シンポジウムII
「トロイダルシステムにおける
電流駆動・電流分布制御の新展開」

Current Profile Control and Formation of Current Hole in Tokamaks

トカマクにおける 電流分布制御と電流ホールの形成

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Contents

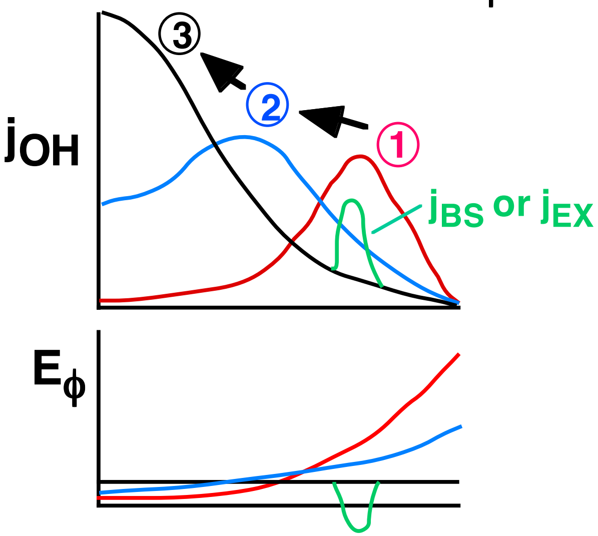
1. Introduction

- 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 l_i.
- Toroidal (parallel to magnetic field) current in tokamaks:

(1) inductive (OH) current

$j_{OH} \propto \sigma_{NC} E_\phi$

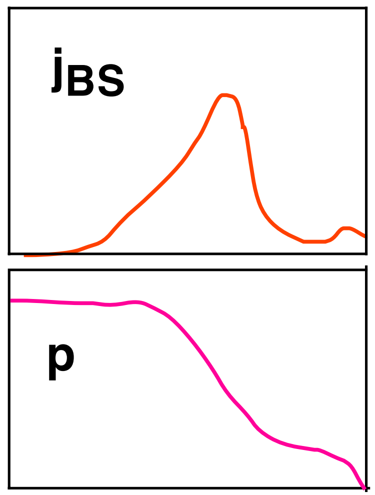
---diffusion of E_ϕ.



(2) bootstrap current

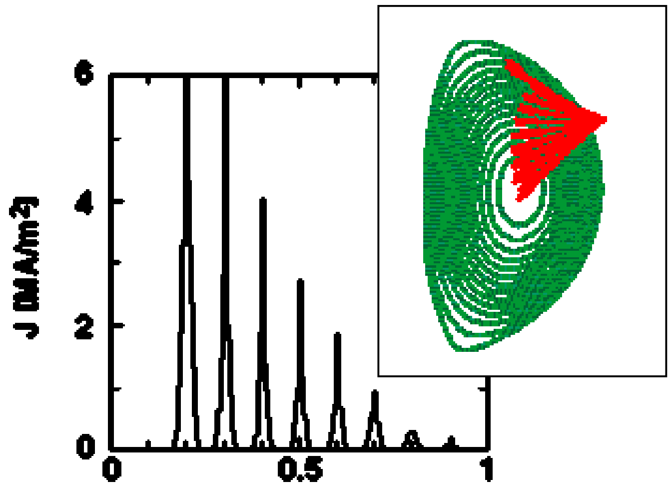
$j_{BS} \propto \nabla p(r)/B_p$

--- heat transport and inner current.



(3) externally driven (by NB/RF) non-inductive current

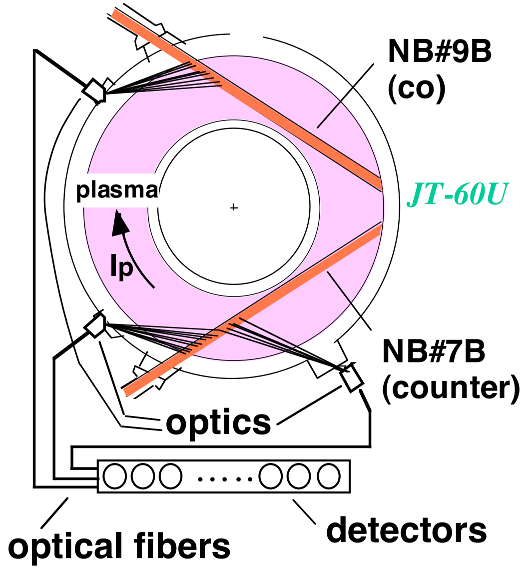
j_{EX} --- controllable.



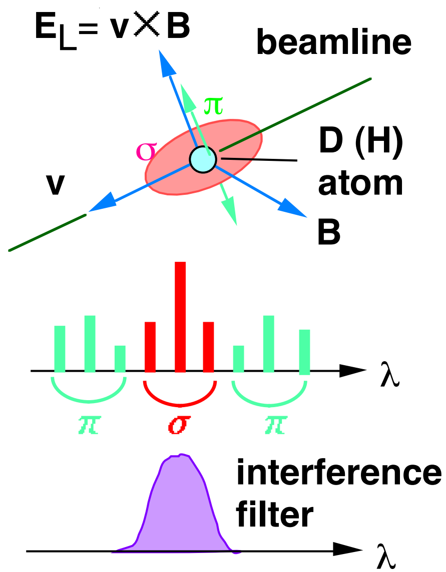
Current profile measurements (1)

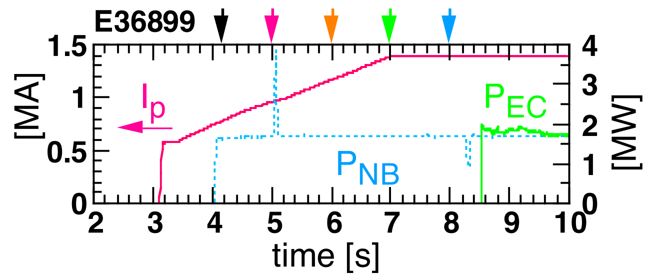
- **q(r) or B_p(r) measurement**
  --- Faraday rotation, motional Stark effect (MSE) ,....

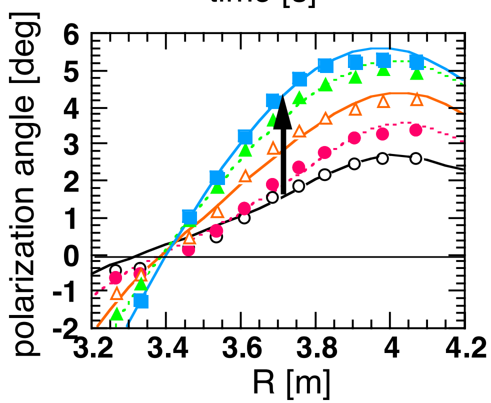
- **Especially, MSE diagnostics is characterized by high spatial resolution (by local measurement) and high accuracy.**



Polarization angle
↓
Direction of vxB
↓
Direction of B
↓
B_p/B_t
↓
q(r), j(r)



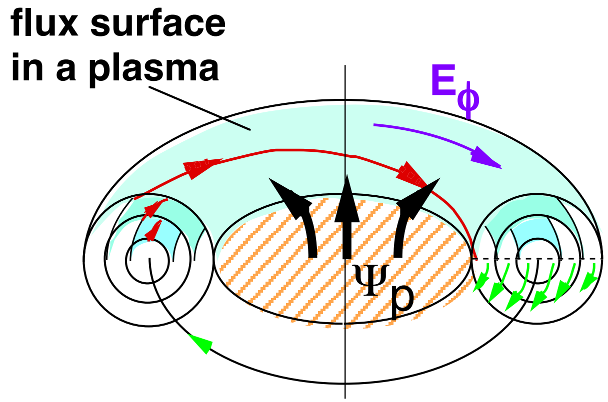


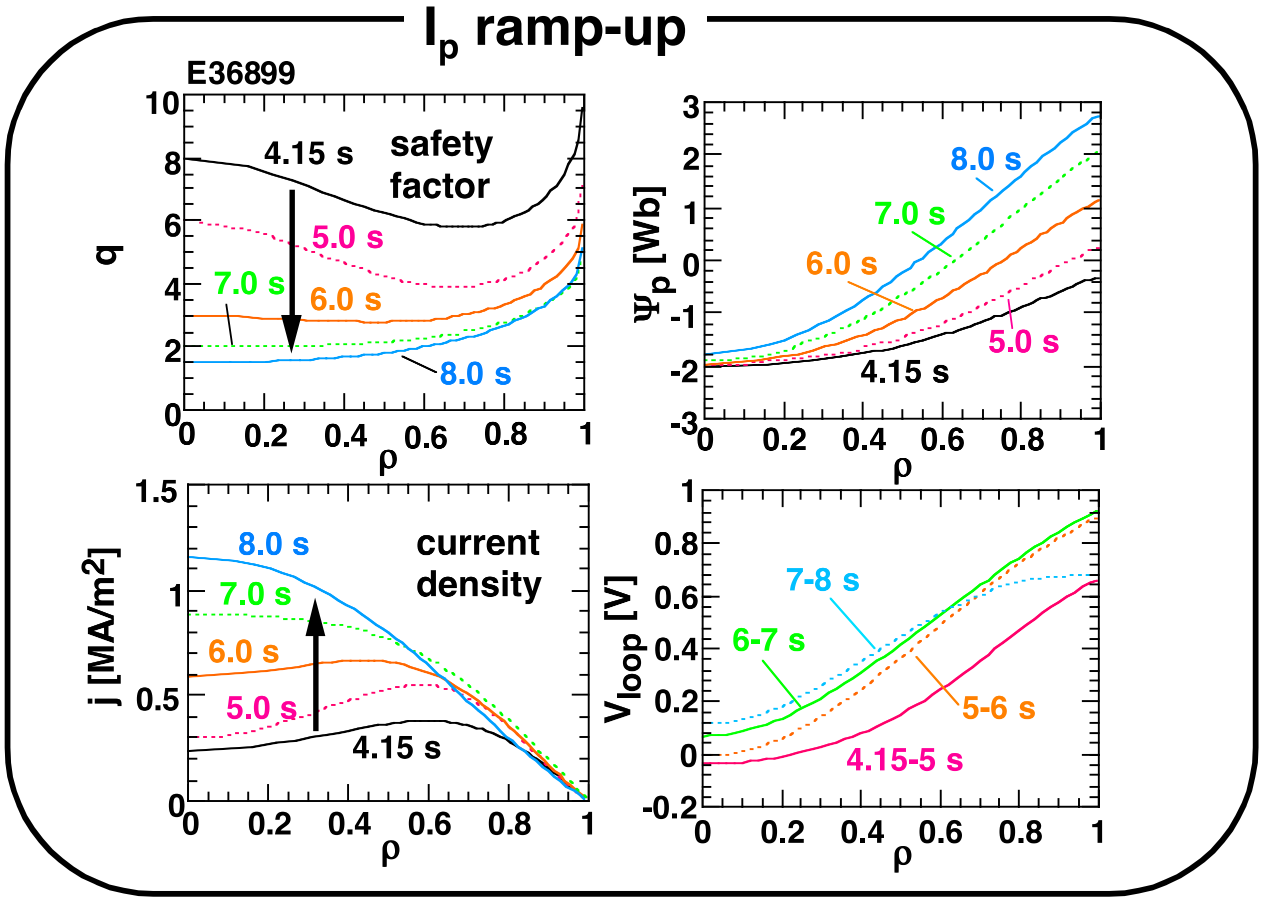


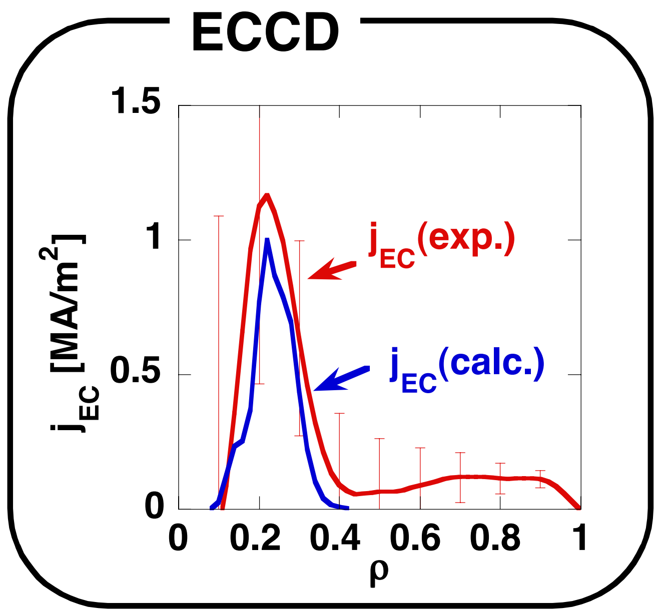
Current profile measurements (2)

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

→ $j_{OH} = \sigma_{NC} E_\phi,\ j_{NI} = j_{tot} - j_{OH},\ j_{EX} = j_{NI} - j_{BS}$





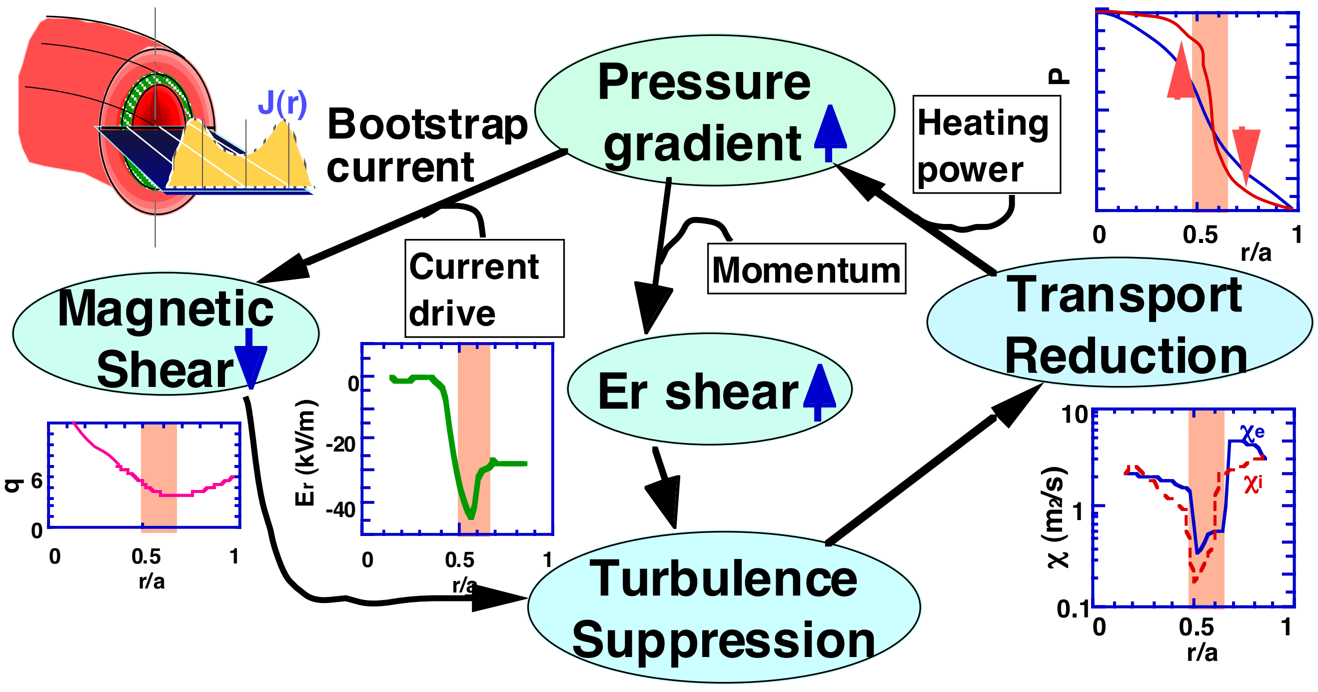


2. Sustainment of large bootstrap current fraction and current profile control

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.**



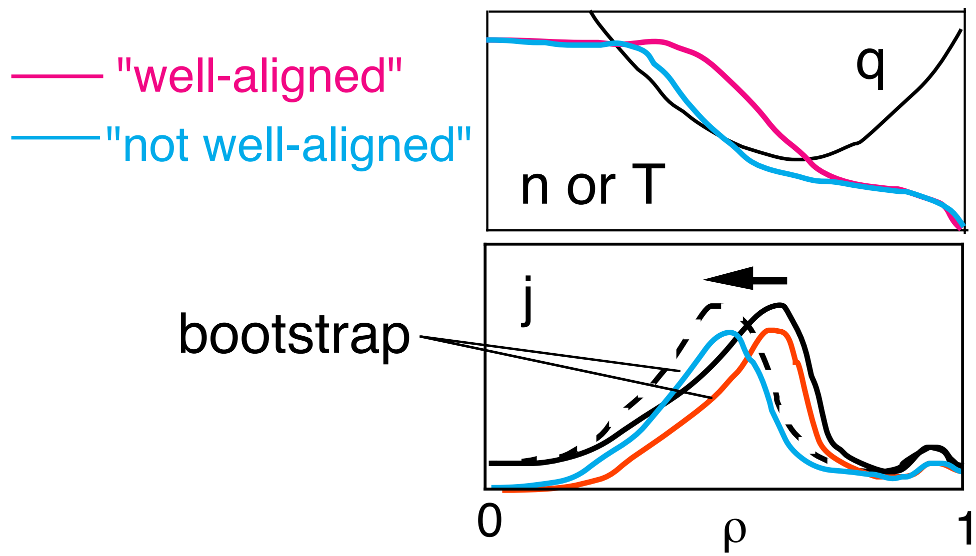
p(r) and j(r) are closely linked to each other

Linkage of p(r) and j(r) under large f_{BS} (cont.)

- **Two issues:**

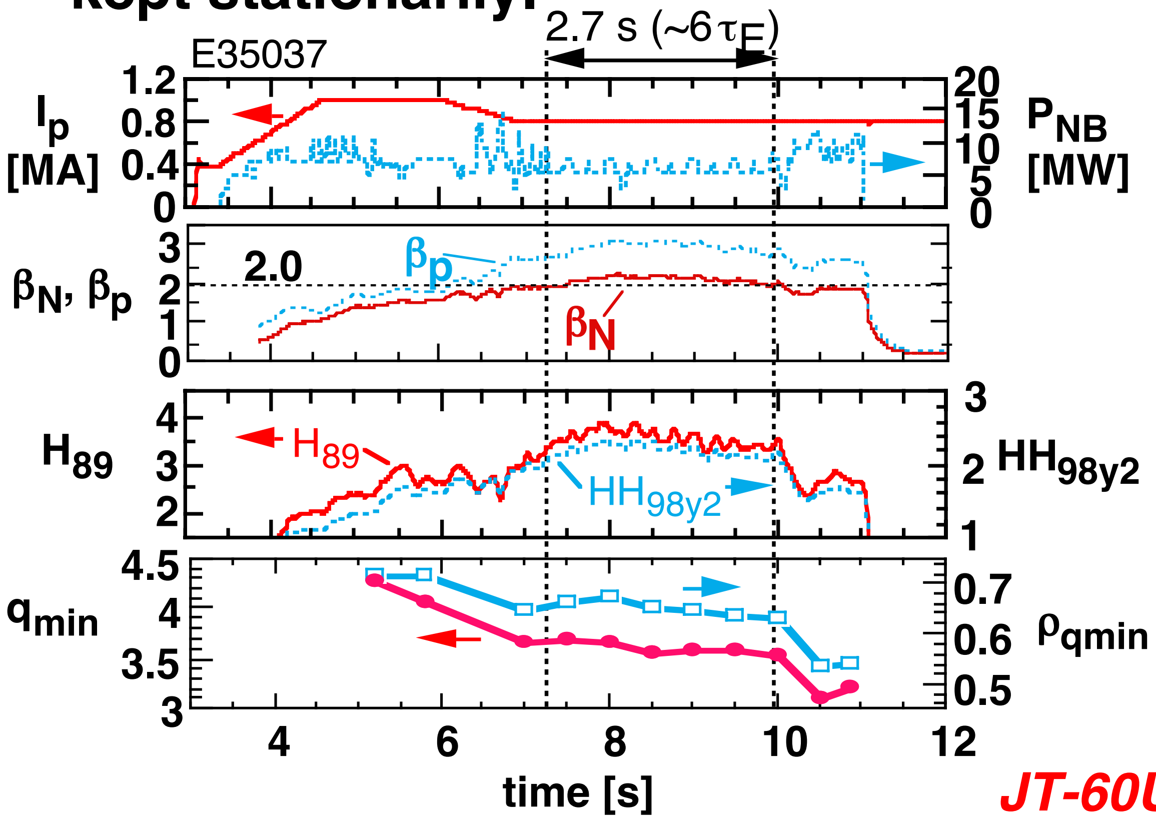
(1) Is there a stationary point where p(r) and j(r) stay in steady state ?

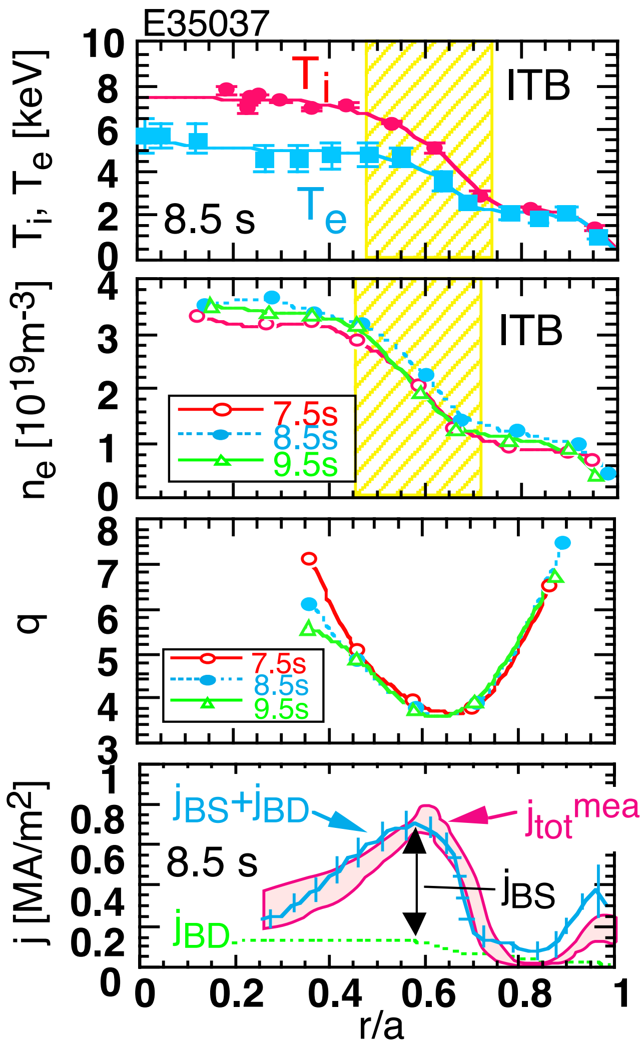
(2) Can j(r) be controlled by small j_{EX} ?



Sustainment of large f_{BS}

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

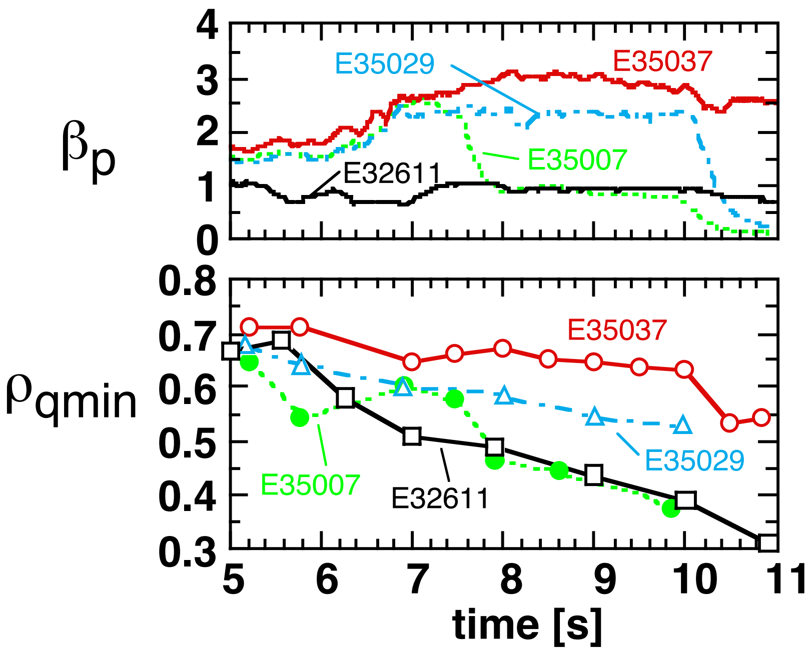




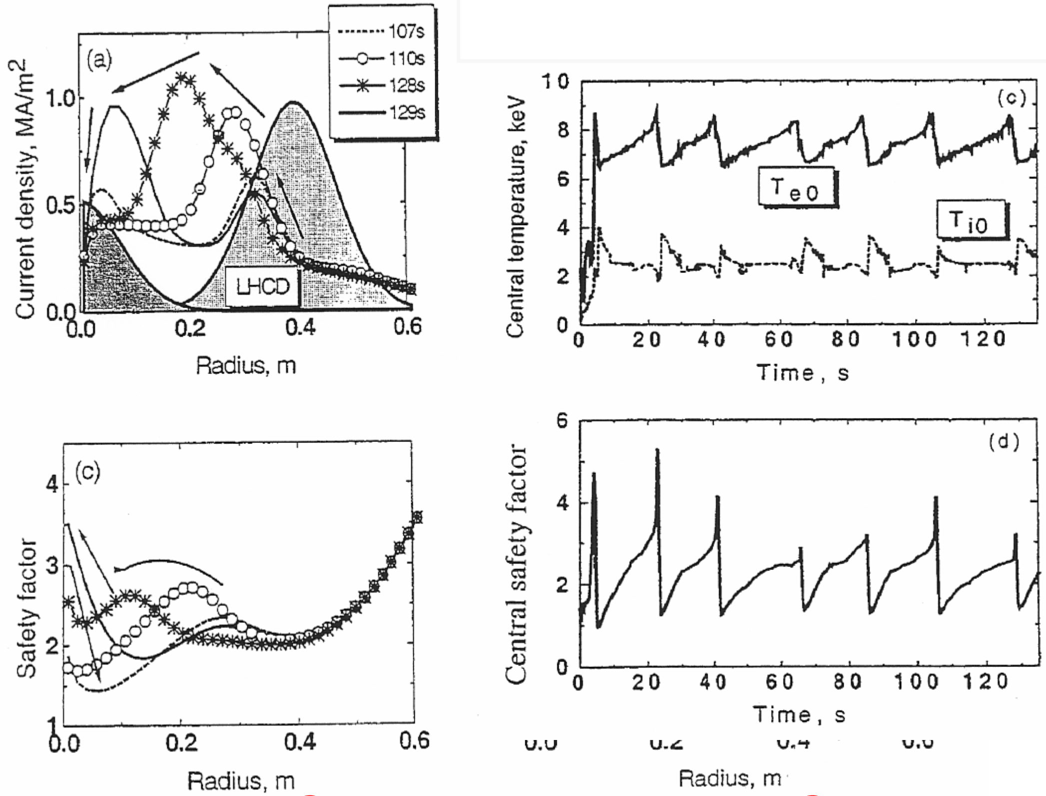
JT-60U

Is there a stationary point ?

- In the experiment, raising β_p (f_{BS}) suppressed the shrinkage of ρ_{qmin}, which is a promising result for steady sustainment of ρ_{qmin} by the bootstrap current.
- Oscillatory behavior may happen in a longer time scale and hence the experiment with a longer duration is needed.



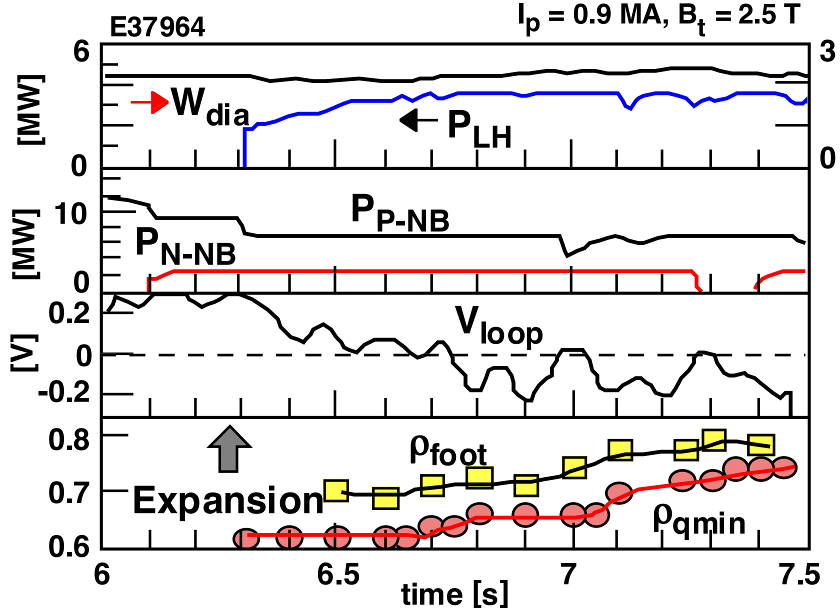
JT-60U experiment

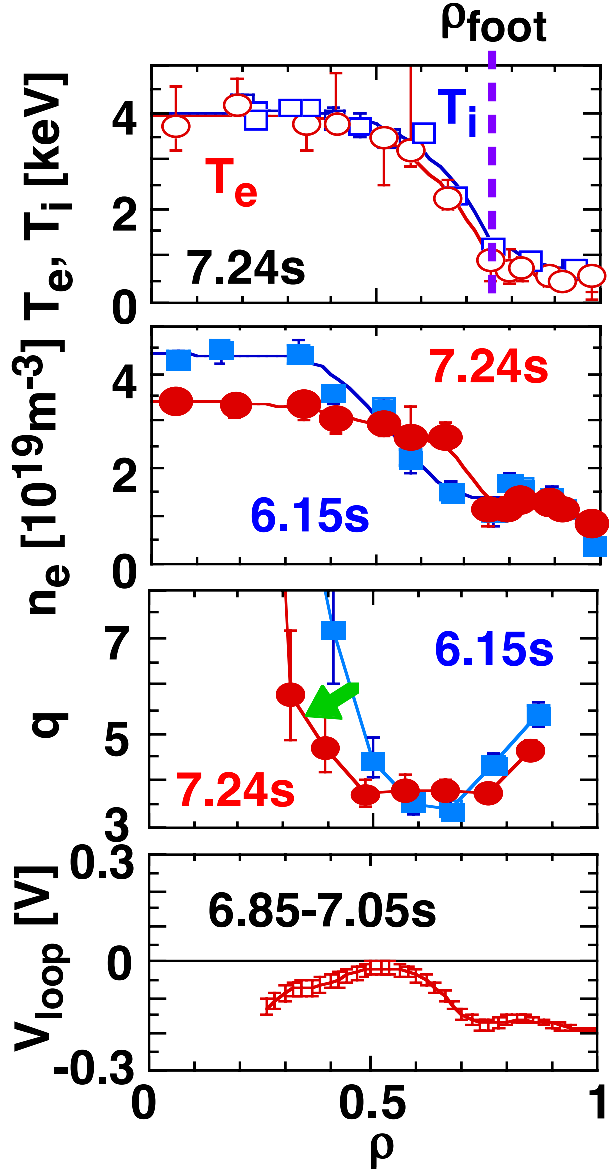


Simulation for Tore Supra

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_{y2}=1.4, β_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.



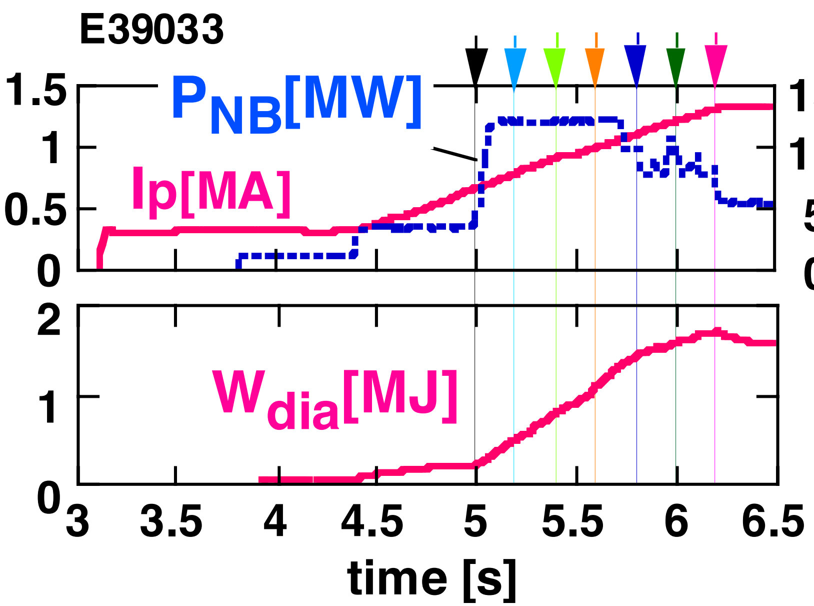


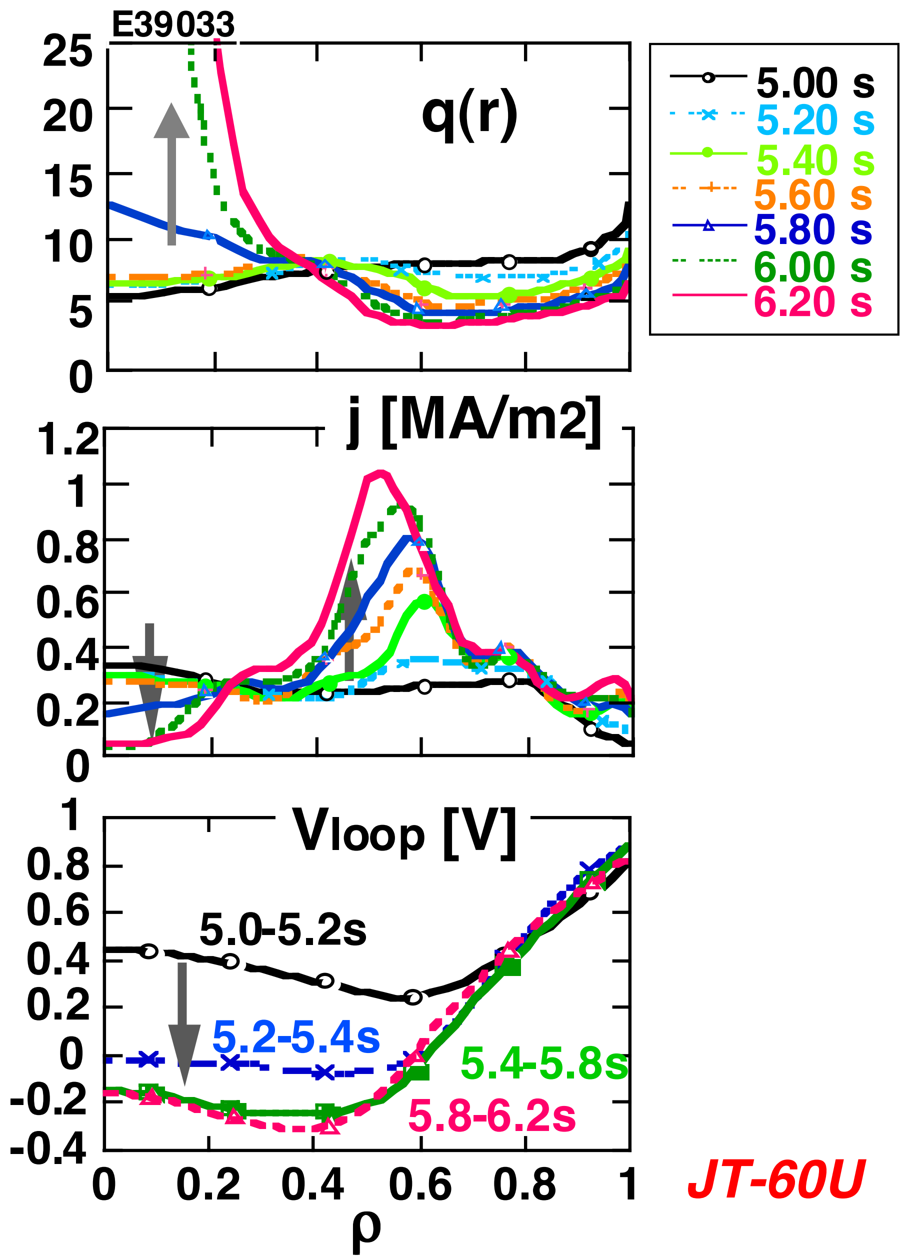
JT-60U

3. Current hole and current drive in a current hole plasma

Current hole as a limit of strong RS and large f_{BS}

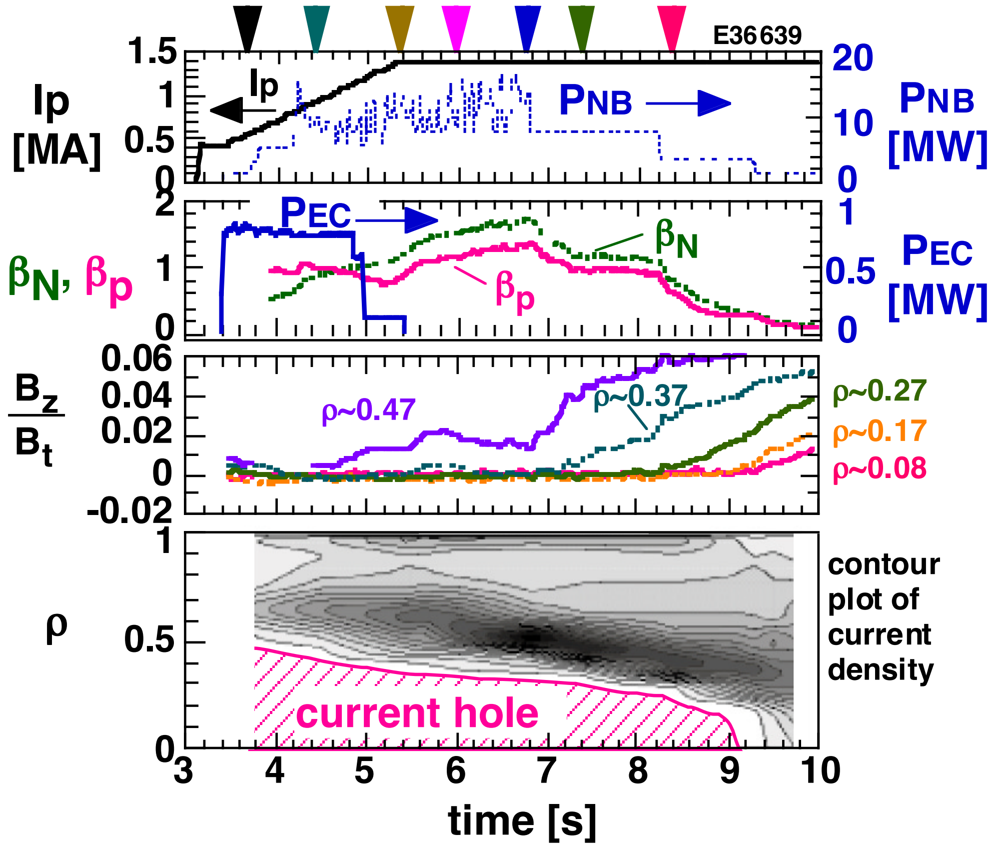
- Increase of off-axis non-inductive (bootstrap) current
  -> Decrease of $E_{tor}(0)$ and j(0)
  (Formation of reversed shear)
  -> j(0) reach zero
  (Formation of current hole)
  No global instability with j(0)=0, and stable sustainment.

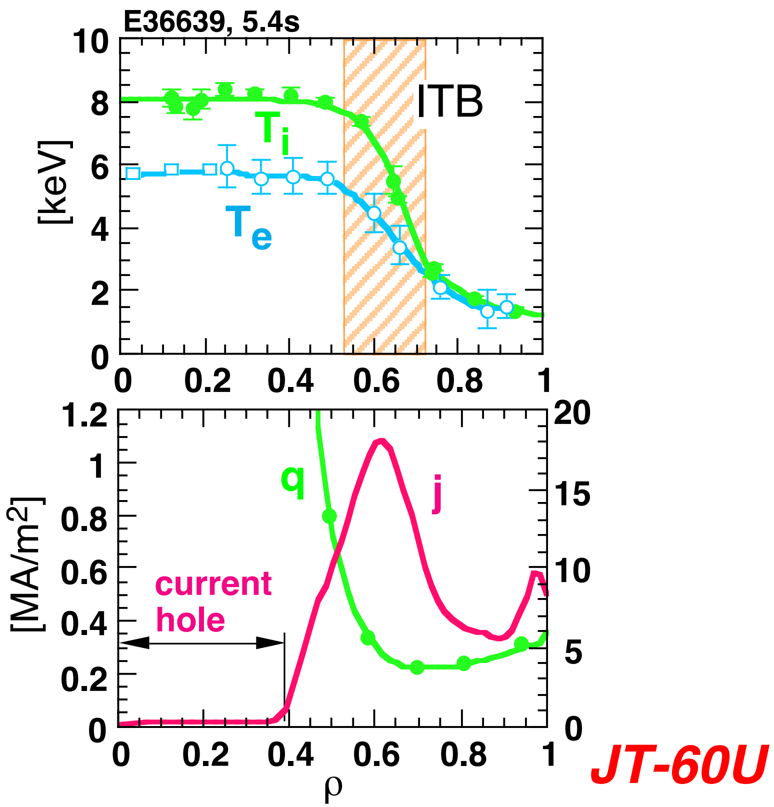




Stable existence of current hole

- 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}.



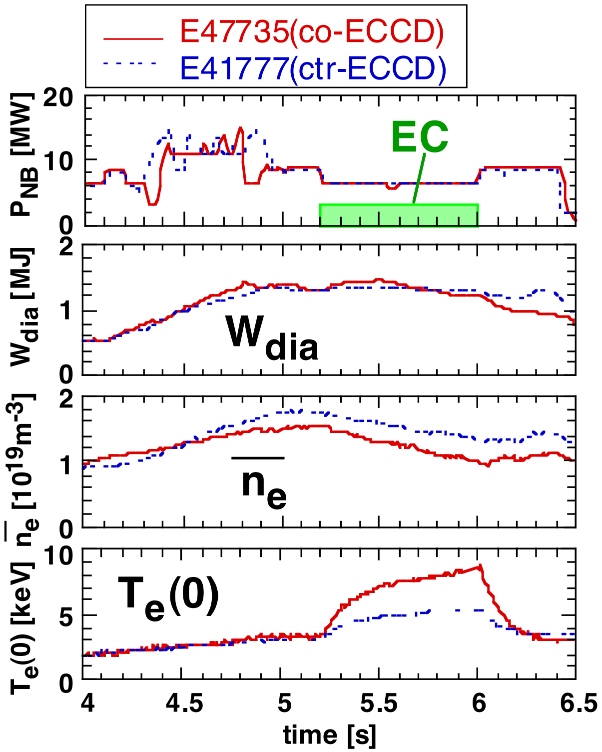


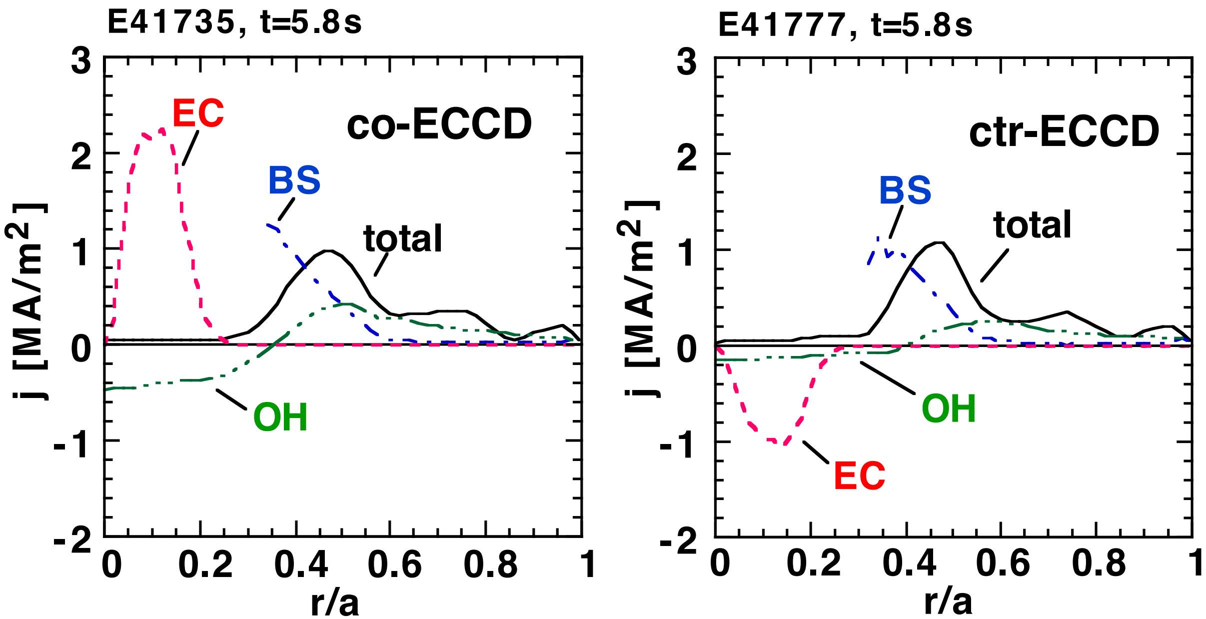
“Current clamp” in a current hole

- A large current hole will be a problem for confinement of α 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 ($\tilde{v} \times \tilde{B}$) due to instability ?
- CD in the center of current hole is difficult

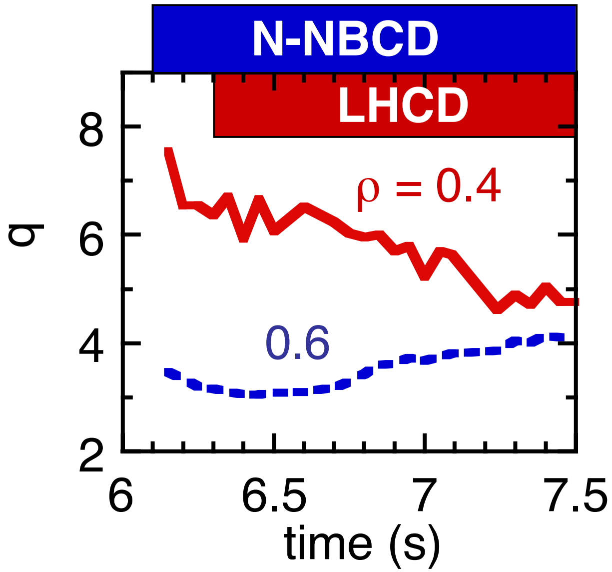
→ ***CD outside the current hole***

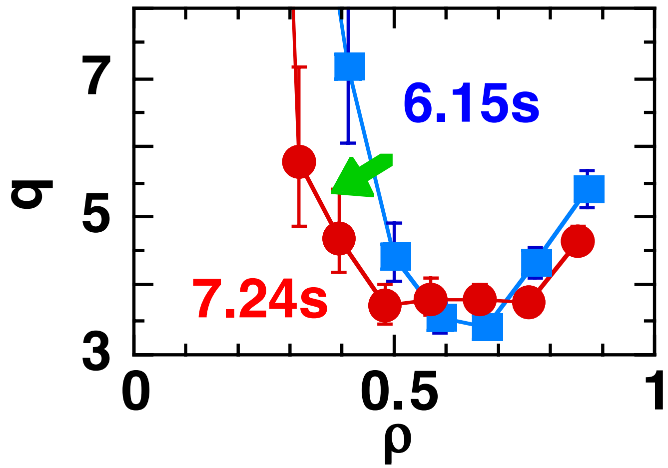




Control of current hole radius

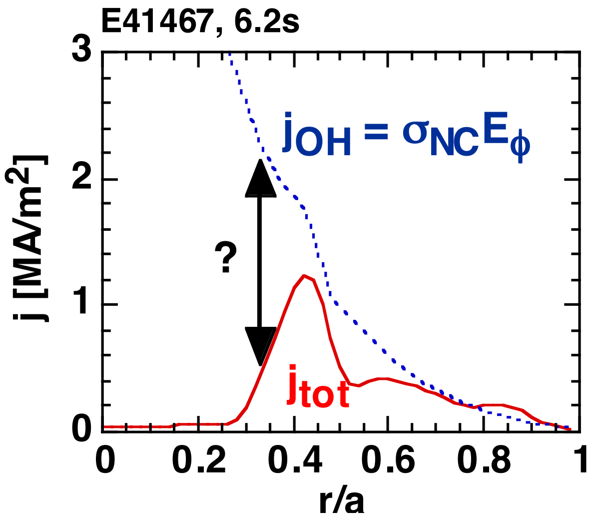
- **Reduction of the central q-value** (outside the current hole) and current hole radius has been demonstrated by central N-NBCD.





JT-60U

- **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

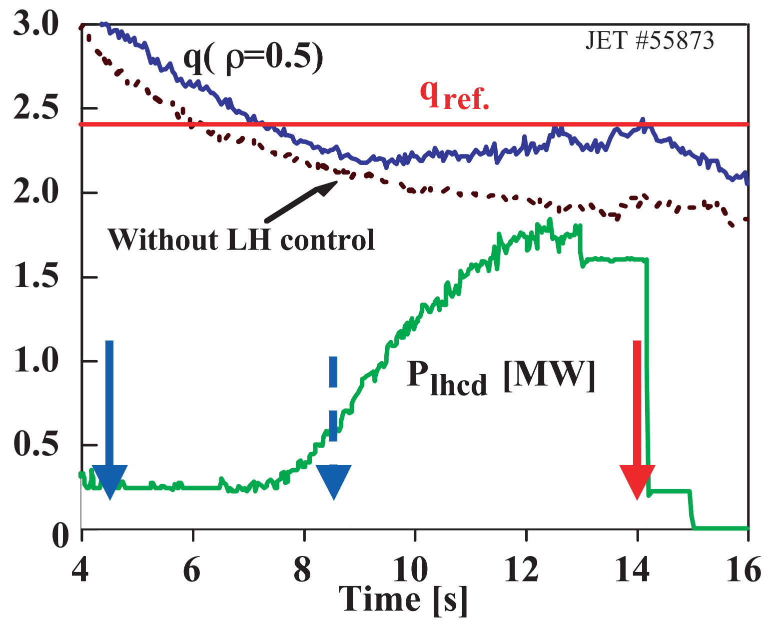
- Development in j(r) measurement has progressed the j(r) control research.
- Control of j(r) with high f_{BS} is important, where p(r) and j(r) are linked through heat transport and E_{ϕ} diffusion.
- Quasi-steady sustainment of 80% of f_{BS} for several τ_E.
  Next: longer sustainment for current diffusion time.
- j(r) control in RS with f_{BS}~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)~0.
- The radius of current hole can be controlled, but the response should be carefully investigated.

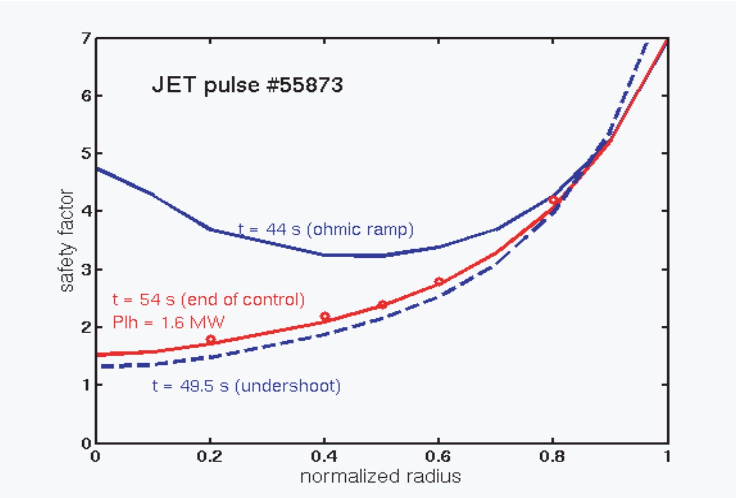
Feedback control of current profile

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

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

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





JET experiment