Plasma profiles and their control

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Outline I

1. Profile control

2. Tokamak profile dynamics
   - Magnetic field diffusion
   - Kinetic transport
   - Coupling to 2D equilibrium

3. Profile control
   - Actuators
   - Sensors
   - Control

Section 1

Profile control

Introduction

- Plasma held place by TF+PF coils, magnetic equilibrium described by Grad-Shafranov equation. To determine equilibrium we need to know the internal profiles $p'(\psi)$, $T(\psi) = RB_\phi$.
- But what determines this internal pressure and poloidal current distribution?

Introduction

- Plasma held place by TF+PF coils, magnetic equilibrium described by Grad-Shafranov equation. To determine equilibrium we need to know the internal profiles $p'(\psi)$, $T(\psi) = RB_\phi$.
- But what determines this internal pressure and poloidal current distribution?
- We will discuss *internal* evolution (=transport) of current, particles and energy.
    - 1D problem: transport $\parallel$ **B** is ∞-fast, only transport $\perp$ **B** evolves slowly. (Q:How slowly?)
    - *Plasma profiles*: important for stability and performance.
    - We will (roughly) derive 1D transport equations for j, T, n.
- What are the actuators? How do they affect profile evolution?

Section 2

Tokamak profile dynamics

Subsection 1

Magnetic field diffusion

B field diffusion in resistive medium

- Ohm's law for resistive MHD:

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j} \tag{1}$$

assume $\mathbf{v} = 0$, $\eta = cst$ and use $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$

$$\mathbf{E} = \frac{\eta}{\mu_0}(\nabla \times \mathbf{B}) \tag{2}$$

Take $\nabla \times$ both sides and use $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$

$$\frac{\partial \mathbf{B}}{\partial t} = -\frac{\eta}{\mu_0}\nabla \times (\nabla \times \mathbf{B}) = \frac{\eta}{\mu_0}\nabla^2 \mathbf{B} \tag{3}$$

Typical time scales

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{\eta}{\mu_0} \nabla^2 \mathbf{B} \tag{4}$$

- Superconducting case: $\eta = 0 \rightarrow \frac{\partial \mathbf{B}}{\partial t} = 0$ (Field frozen in medium)
- Conducting case, typical time scales depend on resistivity and system size $\tau = \frac{\mu_0 L^2}{\eta}$

Time scales w.r.t. shot time

- On what time scale does the plasma **B** field transport evolve with respect to the shot time?

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- Exercise:
  - Calculate typical magnetic diffusion times for TCV, JET and ITER and compare to typical plasma shot times. Recall $\tau = \frac{\mu_0 L^2}{\eta}$ and use $\eta \approx 1.8 \times 10^{-2} T_e^{-3/2}[\mathrm{eV}]$
    - TCV: $L = 0.25\mathrm{m}$, $T_e = 1\mathrm{keV}$, $t_{shot} = 2\mathrm{s}$
    - JET: $L = 1\mathrm{m}$, $T_e = 3\mathrm{keV}$, $t_{shot} = 12\mathrm{s}$
    - ITER: $L = 2\mathrm{m}$, $T_e = 5\mathrm{keV}$, $t_{shot} = 300\mathrm{s}$

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Answer:

- TCV: $0.14\mathrm{s}$
- JET: $11.4\mathrm{s}$
- ITER: $100\mathrm{s}$

NB: Slow internal dissipation of **B** field can not be ignored.

Diffusion of poloidal flux in tokamak

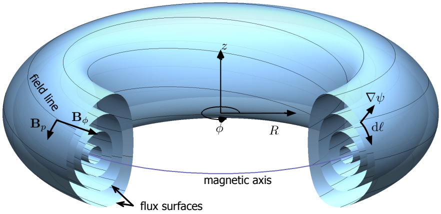
- Sketch of derivation. Full derivations in [1], [2], [3]
- Write Ohm's law (without flows) with conductivity $\sigma = 1/\eta$

$$\underbrace{\mathbf{j}}_{\text{total current}} = \underbrace{\sigma \mathbf{E}}_{\text{inductive/Ohmic current}} + \underbrace{\mathbf{j}_{ni}}_{\text{non-inductive current}} \tag{5}$$

- Project in direction $\parallel$ **B** and average over a flux surface (from Grad-Shafranov equilibrium)

$$\frac{\langle \mathbf{j} \cdot \mathbf{B} \rangle}{B_0} = \frac{\sigma_{\parallel} \langle \mathbf{E} \cdot \mathbf{B} \rangle}{B_0} + \frac{\langle \mathbf{j}_{ni} \cdot \mathbf{B} \rangle}{B_0} \tag{6}$$

Diffusion of poloidal flux in tokamak



- $\psi(R,Z) = \int \mathbf{B} \cdot d\mathbf{A}_Z$, loci of constant ψ define flux surfaces.
- Define toroidal flux through a flux surface:

$$\Phi = \int \mathbf{B} \cdot d\mathbf{A}_\phi = \int B_\phi dA_\phi, \tag{7}$$

associate radial metric $\rho = \sqrt{\Phi}$ and $\rho_N = \rho/\rho_b$ ($_b$ = $_{boundary}$)

Diffusion of poloidal flux in tokamak

Exercise:

- Show that in the case of circular cross section, large aspect ratio ($R/a \to \infty$) and low plasma current ($B_\phi \approx B_0$) it holds that $\rho_N = r/a$, where r is the geometric radius and a is the radius of the LCFS.

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Solution:

- $B_\phi = B_0$, circular cross section, then $\Phi = \pi r^2 B_0$ and $\rho = r\sqrt{\pi B_0}$, $\rho_{edge} = a\sqrt{\pi B_0}$ so $\rho_N = r/a$

Flux Diffusion: Sketch of derivation

- Using vector calculus, differential calculus, plus Maxwell's equations, we can write the equation as a function of ρ:

$$\underbrace{\frac{\langle \mathbf{j}\cdot\mathbf{B}\rangle}{B_0}}_{\sim\frac{1}{\rho}\frac{\partial}{\partial\rho}\rho\frac{\partial\psi(\rho,t)}{\partial\rho}} = \underbrace{\frac{\sigma_{\parallel}\langle \mathbf{E}\cdot\mathbf{B}\rangle}{B_0}}_{\sim\sigma_{\parallel}\frac{\partial\psi(\rho,t)}{\partial t}} + \underbrace{\frac{\langle \mathbf{j}_{ni}\cdot\mathbf{B}\rangle}{B_0}}_{j_{ni}(\rho)} \tag{8}$$

Flux surface averaging

Volume:

$$V = \int dV = \int R\mathrm{d}\phi \frac{\mathrm{d}\psi}{|\nabla\psi|}\mathrm{d}\ell_p = \int \left(\oint \frac{\mathrm{d}\ell_p}{B_p} \right) \mathrm{d}\psi \tag{9}$$

$$\frac{\partial V}{\partial \psi} = \oint \frac{\mathrm{d}\ell_p}{B_p} \tag{10}$$

Flux Surface average of Q:

$$\begin{aligned} \langle Q \rangle &\equiv \frac{\partial}{\partial V} \int Q dV = \frac{\partial \psi}{\partial V} \frac{\partial}{\partial \psi} \oint Q \frac{R d\ell}{|\nabla\psi|} d\psi d\phi \\ &= \oint Q \frac{d\ell_p}{B_p} / \oint \frac{d\ell_p}{B_p} \end{aligned} \tag{11}$$

Flux Diffusion: Sketch of derivation

$$\boxed{\sigma_{||}\frac{\partial\psi}{\partial t} = \frac{F^2}{(2\pi)^4\mu_0 B_0^2\rho}\frac{\partial}{\partial\rho}\left(\frac{g_2 g_3}{\rho}\frac{\partial\psi}{\partial\rho}\right) - \frac{V'}{2\pi\rho}j_{ni}} \tag{12}$$

Where:

- $g_2 = \left\langle\frac{|\nabla V|^2}{R^2}\right\rangle$, $g_3 = \langle 1/R^2\rangle$, $V' = dV/d\rho$. (*Geometric profiles*)
- $F = RB_\phi = R_0 B_0 +$ small correction due to poloidal currents.
- $\sigma_{||}$ is the conductivity (roughly $\sim T_e^{3/2}$)
- j_{ni} is non-inductive current drive (self-generated, or from auxiliary sources)

Flux Diffusion: Sketch of derivation

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Recall: (Ohmic **j**) = (Total **j**) - (non-inductive **j**)
Special cases:

- $j_{ni} = 0$: "Ohmic" plasma: all current sustained by inductive part (LHS). Requires $\frac{d\psi}{dt} > 0 \; \forall \; t$.
- $\frac{d\psi}{dt} =$ constant: *stationary state*. $\frac{\partial}{\partial\rho}\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial t}\frac{\partial\psi}{\partial\rho} = 0$. Fixed plasma current profile (shape) but not steady-state.
- $\frac{d\psi}{dt} = 0$: fully *steady-state* plasma. Plasma current sustained entirely by j_{ni} **desired for reactor**

Non-inductive current drive

Sources of non-inductive current drive: $j_{ni} = j_{bs} + j_{aux}$

- Bootstrap current: self-generated plasma current due to trapped particle orbits. $\sim \nabla p$. Equations in [4], [5]
- Auxiliary current: driven by auxiliary systems: NBI, EC, LH, IC $\rightarrow$ NBCD, ECCD, LHCD, ICCD.

In a reactor, one must maximize the bootstrap current fraction ($\sim$ 70%) since auxiliary current drive has large a capital cost and lowers Q_{fus}. *Most plasma current becomes self-generated*.

Boundary conditions for poloidal flux

Boundary conditions:

- Impose total plasma current

$$\left[\frac{G_2}{\mu_0}\frac{\partial\psi}{\partial\rho}\right]_{\rho=\rho_e} = I_p(t). \tag{14}$$

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Interpretation:

- To have nonzero I_p we need $\left[\frac{G_2}{\mu_0}\frac{\partial\psi}{\partial\rho}\right]_{\rho=\rho_e} \neq 0$, but $\psi(\rho)$ evolution is governed by diffusion equation that evolves to $\frac{\partial\psi}{\partial\rho} = 0$. How do we maintain I_p?

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- Two possibilities
    - Time-varying $\psi(\rho_b)$ (induced current)
    - Use source term (non-inductive current)

Other measures of current distribution

- In practice, physicists like to work with q profile since it is indicative of MHD stability.

$$q(\psi) = \frac{1}{2\pi} \oint \frac{1}{R} \frac{B_\phi}{B_p} d\ell = \frac{T(\psi)}{2\pi} \oint \frac{d\ell}{R^2 B_p} \tag{15}$$

  It can also be shown that $q \equiv \frac{\partial \Phi}{\partial \psi}$.
- Plasma stability, performance, transport is influenced by q and its spatial derivative the *magnetic shear* $s = \frac{\rho}{q} \frac{\partial q}{\partial \rho}$.

Question: response to step in auxiliary current drive

$$\boxed{\sigma_{||}\frac{\partial\psi}{\partial t} = \frac{F^2}{(2\pi)^4\mu_0 B_0^2\rho}\frac{\partial}{\partial\rho}\left(\frac{g_2 g_3}{\rho}\frac{\partial\psi}{\partial\rho}\right) - \frac{V'}{2\pi\rho}j_{ni}} \qquad (16)$$

- Question:
  - Suppose we are in a stationary state with $\frac{\partial\psi}{\partial t} = c$.
  - Qualitatively, what happens if we instantaneously increase j_{ni}?
  - Does the current density profile change instantaneously?
  - Which physical law does this example represent?

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  - Does the current density profile change instantaneously?
  - Which physical law does this example represent?
- Answer:
  - We can not change the 1st term on the LHS since its time evolution is governed by (16) itself! Thus, instantaneously, only the ohmic current density $\sim \frac{\partial\psi}{\partial t}$ changes.
  - This is an example of Lenz's law:
    an inductive circuit resists a change
    in flux. Also called “back-EMF”.

Subsection 2

Kinetic transport

Thermal energy transport equation

- Diffusive transport law for energy density $W = k_B T_e n_e$

$$\frac{\partial W}{\partial t} + \frac{1}{\rho}\frac{\partial}{\partial \rho}\Gamma = \text{Sources} \tag{17}$$

  with diffusive flux $\Gamma = \rho D \frac{\partial W}{\partial \rho}$ with diffusion coefficient D.
- In toroidal geometry, this is more complicated. For each species:

$$\frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}\left[(V')^{5/3} n_\alpha T_\alpha\right]\right) + \frac{1}{V'}\frac{\partial}{\partial \rho}\left(q_\alpha + \frac{5}{2}T_\alpha \Gamma_\alpha\right) = P_\alpha \tag{18}$$

- $V' = \frac{\partial V}{\partial \rho}$ (geometry)
- Similarly for particle transport
- For each species (e^-, i^+, impurities)!

Transport coefficients

- Diffusive/advective fluxes in plasma depend in a complicated way on the plasma itself, nonlinear multi-scale *turbulence*.
- For modeling/control purposes, must resort to simple models.
- Recent breakthrough: Neural Network emulation of Gyrokinetic fluxes from the QuaLiKiz quasilinear gyrokinetic code [6], [7]. Speedup from 1hour to 1ms per time step.

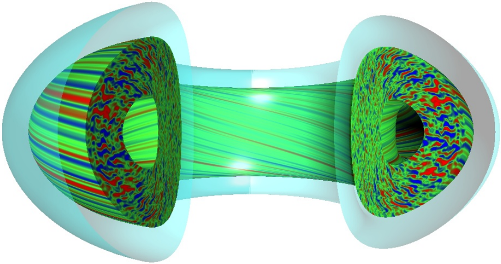


Figure: Gyrokinetic simulations of tokamak turbulence. Source: GYRO/PPPL

Models for diffusive and convective flux

- Transport equation, for species α:

$$\frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}\left[(V')^{5/3}n_\alpha T_\alpha\right]\right)+\frac{1}{V'}\frac{\partial}{\partial\rho}\left(q_\alpha+\frac{5}{2}T_\alpha\Gamma_\alpha\right)=P_\alpha \tag{19}$$

where q_α is the diffusive flux and Γ_α is the convective flux.

$$\frac{q_\alpha}{n_\alpha T_\alpha}=-V'G_1\langle(\nabla\psi)^2\rangle\sum_{\beta\in\text{all species}}\left(\chi^T_{\alpha\beta}\frac{1}{T_\beta}\frac{\partial T_\beta}{\partial\rho}+\chi^n_{\alpha\beta}\frac{1}{n_\beta}\frac{\partial n_\beta}{\partial\rho}\right) \tag{20}$$

$$\frac{\Gamma_\alpha}{n_\alpha}=-V'G_1\langle(\nabla\psi)^2\rangle\sum_{\beta\in\text{all species}}\left(D^T_{\alpha\beta}\frac{1}{T_\beta}\frac{\partial T_\beta}{\partial\rho}+D^n_{\alpha\beta}\frac{1}{n_\beta}\frac{\partial n_\beta}{\partial\rho}\right) \tag{21}$$

Qualitative picture of transport coefficients

- Accurate and simple models for thermal transport do not exist (yet). We can only make some qualitative statements.
- Usually diagonal terms are dominant, e.g. χ_{ee} for electrons.
- Usually diffusive terms are assumed dominant. $D_{\alpha\beta} = 0$
- Then T_e diffusion equation becomes, e.g.

$$\frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}\left[(V')^{5/3} n_e T_e\right]\right) = \frac{1}{V'}\frac{\partial}{\partial \rho}\left(V' G_1 \chi_{ee} n_e \frac{\partial T_e}{\partial \rho}\right) + P_e \tag{22}$$

Qualitative picture of transport coefficients

- Higher plasma current gives more confinement.
- Transport is 'stiff'. Above a critical $\frac{\nabla T_e}{T_e}$, χ_e increases drastically. Increasing $\frac{\nabla T_e}{T_e}$ above this threshold requires much more power (limited by actuators).
- High magnetic shear and low q are 'good' (low transport). Volume-averaged $\langle s/q \rangle$ [8]
- Shear close to 0 or negative is also good, can give 'internal transport barriers' (ITBs). e.g. [9], [10]

Sources and sinks for thermal energy

- Sources
  - Ohmic heating power (resistivity) $\sim \langle \mathbf{j} \cdot \mathbf{E} \rangle$
  - Local heat deposition by auxiliary systems
  - Collisional energy exchange with other species (α particles!)
- Sinks
  - Radiation losses (line radiation, cyclotron radiation, Bremsstrahlung)
  - Conduction (loss to the wall)
  - Collisional energy exchange with other species.

Subsection 3

Coupling to 2D equilibrium

Coupling to 2D equilibrium

In reality, 1D transport is tightly coupled to 2D equilibrium (Grad-Shafranov). Geometric factors g_2, g_3 come from 2D $\psi(R, Z)$ distribution

- Given a pressure and current distribution, GS equation determines 2D equilibrium. Very fast (Alfven = $\mu\mathrm{s}$) timescales
- Given a 2D equilibrium geometry, 1D transport equations evolve distribution of current and pressure. Confinement time scales vs current redistribution time scales. ITER: $\tau_E \sim 5\mathrm{s}$, $\tau_{crt} \sim 100\mathrm{s}$.

In practice: very complicated, strongly nonlinear coupling between two sets of equations. Few good simulators exist.

Section 3

Profile control

Subsection 1

Actuators

Actuators

- Poloidal flux (current distribution)
    - I_p (boundary)
    - $\sigma_{||}$ or j_{BS} (heating changes resistivity or *BS* current)
    - j_{aux} (direct source).
    - Shape changes.
- Thermal transport:
    - Heating (direct source)
    - Change of transport via changing turbulence $q, s, \nabla T_e, \nabla n_e, \ldots$.
- Particle transport
    - Gas (edge)
    - Neutral beam (internal source)
    - Change particle transport.

Subsection 2

Sensors

Sensors (diagnostics) for profile control

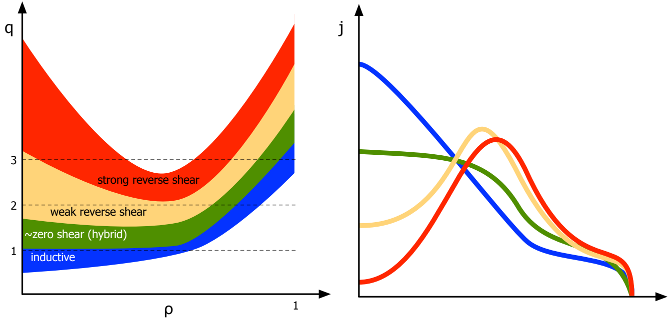
- Kinetic profiles: ECE, Thomson, interferometry, ...
- Magnetic profiles: MSE, Polarimetry, ...
- 2D equilibrium: RT equilibrium reconstruction, ...
- Different sampling rates, varying radial location of measurements, technically challenging diagnostics.
- How to merge information from various sources? *State observers* (Previous lecture)

Subsection 3

Control

Control Objectives

- Obtain plasma with desired profile shapes ("scenario"), possibly in stationary condition, at end of current ramp-up.



- Q: why is the inductive current profile peaked?

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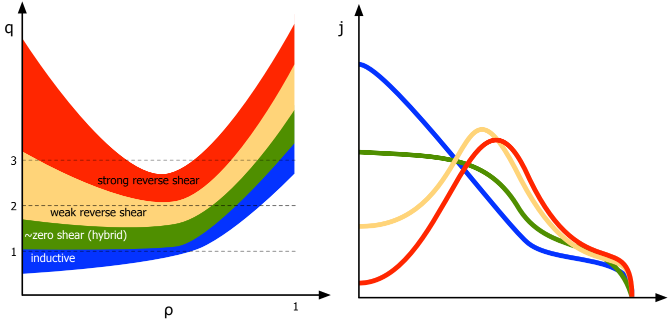

- Q: why is the inductive current profile peaked?
- A: $\sigma_{neo} \sim T_e^{3/2}$

Control strategies

- Open-loop vs closed-loop control
  - Open-loop: design actuator time trajectories to get desired plasma state. (*everyday practice for tokamak operators who program plasma discharges*)
  - Closed-loop: attempt to track a reference: reject disturbances, robust against model uncertainties, etc (*done very rarely - desired in the future*)
- Both can benefit from model-based design tools

Model-based open-loop trajectory design

- Solve open-loop trajectory optimization problem.
- Include cost function (what you want) and constraints (what is possible)
- Simulation examples in literature: [11] [12], [13], to be tested in practice.

Examples of closed-loop profile control

- Non model-based
    - Control q_0 and q_{min} in DIII-D ramp-up using NBI [14]
    - Plasma regime control by LH power in Tore Supra [Imbeaux EPS 2009]
- Model-based: system identification of linear model arond operating point
    - Linear optimal feedback control around set point (JET, DIII-D) [15], [16].
- Model-based: first principle models
    - Model-based controllers tested on DIII-D [17], [18], [**?**]
    - Lyapunov-based controller design [19]
    - Adaptive model based on linearization [20]
    - Model Predictive Control [21], [22]

Bibliography I

- Hinton, F.L. *et al.* 1976 *Rev. Mod. Phys.* **48** 239
- Pereverzev, G.V. *et al.* 2002 *{ASTRA} {A}utomated {S}ystem for {TR}ansport {A}nalysis in a {T}okamak* Technical Report 5/98 IPP Report
- Felici, F. 2011 *Real-Time Control of Tokamak Plasmas: from Control of Physics to Physics-Based Control* Ph.D. thesis Ecole Polytechnique Fédérale de Lausanne EPFL Lausanne
- Sauter, O. *et al.* 1999 *Physics of Plasmas* **6** 2834
- Sauter, O. *et al.* 2002 *Plasma Physics and Controlled Fusion* **44** 1999
- Felici, F. *et al.* 2018 *Nuclear Fusion* **58** 096006
- van de Plassche, K.L. *et al.* 2020 *Physics of Plasmas* **27** 022310
- Citrin, J. *et al.* 2012 *Plasma Physics and Controlled Fusion* **54** 65008
- Connor, J.W. *et al.* 2004 *Nuclear Fusion* **44** R1
- Goodman, T.P. *et al.* 2005 *Plasma Physics and Controlled Fusion* **47** B107
- Felici, F. *et al.* 2012 *Plasma Physics and Controlled Fusion* **54** 025002

Bibliography II

- van Dongen, J. *et al.* 2014 *Plasma Physics and Controlled Fusion* **56** 125008
- Xu, C. *et al.* 2010 *Plasma Science, IEEE Transactions on* **38** 163
- Ferron, J.R. *et al.* 2006 *Nuclear Fusion* **46** L13
- Moreau, D. *et al.* 2008 *Nuclear Fusion* **48** 106001
- Moreau, D. *et al.* 2011 *Nuclear Fusion* **51** 63009
- Ou, Y. *et al.* 2008 *Plasma Physics and Controlled Fusion* **50** 115001 (24pp)
- Barton, J.E. *et al.* 2012 *Nuclear Fusion* **52** 123018
- Argomedo, F.B. *et al.* 2013 *Nuclear Fusion* **53** 033005
- Kim, S. *et al.* 2012 *Nuclear Fusion* **52** 074002
- Maljaars, E. *et al.* 2015 *Nuclear Fusion* **55** 023001
- Maljaars, E. *et al.* 2017 *Nuclear Fusion* **57** 126063