Containing a star on earth: understanding turbulence at 100 million degrees

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Science on Saturday
Princeton Plasma Physics Laboratory
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Outline

• Review of nuclear fusion and how we make fusion on earth
  – Fusion
  – Plasmas
  – Tokamaks
  – Progress in fusion plasma performance

• The importance of turbulence in limiting fusion performance
  – What is turbulence
  – Measurements
  – Simulations
  – Methods to reduce it
  – Different “flavors” of turbulence
What is nuclear fusion?
Energy release occurs due to fusing two small nuclei

mass of deuterium + tritium

mass of Helium + neutron

Tiny difference in mass is converted into energy

Energy = mc^2
Opposite of nuclear fission that powers today’s “nuclear” reactors

- Splitting large atoms also leads to energy release

\[ \text{mass of deuterium + tritium} \quad \rightarrow \quad \text{mass of Helium + neutron} \]

\[ E=mc^2 \]
Why study fusion energy research?

• Fusion products are carbon-free, non-radioactive, inert

• Fuel is available for thousands of years
  – deuterium from sea water
  – tritium breeding from neutron-Lithium fusion reaction

• Inherently safe – only grams (<minute) of fuel in the device
  – no melt down/runaway concerns

• Very little (and short lived) radioactive material compared to nuclear fission

• Compared to non-carbon renewables (solar, wind) fusion is compact and continuous (not intermittent)

• Disadvantages: Hard to do!
Must overcome repulsive electrostatic force to fuse atomic nuclei

- Force between two charged particles increases as they get closer (Coulomb’s law)

  \[
  \text{Electric Force} \sim \frac{(\text{charge 1}) \times (\text{charge 2})}{(\text{distance})^2}
  \]

- Must have very high energy to overcome this repulsive force for the “strong nuclear force” to take over

- Temperatures must be ~150 million C → no longer a gas, but a plasma (Core of the sun ~15 million C)
What is a plasma?
Plasma – the fourth state of matter

- Plasma is ionized gas – atoms and molecules get stripped of their orbiting electrons → becomes a gas of charged particles

States of Matter

- Solid
- Liquid
- Gas
- Plasma

Add Heat

Diagram legend:
- = atom
- = nucleus
- = electron
99% of (known) matter in universe is plasma

- Sun, stars, interstellar and intergalactic medium account for most mass and are largely plasma
Numerous examples of plasmas on or near earth

- Lightning
- Arcs
- TV
- Aurora
- Satellite plasma thrusters
- Semiconductor processing
How do we create and contain a hot plasma on earth?
Recipe to create a fusion plasma

- Establish an appropriate magnetic field
- Inject appropriate gases (in a container at vacuum pressure)
- Heat the gases
Charged particles experience a force in a magnetic field

\[
\text{Magnetic Force} \sim \text{charge} \times \text{velocity} \times (\text{magnetic field})
\]

- Magnetic force acts perpendicular to direction of particle
  \(\rightarrow\) Particles follow circular orbits
Magnetic field confines particles away from boundaries

For a 5 Tesla magnetic field, 100 million C plasma

- Ion radius ~ 3 mm
- Electron radius ~ 0.05 mm

<< 1-2 meter device size
Magnetic field confines particles away from boundaries

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- electron radius ~ 0.05 mm

<< 1-2 meter device size

For comparison
- Earth’s magnetic field – 50 µT
- MRI – 1-3 T
- Junkyard magnet – 1-2 T

But particles easily lost from ends…
Bend the field into a donut-shaped torus
The Tokamak (Russian acronym for “toroidal chamber with magnetic coils”)
Here at PPPL:
National Spherical Torus Experiment-Upgrade (NSTX-U)
Here at PPPL:
National Spherical Torus Experiment-Upgrade (NSTX-U)
Interior of JET tokamak (UK)  

Interior of Alcator C-Mod tokamak (MIT) while operating
MAST tokamak (UK)
We’ve created a magnetically confined plasma – how do we heat it?
How do we heat the plasma?

Heating by electromagnetic (RF) waves

Heating by injecting a beam of energetic neutral particles
Have achieved sufficient temperatures!

~250 million C

TFTR at PPPL (1990’s)

- Model
- Experiment

$P_{\text{inj}} = 15 \text{ MW}$
$P_b = 1.7 \text{ MA}$
$B = 4.5 \text{ T}$

Core

Boundary
So what else do we need to make fusion energy a reality?
Require much more fusion power out than power to heat the plasma – “fusion gain”

\[ Q = \frac{\text{fusion power}}{\text{heating power}} \]

Fusion power \( \sim (\text{pressure})^2 \times \text{volume} \)

\[ Q \sim (\text{pressure}) \times (\text{confinement time}) \]

\[ \text{confinement time} \sim \frac{\text{pressure} \times \text{volume}}{\text{heating power}} \]
Confinement time is a measure of how well insulated the plasma is from the surrounding boundary.

For ignition (a self-sustaining, “burning plasma”)

\[ Q \sim \text{pressure} \times \text{confinement time} > 8 \text{ atm} \cdot \text{s} \ (\text{at } \sim 150 \text{ million } \text{C}) \]

pressure \sim 2-4 \times \text{atmospheric pressure}
confinement time \sim 2-4 \text{ seconds}
Have come very close to “break-even”, or $Q=1$

TFTR (PPPL, 1994)
10.7 MW fusion power
46 MW heating power
$Q=0.23$

JET (UK, 1997)
16.1 MW fusion power
22 MW heating power
$Q=0.7$
Next step: ITER is being built to study “burning plasmas”

- **Goal:** deliver ten times the power (500 MW) it consumes (50 MW) → large fusion gain
  \[ Q = 10 \]

Seven partners
China, EU, India, Japan, Korea, Russia, US
ITER is being constructed in Cadarache, France

- First plasma – 2020
- D-T fusion – 2027
Yes, it’s expensive, but for some perspective…

- ITER ~ $20 B
- International Space Station ~ $150 B
- Large Hadron Collider ~ $9 B
- New gigawatt (GW) coal/nuclear power plant ~ $2-6 B
- US consumes ~ 4,000 billion kW-h of electricity / year
  Average electricity prices ~ 0.10$/kW-h (US EIA)
  ~$400 B / year paid for electricity production
So why is ITER so big (and expensive)?
Need sufficient confinement to maximize fusion gain

Fusion gain

\[ Q = \frac{P_{\text{fusion}}}{P_{\text{heat}}} \sim \text{pressure} \times \text{confinement time} \]

⇒ Maximize confinement time

confinement time \sim \frac{\text{pressure} \times \text{volume}}{\text{heat loss}}

Easiest (conservative) solution – make it big (confinement~V), but...

Increasing volume \rightarrow \text{larger device} = $$$
Better to minimize power required (heat losses) to maintain pressure
What determines the power loss?
Diffusion by collisions will try to relax gradients
Diffusion by collisions will try to relax gradients.
Diffusion by collisions will try to relax gradients

heat flux $\sim D_{\text{collisions}} \times (T_{\text{hot}} - T_{\text{cold}})$

$D_{\text{collisions}} \sim (\text{step size})^2 \times \text{collision frequency}$

$P_{\text{heat}} = \text{Heat flux}$

$1-2 \text{ m}$

[Diagram with a curve showing temperature decline from core to boundary]
Diffusion by collisions will try to relax gradients

heat flux $\sim D_{\text{collisions}} \times (T_{\text{hot}} - T_{\text{cold}})$

$D_{\text{collisions}} \sim (\text{step size})^2 \times \text{collision frequency}$

step size $\sim$ particle orbits $\sim$ mm

collision frequency $\sim$ kHz

$P_{\text{heat}} = \text{Heat flux}$

core $\quad$ boundary

1-2 m
Diffusion by collisions will try to relax gradients

\[ \text{heat flux} \sim D_{\text{collisions}} \times (T_{\text{hot}} - T_{\text{cold}}) \]

\[ D_{\text{collisions}} \sim (\text{step size})^2 \times \text{collision frequency} \]

step size \sim \text{particle orbits} \sim \text{mm}

collision frequency \sim \text{kHz}

\[
\text{confinement time} \sim \frac{1}{D_{\text{collisions}}}
\]

Collisional confinement time estimate \sim 100 \text{ s}
Diffusion by collisions will try to relax gradients

heat flux $\sim D_{\text{collisions}} \times (T_{\text{hot}} - T_{\text{cold}})$

$D_{\text{collisions}} \sim (\text{step size})^2 \times \text{collision frequency}$

step size $\sim$ particle orbits $\sim$ mm
collision frequency $\sim$ kHz

Collisional confinement time estimate $\sim 100$ s
Experimental confinement time $\sim 0.1$ s
Increasing gradients eventually cause small scale instability \Rightarrow turbulence

- Turbulent “eddies” \rightarrow random velocity fluctuations mix hot and cold
- Can be small size, small amplitude (<1%)

But still effective at transport
Where else is turbulence?
Turbulence found throughout the universe - not surprising to find it in tokamaks

- Seemingly random or chaotic flows
  - Deterministic yet unpredictable (e.g. daily weather)
  - Understand through statistical approach (e.g. climate)

- Exists at multiple length & time scales
  - Energy at large scales
  - Dissipated by friction/viscosity at small scales

- Leads to enhanced mixing & transport
  ⇒ Why we’re interested in magnetic fusion
Turbulence is ubiquitous throughout planetary atmospheres
Turbulence crucial to lift, drag & stall characteristics of airfoils
Turbulent mixing of fuel and air critical for efficient & economical jet engines
Turbulence in oceans crucial to the climate, important for transporting heat, salinity and carbon

Perpetual Ocean (NASA, MIT)

nasa.gov
mitgcm.org
Fun with turbulence in art
Starry Night, Van Gogh (1889)
Leonardo da Vinci (1508), *turbolenza*
The Great Wave off Kanagawa, Hokusai (1831)
How does turbulence arise in tokamaks?
Very challenging to diagnose turbulence at 100 million degrees...
Very challenging to diagnose turbulence at 100 million degrees…
Spectroscopic imaging provides a 2D picture of turbulence in tokamaks: cm spatial scales, µs time scales, <1% amplitude

- Utilize interaction of neutral atoms with charged particles to measure density

DIII-D tokamak (General Atomics)

Movies at: https://fusion.gat.com/global/BESMovies
BES videos

https://fusion.gat.com/global/BESMovies

(University of Wisconsin; General Atomics)
Rough estimate of turbulent diffusivity indicates it’s a plausible explanation for confinement

- $D_{\text{turbulence}} \sim (\text{step size})^2 \times \text{“collision frequency”}$

  step size $\sim 5$-7 particle orbits $\sim$ cm’s

  “collision frequency” $\sim 100$ kHz
Rough estimate of turbulent diffusivity indicates it’s a plausible explanation for confinement

- $D_{\text{turbulence}} \sim (\text{step size})^2 \times \text{“collision frequency”}$

  step size $\sim 5$-7 particle orbits $\sim \text{cm’s}$

  “collision frequency” $\sim 100 \text{ kHz}$

  confinement time $\sim \frac{1}{D_{\text{turbulence}}}$

Turbulence confinement time estimate $\sim 0.1 \text{ s}$
Experimental confinement time $\sim 0.1 \text{ s}$
Measurements are challenging and limited – let’s use theory and simulations to help improve understanding
Interpretation aided by theory and nonlinear simulations

- State-of-the-art kinetic codes, 3D space + 2D particle motion
- Self-consistent electric and magnetic fields (Maxwell’s equations)
  - 100’s millions of grid points, or 10’s billions of particle markers
  - Millions of cpu-hours, exploiting up to 200,000 cpu’s (nersc.gov, nccs.gov)
Code: **GYRO**

Authors: Jeff Candy and Ron Waltz
Physically realistic turbulence simulations now capable of reproducing measured behavior

Movies at: https://fusion.gat.com/theory/Gyromovies
Why does turbulence develop in tokamaks?
Analogy for turbulence in tokamaks - density gradient in the presence of gravity

• Higher density on top of lower density, with gravity acting downwards (Rayleigh-Taylor instability)
• Any small perturbation becomes unstable
• Convection mixes regions of different density
Centrifugal force in toroidal field acts like an effective gravity

Unstable in the outer region
Centrifugal force in toroidal field acts like an effective gravity.

Fast parallel dynamics + helical field lines provides stability → gradient must surpass a threshold for instability.
Onset of turbulence reduces the achieved temperature that would have been present due only to diffusion.
Onset of turbulence reduces the achieved temperature that would have been present due only to diffusion

Analogous to convective transport when heating a fluid from below … boiling water (before the boiling)

Rayleigh, Benard, early 1900’s
Can we reduce the turbulence and improve confinement?

If we understand the turbulence, perhaps we can optimize performance.
Can we reduce the turbulence and improve confinement?

If we understand the turbulence, perhaps we can optimize performance

(1) zonal flows
(2) magnetic configuration
(3) flow shear
Self-generated “zonal flows” impact saturation of turbulence and overall transport

Linear instability stage demonstrates structure of fastest growing modes

Large flow shear from instability cause perpendicular “zonal flows”

Zonal flows help moderate the turbulence!!!
Generation of zonal flows in tokamaks similar to “Kelvin-Helmoltz” instability found throughout nature.
Code: GYRO

Authors: Jeff Candy and Ron Waltz
The Jet Stream is a zonal flow (or really, vice-versa)

- NASA/Goddard Space Flight Center Scientific Visualization Studio
Perhaps of interest this week because of the “polar vortex”
Zonal flows reduce the heating power required to maintain a given temperature $\rightarrow$ improved confinement!

Temperature gradient

$$(T_{\text{hot}} - T_{\text{cold}})$$

Heat flux $\sim$ heating power

Influence of zonal flows

diffusion

diffusion + turbulence
Can we reduce the turbulence and improve confinement?

If we understand the turbulence, perhaps we can optimize performance

(1) zonal flows

(2) magnetic configuration

(3) flow shear
Magnetic field topology also strongly impacts turbulence
Similar benefit to confinement through manipulating magnetic configuration

Heat flux $\sim$ heating power

- Diffusion + turbulence
- Influence of magnetic field topology

Temperature gradient

$(T_{\text{hot}} - T_{\text{cold}})$
Can we reduce the turbulence and improve confinement?

If we understand the turbulence, perhaps we can optimize performance

(1) zonal flows
(2) magnetic configuration
(3) flow shear
Turbulence suppression due to flow shear in National Spherical Torus Experiment (NSTX)

• Plasma rotates rapidly (Mach number ~ 1) due neutral beam ions

• Heat transported through ions reduced to level of collisional diffusion, turbulence fluctuations reduced (good!)
Large scale sheared flows can tear apart turbulent eddies, reduce turbulence $\rightarrow$ improve confinement

NSTX simulations

Snapshot of density without flow shear

100 ion radii
6,000 electron radii
$\sim$50 cm

Snapshot of density with flow shear

Heat flux

Lower amplitude
Smaller (tilted) eddies
Reduced transport

mean flow velocity profile
Large scale sheared flows can tear apart turbulent eddies, reduce turbulence, mixing and transport.
In neutral fluids, sheared flows are usually the source of free energy to drive turbulence.

- Thin (quasi-2D) atmosphere in axisymmetric geometry of rotating planets similar to tokamak plasma turbulence.
- Stratospheric ash from Mt. Pinatubo eruption (1991) spread rapidly around equator, but confined in latitude by flow shear.

![Aerosol concentration](image)

Aerosol concentration

Large shear in stratospheric equatorial jet

(Trepte, 1993)
Heat flux \sim heating power

Temperature gradient
\( (T_{\text{hot}} - T_{\text{cold}}) \)

Influence of sheared flow

Diffusion

Diffusion + turbulence
Theory and simulation have led to dramatic improvements in our ability to predict performance!
Theory & simulations have improved quantitative predictive capability

- Remember, predicting “climate” not “weather” – only concerned with statistical averages

Kinsey, 2010
General Atomics
Success in predicting confinement in multiple tokamaks around the world → confidence in ITER

- Considerable work remains to validate the kinetic physics responsible for turbulence, enabling more comprehensive predictions

Kinsey, 2010
While reducing one “flavor” of turbulence is good, it often leads to the onset of other “flavors” of turbulence.
Flow shear reduces turbulence at ion radii scales (cm), electron radii scale (mm) turbulence remains

- Still provides heat loss → plug one leaky hole, another one opens!

6 ion radii
360 electron radii
~2 cm

density fluctuations
Challenge to diagnose even smaller fluctuations – “microwave scattering”

NSTX tokamak (PPPL)

Top View

Side View

Density fluctuations

6 ion radii
360 electron radii
~2 cm
Scattering is the same process used in radars

- **airplane detection**
- **precipitation detection**
- **meteor detection**
At high pressure, magnetic turbulence becomes important → another leaky hole to plug!

NSTX (PPPL)

Fluctuations in magnetic field
Very challenging to measure internal magnetic fluctuations – try to measure changes in microwave polarization

NSTX (PPPL)

- Fluctuations in magnetic field
- Injected and reflected microwaves experience a shift in polarization

• Similar to birefringence in a crystal
Can we optimize pressure & flow shear to reduce all “flavors” of turbulence?

- NSTX presently undergoing an upgrade (stronger magnetic field, heating power) to test these predictions (late 2014)
Summary

• Nuclear fusion offers a promising energy solution
  – Clean, safe, abundant energy, but challenging
  – ITER will demonstrate significant fusion gain, 500 MW, Q=10

• Turbulence is a critical element in determining the performance and size of fusion plasmas
  – Numerous similarities with turbulence throughout nature
  – Requires clever measurements and sophisticated simulations to understand

• There are other scientific, technical and engineering issues that also need solving on the way to fusion energy
  – Steady state operation, tritium management, handling & extracting intense heat flux at boundary

• Need the next generation of fusion scientists! (ITER in ~2027)
Thank you!
With our present understanding of turbulent transport, confident ITER will demonstrate ~500 MW fusion power

• But ITER is big = $$$

• Ideal is to optimize confinement utilizing new physics understanding, innovative diagnostics and simulations

• But also have to cope with other problems…
What problems remain to obtaining electricity from fusion?

• Steady state operation
• Tritium management
• Handling intense heat fluxes at boundary
• Extracting heat

(NFRI – South Korea)
Removing power from the confined plasma sets extreme conditions on materials

**Fusion heat and particles**

must be exhausted to the materials

This leads to heat fluxes on the materials of approximately

\[ Q_{\text{materials}} \approx 10 \text{ MW m}^{-2} \]

*Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)*
Atmospheric reentry and arc welding require handling similar steady-state heat fluxes.

**Mars Curiosity Rover**  
Q ~ 2.3 MW m\(^{-2}\)  
T ~ 3800 K

**Arc Welding**  
Q ~ 40-60 MW m\(^{-2}\)  
T ~ 3900 K

*Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)*
Plasma substantially alters the *macroscopic* surface morphology of materials.

Exposed tungsten altered by PMI

Unexposed tungsten

3D imaging of tungsten melting

Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)
Plasma substantially alters the **microscopic** surface morphology of materials

*Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)*
Thank you!
• 96 slides
  - 17 title + heading/lead slides
  - 17-24 transition + extra photo slides

~ 55-62 slides
Progress in fusion energy has outpaced computer speed
Giant Machine Creates Science

The Onion explains the inner workings of the complex, expensive science thing.

Two glowing yellow particle things + What happens when good science occurs + Note similar color to other particles

A Science Machine

The expensive device will test and execute more science than ever before

1. Scientists make sure machine's On/Off button is switched to On
2. Parts of the machine begin to move, at first slowly, and then rapidly
3. A lot of science begins to generate
4. Many things light up and sounds of thunder happen
5. Science ends

Science Circle
Another Part
Super-Heated Science
Big Tube
Isotopes?
Human Figure
Difference in temperature & height of atmosphere between equator and poles drives latitudinal flows

- Lower temperature, shorter atmosphere
- Higher temperature, taller atmosphere
Coriolis effect turns these flows longitudinally

- An effect of the conservation of angular momentum
Flow shear suppressing transport – air curtains at store/warehouse entrances
Improved confinement means more fusion power for a smaller device = lower Cost of Electricity (COE)

- Caveats: more fusion power for a given device size = more power on plasma facing components – not obvious how to cope with…

Galambos, 1995
Atmospheric reentry solves the problem by ablating material from a heat shield

Ablation rate \( \approx 30 \times 10^{-6} \frac{m}{s} \)

Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)
Atmospheric reentry solves the problem by ablating material from a heat shield.

Ablation cooling is not a solution for 24/7, 365 day/year fusion power plant!

\[ \approx 30 \times 10^{-6} \frac{m}{s} \cdot 10^7 \frac{s}{year} \approx 300 \frac{m}{year} \]
Plasma substantially alters the microscopic surface morphology of materials

Recently, we have discovered that reactor-relevant plasma reforms tungsten surfaces into “fuzz”

Unknowns:
- Physical formation mechanisms
- Effect of confined plasma
- Effect of material longevity
- (Avoidance strategies ?)

Courtesy Zach Hartwig, MIT (http://www.psfc.mit.edu/~hartwig/)