Plasma Physics and Fusion Devices and an Introduction to Plasma materials Interactions (PMI)

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1. What is a plasma?

2. Fusion.

2.1 ITER

3. Plasma materials interactions.

4. Machine Learning and the code HEAT.

1. What is a plasma?

Plasma is a state of matter along with solids, liquids and gases. When a neutral gas is heated such that some of the electrons are freed from the atoms or molecules, it changes state and becomes a plasma.

- It consists of a partially-ionized gas, containing ions, electrons, and neutral atoms.
- The free negative electrons and positive ions in a plasma allow electric current to flow through it.
- Some electrons are freed from their atoms, allowing current and electricity to flow and can react to, both, electric and magnetic fields.

One of the few naturally occurring plasmas found here on Earth is lightning!

2. Fusion

Fusion, the power that drives the sun and stars, combines light elements in the form of plasma — **the hot, charged state of matter composed of free electrons and atomic nuclei** — that generates massive amounts of energy.

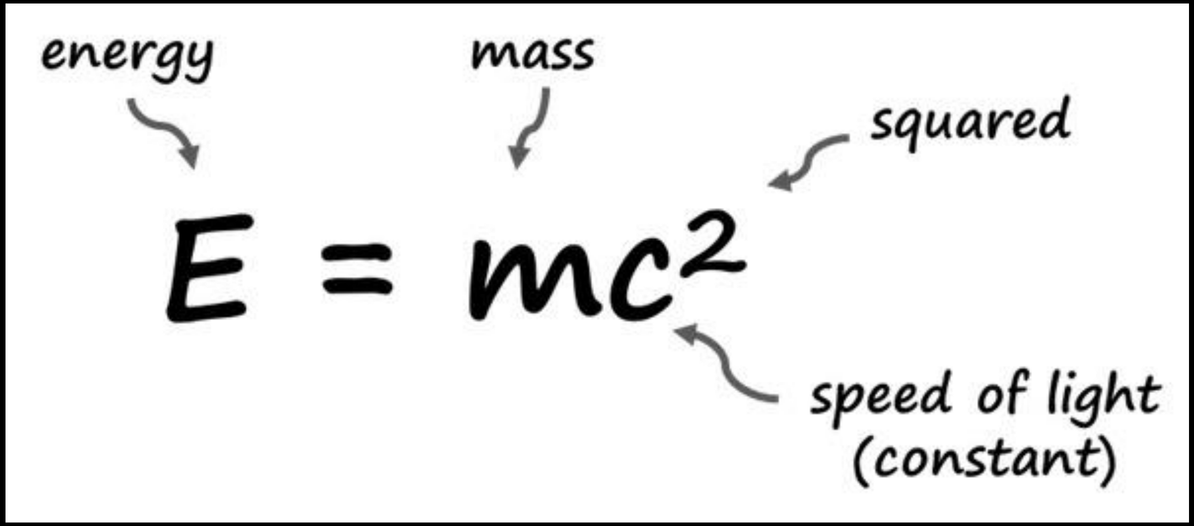
In the core of the Sun hydrogen is being converted into helium. This is called **nuclear fusion**.

It takes **four hydrogen atoms to fuse into each helium atom.** During the process some of the mass is converted into energy.

- Mass of 4 H atoms: 4.03130 AMU
- Mass of 1 He atom: 4.00268 AMU
- 1 Atomic Mass Unit (AMU) equals 1.67×10^{-27}kgs

- The difference between the mass of 4 H atoms and 1 He atom is 0.02862 AMU which is only 0.71% of the original mass.

- If 4 grams of H are converted to He, only 2.8×10^{-3} grams of the mass is converted to energy.



$\mathbf{2.6 \times 10^{11}}$ **Joules**

Enough energy to keep a 60-watt light bulb shining for over 100 years!

On Earth, researchers are trying to build fusion reactors of their own. They seek to maximize the number of ions in a small region and the amount of time that they stay close together. **To do that, fusion reactors heat plasmas to temperatures much hotter than the core of the sun — over 100 million degrees Celsius.**

Strong magnetic fields or high-powered lasers then confine the plasma into small controllable regions where fusion can happen.

Three conditions must be fulfilled to achieve fusion in a laboratory:
very high temperature (to provoke high-energy collisions);

sufficient plasma particle density (to increase the likelihood that collisions do occur); and

sufficient confinement time (to hold the plasma, which has a propensity to expand, within a defined volume).

2.1 ITER

In ITER, fusion will be achieved in a tokamak device that uses magnetic fields to contain and control the hot plasma.

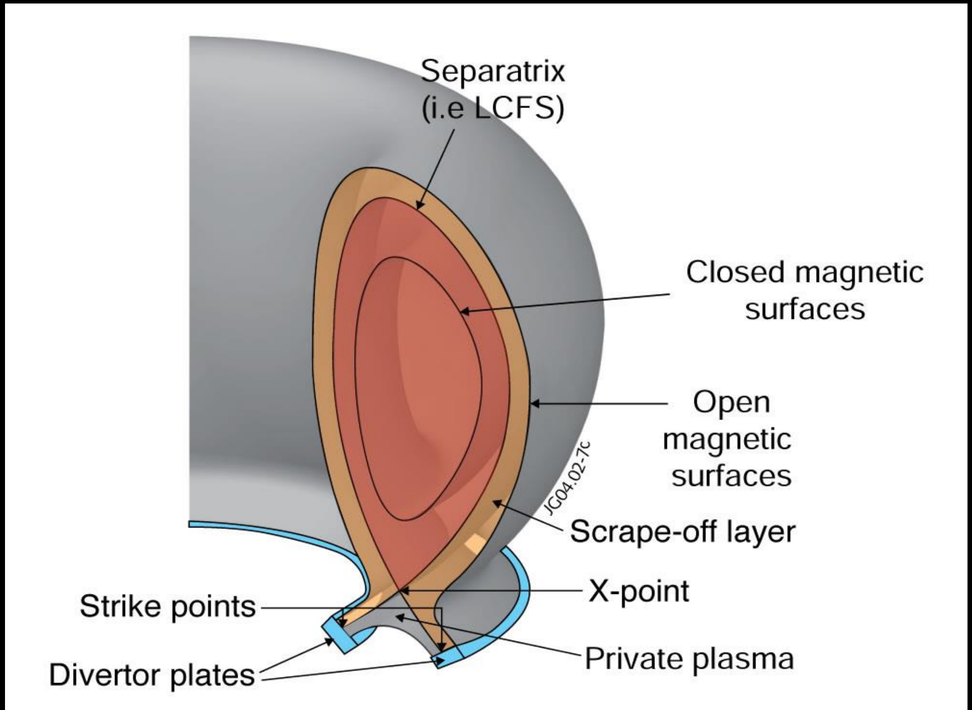
The fusion between deuterium and tritium (DT) nuclei produces one helium nucleus, one neutron, and great amounts of energy.

The tokamak is an experimental machine designed to harness the energy of fusion. Inside a tokamak, the energy produced through the fusion of atoms is absorbed as heat in the walls of the vessel. Just like a conventional power plant.

A fusion power plant will use this heat to produce steam and then electricity by way of turbines and generators.

3. Plasma Materials Interactions (PMI)

The plasma and the wall are a strongly coupled system whose interactions range over an extraordinary width of scale, from eV scale atomic interactions to hundred mega joule disruptions.



It is important to look into the configuration of the Plasma Facing Components (PFCs) of modern tokamaks and their interaction with the plasma. Plasma Material Interactions (PMIs) critically affect tokamak operation in many ways.

Erosion by the plasma determines the lifetime of PFCs and creates a source of impurities, which cool and dilute the plasma.

4. Machine Learning and the code HEAT

- Tokamak power exhaust is a serious engineering challenge for high power tokamaks.

- Mitigating the power loads will require **advanced simulation, real time control, and experimental validation, all integrated into a single analysis.**

- **The engineering limits of plasma-facing components (PFCs) constrain the allowable operational space of tokamaks.** Poorly managed heat fluxes that push the PFCs beyond their limits not only degrade core plasma performance via elevated impurities, but can also result in PFC failure due to thermal stresses or melting.

- **High-precision 3-D heat flux predictions are necessary to accurately ascertain the state of a PFC.**

- A new code, **the Heat flux Engineering Analysis Toolkit** (HEAT), has been developed to provide high-precision 3-D predictions and analysis for PFCs.
- Check this paper: https://www.tandfonline.com/doi/full/10.1080/15361055.2021.1951532
- The link for github page: https://github.com/plasmapotential/HEAT

Thank you!