The Power of the Universe on Earth: Plasma Physics and Fusion Energy

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

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Outline

What is a plasma?
Where do we find them?
Why are we interested in them?
    Fusion energy
    Astrophysics
More on fusion energy.
Charged particles moving a magnetic field.
What is a plasma?

A plasma is an ionized gas.
Plasma is called the “fourth state of matter.”
More than 99% 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...”
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

Catseye Nebula

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

http://www.stsci.edu:80/
Plasmas on Earth

Laboratory Experiments

Lightning

http://FusEdWeb.pppl.gov/
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.

http://demo-www.gat.com/
Mass goes into energy in fusion reaction

Reactants | Fusion | Products
---|---|---
D | 20 keV | 3.5 MeV | 4He
T | 20 keV | 14.1 MeV | n

\[ E=mc^2 \]
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.

From *Stars*, James Kaler
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

Much of plasma physics research has been motivated by the goal of controlled fusion energy.

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?

http://demo-www.gat.com/
Why is Fusion power needed?

<table>
<thead>
<tr>
<th>Country</th>
<th>Consumption (kW-h/capita)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>12000</td>
</tr>
<tr>
<td>Developed World Avg.</td>
<td>6000</td>
</tr>
<tr>
<td>World Avg.</td>
<td>1500</td>
</tr>
<tr>
<td>China</td>
<td>500</td>
</tr>
<tr>
<td>India</td>
<td>250</td>
</tr>
</tbody>
</table>

### 1990 Energy use per capita

- **US**: 12000 kW-h/capita
- **Developed World Avg.**: 6000 kW-h/capita
- **World Avg.**: 1500 kW-h/capita
- **China**: 500 kW-h/capita
- **India**: 250 kW-h/capita

### Projected change in consumption by increasing to world average

<table>
<thead>
<tr>
<th>Country</th>
<th>Energy Use 1990 (GW)</th>
<th>Energy Use 2020 (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>120</td>
<td>500</td>
</tr>
<tr>
<td>India</td>
<td>65</td>
<td>450</td>
</tr>
</tbody>
</table>

### If fossil Catastrophe Looms

For more information see: [http://www.wofe.er.doe.gov/More_HTML/Artsimovich/PKAwPaper.html](http://www.wofe.er.doe.gov/More_HTML/Artsimovich/PKAwPaper.html)
Fuel and waste for coal (most readily)

<table>
<thead>
<tr>
<th>FUEL</th>
<th>COAL PLANT</th>
<th>D-T FUSION PLANT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9,000 T. COAL</td>
<td>1.0 LB D₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0 LB Li⁶</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.5 LB T₂)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WASTE</th>
<th>COAL PLANT</th>
<th>D-T FUSION PLANT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30,000 T. CO₂</td>
<td>4.0 LB He⁴</td>
</tr>
<tr>
<td></td>
<td>600 T. SO₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80 T. NO₂</td>
<td></td>
</tr>
</tbody>
</table>

http://www.pppl.gov
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 and lasers are used to confine the hot plasma.

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, $\tau$, 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 \( \approx 10^8 \) °C (10 keV)
- \( \eta \tau \approx 10^{15} \) Atoms · seconds / cm\(^3\)
- \( \tau \approx 10 \) seconds (magnetic “bottle”)
- \( \eta \approx 10^{14} \) Atoms / cm\(^3\) (10 \(-5\) times the density of air)

Inertial confinement
- Temperature \( \approx 10^8 \) °C (10 keV)
- \( \eta \tau \approx 10^{15} \) Atoms · seconds / cm\(^3\)
- \( \tau \approx 3 \times 10^{-11} \) seconds (microexplosion, inertial “bottle”)
- \( \eta \approx 3 \times 10^{25} \) Atoms / cm\(^3\) (12 times the density of lead!
- \( \sim 1000 \) times the density of liquid DT!)
Power Plant Schematic
Controlling Fusion using Inertia

The Inertial Confinement Fusion Concept

- Laser energy
- Blowoff
- Inward transported thermal energy

Atmosphere formation: Laser beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

Compression: Fuel is compressed by the rocket-like blowoff of the hot surface material.

Ignition: During the final part of the laser pulse, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.

Burn: Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

http://www-lasers.llnl.gov/lasers/nif/nif_ife.html#fusion
Direct vs Indirect Drive
Particles in a Magnetic field
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/
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
Turbulence is everywhere in nature

Turbulent transport is one of the main methods for relaxing gradients


http://info.pitt.edu/~maarten/work/soapflow/soapjpgs/dense.turb.JPG
Progress towards fusion energy

Web References

**Fusion energy and plasma educational sites**

- [http://www.jet.uk/](http://www.jet.uk/)  Joint European Torus

**Astrophysics sites**

- [http://www.gi.alaska.edu/](http://www.gi.alaska.edu/)  Geophysical Institute (Aurora and Sprite info)

Email me at: ffden@uaf.edu
2-D Turbulence

A flowing Soap film is an example of a 2-D system which can exhibit turbulence.

A magnetically confined plasma also exhibits 2-D turbulence because of the magnetic field.

Demo based on model from Univ. of Pittsburgh

For instructions see:
http://info.pitt.edu/~maarten/work/soapflow/howto/howto.html