







Fusion Energy
in a nutshell

Y. Martin

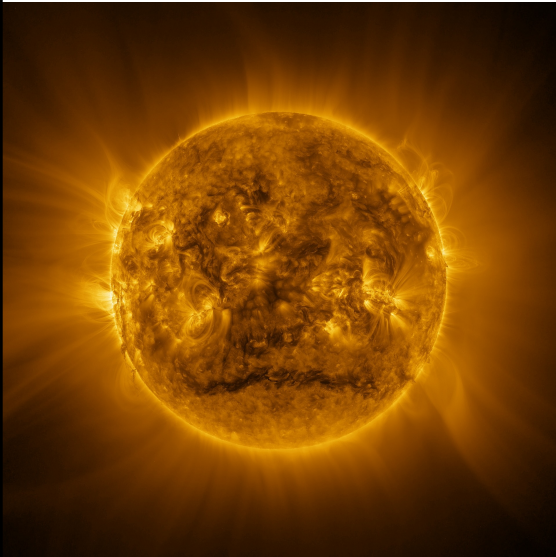
9 Septembre
2026



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Fusion energy





Idea – Goal

- Reproduce the Sun on Earth
- Light atoms fuse together
- Provide mankind with abundant, safe and environmentally-friendly energy
- A scientific and technological challenge

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Outline of the lecture

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- Basics of fusion reactions
- Confinement schemes and devices
- Plasma heating and measurement
- Current state of research
- Future steps
- Race to commercialisation

Outline of the course

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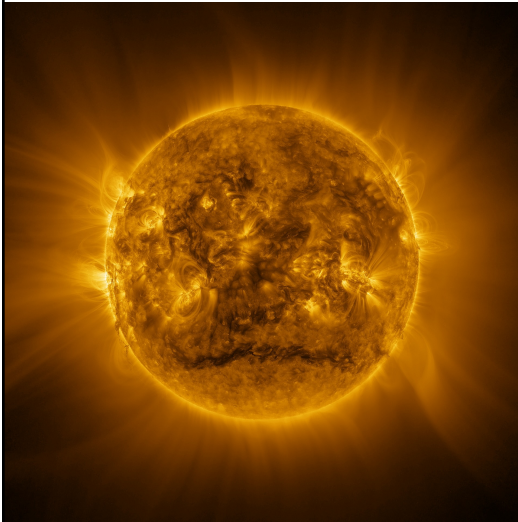
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Fusion reactions in the Sun

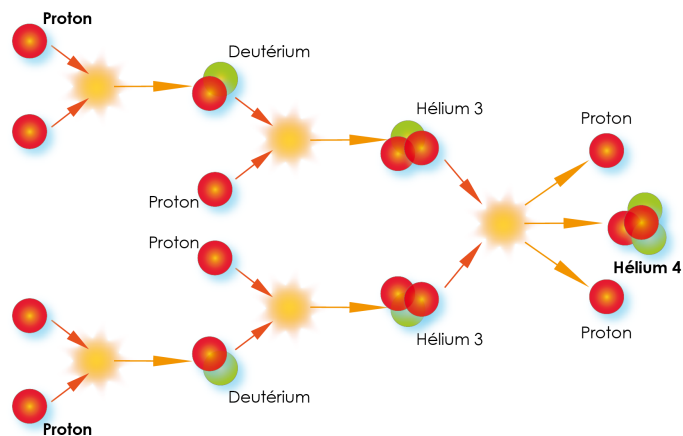
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- 1920: Arthur Eddington suggested Sun's energy comes from fusion of H to He
- 1939: Hans Bethe described proton-proton chain



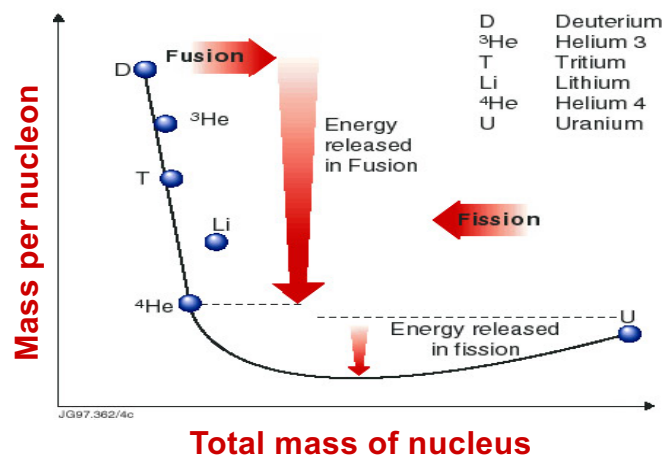
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Difference between Fusion and Fission

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- Nuclear binding energy
- Mass per nucleon
- $E = m c^2$



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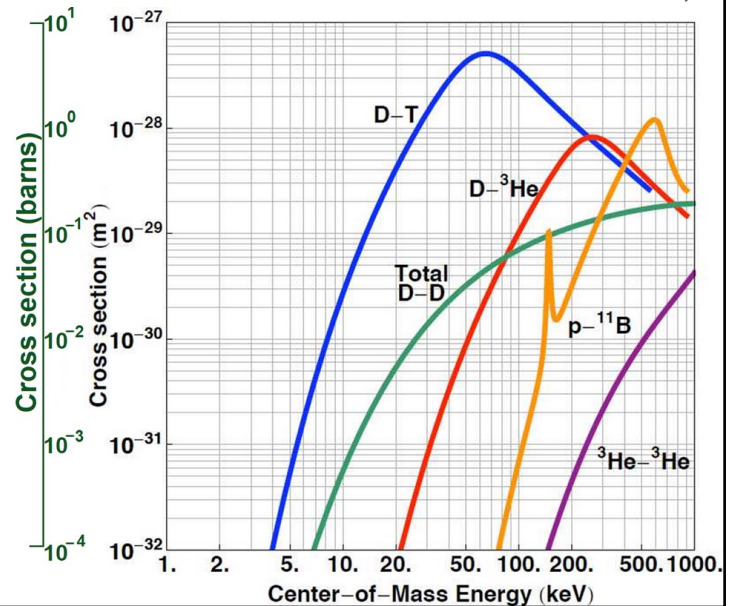
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Fusion reactions – cross section

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- Probability of fusion reactions
- DT reaction is the easiest
- 150M°C
- Lower than maximum
 - Tail of thermal distribution curve is enough
 - Magnetic pressure limits
 - Radiation losses



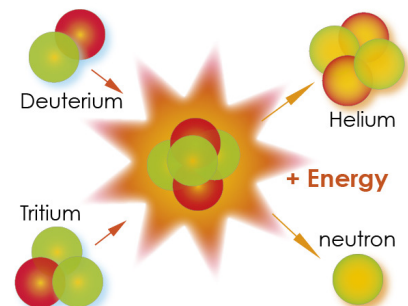
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D-T reaction

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- Deuterium (heavy H): from water (HDO)
 - 1D / 6500H; 33mg/l
- Tritium (super heavy H): radioactive, half life time of ~12.3y, not available in nature
 - T breeding: Lithium + n → T + He
- Fuel: Deuterium and Lithium (Li₆)
 - Almost inexhaustible



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Lawson criteria

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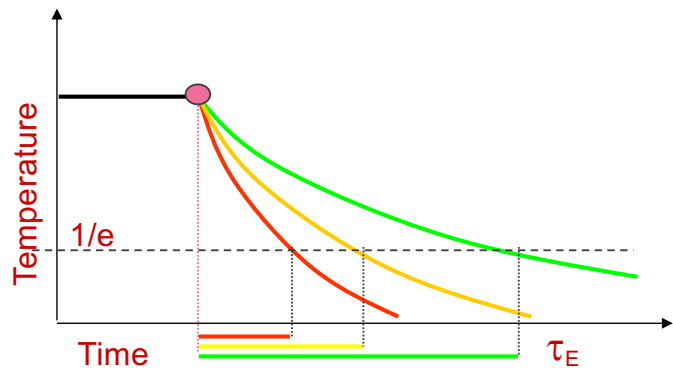
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System has to provide more power than consumed

- Fusion power $\gg$ Input power

Breakeven: $P_{\text{fus}} / P_{\text{in}} (= Q) > 1$

- $n \times T \times \tau > 10^{22} [\text{s/m}^3]$
 - n = plasma density
 - T = plasma temperature
 - τ_E = Energy confinement time



Energy confinement time

- How the energy remains in the plasma

Ignition

- $P_{\text{fus}(\alpha)}$ sustains the plasma temperature

Outline of the course

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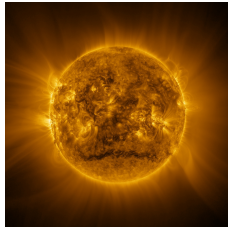
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- Basics of fusion reactions
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Confinement schemes

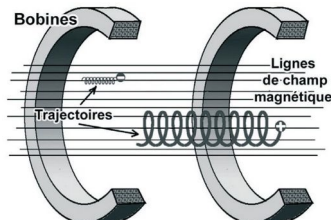
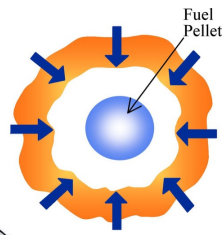
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Different ways to reach the Lawson criteria

- Gravitation (Sun, stars)
- Inertial confinement ($n \gg$, $\tau_E \ll$)
- Magnetic confinement ($n \ll$, $\tau_E \gg$)



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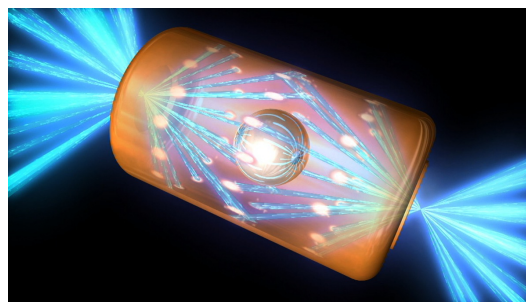
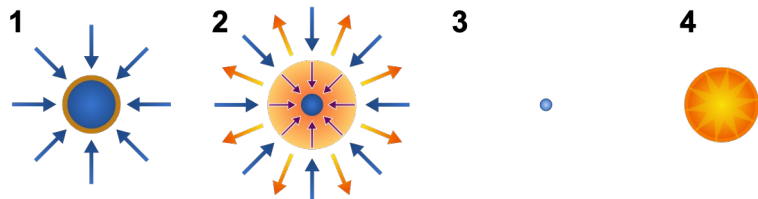
Inertial confinement

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Basic principles

- Direct drive
 - Lasers
 - DT pellet
- Indirect drive
 - Lasers
 - Hohlraum
 - X-rays
 - DT pellet



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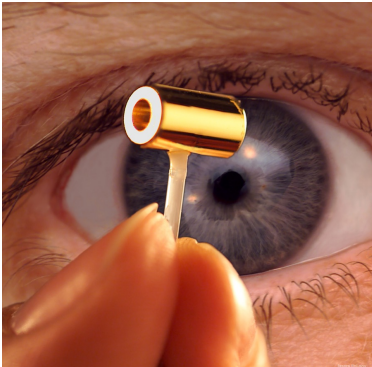
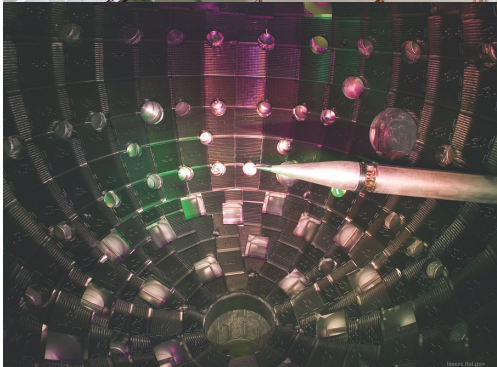
EPFL **Inertial fusion at NIF**

Set-up

- 192 lasers
- Vacuum chamber: 10m Ø
- DT pellet: 2mm Ø

Challenges

- Positioning
- Instabilities

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EPFL **Inertial fusion at NIF**

World record in fusion

- $Q \sim 4$ in Feb 2025

But ... path to power plant is long

- Q_{Elec} ?
 - Laser efficiency is very low
- Repetition rate ?
 - So far, 1-4 experiment / day
 - ... 1 – 10Hz
 - ... 20 – 100 MJ / pellet



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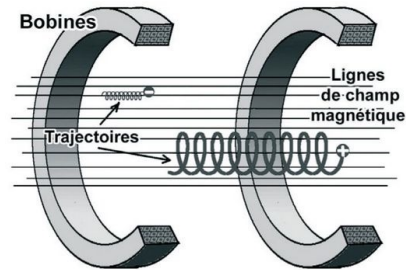
Magnetic confinement

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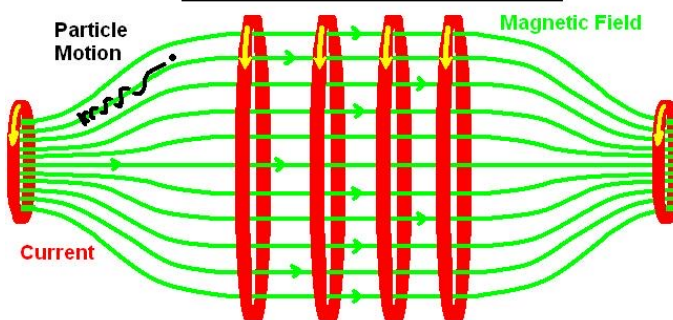
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Linear devices

- Solenoid
 - All particles lost at the end
- Mirror machines
 - Some particles lost at the end



Basic Magnetic Mirror Machine:



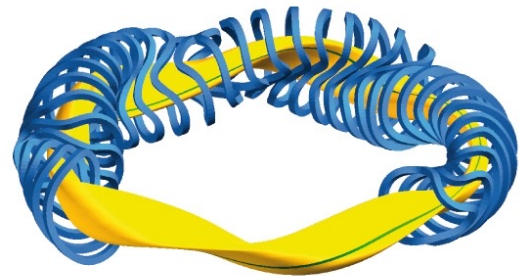
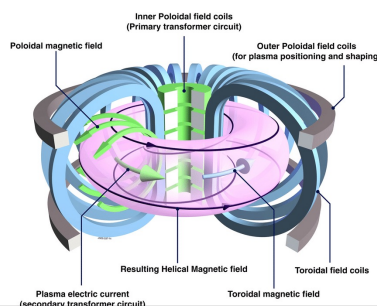
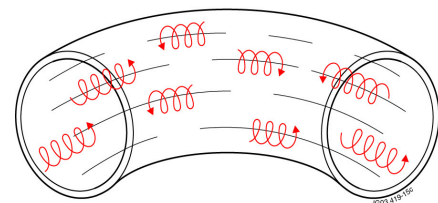
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Toroidal configurations

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- Closed magnetic field lines
- But vertical drift
 - Non-homogeneous toroidal field, $B_\phi \propto 1/R$
 - $\mathbf{v} \propto \mathbf{B} \times \nabla B$, $\mathbf{E} \times \mathbf{B}$
- Need twisted magnetic field lines
 - Tokamak
 - Stellarators



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Magnetic confinement – tokamak

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To-Ka-Ma-K

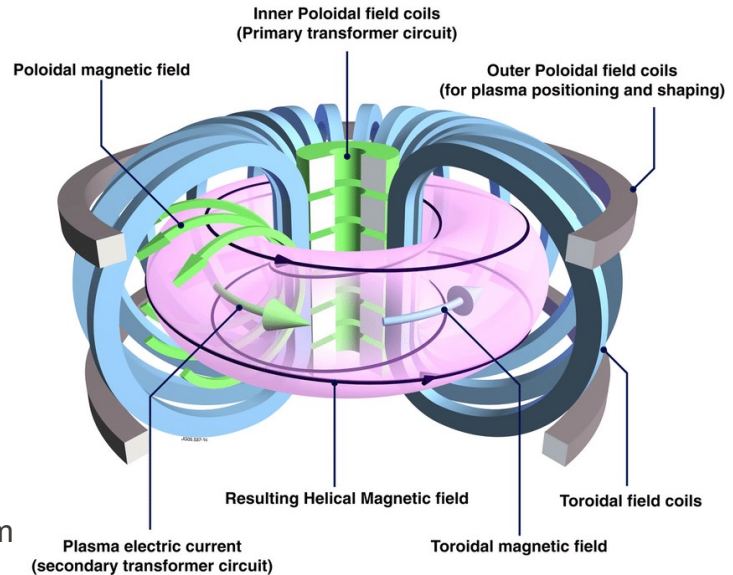
- Toroidalnaja Kamera Magnetrnaja Katuska

Principle

- Vacuum vessel
- Magnetic fields (MF)
 - Toroidal MF coils
 - Poloidal MF coils
 - Position and shaping coils

Size

- R, major radius, 0.4 – 3m
- r, minor radius, R / 3



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Magnetic cage

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Magnetic fields

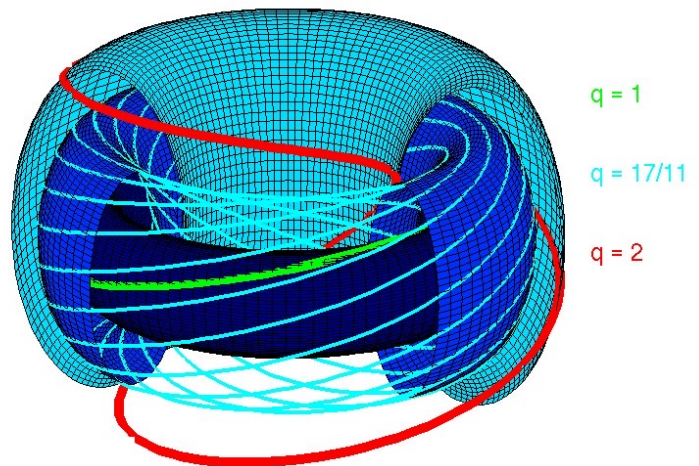
- Toroidal field $B_\phi \propto 1/R$
- Poloidal field $B_\theta \propto r$

Magnetic shear

- Angle of magnetic field lines varies in the radial direction
- Series of nested tori

Pressure gradient

- 1×10^{-4} mb at edge
- 1 atm on magnetic axis



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Outline of the course

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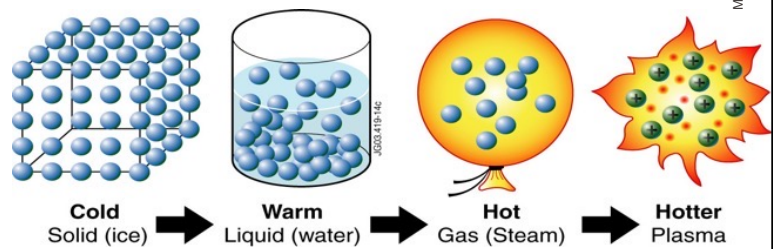
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Plasma

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4th state of matter

- ions + electrons
- Collective phenomena
- 99% of visible part of Universe
- Low pressure



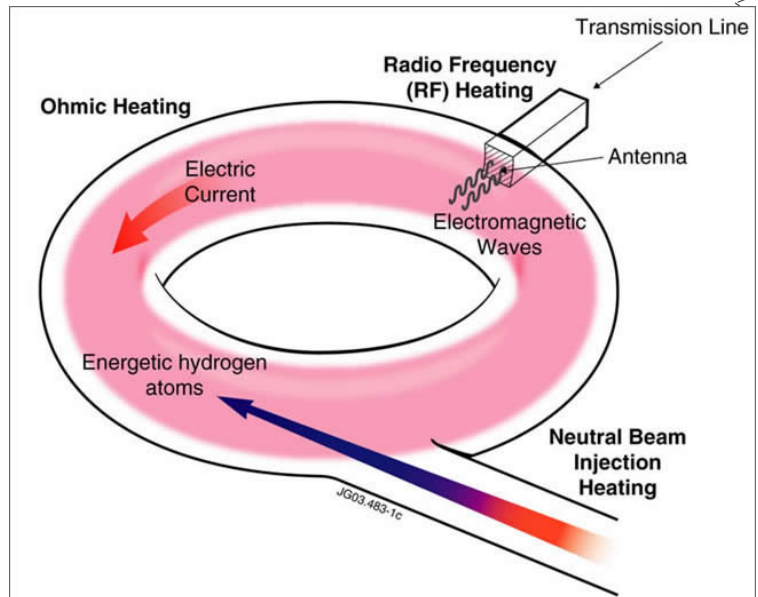
Plasma heating

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Different heating methods

- Ohmic heating
 - $R \propto T_e^{-3/2}$
- Neutral beams
- Microwaves
 - Electron Cyclotron Resonance Heating
 - Ion Cyclotron Resonance Heating



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Neutral beam injection (NBI or NBH)

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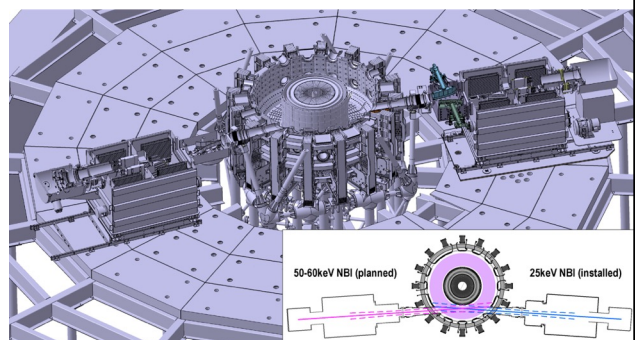
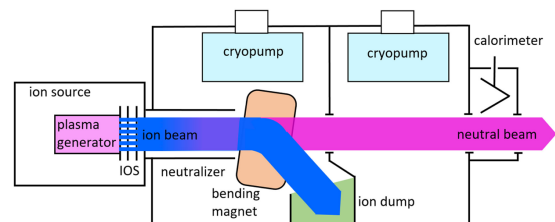
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Principle

- Injection of highly energetic Deuterium ($T_b \sim 10 \times T_i$)
- Collisions to distribute the energy

Set-up

- Deuterium plasma
- Acceleration grids
- Neutralisation (charge exchange)
- Ionisation
- 2 x 1MW



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Electron cyclotron resonance heating (ECRH or ECH)

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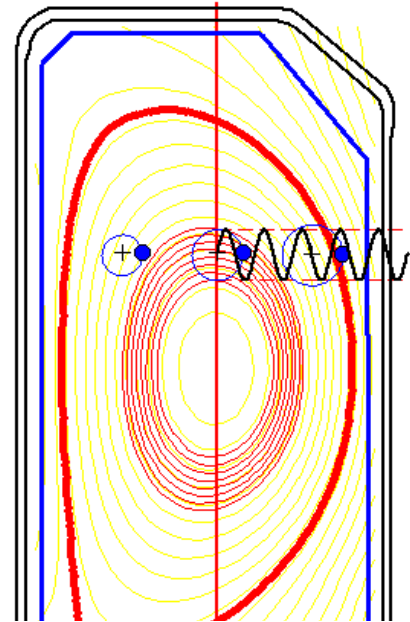
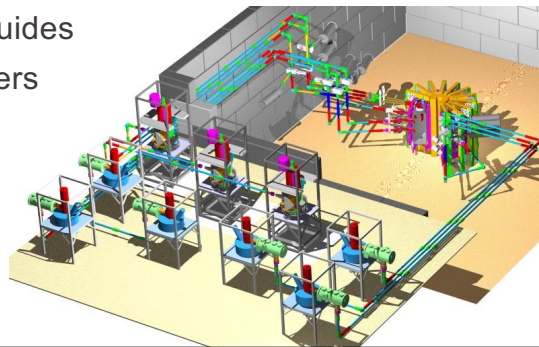
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Principle

- Resonance between EM wave and gyro-motion of electrons ($\sim 100\text{GHz}$)

Set-up

- Microwave sources (gyrotrons)
- Wave guides
- Launchers
- 3.5MW

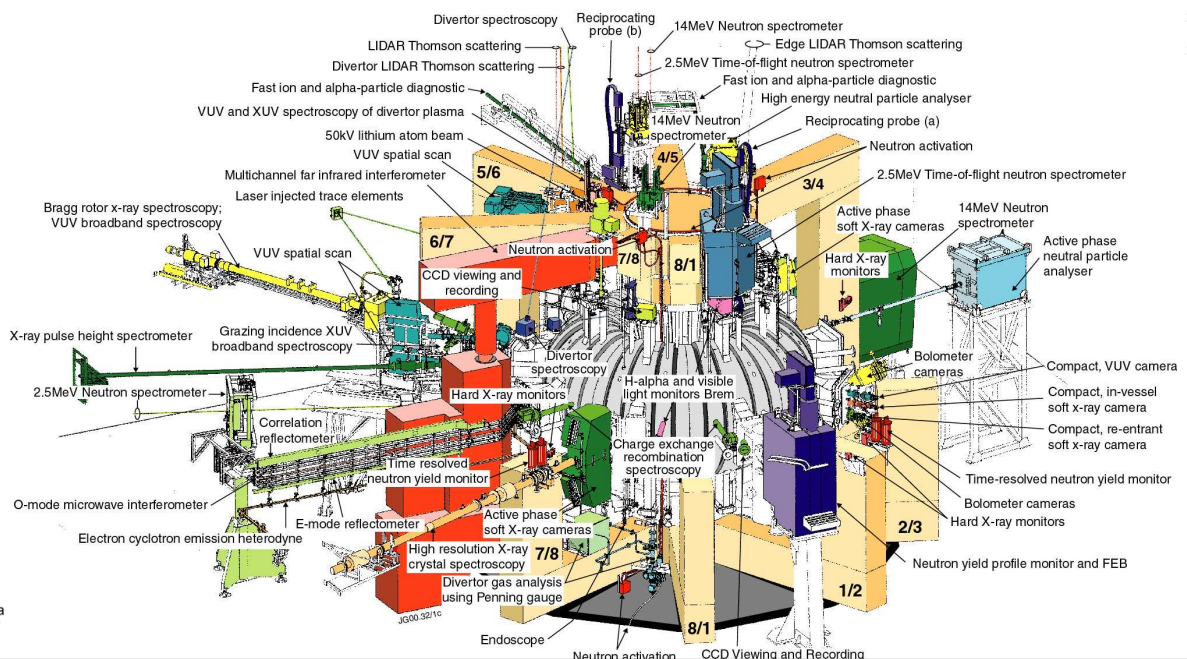


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Measurement systems

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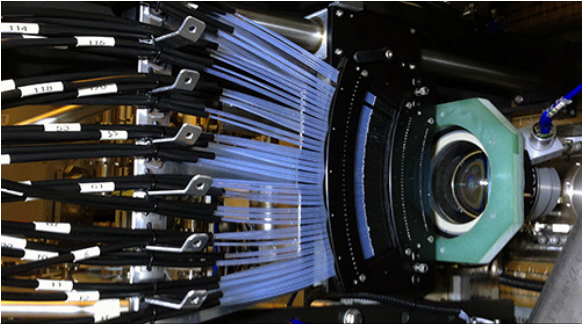


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EPFL **Measurement of T_e**

Thomson scattering

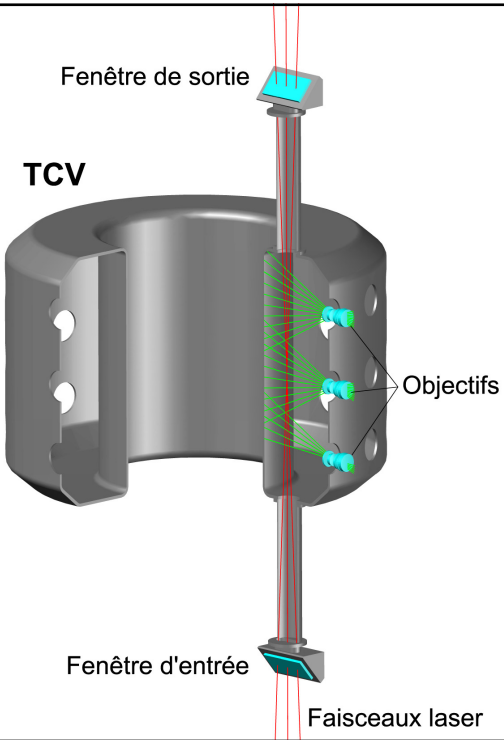
- Pulsed infrared laser beam
- Doppler effect on electrons
- Broadening of spectrum
- Multi-channel (>130)
- Poloidal and toroidal symmetries



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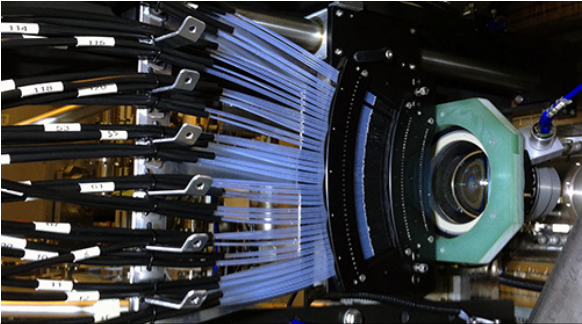


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EPFL **Measurement of density**

Far Infrared Interferometry (FIR)

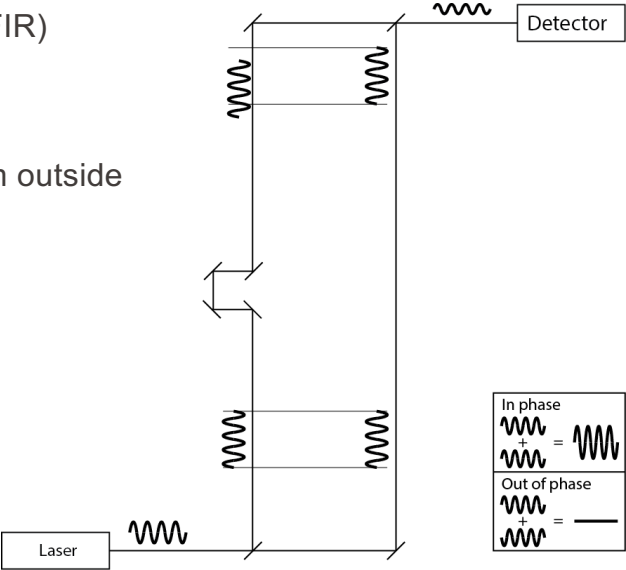
- Laser beam
- Beam splitter
- 1 beam in tokamak, 1 beam outside
- Recombination of beams
- Fringe count



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Outline of the course

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Tokamak à Configuration Variable – TCV

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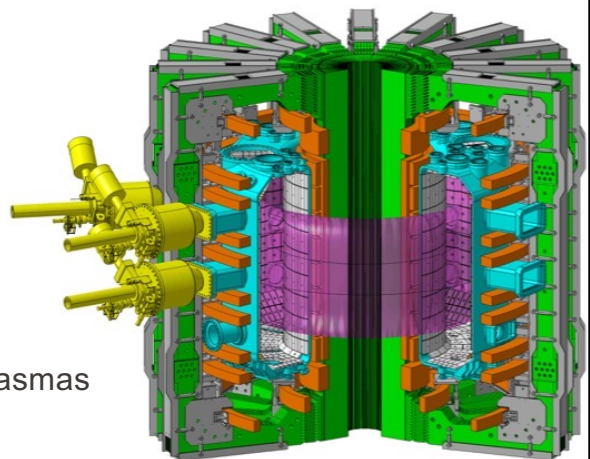
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Set-up

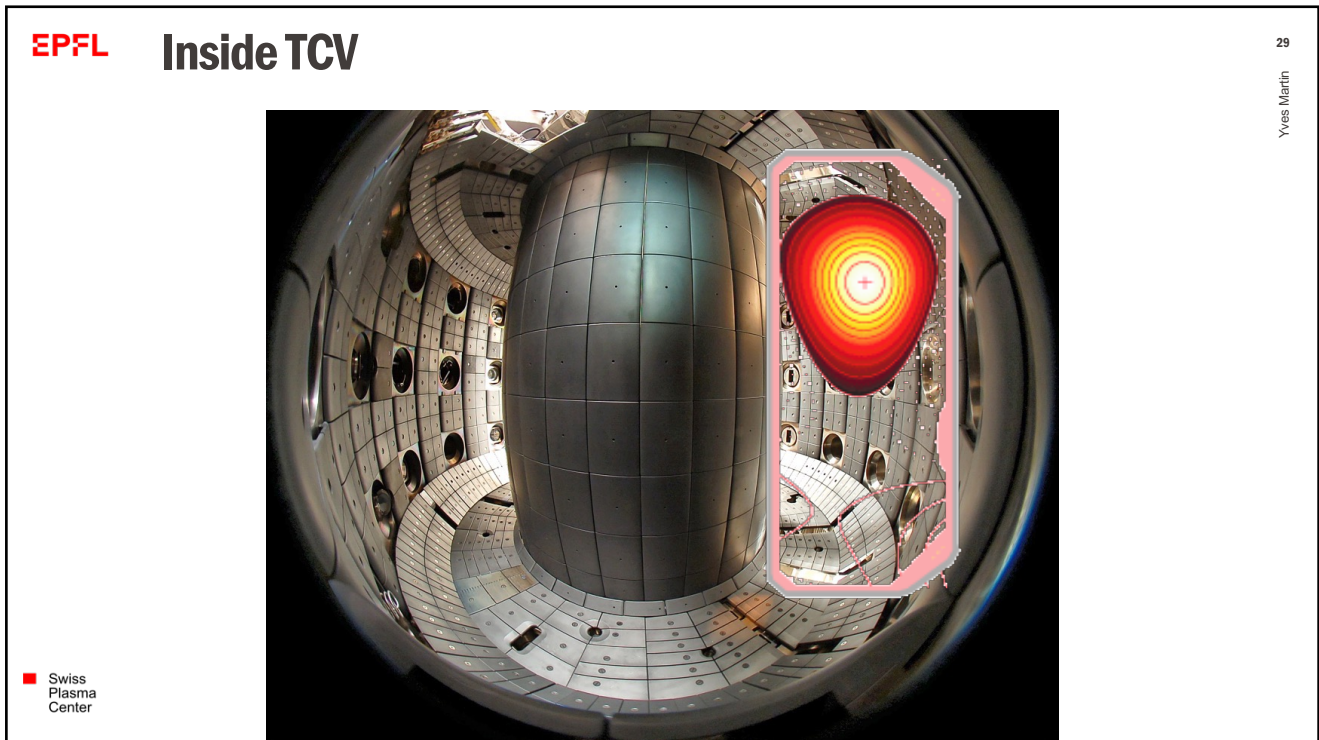
- Medium-size tokamak ($R=0.9\text{m}$)
- 16 poloidal field coils
- $B_\phi \leq 1.5\text{T}$, $I_P \leq 1\text{MA}$
- ECH (3.5MW) & NBH (2MW)
- European device

Scientific goals

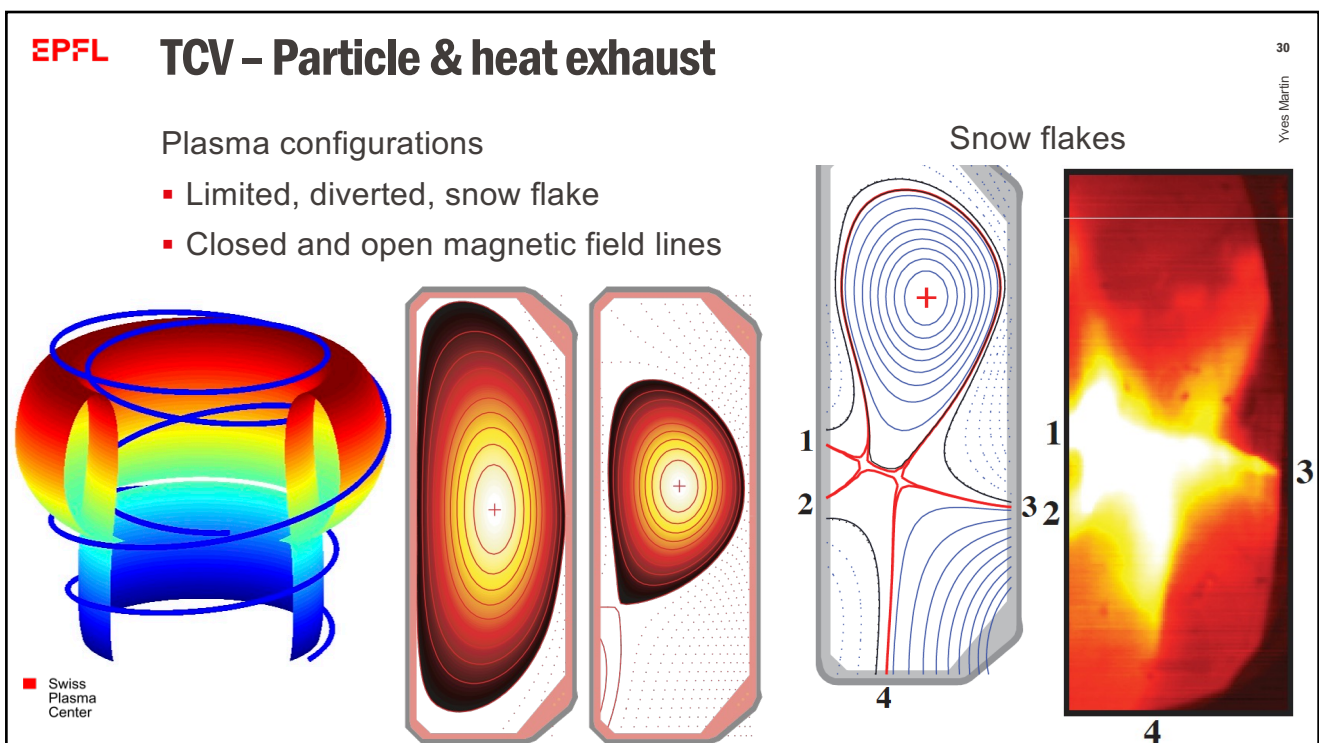
- Better understanding of Deuterium plasmas
- Innovative plasma shapes
- Influence of plasma shape on its characteristics
- Particle & heat exhaust



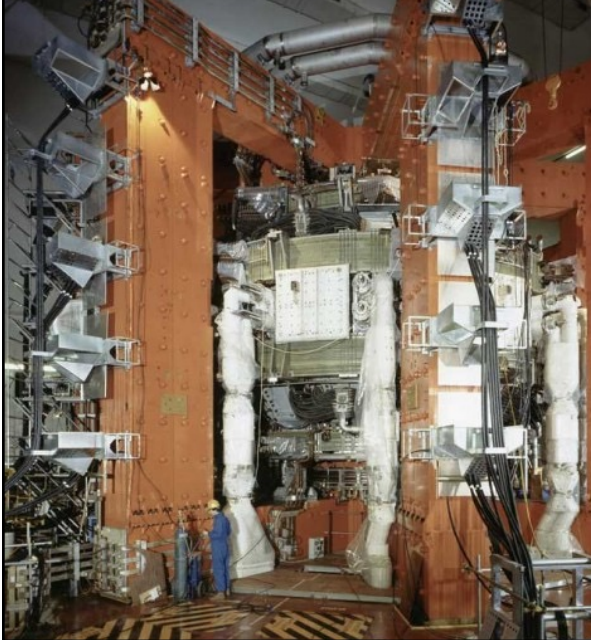
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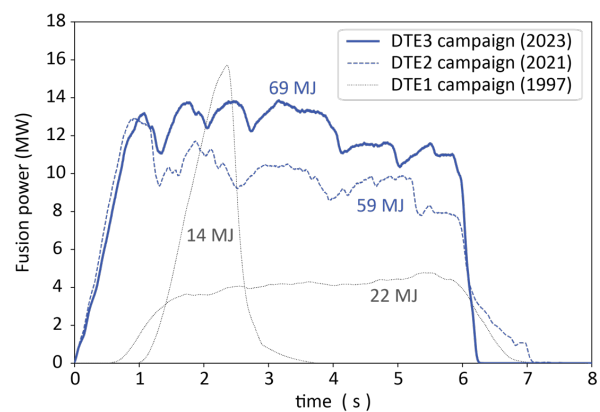
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- Largest tokamak having operated
- Stopped at end 2023 after 40 years
- D-T operation
- World record of fusion energy



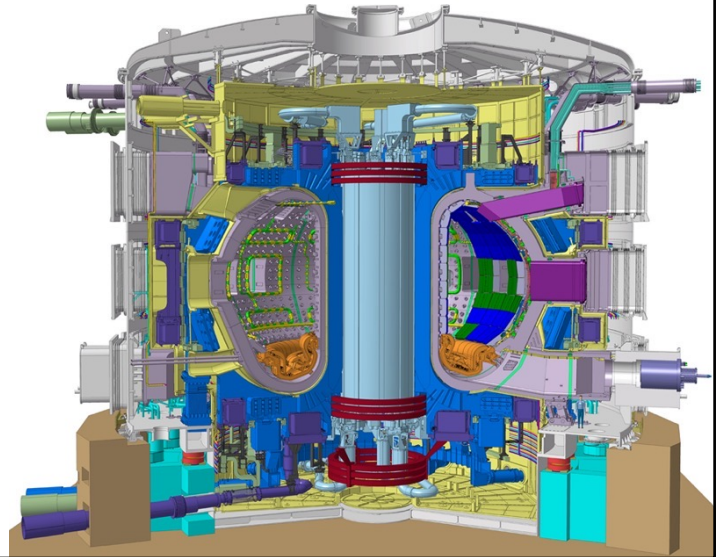
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ITER – Goals & characteristics

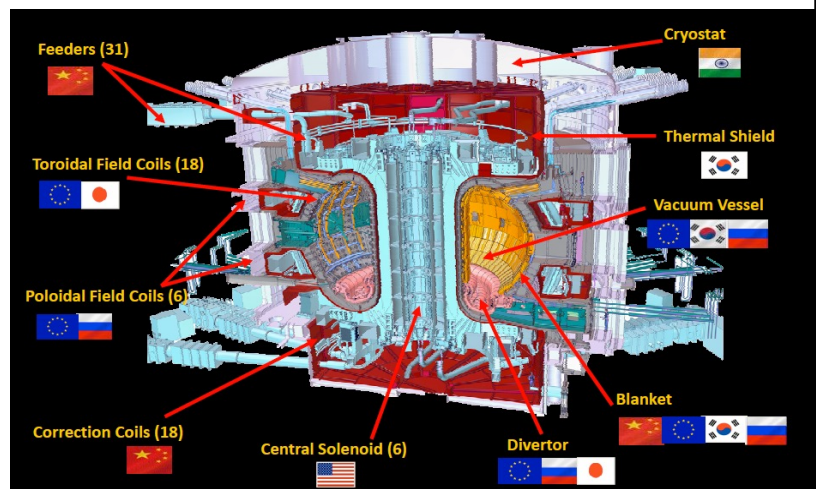
- Proof of scientific and technological feasibility of fusion
- $Q \sim 10$; $P_{\text{fusion}} \sim 10 \times P_{\text{injected}}$
- $P_{\text{fusion}} \sim 500\text{MW}$, 400s
- Heating by α -particles
- Tests of tritium breeding
- $R \sim 6.2\text{m}$
- $I_p \sim 15\text{MA}$
- Superconducting coils
- $P_{\text{add}} \sim 73\text{MW}$



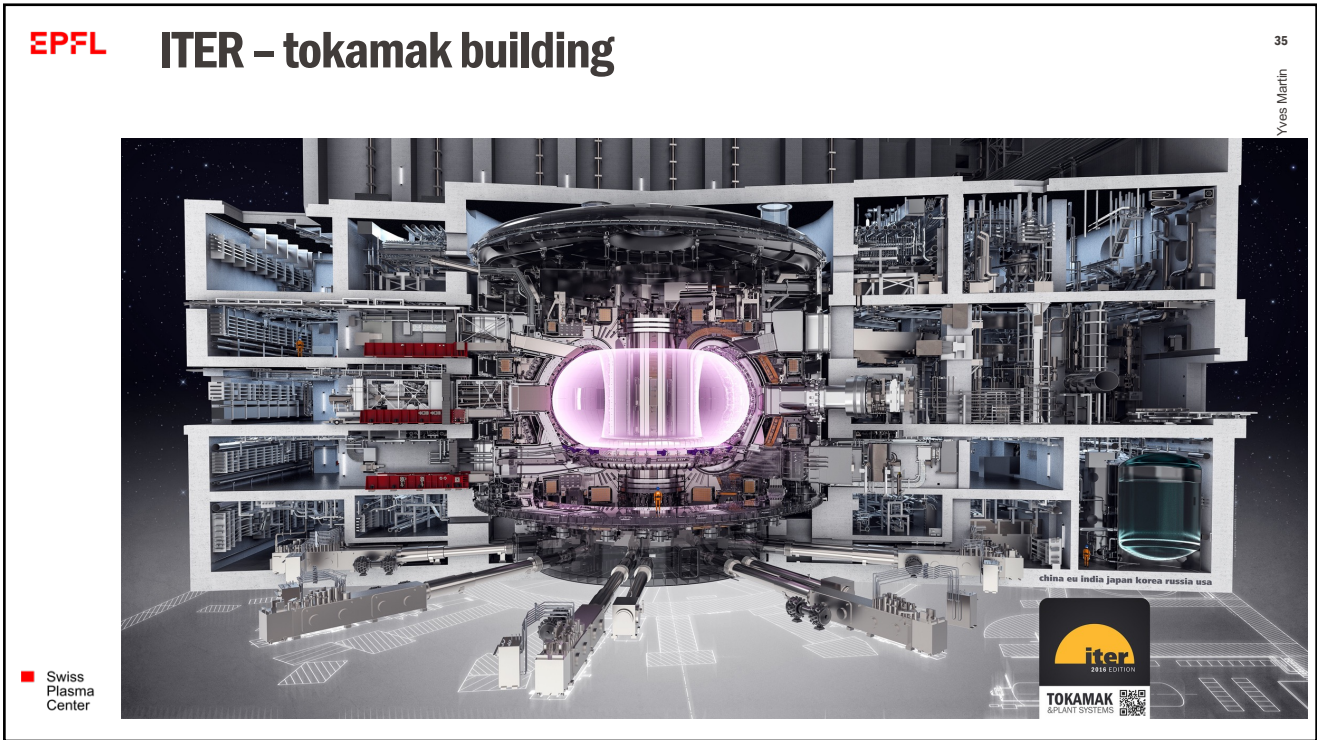
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ITER – organisation

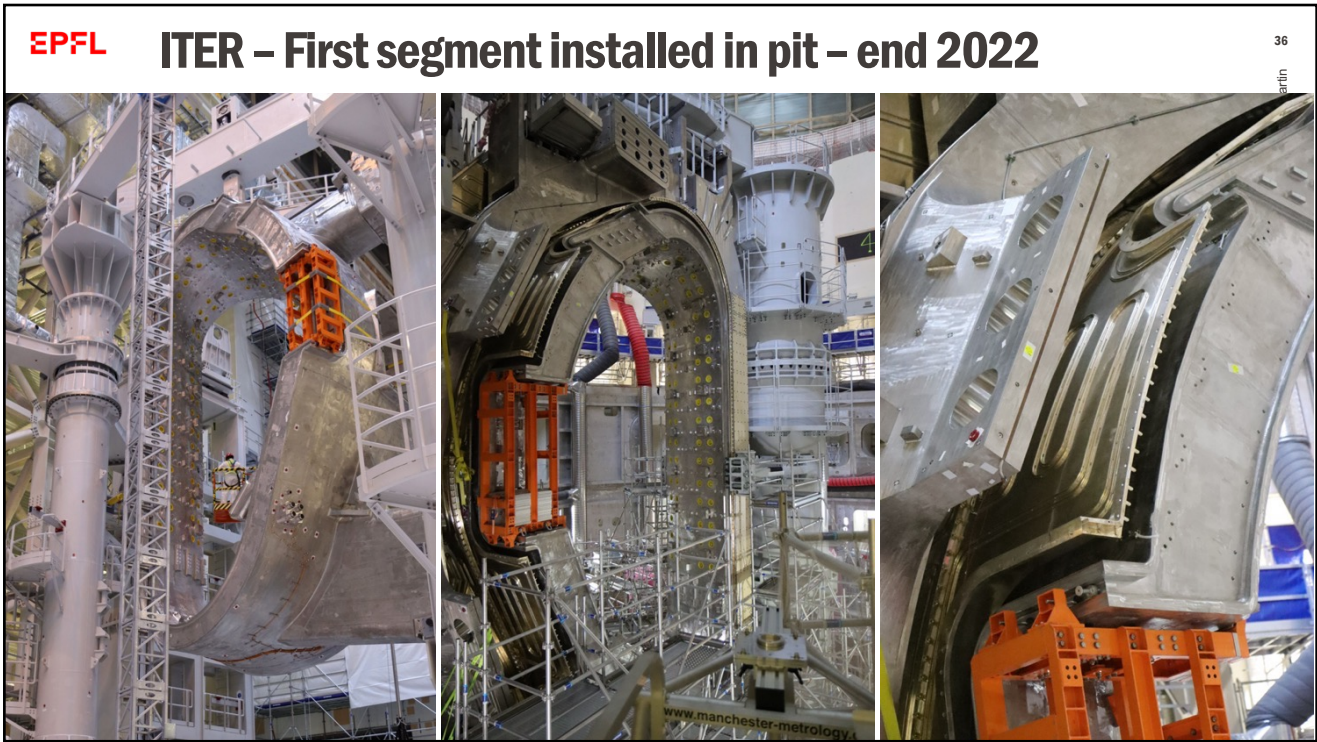
- International collaboration: Japan, Korea, China, India, Russia, EU, US
- In-kind procurement
- Cost $\sim 25\text{b€}$
- EU: 40%
- Assembly phase
- 1st plasma in 2034
- D-T in 2039
- Cadarache, France



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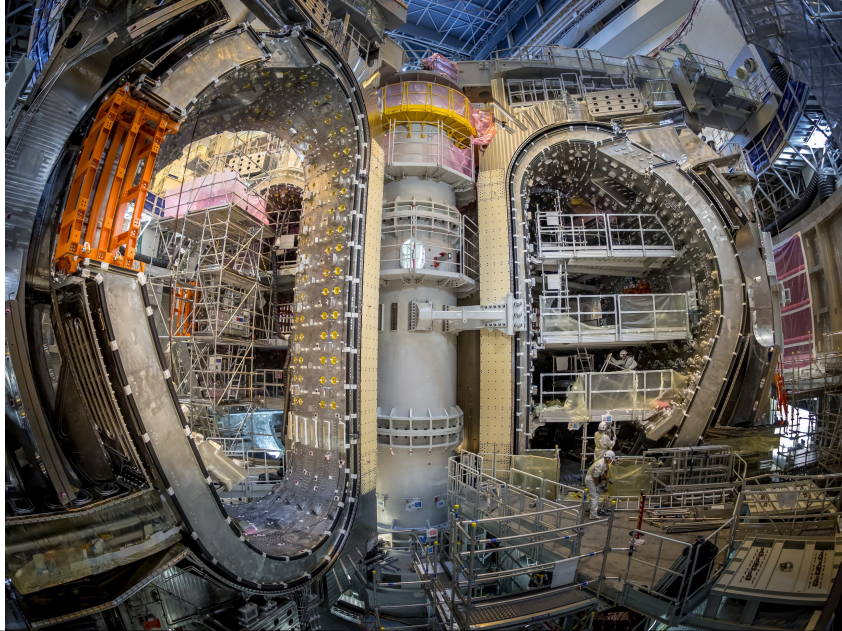


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ITER – Six segments installed in pit – July 2026

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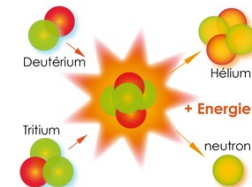
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Energy production

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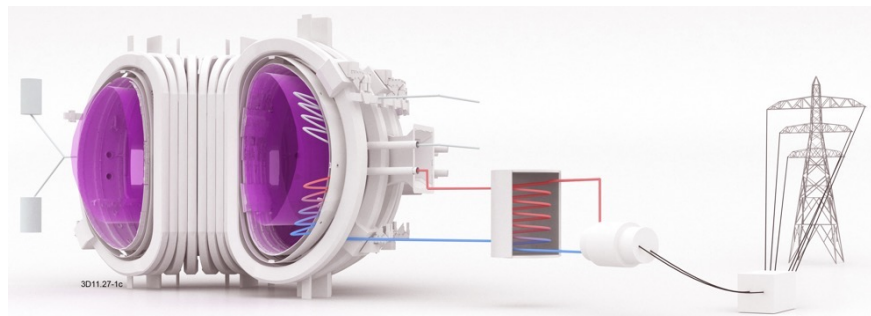
■ D-T reaction

- Kinetic energy
- Helium, confined, plasma heating
- Neutron, exits plasma, enter blanket modules
 - Slowed down, heat, heat transfer fluid, turbine, electricity
 - Collision with Lithium, tritium production



■ Safety

- No chain reaction
- Little fuel inside the reactor
- No waste requiring long-term storage



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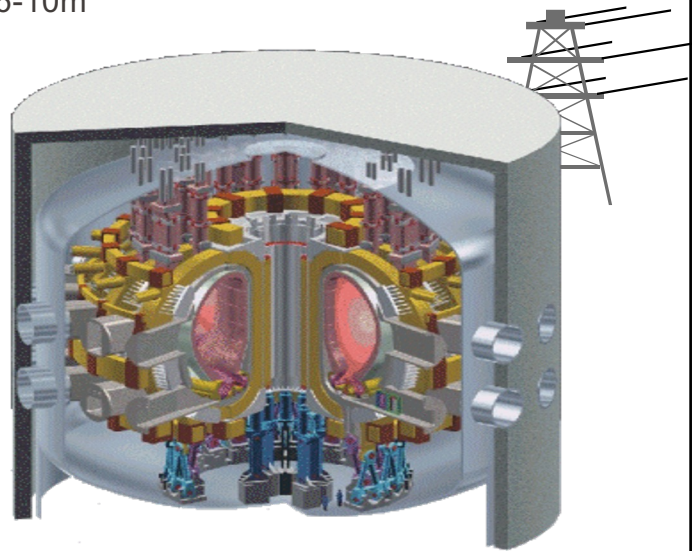
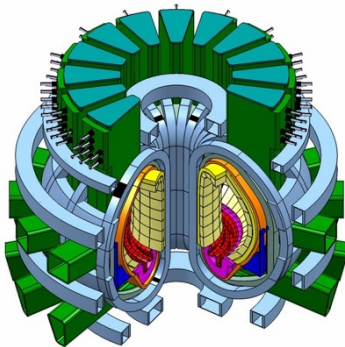
DEMO – design

- Prototype of a commercial reactor
- $Q \sim 40-60$; $P_{\text{elec}} \sim 1\text{GWe}$; $R \sim 6-10\text{m}$
- Design on-going
- Electricity production ~ 2050



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Outline of the course

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Public Private Partnerships (PPP)

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EU (and CH) vision: transfer of technology via PPP

- ITER: Science (public) – providers (private)
- DEMO ($P_{\text{Elec}} \sim 500 \text{ MW}_e$, 24/7, Tritium self-sufficiency, ...)
 - PPP for design, device, heating systems, measurement systems, 1st wall, Tritium cycle, ...
- Future reactors: private (with participation of state)

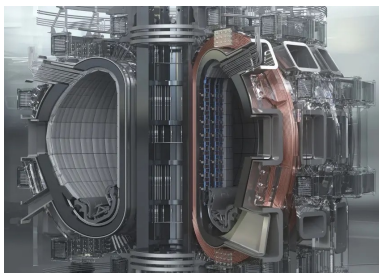
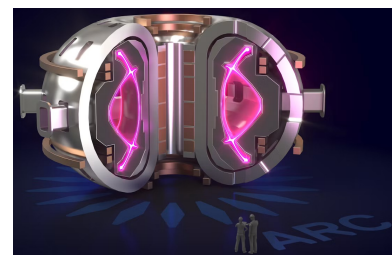


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Commercialisation of fusion energy

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- Numerous start-ups (~60, 14b\$)
 - Diversity of fusion systems; supply chain
 - In US: CFS (2018, 4b\$, tokamak, SPARC in 27, ARC in early 30s)
 - In China: BEST, CFETR
 - In EU: Proxima fusion



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Conclusions

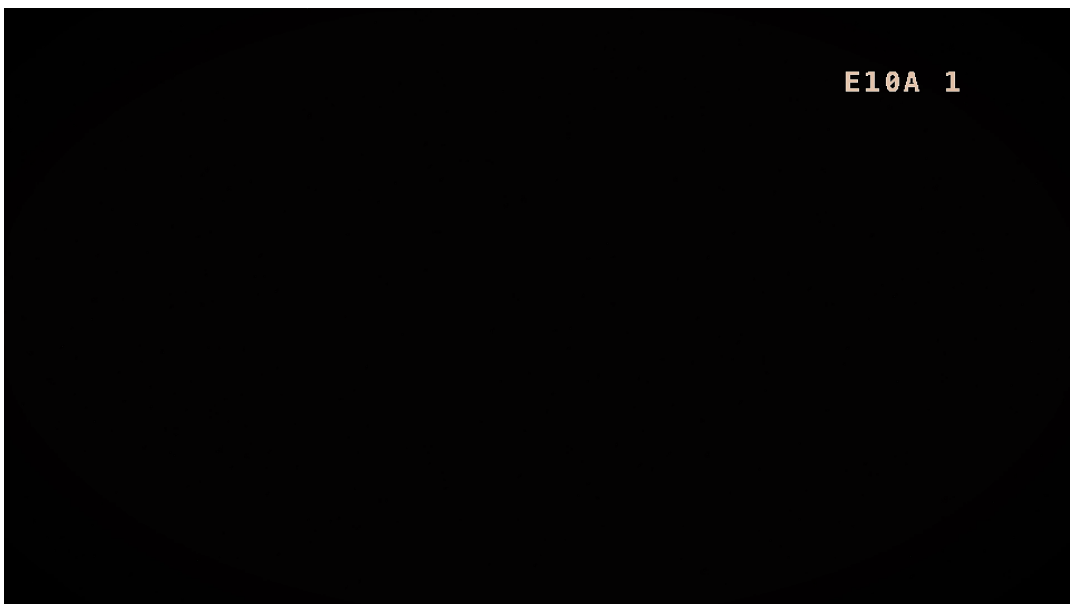
Fusion energy, based on how stars work, is an abundant, safe and environmentally-friendly energy (electricity) source

It recently accelerated towards the commercialisation of fusion

At a recent IAEA meeting on the fusion workforce it became clear, like never before, that we need people to make fusion a reality

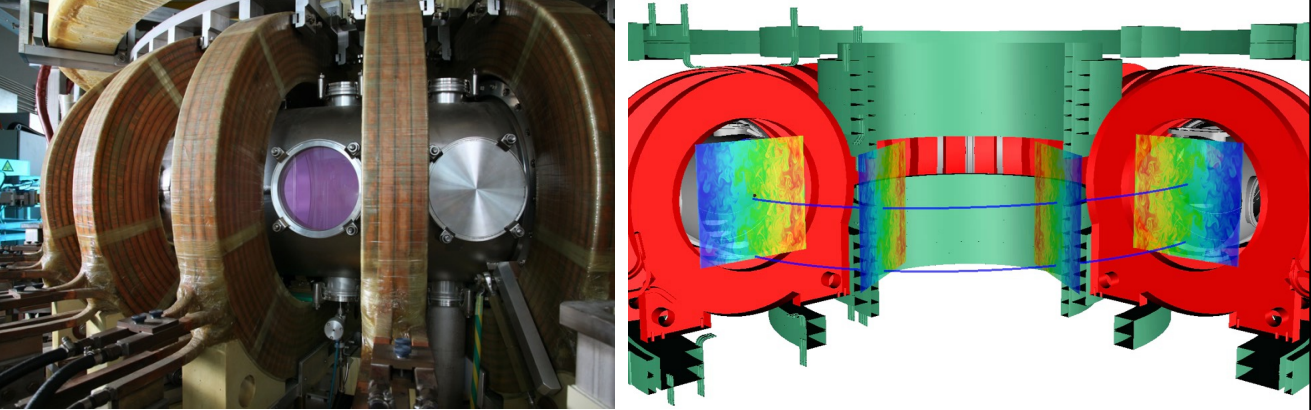
Additional information available on: <https://www.iter.org>, <https://euro-fusion.org>, <https://spc.epfl.ch>, ... and many other sites

Plasma in TCV



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■ Installation permettant la validation des modèles théoriques



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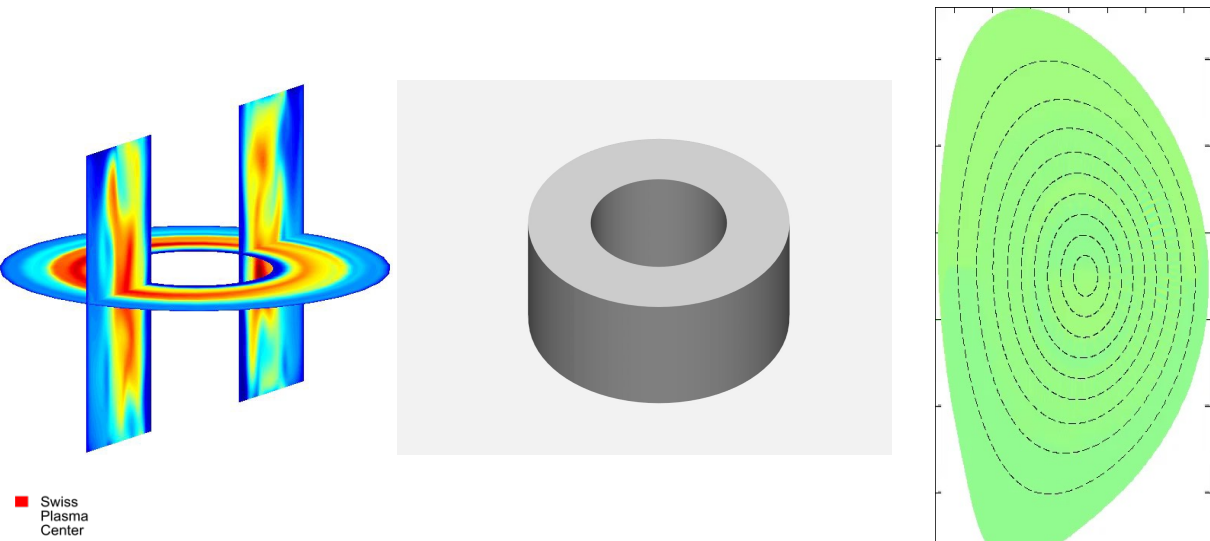
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EPFL Modèles théoriques

■ TORPEX ■ TCV ■ ITER



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