The Power of the Universe on Earth: Plasma Physics and Fusion Energy

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What is a plasma?
Why should we care?
How can we make fusion work?
Where are the difficulties?

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Outline

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- What is a plasma?
- Where do we find them?
- Why are we interested in them?
  - Fusion energy
  - Astrophysics
- More on fusion energy.
- Charged particles moving a magnetic field.

What is a plasma?

A plasma is an ionized gas.

Plasma is called the "fourth state of matter."

More than 99% of the mass of the universe is in the plasma state.

'Plasma' was coined by Tonks and Langmuir in (1929):

> "...when the electrons oscillate, the positive ions behave like a rigid jelly..."

Where do we find plasmas?

Examples of plasmas on Earth:

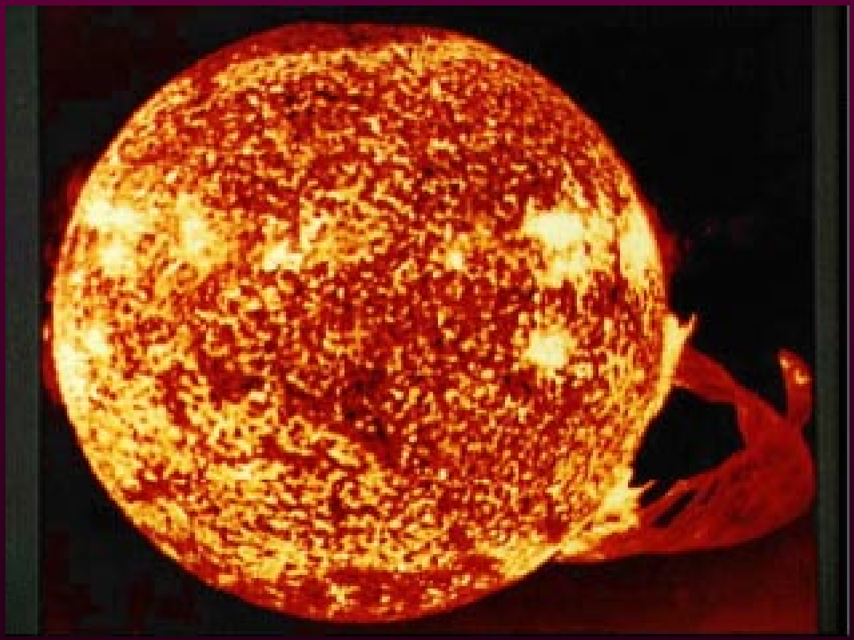
- Lightning
- Neon and Fluorescent Lights
- Laboratory Experiments

Examples of astrophysical plasmas:

- The sun and the solar wind
- Stars, interstellar medium

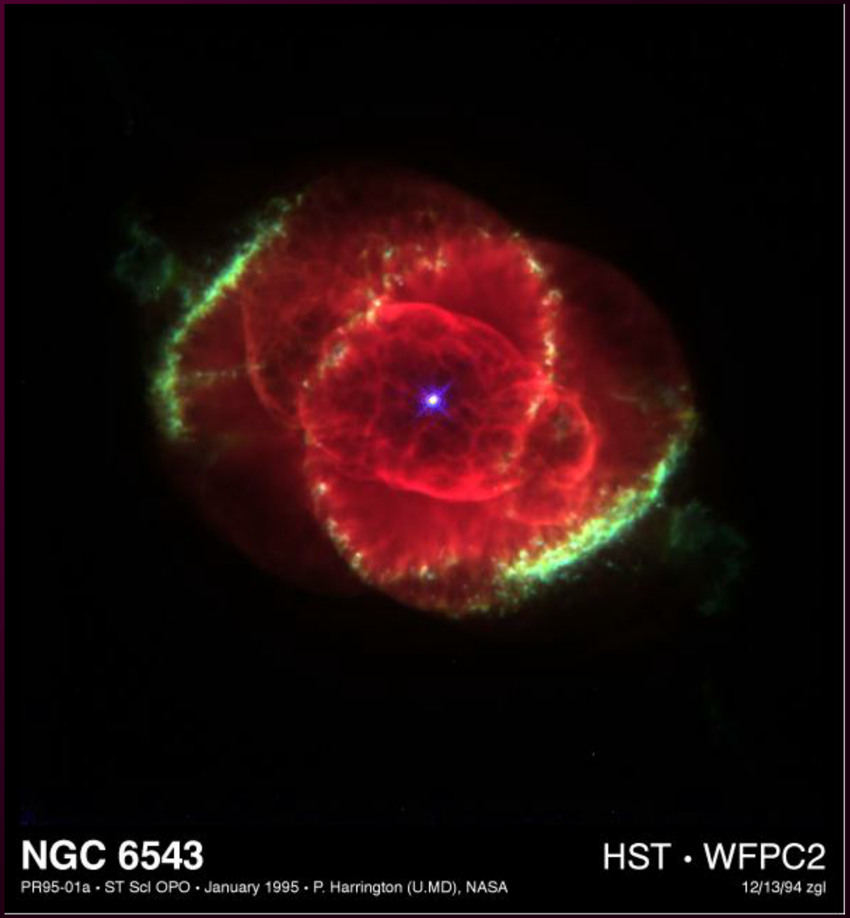
Astrophysical plasmas

The Sun



http://bang.lanl.gov/solarsys/

Catseye Nebula



http://www.stsci.edu:80/

Plasmas on Earth

Laboratory Experiments

http://FusEdWeb.pppl.gov/

Lightning

Why are we interested in plasmas?

Fusion Energy

Potential source of safe, abundant energy.

Astrophysics

Understanding plasmas helps us understand stars and stellar evolution.

Upper atmospheric dynamics

The upper atmosphere is a plasma.

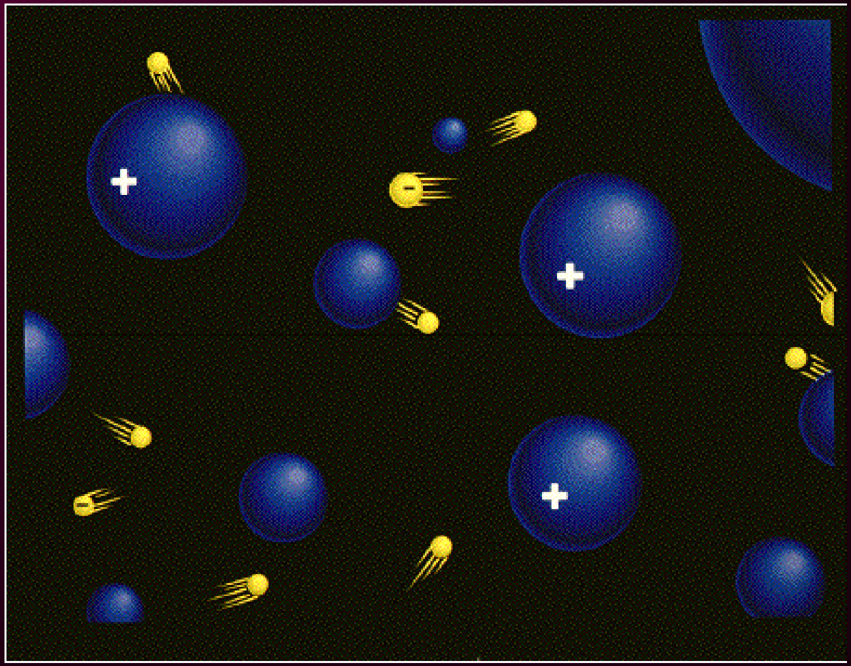
Plasma Applications

Plasmas can be used to build computer chips and to clean up toxic waste.

Properties of plasmas

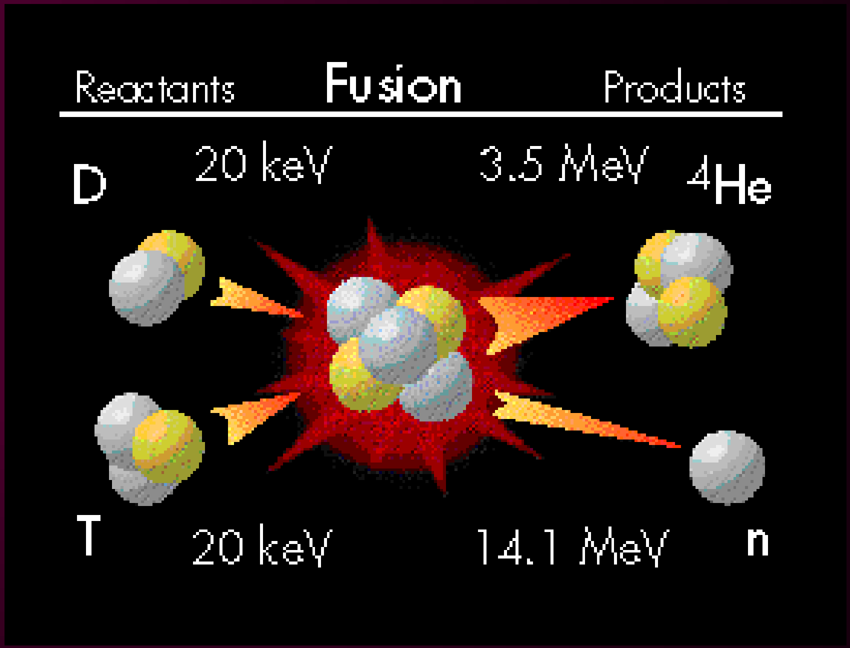
- A collection of positively and negatively charged particles.
- Plasmas interact strongly with electric and magnetic fields.
- Plasmas support many different types of waves and oscillations.

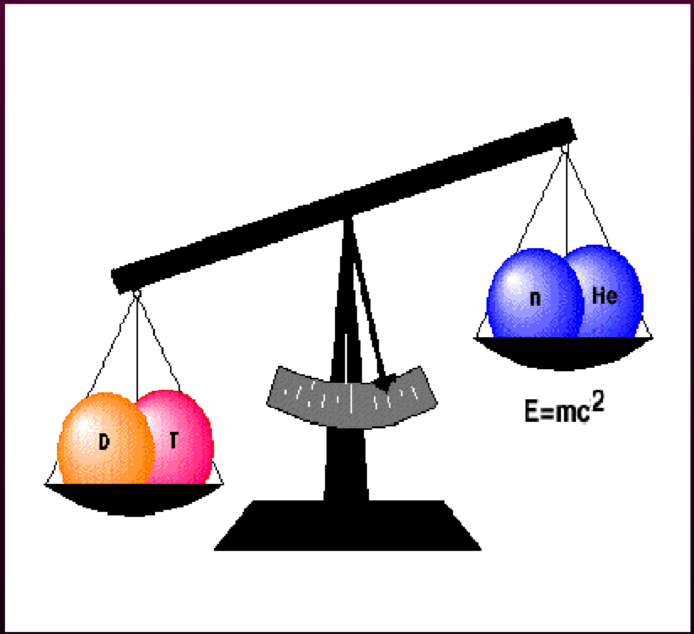
Cartoon of a plasma



http://demo-www.gat.com/

Mass goes into energy in fusion reaction

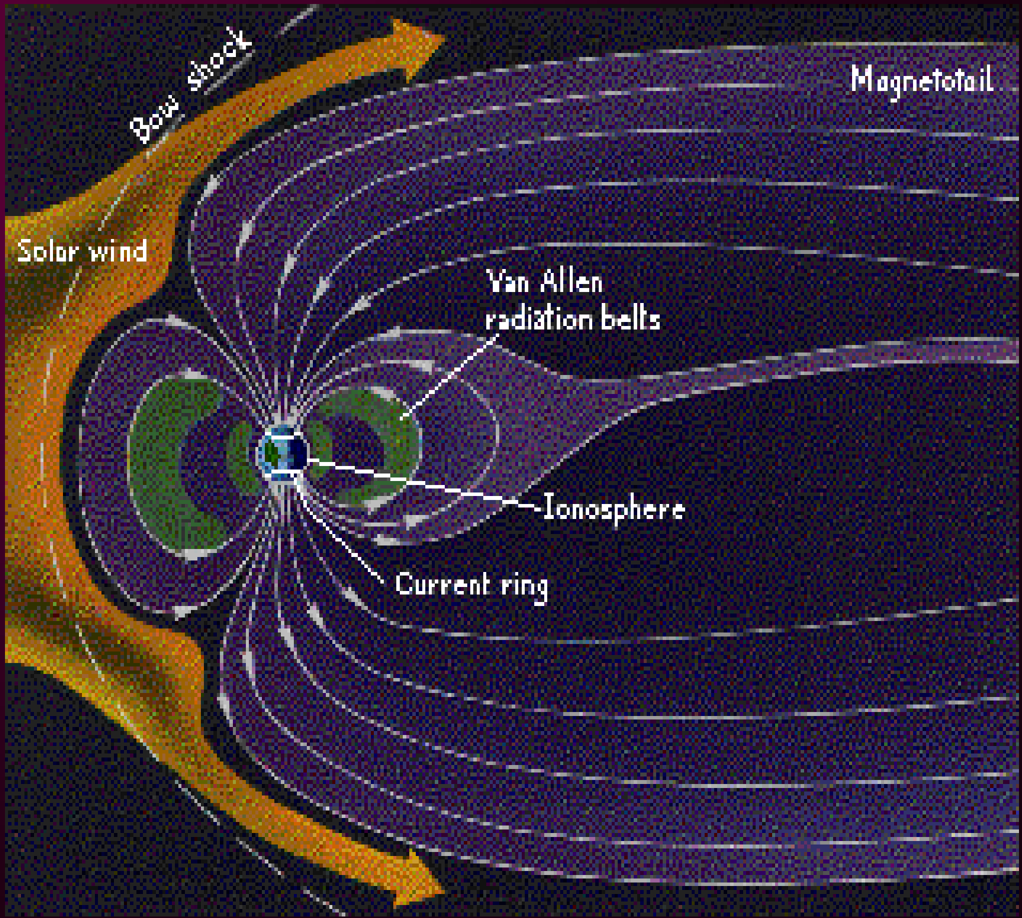




The solar wind (a plasma) interacts with the Earth's magnetic field

The sun emits mass in the form of plasma at velocities of up to 500 km/s.

This solar wind causes the Earth's magnetic field to compress creating a shock wave called the Bow wave.



From ***Stars****, James Kaler*

Interactions between the earth's magnetic field and a plasma can have spectacular results

The northern lights
(aurora borealis)

Photo by David Fritz
http://dac3.pfrr.alaska.edu:80/~pfrr/AURORA/INDEX.HTM

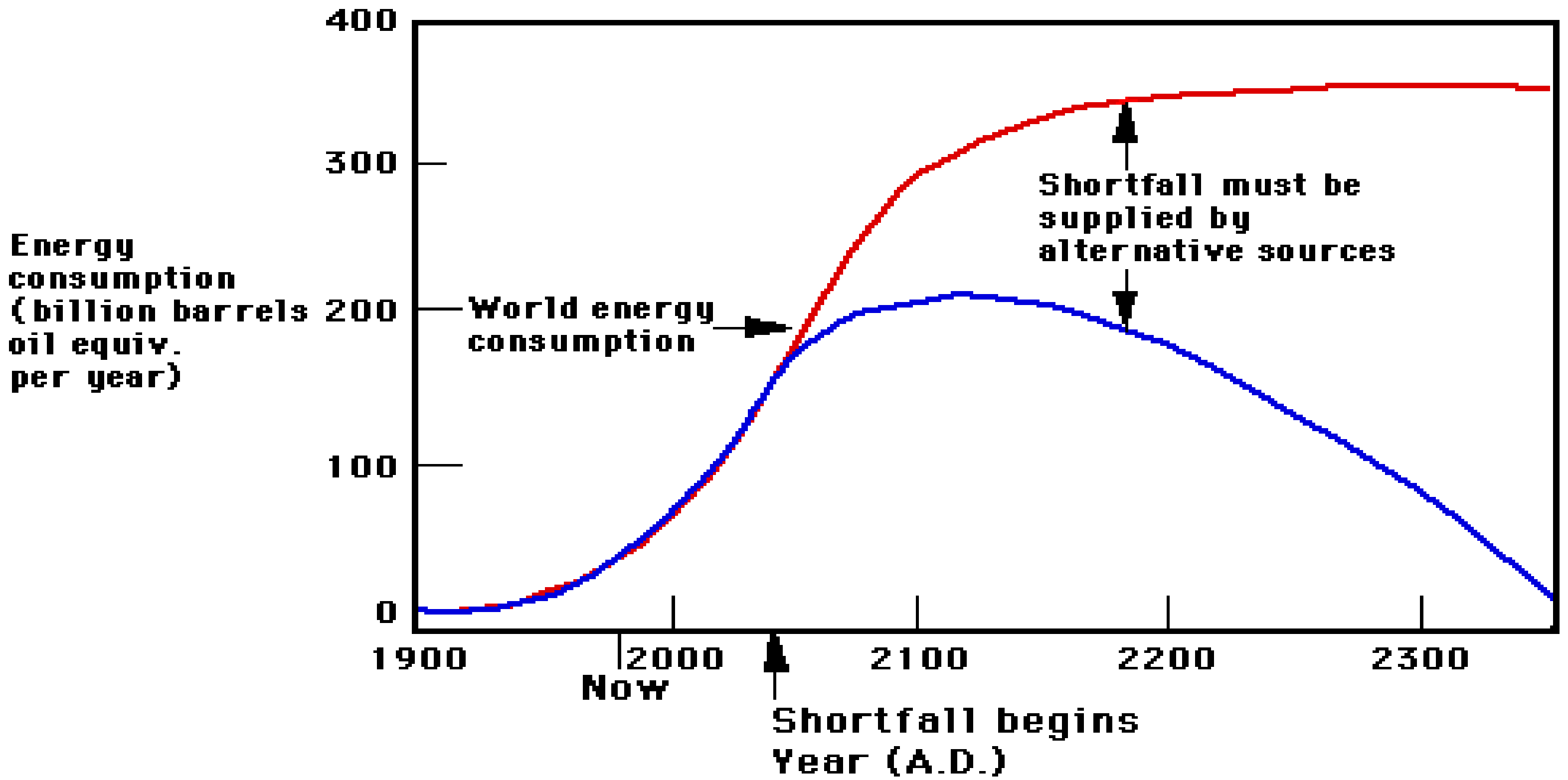
More on Fusion Energy

Much of plasma physics research has been motivated by the goal of controlled fusion energy.

Fusion energy is a form of nuclear energy which is emitted when two light nuclei combine to form a single more stable nuclei.

The sun and stars derive their energy from fusion.

Why do we need new sources of energy?



http://demo-www.gat.com/

Why is Fusion power needed?

Country	Consumption (kW-h/capita)
US	12000
Developed World Avg.	6000
World Avg.	1500
China	500
India	250

1990 Energy use per capita

- **Projected change in consumption by increasing to world average**

Country	Energy Use 1990 (GW)	Energy Use 2020 (GW)
China	120	500
India	65	450

- **If fossil Catastrophe Looms**

For more information see:
http://wwwofe.er.doe.gov/More_HTML/Artsimovich/PKKawPaper.html

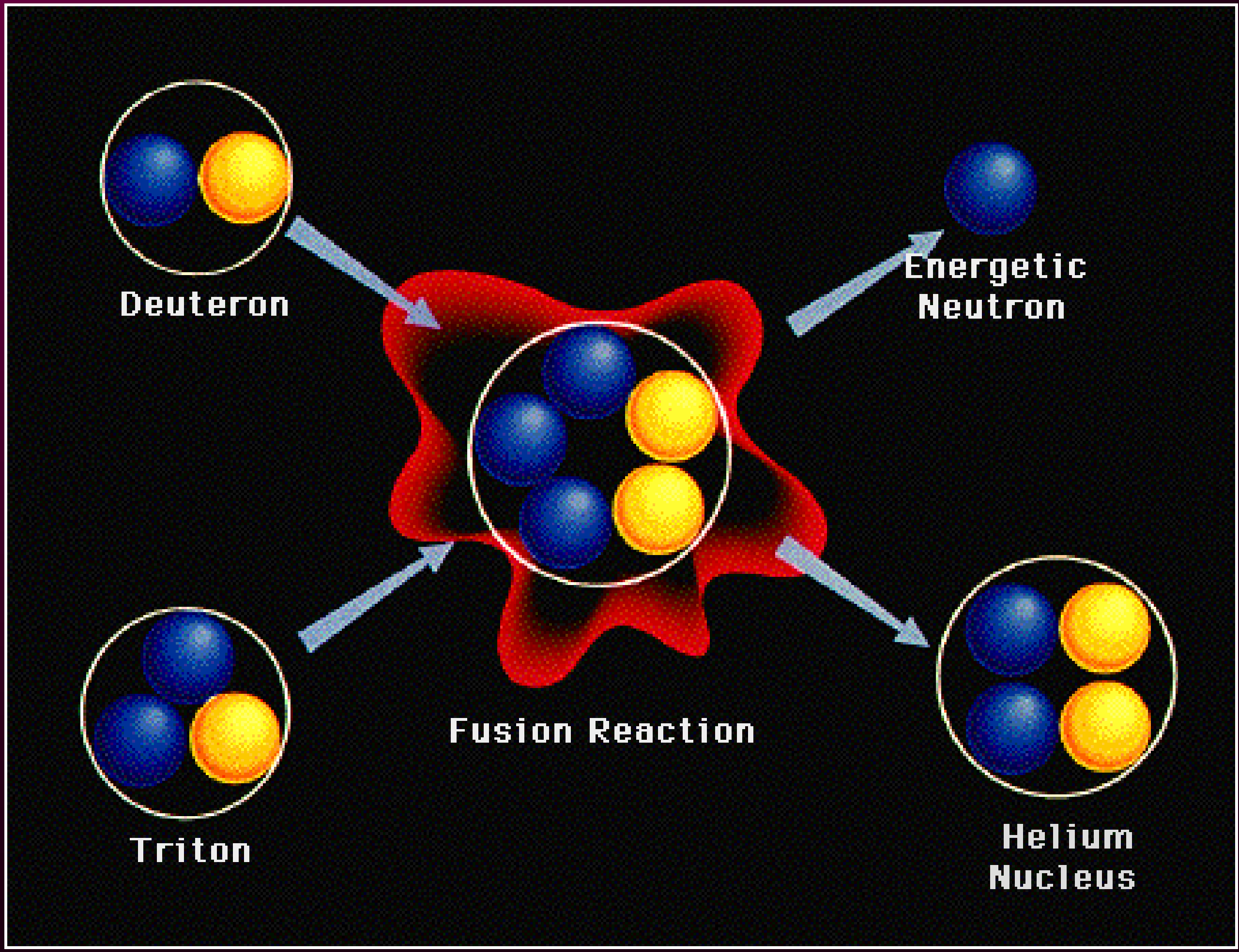
Fuel and waste products

Fuel and waste for coal (most readily

DAILY FUEL CONSUMPTION DAILY WASTE PRODUCTION 1,000 MEGAWATTS		
	COAL PLANT	D-T FUSION PLANT
FUEL	9,000 T. COAL	1.0 LB D_2 3.0 LB Li^6 (1.5 LB T_2)
WASTE	30,000 T. CO_2 600 T. SO_2 80 T. NO_2	4.0 LB He^4

http://www.pppl.gov

Deuterium and tritium combine to form helium, a neutron and fusion energy.



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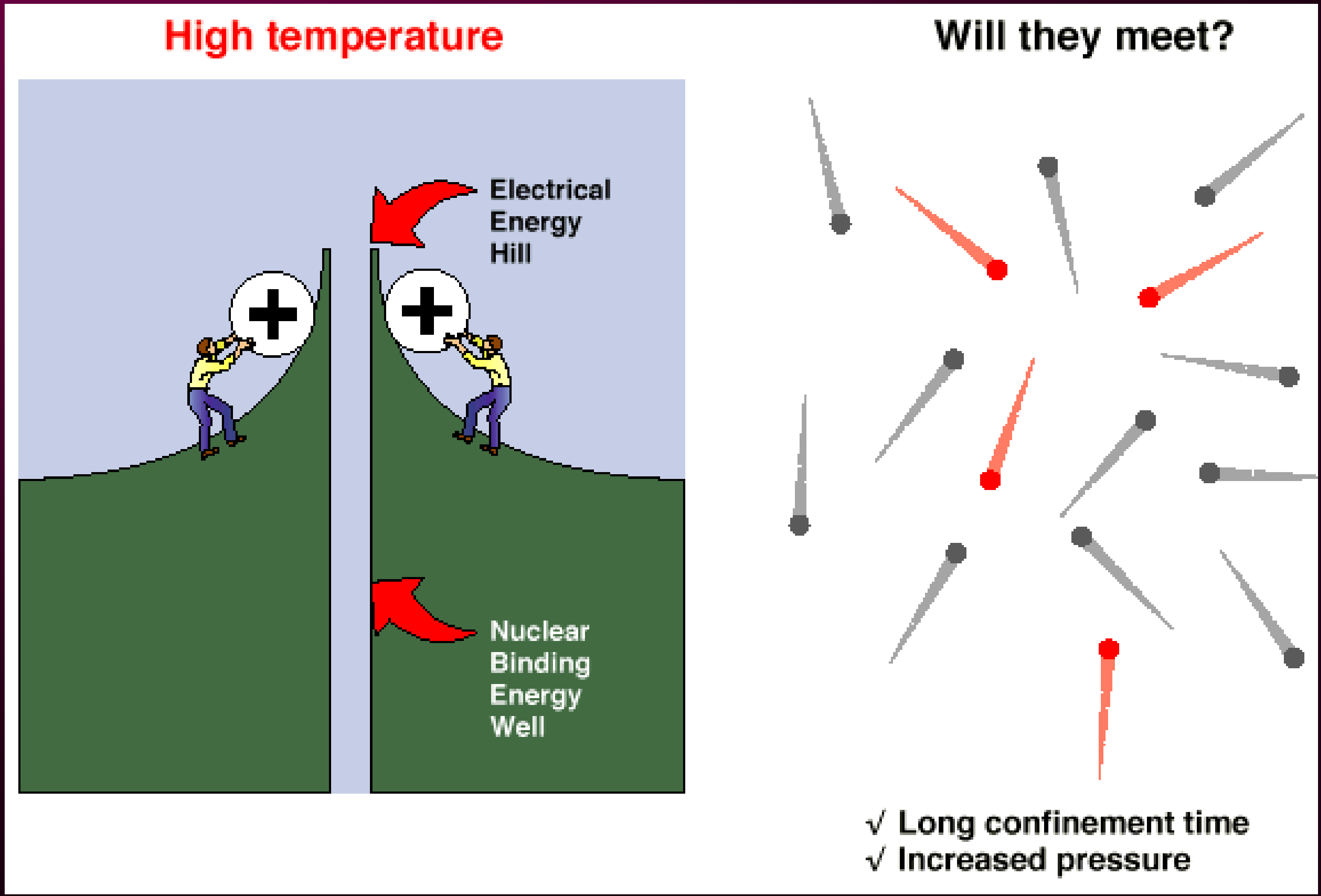
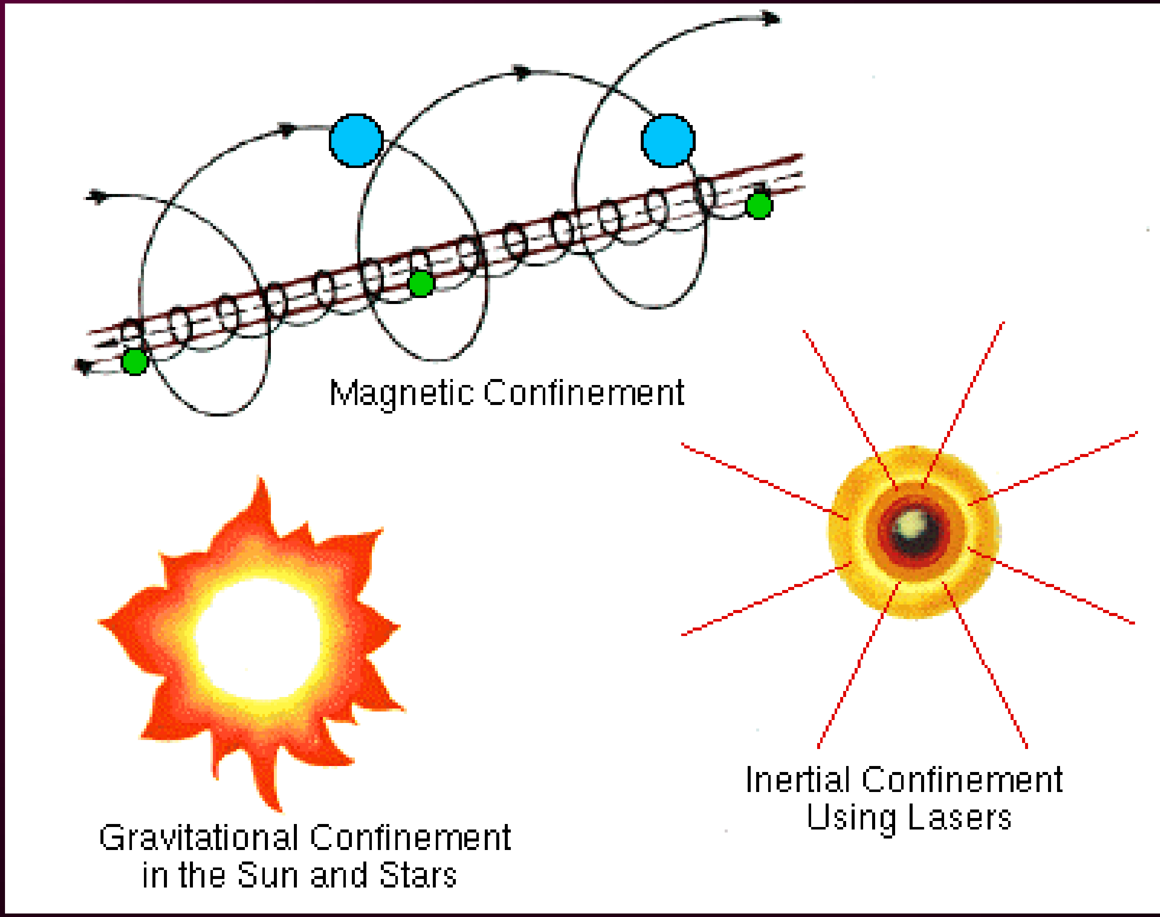
High temperatures and densities are needed



http://lasers.llnl.gov/lasers/education/talk.html

Methods for confinement

- Hot plasmas are confined with gravitational fields in stars.
- In fusion energy experiments magnetic fields and lasers are used to confine the hot plasma.



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What must be achieved to obtain fusion energy?

Contain a high temperature, T, high density, n, plasma for a long enough time, τ, to achieve ignition (power out >> power in).

A measure of plasma performance is thus given by:

$$nT\,\tau$$

density * temperature * confinement time

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Two major approaches to fusion (D–T)

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Magnetic confinement

Temperature ≈ 10^8 °C (10 keV)

$\eta\tau \approx 10^{15}$ Atoms ·seconds / cm^3

$\tau \approx$ 10 seconds (magnetic “bottle”)

$\eta \approx 10^{14}$ Atoms / cm^3 (10^{-5} times the density of air)

Inertial confinement

Temperature ≈ 10^8 °C (10 keV)

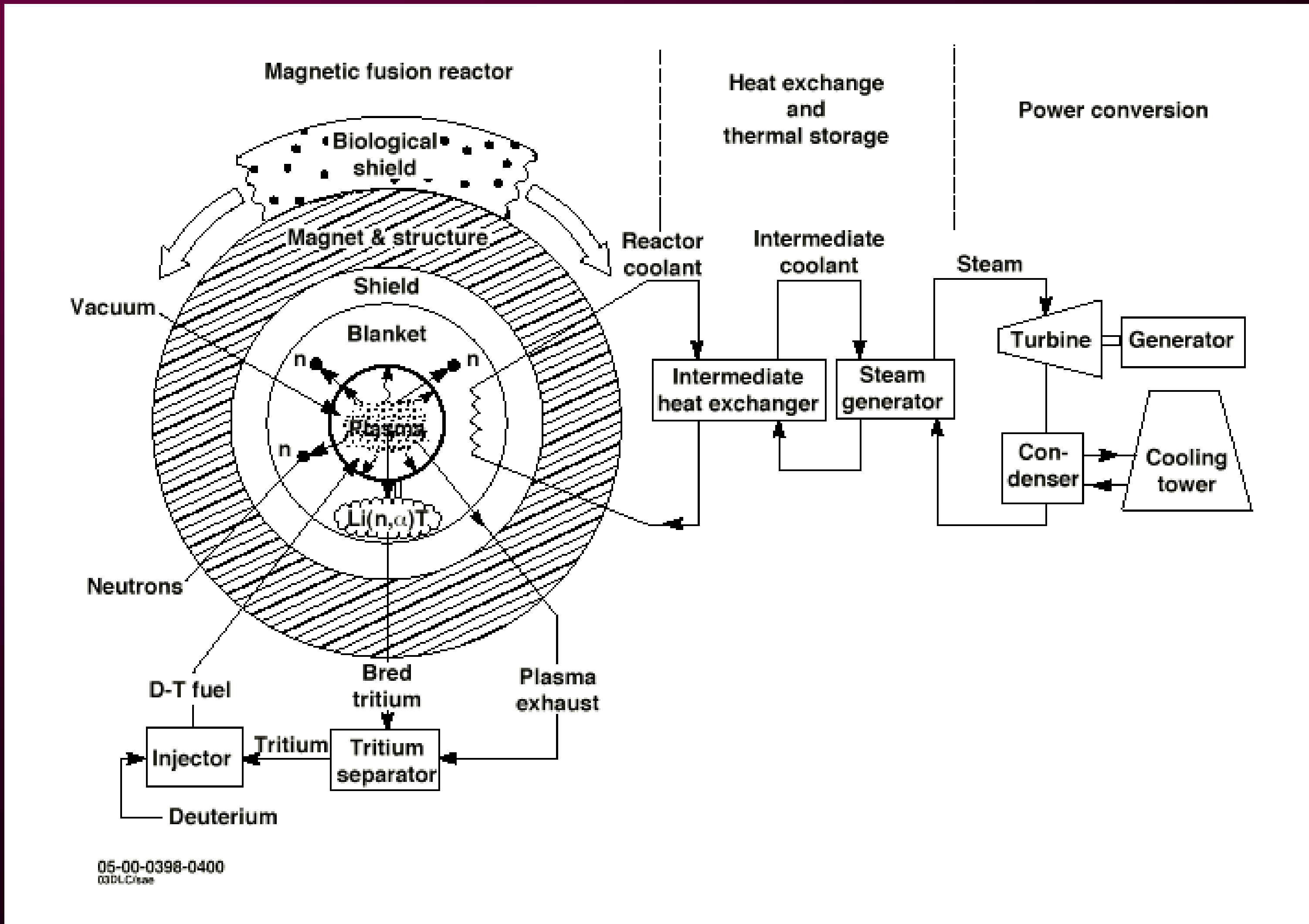
$\eta\tau \approx 10^{15}$ Atoms ·seconds / cm^3

$\tau \approx 3 \times 10^{-11}$ seconds (microexplosion, inertial “bottle”)

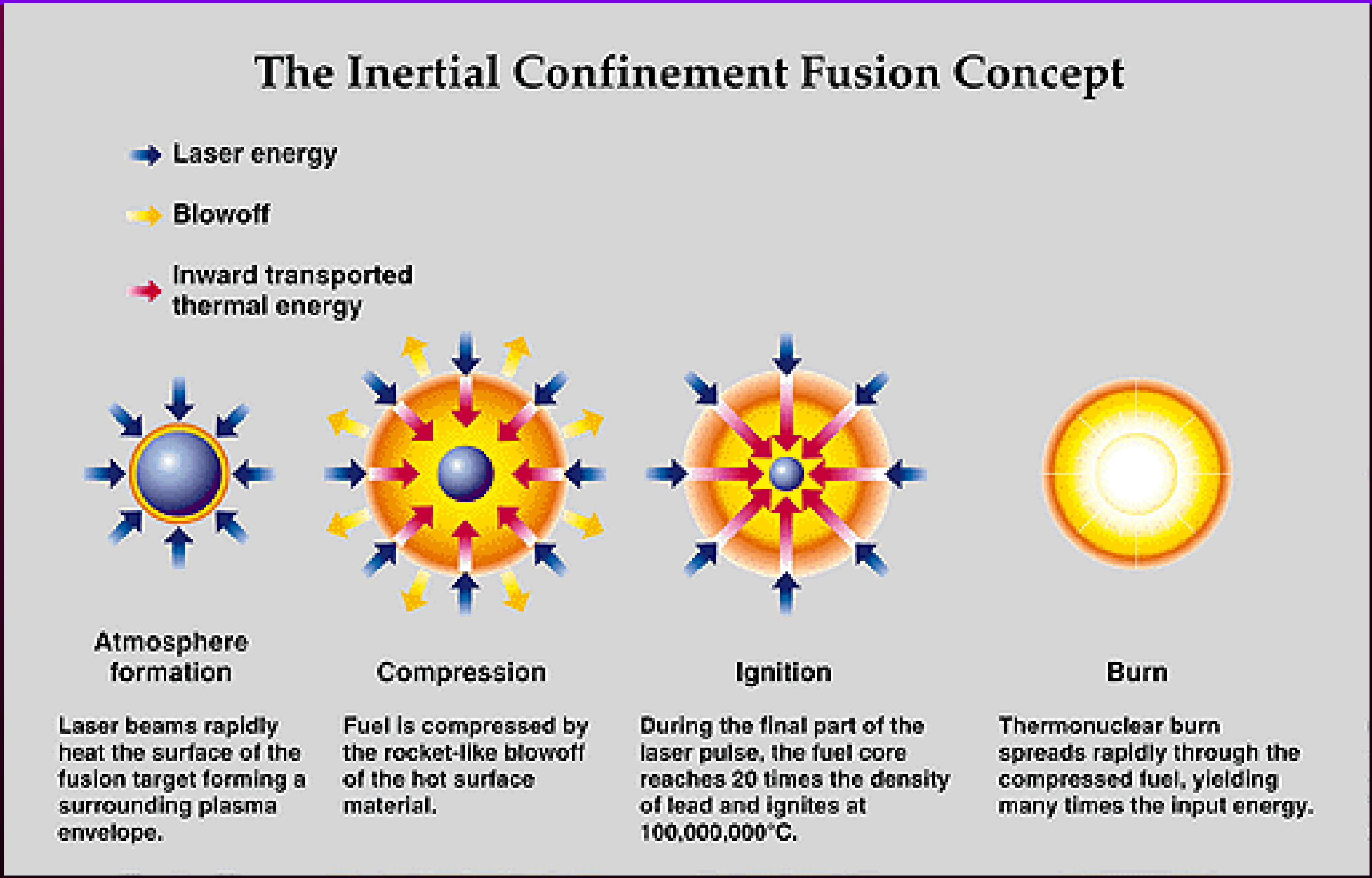
$\eta \approx 3 \times 10^{25}$ Atoms / cm^3 (12 times the density of lead!

~ 1000 times the density of liquid DT!)

Power Plant Schematic

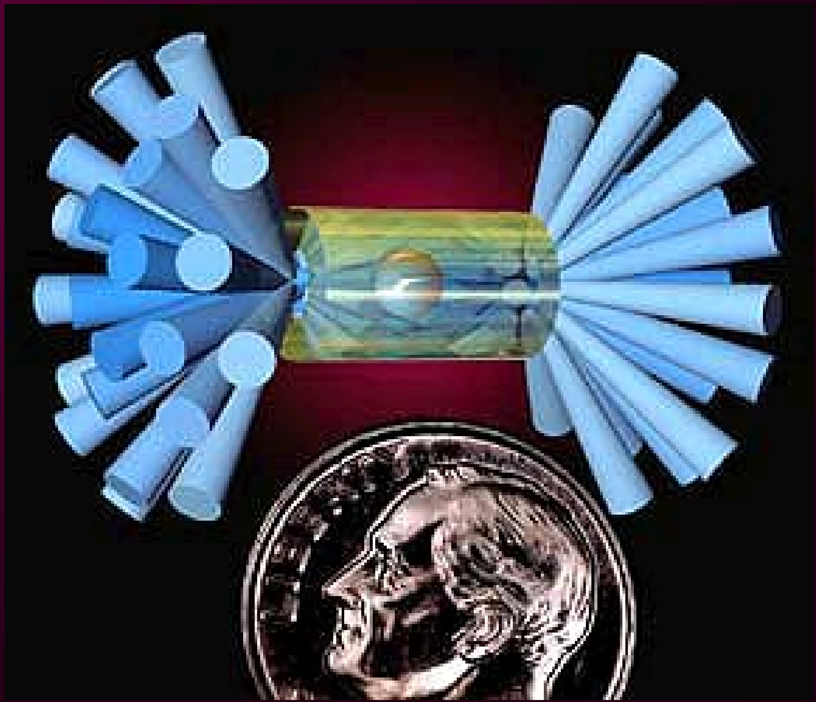


Controlling Fusion using Inertia

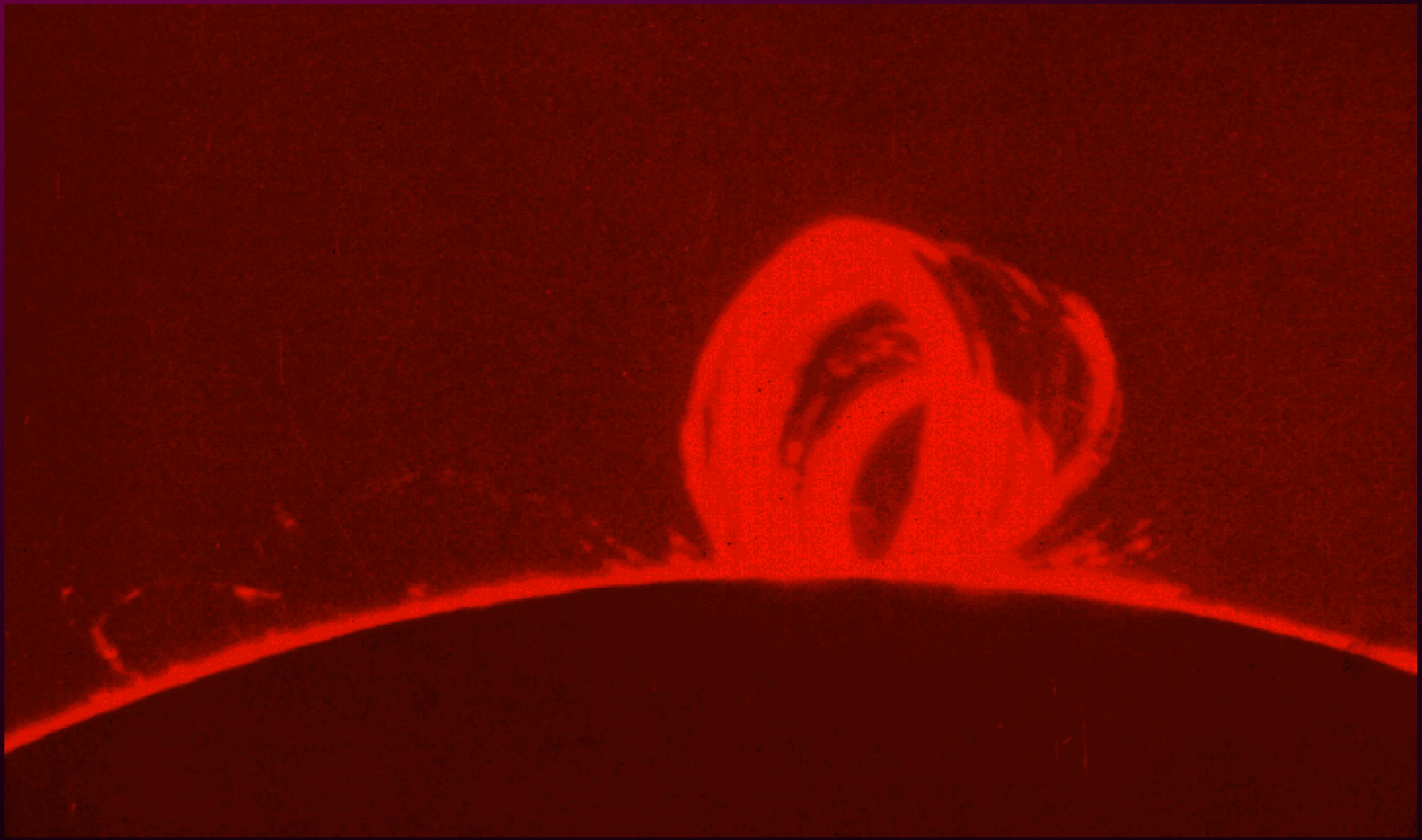


http://www-lasers.llnl.gov/lasers/nif/nif_ife.html#fusion

Direct vs Indirect Drive



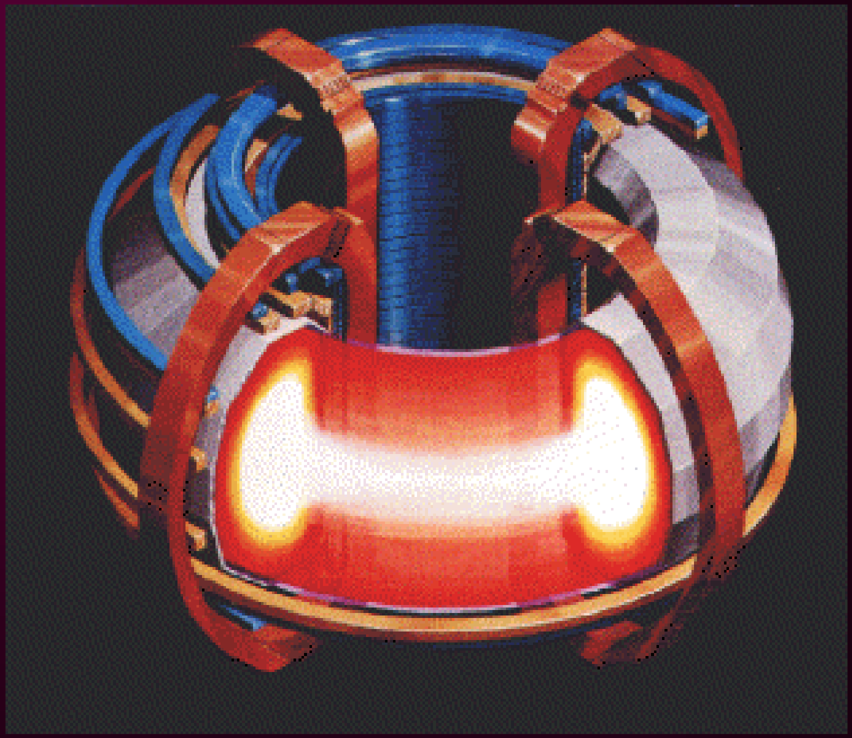
Particles in a Magnetic field



Controlling fusion with magnetic fields

Most magnetic confinement devices in use today have a toroidal shape.

Large magnetic fields are created by driving currents through coils wrapped around the torus.



http://demo-www.gat.com/

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Joint European Torus:
the largest confinement device ever built

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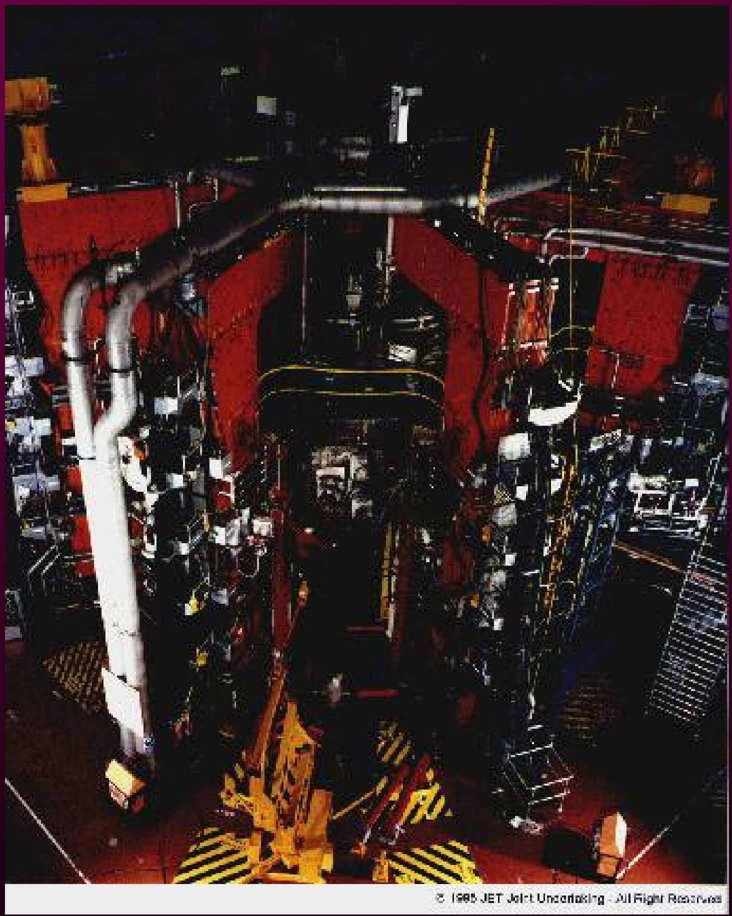
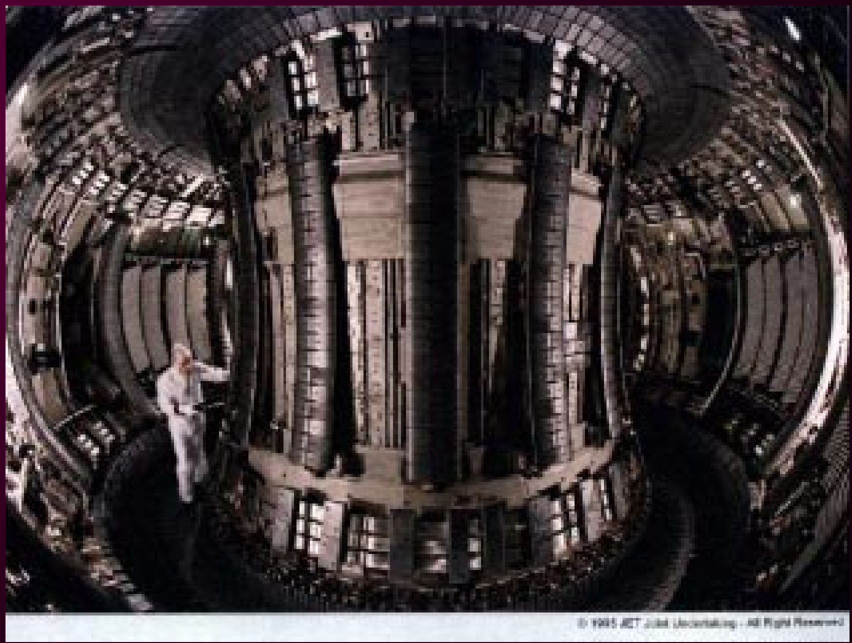


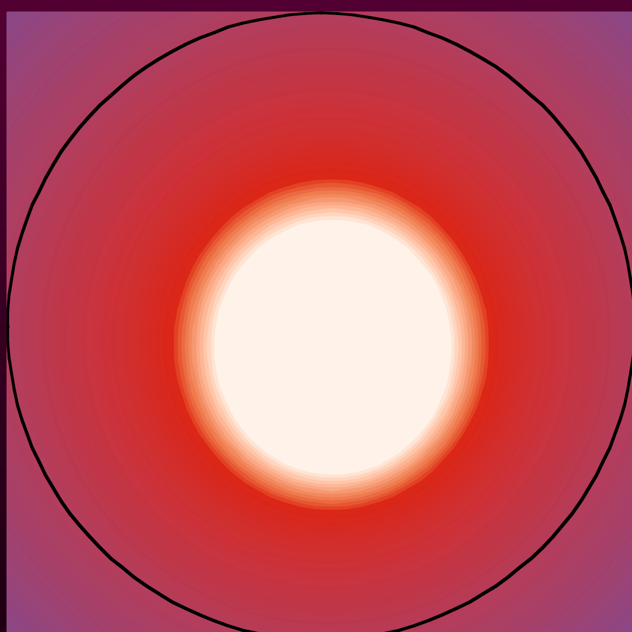
http://www.jet.uk/

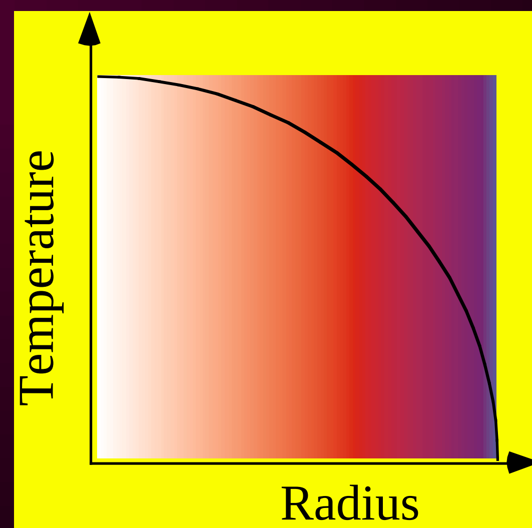


http://www.jet.uk/

Need to control temperature and density

We need the core hot enough for fusion, yet the edge cool enough not to melt the walls





But nature abhors gradients:

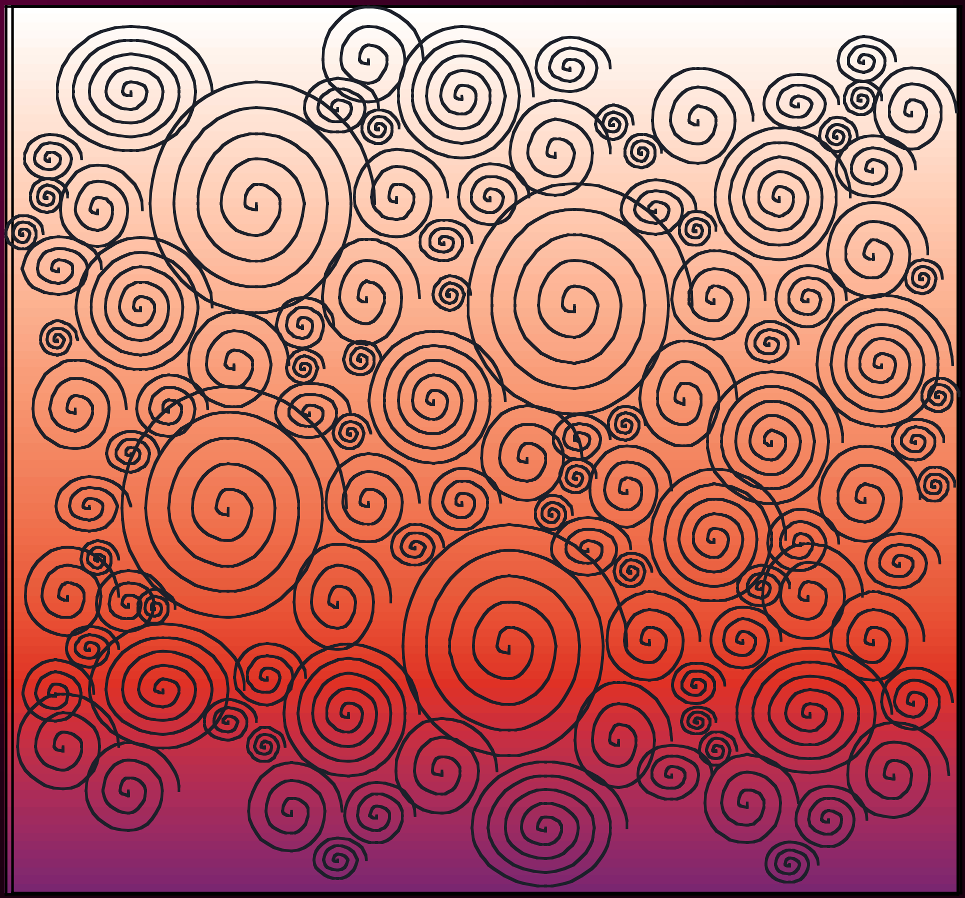
Whenever a slope (gradient) gets too steep, nature finds a way to flatten it out

- Mountains get eroded
- sand and snow avalanche
- turbulence grows to flatten steep slopes in plasmas

We need to control the turbulence

Turbulence moves things down the slope

The turbulence swirls (eddies) move the heat and density toward the edge



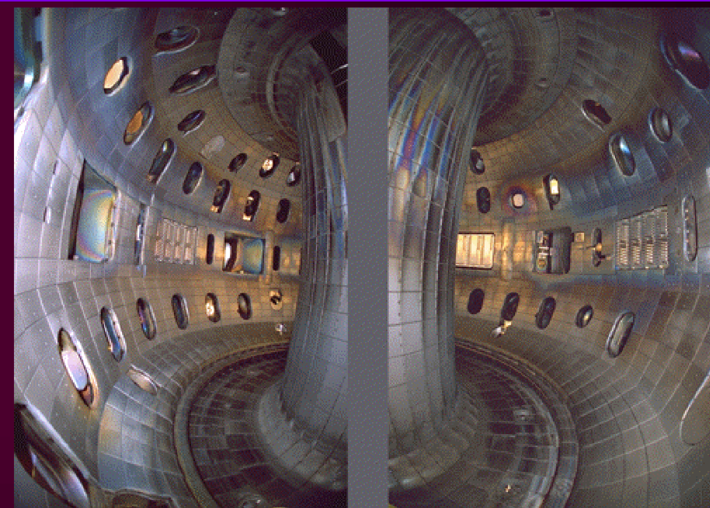
Challenges on the path to Fusion

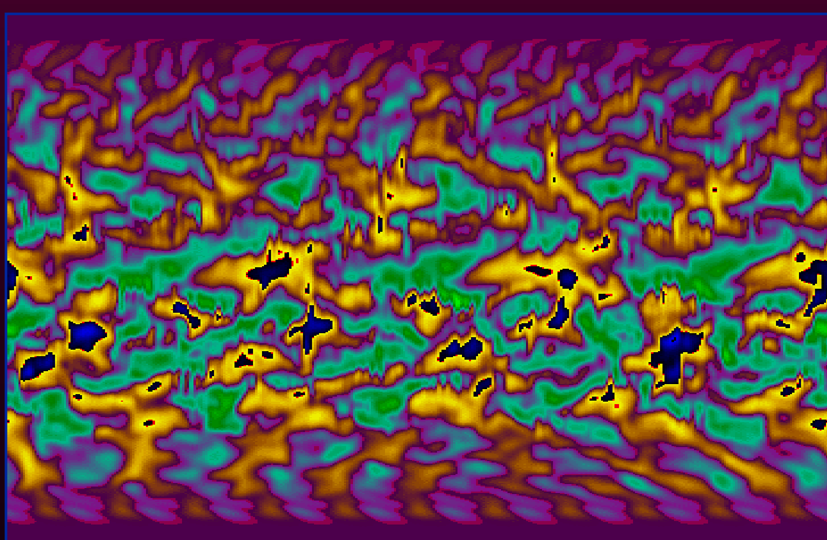
Heating

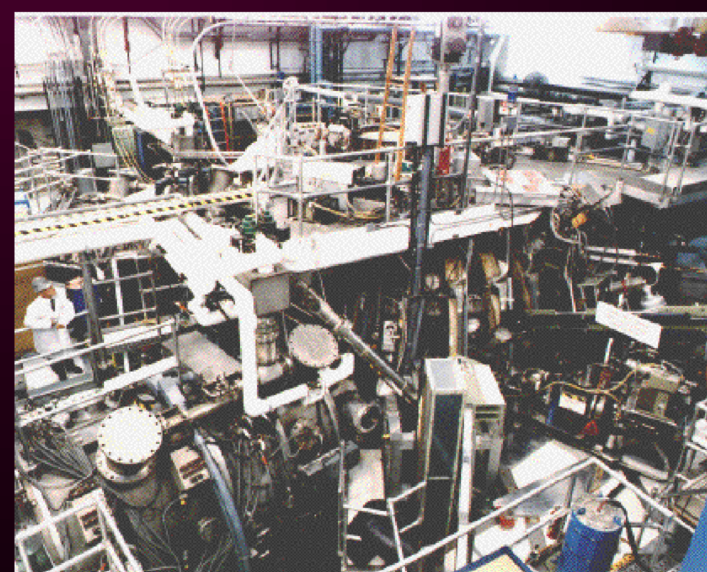
Fueling

Confinement

Plasma physics is on the leading edge of technology

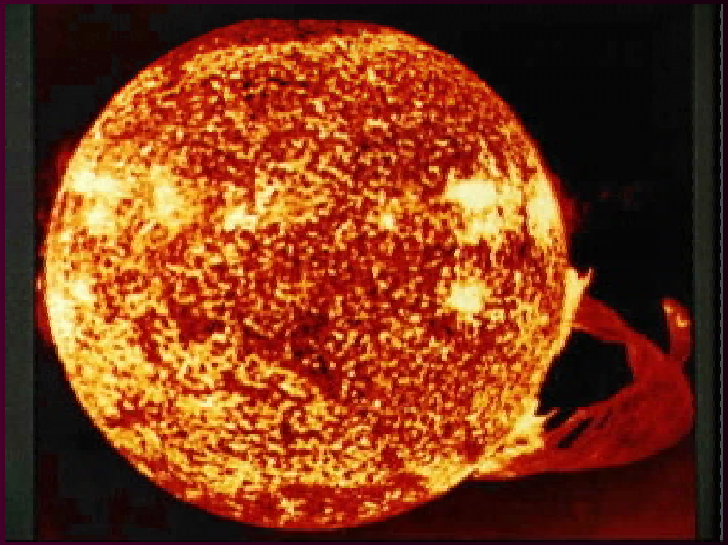




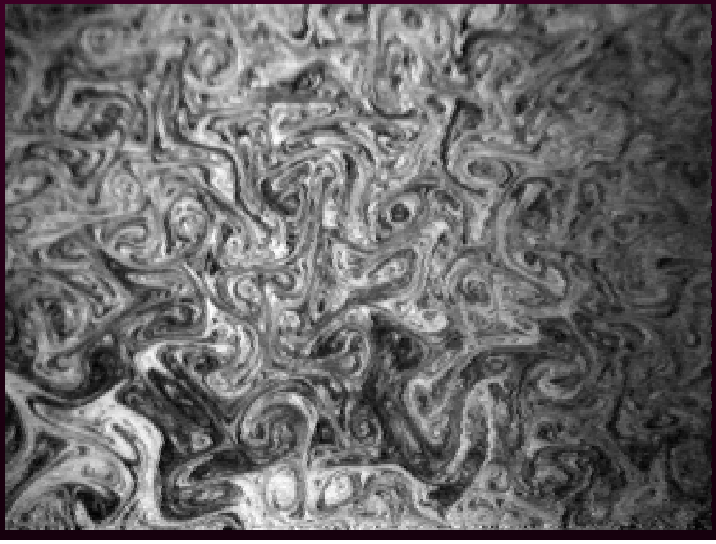


Turbulence is everywhere in nature

Turbulent transport is one of the main methods for relaxing gradients

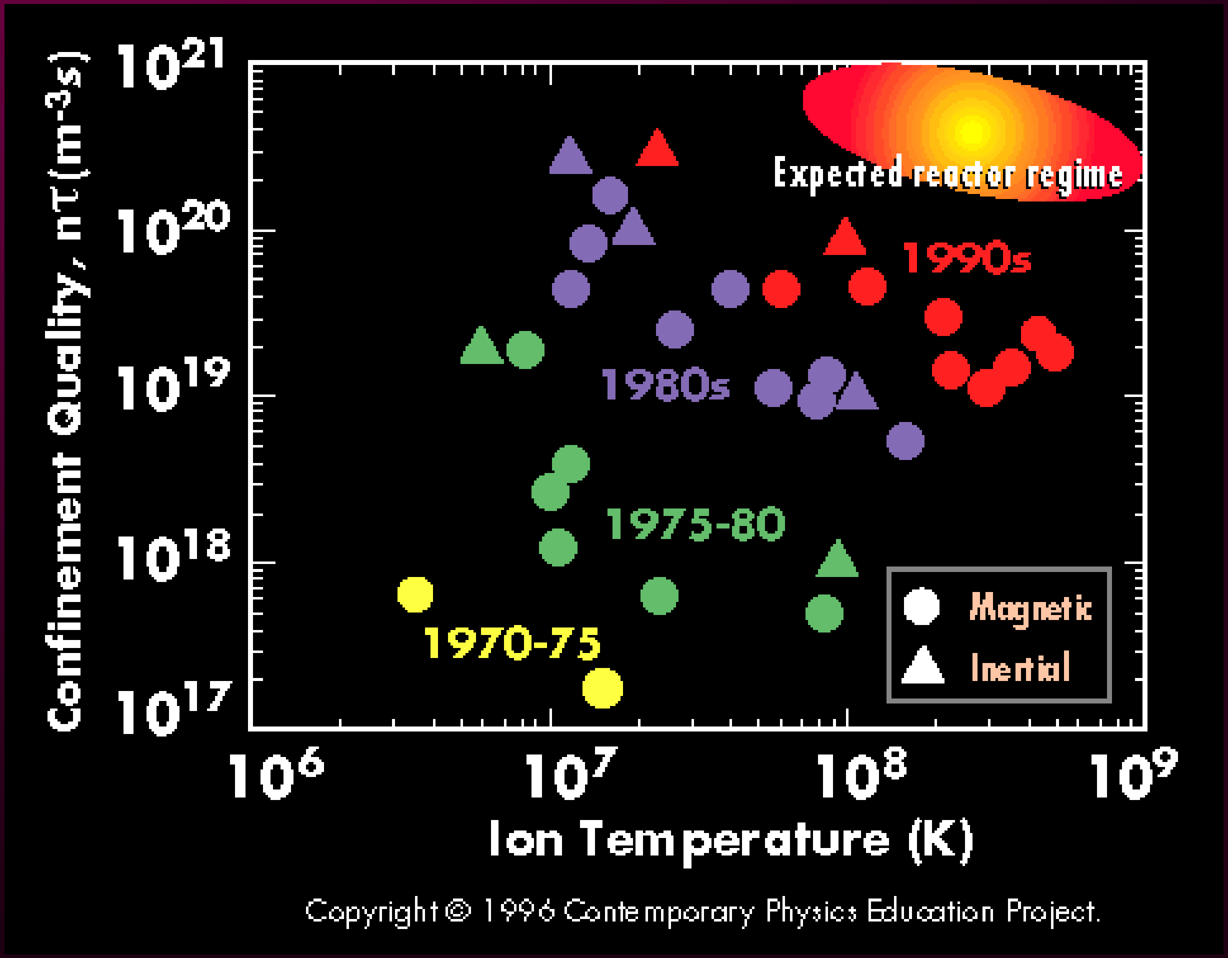


ftp://mojave.wr.usgs.gov/pub/spurr/Spurr.html



http://info.pitt.edu/~maarten/work/soapflow/soapjpgs/dense.turb.JPG

Progress towards fusion energy



http://FusEDWeb.pppl.gov/CPEP/Chart_pages/6.Results.html

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Web References

Fusion energy and plasma educational sites

http://FusionEd.gat.com/ General Atomics

http://FusEdWeb.pppl.gov/ Princeton Plasma Physics Laboratory

http://lasers.llnl.gov/lasers/education/ed.html Lawrence Livermore National Laboratory

http://www.jet.uk/ Joint European Torus

http://www.ornl.gov/fed/fedhome.html/ Oak Ridge National Lab

http://www.ornl.gov/fed/theory/Theory_Home_page.html

http://www.ornl.gov/fed/mhd/mhd.html/ Oak Ridge National Lab

Astrophysics sites

http://umbra.nascom.nasa.gov/spd/ NASA Space Science

http://www.seds.org/billa/tnp/ The Nine Planets

http://www.stsci.edu:80/ Space Telescope Science Institute

http://bang.lanl.gov/solarsys/ Views of the Solar System

http://www.gi.alaska.edu/ Geophysical Institute (Aurora and Sprite info)

Email me at: ffden@uaf.edu

2-D Turbulence

A flowing Soap film is an example of a 2-D system which can exhibit turbulence.

A magnetically confined plasma also exhibits 2-D turbulence because of the magnetic field.

Demo based on model from Univ. of Pittsburgh

For instructions see:
http://info.pitt.edu/~maarten/work/soapflow/howto/howto.html