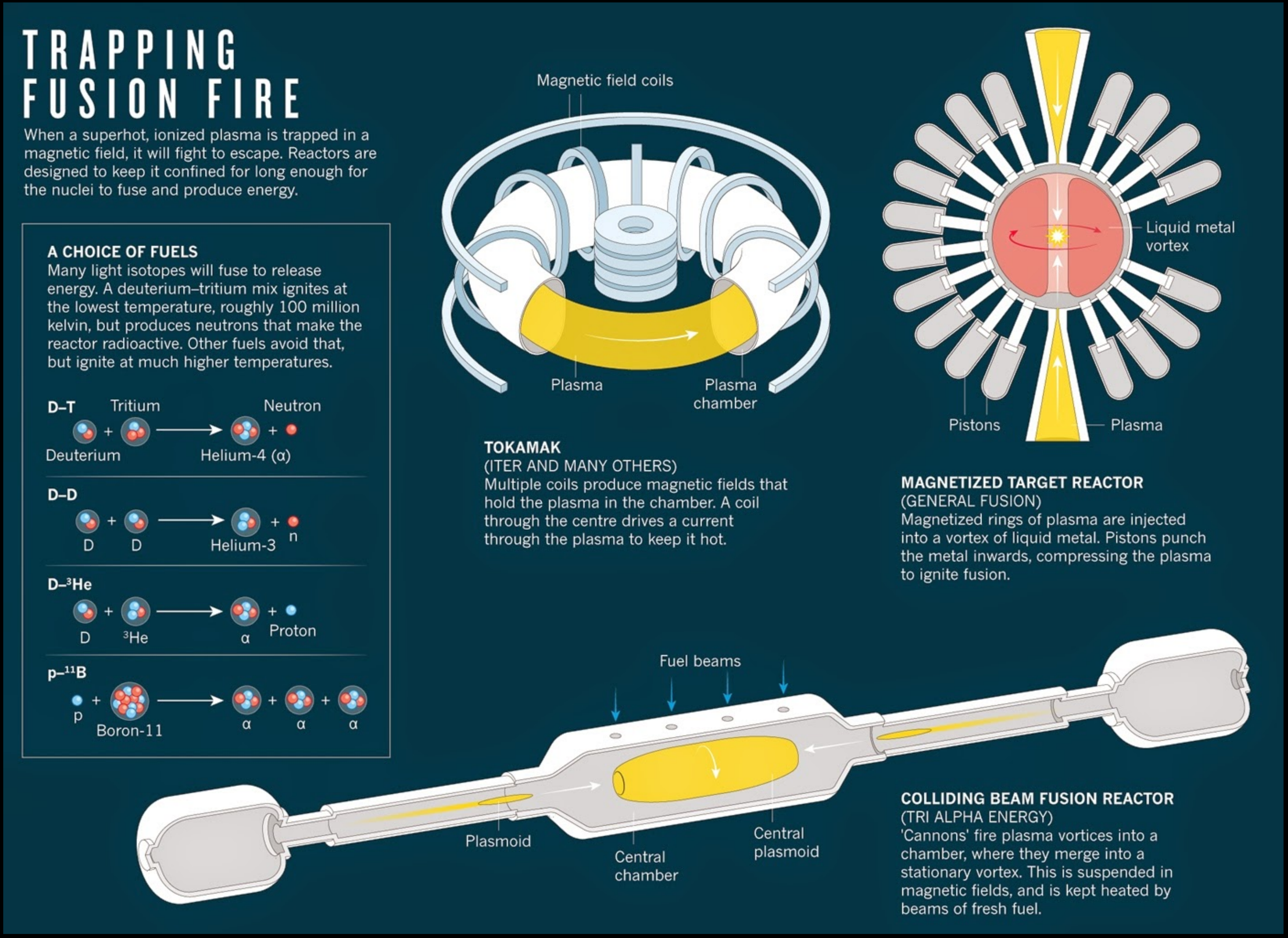
Magnetized Target Fusion

General Fusion



Tri Alpha

Colliding p-B plasmas



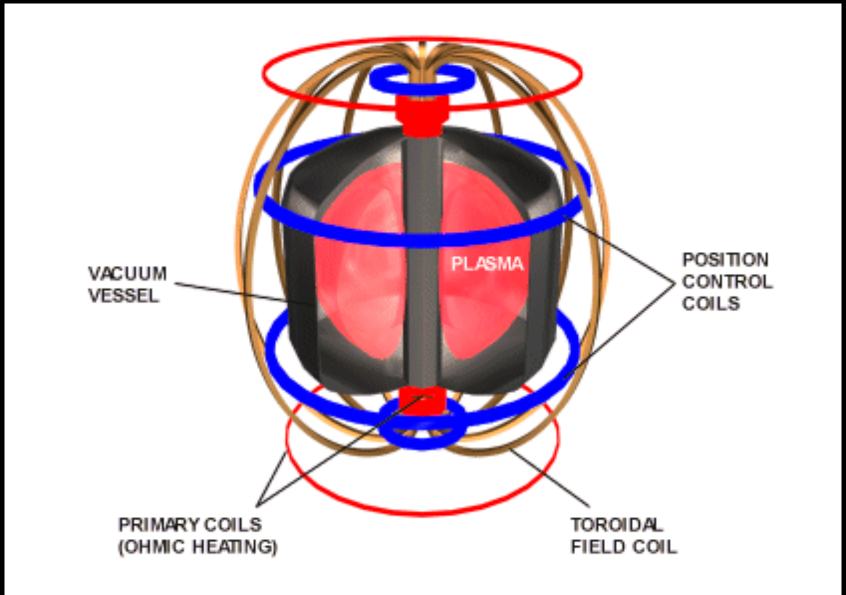
Alternative configurations - classification MCF

High beta, low magnetic field:	• Reversed-field pinch (RFP) • Spherical tokamak
Low beta, high magnetic field:	• Compact tokamak
Low beta, low magnetic field:	• Stellarator

Spherical Tokamak

Advantages:

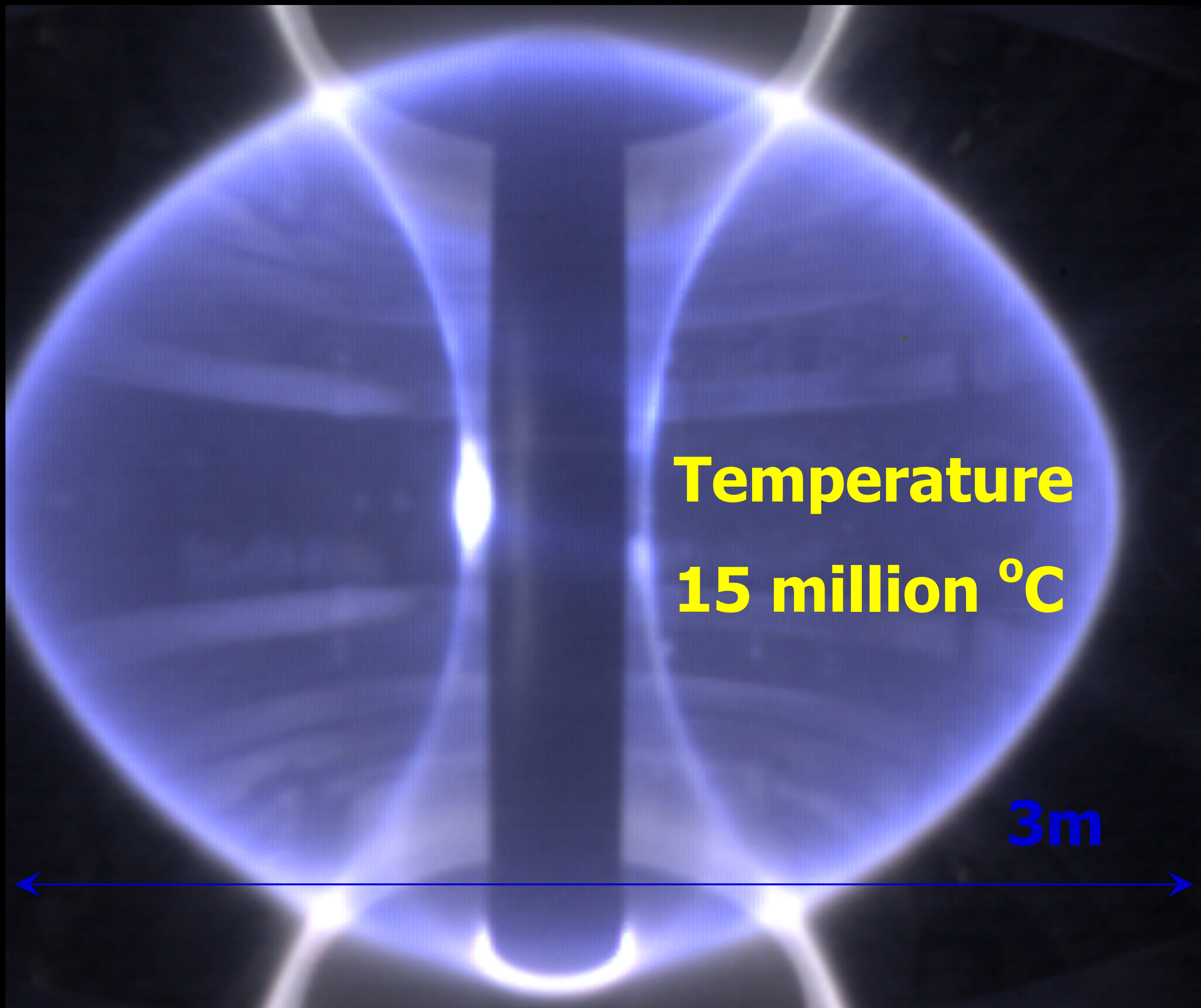
- Smaller than standard tokamak (lower cost)
- Higher plasma pressure
- No disruptions
- Good energy confinement



Drawbacks:

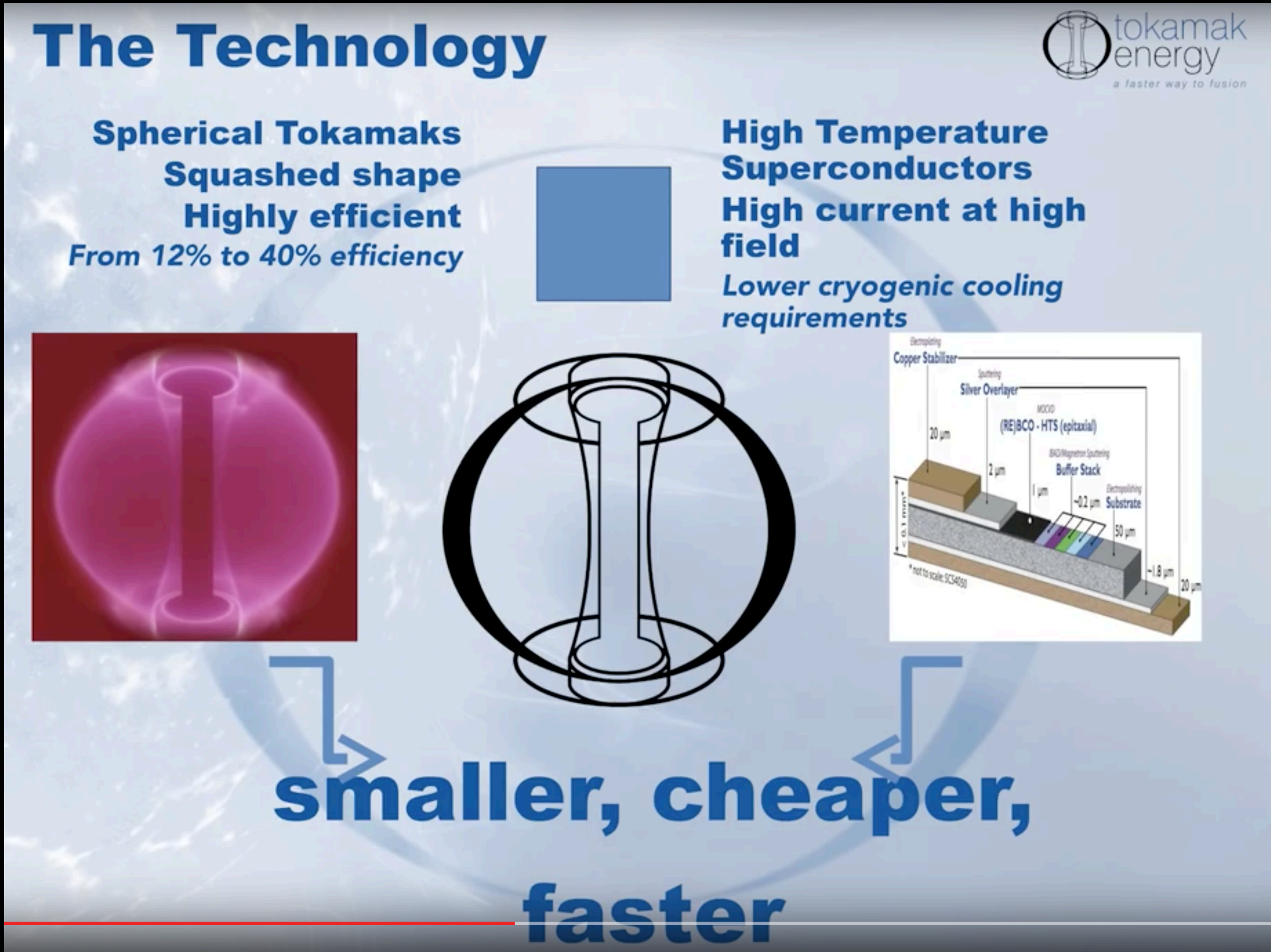
- Inner conductor exposed to heat and neutrons
- Neutron economy is an issue

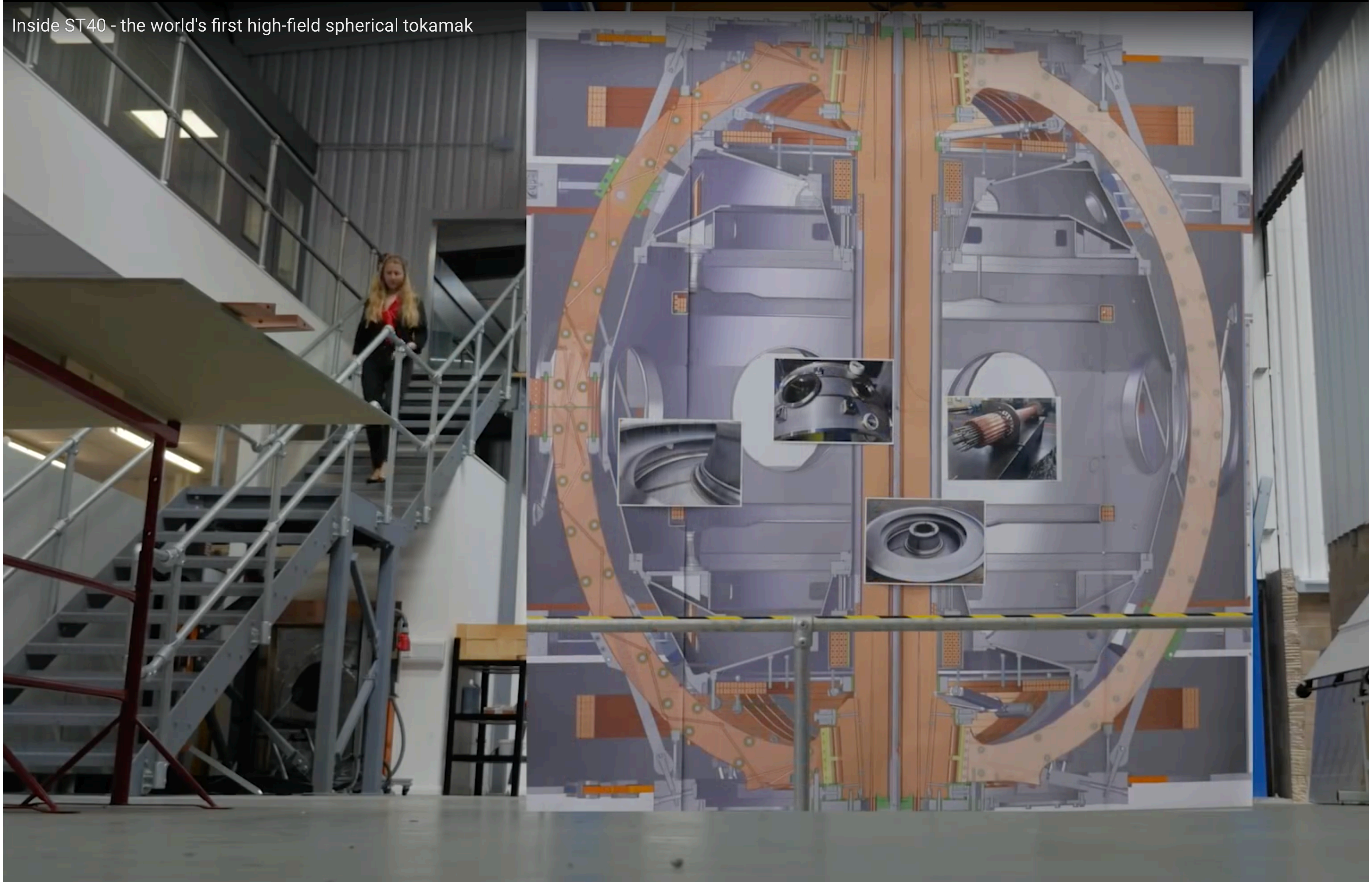
A MAST plasma



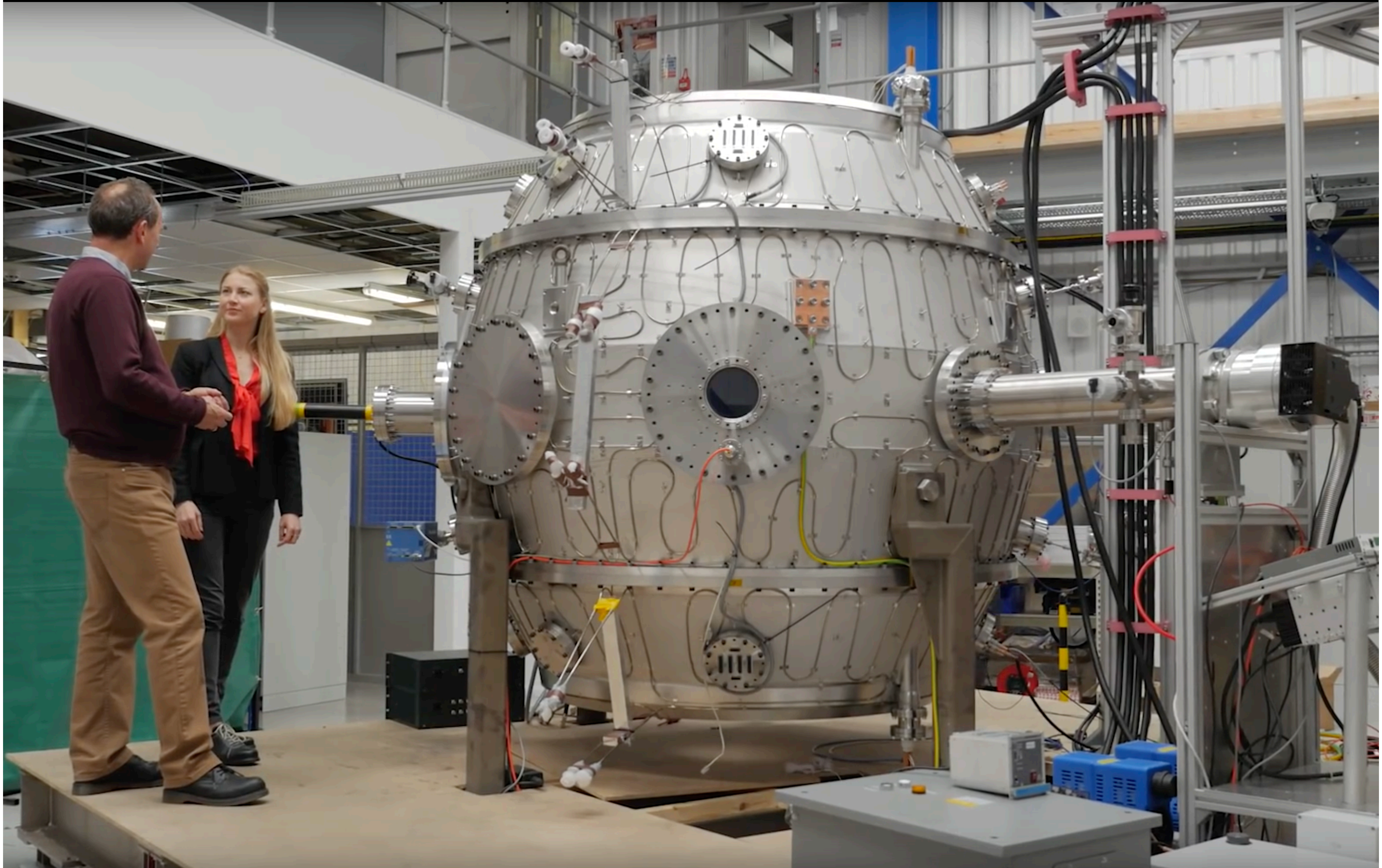
MAST - Culham, England

Tokamak Energy – Superconducting coils
Spherical tokamak



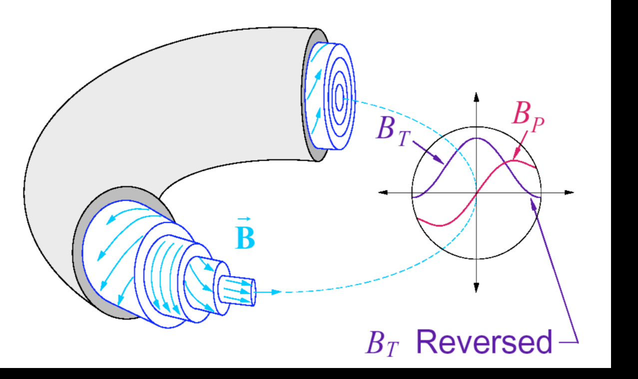


Tokamak Energy – ST 40



Tokamak Energy – ST 40

Reversed-field Pinch (RFP)



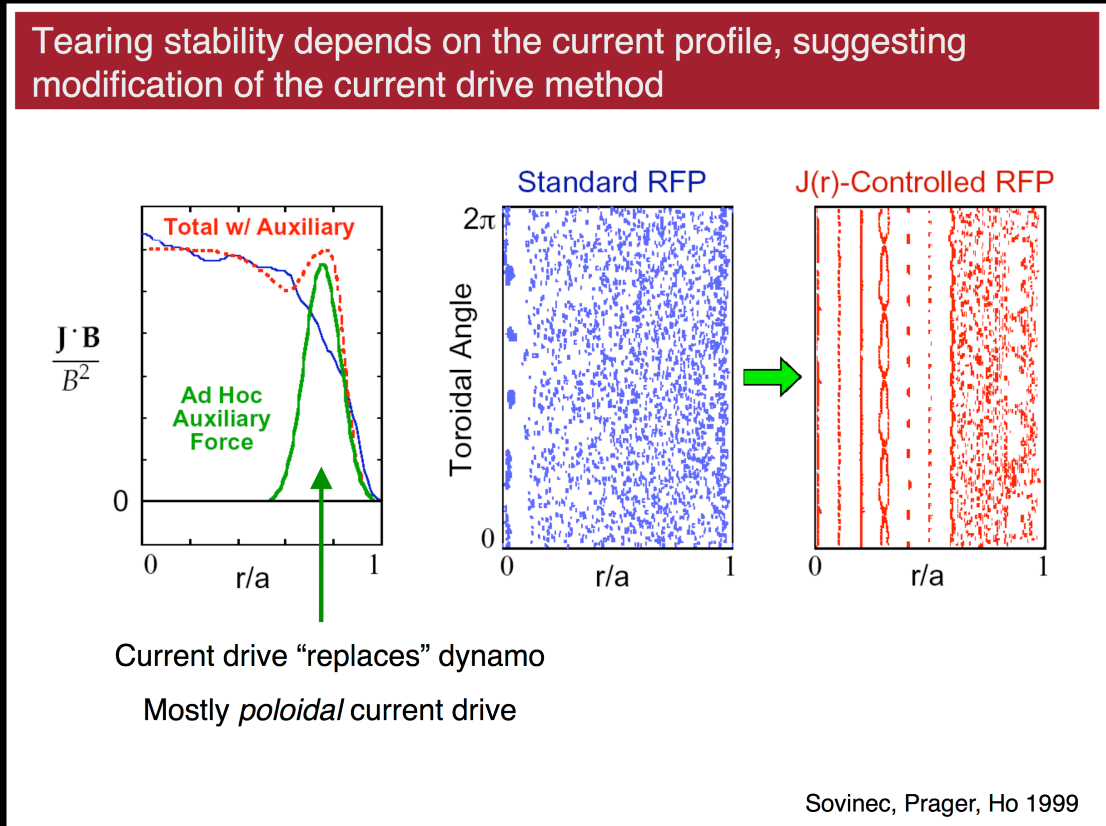
Advantages:

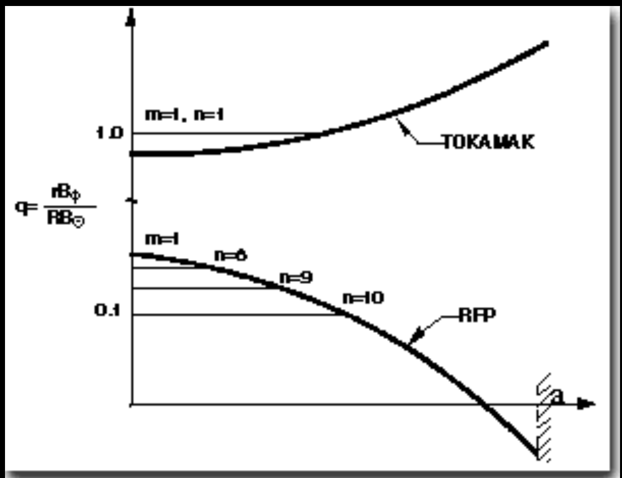
- Smaller than standard tokamak (lower cost)
- Higher plasma pressure
- Lower magnetic field
- Ohmical heating to ignition possible

Drawbacks:

- Limited energy confinement
- Instabilities and current profile must be controlled

RFP characteristics

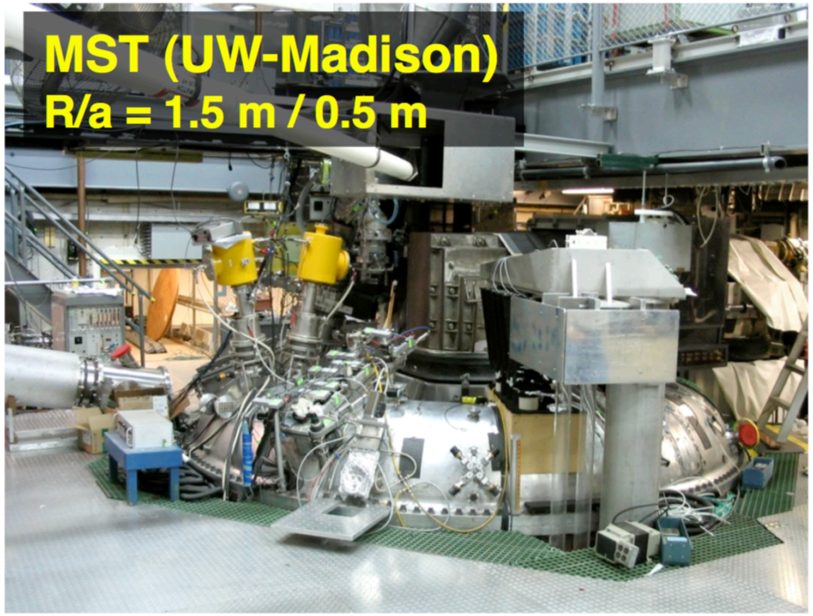


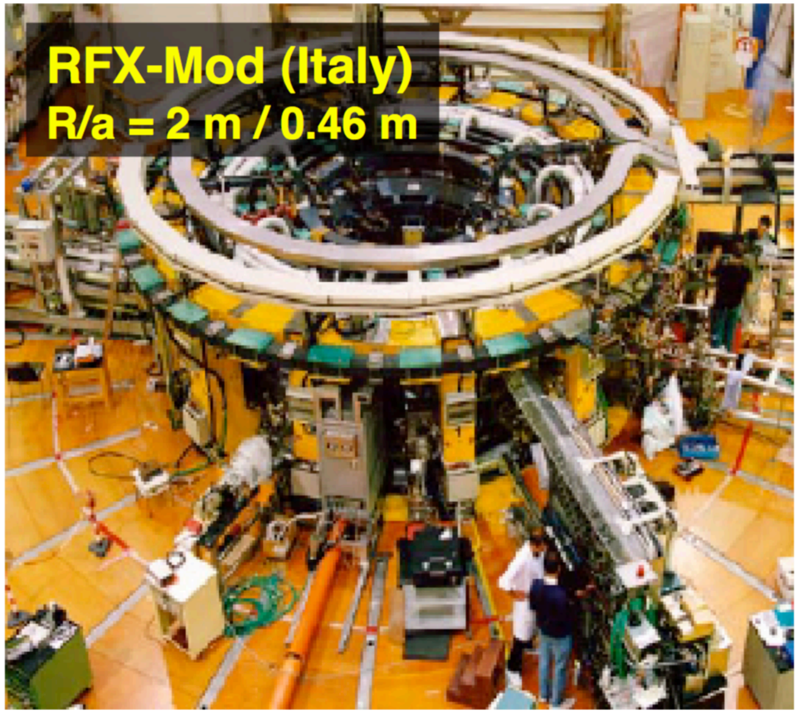


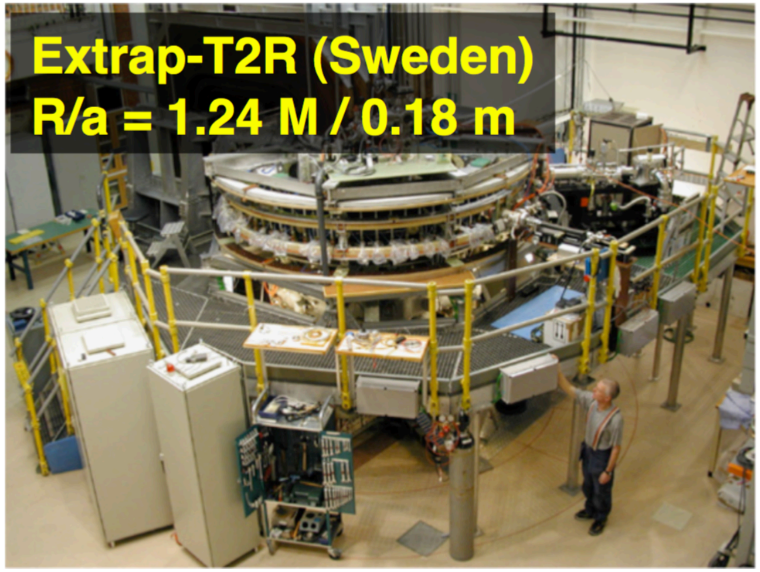
- Small q(r)
- Shear stabilization

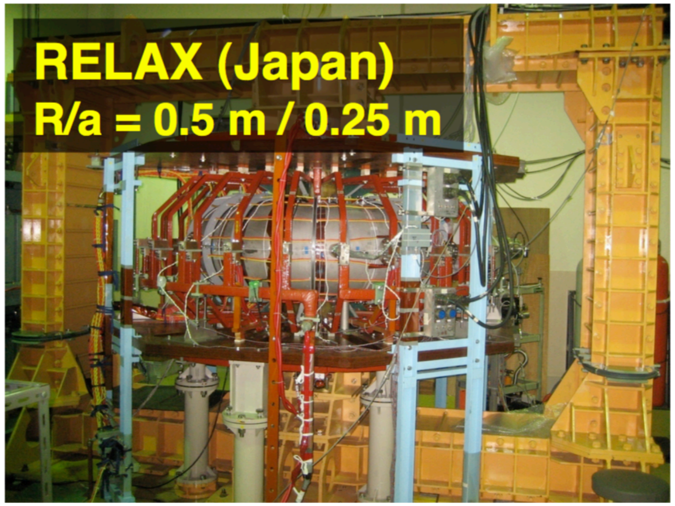
- Stochastic inner plasma region
- Tearing modes stabilized by current profile control

Present RFP experiments



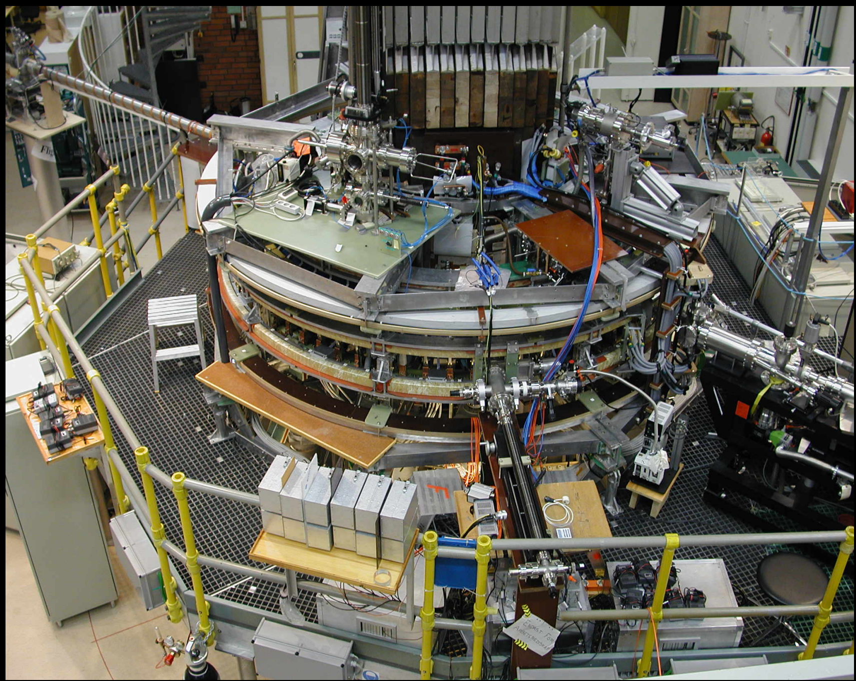


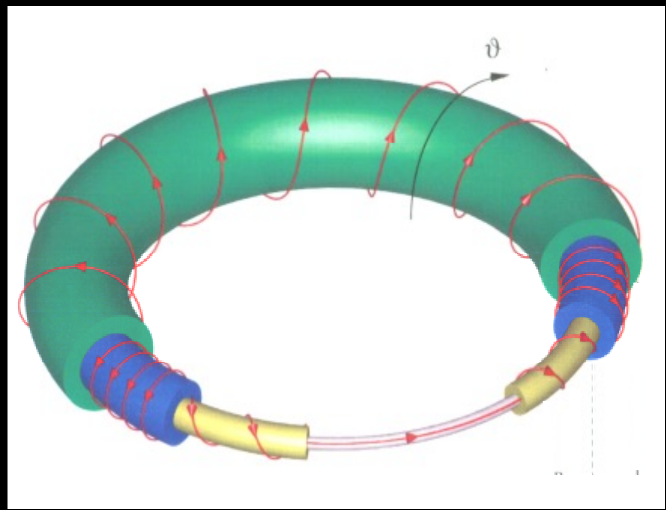




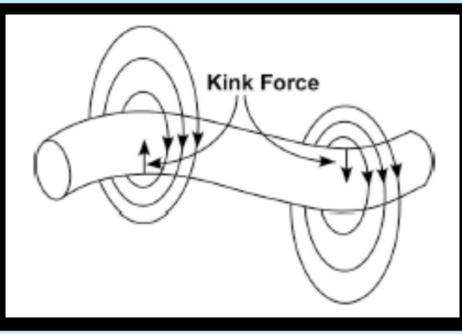
EXTRAP T2R

- One of several specialized experiments in the EU fusion programme
- Experimental group at KTH consists of about 10 persons (researchers, Ph D students, engineers and technicians)
- Research budget ca 10 Mkr/y
- Funding: KTH (60%), VR (20%), EU (20%).



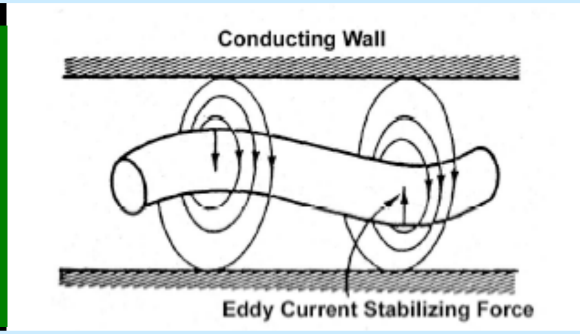


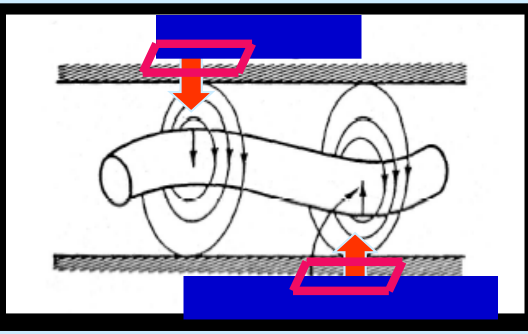
Plasma instabilities
- and feedback stabilisation



1. Plasma instability: small perturbations lead to growing deformations

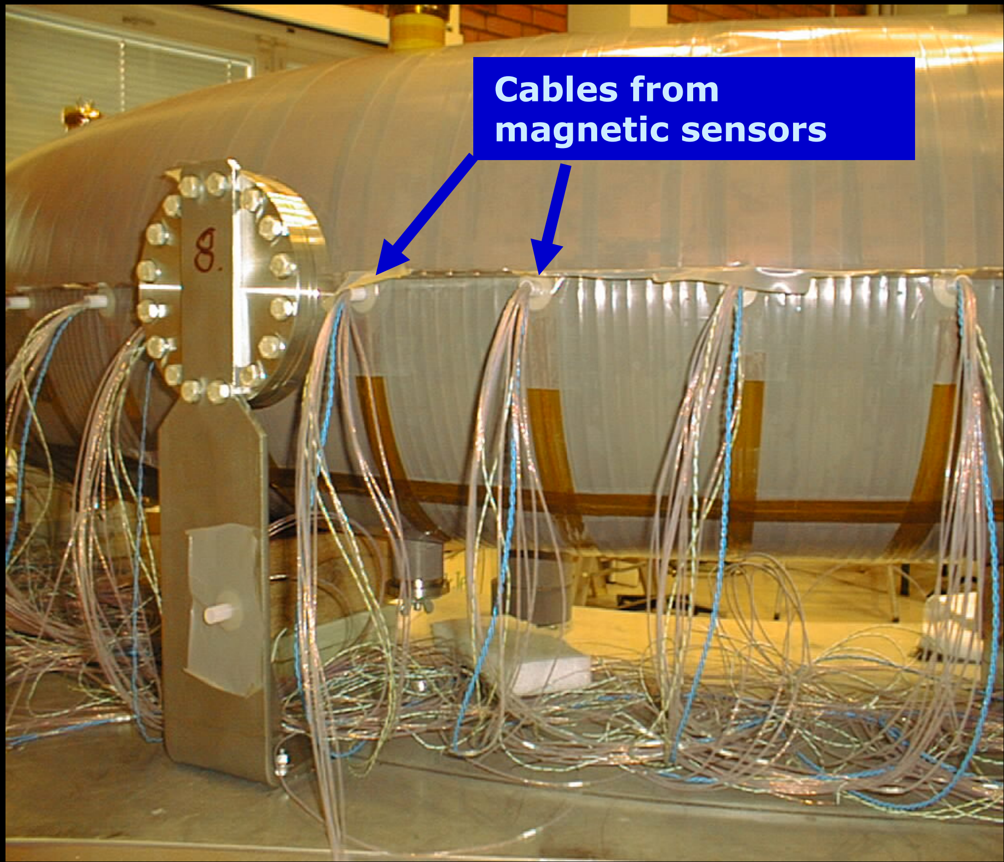
2. Passive stabilisation: an electrically conducting shell confines the magnetic field and provides damping of the perturbation by the magnetic pressure at the wall





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

Sensors for magnetic field mesurements

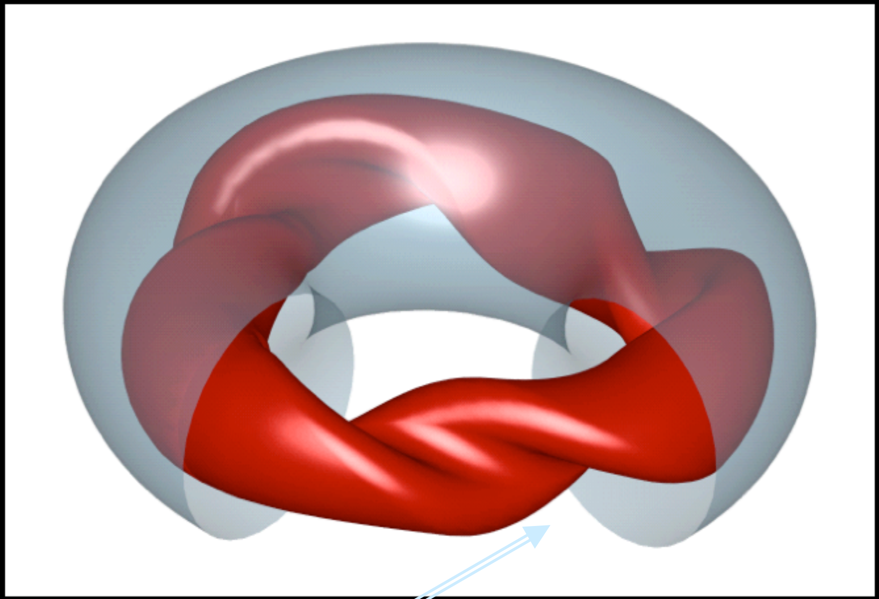


Some 900 magnetic field sensors (electrically insulated)

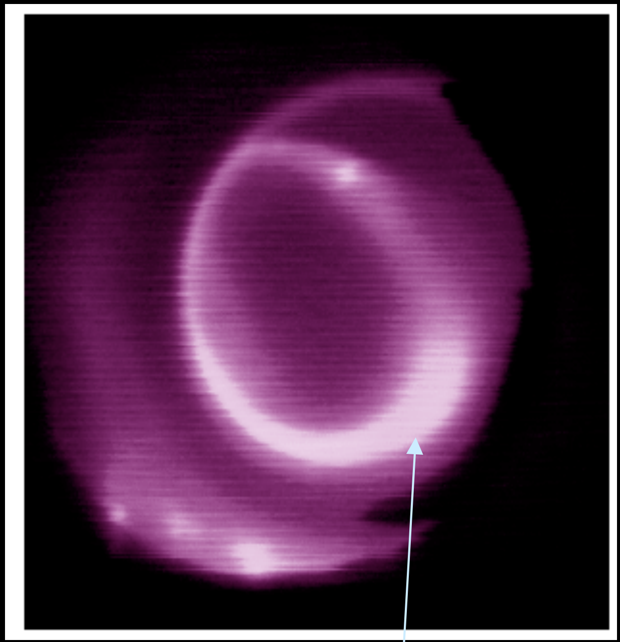
Placed on outside of vacuum chamber

Plasma perturbation in EXTRAP T2R

The plasma deformation grows in time (exaggerated here)

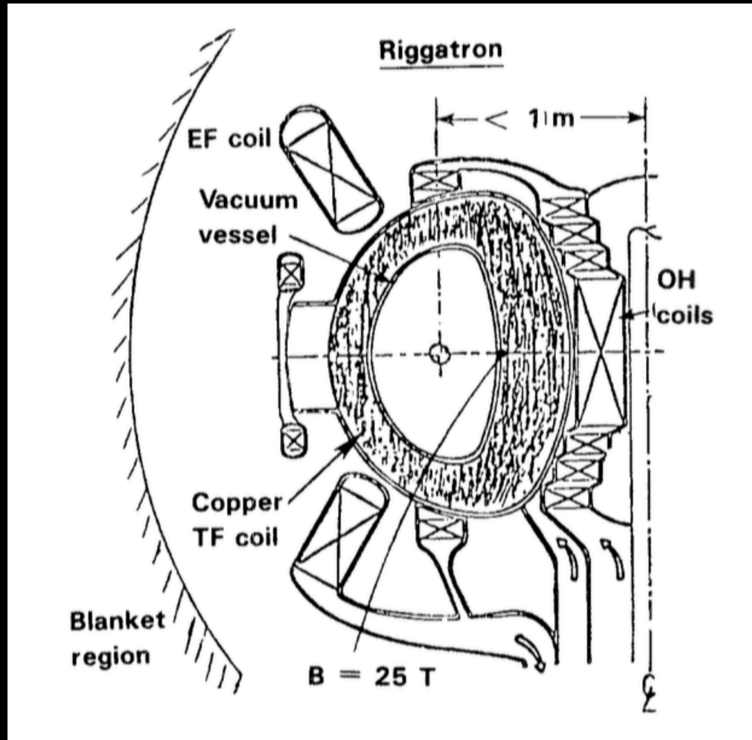


Camera view for picture at the right



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

Compact tokamak (Riggatron)



Advantages:

• High magnetic field => high density

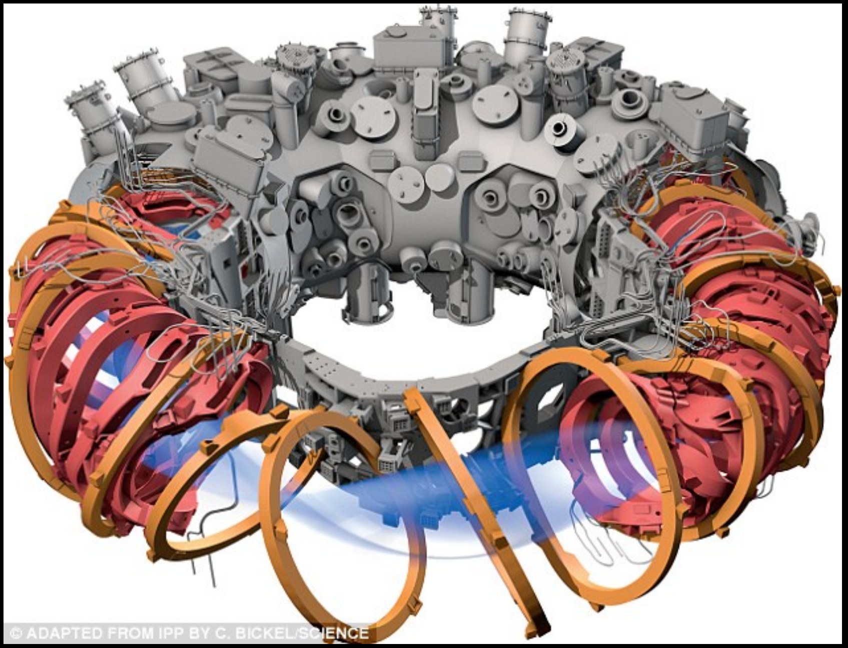
• Extremely compact (R < 1 m)

• Plug-in reactor core => short shut-down

Drawbacks:

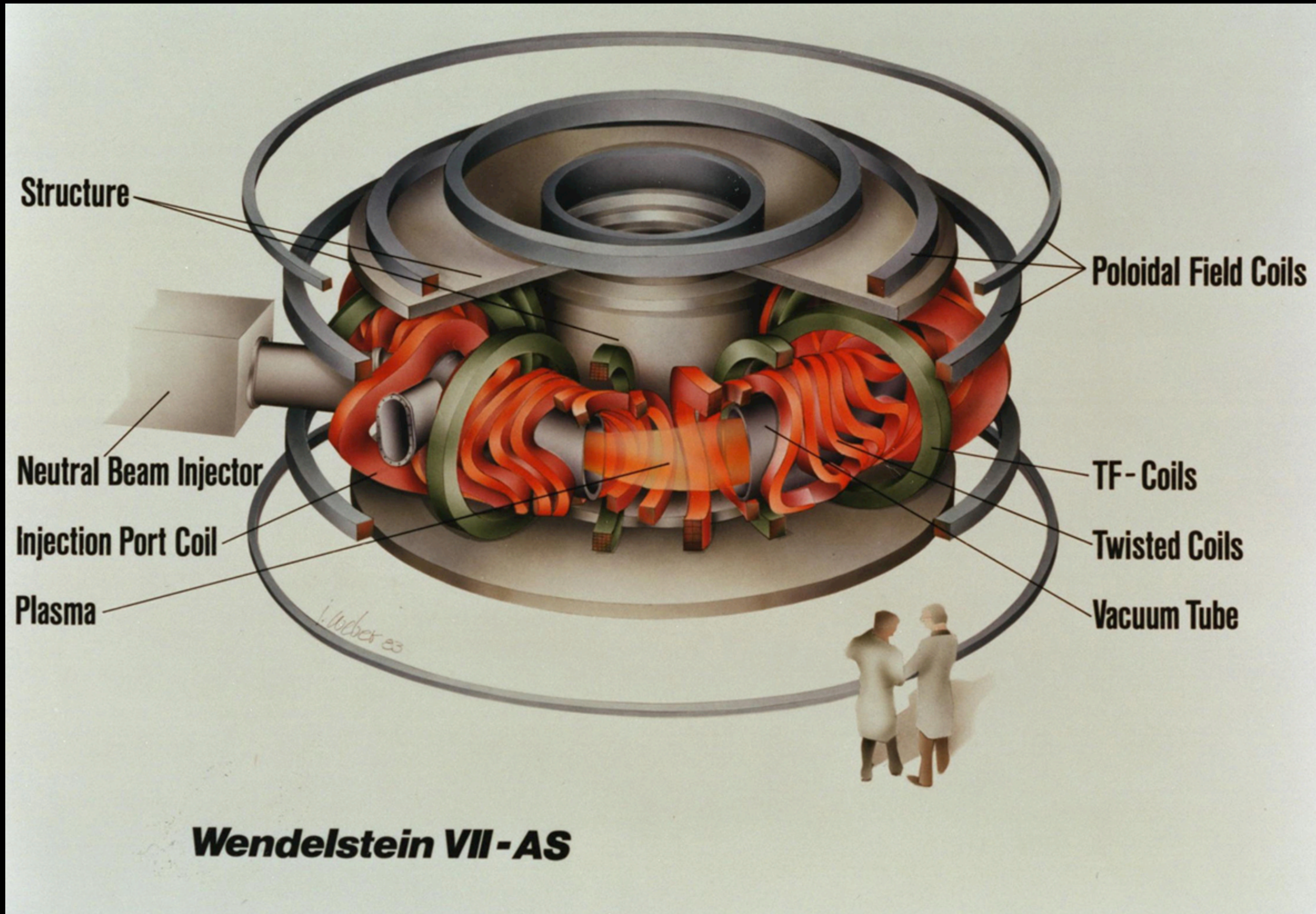
• Copper coils inside blanket

Stellarator



Advantages:
- No plasma current
- Continuous operation
- Good confinement of particles and energy
- Modular reactor – simple service

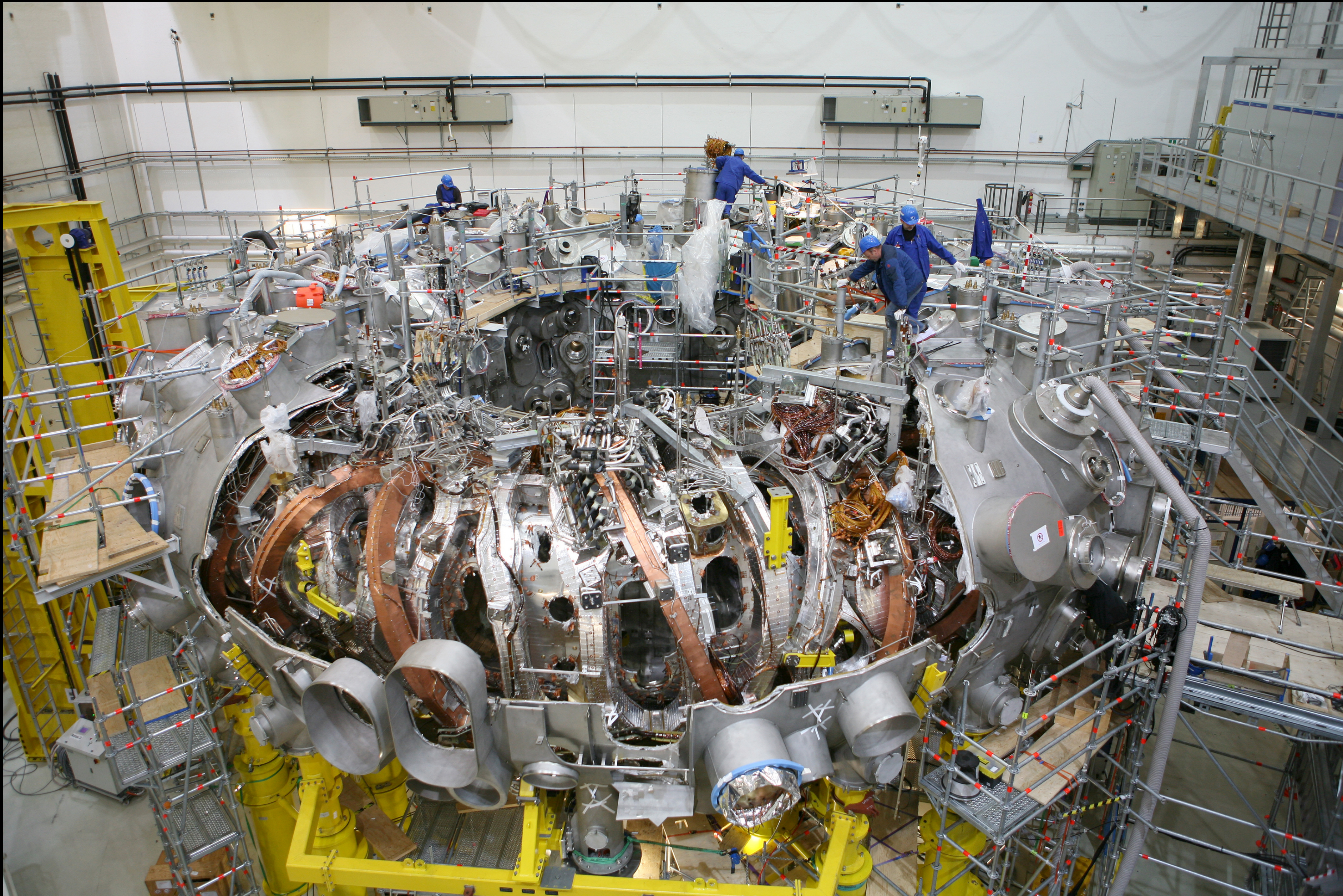
Disadvantages:
- Limited plasma pressure
- Complex 3D theory and experimental diagnostics



Wendelstein VII-AS – Stellarator in Garching,Tyskland

Wendelstein 7-X

Max-Planck-Institut für Plasmaphysik
EURATOM Assoziation



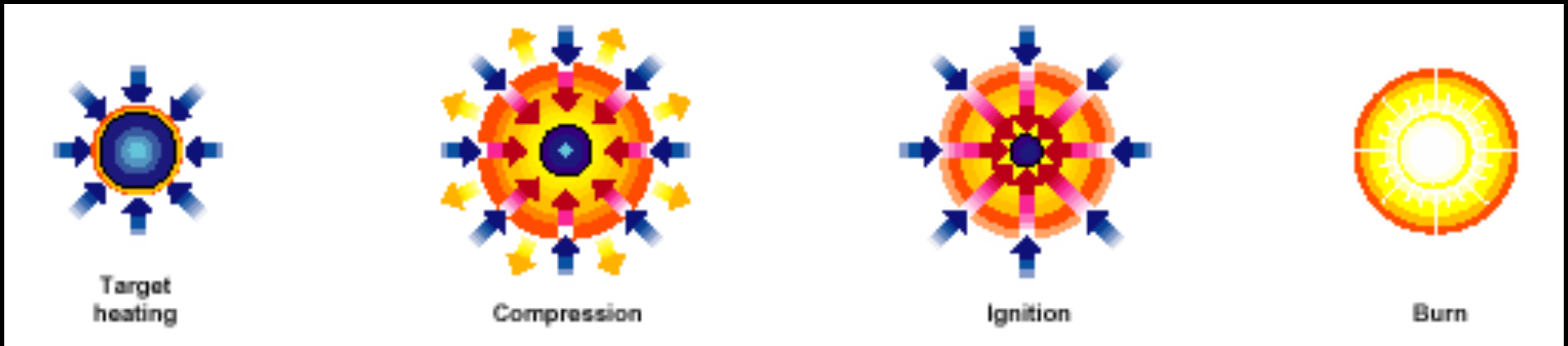
Stellarator – Wendelstein 7-X

Max-Planck-Institut für Plasmaphysik
EURATOM Assoziation

Superconducting coils

Inertial confinement

- Beams of laser light or heavy ions targeted on small pellet of 'fuel' (hydrogen isotopes).
- Surface heating ablates material leading to compression of pellet by rocket action.
- When sufficient temperature and density is reached: fusion occurs.
- For economic power production, need to repeat 5-10 times per second.



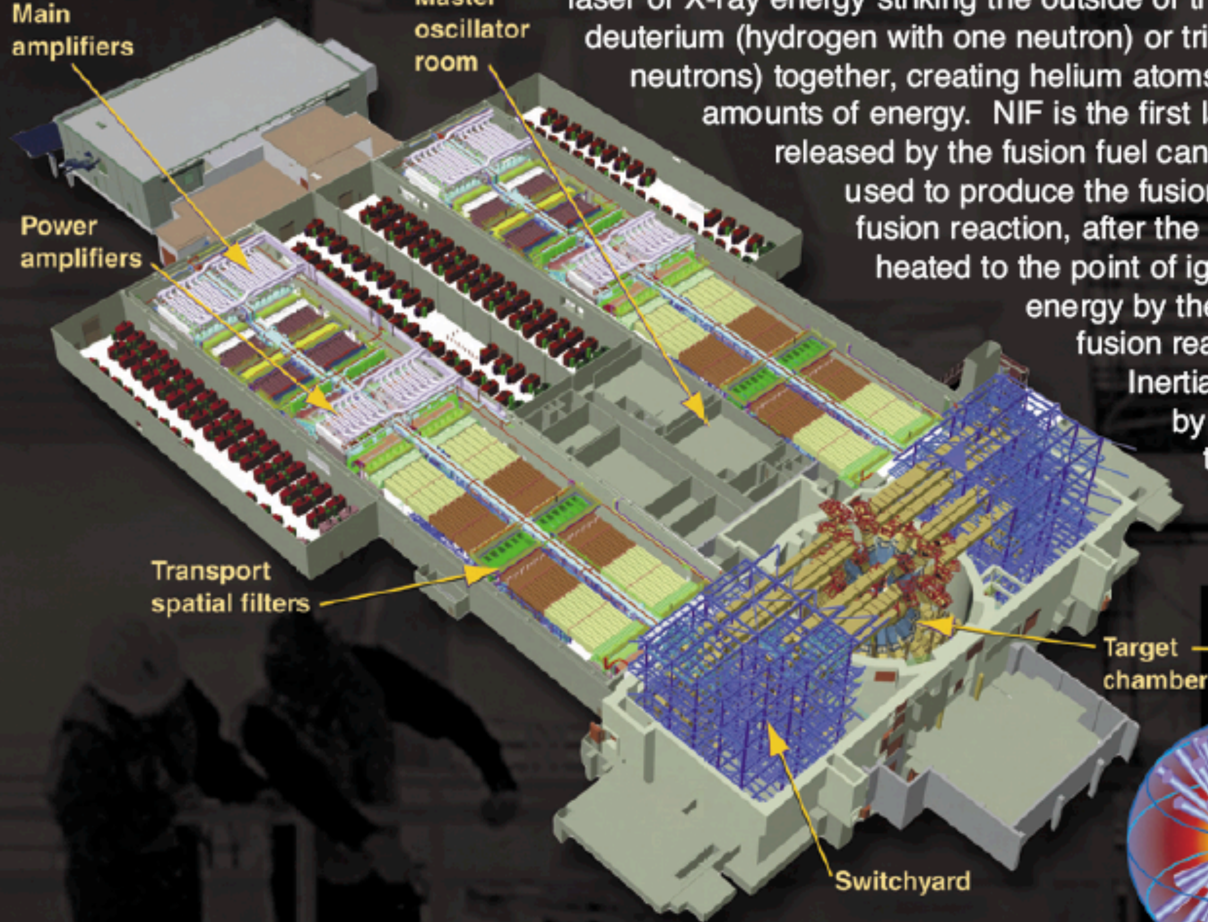
National Ignition Facility (NIF), Livermore, CA (inertial fusion)

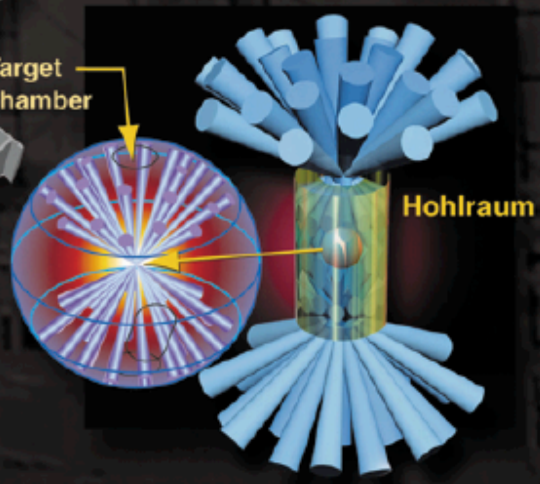
NATIONAL
IGNITION
FACILITY

Inertial Confinement Fusion: How to Make a Star

Inside the 30-foot-wide target chamber, a gold cylinder the size of a dime receives energy from all 192 laser beams simultaneously: about 1.8 million joules over a few billionths of a second (about 500 trillion watts, which is nearly 1,000 times the power generated in the United States over the same time period). This cylinder then produces X-rays that compress and heat a fusion capsule inside the cylinder to temperatures and pressures approaching those in a nuclear explosion or in the sun, igniting the fusion fuel in a self-sustaining reaction and creating a miniature star in the laboratory.

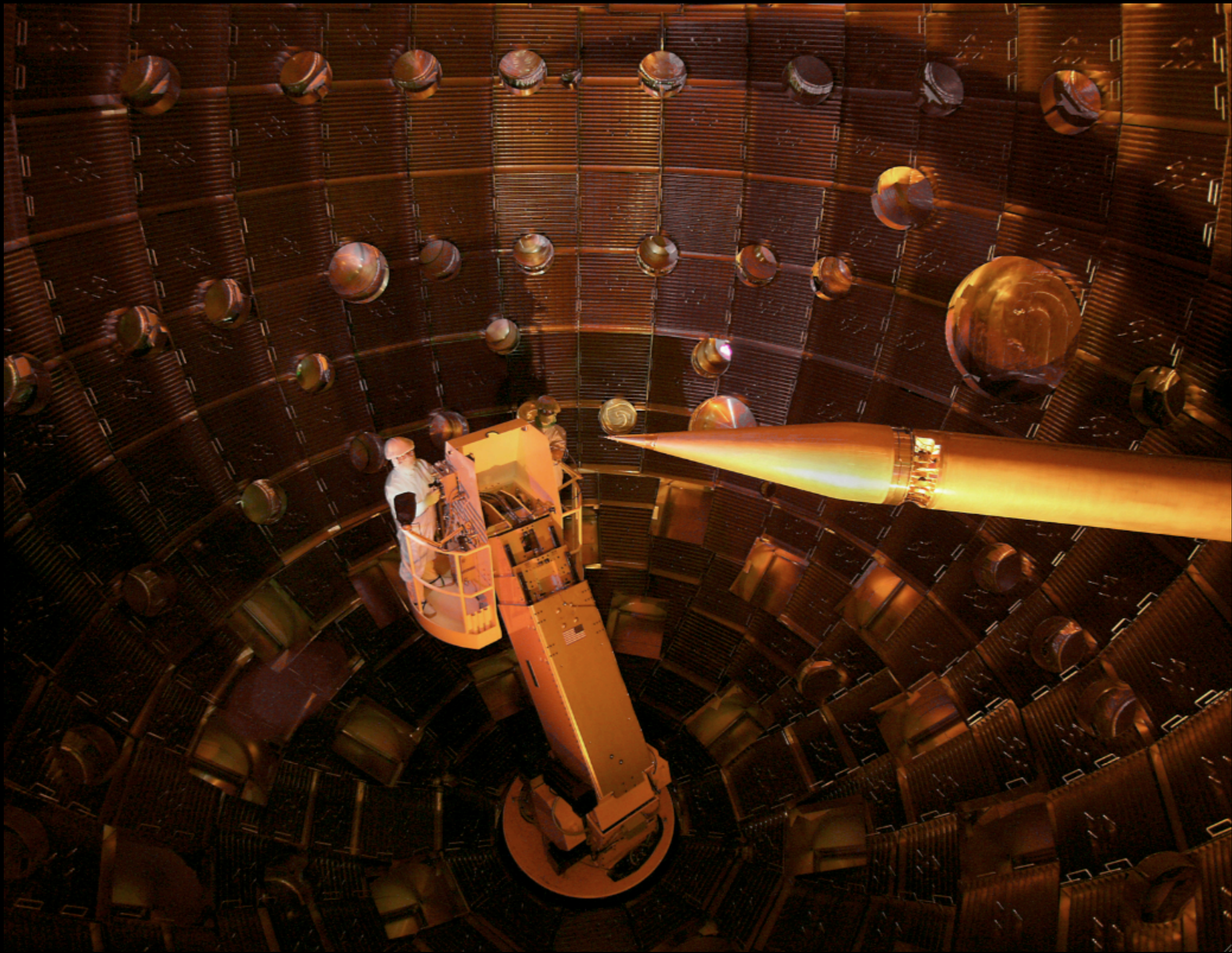
NIF will employ a process called inertial confinement fusion, in which either laser or X-ray energy striking the outside of the target fuses atoms of deuterium (hydrogen with one neutron) or tritium (hydrogen with two neutrons) together, creating helium atoms, extra neutrons and large amounts of energy. NIF is the first laser in which the energy released by the fusion fuel can exceed the laser energy used to produce the fusion reaction. In a self-sustaining fusion reaction, after the capsule is compressed and heated to the point of ignition, the release of fusion energy by the fuel drives the rest of the fusion reactions until the fuel is spent. Inertial confinement fusion is limited by the amount of fusion fuel in the tiny capsule, and is therefore totally controllable.



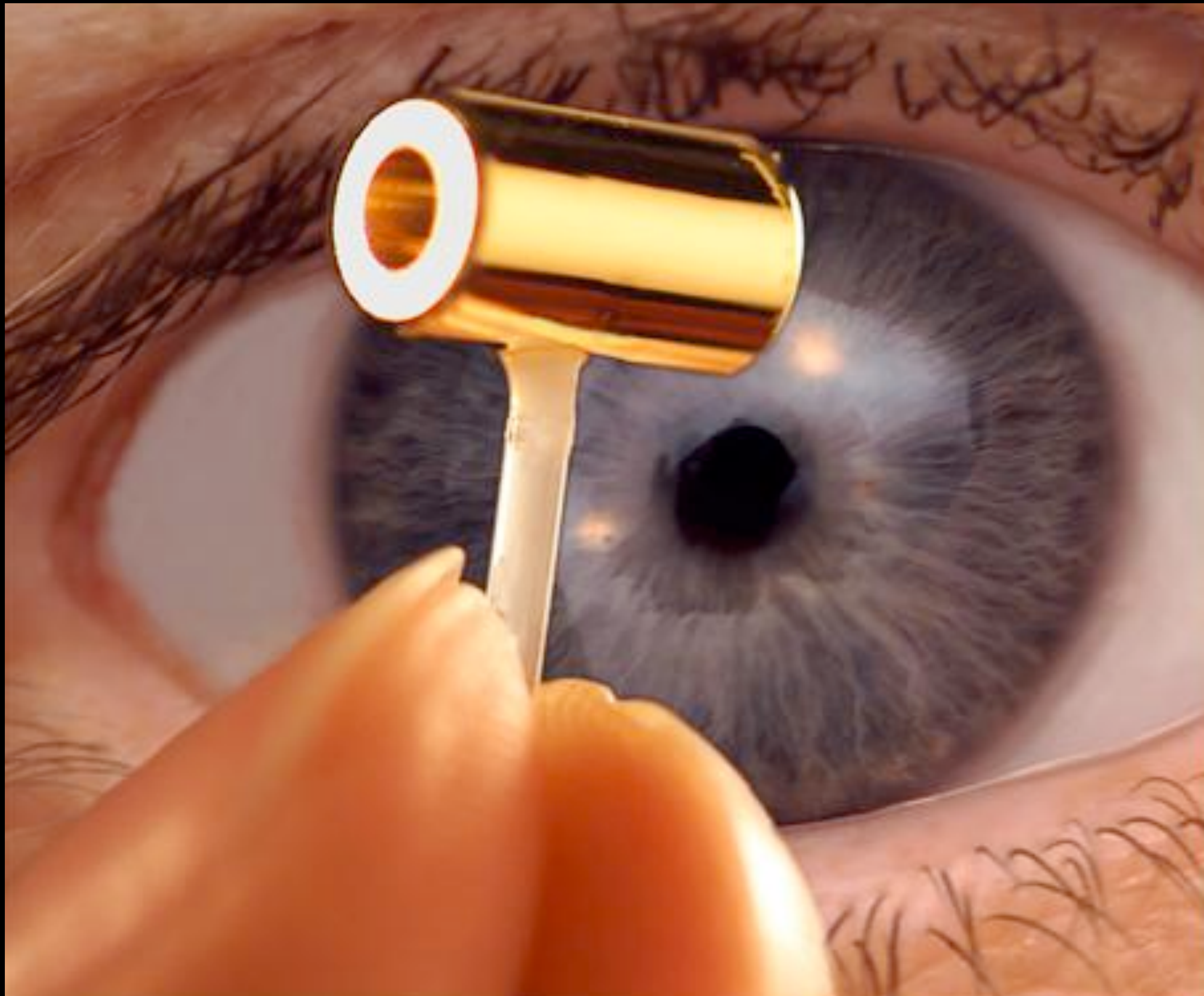


National Ignition Facility (NIF), Livermore, CA (inertial fusion)

National Ignition Facility (NIF), Livermore, CA (inertial fusion)



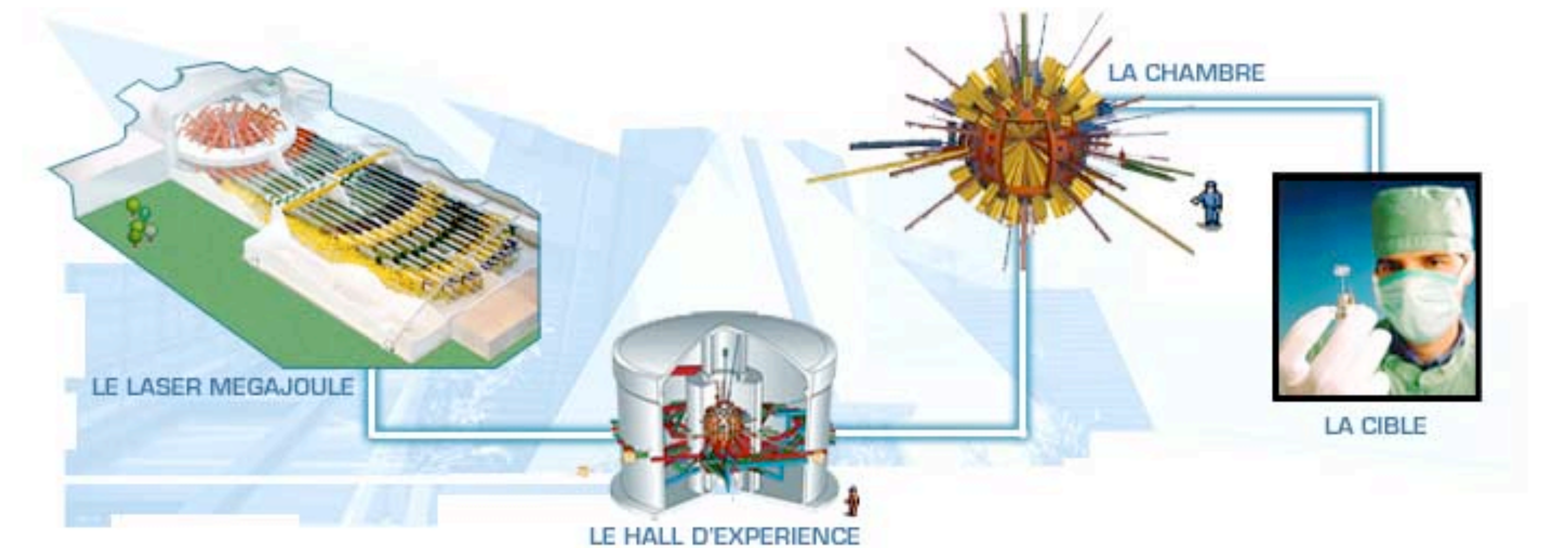
National Ignition Facility (NIF), Livermore, CA (inertial fusion)



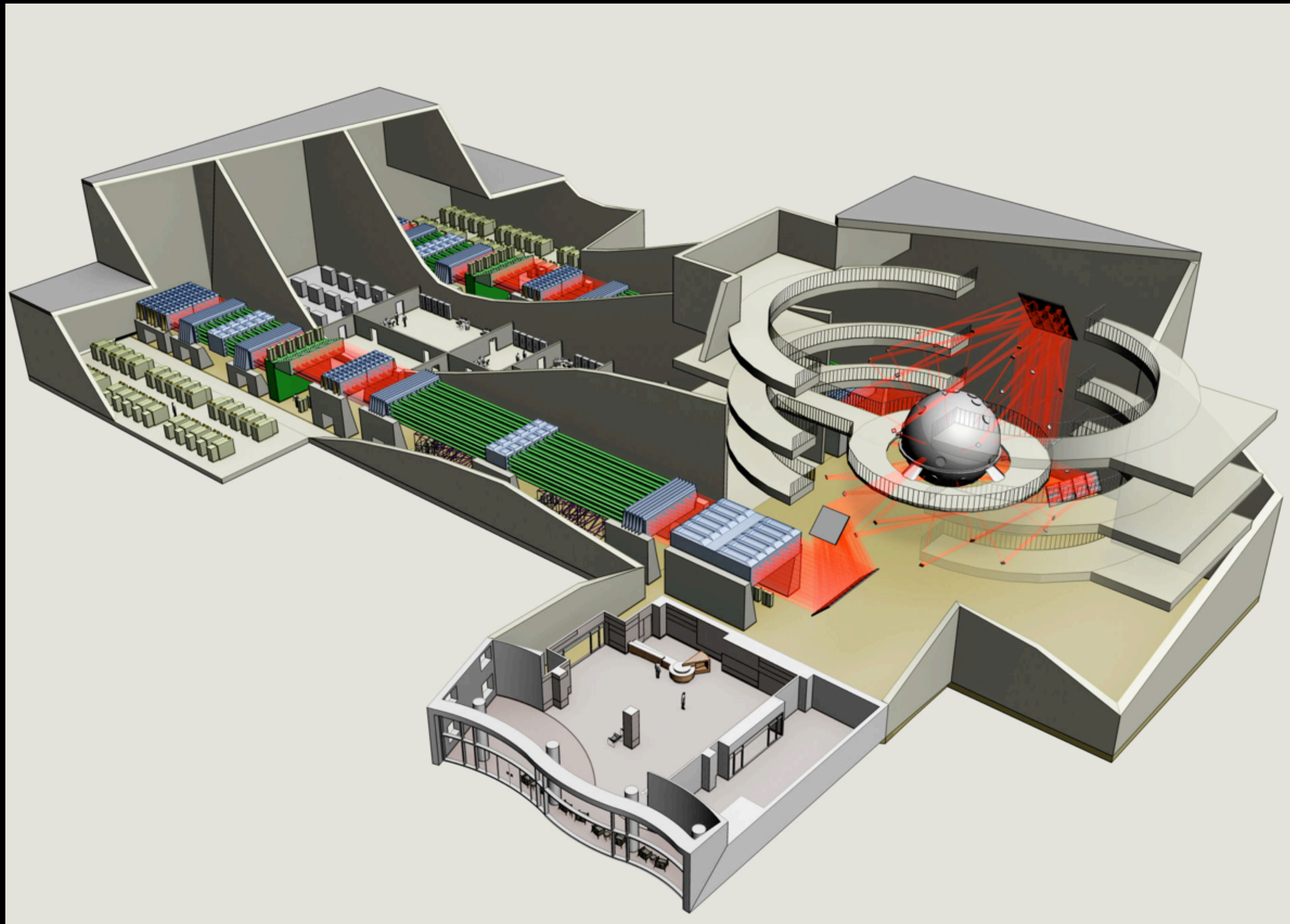
Laser Mégajoule,
Bordeaux, Frankrike (tröghetsfusion)

Du laser à la cible

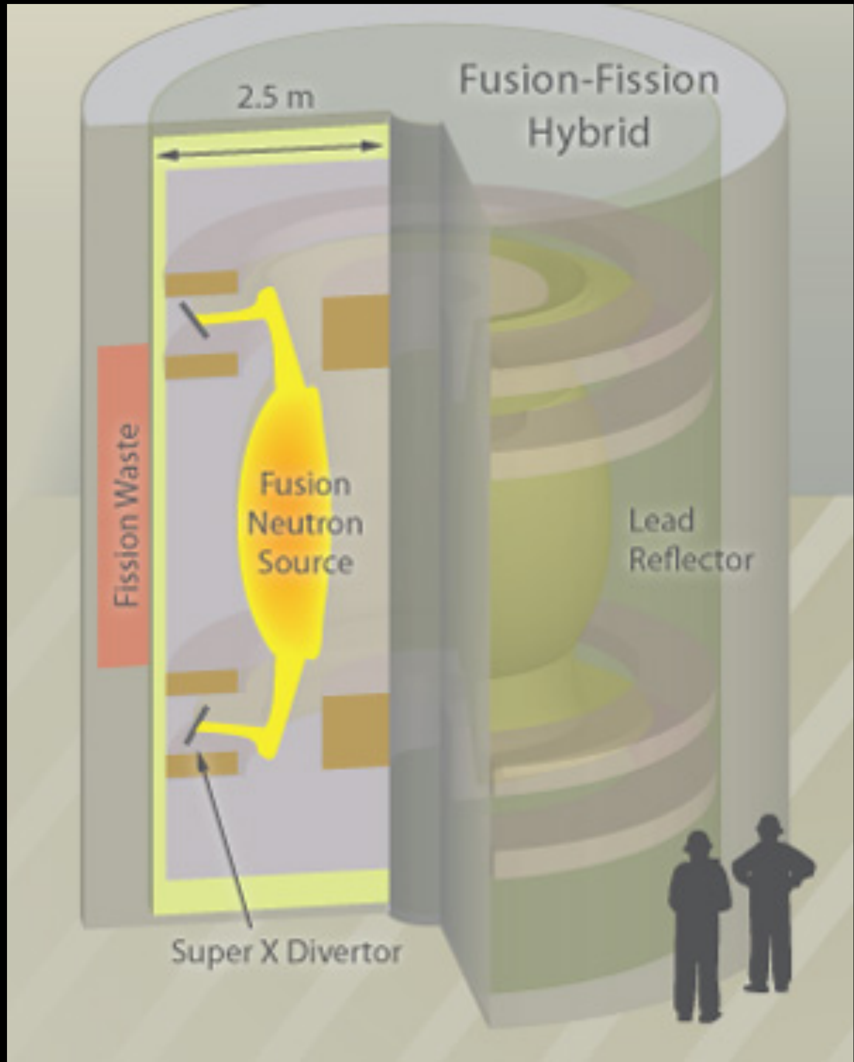
Avec 240 faisceaux lasers regroupés en 60 « quadruplets », concentrés sur une cible de 2,5 mm de diamètre, placée dans une chambre de 10 m de diamètre ; elle-même située dans un hall d'expérience cylindrique de 60 m de diamètre et de 40 m de haut, au centre d'un bâtiment de plus de 300 m de long : **le LMJ est un formidable amplificateur d'énergie lumineuse.** Entre la lumière issue de la source laser, dont l'énergie est comparable à celle que l'on trouve dans les lecteurs de CD, et la chambre d'expérience, **l'énergie aura été amplifiée de plus de mille milliards de fois.**



HiPER, Europa
(High Power laser Energy Research Facility)

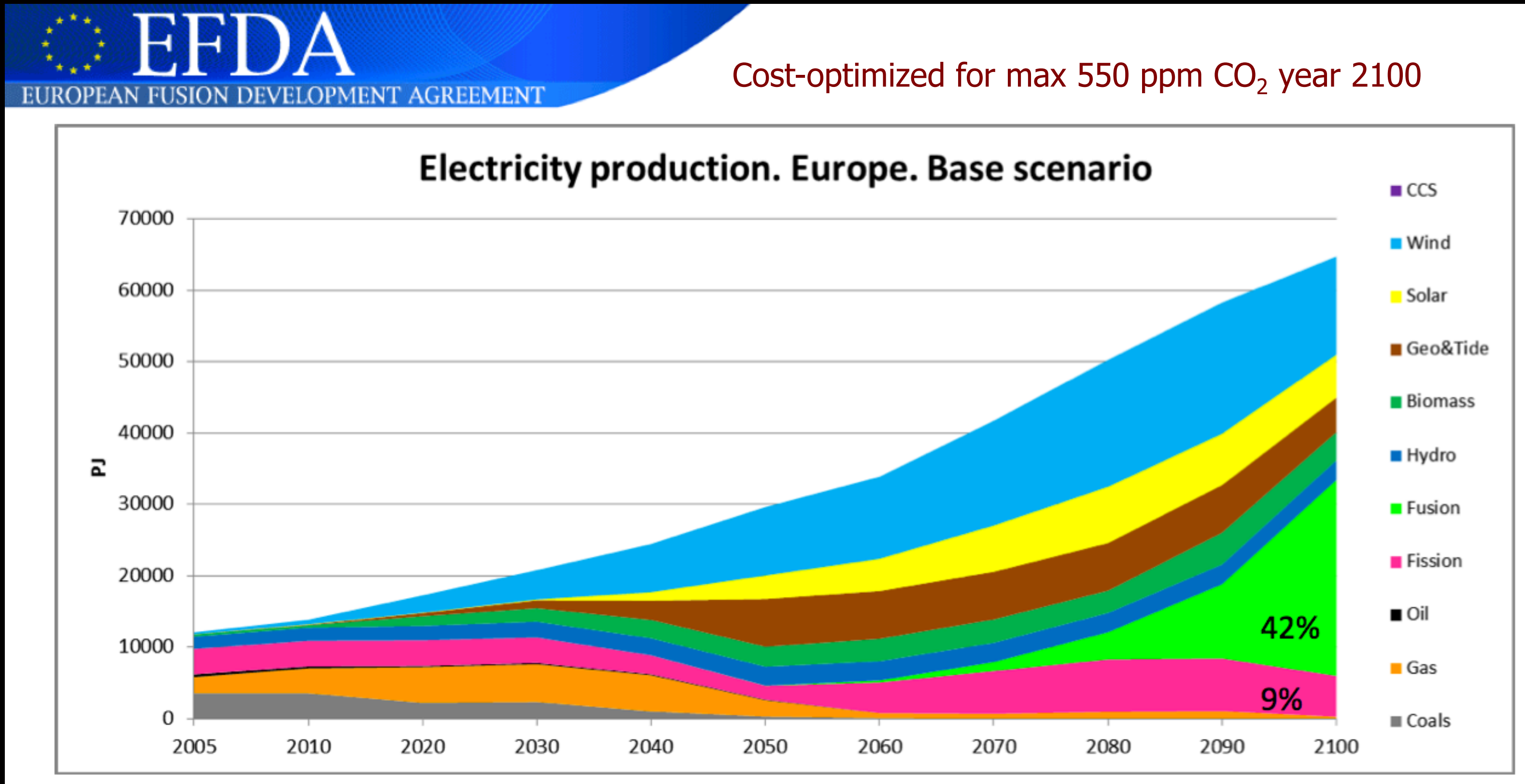


Fusion – fission hybrid



Conclusions

Fusion energy is needed - and is on its way



- Unique sustainable and clean base load power that, with renewables, can phase out fossil fuels
- Fuel for millions of years, over the whole planet
- Good economy when external costs are included