Principles of Magnetic Confinement Fusion, including Auxiliary Heating Methods and Spectroscopic Diagnosis

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SULI summer lecture
July 11, 2019
Princeton, NJ

We need energy research because we have a *looming* worldwide energy crisis

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- World energy use will double by ~ 2045
- Continued reliance on fossil fuel will likely cause unacceptable climate changes
- A substantial R&D program is needed to develop alternative sources of energy
  - Nuclear power from fission plants should be the bridge to the future
    - *Improved public education needed*
  - Fusion energy R & D is one of the high-risk, high-reward ventures in the U.S. and abroad

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Outline

- Fusion reaction basics (*interactive Q/A session*)

- Challenge of managing interactions between the plasma and the surrounding wall - *how do you stop the wall from melting?*

Fusion is a Nuclear Process in which Light Nuclei Fuse into Heavier Ones

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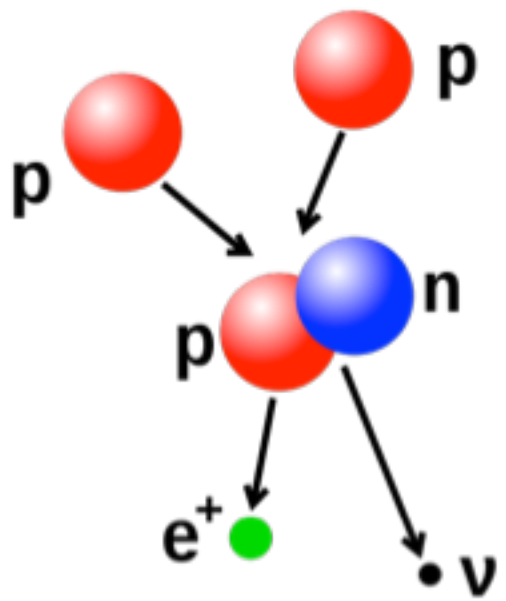

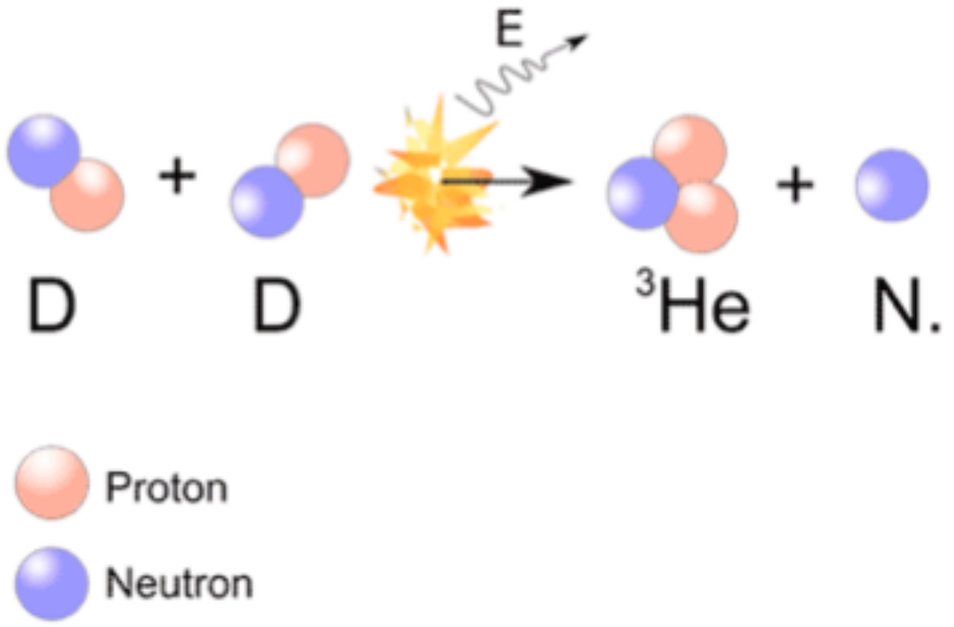

- During fusion, a small part of the reactant mass is converted to energy through Einstein's equation: $E=mc^2$

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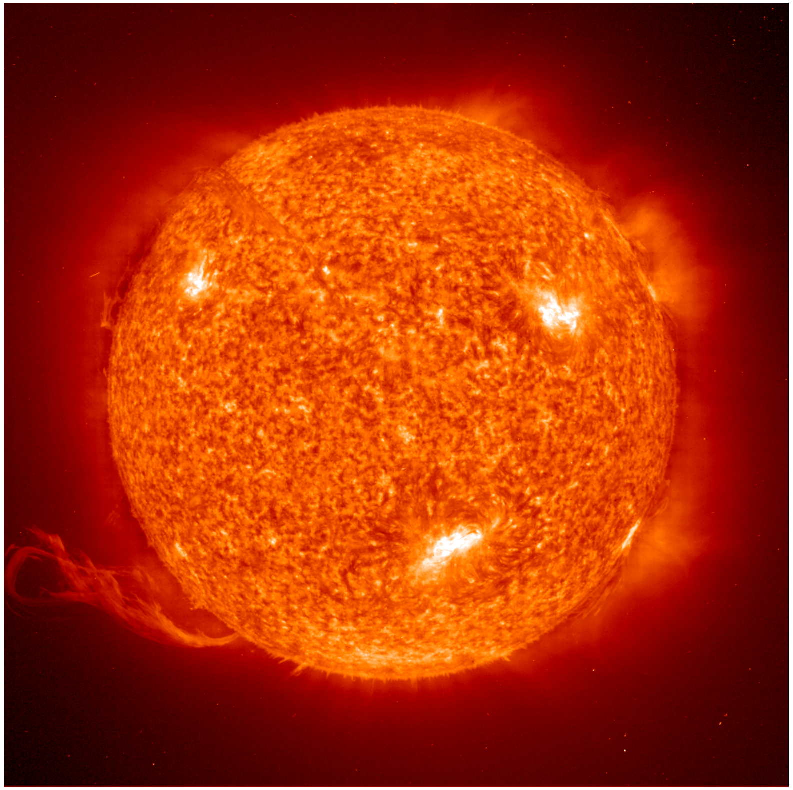
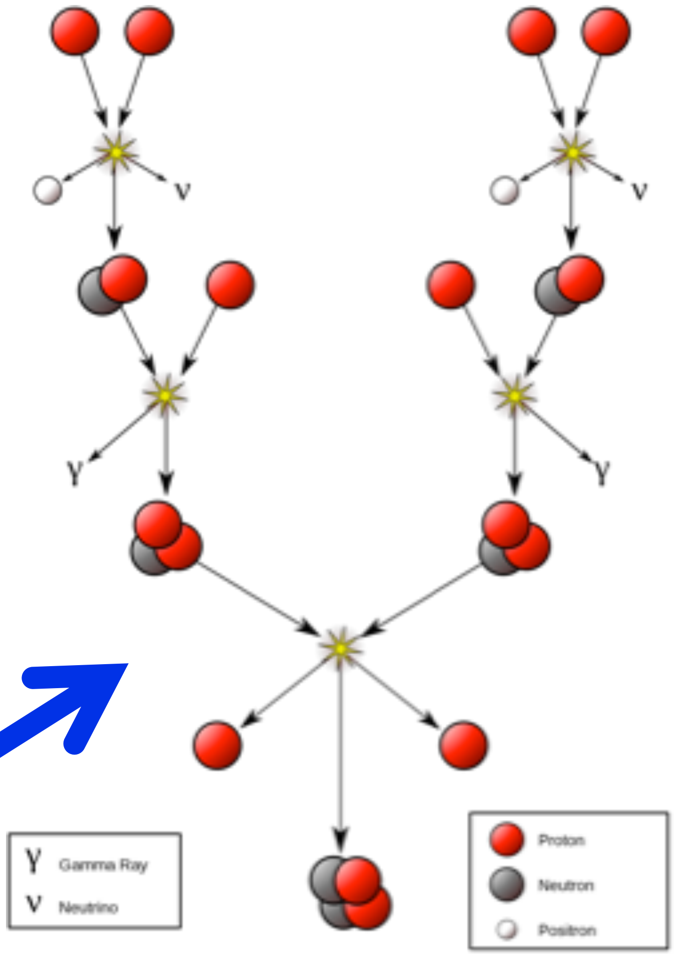
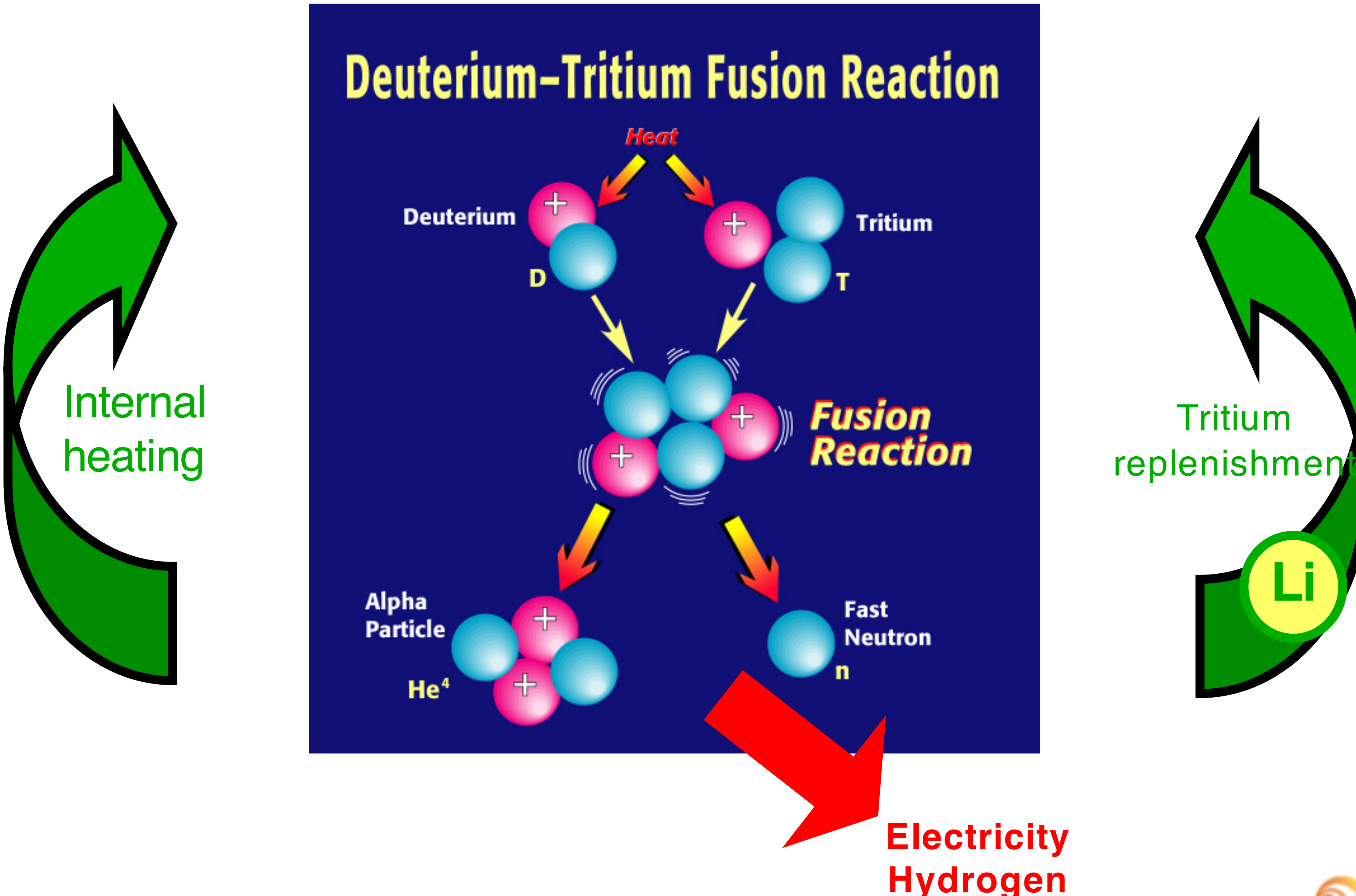
Stellar Fusion is a Naturally Occurring Example





- Shown at right is the proton-proton chain, dominant in our sun

Fusion between deuterium and tritium is the one used in reactor designs



For Conventional Fusion, Atomic Nuclei Must Collide at High Energy

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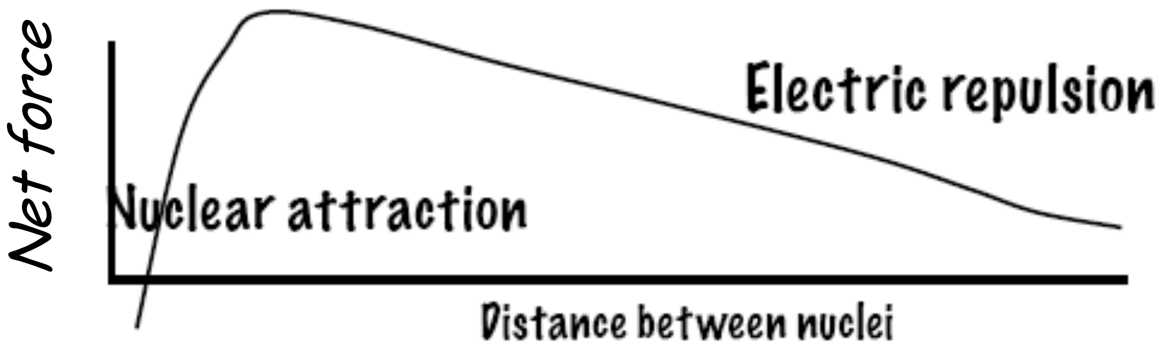
- High energy input is required
  - Atoms heated to high temperatures
  - Electrons break free from nuclei
  - Free electrons, ions form a plasma which has ~ zero net charge
    - Examples: lightning, aurora, fluorescent lights, sun, magnetosphere



- Plasma ions must be heated enough to overcome the longer-range electric repulsion force
- Ions must be close-enough for nuclear attraction force to dominate

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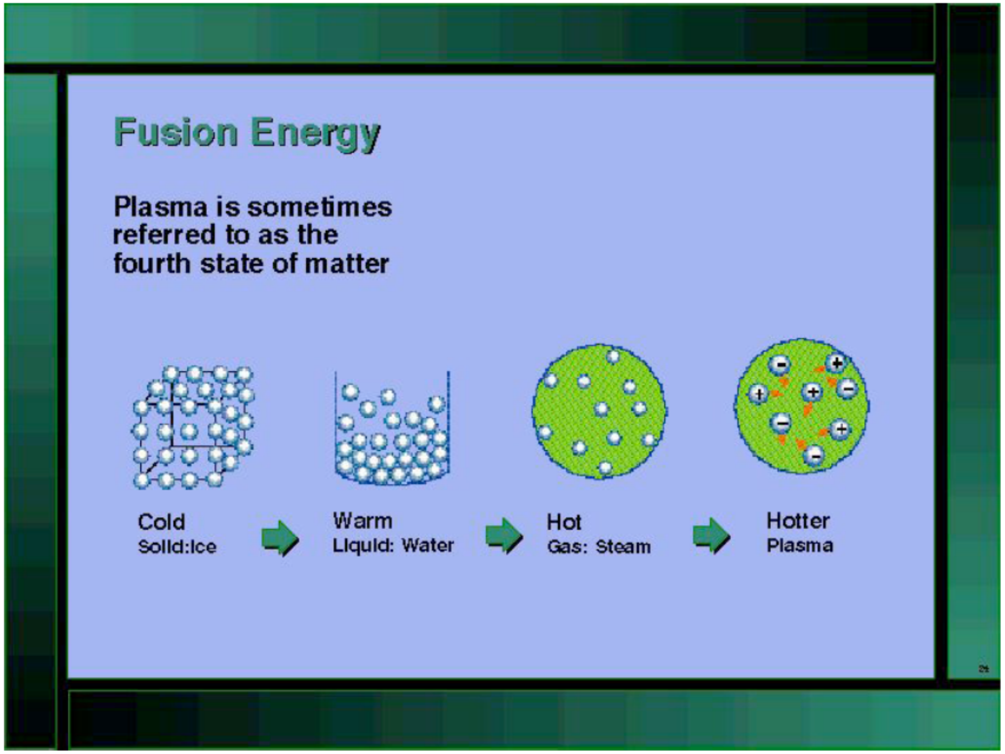
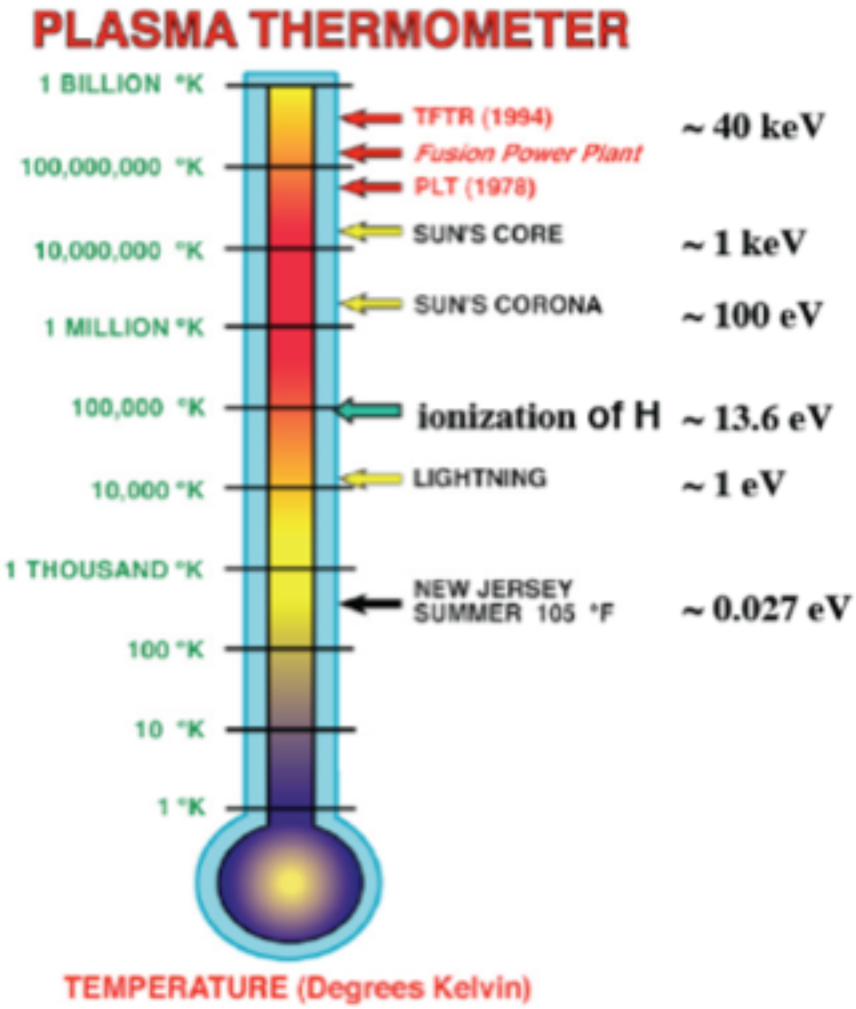
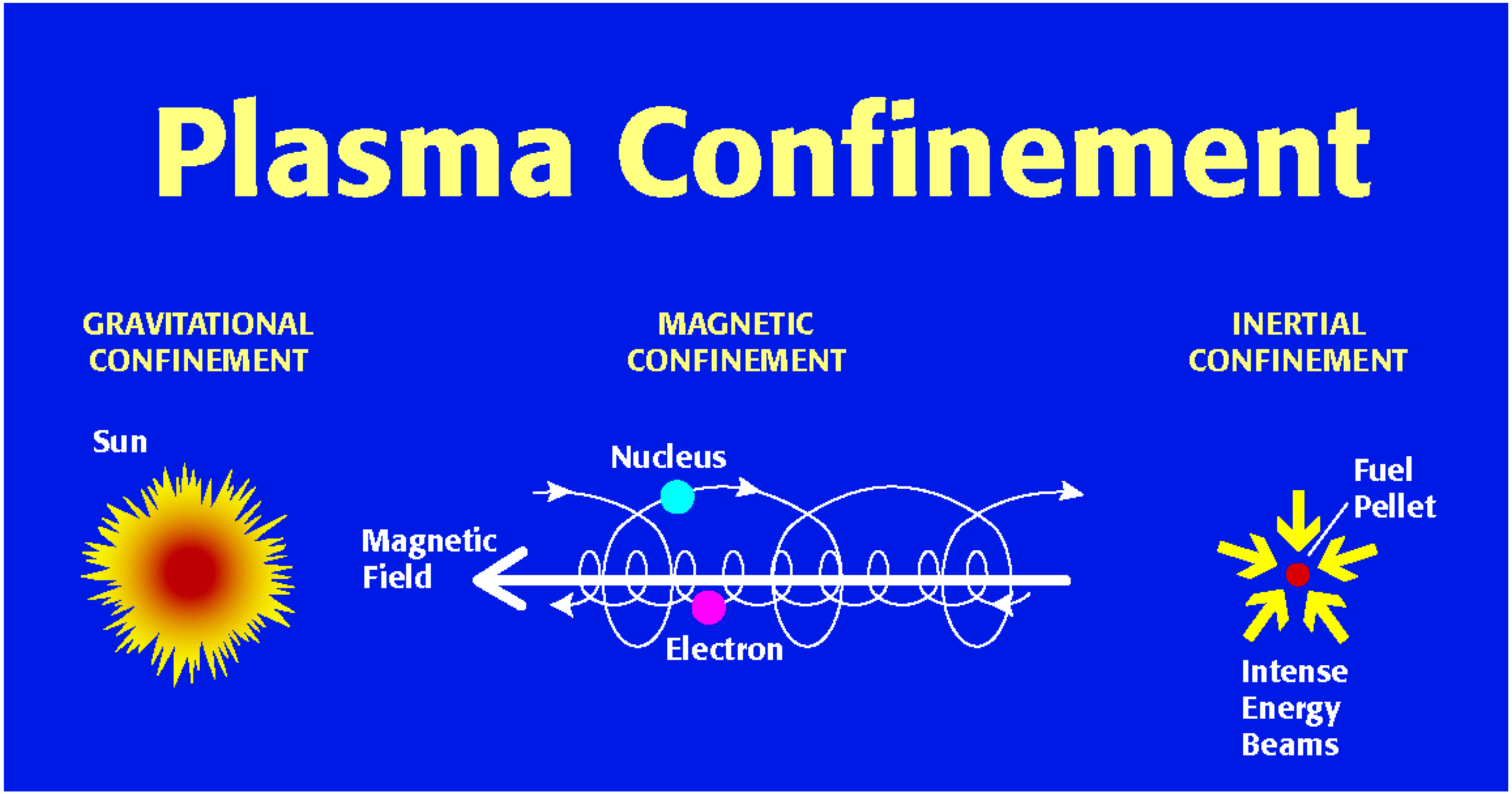
How hot does the plasma need to be for fusion?





There are Several Ways of Confining Plasmas



Requires large amounts of mass!

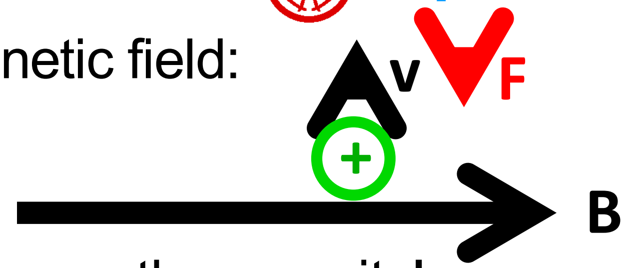
Confines the plasma in the direction across the magnetic field

Energy and defense relevant

Magnetic fields confine the plasma in the direction across the magnetic field

- Force on a charged particle in a magnetic field:

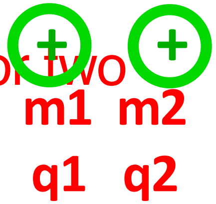
  $F = q\ v\ X\ B$



- Electromagnetic forces are much stronger than gravity!

  $F_{elec} \sim q_1 q_2/r^2$, $F_{gravity} \sim m_1 m_2/r^2$

  $F_{elec} / F_{gravity} \sim 10^{26}$ for two protons!



- Another way to express this:
  - Stars need between 5000 and 25,000 times the mass of the earth for fusion to begin, or about 10^{29} pounds
  - A new international fusion device under construction in France (ITER) uses 20 million pounds of electromagnetic coils to confine the plasma for fusion to 'begin'

    $M_{ITER\_coils} / M_{star} \sim 10^{22}$ (mechanical advantage)

How big is that number? Think of it like a ratio of distances:

The size of an atom to the distance between the sun and Pluto

Issue: magnetic fields don't restrict plasma motion along the field, so plasma leaks out

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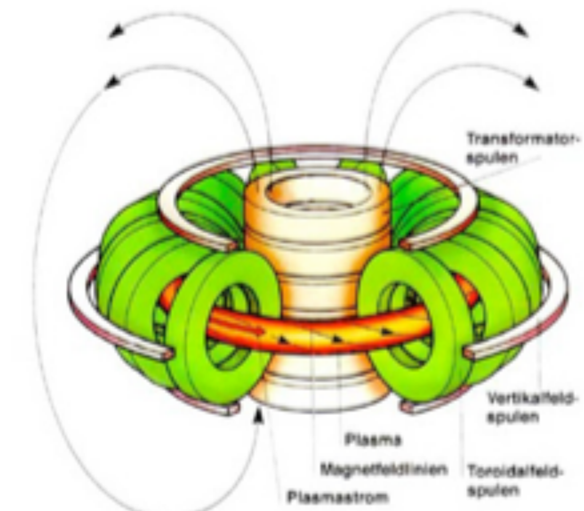
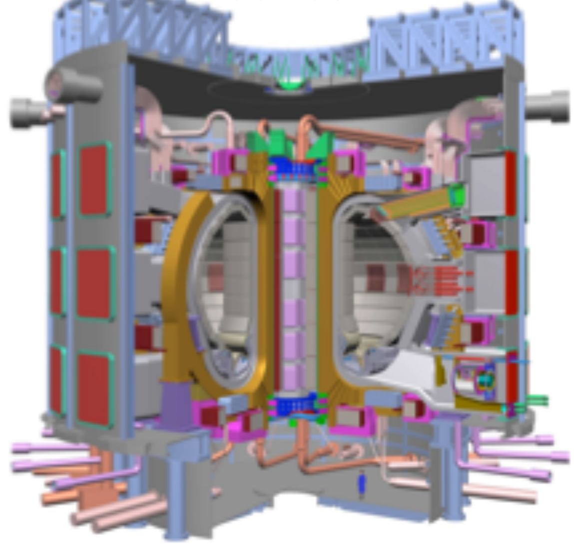
- Force on a charged particle in a magnetic field:

$$F = q\, v \times B$$

- How to solve problem of end losses in a linear fusion device
  - Increase the magnetic field strength at the ends relative to center ('magnetic mirror'), but this is imperfect
  - Bend the linear device into a circle: no beginning or end!



ITER



  - Better, but still imperfect

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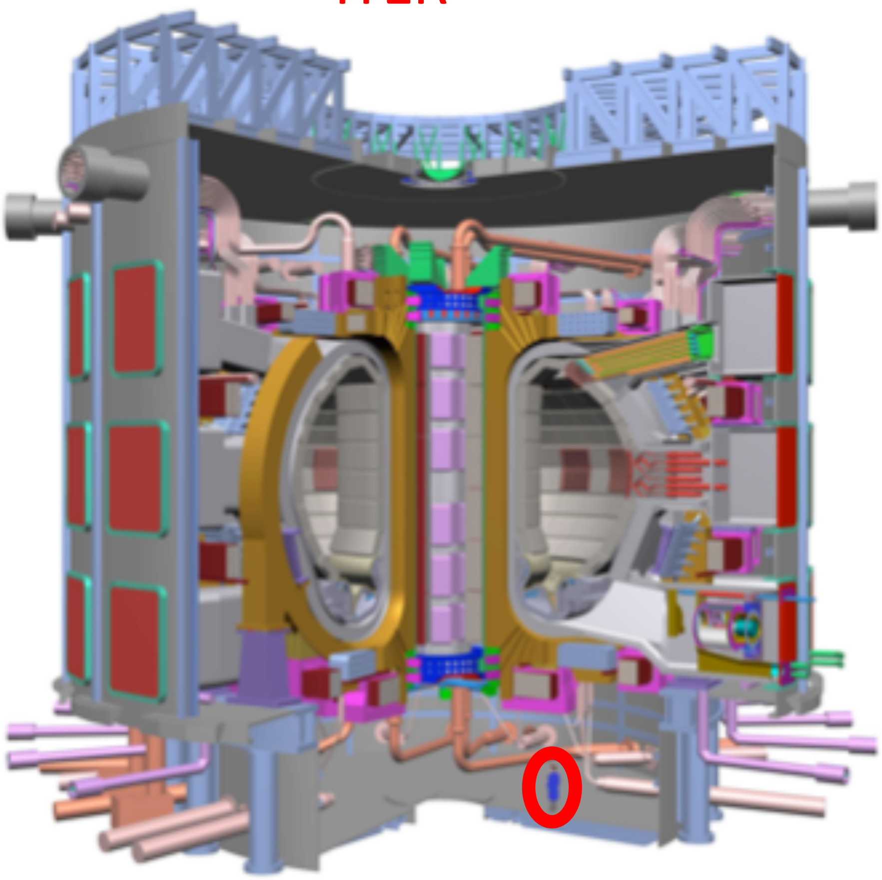
The international fusion community has agreed to build ITER, a giant step toward energy production

ITER



- Seven international partners
  - EU
  - Japan
  - US
  - Russia
  - China
  - Korea
  - India
- Being built in France
  - Construction finished ~ 2018
  - D-T plasmas in 2026
- P_{fusion} = 500 MW for 1000 sec discharges
- P_{fusion} = 250 MW in steady state

How do we heat up the gas to these astonishingly high plasma temperatures?

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- Resistive heating
  - We induce a high current through the plasma (millions of amperes)
  - The plasma has an electrical resistance, and we get resistive or 'ohmic' heating
  - Analogous to resistive heating in a circuit: $P_{heat} = I_{plasma}^2 R_{plasma}$
  - Issue: as plasma gets hotter, R_{plasma} goes down, less efficient

- Wave heating
  - Like heating food, except that the right wave frequencies are determined by plasma properties and magnetic field
  - Most effective heating done by radio waves, not microwaves

- Heating with energetic neutral beams, like accelerators
  - Accelerator portion produce charged particles
  - Those are converted back to neutrals to penetrate magnetic fields
  - The energetic neutrals transfer energy to plasma inside device

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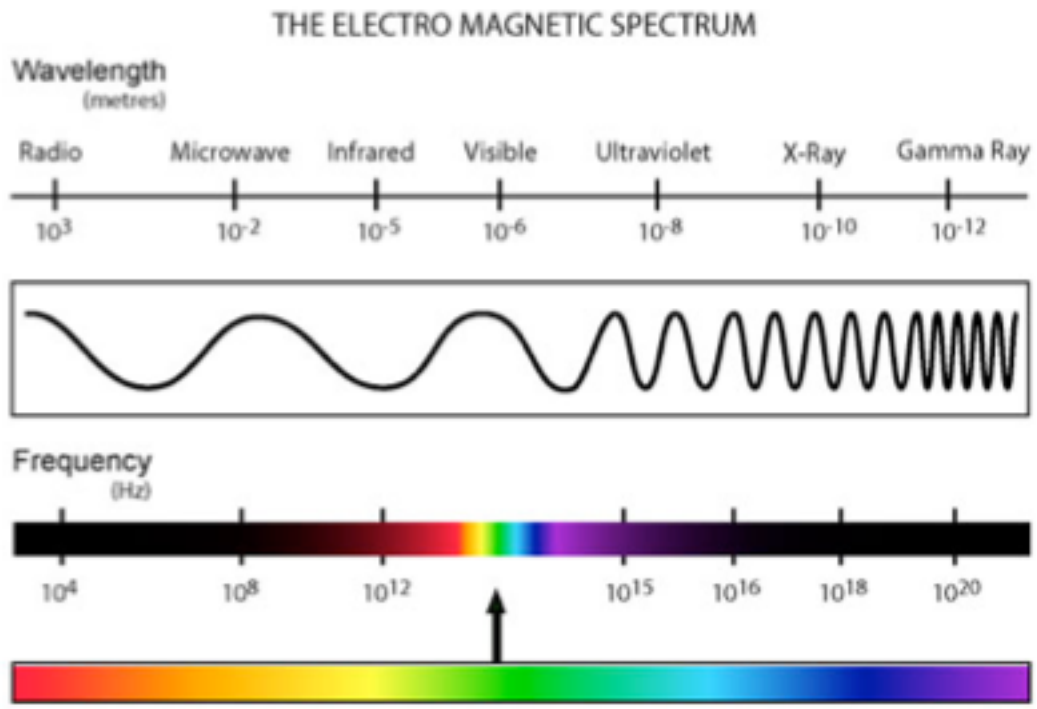
Once we're successful at heating plasmas, how do we measure their properties?

- We measure passive electromagnetic radiation emission
  - Plasma emits in all parts of the spectrum, from the X-ray to the Infrared



  - The most energetic emission (X-rays) come from the center, while the least energetic emission (Infrared) comes very near the wall
  - Visible emission comes from the very edge of the plasma, and can be measured with (fast!) cameras

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- We also actively probe the plasma, e.g.
  - Thomson Scattering: laser beam fired at the plasma, and scattered beam properties tell us local electron density, temperature
  - Charge Exchange Recombination Spectroscopy and Motional Stark Effect: we examine the interaction of the plasma with the neutral beam for information on the ion temperature, rotation speeds, and magnetic field pitch

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Outline

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- Fusion reaction basics
- Challenge of managing interactions between the plasma and the surrounding wall - *how do you stop the wall from melting?*

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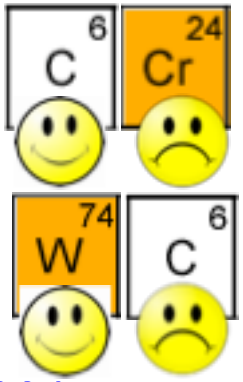
Major challenge: plasma core ~ 150 million K, wall must be kept ≤ 2000 K

- Fusion plasmas must be kept very pure with hydrogen isotopes
  - Impurities from the walls cause a lot of (electron line) radiation that cools the plasma and quenches fusion
  - The radiation gets higher as the atomic number of the impurity increases
  - On the other hand, the rate at which impurities are generated can decrease as the atomic number increases
  - * Helium is a natural by-product (“ash”) of fusion, and it can be tolerated to 10% concentration in the core



- To insure plasma purity, fusion chambers are ultra-high vacuum ~ 10^{-11} atmospheres

Plasma-material interface: how do you keep the hot part hot and the cold part cold?

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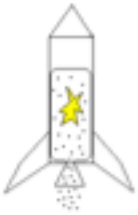
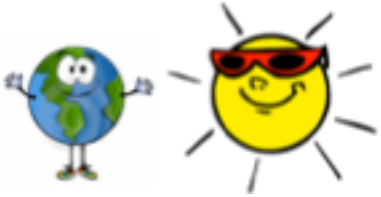
- Basic answer is mass difference
  - In ITER, there is less than ½ gram of deuterium and tritium in the core
  - The total mass of ITER is nearly 50 million pounds; a fraction of this is in the plasma facing components, which will absorb the heat
  - The internal components of ITER will be actively cooled to keep temperature below melt limits

- The present technological heat flux removal limit is about 10 million W/m^2
  - A rocket nozzle has average heat flux of 1 million W/m^2!
  - The sun's radiant heat flux on earth ~ 1400 W/m^2





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Fusion is an exciting research area with engaging science and technology

- Vibrant area with substantial domestic and international effort
- Engineering the plasma-material interface is critical to the success of fusion
- Students can make meaningful contributions!

Thank you for your attention, and this opportunity!