Plasma: the 4th State of Matter and a Path to Fusion Energy use in Electricity Production

Presented by
Rick Lee
Chief Operator, DIII-D Operations
Manager, Fusion Education Program
General Atomics
San Diego, CA

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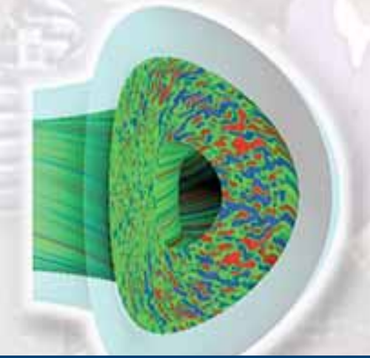


Outline of presentation

States of matter - s, l, g, p

Plasma - what it is

Plasma - examples inside and outside the lab

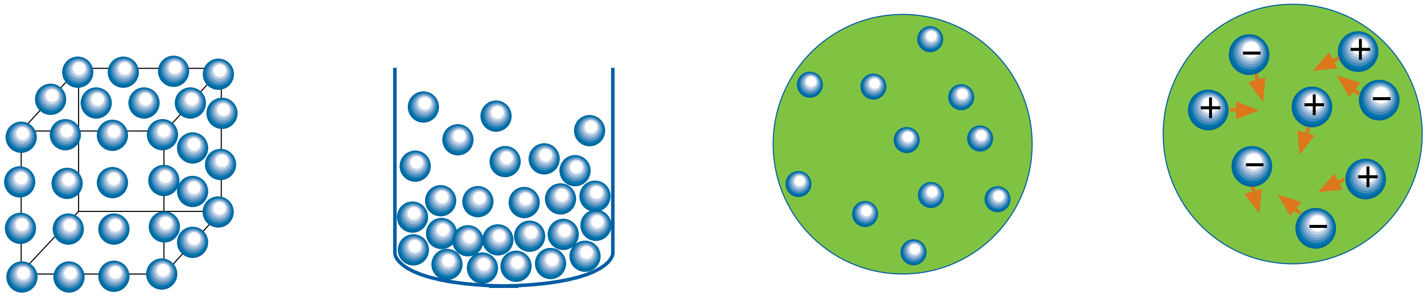
Nuclear fusion - in nature, in the lab

First things first… review of states of matter

Adding energy →

Removing energy ←

Plasma is referred to as the 4th state of matter - it is the 1st step toward fusion



Cold
Solid:Ice

→

Warm
Liquid: Water

→

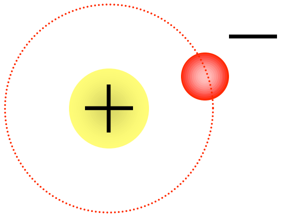
Hot
Gas: Steam

→

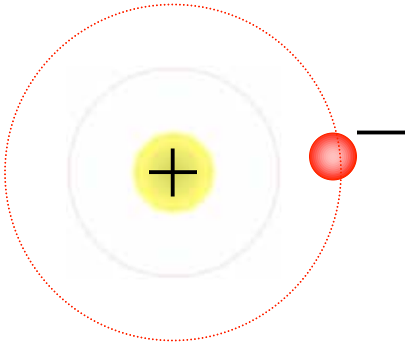
Hotter
Plasma

A review of simple atomic states

Ground state
(neutral)

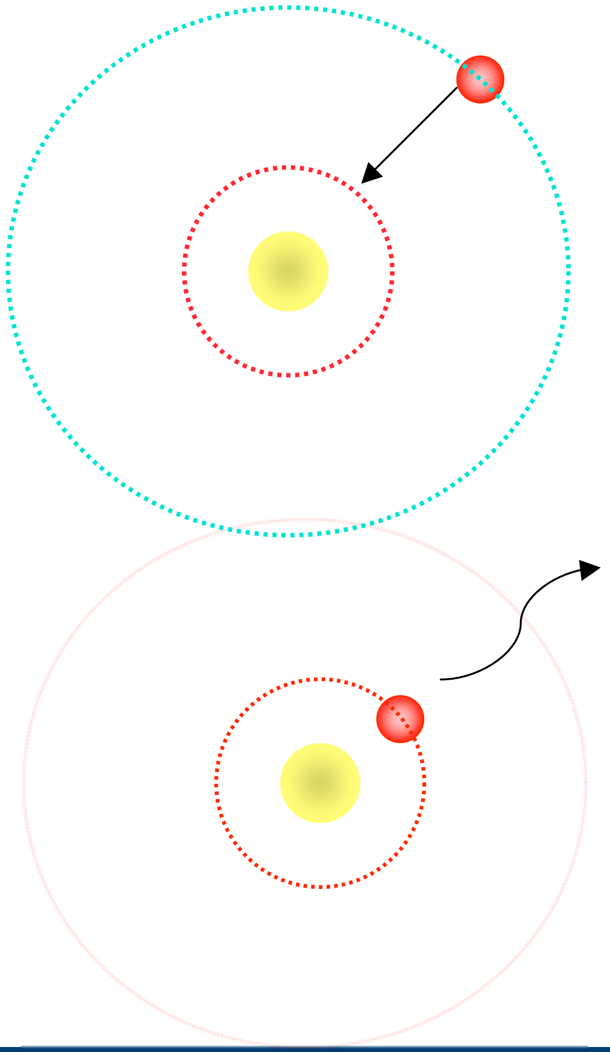


Excited state
(neutral)



Ionized state
(plasma)

Spontaneous emission of electromagnetic energy



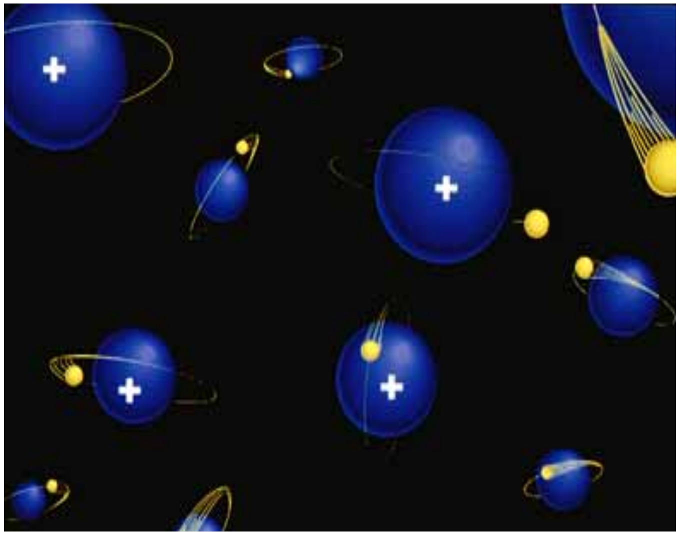
e falls to lower energy level

Some high energy (excited OR ionized) state

Light emitted

Lower energy state

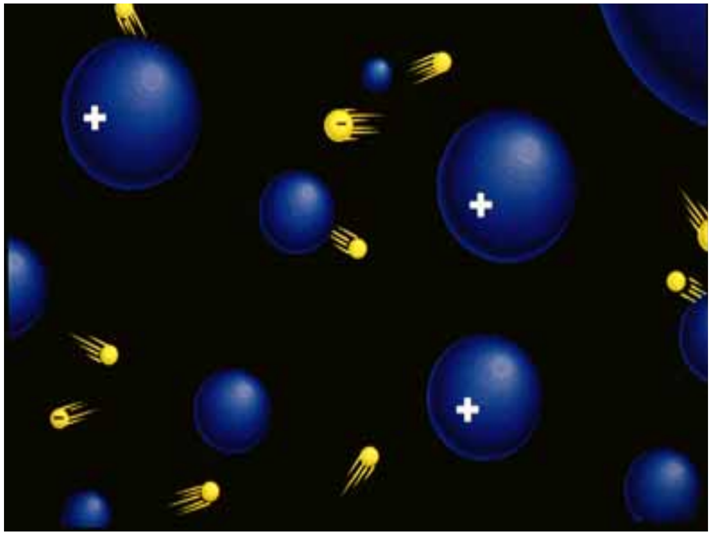
A group of ions form by adding energy to neutral atoms



Neutral atoms having electrons associated with parent atom

Add energy

Plasma having electrons free to move about parent ions



What is a plasma?

- **A plasma is --- an ionized gas.**
- **Plasma is called the “4th state of matter”**
- **About 99% of the visible mass of the universe is in a plasma state of matter. (However, this is relatively little of the overall matter of the universe - only about 5%!)**
- **‘Plasma’ was coined by Tonks and Langmuir in (1929):**

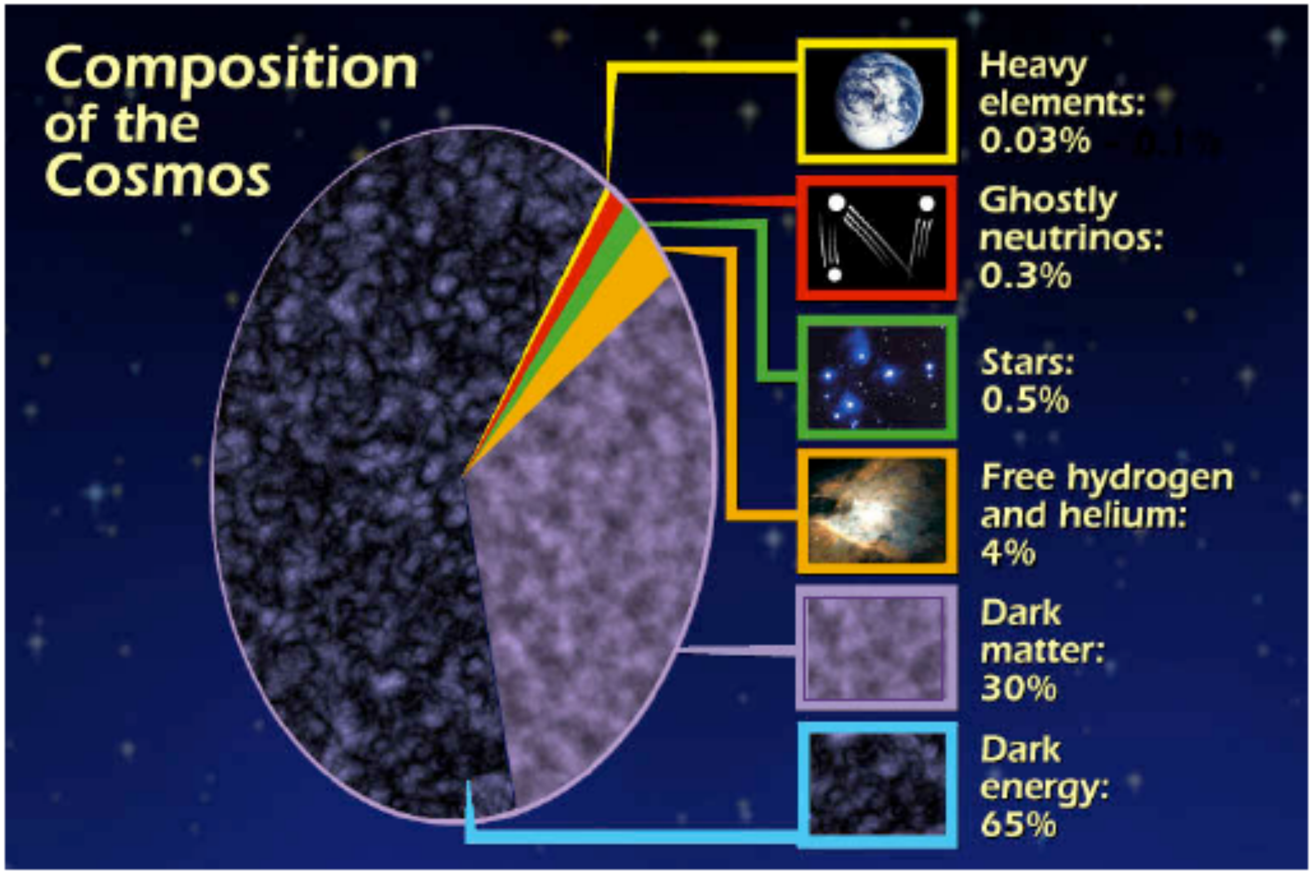
> “...when the electrons oscillate, the positive ions behave like a rigid jelly...”

Why are we interested in plasmas?

- **Astrophysics**
  - Understanding plasmas helps us to understand stars and stellar evolution.
- **Upper atmospheric dynamics**
  - The ionosphere is a plasma.
- **Plasma Applications**
  - Plasmas can be used to build computer chips and lasers, to clean up toxic waste, and drive space craft.
- **Fusion Energy**
  - Potential source of safe, clean, and abundant energy.

We used to know more than we do now….

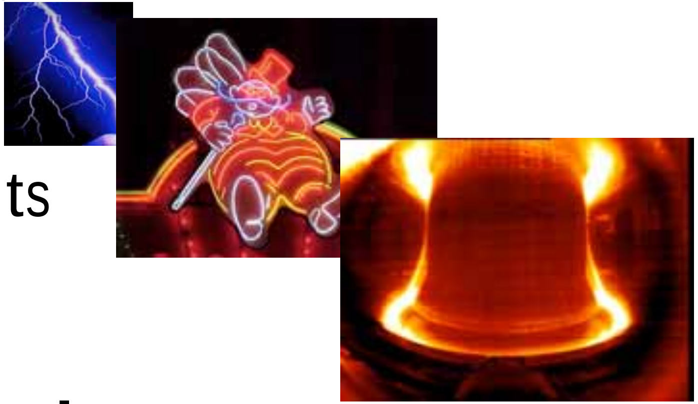
This isn’t your father’s (or mother’s) universe….



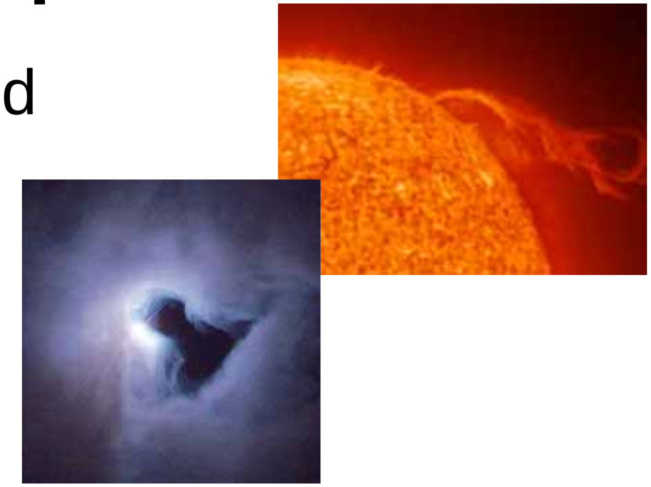
Hubblesite.org

Where do we find plasmas?

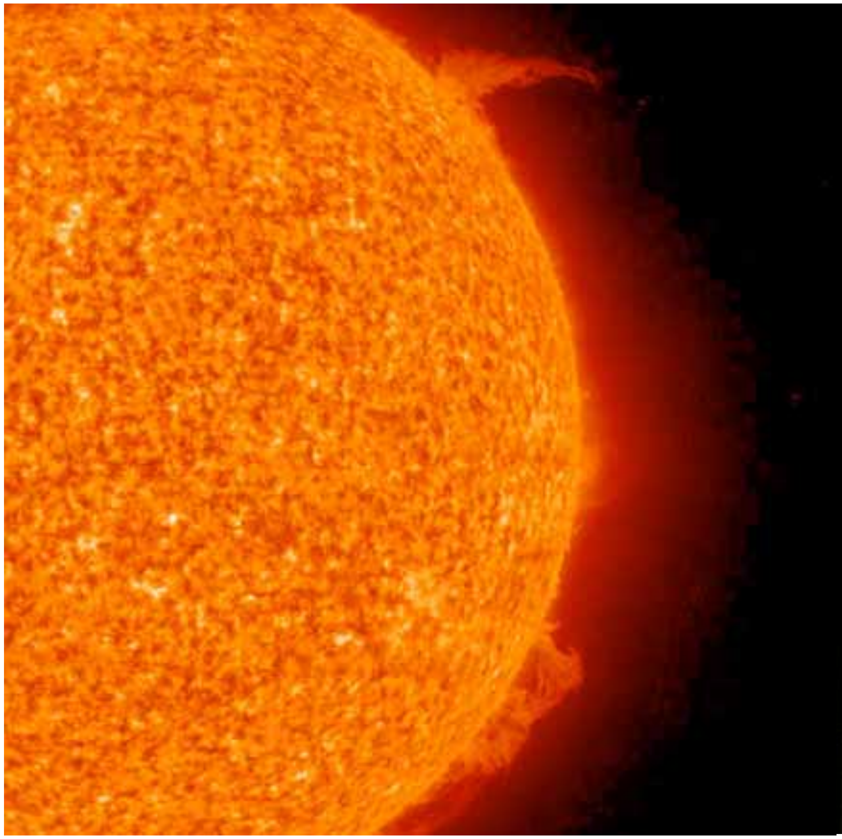
- **Examples of plasmas on Earth:**
  - Lightning
  - Neon and fluorescent lights
  - Laboratory experiments



- **Examples of astrophysical plasmas:**
  - The sun and the solar wind
  - Stars, interstellar medium

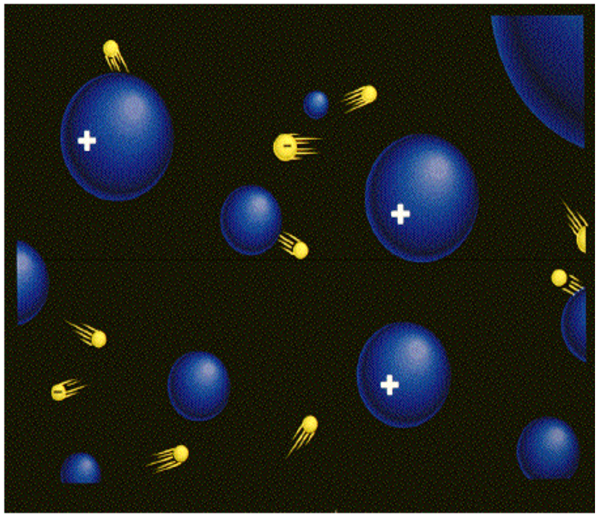


Part of the 0.5%..



Plasma Characteristics

- Equal amounts of positive and negative charge are ‘free’ to move about
- Broad range of particle density, n, of charged particles (so many per volume - not mass per volume!)
- Broad range of thermal energy of the electrons (1eV ~10,600 C)
- Plasmas differ depending on the type of ions (positive or negative) and gas species
- Plasmas interact strongly with electric and magnetic fields.



- Plasmas support many different types of waves and oscillations.

Plasma-based industrial products

- Computer chips and integrated circuits
- Computer hard drives
- Electronics
- Machine tools
- Medical implants a prosthetics
- Audio and video tapes
- Aircraft and automobile engine parts
- Printing on plastic containers
- Energy-efficient window coatings
- Anti-scratch and anti-glare coatings on eyeglasses and other optics

The solar 'wind' can be the origin of planet aurora

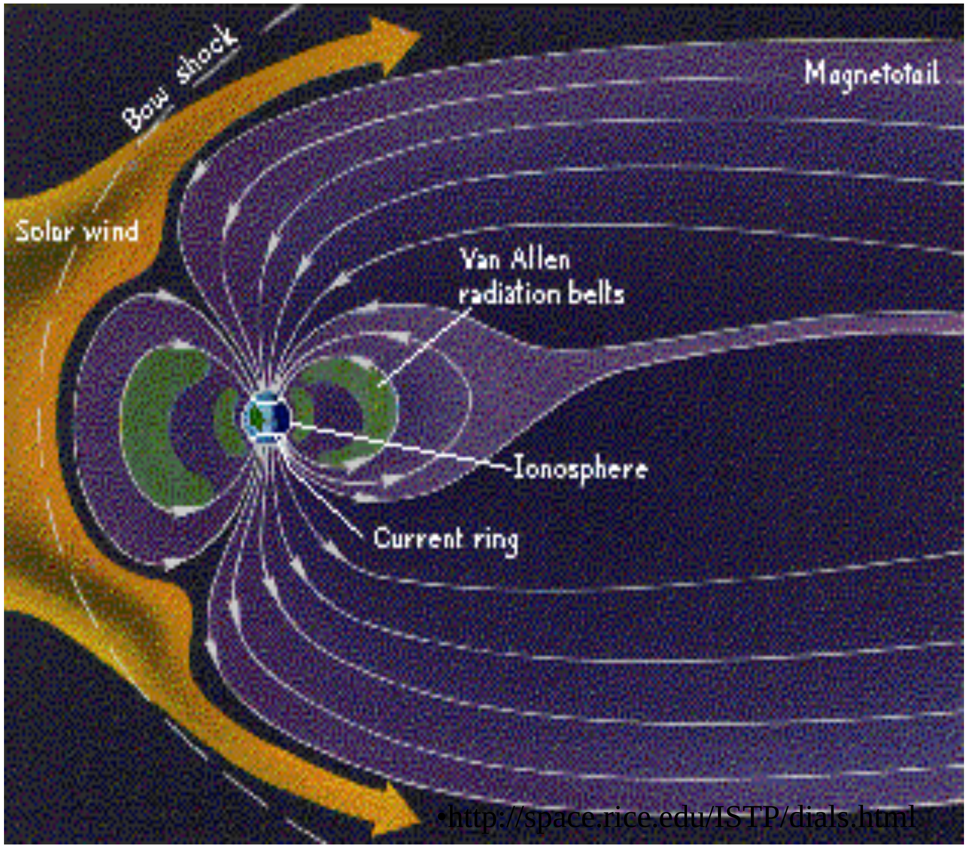
Aurora require:

- plasma source
- ion trapping mechanism
- atmosphere for interaction

On Earth …

- Sun as plasma source
- magnetic field as ion trap
- nitrogen and oxygen atm.

On Jupiter (Io helps as a source) & on Saturn also



•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)
- The southern lights (aurora australis)

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

The solar wind vs. Earth’s magnetic field

- Large solar flares can cause problems with electrical grid, satellites and other spacecraft

- Without the Earth’s protective magnetic field, no atmosphere would have developed because it would have been swept away by highly energetic particles long ago

- Without an atmosphere, ionizing radiation would have kept life from forming

- Let’s hear it for the magnetic field of Earth!!

In the classroom

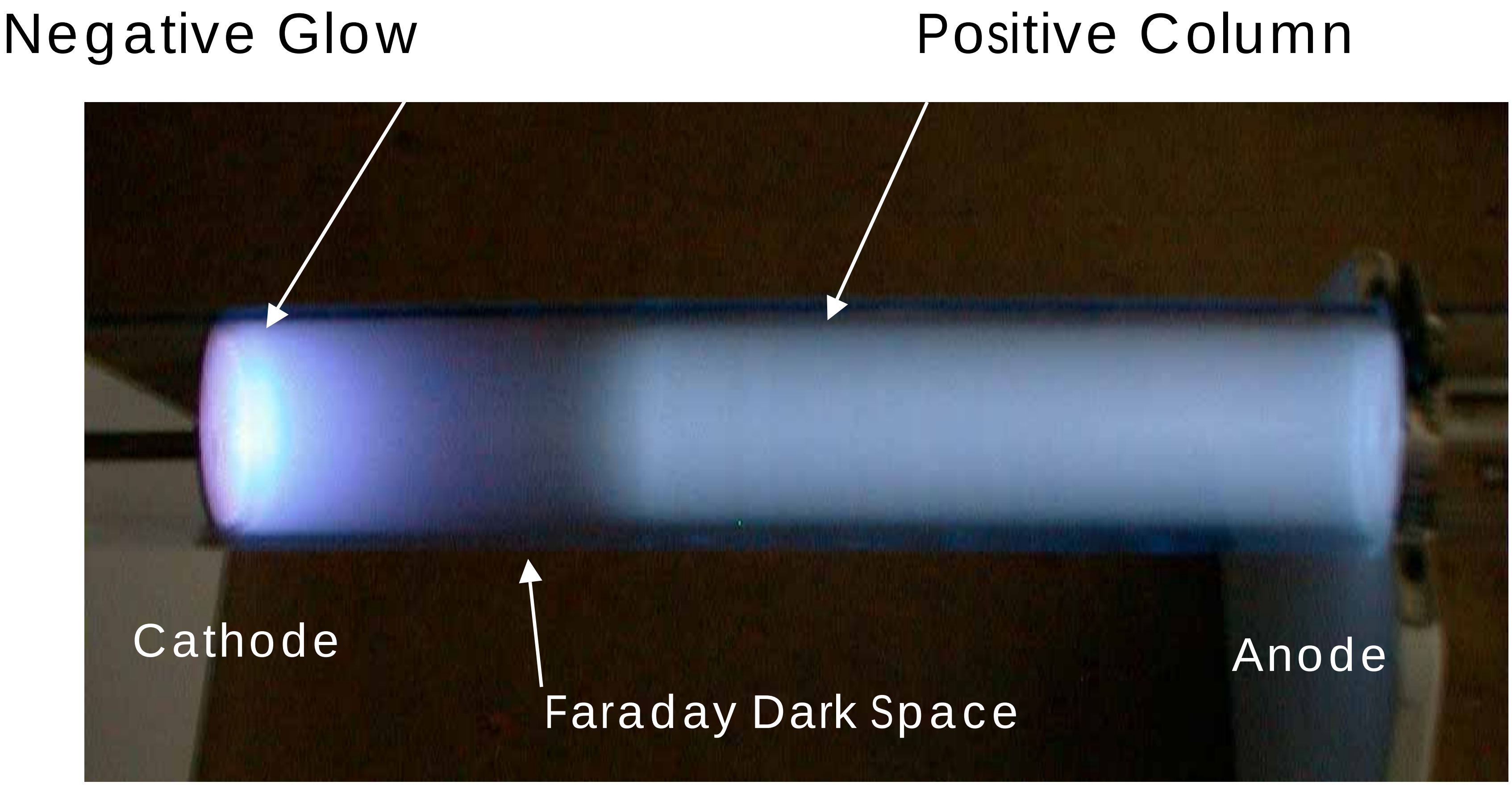
- Be sure to include the Earth’s magnetic field as an important component of the Earth

- Emphasize the interactions among charged particles and magnetic fields

- Earth science is a compilation of ‘universe’ science interactions and processes - not isolated particulars

- Benjamin Franklin championed plasma discharges without knowing it! (Experiments and Observations made on Electricity, 1751)

Classical DC Discharge in a Tube

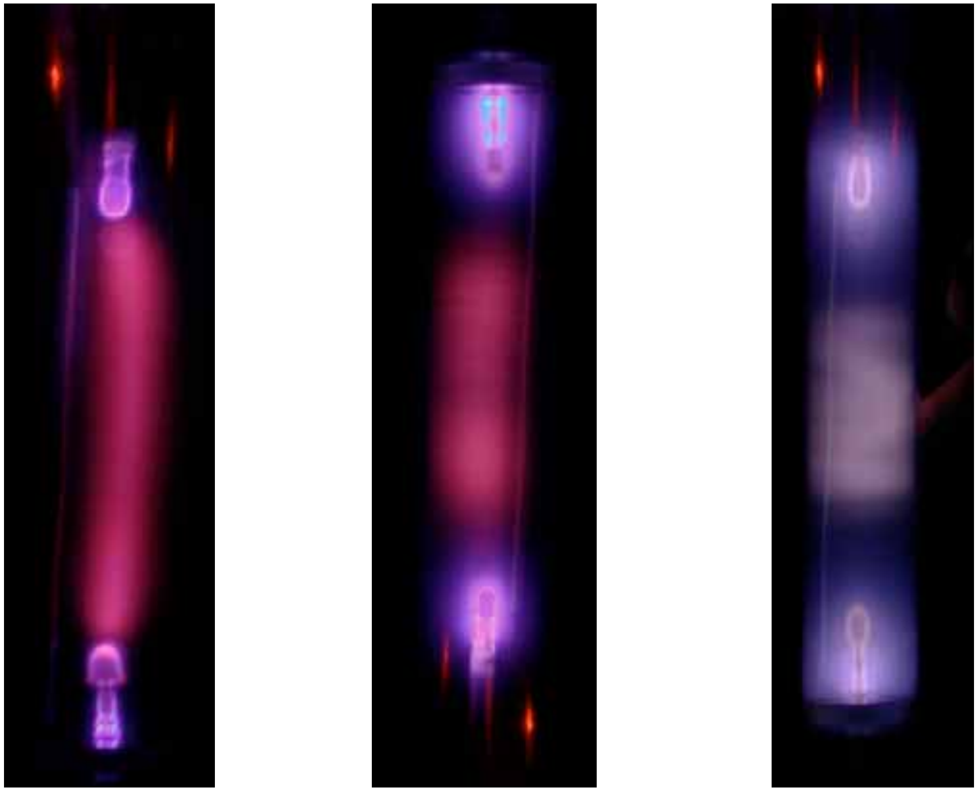


Note: Cathode is electron emitter (recall cathode ray tube of older TV sets)

Plasma appearance is affected by density and mean free path

Density: # per volume

Mean free path: a measure of how far a particle travels before colliding with another



Density	**High**	**Medium**	**Low**
Mean free path	**Low**	**Medium**	**High**

Density and Mean Free Path

Some examples of density (n) as defined by #particles/cm³:

Use Avogadro's number and known relationships to find n(ideal gas) at STP: $N_A = 6.023 \times 10^{23}$ per 22.4 l

$n(\text{air}, N_2, O_2, \text{Ar}) \approx (6.023 \times 10^{23}/22.4 \times 10^3\ \text{cm}^3) = 2.69 \times 10^{19}/\text{cm}^3$

Using $\rho(\text{Hg}) = 13.5\text{g/cm}^3$ & mass of Hg atom = 3.33×10^{-22} g leads to:

$n(\text{Hg}) = (\text{Hg atom}/\ 3.33 \times 10^{-22}\ \text{g})(13.5\text{g/cm}^3) = 4.05 \times 10^{22}/\text{cm}^3$

n (sun center) ≈ $9 \times 10^{25}\ /\text{cm}^3$!

Examples of mean free path

- **MFP is proportional to the energy of the particle and inversely proportional to its cross sectional area and pressure**
- **mfp = $1/(1.41)\pi d^2 p$**

- **mpf (atm) ≈ 90 nm**
- **mfp (high vac, 10-5 atm) ≈ 10 m**
- **mfp (sun center) ≈ a few H diameters**

Small fluorescent tube

- Plasma is conductive -- shown by the arc behavior on the glass
- Electric fields alone can ionize a gas
- The plasma can not be seen if a phosphor coating is present
- Each example here is an argon and mercury plasma

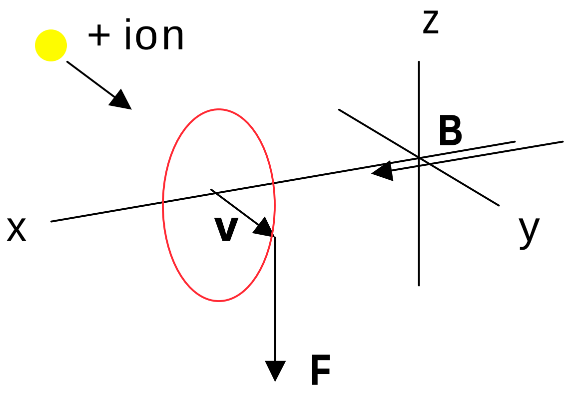
Large Light Bulb Plasma Ball

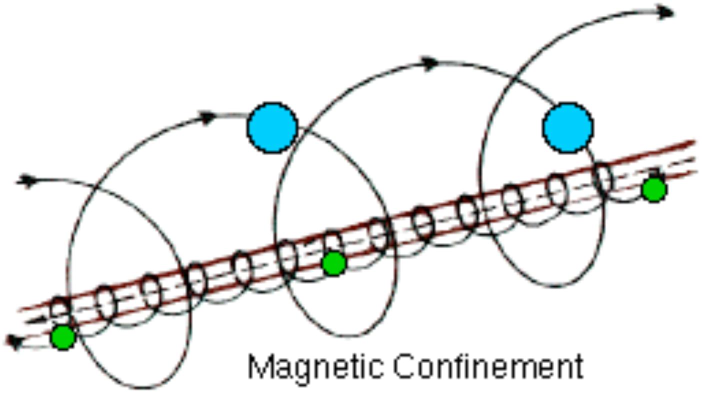
- **To notice**
  - Plasma Colors
  - Shape
  - Attraction
  - Arc Distance
  - Diffusivity

Motion of charge particles in an electric field

- Random thermal activity
- Electric field forces; **F** = q**E** (q is charge, force is in linear direction of electric field)
- Mobility decreases as pressure (particle density) increases
- An electron-atom collision can produce one elec-ion pair
- Electron-ion pairs grow exponentially with distance

Motion of charged particles in a magnetic field





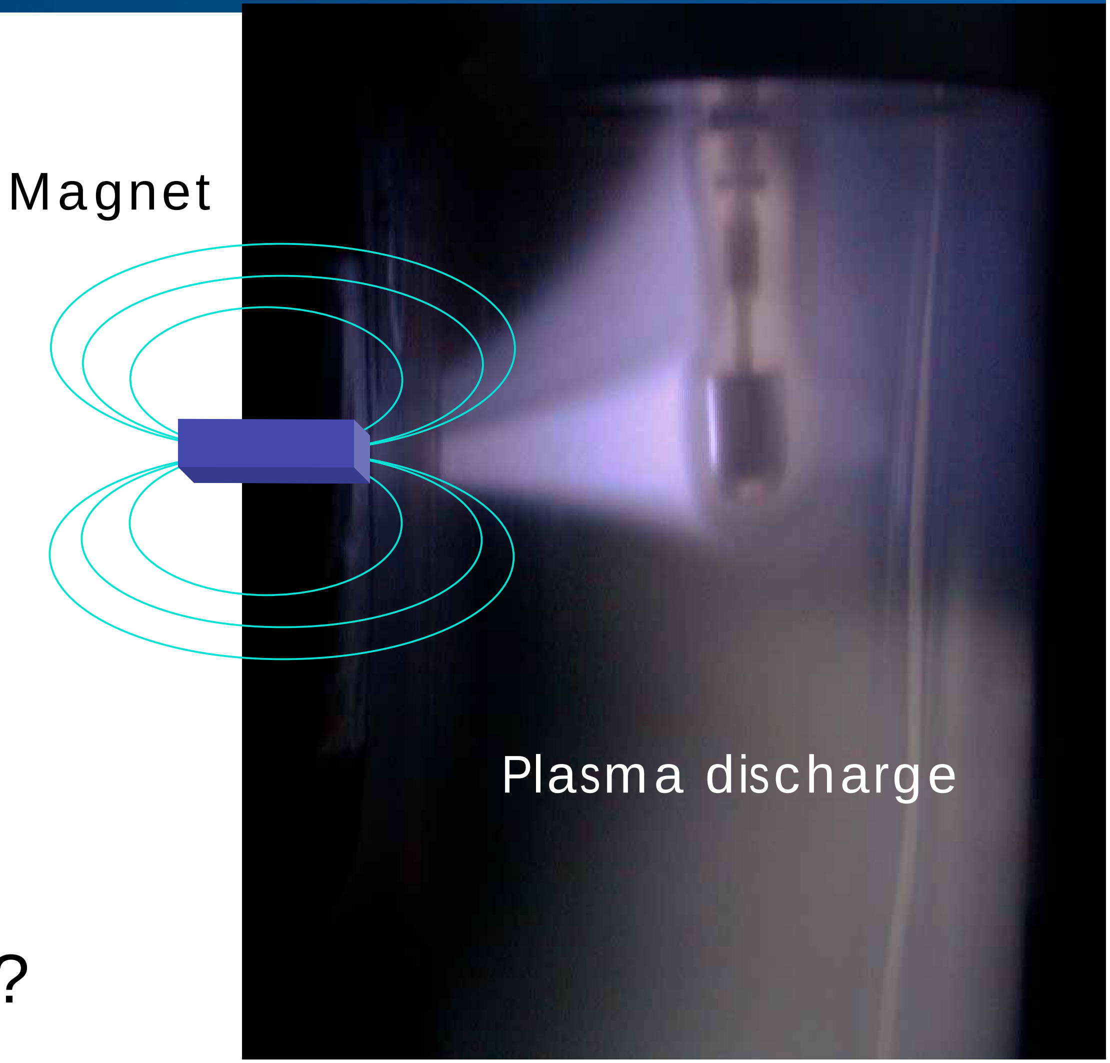
Charged particles (ions and electrons) follow a circular path perpendicular to magnetic field **F** = q(**v** x **B**). The force at any point in space is linear, but because its direction is changing, the final path is circular.

They follow a spiral path if they have some velocity parallel to the magnetic field (**F** = q(**E** + (**v** x **B**))

Magnetic fields cause charges to move in circles

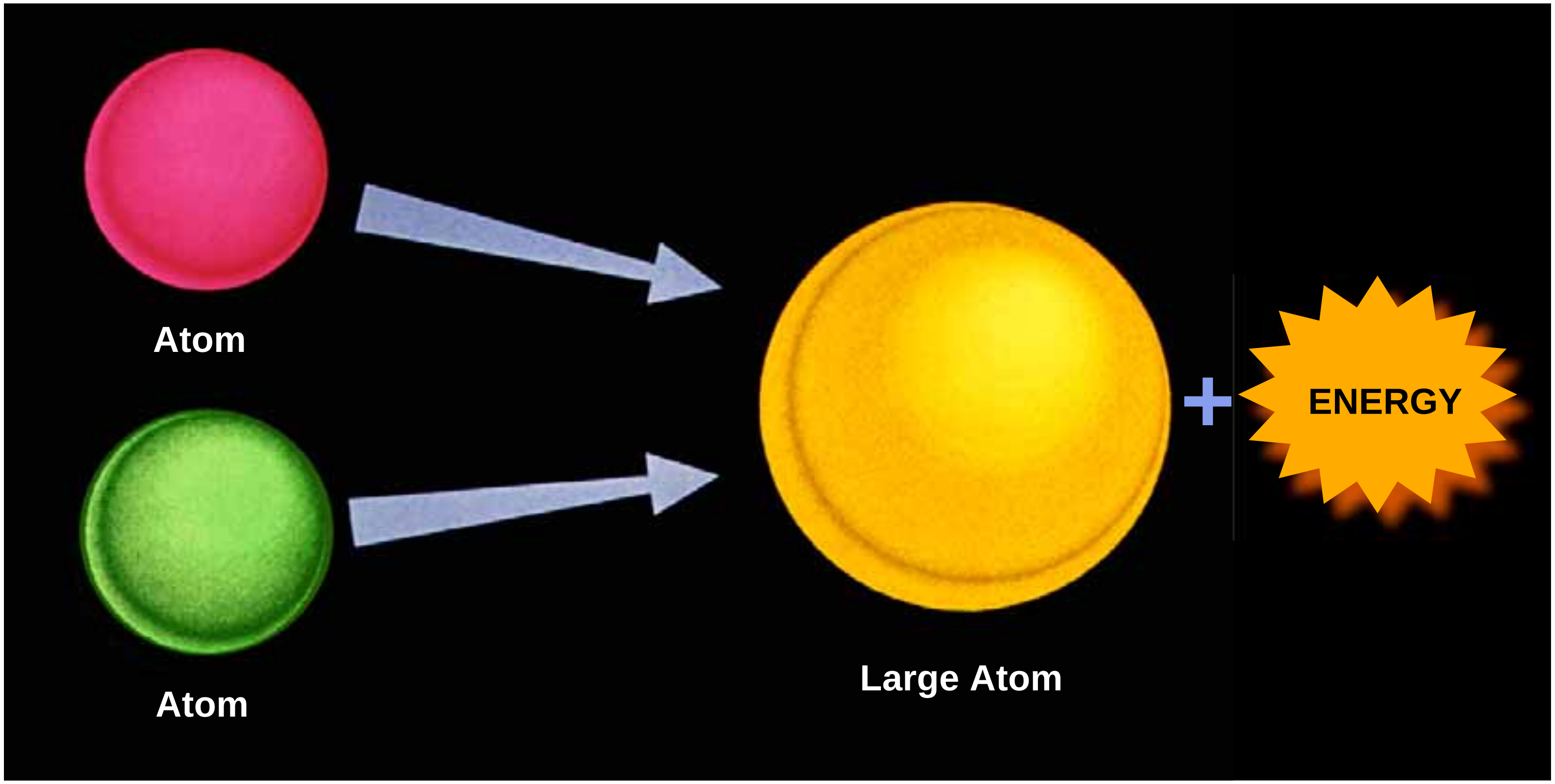
- **To notice**
  - Plasma Colors
  - Shape
  - Attraction

- **Magnetic fields have an effect on moving charged particles**
- $\mathbf{F}=q(\mathbf{v} \times \mathbf{B})$ causes circular motion
- $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$ What type of motion results?



NUCLEAR FUSION

Fusion - basic idea



Conditions must be right for fusion to occur

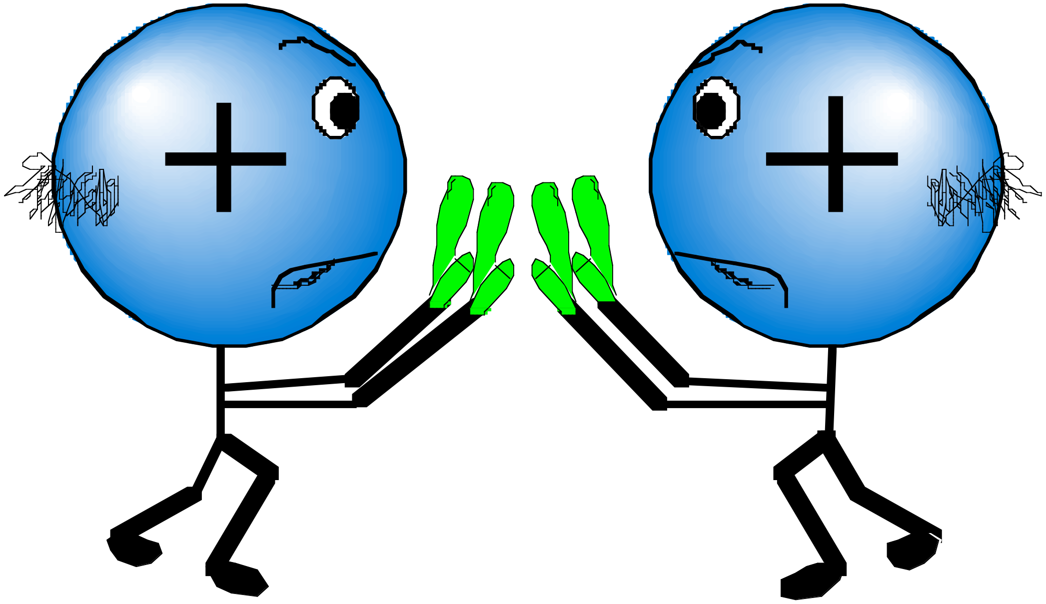
Just as in a chemical reaction, fusion reactions are governed by probabilities. For fusion to occur, the product of the density (n), temperature (T), and energy confinement time (τ) must be greater than some value. This is known as the Lawson criteria,

$$\mathbf{LawCrit = n \times T \times \tau > 10^{21}\ keV\ s/m^3}$$

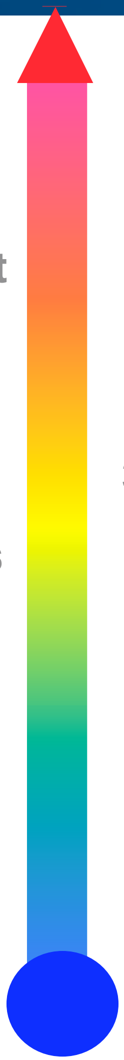
This is good, because in the lab, we can't make n(lab) = n(sun) but we can make T(lab) >> T(sun)!

High temperatures are required to overcome Coulomb forces of plasma ions

Like Charges Repel



The temperature scale covers more than 10 orders of magnitude



Billions °C massive stars, supernovae

100,000,000 °C H nuclei fuse in lab

16,000,000 °C sun's center

100,000 °C lightening bolt

10,000 °C fluorescent light plasma

6000 °C sun's surface

3,400 °C tungsten (W) melts

1,500 °C iron (Fe) melts

100 °C water boils

0 °C Ice

-78 °C dry Ice, solid CO_2

-196 °C liquid nitrogen

-269 °C liquid helium (He)

-273 °C absolute zero

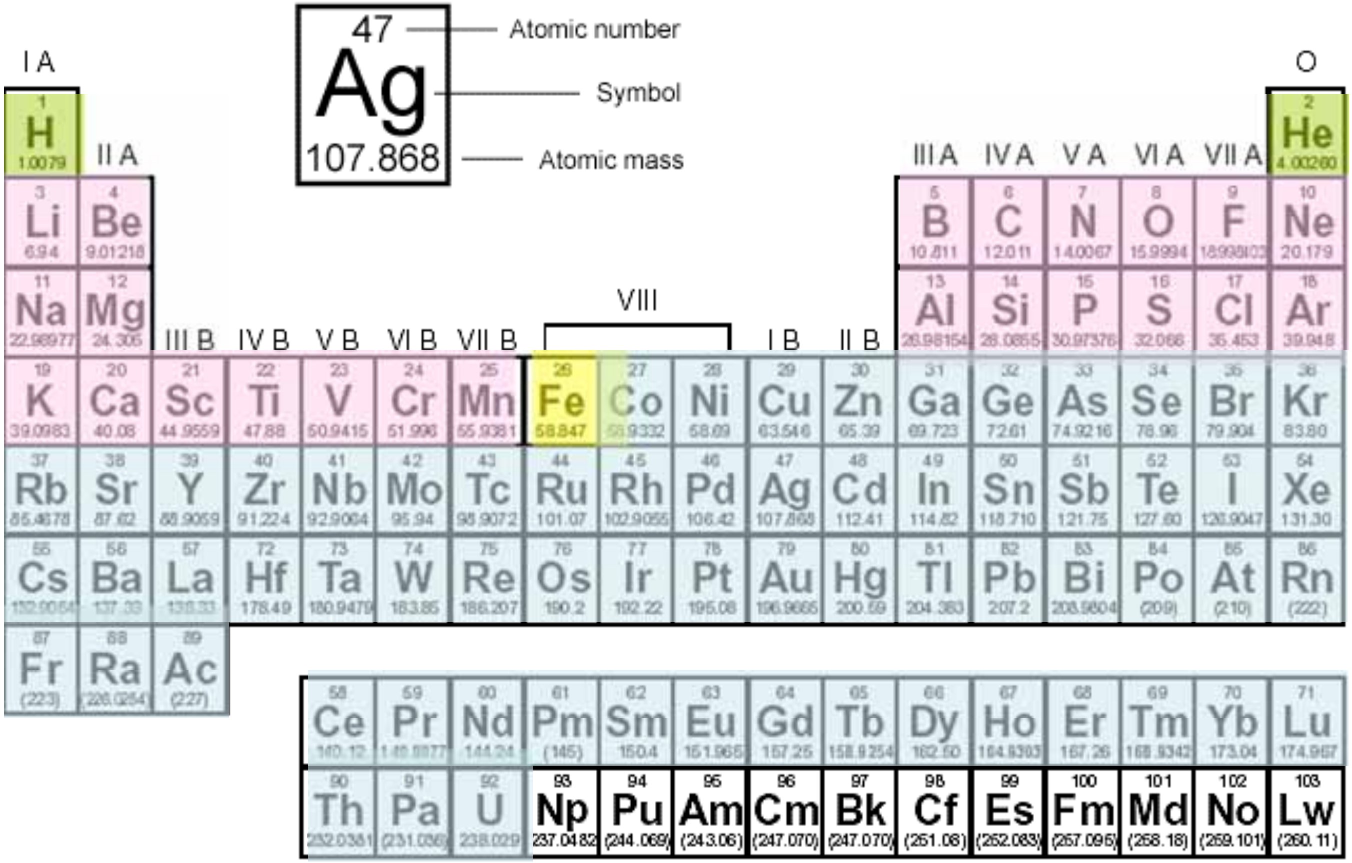
Fusion Built the Periodic Table of Elements - a self portrait

🟩 Mostly of BB origin

🟥 Mostly of H/He fusion origin

🟦 Mostly of SN origin

🟨 Nuclei relatively stable



47 — Atomic number
Ag — Symbol
107.868 — Atomic mass

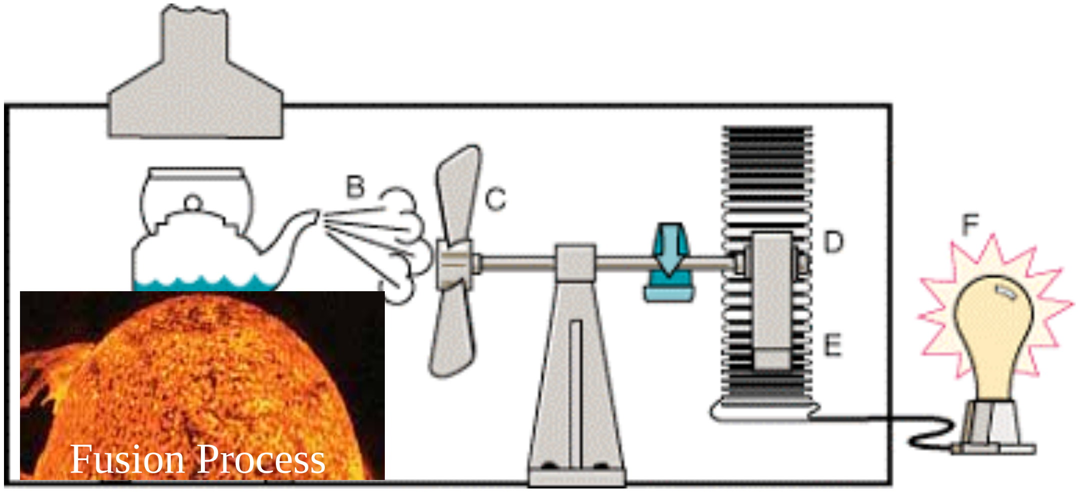
I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	O
1 H 1.0079																	2 He 4.00260
3 Li 6.94	4 Be 9.01218											5 B 10.811	6 C 12.011	7 N 14.0067	8 O 15.9994	9 F 18.998403	10 Ne 20.179
11 Na 22.98977	12 Mg 24.305											13 Al 26.98154	14 Si 28.0855	15 P 30.97376	16 S 32.066	17 Cl 35.453	18 Ar 39.948
19 K 39.0983	20 Ca 40.08	21 Sc 44.9559	22 Ti 47.88	23 V 50.9415	24 Cr 51.996	25 Mn 54.9380	26 Fe 55.847	27 Co 58.9332	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.9216	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.4678	38 Sr 87.62	39 Y 88.9059	40 Zr 91.224	41 Nb 92.9064	42 Mo 95.94	43 Tc 98.9072	44 Ru 101.07	45 Rh 102.9055	46 Pd 106.42	47 Ag 107.868	48 Cd 112.41	49 In 114.82	50 Sn 118.710	51 Sb 121.75	52 Te 127.60	53 I 126.9045	54 Xe 131.30
55 Cs 132.9054	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.9479	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.9665	80 Hg 200.59	81 Tl 204.383	82 Pb 207.2	83 Bi 208.9804	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra 226.0254	89 Ac (227)															

58 Ce 140.12	59 Pr 140.9077	60 Nd 144.24	61 Pm (145)	62 Sm 150.4	63 Eu 151.965	64 Gd 157.25	65 Tb 158.9254	66 Dy 162.50	67 Ho 164.9303	68 Er 167.26	69 Tm 168.9342	70 Yb 173.04	71 Lu 174.967
90 Th 232.0381	91 Pa (231.036)	92 U 238.029	93 Np 237.0482	94 Pu (244.069)	95 Am (243.06)	96 Cm (247.070)	97 Bk (247.070)	98 Cf (251.08)	99 Es (252.083)	100 Fm (257.095)	101 Md (258.10)	102 No (259.101)	103 Lw (260.11)

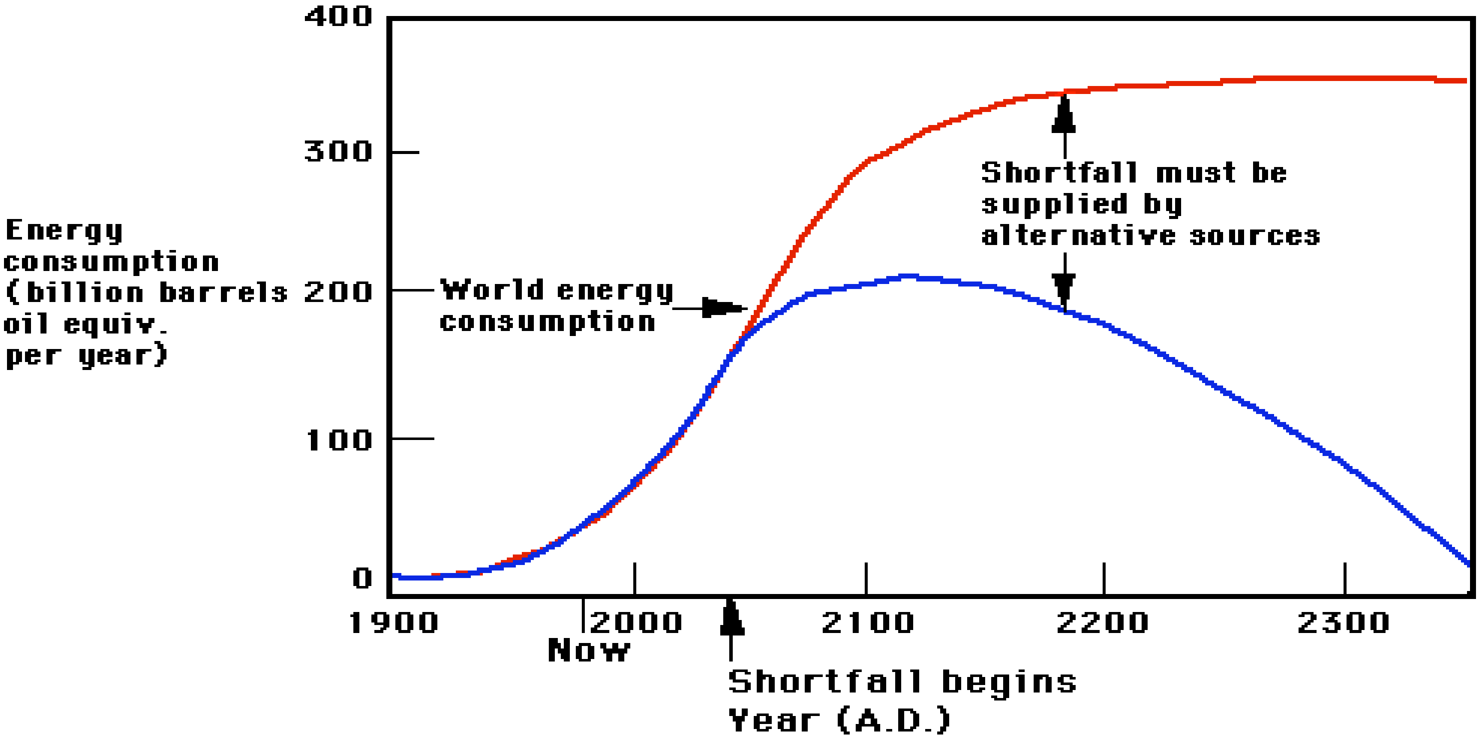
In a nutshell (summary point!), the ultimate goal of the world-wide fusion research effort is…

To use energy from the process of fusion on Earth to

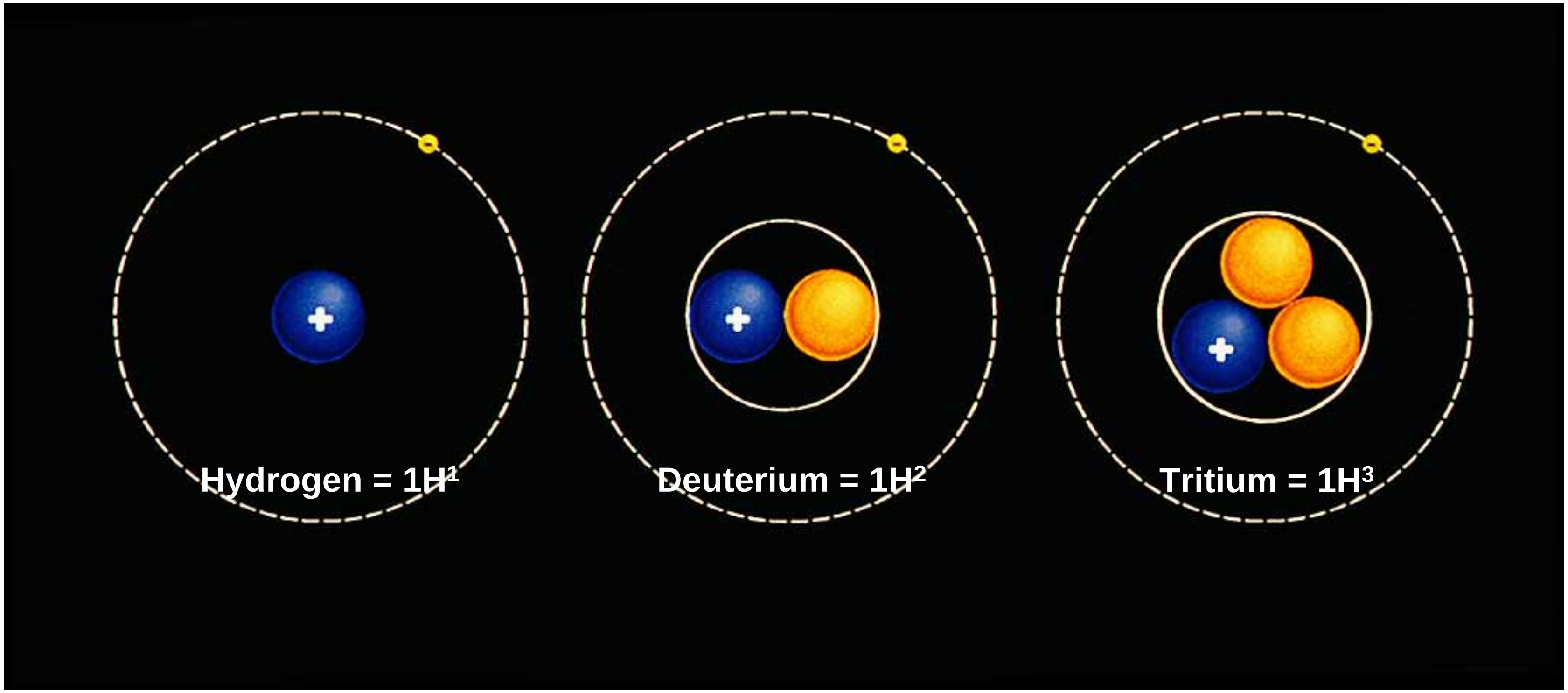
1. heat water
2. make steam
3. turn a turbine (propeller set)
4. turn an electrical generator
5. make electricity



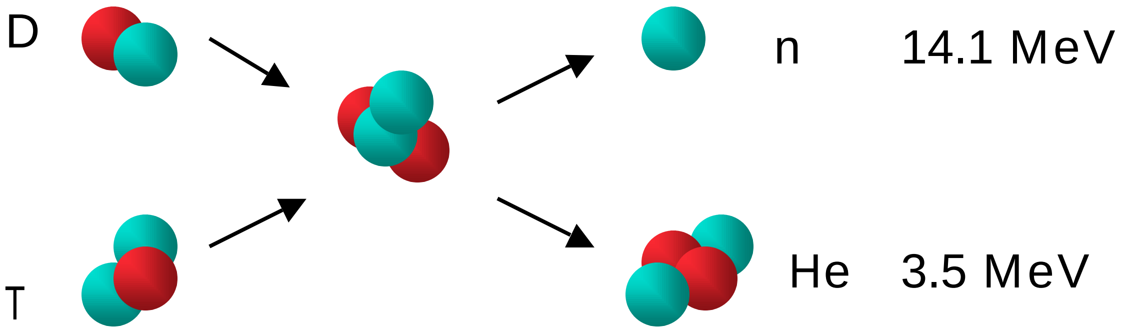
Why do we need new sources of energy?



Review of hydrogen isotopes



Mass ‘goes’ into energy in fusion reaction



Although we say the process “turns mass into energy,” a more correct way to put it is: the origin of the released energy is the rearrangement of nuclear bonds.

Advantages of fusion as an energy producer

- Fusing deuterium and tritium to produce significant energy is achievable

- No CO_2 (or other greenhouse gas) output

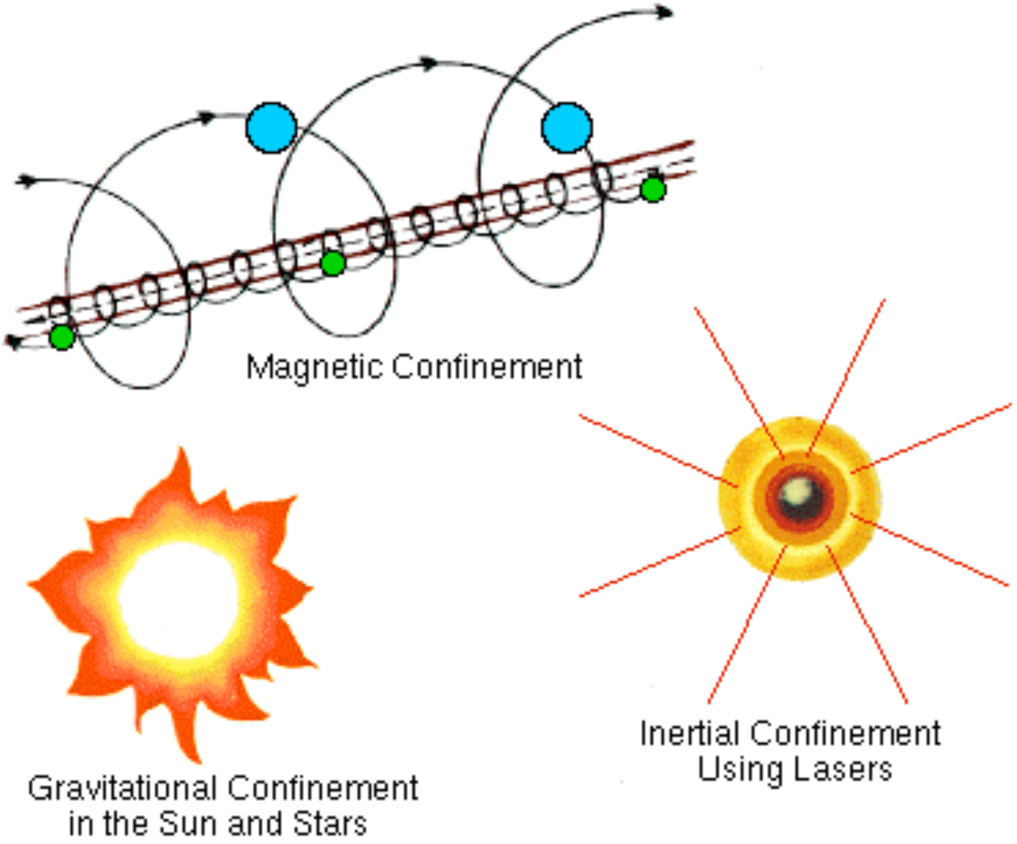
- Fuel resource will last many millions of years
  - Deuterium, a hydrogen isotope, is found in the ocean

  - Tritium is a byproduct of the process and is harvested for reuse

- No radioactive wastes - although there will be local activation of structural materials

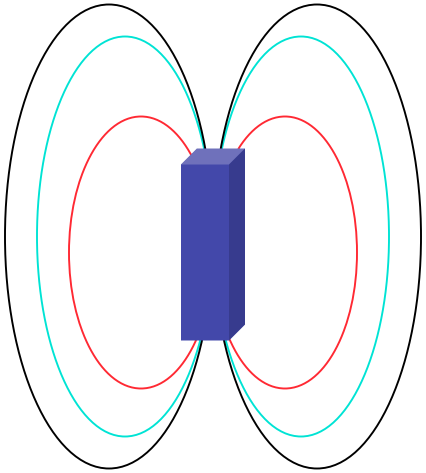
Methods for confinement

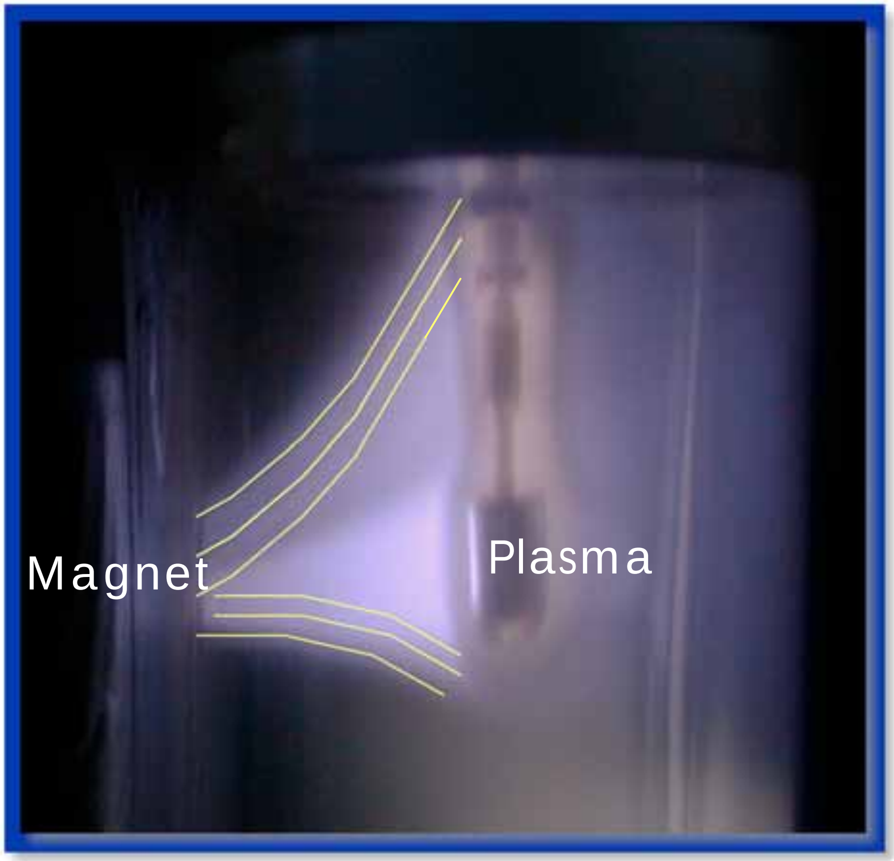
- **Hot plasmas are confined with gravitational fields in stars.**
- **In fusion energy experiments magnetic fields are used to confine hot plasma, and inertial confinement uses lasers.**



Magnetic fields exert a force on moving charges

Plasma can be controlled by a magnetic field, and the effects are observable if the mean free path is long enough.



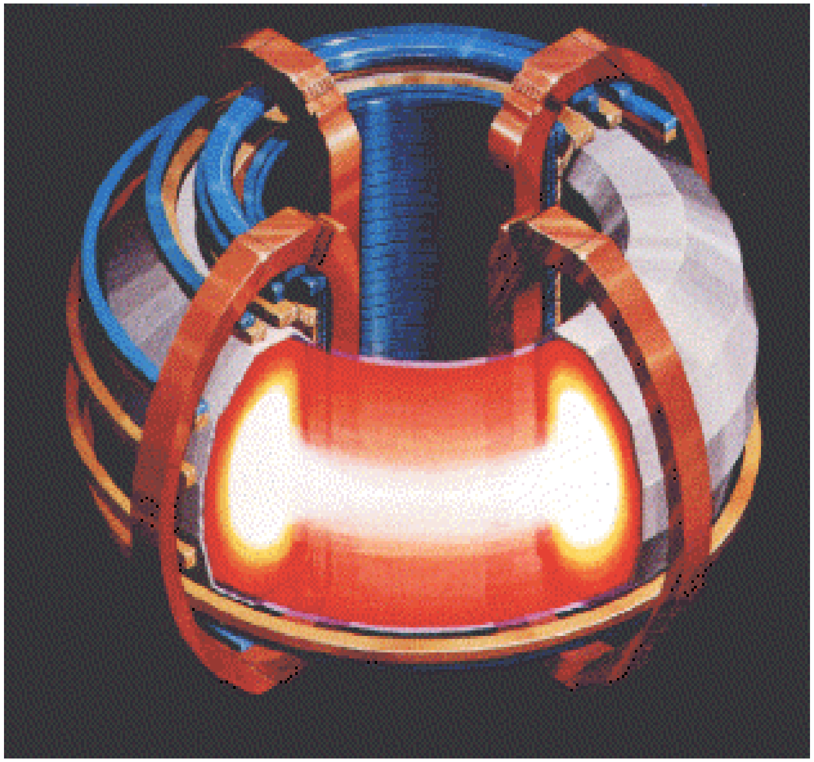


The Magnetic Fusion Reactor

- **How can we fuse these light atoms?**
  - Make a plasma---ionize the gas atoms
  - Heat the plasma---use particle beams and electromagnetic energy (RF, microwave)
  - Hold on to the plasma---use a magnetic field
  - Harness the energy---use a series of heat exchangers involving liquid metals and other fluids

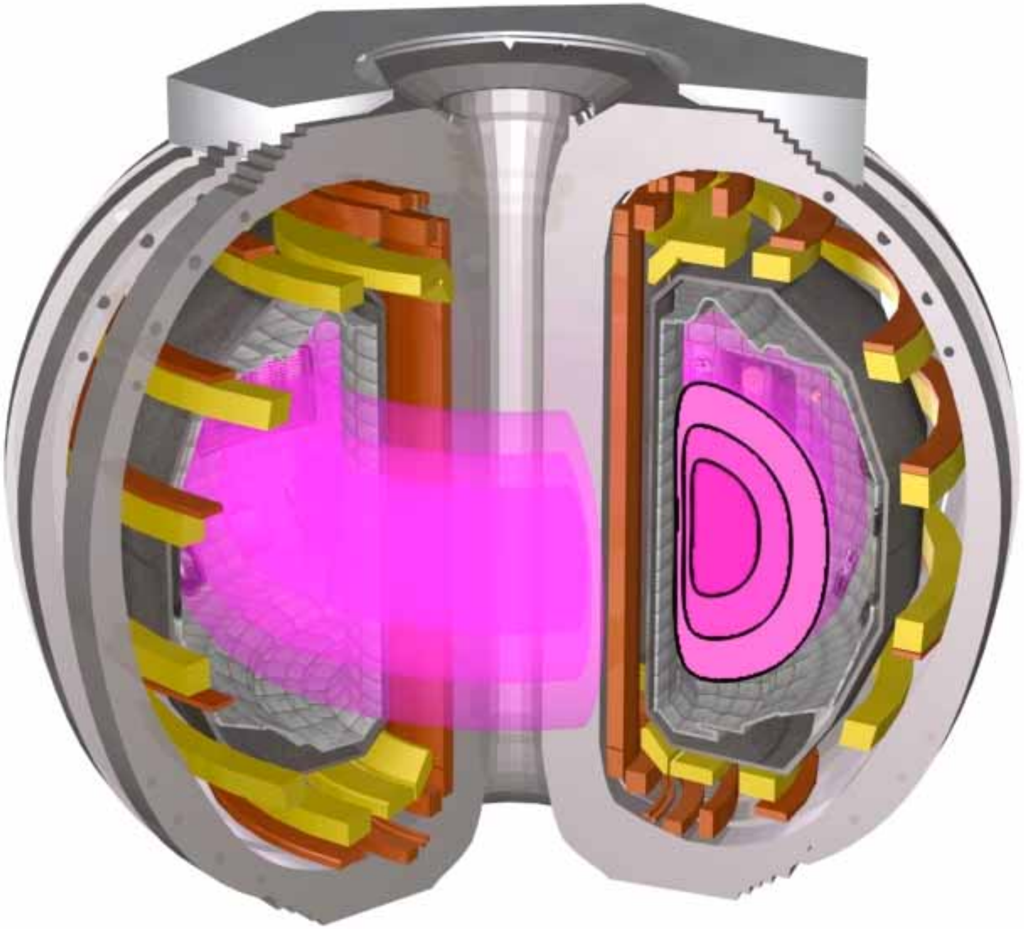
Controlling fusion with magnetic fields

- **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.**

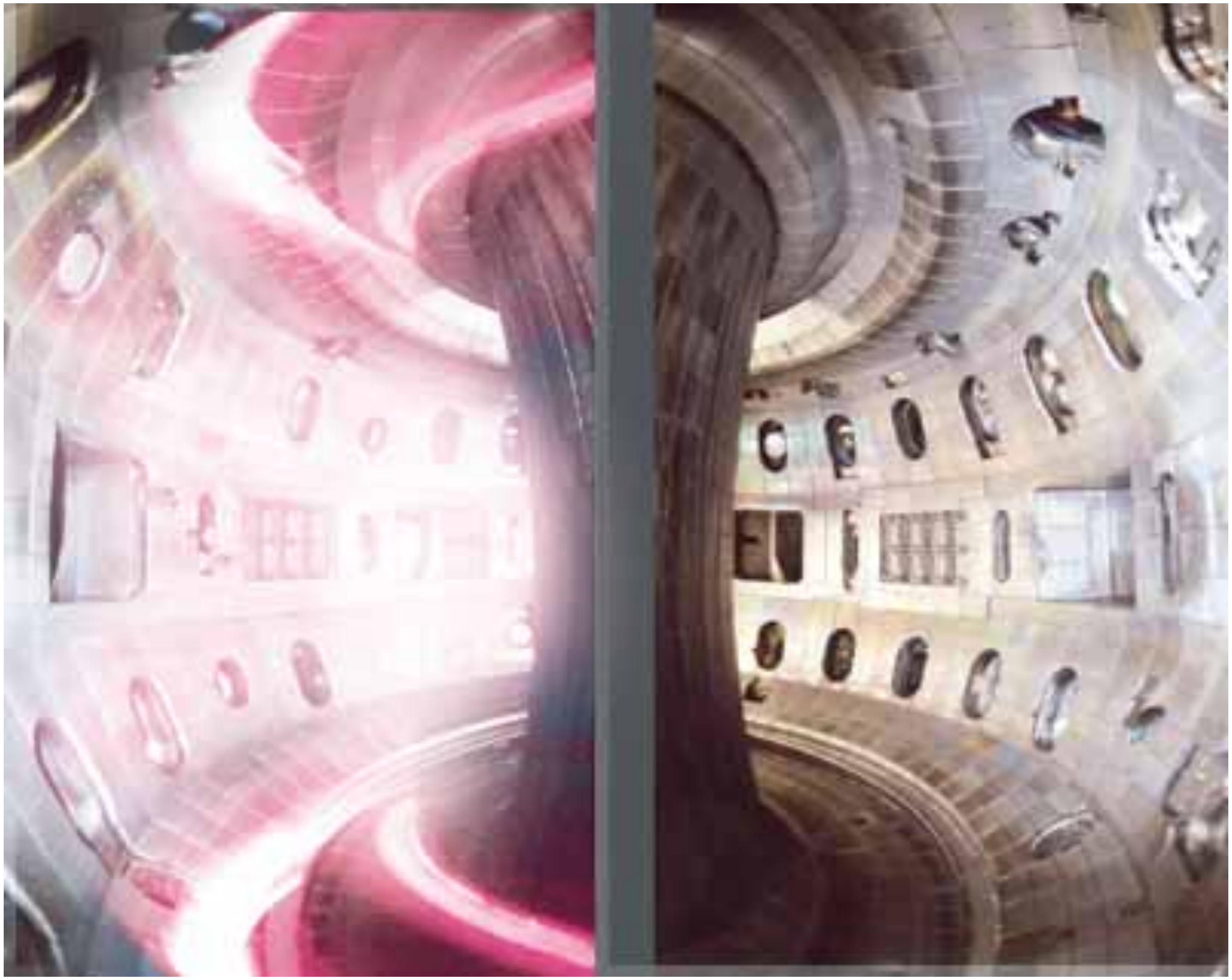


http://demo-www.gat.com/

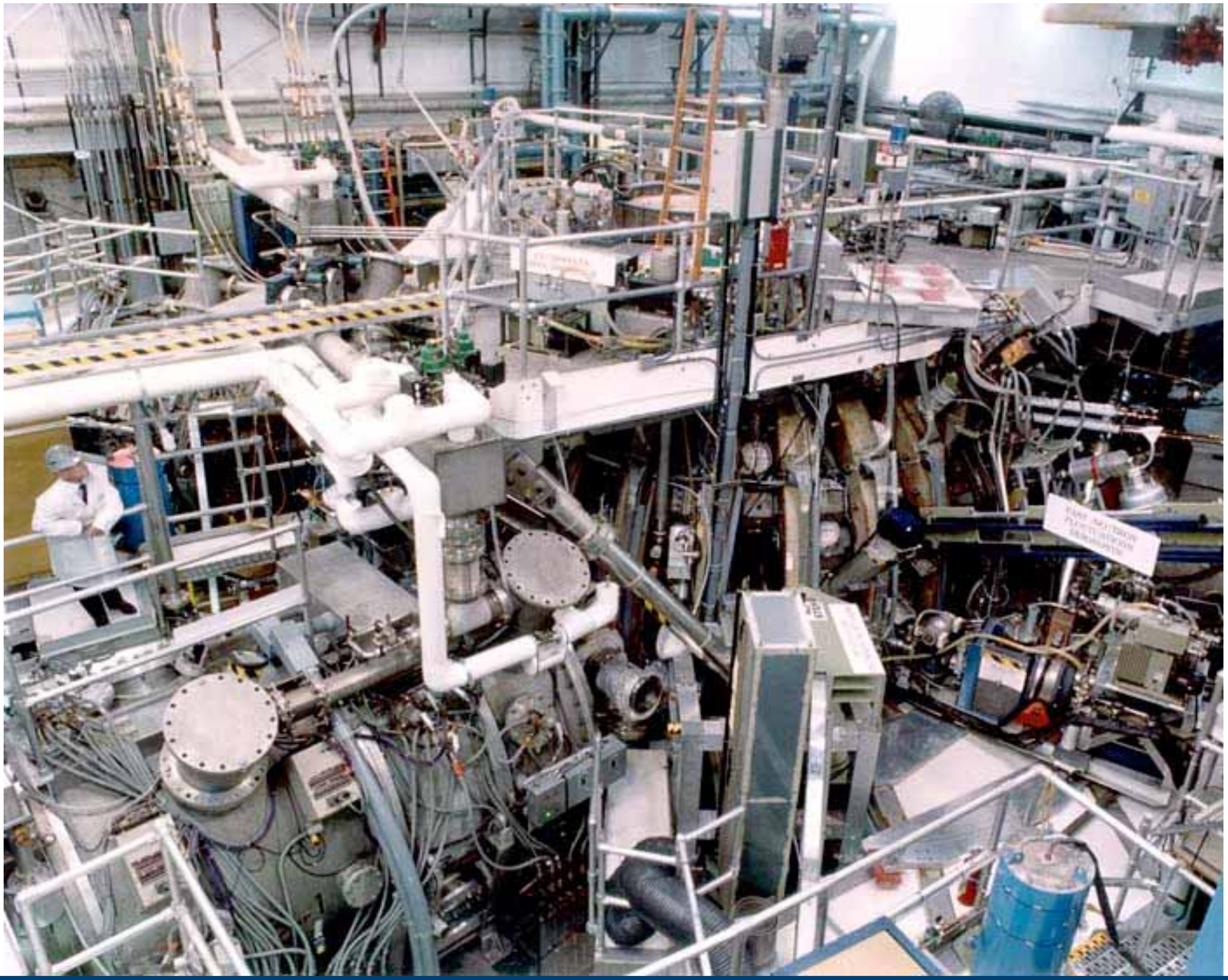
DIII-D Tokamak contains high temperature deuterium plasma



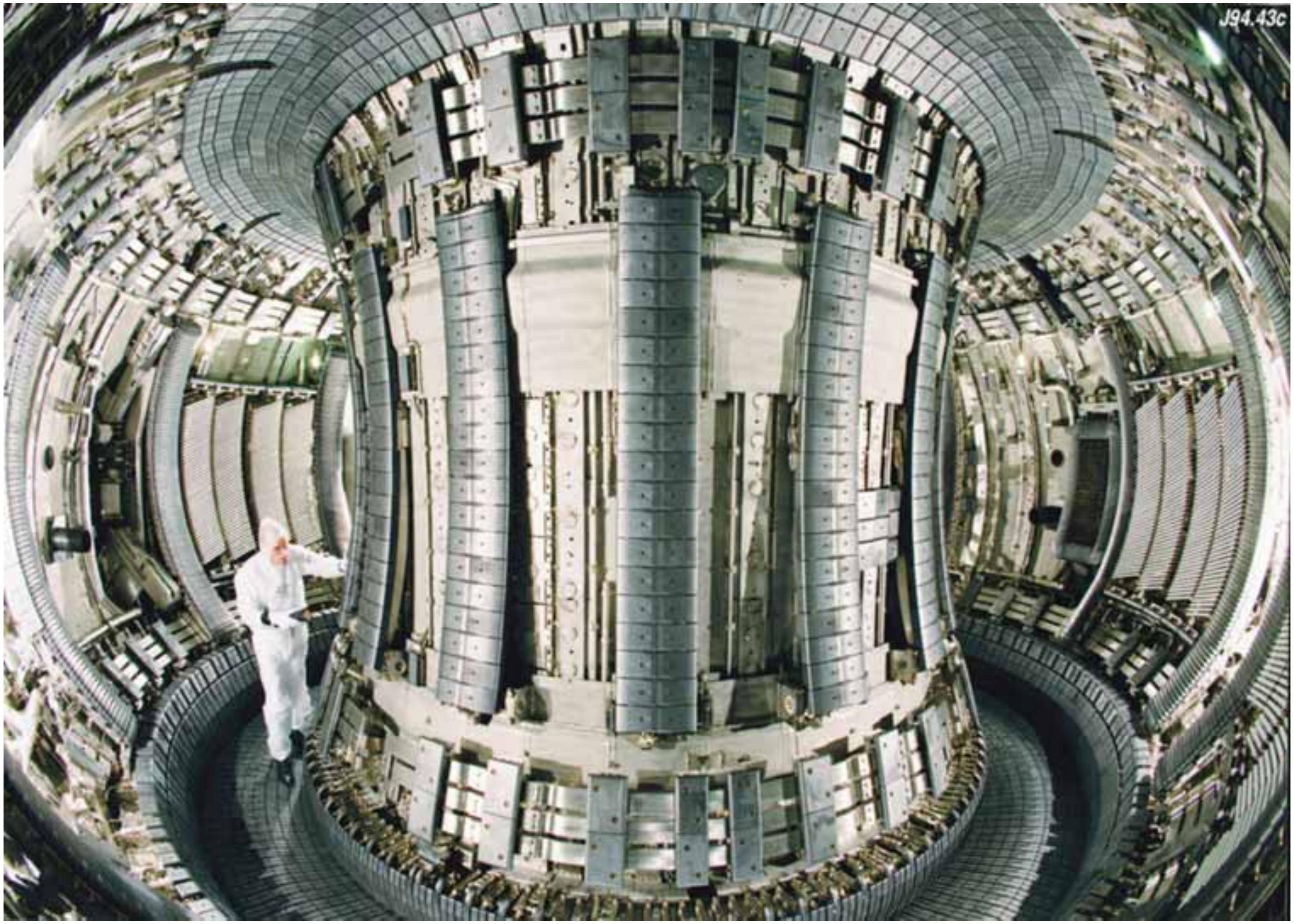
DIII-D with plasma and with no plasma



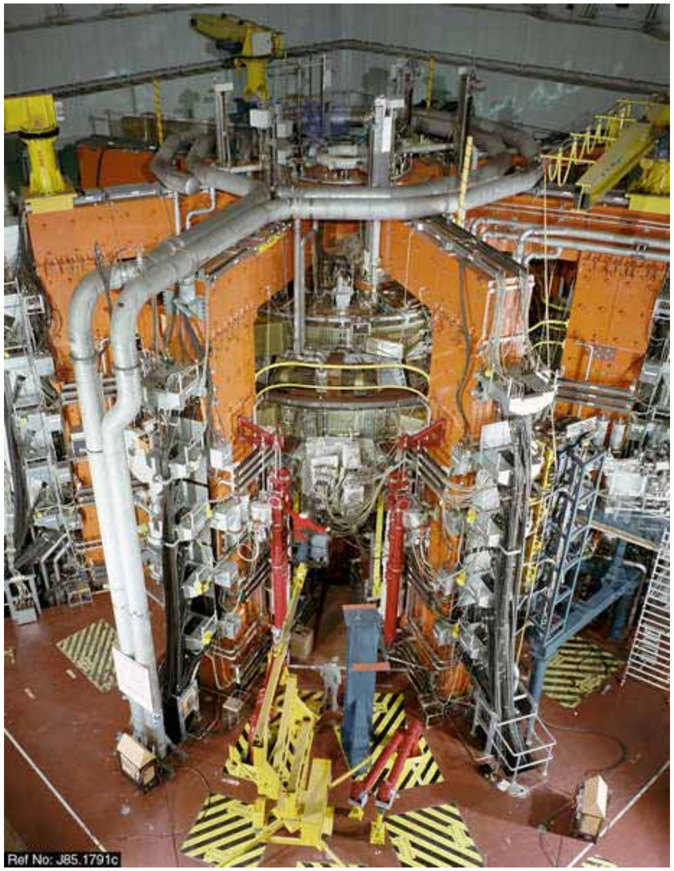
Outside DIII-D - industrial scale experiment

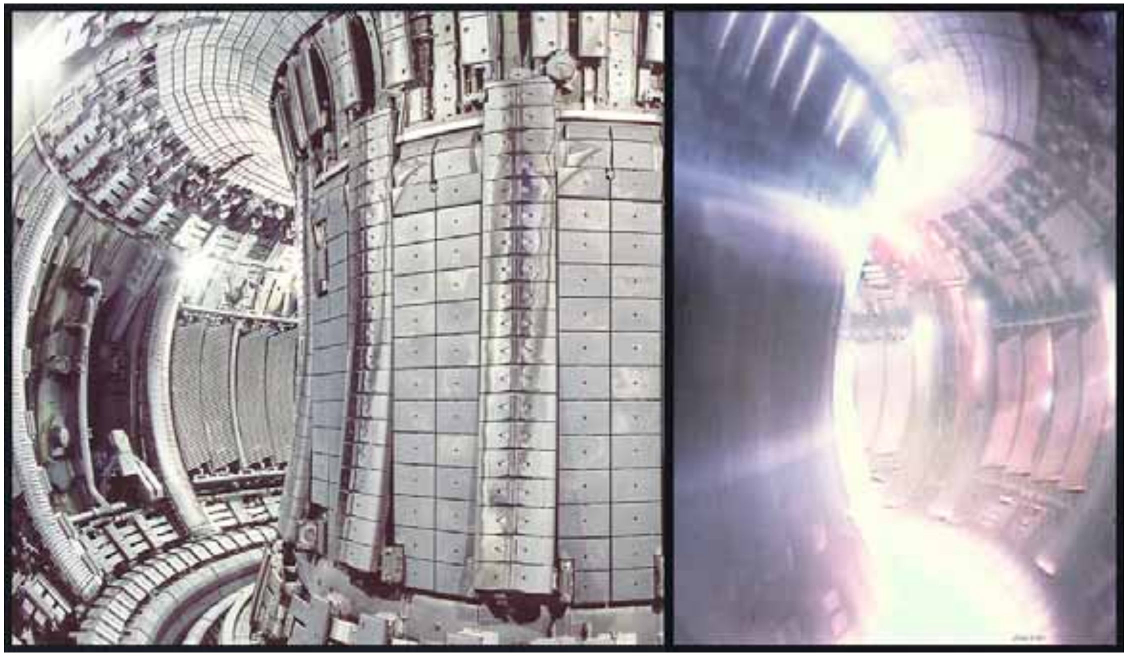


Joint European Torus - JET

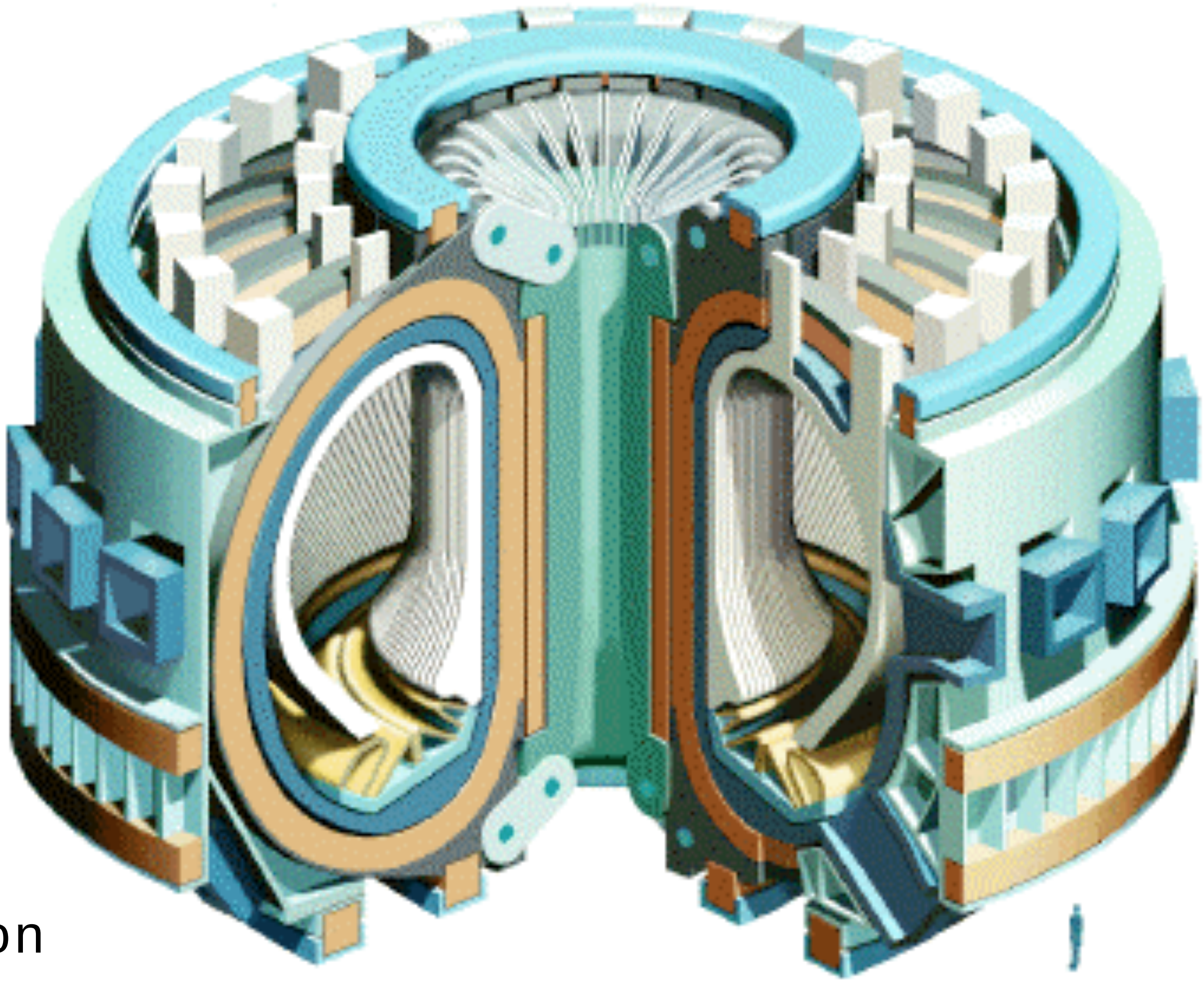


Joint European Torus:
the largest confinement device ever built





ITER - “The Way” in France



International

Large scale

Produce fusion energy

No electricity production

END