An overview of fusion energy research: taming turbulence in magnetized plasmas

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Fusion: Power source of the stars

- Stars shine due to energy released by nuclear fusion reactions (initially p-p fusion)
- Presence of elements heavier than Beryllium is due to fusion in stars
- Extremely long timescale for p-p fusion!
Heavy hydrogen isotopes more suitable for terrestrial fusion

- Deuterium (abundant in seawater) and tritium (radioactive, must be produced from, e.g. Li) have highest fusion cross-section

- Energy released in kinetic energy of alpha particle and neutron (17.6 MeV total)
D-T fusion fuel is highly abundant

- Above: fuel for one family for one year (0.08g D, 0.02g Li)
- “Ash” from fusion reaction is Helium
- Reaction does indirectly produce waste: neutron absorption activation creates radioactivity in structure surrounding plasma
Challenge of fusion in the laboratory: the Coulomb barrier

- Must have moderate energy (100 keV) ions to be able to climb the Coulomb barrier and fuse
Challenge of fusion in the laboratory: the Coulomb barrier

• Easiest approach(?): accelerate beams of Deuterium & Tritium at each other, produce fusion via beam-beam collisions

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- But WILL NOT work to produce net energy. Why?
Fusion in the lab: need confined plasma

- Scattering cross-section $\gg$ fusion cross-section: Need confinement to allow multiple collisions before fusion occurs (fusion of particle beams will not work...)

$\Rightarrow$ Thermonuclear fusion in a confined plasma ($T \sim 10$ keV or 100 Million degrees)
Plasma confinement schemes

Gravity (stars)
Plasma confinement schemes

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Inertial (laser fusion, NIF)
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Magnetic Confinement

Current
Heating a magnetically confined plasma

- Initial heating is Ohmic: run current through the gas (can get you to \( \sim 1 \text{keV} \) (10 million degrees))
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• TFTR, Princeton Plasma Physics Lab (above) used NBI to reach 50 keV (500 million degrees): hottest spot in solar system (maybe the galaxy except for AGN)
Great success in confining hot plasmas and generating fusion power in Tokamaks

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  - 6 atm central pressure (central density $1 \times 10^{20}$ m$^{-3}$)
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- TFTR produced >10MW of D-T fusion power in the early 90’s (bested by JET (UK) later on with 16MW) (but only for ~1s in both cases)
So what’s the hold-up?

We can confine hot plasmas and produce significant fusion power, so why aren’t fusion reactors in use today?
So what’s the hold-up?

• Problem: in current devices the required heating power to reach and maintain fusion temperatures exceeds the fusion power output

• Why? Confinement is not perfect, our magnetic bottle can leak heat at a significant rate

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- Turbulent cross-field transport is the primary cause of the “leak”
Instabilities and turbulence driven by thermal energy gradients

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• Interchange drive is important (analogous to Rayleigh-Taylor). In tokamak, effective gravity provided by magnetic field gradient/curvature

\[ \rho_2 \]
\[ \rho_1 \]
\[ L \]
\[ v \]
\[ g \]

High density

Low density
Simulation of turbulence in a tokamak

- Plasma simulation at the forefront of computational physics, using the biggest supercomputers in the world
- Simulating plasma turbulence is an incredible challenge, the gyrokinetic simulation result to follow is the result of decades of work (and ongoing...) by a large number of physicists
Simulation of turbulence in a tokamak

Mode: Electrostatic
Adiabatic electrons
Flux-tube
Collisionless

Shape: $\kappa = 1.6$, $\delta = 0.4$

Resolution: $(n_r, n_\tau, n_n) = (128, 20, 16)$
$(n_E, n_\Lambda) = (6, 8)$

Time-step: $(c_s/a) \Delta t = 0.1$

Movie shows electrostatic potential

Gyrokinetic simulation by Jeff Candy, Ron Waltz (GA)
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\[ \nu_{\text{drift}} = \frac{\vec{E} \times \vec{B}}{B^2} \]

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Turbulent diffusion estimate

- Turbulent diffusion: random walk by eddy decorrelation

\[ D \sim \frac{(\Delta x)^2}{\Delta t} \sim \frac{L_c^2}{\tau_c} \]

- Eddy size
- Eddy “turnover” time
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\[ v \sim \frac{E}{B} \sim \frac{\phi}{L_c B} \]

\[ L_c \sim 10 \rho_s \]
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Eddy size

\[ \tau_c \sim \frac{L_c}{u}, \quad v \sim \frac{E}{B}, \sim \frac{\phi}{L_c B} \]

Eddy “turnover” time

\[ D \sim \frac{\phi}{B} \sim \frac{T}{B} \]

Bohm diffusion

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Turbulent diffusion estimate

Bohm diffusion

Classical diffusion: \( D_{\text{class}} \sim \rho^2 \nu \sim T^{-1/2} \) \((\nu \sim T^{-3/2})\)

Collisional diffusion weaker as plasma gets hotter
(hot plasmas are “collisionless”)
Turbulent diffusion estimate

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Bohm diffusion

Classical diffusion: $D_{\text{class}} \sim \rho^2 \nu \sim T^{-1/2} \quad (\nu \sim T^{-3/2})$

- Turbulent diffusion coefficient orders of magnitude larger than classical (not shown here)
- More importantly: scaling with $T$ is opposite. As $T$ goes up (more heating power is added) confinement degrades. Consistent with so-called “low-confinement” mode or L-mode in experiments.
Unexpected confinement breakthrough: H-mode

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- Edge transport barrier forms, with steepened gradients (“pedestal”)
- Can maintain much hotter and denser plasma for the same input power (increase in “confinement time”)
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- Edge transport barrier forms, with steepened gradients (“pedestal”)
- Can maintain much hotter and denser plasma for the same input power (increase in “confinement time”)
- During H-mode, strong, localized, cross-field flow (rotation) observed in the barrier region, more on this in a minute...

Data from DIII-D
H-mode has been fundamental to progress in fusion, but still poorly understood

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- Important advances in understanding changes in turbulence and turbulent transport in H-mode (more on this later), but a lot of work remains
  - e.g. don’t know mechanism for H-mode trigger, what determines height of “pedestal”, what sets residual transport in H-mode....
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⇒ To move beyond JET and design the next step experiment, must rely on projections using empirical transport scaling laws
ITER: into the era of burning plasmas

- Huge device, R~6.2m, a~2m
- Superconducting coils, 400s pulse
- 500MW fusion power, Q=5-10
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- $\sim$40B international project (Cadarache, France).
- First fusion plasma in which alpha particle heating will dominate external heating (burning plasma)
- Not a demonstration reactor, but a physics experiment to understand burning plasmas
Transport in ITER

- ITER baseline operation uses H-mode for improved confinement, transport predictions are largely based on empirical scaling laws:

\[
\tau_{E,th}^{ELMy} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} \\
\times M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78}
\] (20)
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→ Motivation for detailed studies of basic physics of turbulence and transport in magnetized plasmas.
UCLA tokamak biasing experiments linked H-mode confinement transition to edge flow

- Research by UCLA tokamak group (Bob Taylor) in the late 80's
- Triggered H-mode not with increased power, but by directly driving edge flow
- Established that edge flow is cause, not effect, of H-mode transition
Progress in explaining H-mode: shear suppression of turbulent transport

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- Heuristic argument: Sheared flow “breaks up” turbulent eddies, smaller eddies means smaller diffusive step size
- Shear flow can be source of free energy/turbulence also (KH), but can stabilize/reduce transport associated with gradient driven modes
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⇒ Basic experiments done at UCLA studying interaction of flow and flow shear with turbulence
The LArge Plasma Device (LAPD) at UCLA

- US DOE/NSF sponsored user facility (http://plasma.physics.ucla.edu)
- Solenoidal magnetic field, cathode discharge plasma (BaO and LaB$_6$)
  - BaO Cathode: $n \sim 10^{12}$ cm$^{-3}$, $T_e \sim 5-10$ eV, $T_i \simlt 1$ eV
  - LaB$_6$ Cathode: $n \sim 5 \times 10^{13}$ cm$^{-3}$, $T_e \sim 10-15$ eV, $T_i \sim 6-10$ eV
- B up to 2.5kG (with control of axial field profile)
- Large plasma size, 17m long, D~60cm (BaO) (1kG: ~300 $\rho_i$, ~100 $\rho_s$)
- High repetition rate: 1 Hz
LAPD Plasma source
LAPD Plasma Profiles

- Low field case (400G) (also shown: with particle transport barrier via biasing*); generally get flat core region with D=30-50cm

- Drift-wave driven turbulence in the edge region (localized to pressure gradient)

Visible light imaging of LAPD turbulence

Fast framing camera (~50k frames per second, ~10ms total time), visible light (neutral He), viewed along B
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Fast framing camera (~50k frames per second, ~10ms total time), visible light (neutral He), viewed along B
• Bias structure in contact with edge plasma, drive radial currents, results in torque, plasma edge rotates
• Even without direct biasing, plasma self-biases, spontaneously rotates
“H-mode” observed in LAPD with driven flow

- With sufficiently large bias, see profile steepening (“H-mode” in LAPD)
- Detailed transport modeling shows that transport is reduced to classical levels during biasing (consistent with Bohm prior to rotation)
- Turbulence in edge (localized on pressure gradient) is modified, turbulent transport eliminated
So what happens to turbulence? Fast framing camera movie (40k frames/s)
Details: documenting the response of turbulence to shear

\[ \langle L_n \rangle (\text{cm}) \]

\[ \langle \gamma_s \rangle \tau_{ac} \]

\[ \langle \Gamma_p / \Gamma_{p(\gamma_s=0)} \rangle \]

\[ 1 / \langle L_n \rangle (\text{cm}^{-1}) \]

Schaffner et al., PRL 109, 135002 (2012)

Data challenges existing models; will be used to test existing and new simulation capability targeted at predicting transport in devices like ITER
Summary/Outlook

- How to keep a magnetic bottle from leaking?: In fusion plasmas, turbulent leakage of heat and particles is a key issue. Sheared flow can suppress transport and lead to improved confinement.

- We’re not done! Lots of physics and engineering problems left to solve, e.g.:
  - Macroscopic instabilities/disruptions (confinement can be too good…)
  - Burning plasma physics (what happens when a plasma self-heats?)
  - Perhaps most importantly: need materials that can withstand extreme heat and neutron fluxes in reactor environment.

- Need bright, young minds to lead the way (send us your students!)