Electric fields in stellarators

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Overview

• Particle orbits and electric fields in stellarators (simplified overview)
  – $1/\nu$ scaling
  – Electric field effects on particle orbits
  – $\nu$ scaling

• Turbulence suppression

• Origin of the electric field

• Extreme electric fields

• Non-neutral plasmas

• The Columbia Non-neutral Torus

• Summary
Particle orbits in stellarators

- A stellarator is a fully 3-D magnetic configuration
- Magnetic field lines are confined - they lie in, and define, toroidal magnetic surfaces
- Particle orbits deviate from field lines due to $\nabla B$ drift
- Passing particles $\sim$ good orbits
- Trapped particles $\sim$ potentially bad orbits
- Complementary situation to magnetic mirror
Neoclassical $1/\nu$ diffusion

- A particle on a bad orbit may leave the stellarator in a time as short as $a/\nu_{VB}$
- If the collision time is shorter than this, it will diffuse out instead:

$$ D = \nu (r_{mfp})^2 = \nu \left( \frac{V_{VB}}{\nu} \right)^2 = \frac{1}{\nu} V_{VB}^2 $$

- A more accurate calculation\(^1\) leads to:

$$ D_{1/\nu} = \frac{1}{\nu} V_{VB}^2 \times \left[ \frac{4}{9\pi} \frac{\varepsilon^2}{\varepsilon_t^2} (2\varepsilon_h)^{3/2} \right] $$

How to avoid terrible confinement

- $1/\nu$ regime gives poor confinement
  - Primary effect of magnetic field (as compared to an unmagnetized plasma) is that $v_{th}$ is replaced by $v_{VB}$ in $D$

- Ways to avoid poor confinement:
  - Carefully tailor magnetic field so that $v_{VB}$ does not cause large deviations from the magnetic surfaces (advanced stellarator, eg. quasi-symmetric ones)
  - Generate a radial electric field sufficiently large to close the particle orbits

- We will focus on the effects of the electric field here.
Effects of electric field on particle orbits

\[ H = q\phi + \mu B + \frac{1}{2} m v_{\parallel}^2 \]

- $H$ and $\mu$ are conserved for collisionless guiding center particles
- Let $\phi_{\text{edge}} = 0$. Note $\mu B \sim m v_{\parallel}^2 \sim kT$
- If $|q\phi_{\text{interior}}| \gg kT$, a collisionless particles cannot leave.

Proof:
- $q\phi < 0$: Particle is electrostatically trapped, $H < 0$
- $q\phi > 0$:
  - $\mu B \sim kT$ because $\mu$ is conserved and $B$ does not vary much
  - Therefore, particle must dump $q\phi$ into $m v_{\parallel}^2$
  - This implies the particle becomes *passing*, i.e. well-confined!
Neoclassical $\nu$ diffusion

- Both species now have confined collisionless orbits and can only leave due to collisions\(^2\)
- Deviation from magnetic surface is still due to $\nu_{VB}$ but the particles circulate ~poloidally due to $\nu_{ExB}$

\[
\delta_r = \frac{V_{VB}}{\omega_{ExB}} = \frac{V_{VB}}{V_{ExB}} r \quad \Rightarrow \quad D = \nu \delta_r^2 = \nu \left( \frac{V_{VB}}{\omega_{ExB}} \right)^2
\]

- More accurate calculation\(^1\)

\[
D_{\nu} = \nu \left( \frac{V_{VB}}{\omega_{ExB}} \right)^2 \times \left( \frac{\varepsilon^2}{2\varepsilon_t^2} \frac{1}{\sqrt{\varepsilon} + 2\varepsilon_h - \sqrt{2}\varepsilon_h} \right)
\]

qφ/kT is important dimensionless parameter

\[ v_{\nabla B} \approx kT \frac{|\vec{B} \times \nabla B|}{qB^3} \approx \frac{kT}{L_B qB} \quad \text{and} \quad v_{ExB} = \frac{|-\nabla \phi \times B|}{B^2} \approx \frac{\phi}{L_\phi B} \]

\[ \Rightarrow \delta_r \approx \frac{v_{\nabla B}}{v_{ExB}} r \approx \frac{kT}{q\phi} r \quad \Rightarrow \quad D \approx v \left(\frac{kT}{q\phi}\right)^2 r^2 \times \left(O(1)\right) \]
Suppression of turbulent transport

- ExB flow suppresses turbulent transport.
- The key parameter is believed to be the ExB shear:
  - Linear stabilization:
    - Decorrelation of otherwise unstable drift waves - sheared apart faster than they can grow
  - Nonlinear transport suppression:
    - Poloidal stretching and radial narrowing of turbulent eddies prevent rapid mixing across magnetic surfaces
- Experimental evidence:
  - Tokamaks: H-modes (ASDEX, 1982), ITBs
  - Stellarators: Growing list of examples
    - W7-AS (HDH), LHD, TJ-II
TJ-II limiter bias experiments

Limiters

Two movable limiters have been used in the experiments, one of them located 2 cm inside the LCFS has been biased up to 400 V, with respect to a second limiter located in the SOL region.

Courtesy of C. Hidalgo and the TJ-II group, CIEMAT, Madrid, Spain.
Biasing induced improved confinement studies

• Modification of edge radial electric fields by limiter biasing.
• Improvement in particle confinement time and reduction of turbulence
• No significant impurity influx.

Where does the electric field come from?

- **Ambipolarity:**
  - Assume, initially, that ions are lost faster than e’s.
  - Negative bias builds up
  - As $e\phi$ approaches $-kT$, ions become electrostatically trapped and very well confined
  - Electron transport also improves but not as dramatically
  - Steady state reached at $e\phi \sim -kT$
  - So-called ‘ion root’ (deficit of ions)
  - Electron root also possible but less common
Other means of creating electric fields

- Limiter biasing (TJ-II)
- Probe biasing (HSX$^4$)
- Electron injection (CHS$^5$, CNT - to be discussed)
- ECRH, ICRH
  - preferential loss of high energy particles of one sign of charge
- Momentum injection
- Generally, self-consistent electric field profile evolution is complicated due to coupling between $E_r$, plasma profiles, and transport coefficients

Extreme electric fields

• Confinement improves dramatically for $|q\phi| > |kT$

• Questions:
  – Can we make a stellarator experiment to explore this regime? My answer: Yes! See following slides...
  – Is it directly relevant to stellarator fusion (or only indirectly)? My answer: Possibly.
    • Difficult. Small changes in electron or ion transport coefficients can neutralize the plasma.
    • Possible negative effects: Impurity control, instabilities
    • Possible mechanisms for driving bias:
      – Edge limiter bias
      – ECRH or ICRH tailored to kick particles into bad orbits
      – Purposely ill-confined fusion alphas - ‘extreme alpha driven ion root’?
The Columbia Non-neutral Torus: A stellarator designed to study $|q\phi| \gg kT$

- Generate the electric field directly through injection of charge onto magnetic surfaces: Create a pure electron plasma
- If desired, one can ionize neutrals to study a partially neutralized electron-rich plasma.
- Initial questions to be answered:
  - Does a generic stellarator confine a pure electron plasma?
    - Is there an equilibrium?
    - Is it stable?
    - What is the confinement time?
Pure electron plasma equilibrium

Low density fluid equilibrium: \[ en_e \nabla \phi - \nabla p = en_e \nabla \times \vec{B} \]

Component along magnetic field: \[ en_e \vec{B} \cdot \nabla \phi = \vec{B} \cdot \nabla p \]

Rapid thermalization along \( \mathbf{B} \): \( T_e = T_e(\psi) \)

Integration along a magnetic field line: \[ n_e = N(\psi) \exp \left( \frac{e\phi}{T_e(\psi)} \right) \]

This equation should be consistent with Poisson’s equation:

\[
\nabla^2 \phi = \frac{e}{\varepsilon_0} N(\psi) \exp \left( \frac{e\phi}{T_e(\psi)} \right)
\]

Solutions to this equilibrium equation exist, and are well-behaved analytically and numerically \(^6,7\)

Stability of perturbed equilibria

Consider the stability of low frequency perturbations that satisfy the following constraints:

- Particle and entropy conservation
- Parallel force balance is maintained
- $T = T(\psi)$ due to thermalization along field lines

It can be shown that the electron plasma equilibrium is stable to all such perturbations\(^8\).

Too good to be true?

We have assumed low density, zero beta, and that parallel force balance and temperature equilibration are strictly satisfied.

There may be other (higher frequency) instabilities.

\(^8\) A. H. Boozer, to be submitted to Phys. Plasmas
Confinement of pure electron plasma

- If \( a/\lambda_D >> 1 \), confinement is excellent. This is because in a pure electron plasma
  \[
  \frac{kT}{|e\phi|} \approx \frac{kT}{a^2 e^2 n_e / \varepsilon_0} \approx \frac{\lambda_D^2}{a^2} \ll 1
  \]

- The \( \nu \)-scaling diffusion coefficient then yields:
  \[
  D \approx \nu \left( \frac{kT}{e\phi} \right)^2 r^2 \times (O(1)) \approx \nu \frac{\lambda_D^4}{a^4} a^2 \Rightarrow \tau_p \approx \frac{a^2}{D} \approx \frac{1}{\nu} \frac{a^4}{\nu \lambda_D^4} \gg \frac{1}{\nu}
  \]
  - Confinement for many collision times!

Confinement of partially neutralized plasma

- As long as \( |e\phi|/kT >> 1 \), confinement will also be excellent \(^9\) (\( \nu \)-scaling)

- But will these plasmas be stable?

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The Columbia Non-neutral Torus (CNT)

- Only 4 circular planar coils (Gourdon 1969)
  - Two internal interlocking (IL) coils inside vacuum chamber
  - Two poloidal field (PF) coils
- DoE Support since Sep. ‘02
- UHV vacuum chamber: Designed to reach $10^{-10}$ Torr range to avoid ion contamination
- Chamber complete, to be delivered June 2004
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Reconfigurable IL coils in vacuum

- Variable iota
- Variable shear
- Variable magnetic surface shape
- Extremely low aspect ratio makes toroidal vacuum chamber impractical
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Very low aspect ratio (~1.5).

The lowest aspect ratio stellarator ever?

T. S. Pedersen et al., accepted in Fusion Science and Technology
Progress towards first plasma

- Vacuum chamber to be shipped first week of June
- All vacuum equipment in house
- All power supplies in house
- Winding of IL coils (~1 month) to start early June.
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Summary: Effects of electric fields in stellarators

- Neoclassical effects:
  - Large
  - Well understood theoretically and consistent with experiments

- Anomalous effects:
  - Suppression of turbulent transport is seen in several experiments and is consistent with ExB shear paradigm

- $|q\phi|/kT$ is a key parameter
  - $|q\phi|/kT >>1$ is interesting and unexplored regime
  - This regime can be studied in a non-neutral stellarator

- CNT is designed to study such plasmas
  - Other goals of CNT:
    - Basic non-neutral plasma physics on magnetic surfaces
    - Create first electron-positron plasma.