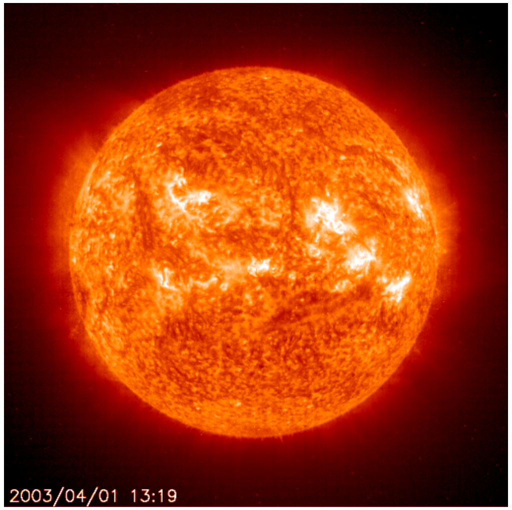
The Path to Fusion Energy

creating a star on earth



S. Prager

Princeton Plasma Physics Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

PPPL PRINCETON PLASMA PHYSICS LABORATORY

DEI SVB NVMINE VIGET

The need for fusion energy is strong and enduring

Carbon production (Gton)

no changes

And the need is time urgent

Best available technology

Goal

Year

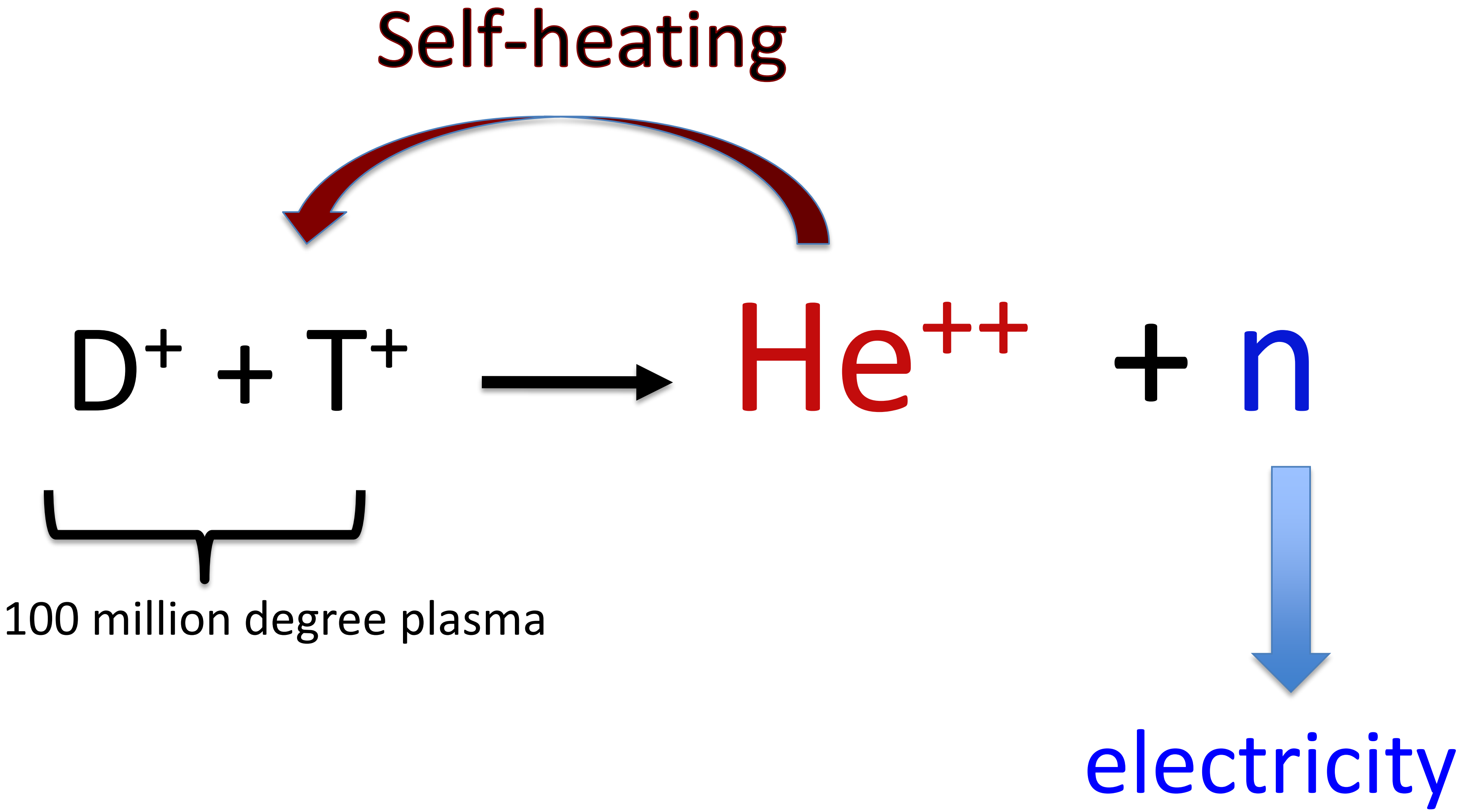
The fusion fuel cycle is carbon-free

$$D^{+} + T^{+} \longrightarrow He^{++} + n$$

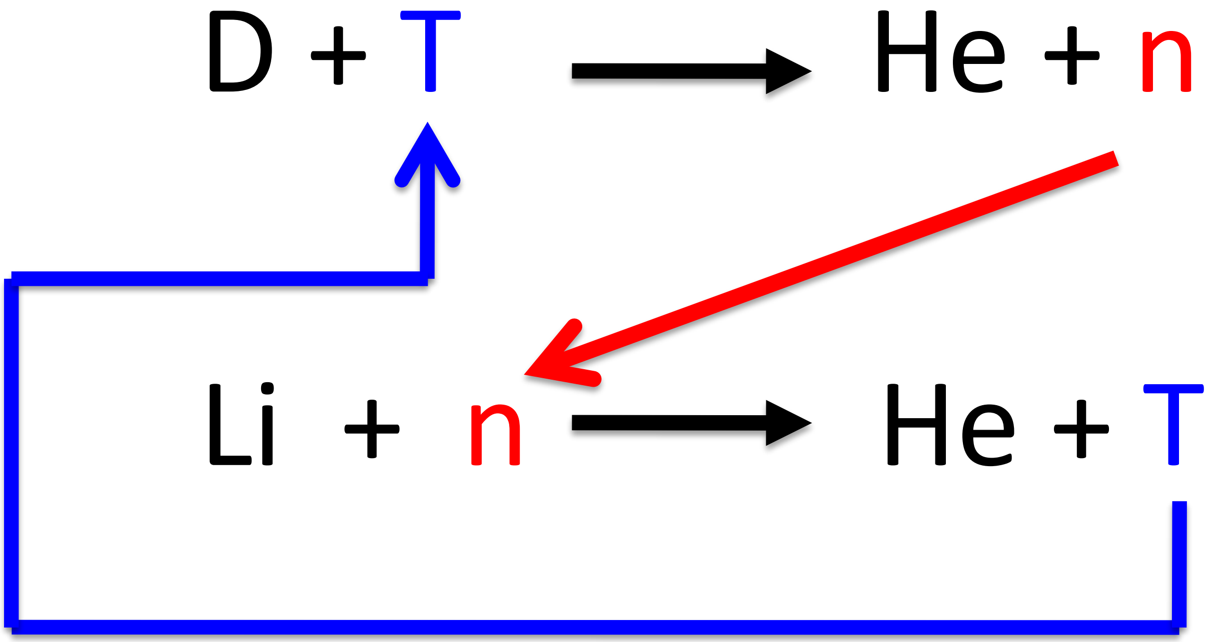
10 keV   10 keV   3.4 MeV   14 MeV

and intense

and self-sustaining



Deuterium obtained from water,
Tritium is bred in the fusion reactor,



Why fusion?

- Nearly inexhaustible

  Deuterium from sea water, Tritium from breeding

- Available to all nations

  reduced conflict over resources

- Clean

  no greenhouse gases, no acid rain

- Safe

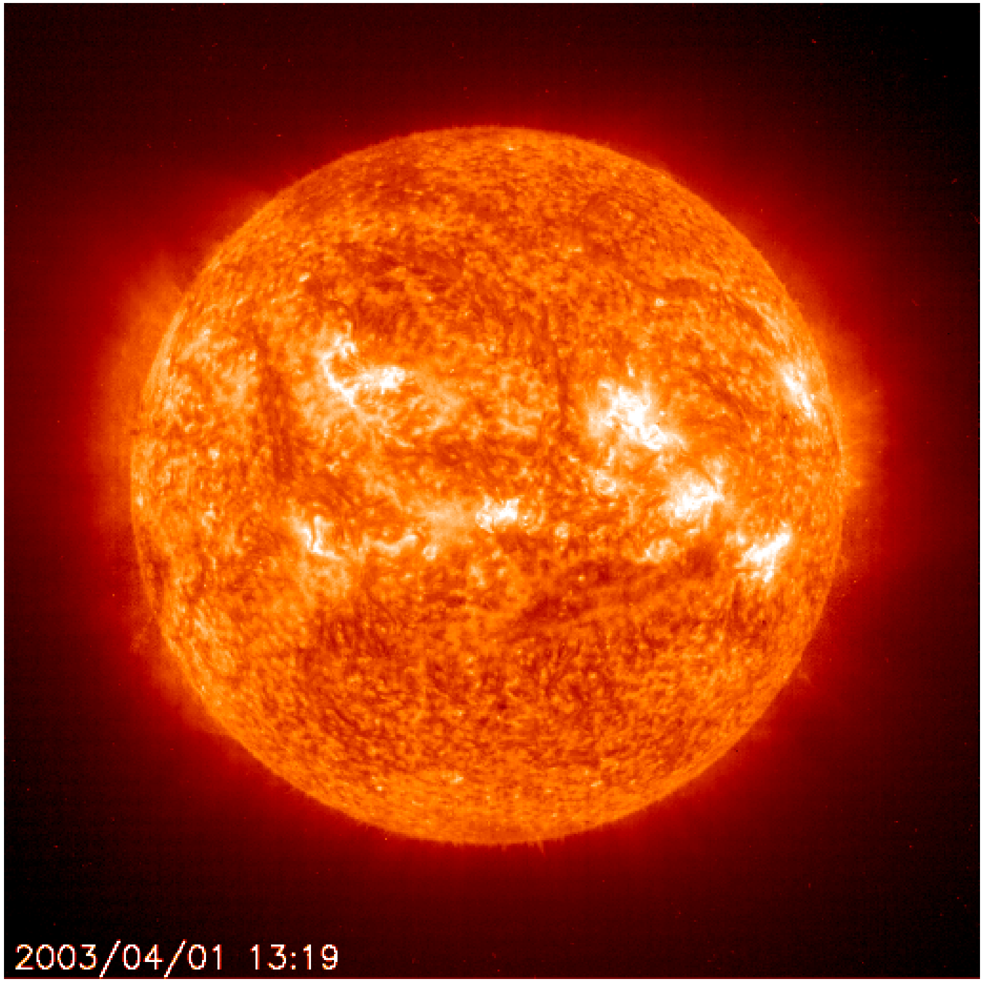
  no runaway reactions or meltdown;
  only short-lived radioactive waste

Daily fuel consumption and waste production

For a 1000 MegaWatt power plant

	Coal plant	**Fusion plant**
fuel	9000 tons coal	1 lb Deuterium 3 lbs Lithium
waste	30,000 tons CO_2 600 tons SO_2 80 tons NO_2	4 lbs Helium

Fusion is one of the largest science and engineering challenges of our era



<u>The Sun</u>
10 million degrees
300 Watts/m^3

<u>Fusion reactor</u>
100 million degrees
10 MWatts/m^3
Surrounded by material

The Fusion Physics Challenge

Confine plasma that is

hot

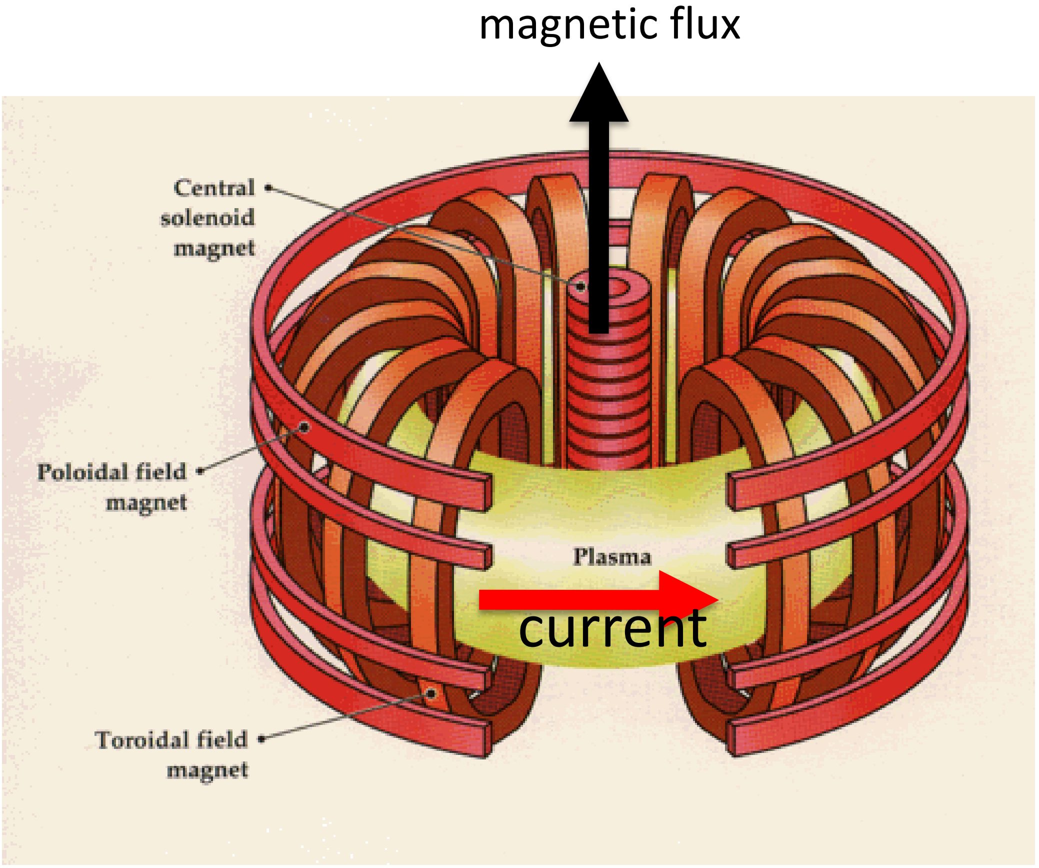
dense

well-insulated (high energy loss time)

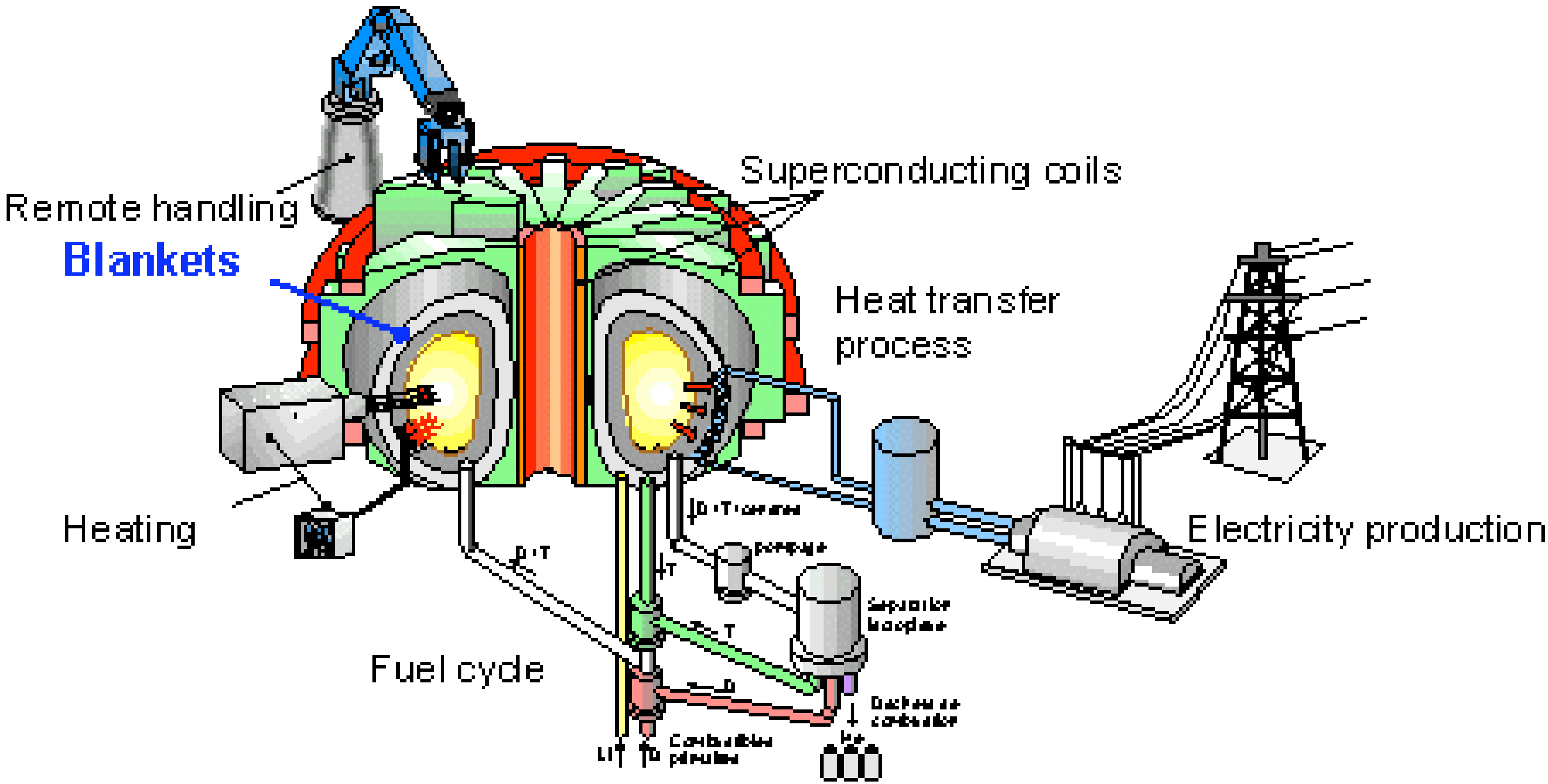
in contact with a material wall

confine a donut-shaped plasma (torus) in a magnetic field

The tokamak

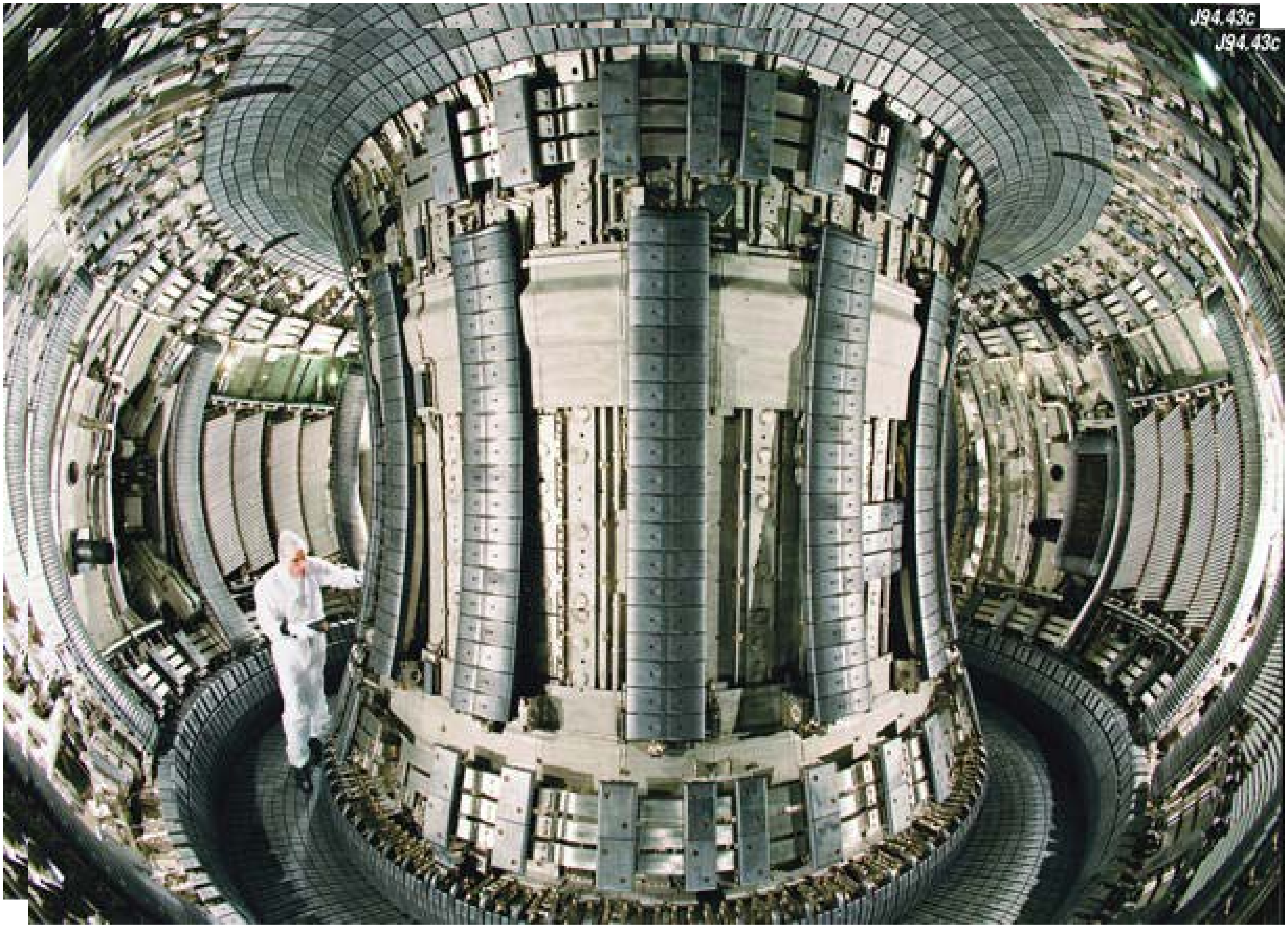


A fusion power plant



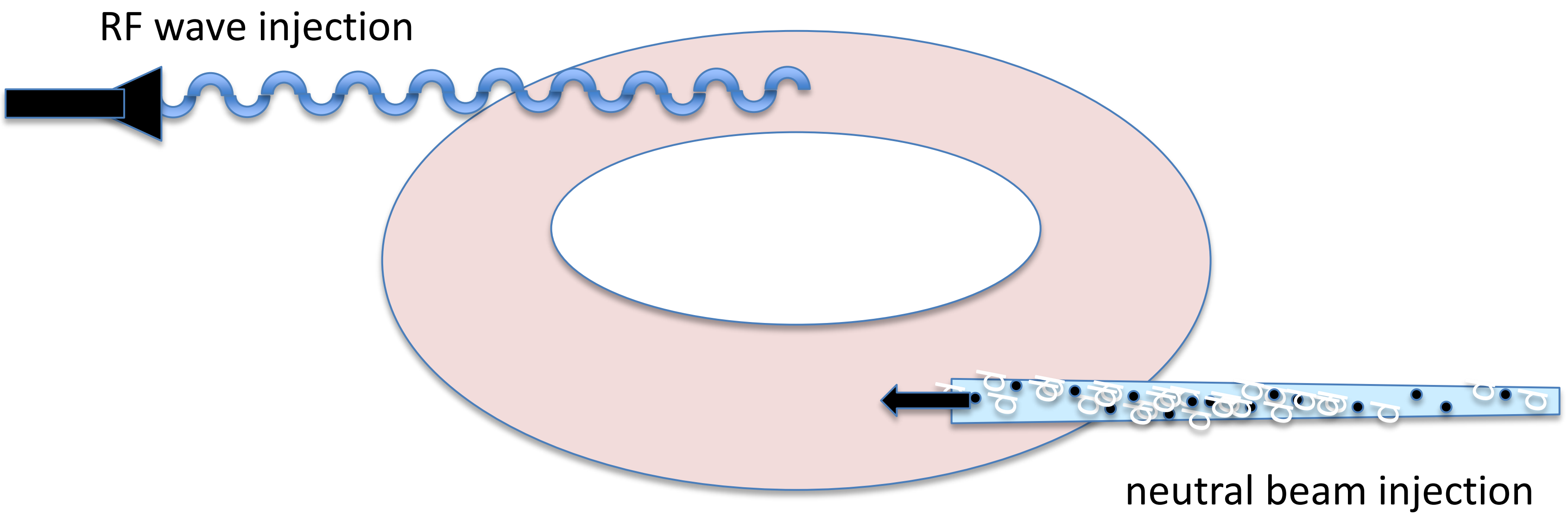
Progress has been enormous

The largest tokamak (JET,England)

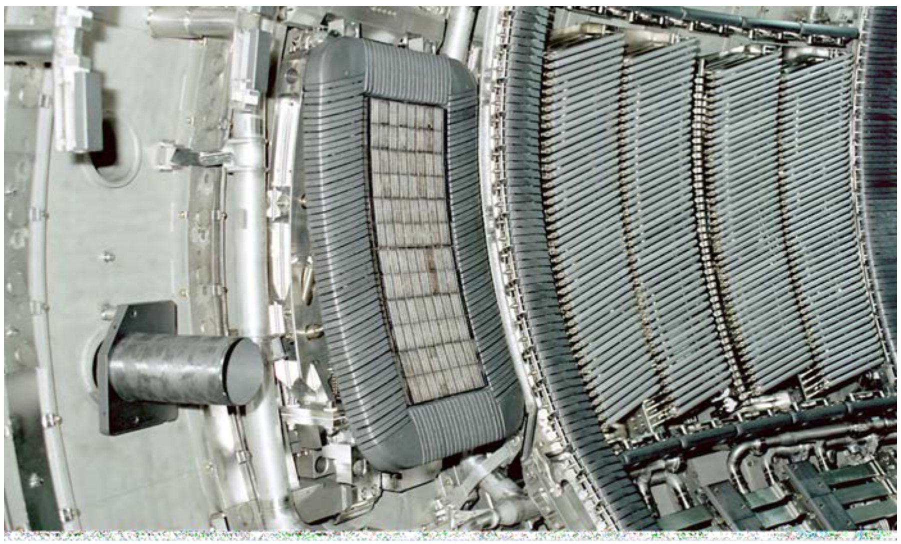


Heating a plasma to astronomical temperatures

- injection of electromagnetic waves
- injection of fast neutral atoms

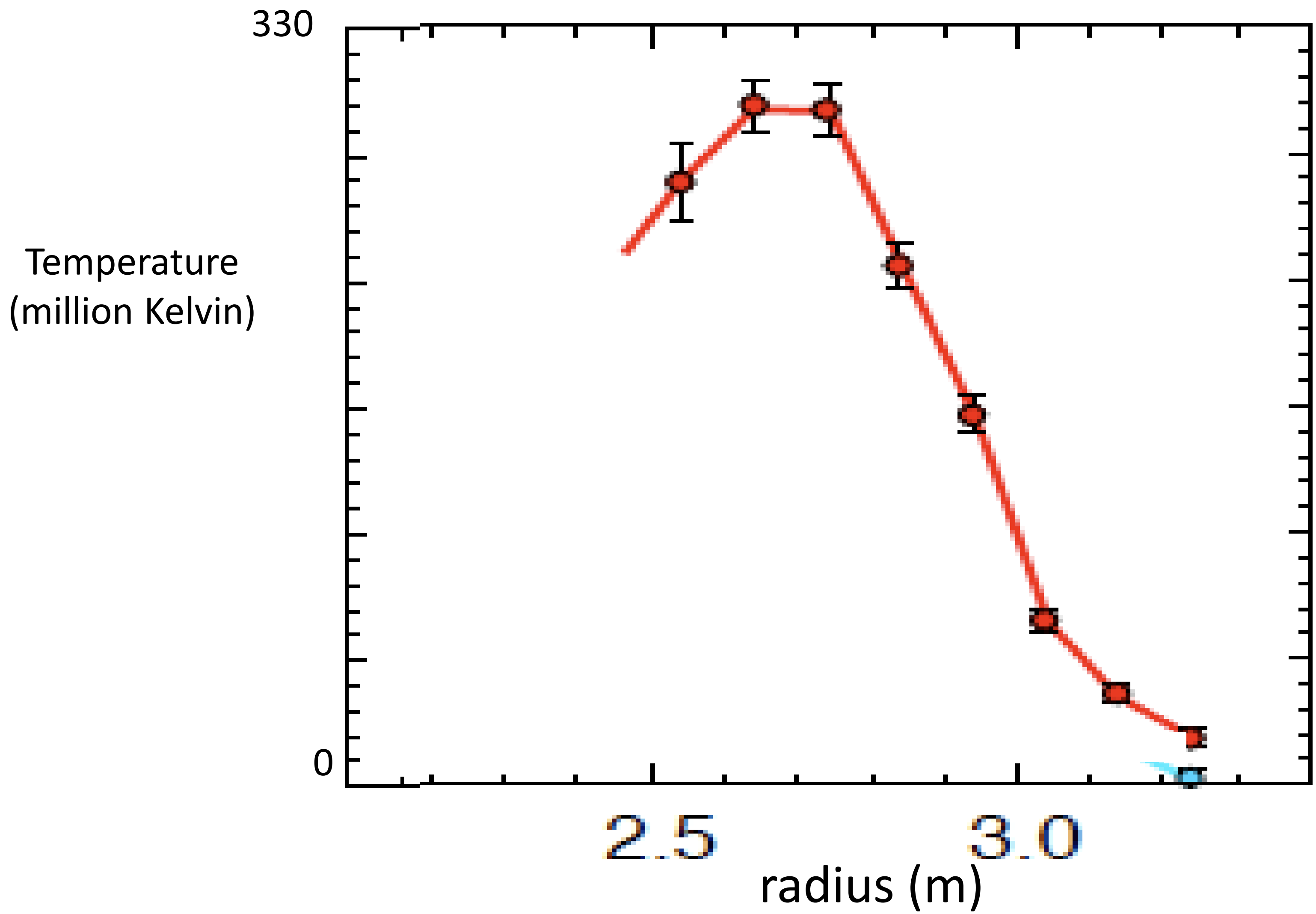


RF antenna



Neutral beam injector

Plasmas produced with temperature ~ 300 million degrees

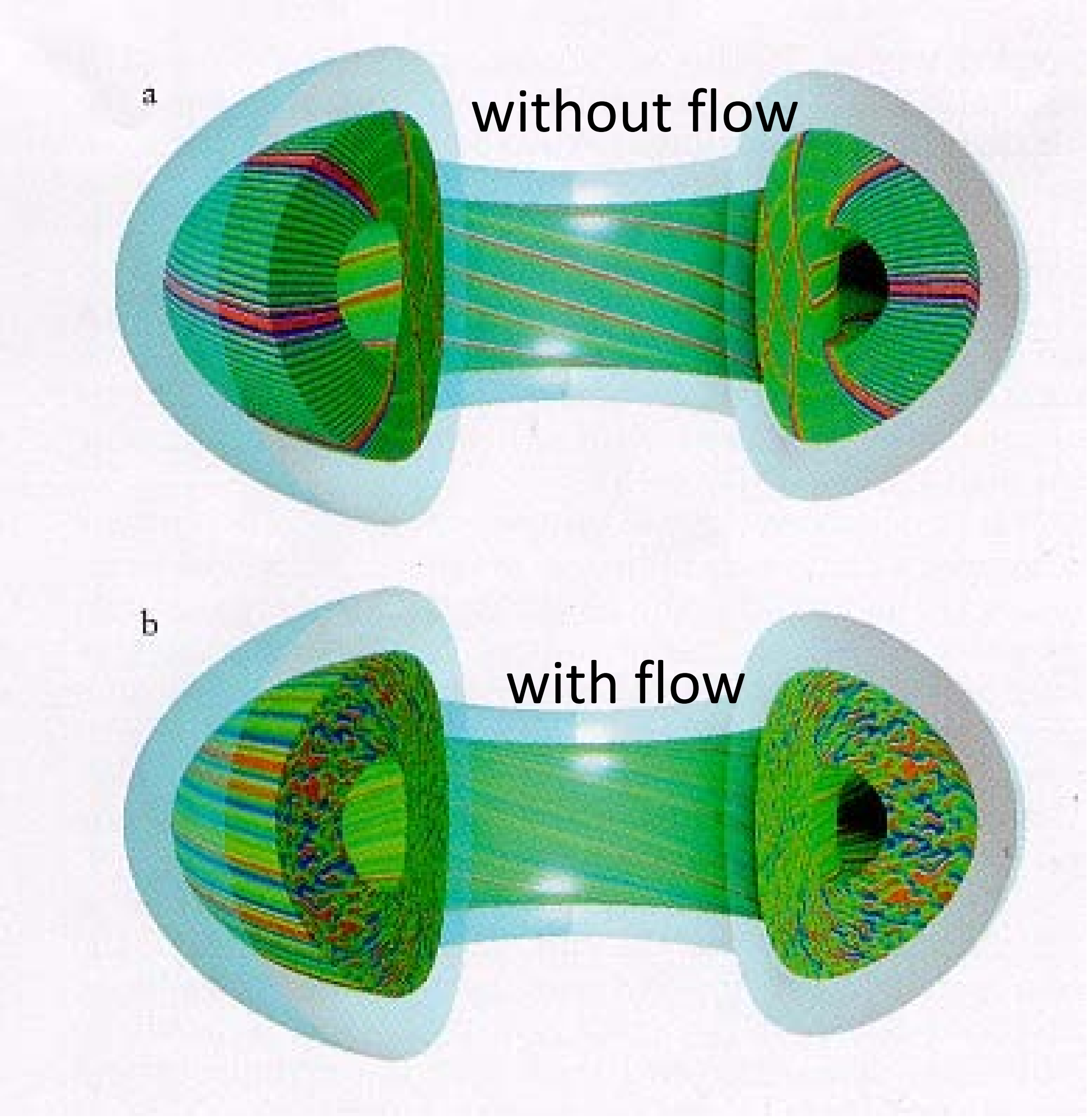


and controlled with remarkable finesse……

control of turbulence

Temperature gradients drive turbulence which degrades confinement

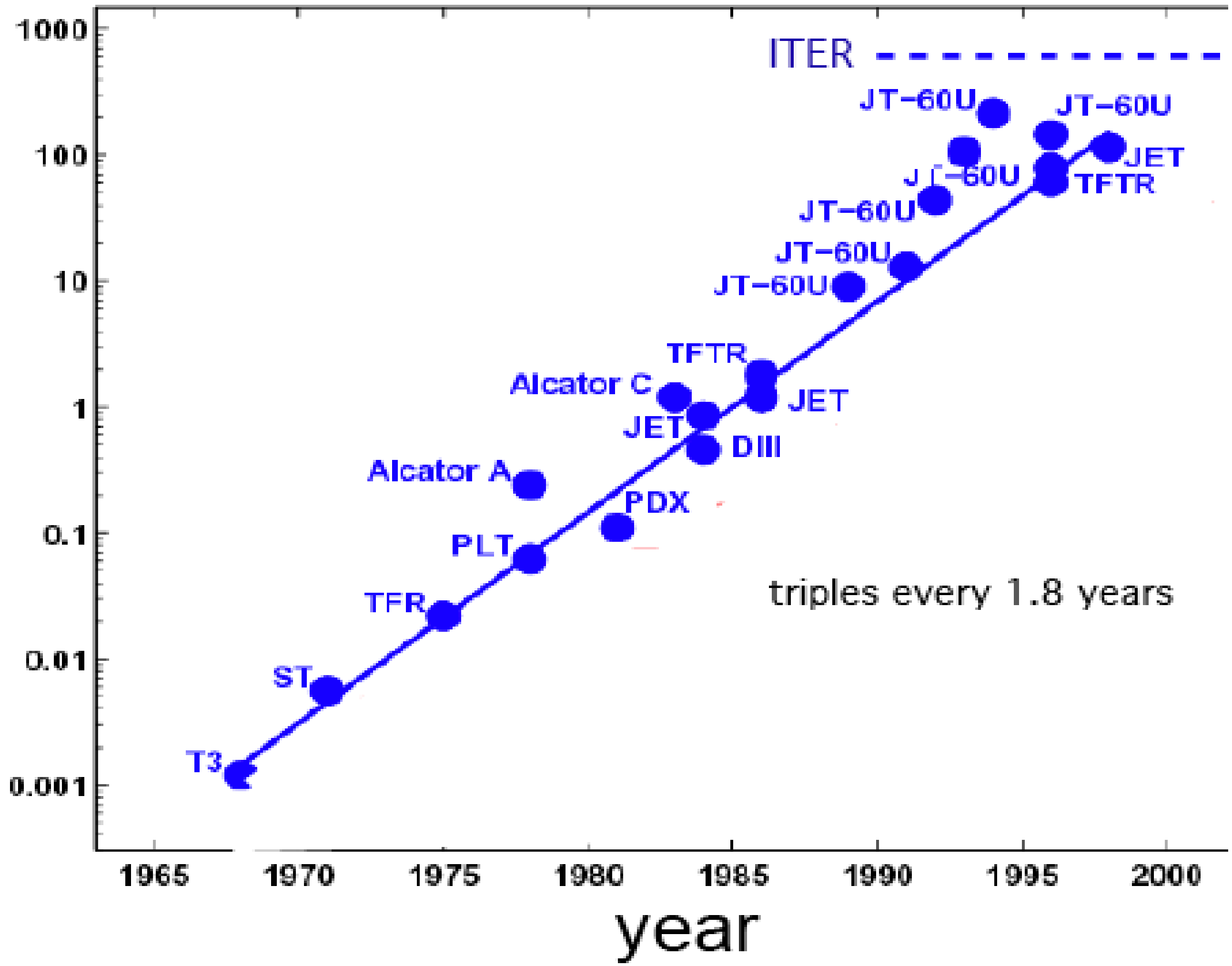
turbulence reduced
by plasma rotation
(computation)



Progress in the fusion triple product

fusion triple product

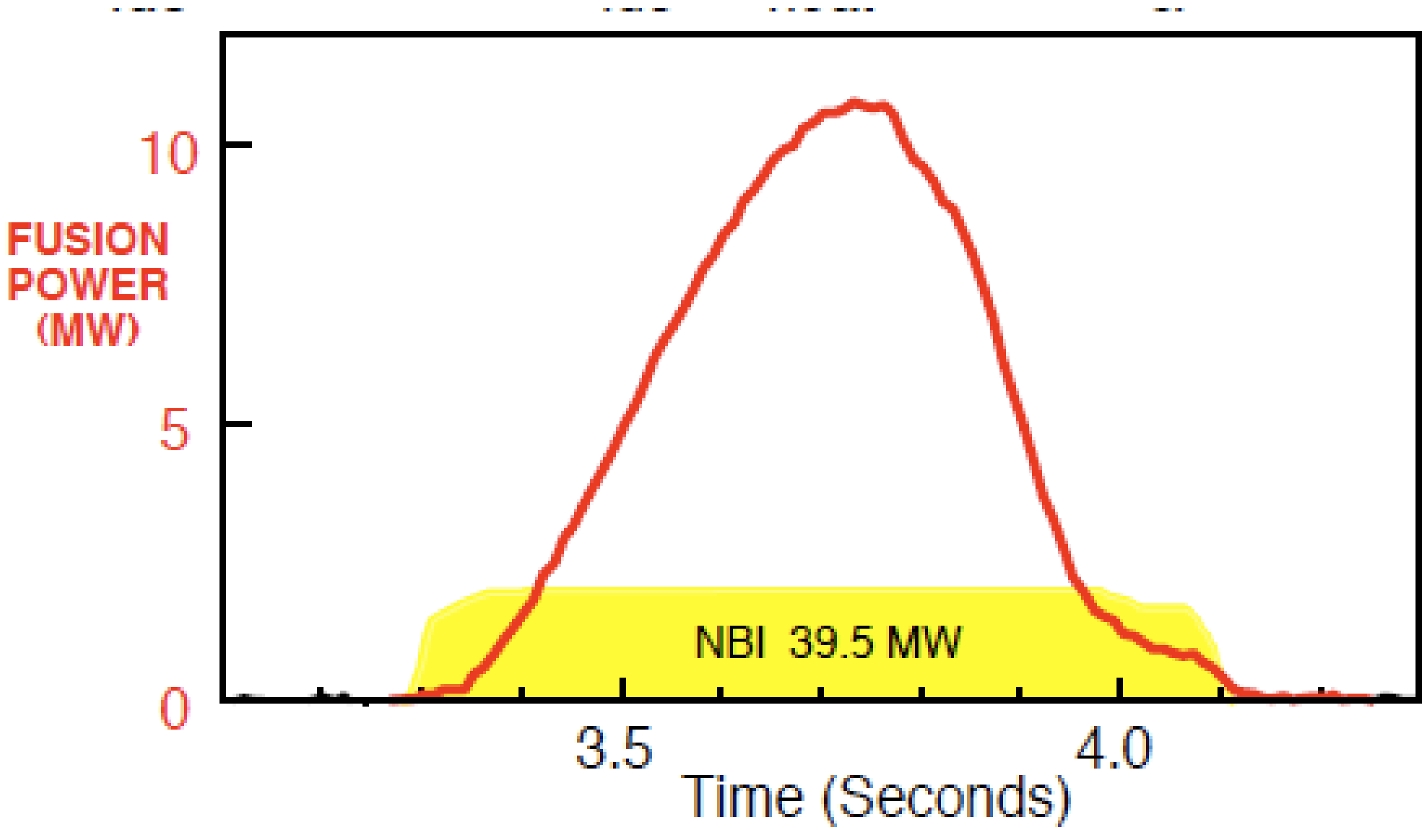
$nT\tau$



10,000-fold increase in 30 years, another factor of 6 for a power plant

We have produced fusion energy

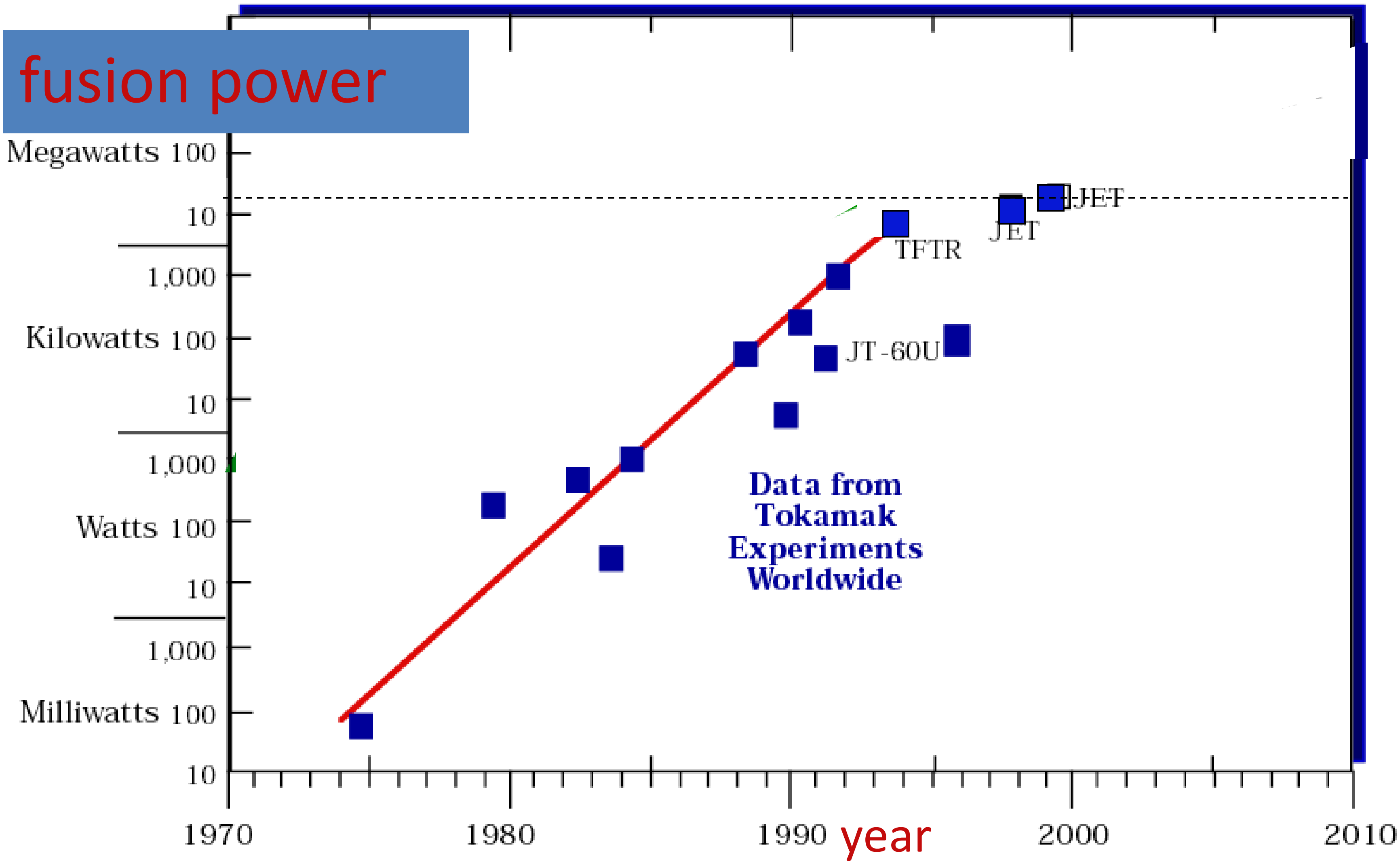
10 MW in 1994



TFTR, PPPL

1997: 16 MW and 10 MJ produced in JET (UK)

huge advance in fusion power



Progress in fusion power halted by lack of facility, not science

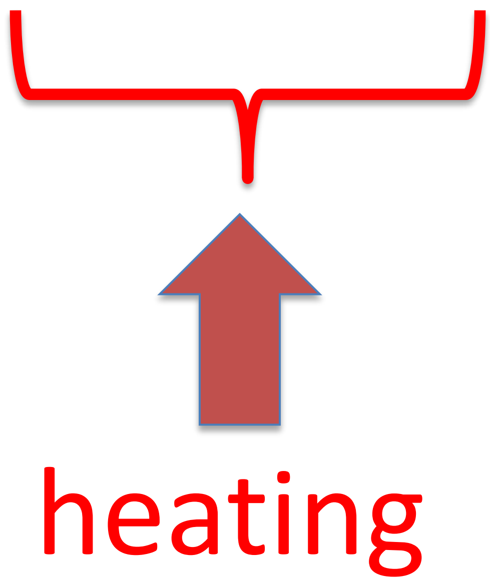
These results in the early 1990s

triggered an increase in the worldwide fusion effort (outside the US)

Next step: a burning plasma

All plasmas to date have been heated externally

$$D^{+} + T^{+} \longrightarrow He^{++} + n$$

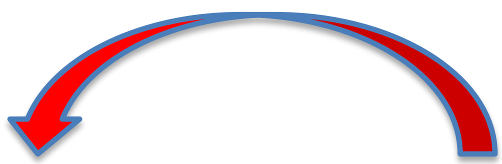


not self-sustaining: remove heating, plasma cools down and fusion stops

The next (international) step in fusion

Produce a burning plasma

Plasma kept hot by fusion energy itself ,
"self-heating"



$$D^{+} + T^{+} \longrightarrow He^{++} + n$$

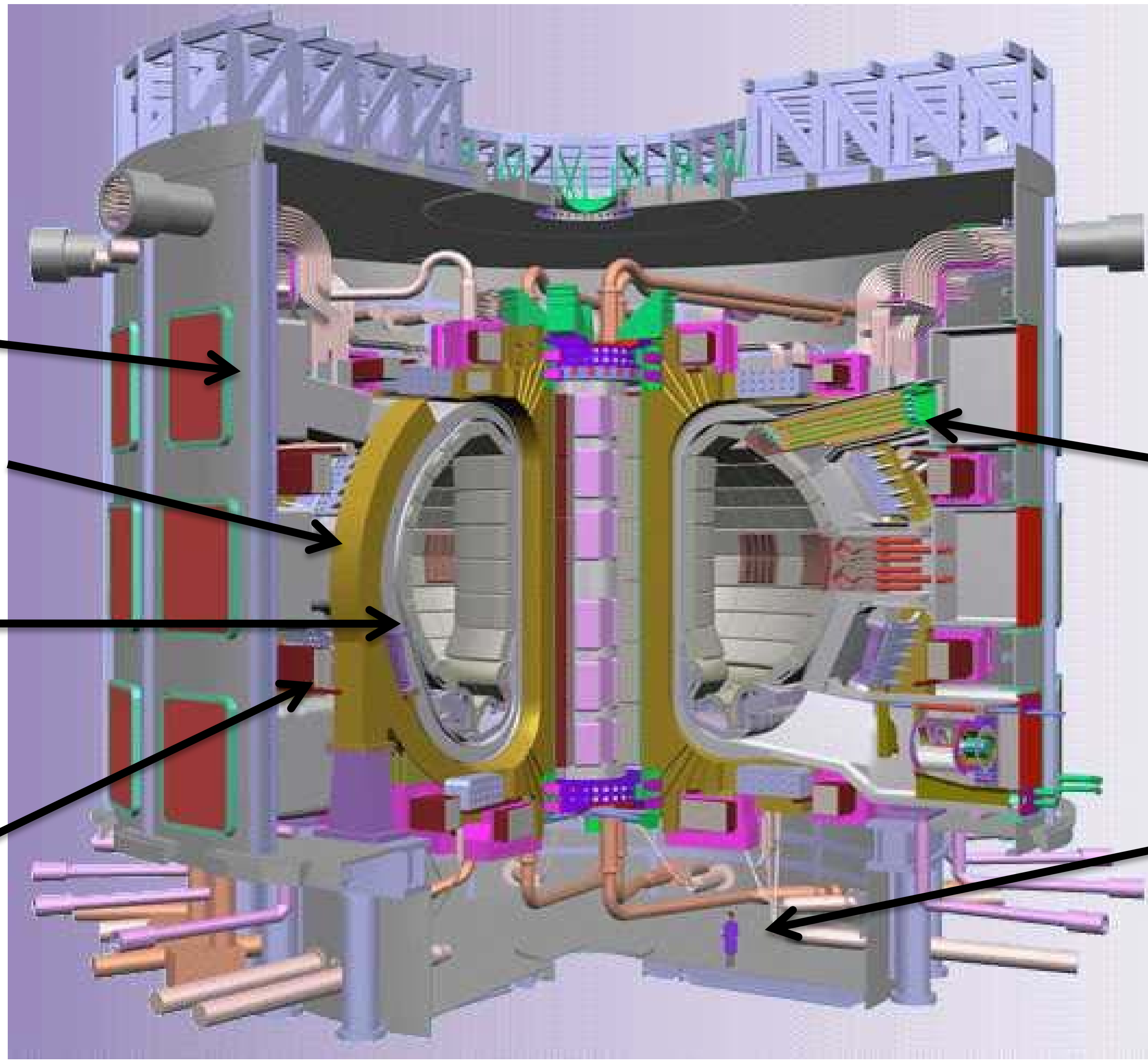
Feedback yields new nonlinear coupling that alters the physics

The international ITER experiment

- A burning plasma
- Will produce 500 Megawatts for 500 seconds
- Will have fusion power gain ≈ 10
- Under construction in France

ITER is reactor scale

(tests key fusion technologies)



cryostat

toroidal field coil (Nb_3Sn, 18))

vacuum vessel (9 sectors)

poloidal field coil

port

scale

ITER is an international partnership

- Consisting of

  the European Union (45%)
  China
  India
  Japan
  Russia
  South Korea
  The United States

- Construction beginning,
  expected completion mid-2020s

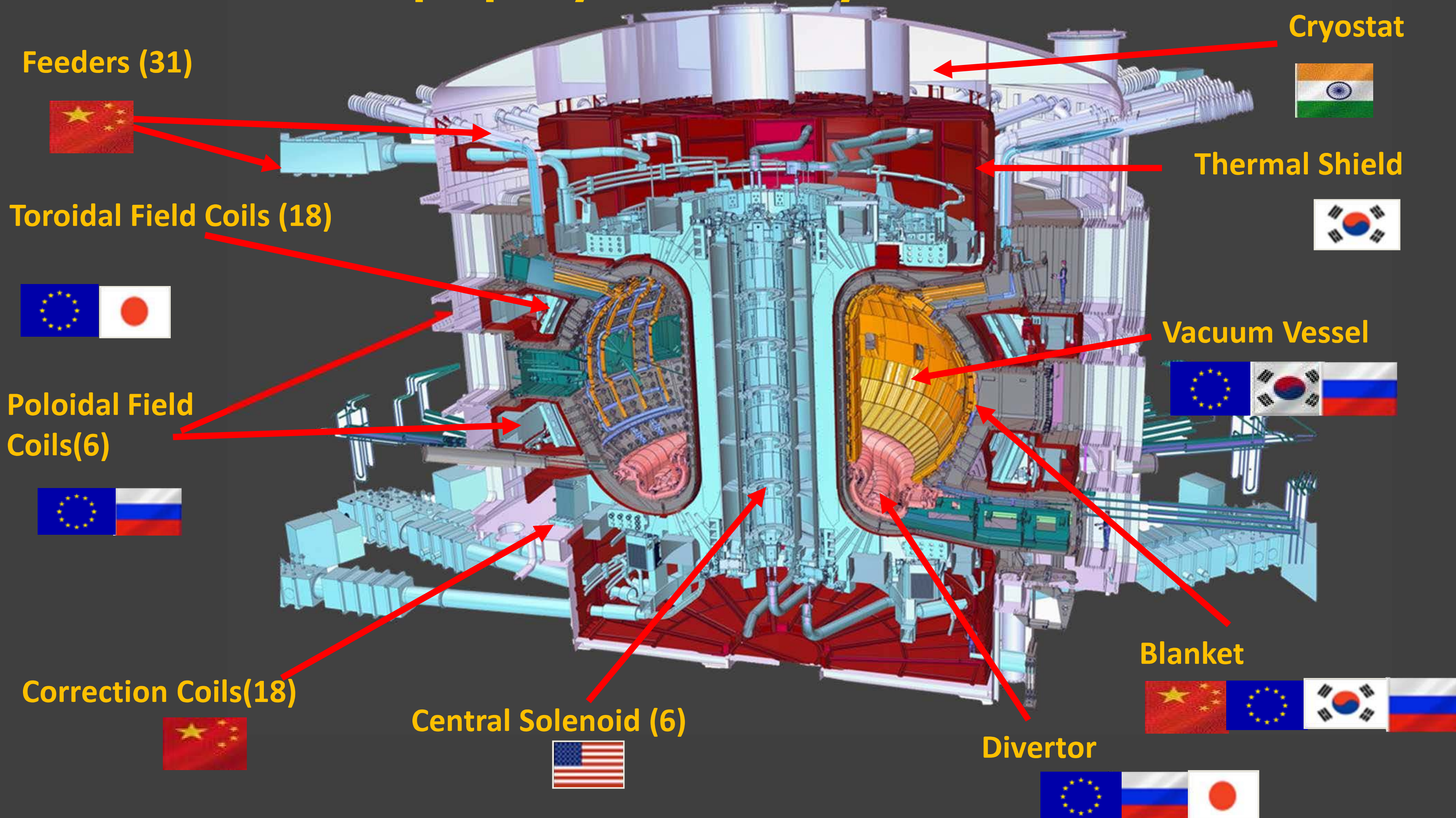
Progress on the ITER platform

The 42-hectare ITER platform is located 35 km to the north of Aix-en-Provence, France (Sept. 2013)

0 000-ton Tokamak Complex buildings.

Who manufactures what?

All intellectual property is shared by the seven members

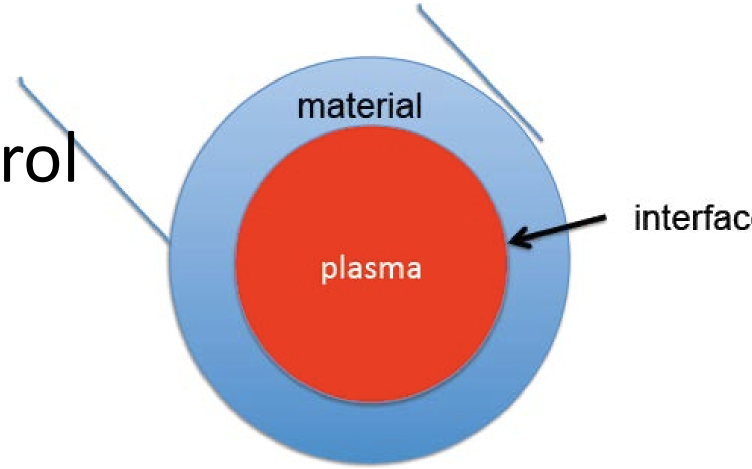


ITER has severe management difficulties

However, ITER will be a landmark science and energy experiment of the 21^{st} century

A vigorous US program is needed to solve remaining challenges for fusion

Remaining Fusion Challenges



- Plasma confinement and control

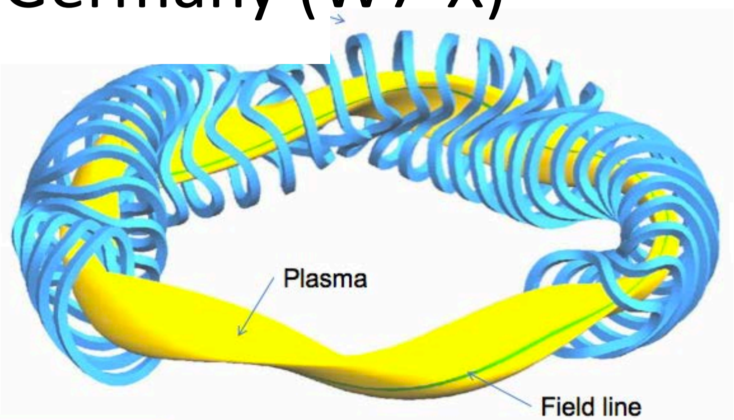
- The plasma-material interface

- Harnessing fusion power

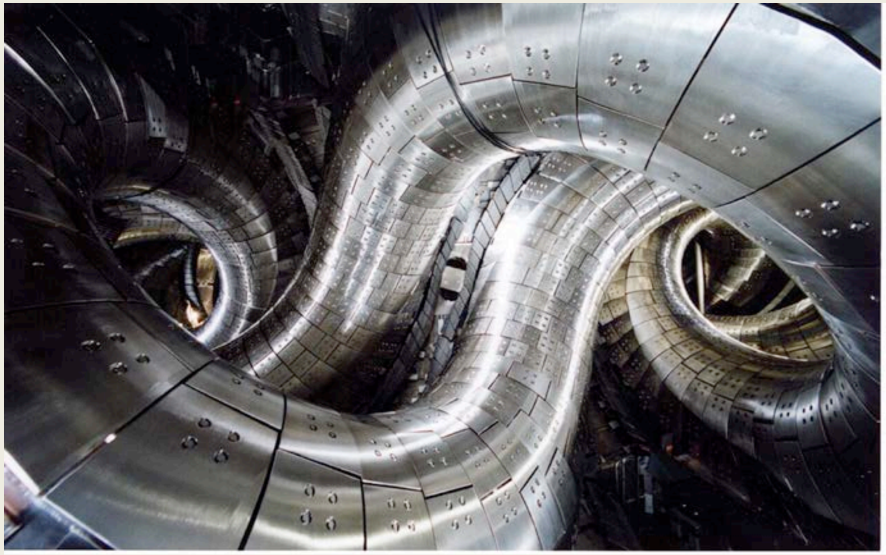
Plasma confinement and control

Modern 3D designs
("stellarators")

Germany (W7-X)

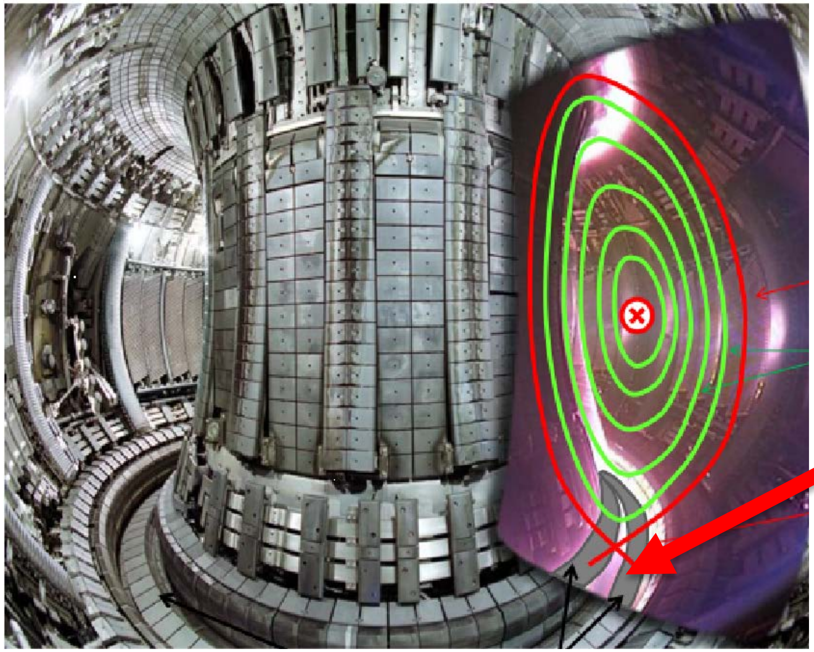


Japan (LHD)



The plasma-material interface

Magnetic channeling
of the heat



Tungsten plate

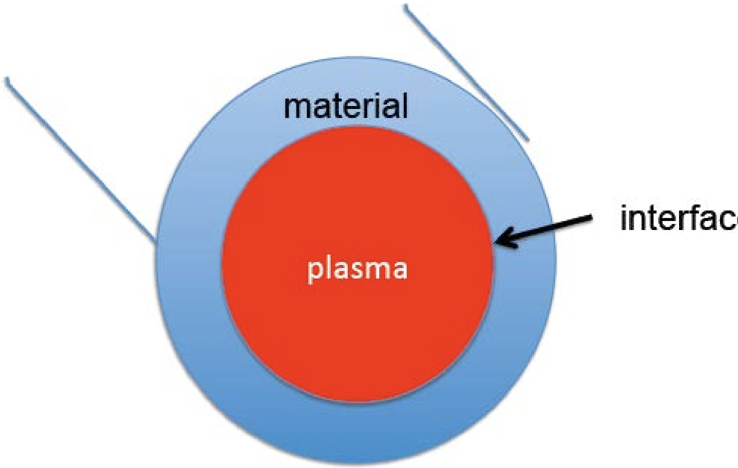
~ 10 MW/m^2

(1/10 heat on solar surface)

Also, exploring liquid metal wall

Remaining Fusion Challenges

- Plasma confinement and control



- The plasma-material interface

Harnessing fusion power

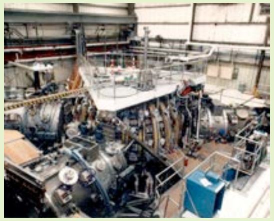
effects of neutrons on materials,

managing neutrons (tritium breeding, power extraction)

We are ready to move to this penultimate step to a first-of-a-kind fusion plant

A roadmap to fusion energy discussed in US

GA



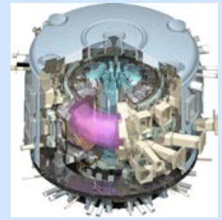
PPPL

MIT

Plasma confinement research program

present

ITER



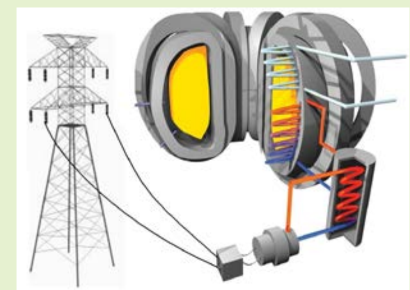
<u>**Base Research Program**</u>

Plasma confinement
Materials science/engineering

US Fusion Facility (integrated system test or pilot plant)

2025 – 2040
The final R&D era

Demonstration Power Plant



~ 2040
The fusion era

The international context

fusion research in other nations is surging,

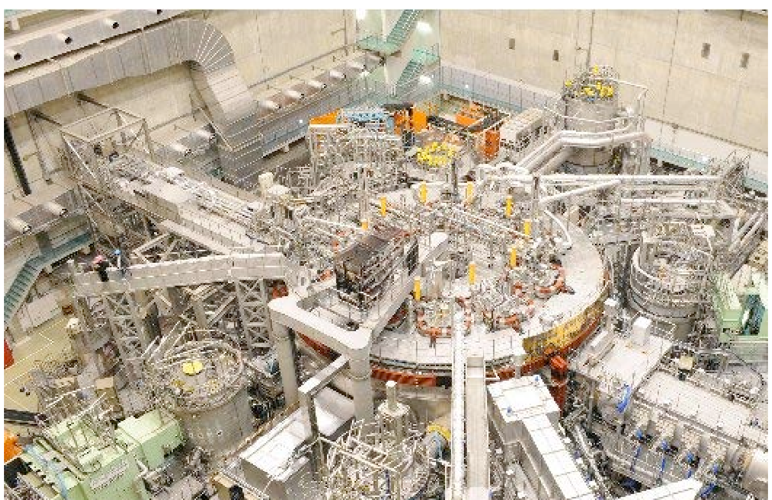
in Asia and the E.U.

The escalating magnetic fusion activity across the world

New major facilities

China: superconducting tokamak

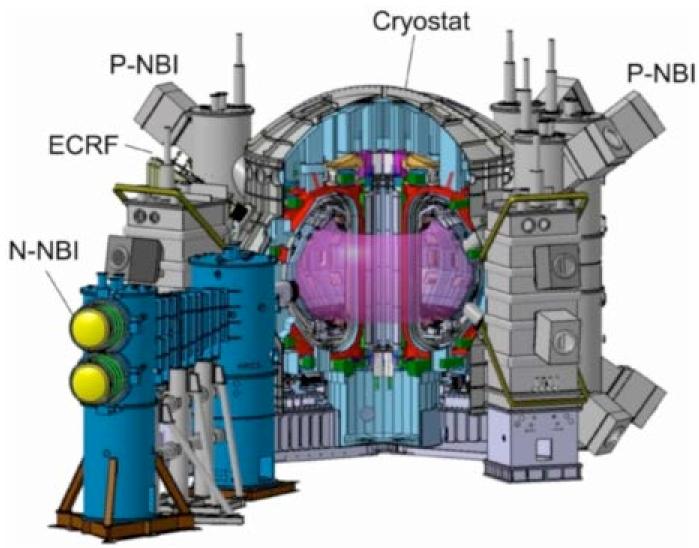
Japan: superconducting stellarator



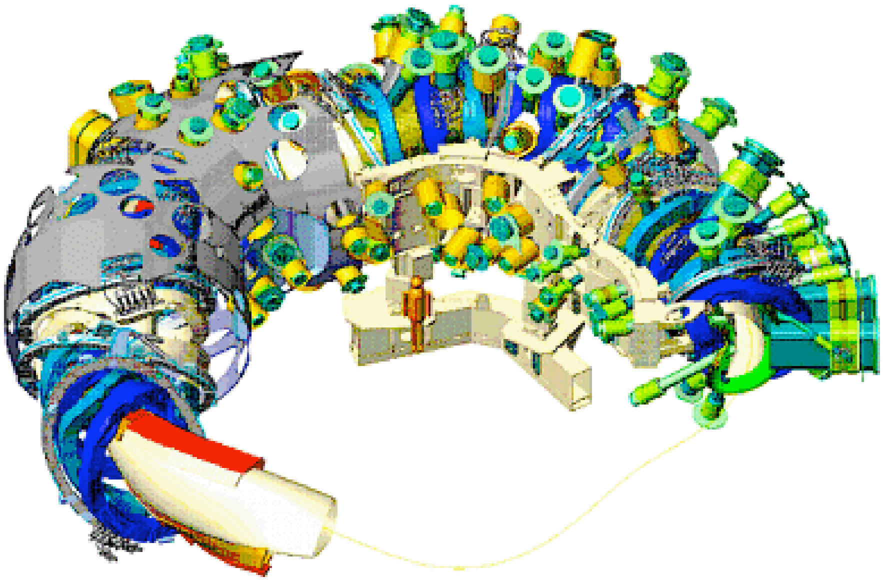
Korea: superconducting tokamak

Major facilities under construction

Japan: superconducting tokamak



Germany: superconducting stellarator

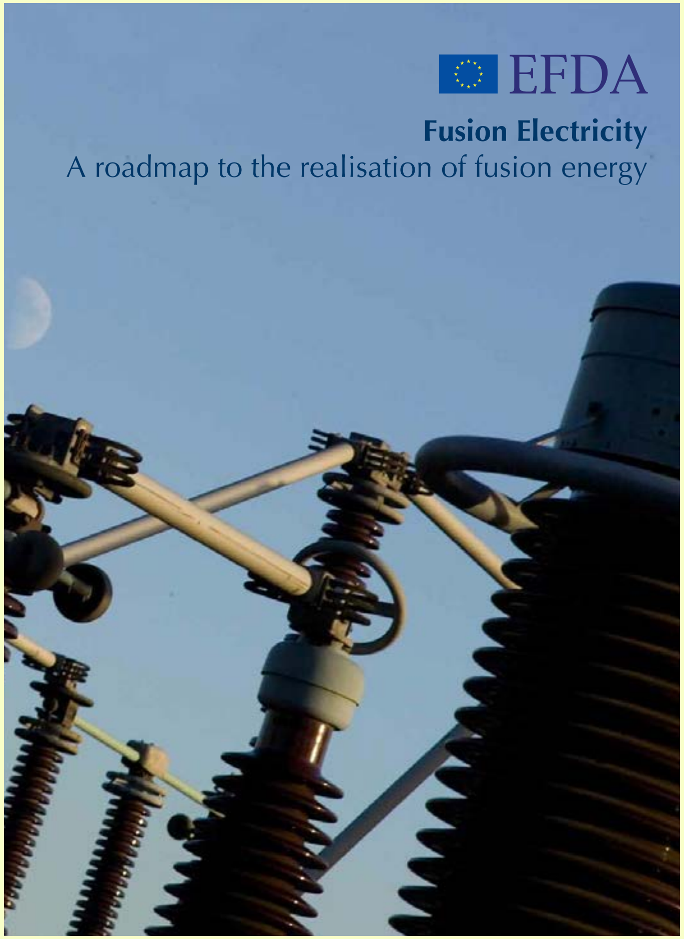


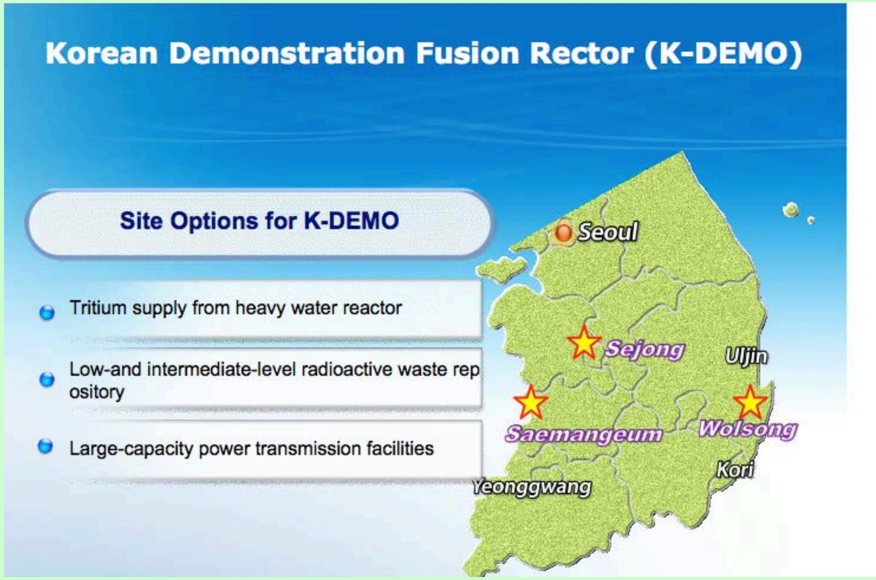
France: ITER

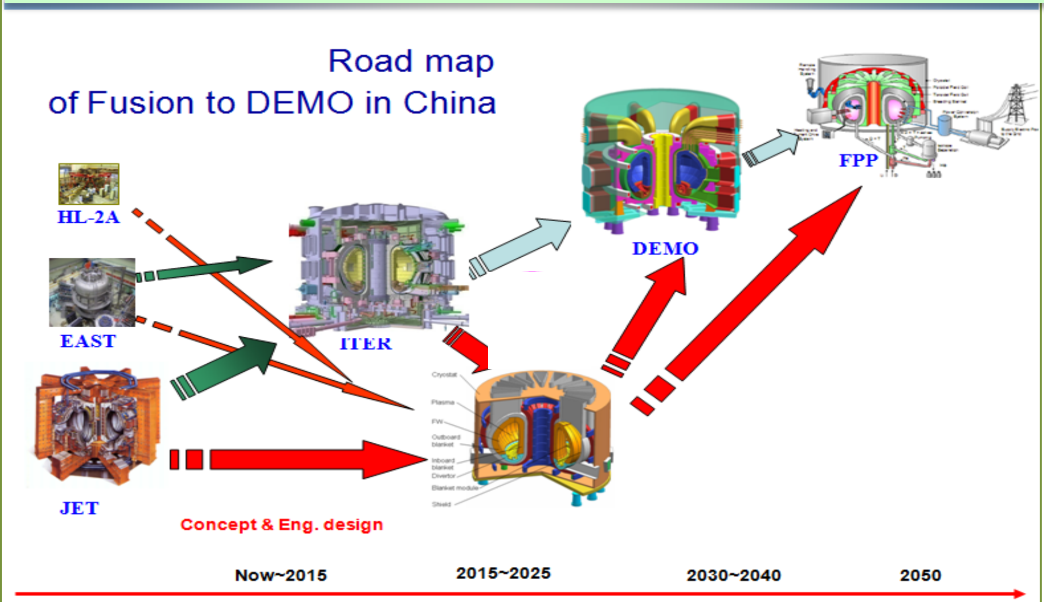
The world has entered the era of superconducting facilities (steady-state)

Our ITER partners are planning for DEMO

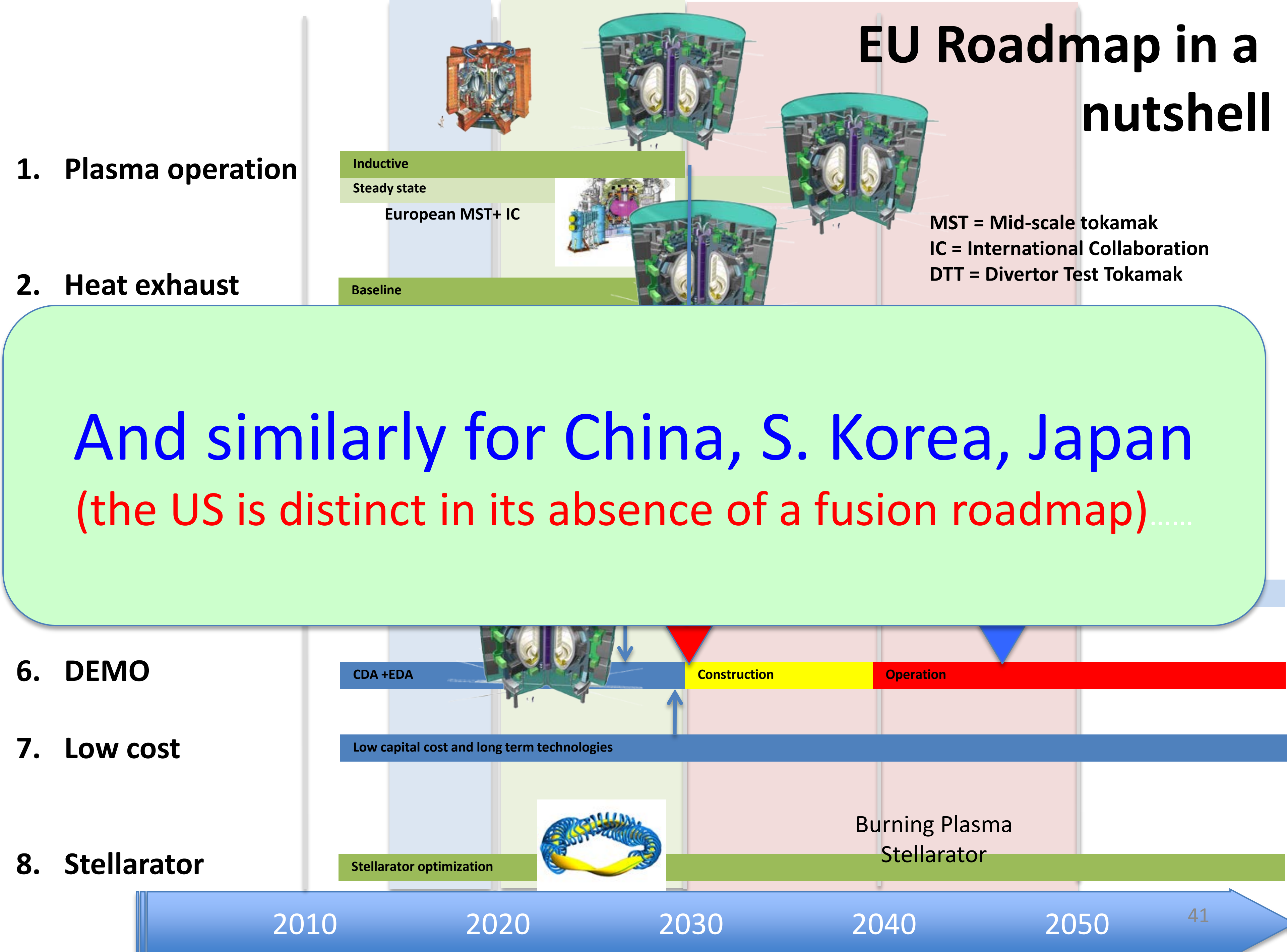
European roadmap







EU Roadmap in a nutshell



And similarly for China, S. Korea, Japan

(the US is distinct in its absence of a fusion roadmap)……

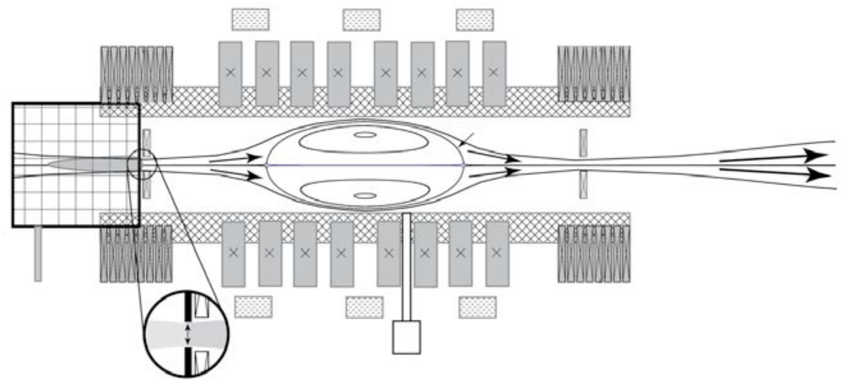
Private investment in fusion

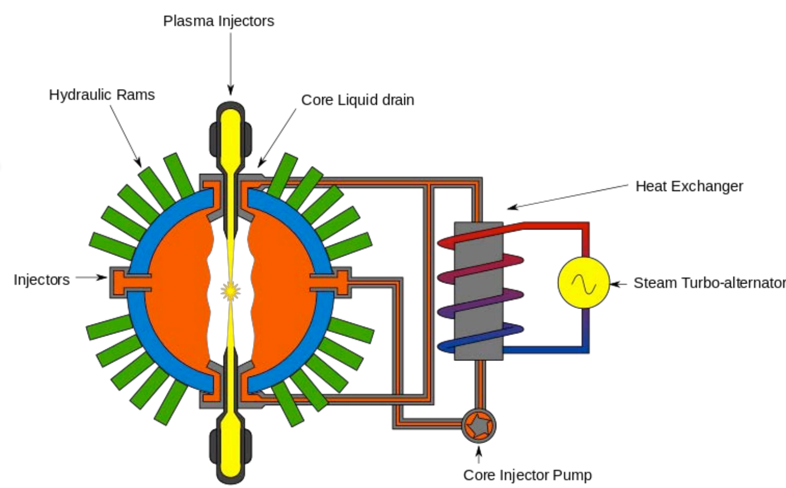
Not extensive, given long time to payoff

Typically, investments focus on options for "smaller, cheaper, faster" approaches

Examples:

- Tri-Alpha Energy (California)
- General Fusion (Canada)
- Tokamak Energy (England)
- Lockheed Martin





Prnceton Plasma Physics Laboratory

enabling a world powered by fusion energy,
leading discoveries in plasma science and technology

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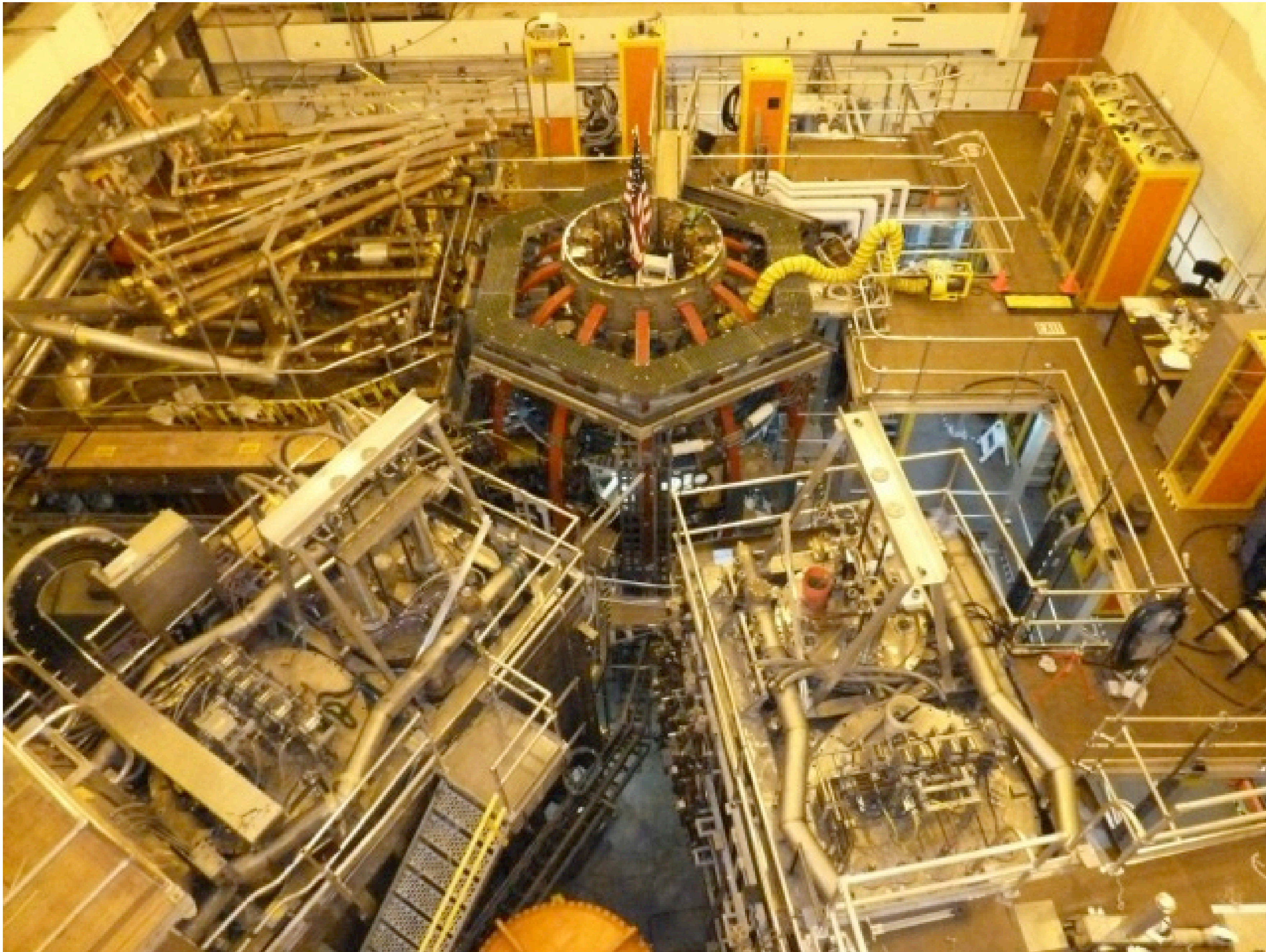
PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

National Spherical Torus Experiment - Upgrade



Why not just buy reactors from China or Korea?

We will suffer

- By not controlling our own energy sources
- By not competing economically
- By not competing scientifically
- By slowing the realization of fusion power

Why has fusion “always been 30 years away”?

- The challenge is more profound scientifically than initially realized

- The needed funding never materialized

  (progress has been as predicted, for the funding received)

Scientific reviews in nations across the world confirm our readiness to NOW proceed aggressively toward a demonstration power plant

To conclude,

- Scientists are confident we can make fusion power for large-scale energy use
- Research challenges remain that will determine economic attractiveness
- If there is societal will, we can have a clean, safe, abundant, domestic fusion energy source in our lifetime
- And the science we learn has enormous value

Technology Assumptions in the IPCC IS92a Scenario

The IPCC's IS92a scenario assumes that significant technological change will take place under a "business-as-usual scenario," that is, a world without climate policy. The following are examples of the IPCC's energy technology assumptions:

- 75 percent of electricity in 2100 will be generated from nonfossil sources compared to roughly 33 percent in 1995.
- 57 percent of energy needs in 2100 will be supplied by fossil fuels—down from 88 percent in 1995.
- Biomass energy in 2100 will be used at a scale that exceeds the total global energy use in 1975.
- End-use efficiency in all sectors and regions will improve at 1 percent per year. This assumption implies a 45 percent improvement in energy efficiency in all sectors and regions by 2050.