The Path to Magnetic fusion Energy

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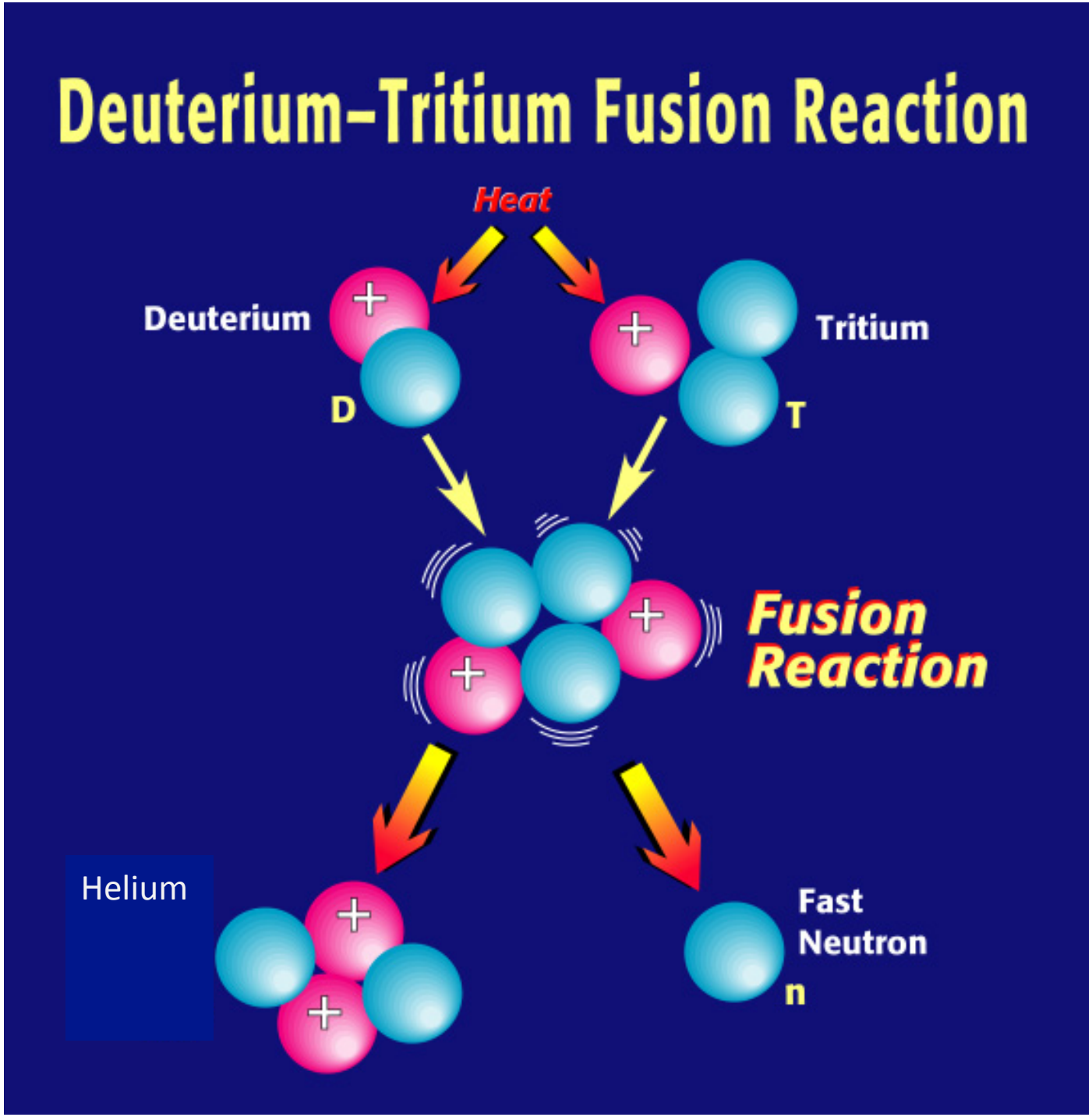
Outline

- Fusion: how it works
- Progress and status
- ITER
- The remaining path to fusion on the grid


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

The fusion reaction

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

10 keV 10 keV 3.4 MeV 14 MeV

The fusion reaction

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

10 keV 10 keV 3.4 MeV 14 MeV

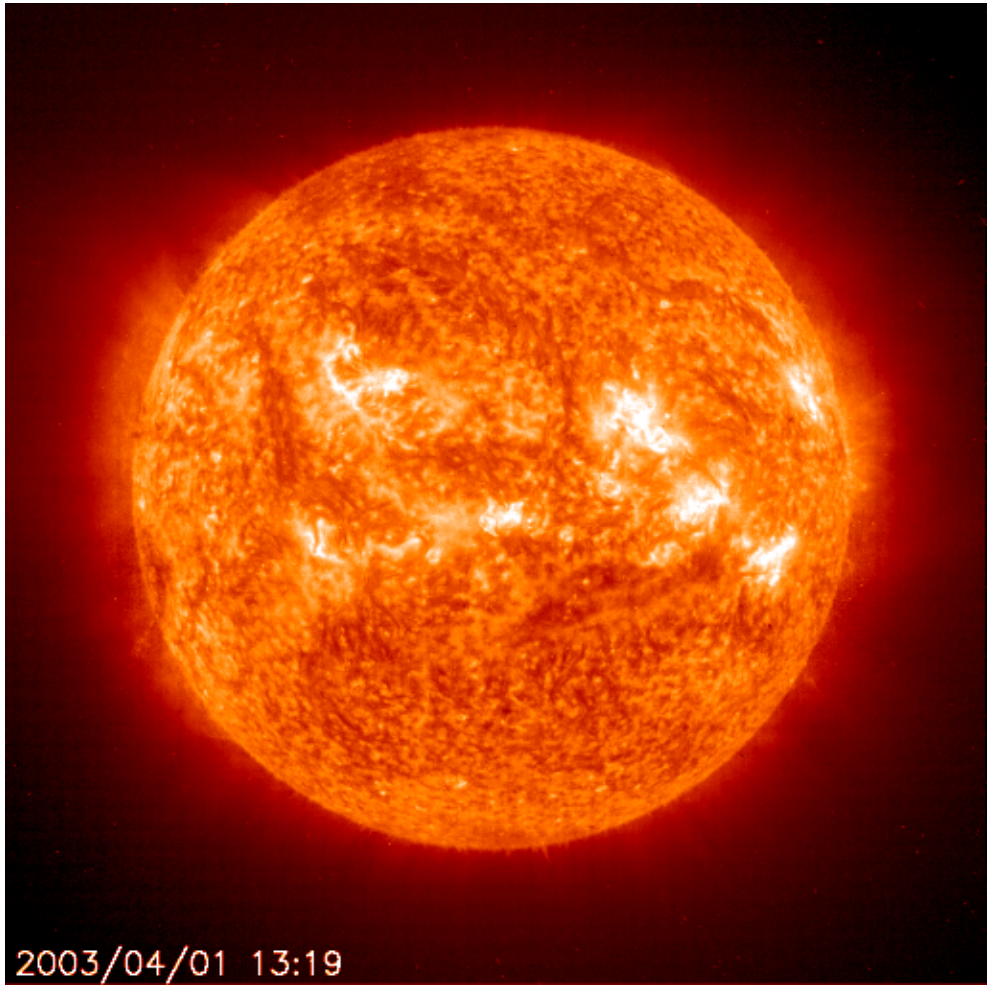
Large energy multiplication,

products of reaction are harmless,

Must smash particles together at high speed to overcome electrical repulsion

Neutrons heat blanket surrounding plasma,
Heat converted to electricity by turbines

Fusion Plasma



Temperature

~ 1 keV in sun,

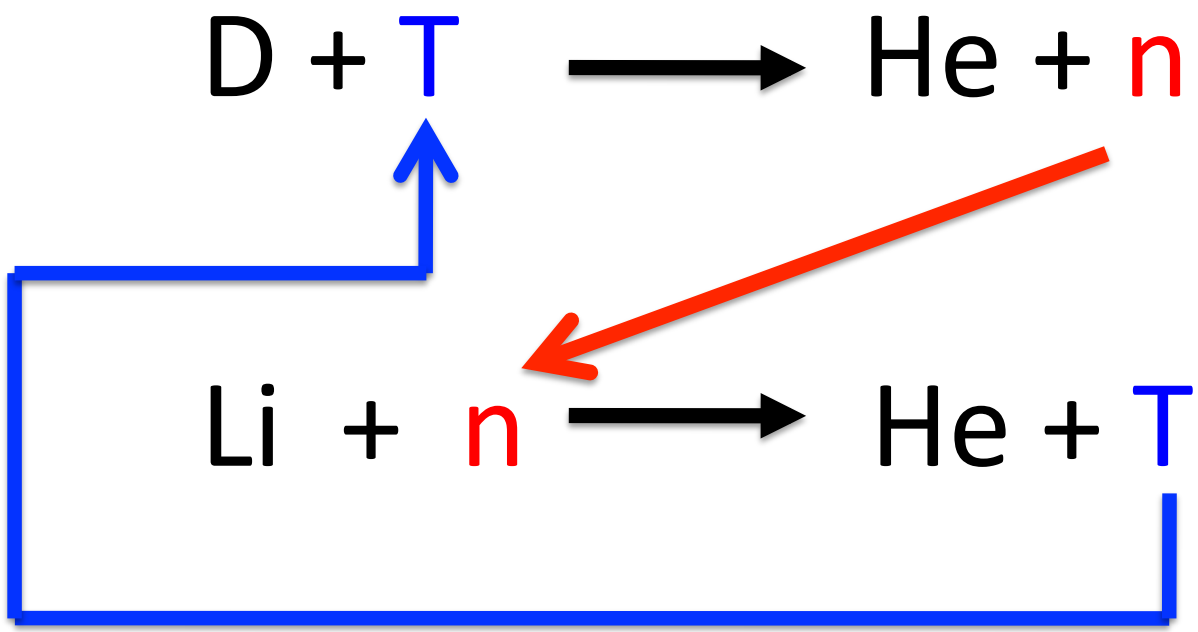
~ 15 keV in fusion reactor

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

In fusion laboratory plasma ~10 MWatt/cubic meter

Tritium is bred in the fusion reactor

Breeding blanket: neutrons bombards lithium to form tritium



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

The Fusion Physics Challenge

Confine plasma that is

hot

dense

well-insulated (high energy loss time)

in contact with a material wall

Fusion reaction rate $\sim \; n_D n_T \underbrace{\langle \sigma v \rangle}_{\text{function of temperature, T}}$

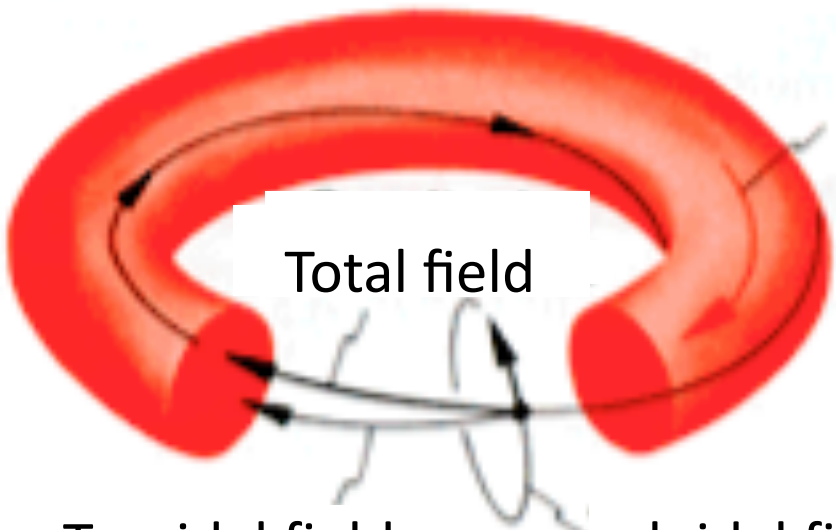
Energy confinement time $\tau = \dfrac{\text{Plasma thermal energy}}{\text{input energy}}$

Plasma requirement for fusion energy system

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

The Tokamak

Magnetic field is helical

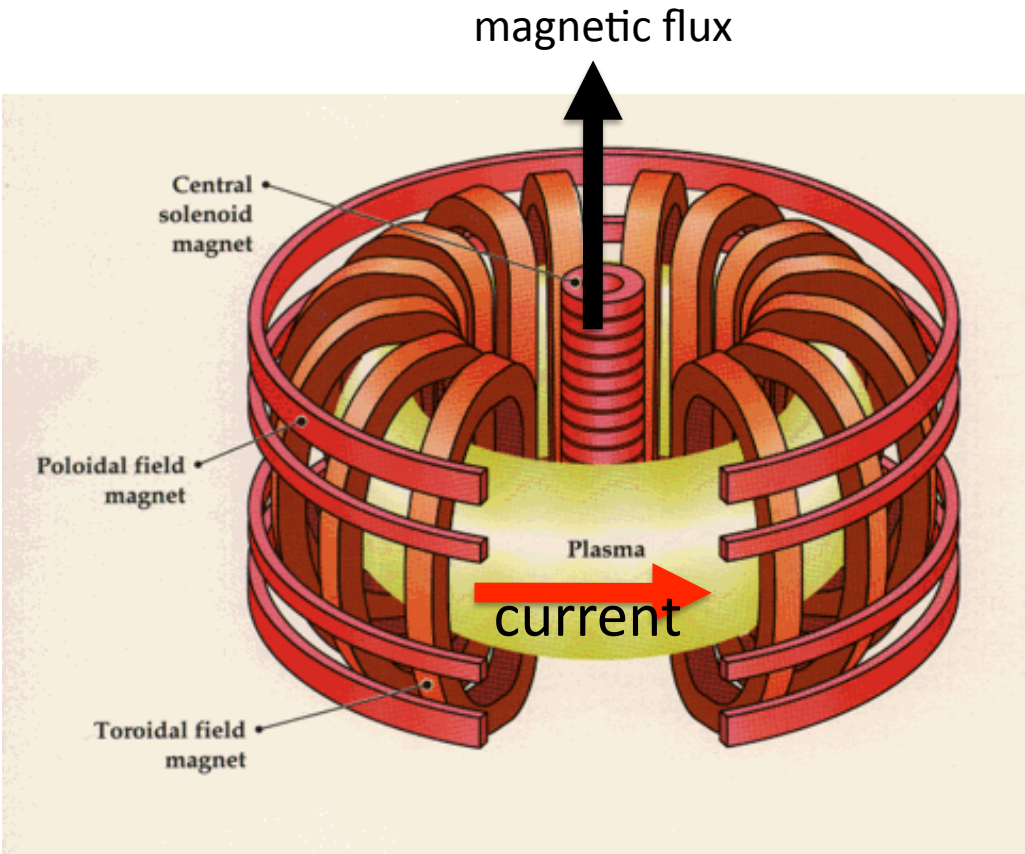


Toroidal field component → stability

poloidal field component → equilibrium

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

The tokamak



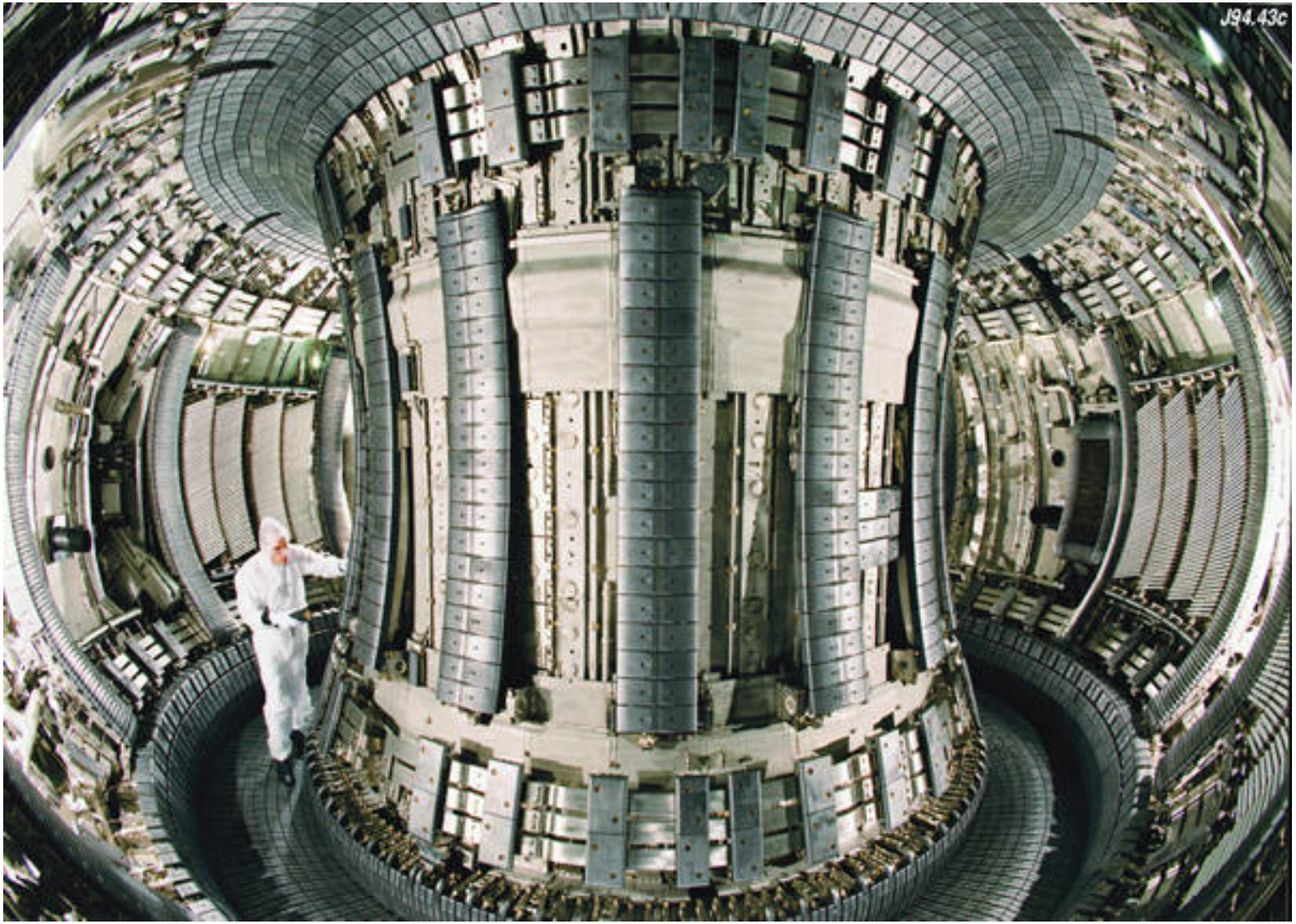
Magnets → $B_{toroidal}$

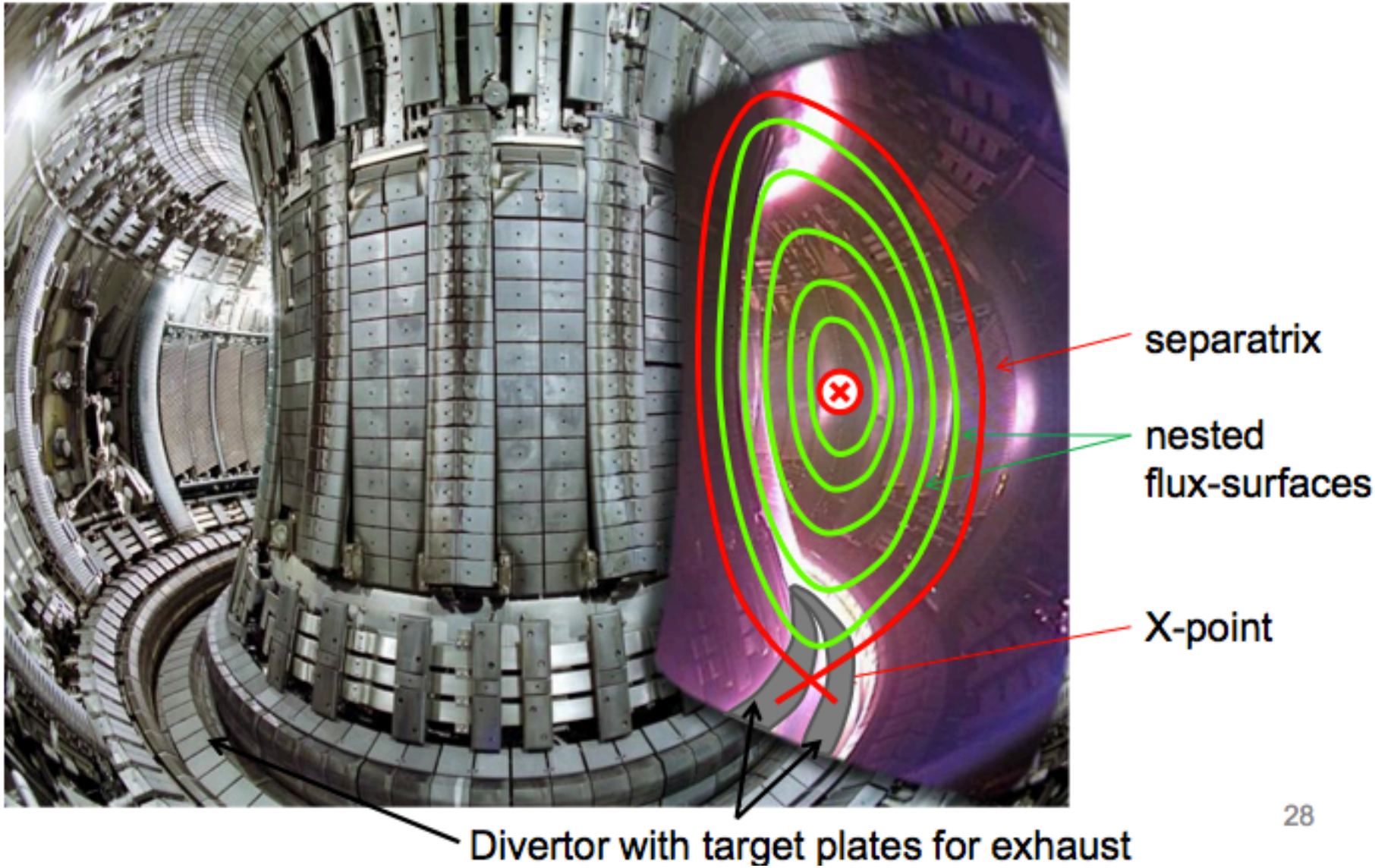
Plasma current → $B_{poloidal}$

Time-varying Magnetic flux → Plasma current

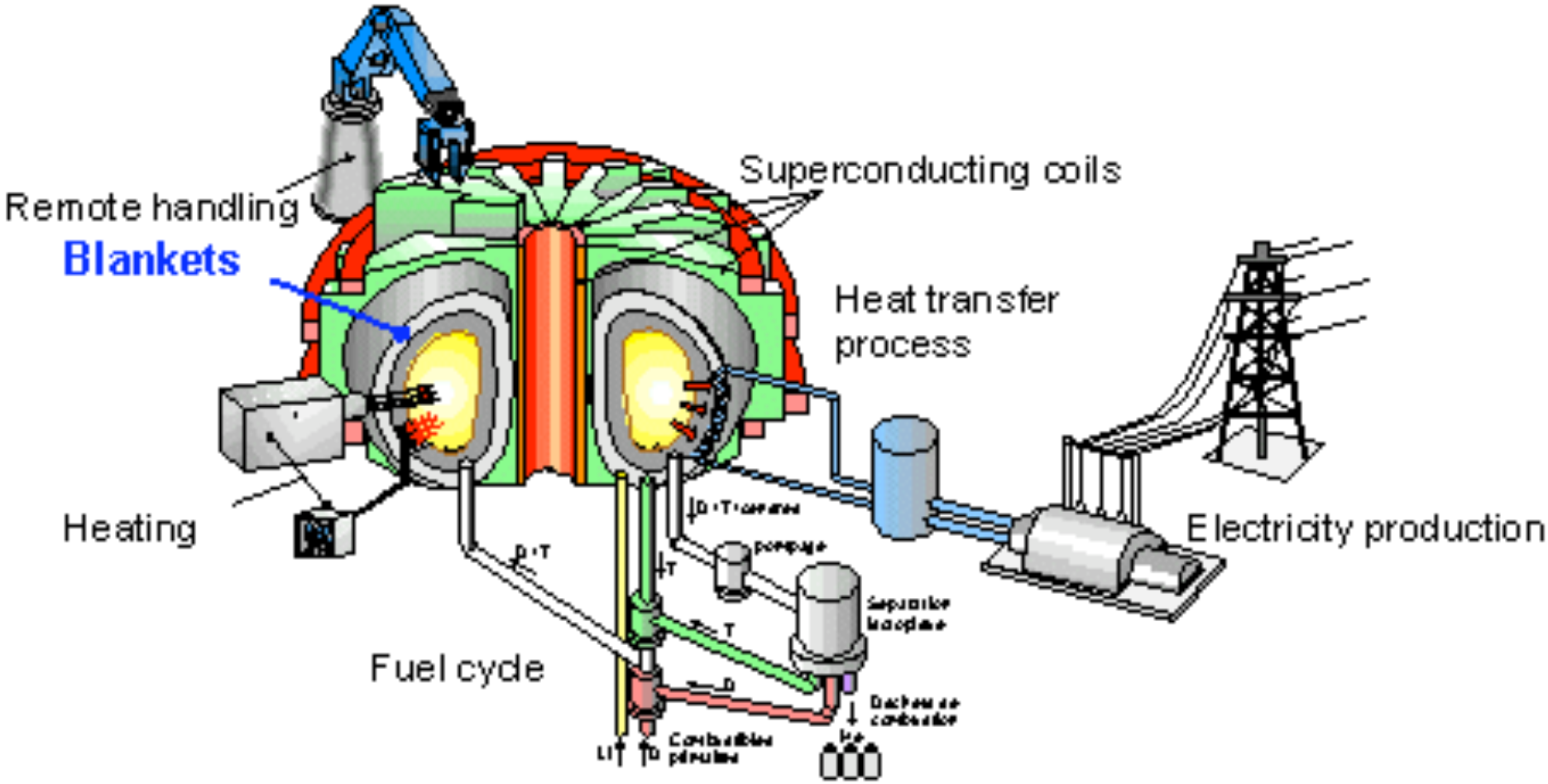
Inductively-driven tokamak is not steady-state

The largest tokamak (JET, England)




separatrix
nested
flux-surfaces
X-point
Divertor with target plates for exhaust

A fusion power plant



Status of magnetic fusion

- Enabling discoveries (examples)

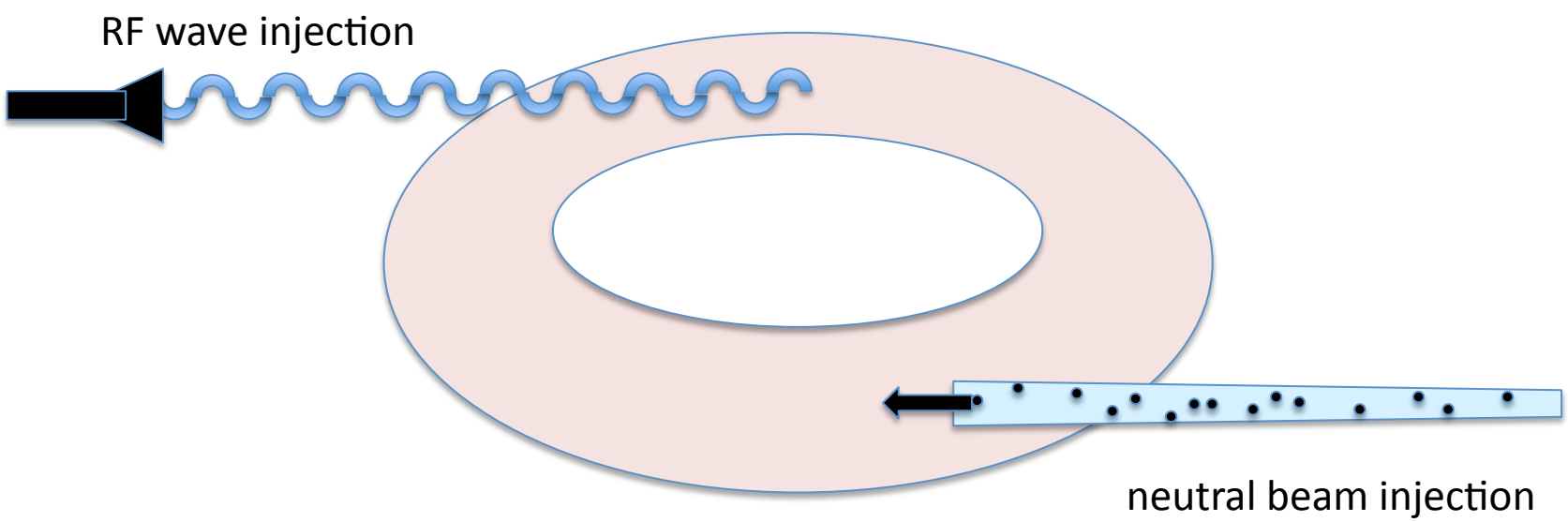
- Progress toward the fusion regime

Plasma requirements

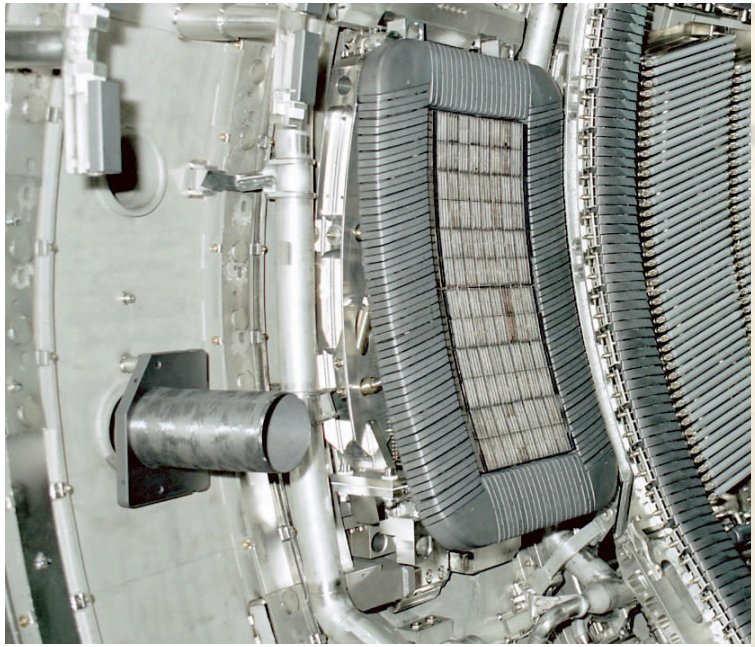
high pressure (fusion power),
high energy confinement (high gain),
continuous operation

Heating a plasma to astronomical temperatures

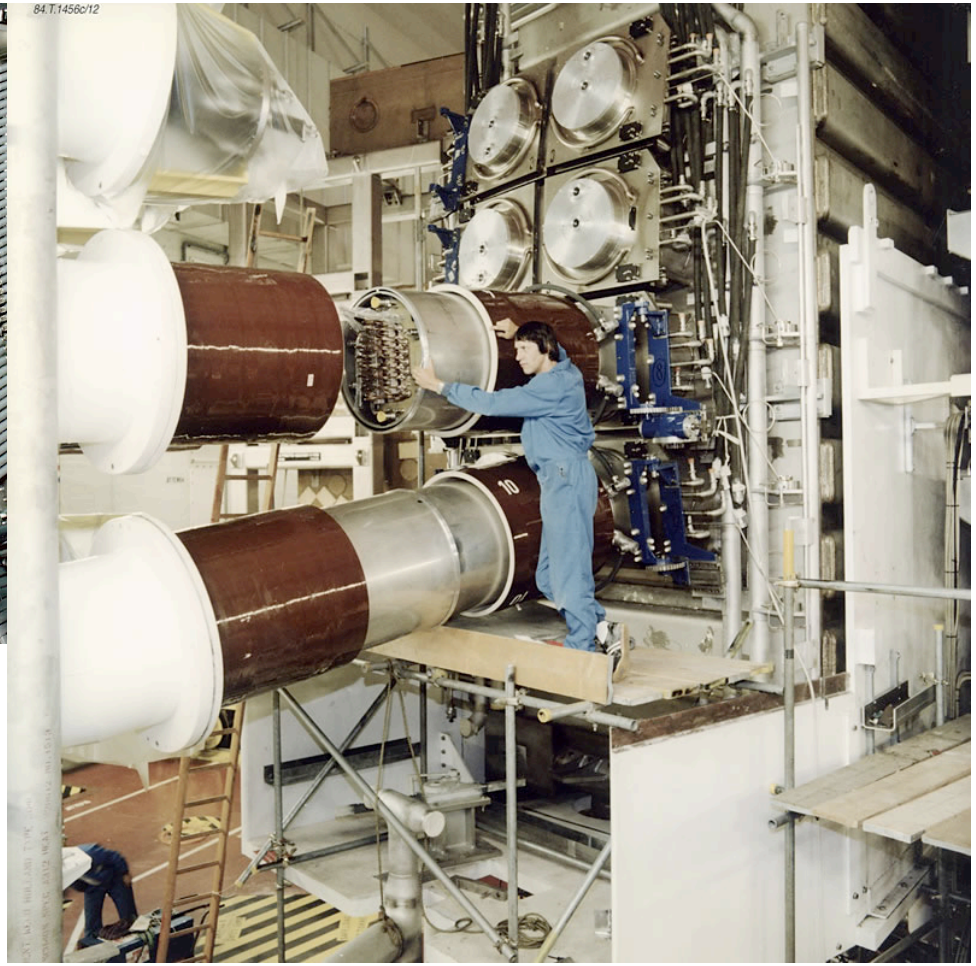
- injection of electromagnetic waves
- injection of fast neutral atoms



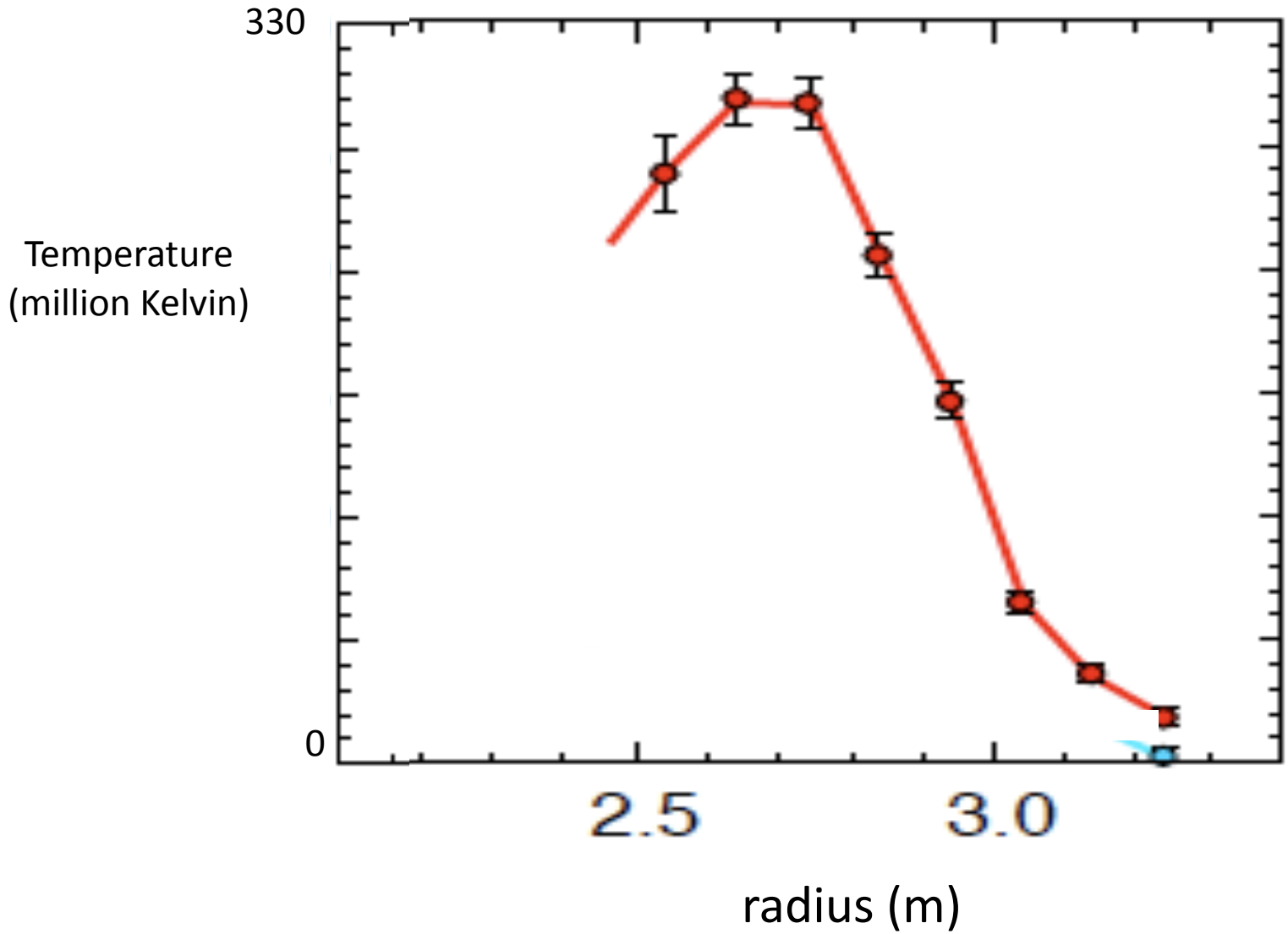
RF antenna



Neutral beam injector



Plasmas produced with temperature ~ 300 million degrees



high pressure achieved by increasing stability limits

magnetic curvature = effective gravity,

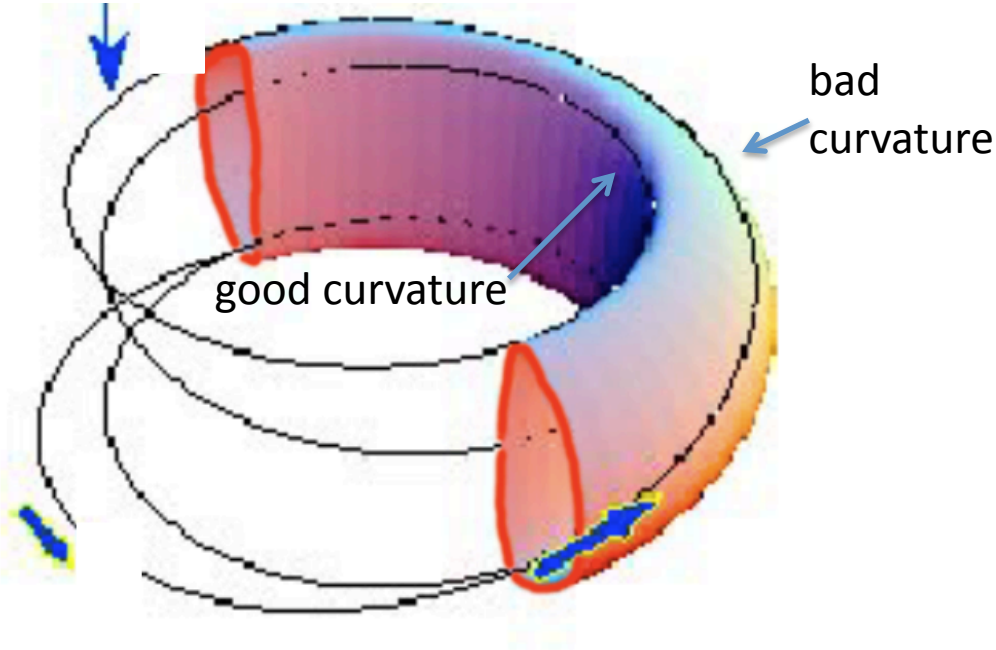
gravitational instability (relative of Rayleigh-Taylor)

nonlinear theory optimizes

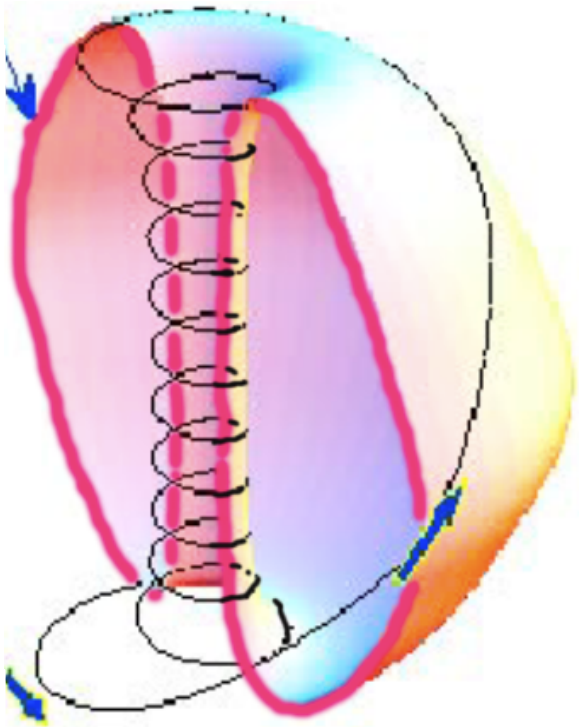
- curvature
- magnetic shear
- plasma compressibility
- pressure gradients

figure of merit $$\beta = \frac{p}{B^2/2\mu_0}$$

Tokamak



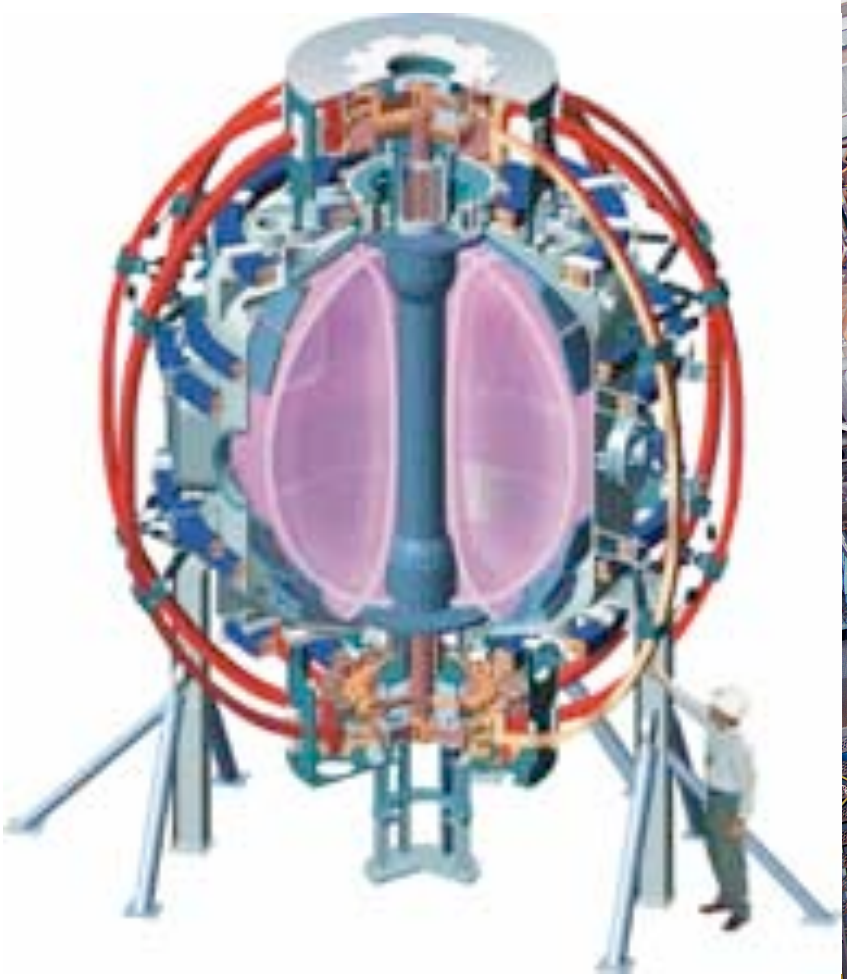
spherical tokamak

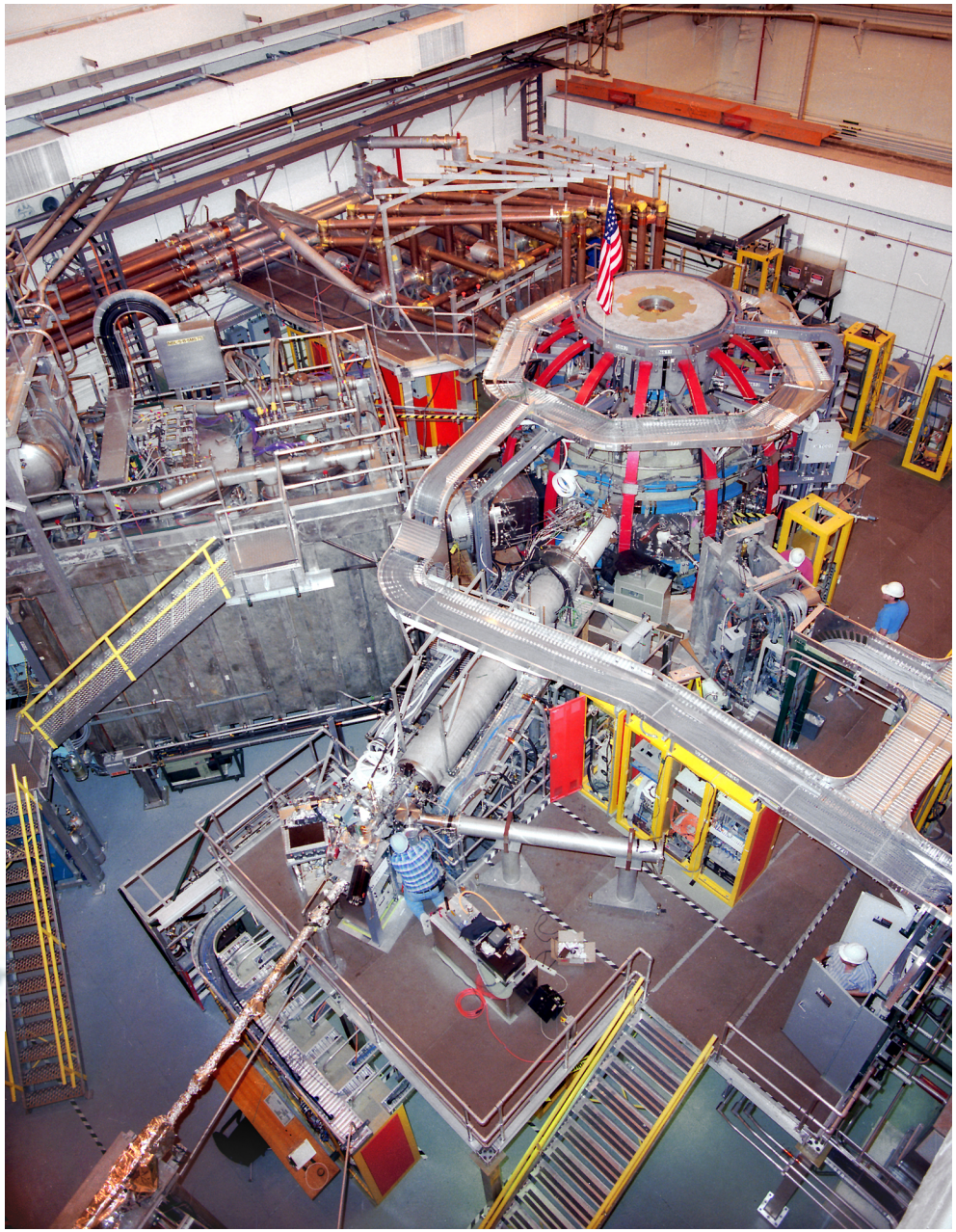


The ST has a strongly curved magnetic field

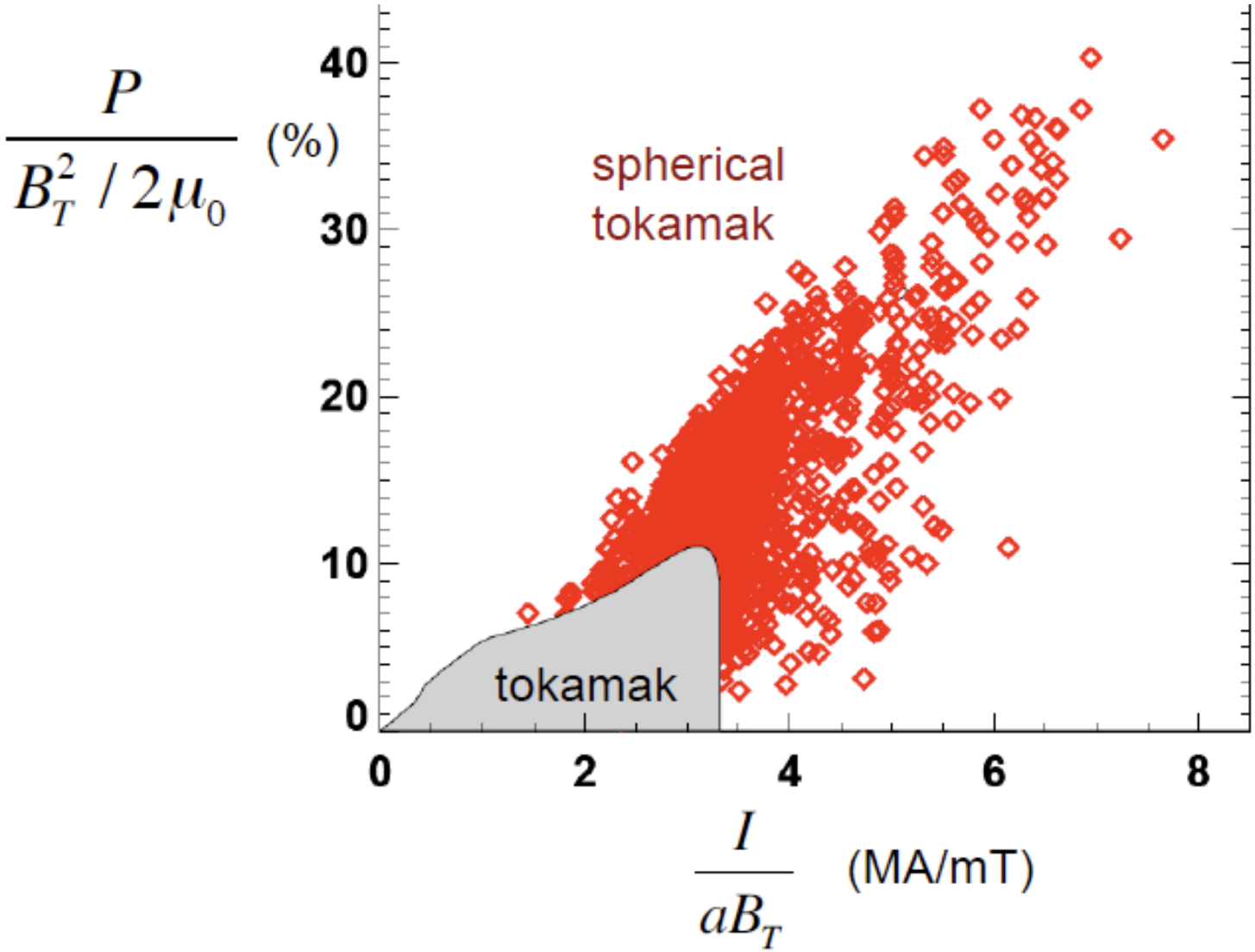
high plasma pressure
(relative to magnetic pressure),
and fairly compact

National Spherical Torus Experiment





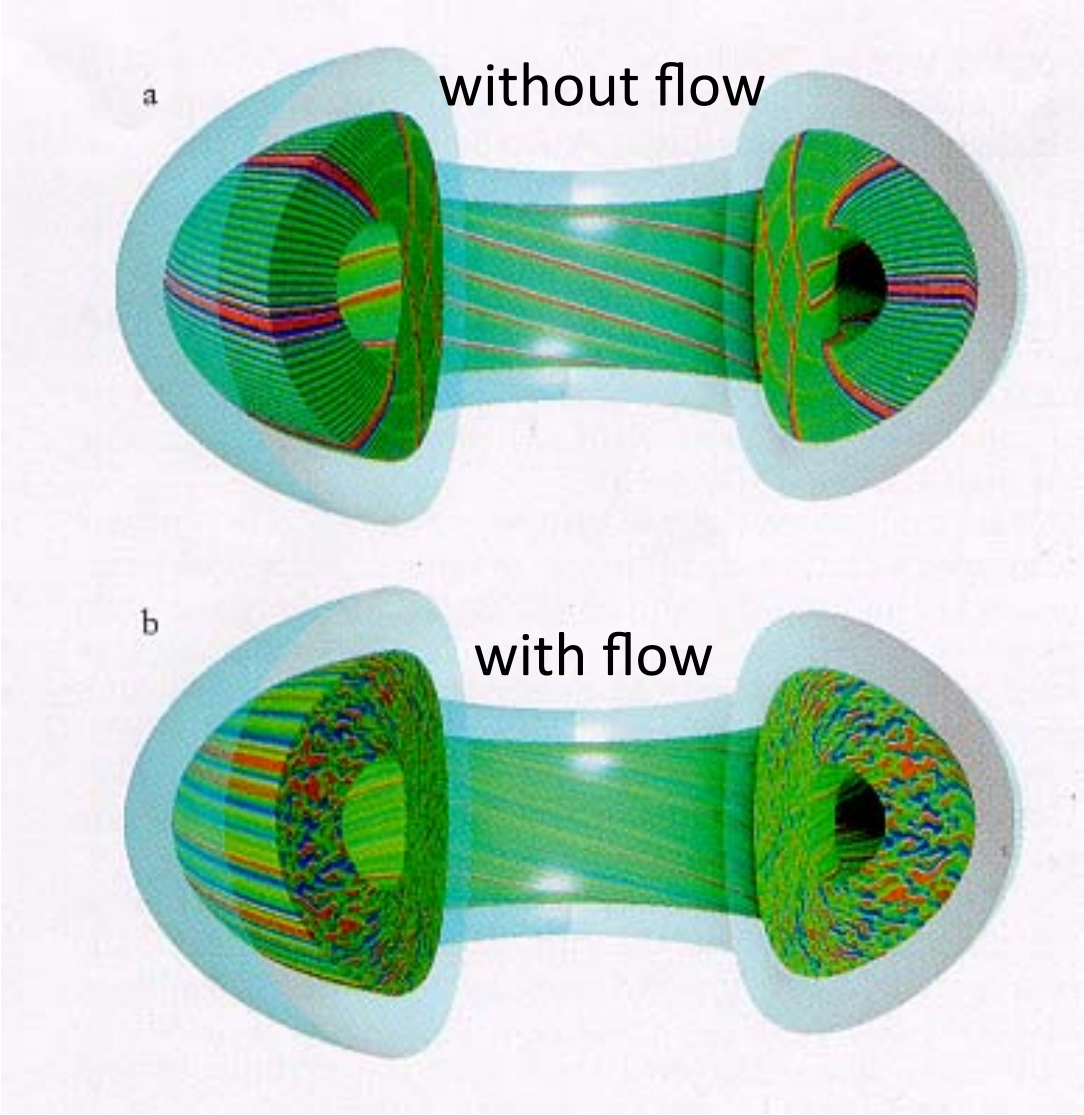
Reactor level beta achieved



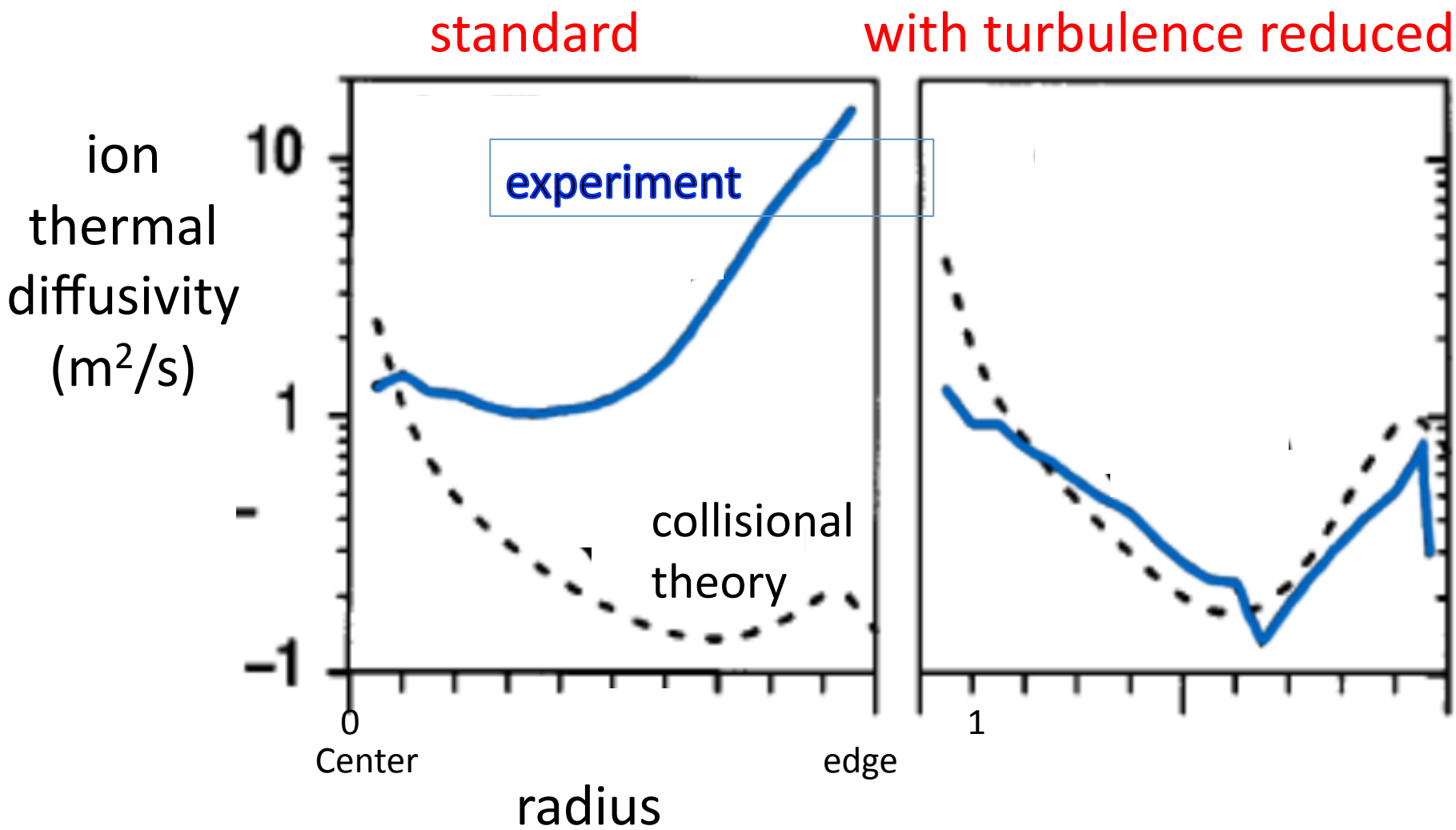
control of turbulent transport

Temperature gradients drive turbulence which degrades confinement

ion turbulence reduced
by driven flow shear
(computation)



Ion transport reduced to collisional level



DIII-D

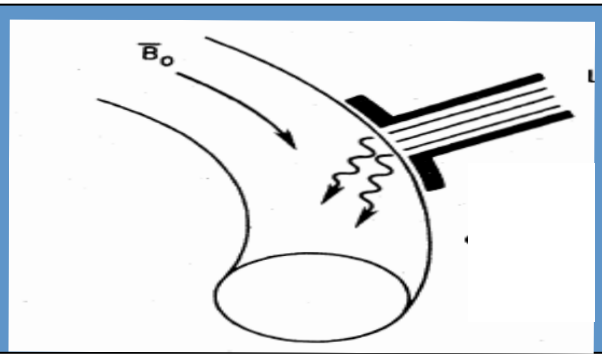
Sustainment of plasma current

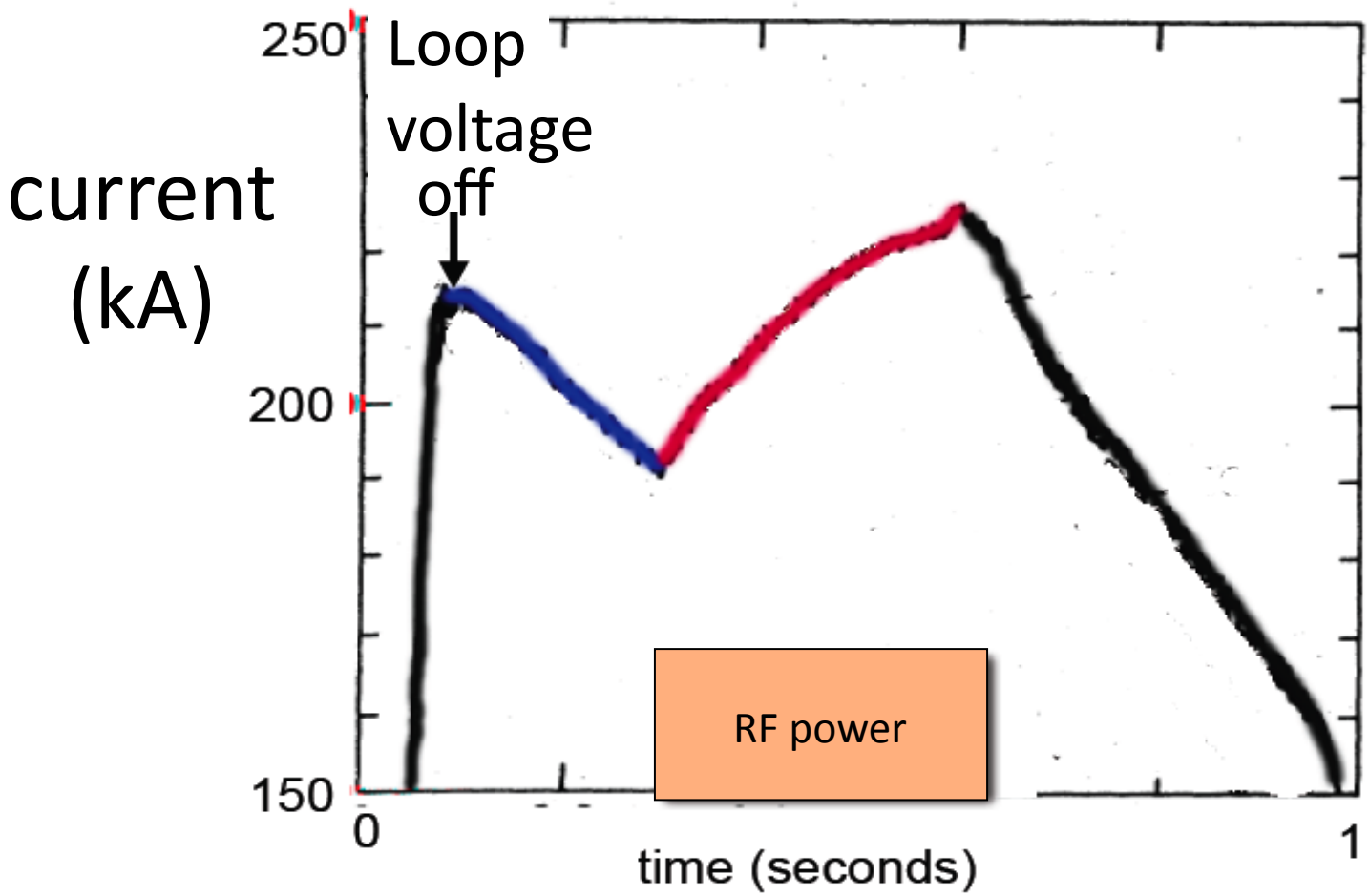
poloidal magnetic field in a tokamak is produced by plasma current

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

Wave-driven parallel currents

Ex: Landau damping of injected wave





PLT

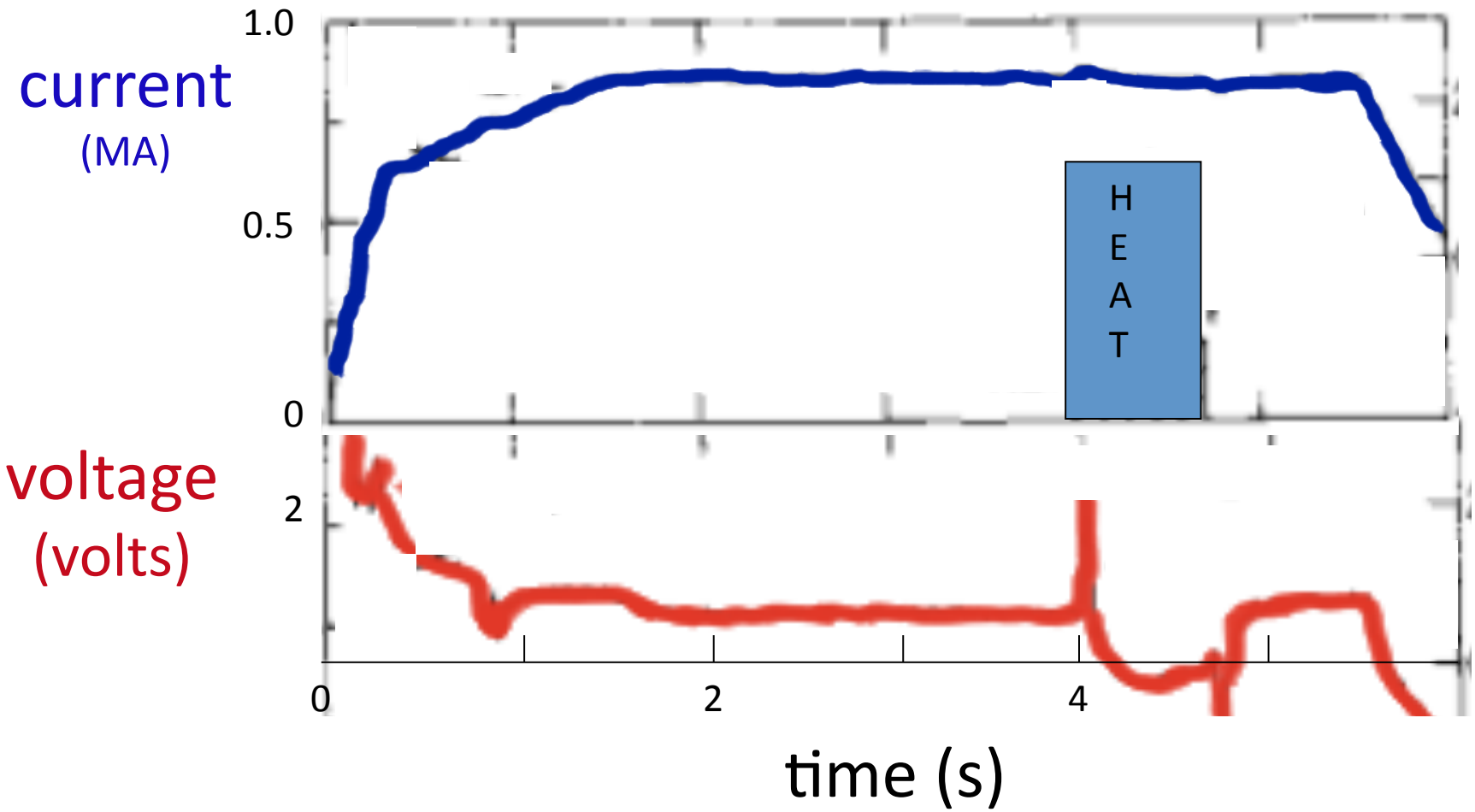
Discovery of bootstrap current

A pressure-driven current in a toroidal plasma

$$j_{\parallel} \sim \frac{1}{B_p}\frac{dp}{dr}$$

radial pressure gradient drives a toroidal current

Experimental identification of bootstrap current

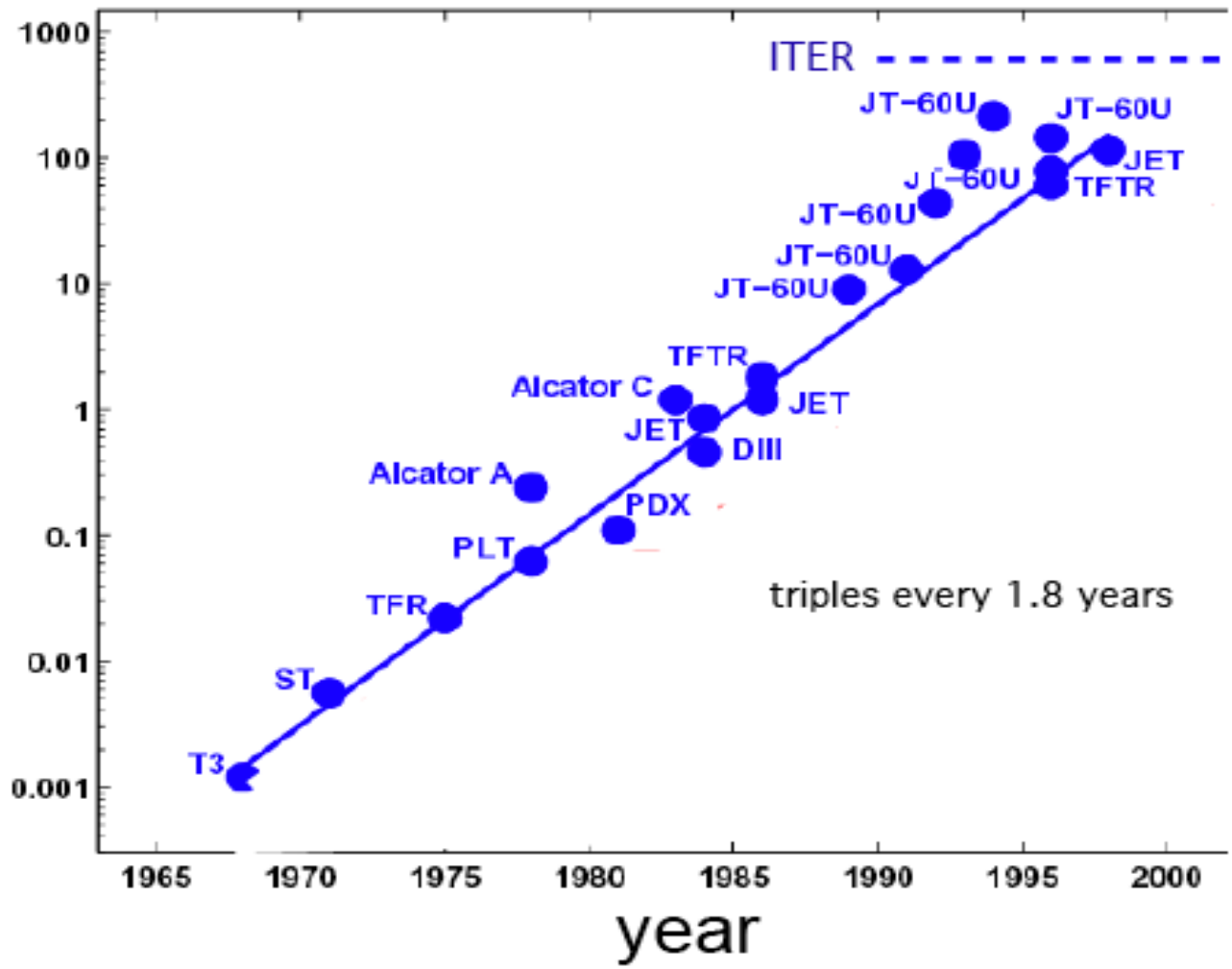


TFTR

Progress in the fusion triple product

fusion triple product

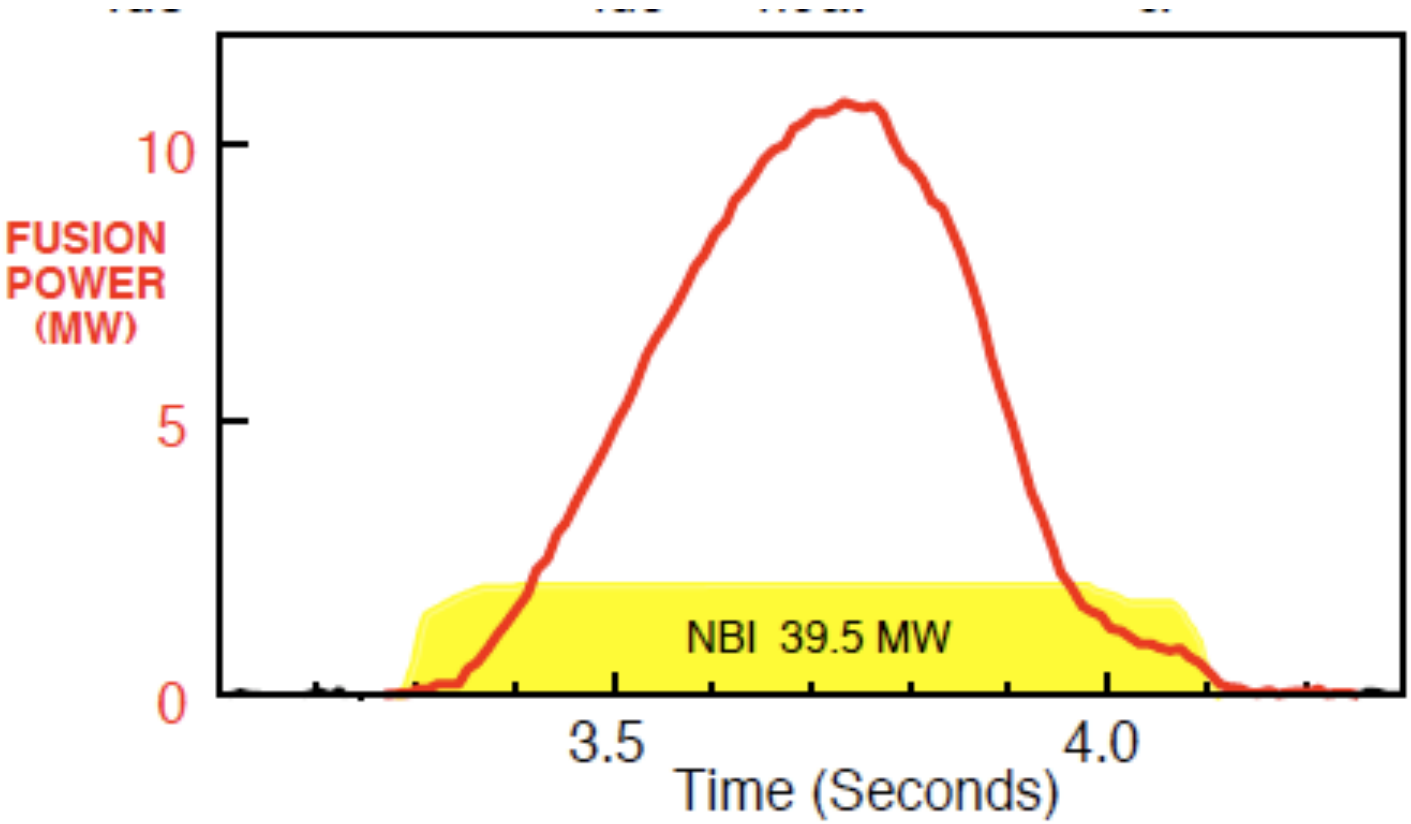
$nT\tau$



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

We have produced fusion energy

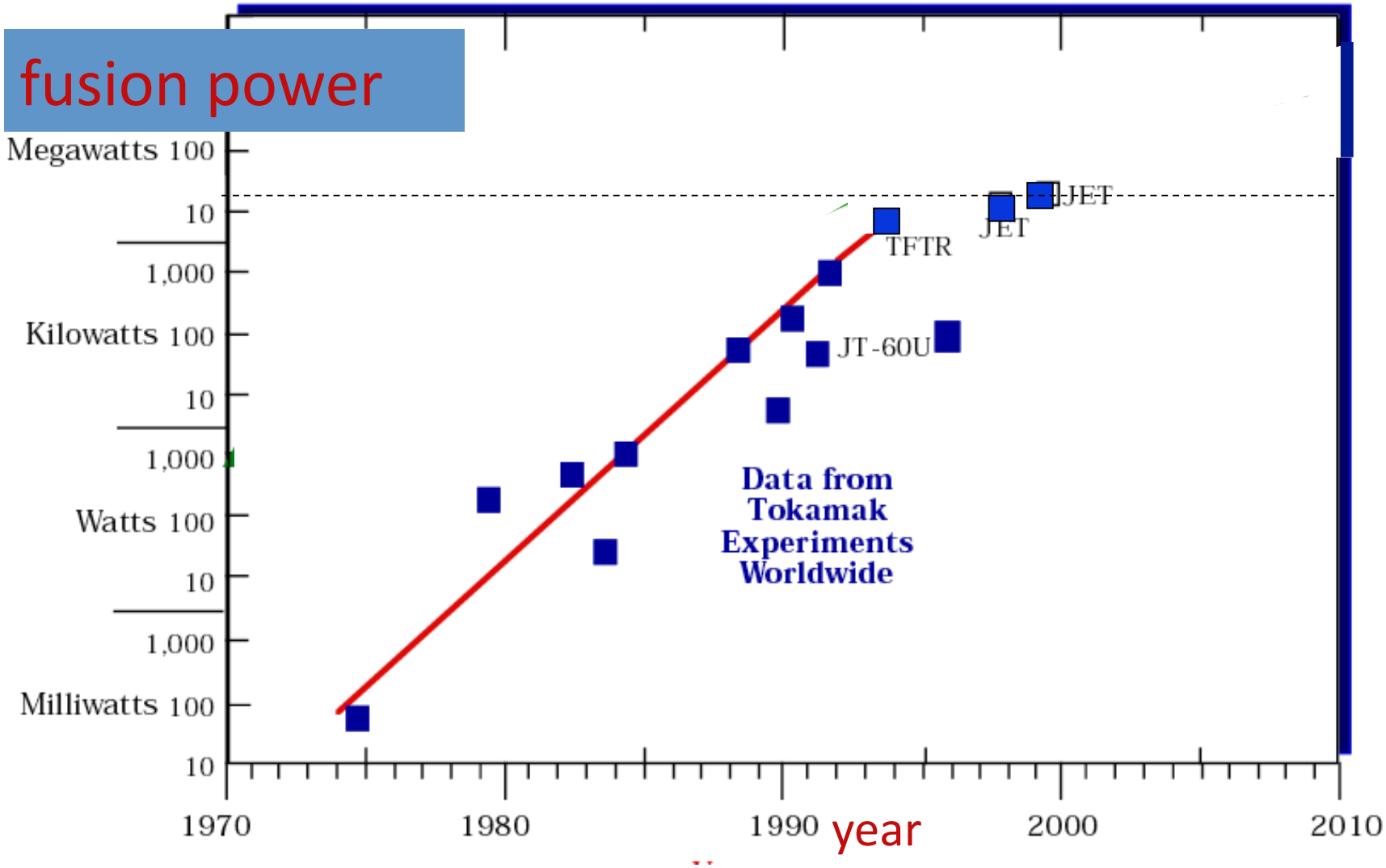
10 MW in 1994



TFTR, PPPL

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

huge advance in fusion power



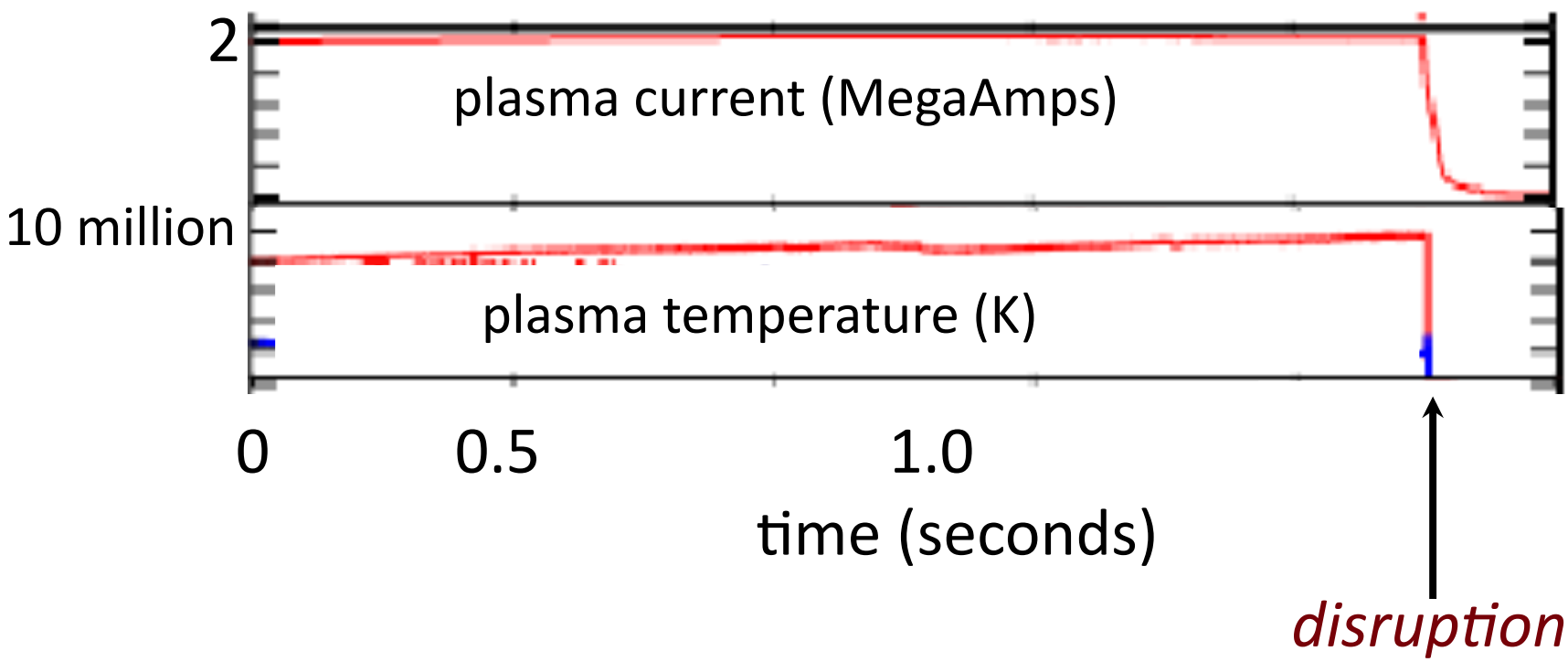
Progress in fusion power halted by lack of facility, not science

The challenge of high performance, steady-state

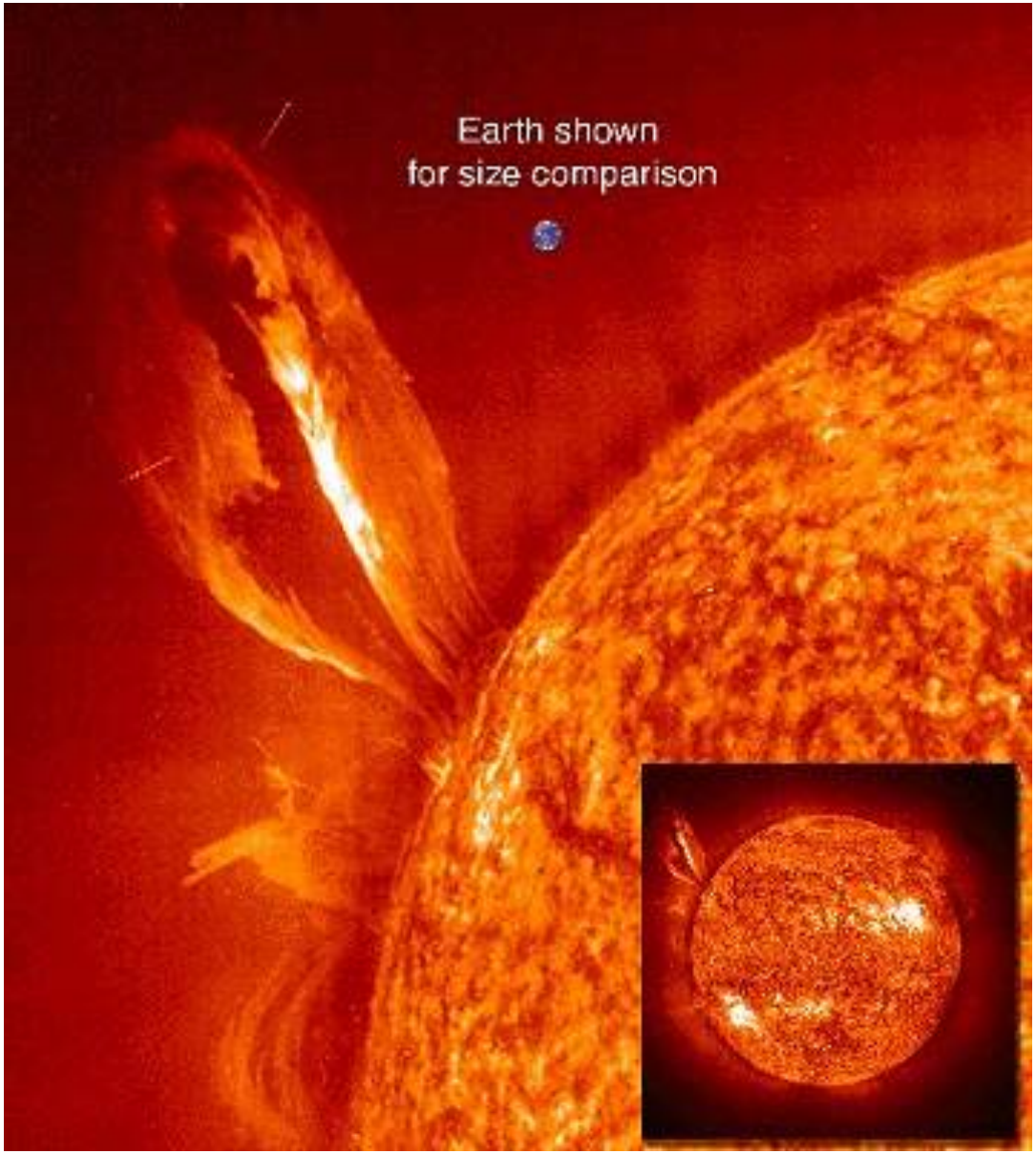
- High pressure for high bootstrap current

Need self-consistent scenario
(P ➡ J ➡ B ➡ stability ➡ P, and self-heating affects the links)

- Need avoidance of disruptions (huge heat load on materials)

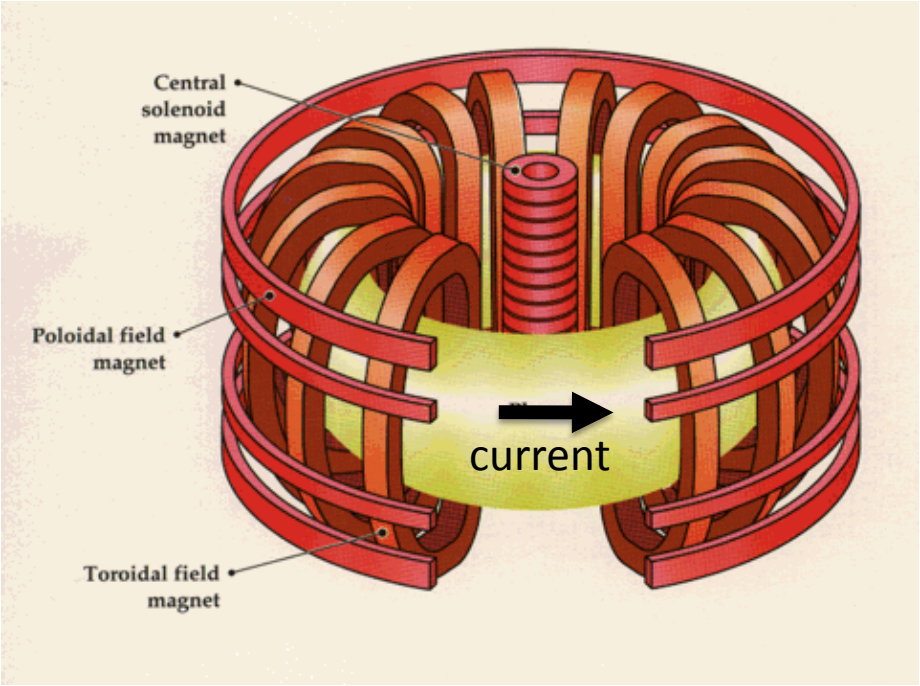


Physics similarities to solar flares



Toroidal confinement with 3D fields

Axisymmetric tokamak (2D)



magnetic symmetry good for confinement

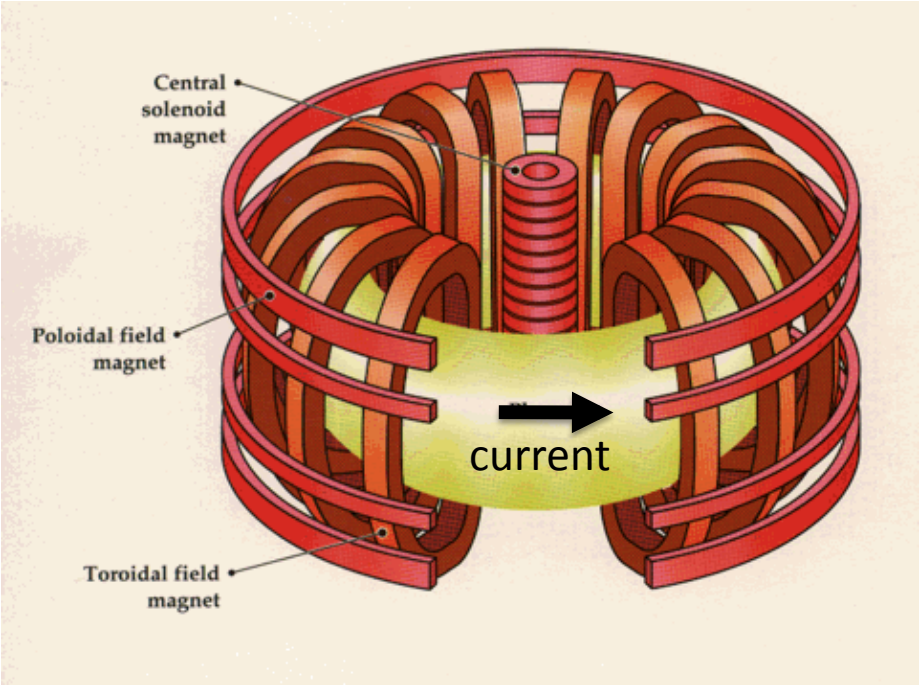
But,

Current makes sustainment challenging,

Current can cause disruptions

Toroidal confinement with 3D fields

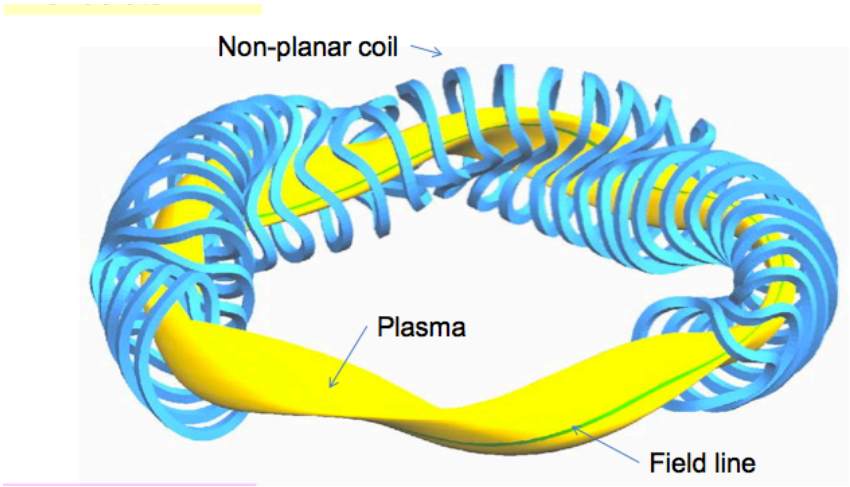
Axisymmetric tokamak (2D)



magnetic symmetry good for confinement

But,
Current makes sustainment challenging,
Current can cause disruptions

Torus with 3D fields



No current needed,
Steady-state,
Disruption-free,
Confinement?

Large Helical Device (LHD)

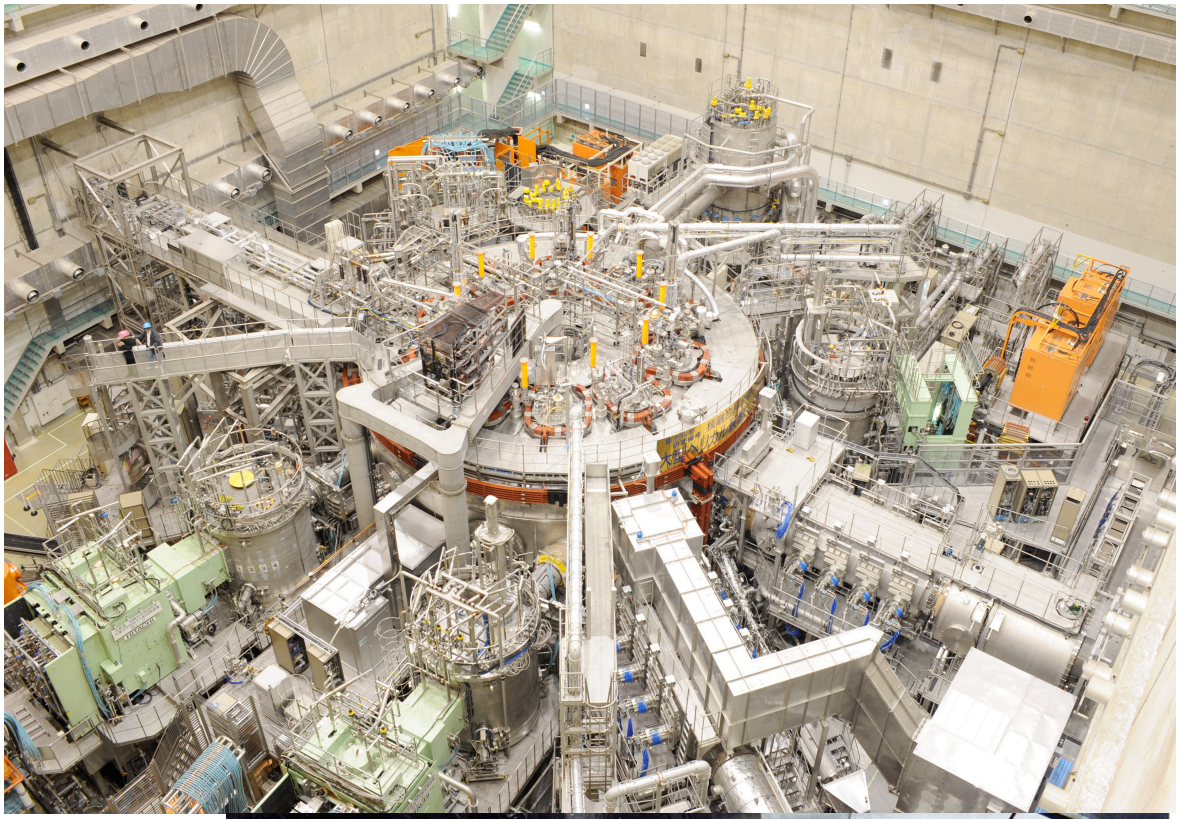
Operating in Japan

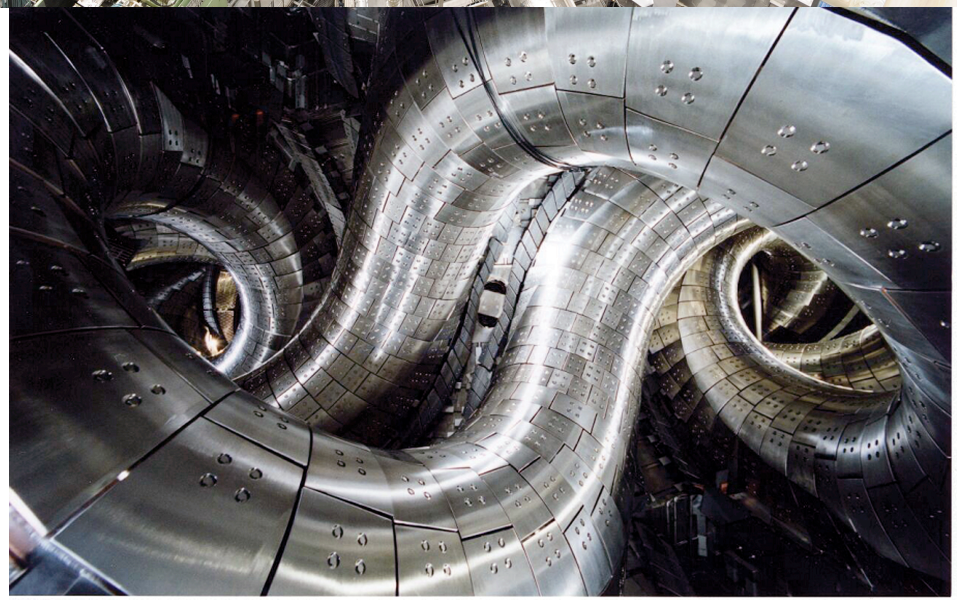
Superconducting

One hour pulses

(not optimized for confinement)

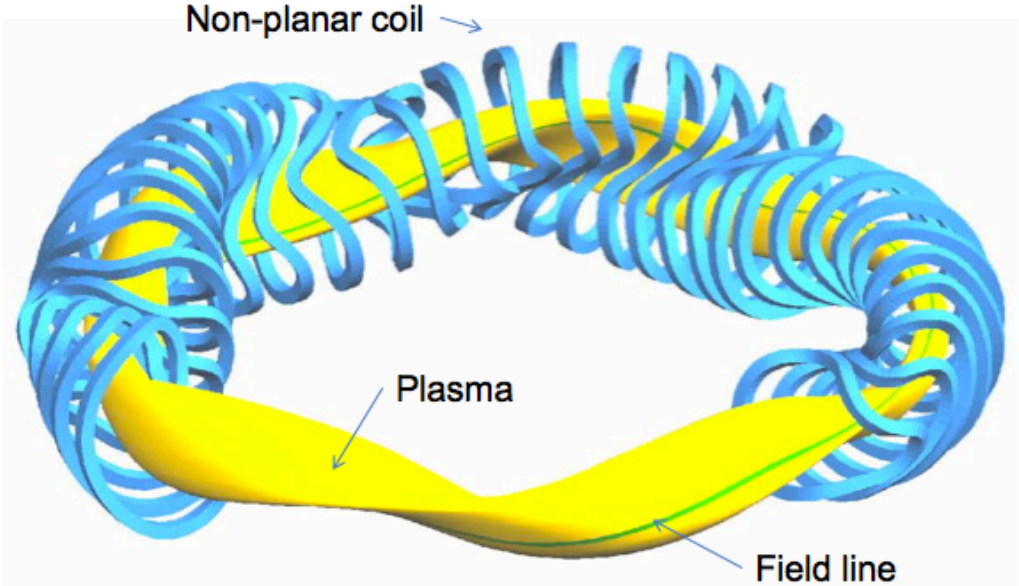
(called stellarators)





Under construction in Germany

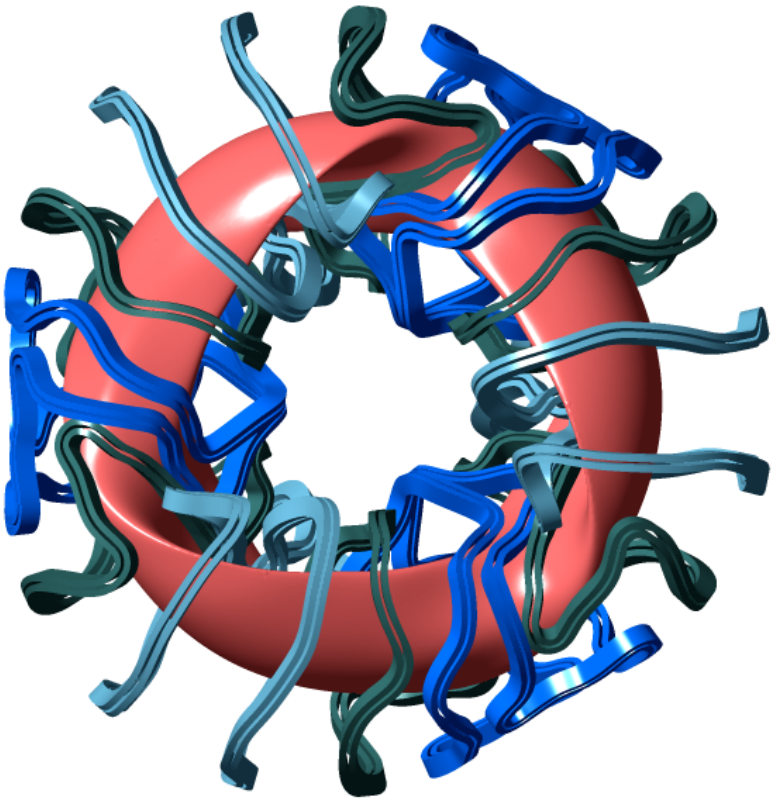
Wendelstein 7-X



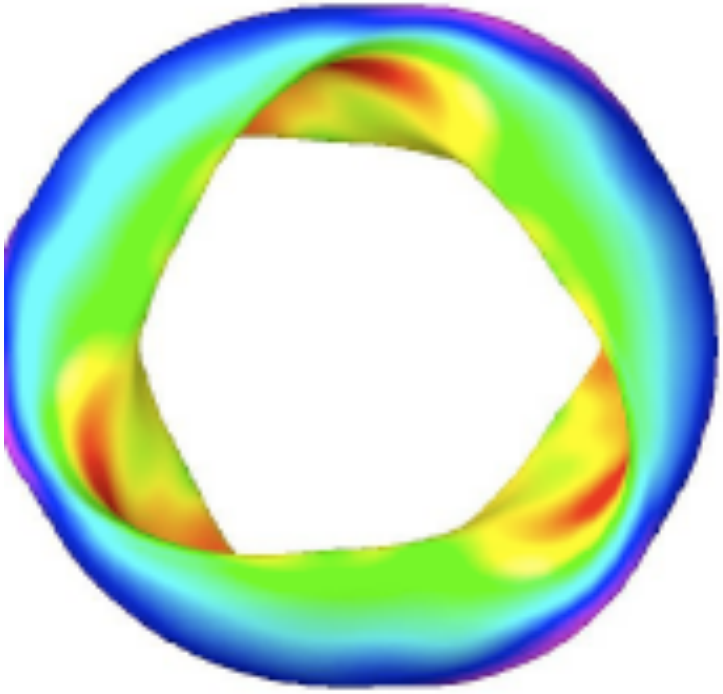
Optimized for confinement

Quasi-symmetry: further optimization of stellarators

Coils



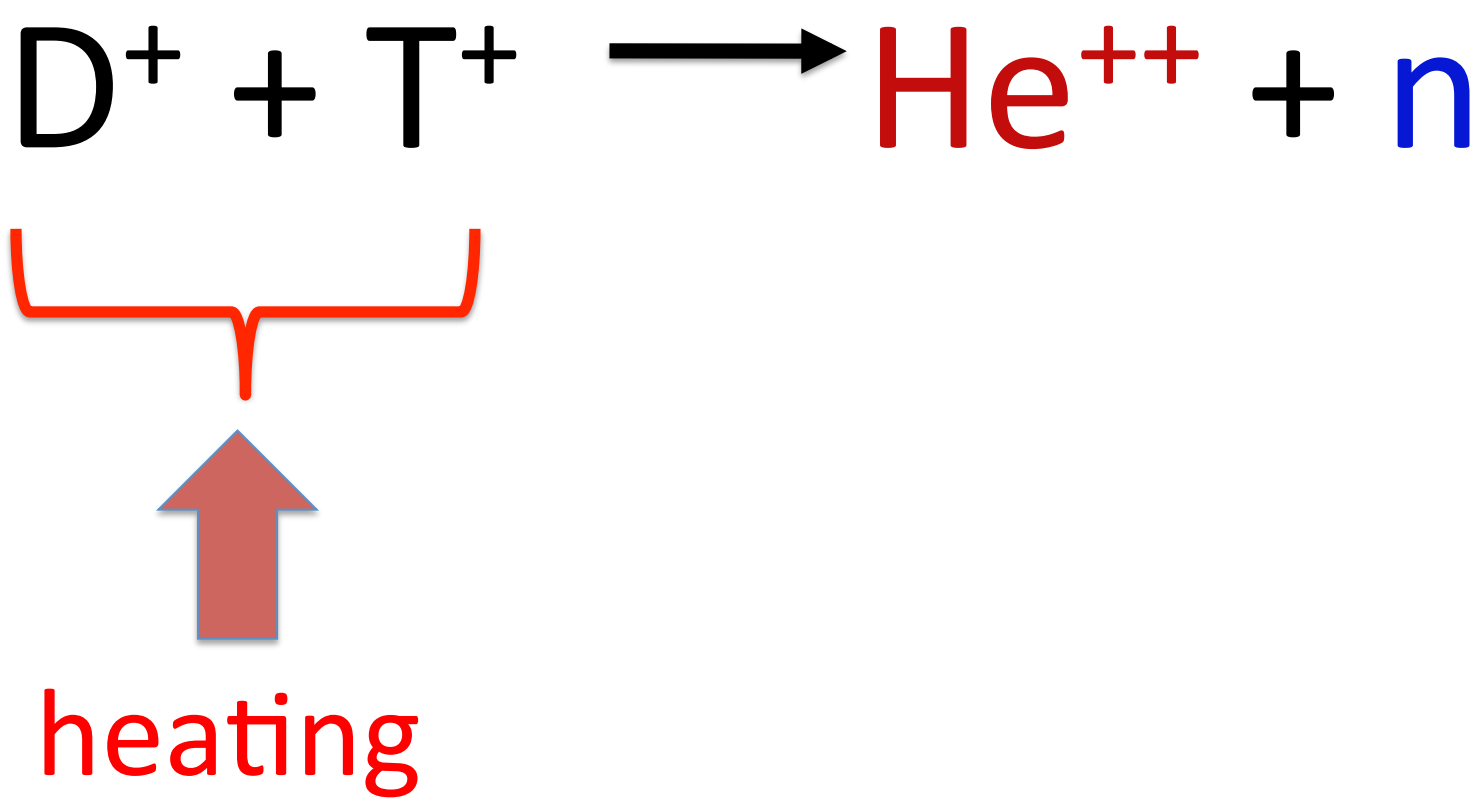
contours of constant $|B|$



Quasi-axisymmetric,
Confinement properties of
2D tokamak with 3D fields

(quasi-axisymmetric designs developed at PPPL)

All plasmas to date have been heated externally



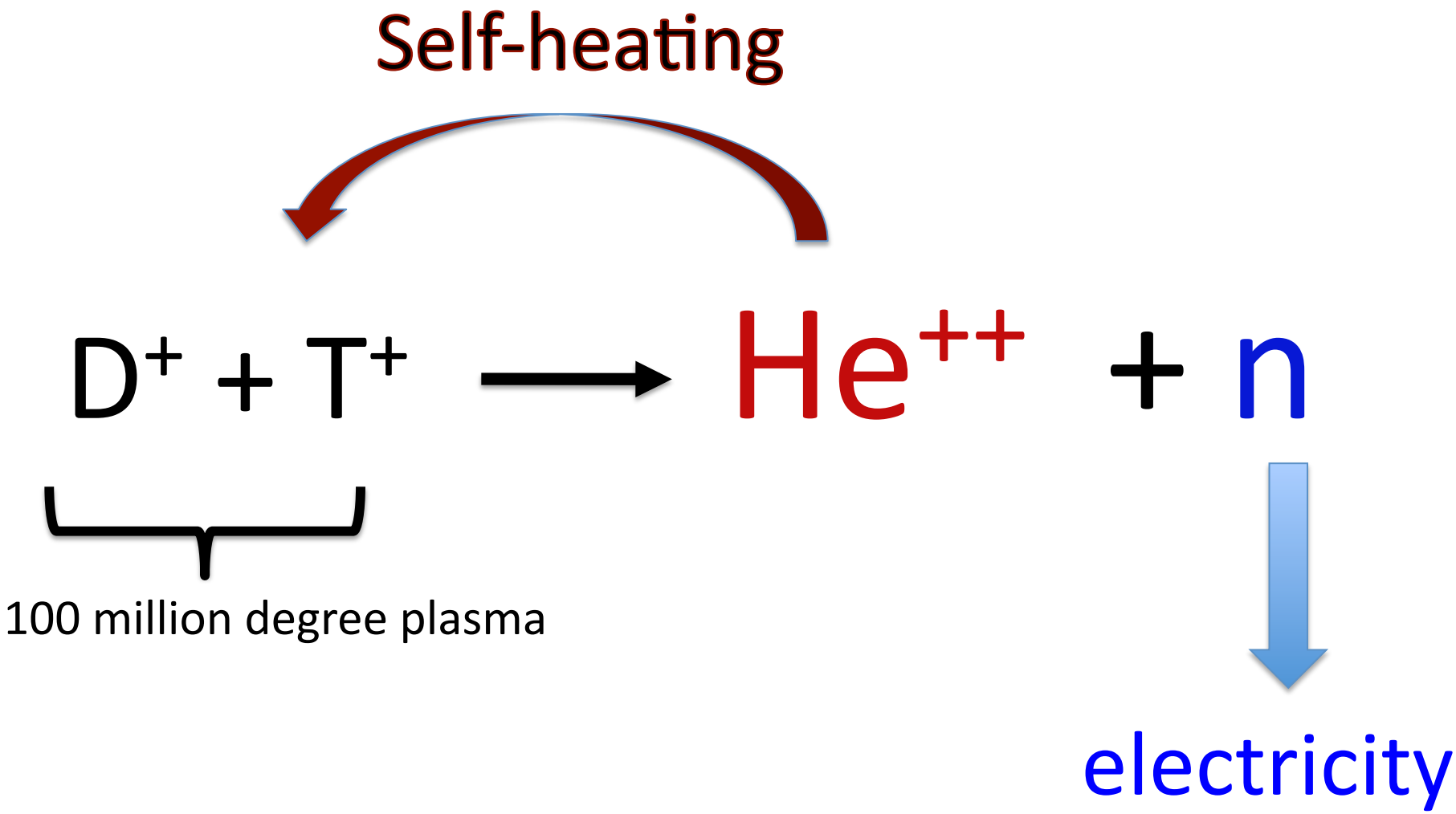
not self-sustaining: remove heating, plasma cools down and fusion stops

The next (international) step in fusion

Produce a burning plasma

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

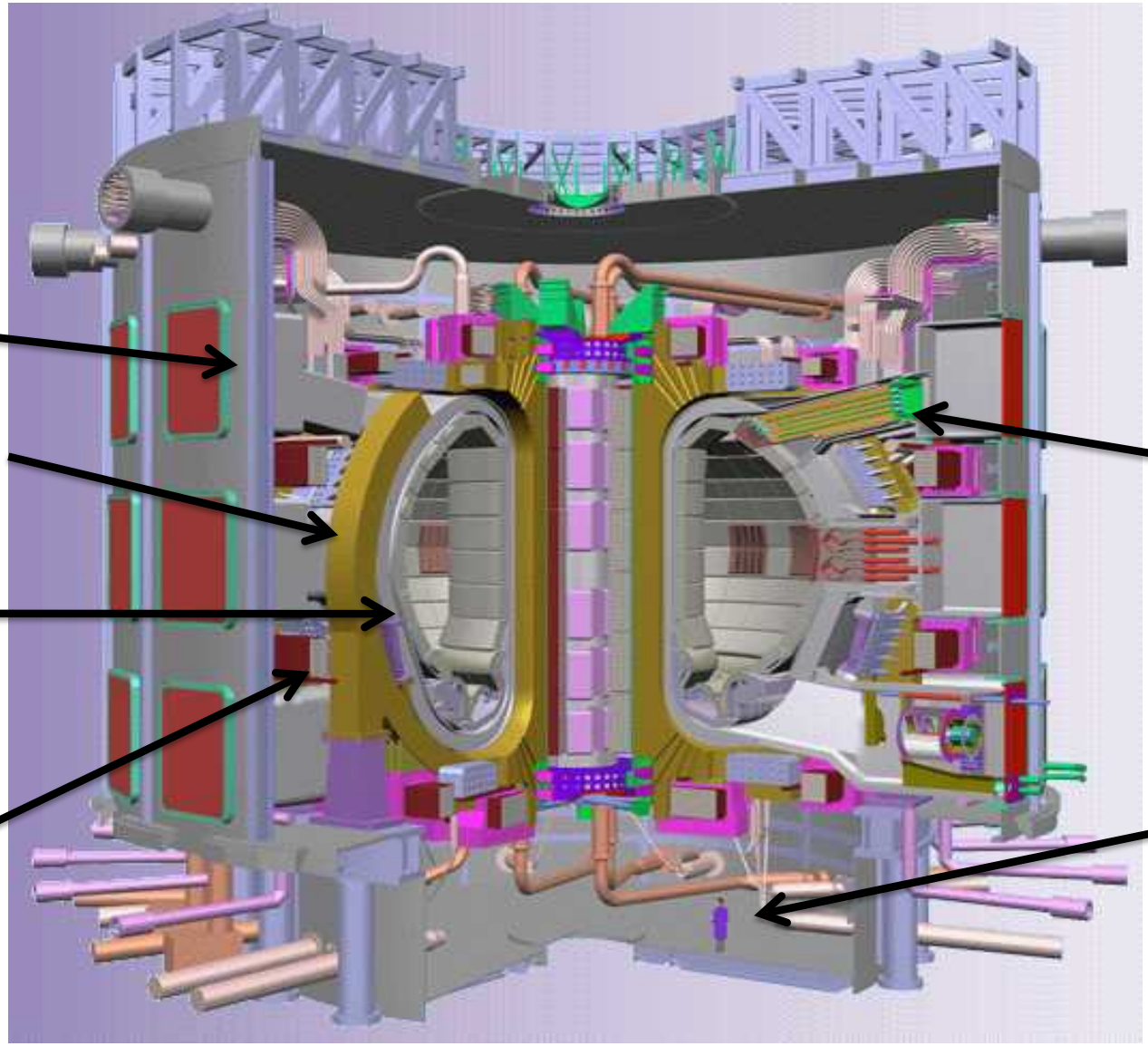
A burning plasma



The international ITER experiment

- A burning plasma
- Under construction in France (south)
- Will produce 500 MegaWatts for 500 seconds
- Will have fusion power gain ≈ 10
- At reactor scale, testing key technologies
  (R = 6.2 m, a = 2m, B = 5.3T superconducting)

ITER is reactor scale



ITER is an international partnership

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

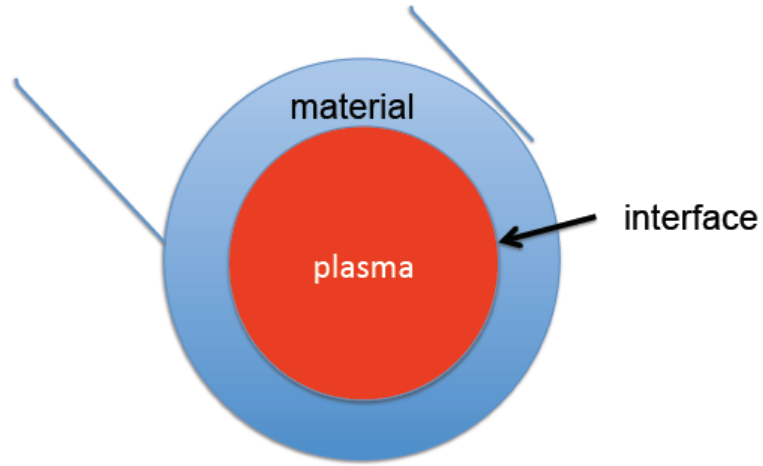
- Construction beginning,
  expected completion around 2020

The site is cleared in France

The next steps

from ITER to a first-of-a-kind power plant

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)

Fusion Challenges

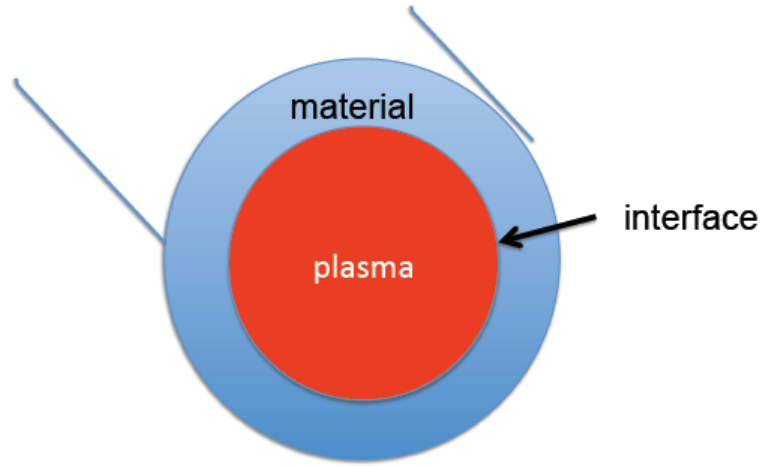
- Plasma confinement and control

burning plasma

steady-state plasma

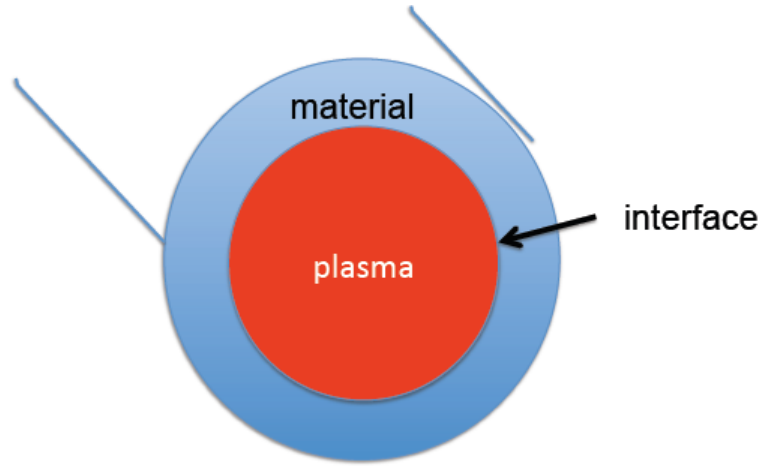
ITER

World program in superconducting tokamaks, stellarators…
(moderately expanded)



Fusion Challenges

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



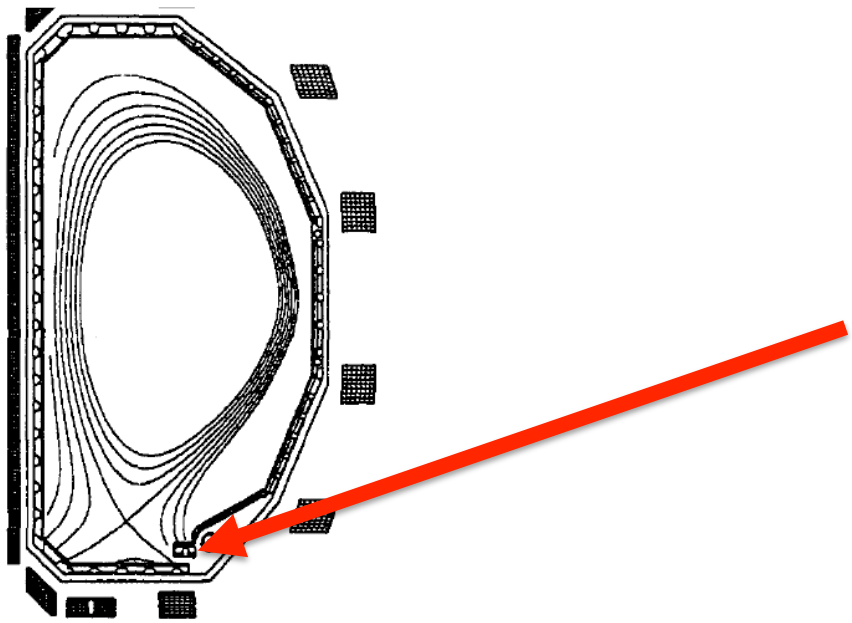
- The plasma-material interface
  - effect of plasma on materials, effect of materials on plasma

Good progress in current experiments

The plasma-material interface

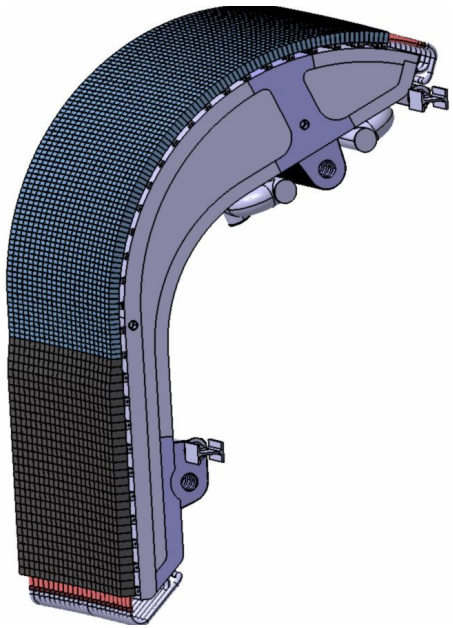
The divertor concept

Magnetically controlling the plasma exhaust



Tungsten plate

~ 10 MW/m^2



Expanded research program needed to extend success at short pulse to steady-state

A liquid lithium wall

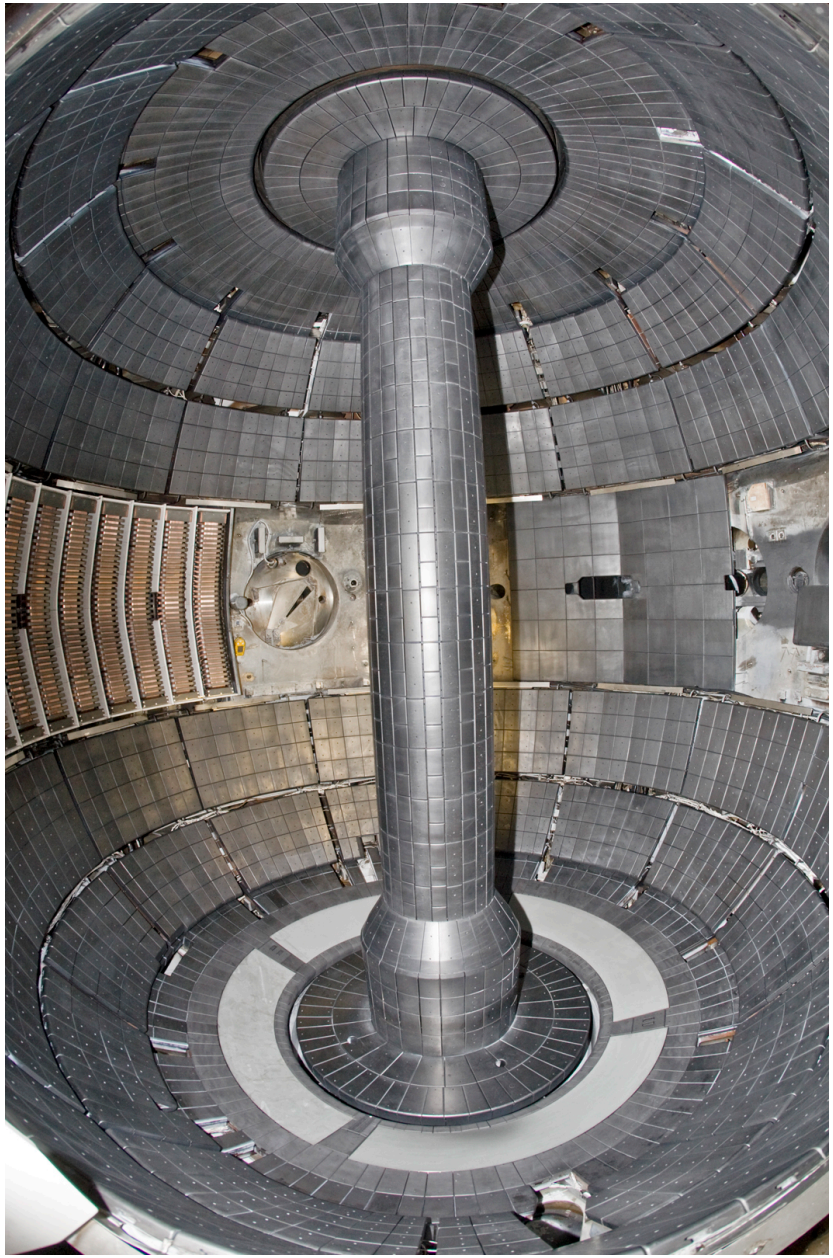
- Reduces problem of materials damage

  no erosion (wall material continually replaced, self-healing), no neutron damage, carries away heat

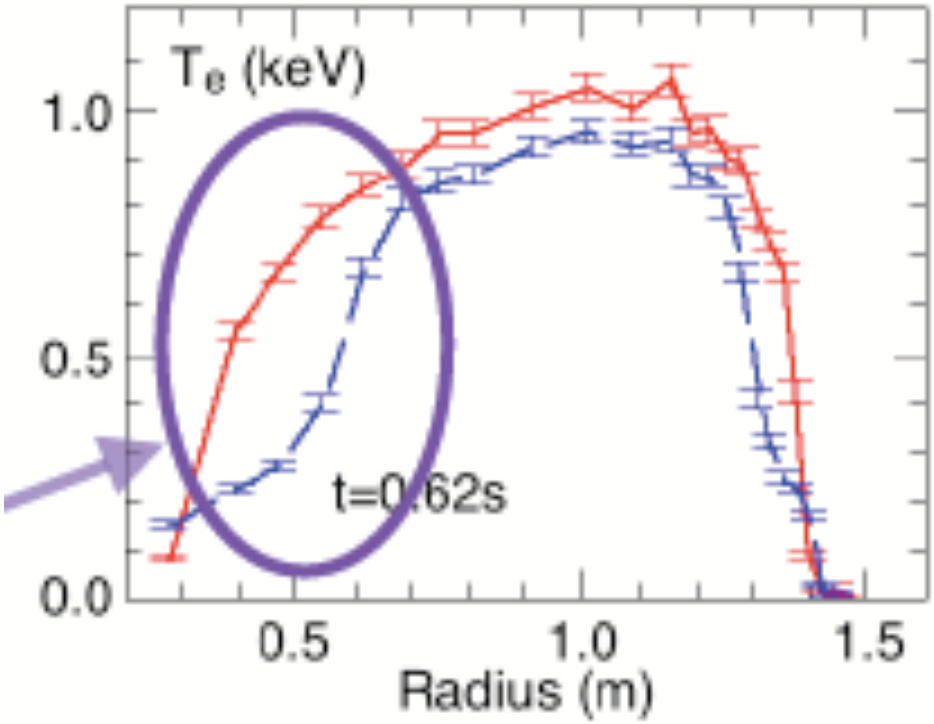
- Improves confinement

  pumps Hydrogen, no reflux of cold gas into plasma, increases edge temperature, reduces temperature gradient, reduces turbulence

Liquid Lithium divertor plate in NSTX



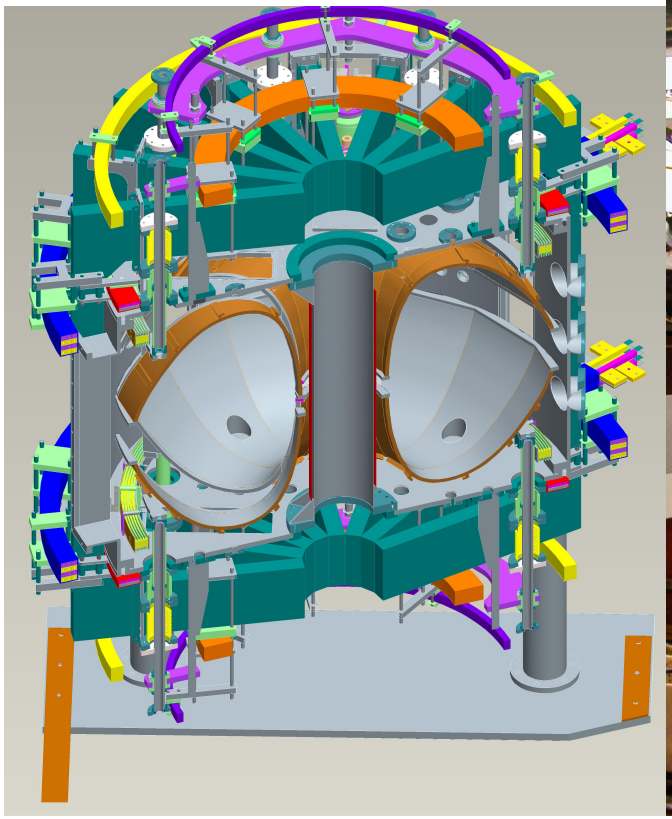
Electron temperature increases

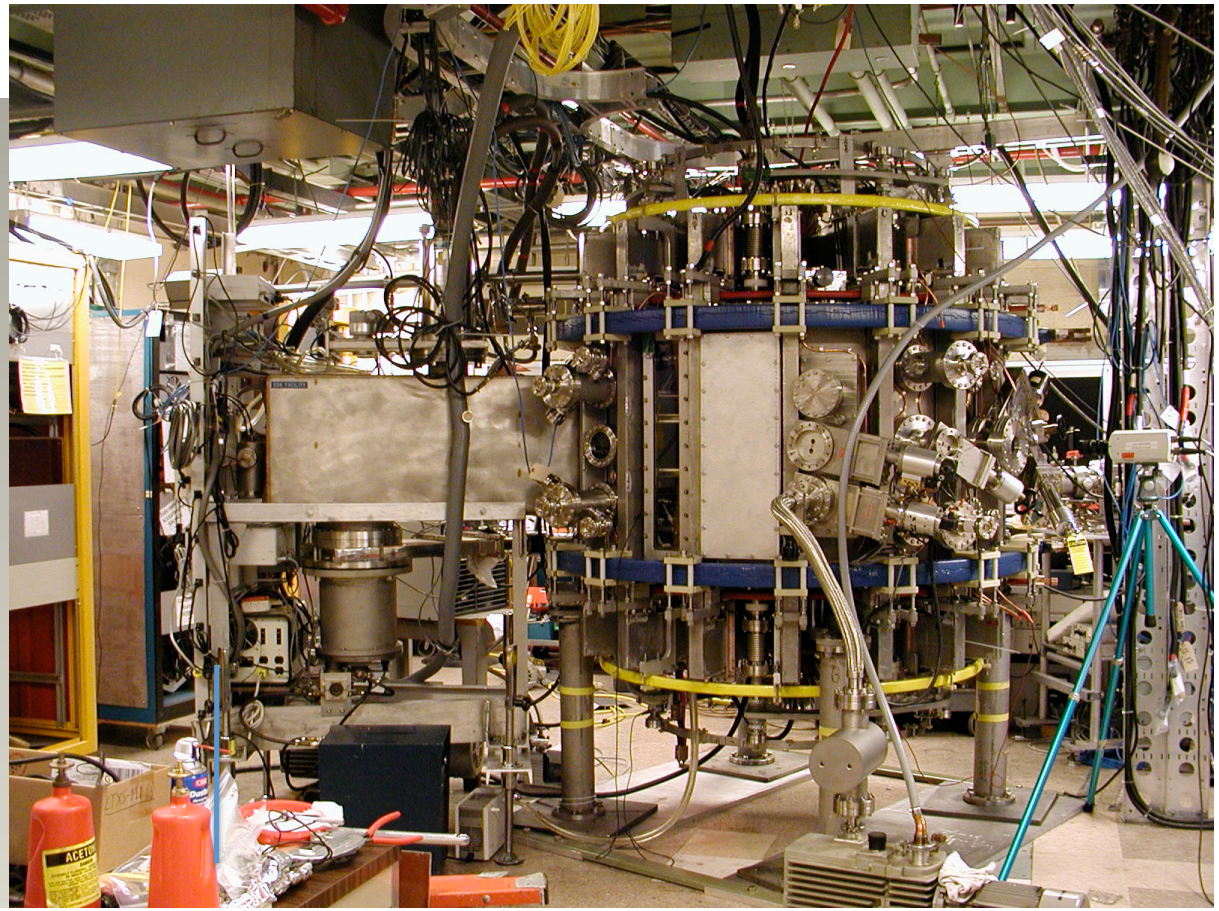


Lithium Tokamak Experiment (LTX)

an exploratory experiment

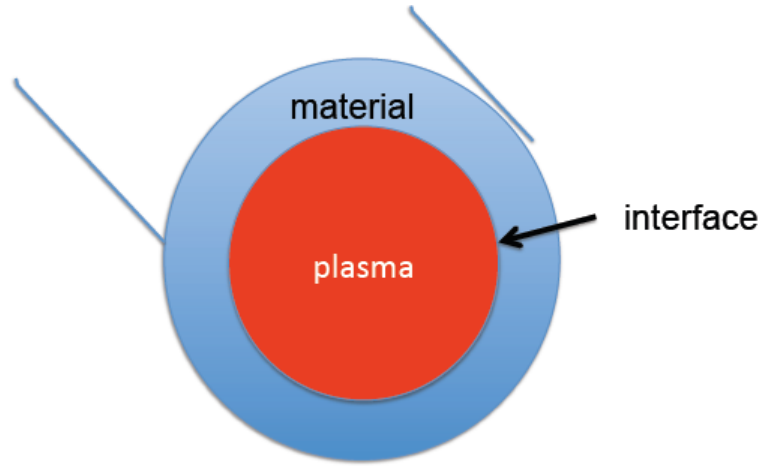
liquid Lithium wall (pool at bottom, coating by evaporation)
Complete liquid coverage





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)

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

The penultimate R &D step

A fusion nuclear facility that, at a minimum,

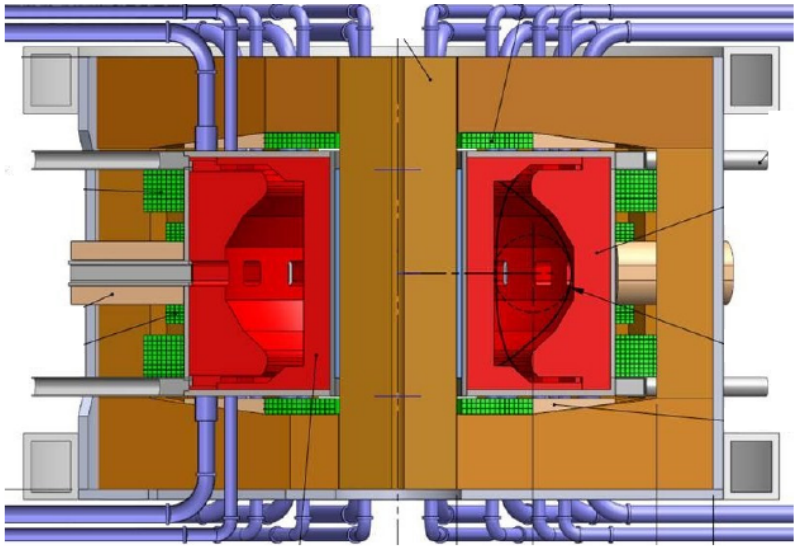
- Generates large neutron fluxes for long time (~ 2 MW/m^2)
- Develops/test materials: low-activation, high strength, high temperature, radiation-resistant)
- Is tritium self-sufficient (breeding blankets)
- Extracts heat from fusion neutrons

The facility, with a focused accompanying research program, would demonstrate all features needed to justify a first-of-a-kind power plant

A range of conceptual designs have been developed

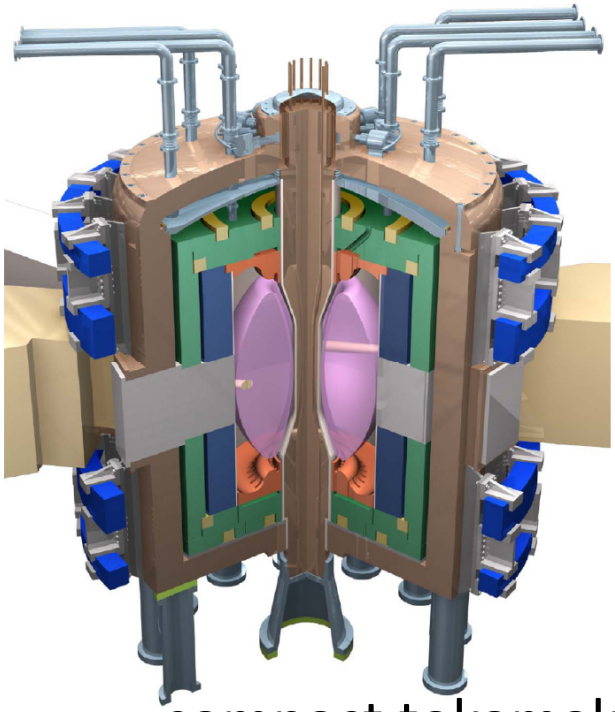
Fusion nuclear science facility: low gain

- Completely address all fusion nuclear science issues (tritium self-sufficiency, neutron effects on materials……)



tokamak

(GA)



compact tokamak

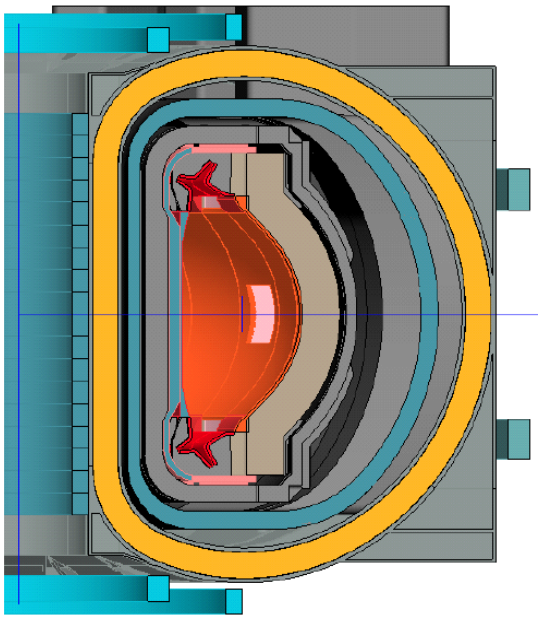
(ORNL)

(copper magnets)

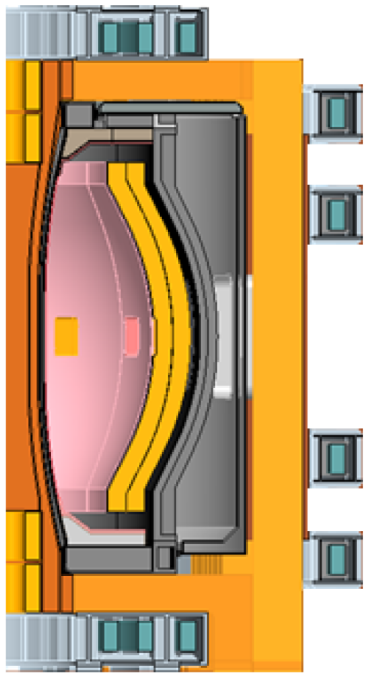
Pilot plant

- Addresses above fusion nuclear science issues, and
- Generates net electricity

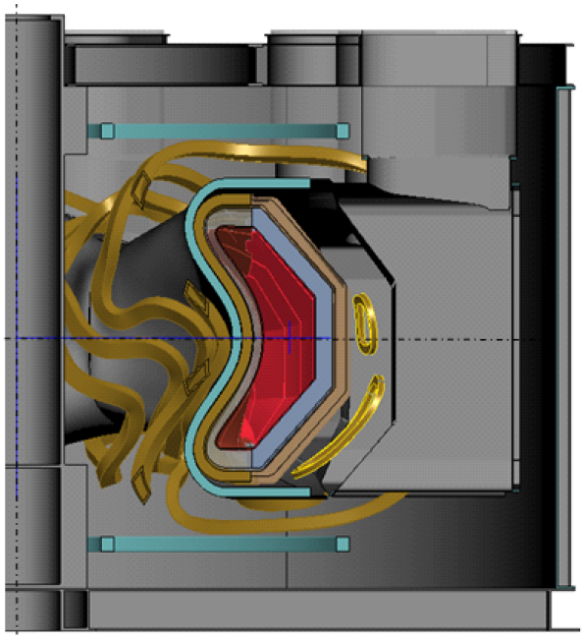
  (requiring high integrated efficiency of plasma, auxiliary systems, blankets)
- Tests reactor maintenance schemes



tokamak



compact tokamak



stellarator

(Superconducting magnets)

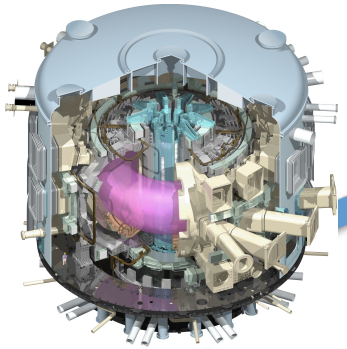
PPPL

The optimal design is a trade-off between risk, scope, cost, timing……

Putting it altogether into a roadmap……

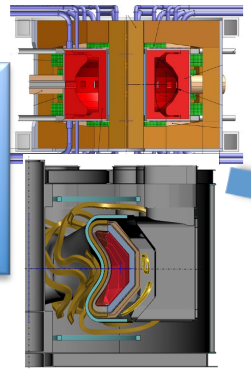
A road to fusion power

ITER



operating~ 2020 - 2040

Fusion Nuclear Facility



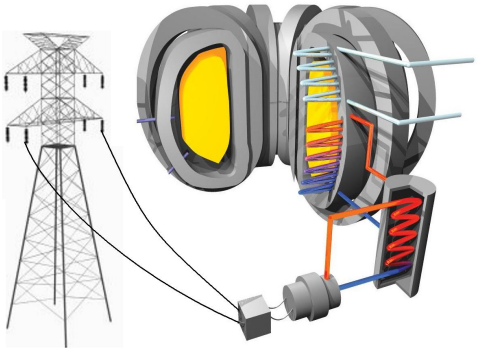
Operating ~ 2025 - 2045

Supporting Physics and Technology

- high performance, steady state
- Materials R&D
- Plasma Material Interface

US and abroad

First-of-a-kind Power Plant



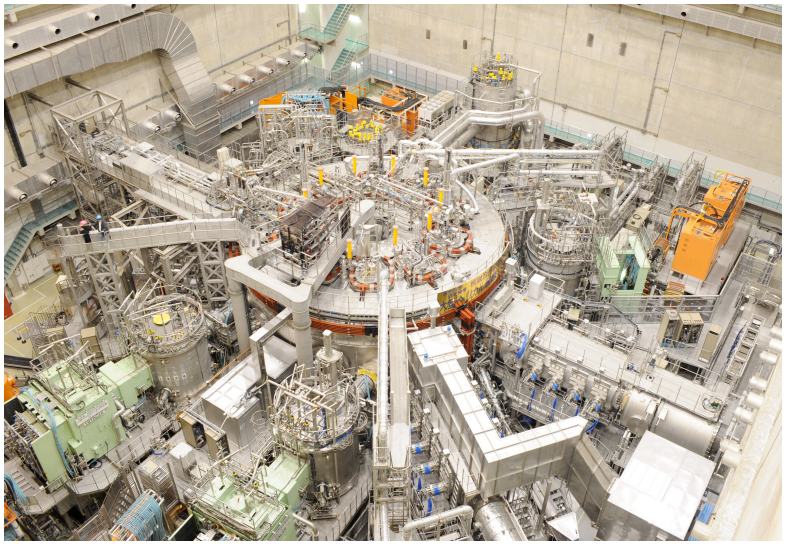
~ 2035

The escalating magnetic fusion activity across the world

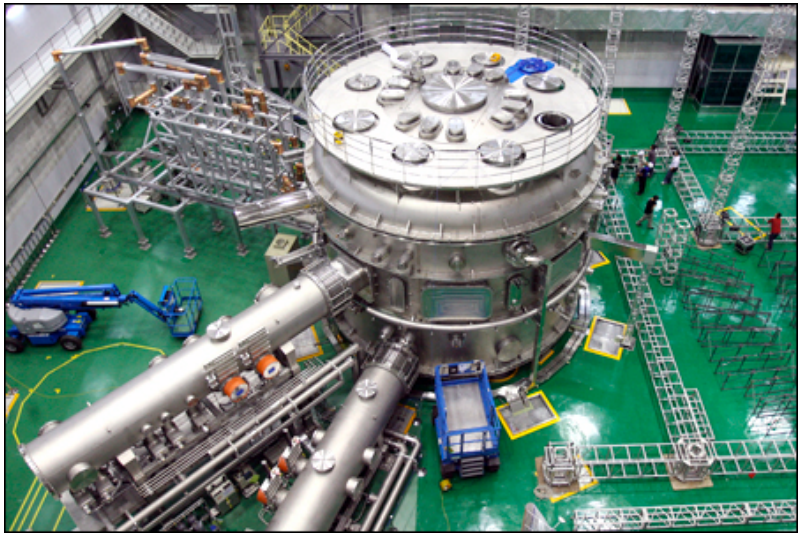
New major facilities

China: superconducting tokamak EAST

Japan: superconducting stellarator



Korea: superconducting tokamak KSTAR

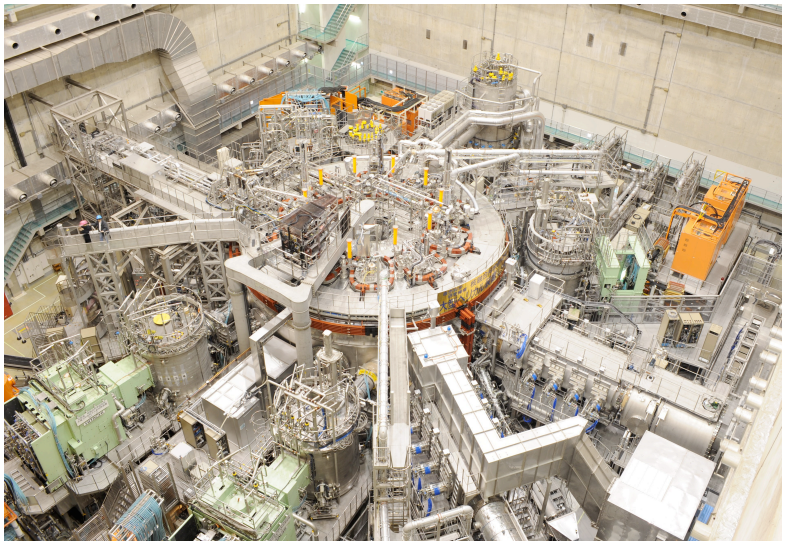


The escalating magnetic fusion activity across the world

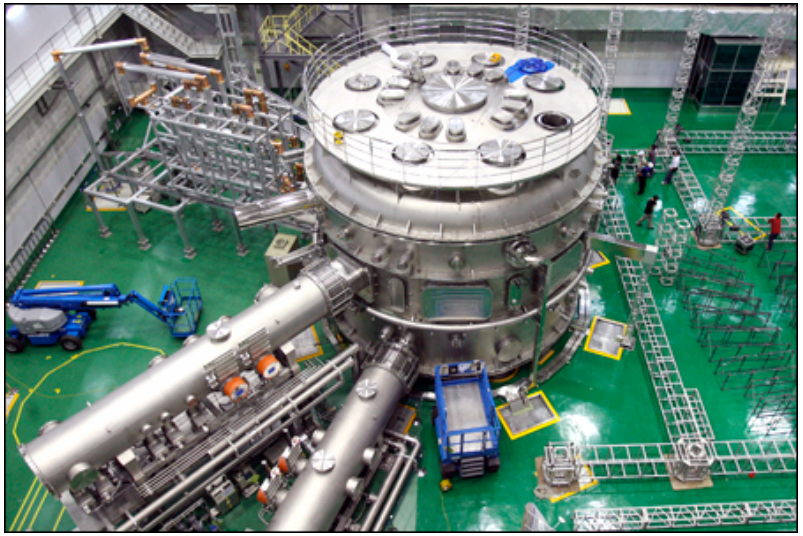
England: JET tokamak

China: superconducting tokamak EAST

Japan: superconducting stellarator

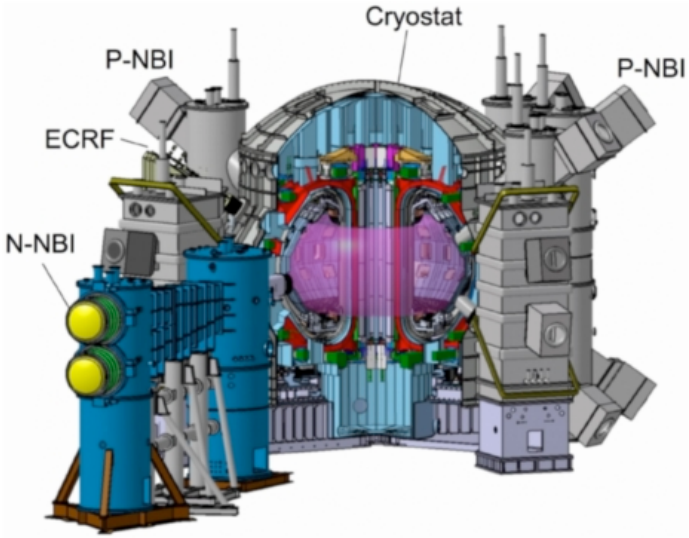


Korea: superconducting tokamak KSTAR

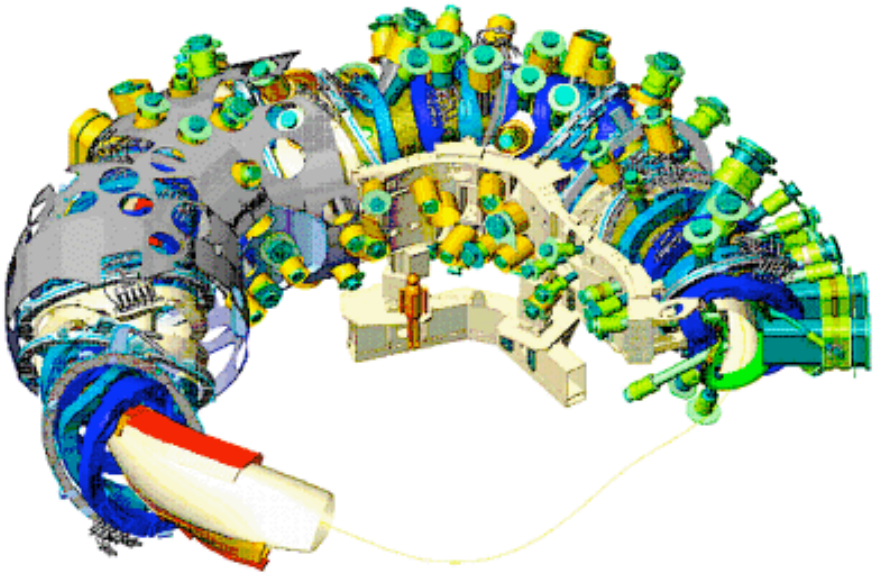


Major facilities under construction

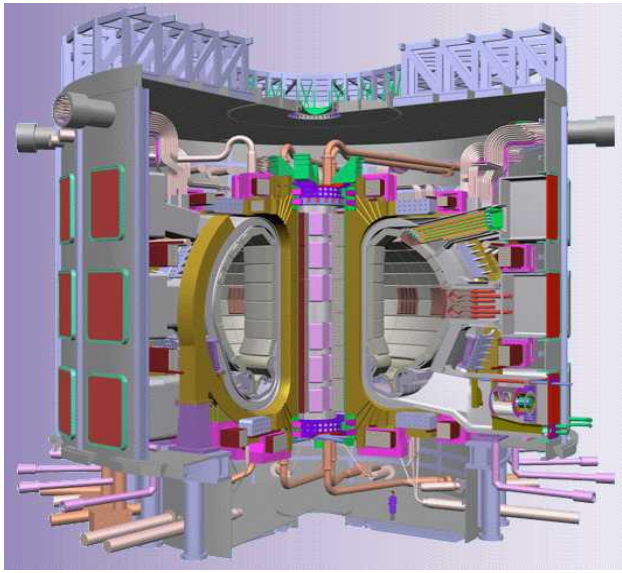
Japan: superconducting tokamak JT60-SA



Germany: superconducting stellarator W7-X

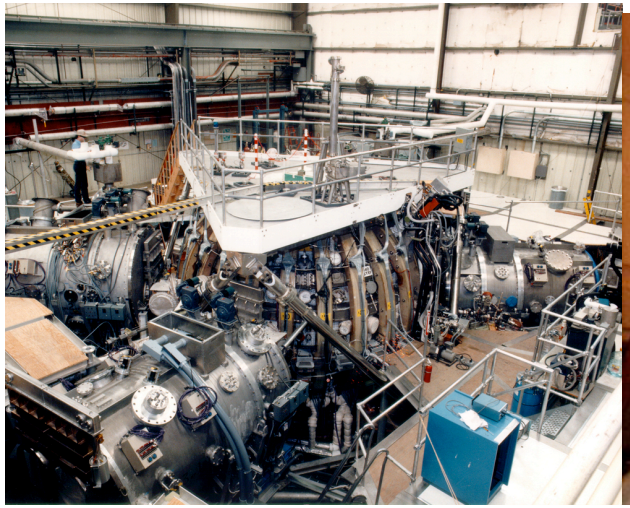


France: ITER



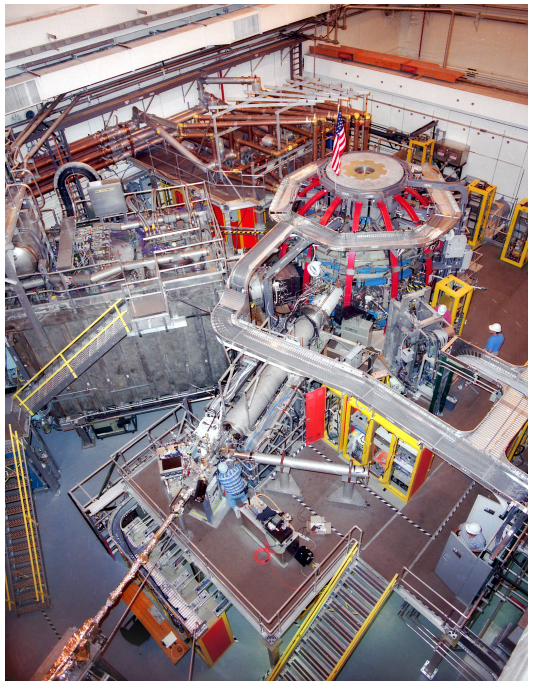
The US operates a strong set of medium-scale experiments

General Atomics: DIIID tokamak



MIT: CMOD tokamak

PPPL: NSTX spherical tokamak



- These facilities advance critical issues for ITER and beyond
- However, the 6 new facilities overseas are all more capable than the US facilities
- US contribution to the world fusion program is needed to meet the R&D challenges
- Reinvigoration of the US program is essential for US competitiveness in fusion

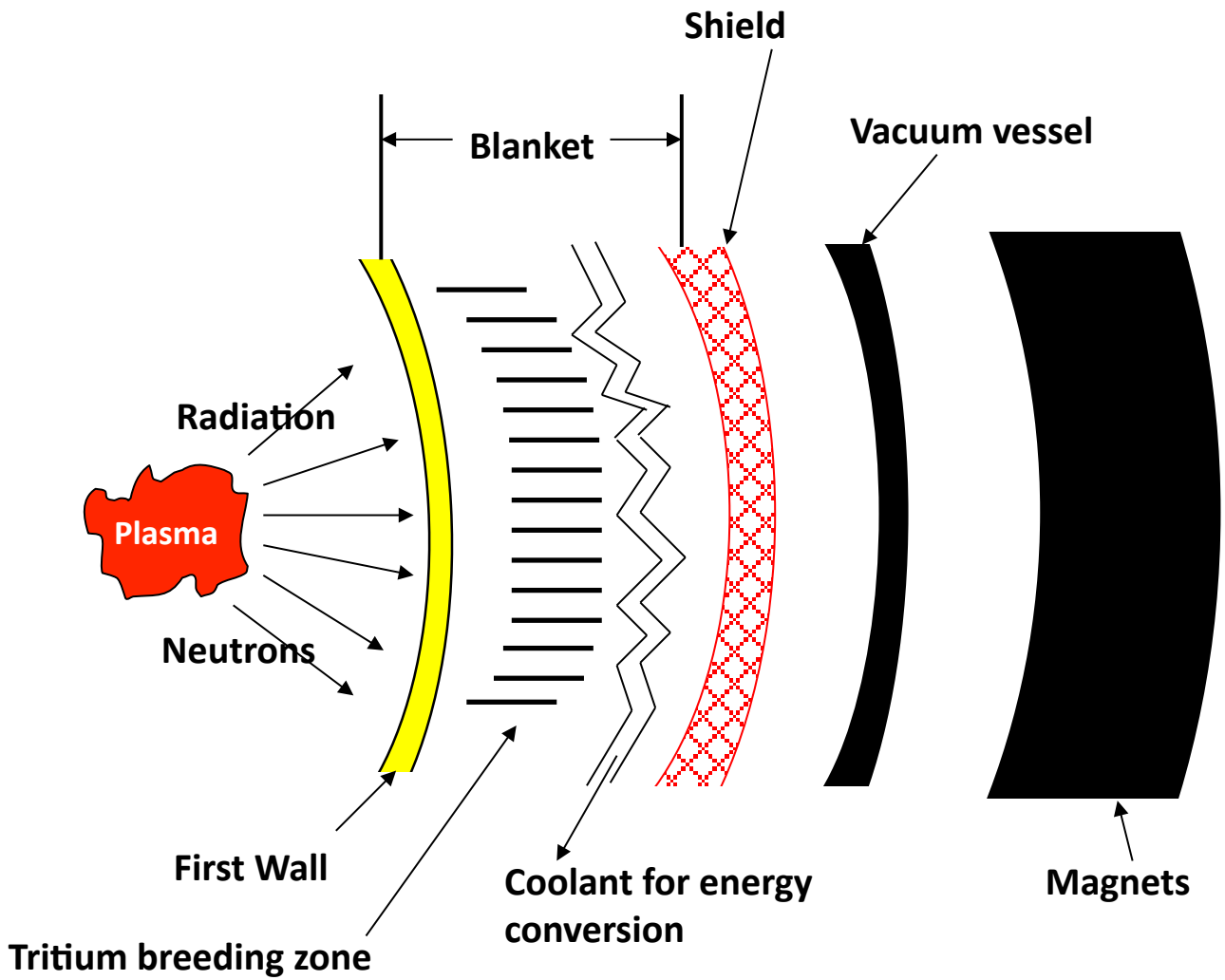
To conclude,

- A new branch of physics has been developed to advance fusion research

- Plasma conditions have been produced near the regime for energy production, we have made fusion power (16 MW for 1 second)

- *We are technically ready to shift into high gear to deliver commercial fusion power*

Backup slides


Shield
Blanket
Vacuum vessel
Radiation
Plasma
Neutrons
First Wall
Tritium breeding zone
Coolant for energy conversion
Magnets

Blanket (including first wall)

Blanket Functions:

A. Power Extraction
- Convert kinetic energy of neutrons and secondary gamma-rays into heat
- Absorb plasma radiation on the first wall
- Extract the heat (at high temperature, for energy conversion)

B. Tritium Breeding
- Tritium breeding, extraction, and control
- Must have lithium in some form for tritium breeding

C. Physical Boundary for the Plasma
- Physical boundary surrounding the plasma, inside the vacuum vessel
- Provide access for plasma heating, fueling
- Must be compatible with plasma operation
- Innovative blanket concepts can improve plasma stability and confinement

D. Radiation Shielding of the Vacuum Vessel

Blanket Materials

1. **Tritium Breeding Material (Lithium in some form)**

   Liquid: Li, LiPb (^{83}Pb ^{17}Li), lithium-containing molten salts

   Solid: Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3

2. **Neutron Multiplier (for most blanket concepts)**

   Beryllium (Be, $Be_{12}Ti$)

   Lead (in LiPb)

3. **Coolant**

   – Li, LiPb – Molten Salt – Helium – Water

4. **Structural Material**

   – Ferritic Steel (accepted worldwide as the reference for DEMO)

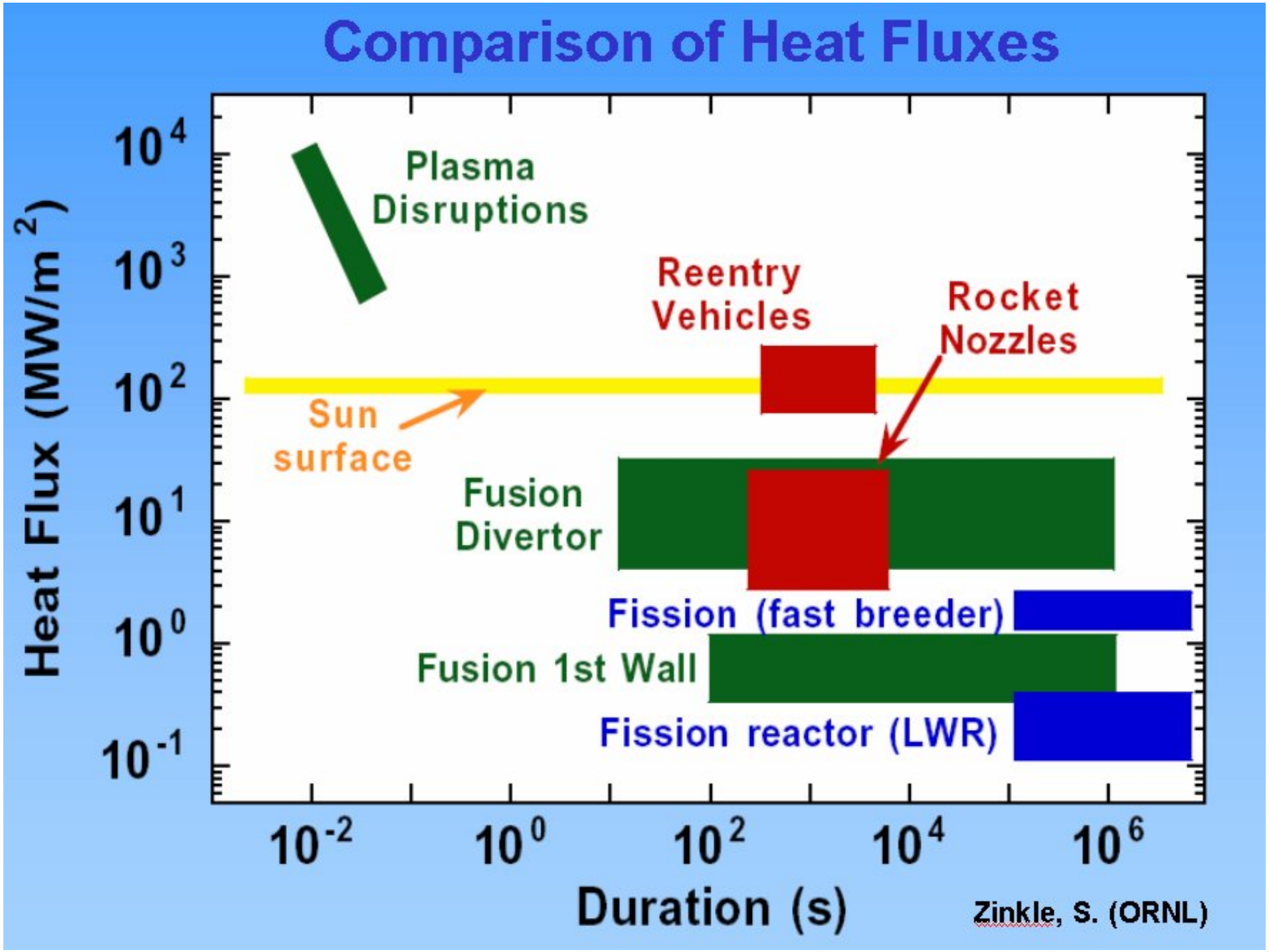
   – Long-term: Vanadium alloy (compatible only with Li), and SiC/SiC

5. **MHD insulators (for concepts with self-cooled liquid metals)**

6. **Thermal insulators (only in some concepts with dual coolants)**

7. **Tritium Permeation Barriers (in some concepts)**

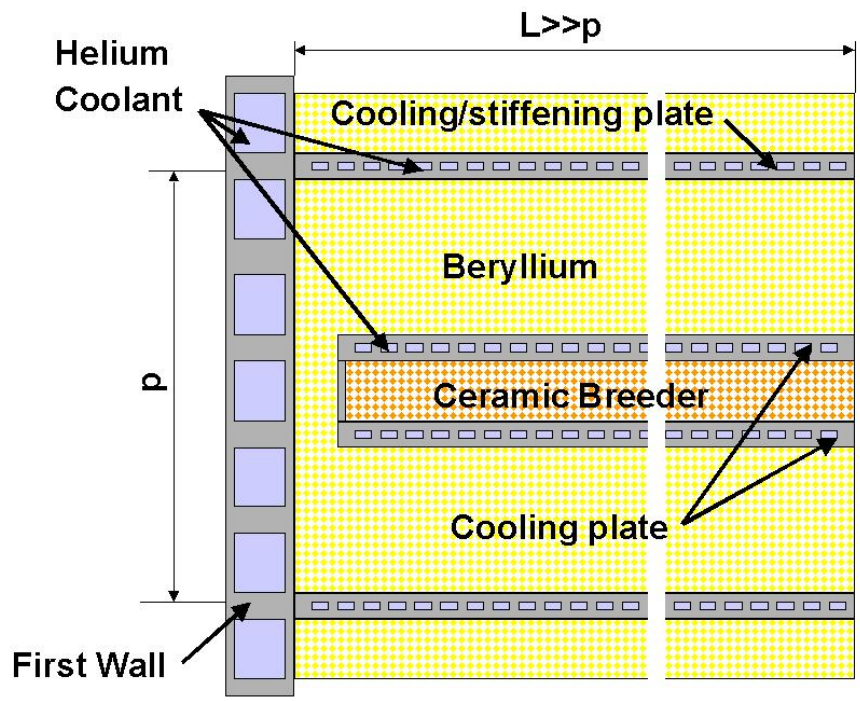
8. **Neutron Attenuators and Reflectors**


Comparison of Heat Fluxes
Heat Flux (MW/m 2)
10 4
10 3
10 2
10 1
10 0
10 -1
Plasma Disruptions
Reentry Vehicles
Rocket Nozzles
Sun surface
Fusion Divertor
Fission (fast breeder)
Fusion 1st Wall
Fission reactor (LWR)
10 -2
10 0
10 2
10 4
10 6
Duration (s)
Zinkle, S. (ORNL)

A Helium-Cooled Li-Ceramic Breeder Concept: Example

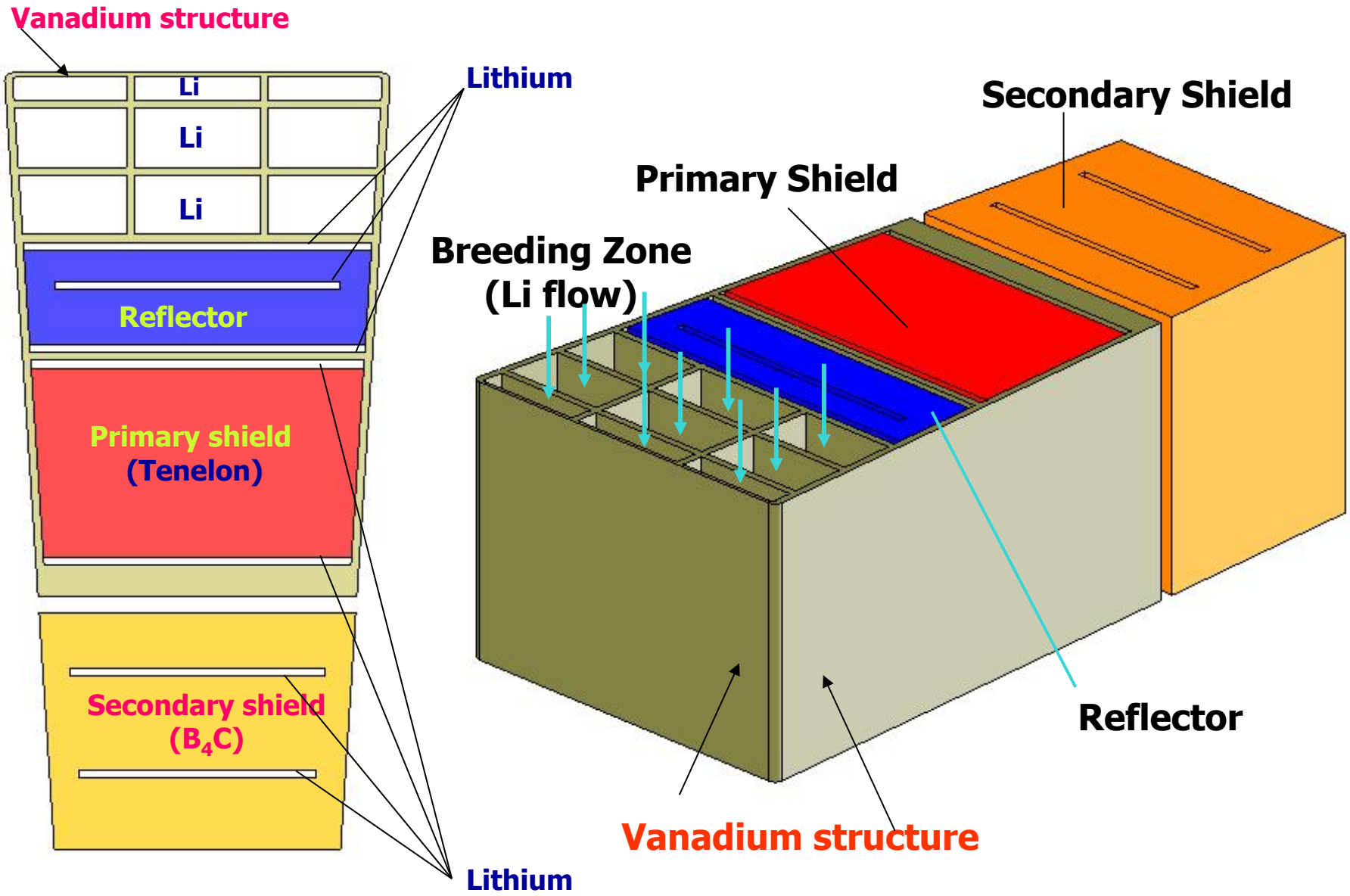
Material Functions

- **Beryllium (pebble bed) for neutron multiplication**
- **Ceramic breeder (Li_4SiO_4, Li_2TiO_3, Li_2O, etc.) for tritium breeding**
- **Helium purge (low pressure) to remove tritium through the "interconnected porosity" in ceramic breeder**
- **High pressure Helium cooling in structure (ferritic steel)**



Several configurations exist (e.g. wall parallel or "head on" breeder/Be arrangements)

Li/Vanadium Blanket Concept



Challenges in fusion power development

Physics:

- confine a plasma magnetically with 1000 m^3 volume
- maintain the plasma stable at 2-4 bar core pressure
- and with 15 MA current flowing in a fluid (tokamak)
- tame plasma turbulence to get the necessary confinement time

Technology:

- 200 Mill ^oC in the plasma core and 4K about 2 m away
- Build magnetic system at 6 T (max. field 12 T) with 50 GJ energy
- Handle n-fluxes of 2 MW/m^2 leading to 100 dpa (displacements per atom)
- Handle α-particle power of 10-20 MW/m^2 onto divertor targets
- Develop low activation material
- Develop T breeding technology
- Provide high reliability and availability of a complex system

The target parameter for fusion

The target of the fusion development obtained from power balance

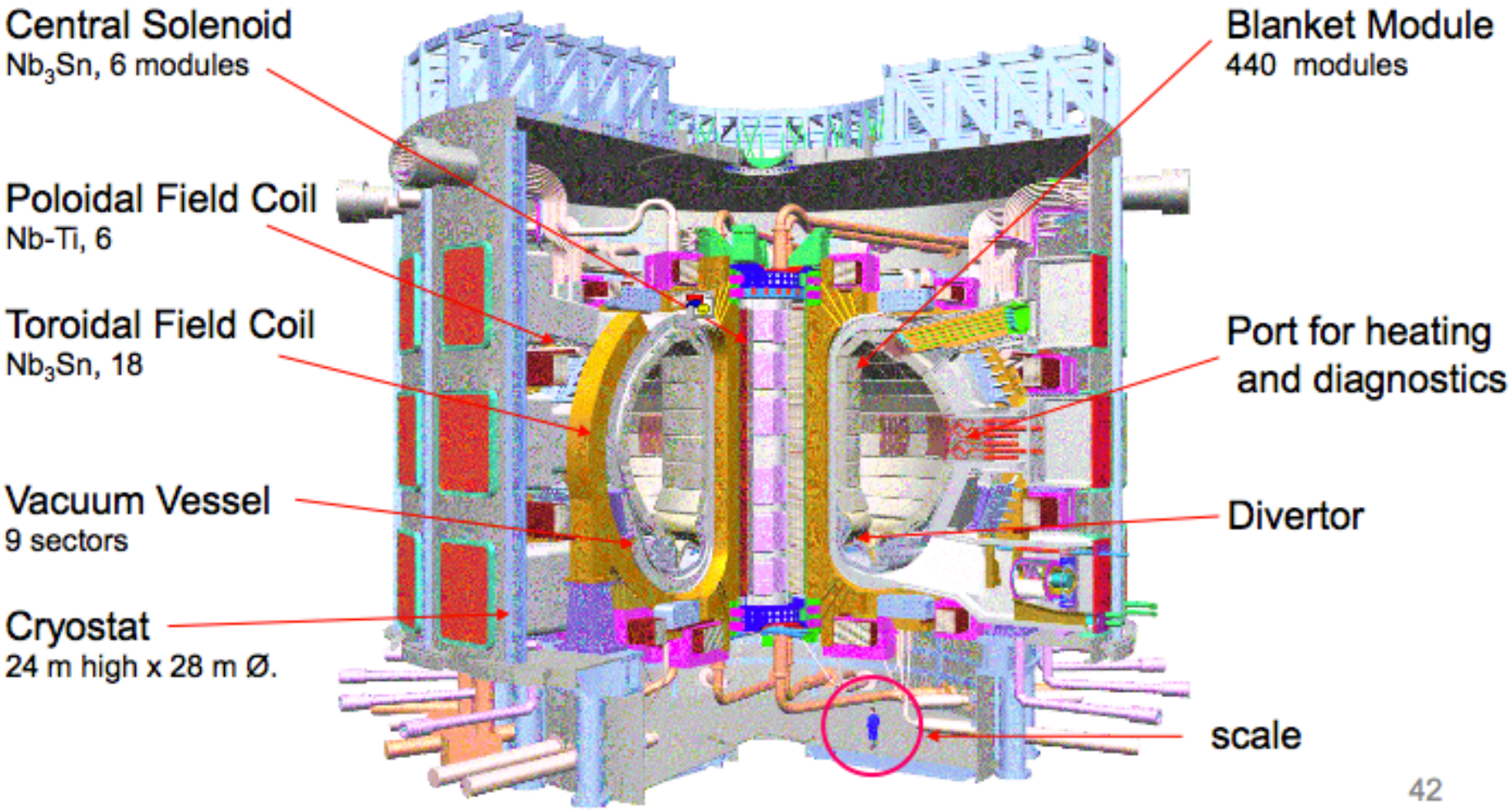
source: fusion power of α-particles (3.5 MeV)
sink: radiation and transport losses

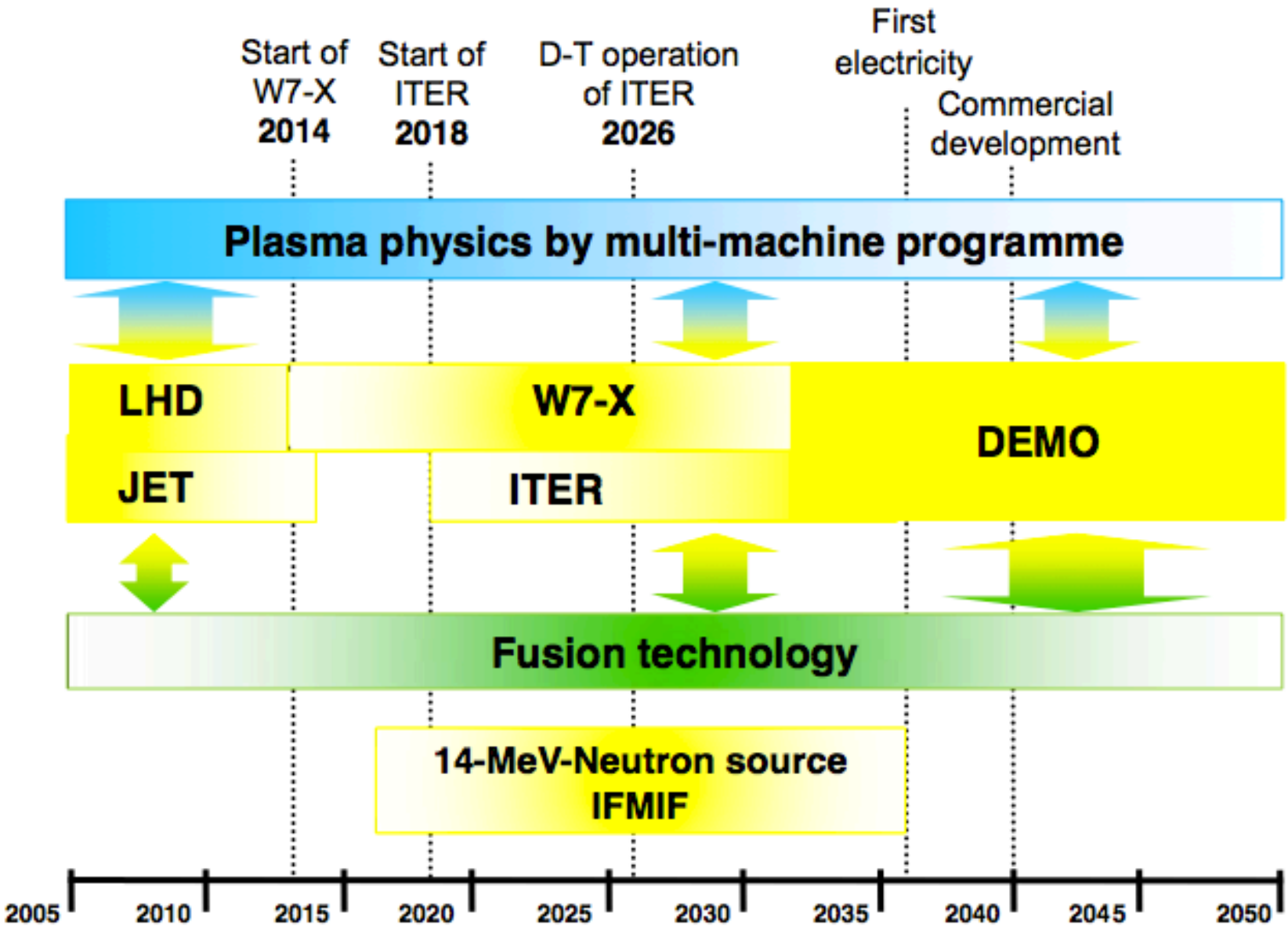
result = triple product: $nT\tau_E > 6\ 10^{21}\ m^{-3}\ keV\ s$

T: 200 Mill degrees required ➔ **400** Mill degrees achieved

n: 2 10^{20} particles/m^3 necessary ➔ **10^{21}** particles/m^3 achieved

τ_E is the energy confinement time – the time for the energy content to decay in case the heating is stopped. **A factor 4 is missing**.


Central Solenoid
Nb_3Sn, 6 modules
Poloidal Field Coil
Nb-Ti, 6
Toroidal Field Coil
Nb_3Sn, 18
Vacuum Vessel
9 sectors
Cryostat
24 m high x 28 m Ø.
Blanket Module
440 modules
Port for heating
and diagnostics
Divertor
scale


Start of W7-X 2014
Start of ITER 2018
D-T operation of ITER 2026
First electricity
Commercial development
Plasma physics by multi-machine programme
LHD
W7-X
DEMO
JET
ITER
Fusion technology
14-MeV-Neutron source IFMIF
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050

Topics beyond ITER

In physics :

- steady-state operation
- Tokamak: current drive with high efficiency

In engineering

- power exhaust
- T-breeding
- remote maintenance
- Reliability and availability

In materials

- ferritic steels optimised for low activation

In economics

- Demonstration of economic electricity prices

The physics of fusion is much more advanced than fusion technology

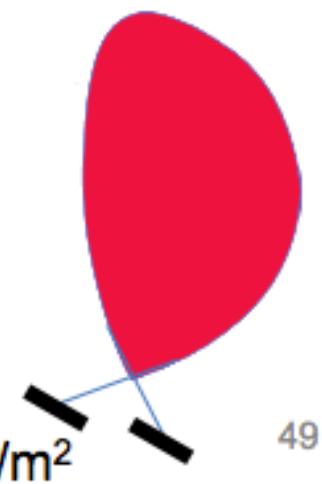
Reason: Technology investment only after demonstration of feasibility.

Issues:

(1) Structural materials – bombarded with 14 MeV neutrons at 2 MW/m^2

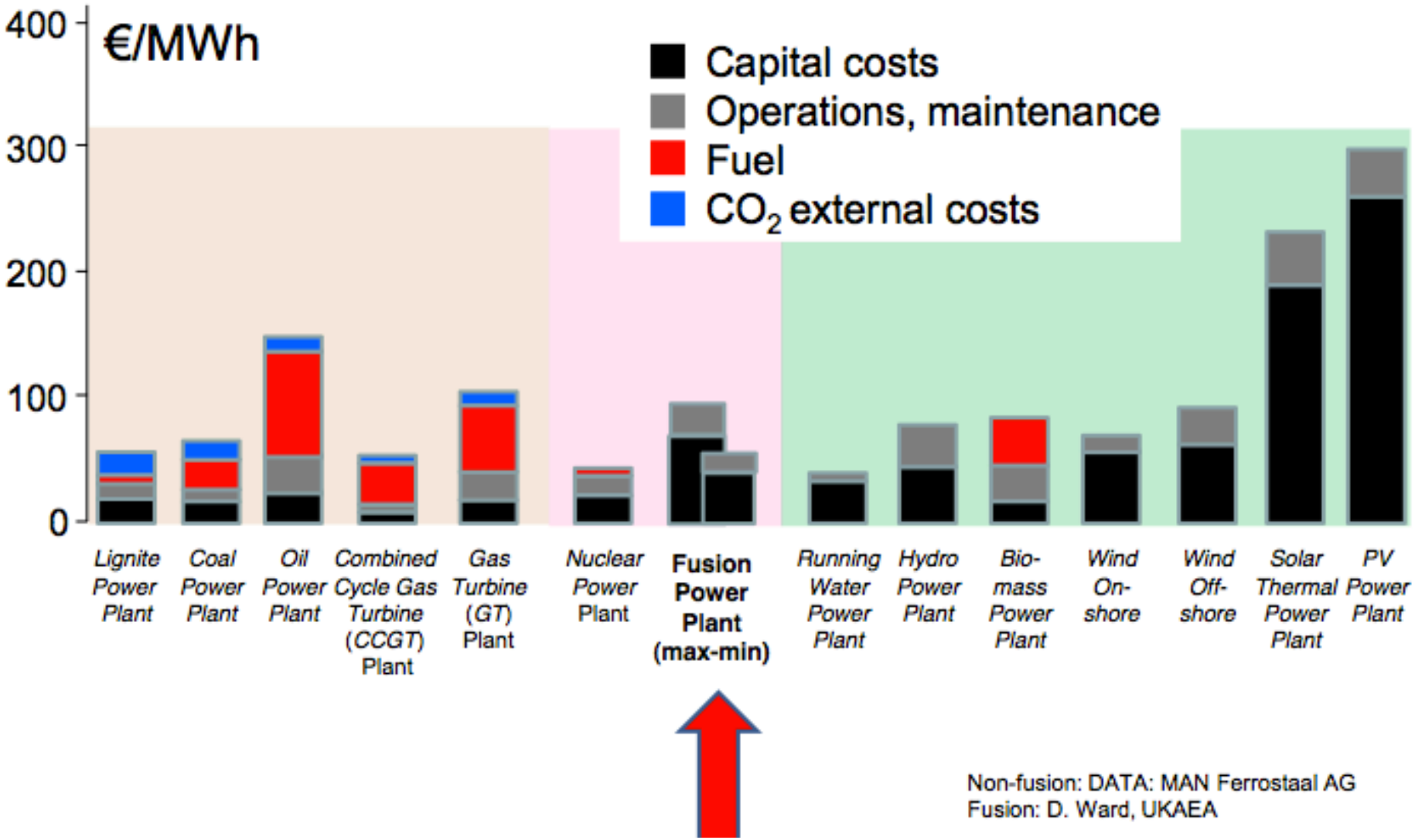
➔ production of lattice defects
30 dpa per year ➔ periodic exchange of first wall (blanket)
material damage ➔swelling, creep, hardening & embrittlement
nuclear reactions ➔ activation, inclusion of He and H

Structural material blanket	Eurofer	SiC/SiC	
Coolant	Water	Helium	LiPb
Breeder	LiPb	Li_4SiO_4	
Structural material divertor	CuCrZr	W alloy	



(2) High heatflux onto divertor targets 10-20 MW/m^2

Cost of fusion electricity



Non-fusion: DATA: MAN Ferrostaal AG
Fusion: D. Ward, UKAEA

Final comment

Fusion has a tremendous potential

There is a clear road-map to commertialize fusion
(of course, there is still no guarantee of final success)

ITER will answer open physics questions related to burNing plasmas

W7-X will demonstrate the quality expected from stellarator optimisation

ITER, IFMIF, DEMO: The programme will move away from science
more toward technology orientation

After the ITER physics and technology programme´- if successful –
fusion can be placed into national energy supply strategies:

Fusion ready by 2050: **YES**

With fusion, we hand over to future generations a clean, safe, sustainable and - in our expectations - economic power source accessible to all man-kind