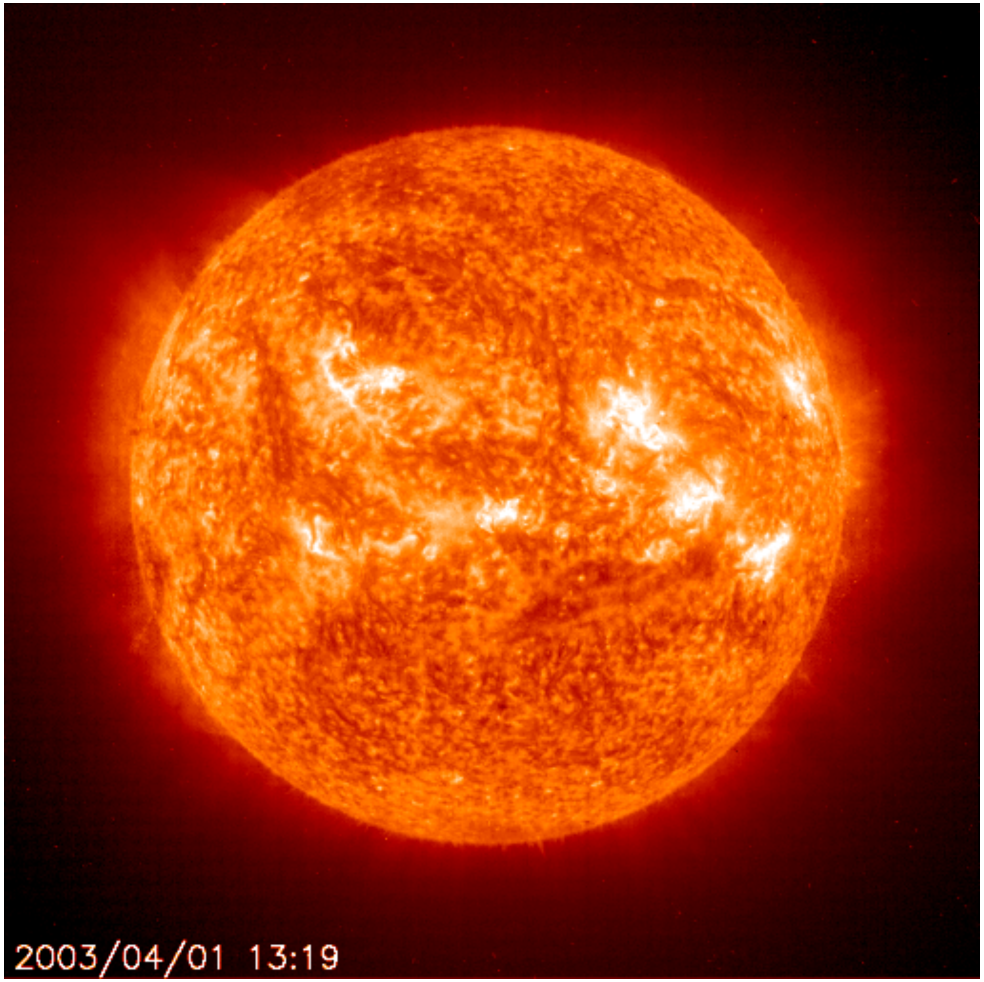
Magnetic fusion energy

Status and challenges

Stewart Prager
Princeton Plasma Physics Laboratory

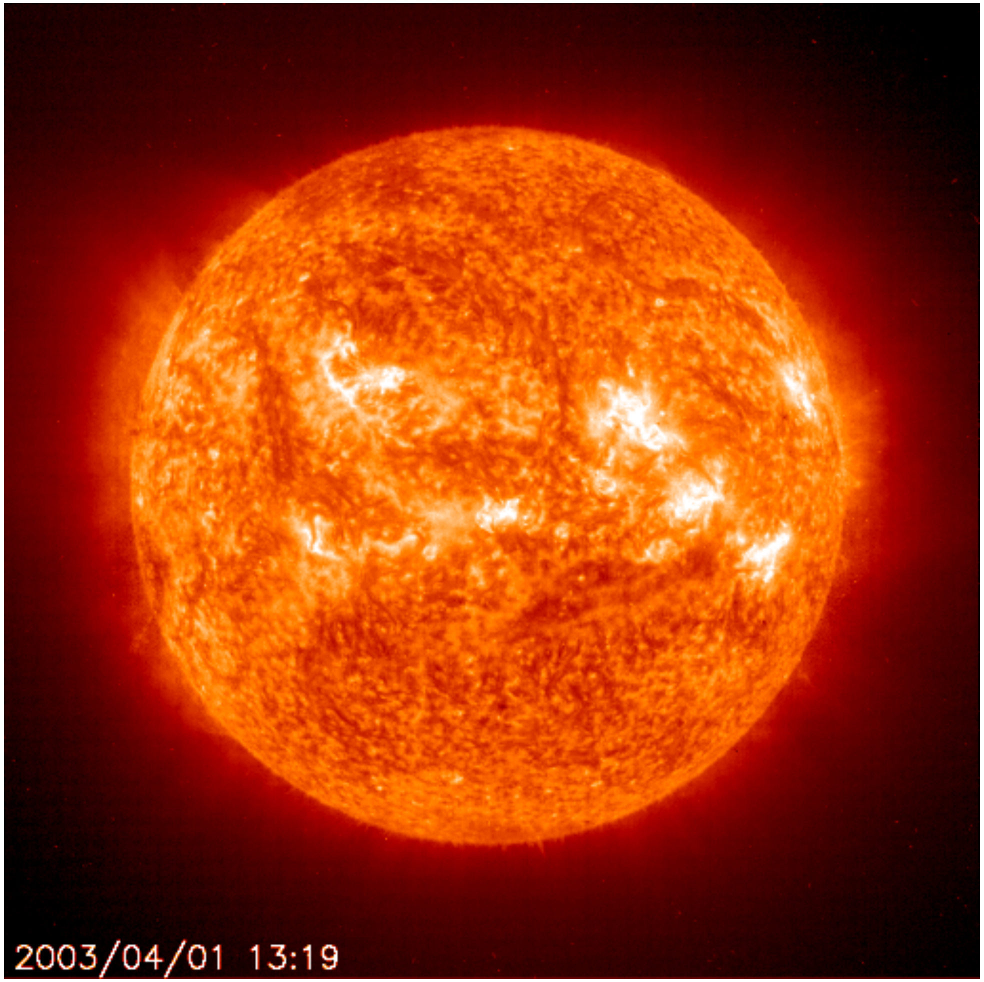
The Sun is a natural fusion reactor



A hot gas of billions of particles – a PLASMA

Particles undergo nuclear fusion reactions

The Sun is a natural fusion reactor



Temperature in sun
10 million degrees

Fusion reactor
100 million degrees
Surrounded by material

A hot gas of billions of particles – a PLASMA
Particles undergo nuclear fusion reactions

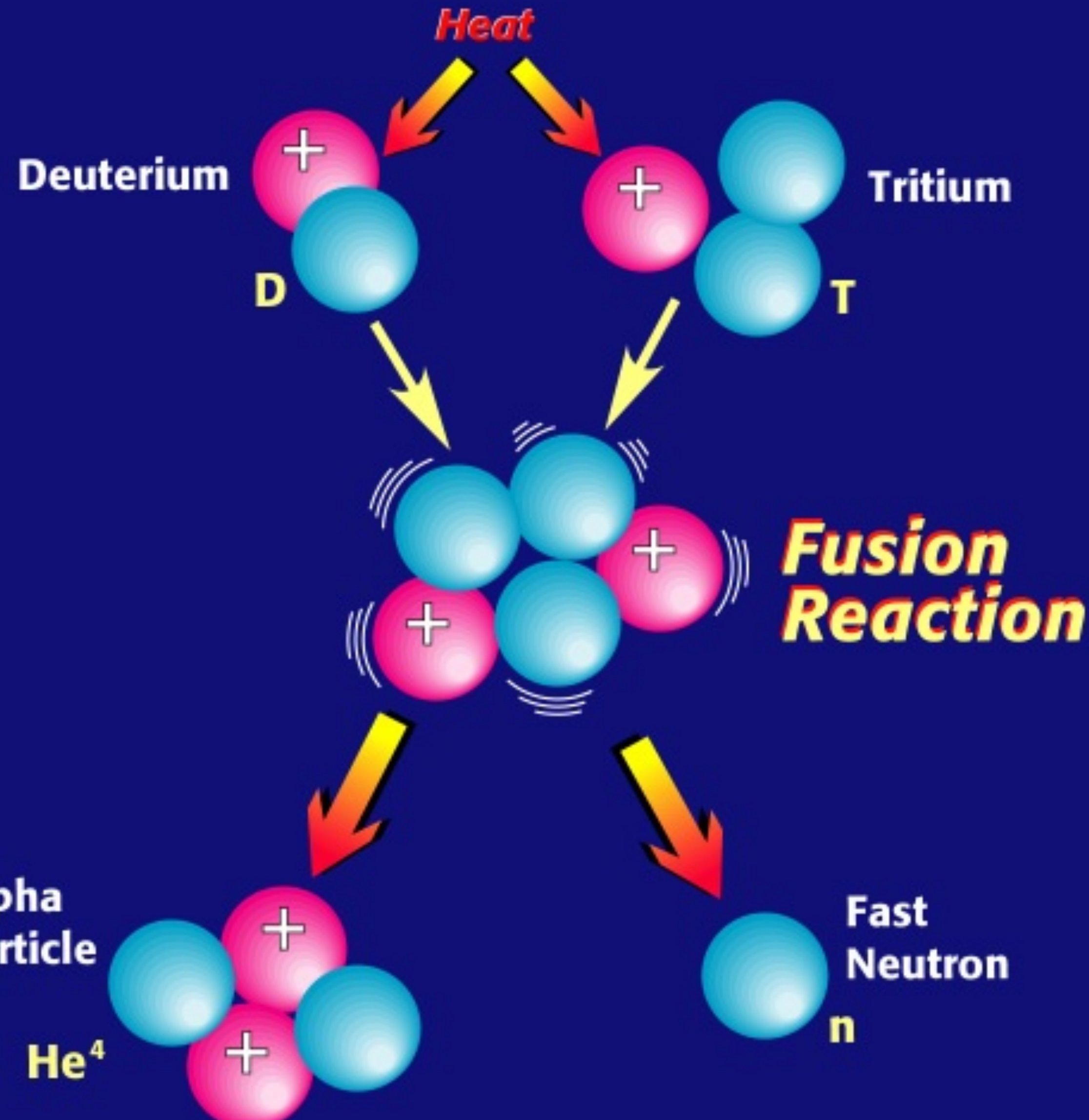
Fusion energy is one of the most difficult science and engineering challenges ever undertaken

It required the development of the new field of plasma physics

Accompanied by the development of fusion engineering

We have come very far along the path

Deuterium–Tritium Fusion Reaction



The fusion reaction

	deuterium +	tritium	→	helium +	neutron
energy	1	1		340	1400

The fusion reaction

deuterium + tritium → helium + neutron

	deuterium	tritium	helium	neutron
energy	1	1	340	1400

need many D and T nuclei moving rapidly

↓

Hot gas of charged particles
(PLASMA)

At temperature of 100 million degrees C

Why fusion?

- Nearly inexhaustible

  Deuterium from sea water, Tritium made from lithium

- Available to all nations

  reduced conflict over resources

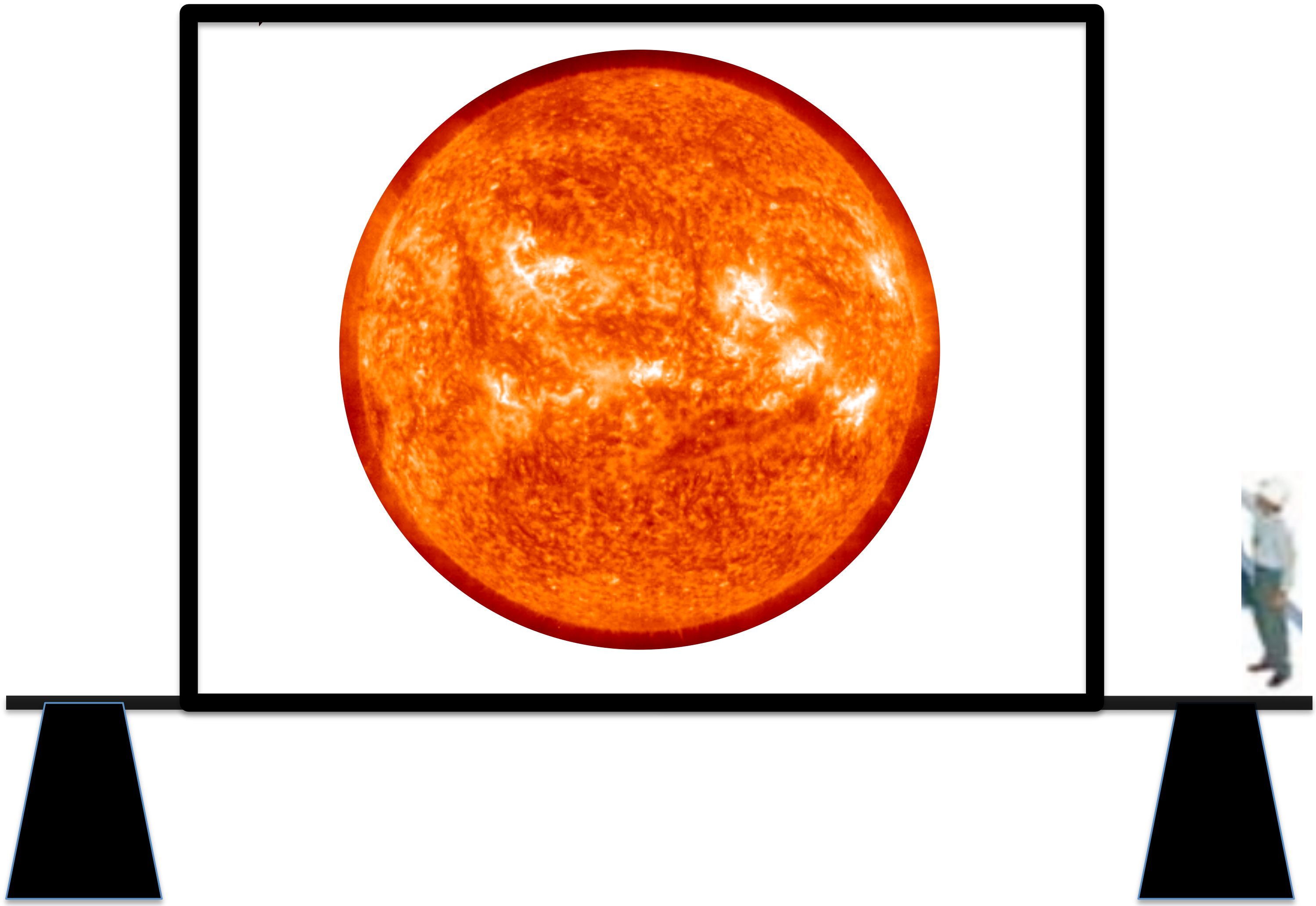
- Clean

  no greenhouse gases, no acid rain

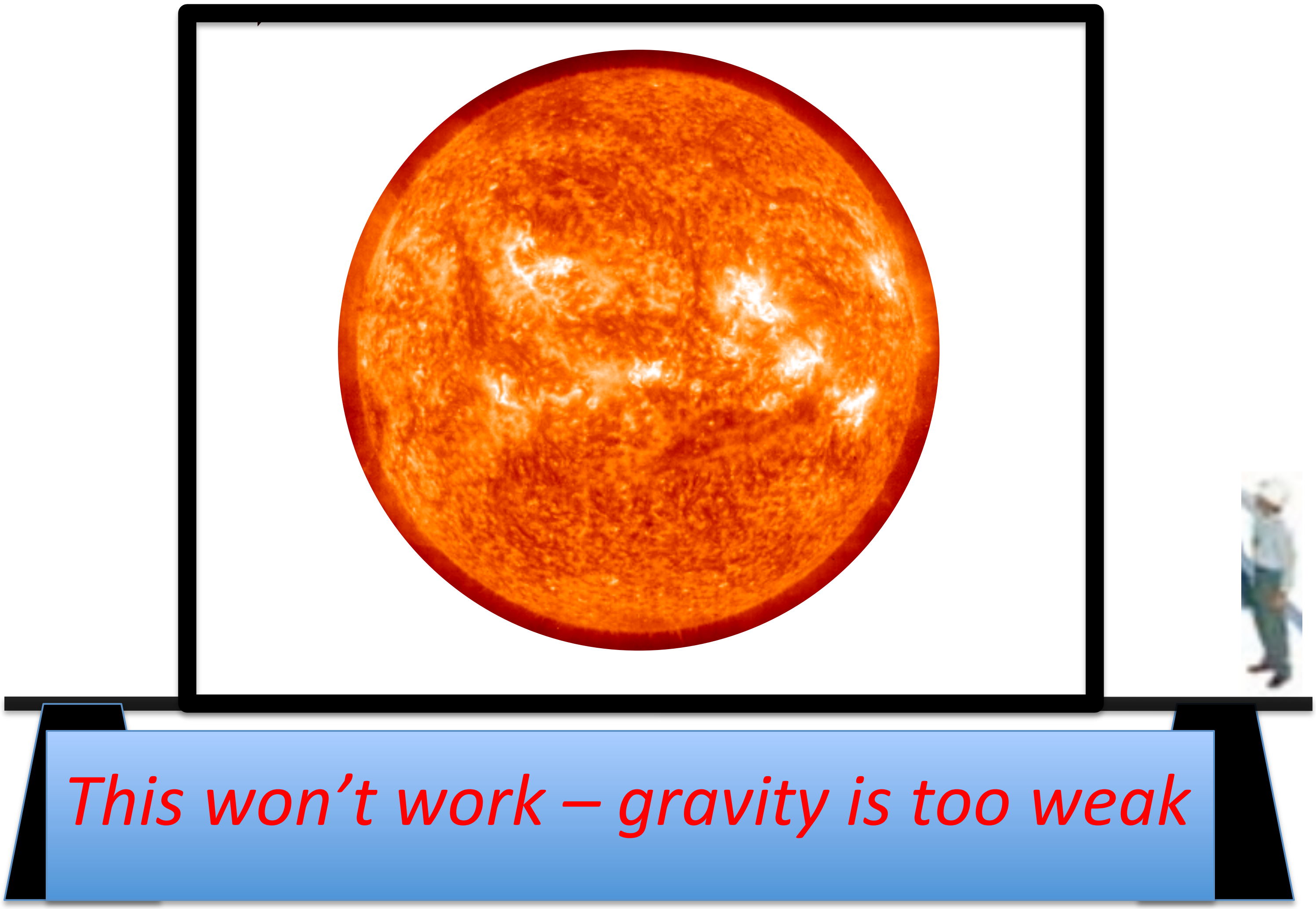
- Safe

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

“create a star on Earth”

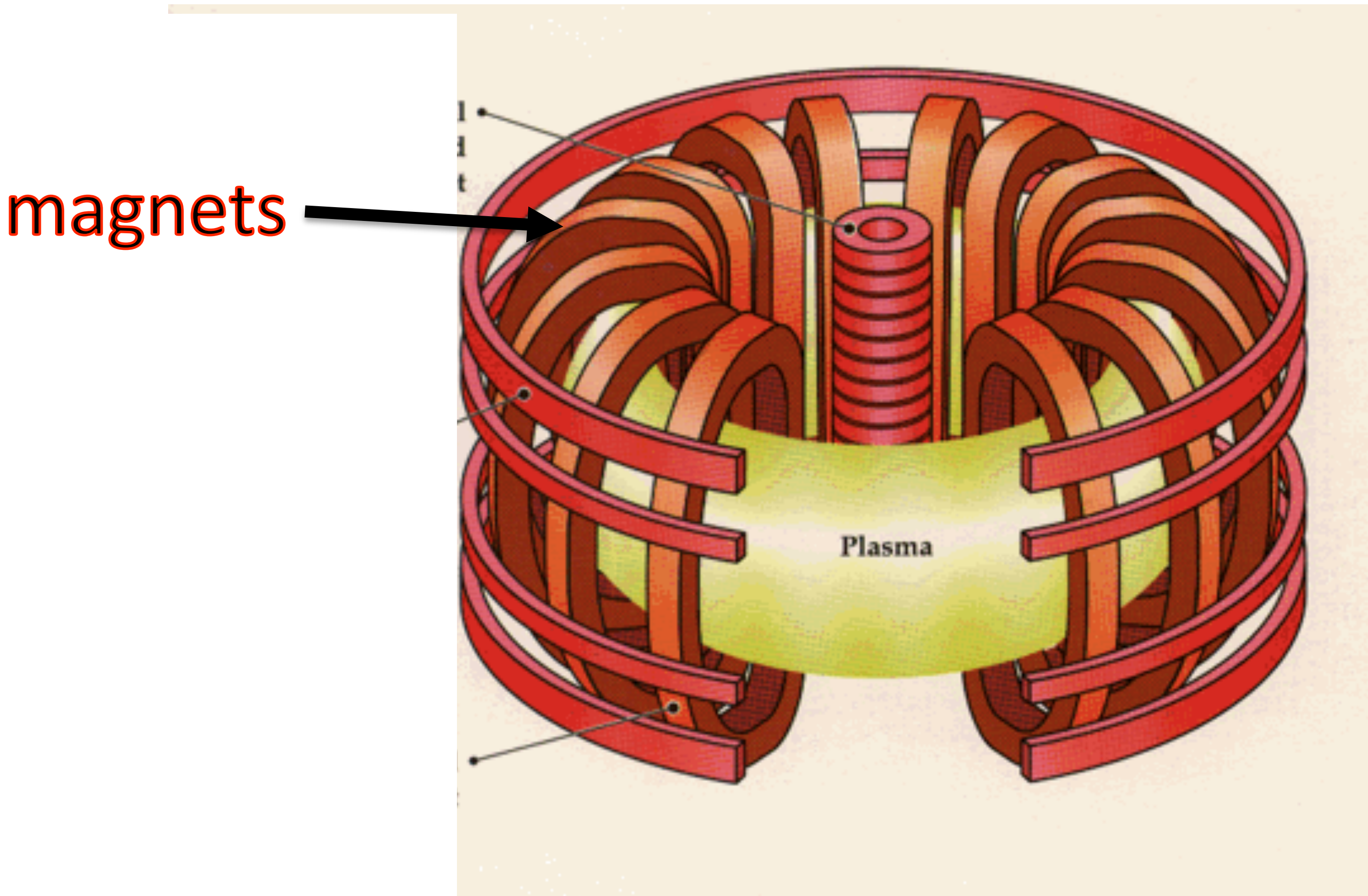


“create a star on Earth”

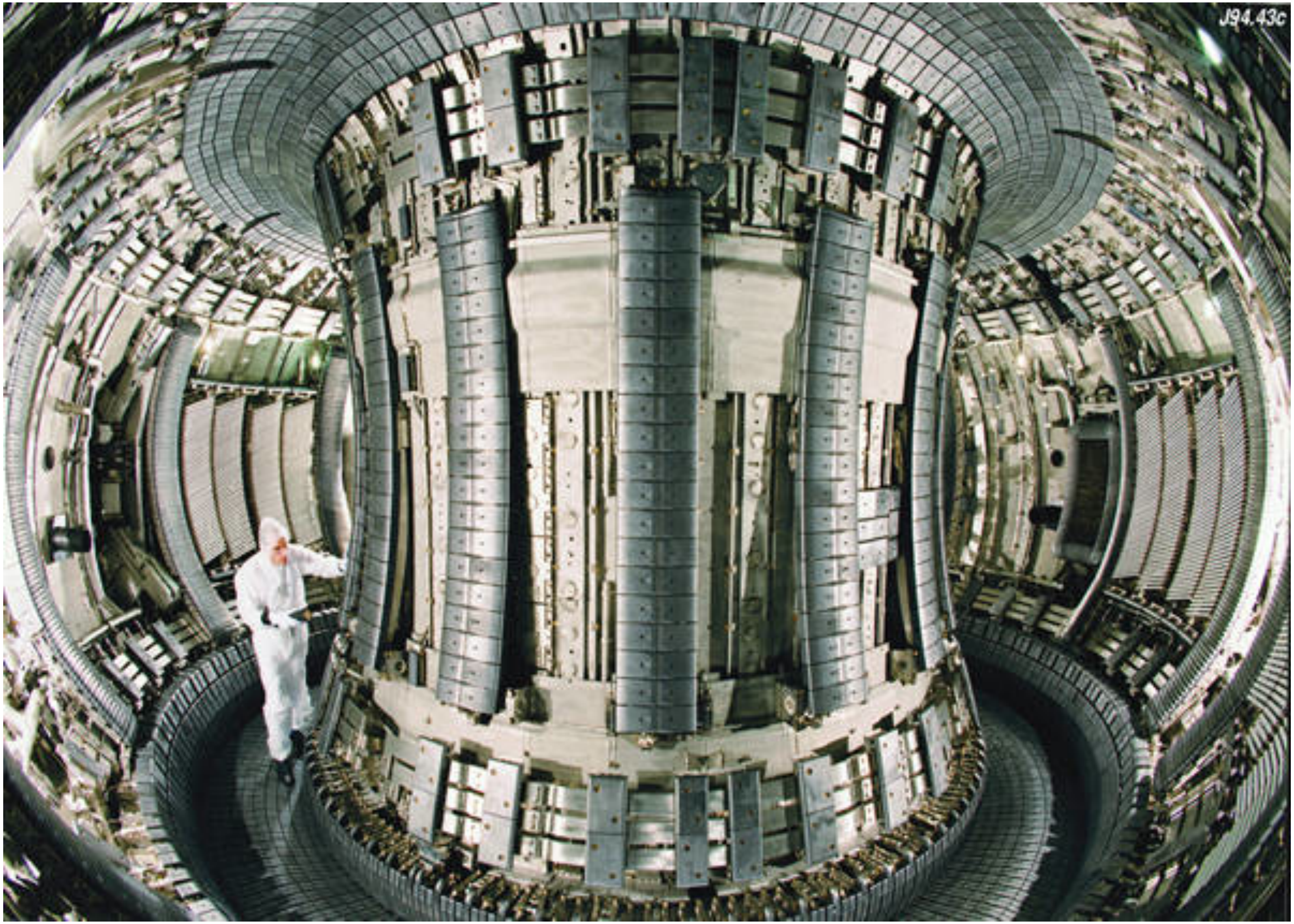


This won’t work – gravity is too weak

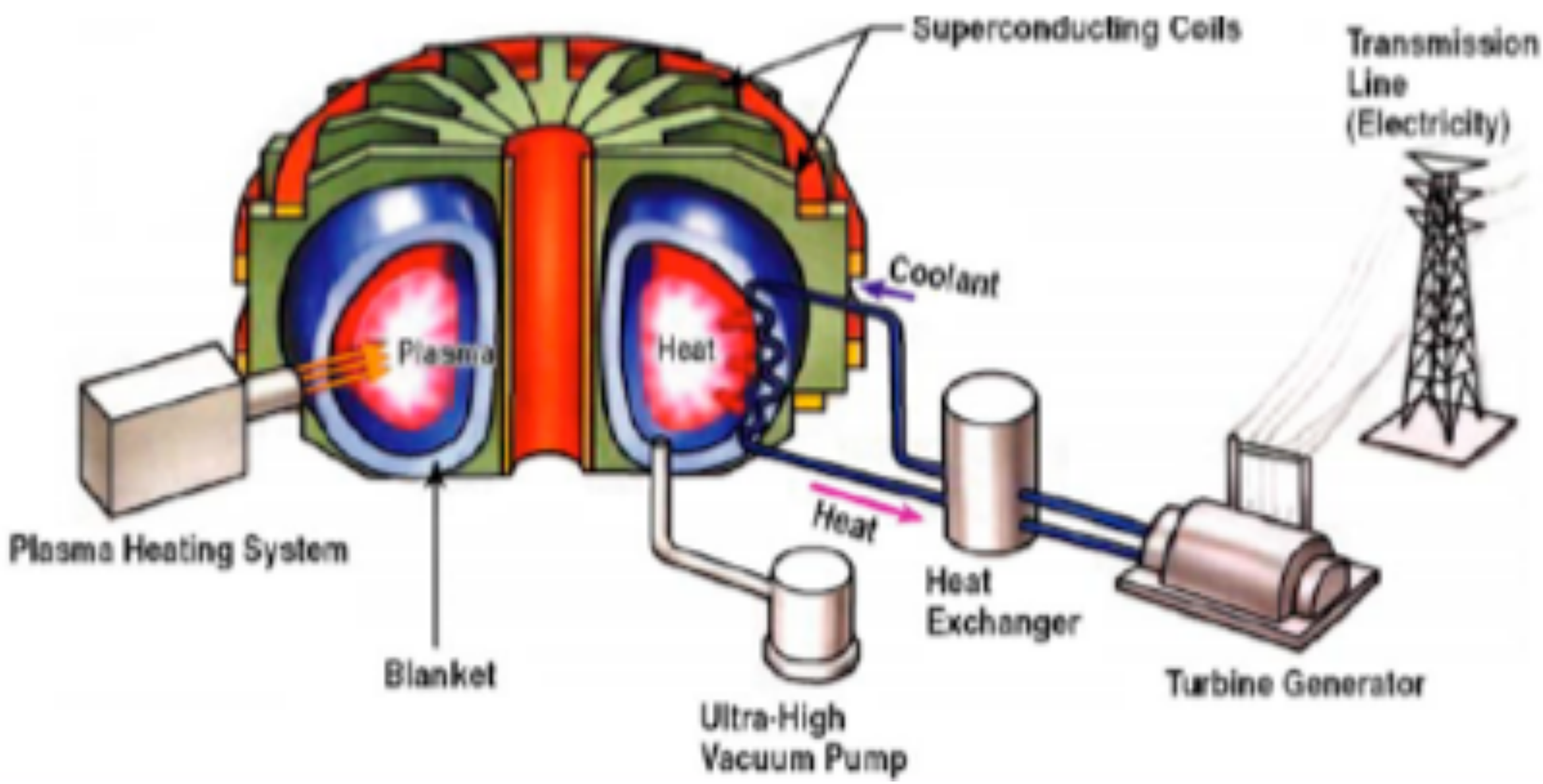
Solution: confine plasma in magnetic cage



The largest tokamak (England)



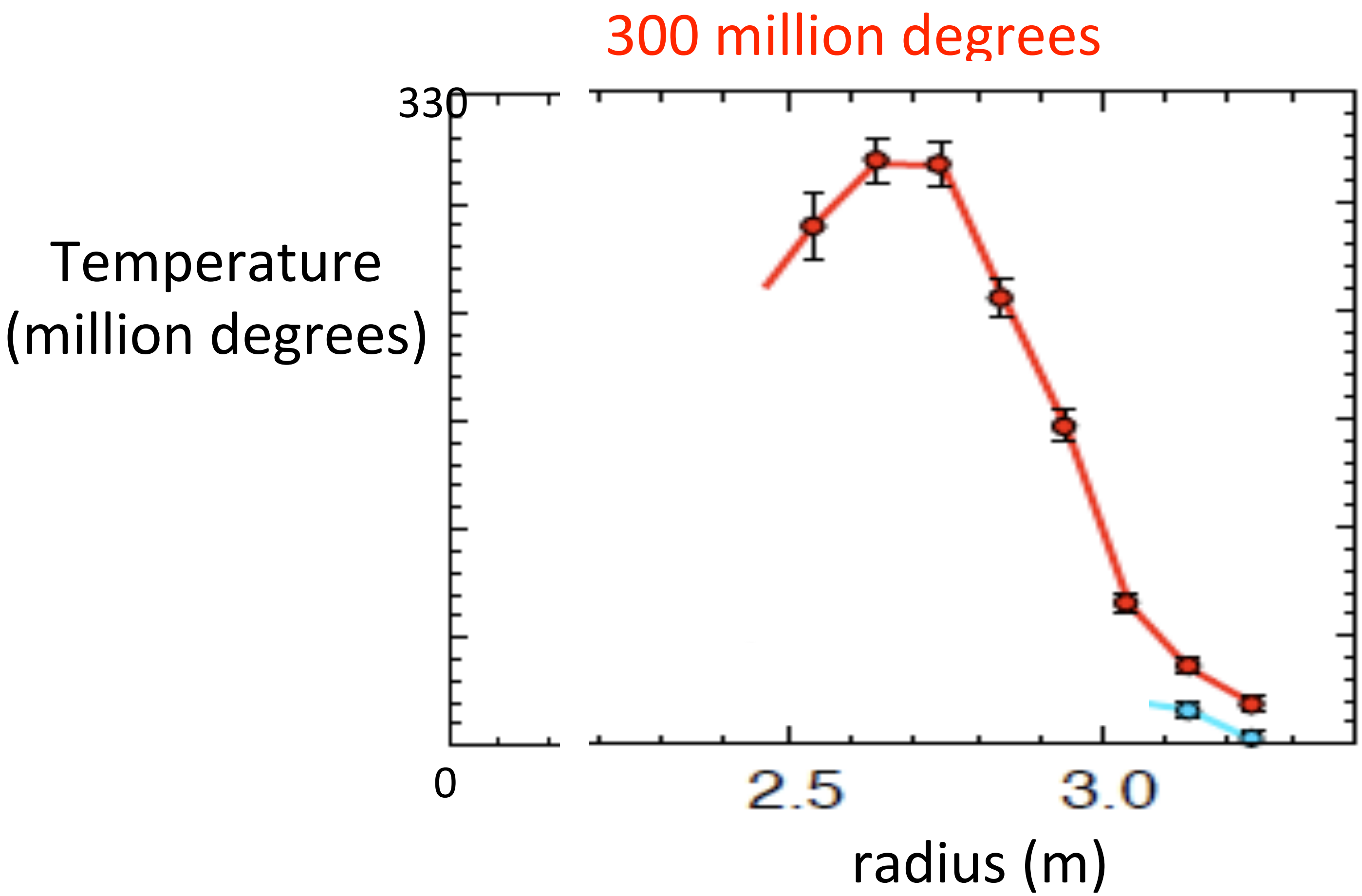
A fusion power plant



not to scale

We have come very far…

Routinely producing plasmas at astronomical temperatures:

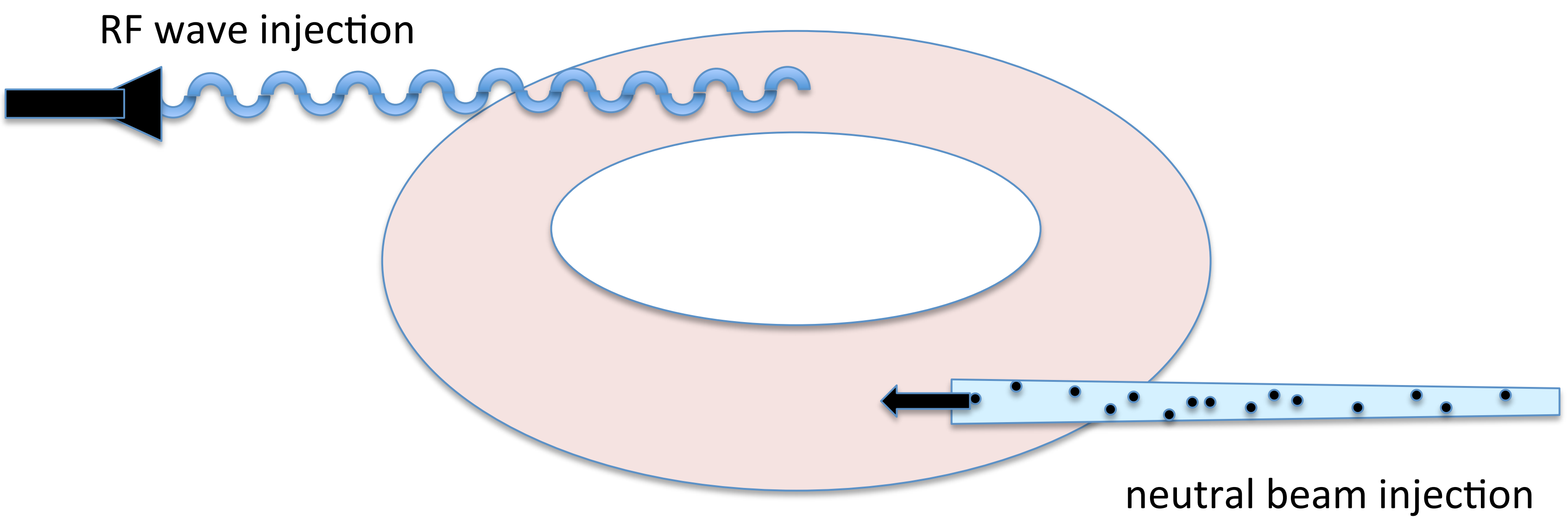


And manipulating hot plasmas with remarkable finesses
(with radio waves, particle beams, magnetic fields…..)

Heating a plasma to astronomical temperatures

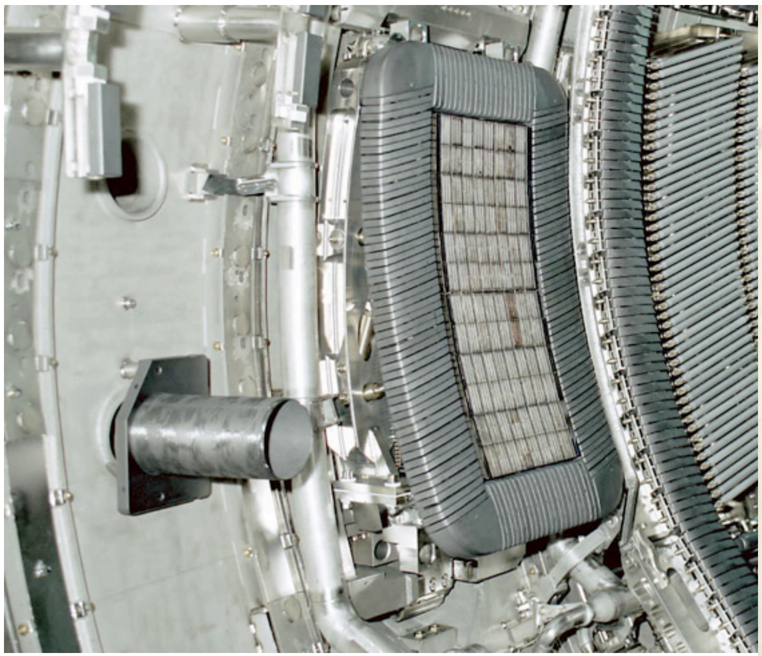
- injection of electromagnetic waves

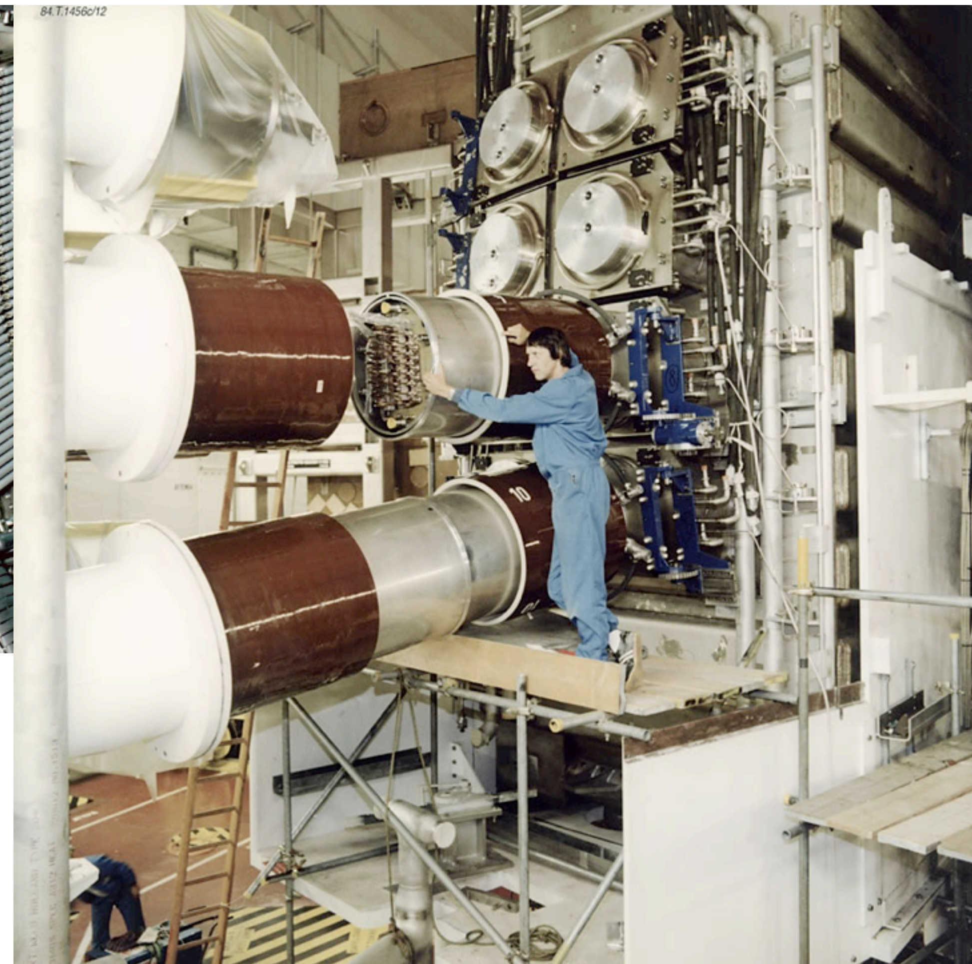
- injection of fast neutral atoms



RF antenna

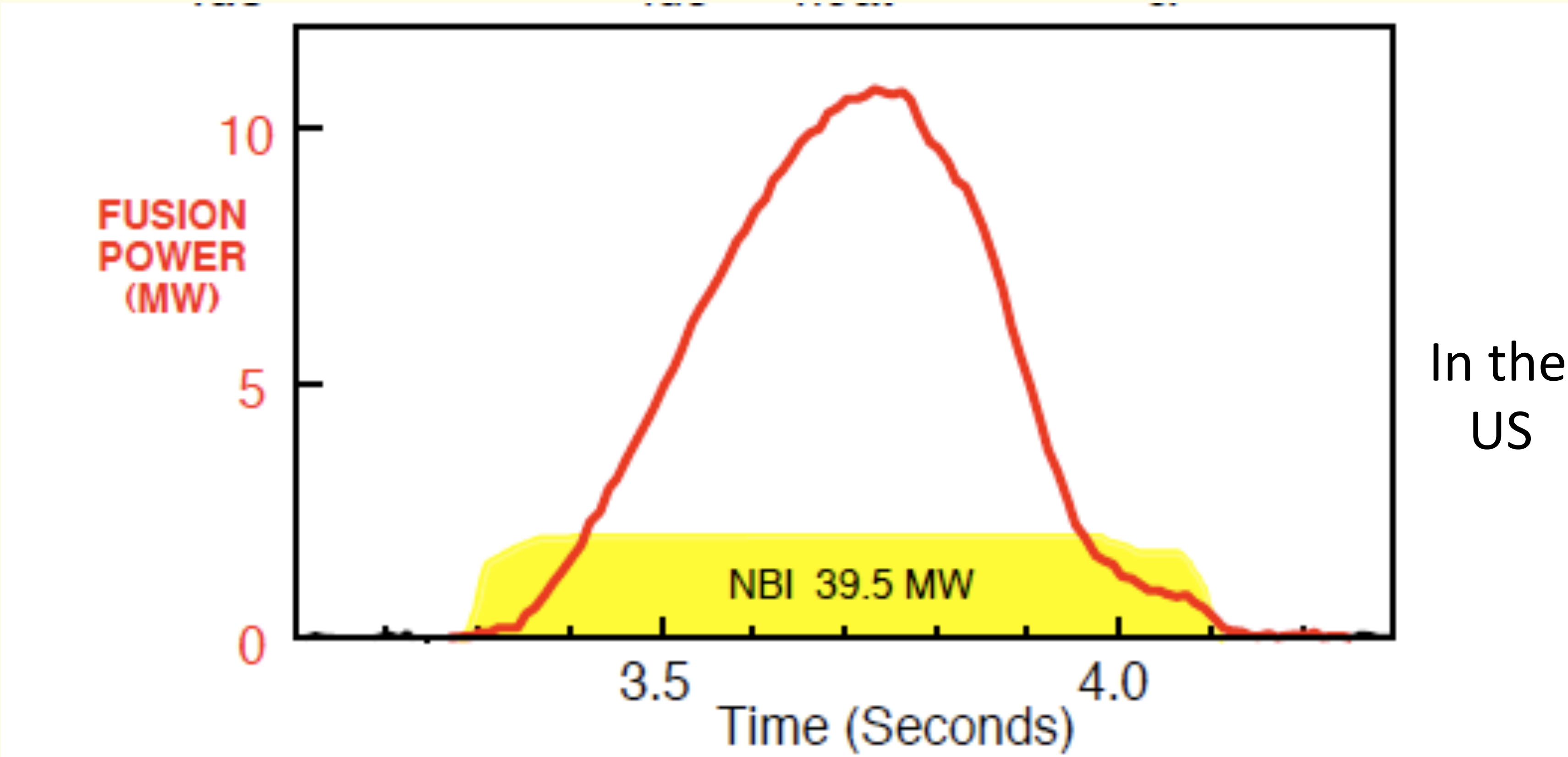
Neutral beam injector





We have produced fusion energy

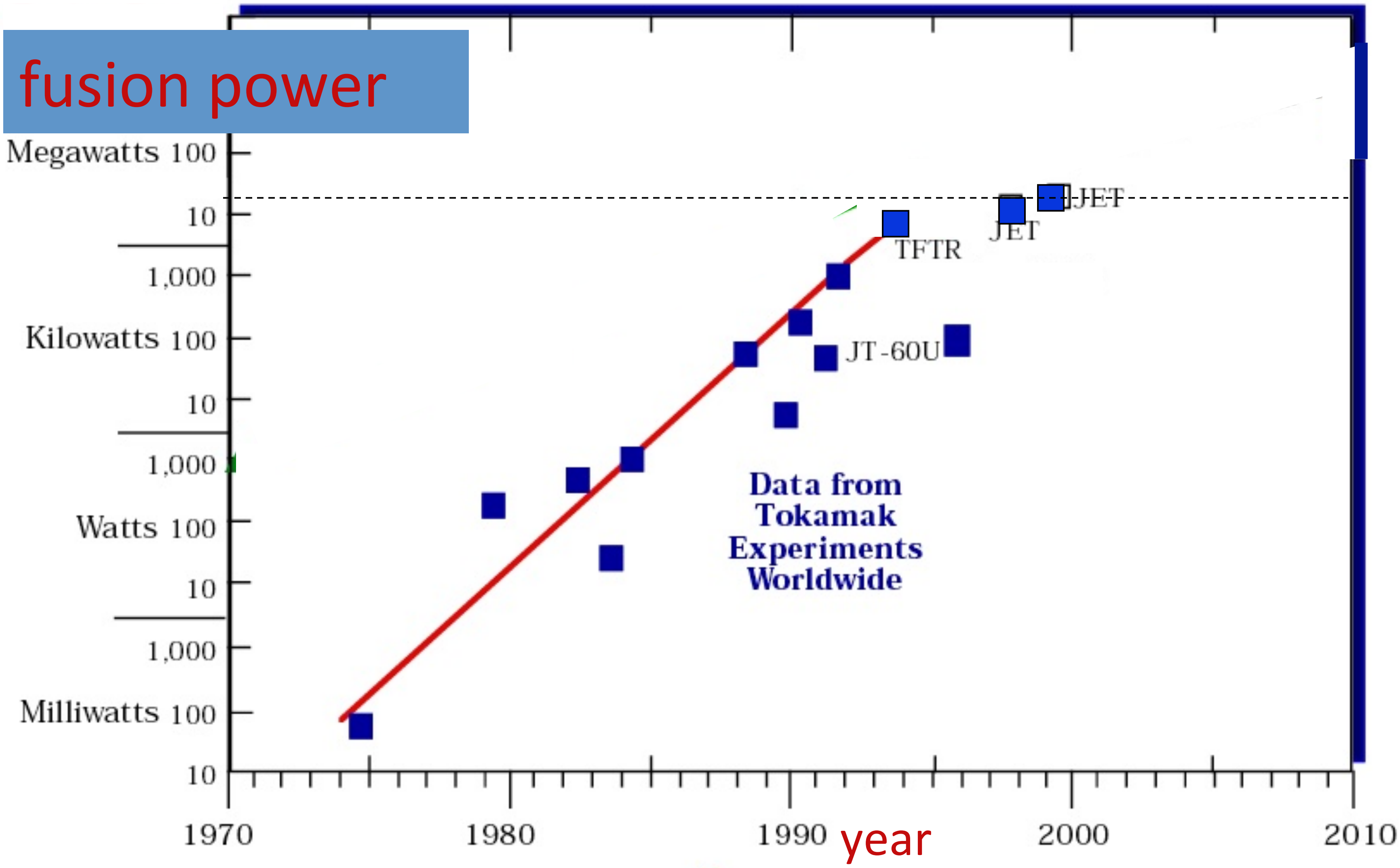
10 MW in 1994



In the US

1997: 16 MW produced in the UK

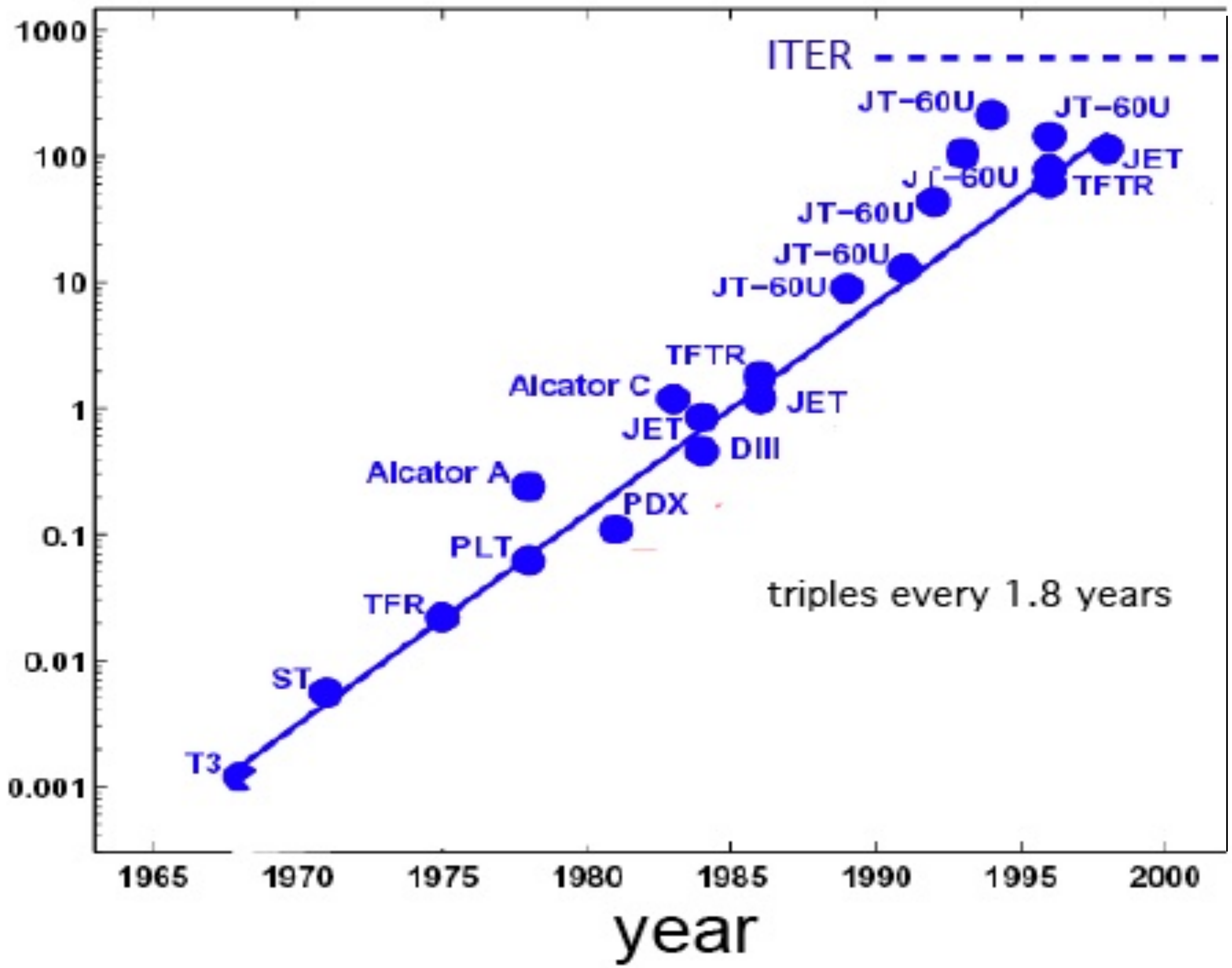
huge advance in fusion power



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

Similar huge strides in key scientific figure of merit
(density) x (temperature) x (energy loss time)

fusion triple product



These results in the early 1990s

triggered an increase in the worldwide fusion effort

We have high confidence that we can make power-plant-scale fusion power,

Questions: how quick? how attractive? how economical?

(reactor design studies predict cost-competitive fusion power – need to prove it)

We know the R&D steps needed to proceed,

The international ITER experiment

Will generate 500 MW of fusion power for 500 seconds,

Study key physics and technology for fusion,
The first burning plasma

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Self-heating

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

100 million degree plasma

electricity

The international ITER experiment

Will generate 500 MW of fusion power for 500 seconds,

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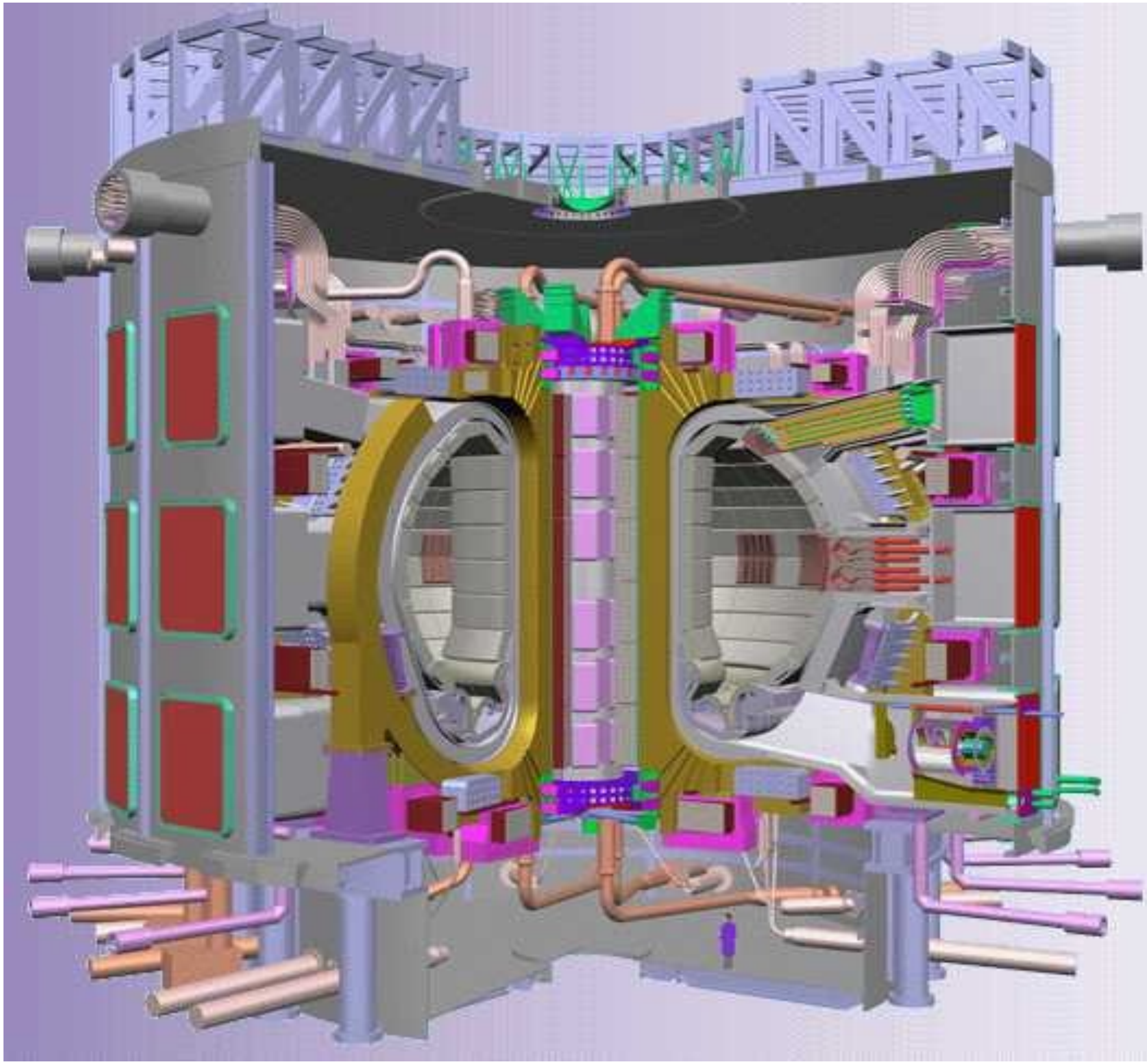
The first burning plasma

Partnership covers half the world's population

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

ITER is a reactor-scale experiment



site preparation
in France

Will operate in 2020

Will operate in 2020

US ITER construction cost:

about $2.5B over about 10 years

The international context

fusion research in other nations is surging,

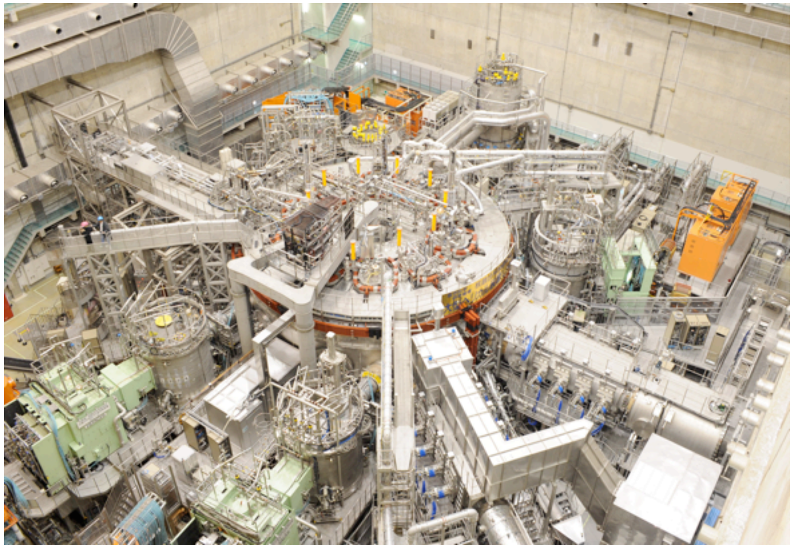
in Asia and the E.U.

The escalating magnetic fusion activity across the world

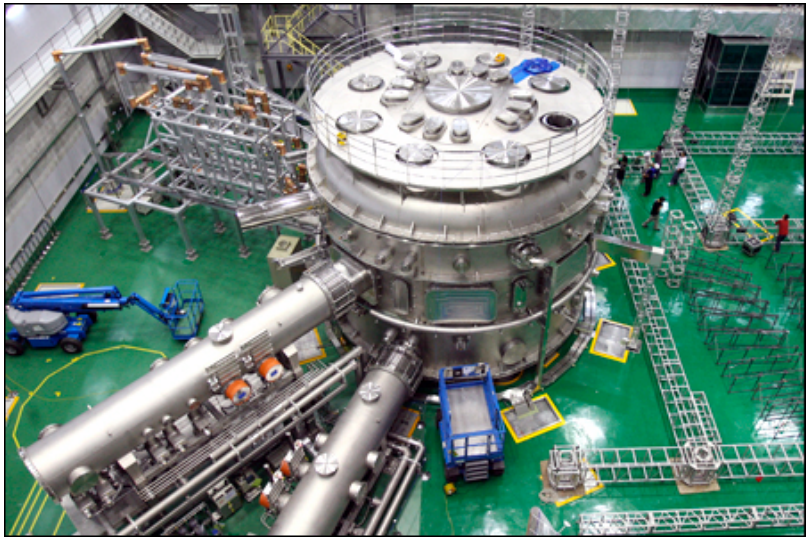
New major facilities

China: superconducting tokamak

Japan: superconducting stellarator



Korea: superconducting tokamak

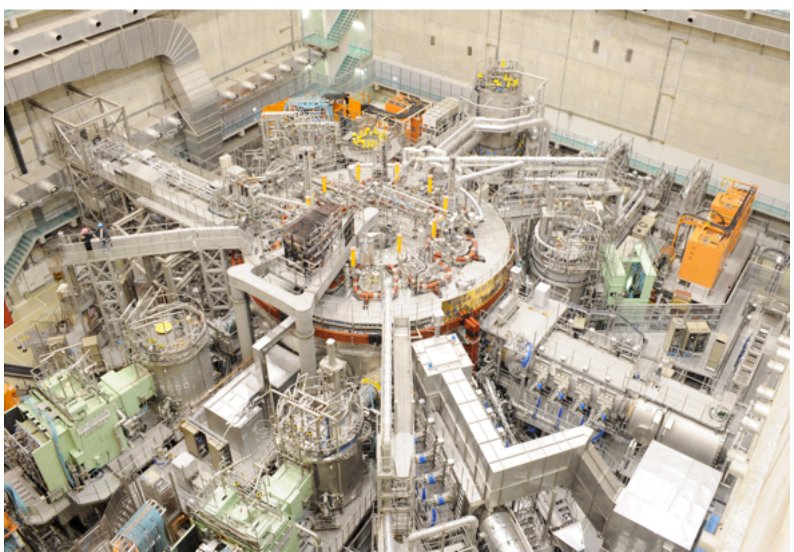


The escalating magnetic fusion activity across the world

England: tokamak

China: superconducting tokamak

Japan: superconducting stellarator



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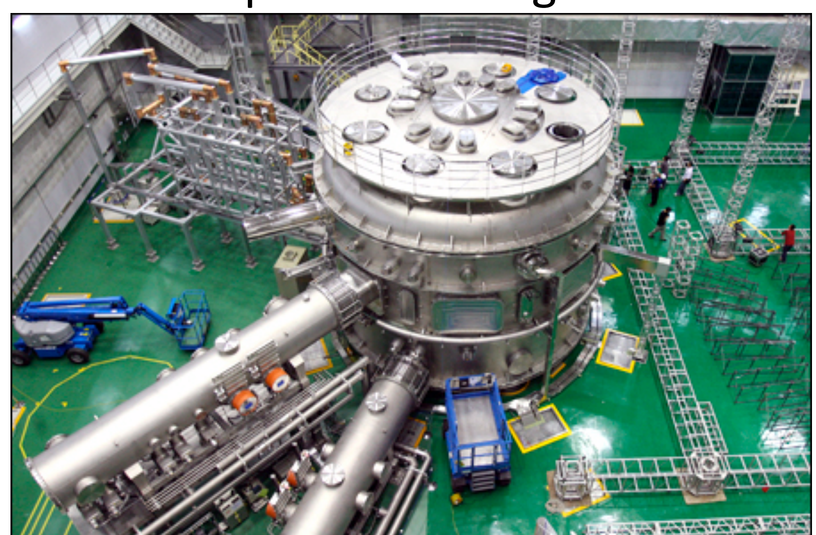
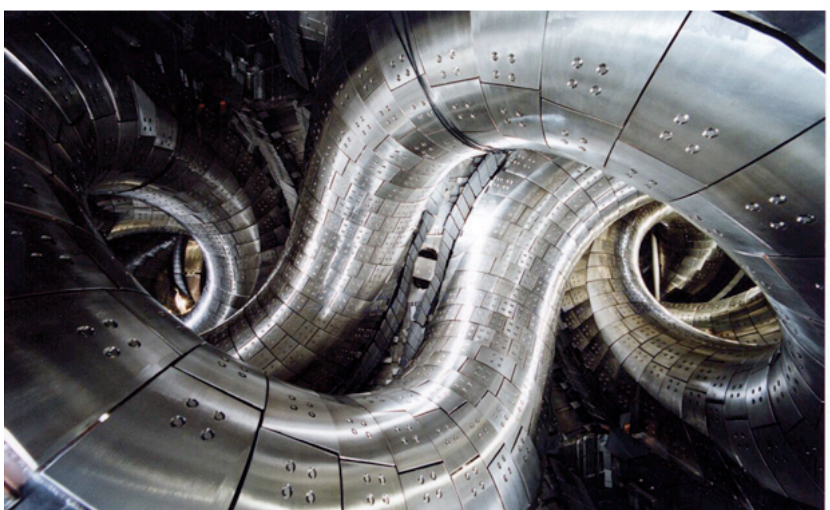


The escalating magnetic fusion activity across the world

England: tokamak

China: superconducting tokamak

Japan: superconducting stellarator



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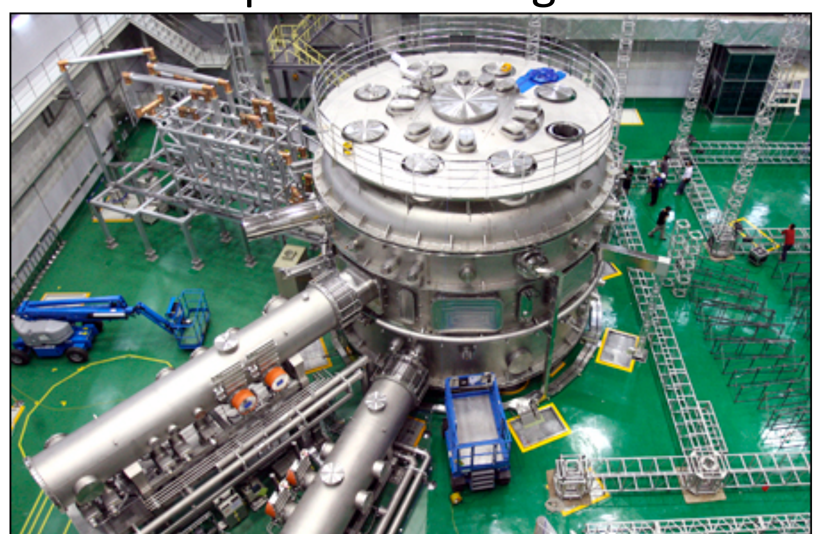
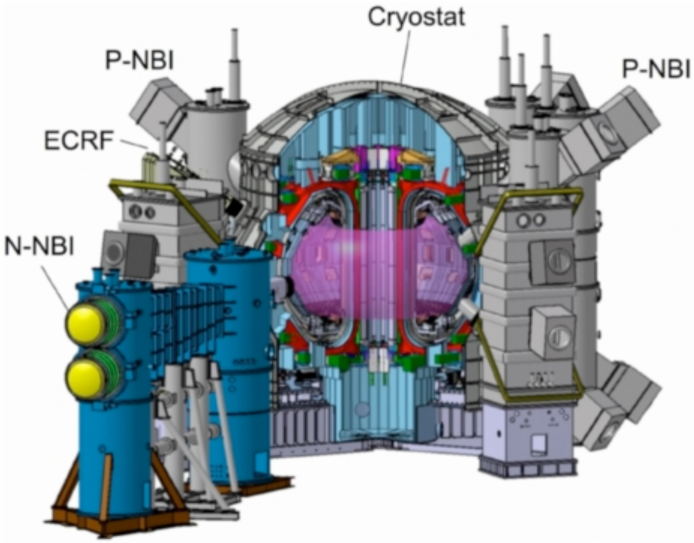
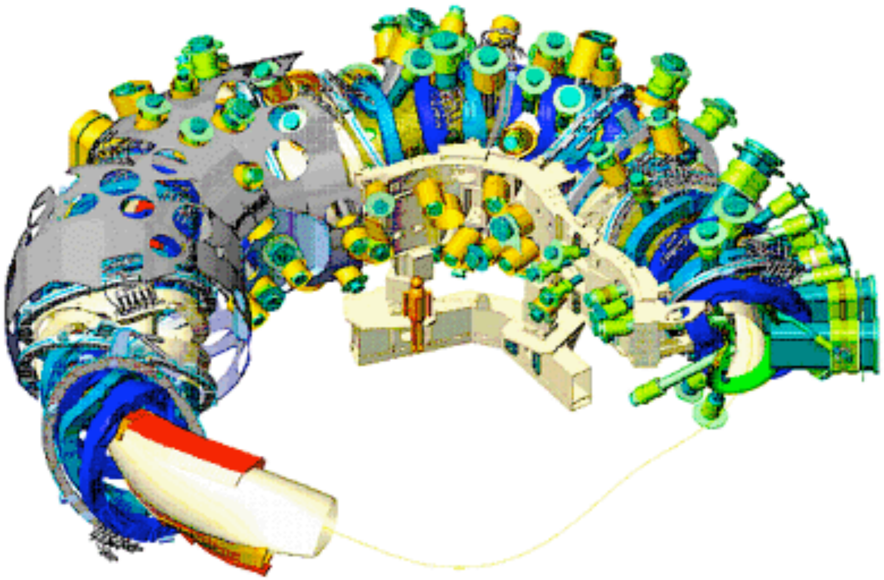


Major facilities under construction

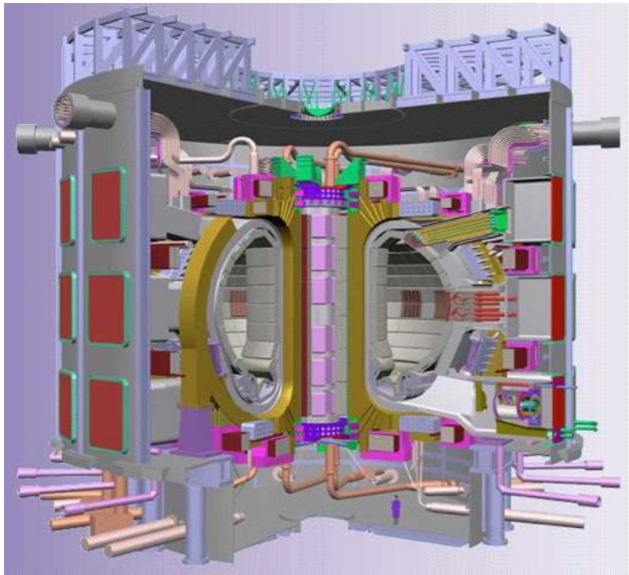
Japan: superconducting tokamak



Germany: superconducting stellarator



France: ITER



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

Major facilities under construction

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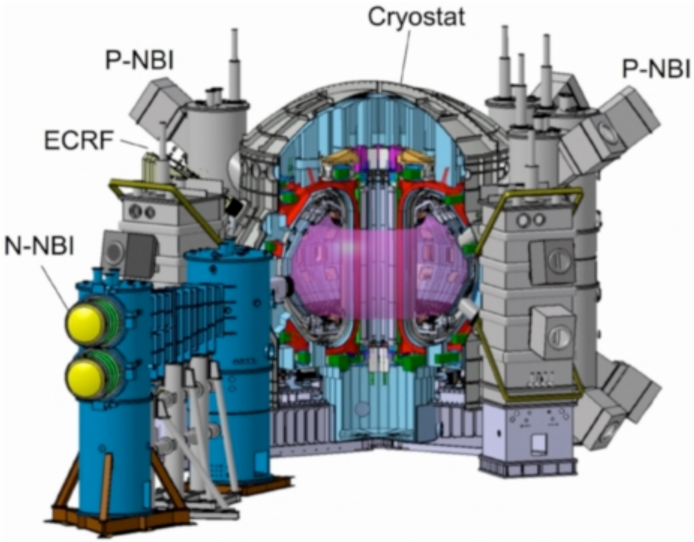

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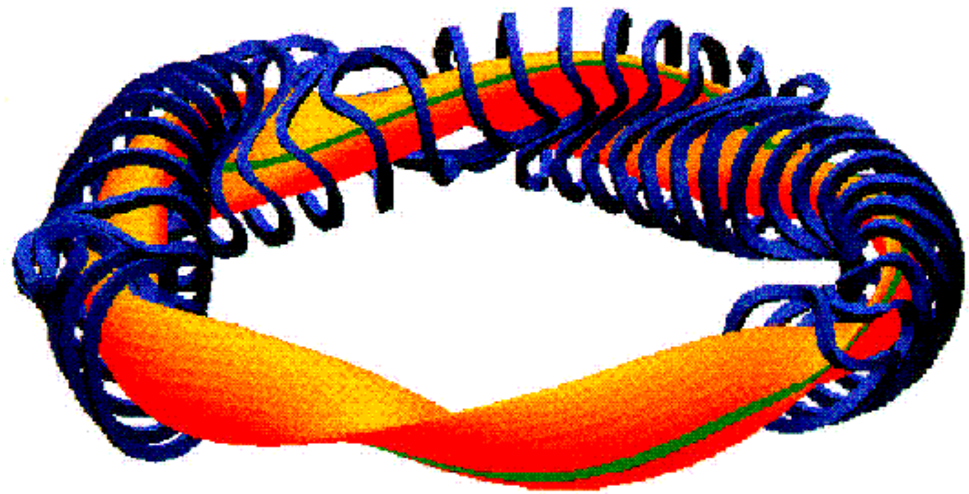

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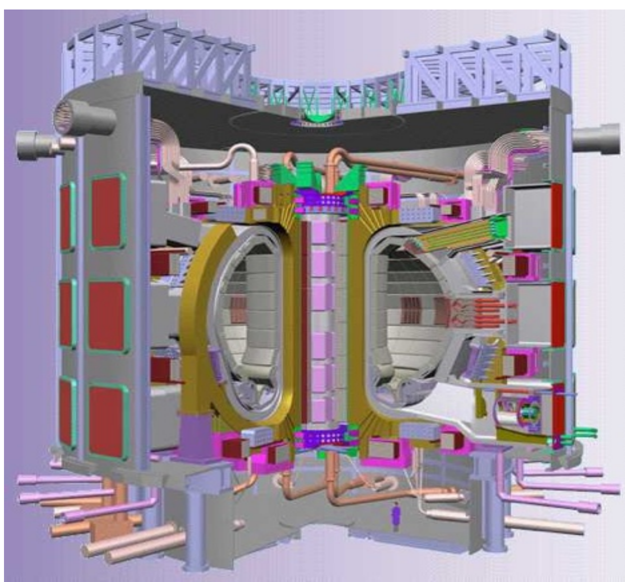
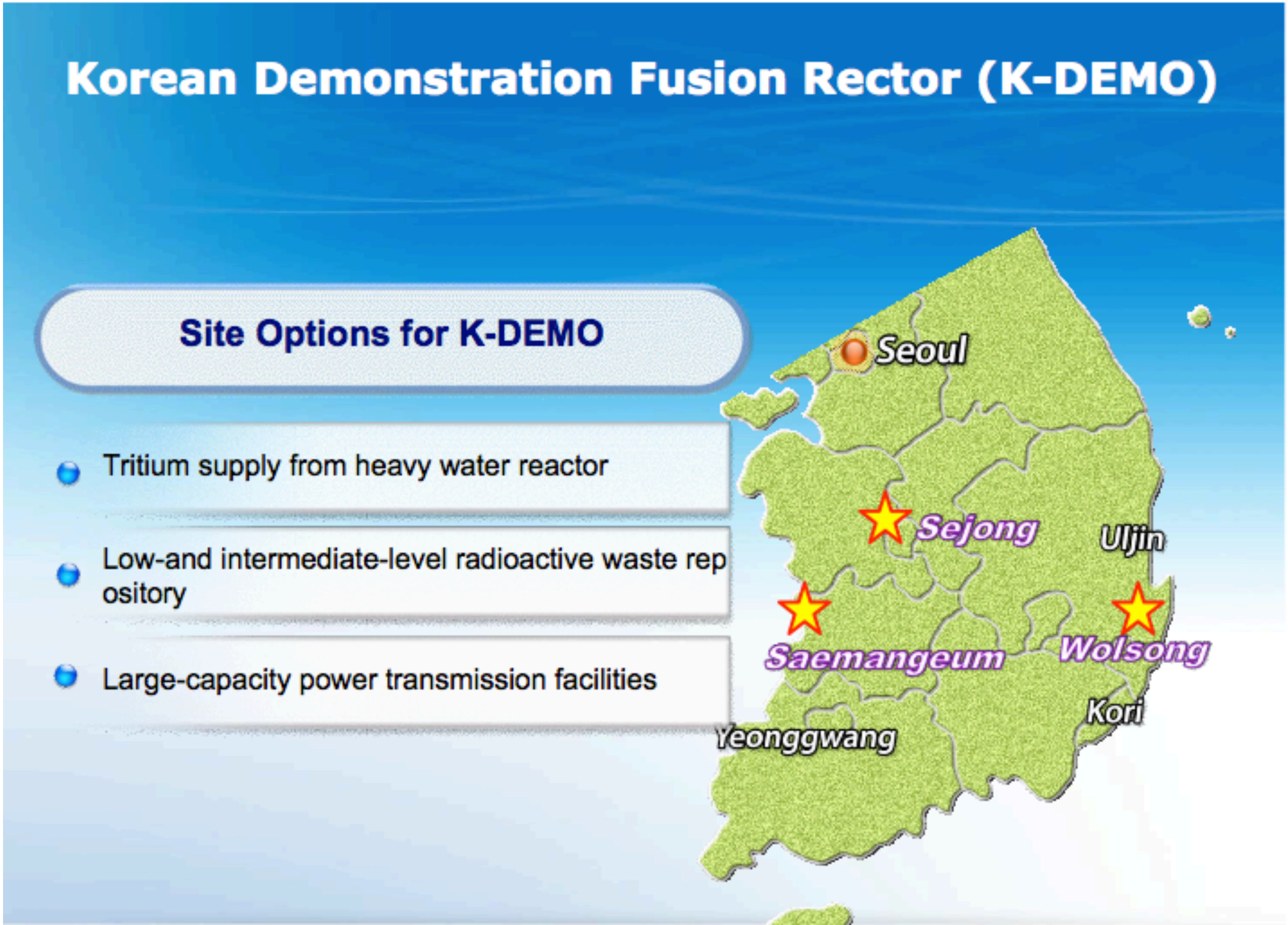


The world has entered the era of superconducting facilities (steady-state)

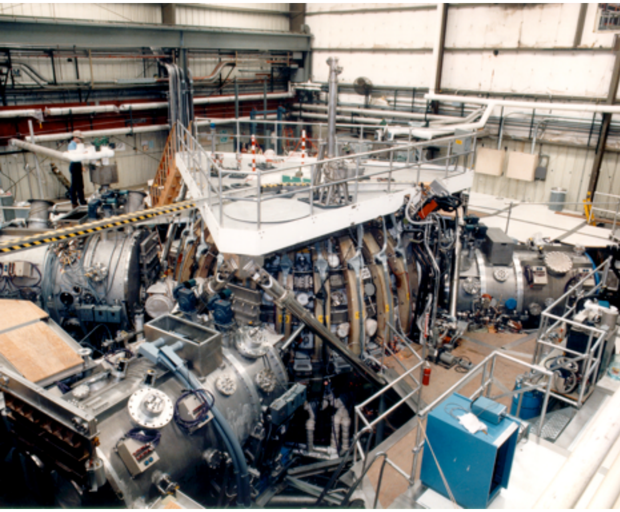
Many nations are planning for a demonstration plant

For example,



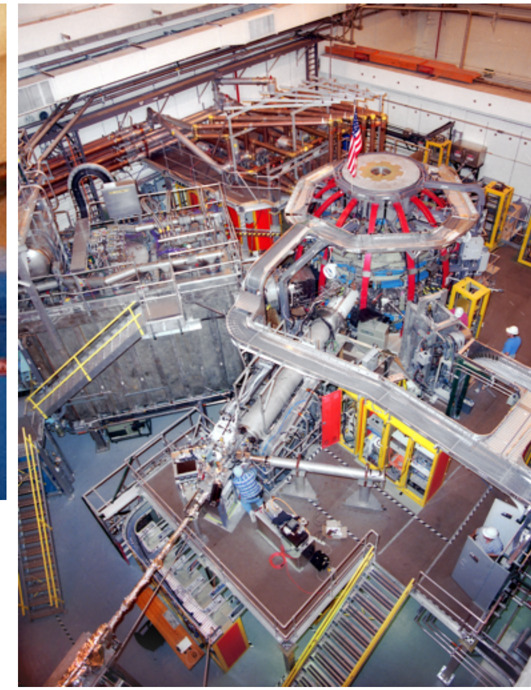
The US operates a strong set of medium-scale experiments

General Atomics



MIT

Princeton (PPPL)



- Performing world-leading fusion research for ITER and beyond

- However, in 10 years, some facilities overseas will, in some ways, be more capable than the US facilities

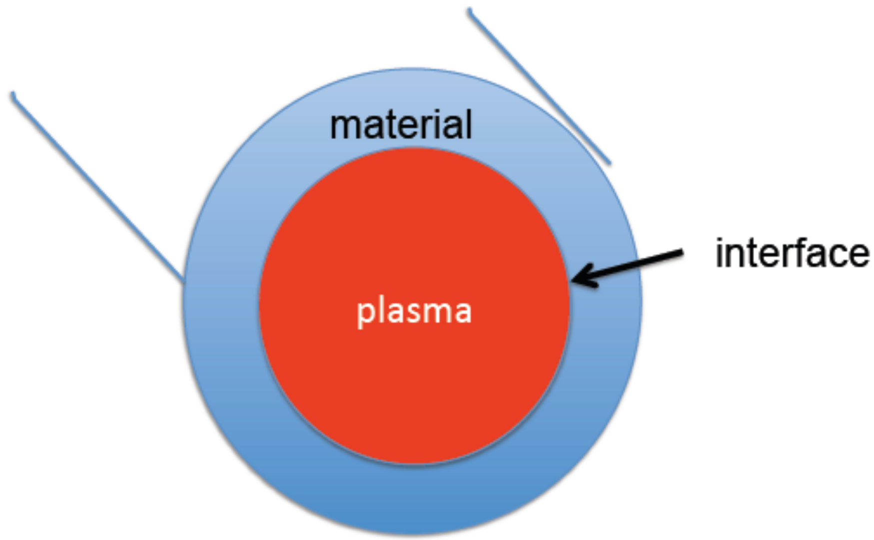
- Need to evolve to new US facilities to attack remaining issues for fusion

US has been the world leader in fusion,

has a fusion science workforce second to none,

on verge of falling behind to second tier

Fusion Challenges



- Plasma confinement and control
  - burning plasma
  - steady-state plasma
- The plasma-material interface
  - effect of plasma on materials, effect of materials on plasma
- Harnessing fusion power (fusion nuclear science)
  - effects of neutrons on materials,
  - managing neutrons (tritium breeding, power extraction)

To conclude,

- Scientists are confident we can make fusion power for large-scale energy use

- Research challenges remain that will determine economic attractiveness, time to commercialization

- If there is societal will, we can have a clean, safe, abundant, domestic fusion energy source in our lifetime

The fusion budget challenge

To fund ITER and a vital domestic program

The fusion budget

(in round numbers)

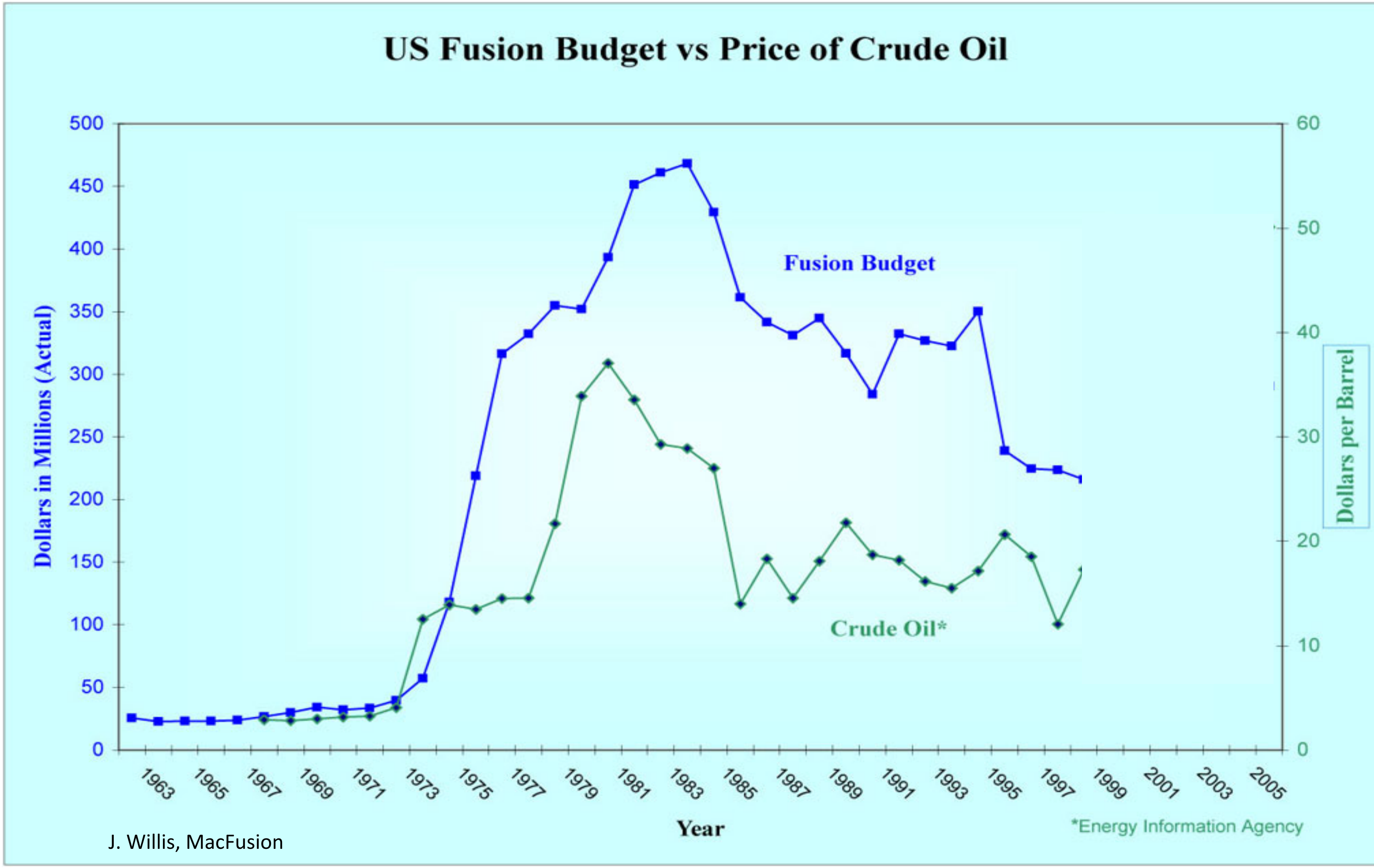
	FY 12	**FY 13 (needed)**	**FY 14 (needed)**
Domestic	$300M	$300M	$300M
ITER	$100M	$200M	$300M
Total	$400M	$500M	$600M

The FY 13 Administration Request

Domestic	\$248M	\$45M cut (16%)
ITER	\$150M	\$45M increase (\$100M needed)
Total	\$398M	constant

We are at a turning point: can dismantle our world class science workforce, or maintain our leadership

The politics of fusion in the US


US Fusion Budget vs Price of Crude Oil
Dollars in Millions (Actual)
Dollars per Barrel
Fusion Budget
Crude Oil*
500
450
400
350
300
250
200
150
100
50
0
60
50
40
30
20
10
0
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
Year
*Energy Information Agency
J. Willis, MacFusion

Steady funding for decades, but declining