“Economic Viability” is the 2nd Frontier of Fusion Research
Turbulent Pinch

- Among the **most remarkable** phenomena of strongly magnetized plasma
- **Self-organization**: turbulent diffusion that is *counter to gradients* and creates highly peaked profiles
- First seen in **magnetospheres** (relatively *simple* to understand)
- Now, seen “*everywhere*” in high-temperature magnetically-confined plasma: like tokamaks & stellarators (relatively *difficult* to understand), gryokinetic codes, ...
- Particles, momentum, heat (!)
- **We do not yet understand** self-consistent, non-local, off-diagonal turbulent transport flux in magnetized plasma
For outer zone e⁻ (~ 0.5 MeV)...

\( \omega_c \gg \omega_b \gg \omega_d \)
An Important Paper ...

GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 9, PAGES 941-944, MAY 4, 1992

ON ARNOL'D DIFFUSION IN A PERTURBED MAGNETIC DIPOLE FIELD

Harry P. Warren, A. Bhattacharjee, and Michael E. Mauel

Department of Applied Physics, Columbia University
Chaotic Transport Maintains Adiabaticity

\[ \text{Adiabatic} \rightarrow (\mu, J) \approx 0 \]

Fig. 2. Thick-Layer Arnol’d diffusion as a function of \( Q \) for \( \epsilon = 0.01 \) and \( \eta = 1.1 \). Each dot represents the value of \( \langle (\Delta J_3)^2 \rangle / \langle J_3 \rangle \) at \( t = 35,000 \). The solid line represents the predictions of the stochastic pump model. Note the attenuation of diffusion at large values of \( Q \).

\[ Q \equiv \omega_b / \omega_d \]

Fig. 3. Poincaré surface of section for energetic protons interacting with two waves. The integers \( m_1 = 7, l_1 = 3, m_2 = 6, \) and \( l_2 = 3 \) are chosen so that the primary resonances of the waves overlap.

\[ \omega - m \omega_d(\mu, J) \approx 0 \]
Low-Frequency Dynamics is **One-Dimensional**
(1D, $k_\perp \rho \ll 1$, Gyro/Bounce/Kinetics, with $(\mu, J)$ constant)

$$\mathcal{H} = \frac{m_e c}{2e} \rho_\parallel^2 B_0^2 + \mu \frac{c}{e} (B_0 + \delta B) - c \delta \Phi$$

$$B_0 \gg \delta B, \quad \delta B = \nabla \times \delta A, \quad \text{and} \quad \delta E = - \nabla \delta \Phi - \frac{1}{c} \frac{\partial \delta A}{\partial t}$$

\[\begin{align*}
\mu & = 0 \ (\omega \ll \omega_c) \\
\dot{j} & = 0 \ (\omega \ll \omega_b) \\
\psi & = - \frac{\partial \mathcal{H}}{\partial \phi} = -c \frac{\partial \delta \Phi}{\partial \phi} + L \frac{\partial \delta A_\phi}{\partial t} \ (\propto \delta E \times B) \\
\dot{\phi} & \approx \mu \frac{c \partial B}{e \partial \psi} - c \frac{\partial \delta \Phi}{\partial \psi} \approx \frac{3 \mu}{e M^2} \psi^2 = \omega_d(\mu, \psi)
\end{align*}\]

Adiabatic → (μ, \dot{J}) \approx 0

Convection Electric Fields and the Diffusion of Trapped Magnetospheric Radiation

THOMAS J. BIRMINGHAM

\[ \frac{\partial \langle \mathcal{Q} \rangle(\alpha, M, J, t)}{\partial t} = \frac{\partial}{\partial \alpha} \left[ \frac{1}{D_{\alpha \alpha}} \frac{\partial \langle \mathcal{Q} \rangle}{\partial \alpha} \right] \]  \hspace{1cm} (5)

\[ D_{\alpha \alpha} \approx \frac{c^2 \mu^2}{4\alpha^2} (\pi)^{1/2} \tau_e \alpha \]  \hspace{1cm} (18)

A reasonable direction to proceed, in view of the paucity of direct experimental evidence of electric fields and their time variations, is to assume that the autocorrelation \( \langle \delta A(t - \tau) \delta A(t) \rangle \) has the form

\[ \langle \delta A(t - \tau) \delta A(t) \rangle = \alpha \exp - \frac{\tau^2}{\tau_e^2} \]  \hspace{1cm} (16)

from dawn to dusk, and is random on the time scale on which the solar wind executes time variations of large spatial extent. (The correlation time \( \tau_e \) is thus typically one hour.)

\( \alpha = \) magnetic flux, \( \Psi \)

dipole field. We describe \( E \) by the potential \( V \)

\[ V = \frac{A(t)r}{\sin^2 \vartheta} \sin \phi \]  \hspace{1cm} (2)

\( A \) being a positive, time-dependent amplitude. The form equation 2 is the fundamental \( m = 1 \) asymmetric mode in Fälthammar's [1965] Fourier expansion of a general longitudinally dependent potential. Since \( r \sin^{-2} \vartheta \) and \( \phi \) are both constant on dipole field lines, \( B \) lines are equipotentials, and \( E \cdot B \) is zero. In the \( \vartheta = \pi/2 \), equatorial plane
Measured Non-axisymmetric Perturbations of Geomagnetic Cavity Determine $D_{\psi\psi}$

\[ \delta A_\phi \sim \frac{L}{4} \left( \frac{R_e}{R_m} \right)^3 - \frac{4}{30} \frac{L^2}{R_e} \left( \frac{R_e}{R_m} \right)^4 \cos \phi + \ldots \]

\[ \delta \Phi \sim - \frac{E_e}{L} \left( \frac{R_e^2}{L} \right) + \frac{E_e L \sin \phi}{m=\pm 1} \]

Nakada and Mead, JGR (1965)

T. Birmingham, JGR (1969)
First Report of Inward Particle Pinch

(Farley, Tomassian, Walt)

VOLUME 25, NUMBER 1
PHYSICAL REVIEW LETTERS
6 JULY 1970

Cosmic Ray Source & Polar Losses

Driven Pinch with Adiabatic Diffusion

Adiabatic $\rightarrow (\mu, \dot{J}) \approx 0$
Naturally Peaked Pressure from Outer, Plasma Sheet Source illustrates “Self-Organization”

\[ P \sim L^{-3.3} \]

AMPTE/CCE-CHEM Measurements
“Quiet Conditions” \( I_{RC} \sim 1 \) MA
(De Michelis, Daglis, Consolini, JGR, 1999)
Van Allen Probes

ScienceExpress, Baker, et al., 28 Feb 2013

New 3rd Radiation Belt (2 MeV e⁻) Discovered
(then annihilated by passage of interplanetary shock)
The Physics of Laboratory Magnetospheres

Levitated Dipole Experiment (LDX)
Collisionless Terrella Experiment (CTX)
What Has Been Discovered...
(Over 15 years of research from four laboratory magnetospheres)

- Low-frequency interchange-like instabilities dominate plasma dynamics showing 2D physics, inverse-cascade, etc… in the laboratory magnetosphere

- The structure and dynamics of drift-resonant and MHD turbulence are well reproduced by bounce-averaged gyrokinetic simulations producing quantitative predictions of the laboratory magnetosphere

- Levitated dipole can achieve > 50% peak beta with levitation showing key connection between laboratory and planetary magnetospheres

- Turbulence drives plasma to very steep profiles and creates strong inward pinch confirming “first principle” transport prediction based on measured fluctuations

- High-beta dipole confinement supports advanced fusion energy concepts showing space physics may have applications to fusion science development
Drift-Resonant (Hot Electron) Interchange Instability

Heating On

Heating Off

± 100 V
Polar Imager: Direct Measurement of Adiabatic Drift-Resonant Transport due to Energetic Particle Interchange Instability

Adiabatic $\rightarrow (\dot{\mu}, \dot{J}) \approx 0$
Turbulent ExB Diffusion from MHD Interchange Fluctuations

\[ D = R^2 \langle E^2 \rangle \tau_c \]

\[ \frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi} \]

\[ \frac{\partial (P\delta V^\gamma)}{\partial t} = \langle H \rangle + \frac{\partial}{\partial \psi} D \frac{\partial (P\delta V^\gamma)}{\partial \psi} \]

QL equations low-frequency turbulence ExB transport:
Single “D” and geometry \( \delta V \) define particle and heat pinch

T. Birmingham, JGR (1969)

N = n\( \delta V \) = Flux tube particle number

P\( \delta V^\gamma \) ~ Entropy Density
LDX: The World’s Largest Laboratory Magnetosphere

Steady-State, High-β, High-Temperature
Density Profile with/ without Levitation

- **Procedure:**
  - Adjust levitation coil to produce equivalent magnetic geometry
  - Investigate multiple-frequency ECRH heating

- **Observe:** Evolution of density profile with 4 channel interferometer

- **Compare:** Density profile evolution with supported and levitated dipole

Alex Boxer, MIT PhD, (2008)
Turbulence drives plasma to very steep profiles and creates strong inward particle pinch in dipole geometry

- Dipole: $\delta V \sim R^4$, creates strongly peaked profiles and ideal conditions for study of turbulent pinch effects: particles, impurities, momentum, energy

\[
\frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi}
\]

\[
D = R^2 \langle E_{\varphi}^2 \rangle \tau_c
\]

$D$ measured from edge fluctuations

Line Density Shows Strong Pinch Only with a Levitated Dipole

Low frequency fluctuations dominate plasma dynamics: interchange & entropy modes

- MHD interchange modes set pressure and density gradient limits in dipole-plasma (*not ballooning*)

- Entropy mode (Kesner, Hastie, *POP*, 2002) **changed our thinking**; not just pressure and density gradients, but also $\eta = d(\ln T)/d(\ln n)$

- Entropy modes generate zonal flows and **nonlinearly self-regulate transport levels** (Ricci, Rogers, Dorland, *PRL*, 2006)

- **Fluctuations disappear** with flat density profiles (Garnier, *JPP*, 2008; and Kobayashi, Rogers, Dorland, *PRL*, 2009)

Turbulence drives plasma to very steep profiles and creates *either* particle or heat pinch in dipole geometry.

Gyrokinetic (GS2) simulations show turbulence drives particles or heat to maintain uniform entropy density:

1. Turbulent self-organization
2. Independent \((n,T)\) flux

\[
\eta = \frac{d \ln T}{d \ln n} \rightarrow \frac{2}{3}
\]

\[
- \frac{d \ln n}{d \ln \delta V} \rightarrow 1
\]

\[
- \frac{d \ln P}{d \ln \delta V} \rightarrow \frac{5}{3}
\]

I\textsubscript{M1} and \textit{I\textsubscript{M2}}. Additionally, currents are added in the upper mirror region. Two currents (\textit{I\textsubscript{M1}} and \textit{I\textsubscript{M2}}) are evenly distributed over a finite set of points in the upper mirror.

4.6 The upper mirror plasma

Magnetic measurements and images from a visible light camera show that often on LDX a plasma is confined in a region referred to here as the upper mirror. The upper mirror is the magnetic mirror that exists between the F-coil and the L-coil. All magnetic field lines in this region are open so any plasma confined in the region must be trapped in the magnetic well. This thesis addresses the upper mirror plasma primarily to assess whether the currents in upper mirror plasma significantly affect the magnetic reconstructions. It is found that often there are significant currents in the upper mirror plasma thus requiring the upper mirror plasma to be incorporated into any current/pressure model. Figure 4.11 shows the upper mirror plasma seen on a visible light camera.

In the last set of levitated and supported shots (100805033-51) the upper mirror plasma was significant. Upper mirror plasma is modeled as two currents, \textit{I\textsubscript{M1}} and \textit{I\textsubscript{M2}}, that are evenly distributed across two sets of filaments. Central mirror plasma, \textit{I\textsubscript{M1}}, can be several kA. Outer mirror plasma is always less than a couple hundred amps.

Figure 4.11: A grayscale visible light image of a plasma shot with magnetic field lines overlaid in yellow, separatrix in red, and current density contours in blue. The upper mirror plasma current is modeled as 2 currents (\textit{I\textsubscript{M1}} and \textit{I\textsubscript{M2}}) distributed over a finite set of points in the upper mirror.

The upper mirror plasma is separated by the mechanical upper catcher into an inner region (inside the catcher) and an outer region (outside the catcher). Figure 4.12 shows the electron cyclotron resonances zones for a typical magnetic configuration on LDX. The locations of the resonances indicate that the inner upper mirror plasma should only form when the 10.5 GHz and/or 6.4 GHz power sources are on (it should not form with just the 2.45 GHz power source). Figures 4.13(a) and 4.13(b) show that the inner plasma is seen on the visible light camera when all power sources are on but is not seen when only the 2.45 GHz source is on.

Instability, or some other unknown event, often causes the inner upper mirror plasma to be rapidly lost. When this loss occurs there is a rapid change in the flux measured by flux loop 11 that coincides with a simultaneous decrease in the visible light emitted from the plasma.

Plasma Current/Equilibrium

Last week:
Matt Davis, \textit{Measurements the electron pressure profile in the Levitated Dipole Experiment (LDX)}, Columbia Dissertation, 2013
Last week:
Matt Davis, *Measurements the electron pressure profile in the Levitated Dipole Experiment (LDX)*, Columbia Dissertation, 2013
Dipole is Toroidal Confinement without Toroidal Field

- **Dipole...**
  - Interchange (*not ballooning*) sets pressure and density gradient limits in dipole-plasma (*compressibility not average good curvature*) with $\beta \sim 100\%$
  - Flux-tubes can interchange globally without bending (*no magnetic shear*)
  - No toroidally circulating particles: all particles have similar response to low-frequency turbulence
  - Flux tube volume increases rapidly with radius, $\delta V \sim 1/L^4$, allowing steep profiles

- **Tokamak...**
  - Ballooning and kinks set pressure limit with $\beta \sim \epsilon/q \approx 5\%$ (shear stabilizes interchange)
  - Short radial scale of fluctuations, drift waves
  - Passing and trapped particles different
  - Flux tube volume nearly constant with radius, $\delta V \sim q$, mixing creates flat profiles
“Fusion has proved to be a very difficult challenge.

The early question was—Can fusion be done, and, if so how? …

Now, the challenge lies in whether fusion can be done in a reliable, an economical, and socially acceptable way…”
Starfire Represented Optimism of early 1980’s

Starfire: 1981
Charlie Baker, Mohamed Abdou, et al. (ANL)
“Most detailed design to date of a year-2000 commercial fusion power reactor.”
Two-year, $5.6 million study by ANL, McDonnell Douglas, and utilities
**Starfire** = $5.7/W_e

**ITER ≥ 34 × Starfire**

<table>
<thead>
<tr>
<th></th>
<th>Starfire (1981)</th>
<th>ITER (2027)</th>
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<tbody>
<tr>
<td><strong>R, a (m)</strong></td>
<td>7.0, 1.9</td>
<td>6.2, 2.0</td>
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<tr>
<td><strong>I_p (MA)</strong></td>
<td>10.1</td>
<td>15.0</td>
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<tr>
<td><strong>B (T)</strong></td>
<td>5.8</td>
<td>5.3</td>
</tr>
<tr>
<td><strong>Duration</strong></td>
<td>continuous</td>
<td>6000 × 7 min</td>
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<tr>
<td><strong>P_{fusion} (MW)</strong></td>
<td>3510</td>
<td>410</td>
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<tr>
<td><strong>P_e (MW)</strong></td>
<td>1200</td>
<td>-250</td>
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<tr>
<td><strong>W_{mag} (GJ)</strong></td>
<td>55</td>
<td>51</td>
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<tr>
<td><strong>Tokamak (tonne)</strong></td>
<td>24,000</td>
<td>23,000</td>
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<tr>
<td><strong>Cost ($M)</strong></td>
<td>6,800</td>
<td>&gt; 27,000</td>
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</table>
1984: A great year for tokamak physics and Turning-point for understanding tokamak limits


EPS Aachen, IAEA London Meeting & DPP Boston Meeting
Today’s 1st frontier for fusion…

“to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes”

should not supersede
Gross’s 1984 challenge…

“the challenge is whether fusion can be done in a reliable, an economical, and socially acceptable way”

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<thead>
<tr>
<th></th>
<th>Starfire (1981)</th>
<th>ITER (2027)</th>
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<tr>
<td>$\beta$, $\beta_N$</td>
<td>6.7, 7.3</td>
<td>2.5, 1.8</td>
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<tr>
<td>$\tau_E$, $H$</td>
<td>3.6, 5.5</td>
<td>3.7, 1.0</td>
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<tr>
<td>$n (10^{20} m^{-3})$, $n_G$</td>
<td>1.0, 1.1</td>
<td>1.0, 0.85</td>
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<tr>
<td>$T$ (keV)</td>
<td>24</td>
<td>9.0</td>
</tr>
<tr>
<td>$\lambda_{sol}$ (mm)</td>
<td>100</td>
<td>~1</td>
</tr>
<tr>
<td>Max Flux (MW/m²)</td>
<td>4</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Neutrons (MW/m²)</td>
<td>3.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Material</td>
<td>Low-Activation SS</td>
<td>B-doped 316L</td>
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</table>
ITER and advances in Alternate Energy Technology have made the issue of fusion’s cost unavoidable

- EIA (April 2013) Utility-scale Cost and Generation:

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<th>Energy Type</th>
<th>Cost</th>
<th>1984</th>
<th>2013</th>
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<tbody>
<tr>
<td>Fission:</td>
<td>$5.5/W_e</td>
<td>37 GWy (96 units)</td>
<td>88 GWy (104 units)</td>
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<tr>
<td>Solar PV:</td>
<td>$3.9/W_e</td>
<td>0</td>
<td>2.5 GWy</td>
</tr>
<tr>
<td>Solar Thermal:</td>
<td>$5.1/W_e</td>
<td>0</td>
<td>2.5 GWy</td>
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<tr>
<td>Onshore Wind:</td>
<td>$2.2/W_e</td>
<td>0</td>
<td>16 GWy</td>
</tr>
<tr>
<td>Offshore Wind:</td>
<td>$6.2/W_e</td>
<td>0</td>
<td>16 GWy</td>
</tr>
</tbody>
</table>

- Fusion research must address “economic viability” and show cost competitiveness
- Holdren (Science, 1978): “Fusion, like solar energy, is not one possibility but many… The most attractive forms of fusion may require greater investment of time and money, but they are real reasons for wanting fusion at all.”
Carbon capture may be a ways off, but ARPA–E is working on it

The goal of ARPA–E’s $40 million, three-year Innovative Materials and Processes for Advanced Carbon Capture Technologies (IMPACCT) program is to **dramatically reduce the cost of extracting CO₂ from flue gases so it can be sequestered from the atmosphere**. All carbon capture technologies consume energy; the current benchmark technology, an absorber–desorber process that uses a monoethanol amine (MEA) solvent, costs around $90 per ton of CO₂ captured—which would add as much as 50% to the cost of producing electricity from coal.

According to ATK claims, the company’s process would cost $48 per ton of CO₂. Other grantees claim similar costs. But Karma Sawyer, IMPACCT program manager, cautions that extrapolating cost-per-ton figures from bench-scale demonstrations—the current status of most CO₂ capture projects—“is not a trivial calculation to make.” **Her program adopted a goal set by DOE’s Office of Fossil Energy in 2008: to limit the cost increase for electricity generated with coal to 35%.** “I can say that our technologies have compelling arguments to make” on reducing the costs, she says.

- Alliant Techsystems (ATK)
- LLNL
- GE Global Research
- University of Notre Dame
- Texas A&M
- Columbia University
A Strategy for Fusion’s 2nd Frontier: “Economic Viability”
How to reduce fusion’s cost per Watt by more than an order of magnitude?

• Fusion research must resolve it’s “science rich” feasibility issues, *but the costs of this research should be commensurate with our target*

• Strengthen efforts to improve performance of the baseline, e.g. *the advanced tokamak, Li walls, novel divertors, stellarators, …*

• Broaden study to include new fusion concepts that promise *significant cost reductions and system simplifications*

• “Economically viable” fusion faces many simultaneous challenges, and *wise policy will move research forward on multiple pathways*
Space Power Facility (SPF)
Plum Brook Facility at Sandusky
World’s Largest Vacuum Vessel ($190M & Nuclear Ready)
Bigger than the ITER Cryostat
Levitated Dipole may Make Possible Tritium Suppressed Fusion

Dipole T-suppressed fusion is an alternate technology pathway that avoids the need to develop breeding blankets and structural materials compatible with 14 MeV neutrons.

ITER
500-700 MW
D-T Fusion

51 GJ
W_B

31 GJ

0.3 GJ
W_p

3 GJ

>400 MW
14 MeV Power

14 MW

Levitated Dipole
600 MW
D-D(3He) Fusion

Turbulent Pinch in a Levitated Dipole may Make Possible Tritium Suppressed Fusion

- Sheffield, Zinkle, Sawan (2002-06)
- No tritium breeding blankets
- No 14 MeV neutrons
- No structural materials problem
- Requires $\tau_p/\tau_E < 1$
- Requires 35 keV
- Requires 10 fold confinement improvement
- Requires stronger, higher-field superconducting magnets
Turbulent Pinch in a Levitated Dipole may Make Possible Tritium Suppressed Fusion

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$(N, P\delta V) \sim$ constant implies peaked density and pressure profiles (if $\gamma > 1$)

Adiabatic mixing implies core parameters determined by edge & compressibility:

$\frac{T_e}{T_p} \sim (4\gamma-3)C_\gamma^{-1} > 50$
Dipole Proof of Performance Scaled from LDX to fit in NASA’s SPF

(a) ITER-Like D-T Tokamak Scaling
(b) LDX-Like D-T Dipole Scaling

Fusion Gain - Magnet Stress - Quench Safety Parameter - Alpha Confinement
But what about our second objective of economic viability? ITER isn't meant to achieve that goal. In addition to clearing our last remaining scientific hurdle, we need to advance a parallel engineering agenda into key reactor technologies that will enable commercial fusion power plants to reliably deliver electricity in a highly competitive market.

This means technological advances in areas such as structural and functional materials, power conversion, and reliability.

Mike Mauel:

“Economic viability” is the second frontier of fusion science and engineering.

This means integrating technology advances with advancements in fusion plasma physics to engineer and test fusion confinement concepts that significantly simplify, reduce capital costs, and improve maintainability.