



Simulating bi-Dimensional Turbulence in Fusion Plasmas

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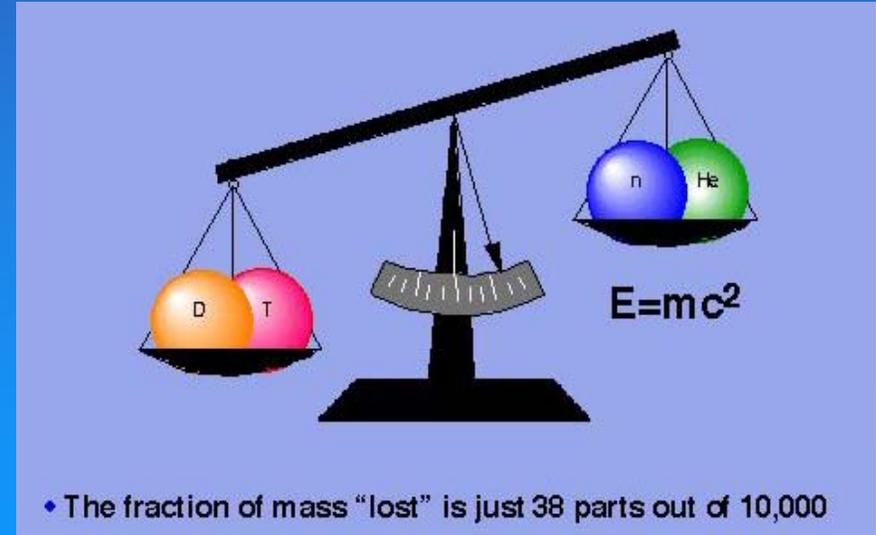
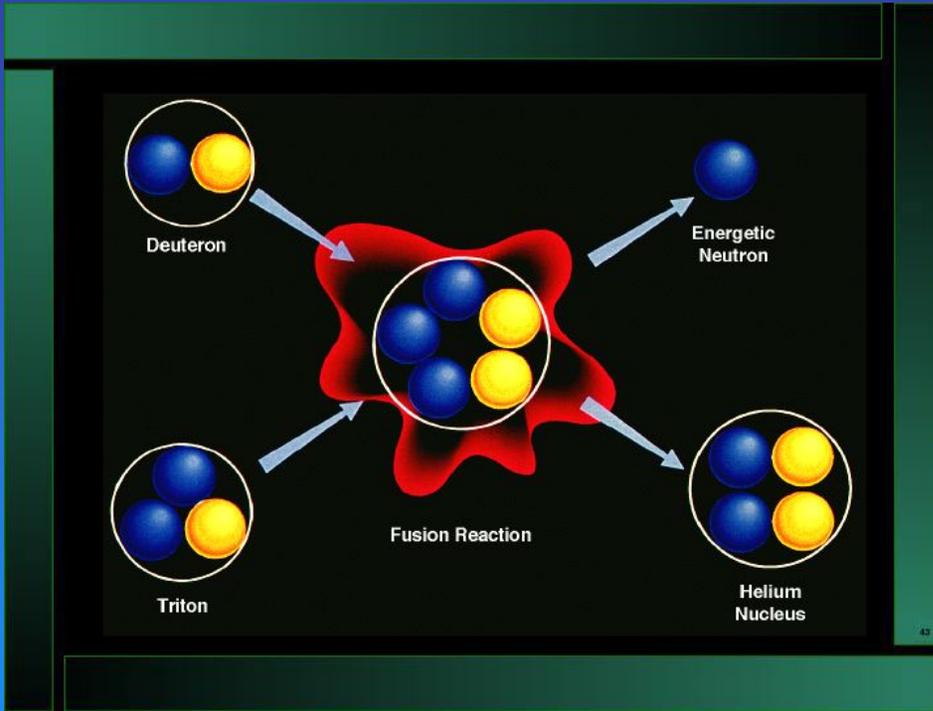


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2. Introduction to Toroidal Magnetic Fusion devices
3. Motion and dynamics in tokamaks
4. Turbulence and the confinement degradation.
5. Simulating 2D electrostatic turbulence
6. Future simulation activity at AUB.

Fusion Occurs when Two Nuclei Unite to Form One

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

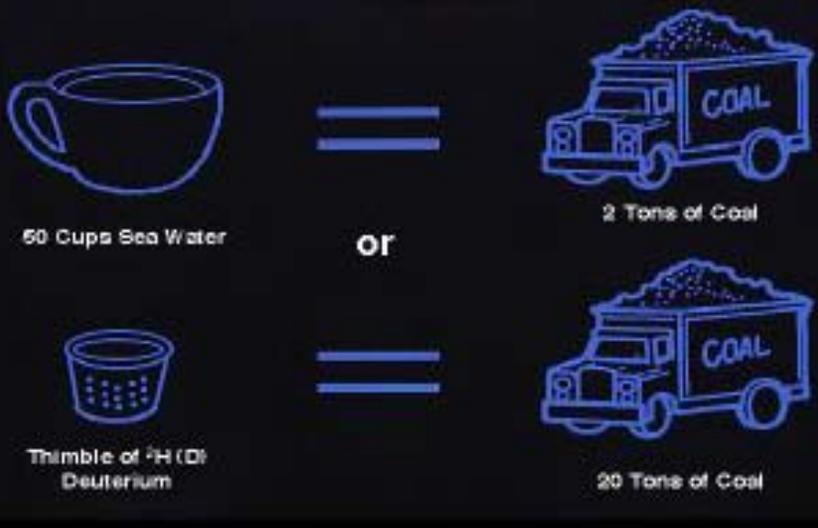


♦ The fraction of mass "lost" is just 38 parts out of 10,000

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

Advantages of Fusion on other ways to Produce Energy

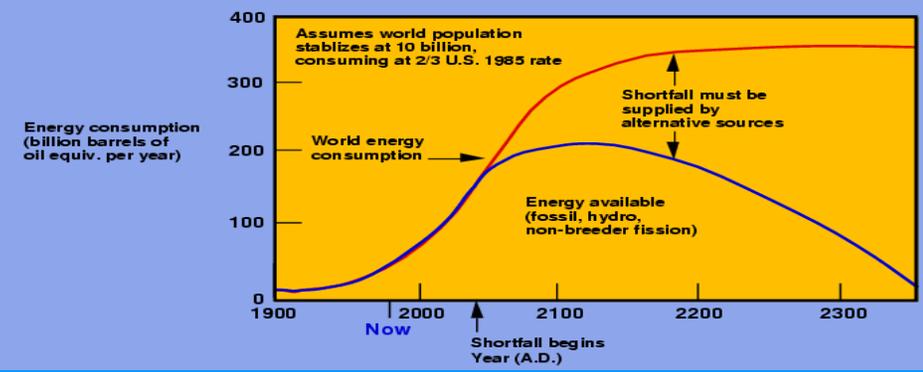
Abundant Energy From Sea Water



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

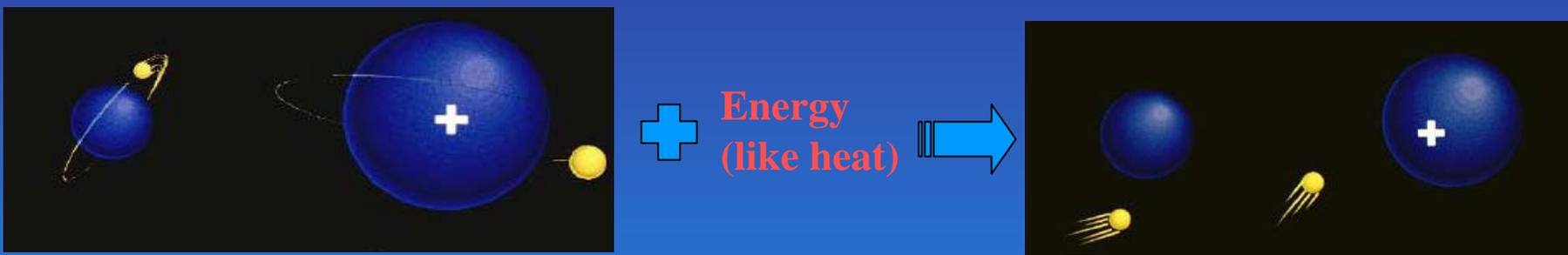
Fusion Energy

The fossil fuel era is almost over. If we continue to burn fossil fuels for energy, they will last only another few hundred years. At our present rate of use, experts predict a shortfall in less than fifty years.

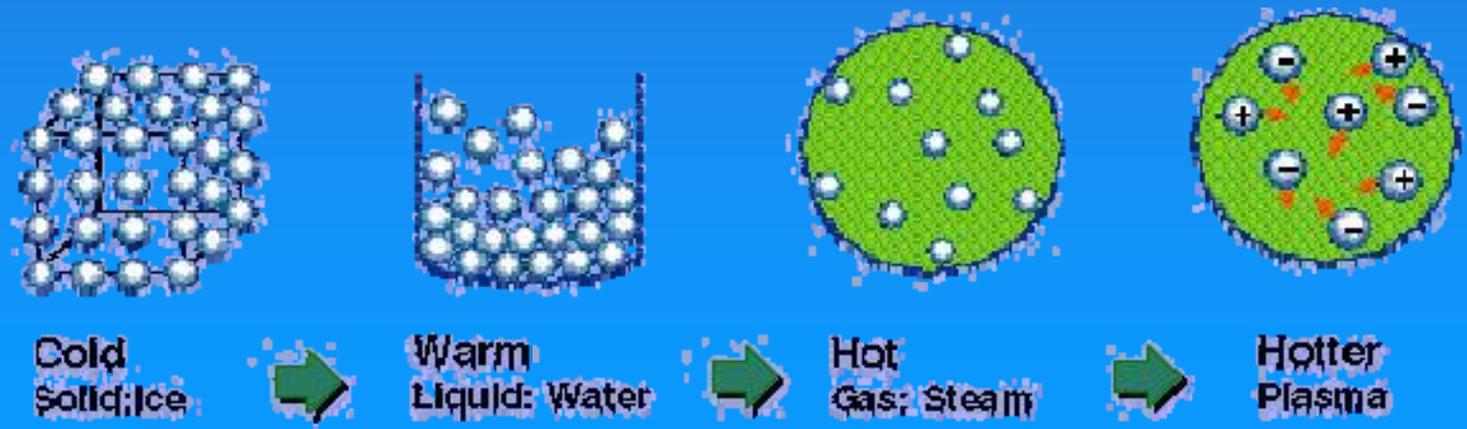


A Plasma is a fully ionized gas globally neutral

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

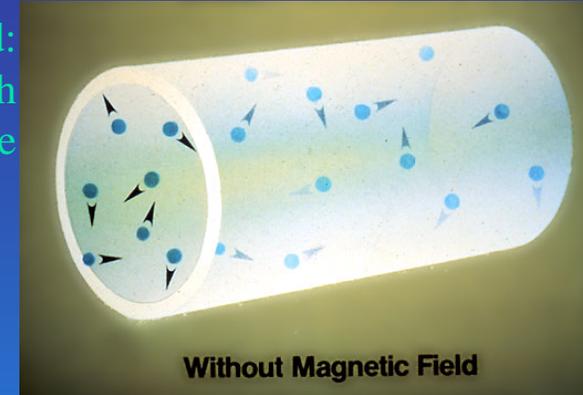


- Plasmas are the most common form of matter, comprising more than 99% of the visible universe.
- Plasmas carry electrical currents and generate magnetic fields, due to their ions and electrons.

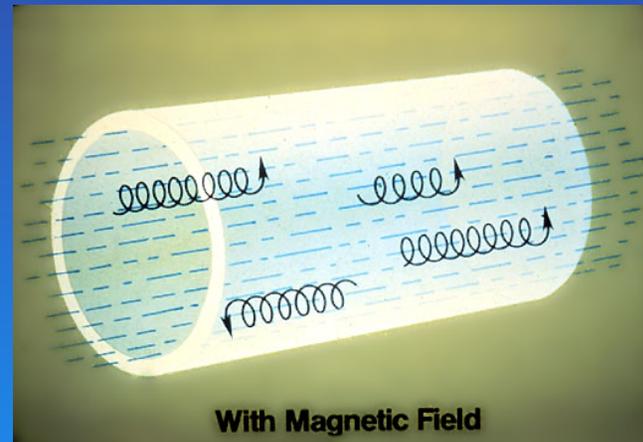


The Route Towards a Confined Plasma or How to Make Particle Go Round-and-Round

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



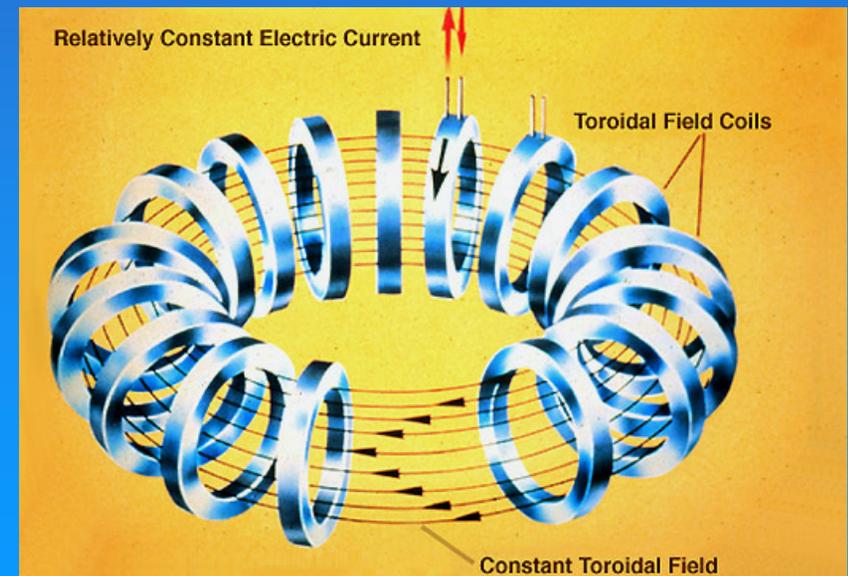
Adding a magnetic field with parallel set of coils:
Particles trajectories are parallel to B



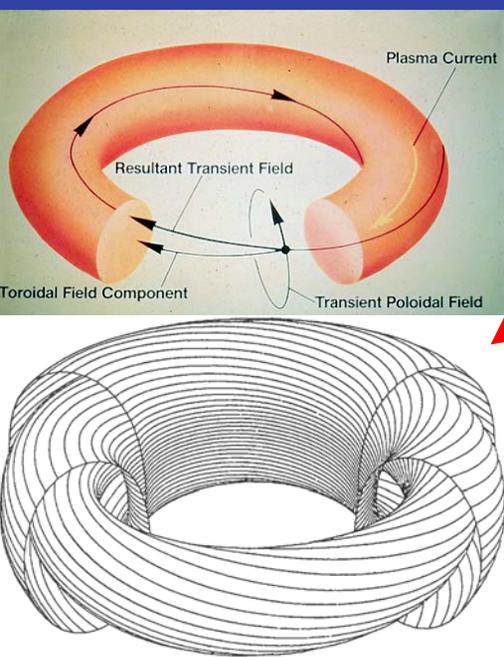
Closing the loop by the making the coils form a torus:
Particles go round and round
Particles are thus Confined



The tokamak configuration



Closed and open field lines

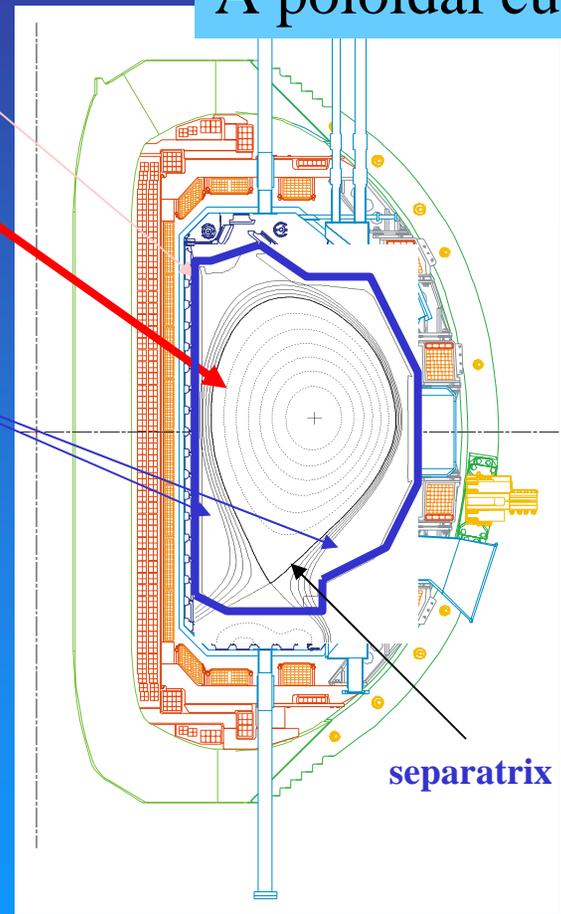
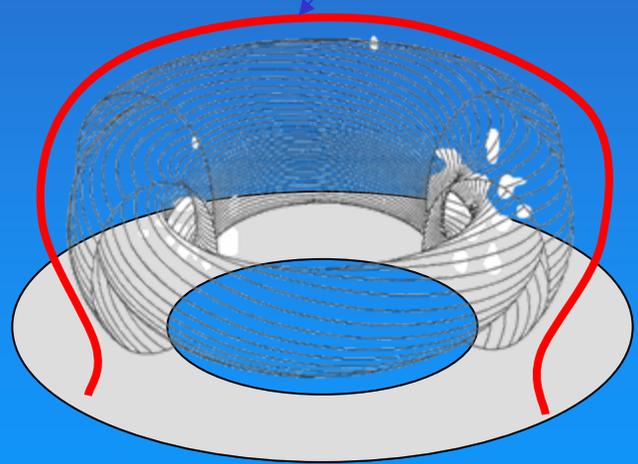


The first wall

A poloidal cut

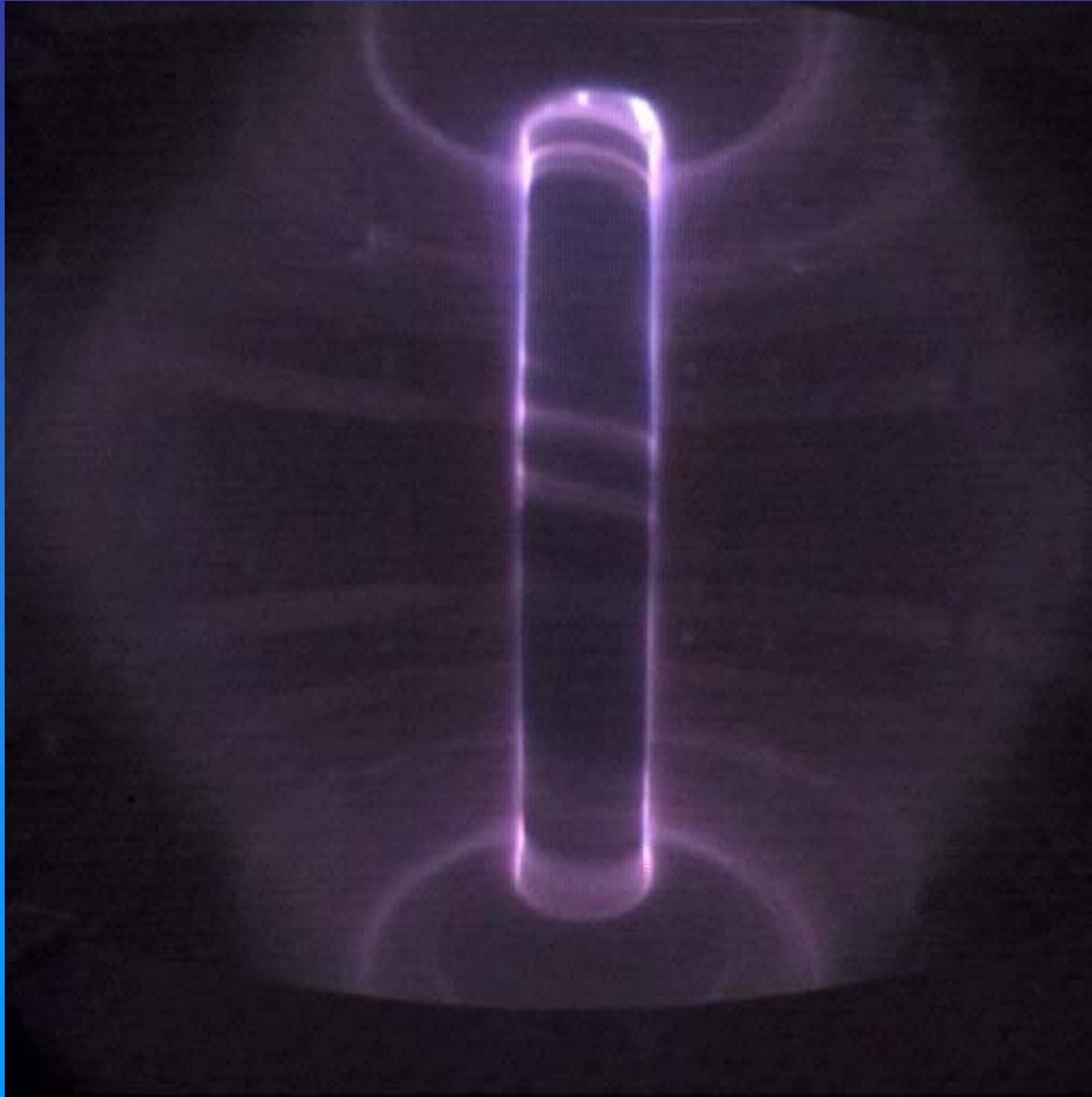
Closed field line

Open field line
"scrape-off layer"
"SOL"

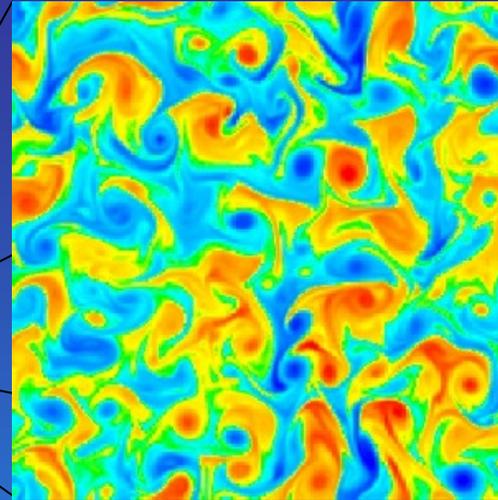
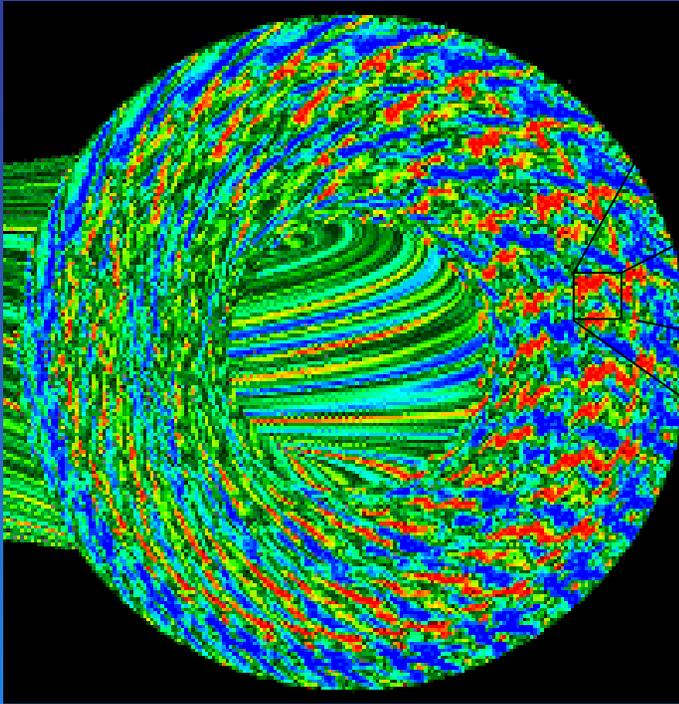


A particle (ion or electron) is completely lost once it moves outside the separatrix from the closed field line confined zone into the open field line unconfined zone.

A MOVIE of the Start-up Phase (MAST)



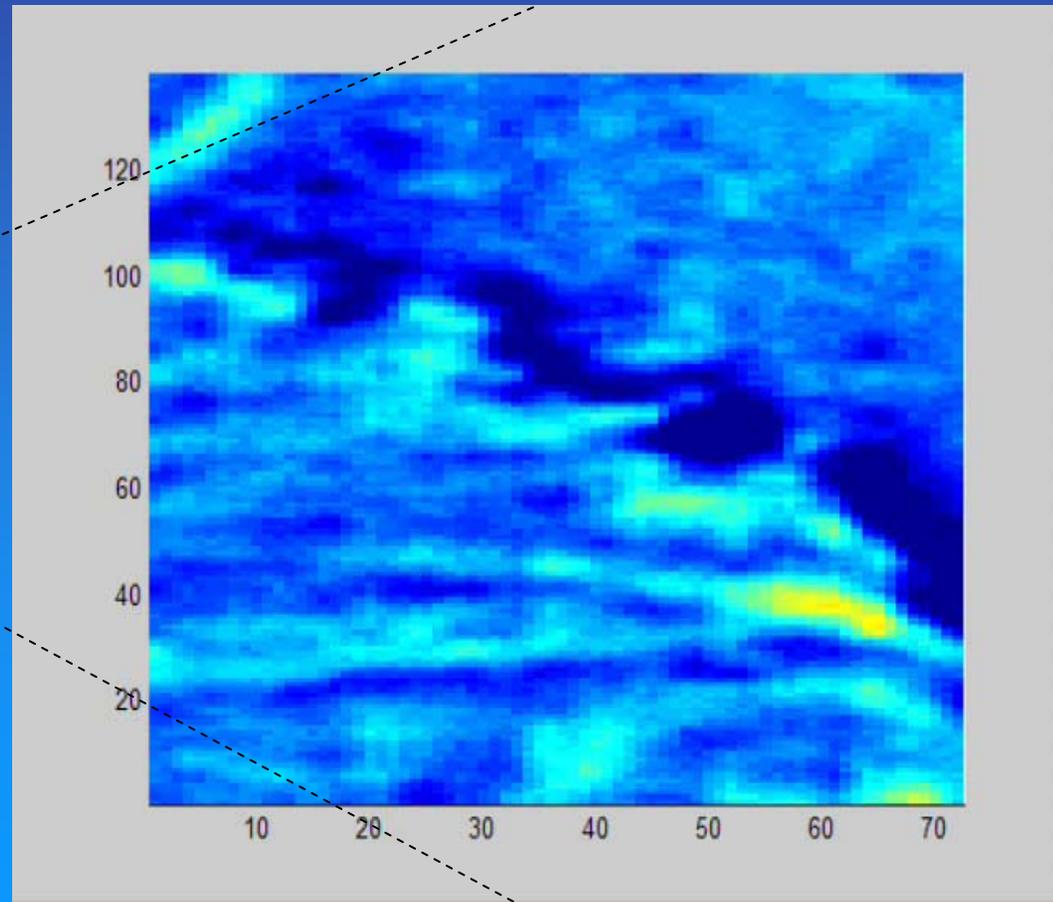
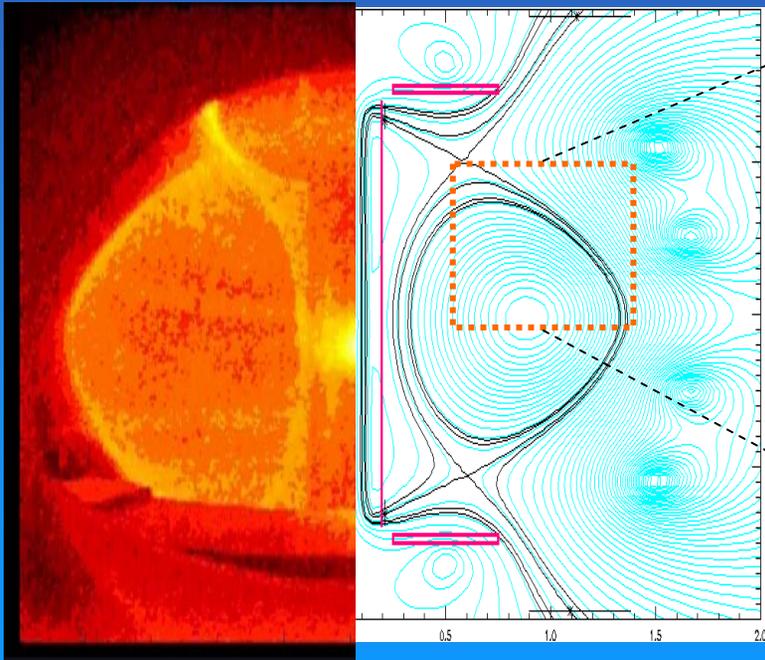
Confinement is degraded by Turbulence



**The size of an eddy
is ~ few centimeters**

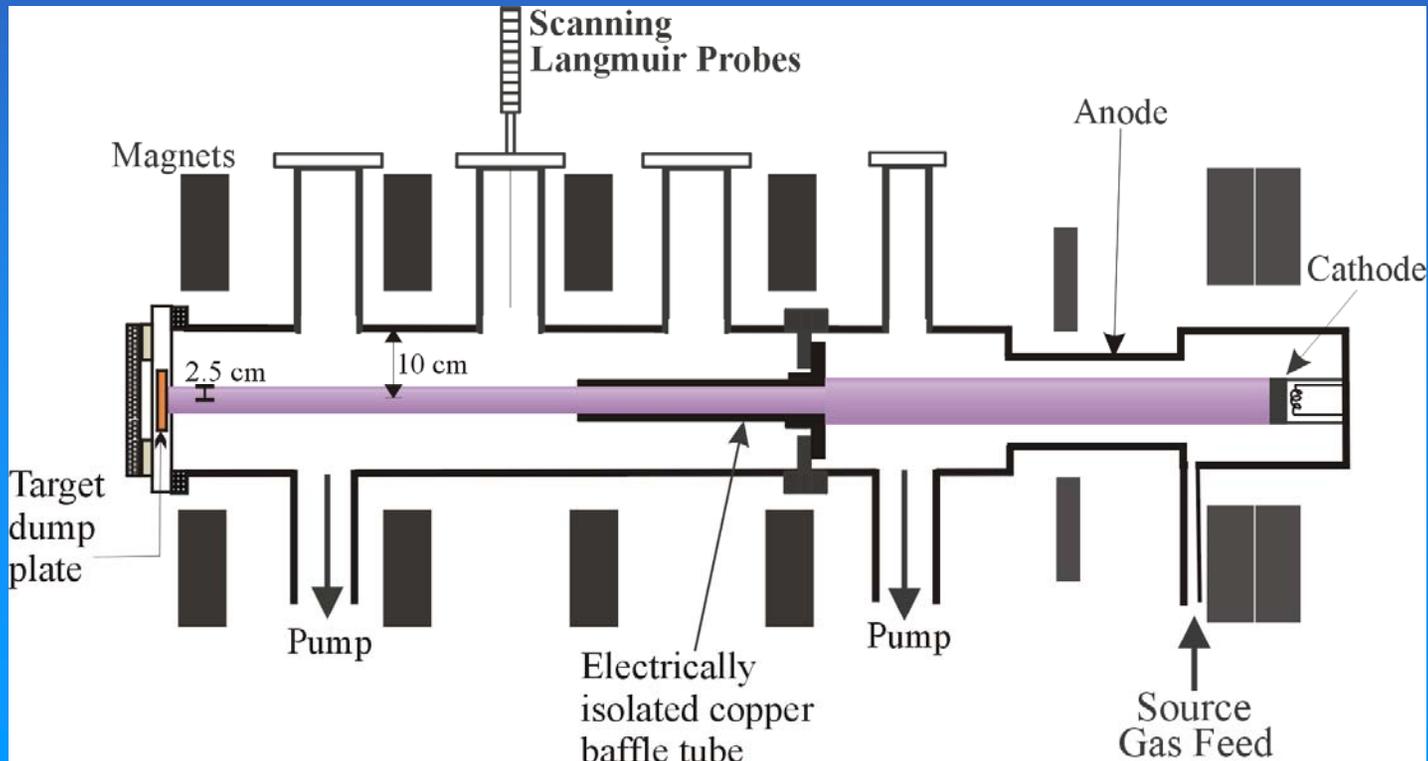
- Instead of particles motion in the plane perpendicular to B occurs with sub-micron steps, they are now convected in eddies with a radius of rotation of few centimeters.
- Particles are lost much easier.
- Turbulence leads to radial transport that is the main source of confinement degradation in fusion devices.

The structures extend radially far from the separatrix with elongated structures and they have large velocities.



Future research fusion activity at AUB

Plasma physics in linear devices and relevance to Research on Fusion Energy

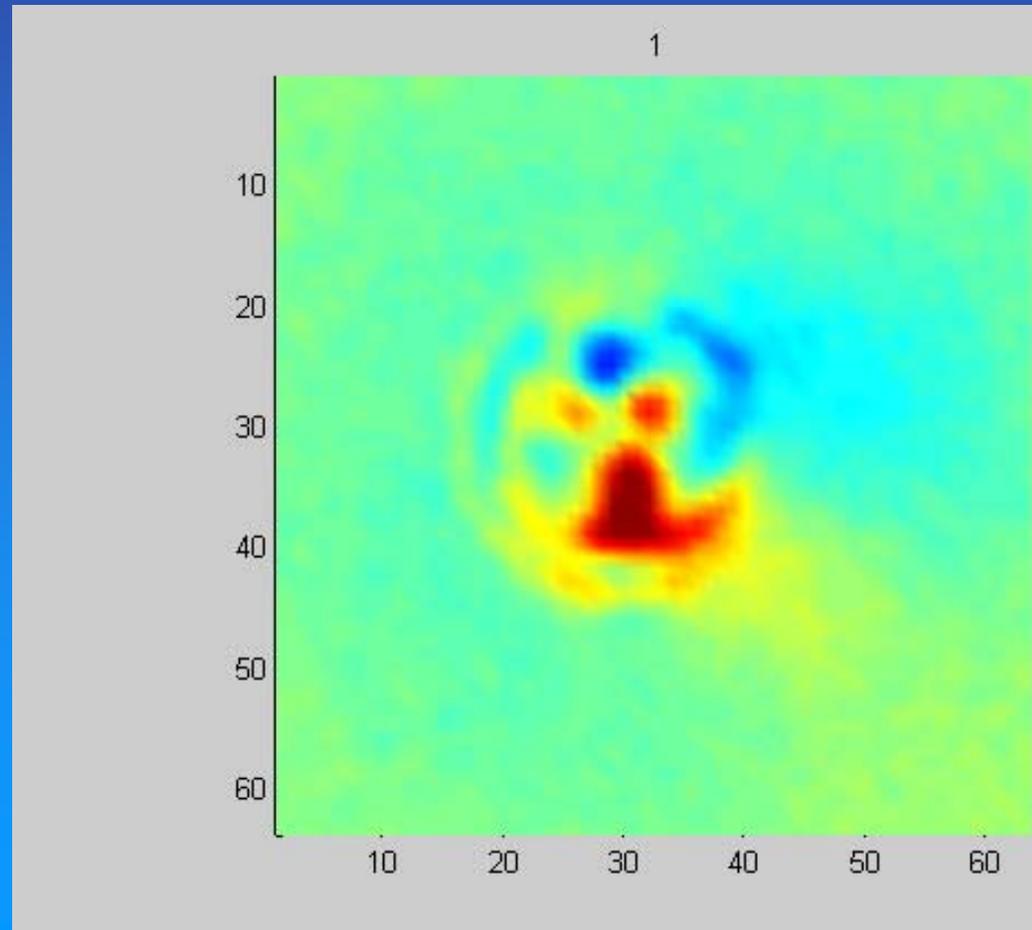


The system transits from low to high mode number fluctuations in time and can remain in one of the modes for relatively long time.

- One can no longer speak of “stationary turbulence”...
- Outside long jets of plasma are observed to occur when the instability mode number is about unity.



Strong relationship between core fluctuations and outside intermittency



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



Goal 1: Simulate the non-stationary aspect of the fluctuations inside the main plasma

The equations used are the Navier-Stokes equations for electrons and ions subject to the Lorentz force

1 - Conservation of the number of electrons or ions :
$$\frac{\partial n_\alpha}{\partial t} + \vec{\nabla} \cdot (n_\alpha \vec{v}_\alpha) = 0$$

2 - Conservation of momentum :
$$m_\alpha n_\alpha \left[\frac{\partial \vec{v}_\alpha}{\partial t} + (\vec{v}_\alpha \cdot \vec{\nabla}) \vec{v}_\alpha \right] = -\nabla p_\alpha + q_\alpha n_\alpha (\vec{E} + \vec{v}_\alpha \times \vec{B}) + \mu \nabla^2 \vec{v}_\alpha$$

Several assumptions are to be made in order to simplify the problem

Simplifying features will be taken into account such as the limited number of poloidal modes.



Assumptions leading to the Hasegawa-Wakatani set of equations

- The magnetic field is large enough that static so that $\frac{\partial}{\partial t} \ll \omega_c \left(= \frac{qB}{m} \right)$
- The particle density follows the quasi-neutrality condition: $n_e \approx Zn_i$
- The first order ion particle density is a function of position, but not time.
- The second order particle density which causes a charge density and thus an electric potential can change with time.



The Hasegawa-Wakatani (HW) Model

- HW model describes evolution of density fluctuation (n) and vorticity $\xi = \Delta^2 \phi$ (where ϕ is the electrostatic potential)
- ξ is the vorticity

$$\frac{\partial}{\partial t} \zeta + \{\varphi, \zeta\} = \alpha(\varphi - n) - D_\zeta \nabla^4 \zeta$$

$$\frac{\partial}{\partial t} n + \{\varphi, n\} = \alpha(\varphi - n) - \kappa \frac{\partial \varphi}{\partial y} - D_n \nabla^4 n$$

$$\{a, b\} = \partial a / \partial x \partial b / \partial y - \partial a / \partial y \partial b / \partial x$$

$$\nabla^2 = \partial^2 / \partial x^2 + \partial^2 / \partial y^2$$

D_ζ and D_n are dissipation coefficients

$$\kappa \equiv -\partial / \partial x \ln n_0$$

$$\alpha \equiv \frac{T_e k_z^2}{\eta n_0 \omega_{ci} e^2} : \text{adiabaticity parameter}$$

$\alpha \sim 0$ describes fluid flows

$\alpha \gg 1$ describes plasma flows



One prospective idea Computational domain

Gaussian 0th order density profile

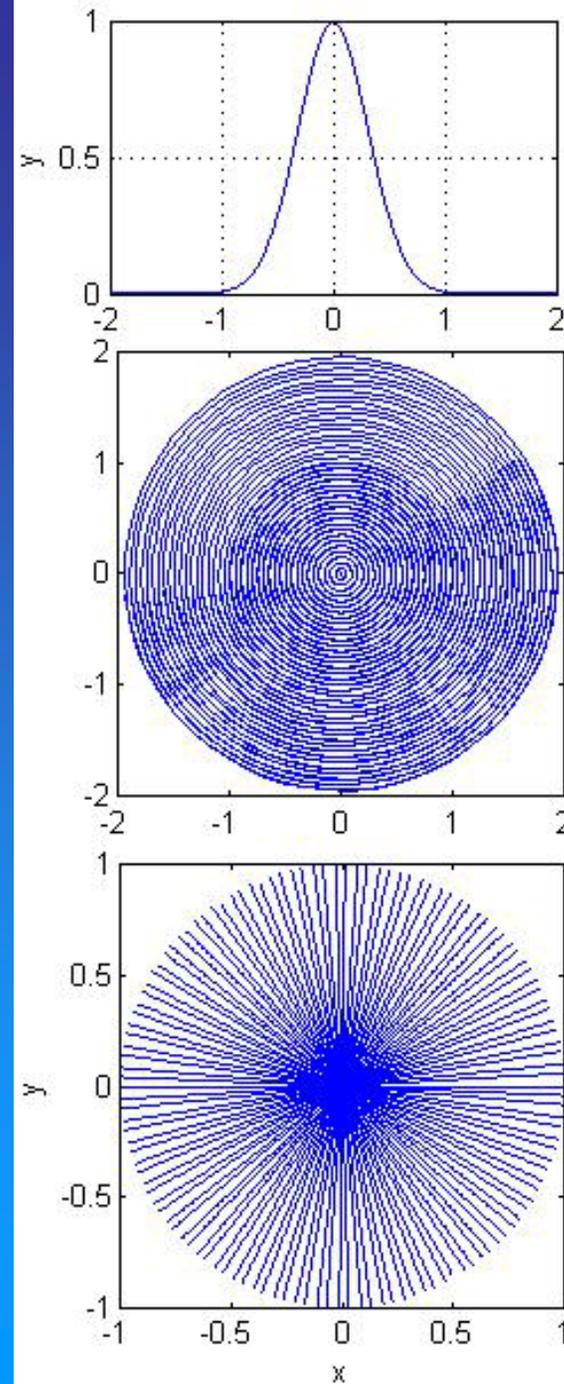
periodic in θ

Hasegawa-Wakatani

- 1- Cartesian coordinate to polar coordinate
- 2- Fourier in the θ direction
- 3- Limit the values of k_θ
- 4- Inverse Fourier back to θ

finite in r

Dirichlet boundary condition at $r = +/-2$



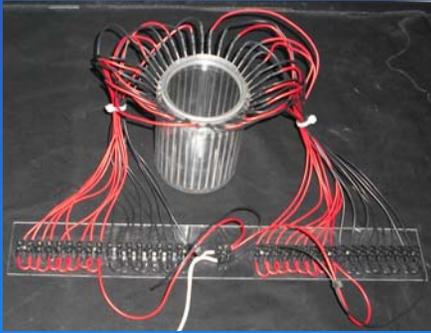


Goals:

- Goal 1: Reproduce the experimental results of alternating low poloidal mode numbers which is giving the impression of a broadband turbulence.
- Goal 2: Simulate the coherent structures outside the main plasma where density was originally equal to 0.
- Understand the instability behavior as a function of the initial form of the density profile.
- Comparison with the experiment should be made for the first time giving insights into the various mechanisms for instability saturation.

Future work on turbulence 1:

Simulation of quasi-2D incompressible turbulence and comparison with the experiment.



Future Work 2: Simulating tokamak geometry with 2D turbulence

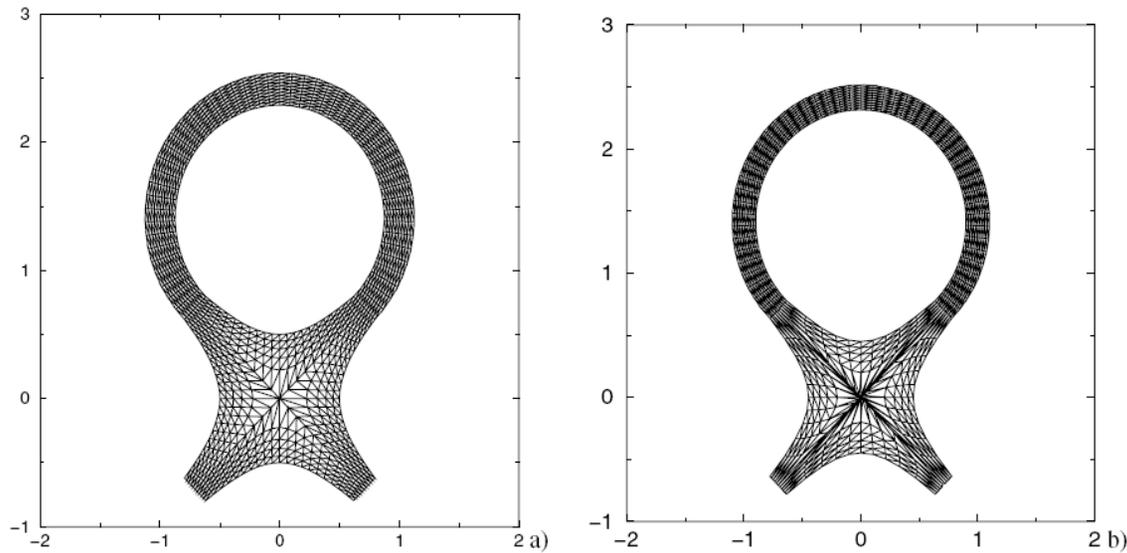


Fig. 1 Schematic diagram of (a) a regular mesh (equi-distant in x and y) and (b) a mesh with the X-point singularity (equi-distant in action-angle space). The singularity causes a problem in distorting the shape of the finite elements. Note the mesh size here is coarse for the illustration purpose.