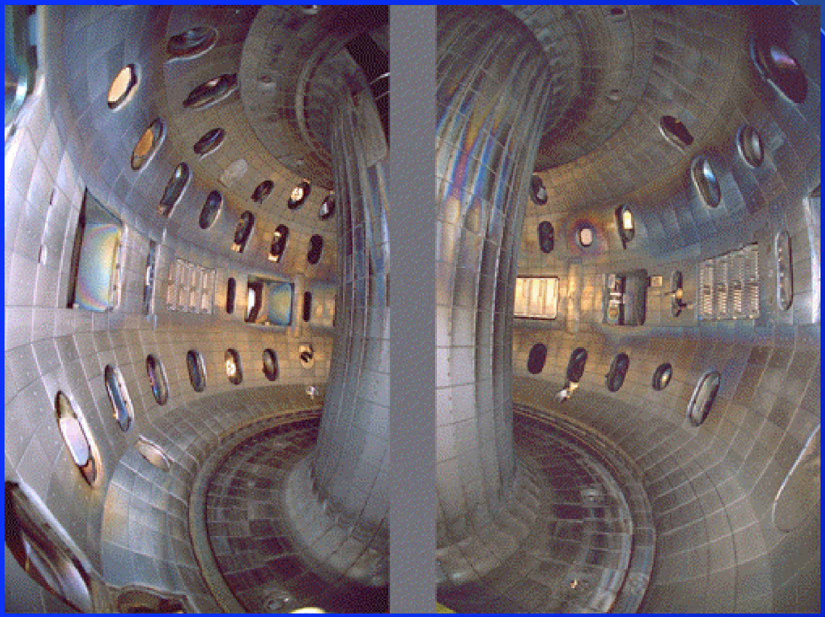
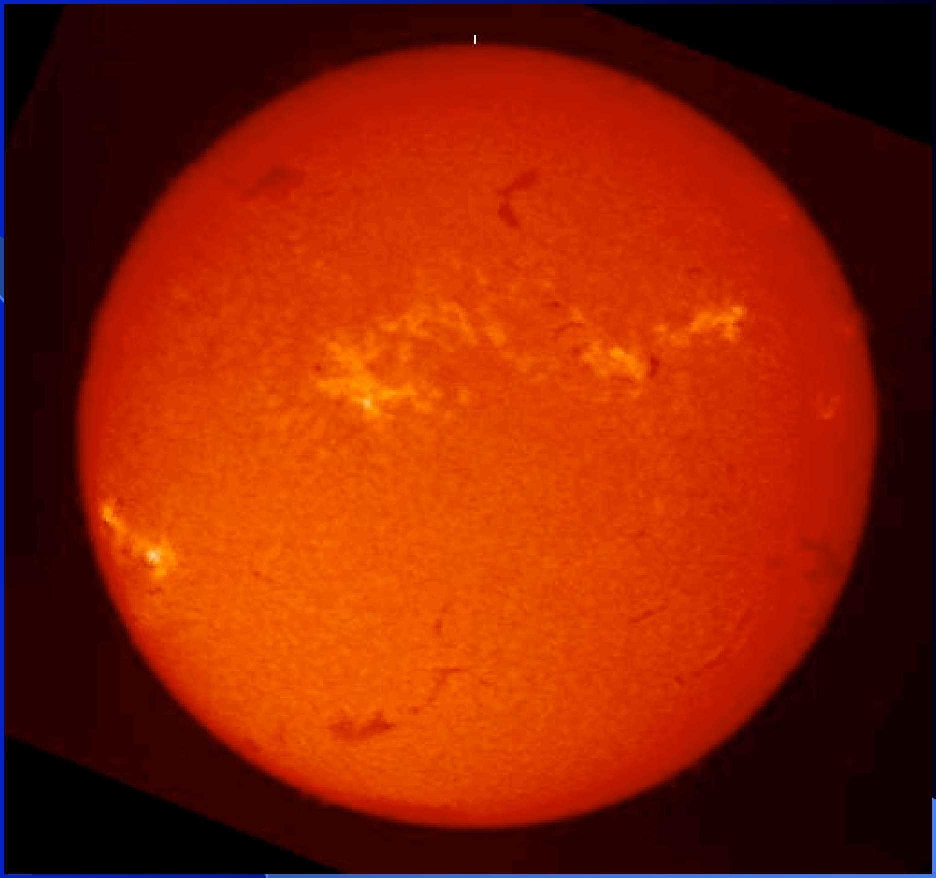
The following slide show is a compilation of slides from many previous similar slide shows that have been produced by different members of the fusion and plasma physics education community. We realize that some of the information contained herein must be updated. Please send comments, complaints, and suggestions to: rick.lee@gat.com. This slide show is intended to be used by students and teachers; downloading this file for educational purposes is highly encouraged.

Plasma: the 4th State of Matter and a Path to Fusion Energy

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





Outline

- What is a plasma?
- Where do we find them?
- Why are we interested in them?
  - Fusion energy
  - Astrophysics
  - Plasma processing

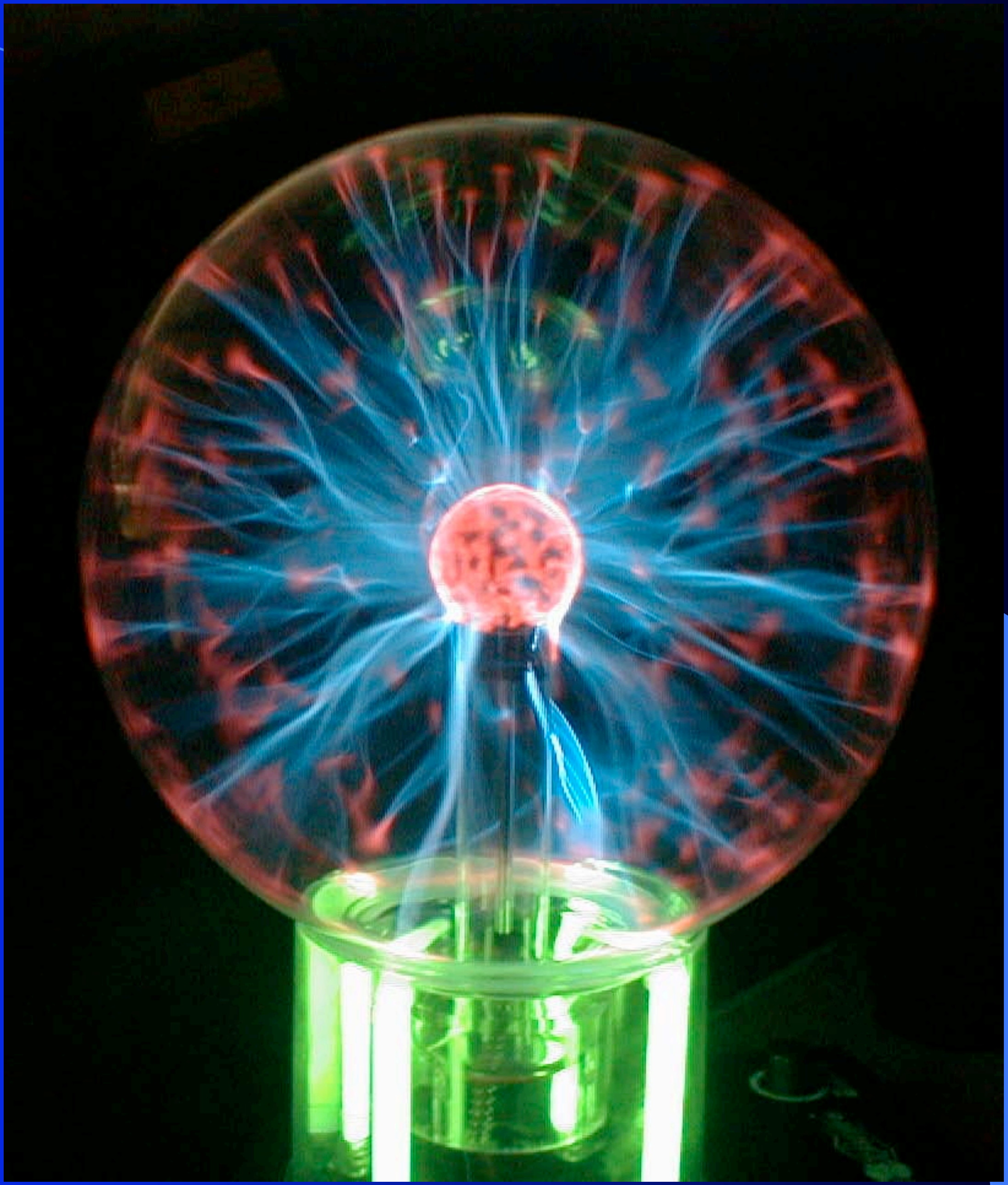
What is a plasma?

- A plasma is an ionized gas.
- Plasma is called the "fourth state of matter."
- Much of the mass of the universe is in the plasma state.
- 'Plasma' was coined by Tonks and Langmuir in (1929):

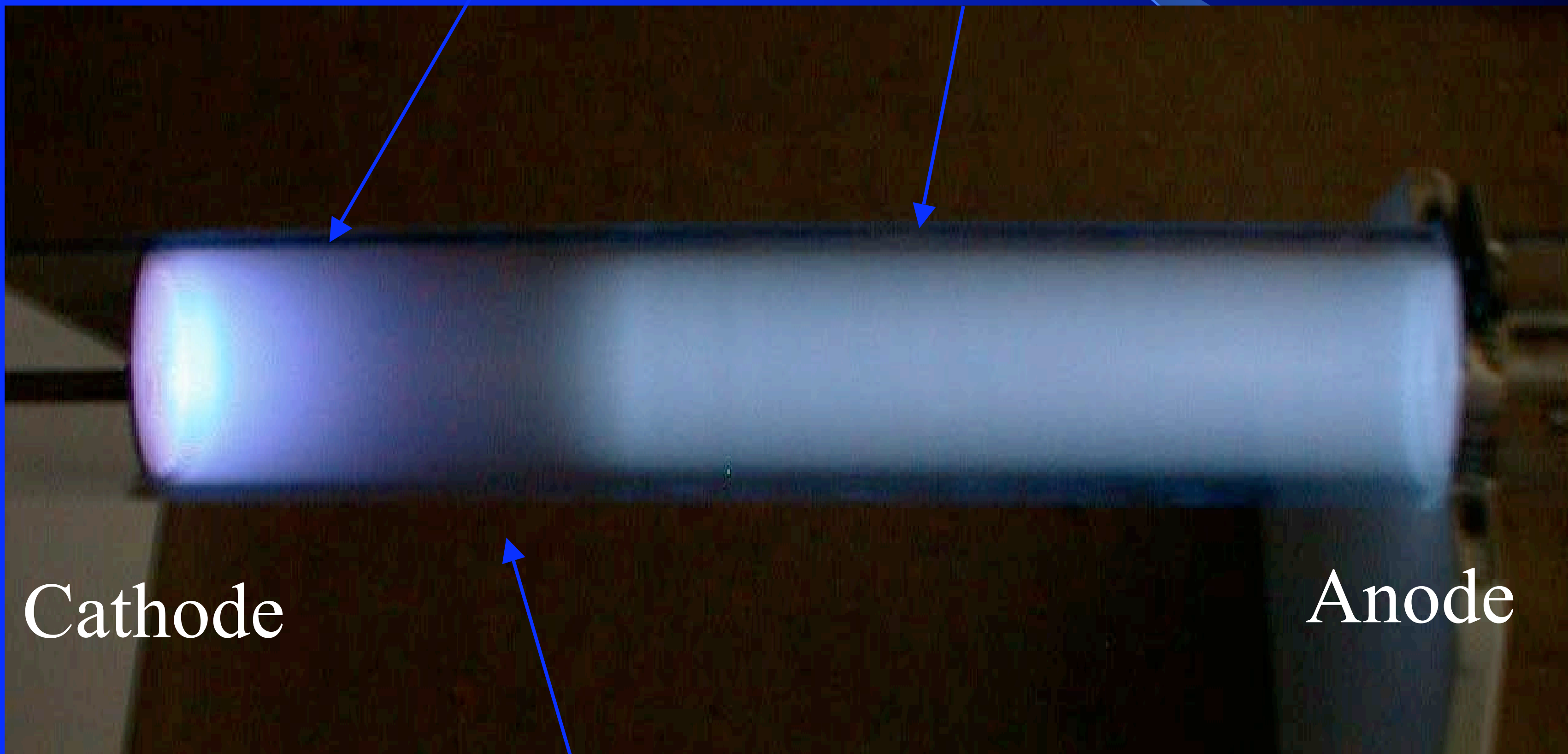
  "...when the electrons oscillate, the positive ions behave like a rigid jelly..."

Commercial plasma balls contain mixtures of helium, neon, argon, and other gases. Once the power is switched on, some of the neutral gas molecules have one or more electrons ripped from them, thus producing

Plasma………

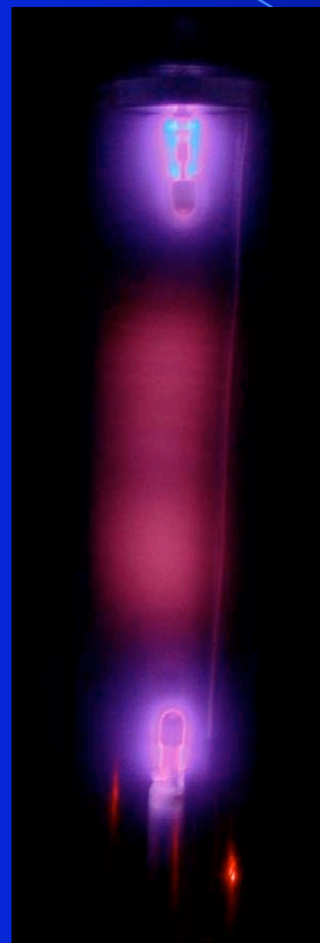


Classical DC Discharge in a Tube



Plasma is Affected by Density and Mean Free Path

High



Medium

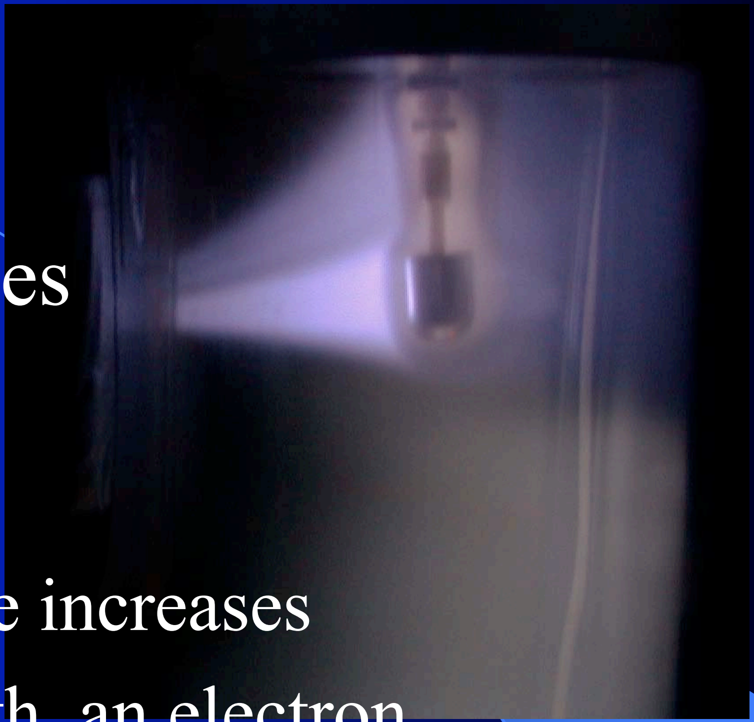
Low

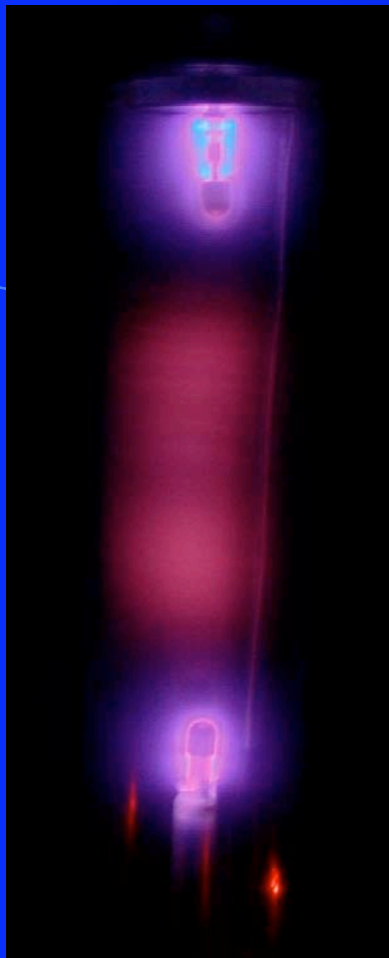
Small Light Bulb Plasma

- Same as large bulb except
  - Current density is higher
  - Sound is louder---what does this mean?
  - Colors are similar to the large bulb but more intense

Drift

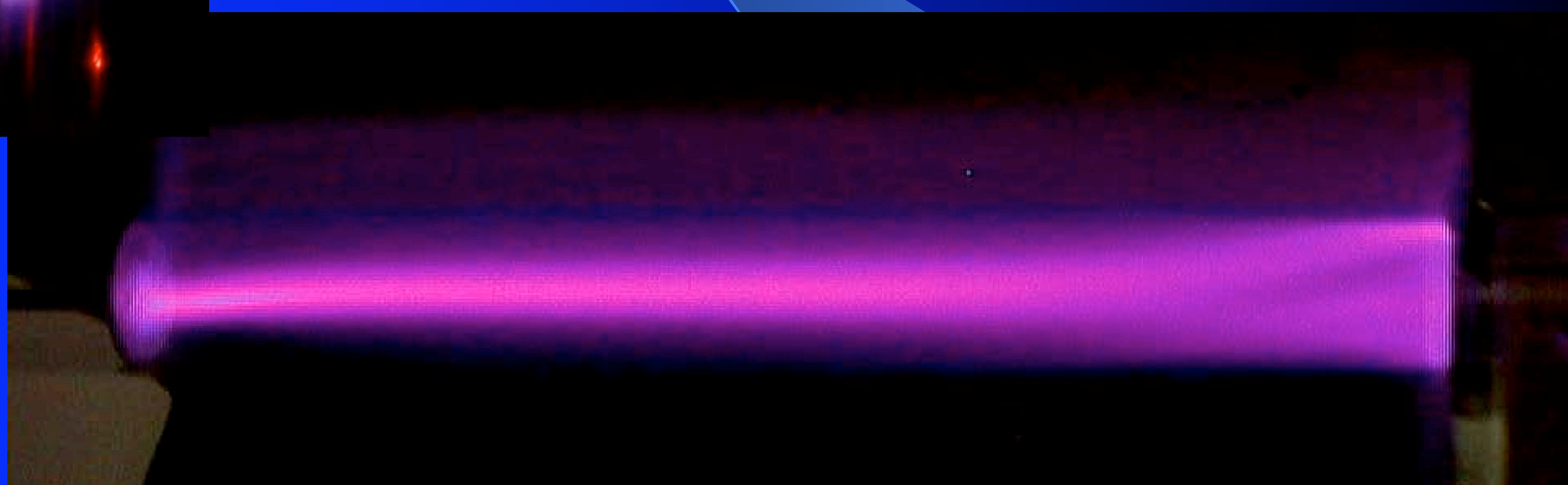
- The motion of charge particles
  - Random thermal activity
  - Electric field forces
  - Mobility decreases as pressure increases
  - After 1 electron mean free path, an electron may produce one electron-ion pair
  - Ion pairs grow exponentially with electron distance



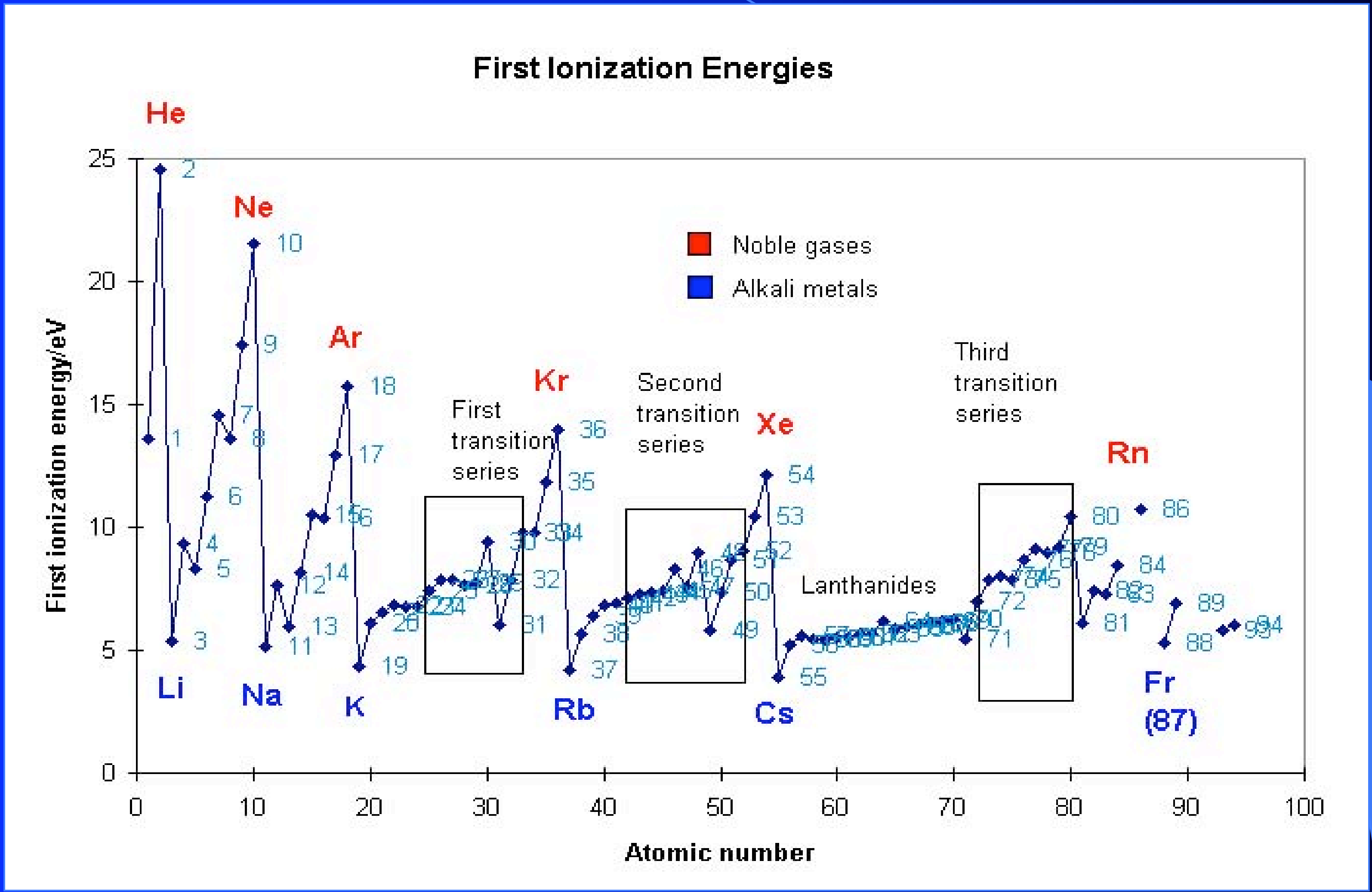


AC Plasma

- Typically used for lighting
- Both ends become the cathode and anode
- At high pressures the dark spaces are thin and current densities high



Ionization Energies

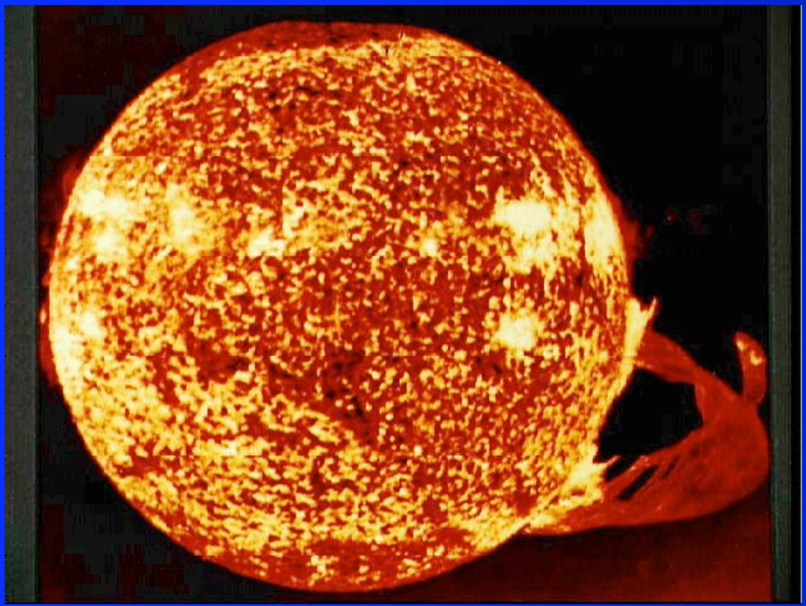


Where do we find plasmas?

- 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

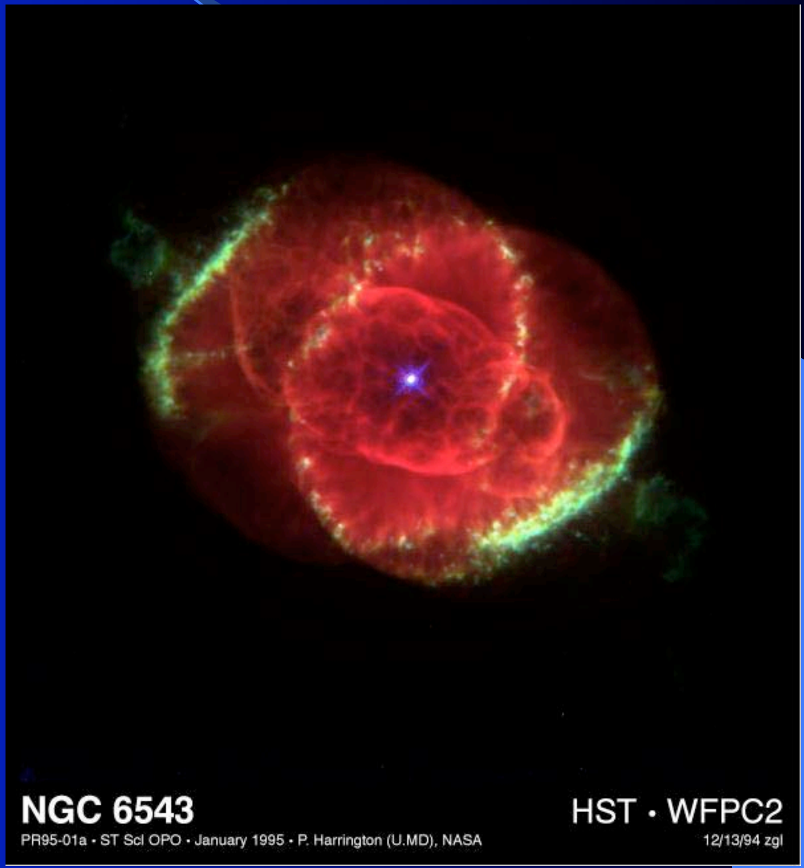
Astrophysical plasmas

The Sun



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

Catseye Nebula



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

Plasmas on Earth

Laboratory Experiments

http://FusEdWeb.pppl.gov/

Lightning

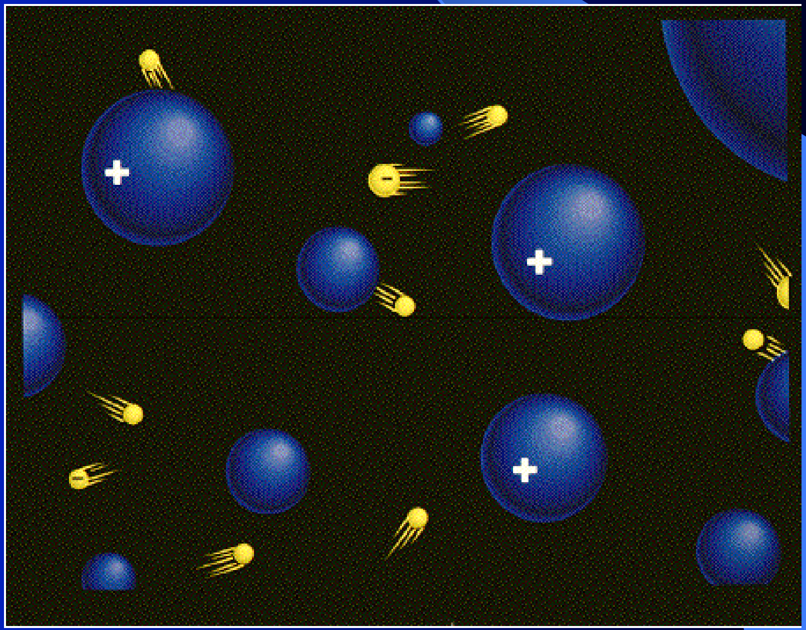
Why are we interested in plasmas?

- 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

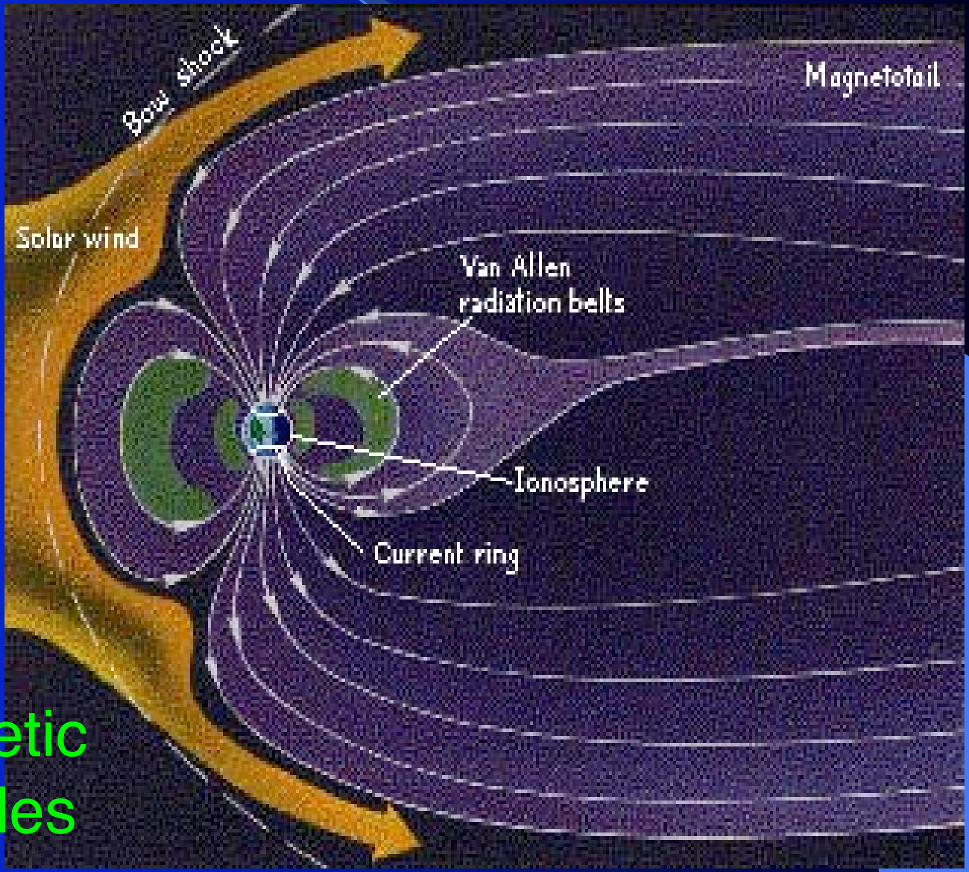


The solar wind (a plasma) interacts with the Earth's magnetic field

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

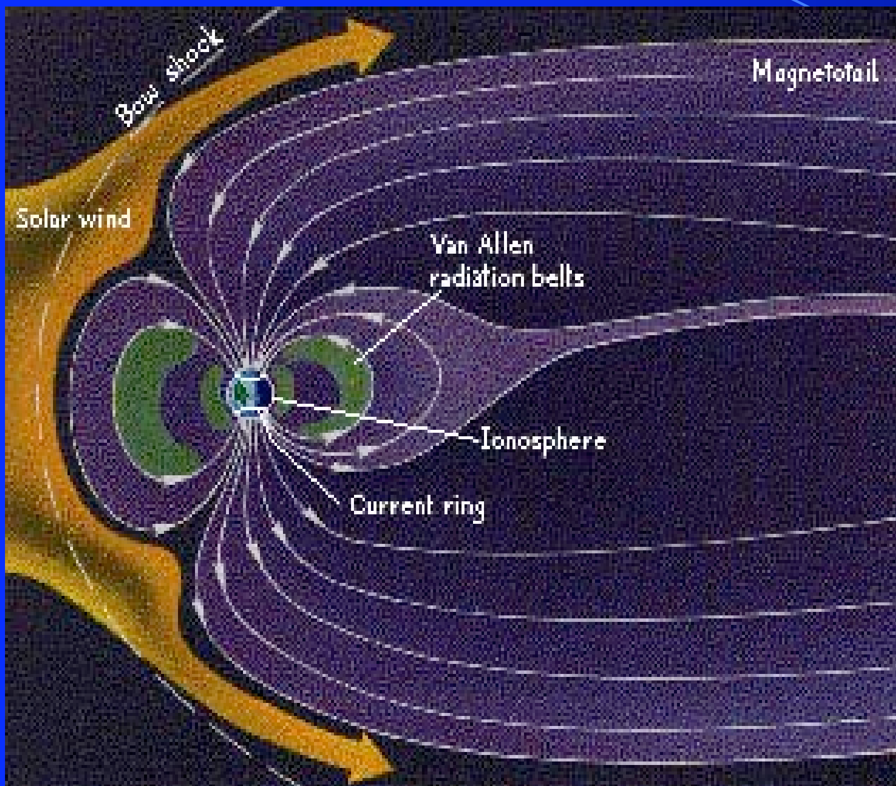
This solar wind causes the Earth's magnetic field to compress creating a shock wave called the Bow wave.

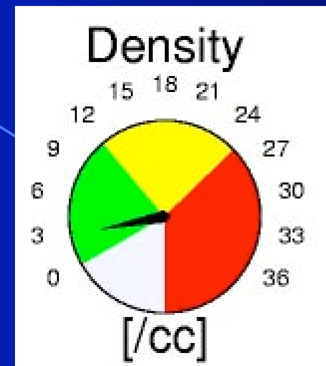
Particles trapped in the magnetic field may interact with molecules In the atmosphere to produce Aurora.

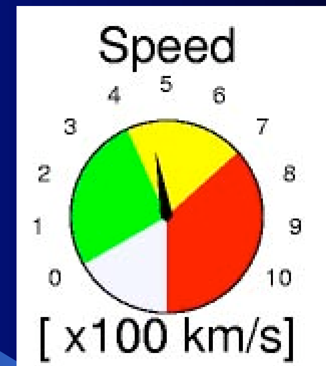


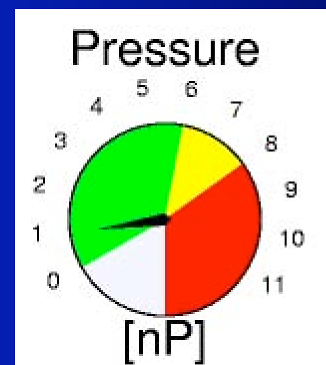
From Stars, James Kaler

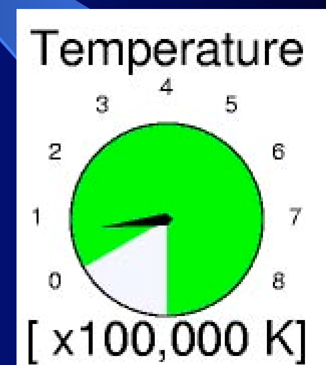
Solar Wind



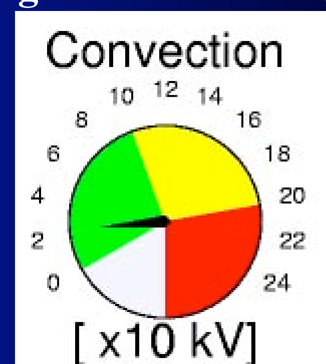




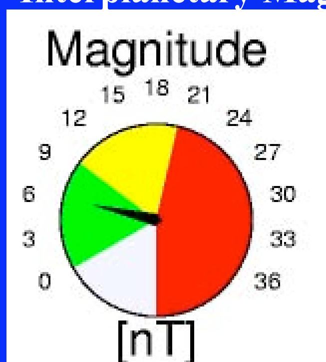


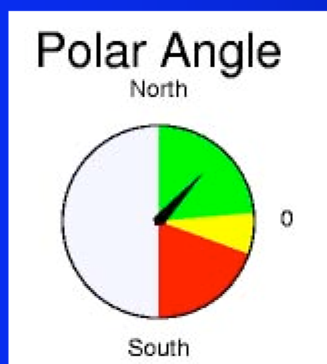


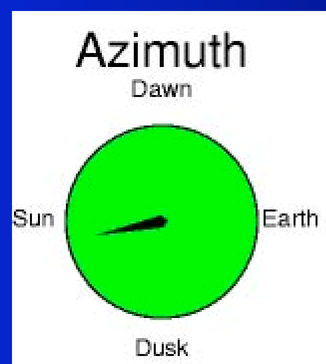
•Voltage Across Polar Cap



•Interplanetary Magnetic Field







•http://space.rice.edu/ISTP/dials.html

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

- The northern lights (aurora borealis)

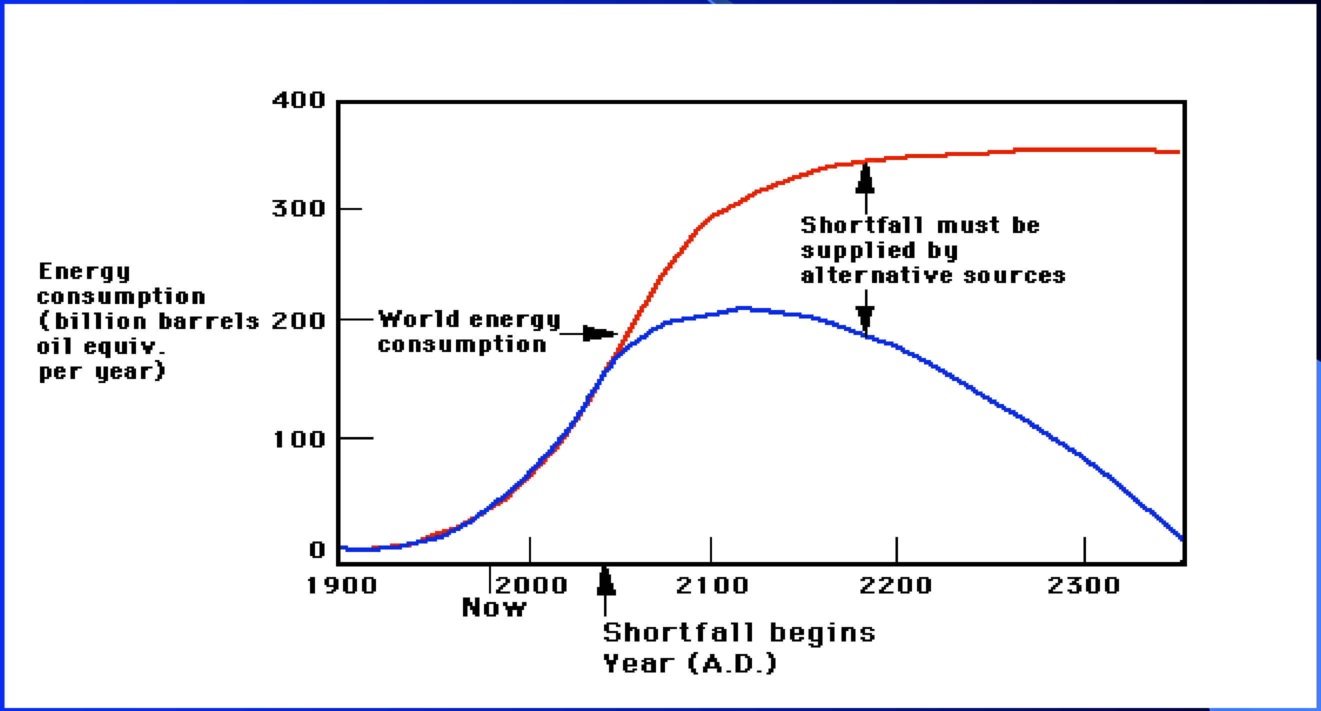
Photo by David Fritz
http://dac3.pfrr.alaska.edu:80/~pfrr/AURORA/INDEX.HTM

More on Fusion Energy

- The goal of achieving controlled fusion energy has prompted much study into plasma physics.
- 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.

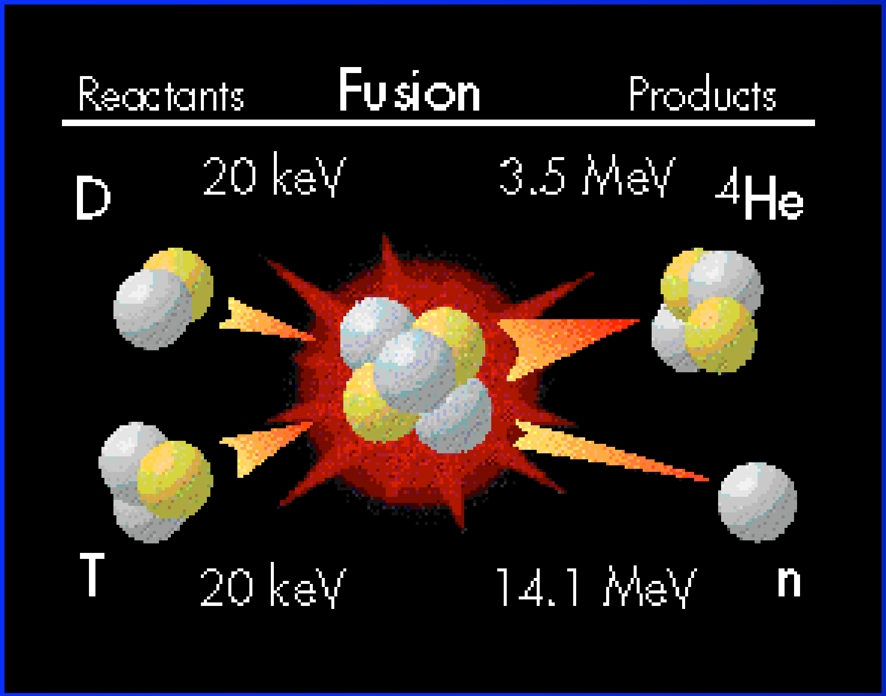
Why do we need new sources of energy?

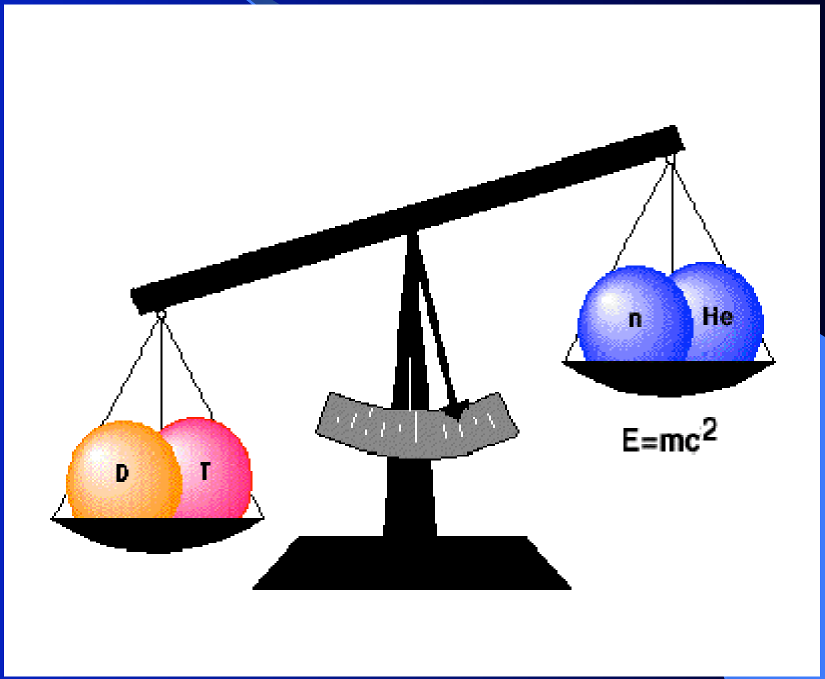
As the population increases, so does the demand for energy. However, we have limited resources in the form of fossil fuels and this energy source must supplemented by alternative long term sources, such as fusion.



http://fusioned.gat.com/

Mass goes into energy in fusion reaction





The small reduction in mass of the products compared to the mass of the reactants leads to very large energy production.

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

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

Fuel and waste products

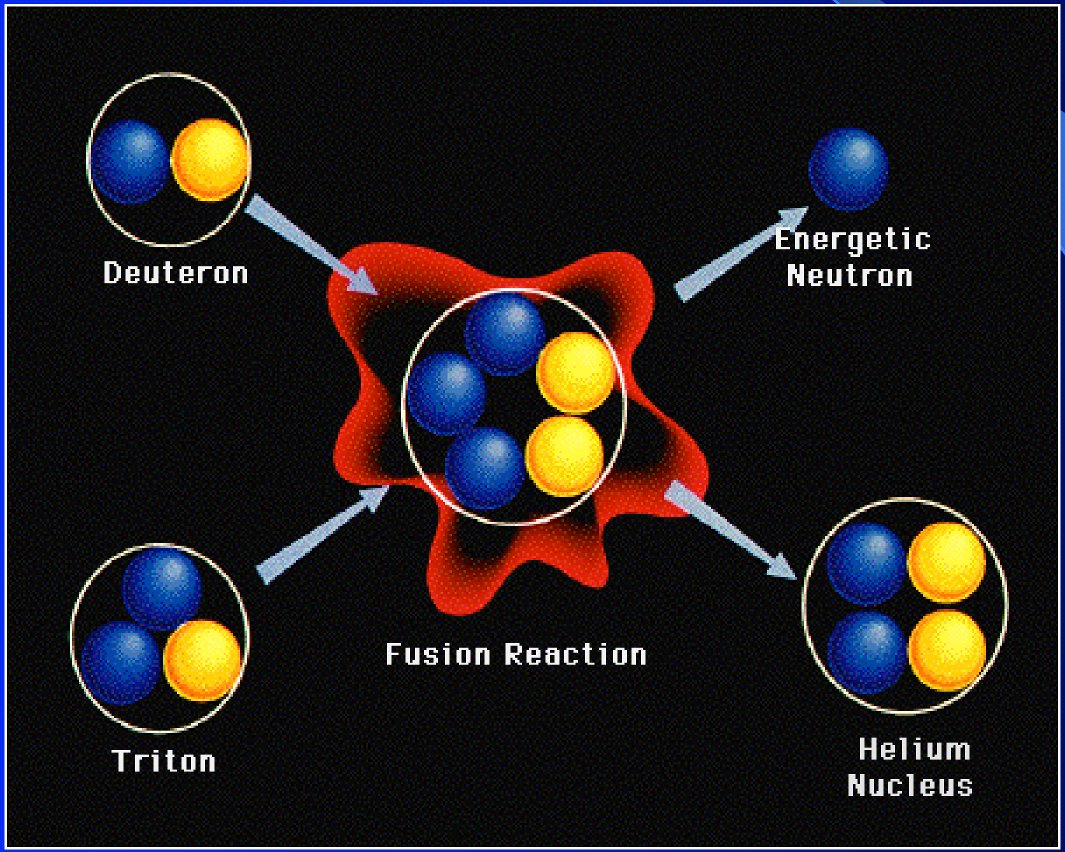
- **Fuel and waste for coal plants(most readily available energy source) vs D-T fusion plant**

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

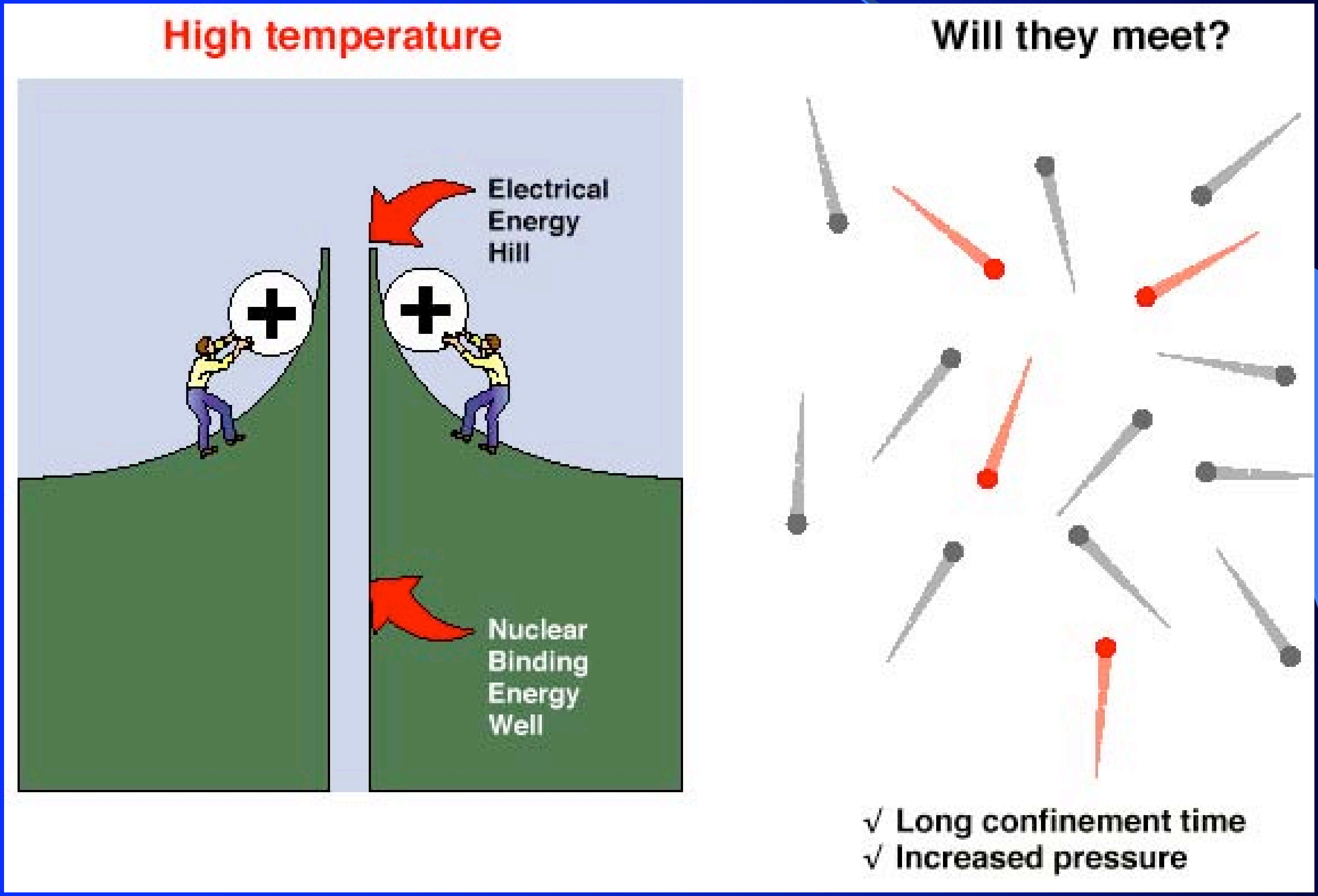
http://www.pppl.gov

Under the right conditions, deuterium and tritium combine to form helium, a neutron, and fusion energy



http://FusEdWeb.pppl.gov/

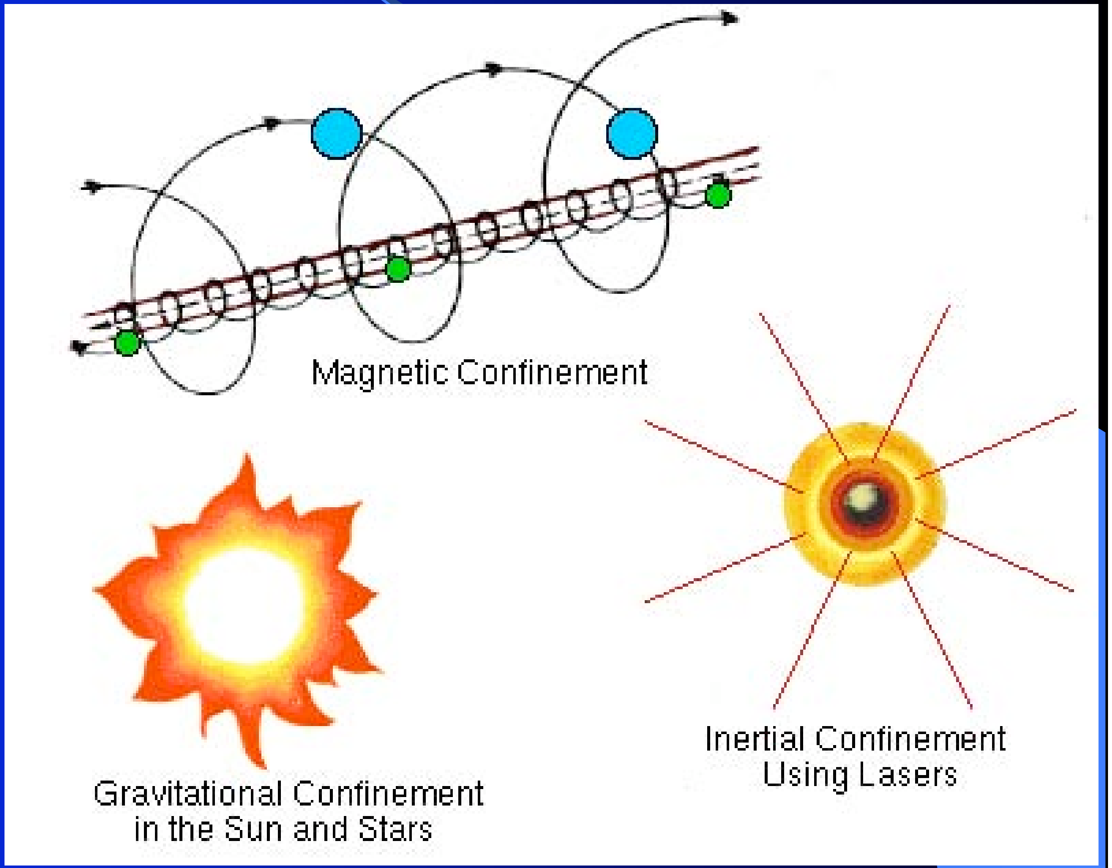
High temperatures and densities are needed



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 are used to confine hot plasma, and inertial confinement uses lasers.



http://FusEdWeb.pppl.gov/

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:

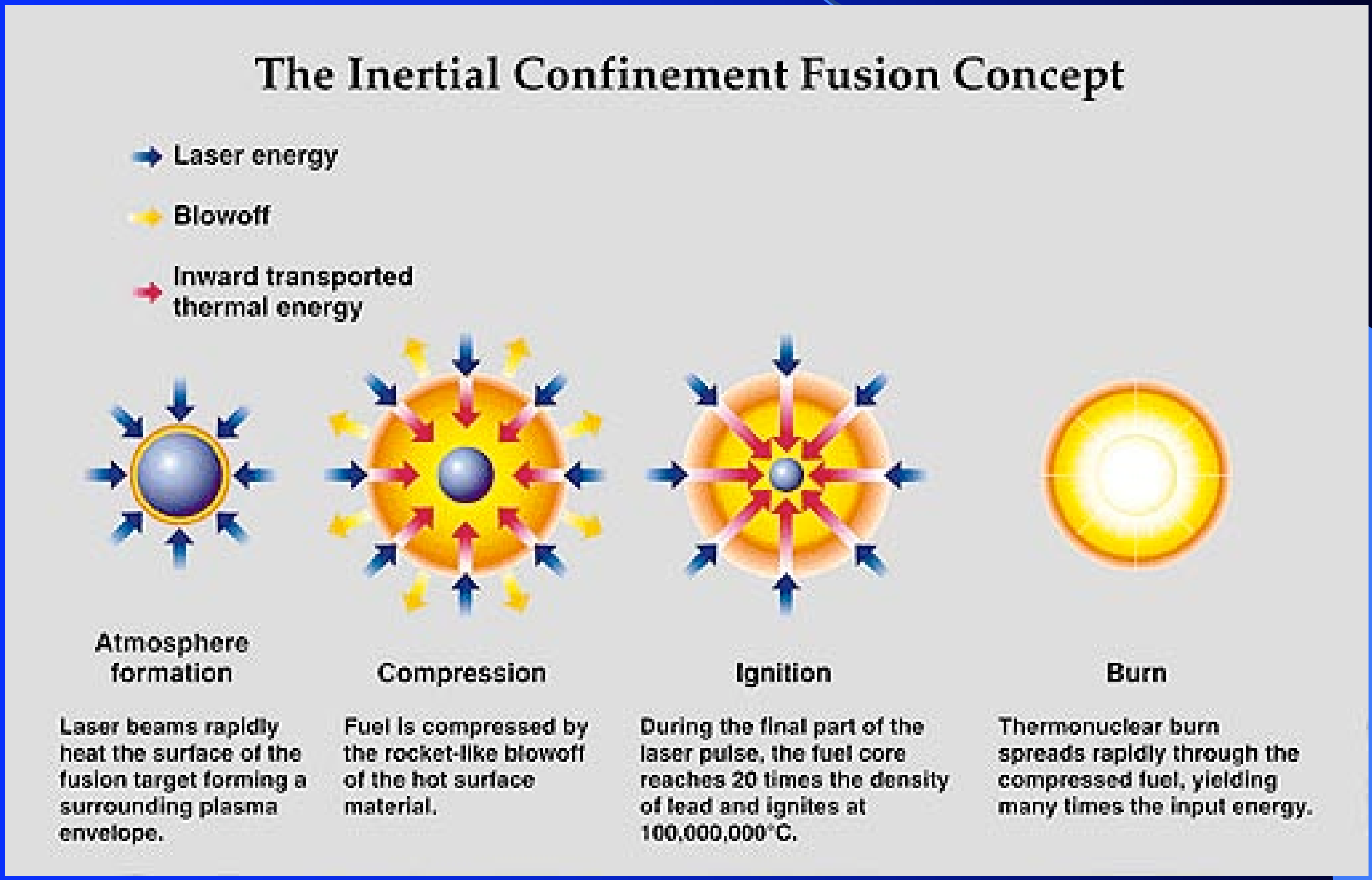
$$nT\tau$$

density * temperature * confinement time

Two major approaches to fusion (D–T)

- **Magnetic confinement**
  - **Temperature ≈ 10^{8} °C (10 keV)**
  - nτ ≈ **10^{15} atoms ·seconds / cm ^{3}**
  - τ ≈ **10 seconds (magnetic "bottle")**
  - n ≈ **10^{14} atoms / cm ^{3} (10^{-5} times the density of air)**
- **Inertial confinement**
  - **Temperature ≈ 10^{8} °C (10 keV)**
  - nτ ≈ **10^{15} Atoms ·seconds / cm ^{3}**
  - τ ≈ **3 × 10^{-11} seconds (microexplosion, inertial "bottle")**
  - n ≈ **3 × 10^{25} Atoms / cm ^{3} (12 times the density of lead!**
  - **~ 1000 times the density of liquid DT!)**

Controlling Fusion using Inertia

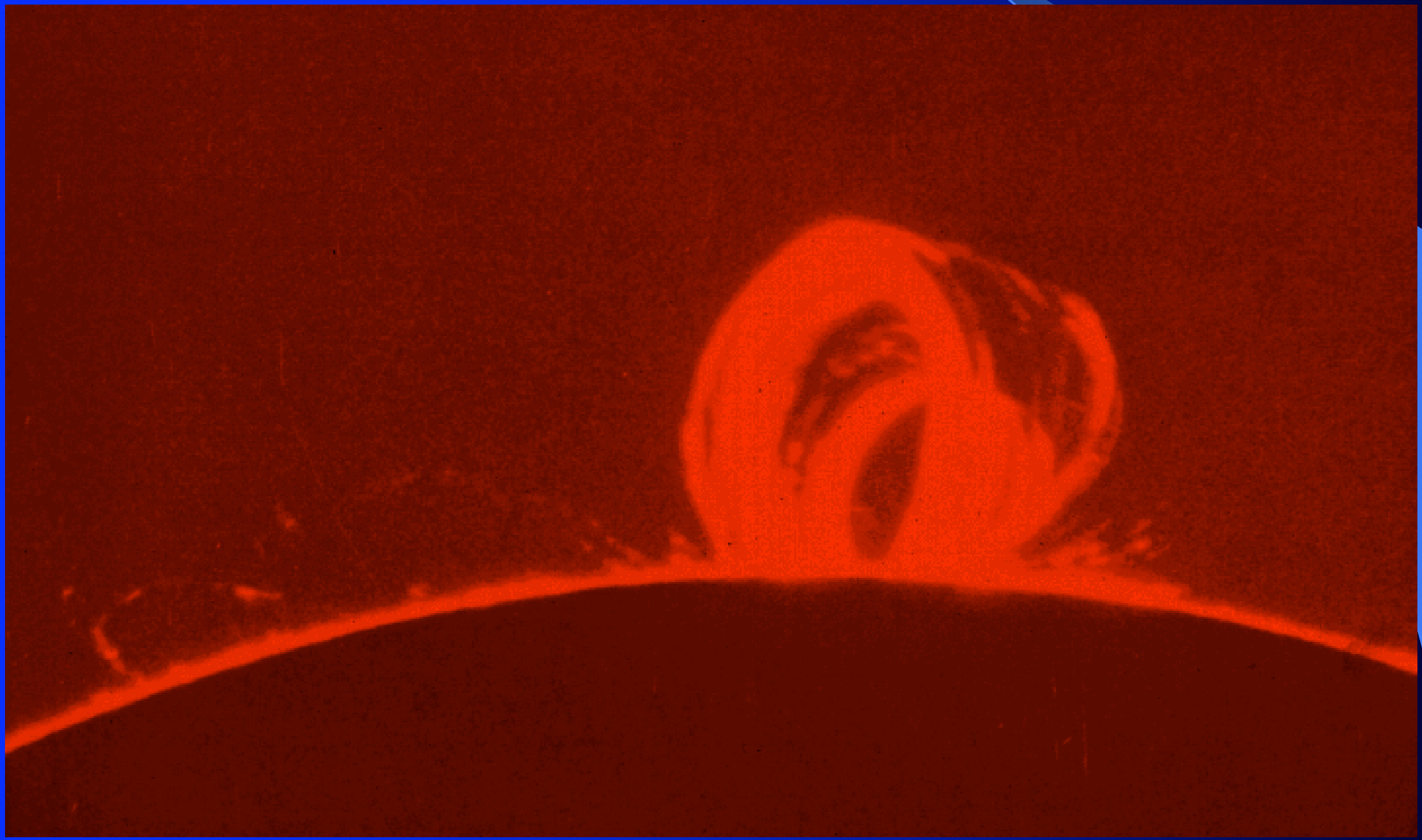


- http://www-lasers.llnl.gov/lasers/nif/nif_ife.html#fusion

Direct vs Indirect Drive

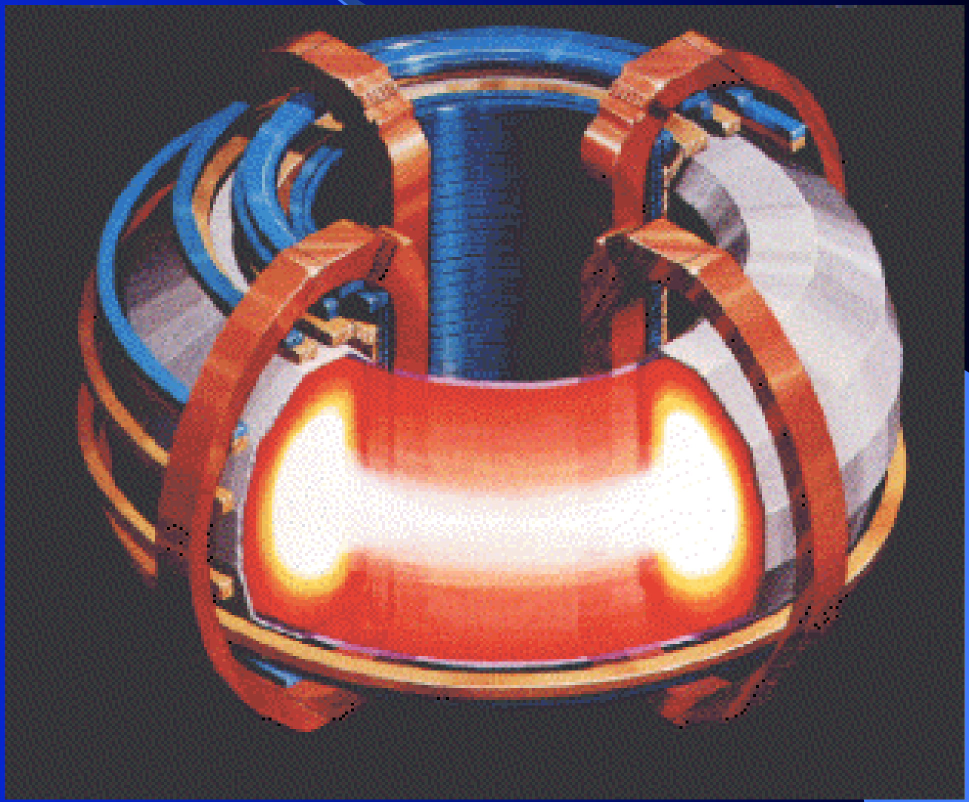
Particles in a Magnetic field

Moving charged particles will feel a force when placed in a magnetic field. $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$.

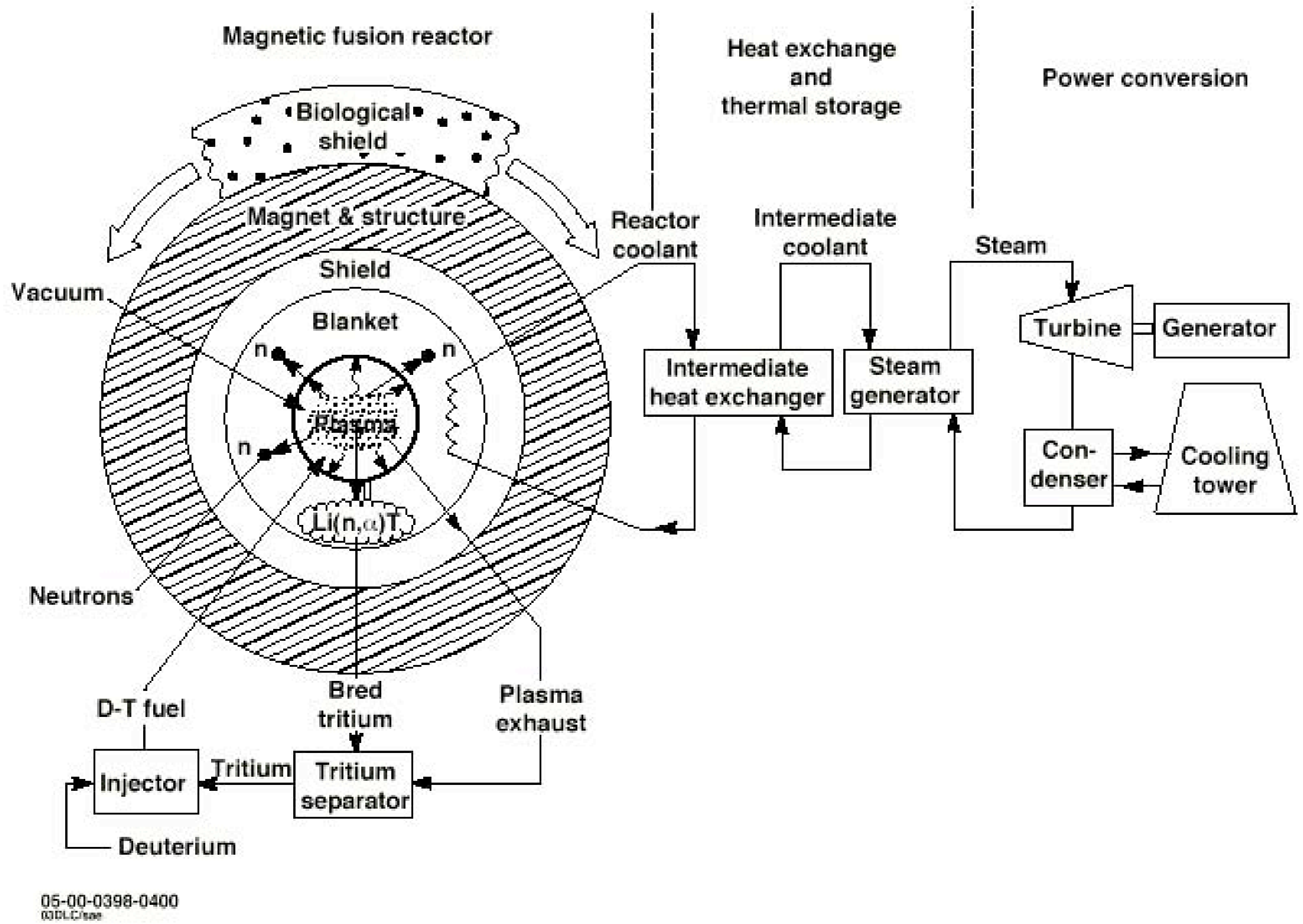


Much research has gone into controlling fusion with magnetic fields

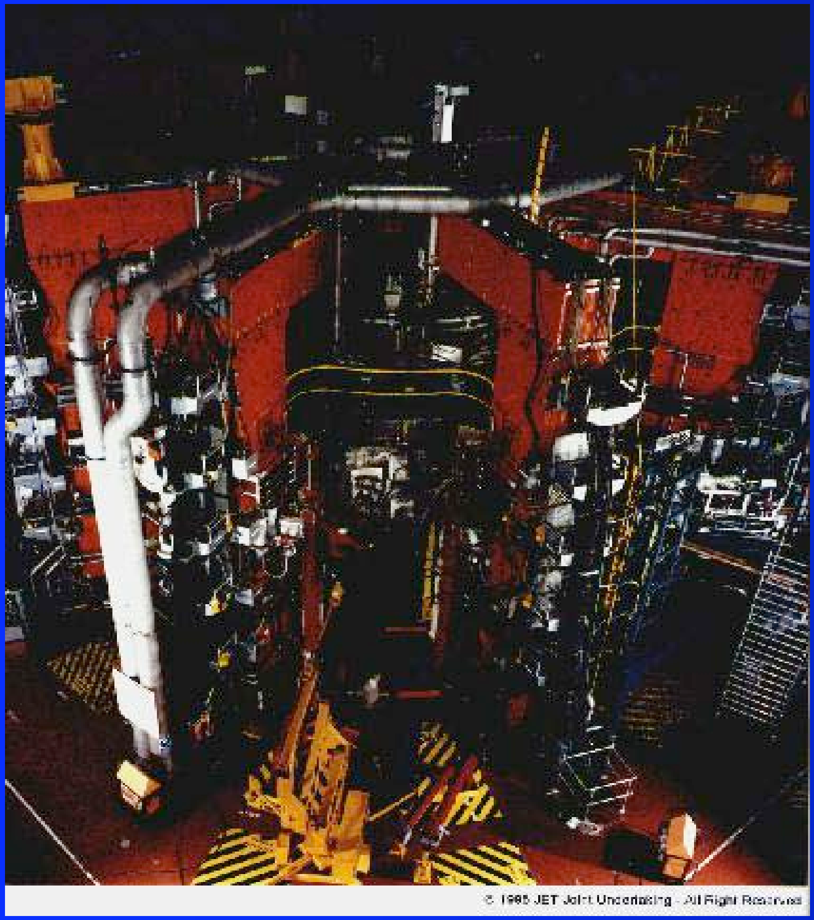
- Most magnetic confinement devices in use today have a toroidal shape.
- Large magnetic fields are created by driving currents through coils wrapped around the torus.

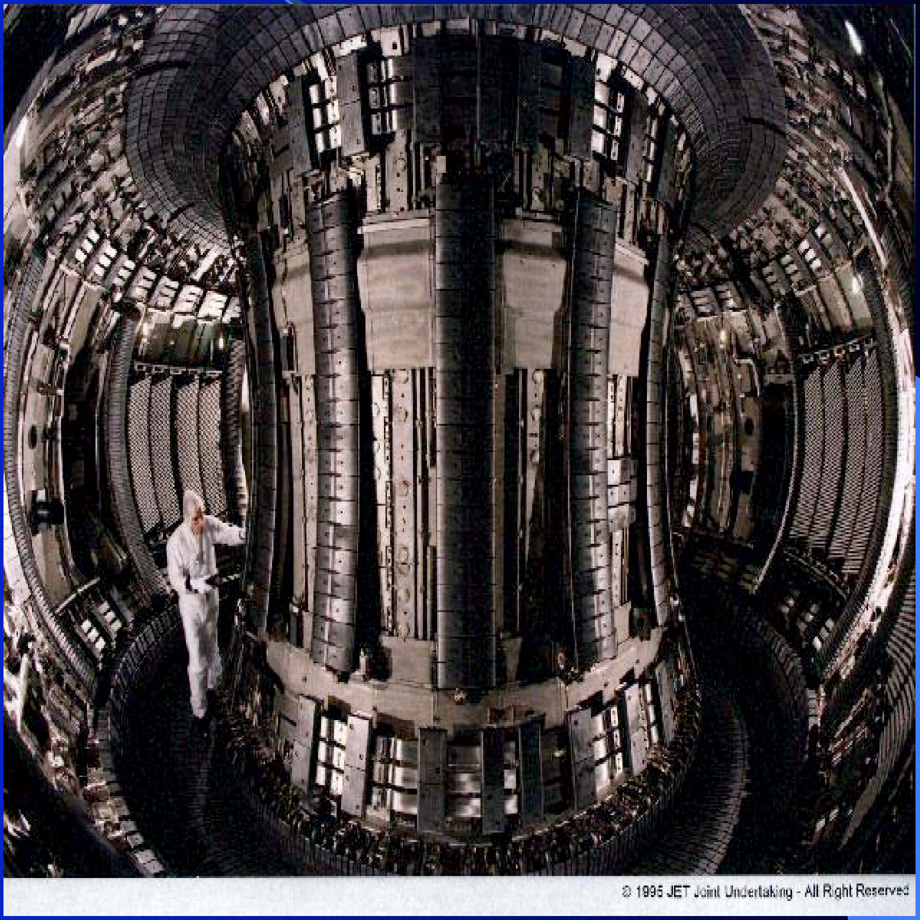


A simplified power plant schematic shows the reaction chamber, magnets and confining structure, and the proposed lithium blanket that would be used as a heat transfer fluid



Joint European Torus:
the largest confinement device ever built

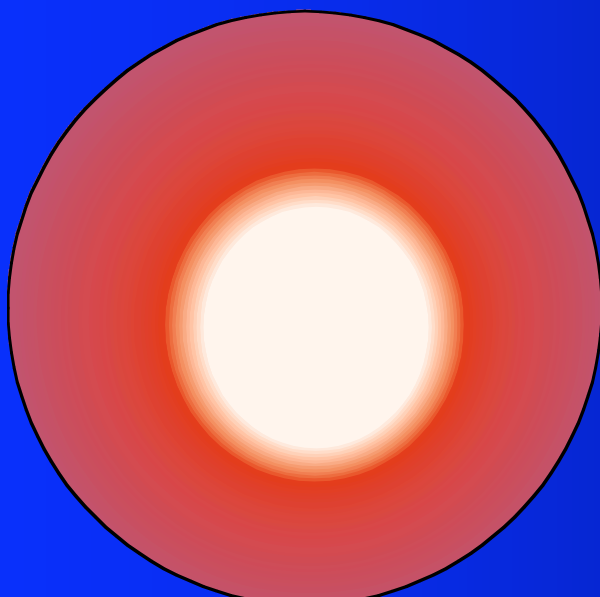


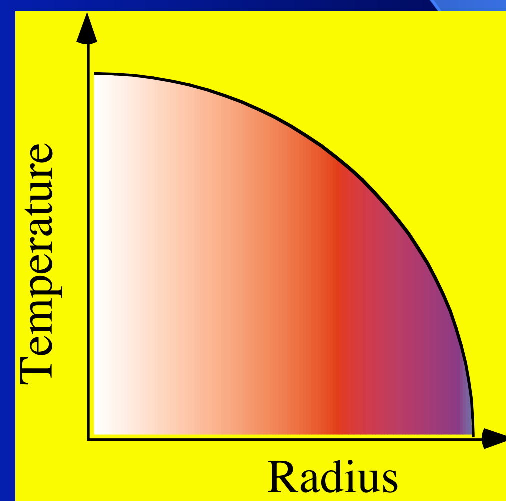


http://www.jet.uk/

Need to control temperature and density

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



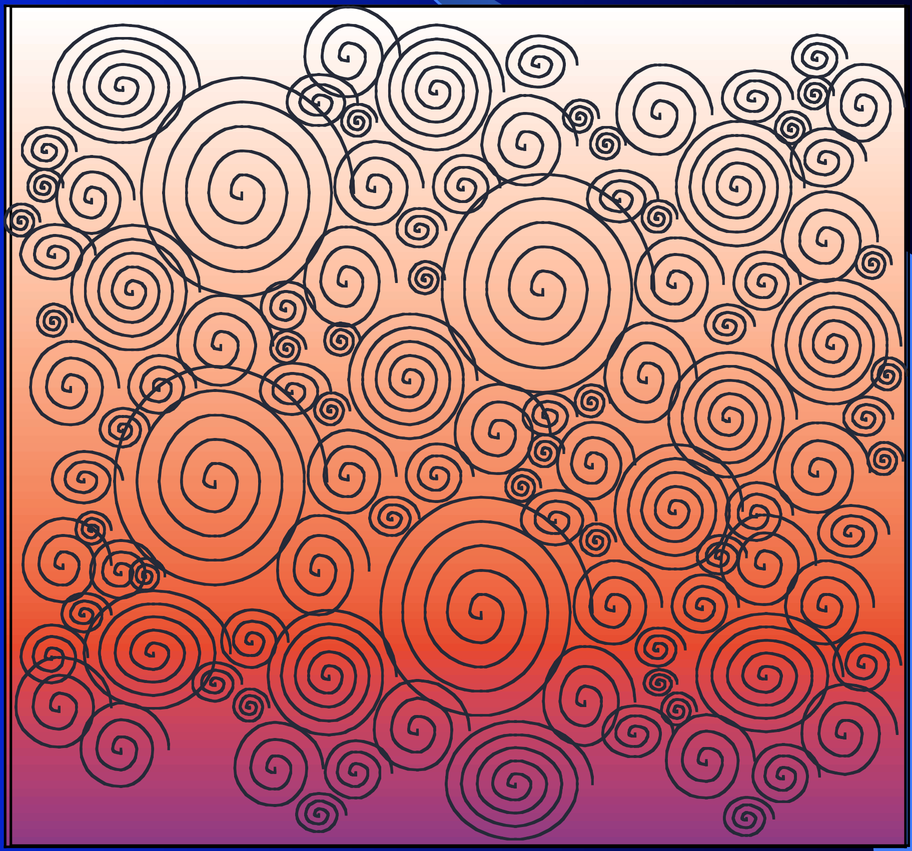


But nature abhors gradients:

- 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

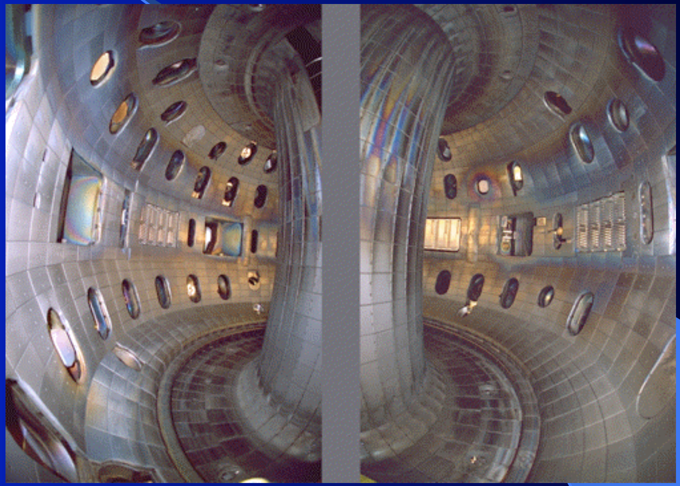
Turbulence moves things down the slope

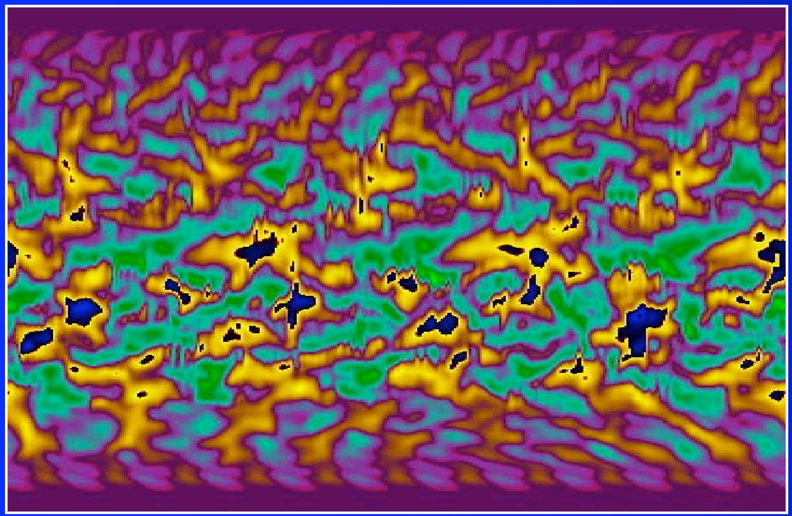
- The turbulence swirls (eddies) move the heat and density toward the edge

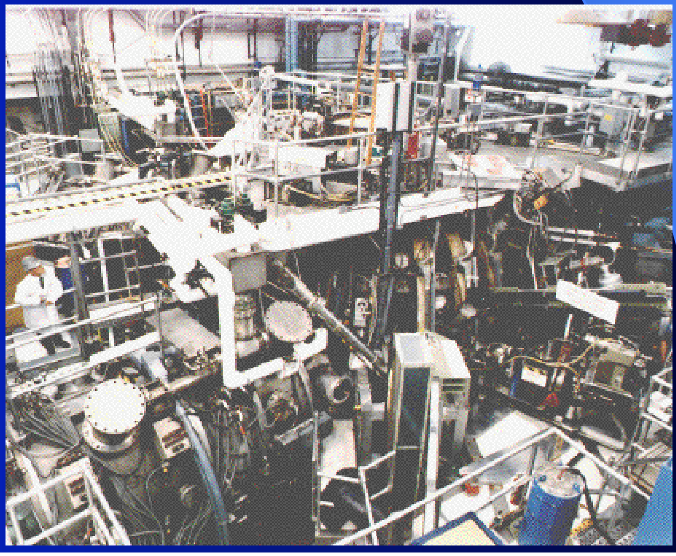


Challenges on the path to Fusion

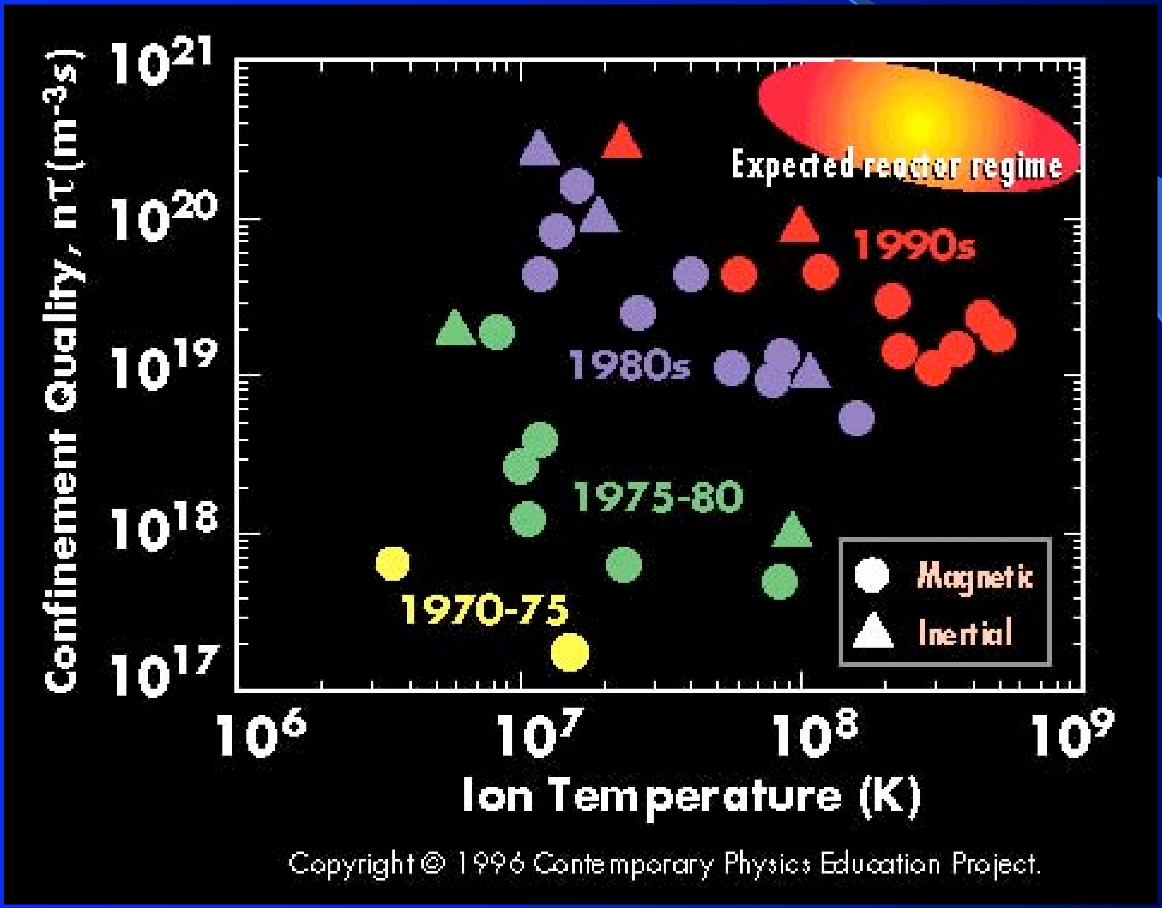
- Heating
- Fueling
- Confinement
  - Plasma physics is on the leading edge of technology







Progress towards fusion energy



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

Web References

- <u>Fusion energy and plasma educational sites</u>
  - 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
- <u>Astrophysics sites</u>
  - 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)
  - http://www.sec.noaa.gov/ NOAA Space weather site

Plasma is Coming to Denver Fall of 2005

- APS/Division of Plasma Physics meeting
- Teachers Day
- Student
- Plasma Expo (interactive booths)

- See http://fusioned.gat.com -bookmark
- Keep an eye on (Upcoming events)