THE PLASMA CONNECTION

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Harnessing the power of the sun: Plasmas for fusion energy

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In the beginning, there was light

And that light came from fusion energy and created everything that we know today. When you look up into the sky, you see the sun - this bright life-giving source that helps trees grow and gives us life. We would not exist without the sun. When I look up into the sky, I see a brilliant fiery ball of plasma - an energy source. Deep inside the core of the sun is a burning plasma filled furnace that gives stars their life force. The driving reaction that powers this furnace is fusion. Beyond the science, I see hope in a world where we have fought wars over energy and resources for energy production. I see an amazing challenge. I see the challenge of harnessing the power of fusion energy to provide a clean source of energy here on Earth. Fusion is the process of combining two nuclei to form one new nuclei. For this process to occur on Earth, we need to heat the fuel to temperatures ten times hotter than the surface of the sun. And intertwined within this grand challenge is plasma - the state of matter that is crucial to achieving the conditions for fusion. We don’t yet have the infrastructure to utilize this clean energy source that powers the sun and that’s what drives my research.

Less than 100 years ago, scientists thought our sun was made out of the same elements that comprised the Earth. Scientists also thought that the sun and stars were fueled by chemical reactions burning their constituents. It wasn't until Cecilia Payne looked at characteristic signatures of light emitted by the sun (called spectral line emission) and observed that helium is many thousands of times more abundant, and hydrogen was one million times more abundant in the Sun than on Earth. These observations also showed that hydrogen is the most abundant element in the Universe. Cecilia made this discovery while performing her PhD thesis research in 1925 and her observations were widely dismissed at the time. This discovery that stars are composed largely of the two lightest elements would later lead scientists to discover that nuclear fusion of hydrogen nuclei into helium is the process that powers the Sun and the stars in the universe. A large amount of energy is required for these light nuclei to overcome the repulsive Coulomb force to fuse light, positively charged nuclei together. At these extreme temperatures, electrons are stripped from their nuclei, matter is in the plasma state (figure 1) and must be cleverly confined. Plasmas and fusion are the most dominant state of matter and reaction, respectively, in our observable universe and both are essential to life and our future.

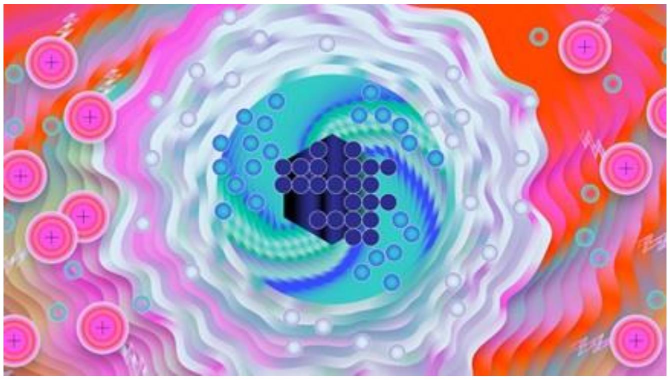

Fig. 1 The four states of matter by Ana Kova for the U.S. Fusion Outreach (USFusionEnergy.org). Plasmas are ionized and can be described as an electrically charged gas as depicted in this image.

The science of fusion – where the triple product reigns supreme

One of the great challenges to harnessing the power of fusion energy on Earth is reaching the extreme temperatures required for the fusion reaction to occur, confining the plasma fuel and reaching massive pressure to overcome the tremendous physical forces and fuse. The sun relies on burning plasma to fuel and sustain it. When the bulk of the plasma heating comes from the fusion reactions involving the plasma ions, it has reached the burning plasma state and is self-heating. In this burning plasma regime, the self-heating power exceeds all external heating, so no external heating is required! The extreme pressure produced by the sun's immense gravity provides the conditions for sustained fusion reactions to occur. On Earth, however, we need to be more clever to reach this burning plasma state.

The fusion process only occurs under specific conditions. Three conditions must be met for fusion to occur: (1) enough particles (density) are required at (2) high enough temperatures and (3) confined for times long enough (pulse length) to fuse the positively charged nuclei together and sustain the fusion reaction. If these conditions aren't satisfied, then no fusion will happen (this is why a runaway reaction process is unable to occur for fusion). This figure of merit is called the Lawson criterion, or sometimes referred to as the triple product, and compares the rate of energy generated by the fusion reactions in the fusion fuel to the energy lost to the environment. Net energy is achieved when the energy produced by the fusion reactions exceeds the energy put into the fuel. Ignition is achieved when the plasma becomes self-sustaining and no external heating is needed due to self-heating of the system.

There are several methods most likely to yield sustained fusion reactions on Earth using different ways to apply pressure to confine plasma. These confinement approaches broadly fit into the following categories: magnetic fusion (MFE), inertial fusion energy (IFE), and magneto-inertial fusion (MIF). Each of these methods brings unique challenges and tradeoffs in the values of density, temperature and confinement time required to achieve a burning plasma.

MFE relies on creating magnetic bottles to confine the electrically charged plasma particles. When these charged particles encounter a magnetic field, they experience a force that causes the particles to rotate around the magnetic field, confining them along magnetic field lines. This sustained confinement scheme requires a delicate balance between plasma pressure and magnetic pressure to confine the plasma fuel - kind of like confining jelly with rubber bands. This sounds like an impossible challenge, but we've gotten really good at it (Figure 2).

The IFE process initiates fusion reactions by using lasers to compress and heat small targets, the size of a peppercorn, that are filled with fuel. The compression process leads to extremely dense plasmas - this relaxes the requirements on confinement time and requires pulsed operation. MIF takes more of a middle of the road approach combining both magnetic and inertial techniques in an effort to reach fusion conditions. These are also pulsed devices and have more relaxed requirements on the confinement time compared to MFE devices.

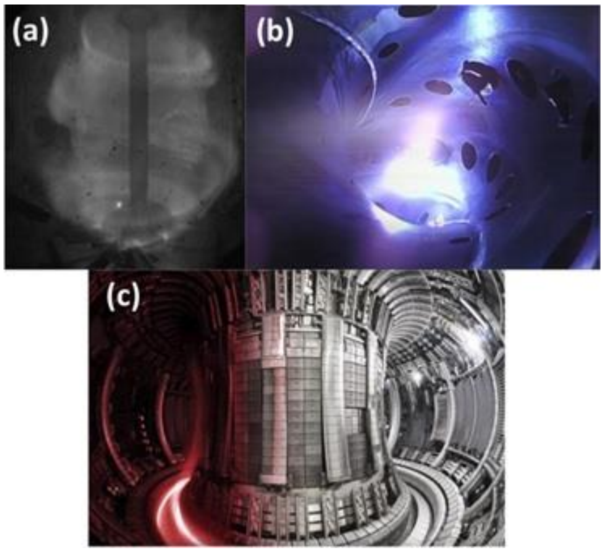

Fig. 2 Several plasmas being confined for fusion energy development are shown. (a) Pegasus-III Experiment at the University of Wisconsin-Madison, (b) Hybrid Illinois Device for Research and Applications at the University of Illinois at Urbana-Champaign (photo from Dr. Dan Andruczyk), and (c) the Joint European Torus (photo from EUROFusion).

A new hope

Fusion has the potential to provide clean, green energy to the world with zero carbon emissions. The fuel for fusion is hydrogen isotopes, a fuel source that is widely available and provides enough fuel for thousands of years. Fusion is independent of geography, environmental conditions and has a compact footprint. Another major benefit is that fusion is incredibly energy dense - using the deuterium found in two bathtub's worth of water and the lithium from 5 laptop batteries (used to breed tritium), enough energy can be provided for your entire lifetime with no pollution. This minimal amount of fuel for fusion energy is equivalent to burning 280 tons of coal that would release 380 tons of pollution. In a world where violent conflicts have begun over energy access and energy resources, fusion gives us hope for a more peaceful world. As the world transitions to renewable, green energy, fusion can step in to complement a diverse energy portfolio.

Harnessing fusion energy is a grand engineering challenge, and we are getting closer to commercializing fusion energy. Since the 1990s, funding for fusion research has focused on the science of fusion, leading to significant improvements in plasma confinement. Advances in additive and advanced manufacturing have led to the use of new materials and the ability to design complex structures to survive in the harsh fusion environment. High performance, new levels in supercomputing now enable modeling of entire fusion reactors - from the plasma core to auxiliary components - to design and predict performance in a fusion pilot plant. High-temperature, flexible superconductors have recently become available and provide access to more compact devices, which can be a game changer when it comes to fusion power. These major recent advances in technology coupled with consensus among the U.S. fusion community has shifted the focus to fusion energy commercialization and we are all racing to harness the power of fusion with an urgency to address climate change.

The first step to demonstrate the feasibility of controlled fusion on Earth is to achieve net energy gain for the fuel - that is, proving that we can produce more energy from the fusion reactions in the fuel than the amount of energy that goes into the fuel. And the National Ignition Facility (NIF), an inertial experiment, demonstrated just that in December 2022! These NIF breakthrough results, along with record-breaking fusion yield for magnetic confinement fusion in the Joint European Torus experiment earlier in 2022, demonstrate how investment in modeling and detailed physics understanding is paying off with these recent advances. All fusion experiments to date have been science experiments designed to understand how to achieve fusion conditions here on Earth. Our field should see a few more experiments, U.S. based company Commonwealth Fusion Systems is building SPARK and an international experiment called ITER, on the horizon that will explore burning plasma physics and are designed to reach breakeven conditions.

Next - we will need to tackle the engineering challenges required to generate electricity. While there are still many challenges that lie ahead for fusion, the potential benefits are huge and I'm incredibly excited to see what's next in this field as we continue to push innovation and drive towards a cleaner, more sustainable and equitable and just future. Fusion energy and plasmas are fundamental to our existence and to our future.

Text and images by S. J. Diem; Edited by M. Laroussi.

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Suggested Reading:

1. Patrick A Wayman, Cecilia Payne-Gaposchkin: astronomer extraordinaire, Astronomy & Geophysics, Volume 43, Issue 1, February 2002, Pages 1.27-1.29, https://doi.org/10.1046/j.1468-4004.2002.43127.x - link

2. Powering the Future, Fusion & Plasmas - https://usfusionandplasmas.org

3. The USFusionEnergy.org website is where you can learn more about fusion energy and job opportunities in the U.S. - https://usfusionenergy.org

4. Samuel E. Wurzel and Scott C. Hsu, Progress toward fusion energy breakeven and gain as measured against the Lawson criterion, Physics of Plasmas 29, 062103 (2022) - link

5. Control real plasmas with the Remote Glow Discharge Experiment (RGDX): https://scied-web.pppl.gov/rgdx/

6. Lawrence Livermore National Laboratory, National Ignition Facility achieves fusion ignition - link

7. Elizabeth Gibney, Nuclear-fusion reactor smashes energy record, Nature, 09 February 2022 - link

ABOUT THE AUTHOR

Steffi Diem is a professor at the University of Wisconsin-Madison and is the principal investigator of the Pegasus-III Experiment, a fusion energy and plasma science experiment focused on studying unique and innovative plasma startup techniques in an effort to reduce the cost and complexity of future fusion power plants. She is also the co-leader of the U.S. Fusion Outreach Team and co-designed the USFusionEnergy.org website. Diem was also a featured speaker at the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy in March 2022.