Magnetic fusion energy

from physics to DEMO

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Outline

8:30	Introduction	S. Prager
	Fundamentals/accomplishments	
9:15	Power plant designs	F. Najmabadi
9:50	Break	
10:05	Remaining challenges	R. Stambaugh
10:40	Roadmap to DEMO	R. Fonck
11:25	Discussion	
12:00	Adjourn	

Why fusion?

- Nearly inexhaustible

  deuterium from sea water, tritium from breeding from lithium

- Clean

  no greenhouse gases, no acid rain

- Safe

  passive safety;

  only short-lived radioactive waste

- Available to all nations

  reduced conflict over resources

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The imperative for fusion energy is ever increasing

From 1958 to 2011

- Plasma physics developed into mature field of science
- Fusion plasma technology developed into mature field of engineering
- Experiments have evolved from milliwatts to megawatts, fusion conditions produced in lab
- ITER brings the world's capabilities together to establish the physics and technology of a burning plasma

  (500 MW fusion power)

From 1958 to 2011

- Plasma physics developed into mature field of science
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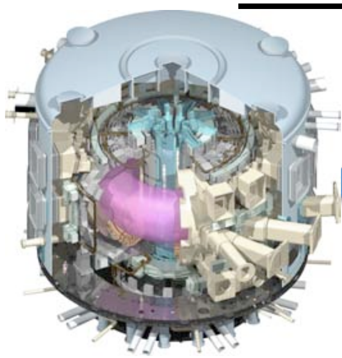
We are ready now to breakout into an energy development program, leading to a demo power plant in about 25 years

Moving forward: 4 challenges

- Demonstrate and explore burning plasmas
- Create high performance, steady-state plasmas
- Tame the plasma-material interface
- Harness fusion power

Roadmap to DEMO

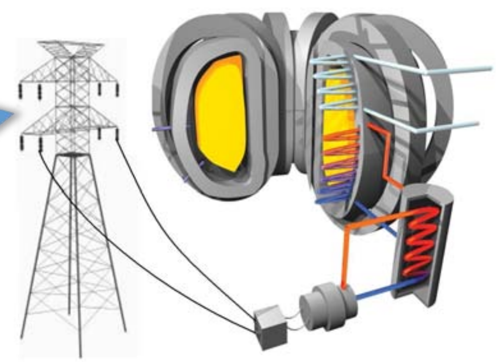
ITER



~ 2020 start

Burning plasmas

Demonstration Power Plant



Fusion Nuclear Facility

~ 2025 start

Harness fusion energy

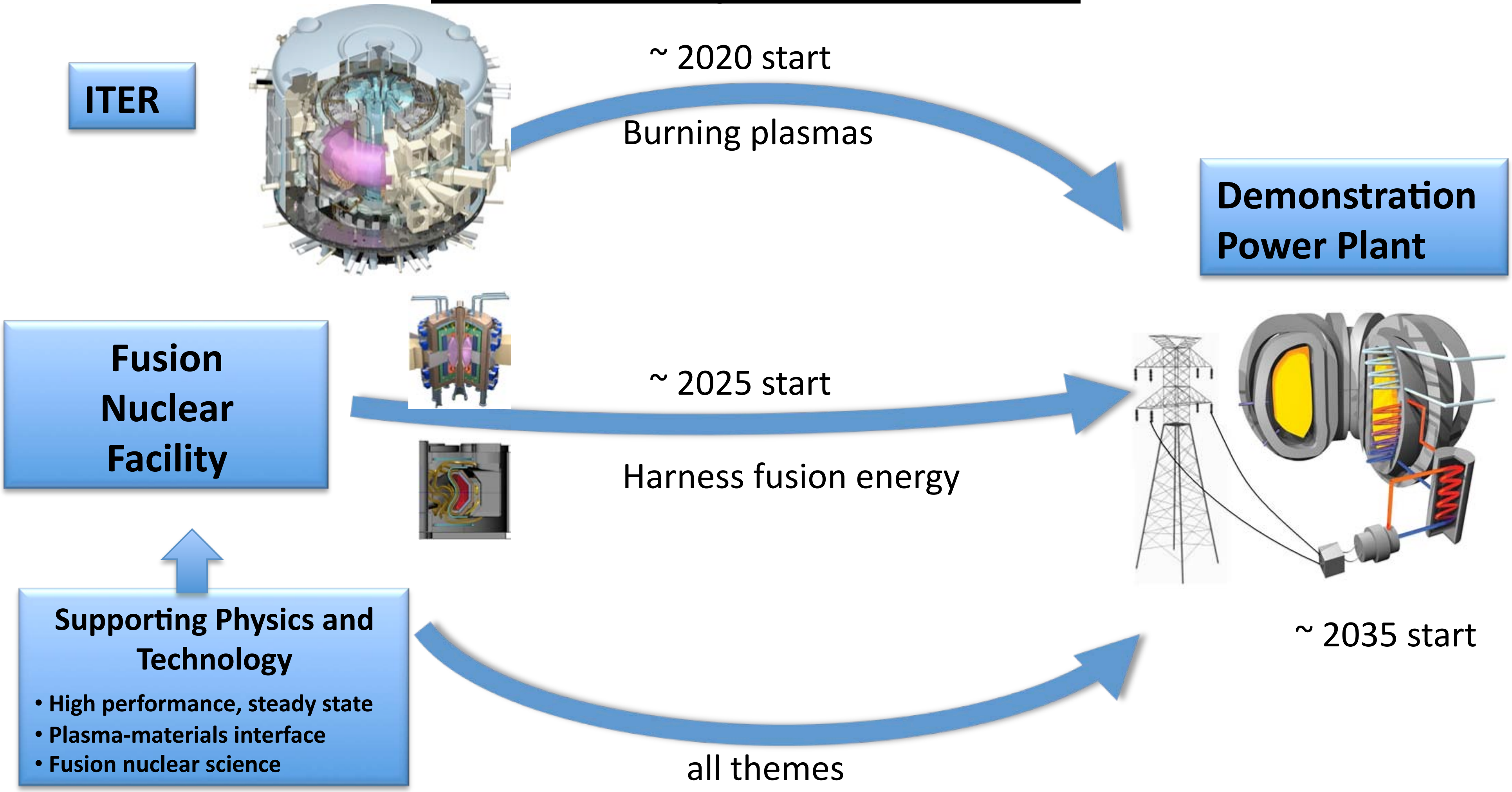
Supporting Physics and Technology

- High performance, steady state
- Plasma-materials interface
- Fusion nuclear science

all themes

~ 2035 start

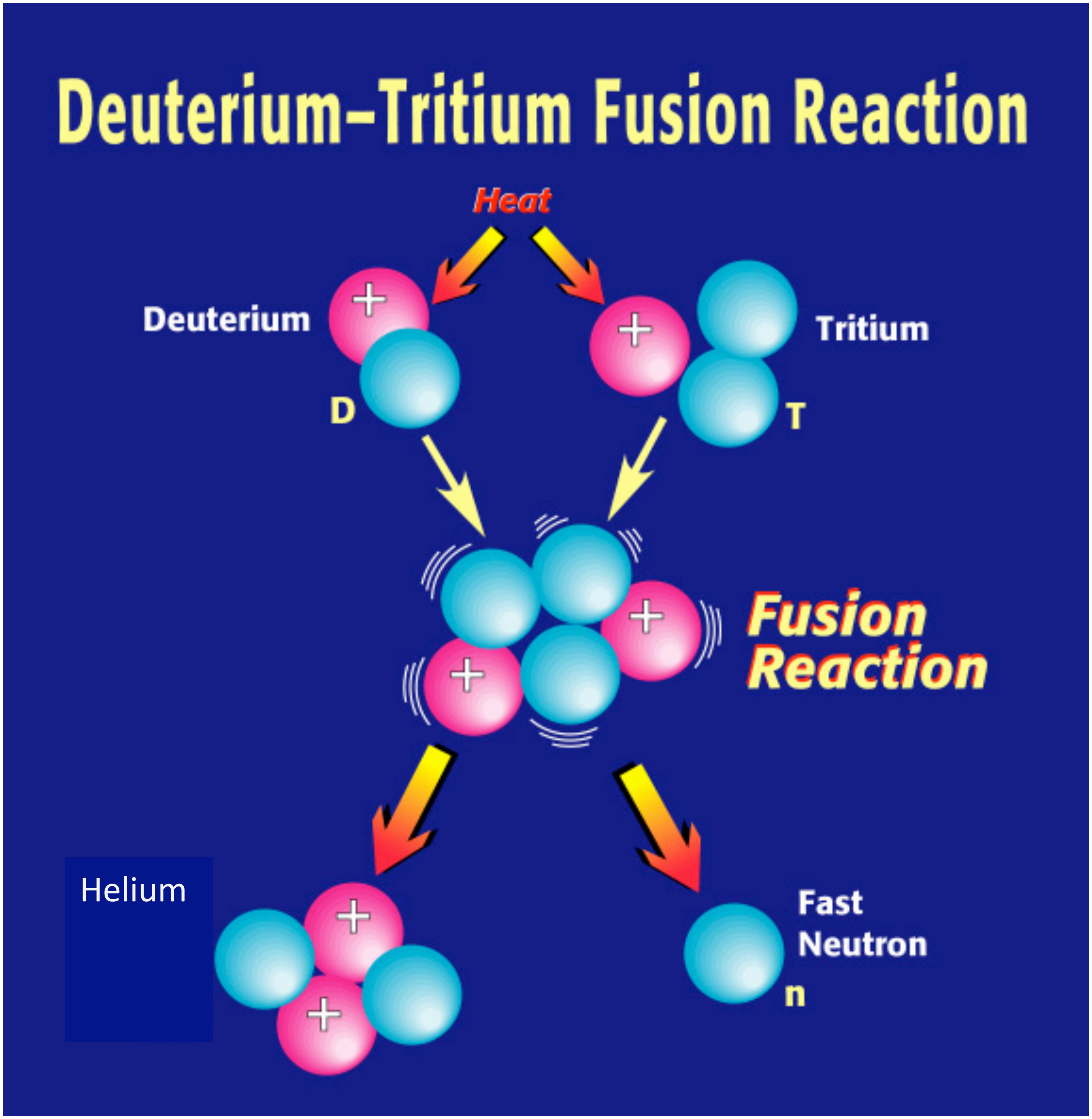
Roadmap to DEMO



Magnetic Fusion Energy

fundamentals, accomplishments, status

S. Prager
Princeton Plasma Physics Laboratory



Deuterium–Tritium Fusion Reaction
Heat
Deuterium
D
Tritium
T
Fusion Reaction
Helium
Fast Neutron
n

The fusion reaction

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

15 keV   15 keV   3.4 MeV   14 MeV

150 million degree plasma

The fusion reaction

Self-heating

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

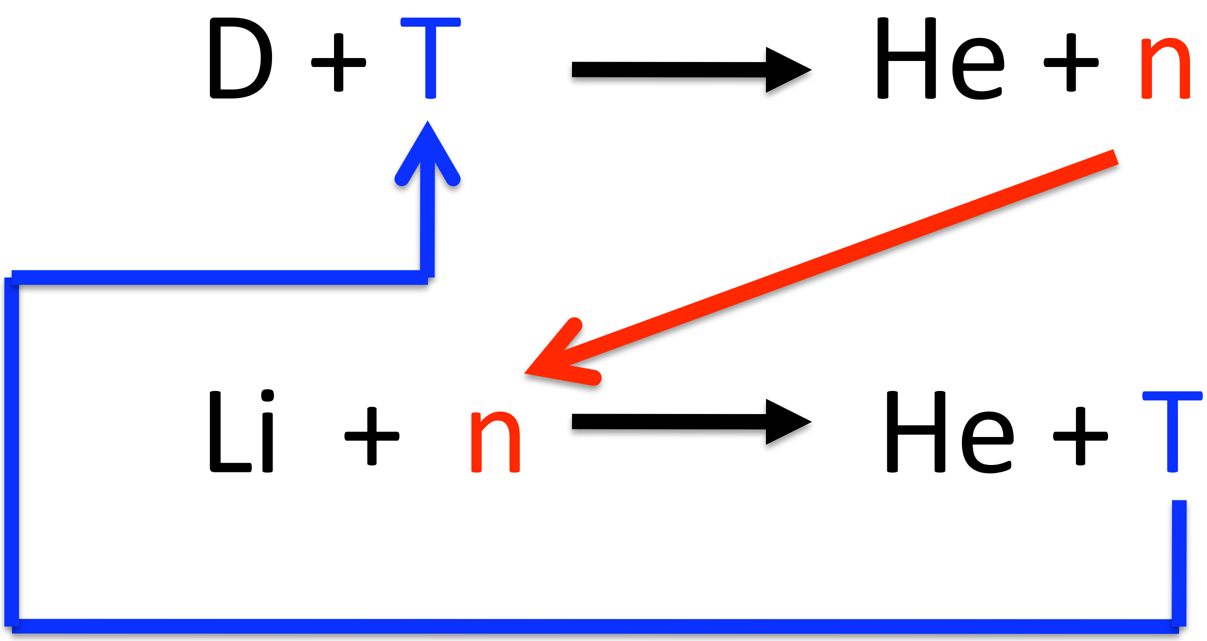
15 keV 15 keV 3.4 MeV 14 MeV

150 million degree plasma

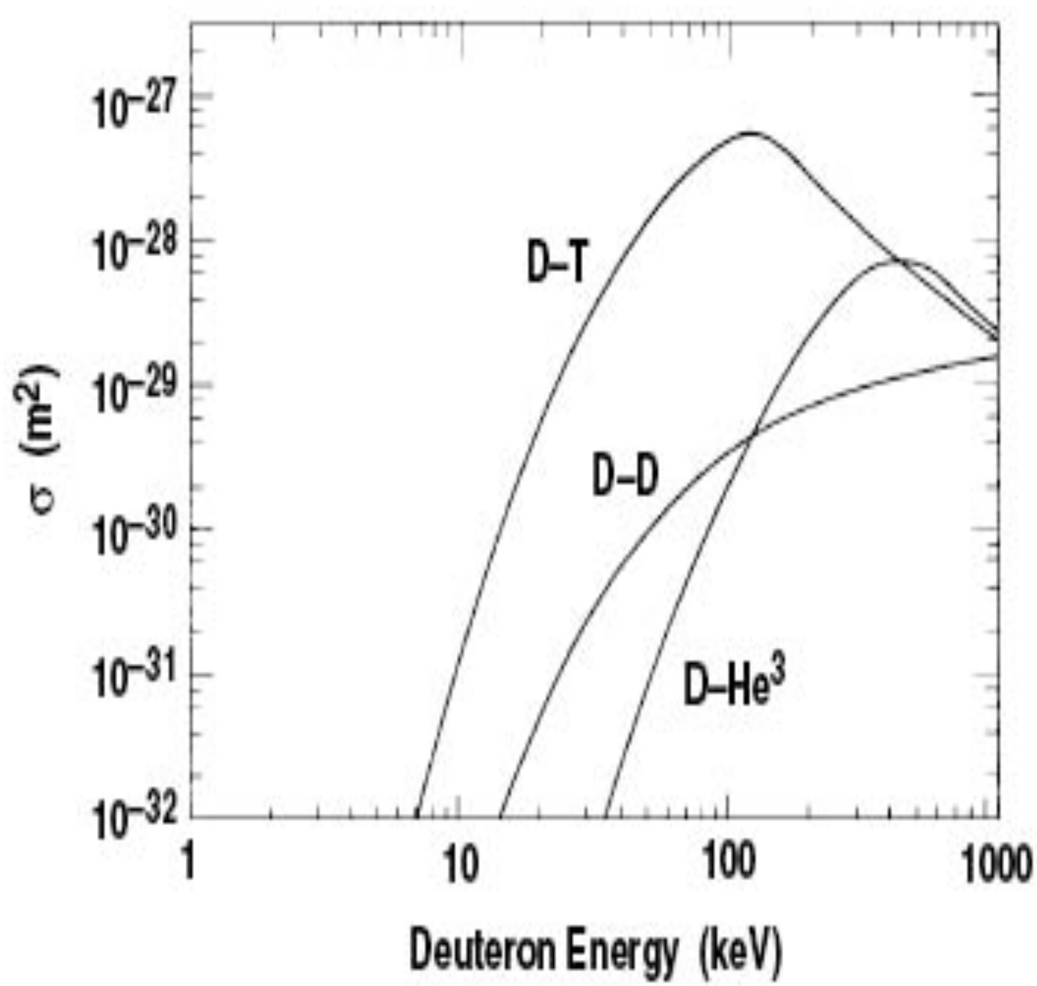
electricity,
tritium breeding

Tritium is bred in the fusion reactor

Breeding blanket: neutrons bombard lithium to form tritium

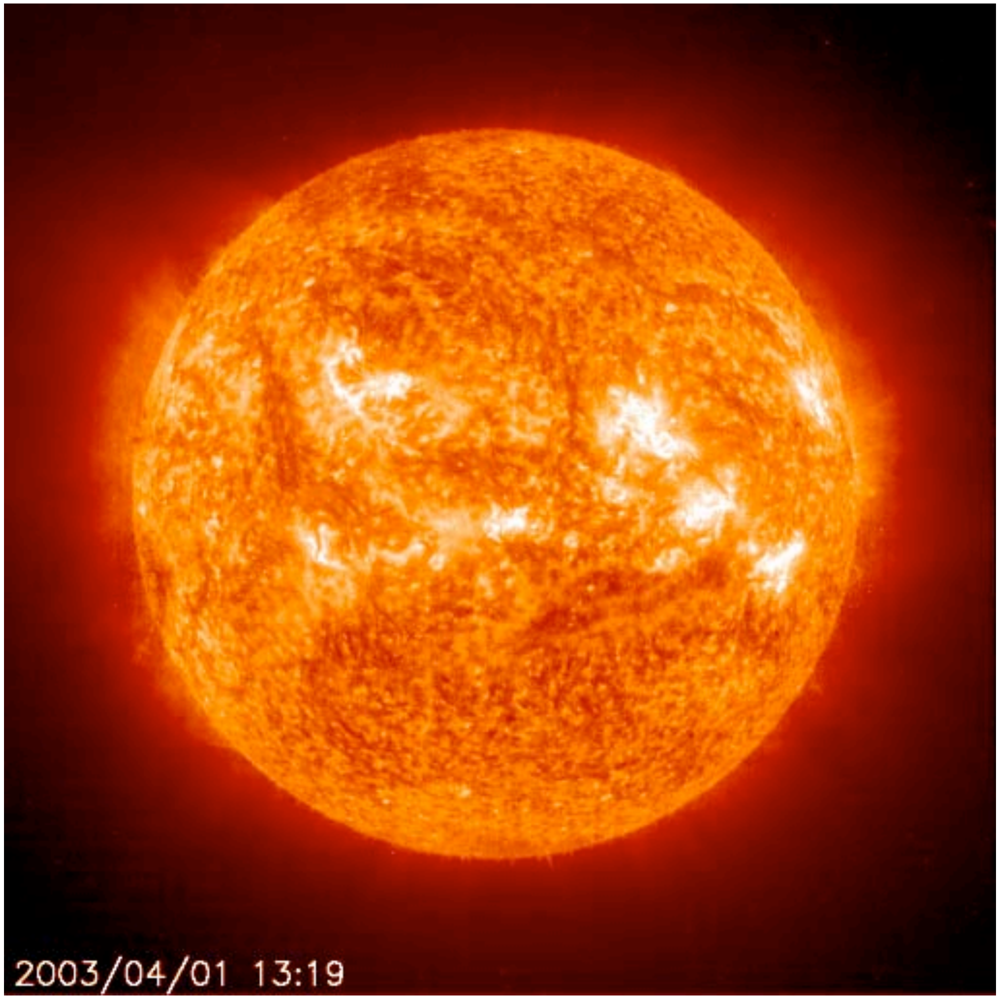


DT has the largest fusion cross-section



Other fuel cycles require much greater plasma performance

Fusion Plasma



Temperature

~ 1 keV in sun,

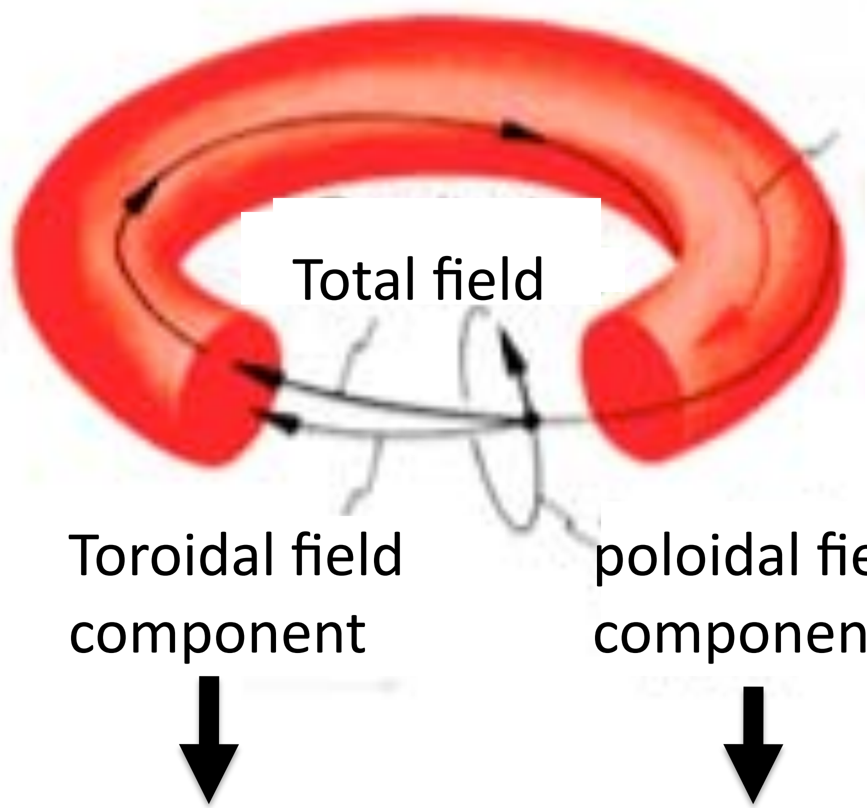
~ 15 keV in fusion reactor

Fusion power density in sun ~ 300 Watt/cubic meter,

In fusion laboratory plasma ~10 MWatt/cubic meter

The Tokamak

Magnetic field is helical

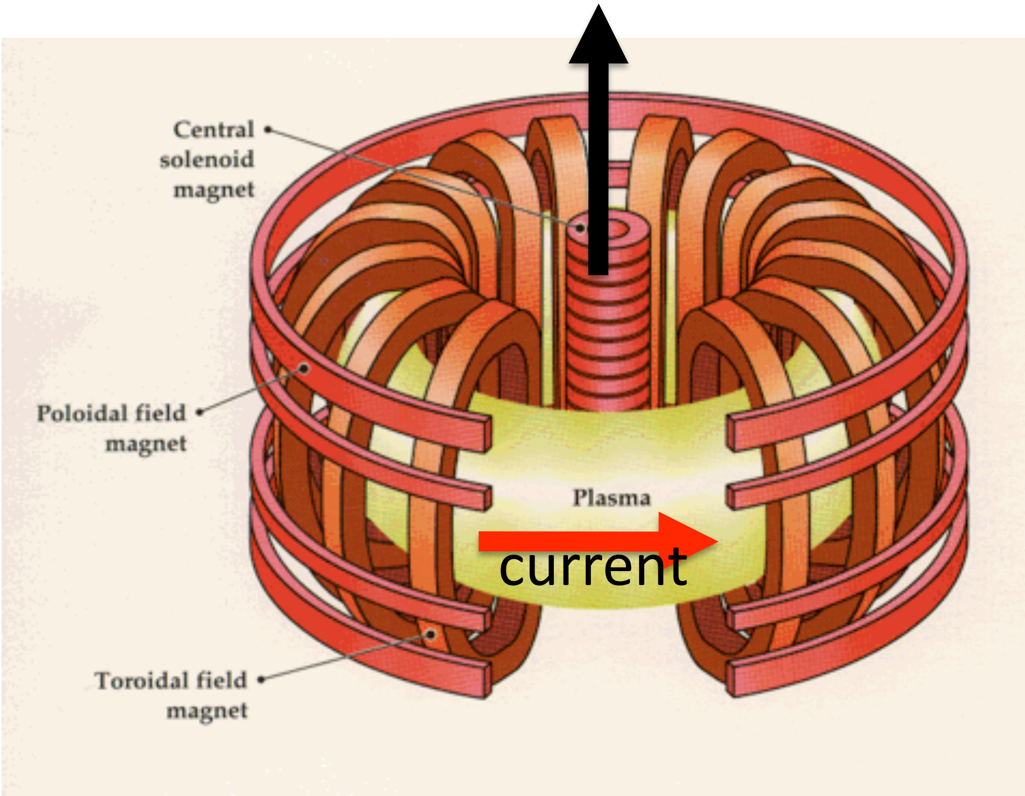


stability | equilibrium

B is axisymmetric (2D), toroidal angle is ignorable, $\partial B / \partial \varphi = 0$

The tokamak

magnetic flux

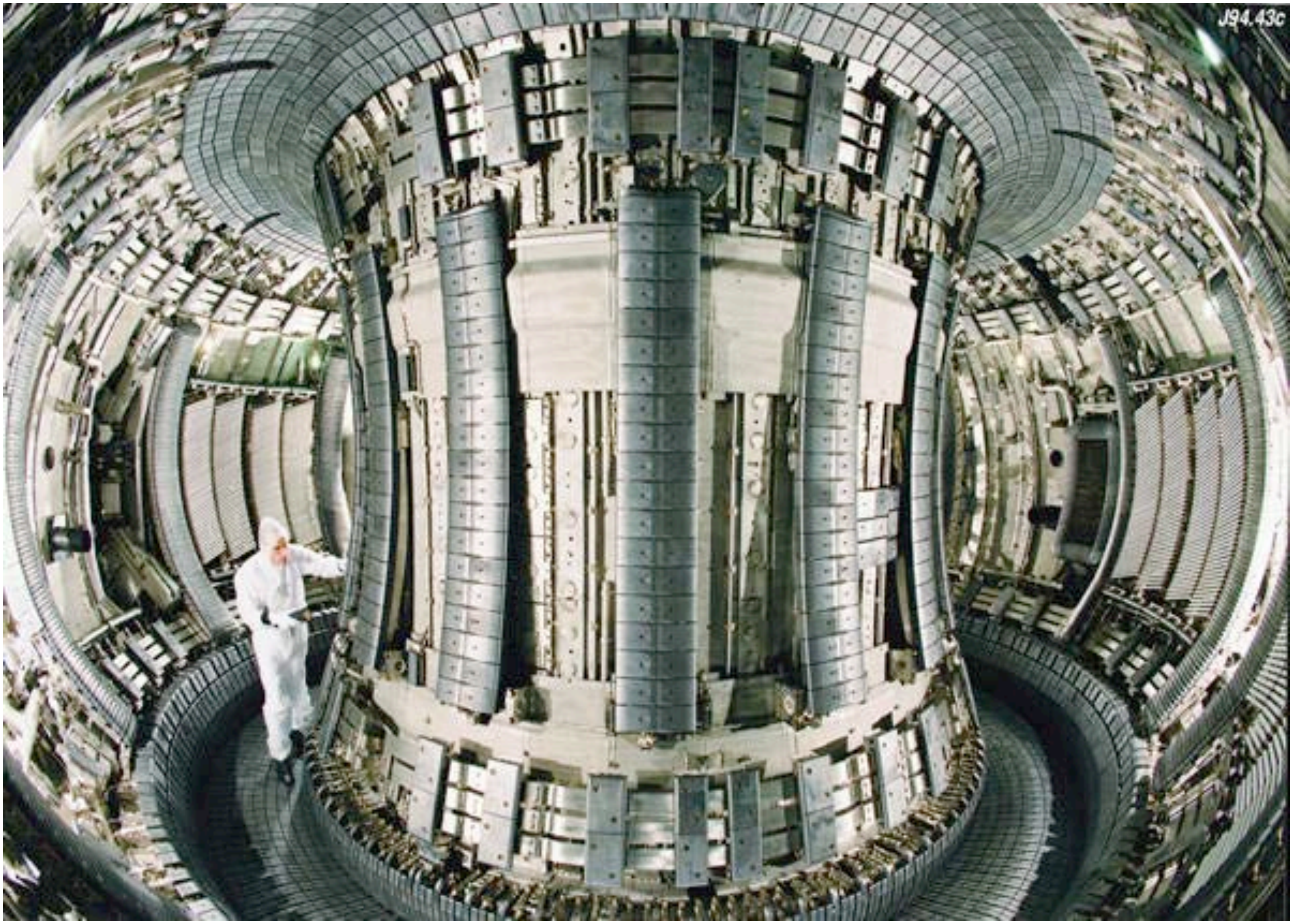


Magnets → $B_{toroidal}$

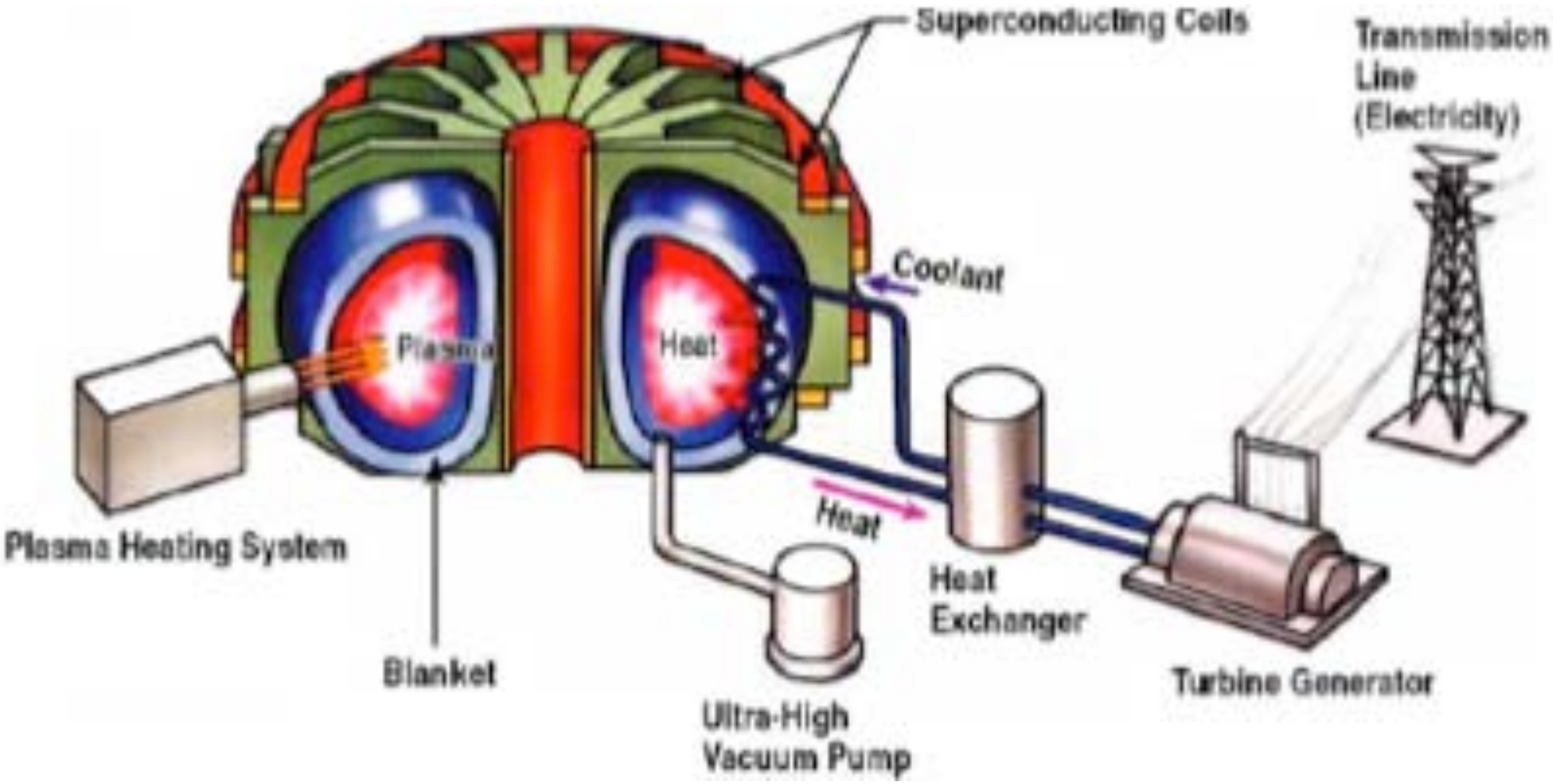
Plasma current → $B_{poloidal}$

Time-varying Magnetic flux → Plasma current

The largest tokamak (JET, England)

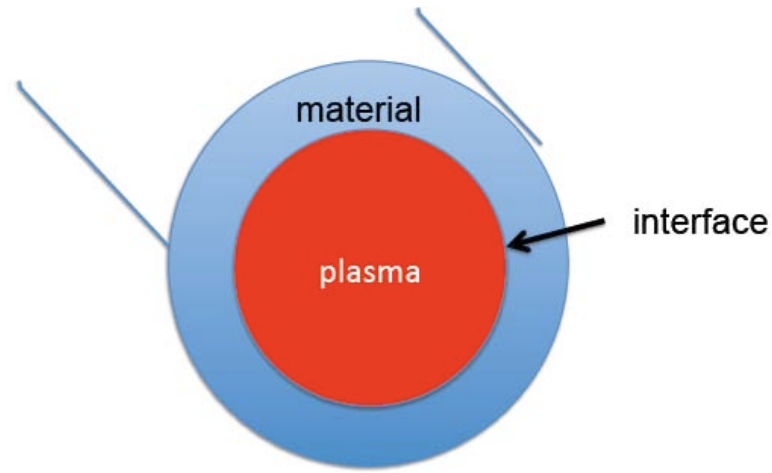


A fusion power plant



not to scale

Fusion Challenges



- Plasma confinement and control

  high quality plasma confinement
  steady-state
  burning plasmas

- 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)

Physics challenges of the fusion core

Confine plasma that is

- hot
- dense
- well-insulated
- steady-state

The Fusion-Core Physics Challenge

Confine plasma that is

- hot
- dense

} High pressure, high fusion power

- well-insulated } High energy gain
- steady-state } Continuous, reliable operation

Fusion reaction rate $\sim n_D n_T \underbrace{\langle \sigma v \rangle}$

function of temperature, T

Energy confinement time $\tau = \dfrac{\text{Plasma thermal energy}}{\text{input energy}}$

Plasma requirement for fusion energy system

fusion triple product $nT\tau \geq 6 \times 10^{21}$ keV-s/m^3

Status of magnetic fusion

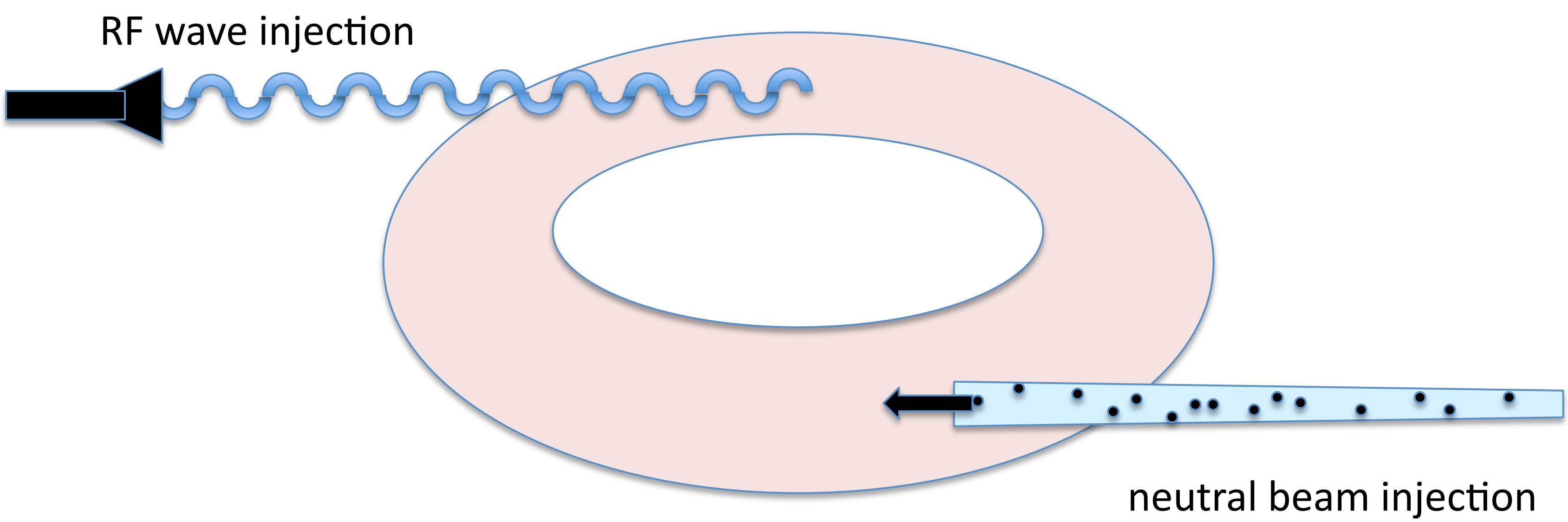
- Enabling discoveries (examples)

- Progress toward the fusion regime

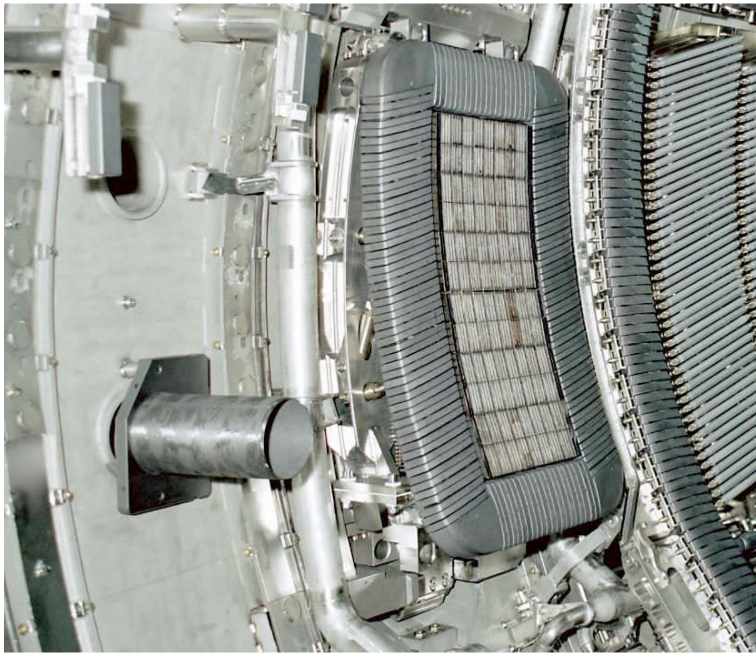
  High pressure, well-confined, steady-state plasmas

Heating a plasma to astronomical temperatures

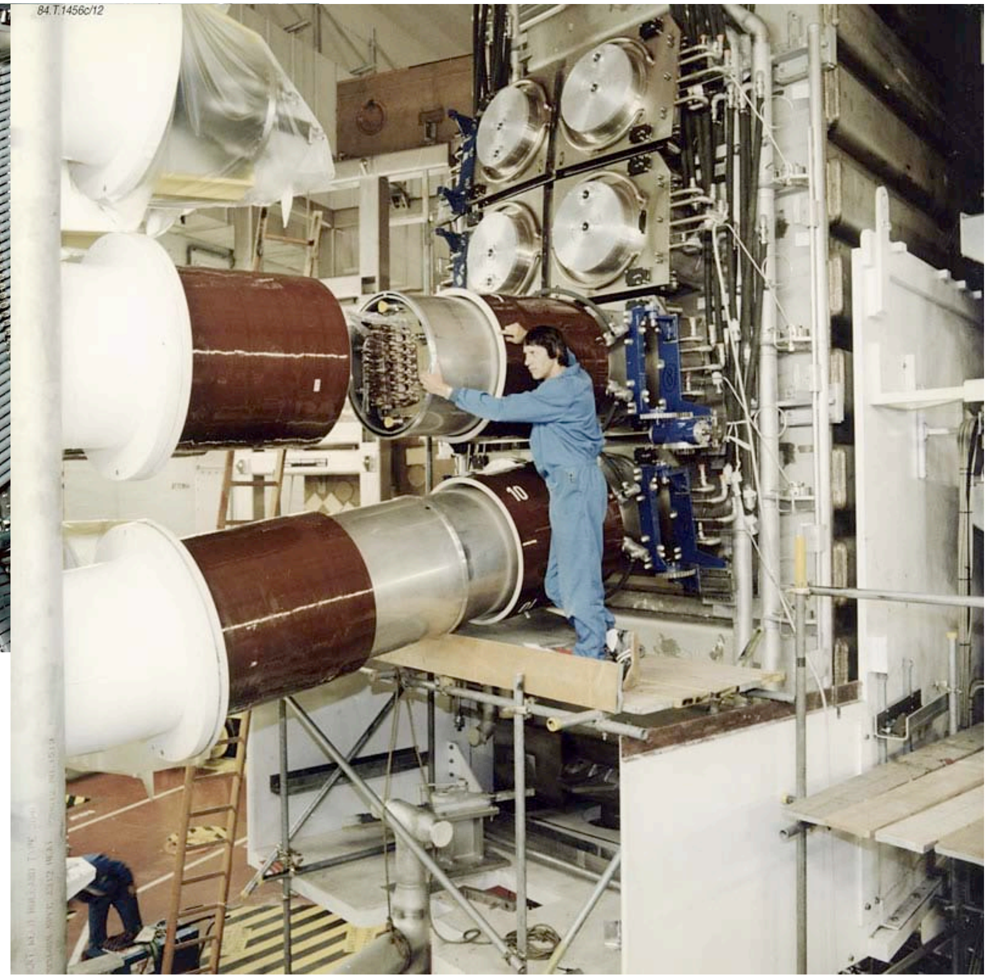
- injection of electromagnetic waves
- injection of fast neutral atoms



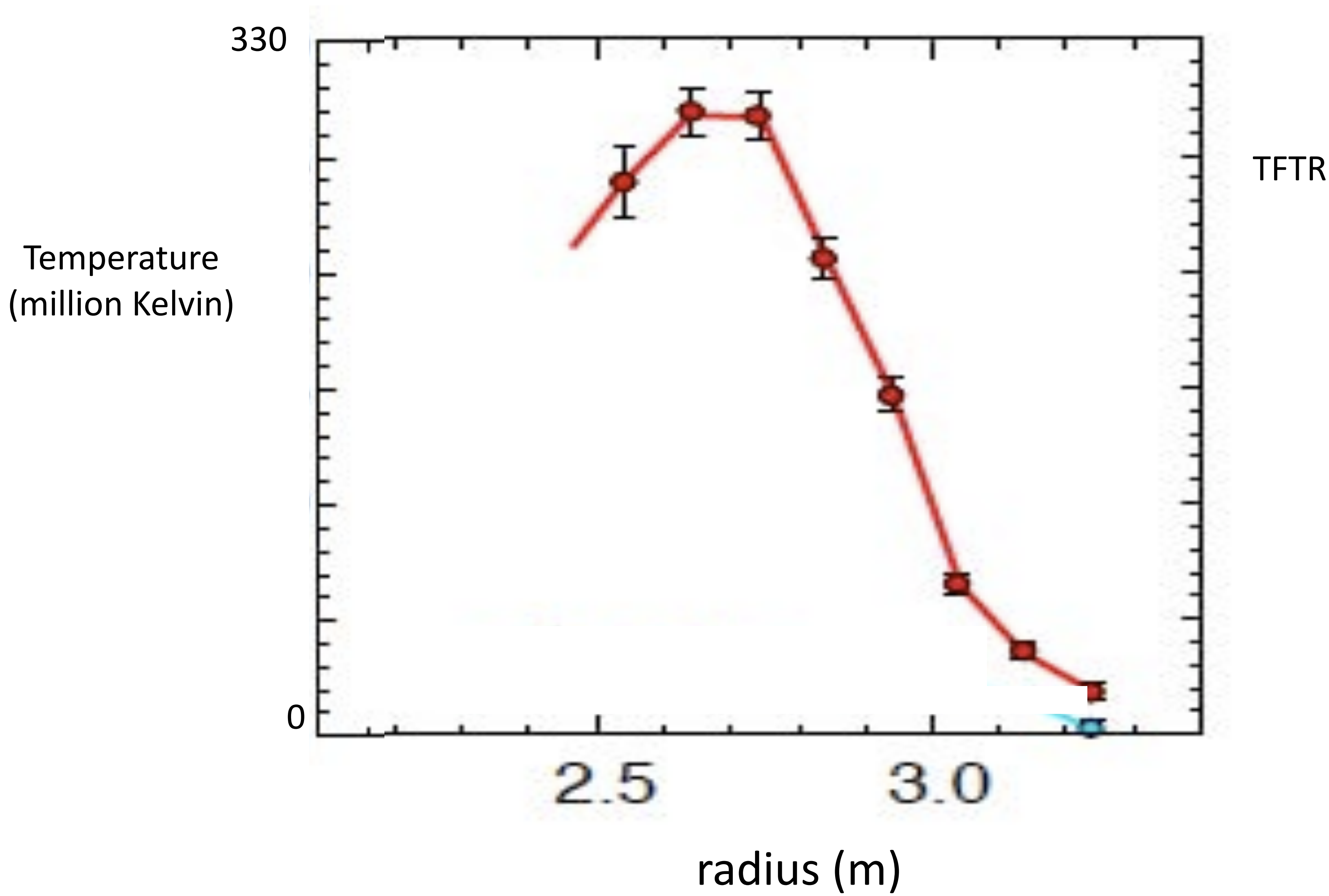
RF antenna



Neutral beam injector

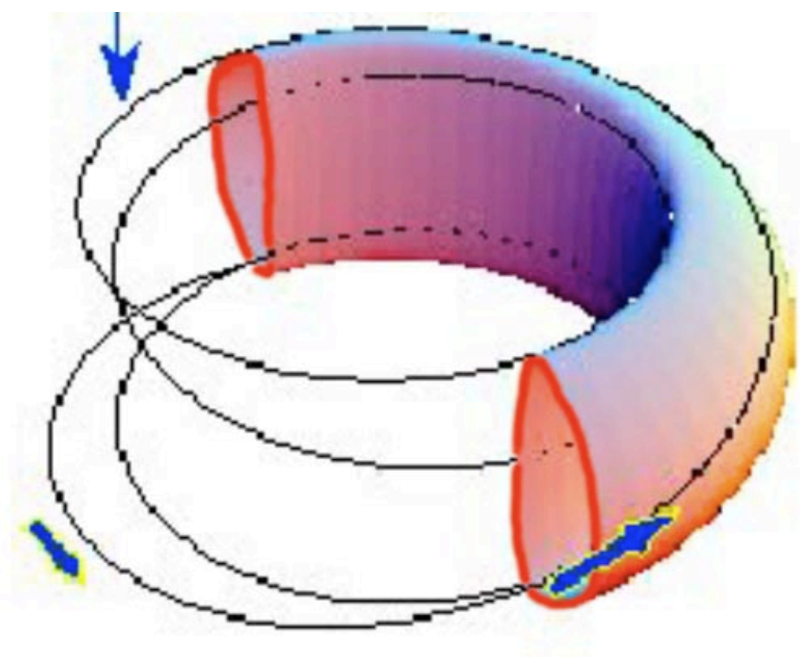


Plasmas produced with temperature ~ 300 million degrees



high pressure achieved by tailoring magnetic geometry

$$\text{figure of merit} = \frac{\text{plasma pressure}}{\text{magnetic pressure}} \approx \frac{\text{fusion energy}}{\text{cost}}$$



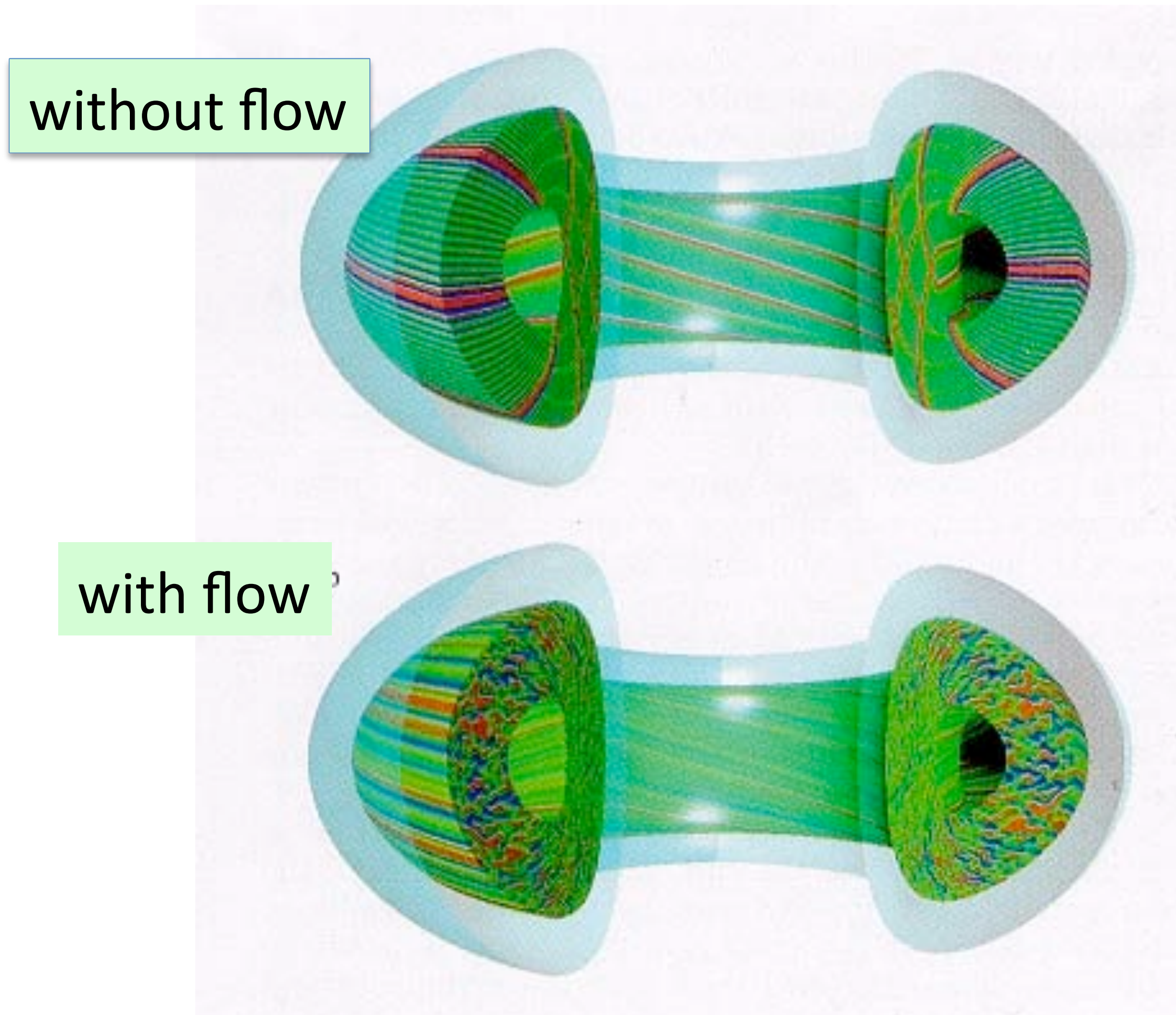
achieved figure of merit > 5%

sufficient for reactor

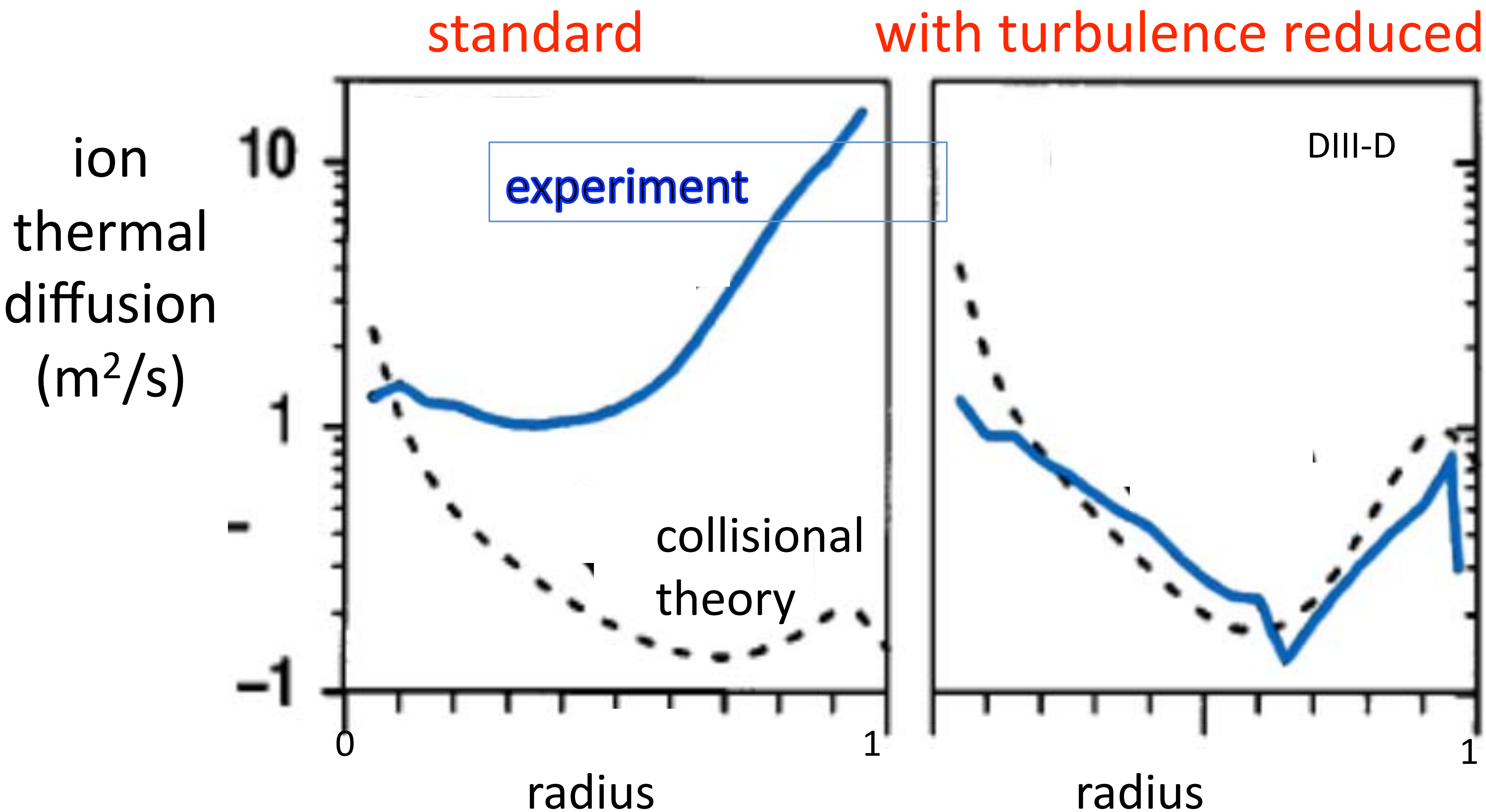
Obtaining high gain: suppressing turbulent transport

Can now calculate energy transport from turbulence

turbulence reduced
by plasma flow
(computation)



Ion transport reduced to minimal collisional level

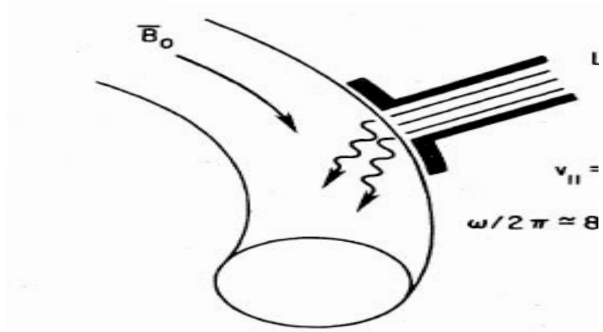


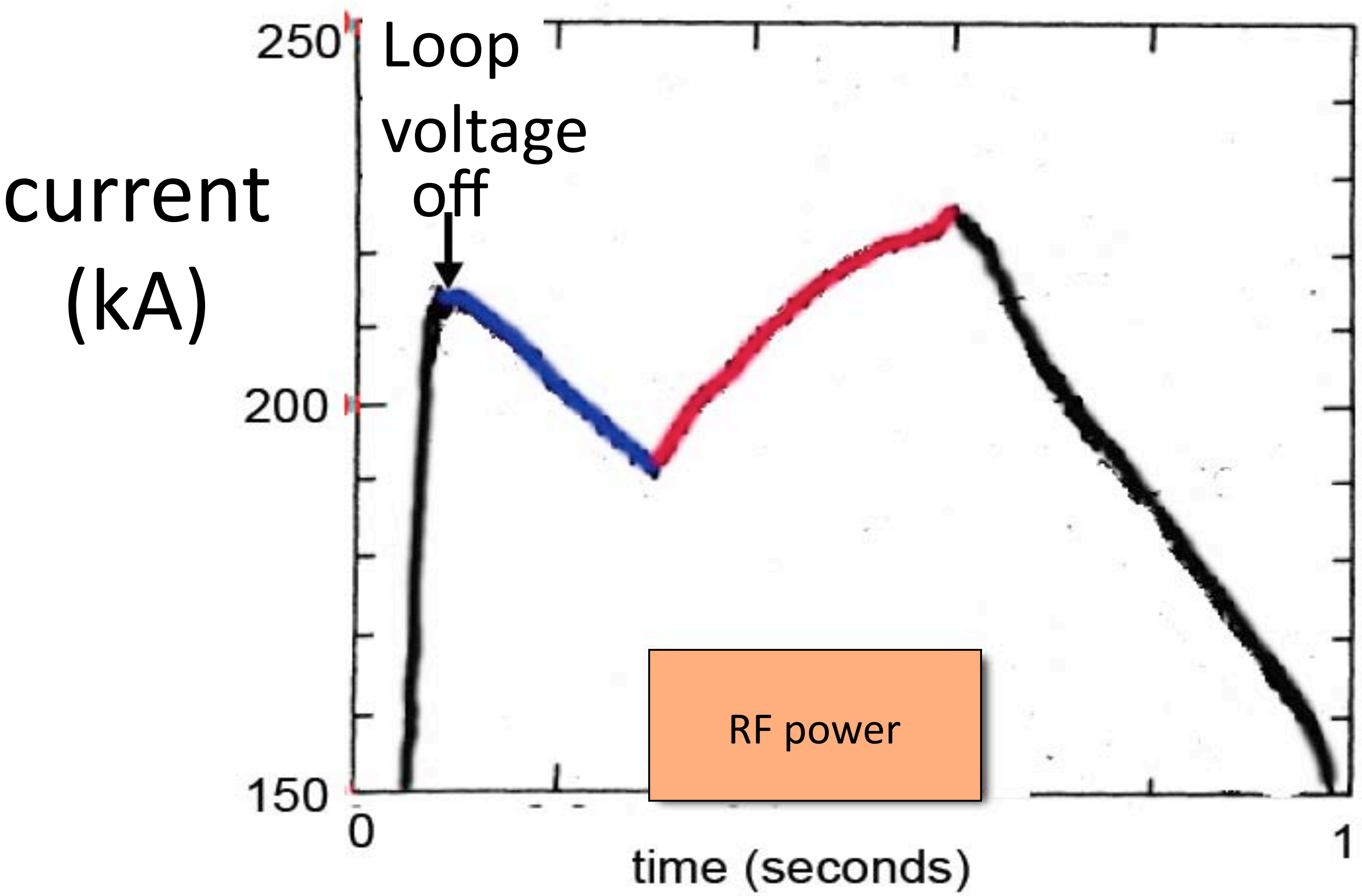
Sustainment of plasma current

magnetic field in a tokamak is partly produced by plasma current

- Current drive by waves
- Self-driven “bootstrap current”

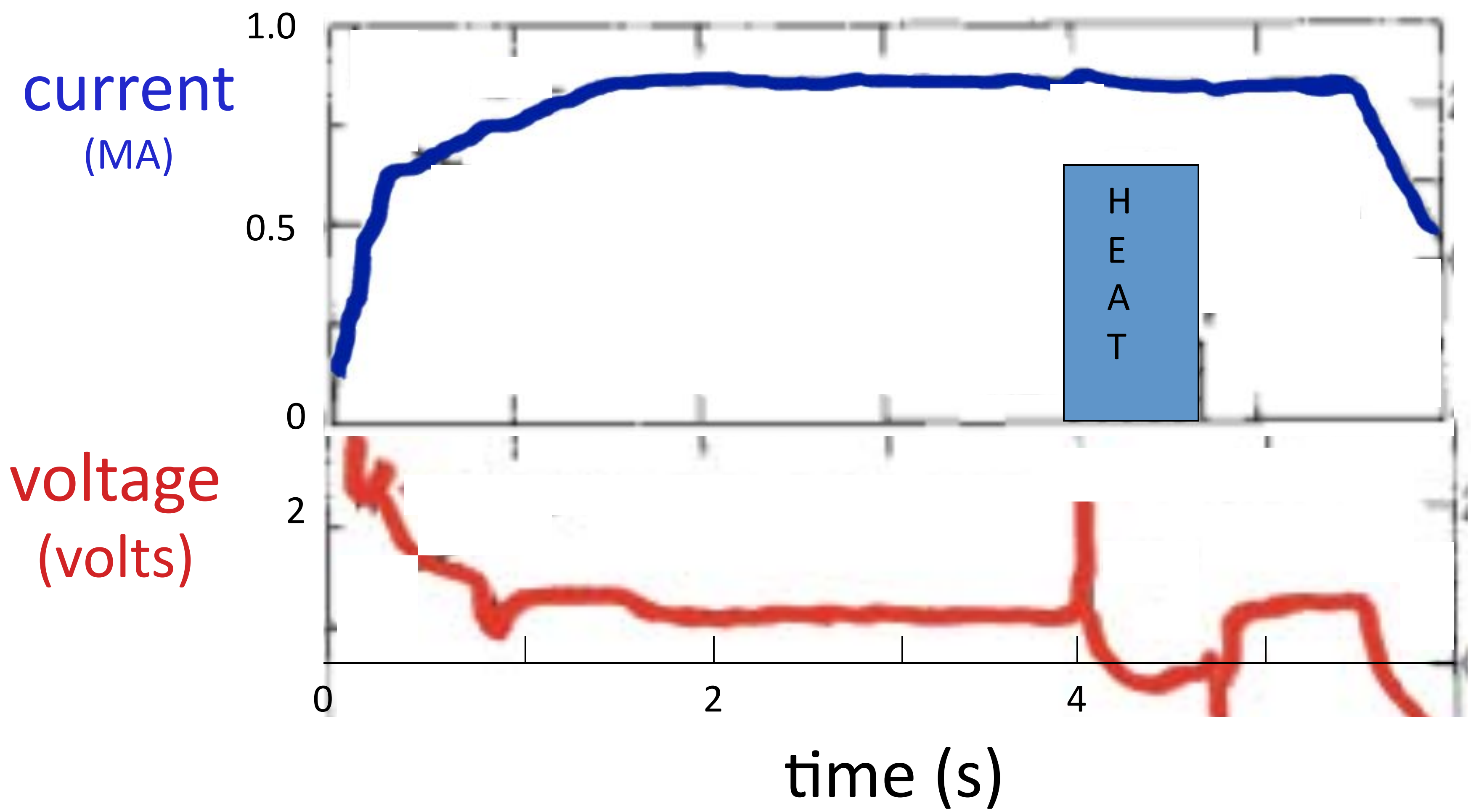
Wave-driven parallel currents





PLT

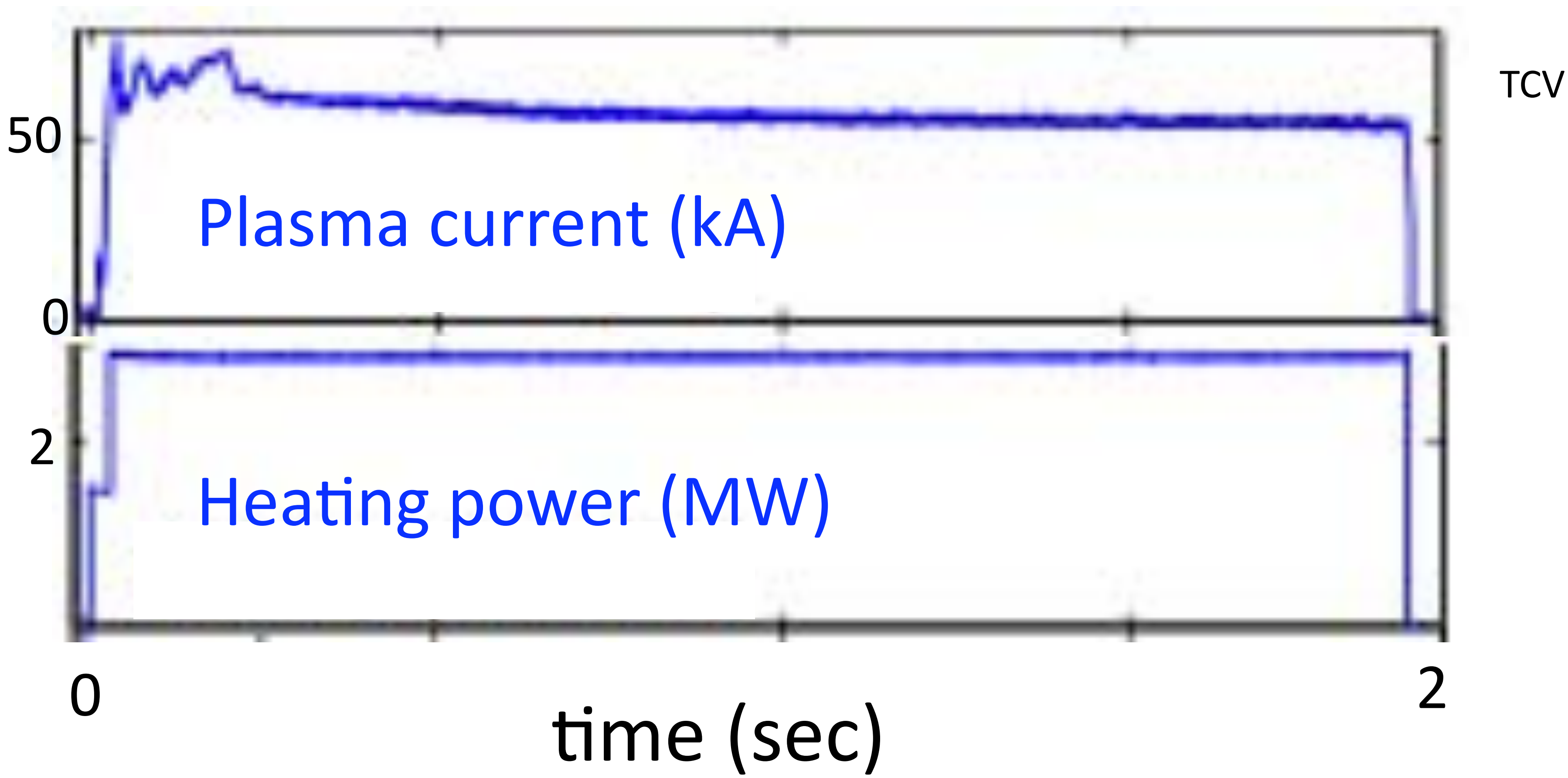
Steady state possible via current driven by plasma pressure



TFTR

Steady state possible via pressure-driven current

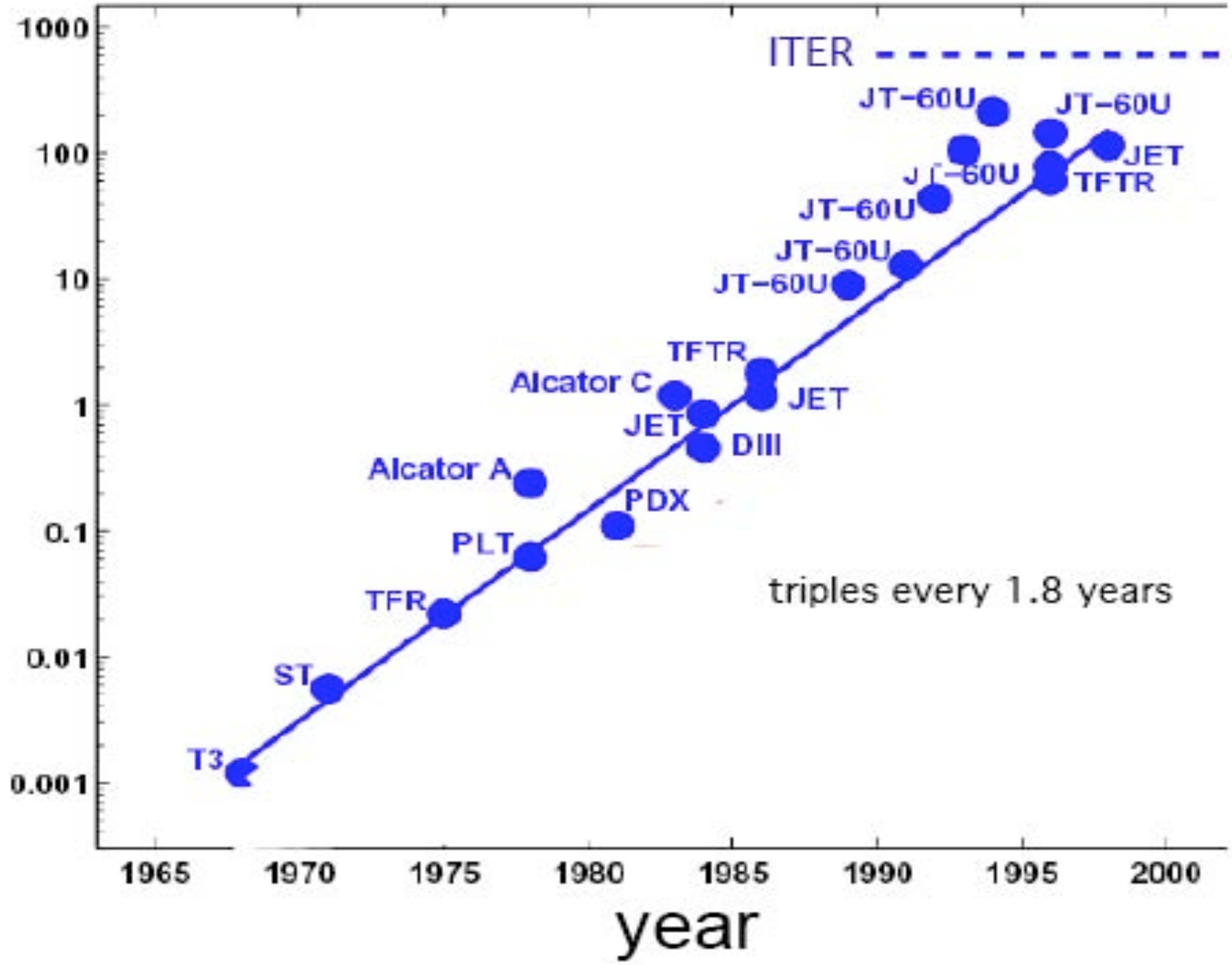
(voltage = 0)



Progress in the fusion triple product

fusion triple product

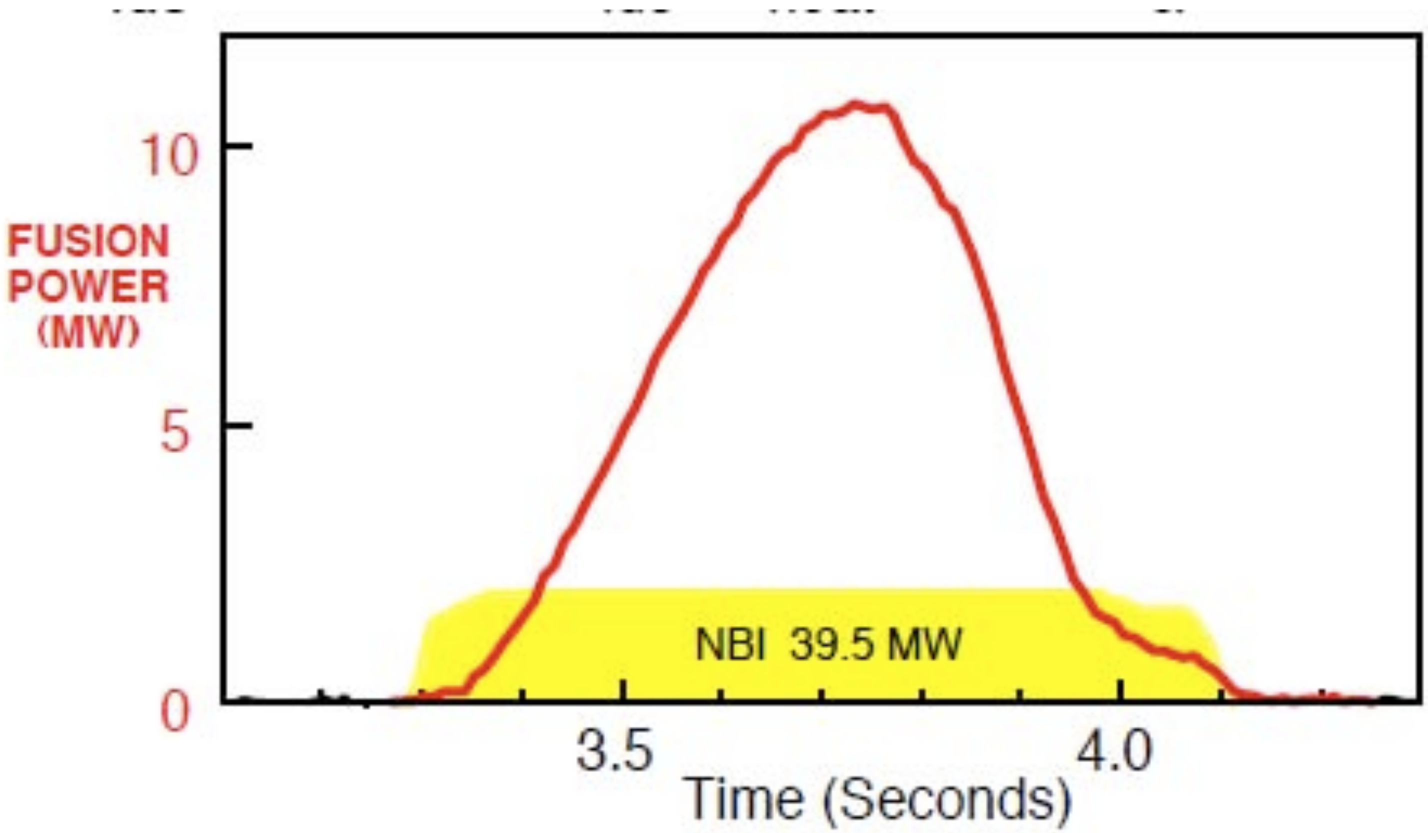
$nT\tau$



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

We have produced fusion energy

10 MW in 1994

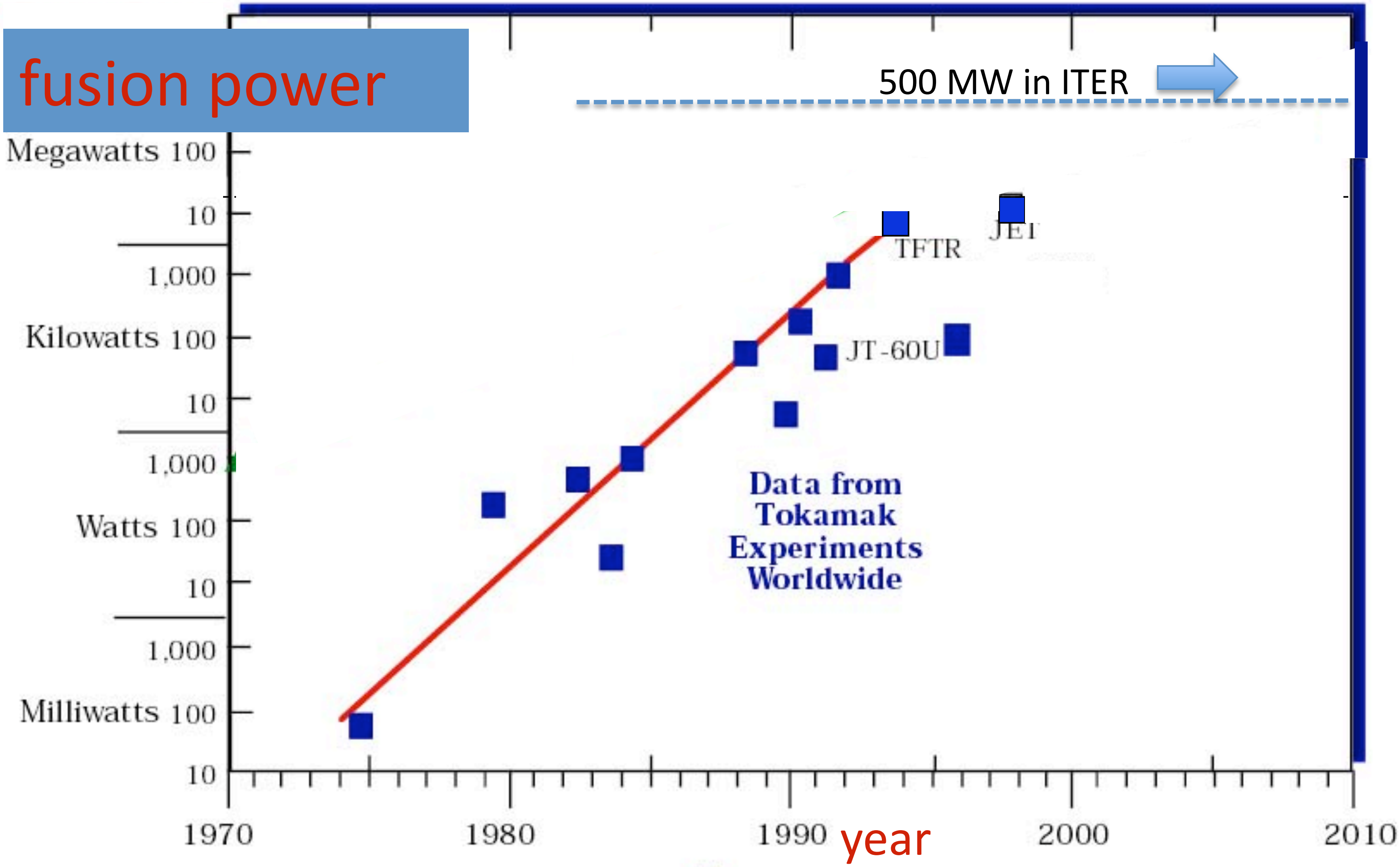


TFTR

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

ITER will produce 10^5 – 10^6 MJ per pulse

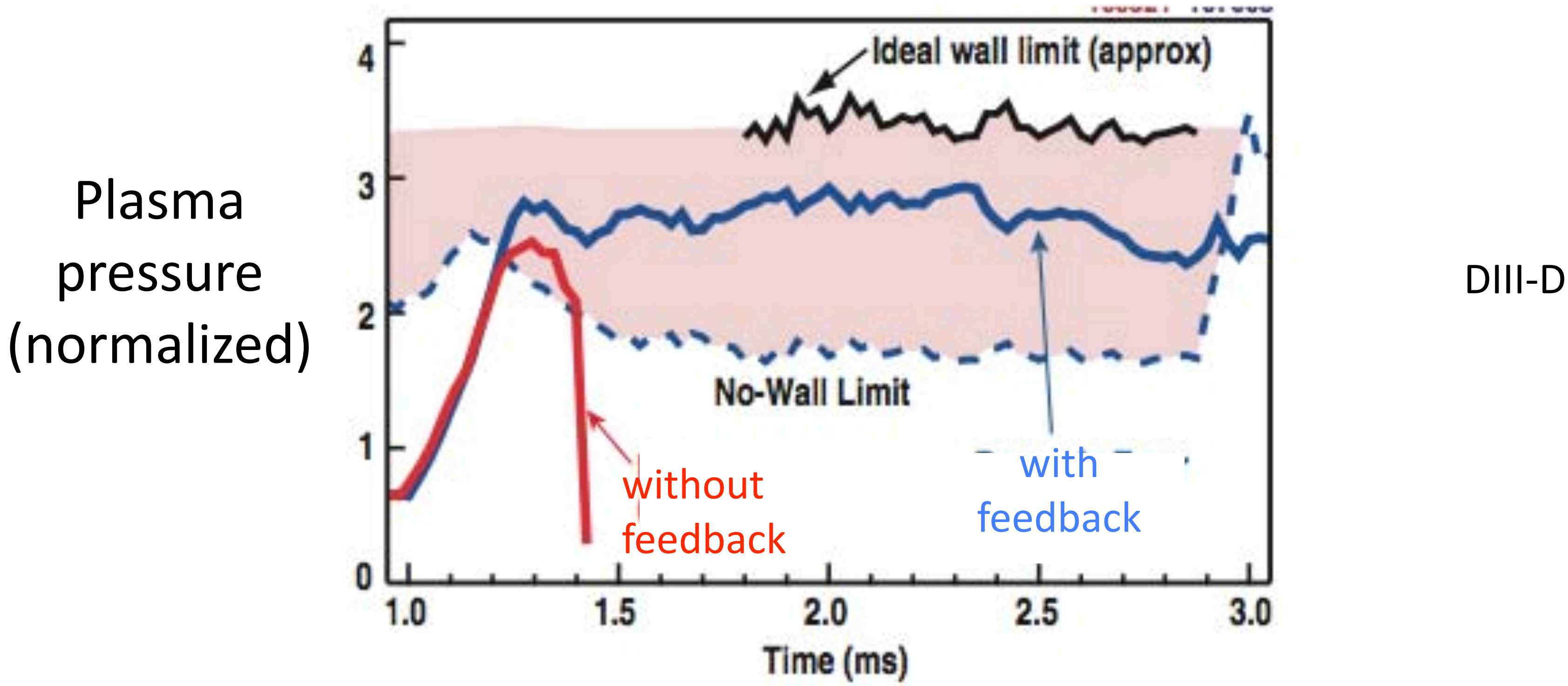
huge advance in fusion power



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

The challenge of steady state tokamaks

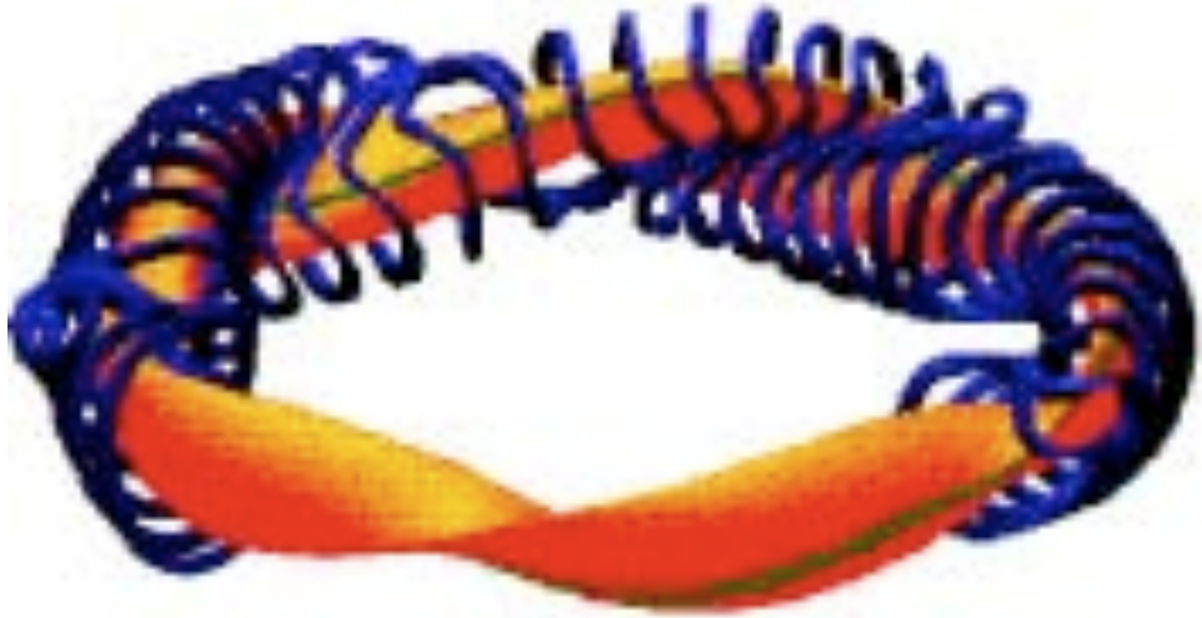
- Must sustain current (via bootstrap current)
- Need to avoid disruptions (sudden terminations of plasma)



Disruption strategy: avoid, actively control or mitigate effects

3D systems for disruption-free, steady-state

complex magnets



No current needed - only magnets
Steady-state,
No disruptions
"stellarators"

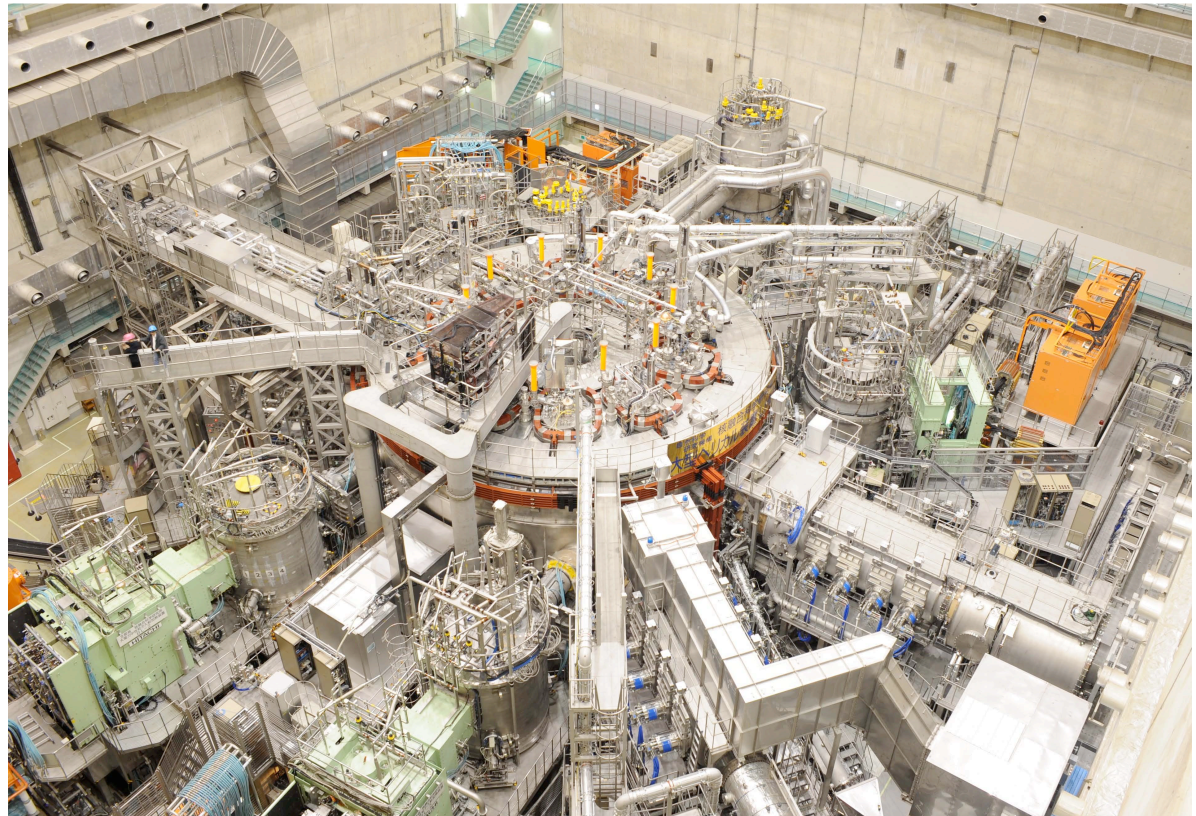
<u>Large Helical Device (LHD)</u>

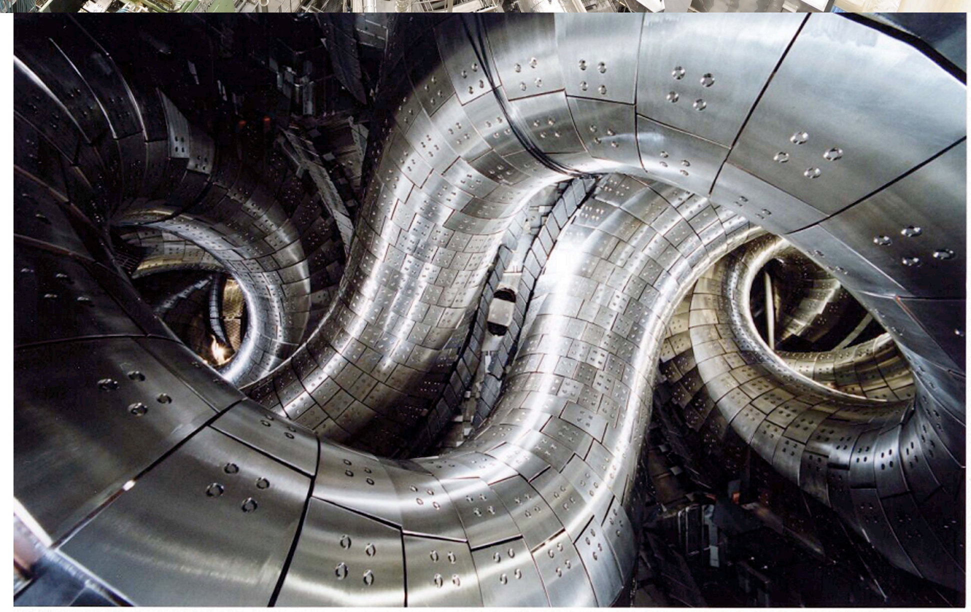
Operating in Japan

Superconducting

One hour pulses

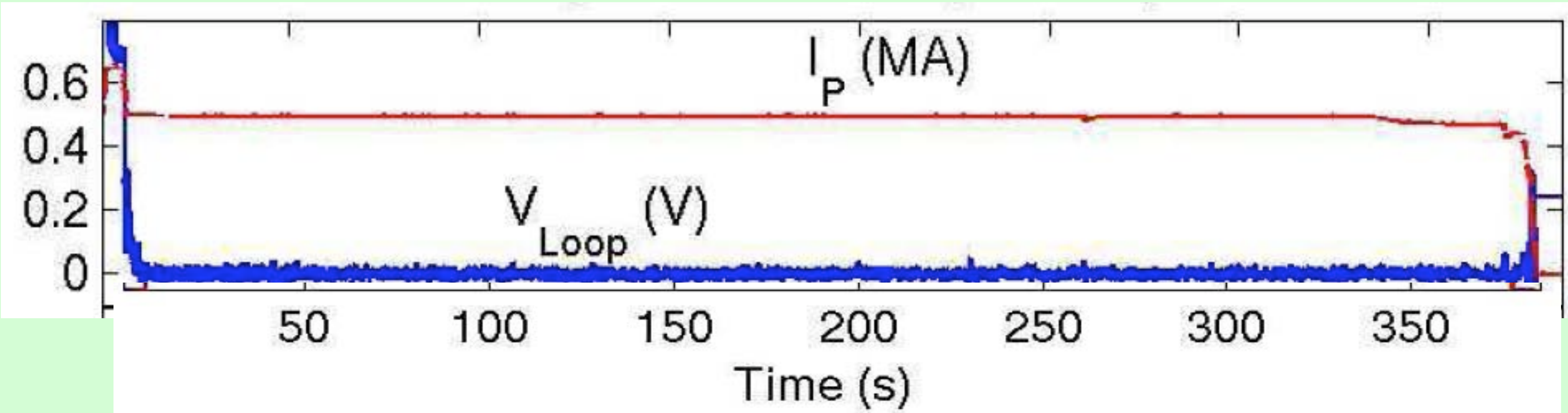
No disruptions



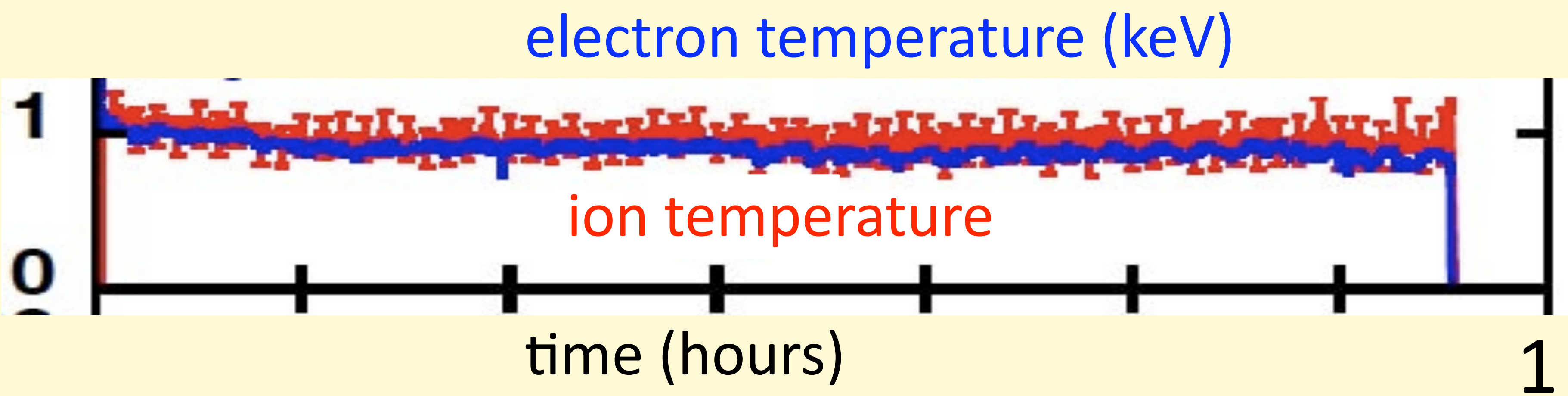


Sustainment

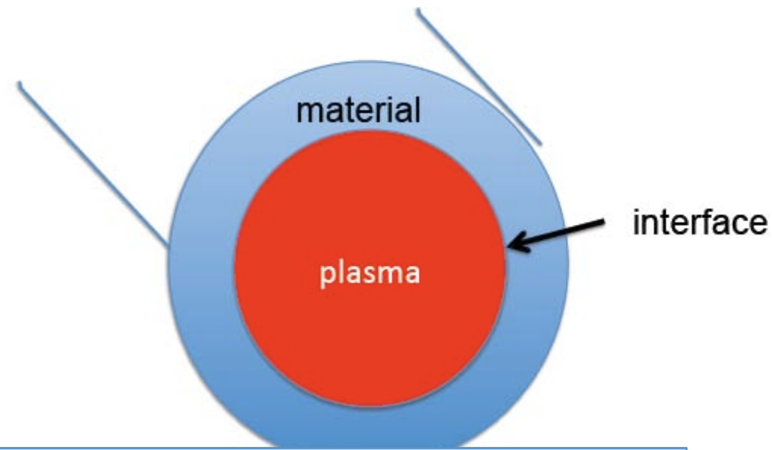
Tore Supra tokamak (6 minutes)



LHD stellarator (1 hour)



Fusion Challenges



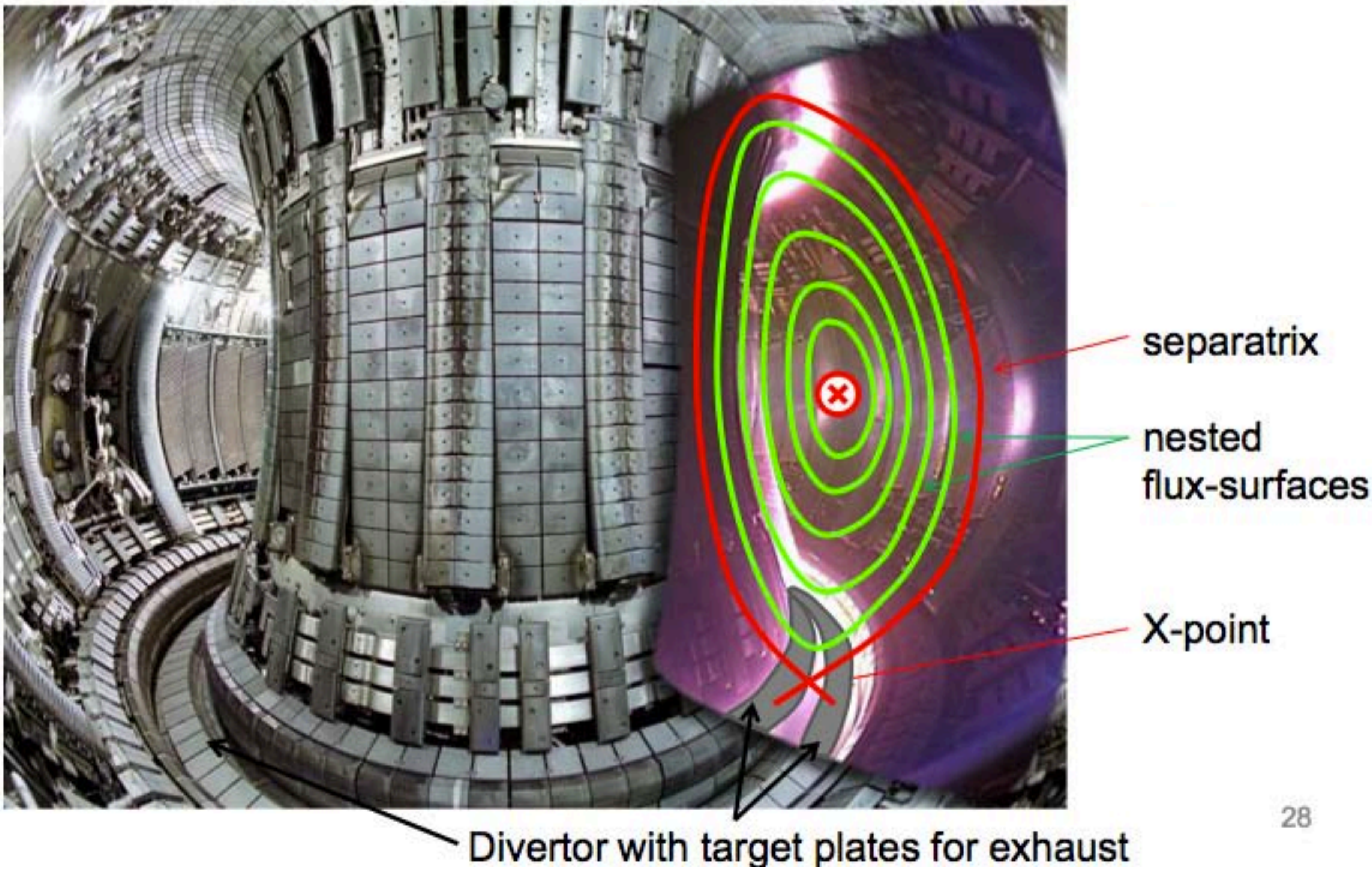
- Plasma confinement and control
  - burning plasma
  - steady-state plasma

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)

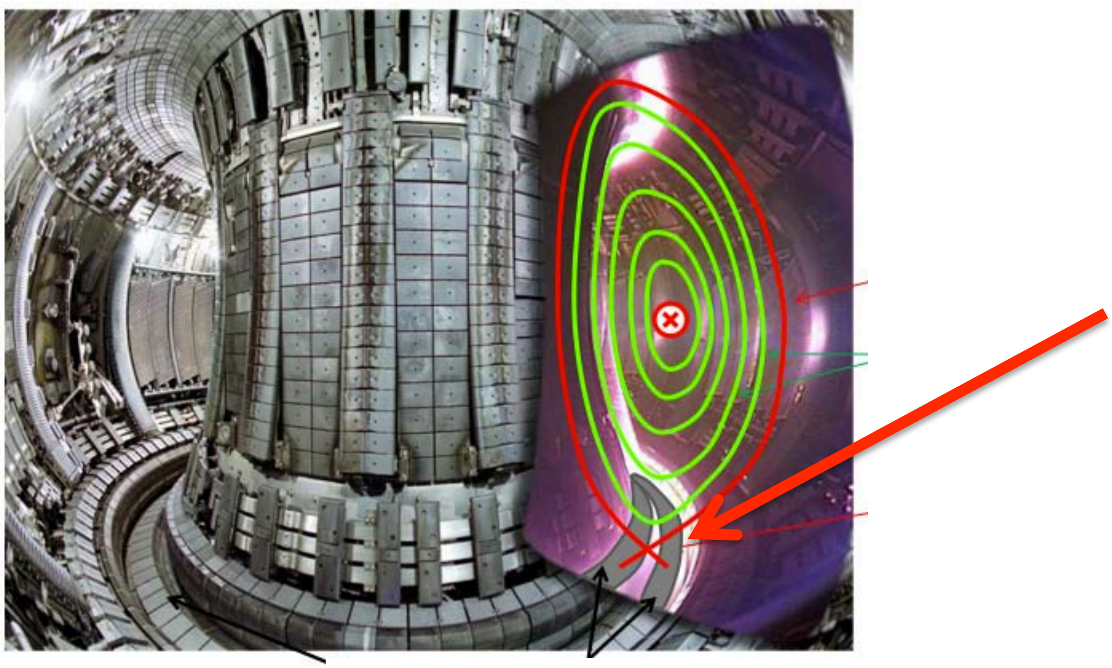
The divertor concept



The plasma-material interface

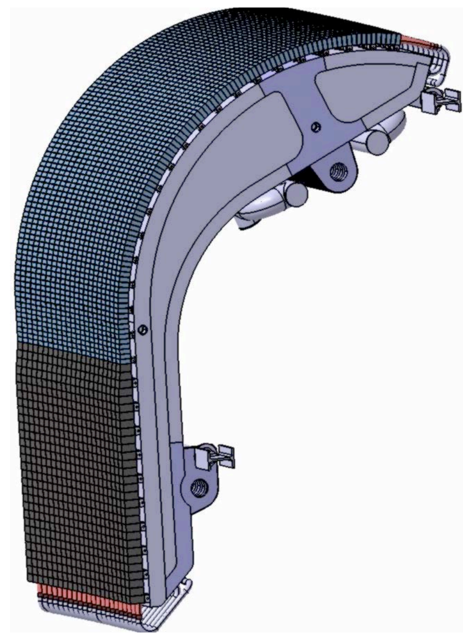
The divertor concept

Magnetically controlling the plasma exhaust



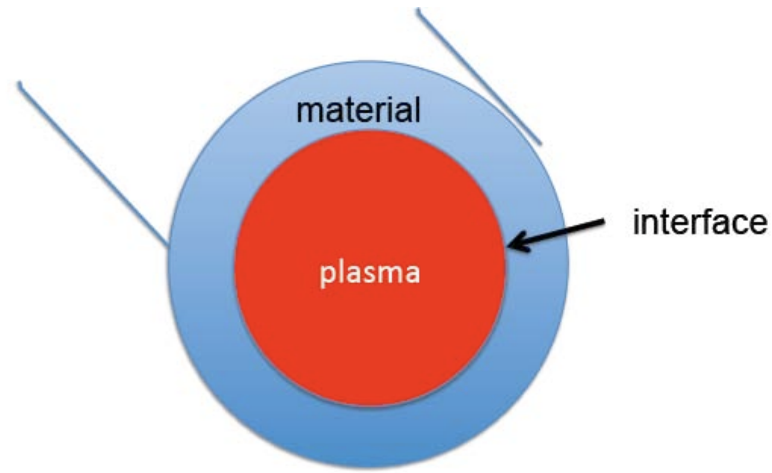
Tungsten plate

~ 10 MW/m^2



Operates successfully in existing short-pulse experiments

Fusion Challenges



- Plasma confinement and control
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Harnessing fusion power (fusion nuclear science)
effects of neutrons on materials,
managing neutrons (tritium breeding, power extraction)

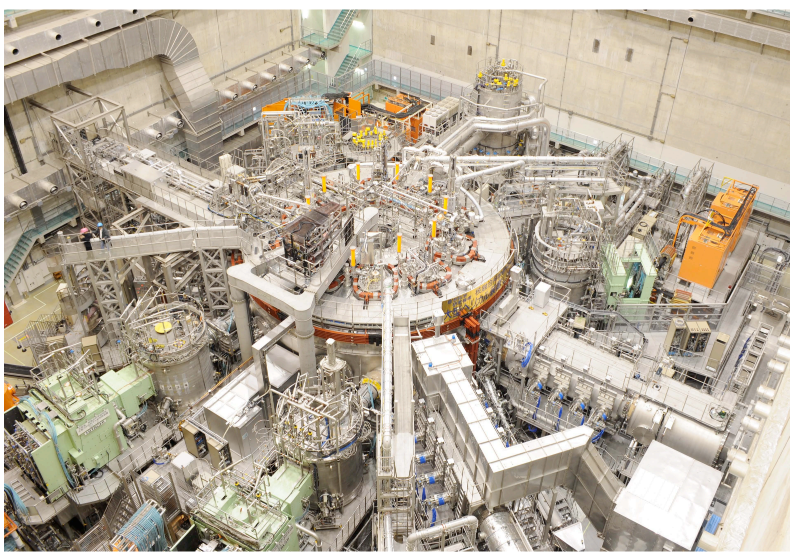
Concepts for low activation structural materials and breeders (liquid, sold) developed; awaits R & D and testing (following talks)

The escalating magnetic fusion activity across the world

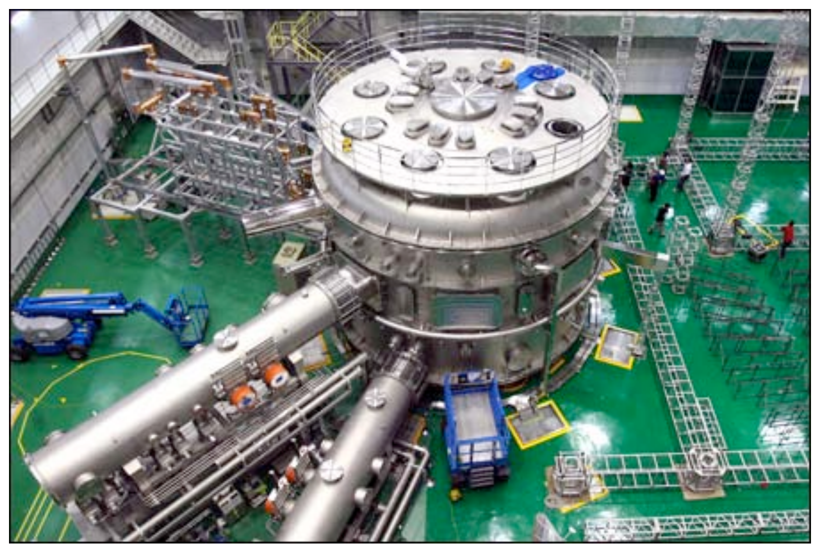
New major facilities

China: superconducting tokamak EAST

Japan: superconducting stellarator



Korea: superconducting tokamak KSTAR

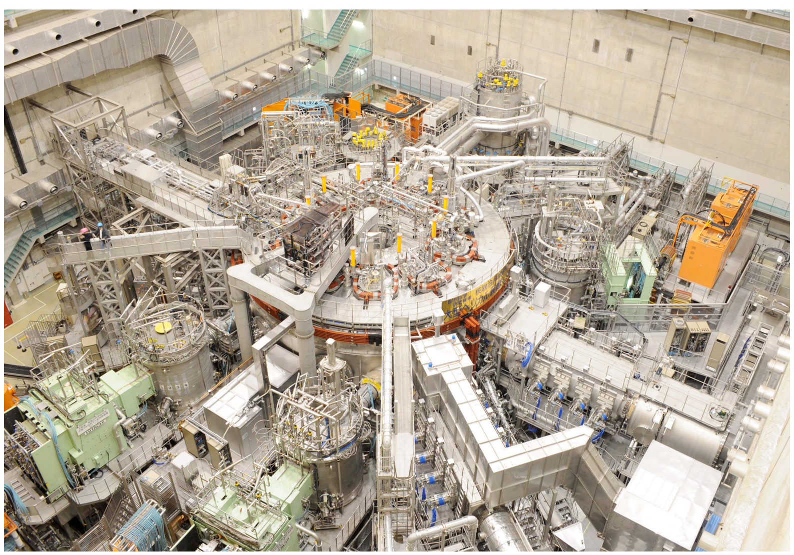


The escalating magnetic fusion activity across the world

England: JET tokamak

China: superconducting tokamak EAST

Japan: superconducting stellarator



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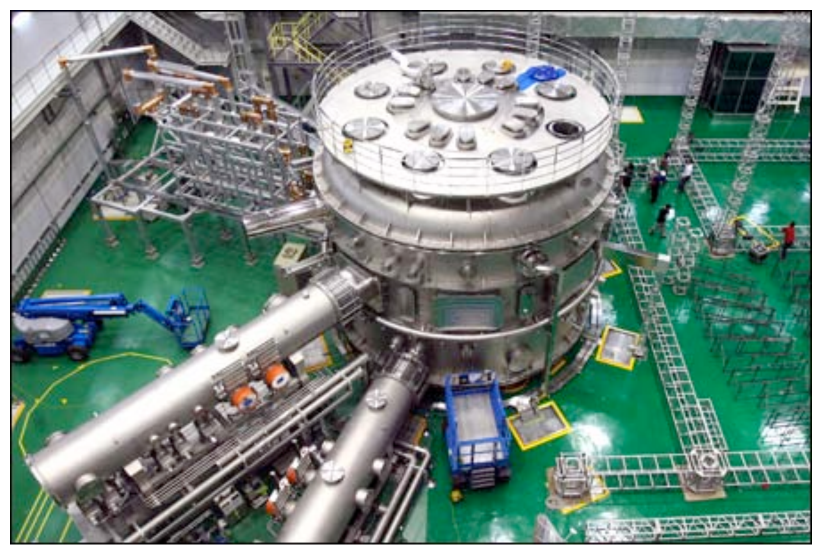
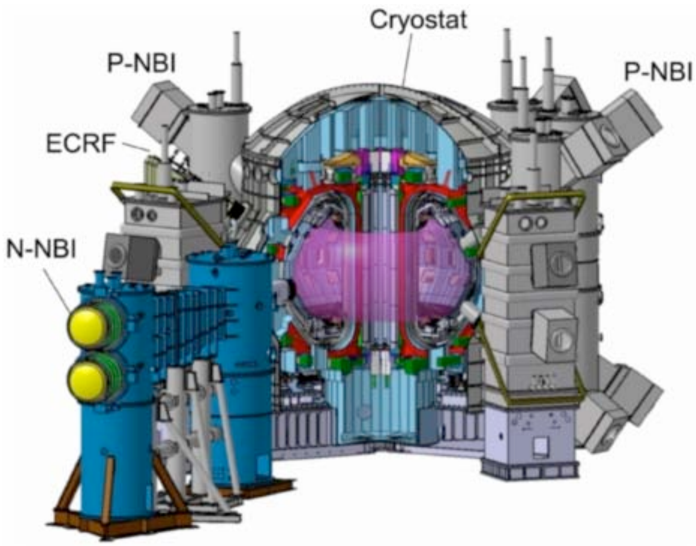
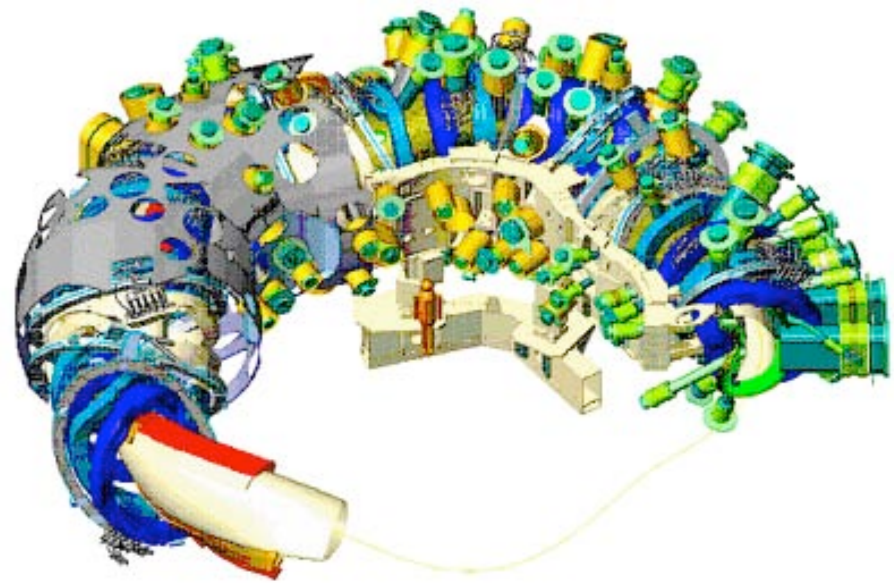


Major facilities under construction

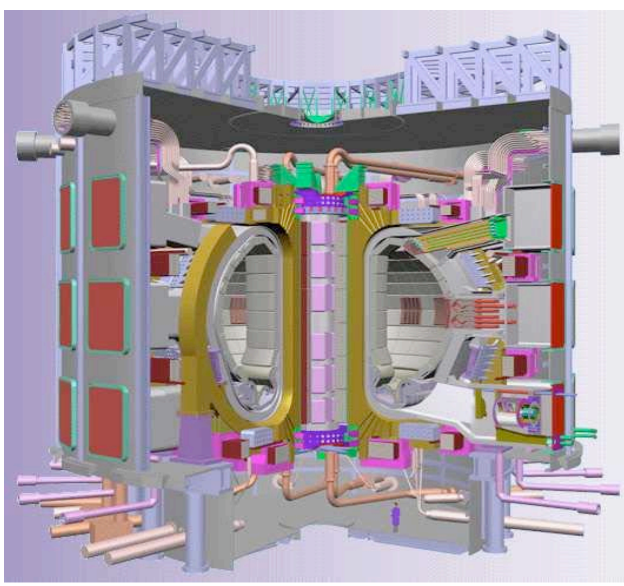
Japan: superconducting tokamak JT60-SA



Germany: superconducting stellarator W7-X



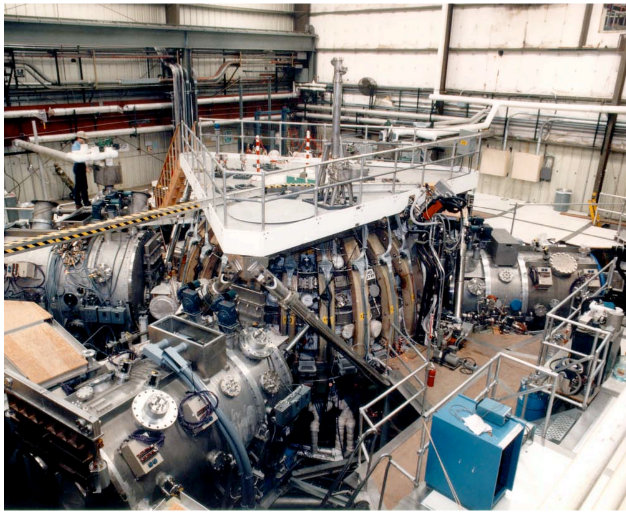
France: ITER



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

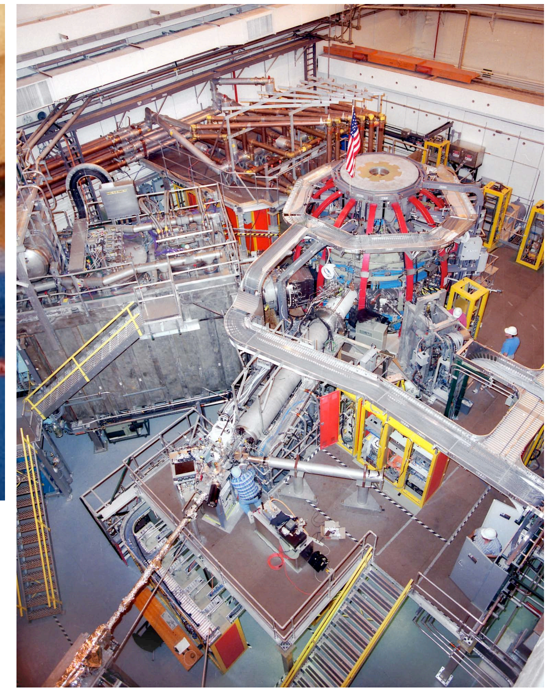
The US operates a strong set of medium-scale experiments

General Atomics: DIIID tokamak



MIT: CMOD tokamak

PPPL: NSTX spherical tokamak



- Performing world-leading fusion research for ITER and beyond
- However, in 10 years, the new facilities overseas will be more capable than the US facilities
- Ready to move to new facilities to attack remaining issues for fusion

To conclude,

- A strong scientific basis exists for MFE

- Progress enabled by development of plasma and fusion technology

- Plasma conditions have been produced near the regime for energy production

  temperatures needed for fusion achieved
  pressure needed for fusion achieved
  confinement is will be validated in ITER
  entering the steady-state era with new superconducting facilities

  fusion power has been produced (16 MW, 1 sec),
  safely operated with DT
  large, complex fusion facilities operated successfully

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We are technically ready to shift to an energy development program to make fusion energy a reality