# Fusion research: challenges, news and examples of academic involvement

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# *Last News from GOLEM and COMPASS!*

**The GOLEM tokamak**
arrived into its new location in this building
on 12th December 2007

# H-mode achieved

## NBI and Ohmic H-mode achieved at COMPASS tokamak on 29th November 2012

- Ohmic H-mode – gradual decrease of $D_\alpha$ signal and its fluctuation observed during plasma current ramp-down => transition to Type III ELMs and ELM free period
- NBI H-mode – 10 ms after start of NBI (210 kW ) rapid decrease of $D_\alpha$ signal end increase of stored energy observed

The COMPASS tokamak


L-mode


H-mode

# *Fusion Research*

- Overview and news
  - Do we need fusion?
  - ITER current status
- Challenges
- Academic involvement: some examples
  - Development and validation of diagnostic tools for turbulent fluctuations and transport (probes, fast imaging,...)
  - Dust tracking
  - Plasma-wall interaction (lab studies)
  - Participation in experimental campaigns on large devices
  - Education
- The ESTELL project

# Energy: a major challenge for the 21st century

**China 2006: + 105 GW, 90% coal!**
**More than the total French electricity per year (80 GW)**

**Today: > 80 % of primary energy comes from fossil resources**

**Gaz & petrol consumption exceeds new discoveries**

**EU highly dependant for its energy (> 50 %)**

Energy = 4000 billions euros per year

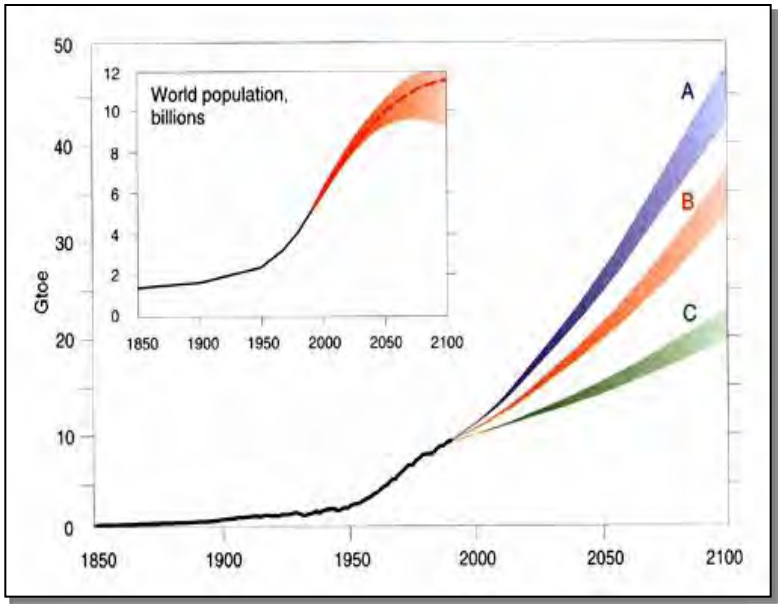
## Back to coal or do better ?

Moderate consumption, renewable energy, fission, fusion

**Fusion presents major advantages**

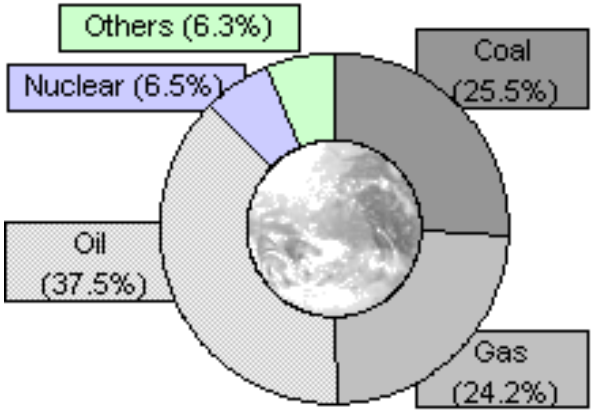
but requires advances in physics and technologies

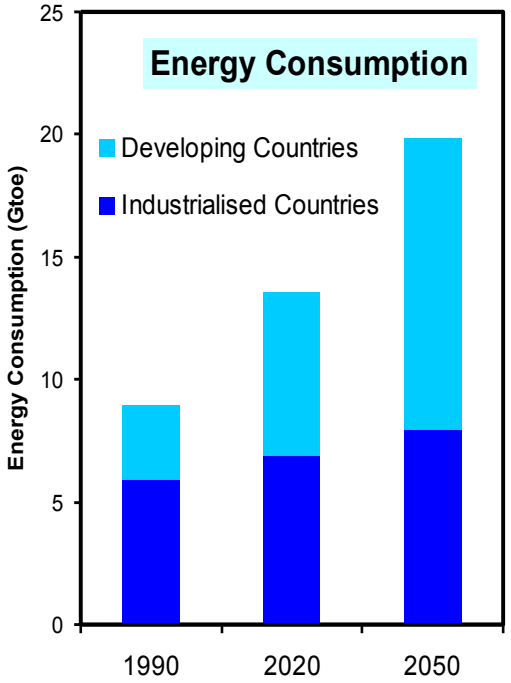
# Trends in global energy consumption




**A : strong growth**
**B : moderate growth**
**C : green scenario**

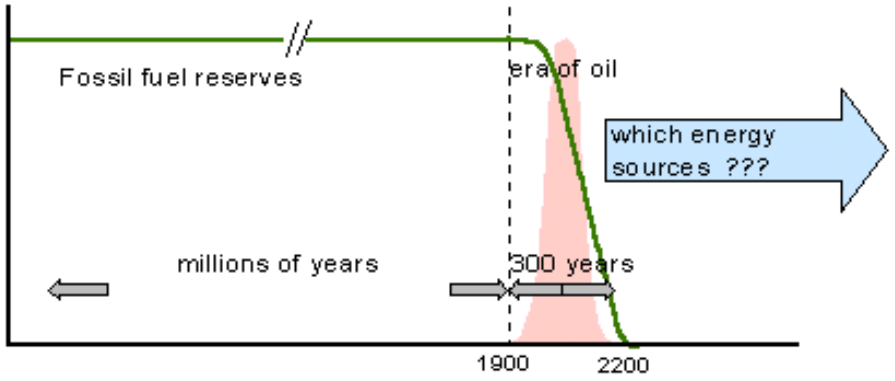
3 scenarios



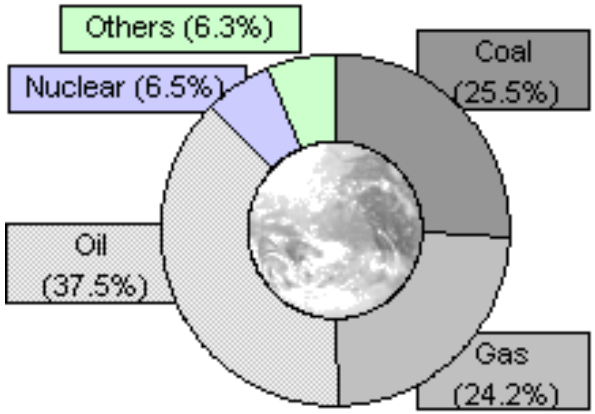

Energy consumption forecasts:

- between 20 and 40 Gtoe in 2100
- much more higher growth in electricity demand

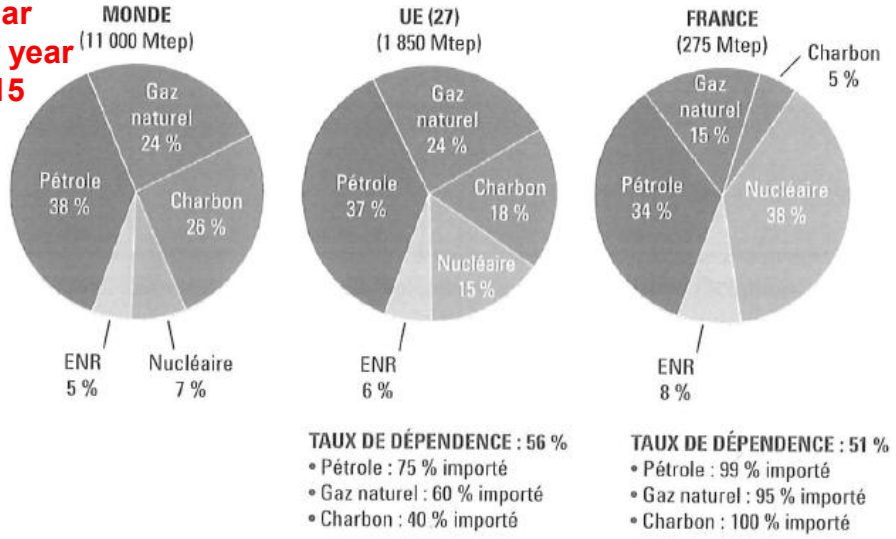


# Primary energy and electricity production

Structure of the primary global energy consumption (2007)

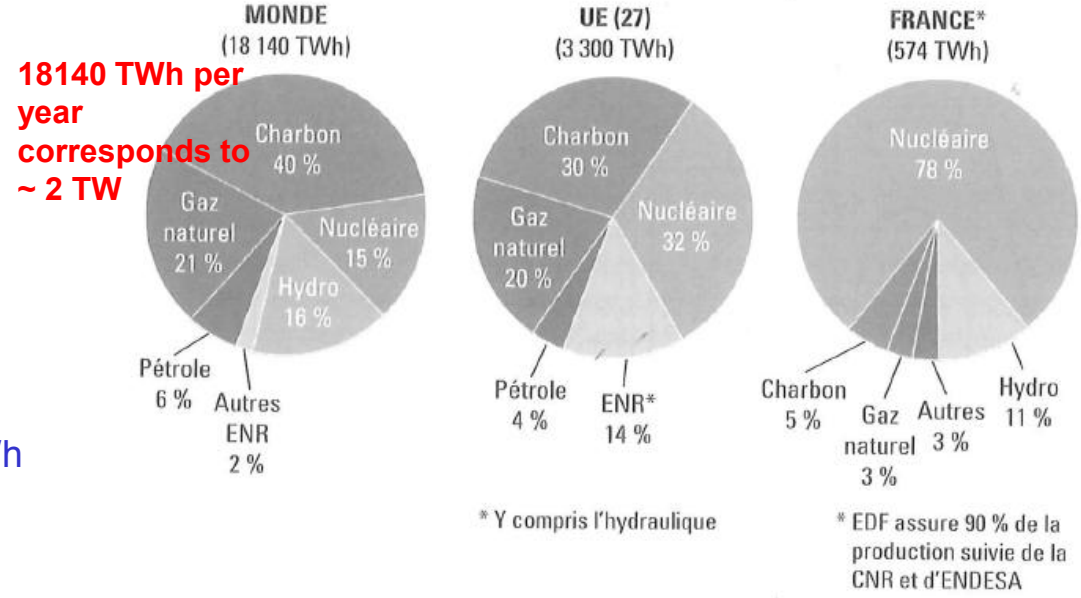



**11 000 Mtep per year ~132 000 TWh per year corresponds to ~ 15 TW**




Structure of Electricity production (2007)

**18140 TWh per year corresponds to ~ 2 TW**




1 Mtep = $10^6$ tonne oil equivalent , and
1 tep or toe corresponds to ~ 12 000 kWh
1 TW = 24x365 = 8760 TWh/year

# Energy and Power: Useful numbers

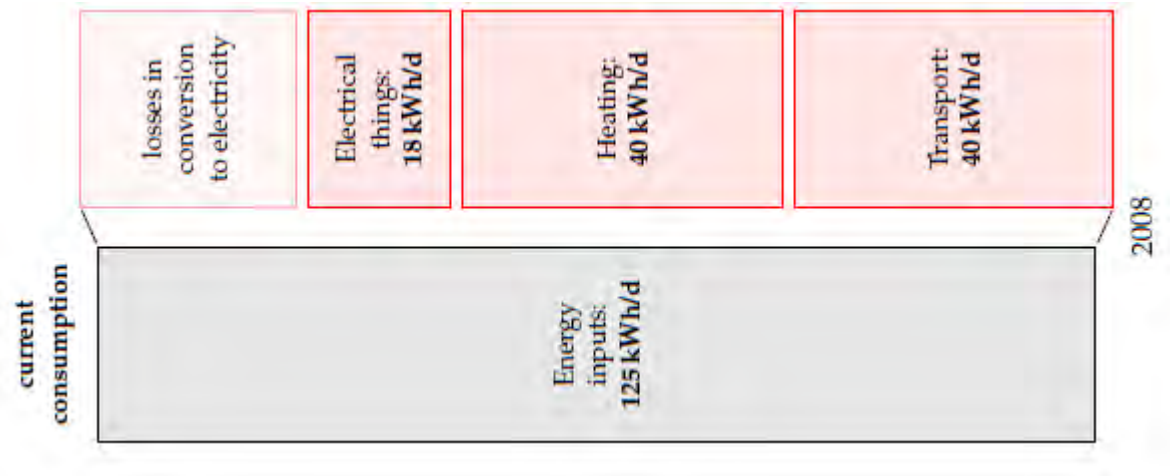
- The joule (J) and the watt (W), one joule per second (J/s), are the standard international units of energy and power, respectively.

  But these units are far too small and the following are preferred:

  **Energy → 1 kWh** = 3.6 million joules **(3.6 MJ = $3.6\times10^6$ J)**

  **Power → 1 kWh/d** (1 kWh per day) **~ 40 W,** with 1 kW ~ 24 kWh/d

- Useful relations:
  - 1 oil barrel (159 l, ~ 0.136 tonne) → 1632 kWh
  - 1 tonne oil (tonne oil equivalent or **1 toe**) → **12 000 kWh**
  - 1 TW (terawatt) = $10^3$ GW (gigawatt) = $10^6$ MW (megawatt) = $10^9$ kW (kilowatt) = $10^{12}$ W
- Needs:




Current consumption per person in "cartoon Britain 2008". [From MacKay, http://www.withouthotair.com/, UIT Cambridge, 2008]

# The challenges of energy supply

- Global energy production is expected to increase by around 60% between 1999 and 2020.
- If production rates remain at present levels, the fossil fuels will be exhausted in about 40 years (oil), 70 years (gas), and 250 years (coal). The actual lifetimes will depend on the rate of production and new discoveries.
- The greenhouse effect is a natural phenomenon due to absorption of infrared radiation by the Earth's atmosphere.

  The main greenhouse gas is water vapor. Carbon dioxide, methane, CFCs, and other greenhouse gases enhance the effect of water vapor by increasing its amount.
- Carbon dioxide concentrations have risen from about 280 parts per million in 1750 to about 380 parts per million today, mainly due to human activity, and there has been an associated marked rise in temperature, called global warming, since the 1970s.

# Energy plans for Europe

**Renewables:**

- Wind (~ 2W/m$^2$):
  - 10% of the available space filled with wind farms $\Rightarrow$ 360 W
  $\Rightarrow$ 9 kWh/d per person
- Hydroelectricity: current power 590 TWh/y (67 GW) $\Rightarrow$ 3.2 kWh/d (500 millions inhabitants). If doubling $\Rightarrow$ 6.4 kWh/d per person
- Wave: 4000 km coastline with 10 kW/m $\Rightarrow$ 2 kWh/d per person
- Tide: 2.6 kWh/d per person
- Solar photovoltaics and thermal panel on roofs:
  - 10 m$^2$ of roof mounted PV panels $\Rightarrow$ 7 kWh/d (high-grade energy)
  - 2 m$^2$ of water-heating panels $\Rightarrow$ 3.6 kWh/d (low-grade energy)

$\Rightarrow$Total **30.6 kWh/d per person**

Solar farming required: 5% of Europe area (450 m$^2$ per person)
$\Rightarrow$ 54 kWh/d per person
Problems = (i) cost; (ii) getting power in the winter

- Crops (plants capture 0.5 W/m$^2$ or 5 kW/ha) $\Rightarrow$ 12 kWh/d per person

$\Rightarrow$ Total **96.6 kWh/d per person < 125**

The bottom line: Europe cannot live on its own renewable. If the aim is to get off fossil fuels, Europe needs nuclear or solar power in other people's desert, or both.

# Energy scenarios for the future

**Two main approaches:**

- one dominant energy source (historically: wood, coal, oil, gas, …
- simultaneous use of a whole range of energy sources

- **Energy sources must fulfil the following criteria:**
  - **Acceptable environnmental constraints ($CO_2$, waste)**
  - **Economically viable & socially acceptable**
    - **Safety in regards to major accidents**
    - **Large scale Production**
    - **Secure providing (limited importations)**

- **Development of existing and new sources:**

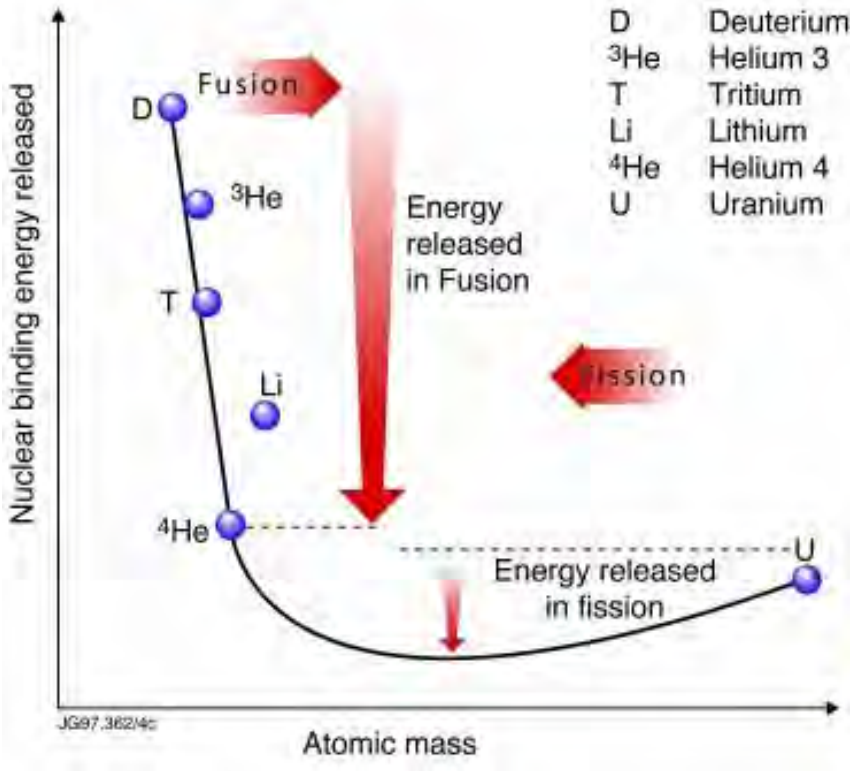
| | |
|---|---|
| Fossil fuels | **Renewable energies** |
| Fission | **Fusion** |

- **All options must be developed**

# *Thermonuclear Fusion: General Principles*

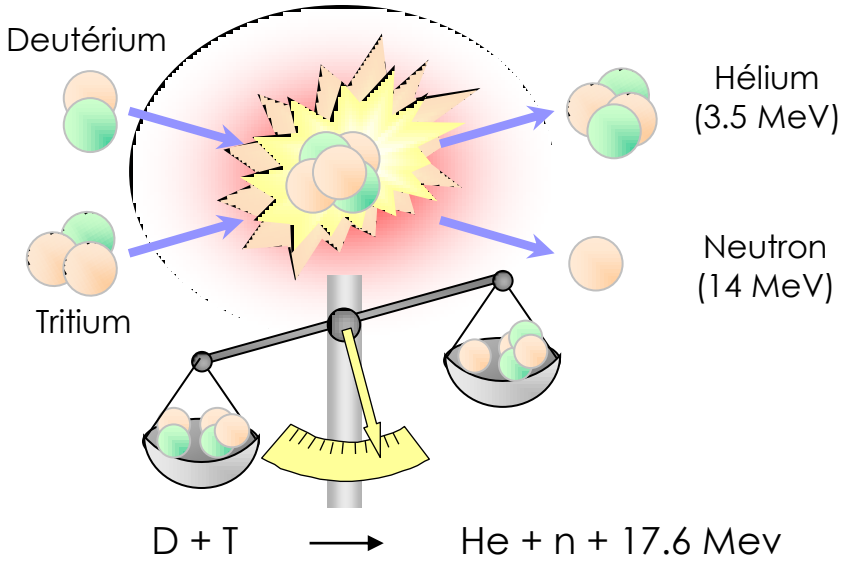
# Thermonuclear fusion: general principles

## Fusion and Fission




**The released energy per unit of mass is**

**1 to 10 millions greater than in a chemical combustion reaction**




The fusion of two light nuclei releases energy: it is the energy source of our Sun and other stars

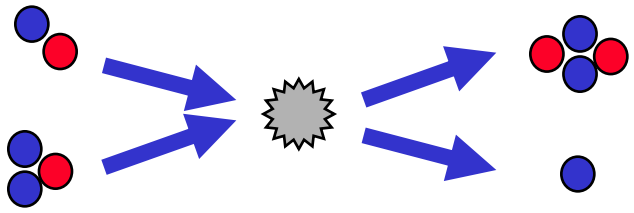
Because of the natural electrostatic repulsion of nuclei, fusion reactions require an energy supply

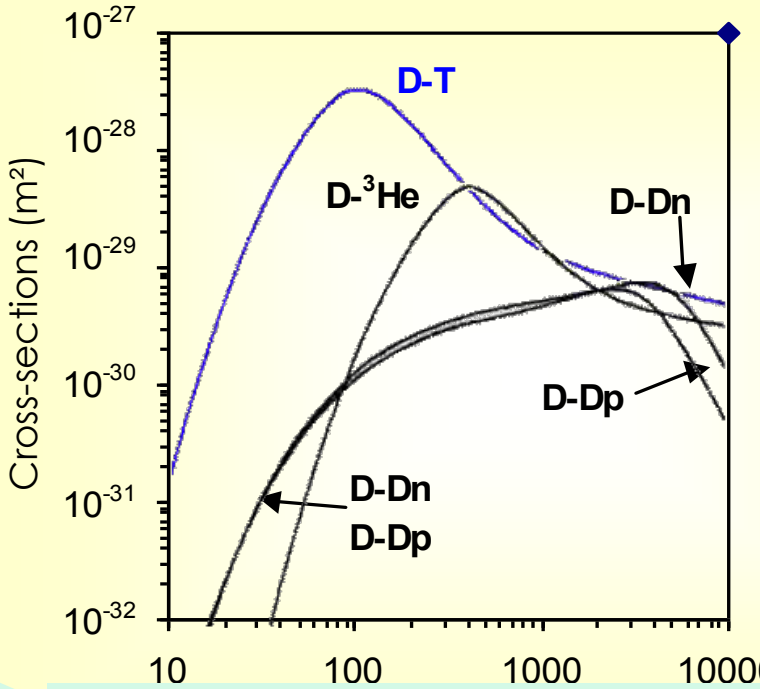
# Fusion reactions – cross sections

- Fusion reactions cross-sections are ~600 smaller than fission cross-sections

- The D + T → He + n reaction is the most accessible one.

- Very high temperatures are required (> 100 millions degrees) to overcome the Coulomb barrier






| | | | |
|---|---|---|---|
| D + T | → | $^4$He (3.56 MeV) + n (14.03 MeV) | [17.59 MeV] |
| D+D 50% | → | $^3$He (0.82 MeV) + n (2.45 MeV) | [3.27 MeV] |
| D+D 50% | → | T (1.01 MeV) + p (3.02 MeV) | [4.03 MeV] |
| D + $^3$He | → | $^4$He (3.71 MeV) + p (14.64 MeV) | [18.35 MeV] |
| Production of tritium : n + $^6$Li | → | T + $^4$He | [4,78 MeV] |
| n + $^7$Li | → | T + $^4$He + n | [- 2,47 MeV] |

# Power balance

## *Fusion Power*

- $P_{fus}$ = number of reactions per second
  $\times$ energy released by one reaction
- $P_{fus} = n_D\, n_T\, \langle\sigma.V\rangle_{DT}\, Q_{DT} = P_{neut} + P_{\alpha}$
- $Q_{DT}$ = 17,6 MeV = $2{,}8.10^{-12}$ J
- $P_{neut} = 0{,}8\, P_{fus}$ $\quad P_{\alpha} = 0{,}2\, P_{fus}$

**In one year, a 1 $GW_e$ power plant would need**

**100 kg (D) + 150 kg (T) instead of**

**~ 700 000 tonnes of oil or**

**~ 30 t of uranium enriched to 3% of $^{235}U$**

## *Power released in the plasma*

- $P_{DT\ (W/m^3)} = P_{\alpha} = 5.6\times10^{-13}\, n_D\, n_T\, \langle\sigma.V\rangle_{DT}$
- **D-T Mixture 50/50 : $n_D = n_T = n_i / 2$**

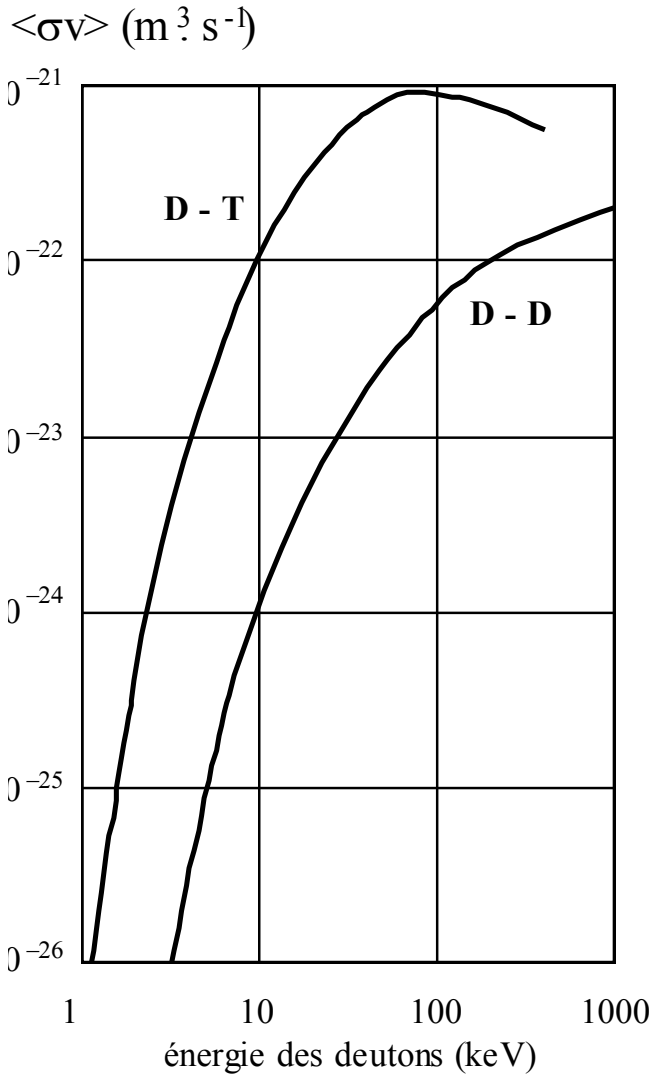
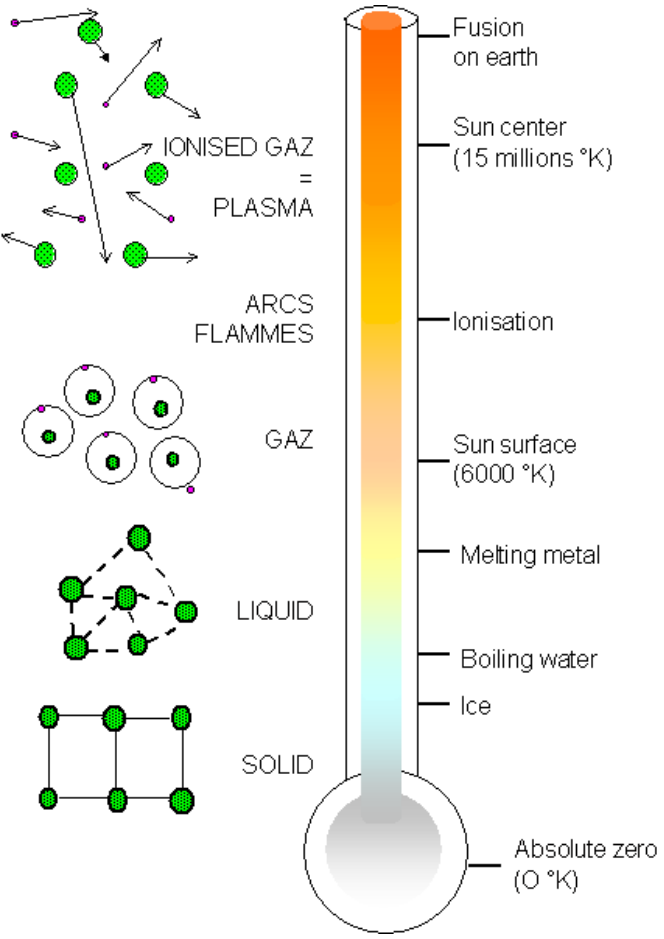
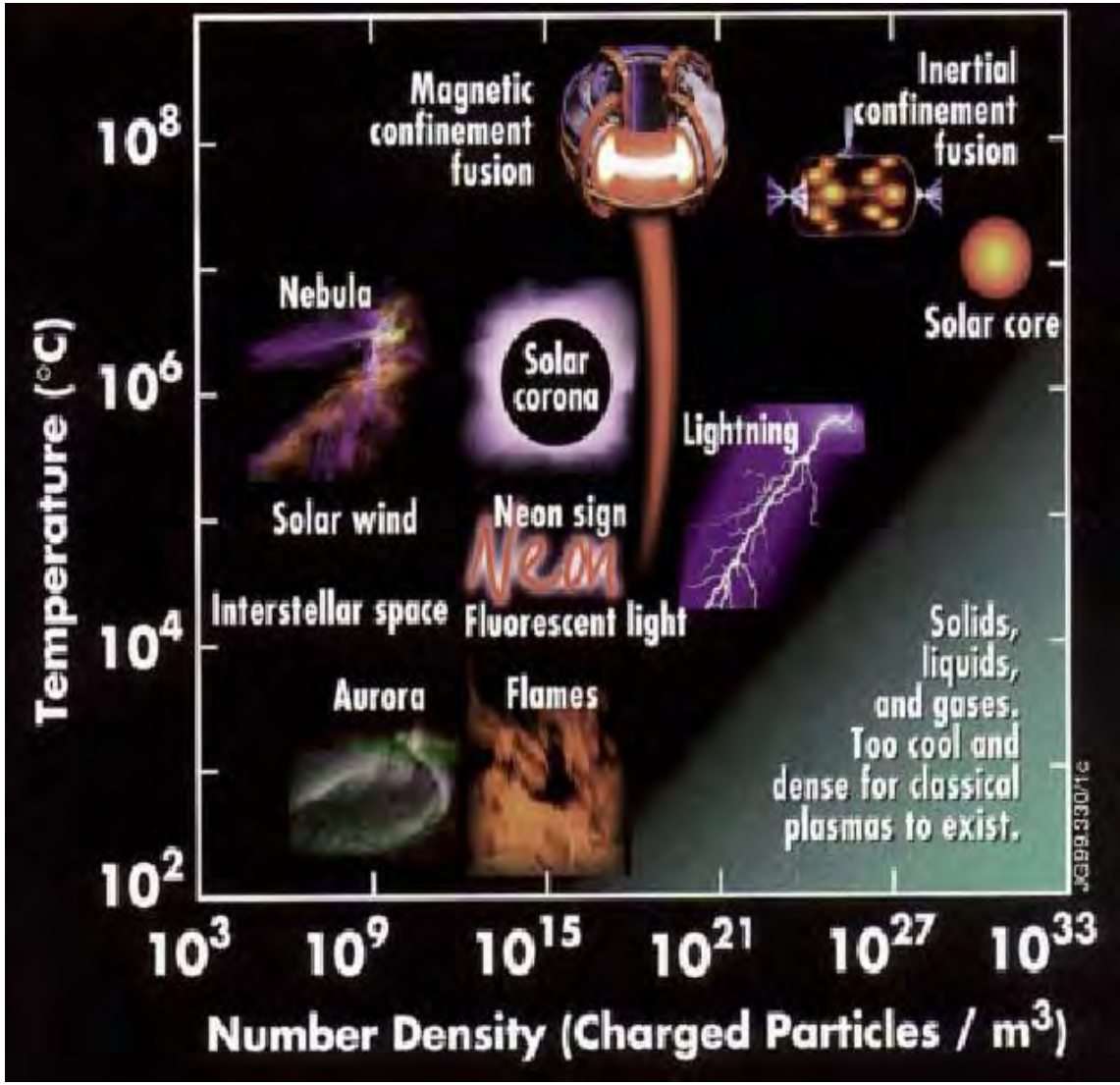



**Fig. 7.2 : Moyenne du produit $\langle\sigma v\rangle$ obtenue pour une distribution maxwellienne sur v.**

# Plasma: the fourth state of matter



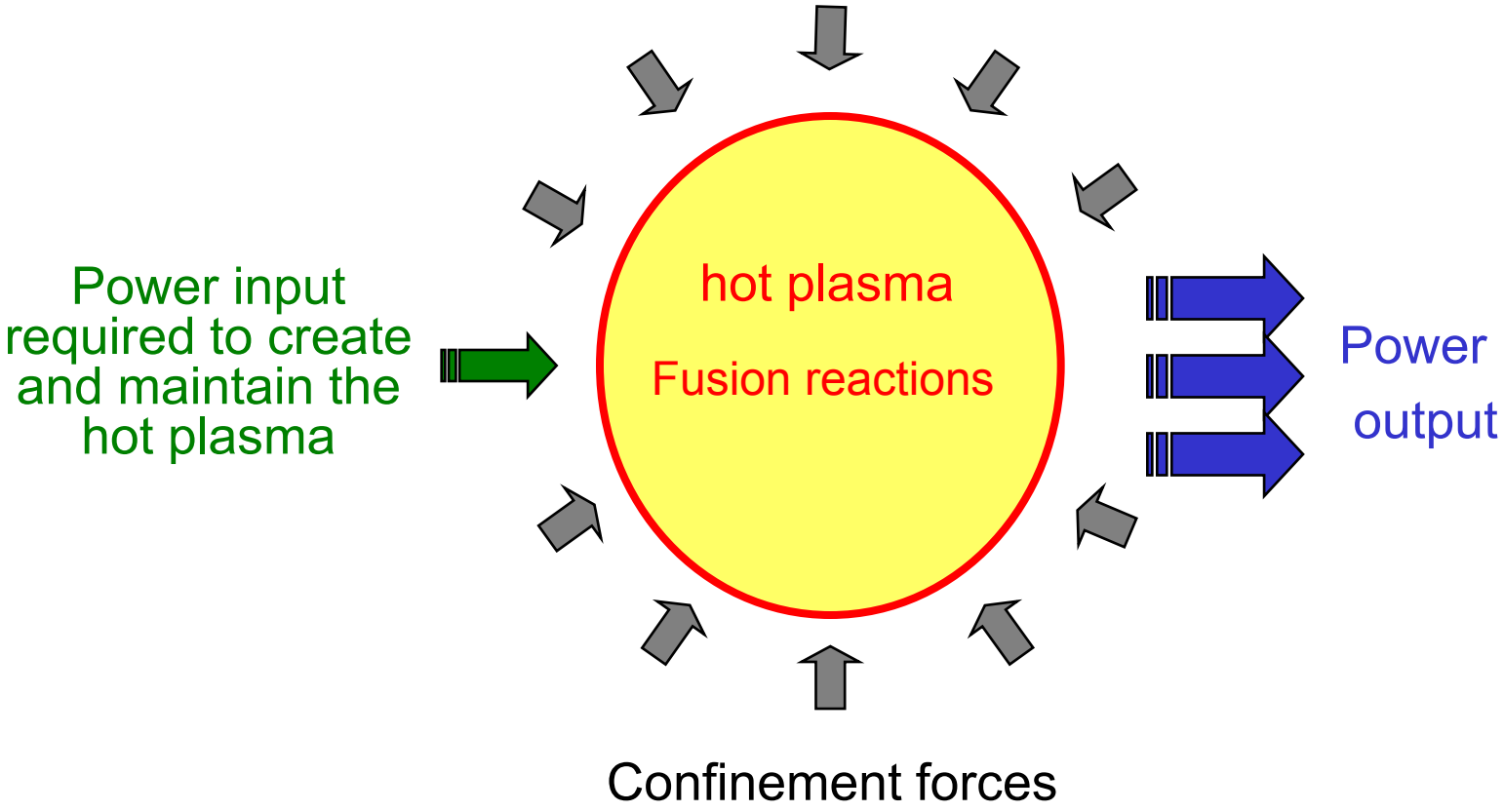

- a plasma is an electrically neutral ionized gas
- Plasma is the most widespread form of matter in the universe (~99%)

*1 electron-Volt (eV) ~ 11600° K*

"The mixture D-T must be maintained at

$T_i \sim 2 \times 10^8$ degrés

in order to have a sufficient reactivity"

# The Lawson criterion

$P_{losses} = W/\tau_E$ , where $W = (3/2)(n_i T_i + n_e T_e) = 3 n_i T_i$

where $\tau_E$ Energy confinement time

$$(n_i^2 < \sigma V >_{DT} Q_{DT}/4)(0{,}2 + 1/Q) \geq 3 n_i T_i / \tau_E$$

$$\Rightarrow \quad n_i \tau_E \geq 3\, T_i / (< \sigma V >_{DT} Q_{DT}/4)(0{,}2 + 1/Q) \quad \text{or}$$

$$n_i \tau_E \geq g(T_i)$$

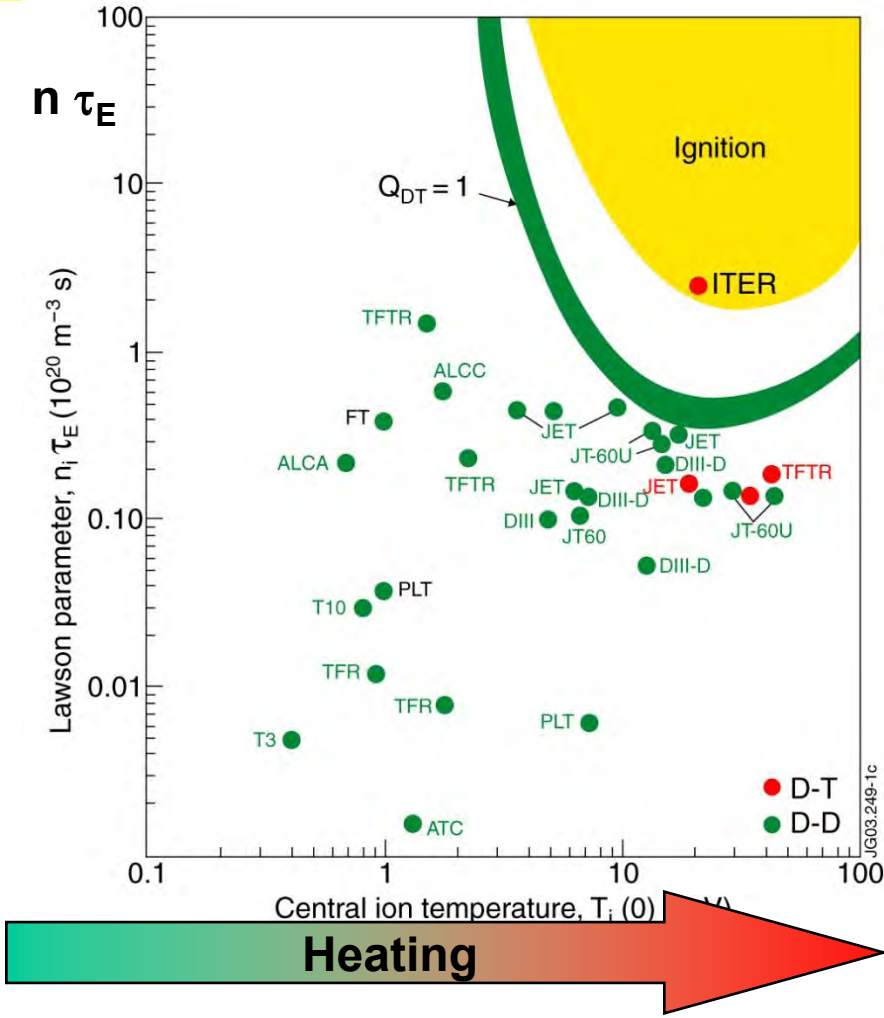
$g(T_i)$ minimum for $T_i \approx 26$ keV

wiht $Q_{DT} = 17{,}6.10^3$ keV, $Q \rightarrow \infty$

$< \sigma V >_{DT} \approx 1.1 \times 10^{-24} (T_i)^2$ [MKS]

if $10 \leq T_i \leq 30$ keV

$$\underbrace{n_i\, T_i}_{\textit{Pressure}}\, \tau_E > 3 \times 10^{+21} \text{ (keV. m}^{-3}\text{.s)}$$

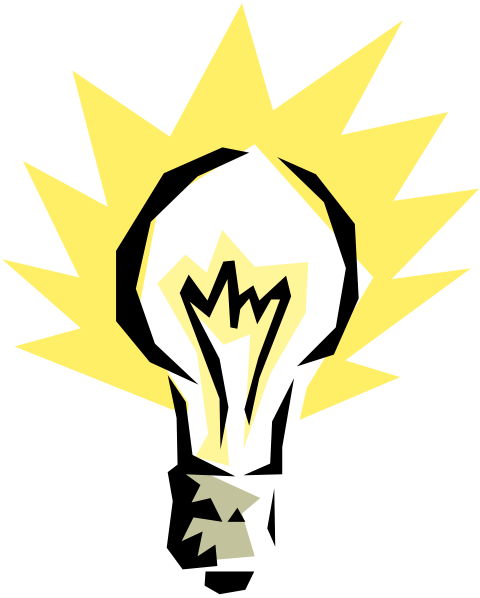



Ignition: If pressure and energy confinement time $\tau_E$ are such that the Lawson criterion is satisfied, then $\alpha$ ($He^{++}$) particles alone are suficient to maintain the temperature.

# The power balance

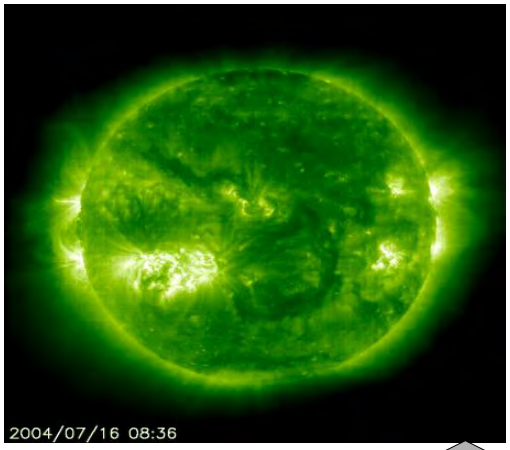
- $P_{fus} = P_{neut} + P_{\alpha} \approx 5\, P_{\alpha} \approx 5(n_i^2 < \sigma V >_{DT} /4)E_{\alpha}$ (D-T 50/50)
- $dW_P/dt = P_{inj} + P_{\alpha} - P_{losses} = 0$
- $Q = P_{fus} / P_{inj}$ (Power amplification)

| | | |
|---|---|---|
| **Break-even** | $Q = 1$ | $P_{fus} \geq P_{inj}$ |
| **Ignition** | $Q = \infty$ | $P_{\alpha} \geq P_{losses}$<br>$P_{inj} = 0$ |

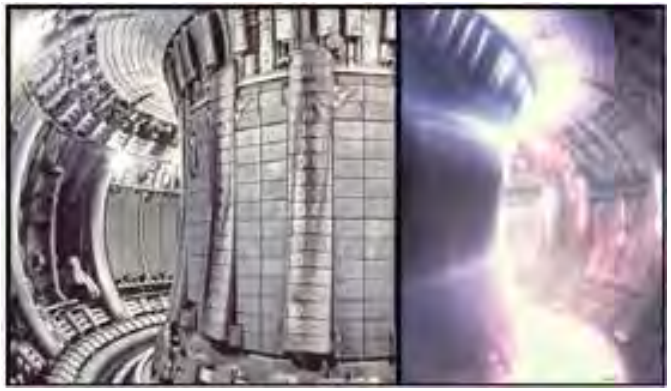


# Three methods to achieve fusion

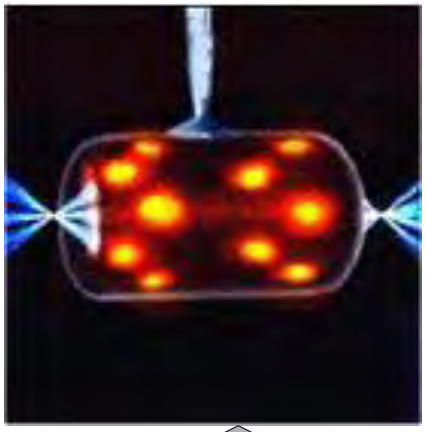
**Sun**




**Tokamak JET/ITER**

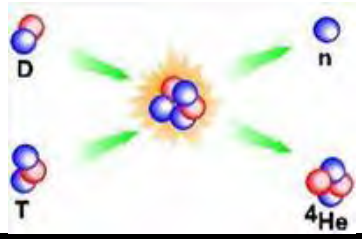


**Lasers on target**



| **Confinement:** | **gravitational:** | **magnetic:** | **inertial :** |
|---|---|---|---|
| Size: | $1.3\times10^{8}$ m | 10 m | $10^{-2}$ m |
| Duration: | $3\times10^{16}$ s | 400 s | $10^{-8}$ s |
| Pressure: | $10^{9}$ atm | 2 atm | $10^{9}$ atm |

Temperature: ~ 100 million deg ⇔ thermal energy ~ 10 keV




**Ignition condition:**

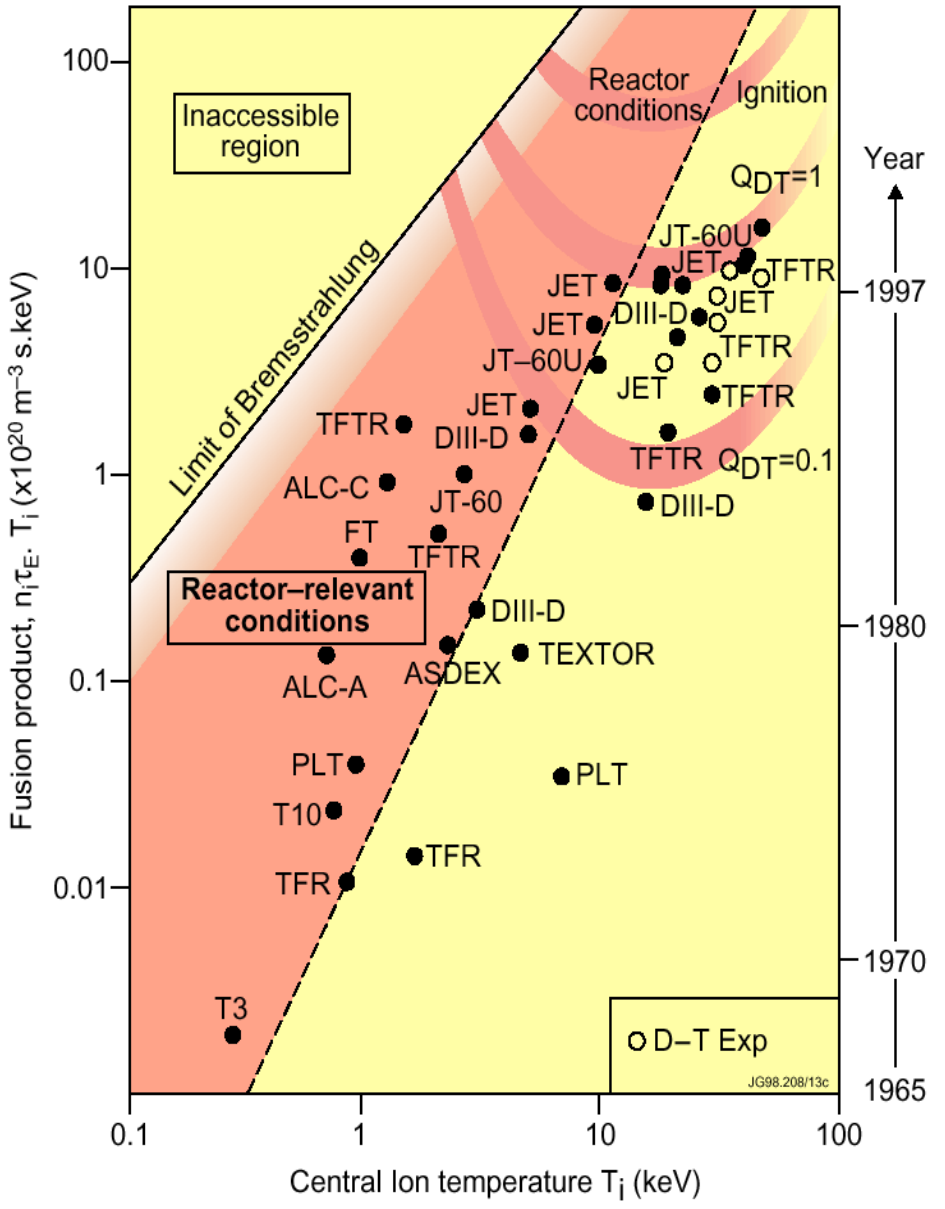
**$nT_i\tau_E \sim 10^{21}$ m$^{-3}$.keV.s ~ 1 bar.second**

**$\tau_E$ = Energy confinement time**

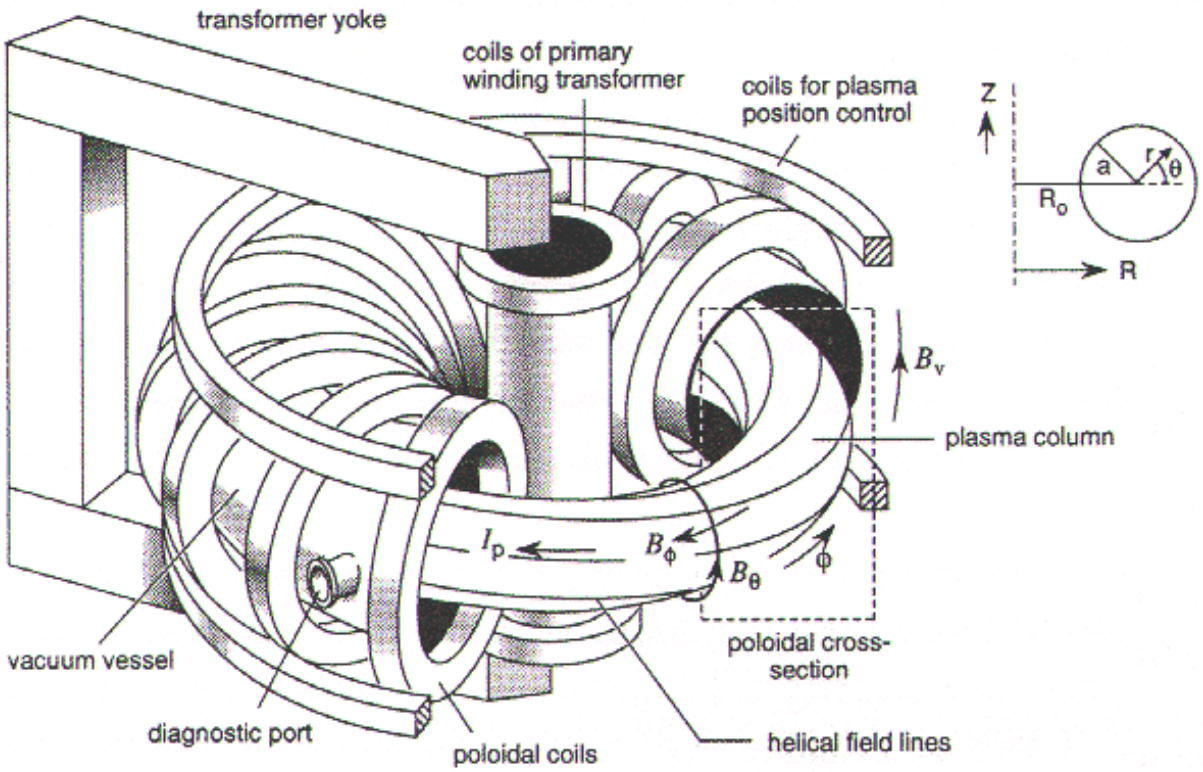
# Past achievements

**Performances are measured with respect to the Lawson criterion**

- From every new machine a big progress has been made.
- With JET the break-even (Q=1) has been reached
- A factor of 6 in $nT\tau$ is still required
- ***This will be possible from ITER***



# Castor alias GOLEM




major radius: R= 0.4 m

minor radius:

a= 0.085 or 0.060 m

toroidal magnetic field:

$B_t < 1.5$ T

plasma current I < 25 kA

pulse length t < 50 ms

plasma density:

$n_e = 0.2\text{-}3.0 \cdot 10^{19}$ m$^{-3}$

electron temperature:

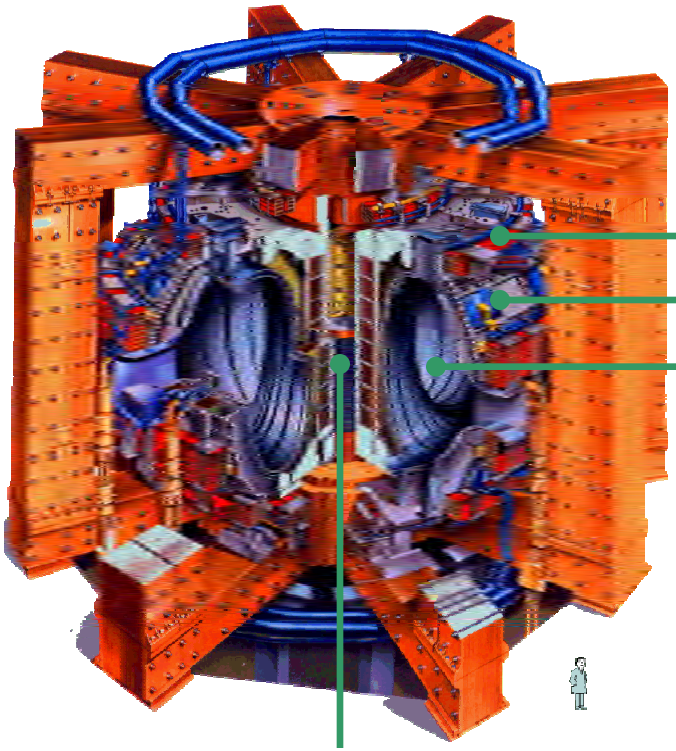
$T_e(0) < 200$ eV

ion temperature:

$T_i(0) < 100$ eV

The CASTOR (Czech Academy of Sciences TORus) device is a tokamak with a circular cross section. The last closed magnetic surface is defined by a poloidal limiter made of molybdenum. Hydrogen is used as a working gas. As a source of energy for the toroidal magnetic field, 1 MJ condensor bank is used. A delay LC line with the energy of several tens of kJ generates and heats the plasma. The plasma position is stabilized by a feedback system.

# The European JET Tokamak

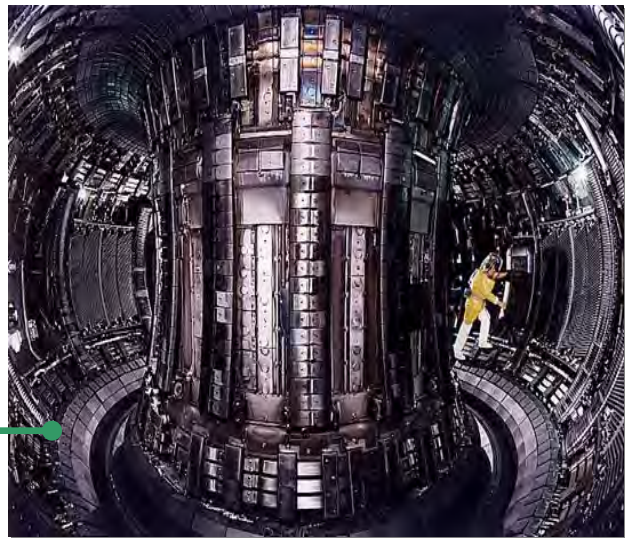


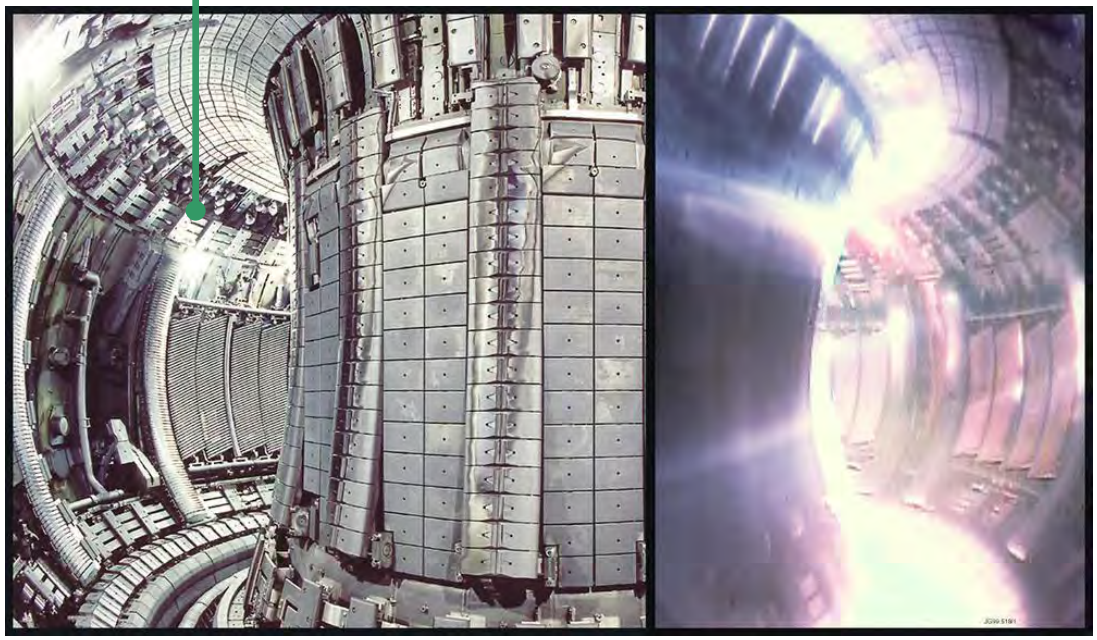
poloidal coil

toroidal coil

Vacuum vessel

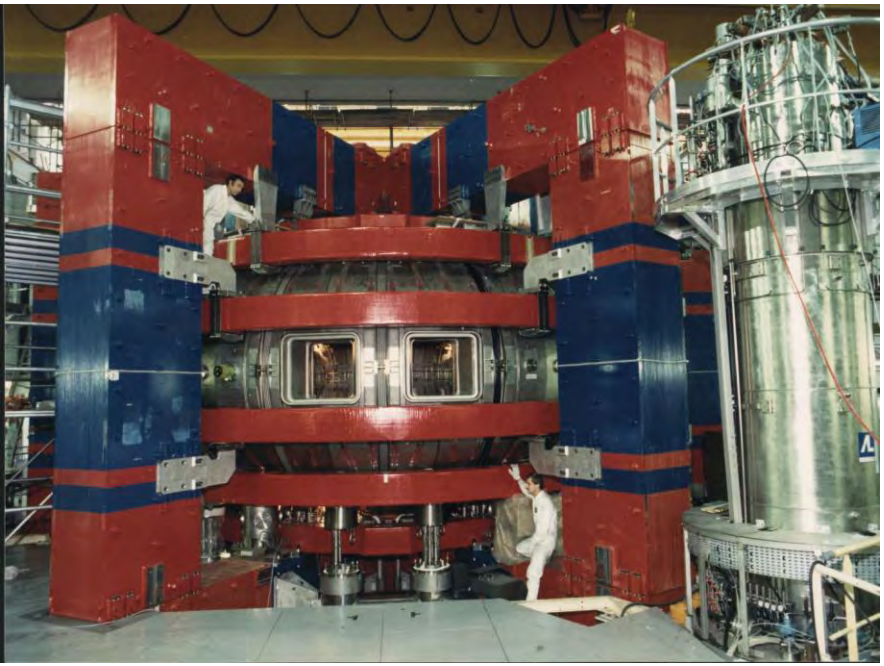
Central solenoid

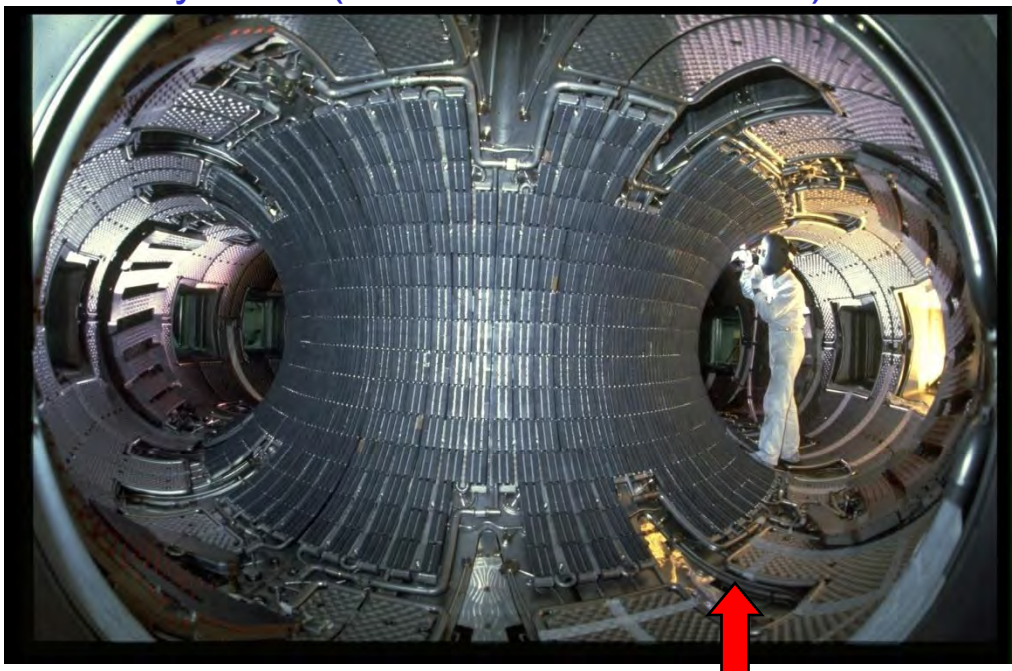




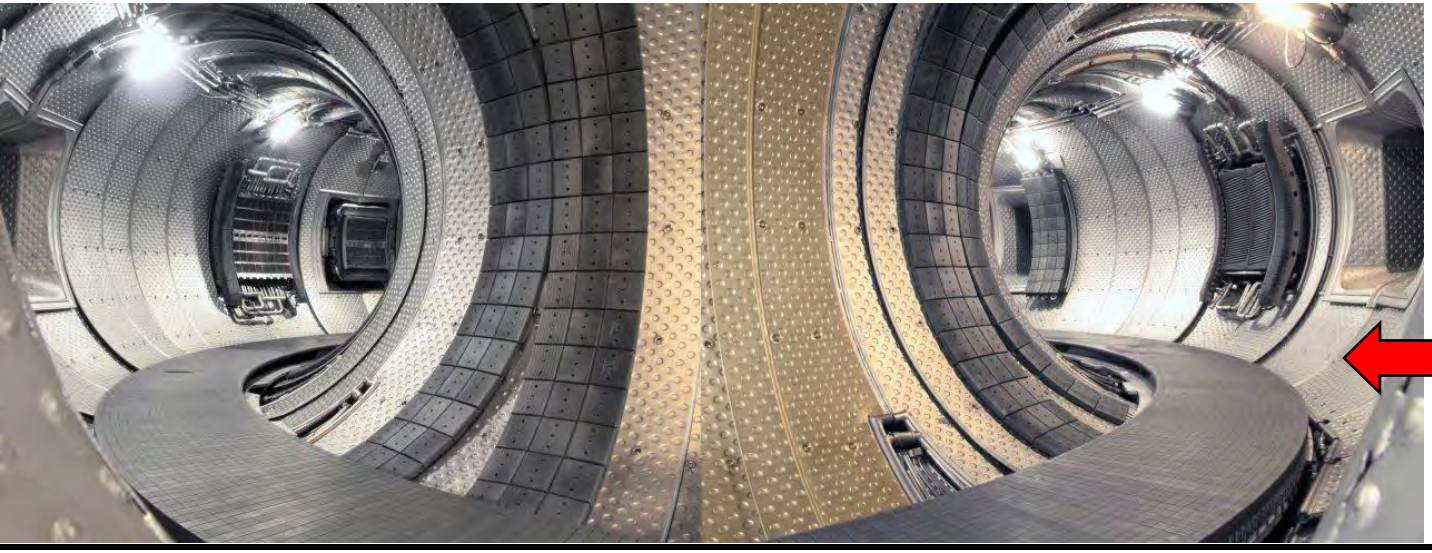
# Tore Supra

World record for extracted energy in steady state (>1000 MJ for 6mn30s)





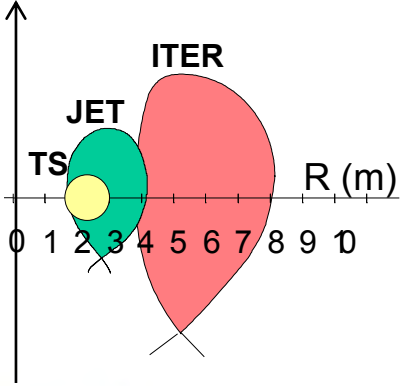
*until 1999*



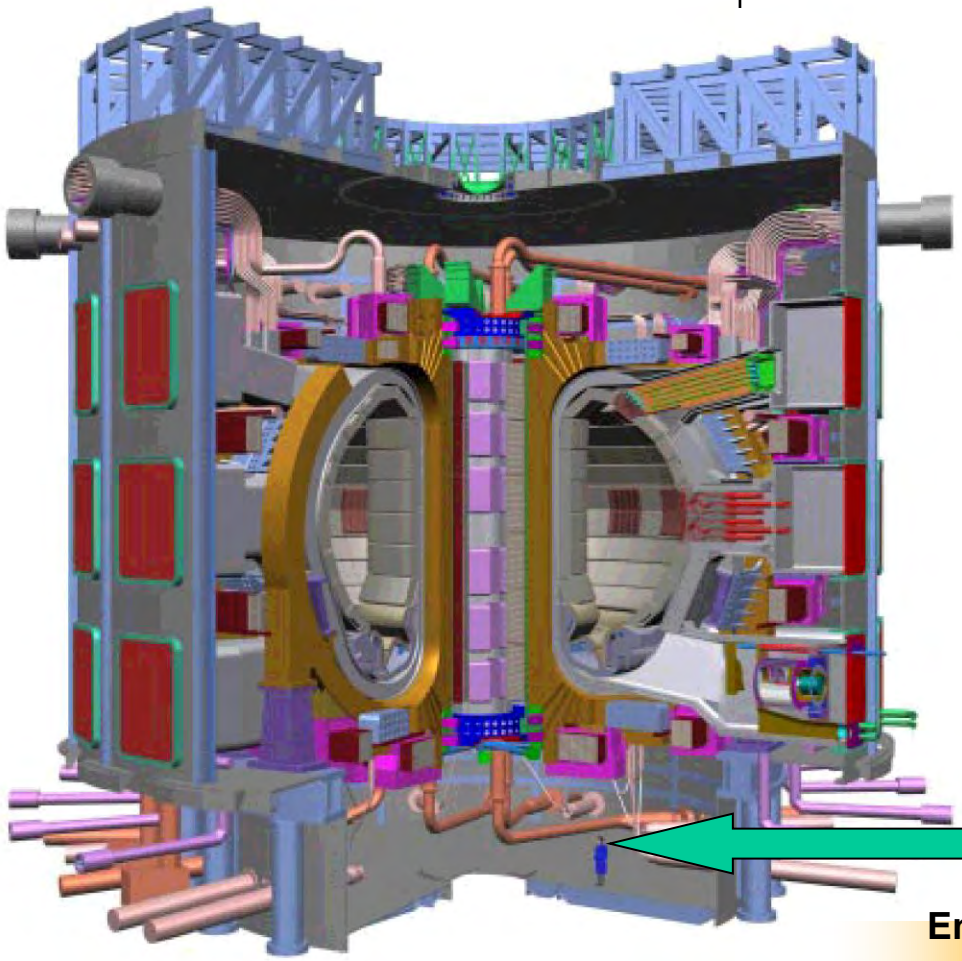
*CIEL Componants (2002)*

# ITER

Size: 2 x JET




| Main Parameters | ITER |
|---|---|
| R : major radius (m) | 6.2 |
| a : minor radius (m) | 2.0 |
| Magnetic field (T) | 5.3 |
| Plasma current (MA) | 15 |
| Fusion Power (MW) | 500 |
| Pulse duration (s) | 400 |
| Amplification factor (Q) | 10 (ignition possibly) |
| Construction costs | ~ 2×4.6 G€ |



Fusion Power: 500 MW

Power Gain : 10

- **demonstrate D/T burning**
- Tritium breeding blanket
- Flexibility ➔ optimize DEMO parameters

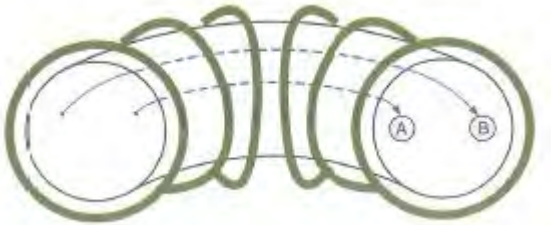
**Homo sapiens sapiens**

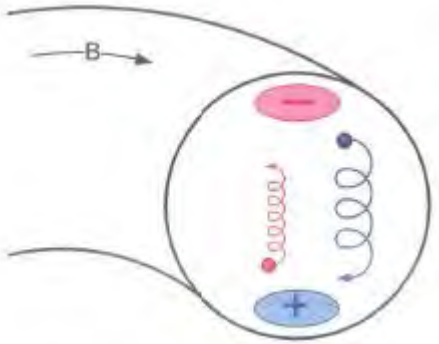
**Engineering** **Construction** **Exploitation**

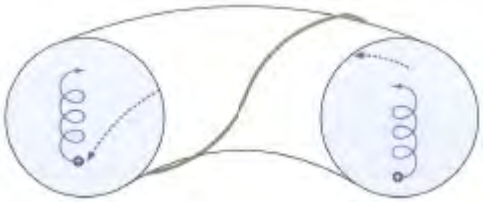
**1990** **2006** **2015** **2035**

# The magnetic bottle

- 3 ways to achieve magnetic confinement in a closed volume
  1. Driving a toroidal current → tokamaks, RFPs
  2. Elongating the flux surfaces and making them rotating poloidally as one moves around the torus
  3. Making the magnetic axis non planar



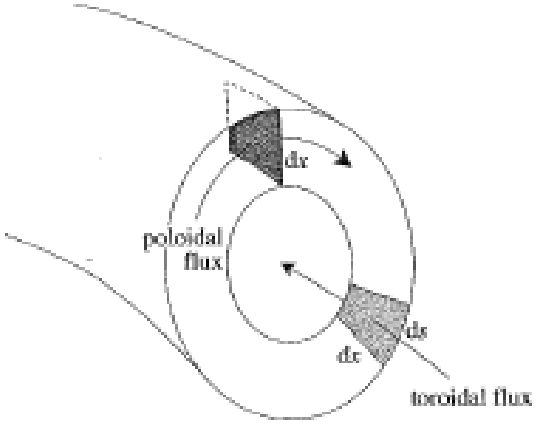



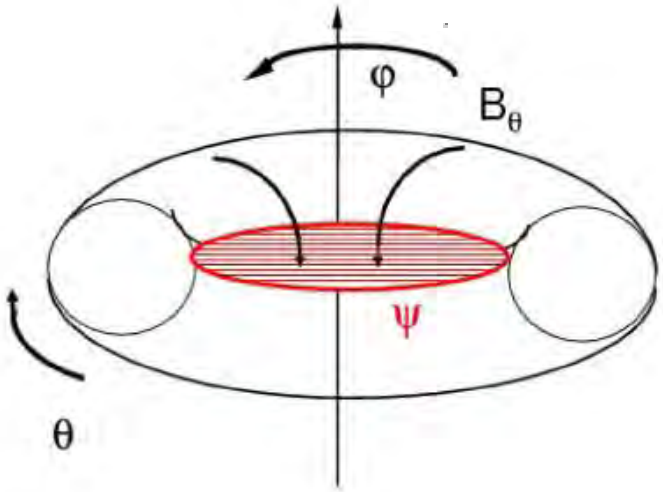



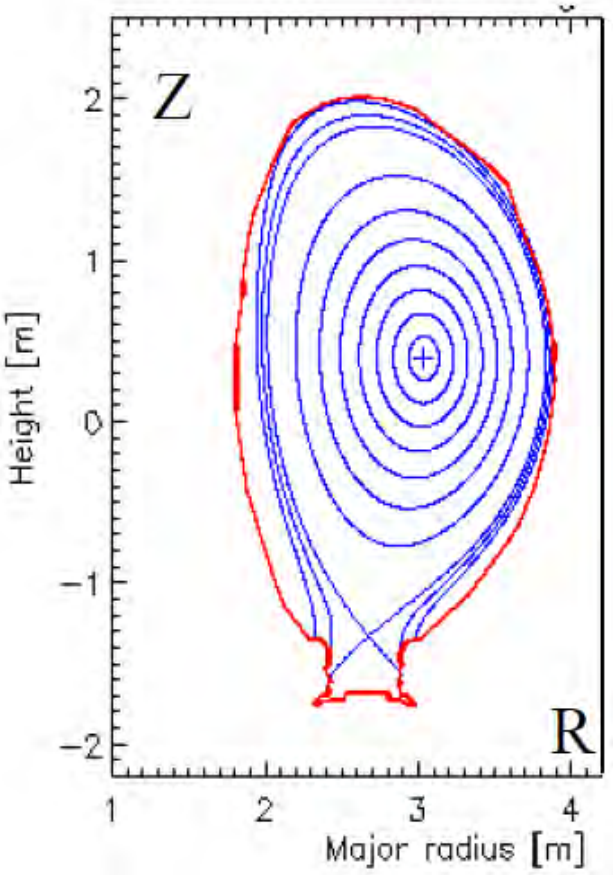
- Tokamaks and Stellarators

# Magnetic surfaces

- Field lines are winded on torii called magnetic surfaces.
- Each magnetic surface is labelled by its poloidal flux $\psi$

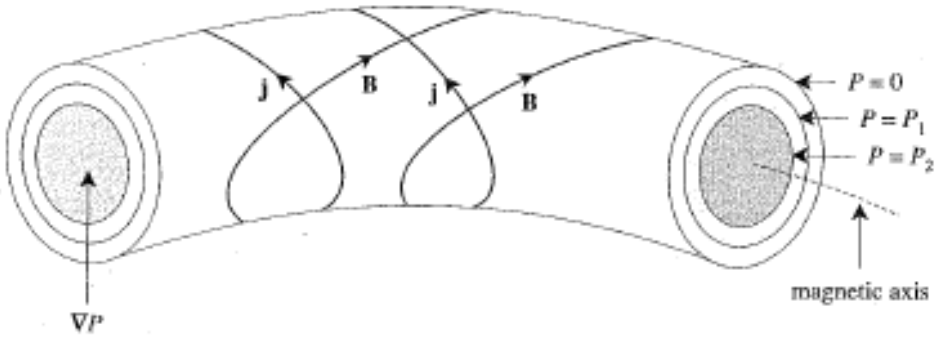


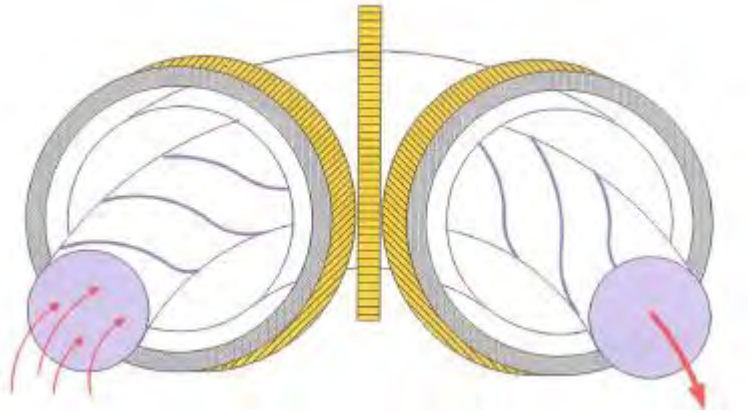



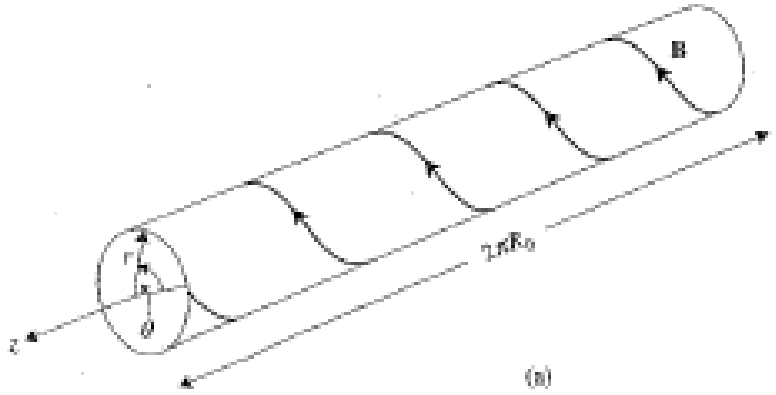
# MHD Equilibrium and stability

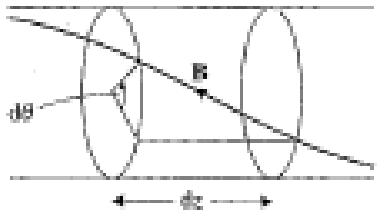
- Nested isobaric surfaces



- Screw pinch definitions
  - Rotational transform and/or Winding number (safety factor q)

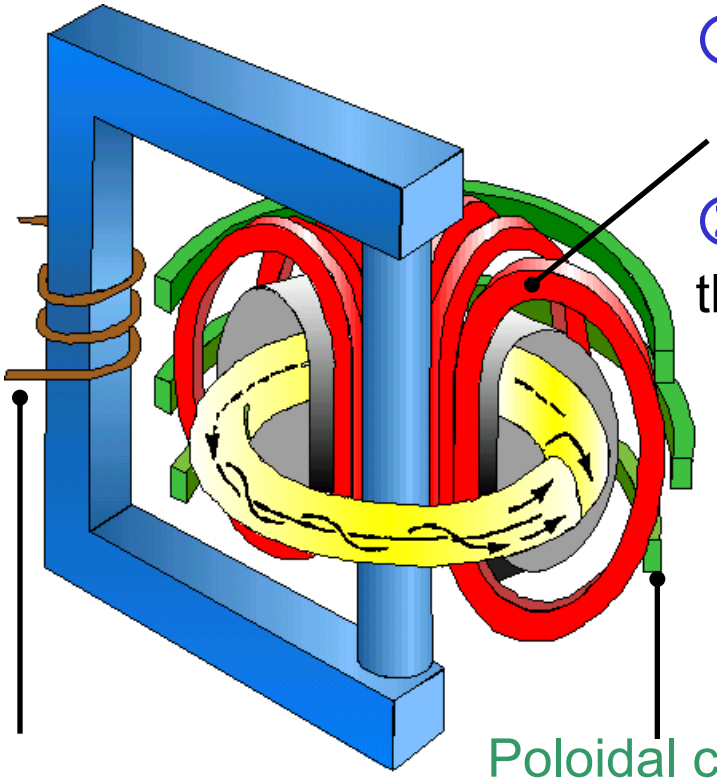


# The Tokamak: how does it work?

*tokamak (contraction of Russian words, *toroidalnaya* , *kamera*, *magnitnaya*)

- Tokamak = transformer whose secondary is the plasma
- The confinement is performed by the combination of **two** magnetic fields:



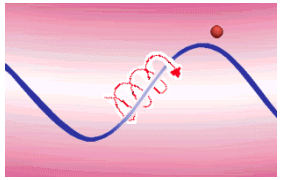
Primary Circuit

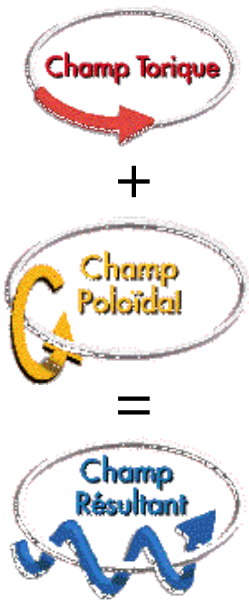
Poloidal coils

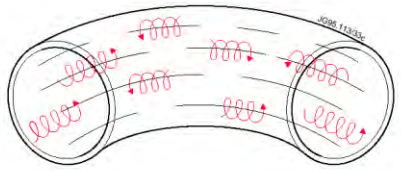
① The **toroidal** filed generated by **toroidal coils**

② The **poloidal** field created by the toroidal plasma current

Charged particles trajectories roll around the resulting field lines





$$\langle \beta \rangle = \frac{\langle p \rangle}{B_0^2 / 2\mu_0} : \ 3-5\%$$

# Heating the plasma

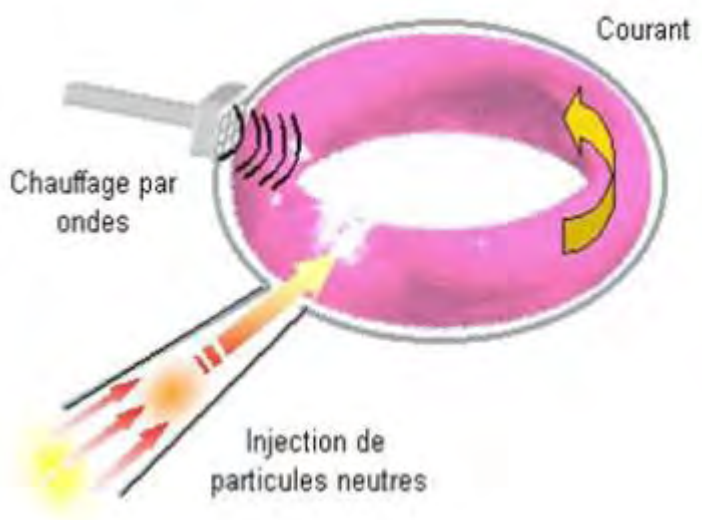
- The ohmic regime:

A first mechanism is the natural Joule heating due to the current flowing in the plasma, (and used to create **the tokamak magnetic configuration**). Just like the filament of a light bulb heats up when current passes throug,h the plasma temperature will rise as a result of intense current (of the order of MA) passing through it. Unfortunately, this effect is proportional to the resistance of the plasma which tends to collapse when the temperature increases, saturates and achieves only limited temperatures (of the order of 10 million degrees). This heating regime is called ohmic regime.

- Additional heating

To achieve the required temperatures, we therefore use additional heating systems. They are classified into two families:

• heating by injection of **neutral particles** of high energy, e.i., the plasma is heated through the collisions between the high energy particles injected and the plasma particles.

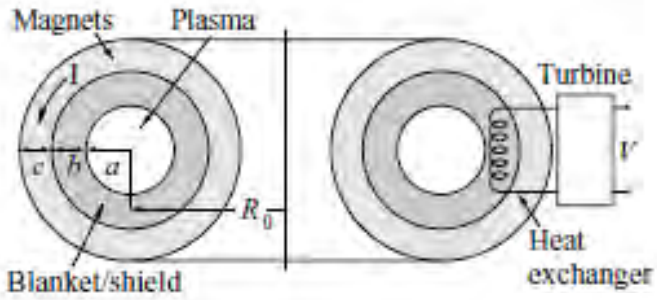


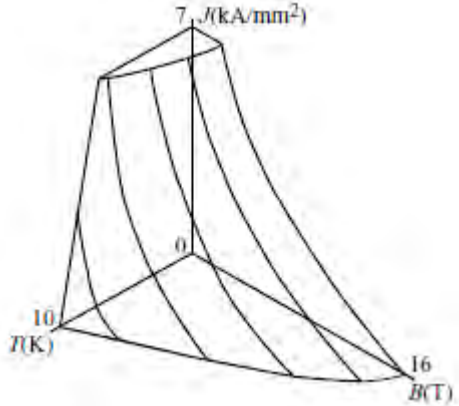

• **the RF heating**, which is to couple to the plasma a wave a resonance with a class of particles in the plasma, (i.e. at the same frequency → **LH, ICRH, ECRH**) and communicate their energy, like a microwave oven which heats a meal by waving water molecules

# Design of a generic fusion reactor

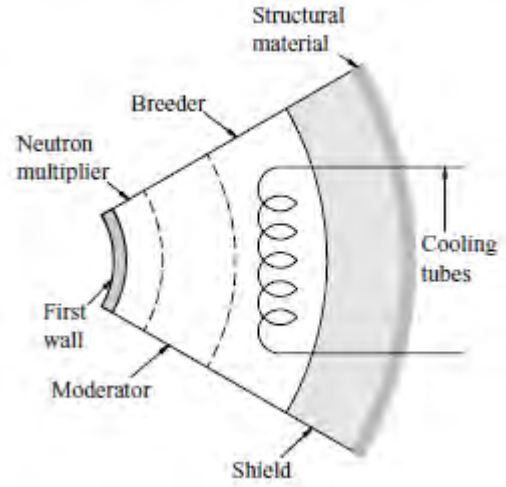
- Design parameters

| Quantity | Symbol |
|---|---|
| Minor radius of the plasma | $a$ |
| Major radius of the plasma | $R_0$ |
| Thickness of the blanket-and-shield | $b$ |
| Thickness of the magnets | $c$ |
| Plasma temperature | $T$ |
| Plasma density | $n$ |
| Plasma pressure | $p$ |
| Fusion power density | $S_f$ |
| Energy confinement time | $\tau_E$ |
| Magnetic field | $B$ |
| Normalized plasma pressure | $\beta$ |



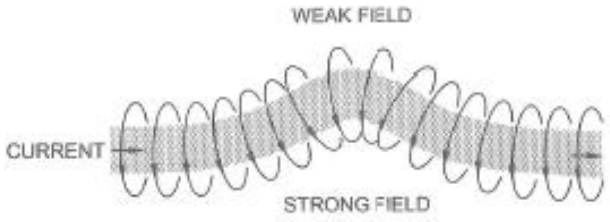

- Design goals, engineering and nuclear constraints
  - Electric power $P_E$ = 1000 MW
  - Wall loading limit $P_w$ = 4 MW/m$^2$
  - Superconductors, $B_{max}$ = 13 T
  - Structural material, $\sigma_{max}$ = 300 MPa
  - D-T fusion cross-section
  - Blanket: neutron moderation and tritium breeding
- Design of the reactor

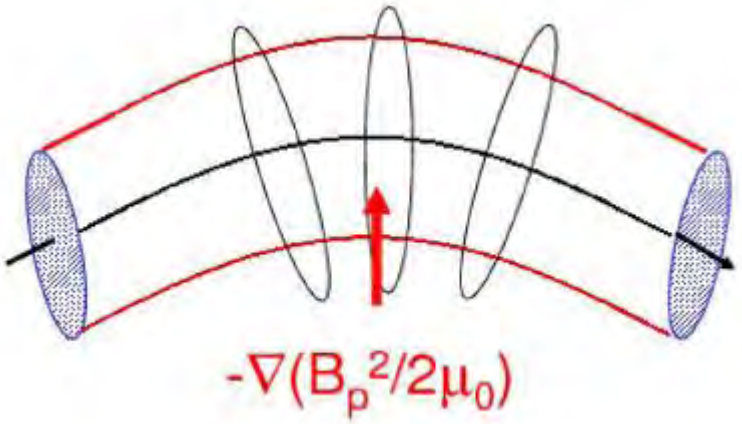


# Kink and sausage instabilities

- Kink instability
  - A flexible wire plunged into a

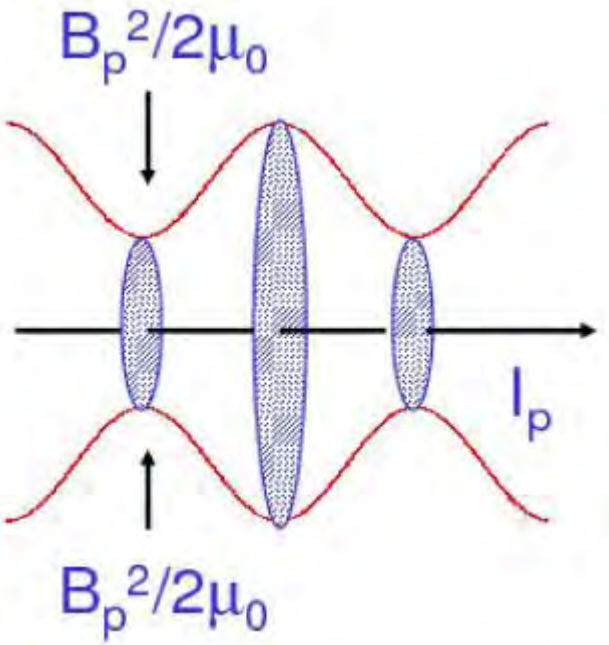
  Magnetic field is unstable
  - In a z-pinch bending tends to amplify




- Sausage instability
  - In a z-pinch compression zones

  (intense poloidal field) tend to amplify

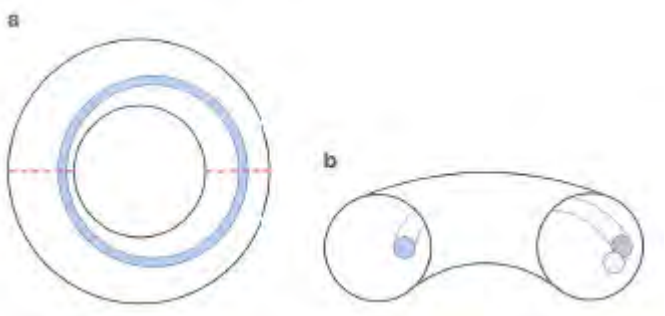


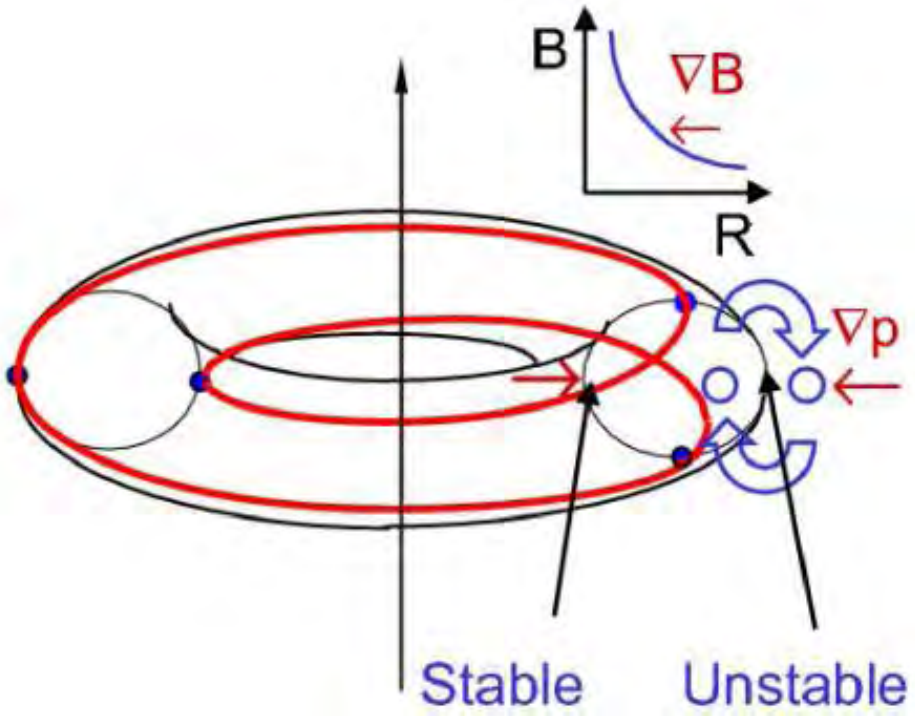
# Interchange stability in a tokamak

- Low (high) field side is locally unstable (stable) connected via field lines (ballooning modes)
- Set a β (or pressure) limit

  Troyon limit $\beta_N$

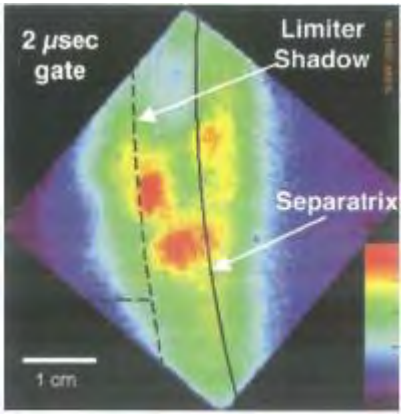
$$\beta_N \equiv \beta\,(\%)\frac{aB}{I} \sim 3.5$$

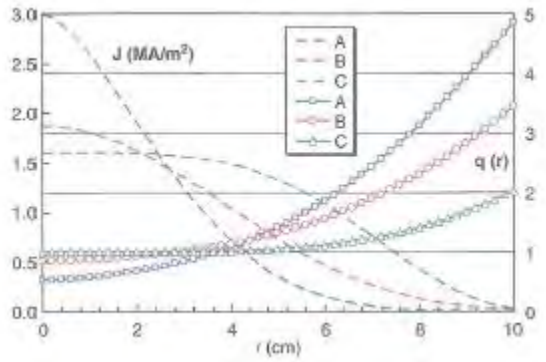


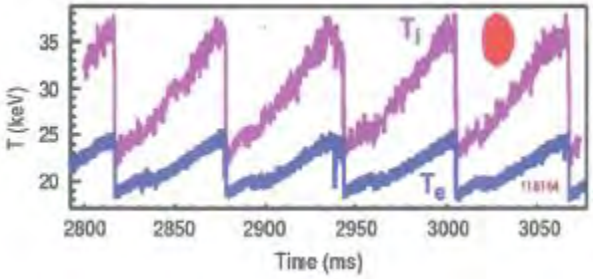



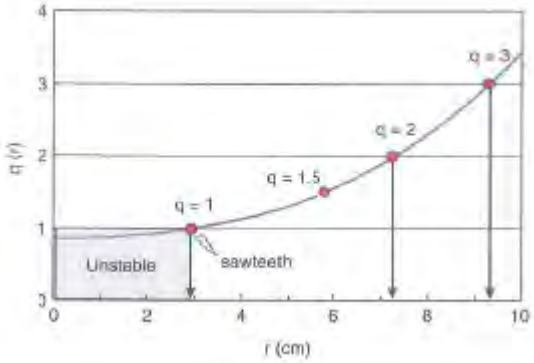
# Magnetic islands and sawtooth

- Kruskal-Shafranov limit



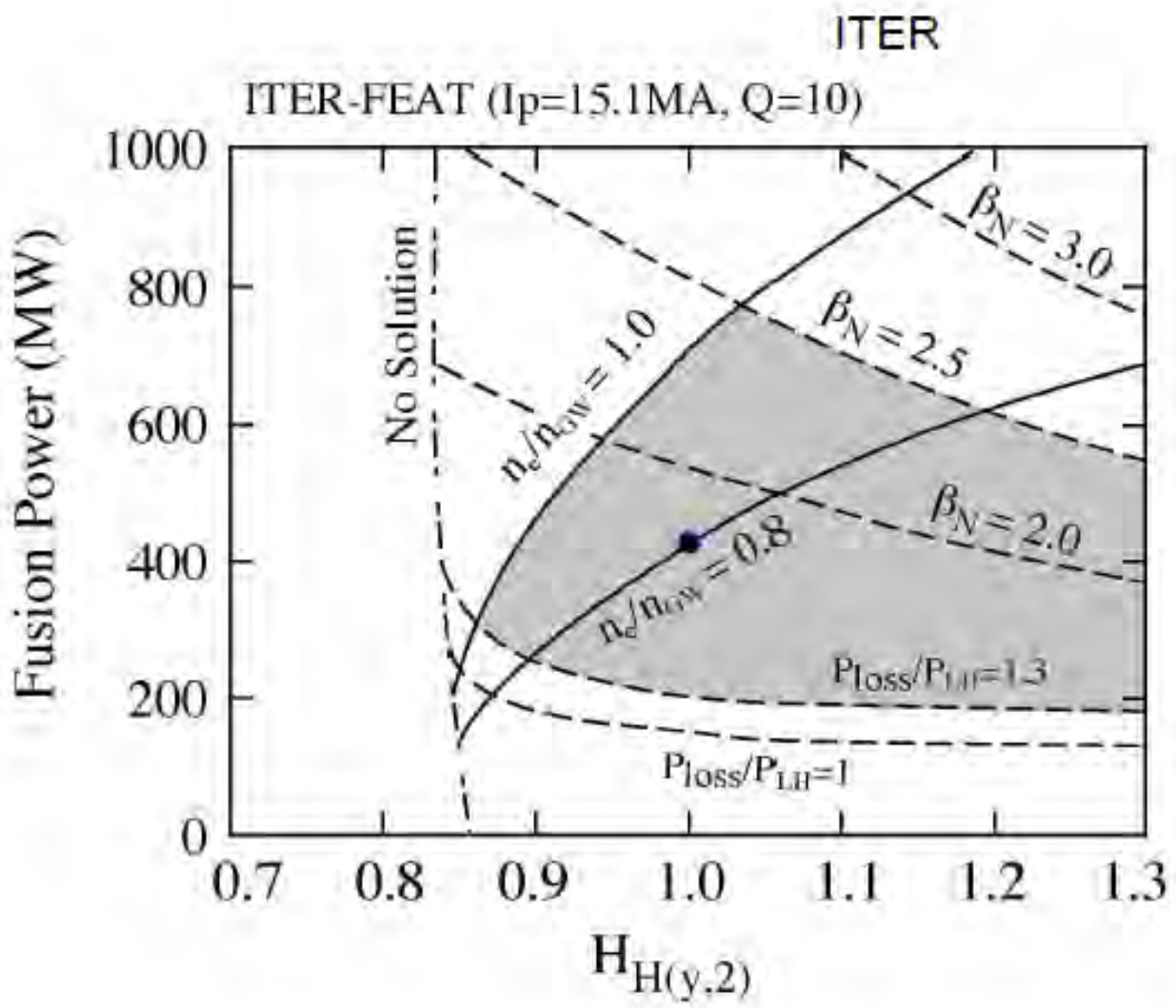



# Stability diagram for ITER

**Compromise between various constraints:**

- density limit
  $n/nGw = 1$
- β limit
- Confinement



# MHD Stability. Conclusions

- Equilibrium is essentially a balance between the pressure gradient and the Lorentz force $\rightarrow$

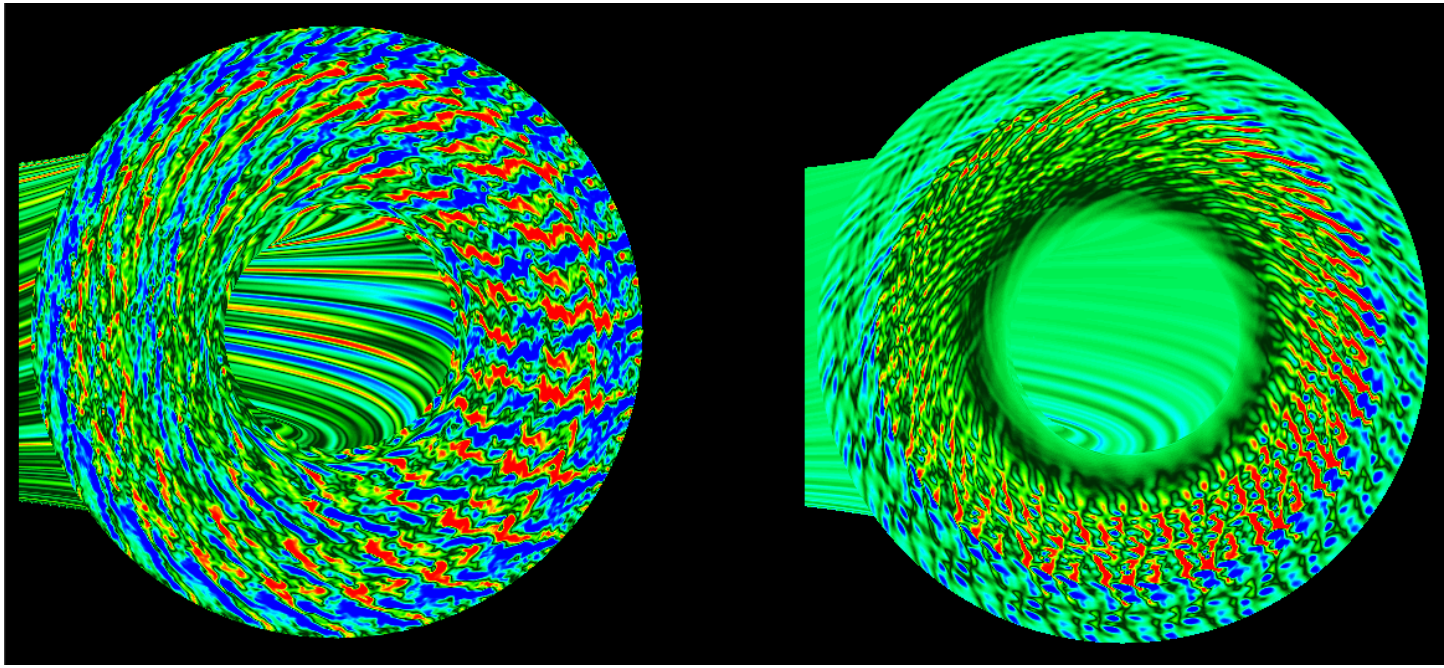
  Grad-Shafranov equation

- Two main instabilities:
  -interchange (pressure driven),
  -kink (current driven).

- ITER target plasmas are stable with respect to the main MHD instabilities.

# Turbulence, transport and confinement

**A shear flow (right) tears the swirls and thus decreases the convective cross-field turbulent transport**



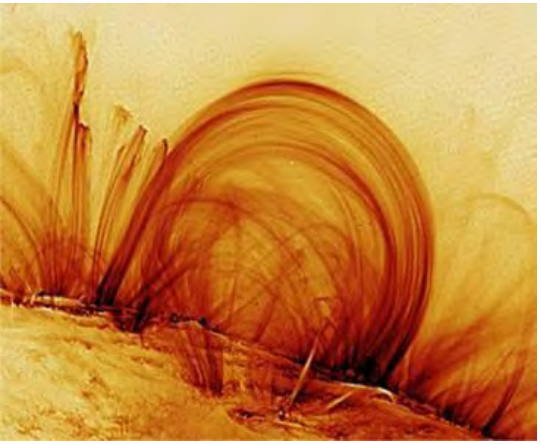
**Example of very demanding numerical simulations to study methods to suppress turbulence**

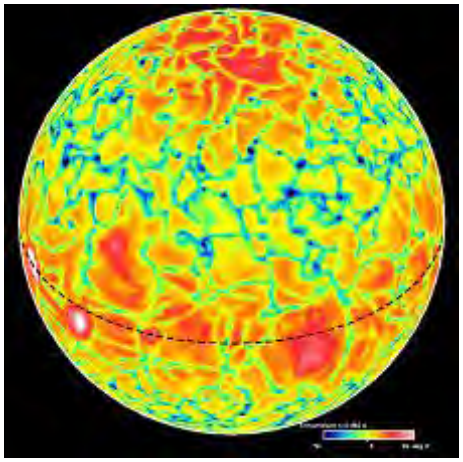
- Nonlinear Physics: theoretical predictions are difficult
- Turbulent transport.
- Degradation of the confinement.

# Scientific aspects: comparison between sun and tokamak

## Sun

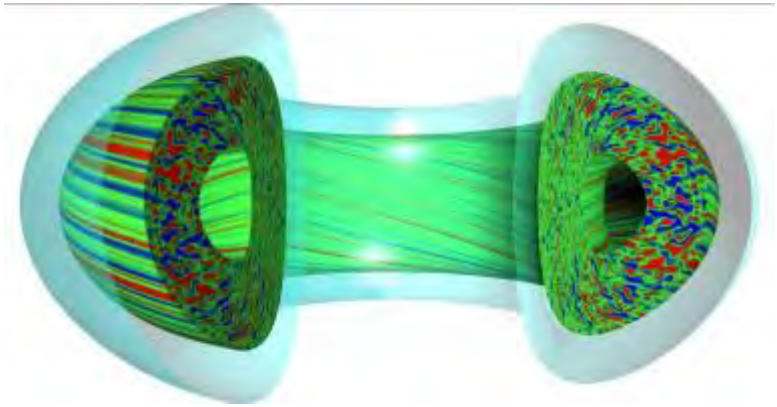
- Thermoconvection
- Magnetic field generation (dynamo)
- Solar eruptions





## Tokamak

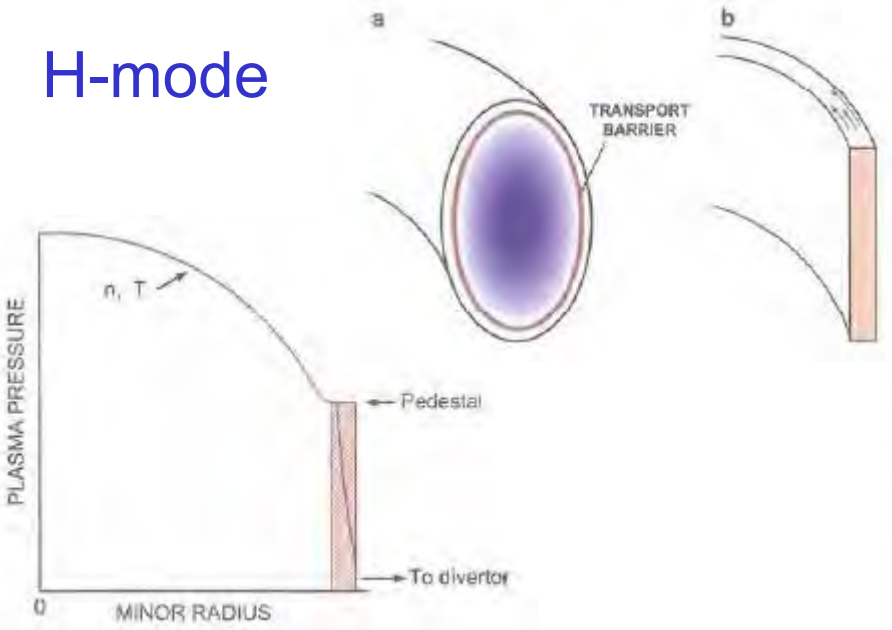
- Turbulent transport
- Mean velocity flow generation
- Relaxations (disruptions)

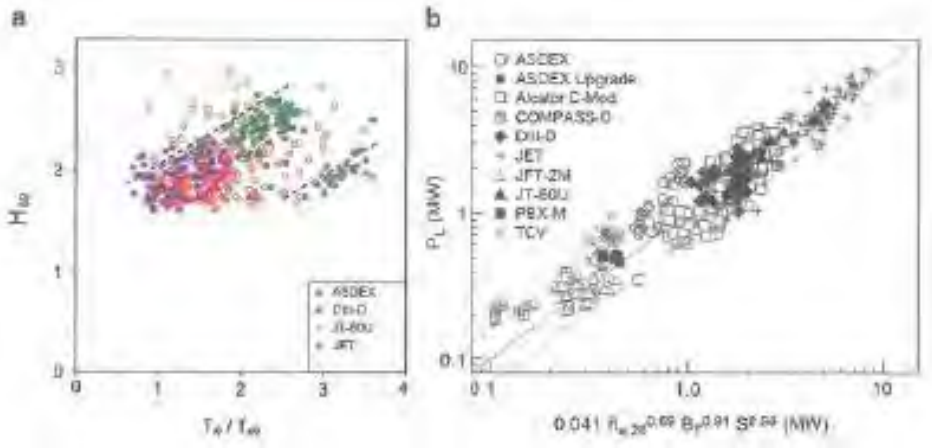


- Large number of similarities between fusion plasmas on earth and stars.
- The main problems in solar physics are thermoconvection, dynamo effect, and les eruptions.
- Similar research topics exist in tokamak plasmas.
- The main objective in building Tokamaks is to produce energy. They are also very interesting from the point of view of fundamental physics .

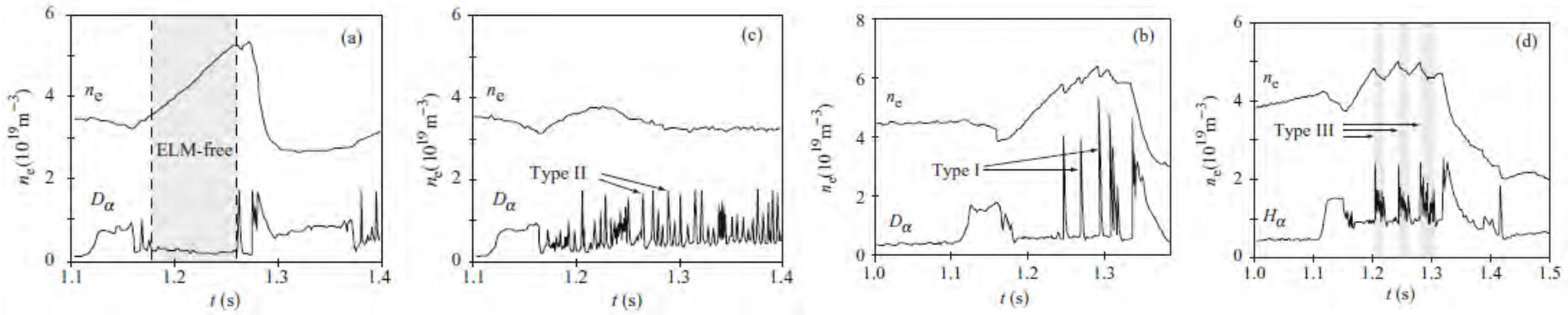
# L- vs. H-mode, Edge Localized Modes

- H-mode




- ELMs



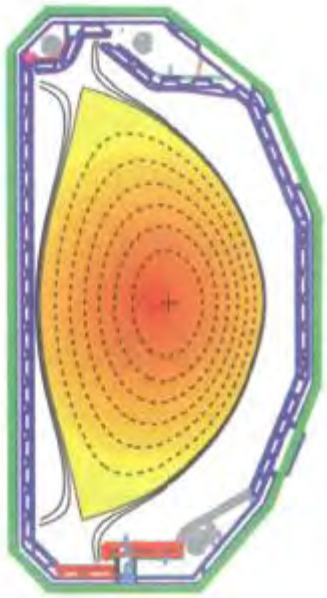
# Scrape-off layer

- In the edge : field lines are intercepted by plasma facing components
- Charged particles follow field lines

→ a thin boundary layer develops at the edge:

**the Scrape-Off Layer**

- The width of the the SOL is small: most of the heat is deposited in a layer whose width is ~1cm



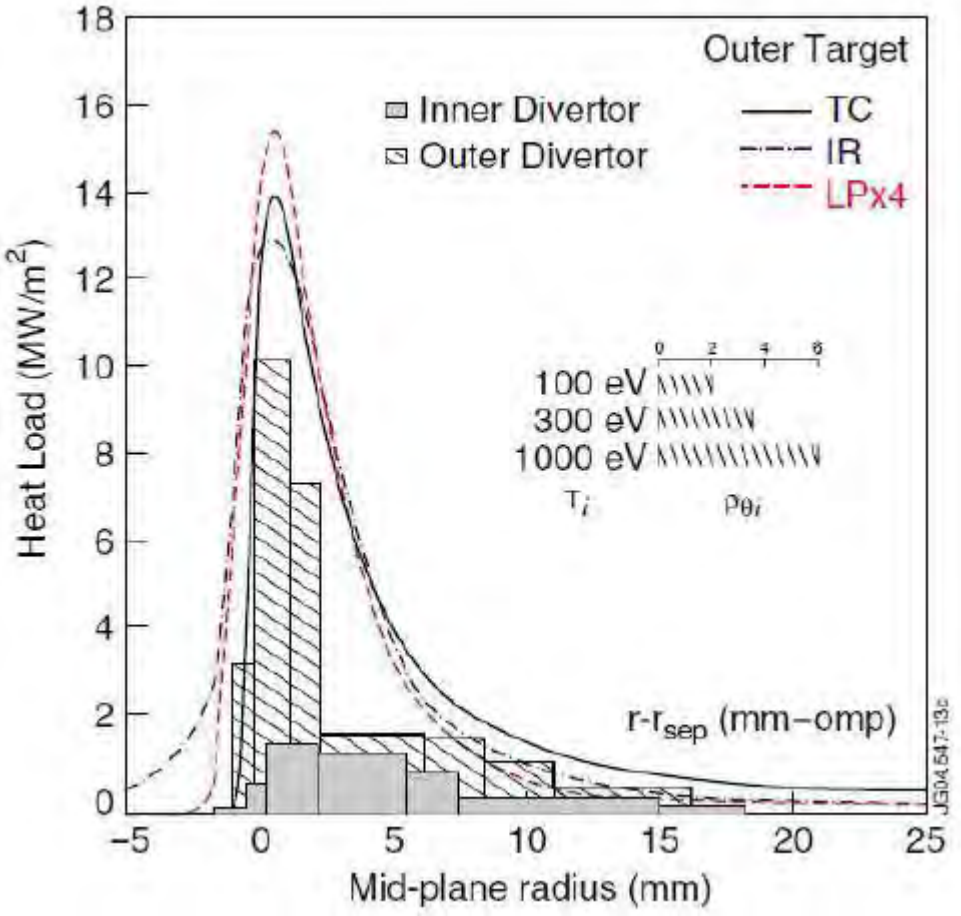
# Heat exhaust: a challenge

- ITER : 120 MW must be extracted by plasma facing components.
- Heat flux across the separatrix

  $q_{\perp}$=0.2 MW/m$^2$
- Parallel heat flux

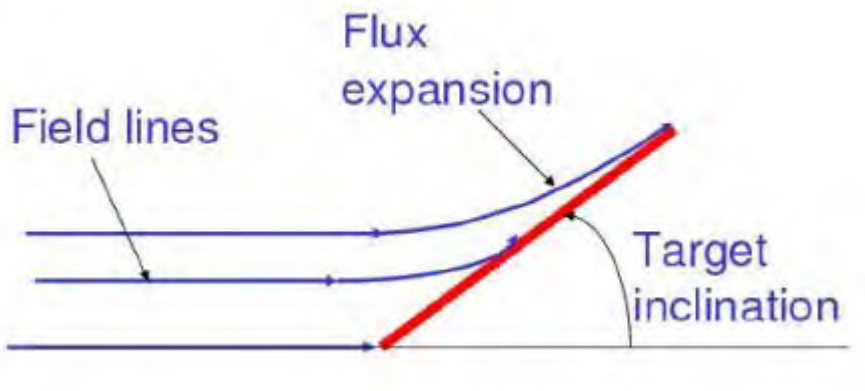
  $q_{//} \approx q_{\perp} qR/\lambda \approx$ 1GW/m$^2$
- If incidence is normal: well beyond technology capabilities

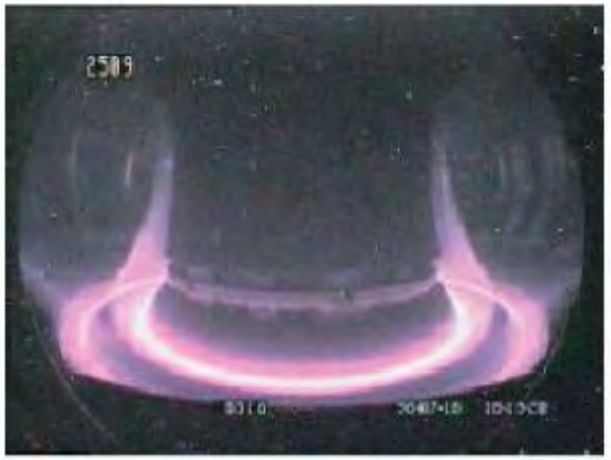
  ($\approx$ 10 MW/m$^2$)



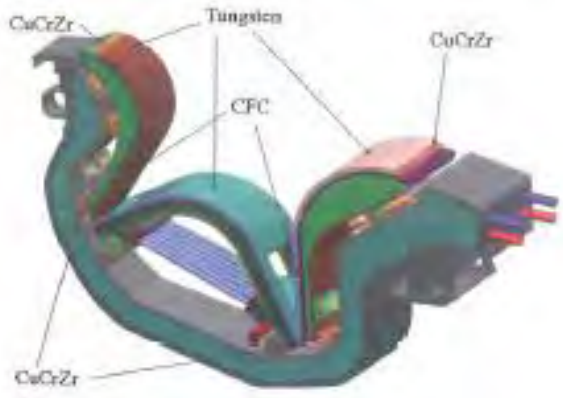
# Solutions

- Geometry (field line inclination, flux expansion, …)
- Radiation: photons do not follow field lines!



An appropriate device: **the divertor**



# *Edge plasma: Summary and Conclusions*

- It is essential to reduce the particle and heat fluxes on the divertor plate

- Sheath potential is not sufficient to reduce enough the fluxes

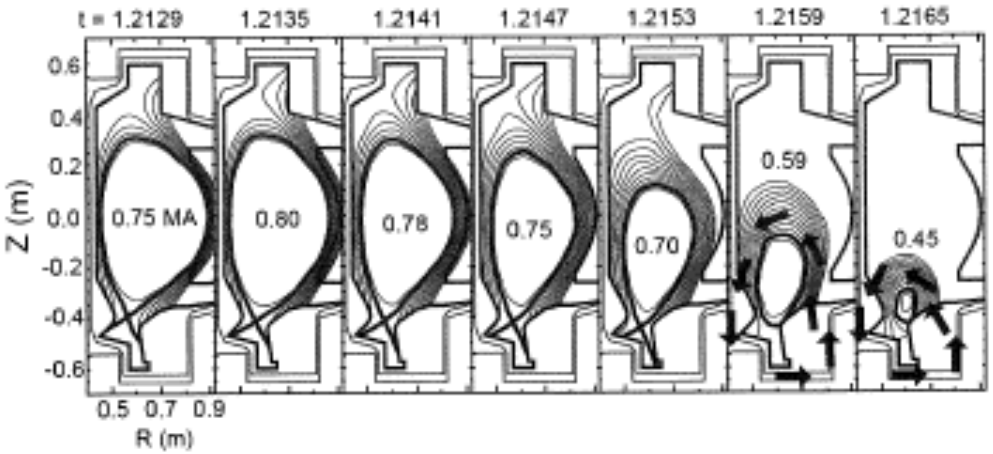
- An optimum regime is reached by producing a neutral “cushion” in the divertor: detachment

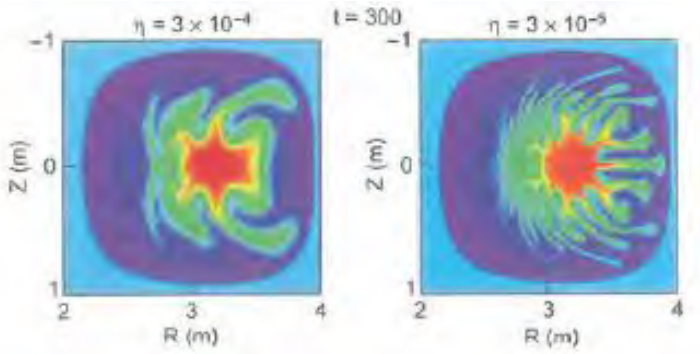
- However detachment may lead to a disruption

# Disruptions

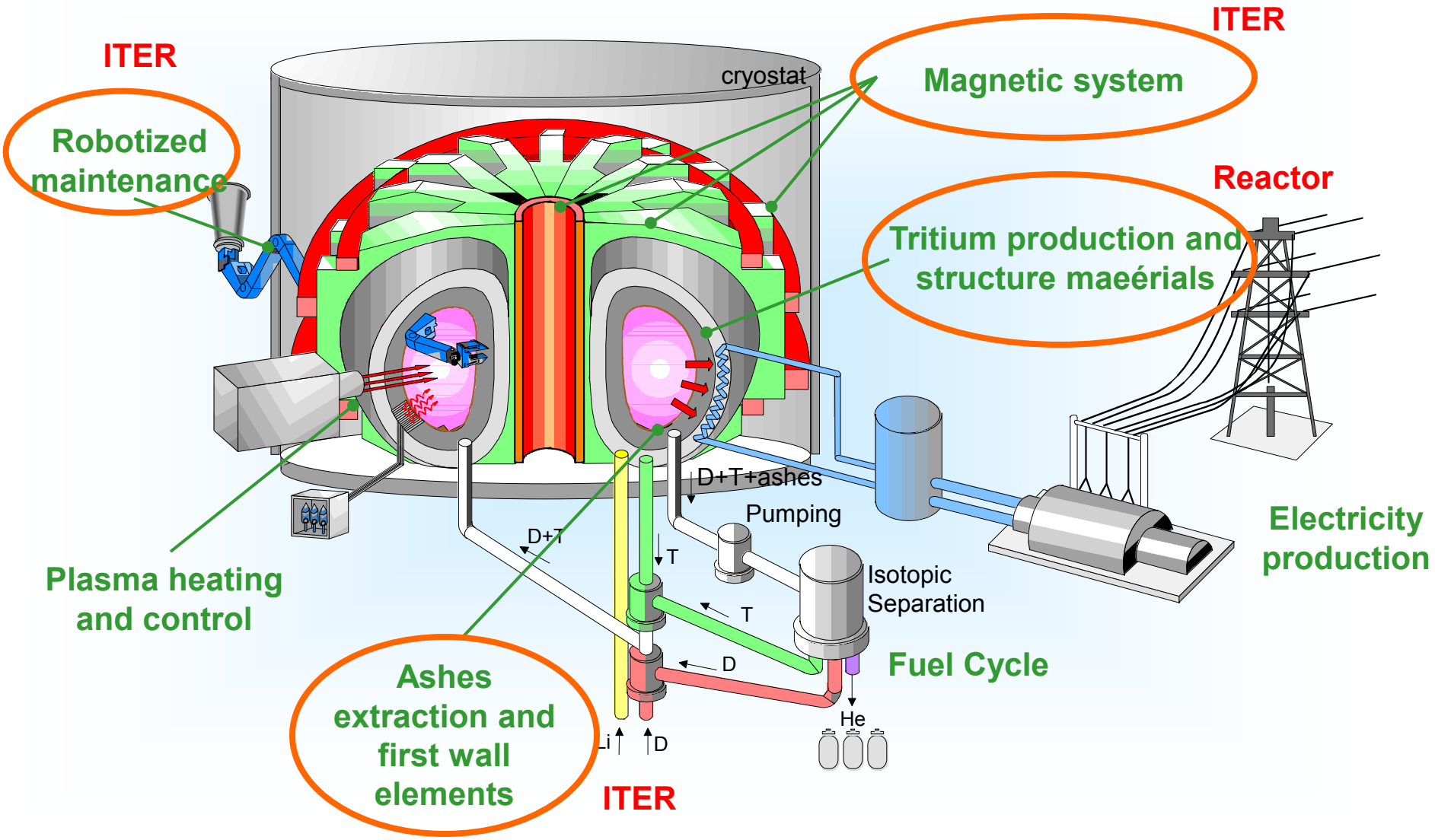
- Strong cooling may lead to a local decrease of temperature
- Because of Ohm's law $\sigma(T)\, J = E$, this may lead to a peaked current density $J \rightarrow$ kink instability
- In usual conditions, this defines a density limit

  $n_G$ ($10^{20}$ $m^{-3}$) = $I_p$ (MA)/$\pi\kappa a^2$ (Greenwald limit)
- Massive impurity injection also leads to a disruption



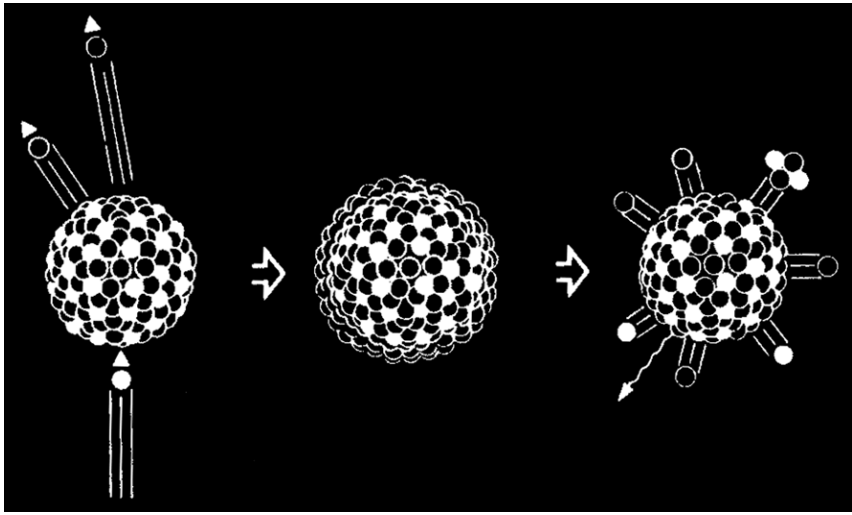



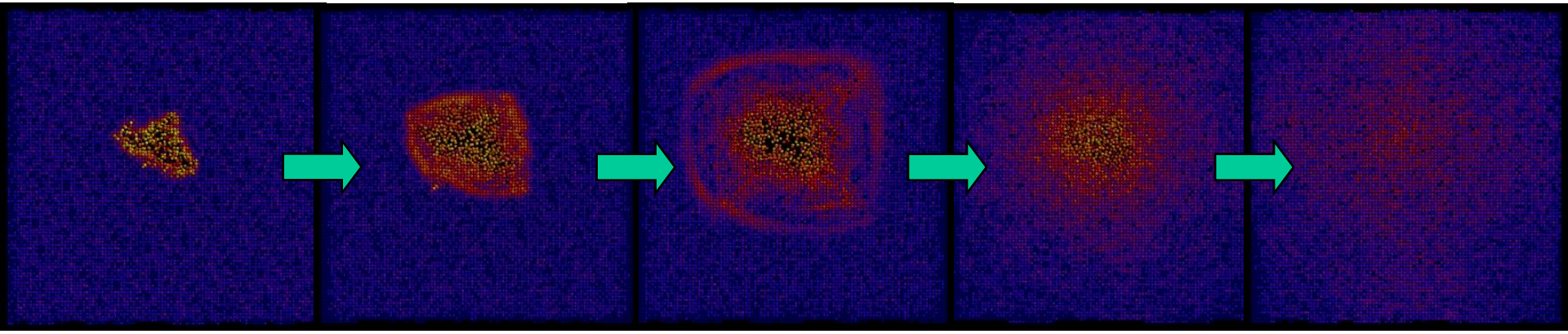
# Four technological challenges faced by fusion



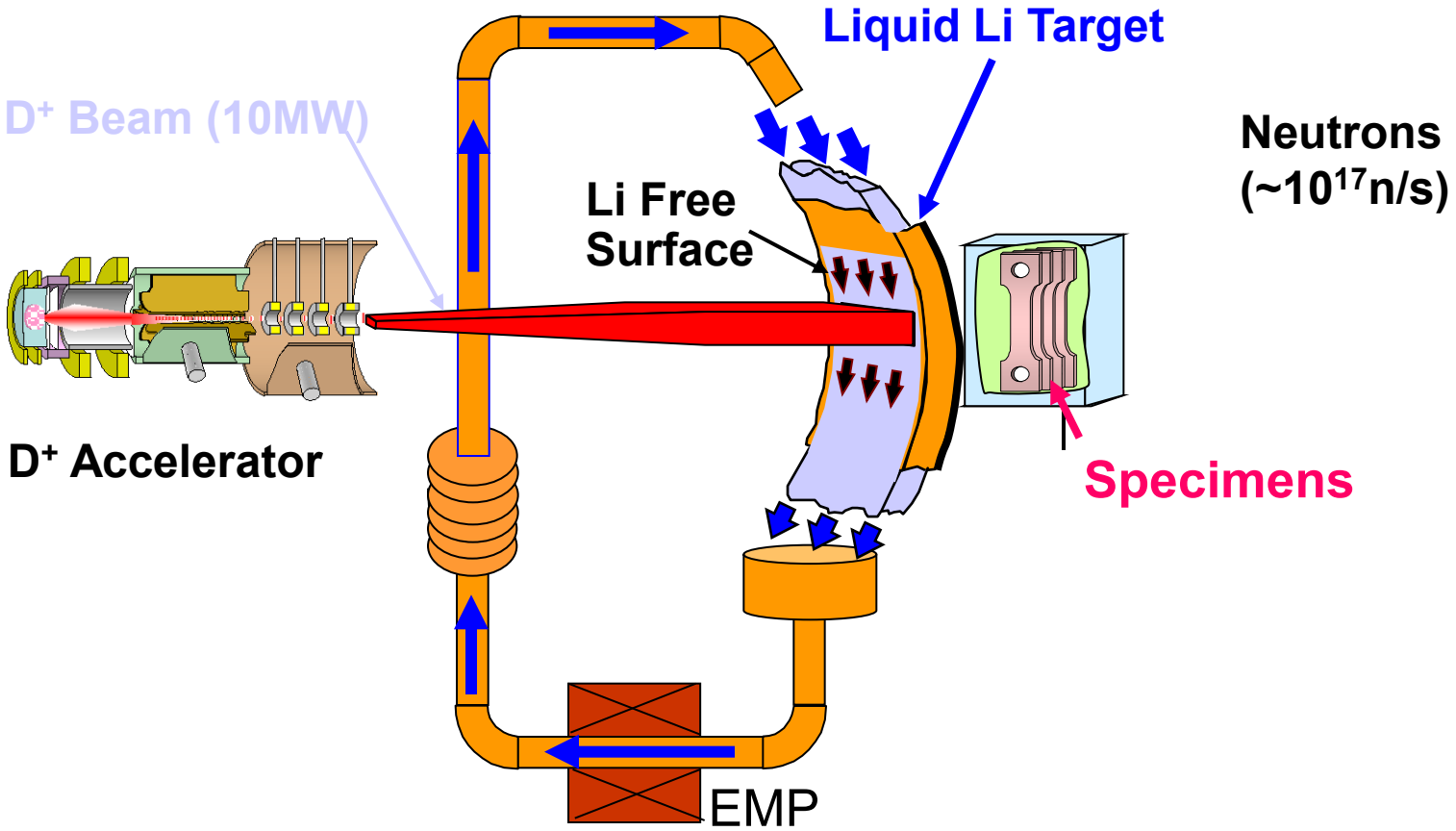
# Effects of 14 MeV Neutrons on materials

- The 14 MeV neutrons will produce transmutation, nuclear reactions and atomic displacement cascades inside the materials.



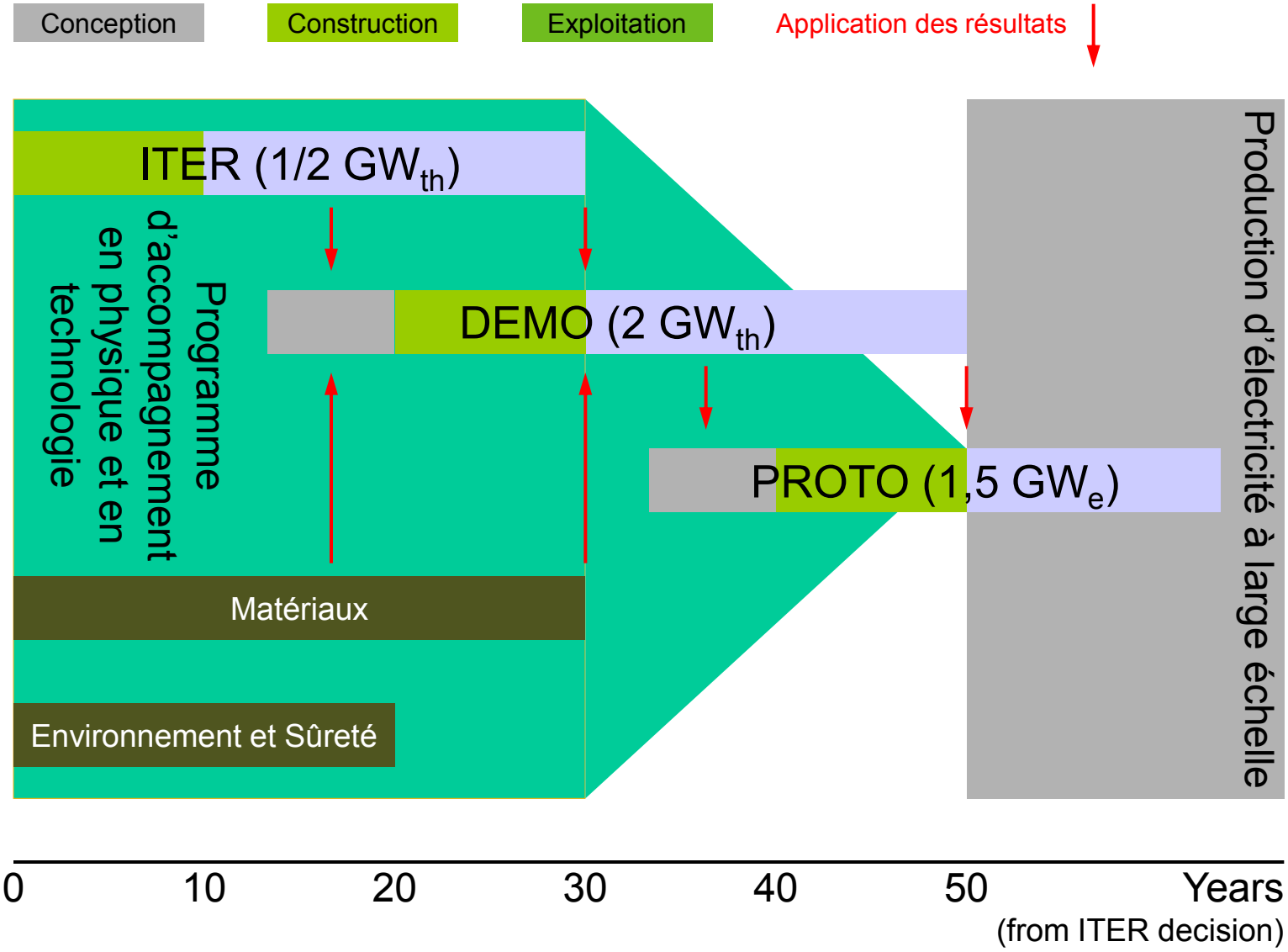


# Irradiation facility: IFMIF
## Schematic View




**EVDA phase in progress in Aomori**
**Within EU/Japan broader approach**

# Perspectives for fusion energy



# A commercial fusion reactor: when ?

**History**

~ 100 years

***1900-1940*** *: explanation of solar energy origin*
***1952*** *: H -bomb*
***1958*** *: 1st theory of magnetic confinement, Sakharov & Tamm*
***1969*** *: validation of Tokamak configuration, Lev Artsimovitch*
***1997*** *: 16 MW of fusion power in JET*
*.....*
***Middle of 21st century : prototype of a fusion reactor***

*A delay of 100 years between the concept and the applications not unusual*

***Ex : fuel cell***
- *Principle : William R. Grove (1839)*
- *1 kW prototype F.T. Bacon (1953)*
- *1er vehicle equipped with fuel cells (1990)*

***Ex: Solar Cells***
- *Principle : Antoine Becquerel (1839)*
- *1st Si solar cells (satellites) (1958)*

# *ITER: status and challenges*

- The ITER project is a huge undertaking!
- ITER is primarily an experiment
  but also a major technology test bed
- An essential step towards a DEMO reactor
  (or equally a demonstration that one may not work)

# 21 November 2006, historical date

# ITER Objectives 1/3

## Performance and Testing Requirements

- Achieve inductive plasma burn with power amplification, Q (ratio of fusion power to auxiliary heating power), of at least 10, under stationary conditions on the timescales of plasma processes;
- Aim at demonstrating steady-state operation with Q > 5;
- Do not preclude the possibility of controlled ignition.
- Integrate the technologies essential for a fusion reactor (e.g. superconducting magnets, remote maintenance);
- Test components for a future reactor (e.g. divertor and torus vacuum pumps);
- Test tritium breeding module concepts for DEMO.

# ITER Objectives 2/3

## Design Requirements

- Engineering choices and design solutions make maximum use of existing R&D ;
- Machine parameters give confidence in achieving the required plasma and engineering performance.
- The design permits advanced modes of plasma operation and a wide operating range.
- Inductive flat top capability ~ 300-500 s
- Operation limited to a few 10s of thousands of pulses
- Able to support equilibria with high bootstrap current fraction and plasma heating dominated by alpha particles.
- Average neutron flux > 0.5 $MW/m^2$
- Average fluence > 0.3 $MWa/m^2$
- Later installation of tritium breeding blanket should not be precluded.

# ITER Objectives 3/3

## Operation Requirements

- Burning plasma experiments should address confinement, stability, exhaust of helium ash, and impurity control.
- Steady state experiments should address issues of non-inductive current drive and other means for profile and burn control and for achieving improved modes of confinement and stability.
- Operating modes should have sufficient reliability for nuclear testing.
- The device is anticipated to operate for ~ 20 years, using externally supplied tritium.

# ITER site: Cadarache (Provence)

**ITER:** 2000 pers (construction)
1000 pers (exploitation)

**CEA Centre** : 4500 pers


ITER

*autonomous site*

Vinon-sur-Verdon

CEA boundary

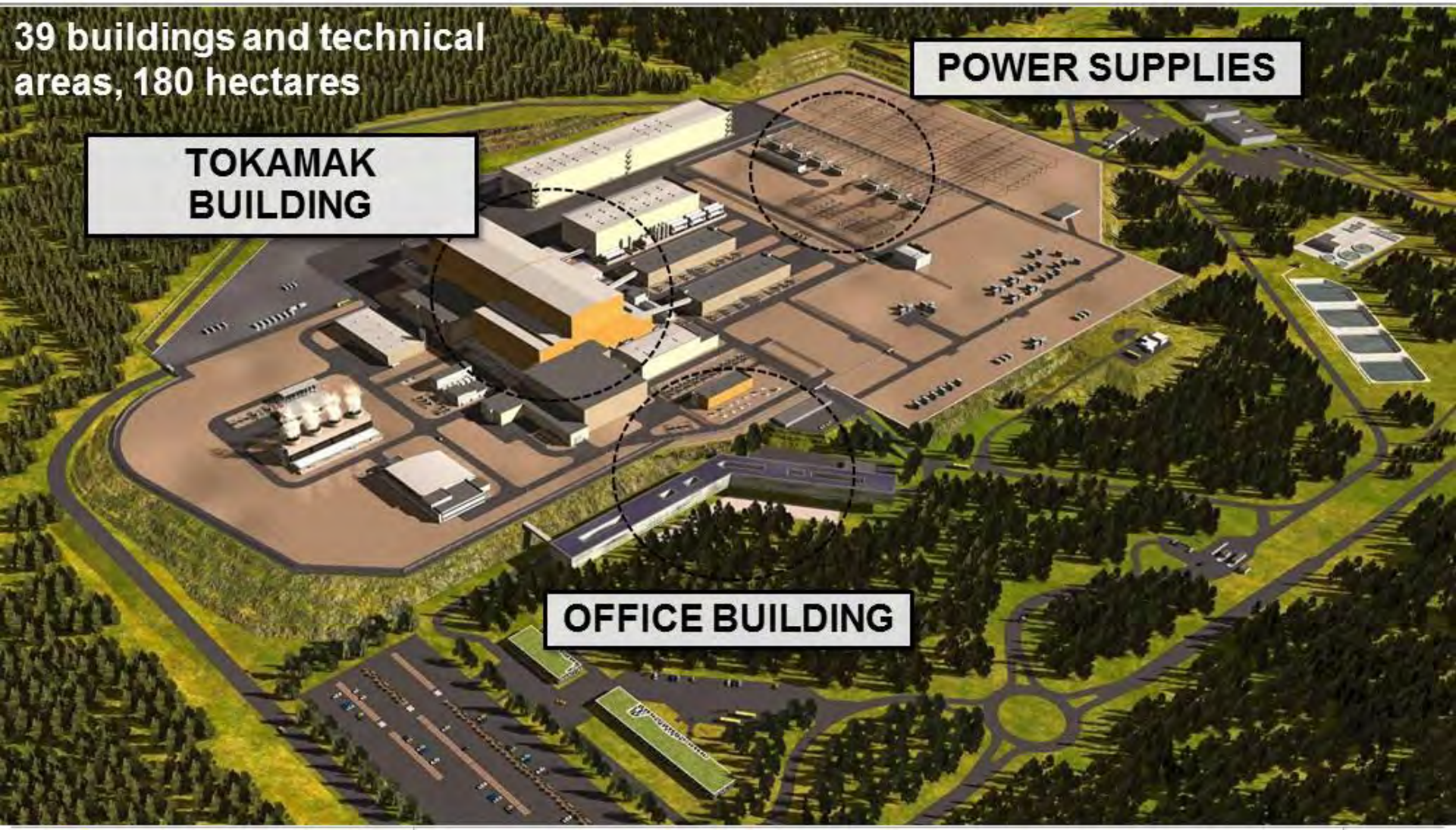
CEA

400 kV line

Tore Supra

# ITER site: Cadarache (Provence) 2012

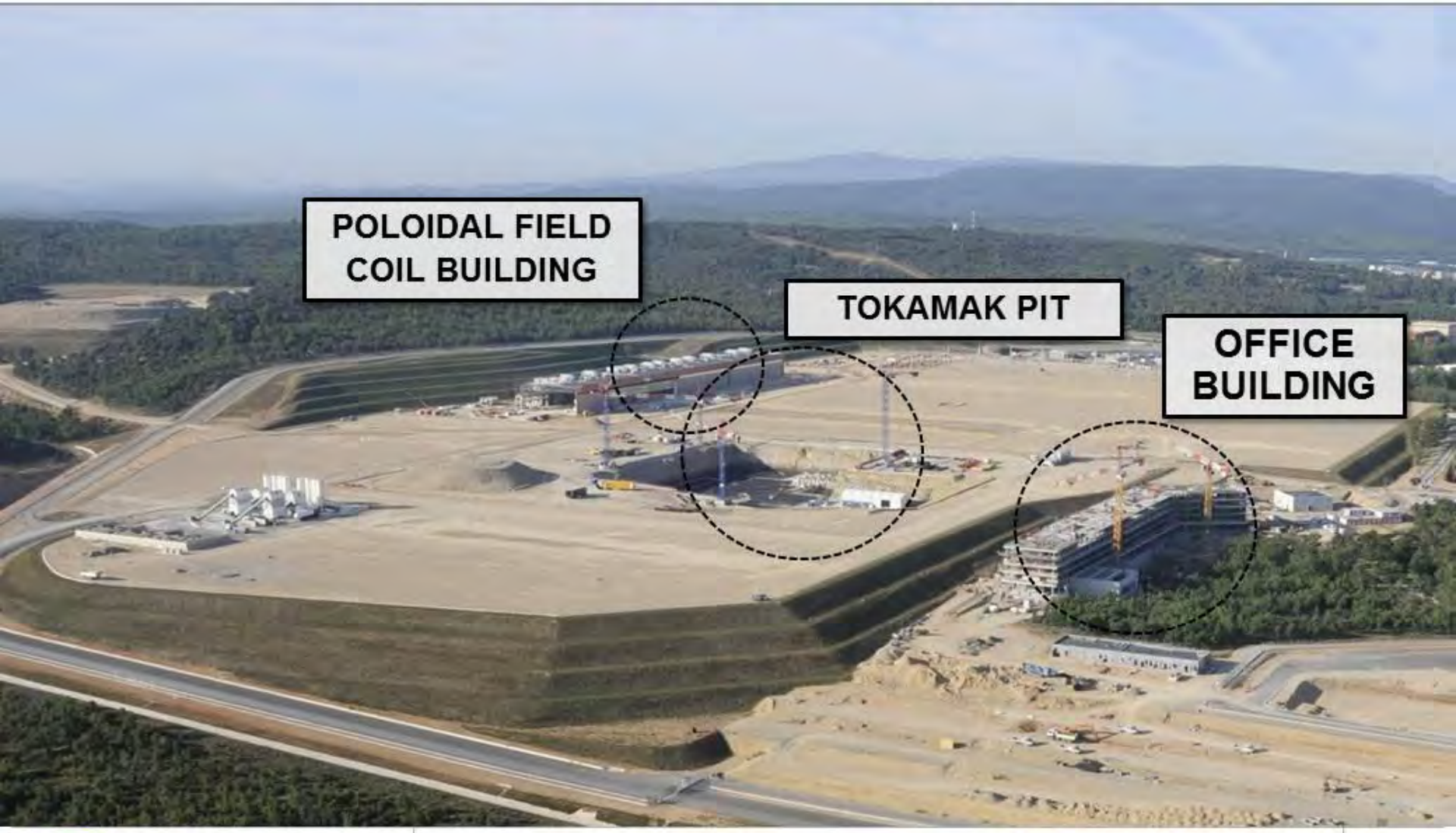

# Site construction complete (2019)



# Site platform is ready (2009), after 4 years of work

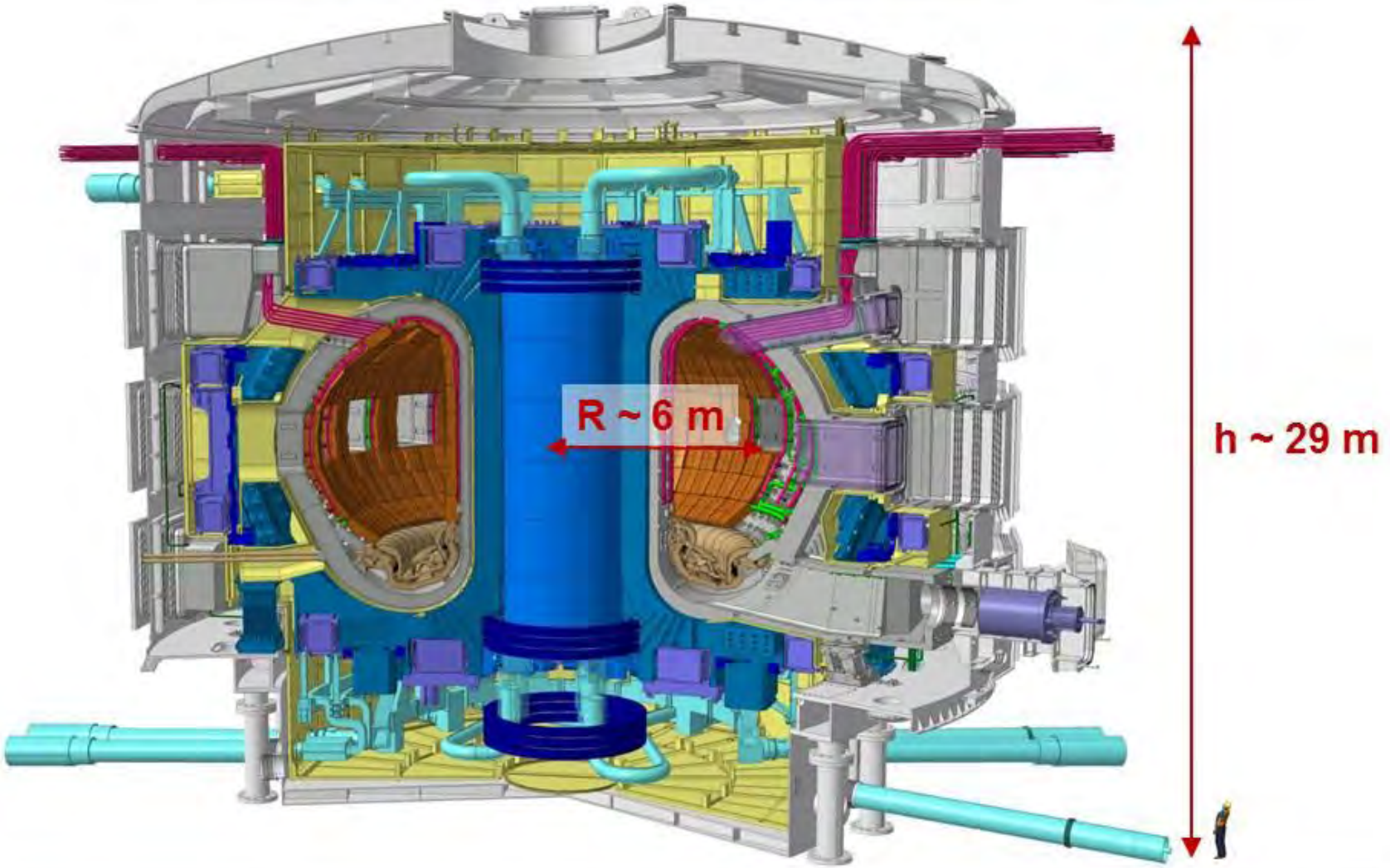
## 40 ha platform, 2.5 million $m^3$ of earth moved, good bedrock (100 t $m^{-2}$)

# Platform status - Sept 2011



# Status of the tokamak complex construction

# The ITER device



# Design goals

## 1 Physics

- Produce a significant fusion power amplification factor ($Q \geq 10$) in long-pulse operation
- Aim to achieve steady-state operation of a tokamak ($Q = 5$) and retain the possibility of exploring 'controlled ignition' ($Q \geq 30$)

## 2 Technology

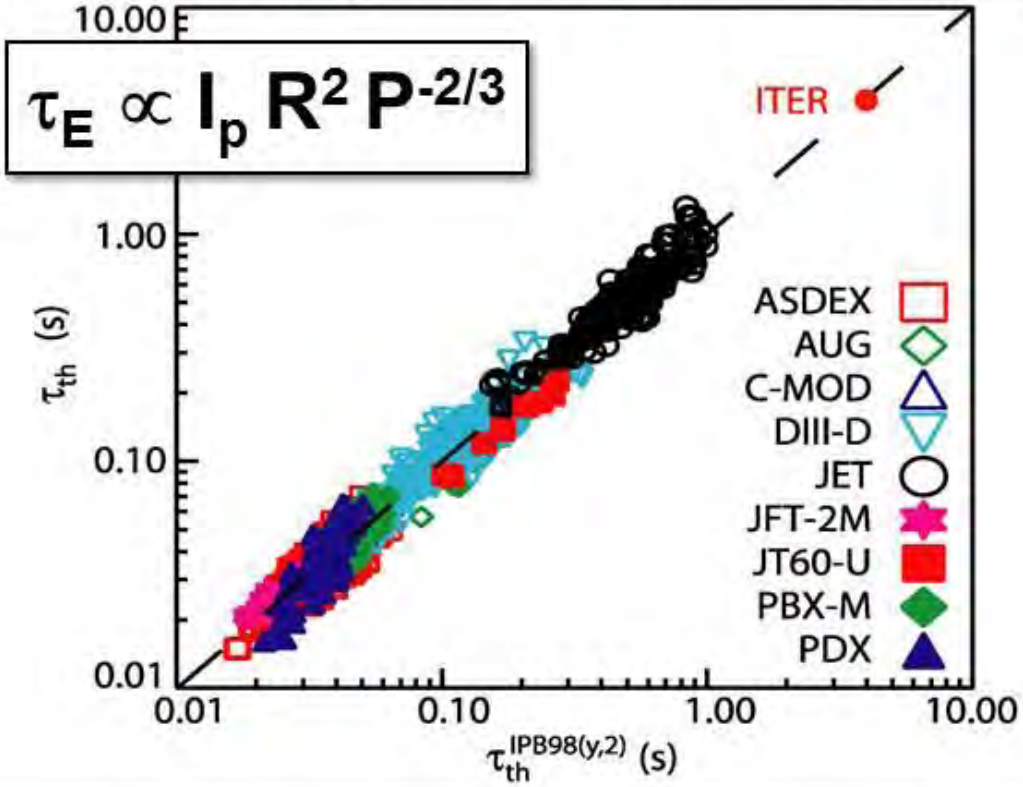
- Demonstrate integrated operation of technologies for a fusion power plant
- Test components required for a fusion power plant
- Test concepts for a tritium breeding module

# ITER reference scenario for Q =10

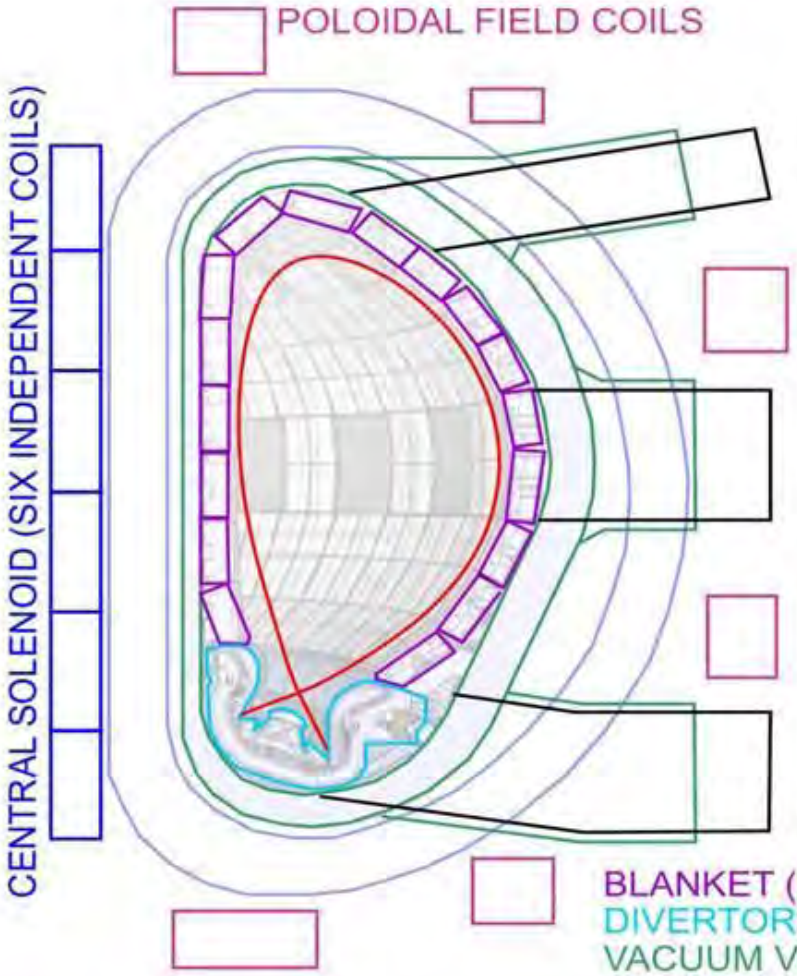
Type I ELMing H-mode: robust mode of operation in today's tokamaks

- L-mode confinement is ~2× less than H-mode (Type-I), generally speaking → in the current ITER design, Q=10 in L-mode is "highly unlikely"

IPB98(y,2) TYPE-I ELMing H-MODE SCALING FROM EXPERIMENT



# Overview of major systems




ELECTRON CYCLOTRON H&CD (20 MW)
DIAGNOSTICS
GAS FUELLING
DISRUPTION MITIGATION SYSTEM
FUSION POWER SHUTDOWN SYSTEM

ION CYCLOTRON RESONANCE H&CD (20 MW)
NEUTRAL BEAM HEATING (33 MW)
DIAGNOSTICS
TRITIUM BREEDING MODULES (TBMs)
REMOTE HANDLING ACCESS
DISRUPTION MITIGATION SYSTEM
FUSION POWER SHUTDOWN SYSTEM

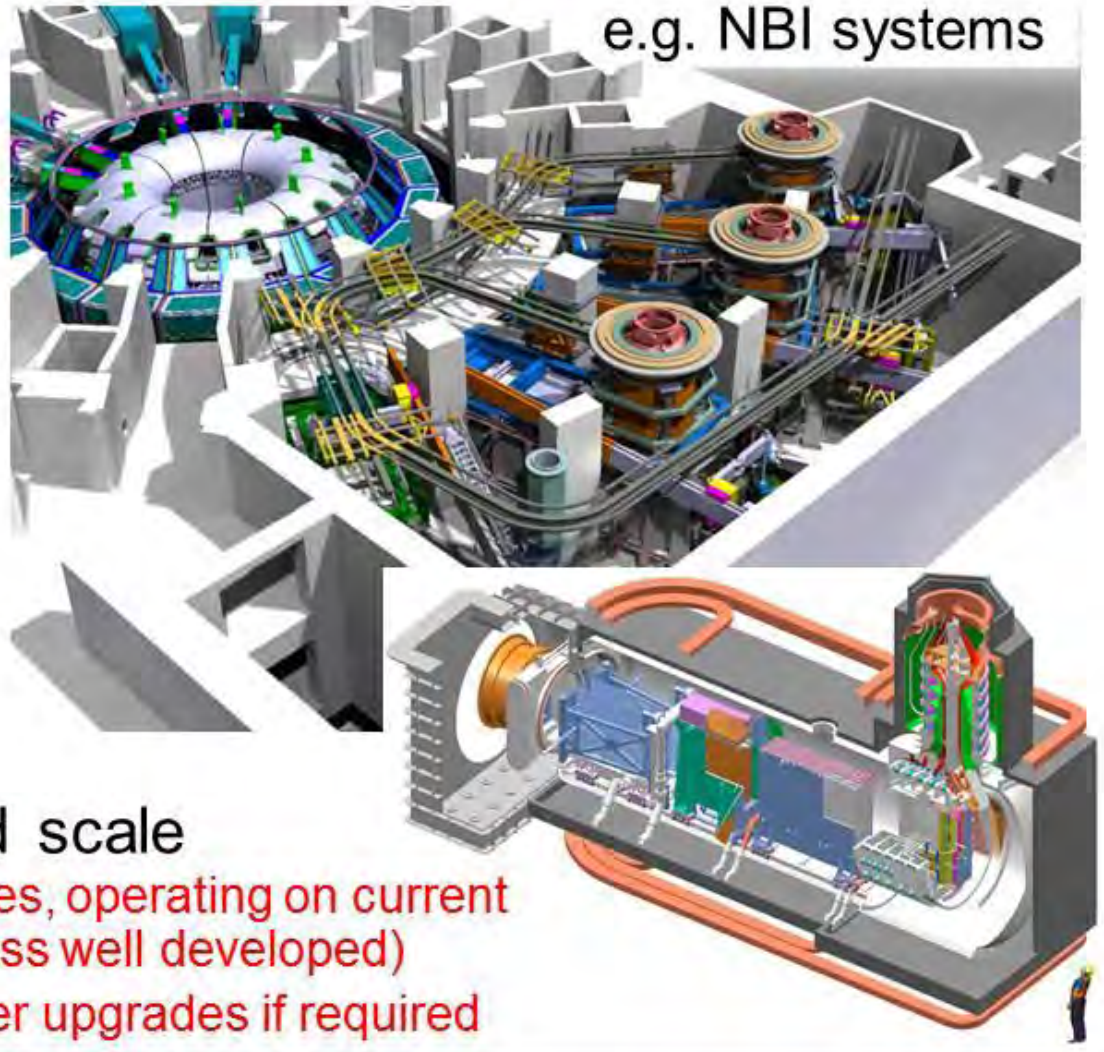
DIAGNOSTICS
GAS FUELLING
PELLET LAUNCHERS (FUELLING + ELM CONTROL)
DIVERTOR CASSETTE ACCESS
IN-VESSEL VIEWING SYSTEM
CRYO-PUMPS

BLANKET (NEUTRON SHIELD)
DIVERTOR (REMOVABLE)
VACUUM VESSEL (DOUBLE WALL)
TOROIDAL FIELD COILS (~5 T ON AXIS)

# Heating the Plasma

| System | Power |
|---|---|
| NBI<br>–ve ion, 1 MeV | 33 MW |
| ECH & CD<br>170 GHz | 20 MW |
| ICRH & CD<br>40 – 55 MHz | 20 MW |

$P_{aux}$ for $Q_{DT}$ = 10 nominal scenario: 40 – 50 MW



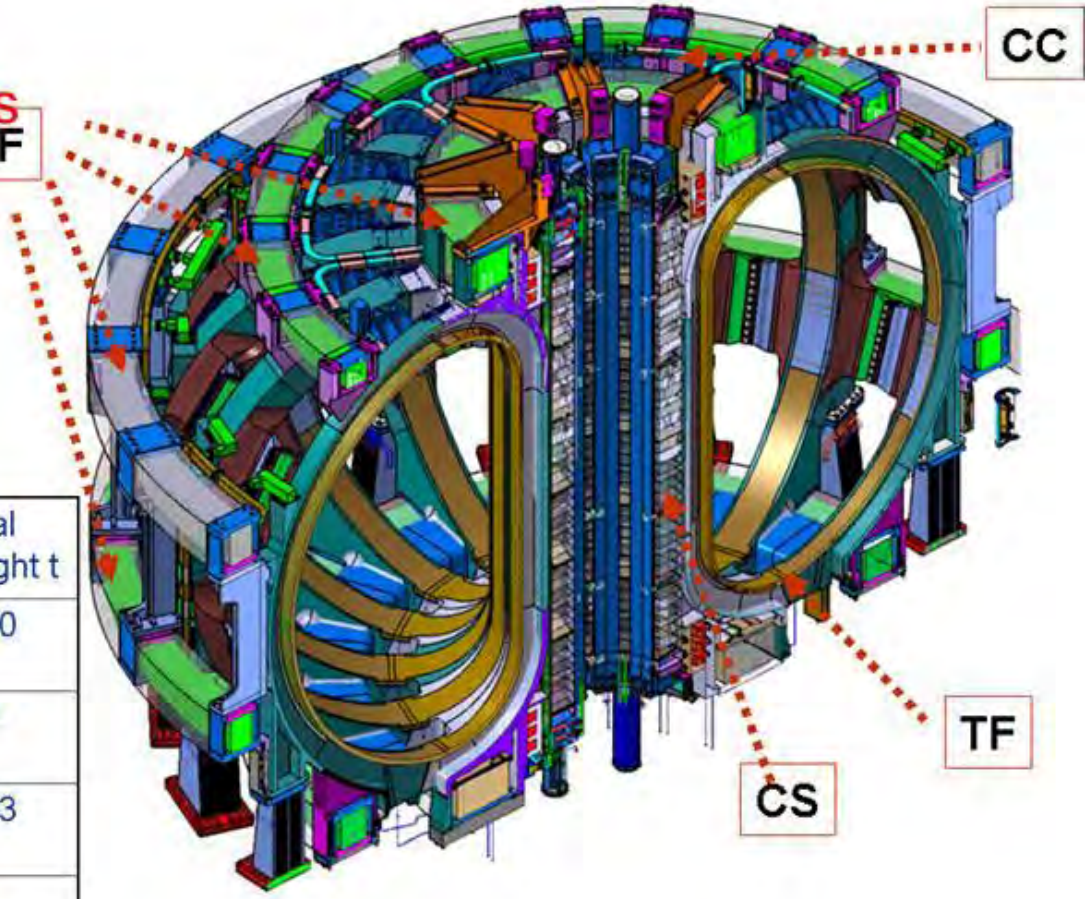

All are on an unprecedented scale

- Upscale from known technologies, operating on current tokamaks (-ve ion NBI source less well developed)
- Systems have flexibility for power upgrades if required

# ITER - Magnet Systems

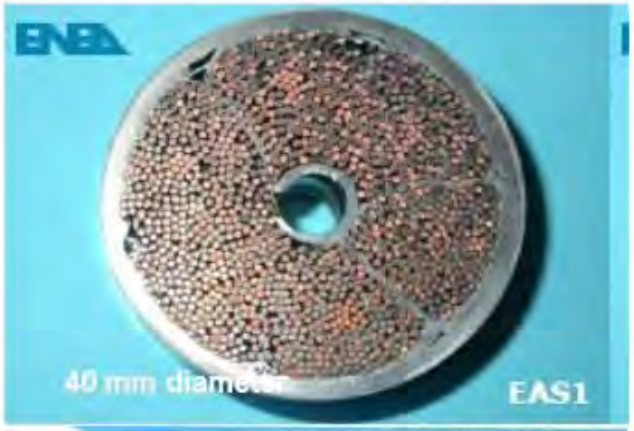
48 superconducting coils

- 18 Toroidal Field coils
- 6 Central Solenoid modules
- 6 Poloial Field coils
- 9 pairs of Correction Coils




| System | Energy GJ | Peak Field | Total MAT | Cond length km | Total weight t |
|---|---|---|---|---|---|
| Toroidal Field TF | 41 | 11.8 | 164 | 82.2 | 6540 |
| Central Solenoid | 6.4 | 13.0 | 147 | 35.6 | 974 |
| Poloidal Field PF | 4 | 6.0 | 58.2 | 61.4 | 2163 |
| Correction Coils CC | - | 4.2 | 3.6 | 8.2 | 85 |

# Toroidal field conductor procurement



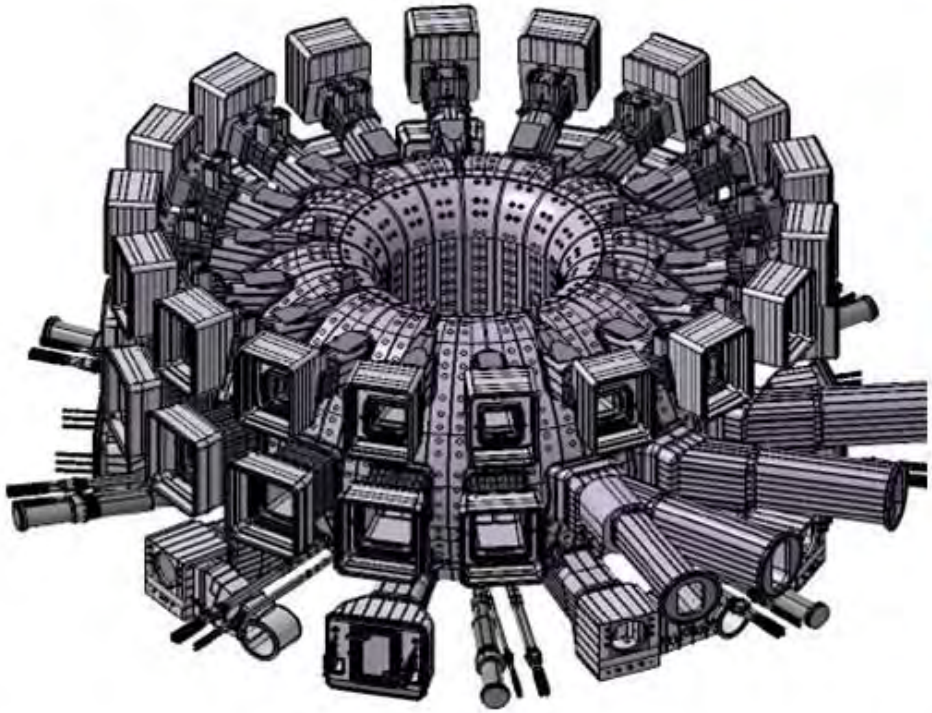


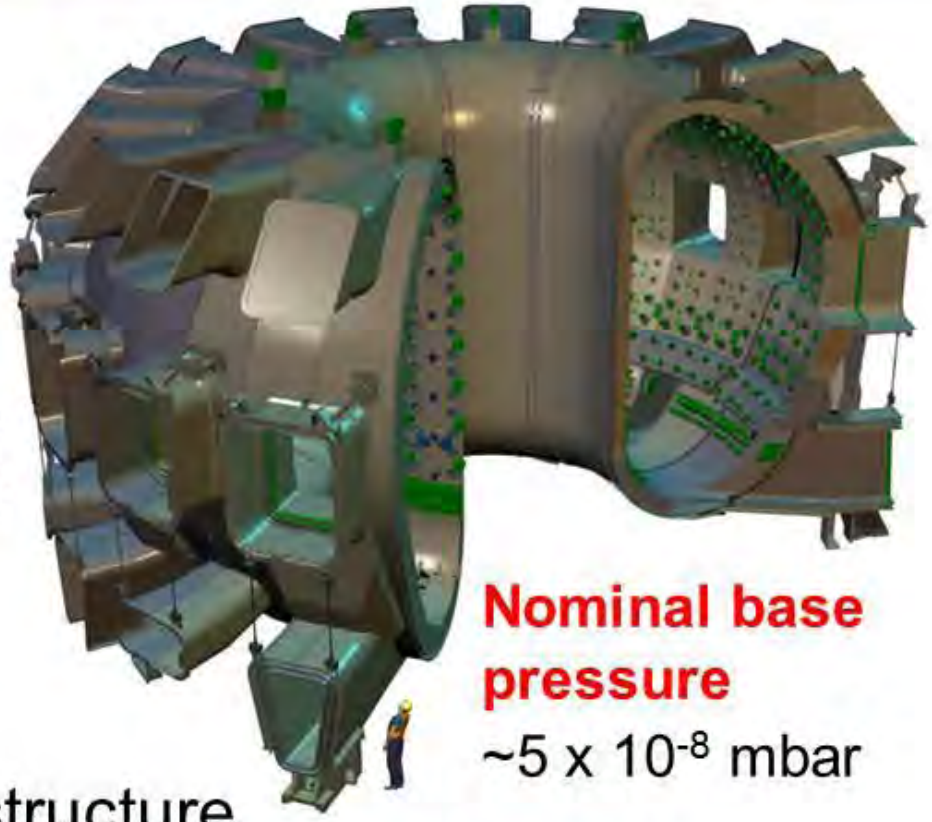
Facts

- ~90 km / 450 tonnes of $Nb_3Sn$ conductor (largest such superconductor procurement in history)
- ~150,000 km of strand
- Operates at ~5 Kelvin
- 11.8 T peak field
- 68 kA peak current in coils

Manufactured by EU, JA, RF, CN, KO & US

# Vacuum Vessel





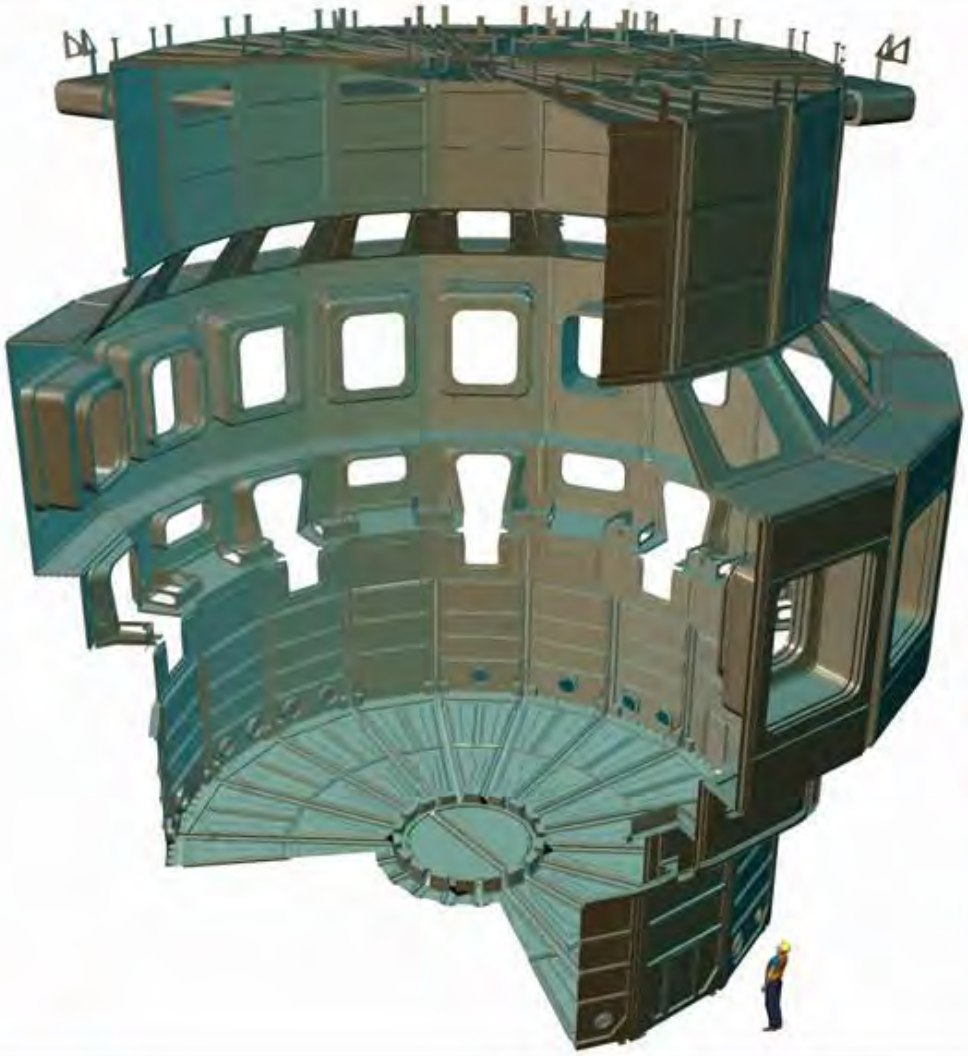
**Nominal base pressure**

~5 x $10^{-8}$ mbar

Double-walled, stainless steel structure

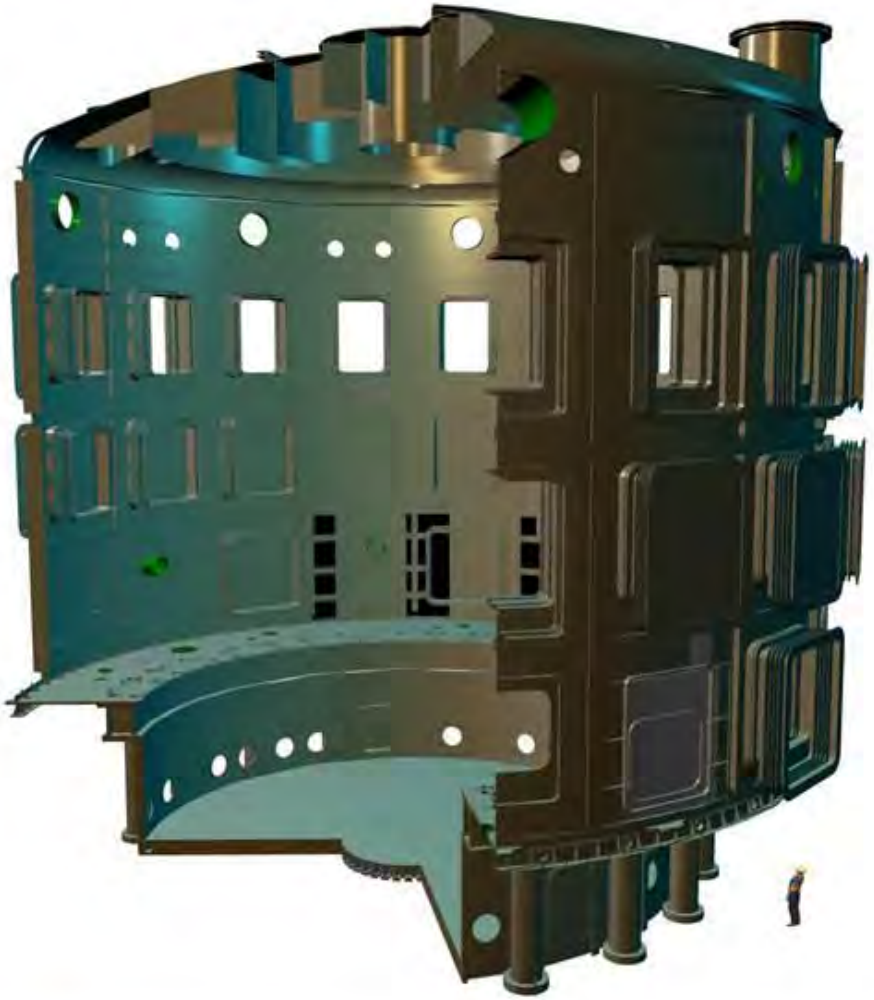
- 19.4m outer diameter, 11.3 m height, SS 316 L(N)-IG, 5300 t
- Primary tritium containment barrier, bakeable to 200°C
- Must withstand enormous vertical forces during disruptions

# Main inner heat shield



- Provides barrier for thermal loads from warm components to the superconducting coils (4.5K)
- Operates at 80 K (gaseous He in cooling pipes)
- Stainless steel panels are silver coated to reduce emissivity
- Mass: ~1000 t
- A smaller shield isolates the TF coils from the vacuum vessel

# ITER Cryostat: vacuum insulation for SC coils



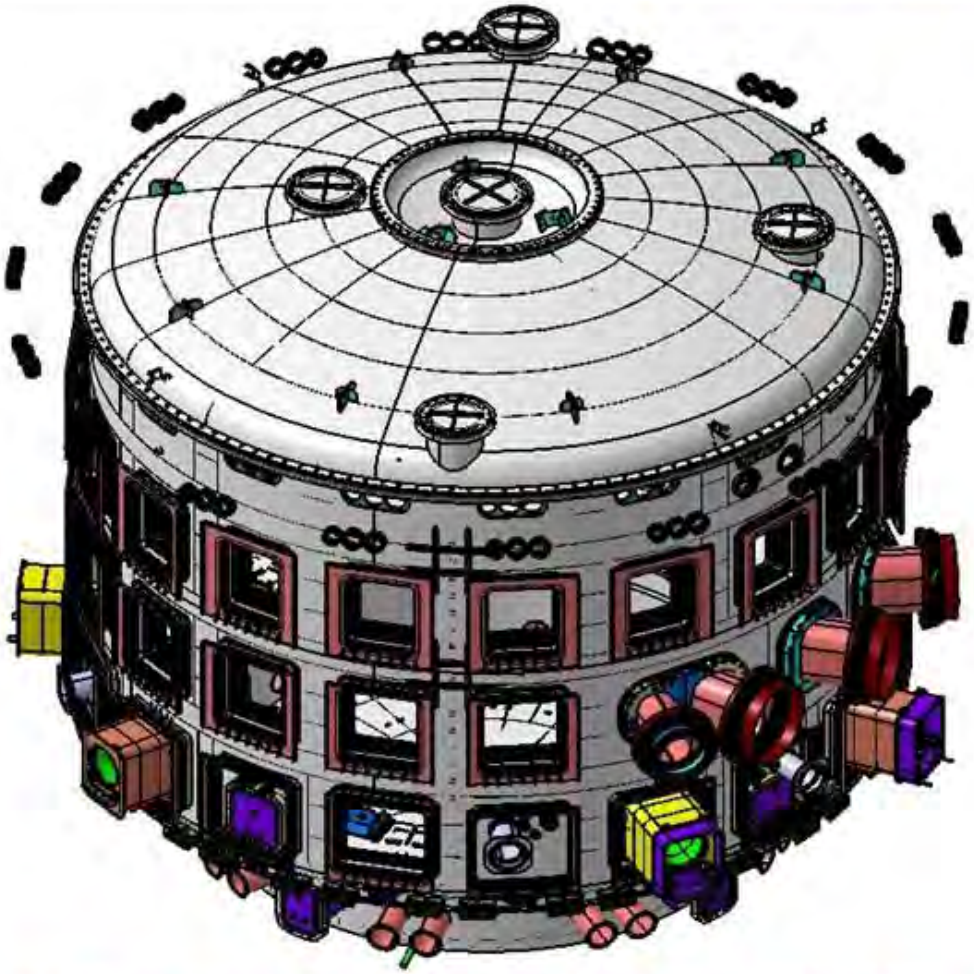
## Outer thermal shield

- Diameter: 29.4 m
- Height: ~29 m
- Mass: ~3500 t
- Base pressure $<10^{-4}$ mbar

## IN-DA will manufacture

- Contract signed with L&T Ltd on 17 August 2012
- Will be dispatched in 54 modules to ITER
- Largest high vacuum pressure chamber ever built

# ITER Cryostat



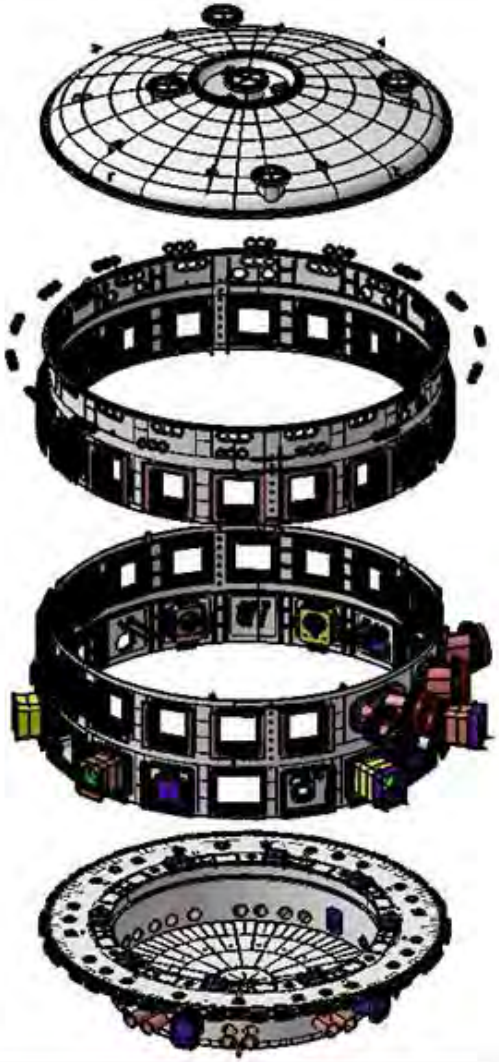
Transfers loads to tokamak floor

Top lid

Upper cylinder

Lower cylinder

Base section



# Principal plasma-facing components (PFC)

**First wall/blanket** → heat exhaust, impurity management, nuclear shielding

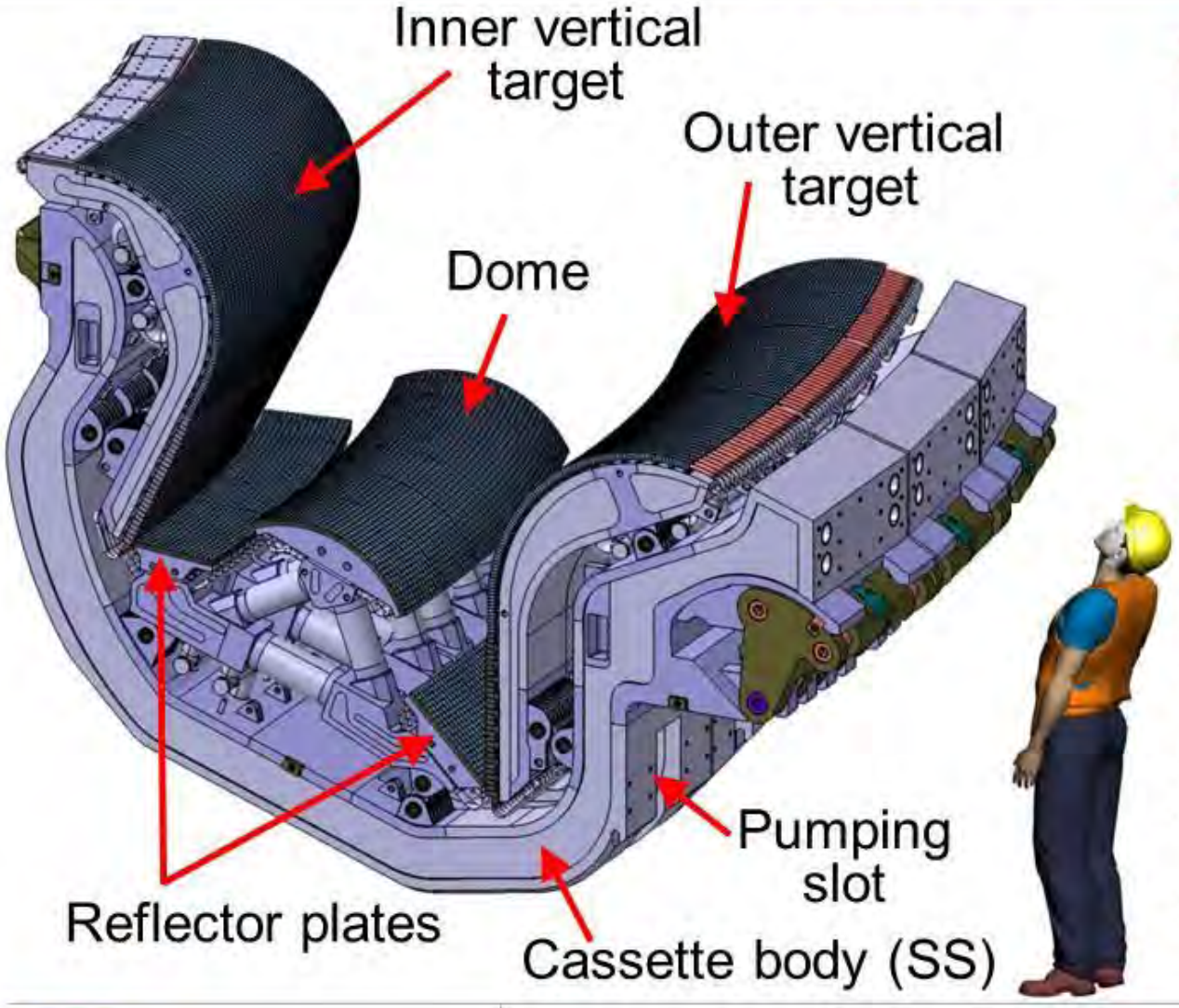
SS shield block ~3.5 t (1800 t in total)

Beryllium

Carbon fibre composite (CFC) & W

**Divertor** → particle and heat exhaust

# Divertor



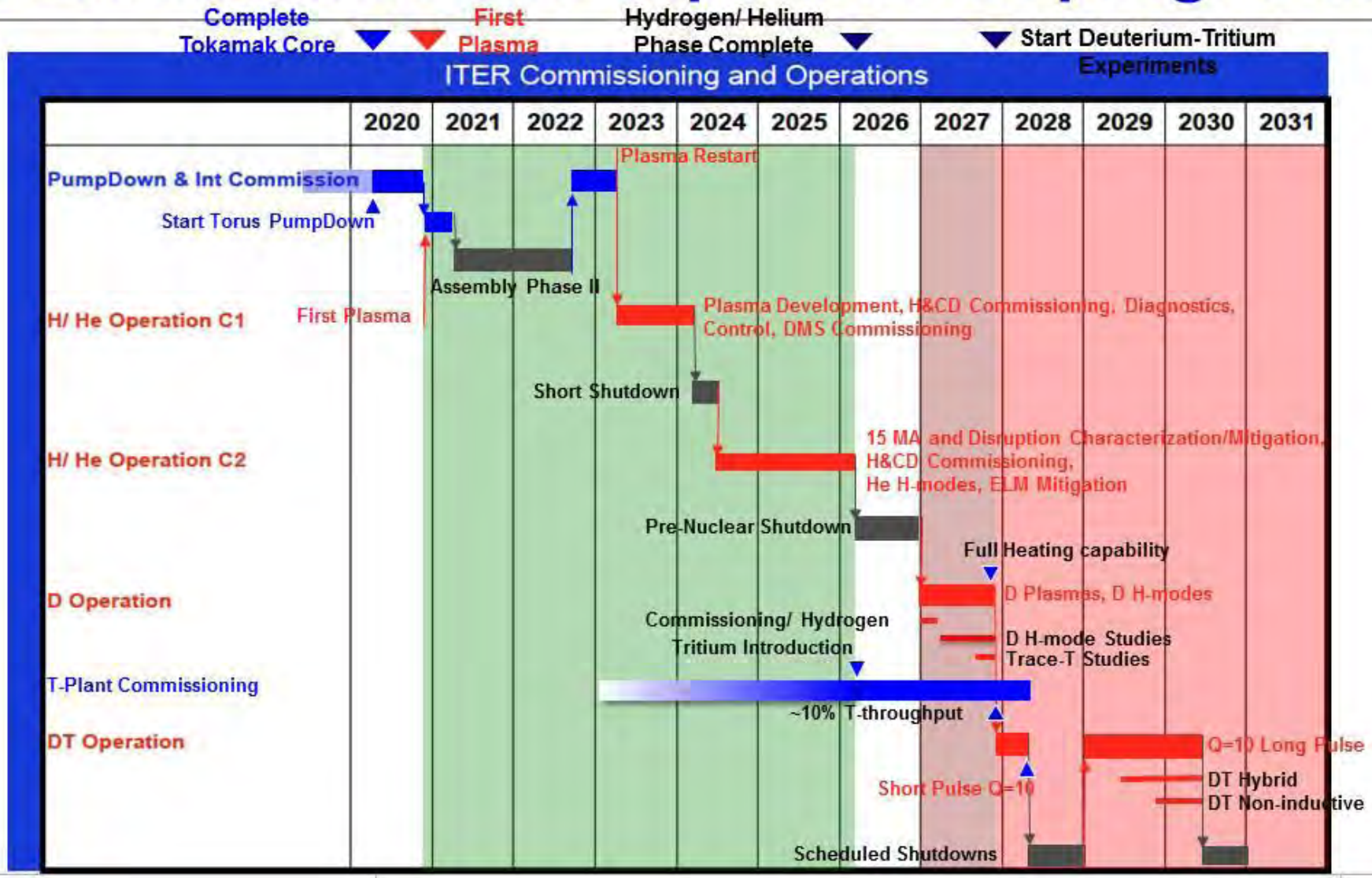

54 divertor assemblies (~8.7 tonnes each)

4320 actively cooled heat flux elements

Bakeable to 350°C

All plasma-facing components will be in tungsten for the nuclear phase and possibly now right from the start of operations

# ITER schedule and experimental programme



# Some key operational/physics challenges

# How is ITER different for physics & tokamak operation?

Burning plasma: self-heated by $\alpha$-particles
- non-linearity in total heating power due to dependence on plasma profiles
- MHD: sawtooth suppression by $\alpha$-particles, fast particle modes

Plasma control (position, shape, fuelling, heating, stability, exhaust)
- time constant for position control is >1s → very easy to damage plasma-facing components (e.g. on inner wall of vacuum chamber)
- very complex control matrix

Very high stored energy
- disruptions, ELMs, melting of metallic PFCs

High plasma current (15 MA for Baseline Q = 10 scenario)
- runaway electron damage of PFCs, huge disruption forces

High ion fluence (integrated plasma flux) to PFCs
- erosion of PFCs and migration of wall material, dust formation

# Stored energy: disruptions and heat loads to the wall

Disruption → total loss of stored energy in < 100 ms

EXPECTED DISRUPTION HEAT LOADS

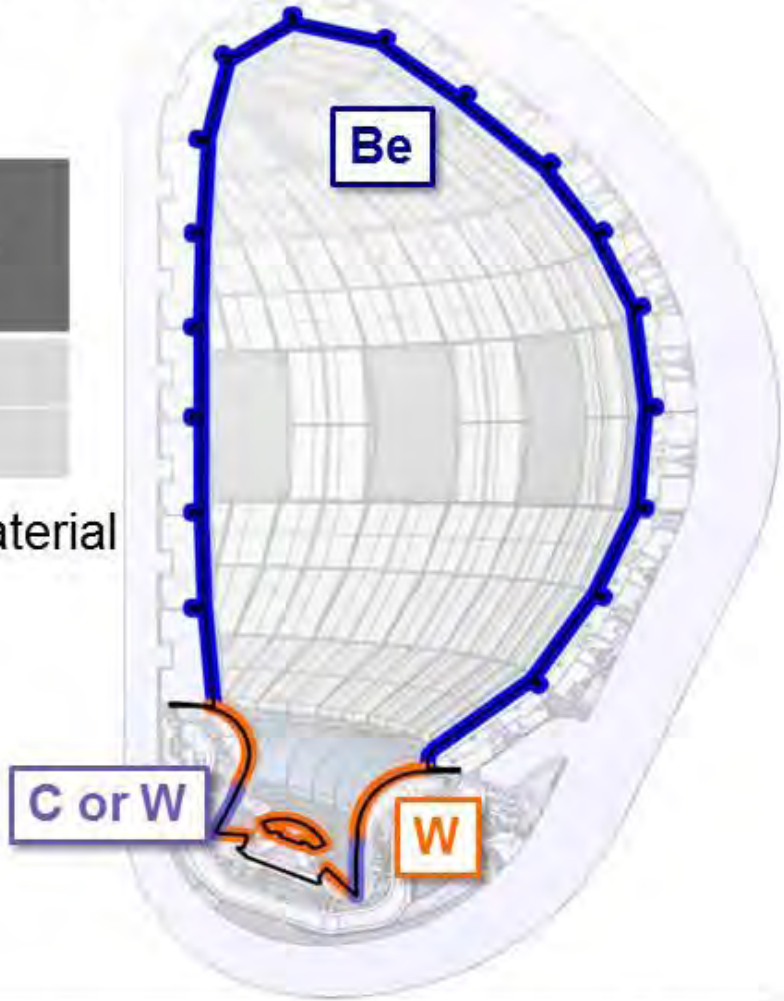
| Material | Melt Parameter (MJ $m^{-2} s^{-1/2}$) | Worst Case Disruption Load (MJ $m^{-2} s^{-1/2}$) |
|---|---|---|
| W (divertor) | 50 | **388** |
| Be | 28 | **570** |

NB: These numbers don't tell you the amount of material melted, just that some melting will occur

- (and perhaps some protection from "vapour shielding")

Disruption mitigation is required (and also careful operation) to minimise PFC melting

- NB: 10-15 MA L-mode @ 40 MW also a risk, not just Q=10



# Stored energy: disruption mitigation

"Massive gas injection" (MGI) → leading candidate for ITER

- fast valves to introduce strongly radiating gas (Ar, Ne) → spread energy over a large area

JET MGI, Ne injection, 2 MA, 3 T [A. Alonso, M. Lehnen, EFDA-JET]

Major ITER system → not yet fully specified

But it will be soon!

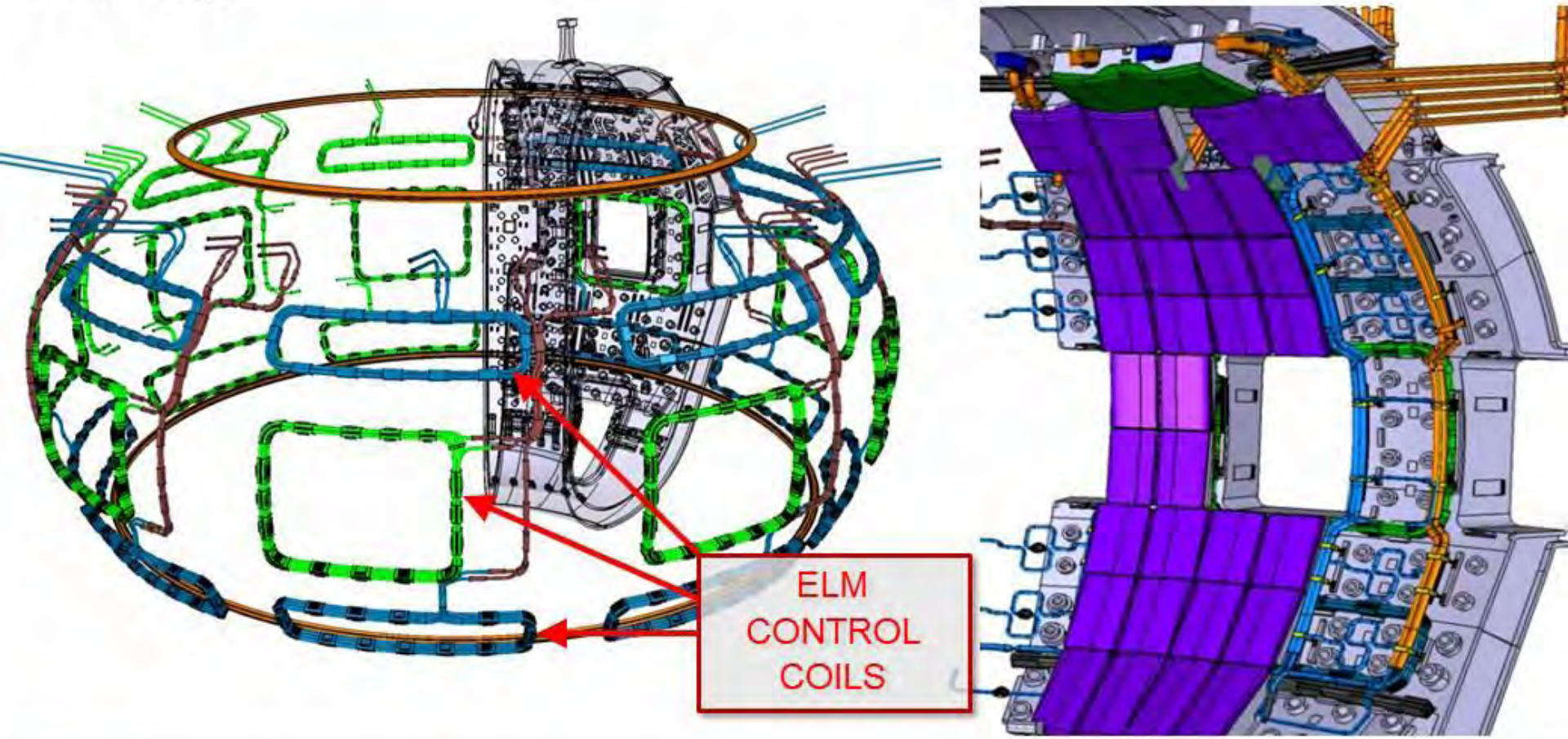
- intense area of study: experiment and modeling

Triggering also a challenge, i.e. accurately predicting a disruption at some $-\Delta t$, not too many false positives

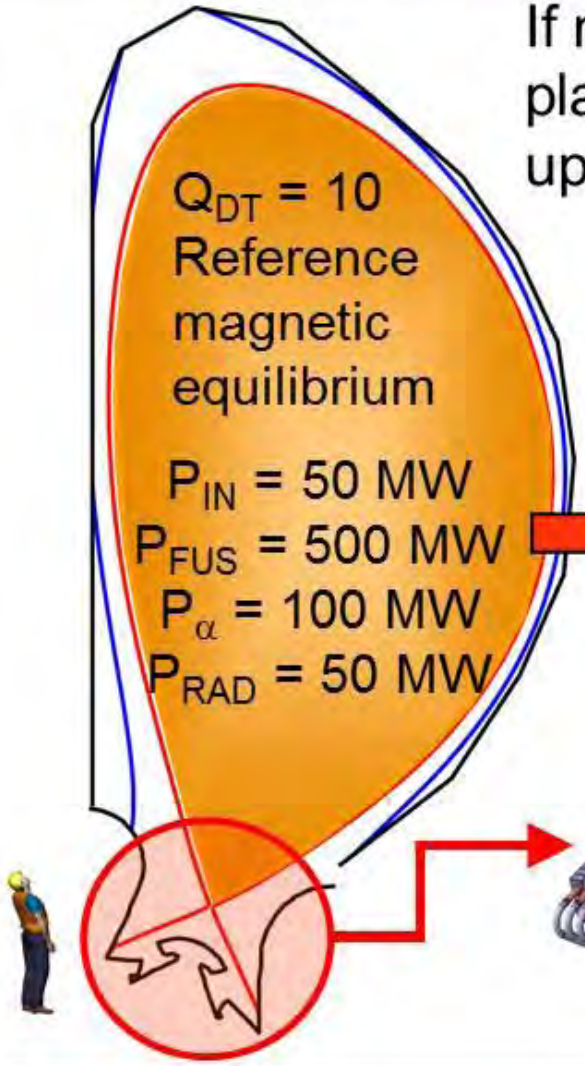
- algorithms under development on existing machines
- want very fast gas valves that are close to the plasma (can tolerate neutrons)

# Stored energy: ELM control coils

Design activity underway with good progress → integration challenge



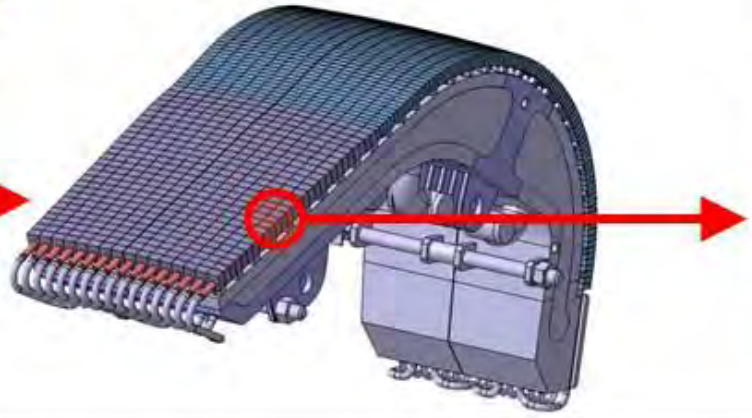
# Power exhaust: stationary energy flux




If nothing was done to prevent it, ITER burning plasmas are capable of steady power flux densities up ~40 $MWm^{-2}$ on the divertor targets

- Actively cooled monoblock technology now mature up to ~10 $MWm^{-2}$ → progress in the EU towards 20 $MWm^{-2}$ for W. Critical heat flux reached in 2-3 secs for 40 $MWm^{-2}$

**$P_{OUT}$ ~ 100 MW (~90% to the divertor)**

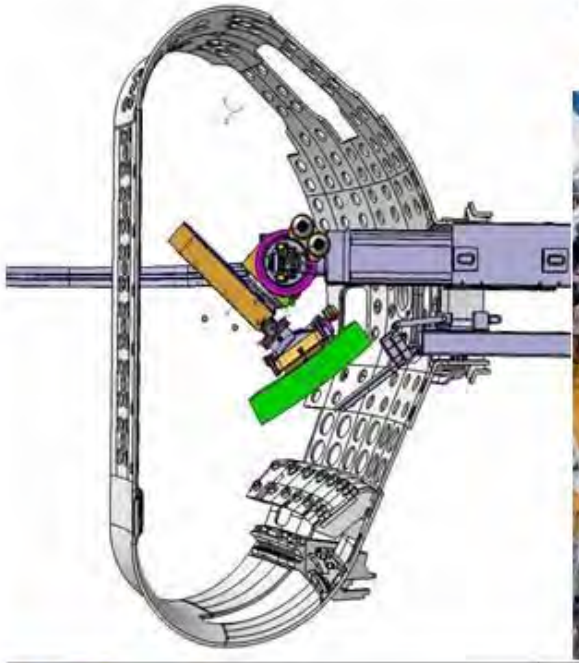


CFC or W monoblock

# Remote handling

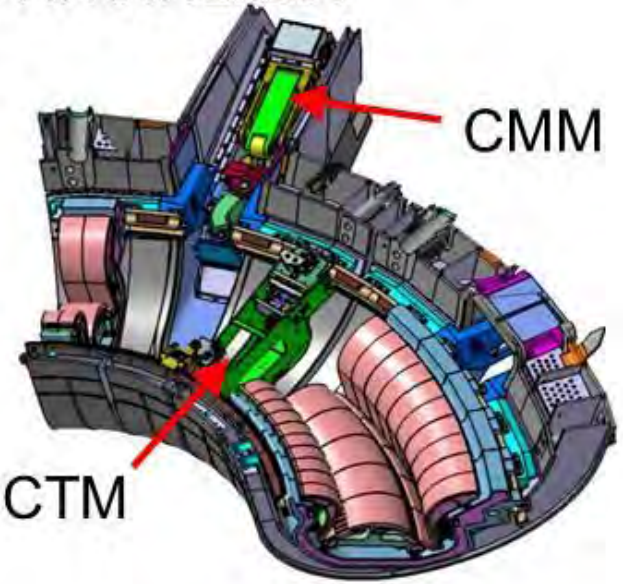
A major part of the ITER effort → extremely challenging to repair and replace complex and heavy components in a nuclear environment

- Dedicated, state-of-the art systems for both Blanket and Divertor
- Divertor replacement 3-4 x in the machine lifetime (~6 months to exchange)
- First wall panels at least once



On-rail module transporter
- procured by JA

Divertor RH procured by EU → **major role played by Finland VTT/TUT/TEKES !**



# How is ITER different for physics & tokamak operation?

Routine operation at Q = 10 (hopefully!) → means operating near design limits

- ITER is the first tokamak that can regularly exceed the technological limits of actively cooled PFCs
- Extremely robust machine protection system mandatory

Nuclear operation (tritium and neutrons)

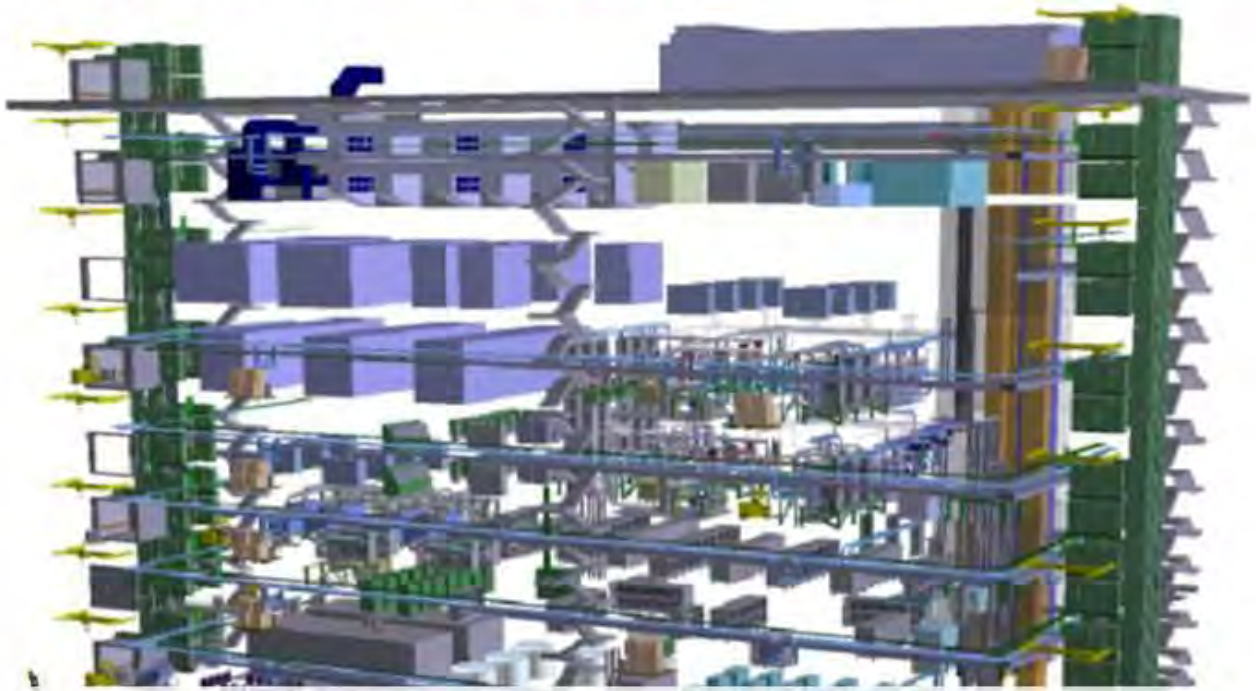
- retention of tritium on PFCs
- tritium reprocessing
- tritium breeding test modules (TBMs)
- remote handling is required for 100% of in-vessel work during the nuclear phase
- dust inventory
- (diagnostic design)
- (TF coil heating)
- LICENSING

# Nuclear operation: tritium reprocessing – the T-Plant

Of the ~ max 100 g of tritium fuel per Q=10 pulse, only ~0.3% will be burned by fusion reactions → T reprocessing is required

- using existing technologies but on a much larger scale (~factor 10)

7 floors
(2 below ground level)
L = 80 m
W = 25 m
H = 35 m

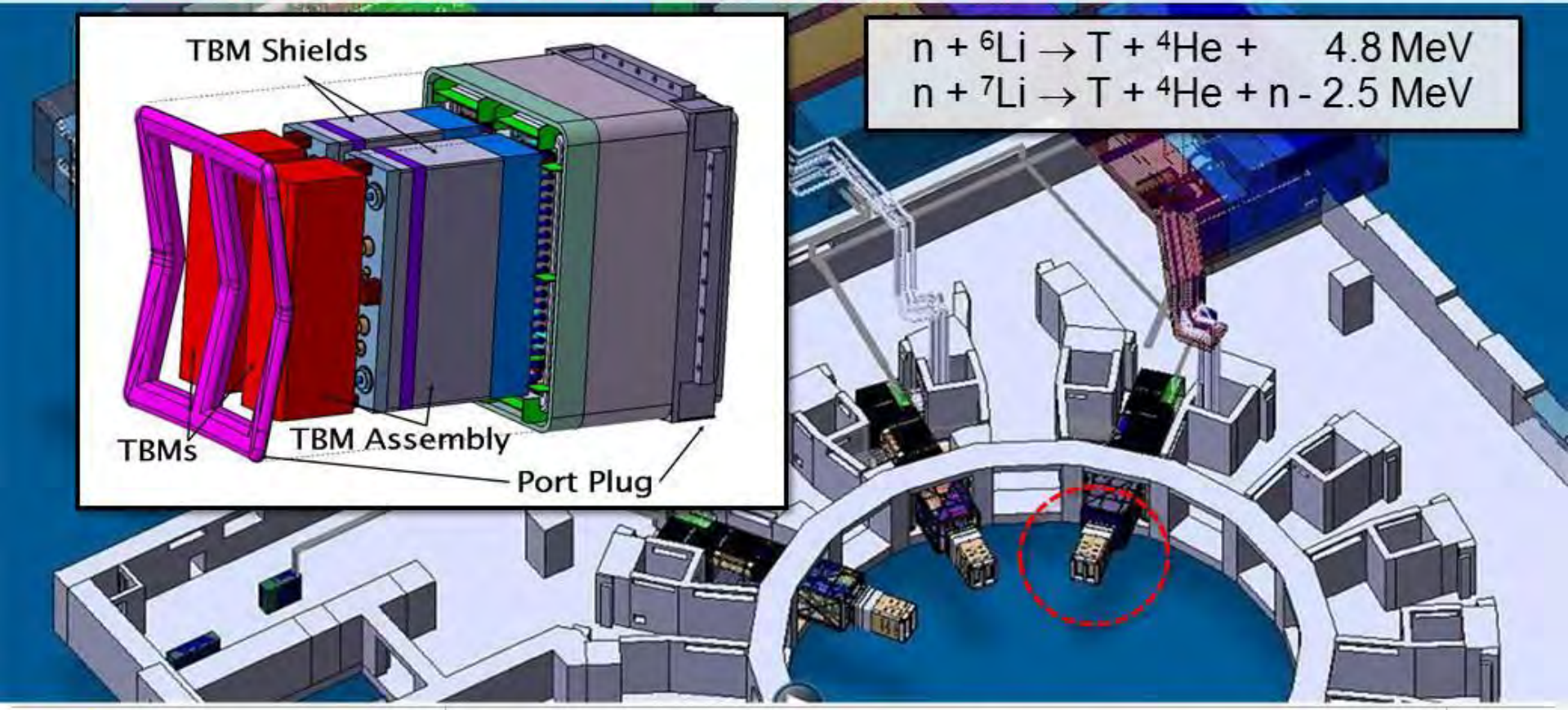


A maximum of 4 kg of tritium can be held on the ITER site → only about 20 kg of tritium anywhere on Earth at any one time

# Nuclear operation: tritium breeding modules (TBMs)

Tritium fuel cycle is a major challenge for all DT fusion devices → ITER will test concepts

- 6 modules with different designs, all ITER parties involved



Institut Jean Lamour

UNIVERSITÉ DE LORRAINE

cnrs dépasser les frontières

FR FCM

# *Development and validation of diagnostic tools for turbulent fluctuations and transport (probes, fast imaging,...)*

- The Mirabelle device
- Drift waves and flutes modes – Dynamical states
- Turbulent transport → Probes
- Fast imaging of turbulent structures

# *Characterization of turbulence and transport in the edge plasma*

- Essential role played by intermittent and large scale structures ("blobs") in the cross-field energy and particle transport to the wall in the far Scrape-Off-Layer (SOL)
- From many experimental studies carried out in several machines (toroidal : Tore-Supra, W-7AS, Alcator-C, NSTX, D-IIID, … and linear machines as well →

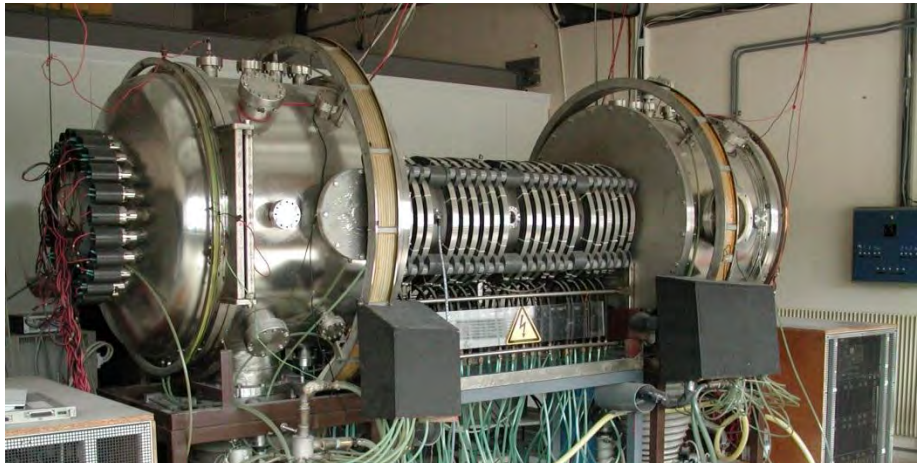
  radially propagating "blobs" are responsible for ~50% of the transport

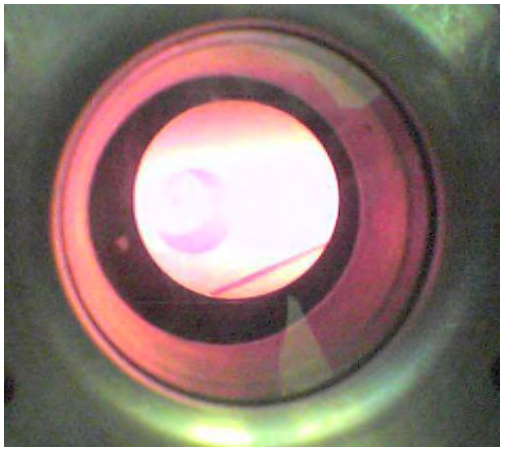
- Open questions:

  - Origin and formation of these "blobs" (core plasma, relation with ELMs?, near the separatrix, inverse cascade process?), propagation velocity, time and size scales,

  → need for improved or new diagnostics (probes arrays, **fast imaging**, …), signal processing methods, comparison with numerical simulations,

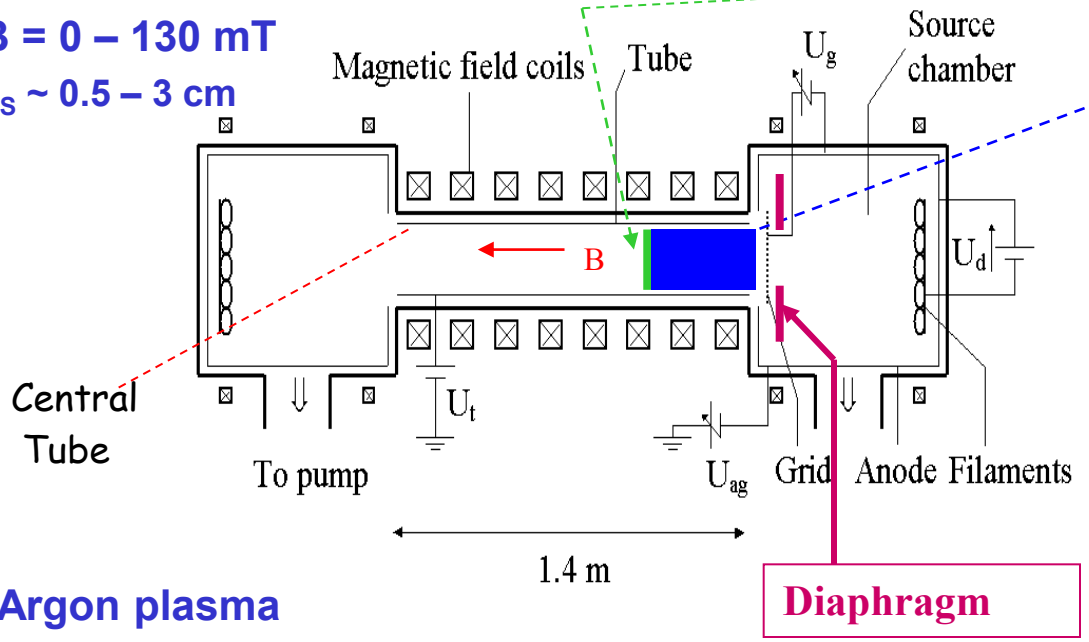
# MIRABELLE: a linear, magnetized, low-$\beta$ plasma device



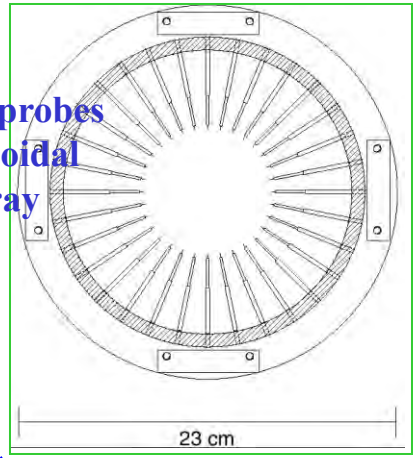


**B = 0 – 130 mT**

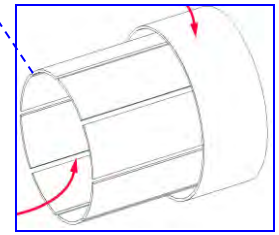
**$\rho_s$ ~ 0.5 – 3 cm**




**Argon plasma**




**32 probes poloidal array**

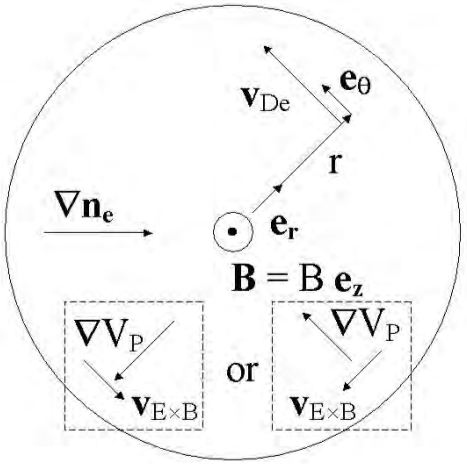


**8 plates Exciter**

**$P$ ~ 5.10$^{-5}$ à 5.10$^{-4}$ torrs; $T_e$ ~ 1 – 3 eV, $T_i$ ~ 0.02 eV; $n_e$ ~ 10$^{15}$ – 10$^{16}$ m$^{-3}$**

# Low frequency instabilities: Drift Waves

## Magnetic Confinement ➔ transverse gradients



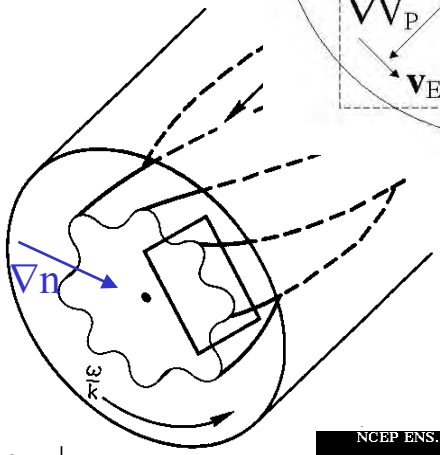

➔ 2 mechanisms: drift waves and rotation induced instabilities (Kelvin-Helmholtz, Rayleigh-Taylor)

### 1- Drift waves:

driven by a radial density gradient

collective oscillations of electron and ion populations

propagation: *mainly* azimuthal




$$\omega = \frac{\omega^*}{1+\rho_s^2 k_\theta^2} \text{ with } \omega^* = k_\theta V_{De}\,,\ k_\theta = \frac{m}{r}\,, \text{ and } \rho_s = c_s/\Omega_i$$

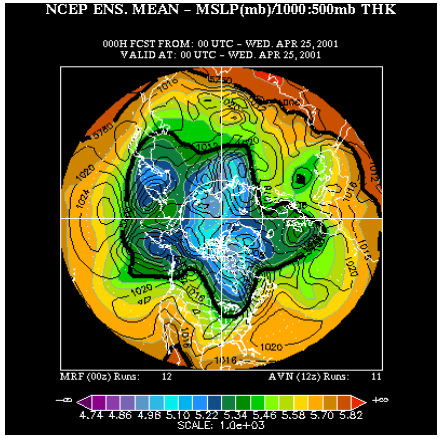
$\rho_s = 0.5 - 3$ cm, $f = 3 - 20$ kHz

$$V_{De} = -KT_e \frac{\left|\frac{\partial n_o}{\partial r}\right|}{q n_o B} e_\theta$$

$$v_{dw} = v_{dia}/\sigma \pm E/B$$

close analogy with Rossby waves (F. Lorentz ⇔ F. Coriolis)

*[M.V. Nezlin & E.N. Snezhkin, Rossby vortices, spiral structures,solitons, Springer-Verlag, 1992 p.43-66.]*




**Bilder: NOAA/ ForecastSystems Laboratory**

# LF instabilities: rotation induced instabilities

## 2- the Rayleigh-Taylor instability:

driven by a radial gradient of the plasma potential

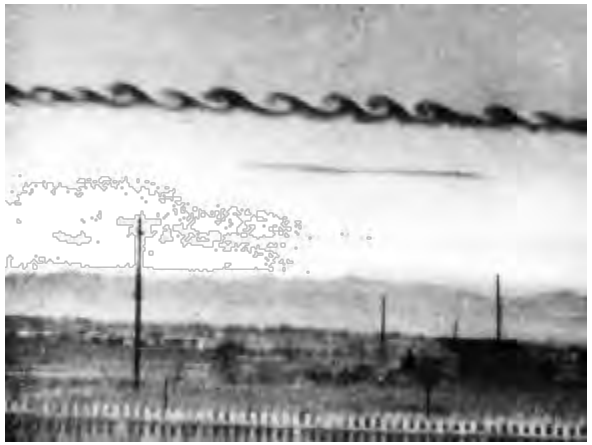
plasma rotation ➔ centrifugal force ~ effective gravity

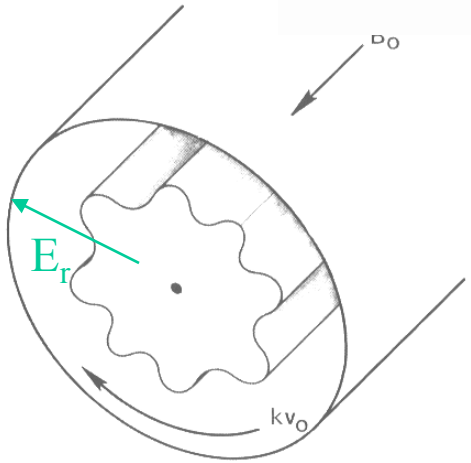
purely azimuthal propagation → flute modes

## 3- the Kelvin-Helmholtz instability:

driven by a poloidal velocity shear

purely azimuthal propagation → flute modes

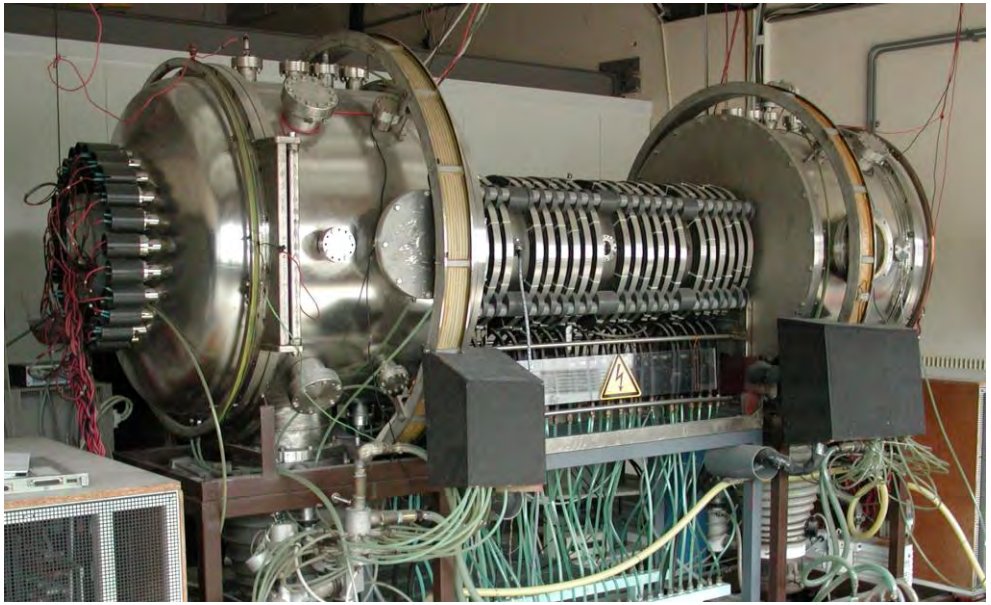





K-H: a typical hydrodynamic instability

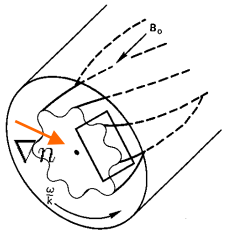

*in Plasmas: Horton & Tajima, Phys. Fluids **30** (1987) 3485*

# Mirabelle device: a linear, magnetized, low-$\beta$ plasma

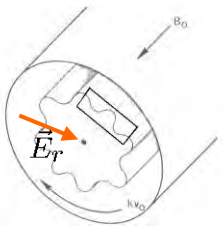


| | |
|---|---|
| plasma density | $10^{15}$–$10^{16}$m$^{-3}$ |
| magnetic field | 20–120 mT |
| electron temperature | 1-5 eV |
| ion temperature | <0,05 eV |
| argon pressure | $(1–3)\cdot10^{-4}$ mbar |
| Larmor radius $\rho_s$ | 0,5–3 cm |
| density gradient length | 2–5 cm |
| instability frequency | 3–15 kHz |
| ion cyclotron frequency | 8-60 kHz |
| Collision frequencies $\nu_{in}, \nu_{en}$ | ~ 1 kHz |

Possible plasma regimes:

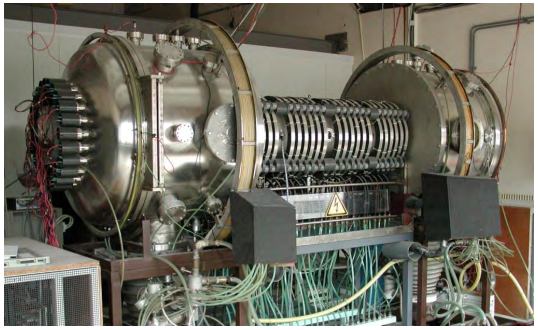


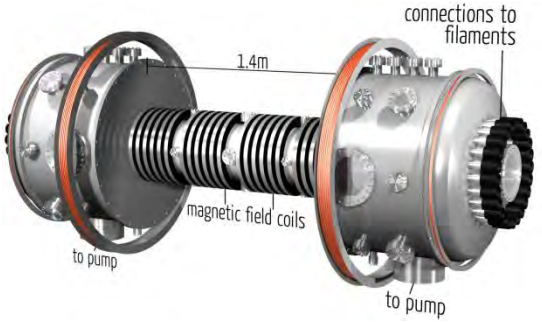

Drift waves




Flute modes

- without control
  - Periodic
  - Periodic pulling
  - Intermittence
  - Weak turbulence
- controlled
  - controlled
  - forced






# Main findings and physics pictures

1 Characterising and selecting LF instabilities

2 Routes to spatio-temporal chaos and turbulence

3 Acting on LF modes

4 Cross-field transport

5 Characterisation of nonlinear mode couplings

# Dynamics of LF Instabilities: Summary

- Characterization of the observed LF instabilities in the the low-β plasma colomn of the Mirabelle device ⇒

  - without a limiter only drift waves are observed

  - by using a limiter, that creates a strong velocity shear at the edge at low magnetic field strength, a **transition from drift waves to the Kelvin-Helmholtz instability** is observed when *B* is decreased.

- As for drift waves the transition from regular state to spatio-temporal chaos and turbulence follows the quasi-periodicity (or Ruelle-Takens-Newhouse) route.

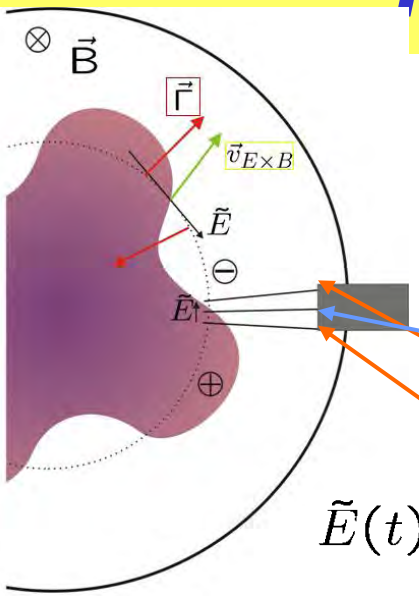
- Spatio-temporal open-loop synchronization was studied for each kind of low-frequency instability and turbulence as well.

  - t**he efficiency** of mode-selective control **on the Kelvin-Helmholtz instability and turbulence was demonstrated** as previously for drift wave turbulence.

  - By using the same octupolar arrangement we also drive a regular state to a turbulent one.

  - The radial dependence was also studied

# Transport measurements




$$< \Gamma >= \frac{1}{B} < \tilde{n} \cdot \tilde{E} >$$

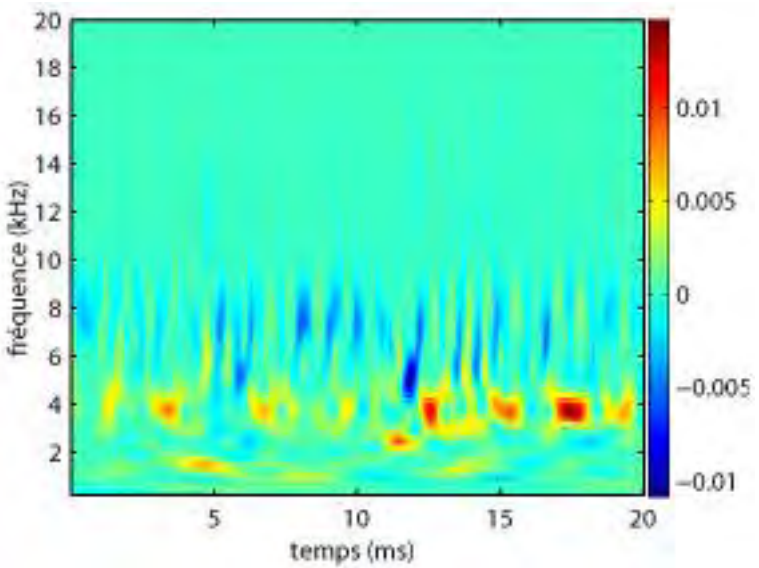
Flux function of time and frequency:

$$\Gamma(f,t) = \frac{2}{B} \underbrace{|W_n(f,t)W_E^*(f,t)|}_{\text{cross-spectrum}} \underbrace{\cos(\varphi[W_n(f,t)W_E^*(f,t)])}_{\cos(\alpha_{nE}(f,t))}$$

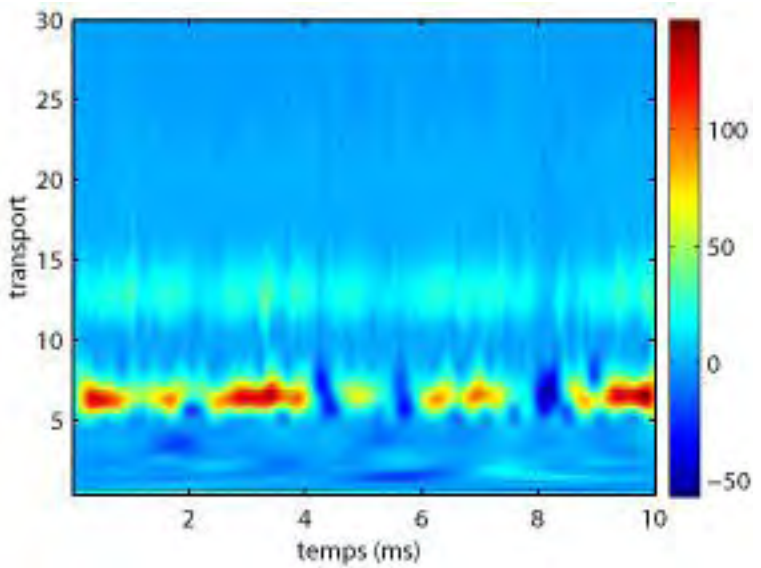
$\tilde{I}_{sat}(t) \propto \tilde{n}(t)$

Mean flux: $< \Gamma > \propto |\tilde{n}| \cdot |\tilde{E}| \cdot cos(\alpha_{nE})$

$$\tilde{E}(t) = \frac{V_3(t) - V_1(t)}{d}$$



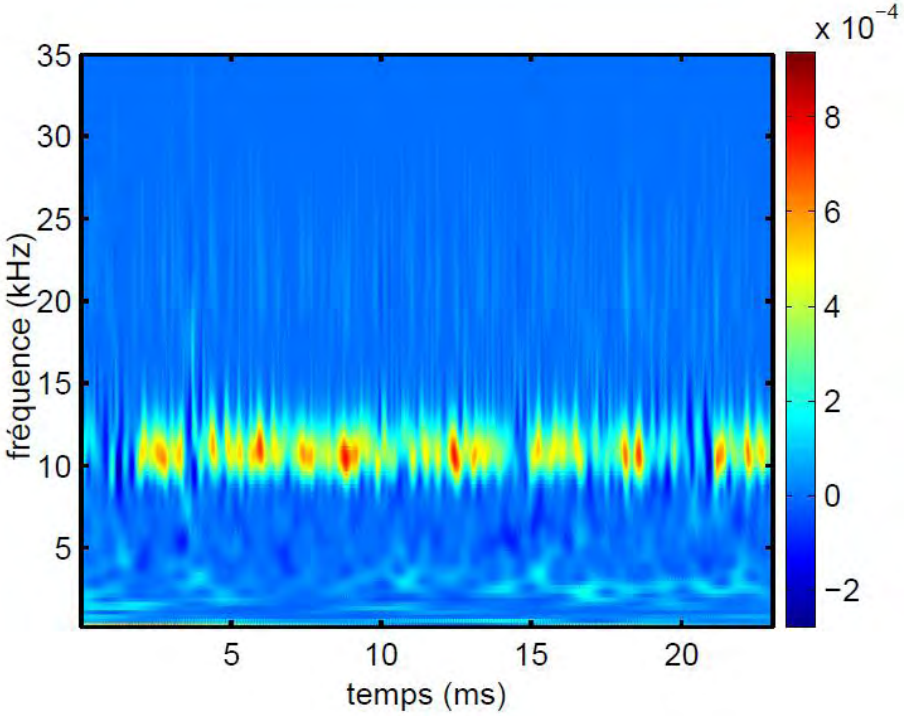

Drift waves (2 modes)

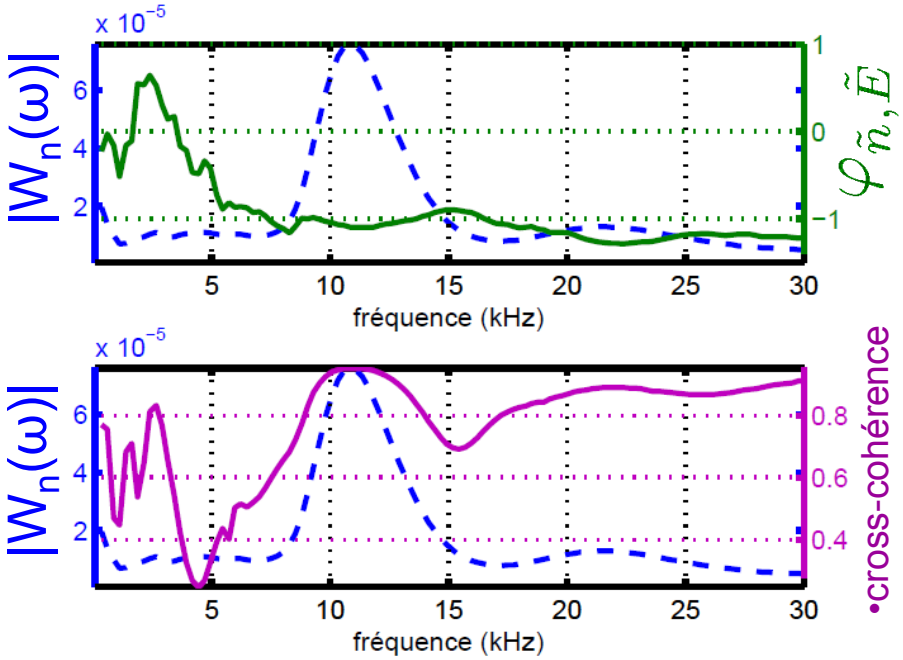



Flute mode

# Transport measurements

## Regular drift wave

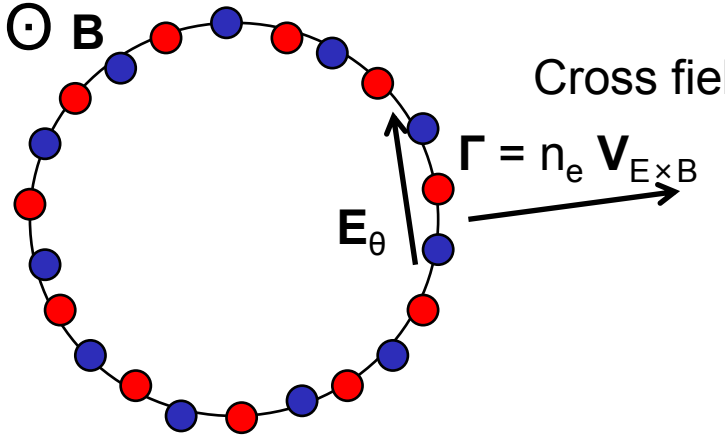



Transport : outwards, one single frequency

with $\varphi_{\tilde{n},\tilde{\phi}}$ close to 0.2 π

# Cross-field transport

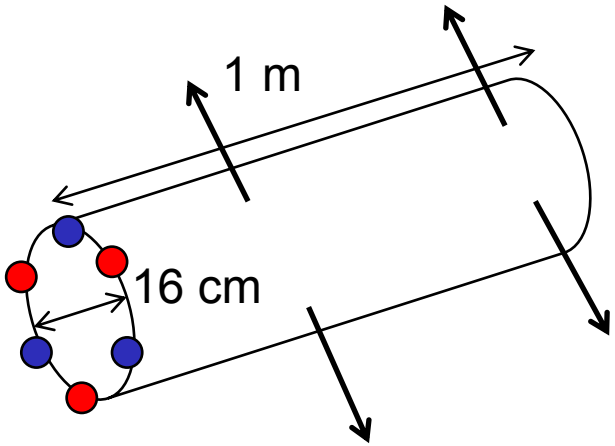



Cross field transport measurement over a full circumference

Floating probe
Biased probe

Mean flux measured with the probe array at r = 8cm: $\Gamma = 9.6\ 10^{17}$ part. $m^2.s^{-1}$

Number of particles that are crossing the cylindrical surface: $4.8\ 10^{17}$ part.$s^{-1}$



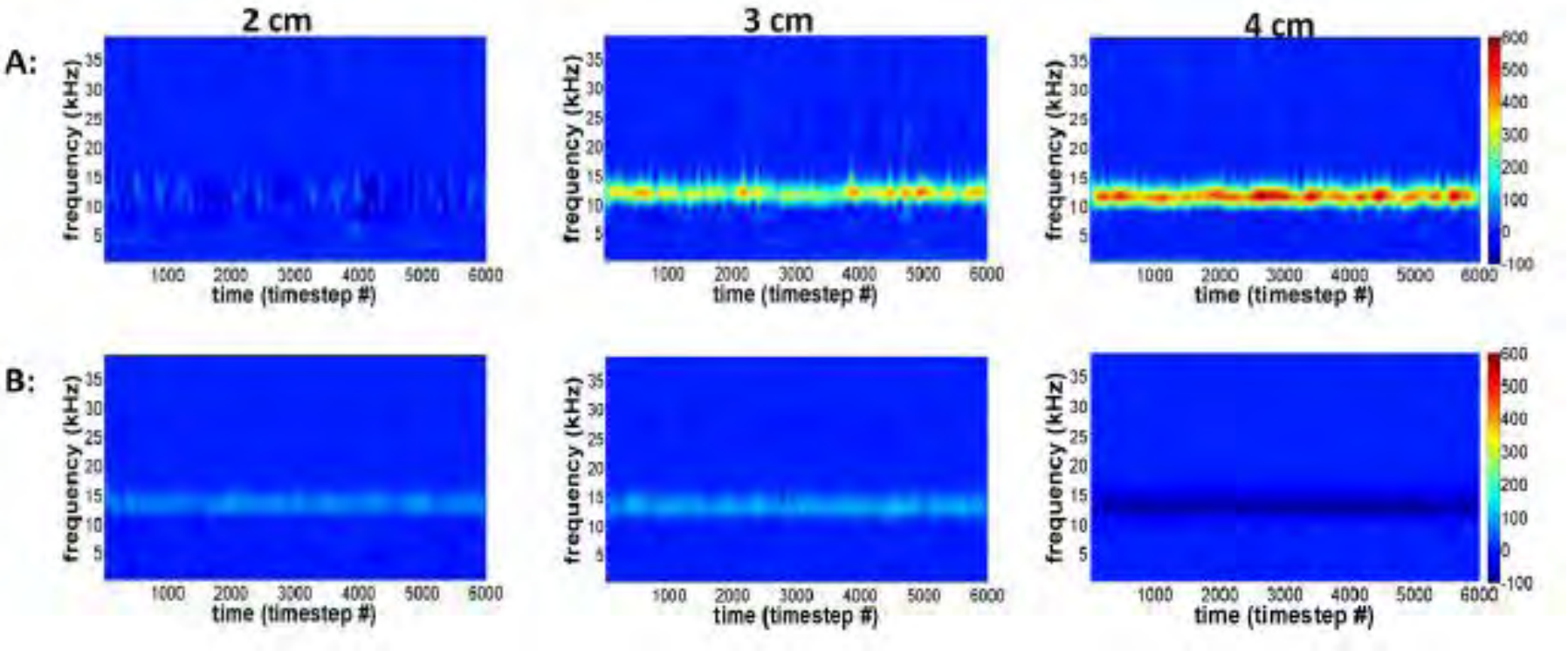

Total number of particles in the cylinder (using measured mean density): $2.6\ 10^{14}$ part

Time needed to empty the device ≈ 0.5 ms

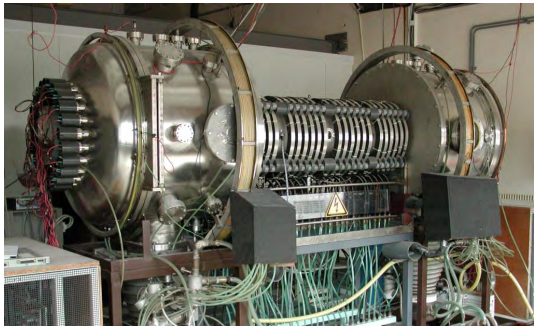
Same order as the plasma decay time obtained by afterglow measurements

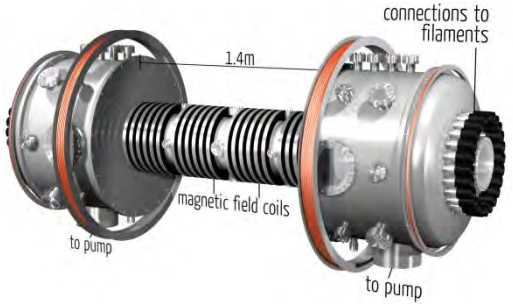
T. Pierre, G. Leclert, and F. Braun, Rev. Sci. Instrum, 58 (1), January 1987

# Measurement of the cross-field transport




Cross-field transport measurements with emissive probes (A) and cold probes (B).






# Future plans

## short time prospects

**Implementation of new diagnostic tools**

- New probe array dedicated to transport measurement
- ball-pen probe
- Collective scattering

**Comparison experiments / CYTO 3D simulations**

# Diagnostics tools for turbulence and transport

## ANR SEDIBA -Tasks 3 (IJL)

**G. Bonhomme, S. Heuraux, N. Lemoine, F. Brochard, G. Bousselin**

*Institut Jean Lamour, CNRS – Université de Lorraine*

*Dpt p2M, Faculté des Sciences*

*BP 70239, 54506 Vandoeuvre-lès-Nancy*

# TASK 3: VALIDATION OF THE SYNTHETIC CAMERA DIAGNOSTIC

Objectives: This task aims at testing the validity of the synthetic camera diagnostic module to be implemented in the SOLEDGE3D code. It is divided into 2 sub-tasks.

- The first one will focus on experiments with fast cameras in a laboratory experiment, in order to refine the interpretation of the physical picture linking plasma fluctuations to light fluctuations, to be used in Tasks 1 and 2.
- The second one will be centered on the development and validation of analysis tools to be applied to experiments and simulations presented in Task 6.

# WP 3.1 - Fast Camera testing in dedicated laboratory experiments

- Fast imaging with two cameras (located at both ends) in Mirabelle →

Makes it possible to follow simultaneously the spatio-temporal evolution of two species

  - Photron Camera (non intensified) + interferential filters → neutrals atom. transitions (e.g. Ar, 420 nm et 765 nm)
  - Intensified Camera (Phantom ?) → ion atom. transitions

Experiments in pure Ar or He plasmas, then with injected impurities

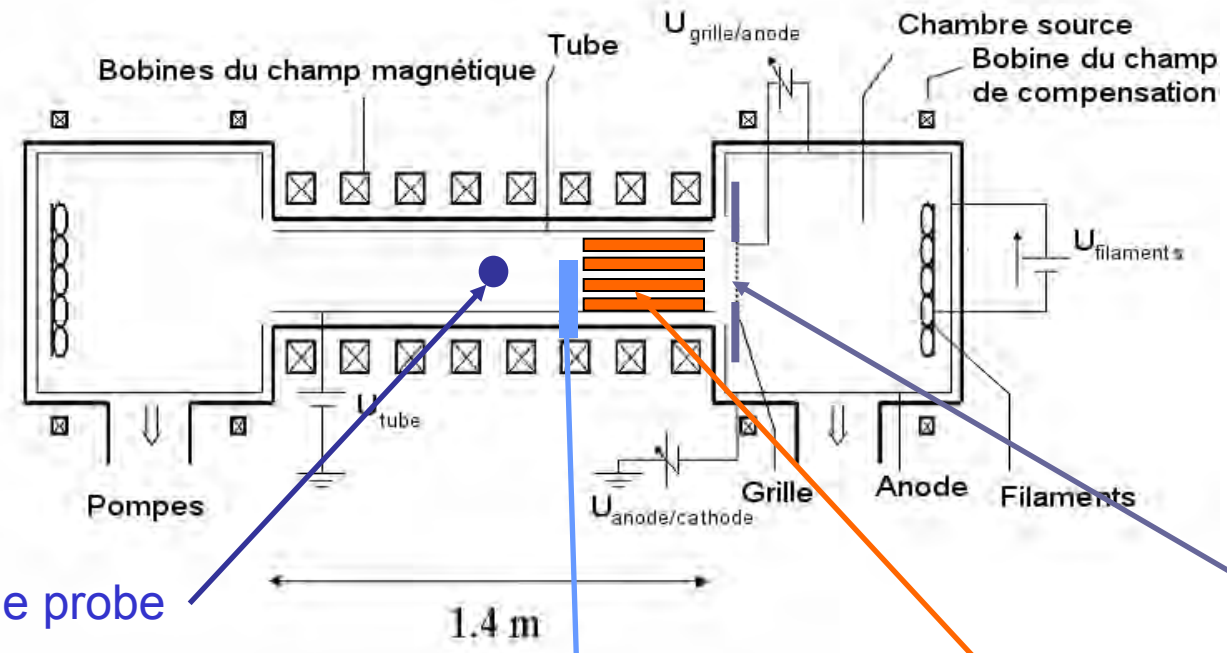
- Probe Measurements
  - New poloidal probes array IRIS, emissive probes, ball-pen, plane probes

→ Spatio-temporal dynamics, Turbulent transport measurement

→ Measurement of the radial parallel current profile

→ Excitation of blobs

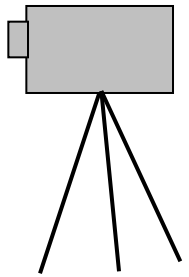
# Plasma control and diagnostics



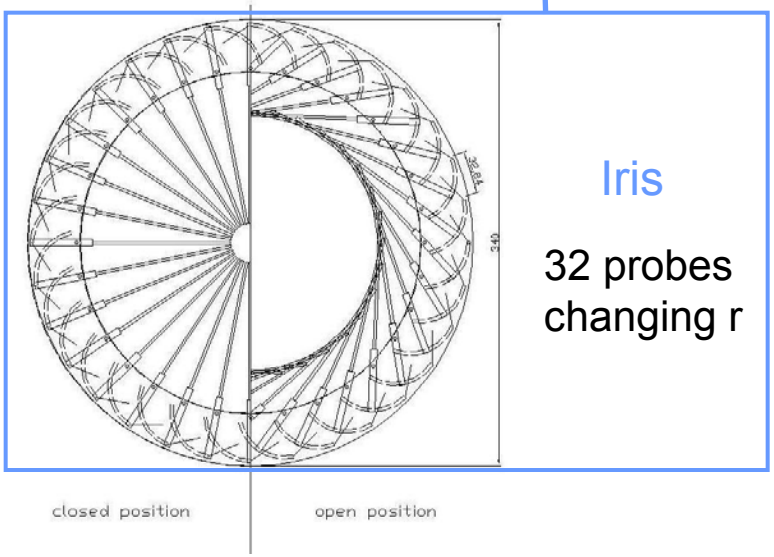

triple probe

limiter

Photron SA1.1



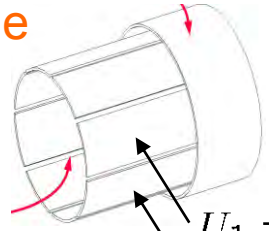
fast camera with intensifier




Iris

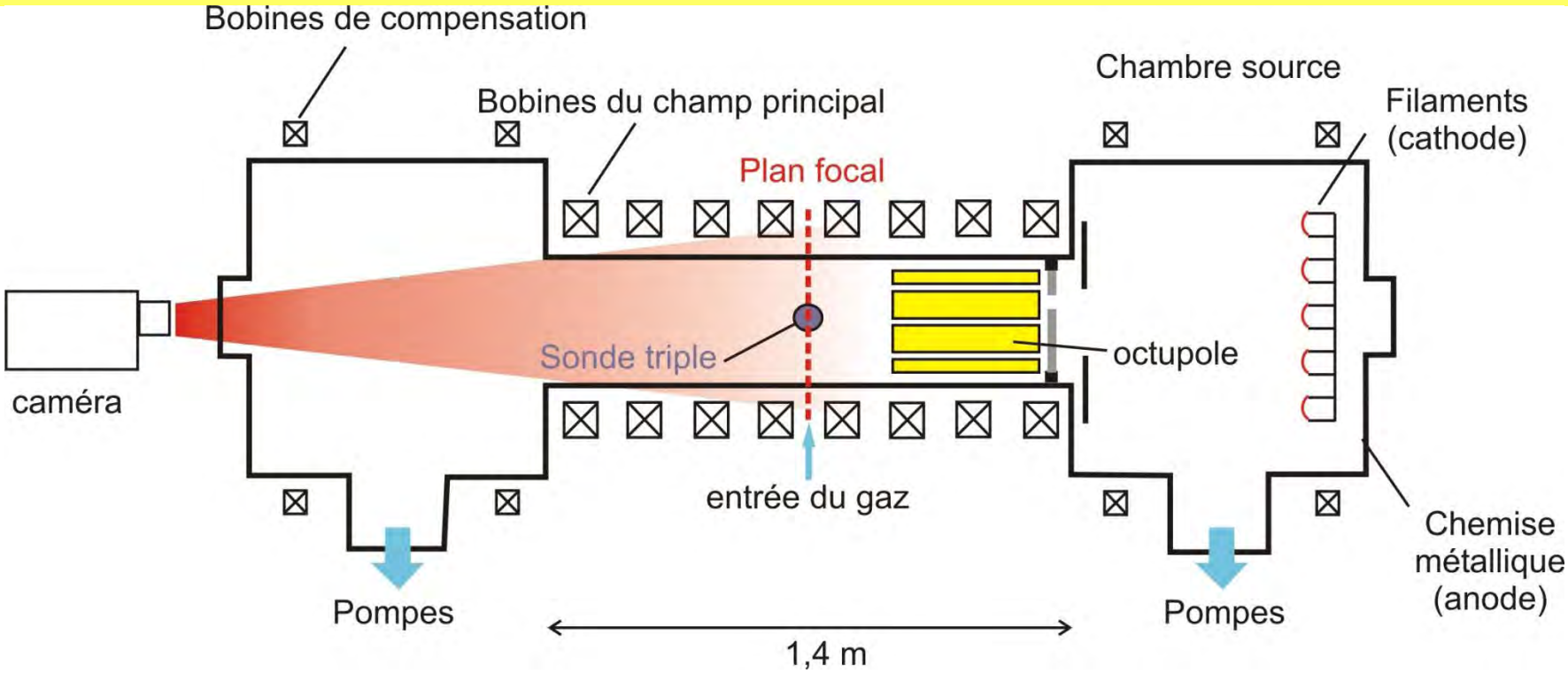
32 probes changing r

Octupole




Collective scattering (CO2 laser)
Study of turbulence and transport
($k_r$ and $k_\theta$ spectra)

# Mirabelle: schematic view with diagnostics




Camera Photron SA1.1

Light intensifier Hamamatsu C10880

max efficiency wavelength 430 nm, gain ~1000

gating time 40 ns without filters, 8 μs with filters

Interference filters: 420 nm, 765 nm (neutral Ar)

428 nm $Ar^+$

200 mm, f=4. lens

Without the light intensifier

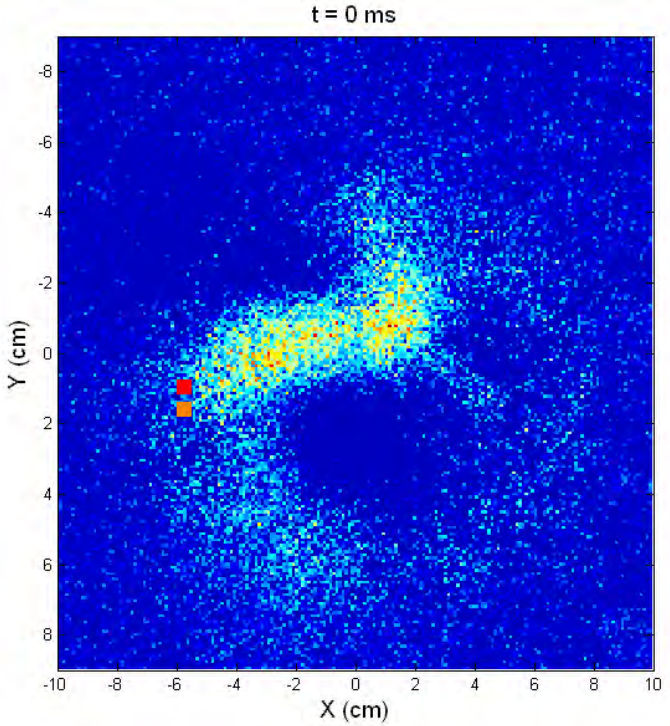
50 mm, f=1.2 lens

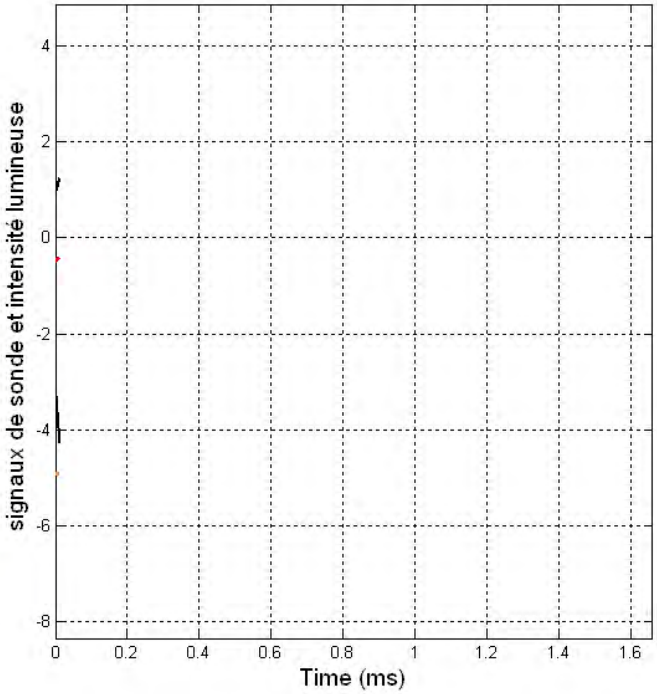
⇒ Field of depth ~ 5 cm

0.75 mm/pixel

Max radial shift due to parallax error ~ 3 %

# Direct comparison: Probe vs. Fast Imaging




- Lower probe

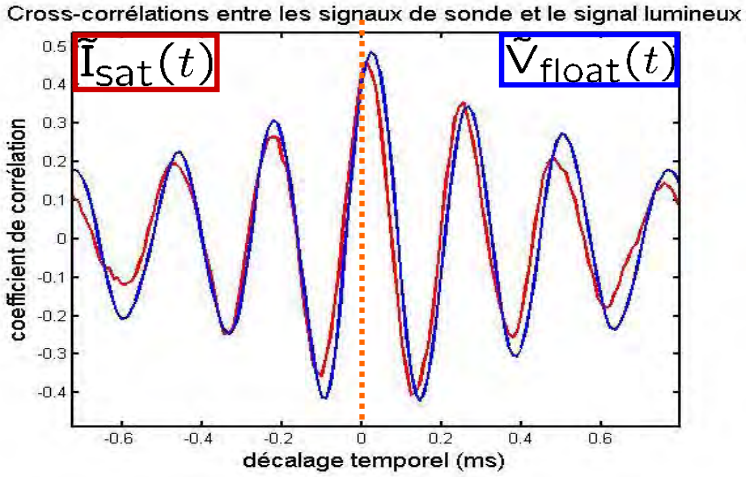
$\tilde{I}_{sat}(t) \propto \tilde{n}(t)$

Light Intensity

- Upper probe

$\tilde{V}_{float}(t)$

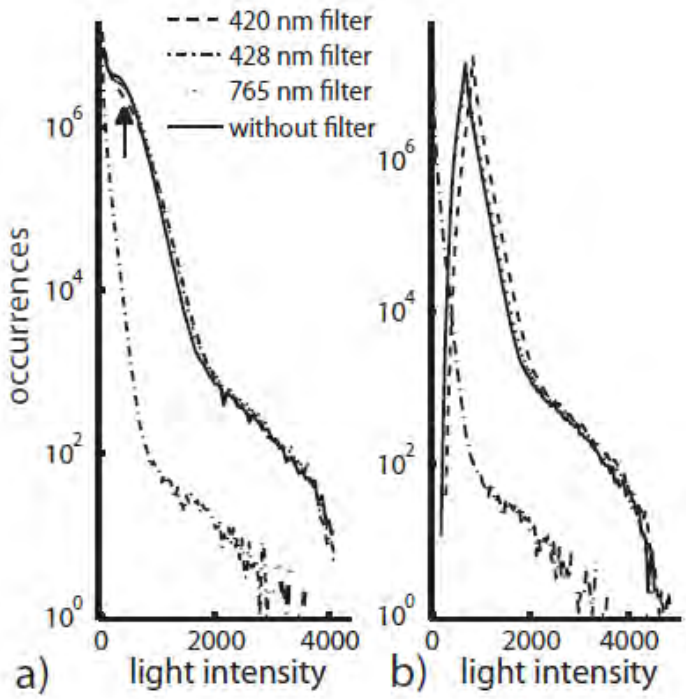
Light intensity




Plasma: irregular state

Good agreement between both diagnostics, especially for $\tilde{I}_{sat}(t)$
the recorded fluctuations of light intensity provide a visualization of the density fluctuation dynamics in the plasma column

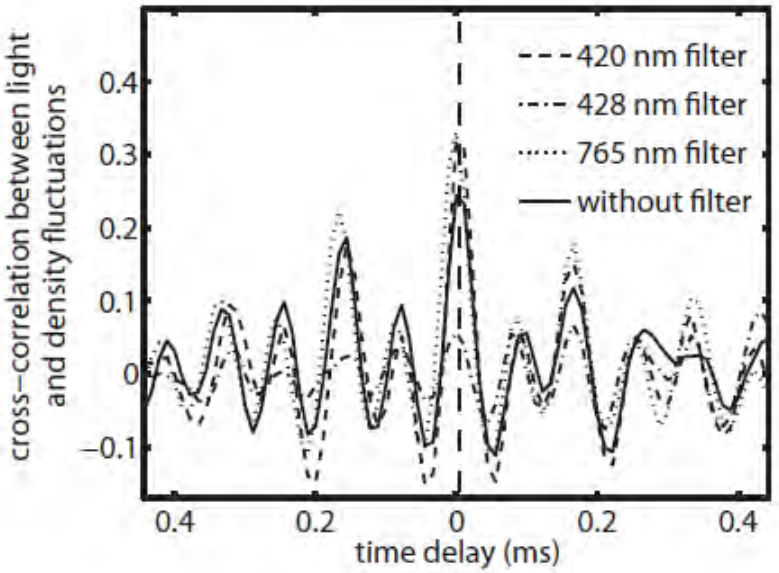
# Light fluctuations




Histograms of light intensity.

a) Histograms computed from the original images.

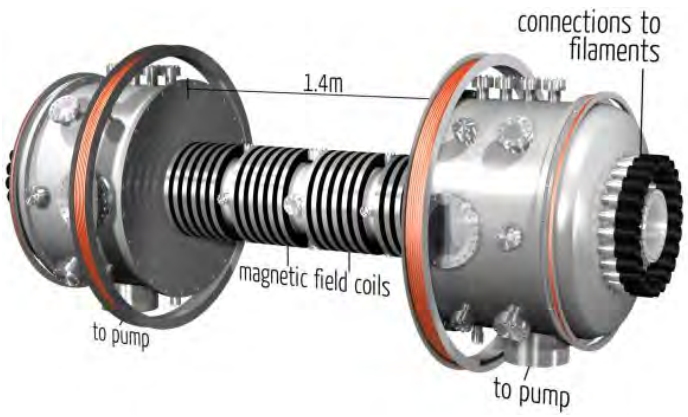
b) Histograms computed after subtraction of the corresponding average image.




Cross-correlation between the ion saturation current fluctuations and the light intensity fluctuations recorded without filter and with three different filters

*Spectroscopic interpretation and velocimetry analysis of fluctuations in a cylindrical plasma recorded by a fast camera*, S. Oldenbürger et al., Rev. Sc. Instr. (2010)

# Ongoing activities



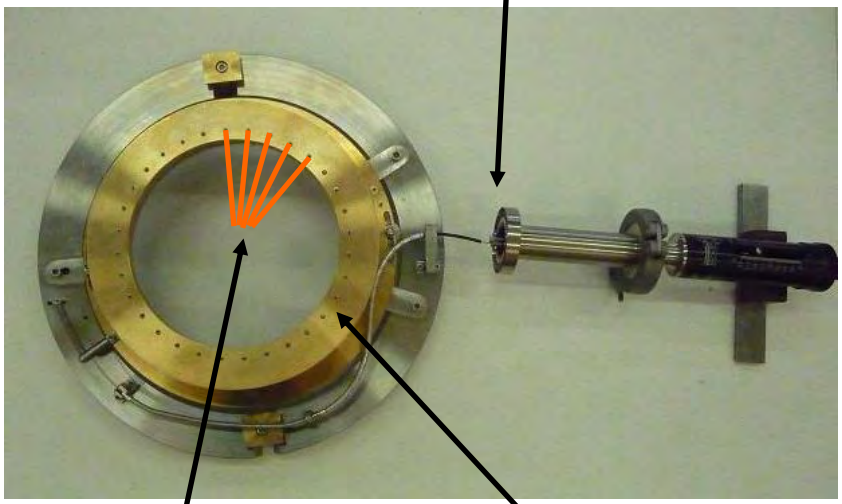

Implementation of new diagnostic tools

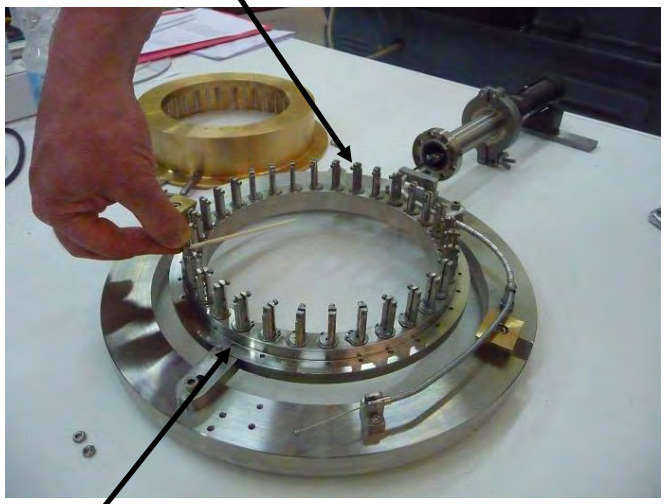
- Emissive probes
- Ball-pen probe
- New IRIS probe array dedicated to transport measurement

Implementation of a telescope instead of camera lens for fast imaging

Comparison experiments / CYTO 3D simulations

# New poloidal probe array IRIS

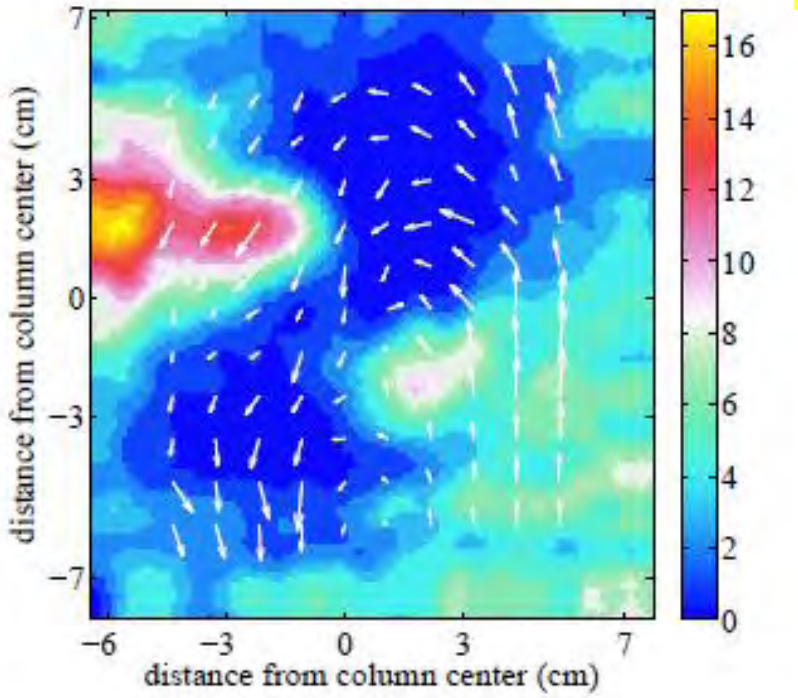


# *WP 3.2 – Development and validation of analysis tools for the camera*

- Developping data ptocessing tools for characterizing and tracking of turbulent structures from fast imaging. (e.g. TIV)
- Addressing the tomographic reconstruction problem
  - The light collected by the camera is emitted by a volume extended source → currently underway: comparing the results obtained from a simple experiment with a ray-tracing code, seeking for the possible advantages brought by replacing the camera lens by a telescope?
  - In toroidal geometry a tomographic inversion is necessary to reconstruct the poloidal cross-section images → continuation of the task initiated by Romain N'guyen
- Testing the developed methods on numerical simulations results
  - CYTO 3D
  - SOLEDGE3D

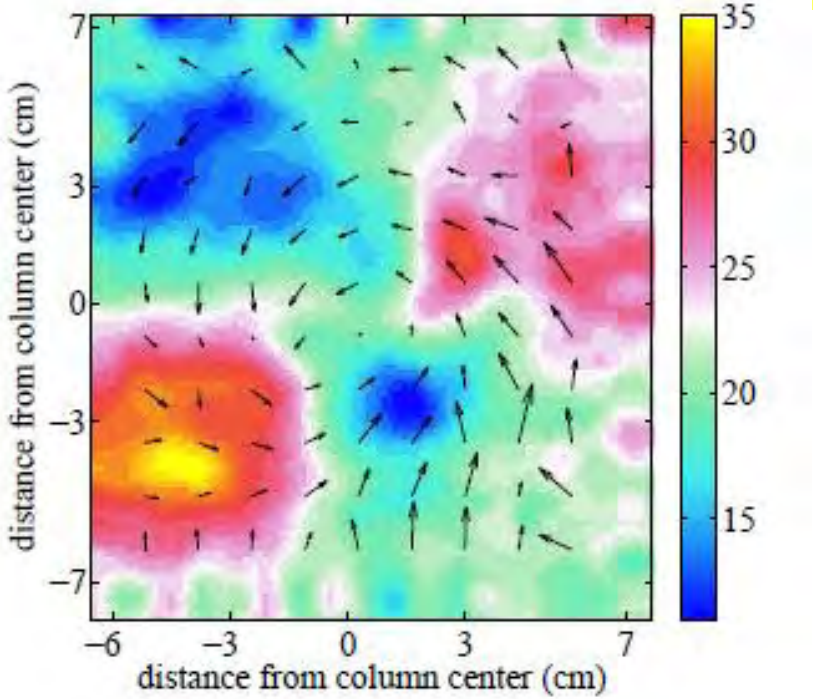
# Application of the „TIV" to Mirabelle




Velocimetry performed on a pair of fast camera frames. Superposition of the recorded light intensity and the quiver plot for the velocities

Photron SA 1.1, up to 90 000 - 180 000 frames/s, around 200x200 pixels

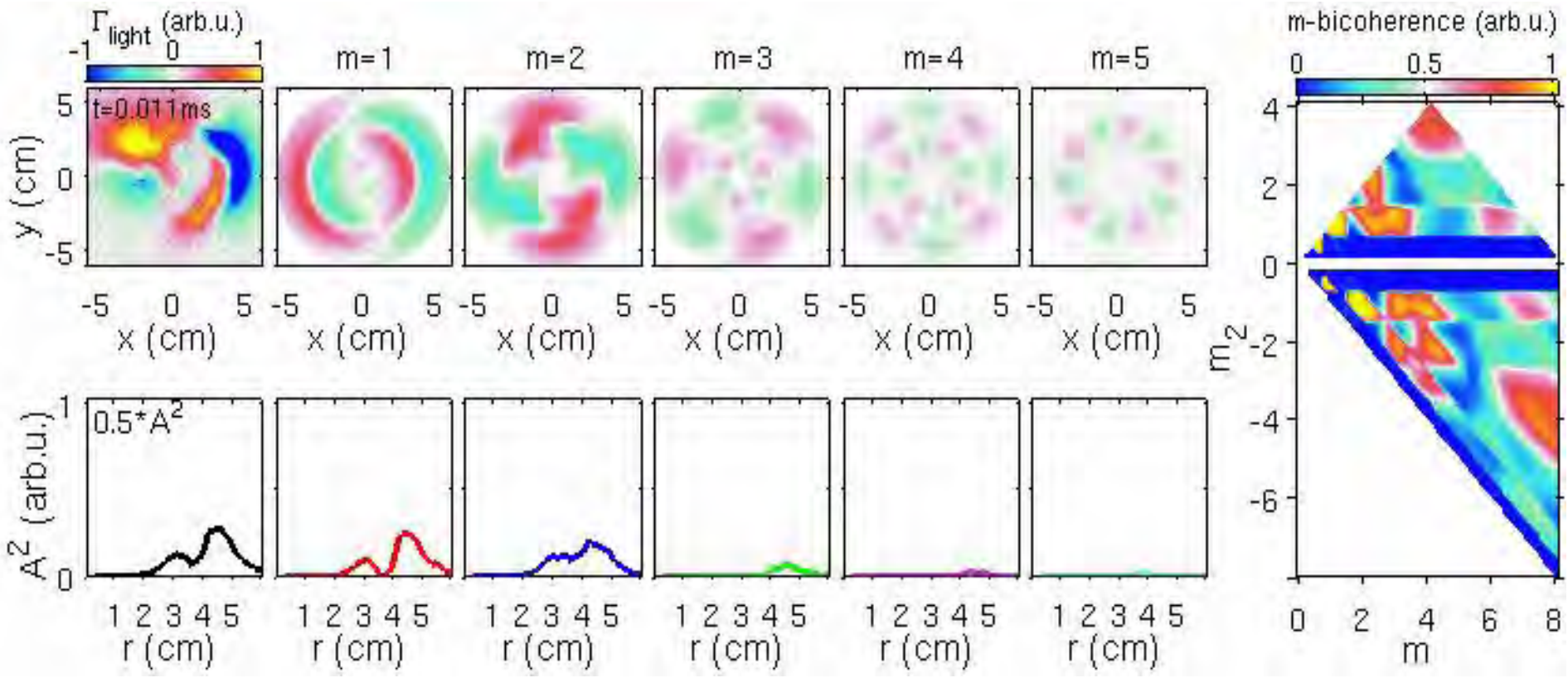
- pixel~ 0.8 x 0.8 mm$^2$
- exposure time: 1 - 3 µs



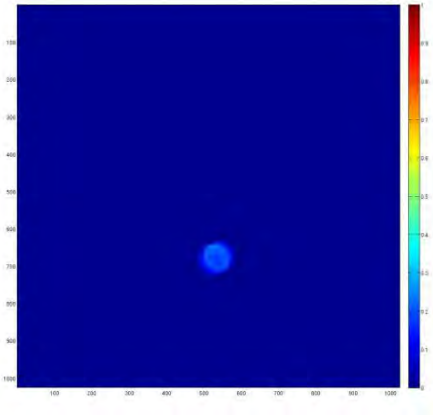

Average velocities obtained from 150 image pairs. Superposition of the first frame of the image sequence and the quiver plot for the velocities.

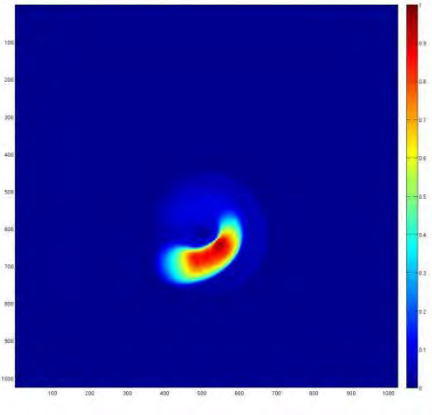
Stella Oldenbürger, PhD thesis, (2010)

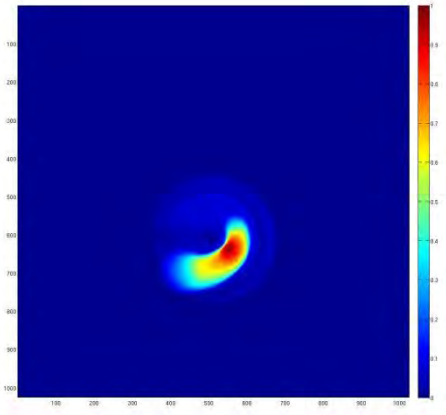
# Decomposition of drift wave turbulence (in He)



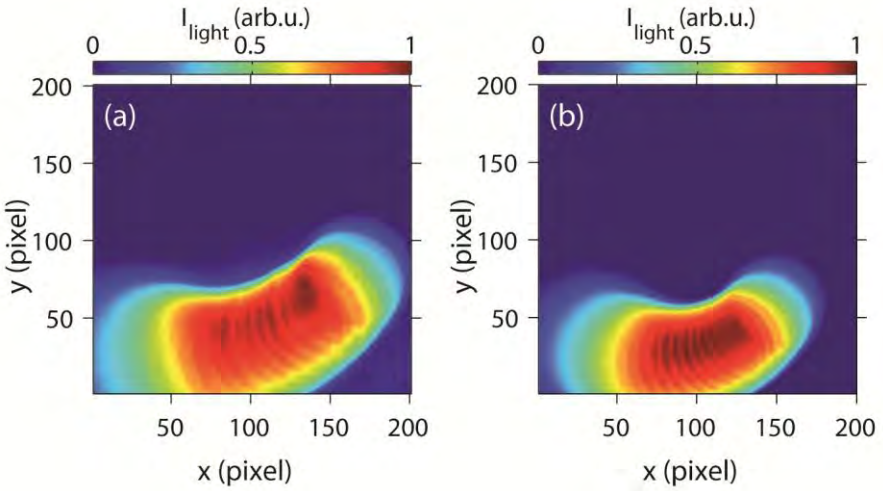
# Pb. Tomographic Reconstruction

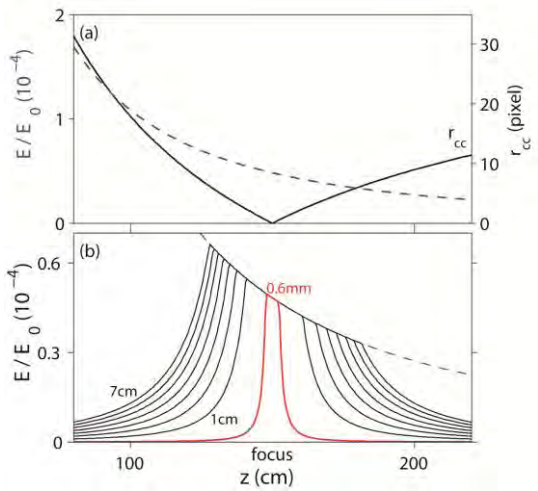






Experiments (simulating a m=1 drift wave)




Ray-tracing Simulations

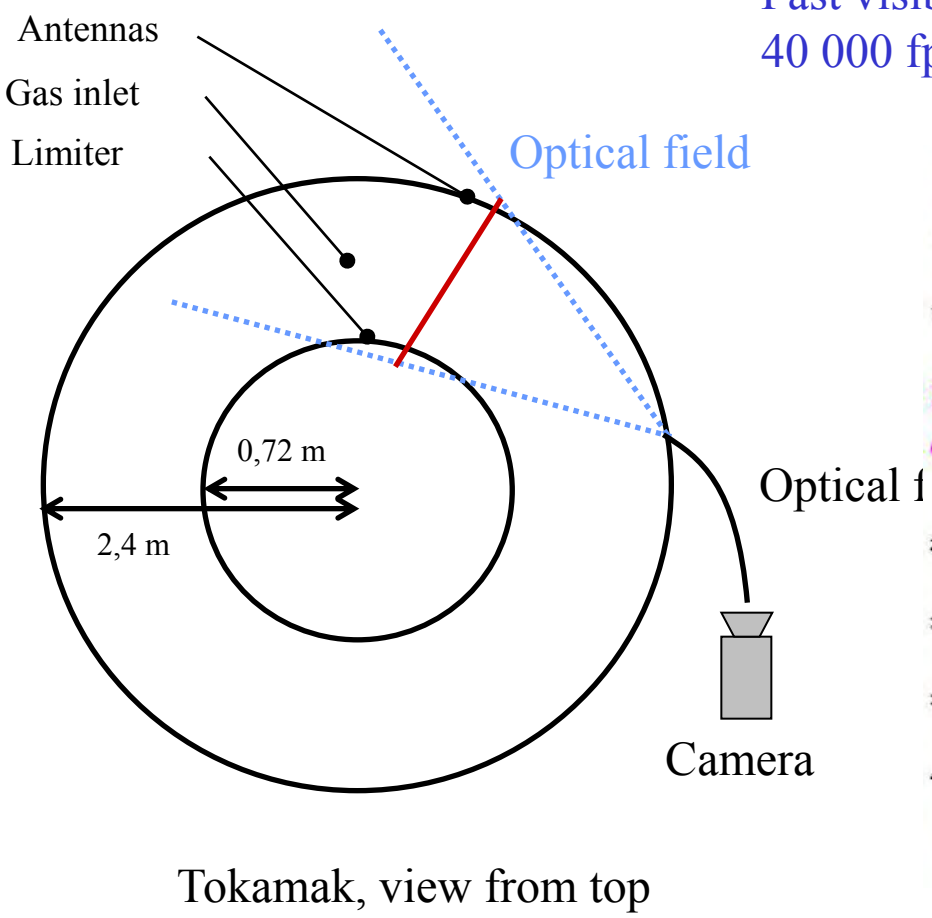
# Experimental campaign on Tore-Supra

For the first time, synchronous measurements with:

poloidal array of probes

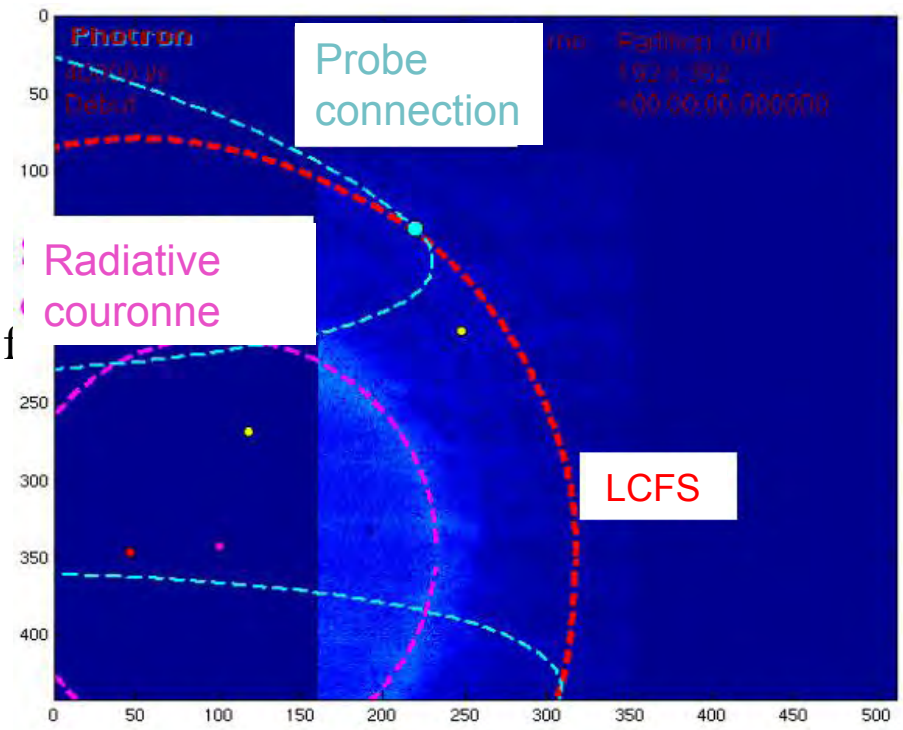
Doppler back-scattering and fast reflectometry

fast imaging



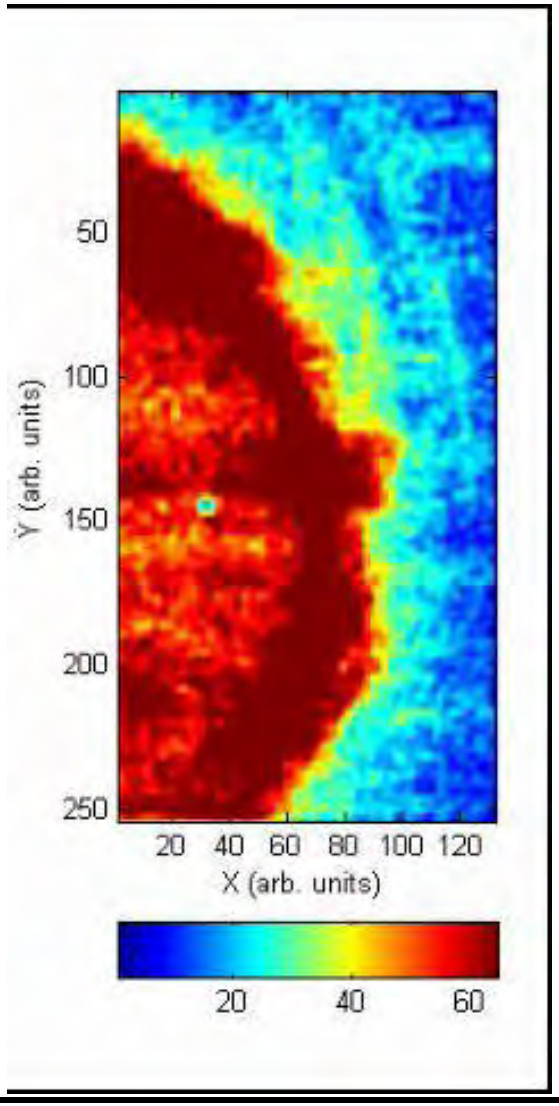

Tokamak, view from top

Fast visible commercial camera: Photron SA1.1
40 000 fps, Shutter 20 µs

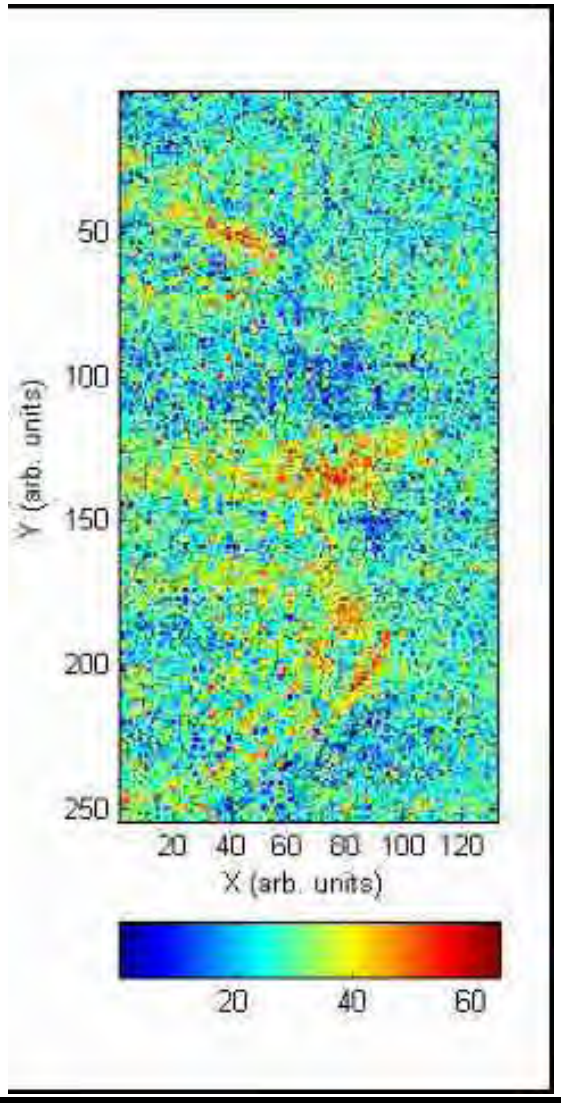


# Video Processing (Shot #TS42967)

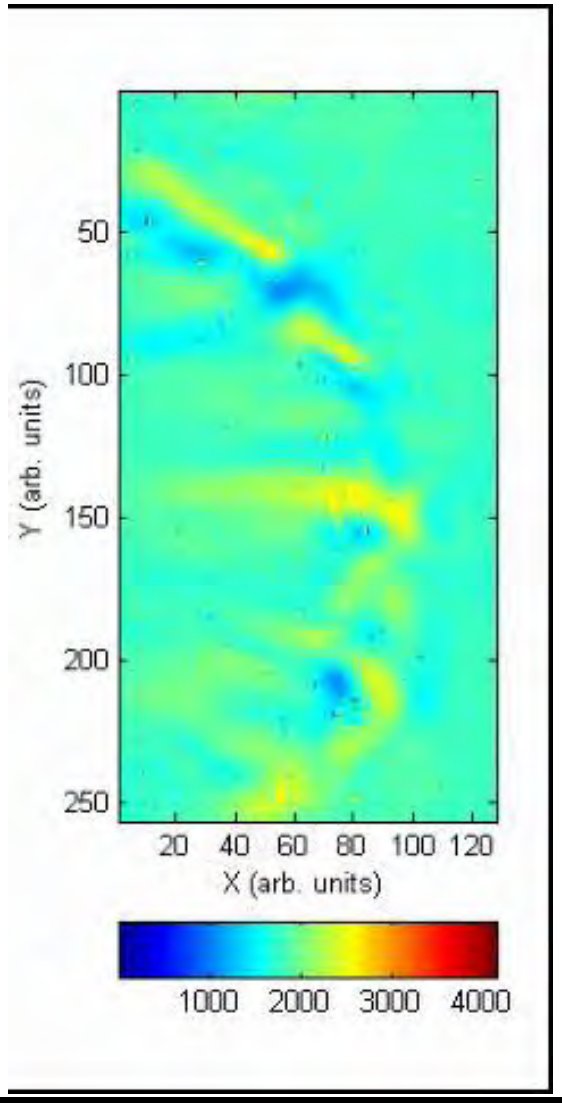
Raw movie




Fluctuations
(background removed)




After 2D wavelet denoising
(Kingsbury, NL thresholding)



# Video Processing – « TIV »

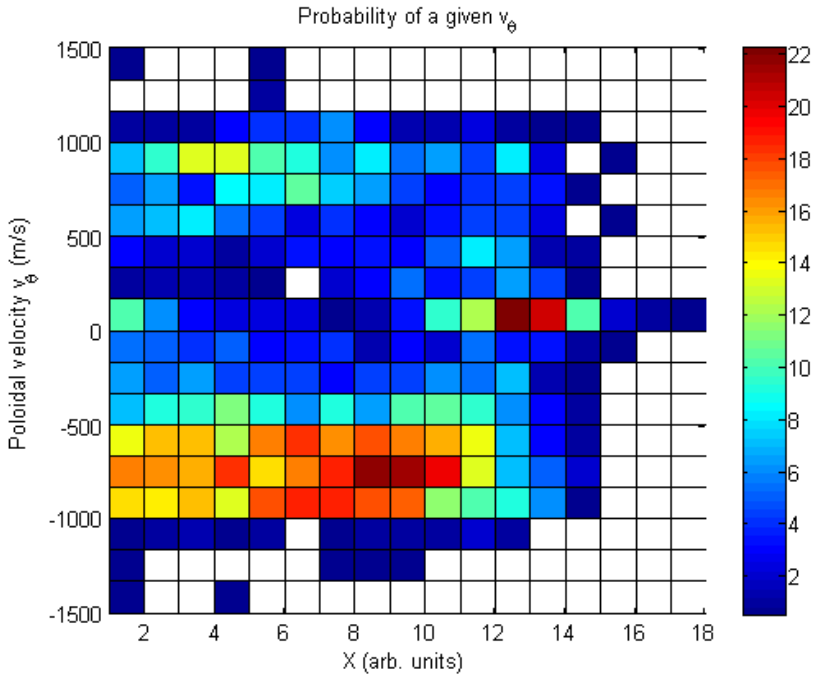
Principle of the MQD algorithm[1]

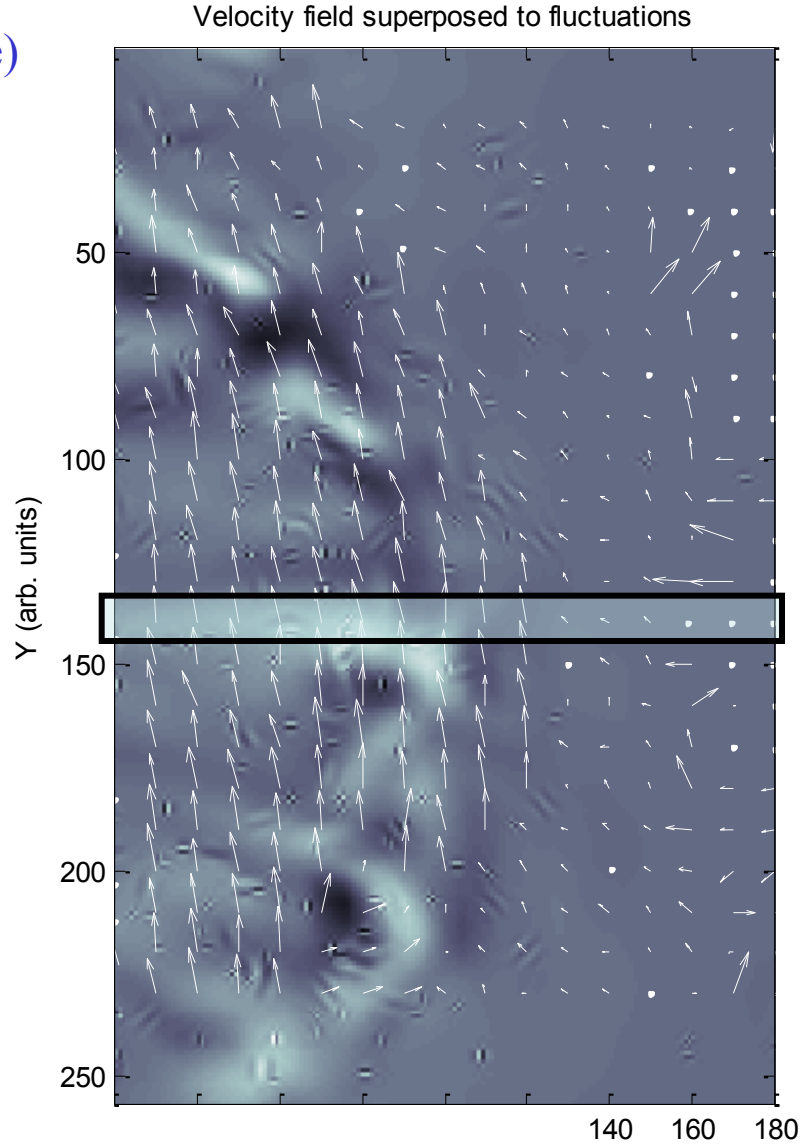
MQD (Minimum Quadratic Distance) looks at the minimum of the squared difference between sub-windows

[1]Sveen & Cowen

Spurious vectors

⇒ 200 pairs of frames (5 ms), Most likely velocity in PDF, in each sub-window

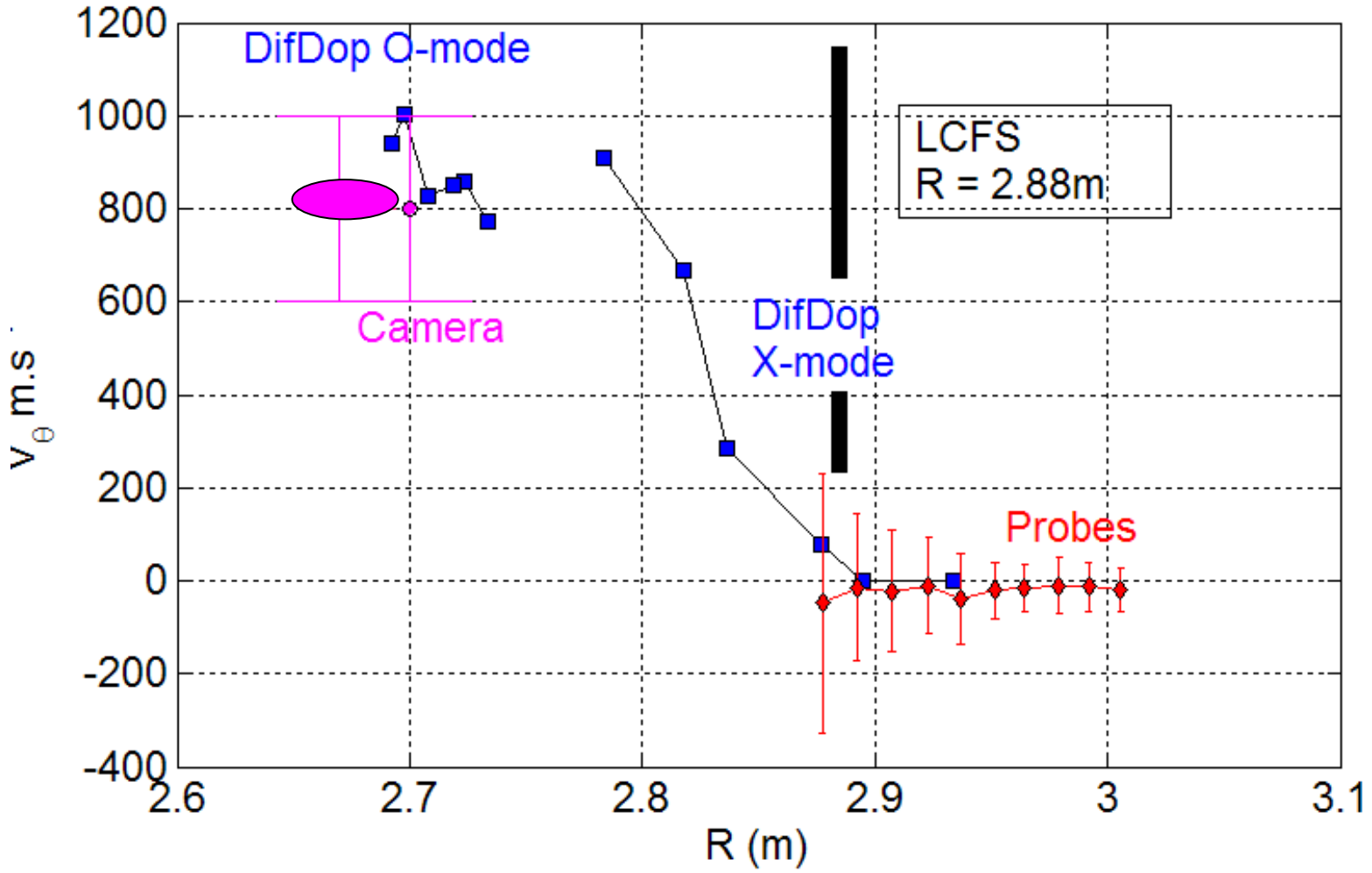



$$R(s,t) = \frac{1}{MN} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \left[ F'(i,j)^2 - 2F'(i,j)F''(i+s,\ j+t) + F''(i+s,\ j+t)^2 \right]$$

# Diagnostics comparison

Poloidal velocity profiles, detached plasma



# Tomographic reconstruction of Tokamak edge light emission

R. Nguyen van yen et al., Nuclear Fusion 52, 013005 (2012)

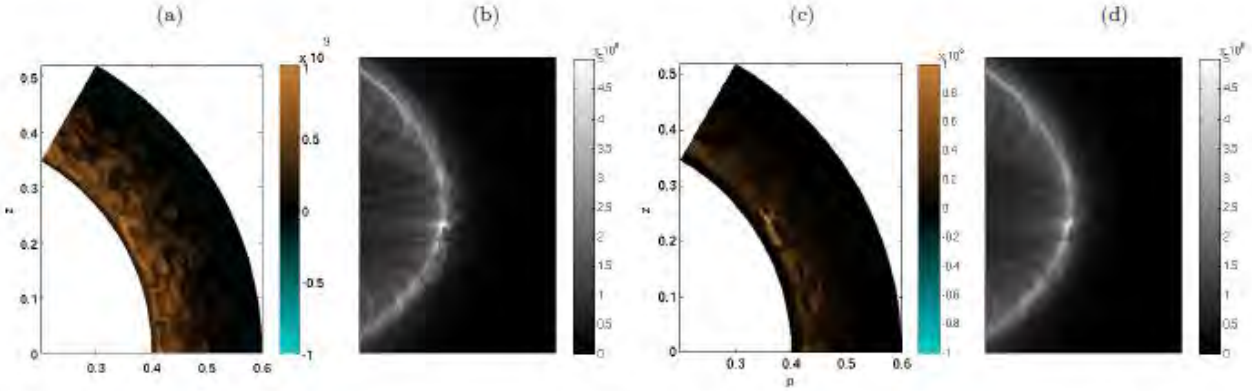



FIG. 7: Inversion test with artificial image generated from the TOKAM code. (a) Emissivity in the $(r, \theta)$ plane obtained from TOKAM run. (b) Artificial camera image obtained by stacking method. (c) WVD-inverted emissivity $S_R$. (d) Denoised image $I_R$ obtained by applying $K$ to $S_R$.

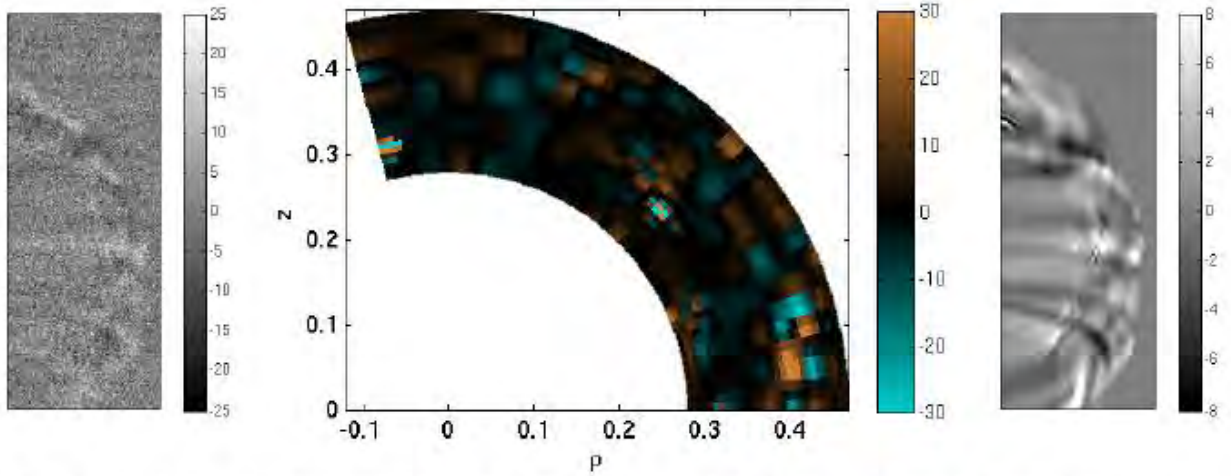


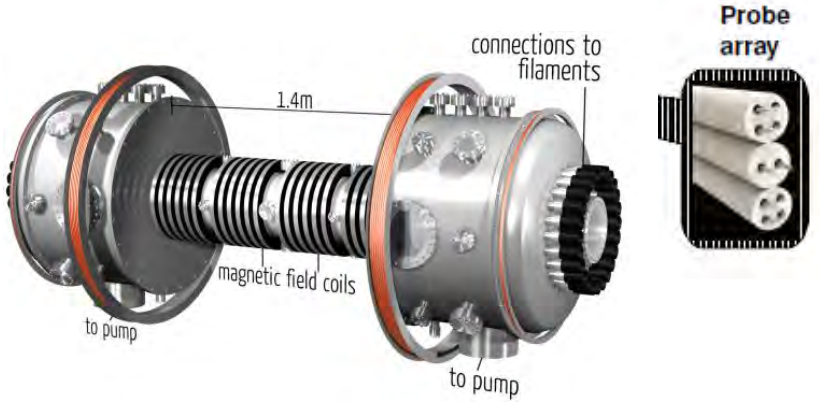

FIG. 8: Inversion test with experimental movie from Tore Supra shot 42967. Left: movie frame. Middle: WVD-reconstructed emissivity map $S$ in $(r, \theta)$ plane. Right: denoised movie frame regenerated by applying $K$ to $S$.

# Comparison of ball-pen and emissive probe measurements in a low-temperature magnetized plasma

G. Bousselin, J. Cavalier, N. Lemoine, G. Bonhomme

*Institut Jean Lamour,* UMR CNRS 7198, Dpt P2M, University of Lorraine,
BP 70239, F-54506 Vandoeuvre-lès-Nancy, France
French Research Federation in Magnetic Fusion – ITER

# Experiment




**Radially movable probe array:**

- Langmuir probe
- Emissive probes
- Ball-pen probe

➢ $T_e$ , $n_e$ , $\phi_p$ profiles
➢ $n_e$ , $\phi_p$ fluctuations
➢ Crossfield transport

## Experimental conditions:

- Helium and Argon plasma
- 3 working pressures:
  $P_0 = 2\times10^{-4}$ mbar
  $P_1 = 4\times10^{-4}$ mbar
  $P_2 = 5\times10^{-4}$ mbar
- Magnetic field: 5-80 mT
- 3 probes with ≠ diameters:

d=1mm, d=0.6mm, d=0.3mm

| Parameters | Helium | Argon |
|---|---|---|
| $\rho_{ci}$ | 0.4-6 mm | 1-20 mm |
| $\rho_{ce}$ | 0.05-1 mm | 0.05-1 mm |
| $\omega_{ce}$ | 1-10 GHz | 1-10 GHz |
| $\omega_{ci}$ | 0.1-2 MHz | 0.01-0.2 MHz |
| $\lambda_D$ | 50-700$\mu$m | 40-300$\mu$m |
| $\nu_i = \nu_{ii} + \nu_{i0}$ | 0.3-30 MHz | 0.3-20 MHz |
| $\nu_e = \nu_{ee} + \nu_{e0}$ | 0.3-2 MHz | 0.5-2 MHz |
| $\lambda_i \sim \lambda_{ii}$ | 100-600 $\mu$m | 50-500 $\mu$m |
| $\lambda_e$ | 1-3 m | 5-20 m |
| $\beta_e = \frac{\Omega_{ce}}{\nu_e}$ | $\gg 1$ | $\gg 1$ |
| $\beta_i = \frac{\Omega_{ci}}{\nu_i}$ | $< 1$ | $\ll 1$ |
| $\sigma_{e,0}$ | $7 \times 10^{-20}\ m^2$ | $1 \times 10^{-20}\ m^2$ |
| $\sigma_{i,0}$ | $6.9 \times 10^{-19}\ m^2$ | $1.3 \times 10^{-18}\ m^2$ |

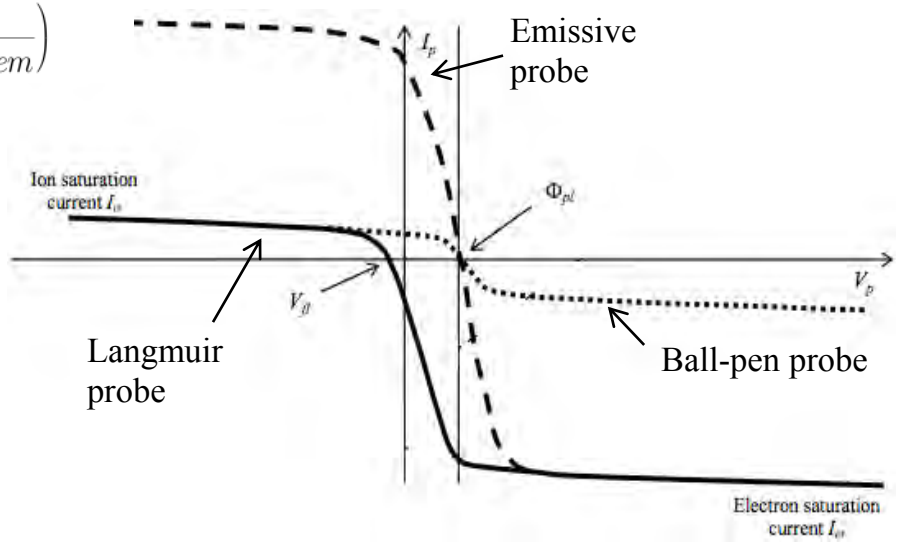
# Principle

**Langmuir probe theory:** $$\Delta = \frac{(\phi_p - V_{fl})}{T_e} = \ln\left(\frac{I_{es}}{I_{is}}\right) = \ln(R) \quad (1)$$

- $\Phi_p$ measured from 1st derivative of IV characteristics or calculated from $\Delta$ (knowing $V_{fl}$ and $T_e$).

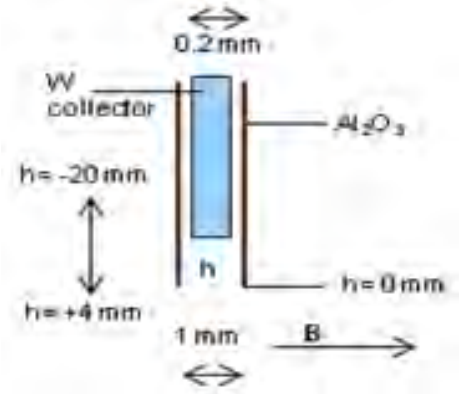
**Emissive probe:** $$\Delta = \frac{(\phi_p - V_{fl})}{T_e} = \ln\left(\frac{I_{es}}{I_{is}+I_{em}}\right)$$

- Emission current $I_{em}$ adds to electron and ion currents from the plasma.
- Increasing $I_{em}$ , the emissive probe floating potential approaches the plasma potential




**Ball-pen probe:**

- Consits of a movable Langmuir probe-like (metallic conductor placed inside an insulating tube).
- Probe axis oriented perpendicular to the magnetic field
- Utilizes the electron gyromotion to reduce $I_{es}$ down to the level of $I_{is}$.
- The ratio $R = I^-_{sat} / I^+_{sat}$ can be adjusted to one.



# Ball-pen probe design

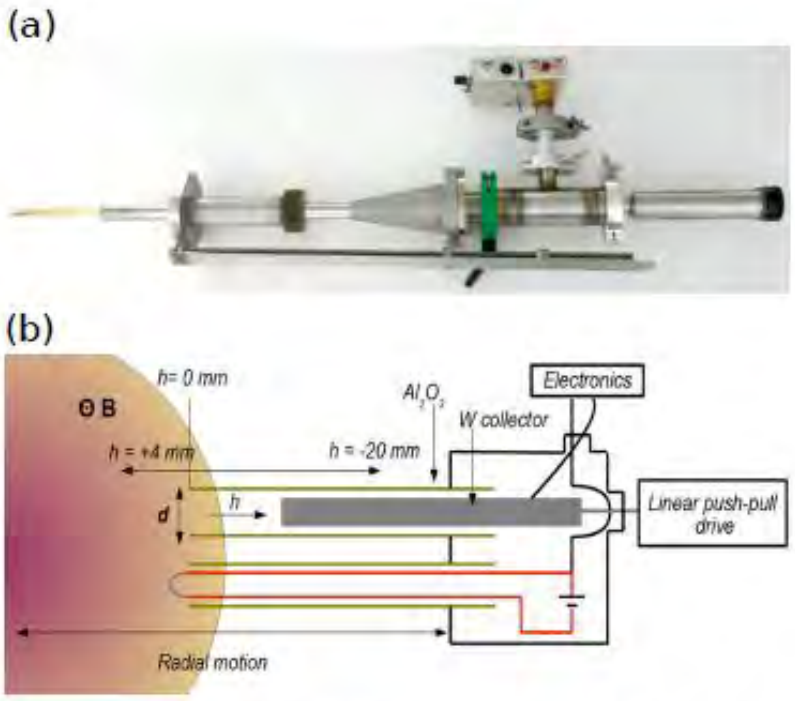
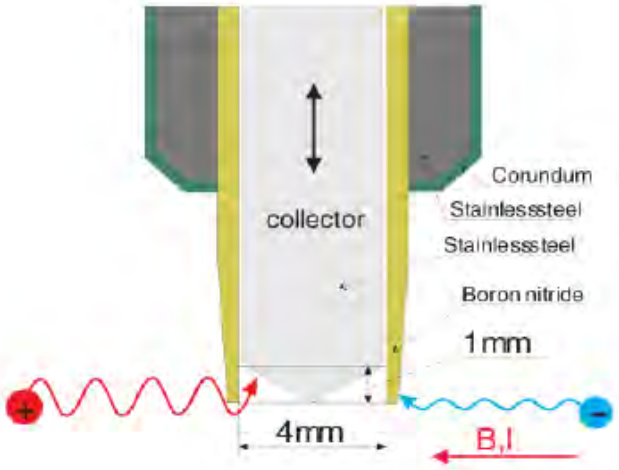
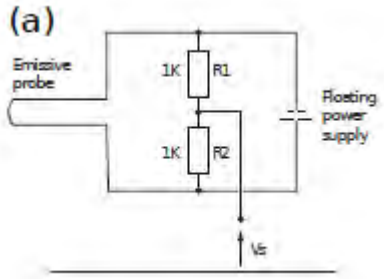
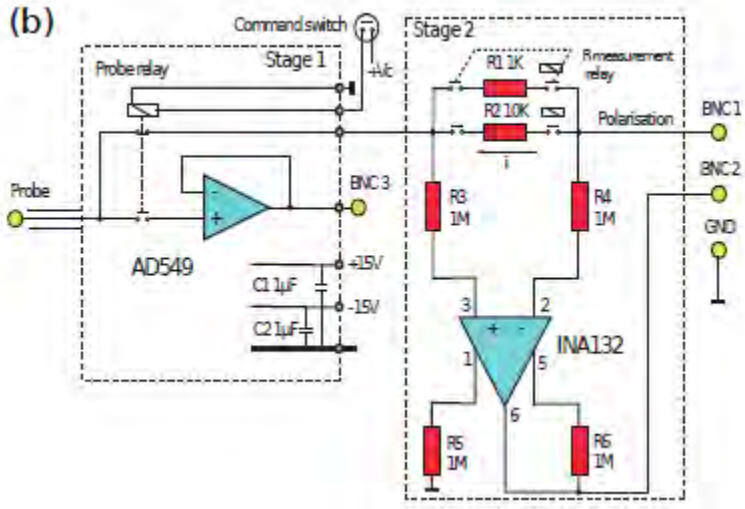



FIG. 2. (a) Photography of the radially movable probe array. (b) Scheme of the probe array constituted of one ball-pen probe (top) and one emissive probe (bottom).



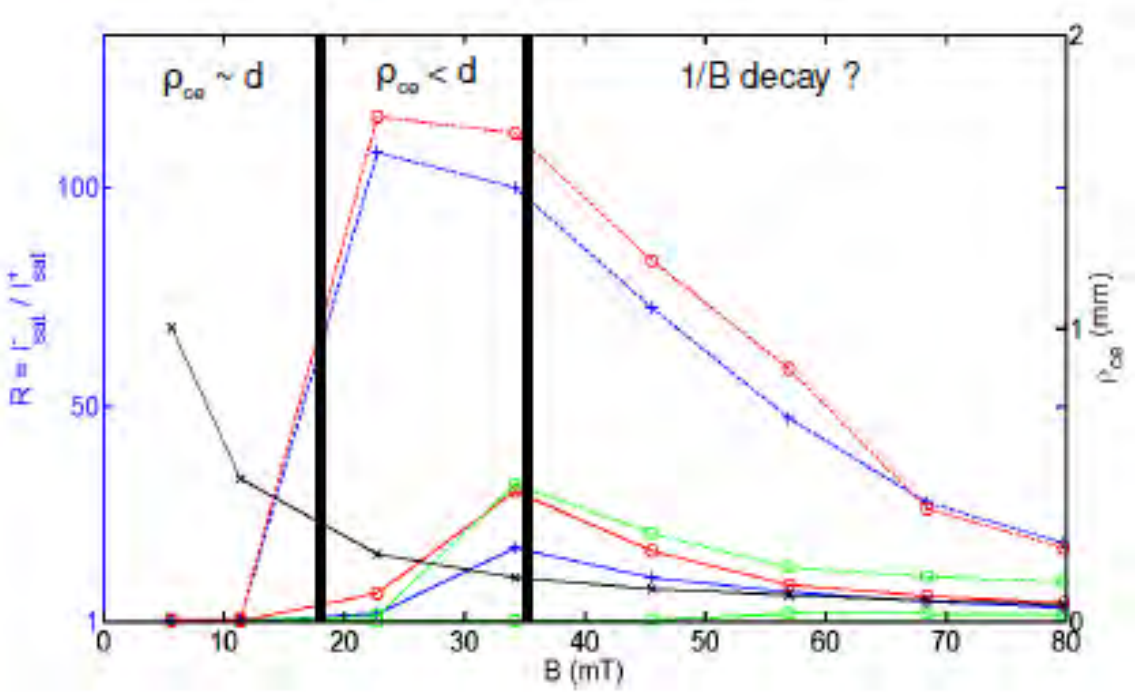



# *First results* → *Design and validation of the ball-pen probe for measurements in a low-temperature magnetized plasma*, G. Bousselin et al., submitted to RSI, (*accepted 11.12.202)*

**Observations:**

$\beta_e >> 1$ → $e^-$ magnetized → transport driven by *ExB* drift.

$\beta_i < 1$ → transport driven by collisions.




**3 regimes :**

- **$\rho_{ce} \sim d$**

*ExB* drift limited by probe geometry and $\sigma_{e\perp} \sim \sigma_{i\perp}$

- **$\rho_{ce} < d$**

*ExB* shielding no longer effective and $\Gamma_e = n_e v_{ExB}$

- **1/B decay** not yet understood, to be investigated

**Ratio of the electron saturation current over the ion saturation current calculated from Eq. (1)**

# Ball-pen: Floating potential vs. h

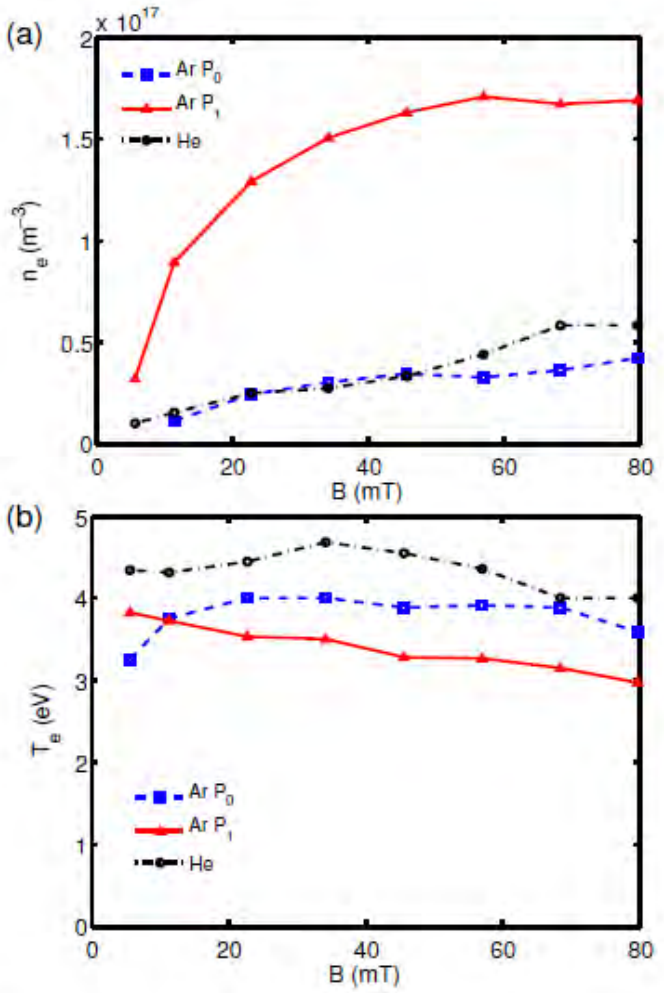



FIG. 4. (a) Electron densities obtained for the three different discharges (argon at $P_0 = 2 \times 10^{-4}$ mbar and $P_1 = 4 \times 10^{-4}$ mbar and helium with adjusted working pressure) with respect to the magnetic field. (b) Corresponding electron temperature.

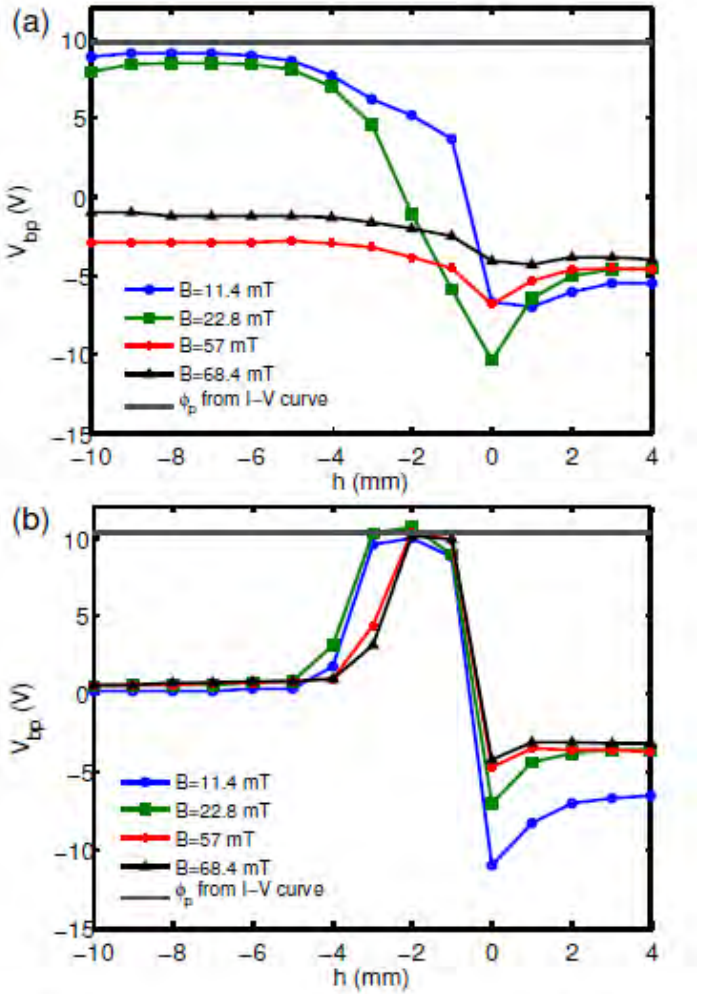



FIG. 5. Representative examples of ball-pen probe floating potential $V_{bp}$ with respect to the depth of the collector $h$. Argon plasma at $P_0 = 2 \times 10^{-4}$ mbar. $V_{ac} = 8$ V, $V_g = 8.5$ V. (a) Tube diameter $d_1 = 1$ mm. (b) Tube diameter $d_3 = 0.3$ mm.

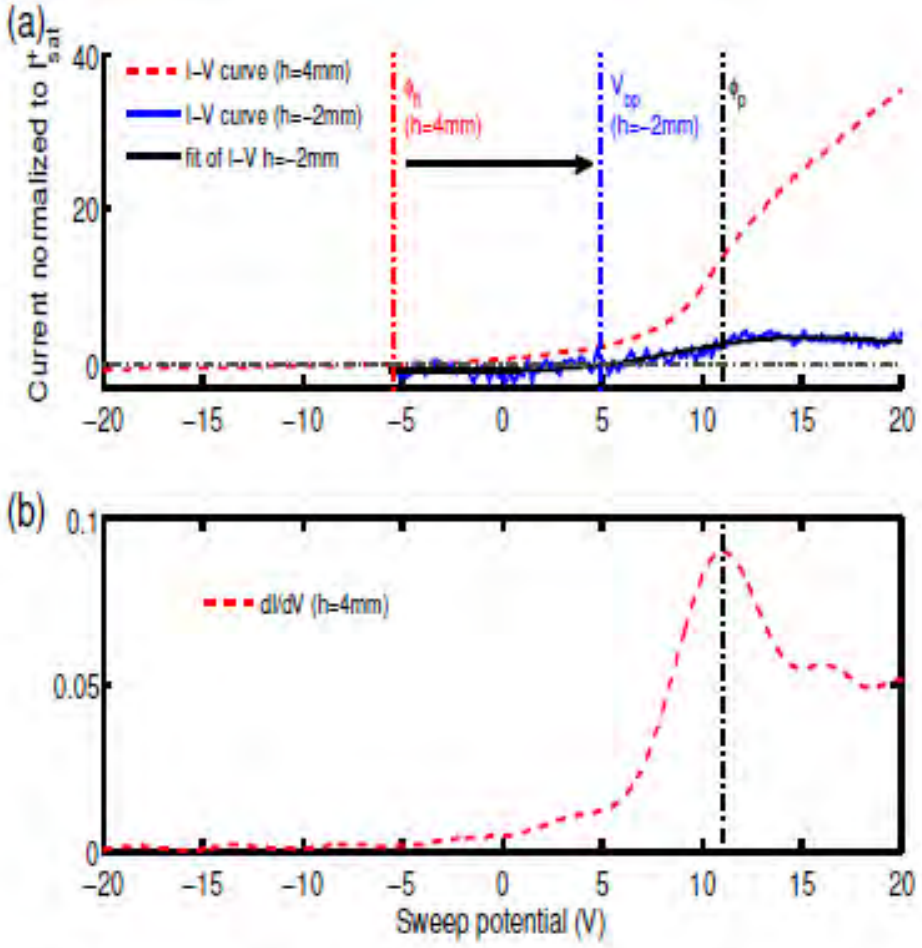



FIG. 6. (a) Normalized current-voltage characteristics recorded with the tube diameter $d_1$ at $h = 4$ mm and $h = -2$ mm. The discharge parameters are: argon plasma at $P_0 = 2 \times 10^{-4}$ mbar. $V_{ac} = 8$ V, $V_g = 8.5$ V, $B = 11.4$ mT. The shift of the floating potential of the ball-pen probe towards the plasma potential can be observed. (b) First derivative of the characteristic corresponding to $h = 4$ mm is also presented to show the determination of $\phi_p$.

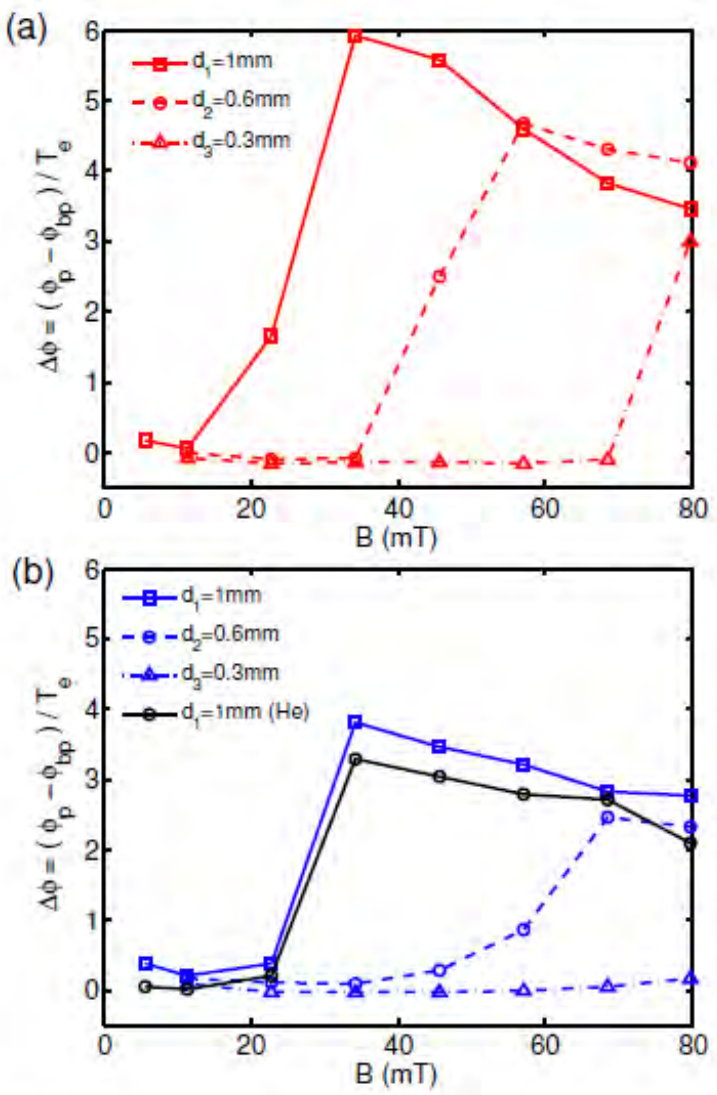



FIG. 7. Dependence of the normalized difference $\Delta\phi = (\phi_p - V_{bp})/T_e$ with the magnetic field $B$. (a) Argon plasma at $P_1 = 4 \times 10^{-4}$ mbar. (b) Argon plasma at $P_0 = 2 \times 10^{-4}$ mbar and helium plasma conditions corresponding to the same electron density than the argon case.

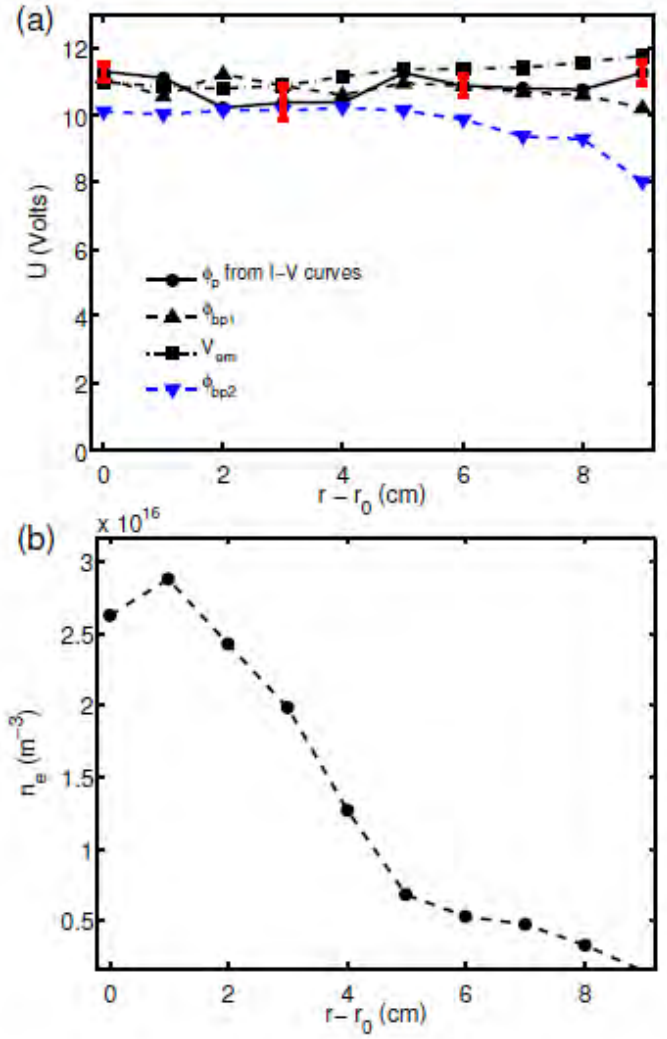



FIG. 8. (a) Radial profiles of two different ball-pen probe floating potentials ($\phi_{bp1}$ and $\phi_{bp2}$), emissive probe floating potential ($V_{em}$) and plasma potential ($\phi_p$) obtained from $I$-$V$ characteristics in the following plasma regime: argon plasma at $P_0 = 2 \times 10^{-4}$ mbar, $V_{ac} = 8$ V, $V_g = 8.5$ V, $B = 34$ mT. (b) Corresponding electron density profile.

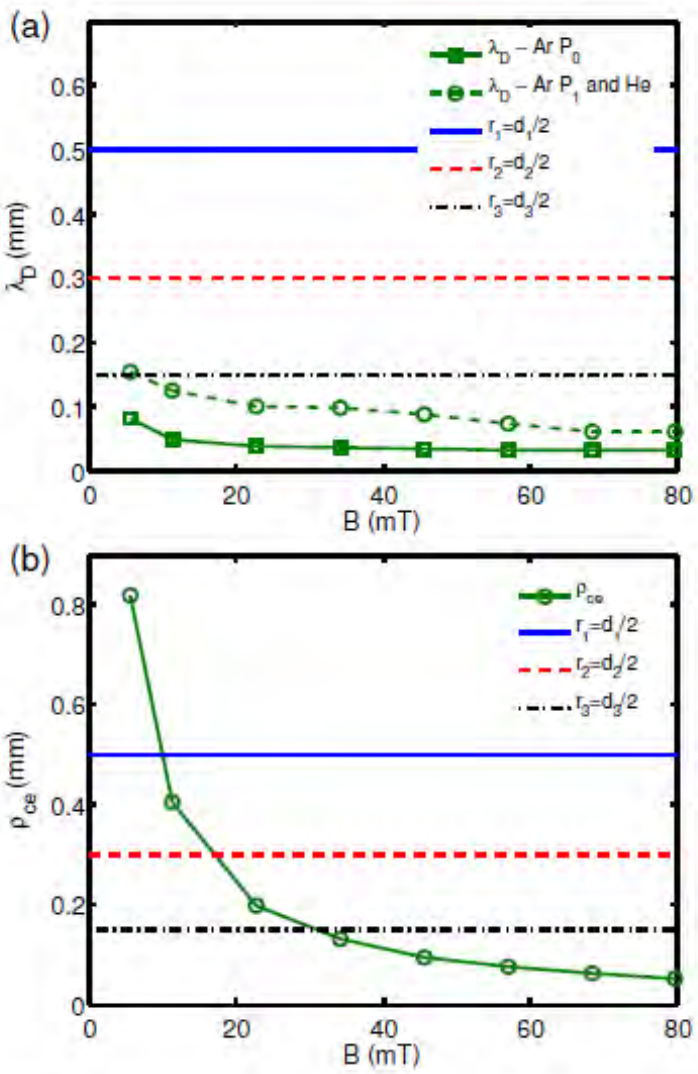



FIG. 9. Comparison of the characteristic lengths with the tubes radii. (a) Debye lengths corresponding to the different experimental conditions. (b) Electron Larmor radius corresponding to the argon plasma at $P_1 = 4 \times 10^{-4}$ mbar.

# Ball-Pen probe: Conclusions – Prospects

- On the Mirabelle device, the plasma potential was successfully measured with the ball-pen probe at low pressure and for different gases.
- However, for high pressures the potential of the probe did not reach the plasma potential. The reason would be linked to the electron Larmor radius.
- At low plasma densities (high impedance) the design of the measurement circuit is also a very sensitive issue.
- In next experiments, the size of the probe has been modified to investigate geometry effects on the measurements.
- Through these systematic experiments a better understanding of the ball-pen behavior was achieved, but comparison with numerical simulations will be highly valuable.

Institut Jean Lamour

UNIVERSITÉ DE LORRAINE

cnrs dépasser les frontières

FR FCM

# *Reflectometry and Antenna*

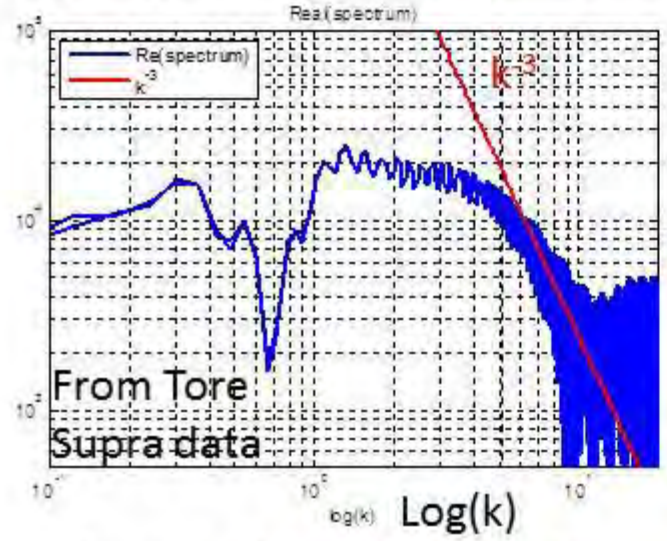
- Reflectometry modelling, S. Heuraux
- Antenna design and sheath, E. Faudot

# Turbulence characterization using reflectometry: Developments of new diagnostics using EM waves

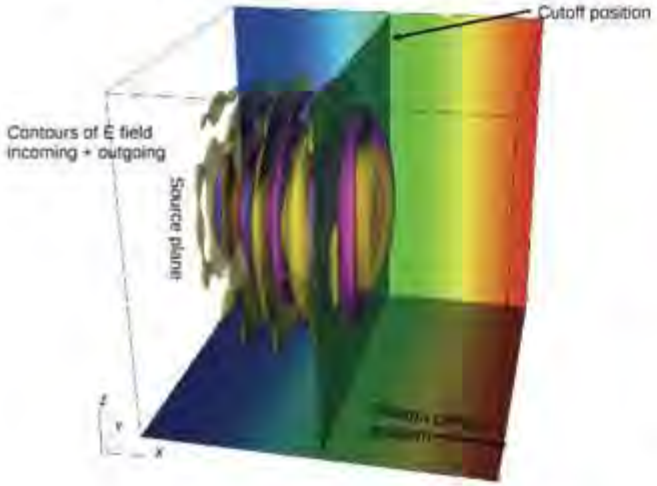
S. Heuraux, N. Kosolapova (PhD), E.Gusakov (Invited), A. Popov(Invited)

New concept

S(k) using radial correlation reflectometer




1st results of the ERCC 3D code




Role of resonances (Basic Physics):,

NL Theory written for coherent dn $k_f$= 2 k(x)

and verified by simulations

In turbulent plasma with wide S($k_f$) =>

Electromagnetic flux ⇔ Born approximation

S.Heuraux et al Contrib. Plasma Phys. **51**, 126 (2011).

E. Gusakov et al Physica Scripta **84**, 04504 (2011).

New concepts (development of diagnostics)

Using radial correlation reflectometry

Applied to Tore Supra, FT_2, JET

Using hoping frequency reflectometer

N. Kosolapova et al Plas. Phys. Cont. Fusion **54**, 035008 (2012)

E. Gudakov Plas. Phys. Cont. Fusion **54**, 045008 (2012)

Coupling with turbulent code (synthetic diagnostics)

With GEMR, tokam_2D

Blob detection and dynamics of the turbulence

To be published in Rev Sci Instrum.

Code ERCC EFDA ITM_ERDG (new tool developments)

New Numerical scheme (unconditional) ERCC 3D Kernel

Reversible Near_Far field propagator to be published in Fus.Sci.Tech

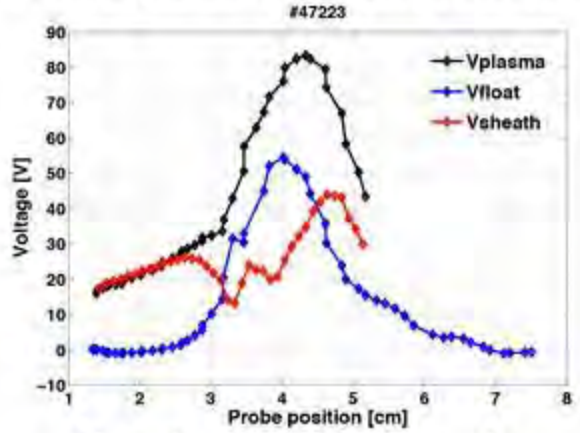
15 papers (2008-2012), Ioffé Institute St Petersburg, IPFN IST Lisbon, IRFM CEA_Cadarache

# Antenna-plasma Coupling RF sheath physics :

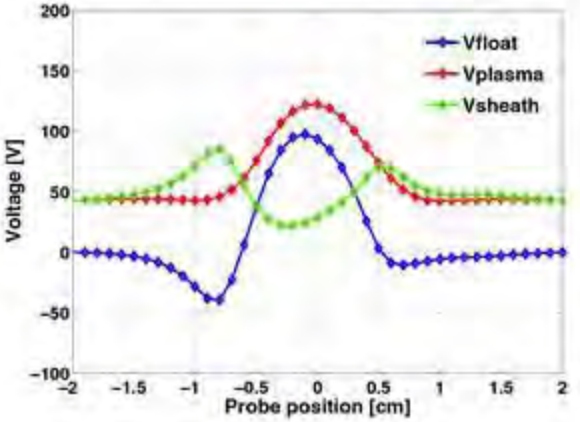
## Generation of rectified potentials DC by RF - Measurements by Langmuir probes in RF

E. Faudot S.Heuraux

Tore supra Experiment (M. Kubic)




Simulations SEM on the probes measurements




$U_\perp$=4 kms$^{-1}$

$\lambda_n$ = 3 cm

Fluid modeling and SEM code* : (theory and modeling)

including convection term $U_d$, conductivity $\sigma_\perp$, inertial current, anomalous viscous current, collisions ion-neutrals)

\+ Coupling between rectified potential and density

ALINE Experiment on RF sheath ( IJL Experiment)

RF sheath Physics (basics in magnetized plasma column)

Ionisation processes to take into account for n > 0.5 MHz

SSWICH project (simulation european project)

**Self-consistent Sheaths & Waves for IC Heating****

(IRFM, ERM Bruxelles, IJL, IPP-Garching) using

COMSOL multiphysics simulation models

- PML description multi-modes in anisotropic plasma
- Sheath boundary conditions
- ITER and Tore Supra simulations

Role of DC anomalous perpendicular conductivity $s_\perp$ (Basic)

$V_{DC}$ + RF + turbulence Simulations PIC

* **E. Faudot et al** Phys of Plasmas **17**, 042503 (2010) **L. Colas *et al*** Phys. of Plasmas **19**, 092505 (2012).

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# *Plasma-Wall Interaction*

- Dust tracking, F. Brochard
- Plasma surface interaction (lab studies), L. De Poucques

# Multi-machine investigation of dust mobilization, transport and impact on plasma performance

Joined research effort between Nancy University, IPP Garching and FZ Jülich: fast imaging of plasma-wall interactions in ASDEX Upgrade and TEXTOR tokamaks.

An algorithm, TRACE (Tracking and Classifying pinpoint Events), has been developed at Nancy University to analyze automatically the video data. TRACE able to characterize micrometer size dust (mobilization, trajectories), hot spots, unipolar arcs, (depending on frame rate), can also accurately detect disruptions and ELMs.

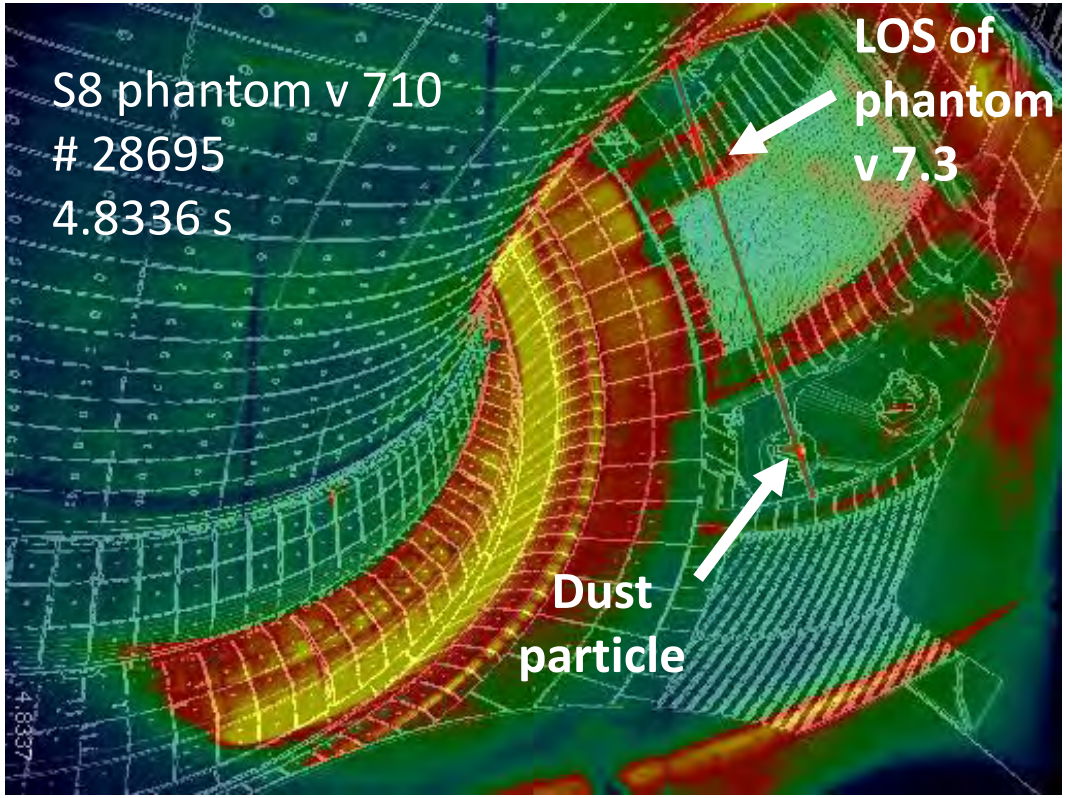
Fast imaging (typ. 10000fps) is routinely used on ASDEX Upgrade since 2008. 2268 shots have been analyzed with TRACE (~24 TB video data, 14370s plasma operation). Main findings are:

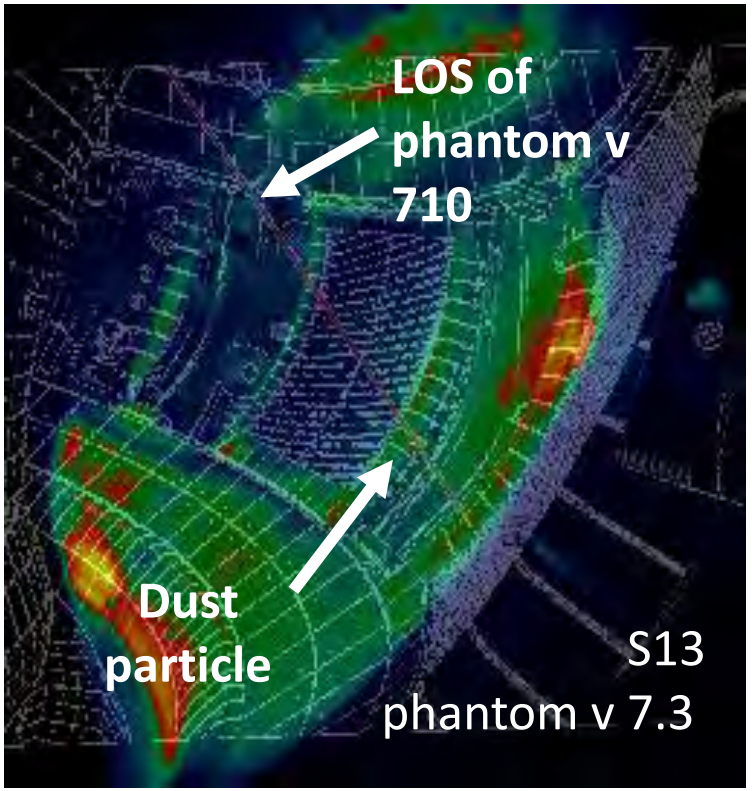
-No decreasing of dust amount with plasma operation time, no significant impact of device opening on dust generation

- Dust mobilization only in specific discharge conditions: mainly disruption (especially when preceded by plasma vertical displacement), type I-ELMs, and inefficient coupling of heating power (NBI, ECRH).

- highest amount of dust observed at intermediate heating power (3 MW< P < 7 MW), and not at higher power

# Multi-machine investigation of dust mobilization, transport and impact on plasma performance




Stereoscopic camera measurements enables to get 3D trajectories. Experiments since 2011 on ASDEX Upgrade (wide angle view, accuracy ~9mm).

Experiments were performed on TEXTOR in 2012 with injected calibrated dust (W spherical and C-flakes). Narrow view, accuracy ~mm. Coupling with DUSTT simulations in 2013.

INPUT for modeling, ITER predictions.

PhD Xavier Glad

# Context and application

## TOKAMAKS:

- Plasma interactions between hydrogen isotopes and first wall: beryllium, tungsten, **carbon**, etc.
- **Physical and chemical erosions (*i.e.* etching and re-deposition) of the carbon compound**
  → sputtering → dust formation and re-deposition
  → tritium retention
  → energy losses
- Phenomenon **unavoidable** but it could be **limited**

### OBJECTIVE:

Improve the understanding of the carbon chemical erosion processes when facing the tokamak scrape-off-layer

## LABORATORY PLASMAS:

- Allow to approach the conditions of the SOL[1]:
  - $T_e$ < 5 eV
  - $n_e$ ~$10^{12}$ $cm^{-3}$
  - low pressure $p$
  - incomplete ionization $\alpha$
- Accessibility, low budget, diagnostic flexibility

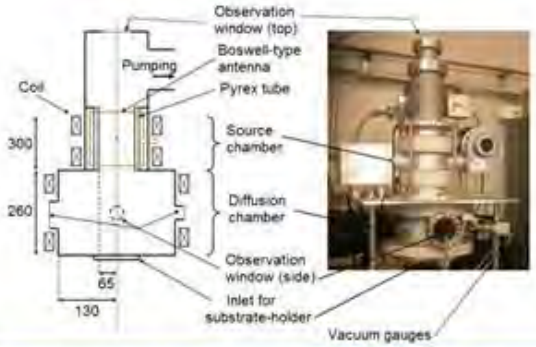
### OBJECTIVE:

**Obtain the highest erosion rate *i.e.* the highest atomic hydrogen flux available**

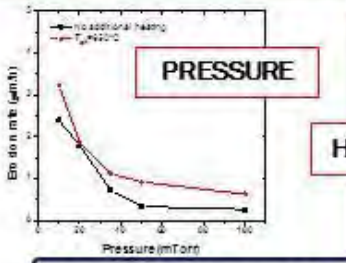
- RF plasma reactor using a Boswell-type antenna
- Investigation of the different working parameters influence on the erosion rate

[1] J.P. Sharpe et al., *Fusion Engineering and Design* 63-64 :153, 2002.

# Work overview



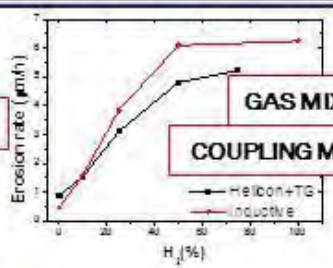

**EXPERIMENTAL APPARATUS**




PRESSURE

Helicon+TG mode

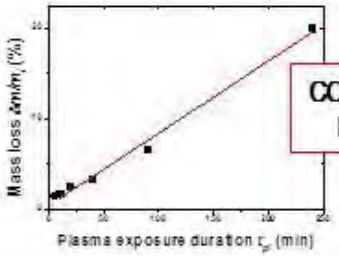
Inductive mode




GAS MIXTURE

COUPLING MODES

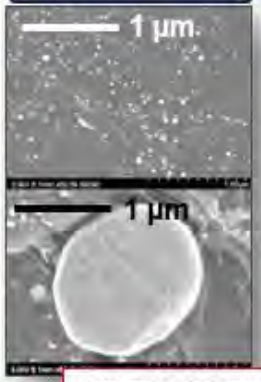
**INFLUENCE OF THE WORKING PARAMETERS**



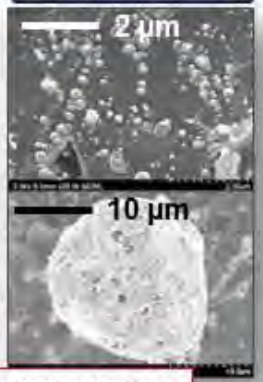

CONSTANT EROSION RATE: 6.0 µm/h

**EROSION KINETICS**

$t_{pl}$ = 5 min




$t_{pl}$ = 240 min




UP TO ø20-30 µm DUST WITH A 4 cm² GRAPHITE SAMPLE (NO HYDROCARBON ADDITION)

- Constant erosion rate but dust particles size and porosity growing with time
- Porous carbon structures similar to those obtained in tokamaks[1][2]: the core of the tritium retention issue

**PROSPECTS**

High resolution micro-Raman spectroscopy, TEM, hydrogen retention.

High resolution OES, Langmuir probe, TALIF.

**CORRELATIONS**

Study of the plasma/wall interactions in a $h_2$ plasma (+He: byproduct of the D/T fusion)

**THE AIM IS TO UNDERSTAND THESE INTERACTIONS IN AN ATTEMPT TO LIMIT THEM, AS WELL AS DUST TRANSPORT, IN FUSION PLASMA DEVICES.**

[2] M. Richou *et al.*, *Carbon*, 45 :2723, 2007.

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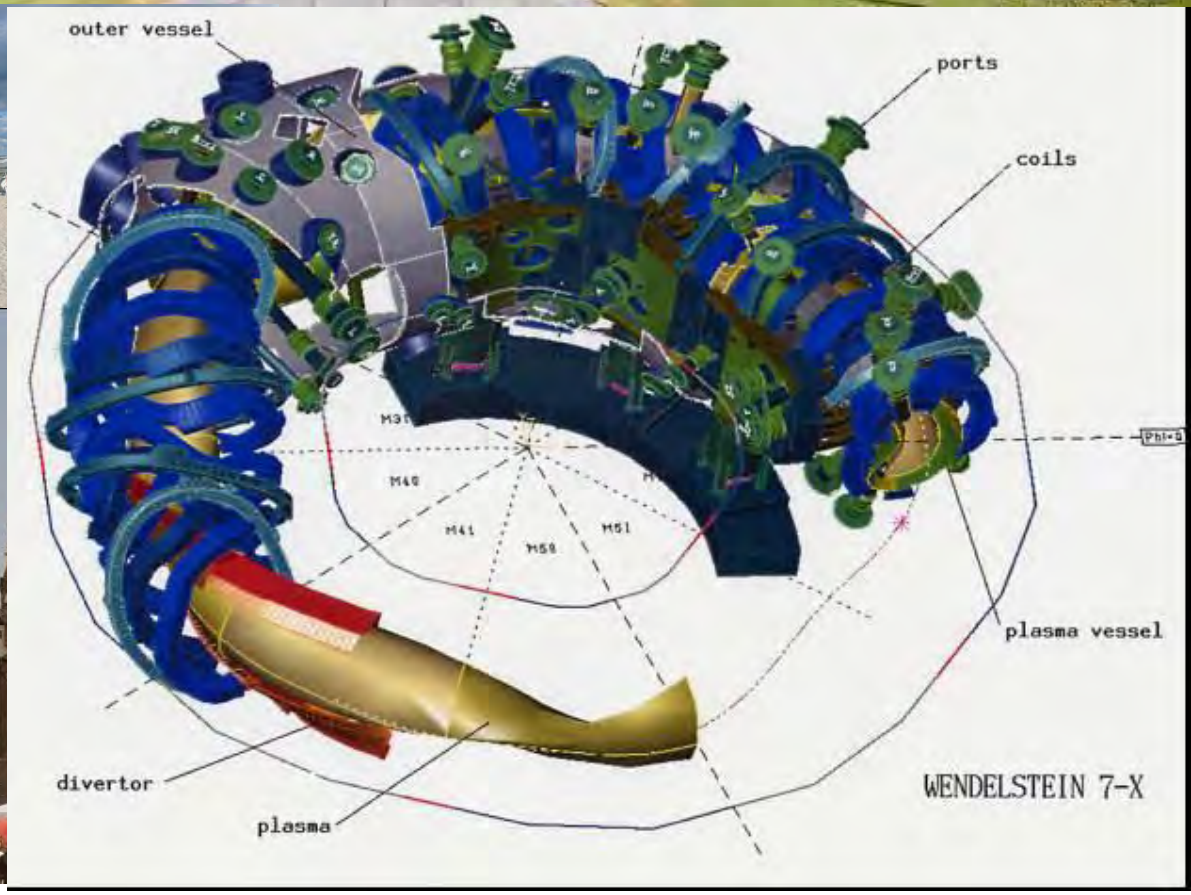
# *Stellarators and our ESTELL project*

# Stellarators vs. Tokamaks

- Three ways of producing a rotational transform:
  1. Driving a toroidal current → tokamaks, RFPs
  2. Elongating the flux surfaces and making them rotating poloidally as one moves around the torus
  3. Making the magnetic axis non planar
- Advantages and drawbacks of Stellarators:
  - Macroscopic equilibrium:
    - No current driven MHD instabilities that limit the performance
    - No disruptions
    - No Greenwald limit for the density
    - Higher $\beta$ (pressure) limit than tokamaks
  - Neoclassical transport → a critical issue (advantage of symmetry)
  - Micro-instabilities and turbulence
  - Edge and divertor physics

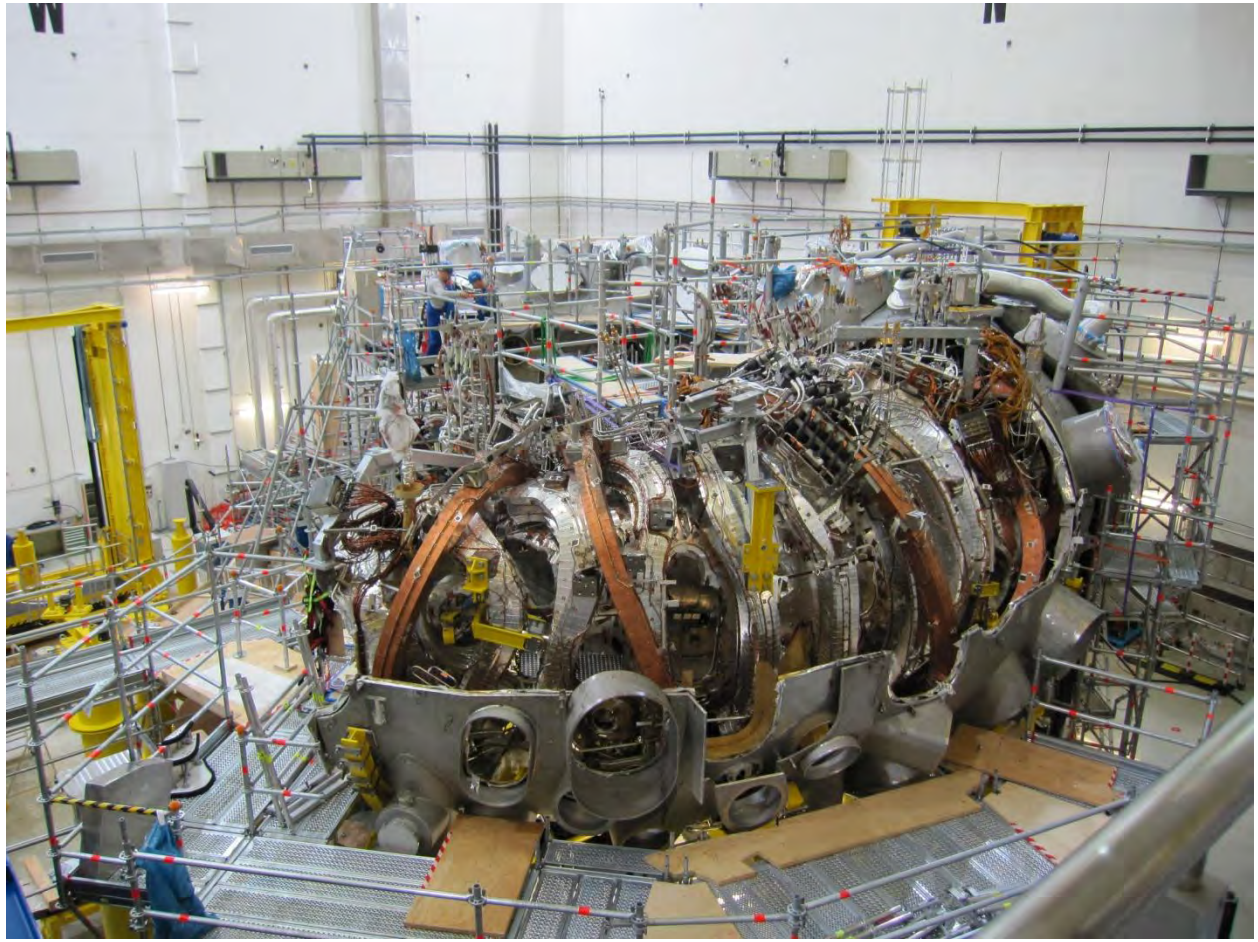
P. Helander et al., PPCF, 54 (2012) 124009

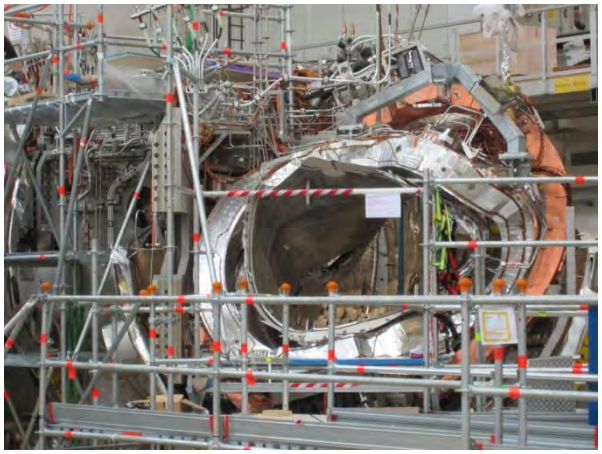
# The Stellerator Wendelstein 7-X
# Max-Planck-Institut für Plasmaphysik, Greifswald

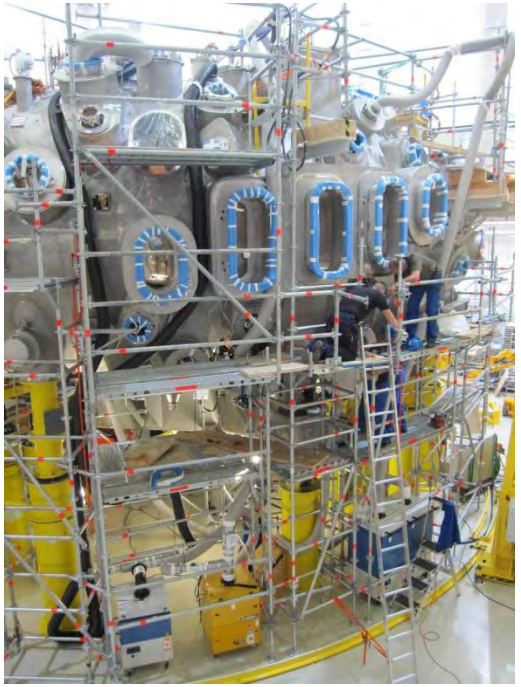



# The Stellerator Wendelstein 7-X
# Max-Planck-Institut für Plasmaphysik, Greifswald

## Status in Oct. 2010

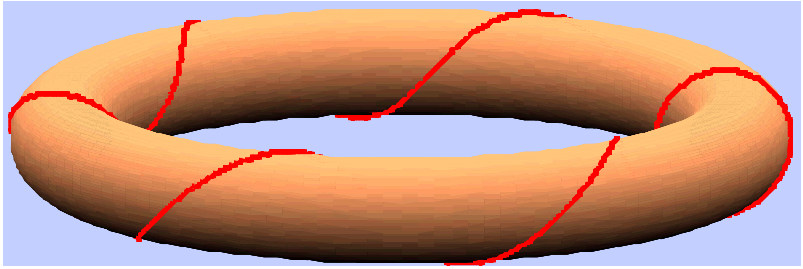


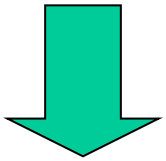


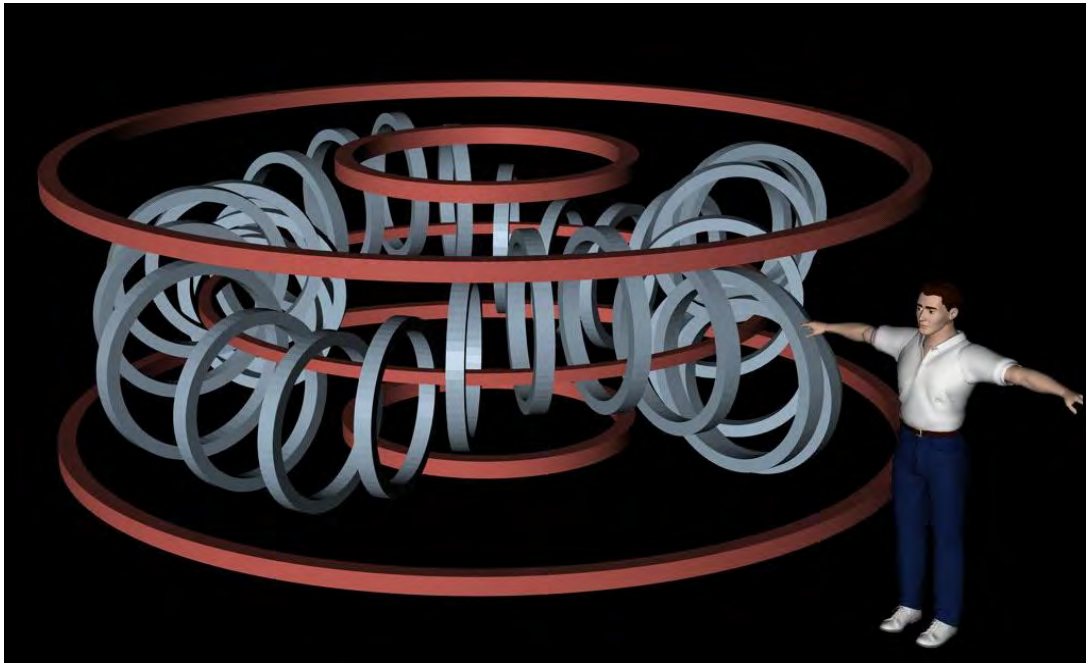


# From ESTELL 1.0 to ESTELL 2.0

Simplest (technically) and cheapest solution: heliac configuration







Foreseen Parameters:

R ~1.5 m

$D_{plasma}$ ~0.3 m

B = 0.5 T ($\rho^*$ ~$10^{-2}$)

$P_{ECR}$ : 50-100 kW

$P_{RF}$ : ~ 10 kW

Expected plasma parameters:

$T_e$ ~ 100 eV

$T_i$ ~ 10 eV

$n_e$ up to $10^{19}$ $m^{-3}$

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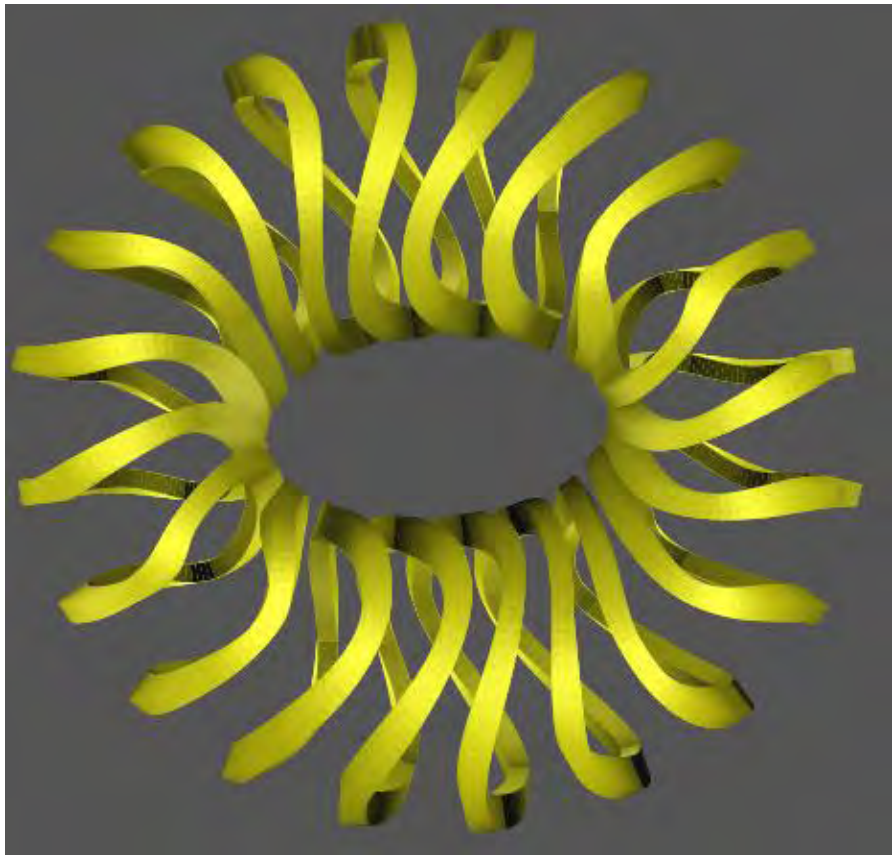
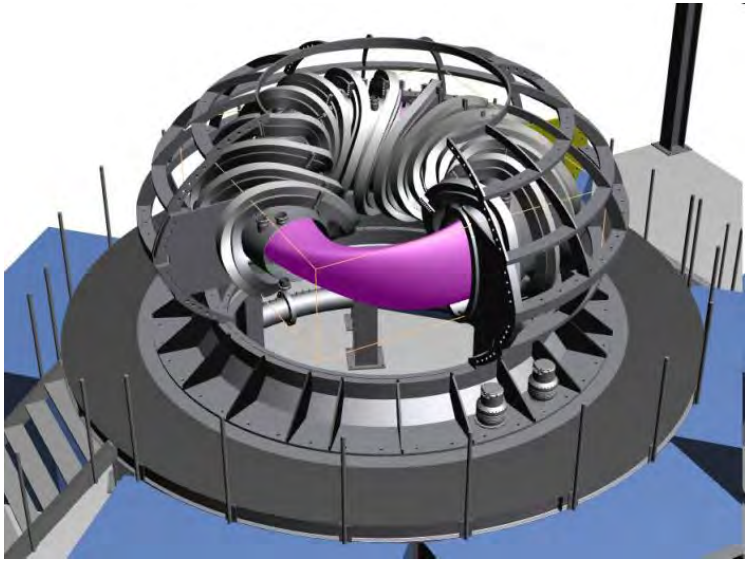
# The ESTELL Project

*Evolutive*

*STELlarator*

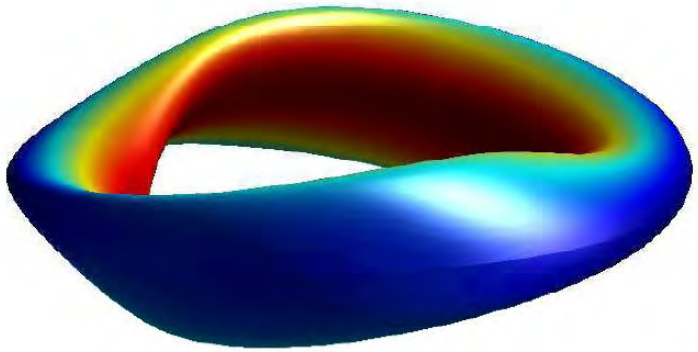
*of Lorraine*





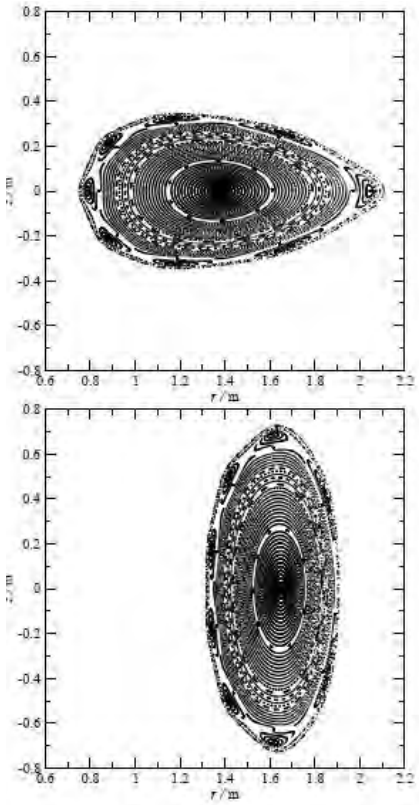
# Magnetic configuration

(1) M. Drevlak et al., *Design of a low-aspect-ratio, low-beta, quasi-axisymmetric stellarator*, private comm.

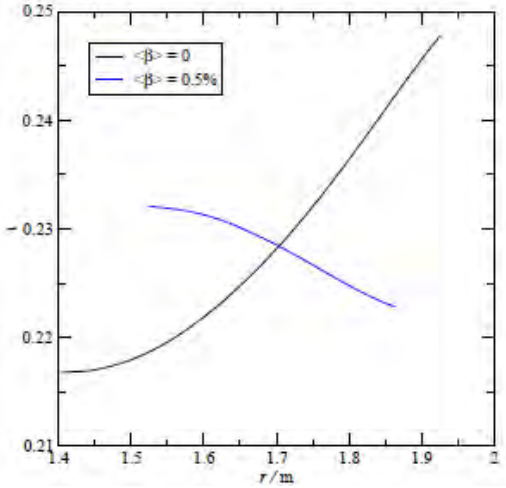


*Plasma boudary with the strength of the magnetic field on it.*

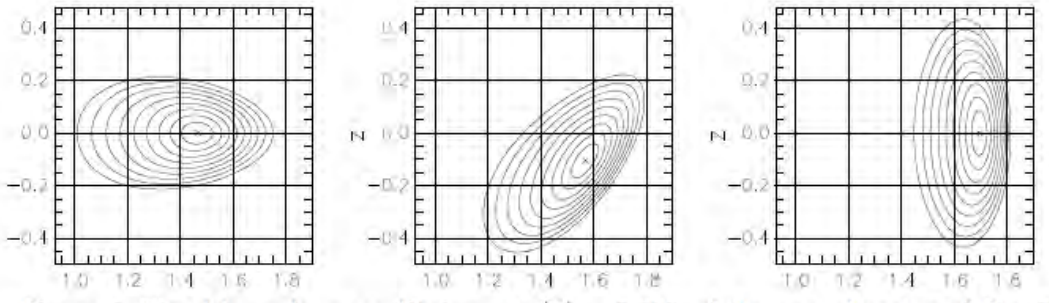
*Poincaré cuts of the vacuum field produced by coil set with identical current.*




Magnetic Configuration calculated at IPP Greifswald

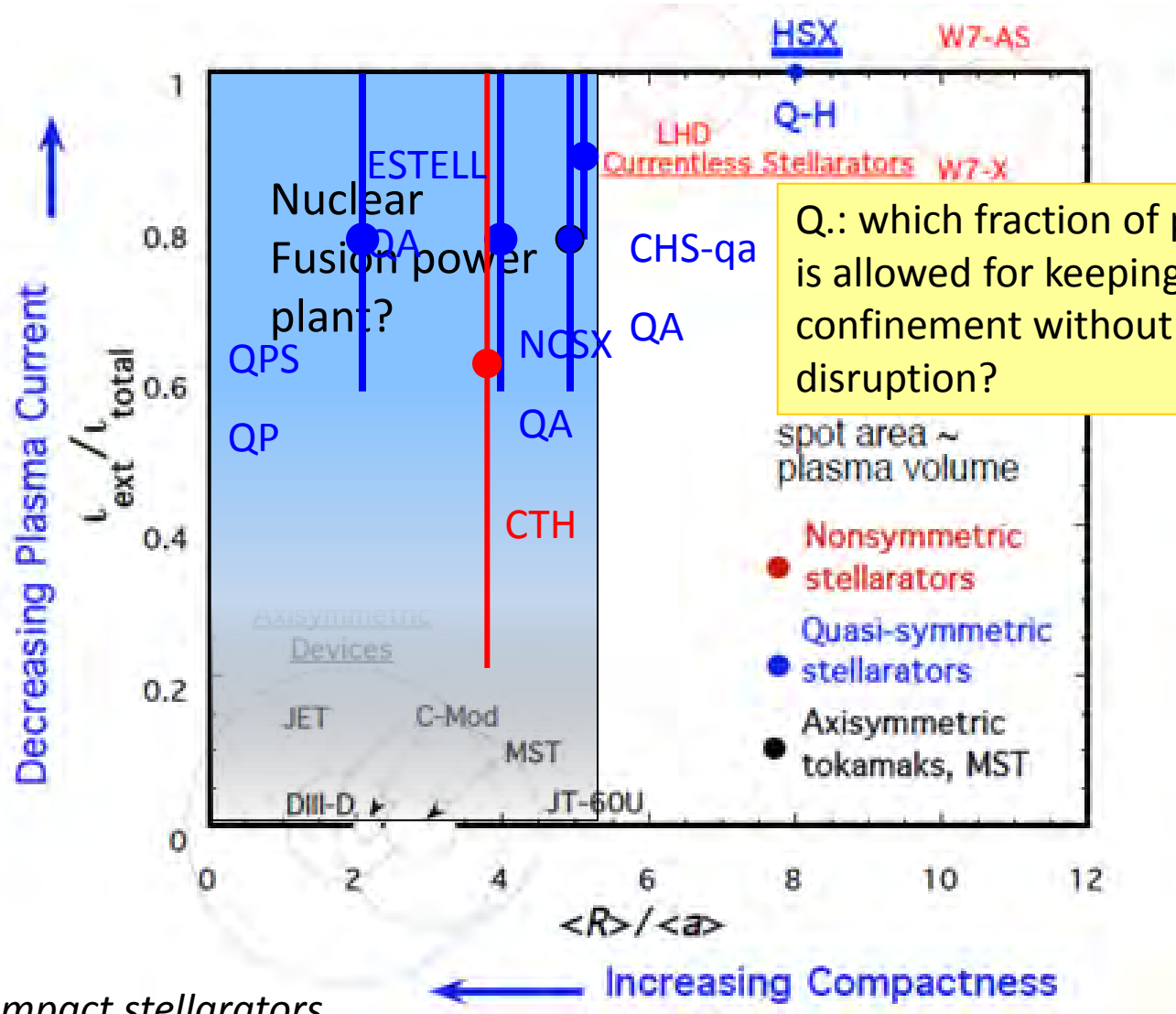



*ι profiles at <β> = 0 and <β> = 0.5%.*




*Fixed-boudary equilibrium at <β> = 0.5%.*

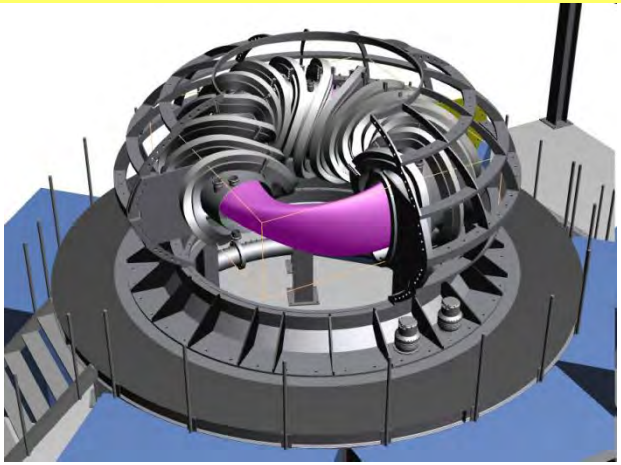
# International Context




Q.: which fraction of plasma current is allowed for keeping a good confinement without risking any disruption?

*Source : US compact stellarators programme*

# The ESTELL device parameters



Major Radius: 1.4 m

Average plasma minor radius: 0.28 m (R/a = 5)

Plasma Volume: 3 $m^3$

Number of field period: 2

Rotational transform: 0.23

Number of modular coils: 20 (of 5 kinds; 5 power supplies to vary helical ripple)

Magnetic field strength: B ≤ 0.5 T (1 T in pulsed mode?)

β (0.5 T, 200 kW ECRH): 0.5%

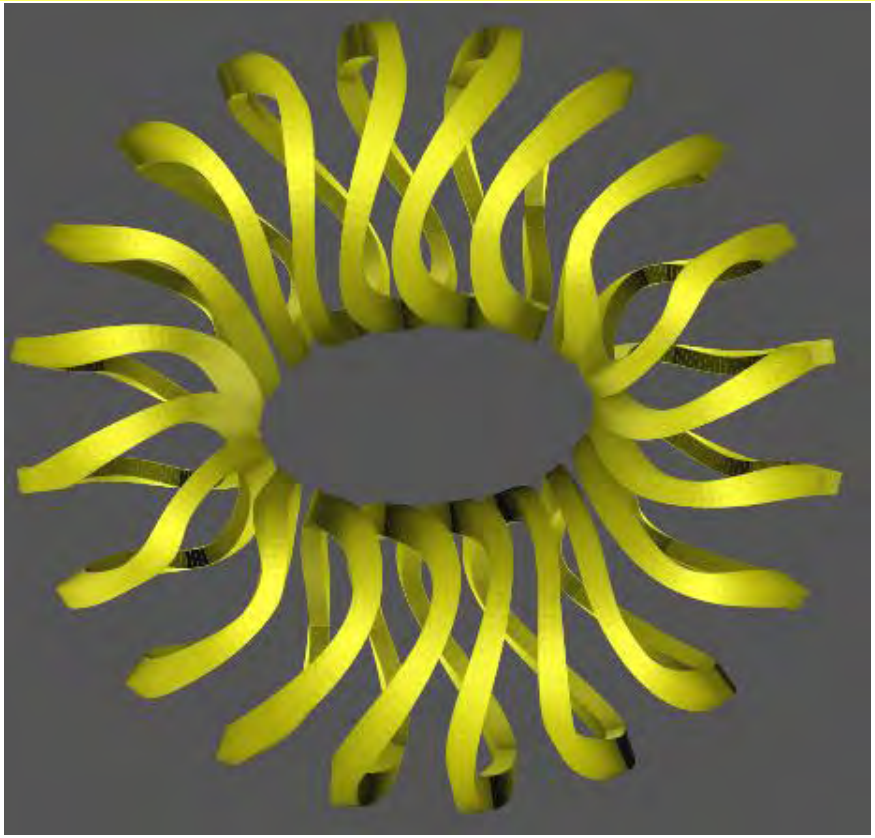
Pulse length: ~ 20 s / continuous

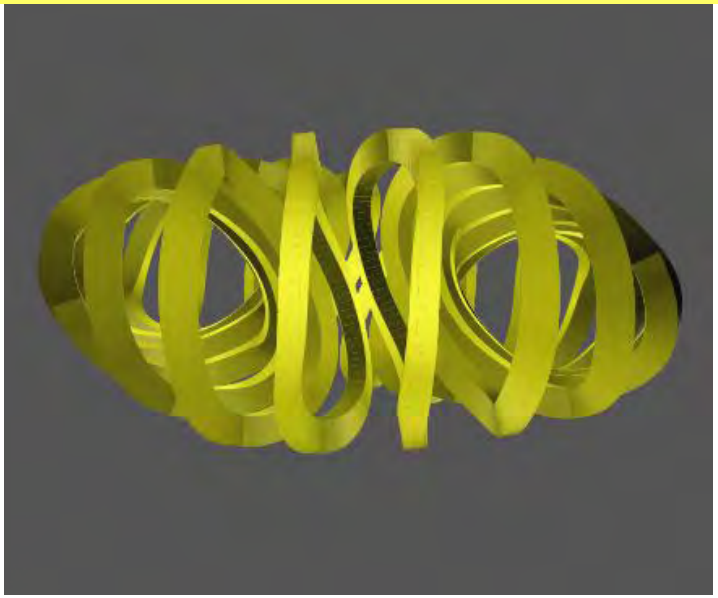
Heating power (ECRH, 28 GHz cw): 200 kW for starting (possibility of some LH and ICRH later)

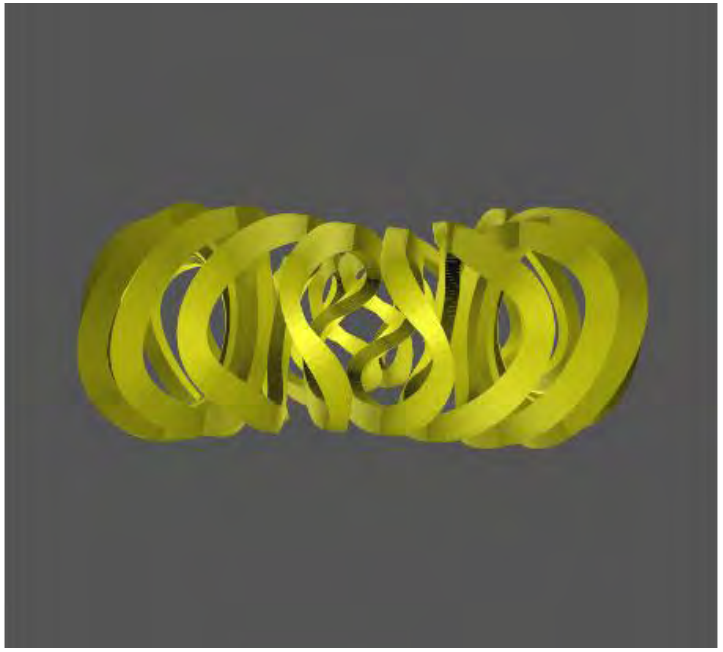
Electron density: ~ $5.10^{18}$ $m^{-3}$ (cut-off $10^{19}$ $m^{-3}$) (a few $10^{19}$ $m^{-3}$ if LH)

Central electron temperature: 1 keV (with a tail of the distribution at 1 MeV)

# The ESTELL Project







- Coil set (20 modular coils of 5 different kinds, 10 coils/period), Flexibility enabled by 5 independent power supplies, in addition to LH and ECCD.

- Small rotational transform (ι~0.2) allowing: easy machining and coils winding, great accessibility for diagnostics (up to 80 cm between adjacent coils, mini 17 cm)

# Scientific Motivations 1/2

CONFINEMENT: Demonstrate potential benefits of quasisymmetry in general, and specific properties of quasi axisymmetry (QA), for future fusion reactors.

- transport of suprathermal electrons according to the degree of QA
- explore stellarator/tokamak hybrid configuration, with finite but non negligible bootstrap current
- fill (partly) the hole left by the cancellations of NCSX (US) and CHS-qa (JP)
- compare relative properties of QA and Quasihelical symmetries (HSX)

PLASMA PHYSICS investigations:

- Edge plasma turbulence and transport in QA geometry
- RF heating and related RF sheath physics, including test-bed for ICRF alternative geometry antennas
- Plasma Wall Interaction (PWI)
- Diagnostics
- more generally, fill the gap between the physics in laboratory experiments and fusion devices

# Scientific Motivations 2/2

EDUCATION: exceptional tool for educating young scientists and engineers (in Nancy: National Master http://www.sciences-fusion.fr/ , Erasmus Mundus Master FUSION-EP www.em-master-fusion.org/ and Doctoral College FUSION-DC www.em-fusion-dc.org/ and FUSENET Association http://www.fusenet.eu/ )

$\Rightarrow$ Opportunity to have a machine at top level with international visibility.

Astrophysics studies

Study of 3D magnetic reconnection: the ESTELL versatile coil power supply system makes it possible to shape magnetic islands. Then their dynamics and the reconnection process can be studied.

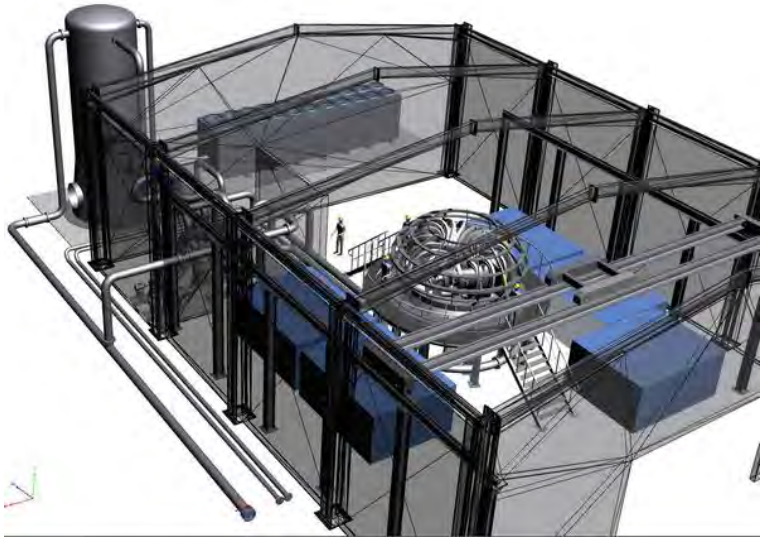
- ESTELL plasma parameters are relevant for astrophysics issues.

- ESTELL magnetic field geometry gives the opportunity to study 3D reconnection with bent magnetic field lines.

$\Rightarrow$ ESTELL is also supported by several astrophysics institutes.

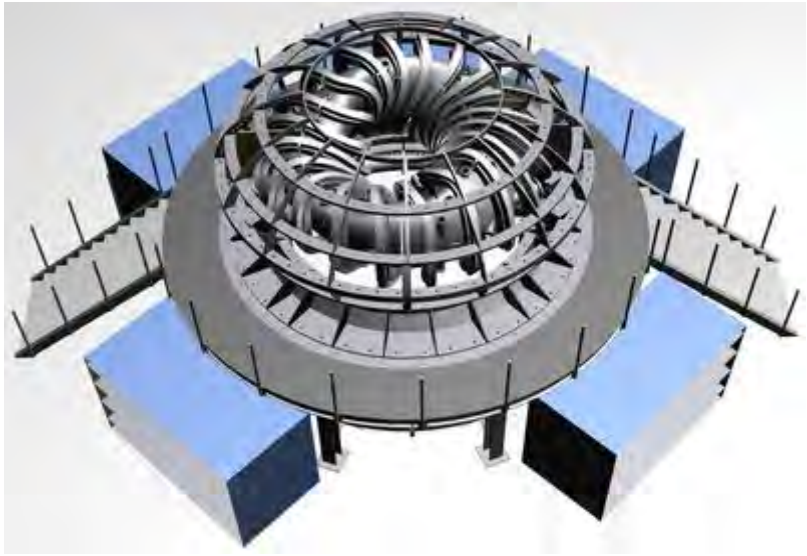
# The ESTELL Project: Design issues

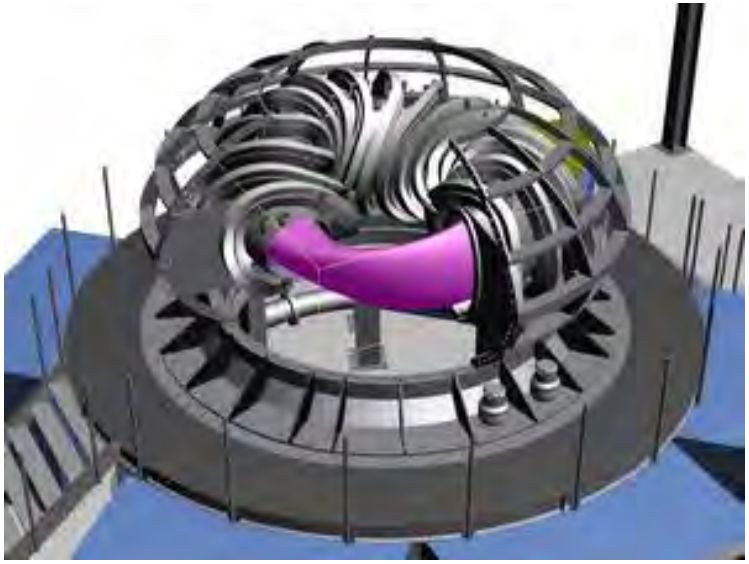
-A dedicated building on a new site in Nancy



Sketch of ESTELL experimental Hall

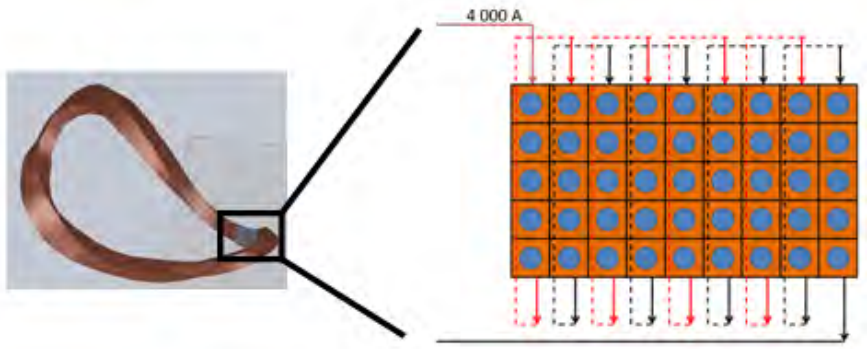
- conceptual drawings of the ESTELL assembly





# Main elements of the assembly

- 20 modular copper coils: similar as for W-7AS (~ 1.25 M€)




- Vacuum vessel with main coil supporting structure: (~ 2 M€)
  - The assembly is divided into quarters, connected with a flange, and can be easily disassembled.

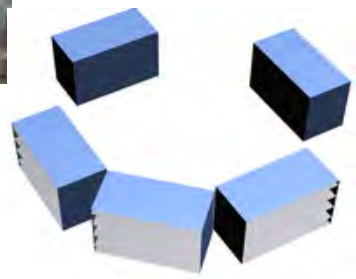
- Heating systems: (~ 3 M€)

  ECR heating: 2 long pulse (20 s) gyrotrons

  100 or 200 kW each, frequency 28 GHz

- Power supplies: total power ~ 10 MW (~ 3 M€)

- Power converters from 20kV to 380 V
- Five 1.4 MVA bridge rectifiers (4 kA, 87 V for each coil)
- Two separate 200 kW bridge rectifiers for operating the gyrotrons

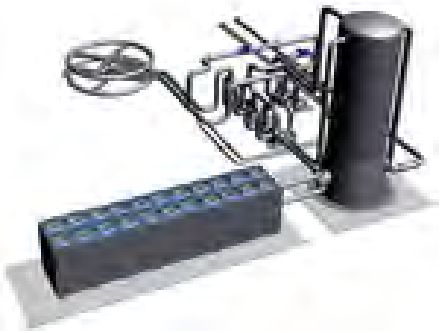


# Main elements of the assembly

- Cooling system: (~ 1 M€)

  - two cooling groups of 1.25 MW each, 50 $m^3$ water tank → will allow repetition of 40 sec discharges every 15 minutes.

- Supporting structure (~ 0.1 M€)



- Supervision and command control (~ 0.9 M€)

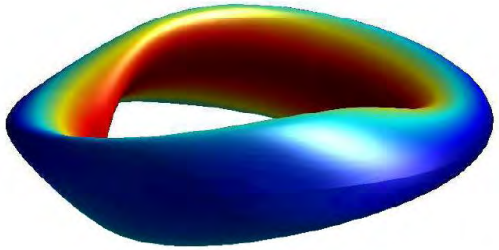
- Main diagnostics and accessories: (~ 2 M€)

  - 40 Mirnov coils,
  - Millimetric-wave interferometer (similar TCV),
  - Reflectometer (as in Tore-Supra, X mode, 13.5 – 20 GHz and 20.25 – 30 GHz)
  - ECA diagnostics for $T_e$ and fast electrons,
  - XUV camera, Fast visible camera & intensifier, IR fast camera, Probe systems,
  - Precision manipulator with airlock (PWI studies),
  - Data acquisition, Data storage

# Soutiens internationaux et Collaborations

EUROPE

•Calculation of ESTELL magnetic configuration at Max-Planck Institute Greifswald. Participation of IPP-Greifswald as full partner of the Equipex project. ESTELL envisaged as satellite experiment of W7-X stellarator.



•Support of CIEMAT (Spain),

• IFP (Italy) : 3D magnetic reconnexion… (discussions)

• Support of European partners involved in Fusion Education (Fusion-DC, Fusion-EP).

•Scientific golas : objectives 3 & 4 of the EURATOM Fusion roadmap.

JAPAN

Collaborations with the National Institute for Fusion Studies (Nagoya) and Kyushu University : scientific participation to the research program, design of diagnostics dedicated to ESTELL, students internship & mobility.

# Soutiens internationaux et Collaborations

USA

- Strong scientific and technical support of the Princeton University: magnetic reconstruction codes, possible participation in the operation costs (dedicated application to DOE) and in the device operation.
- Scientific collaboration with the University of WISCONSIN (joined scientific program with the HSX device).
- Support from UCLA (in particular regarding astrophysics studies)

- Students exchanges.

# Summary: ESTELL, a worldwide open facility

• ESTELL to be built (?) at Nancy University, in a dedicated building nearby the Institut Jean Lamour (IJL). IJL laboratory is composed of 438 people, (researchers, professors and assistant-professors: 155, PhD students: 107, Post-docs: 23, technicians and engineers: 95). ESTELL will be essentially managed by a team gathering 18 plasma physicists and engineers and will benefit from the workshop of IJL (main ESTELL components designed and built by private companies).

• Magnetic configuration designed at IPP Greifswald.

• Advanced contacts for international collaborations with IPP Greifswald (theory), PPPL-Princeton (theory, equilibrium reconstruction, technical support), UCLA, Wisconsin-Madison (HSX), NIFS & Kyushu University (diagnostics, theory). Other partners welcome!

• Education: Nancy University part of the Erasmus Mundus Master Programme Fusion-EP and FUSENET (European Fusion Education Network), and coordinating the new European Doctoral Federation in Fusion Science and Engineering (EDF-FS). Also leading core partner of the International Erasmus mundus Doctoral College FUSION-DC which has just been selected (July 2011).

# More infos…

http://estell.blog.uhp-nancy.fr/

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# *European initiatives in Fusion Education*

# Historical overview of the new initiatives in Fusion Science and Engineering Education

## At Master level

- **French national Master "en Sciences de la Fusion"**, started in 2006
  **http://www.sciences-fusion.fr/**
- **European Master Erasmus mundus "Nuclear Fusion Science and Engineering Physics" FUSION-EP** **http://www.em-master-fusion.org/** , started in 2006
  **Common Approach: Generic Master (Physics, Electrical Engineering, Material Science, ...) with Fusion accents through elective courses**

**Strong European coordination through the EURATOM programme**

⇒ **FUSion Education NETwork (FUSENET),** started in 2008

## Doctorate

- **Joint Doctorate in Fusion Science and Engineering and European Doctoral Network, Padova-Lisbon-München**
- **European Doctoral Federation in Fusion Science FUSSION-EDF,** started in 2010
- **Erasmus mundus "Doctoral College in Fusion Science and Engineering" FUSION-DC**
  accepted in 2011, starts September 2012 (enrollment of first PhD students)