Introduction to
Magnetic Thermonuclear Fusion and
Related Research Projects

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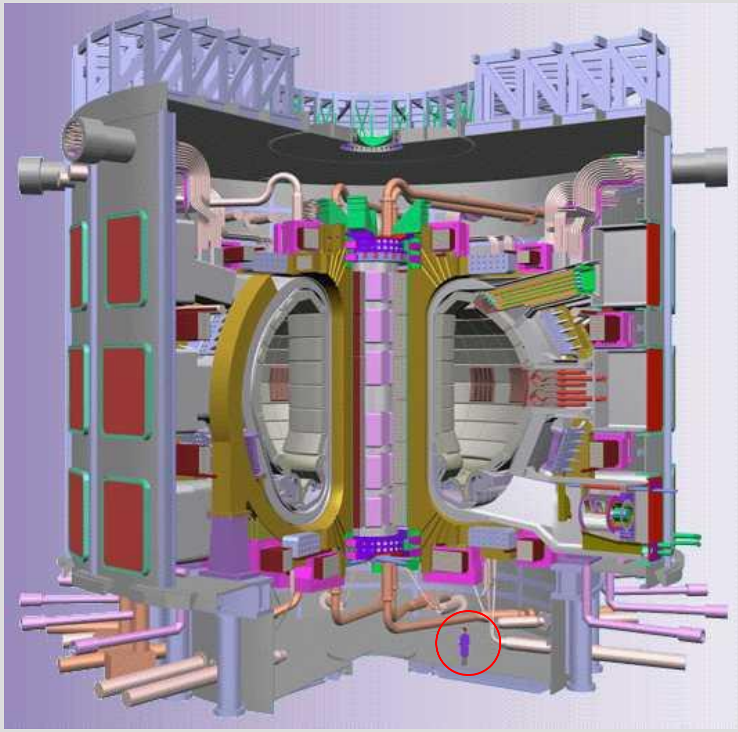
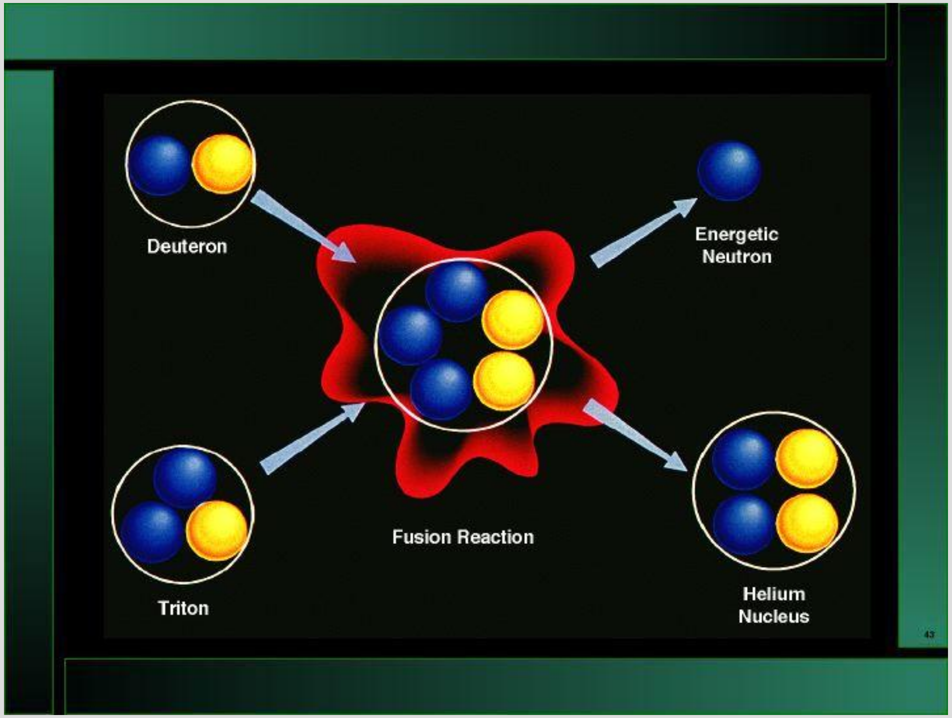
Outline

1. A Brief Introduction to Magnetic Fusion and to what is a plasma
2. Research on Turbulence
   1. Experimentally by collaboration with international teams working on tokamaks and other confined plasmas.
   2. Experimentally by building our own [LPLD)
   3. Theoretically by acquiring the know-how to perform numerical simulations.
3. Other projects studied at AUB: Disruptions, Plasma Facing Components

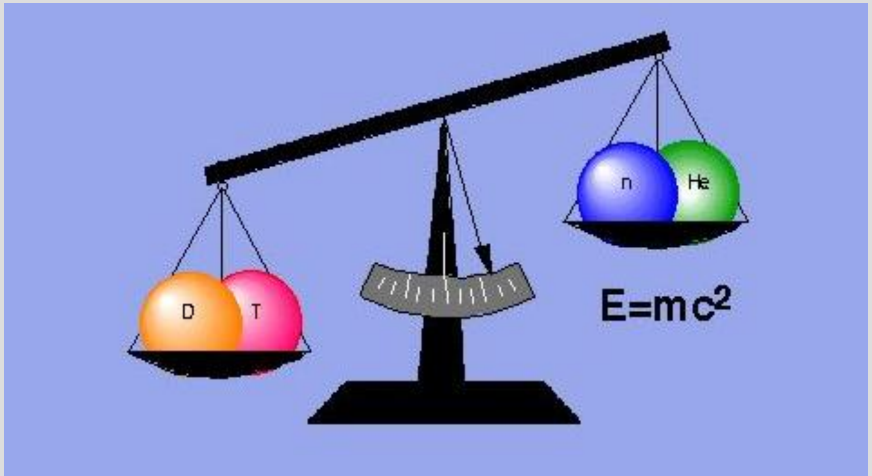


Fusion Occurs when Two Nuclei Unite to Form One



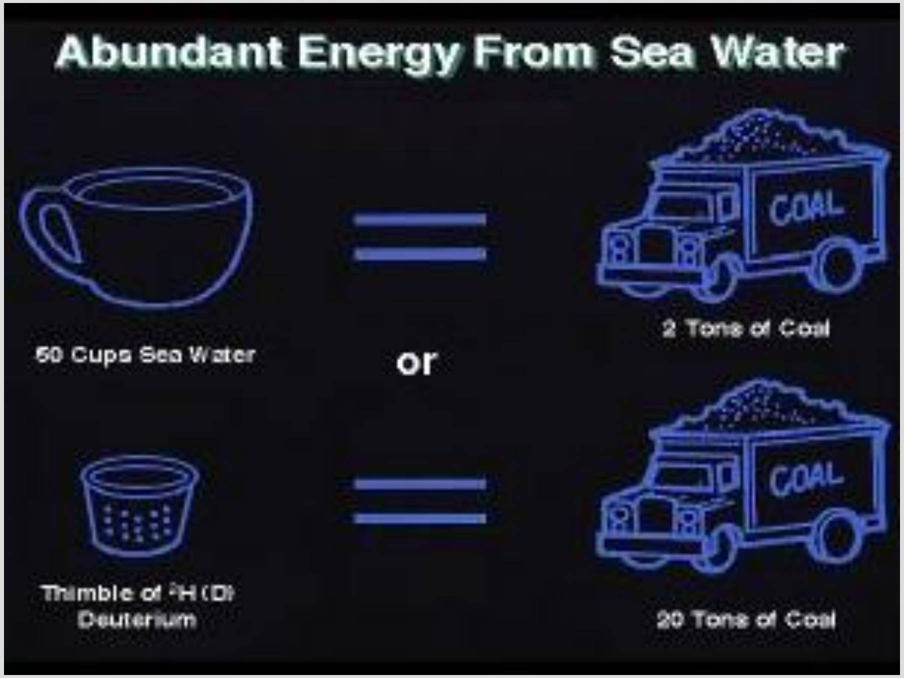
Reaction		Ignition Temperature		Output Energy
Fuel	Product	(millions of °C)	(keV)	(keV)
D + T	^{4}He + n	45	4	17,600

The Energy Results from the Difference in Mass between the Initial and the Final Nuclei

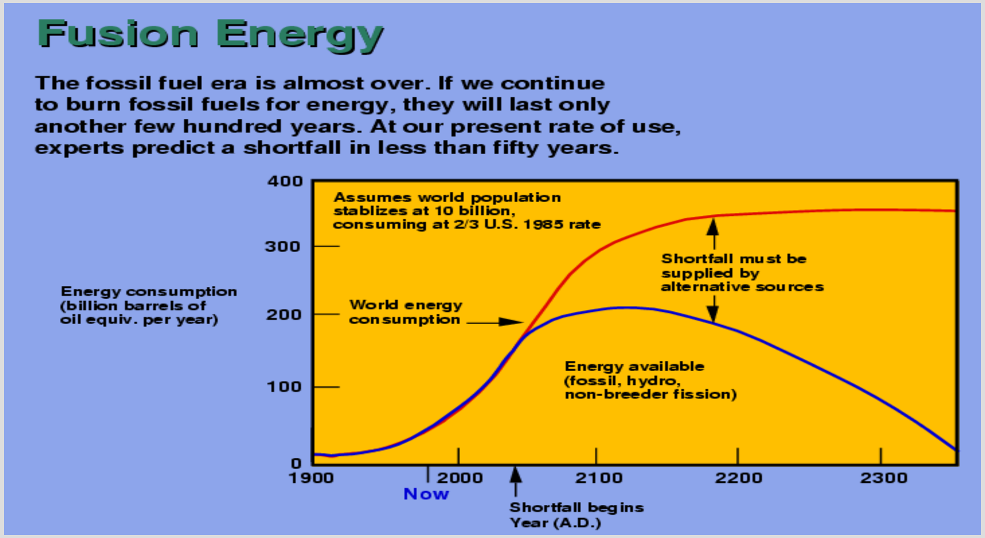


- The fraction of mass "lost" is just 38 parts out of 10,000

Advantages of Fusion on other ways to Produce Energy

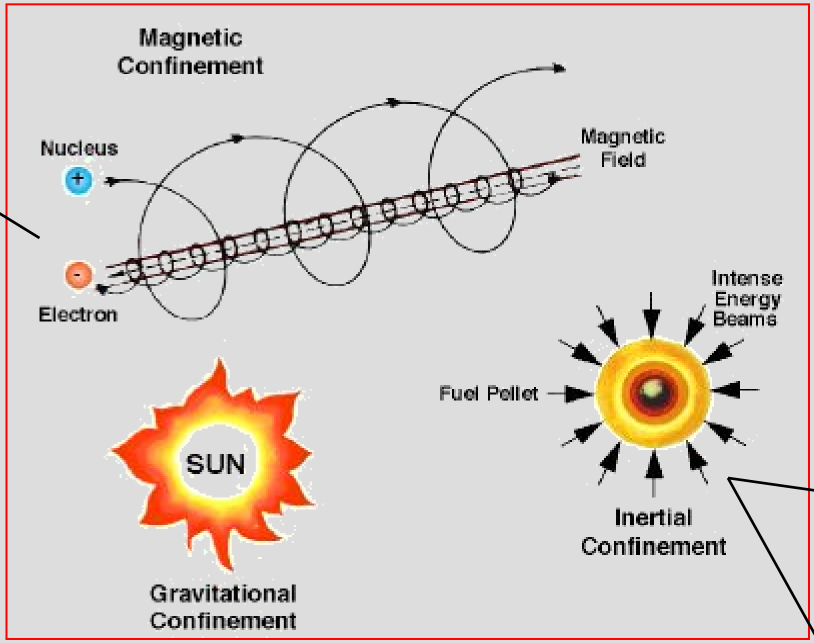


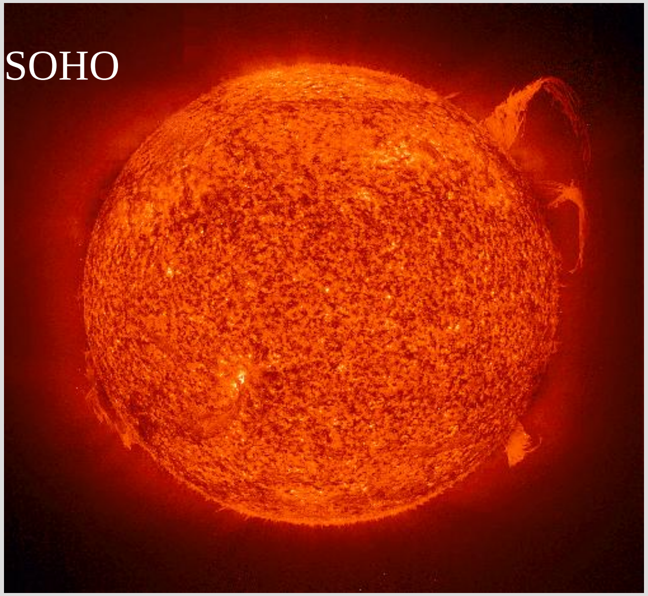
- Abundant Fuel Supply on Earth and Beyond
- No Risk of a Nuclear Accident
- No Air Pollution or CO2 generation
- No High-level Nuclear Waste
- No Generation of Weapons Material

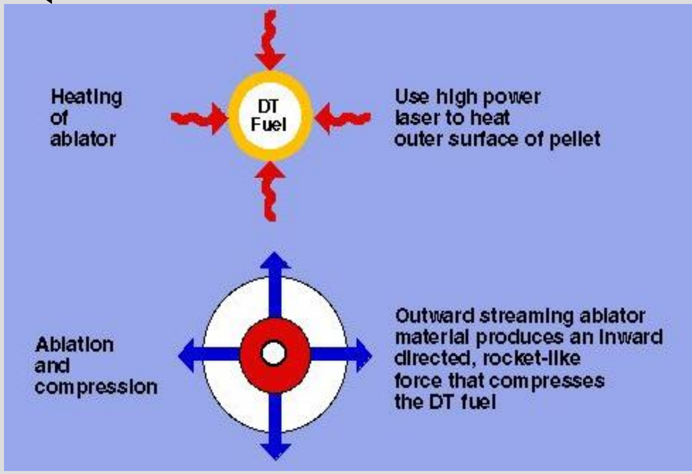


Three Ways to Achieve Fusion

This presentation

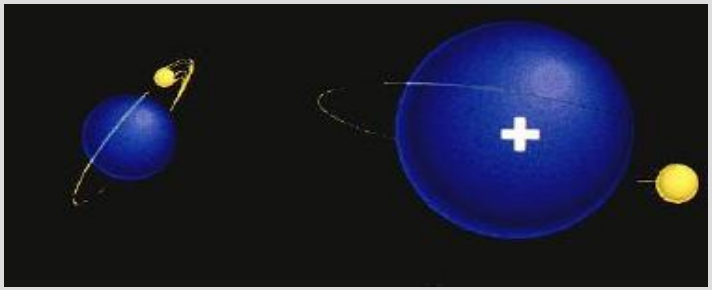




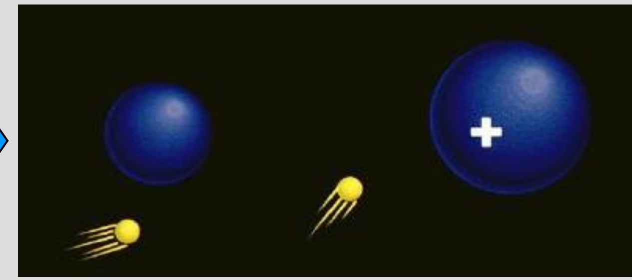


A Plasma is a fully ionized gas globally neutral

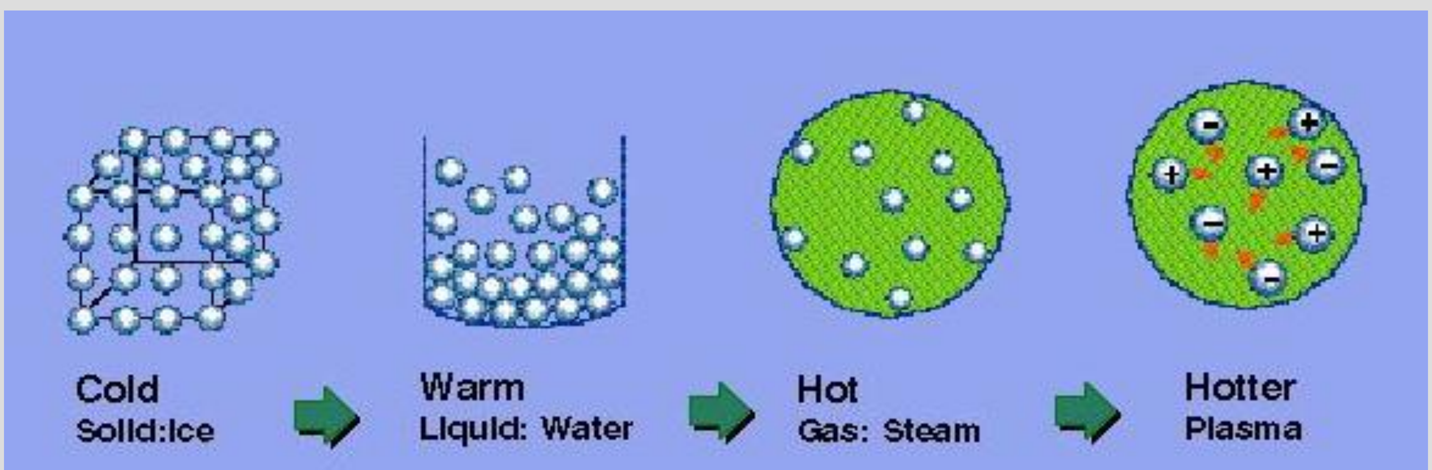
Interaction between nuclei => we must get rid of the electrons ⇔ ionization



+ Energy (like heat) ⇒

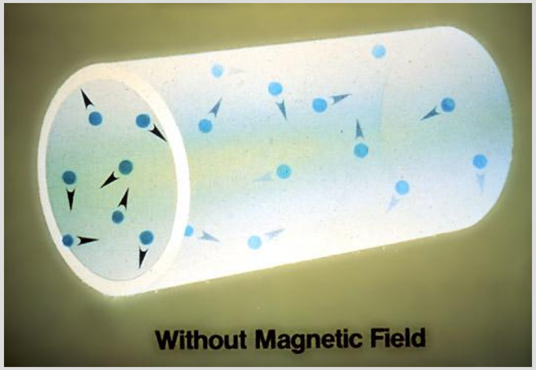


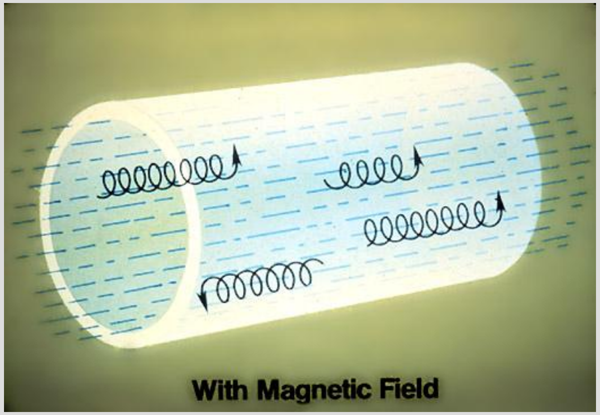
- Plasmas are the most common form of matter, comprising more than 99% of the visible universe.
- Plasmas carry electrical currents and generate magnetic fields, due to their ions and electrons.



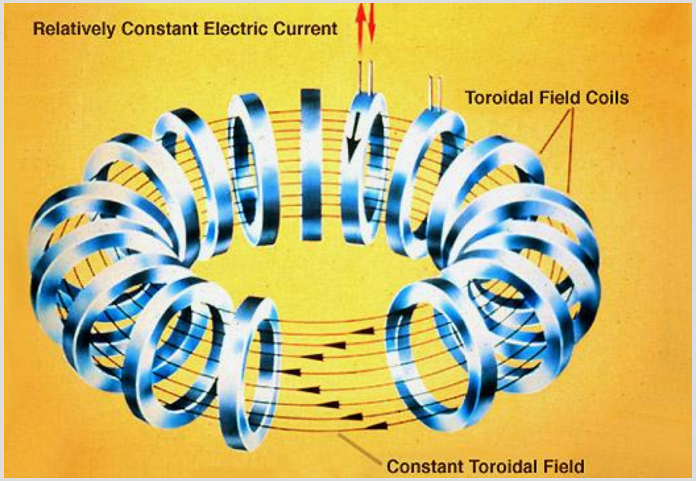
The Route Towards a Confined Plasma or How to Make Particle Go Round-and-Round

Plasma without a magnetic field:
Particles tend to get away from each other due to their high temperature



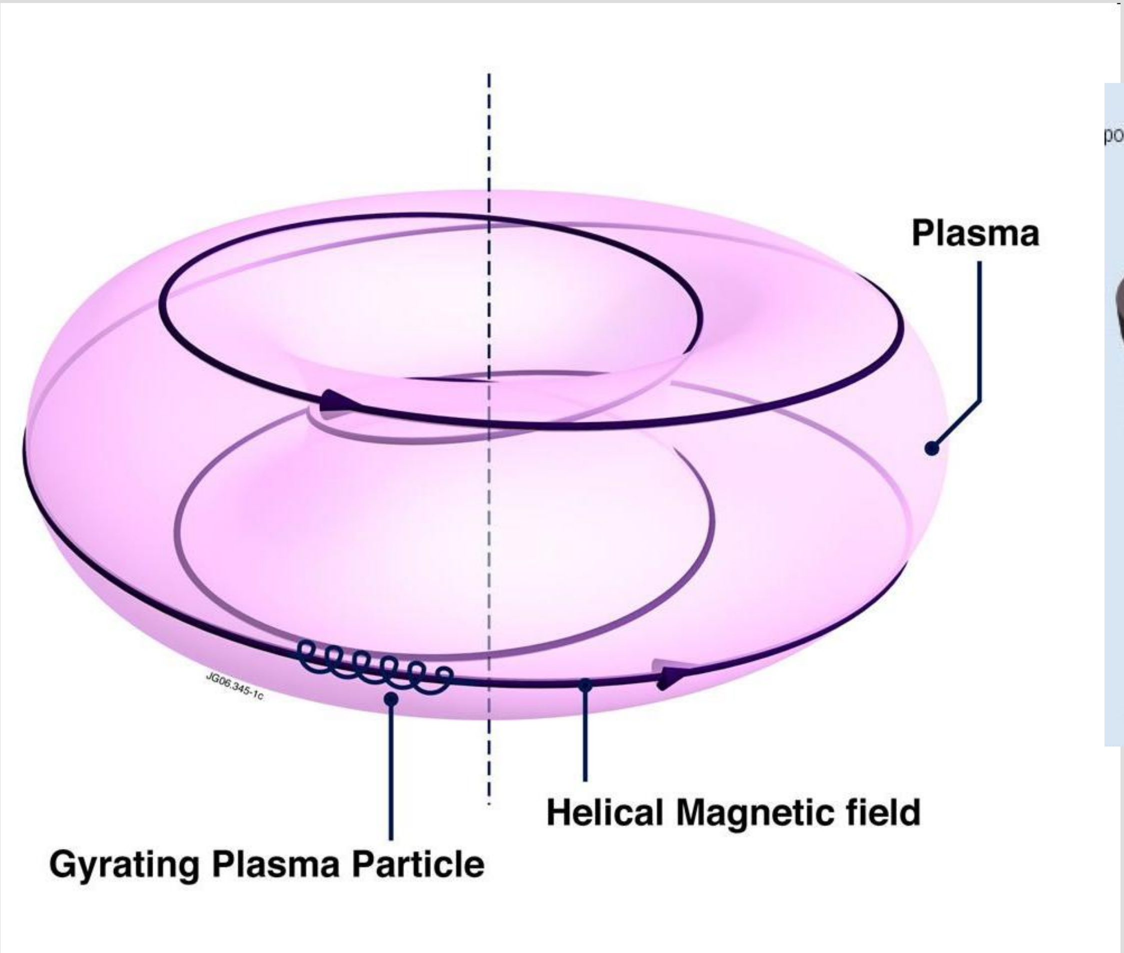


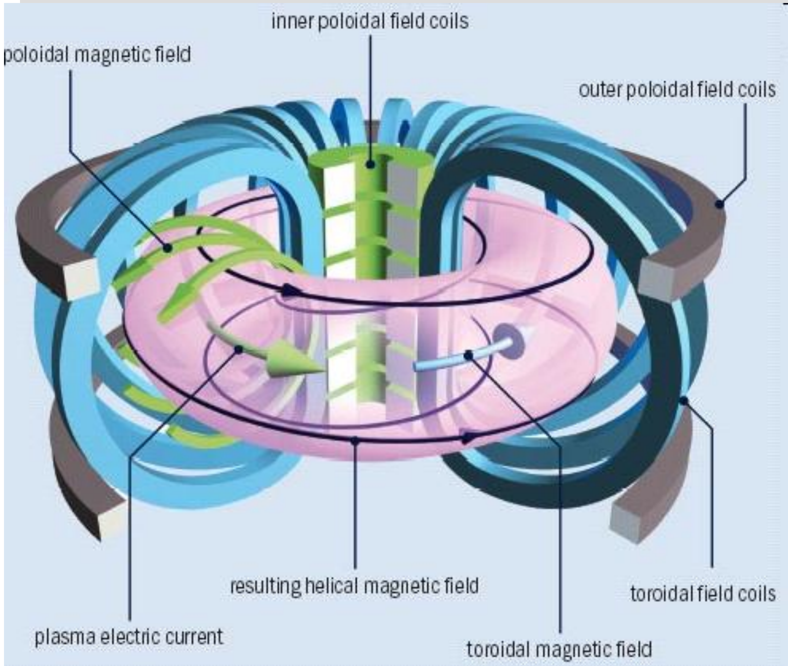
Adding a magnetic field with parallel set of coils: Particles trajectories are parallel to B



Closing the loop by the making the coils form a torus: **Particles go round and round**
⬄ Particles are Confined

Particle Trajectories Inside a Tokamak





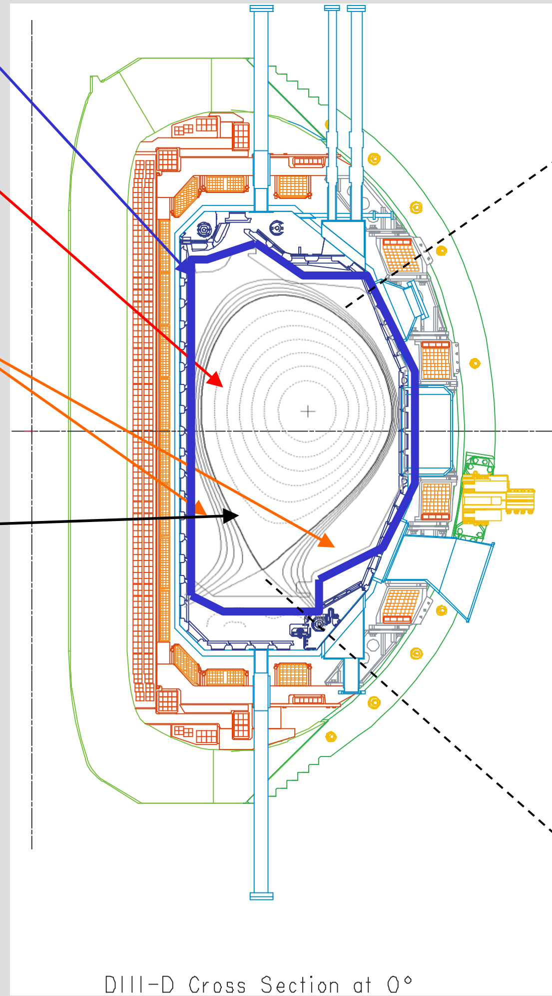
Confined vs. unconfined regions

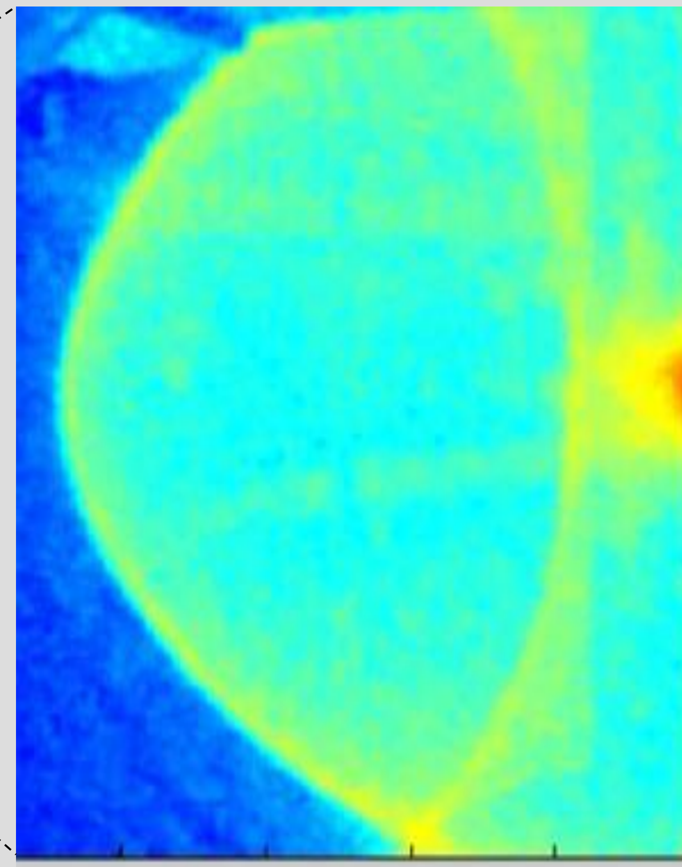
The first wall

Closed field line

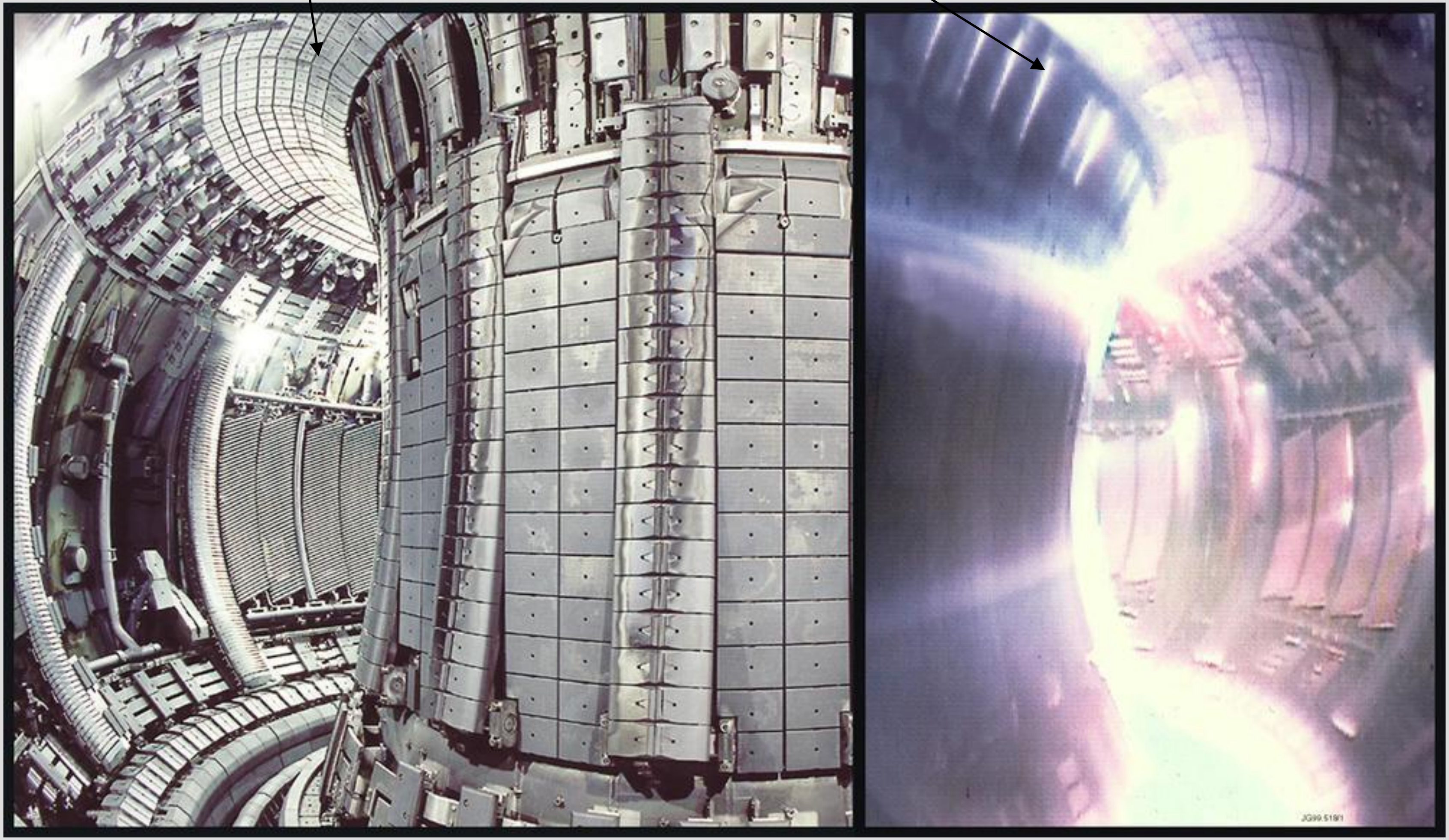
Open field line
“scrape-off layer”
“SOL”

separatrix

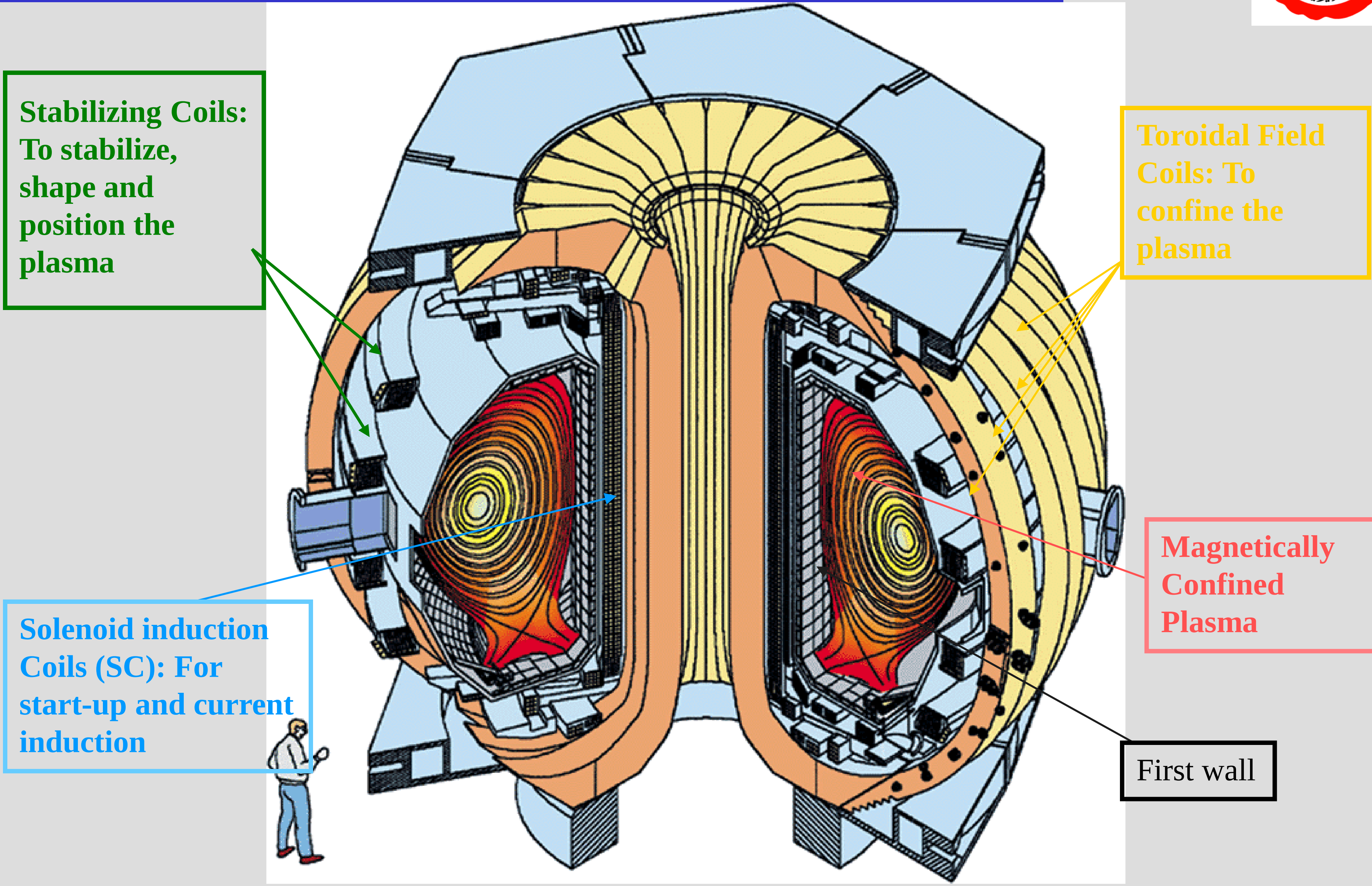




The JET (Joint European Torus) tokamak from Inside without plasma and with plasma

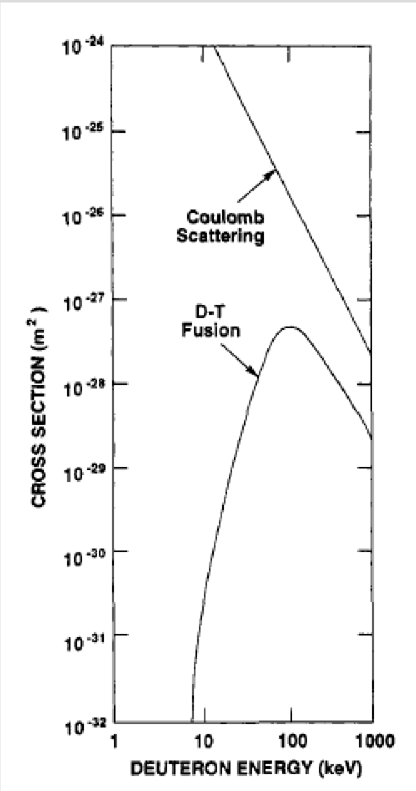


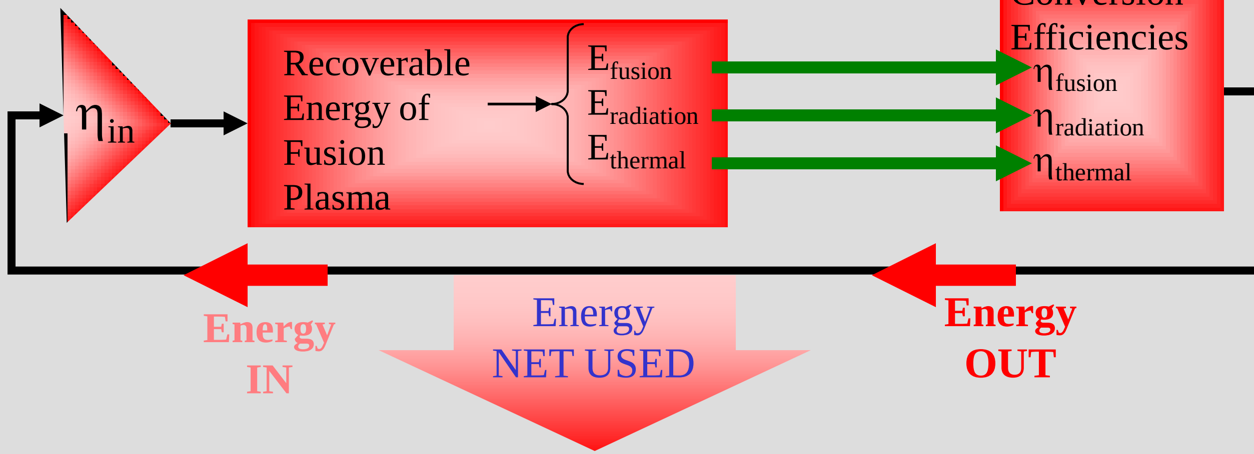
The Main Control "Knobs" in a tokamak are the Magnetic Fields

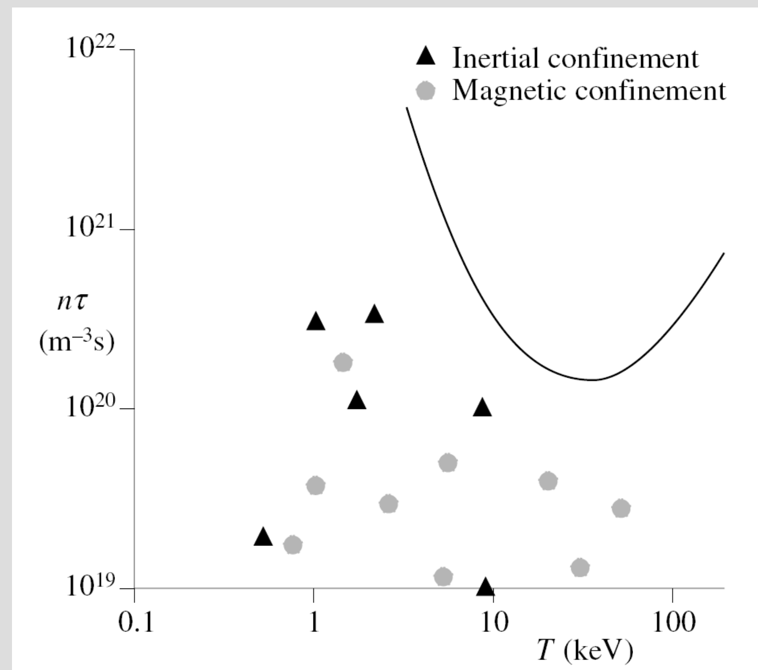


Movie on the MAST tokamak showing the plasma of a discharge
Note that what is seen is the "cold" plasma

Confinement and Energy Production





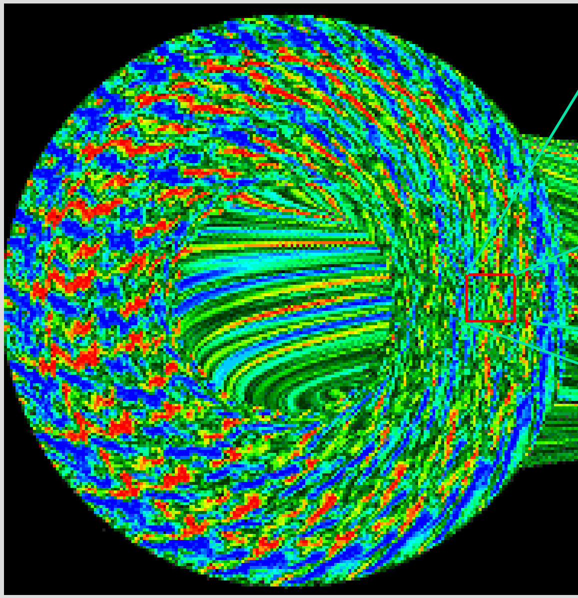


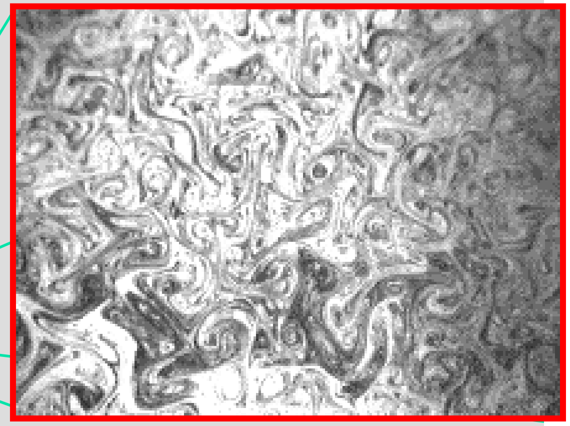
We call **Ignited Plasma** the state where no external Power needed to be delivered

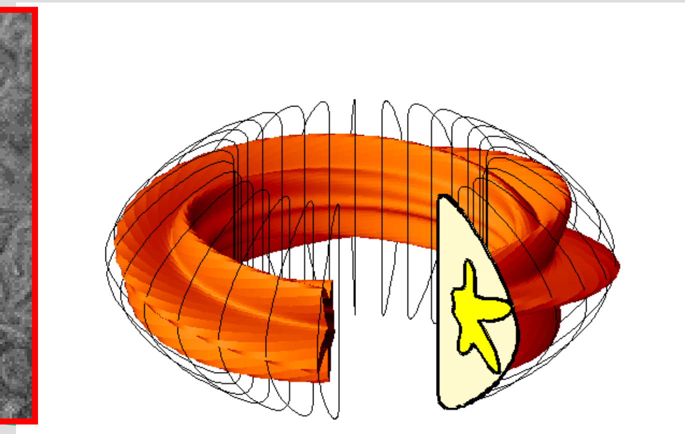
$n \sim 10^{20}$ m^{-3}, T=30 keV, $\tau_E \sim 2.7$ seconds

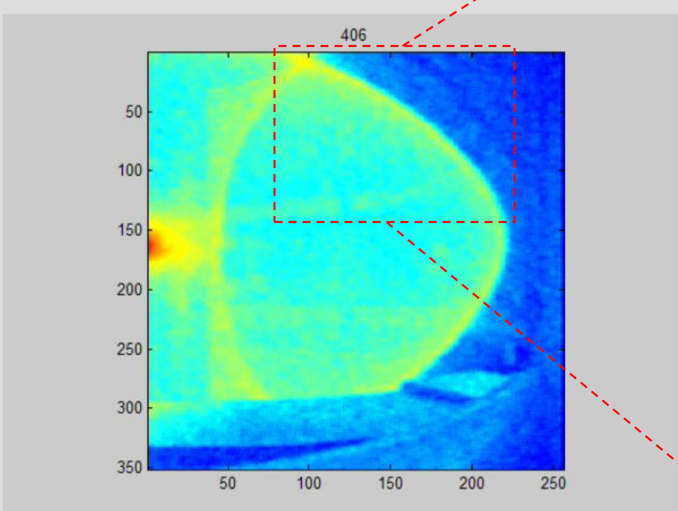
Turbulent transport of particles and energy from the confined region to the walls

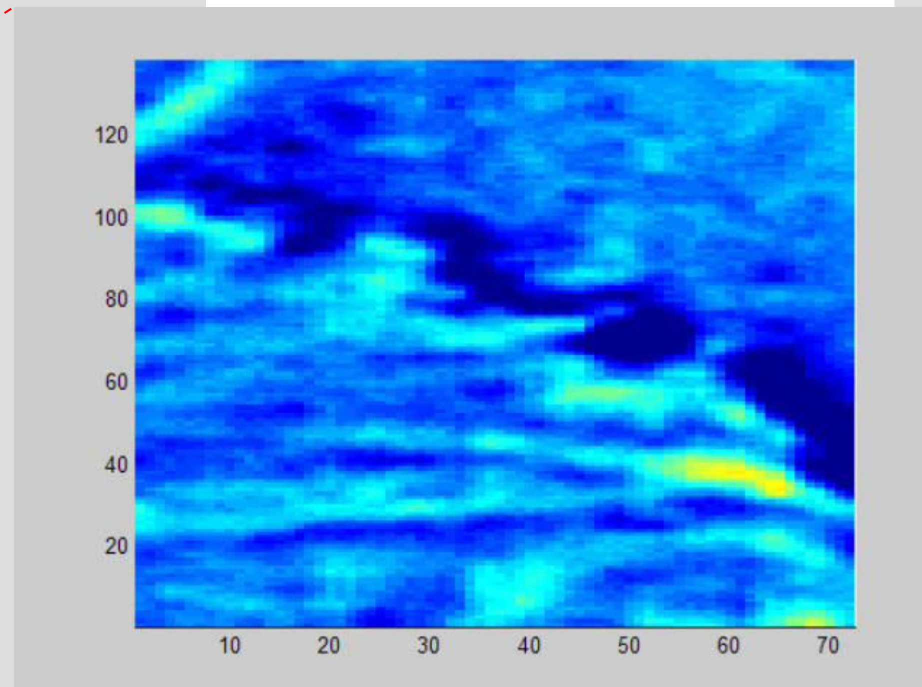
Turbulence decreases the confinement time of magnetic confinement devices





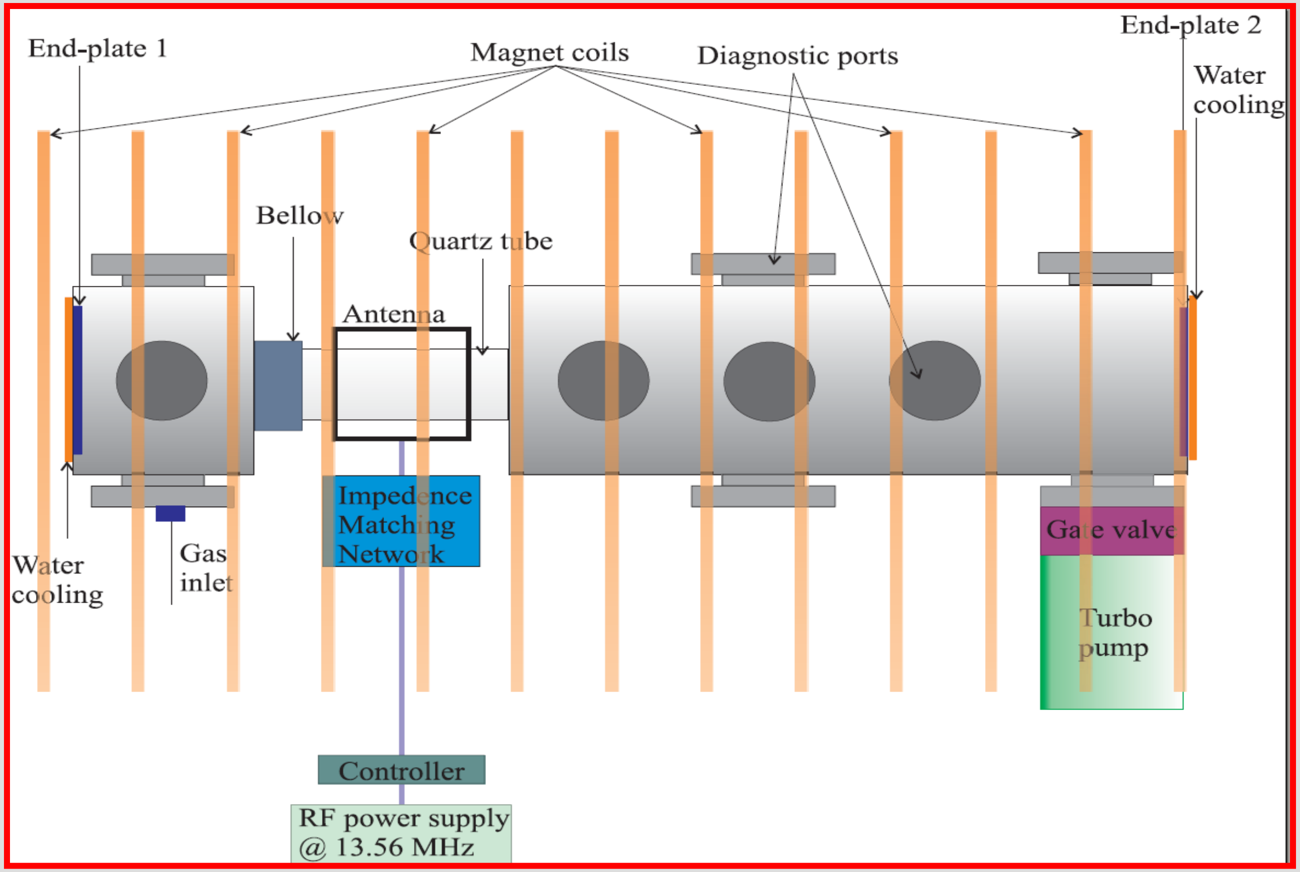






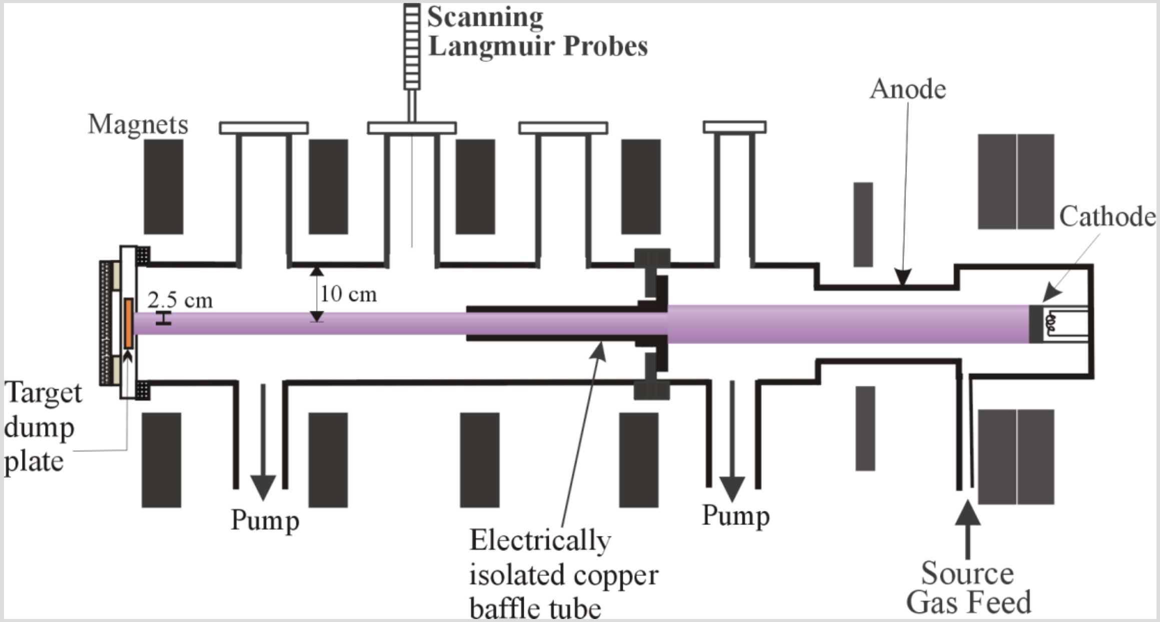
Lebanese Linear Plasma Device [LLPD)

- We are in the process of building a plasma simulator at the Physics Department of AUB. It consists of:
  - a vacuum chamber
  - an RF power source (2 MW)
  - an axial magnetic field about 1000 G.
  - Diagnostics



Convective Transport in Magnetic Fusion Devices: What can we learn from linear devices?

Turbulence is studied in linear devices such as PISCES described below and CSDX (later) where the magnetic geometry is simpler and the plasma is better diagnosed



Plasma Parameters:

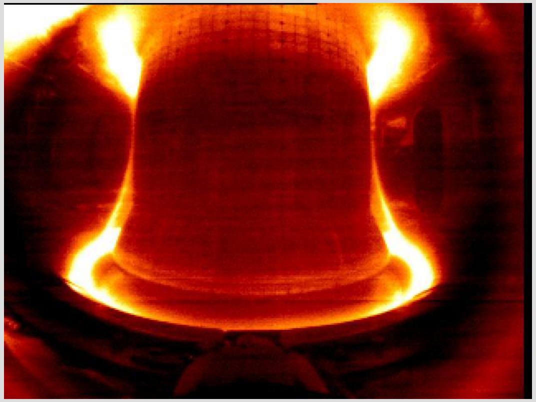
- $n_e \sim 5 \times 10^{17}\ m^{-3}$
- $T_e \sim 15$ eV
- B = 0.12-0.2 T
- Gaz type: Hydrogen, Argon …
- Plasma radius = 2.5 cm
- Vessel length = 1 m
- Vessel radius = 10 cm

Comparing the Tore Supra (France), Alcator C-MOD (USA) , MAST (UK) tokamaks and PISCES (USA)

Tore Supra tokamak

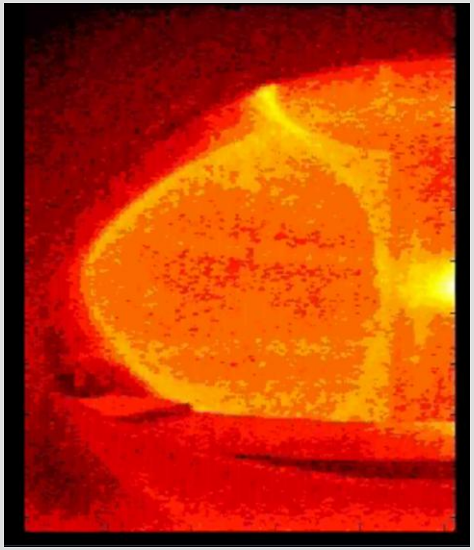
- a = 76 cm, R = 2.32 m
- B_T = 3.5 T, Ip =1 MA
- limiter machine

Alcator C-MOD tokamak



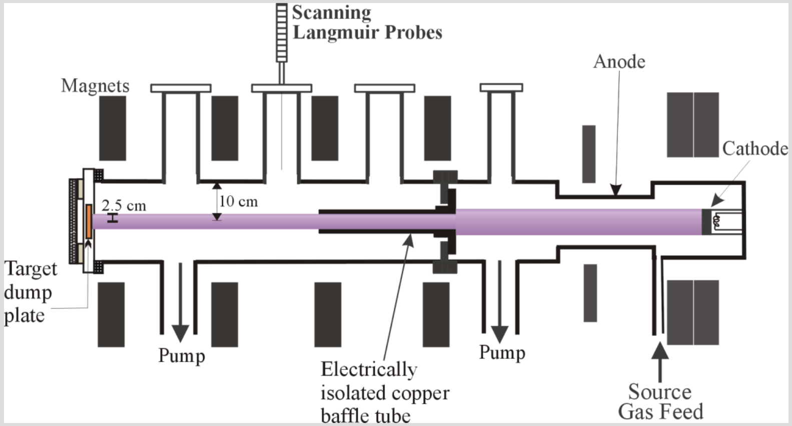
- a = 21 cm, R = 70 cm
- B_T = 5.3 T I_p ~ 0.8 MA
- divertor machine

MAST Spherical tokamak



- a = 52 cm, R = 73 cm
- B_T = 0.6 T, I_p =700 kA
- First wall far from the LCFS

PISCES

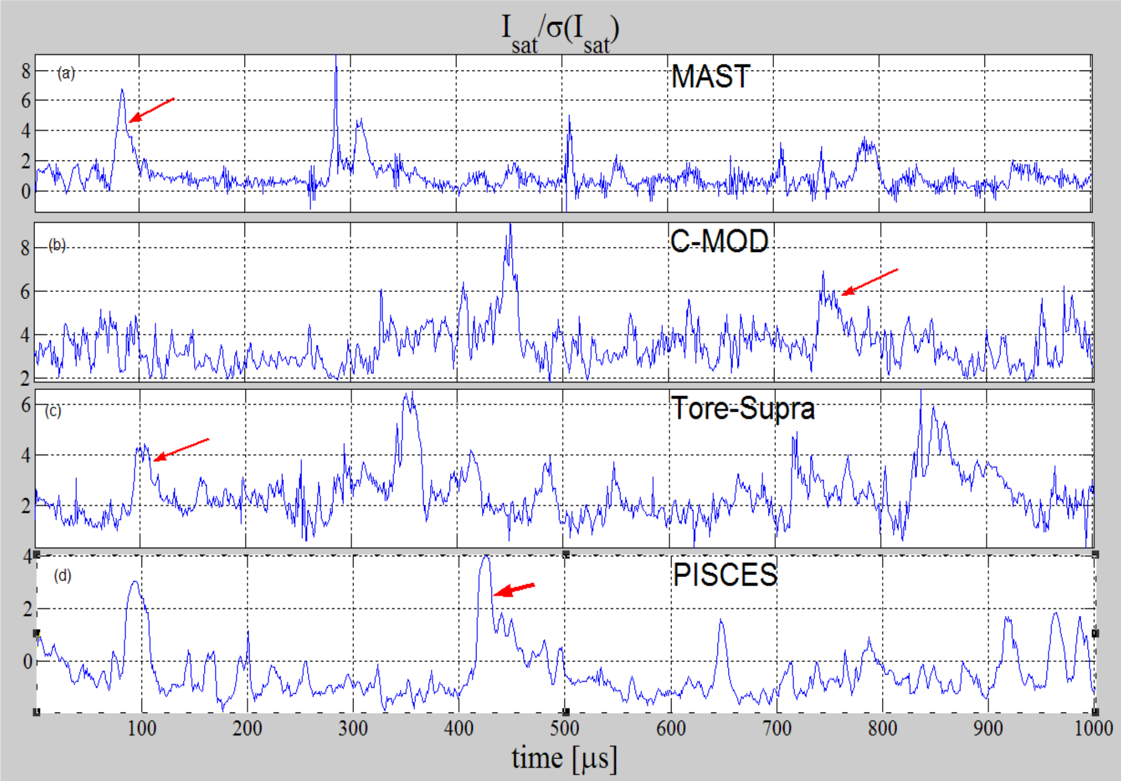


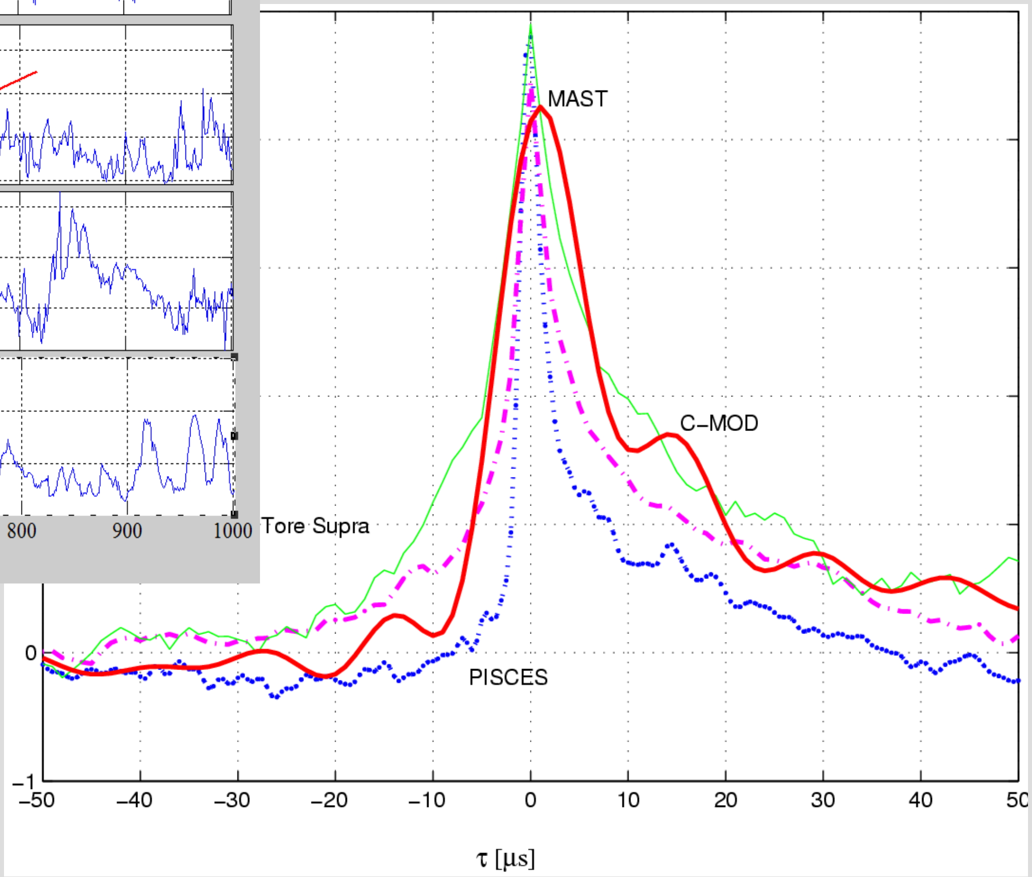
$n_e \sim 10^{17}$ m^{-3}, $T_e \sim 10$ eV,
B = 0.12-0.24 T

- Plasma radius = 2.5 cm
- Vessel radius = 10 cm

Similarity of the avaloid temporal signature

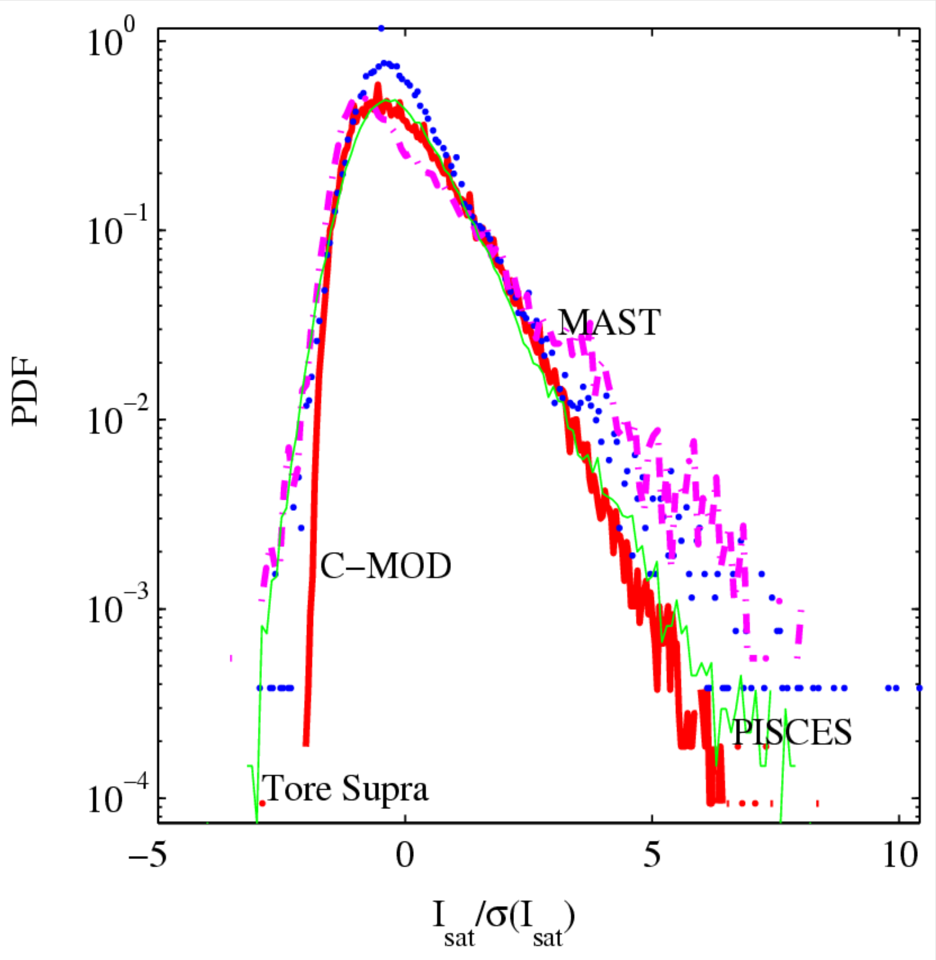
- Non-conservation of mass
- Asymmetric shape





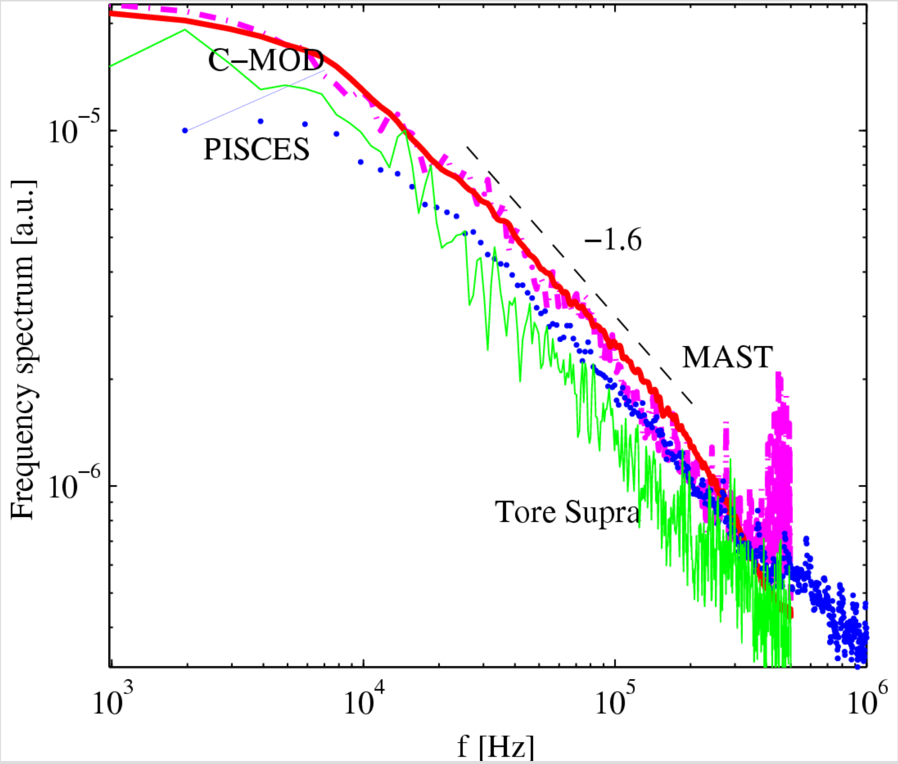
Similarity of the PDF of I_{sat} fluctuations

- Gaussian for negative fluctuations
- Strongly Skewed for positive fluctuations



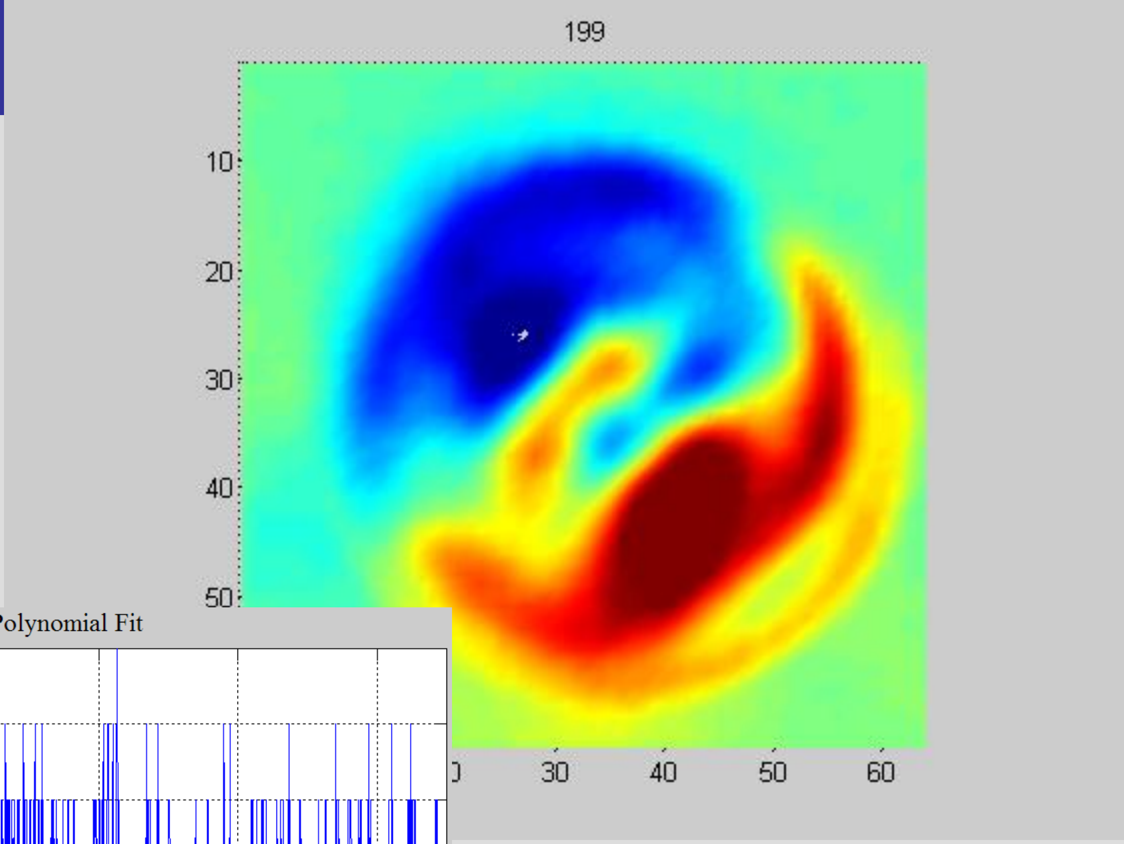
Similarity of the power spectra of I_{sat}

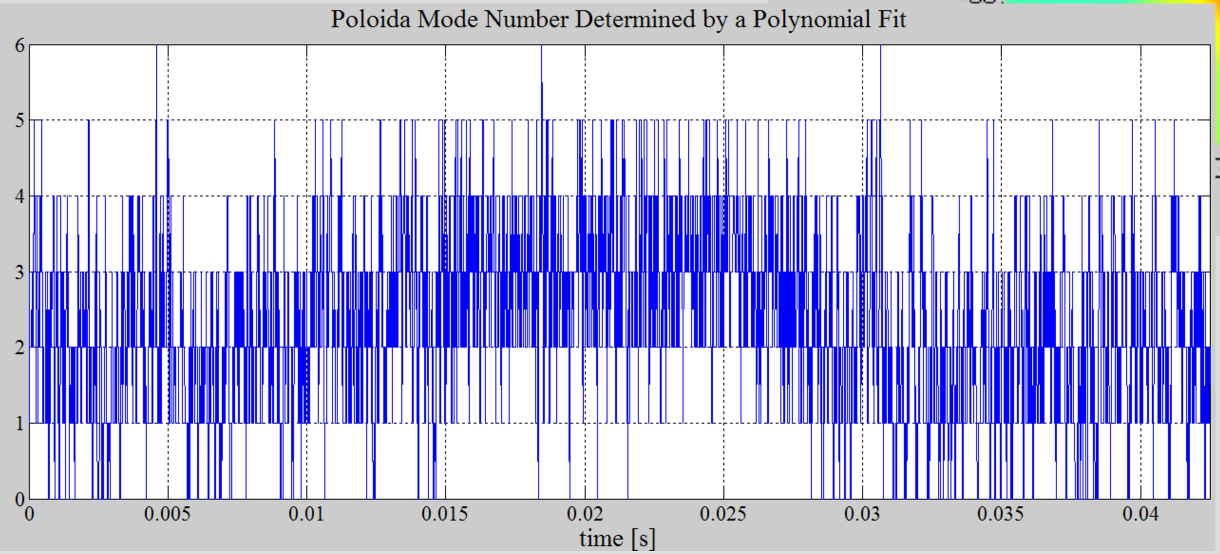
- One scaling region
- approximately the same scaling exponent -1.6
- Large scales



Inside the main plasma column

- The system transits from low to high mode number fluctuations in time and can remain in one of the modes for relatively long time.
- One can no longer speak of "stationary turbulence"…

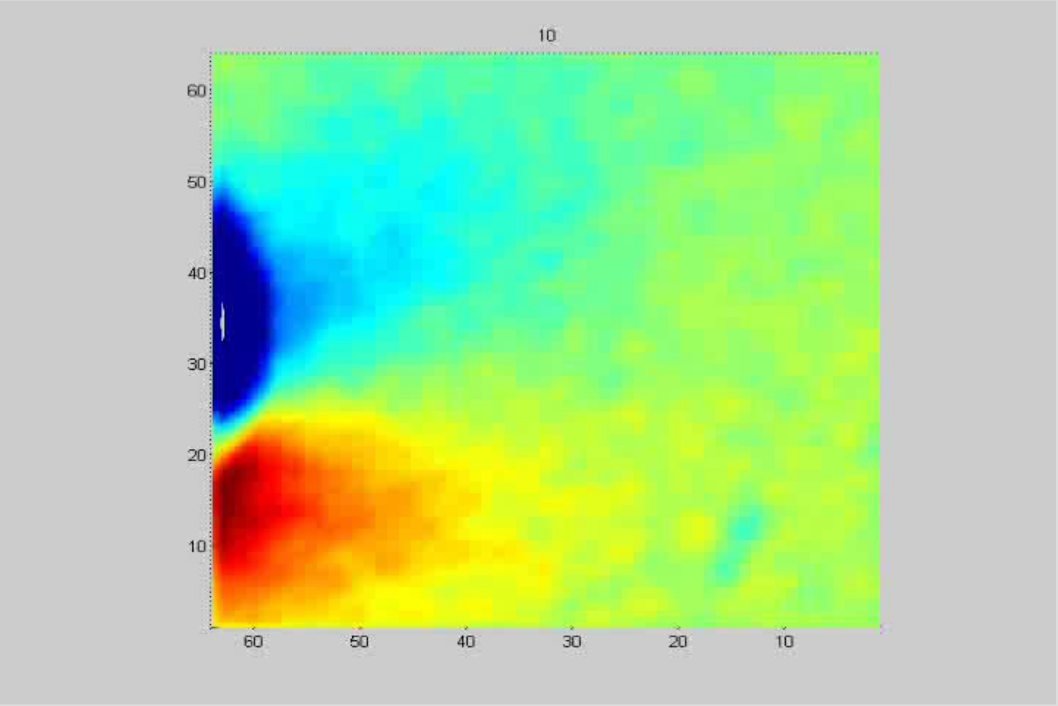


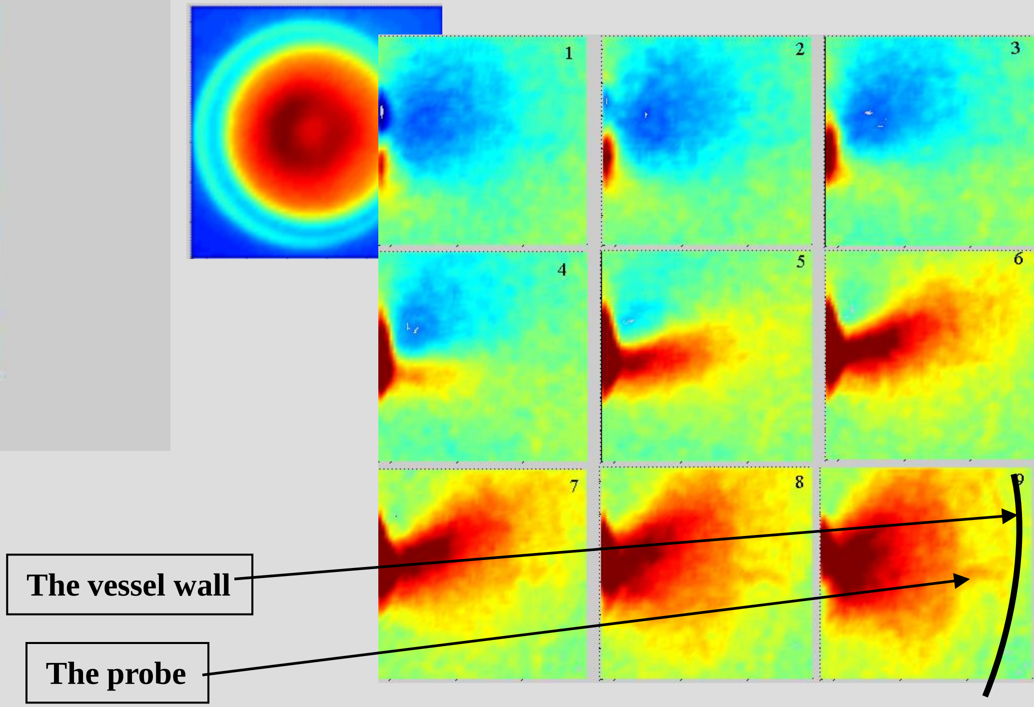


Camera settings:
Integration time 1 μs
Time between frames 15 μs
32x32 pixels

Shifting the viewed area to outside the main plasma
Fast Imaging allows the observation of the growth of avaloids, their scale lengths and velocities

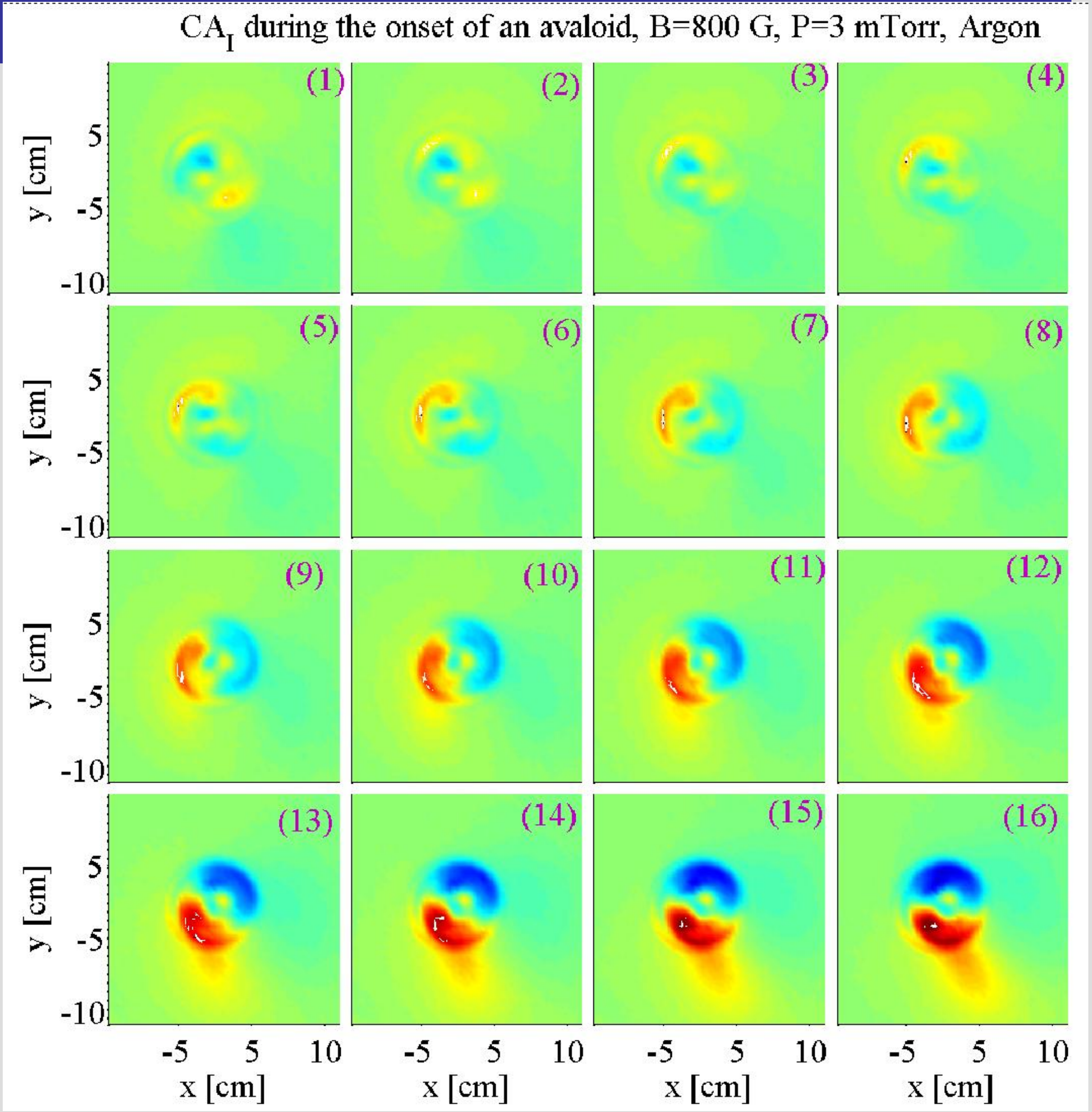
No detachment of the structure, hence, it is not a "blob" but rather has a finger-like shape



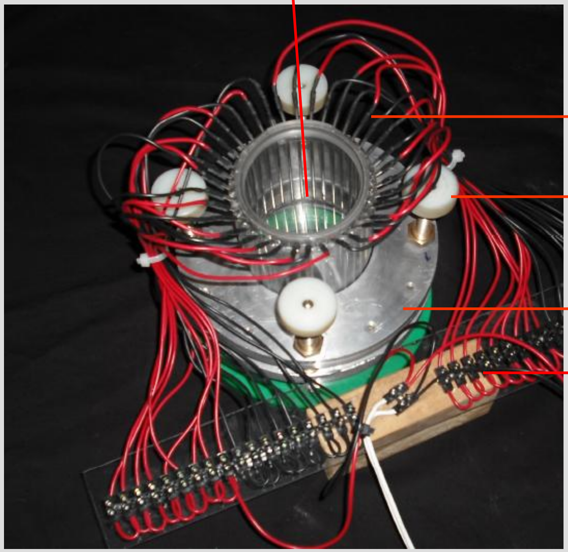


Camera setting:
Integration time 1 μs
Time between frames 15 μs
32x32 pixels

The conditionally averaged movie reveals that the onset of avaloids is associated with the non-linear evolution of the poloidal number m=1 instability.



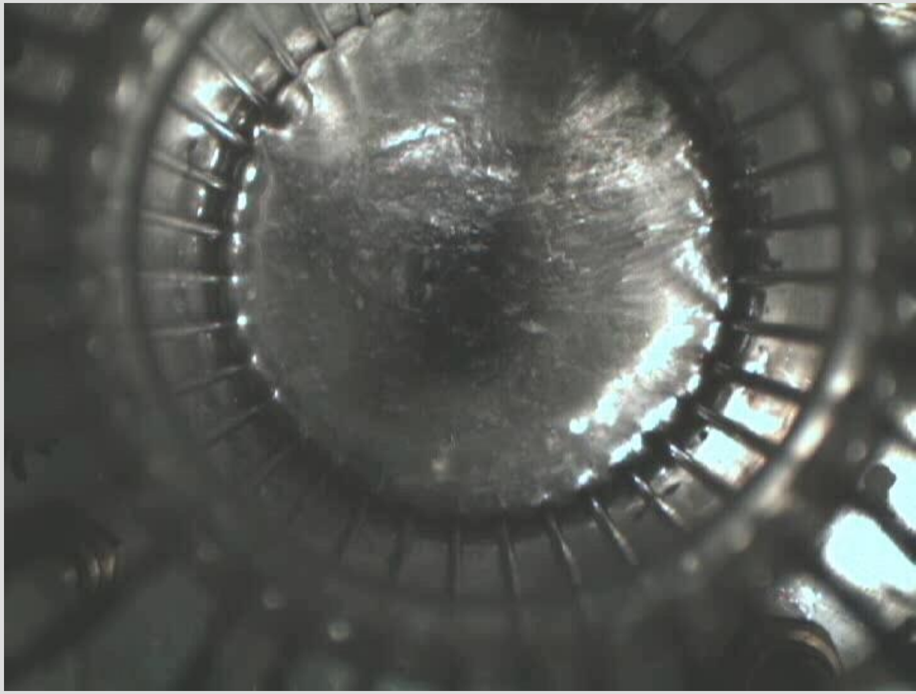
Quasi 2D turbulence, the liquid Gallium Experiment (L. Zaidouny)



The experimental setup:

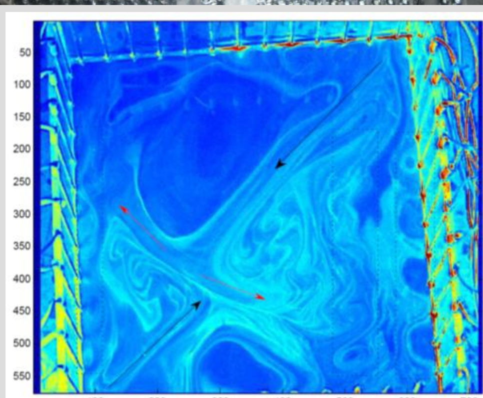
- A set of biased electrodes with variable number
- A strong axial magnetic field
- Liquid gallium with different height is poured in

Movie showing motion of gallium in the bulk



Quasi-2D turbulence, using Electrolytes (L. Moubarak)

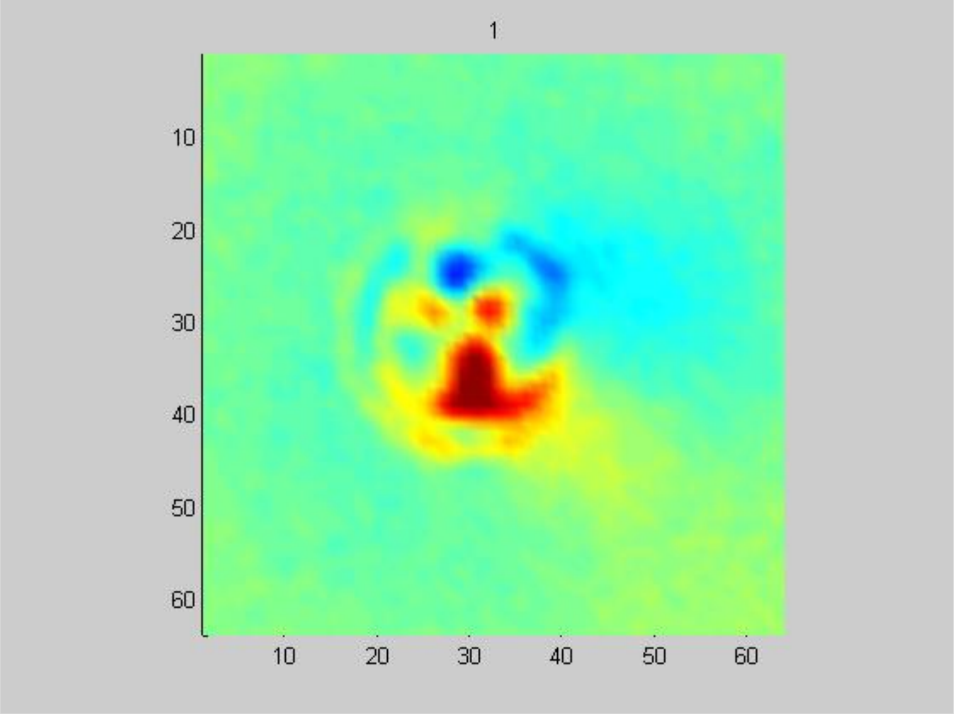
This setup uses the same basic idea as the liquid gallium one but uses a solution of KOH



Vortices are reported in the solution as a consequence of electromagnetic forcing
This leads to rather complex dynamics at low Reynolds numbers

Numerical Simulation of turbulence (F. Hariri)

- The goal is to develop a code simulating plasma turbulence in two dimensions.
- Our first application is to simulate the non-stationary behavior of turbulence that is observed in linear plasma devices.
- We shall use the Hasegawa-Mima and the Hasegawa-Wakatani models for turbulence
- Apply numerical schemes that do not generate artificially vorticity and energy as they both have to be conserved.



⇒ Ion continuity equation

$$\frac{\partial n}{\partial t} + \nabla\cdot(n\mathbf{u}) = 0$$

⇒ Ion momentum balance equation

$$m_i n\left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right] = -\nabla p_i + en(\mathbf{E}+\mathbf{u}\times\mathbf{B}) + \mathbf{F} - \nabla\Pi$$

$$\frac{\partial}{\partial t}(\nabla^2\phi-\phi)-[(\nabla\phi\times\hat{z})\cdot\nabla]\left[\nabla^2\phi-ln\left(\frac{n_0}{\omega_{ci}}\right)\right]=0$$

Hasegawa-Mima equation

$$\left(\frac{\partial}{\partial t}-\nabla\phi\times\hat{z}\cdot\nabla\right)\nabla^2\phi = c_1(\phi-n)+c_2\nabla^4\phi$$

$$\left(\frac{\partial}{\partial t}-\nabla\phi\times\hat{z}\cdot\nabla\right)(n+ln n_0) = c_1(\phi-n)$$

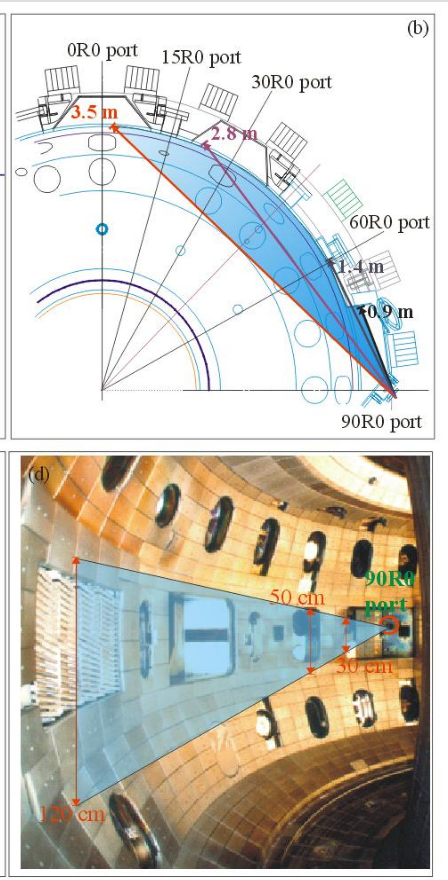
Hasegawa-Wakatani equations

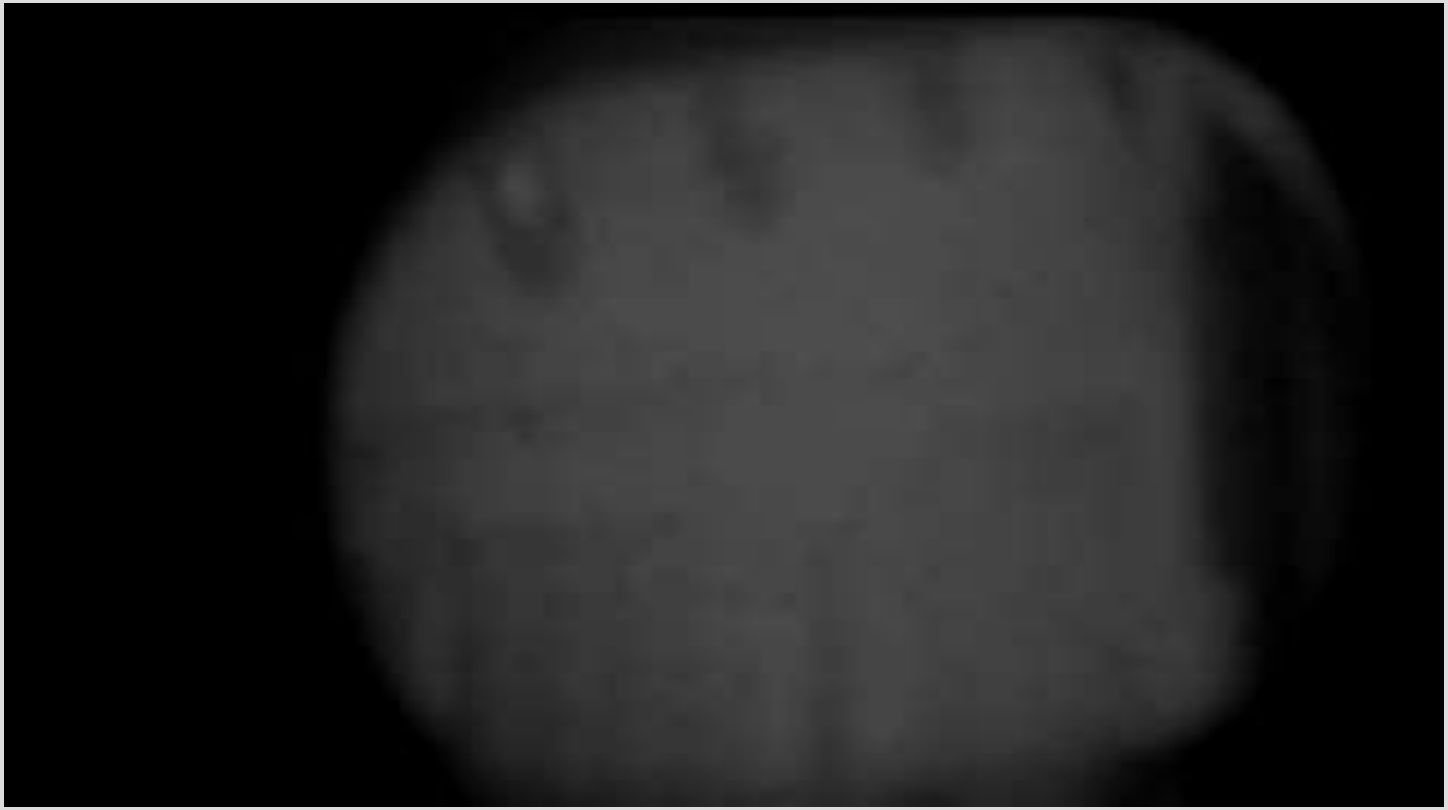
Simulating disruption mitigation in tokamaks I (R. Hajjar)

Disruptions are an abrupt and violent halt of the plasma.

- Most of the plasma energy is dumped on the walls
- Most of the magnetic energy is also dumped into the vessel structure

It is one the main parameters limiting the life-time of tokamaks and causing a high risk of a large damage



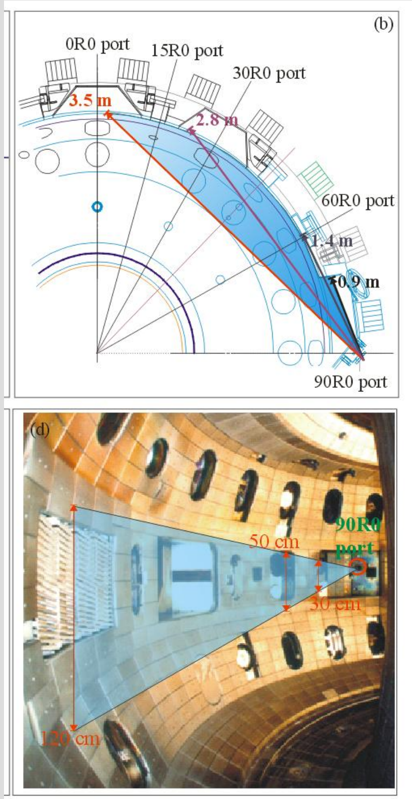


Simulating disruption mitigation in tokamaks II (R. Hajjar)

It is proposed to **mitigate disruptions** by using a massive gas jet which as it penetrates the plasma, density is increased by ionization which also leads to the decrease of temperature.

The questions we want to answer by numerical simulations:

- How deep will the jet penetrates
- How fast will the jet penetrates
- The type of gas to use
- The design of the setup will it help?



Tungsten Coating for Fusion Application (W. Kassem)

Fusion first wall is a major issue as it not only determines its life-time but also dictates the quality of the plasma by the type and the amount of impurities that it releases back into the plasma.

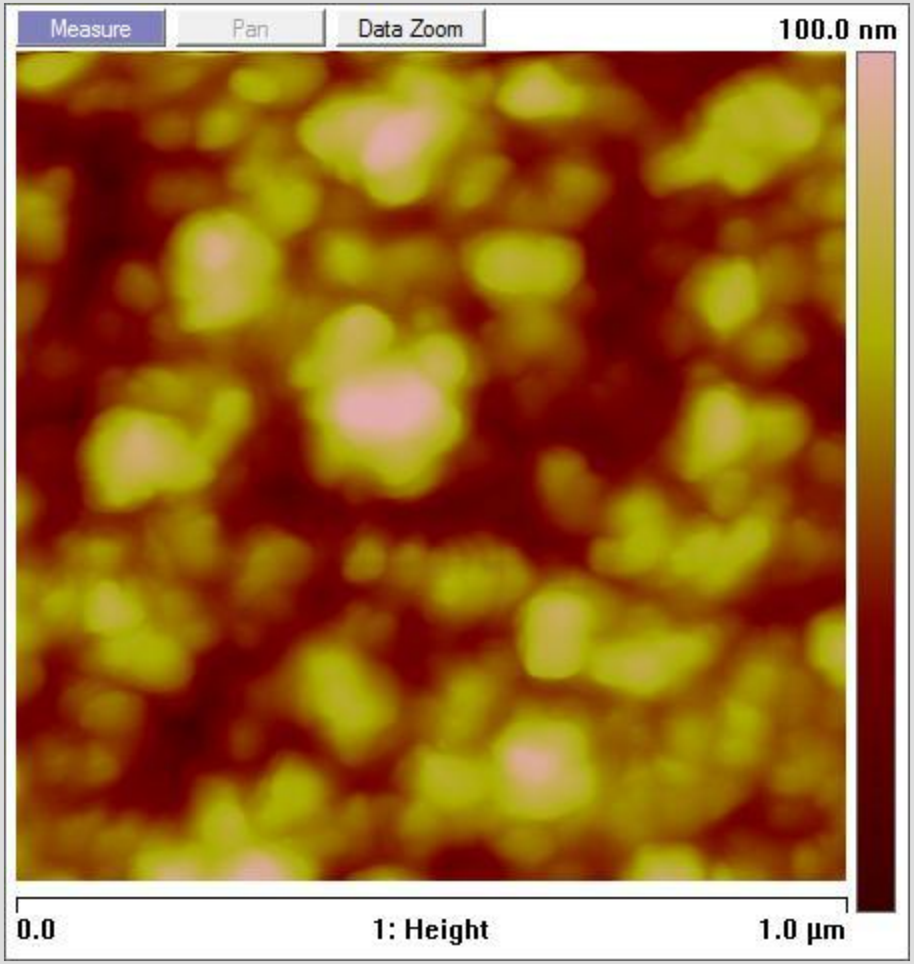
Our goal is to understand and quantify the growth of tungsten films on graphite using, and for the first time, pulsed laser deposition (PLD)

We attempt to grow Tungsten thin films using a KrF excimer laser with

- 20 ns pulse
- Wavelength 248 nm
- 100 to 600 mJ (up to 30000 MW/m^2)

Surface properties as a function of the Laser Energy

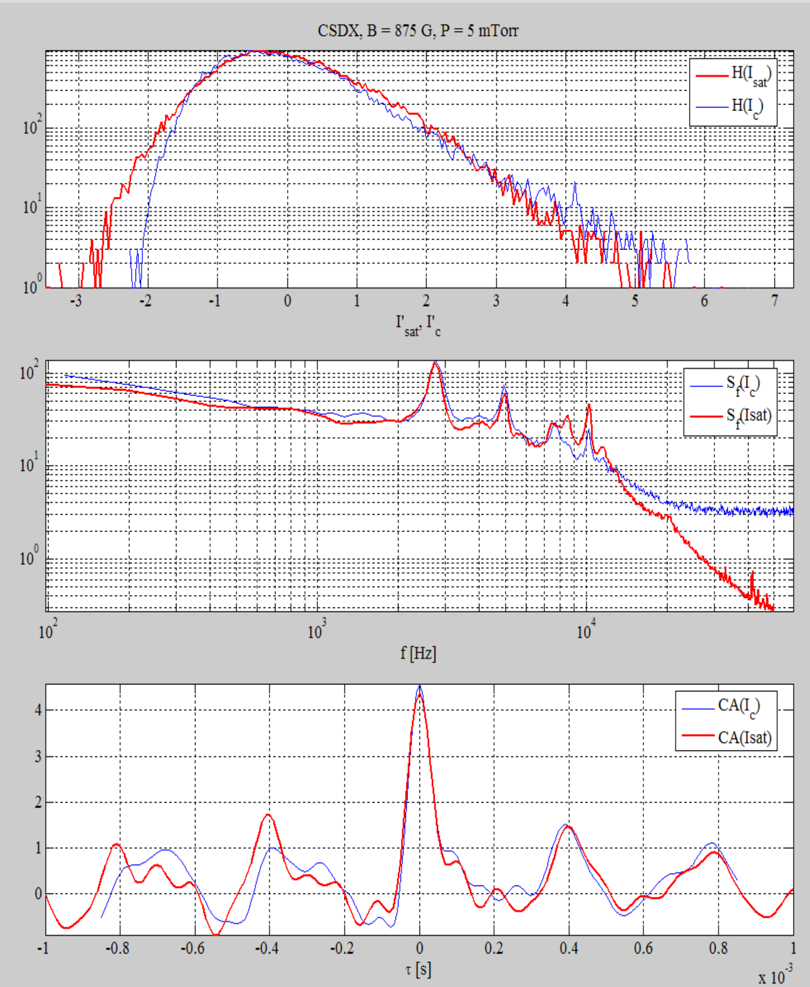
250 mJ 320 mJ 420 mJ 512 mJ 612 mJ

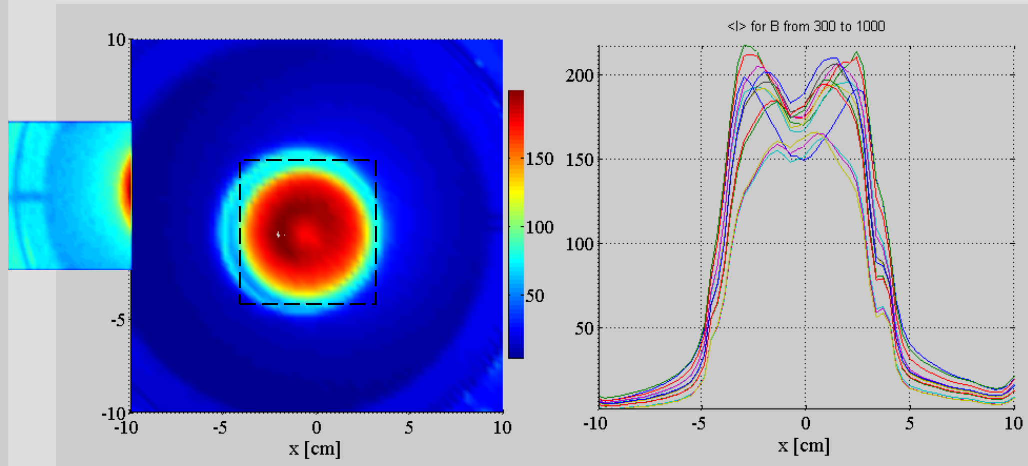


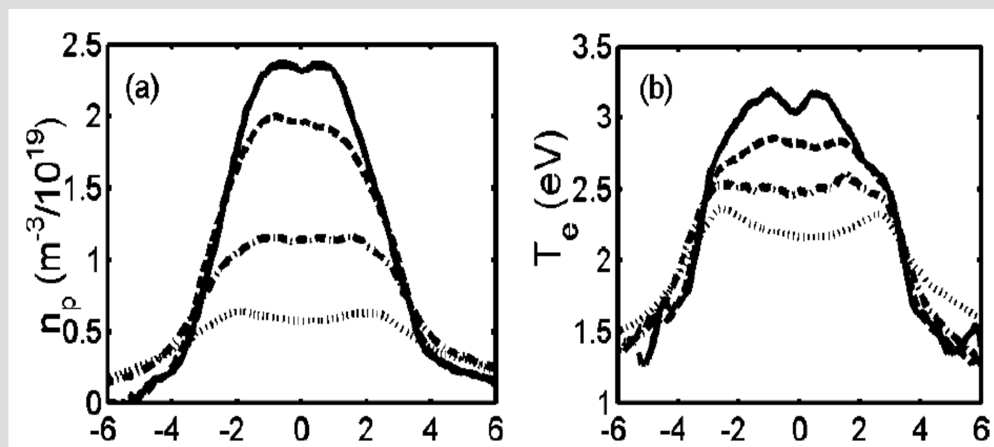
Conclusion

- Various experimental and theoretical research projects are being developed at AUB to understand turbulence in fusion plasmas.
- Fusion is an exciting project where physicists and engineers work hand-in-hand to achieve their common goal. **Fusion is a strategic issue.**
- The main application is to study **fundamental** issues encountered in magnetic fusion plasmas
- These issues are also common to other scientific areas such as: ocean dynamics, atmospheric science, astrophysics, surface science, fluid dynamics etc.
- *Acknowledgement: Part of this work is funded by the CNRSL*

Good agreement between the images profiles and fluctuations and those done using Langmuir probe for scales above 3 mm set by the view line integration.







M. Burin et al PoP 2004