Current Profile Control and Formation of Current Hole in Tokamaks

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1. Introduction

- \( j(r) \) or \( q(r) \) is closely related to transport and stability in tokamaks.
  - Formation ITB with negative/weak magnetic shear.
  - Stability improvement with high \( I_i \).
- Toroidal (parallel to magnetic field) current in tokamaks:
  - (1) inductive (OH) current
    \[ j_{OH} \propto \sigma_{NC} E_\phi \]
    --- heat transportdiffusion of \( E_\phi \).
  - (2) bootstrap current
    \[ j_{BS} \propto \nabla p(r)/B_p \]
    --- heat transport inner current.
  - (3) externally driven (by NB/RF)
    non-inductive current
    \[ j_{EX} \] --- controllable.
Current profile measurements (1)

- $q(r)$ or $B_p(r)$ measurement
  --- Faraday rotation, motional Stark effect (MSE),

- Especially, MSE diagnostics is characterized by high spatial resolution (by local measurement) and high accuracy.

**Polarization angle**

Direction of $v \times B$

Direction of $B$

$B_p / B_t$

$q(r), j(r)$
Internal toroidal electric field $E_\phi(r)$ can be evaluated in addition to $q(r)$ from time evolution of equilibrium; $E_\phi(r) = -d\Psi_p(r)/dt$

$$j_{OH} = \sigma_{NC} E_\phi, \quad j_{NI} = j_{tot} - j_{OH}, \quad j_{EX} = j_{NI} - j_{BS}$$
2. Sustainment of large bootstrap current fraction and current profile control
Linkage of $p(r)$ and $j(r)$ under large $f_{BS}$

- In steady operation of tokamak, $j_{OH}$ is zero and most of the plasma current ($>70\%$) should be carried by $j_{BS}$ while the rest by $j_{EX}$. (Large $j_{OH}$ can be locally and transiently generated even in full CD plasma.)

Study on high $f_{BS}$ plasma is important.

$p(r)$ and $j(r)$ are closely linked to each other.
Two issues:

(1) Is there a stationary point where $p(r)$ and $j(r)$ stay in steady state?

(2) Can $j(r)$ be controlled by small $j_{EX}$?
Sustainment of large $f_{BS}$

- In JT-60U, high beta ($\beta_N > ~ 2$), high confinement (HH $> ~ 2$) RS with $f_{BS} \sim 80\%$ and $f_{CD} \sim 100\%$ was maintained for 2.7 s.
- Current profile was mainly determined by the bootstrap current.
- During 2.7s, $\rho_{q_{\min}}$ and $q_{\min}$ were kept stationarily.

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In JT-60U, high beta ($\beta_N > ~ 2$), high confinement (HH $> ~ 2$) RS with $f_{BS} \sim 80\%$ and $f_{CD} \sim 100\%$ was maintained for 2.7 s.
Is there a stationary point?

- In the experiment, raising $\beta_p$ ($f_{BS}$) suppressed the shrinkage of $\rho_{q\text{min}}$, which is a promising result for steady sustainment of $\rho_{q\text{min}}$ by the bootstrap current.

- Oscillatory behavior may happen in a longer time scale and hence the experiment with a longer duration is needed.
Current profile control demonstrated in RS

- Full non-inductive CD with BS(62%), LHCD and N-NBCD.
- The radii of $q_{\min}$ and ITB-foot expanded by peripheral LHCD. $HH_y=1.4$, $\beta_N=2-2.2$, $n_e/n_{GW}=0.8$ due to large ITB radius.
- Reduction of the central $q$-value by central N-NBCD.
- Feedback control of $q(r)$ with real-time $q(r)$ measurement, demonstrated in JET, should be applied in future.
3. Current hole and current drive in a current hole plasma
Current hole as a limit of strong RS and large $f_{BS}$

- Increase of off-axis non-inductive (bootstrap) current
  -> Decrease of $E_{\text{tor}}(0)$ and $j(0)$ (Formation of reversed shear)
  -> $j(0)$ reach zero (Formation of current hole)
  No global instability with $j(0)=0$, and stable sustainment.

![Graphs and plots](image)
Stable existence of current hole

- The current hole was observed in JT-60U and JET. It persists stably (several seconds) without any global instabilities in JT-60U.
- High temperature plasma confined by off-axis $B_p$ and ITB.
- Extends operation region of $j(r)$ and enables very high $f_{BS}$. 

![Graph and diagram showing the stable existence of current hole in JT-60U and JET, with various parameters such as current density, plasma beta, and temperature profiles.](image-url)
“Current clamp” in a current hole

• A large current hole will be a problem for confinement of $\alpha$ particles in reactors. Control of current hole radius is required.
• No response to ECCD in the current hole both for co- and counter-CD. (“current clamp”).
• Some mechanism to maintain the structure.
  --- anomalous resistivity? dynamo ($\tilde{v}x\tilde{B}$) due to instability?
• CD in the center of current hole is difficult

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E47735 (co-ECCD)  E41777 (ctr-ECCD)

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CD outside the current hole
Control of current hole radius

- Reduction of the central q-value (outside the current hole) and current hole radius has been demonstrated by central N-NBCD.

- The response of \( j(r) \) seems to be unordinary even outside the current hole. This should be investigated for the \( j(r) \) control outside the current hole.
4. Summary and discussions

- Development in $j(r)$ measurement has progressed the $j(r)$ control research.

- Control of $j(r)$ with high $f_{BS}$ is important, where $p(r)$ and $j(r)$ are linked through heat transport and $E_{\phi}$ diffusion.

- Quasi-steady sustainment of 80% of $f_{BS}$ for several $\tau_E$. 
  Next: longer sustainment for current diffusion time.

- $j(r)$ control in RS with $f_{BS} \sim 60\%$ demonstrated. 
  Next: (i) evaluate controllability in larger $f_{BS}$, and (ii) apply feedback control with real-time $q(r)$ measurement.

- Current hole appears as a limit of strong RS and high $f_{BS}$. 
  Stable existence and mechanism for clamping $j(0) \sim 0$.

- The radius of current hole can be controlled, but the response should be carefully investigated.
Feedback control of current profile

- Real time $q(r)$ from polarimetry (Faraday rotation).

- LHCD power was controlled to minimize $q - q_{\text{ref}}$.

- At present, low beta, small $f_{\text{BS}}$ plasma. Application to large $f_{\text{BS}}$ plasma is expected.