TH/1-6

Profile Formation and Sustainment of Autonomous Tokamak Plasma with Current Hole Configuration

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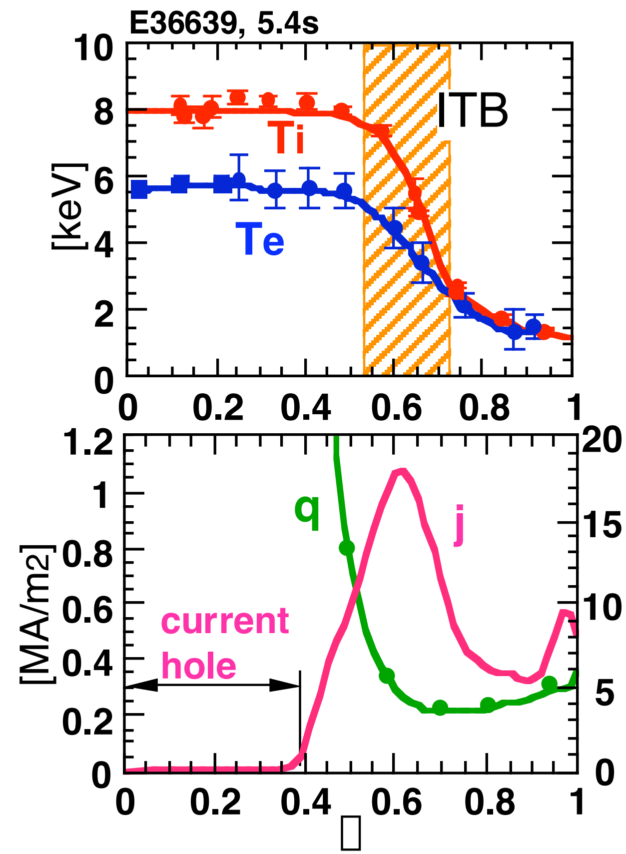
Introduction

Current hole (CH) with nearly zero current in the central region has been observed in tokamaks.

In a CH plasma, high confinement is achieved due to the formation of strong internal transport barrier (ITB) of box-type in the reversed-shear (RS) region.

In JT-60U, the CH plasma has an autonomous property because of the interaction between pressure and current profiles through large bootstrap current.

It is necessary to clarify the physical mechanism of profile formation and sustainment of the autonomous CH plasma.

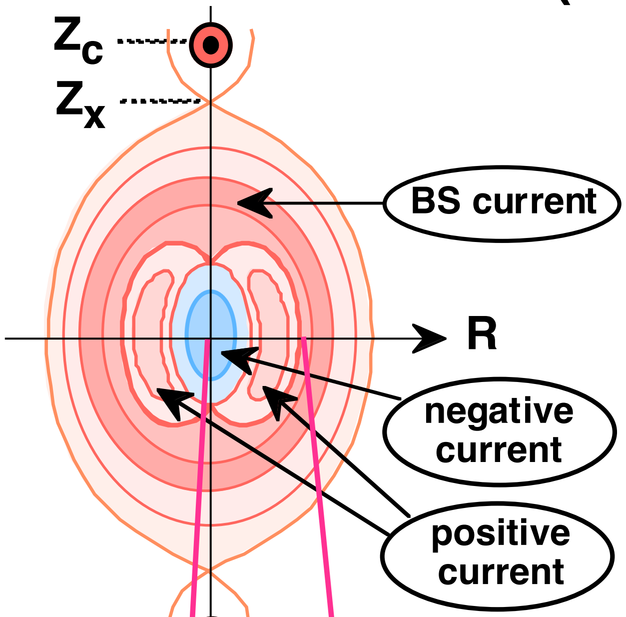


T.Fujita, et al., PRL 2001

Purpose of this paper

We investigate the profile formation and sustainment of the autonomous CH plasma by 1.5D transport simulations for JT-60U parameters.

1.5D transport code with the current limit model inside Current-Hole (CH) based on the ATMI equilibrium



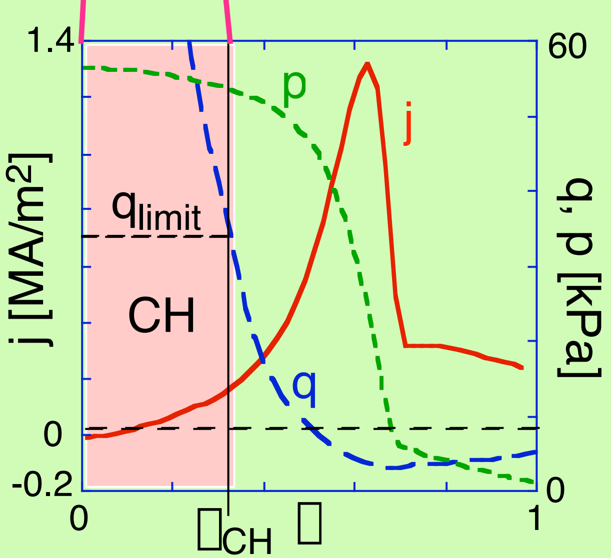
Central zero current equilibrium is difficult to be treated by 1.5D transport code.

Current inside CH is limited for the stable ATMI equilibrium.

$$q_{ATMI} > \square_1^{\ 2} \frac{Z_c^{\ 2}}{a\left(Z_c \square Z_x\right)} q_a \equiv q_{A0}$$

(T.Takizuka, JPFR 2002.)

Safety factor inside CH is limited by $q_{limit}=q_{A0}$ in the MHD equilibrium calculation.

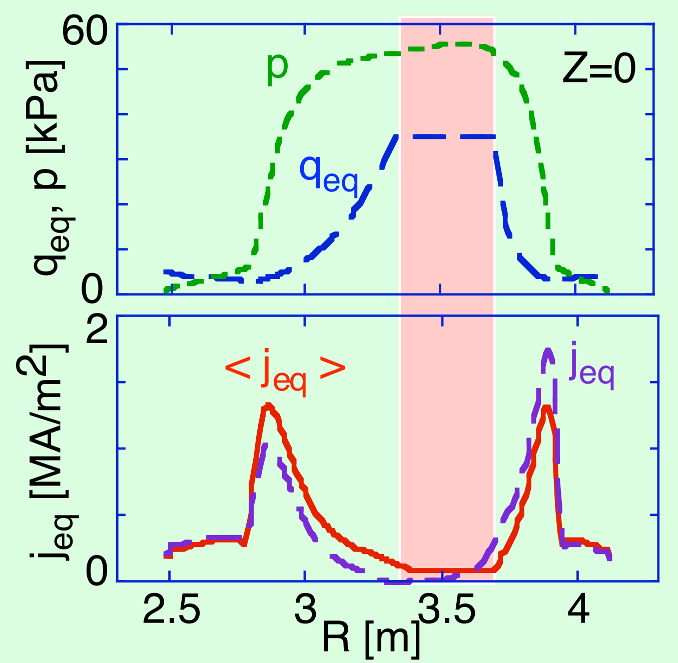


1D transport

Negative current inside CH

$q_{eq}(\square), n(\square), T(\square)$

Geometry



2D MHD equilibrium

Transport model for strong ITB

Diffusivities in the transport eqs. : $$\chi_i = \chi_e = \chi_{neo,i} + \chi_{ano}$$

$$D_i = C_D D_{neo,i} + D_{ano}$$

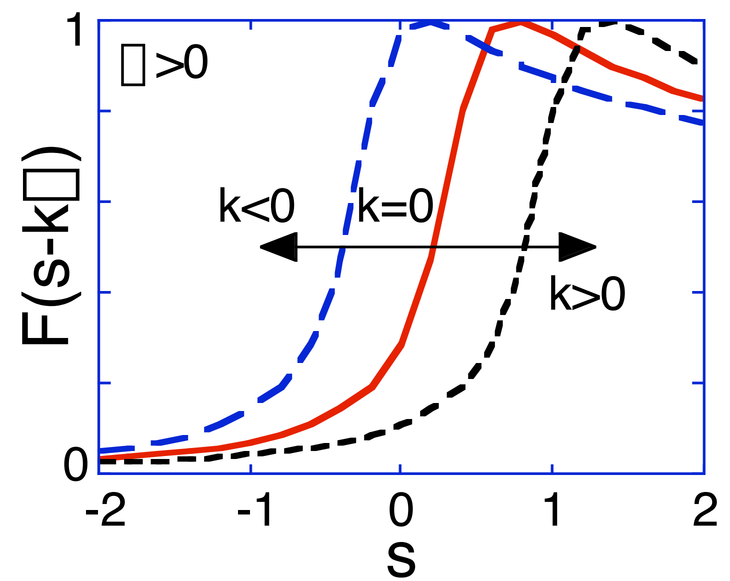
Anomalous transport :

Negative magnetic shear is effective to stabilize the ballooning mode and micro-instabilities.

$$\chi_{ano} = D_{ano} = \chi_0 F\left(s - k\alpha\right)$$

χ_0 : arbitary anomalous diffusivity

k : arbitrary constant



F with k=1 was originally developed for the ballooning type turbulence model.
(A.Fukuyama, PPCF 1995.)

Dependence on s and α (k >0) is similar to that in the micro-instabilities evaluated by GLF23. (R.E.Waltz, PoP 1997.)

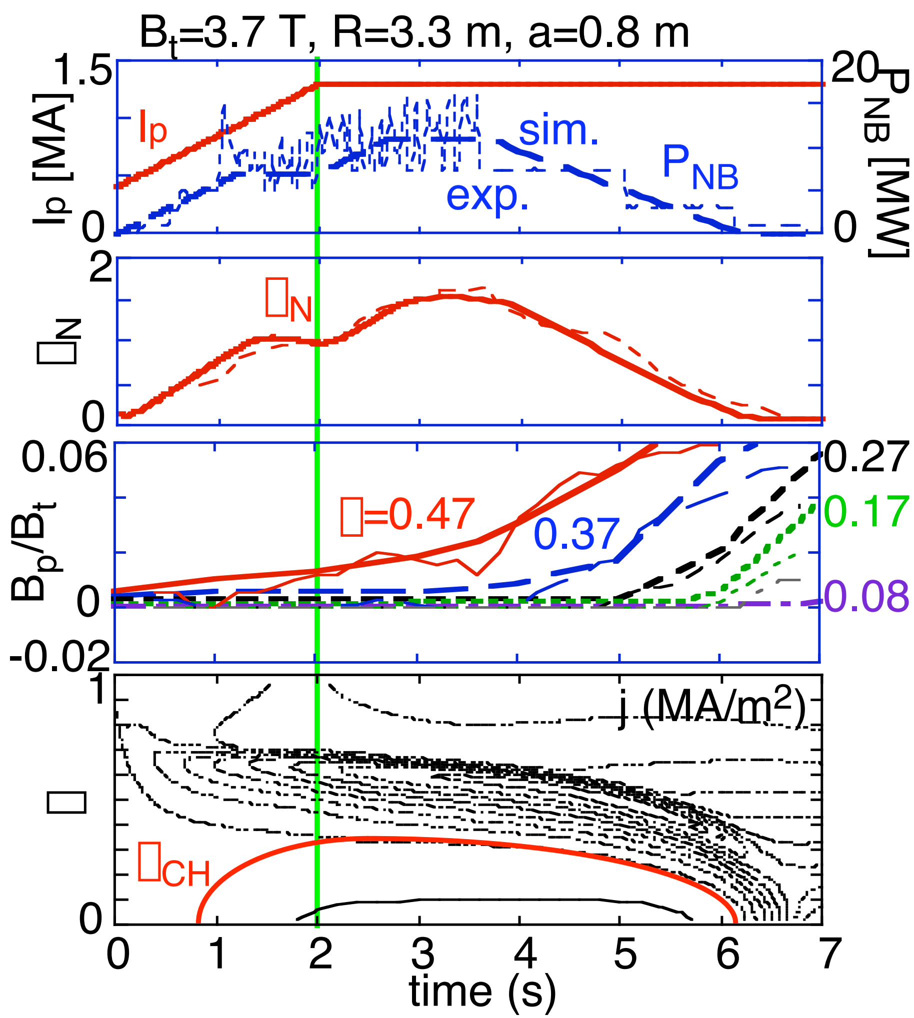
But, k~0 is found to be reliable from the comparison with JT-60U experiments.

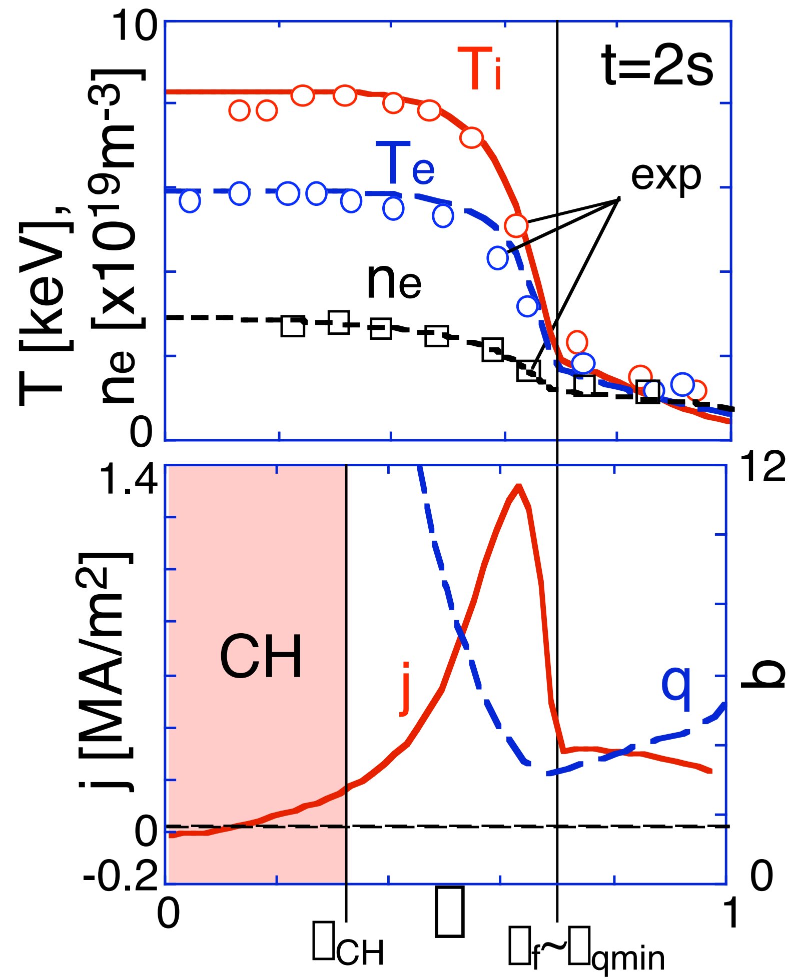
Comparison with JT-60U Experiment

Sharp reduction of anomalous transport in the RS region can reproduce the JT-60U experiment.

Transport becomes neoclassical-level in the RS region, which results in the autonomous formation of profiles with ITB and current hole.

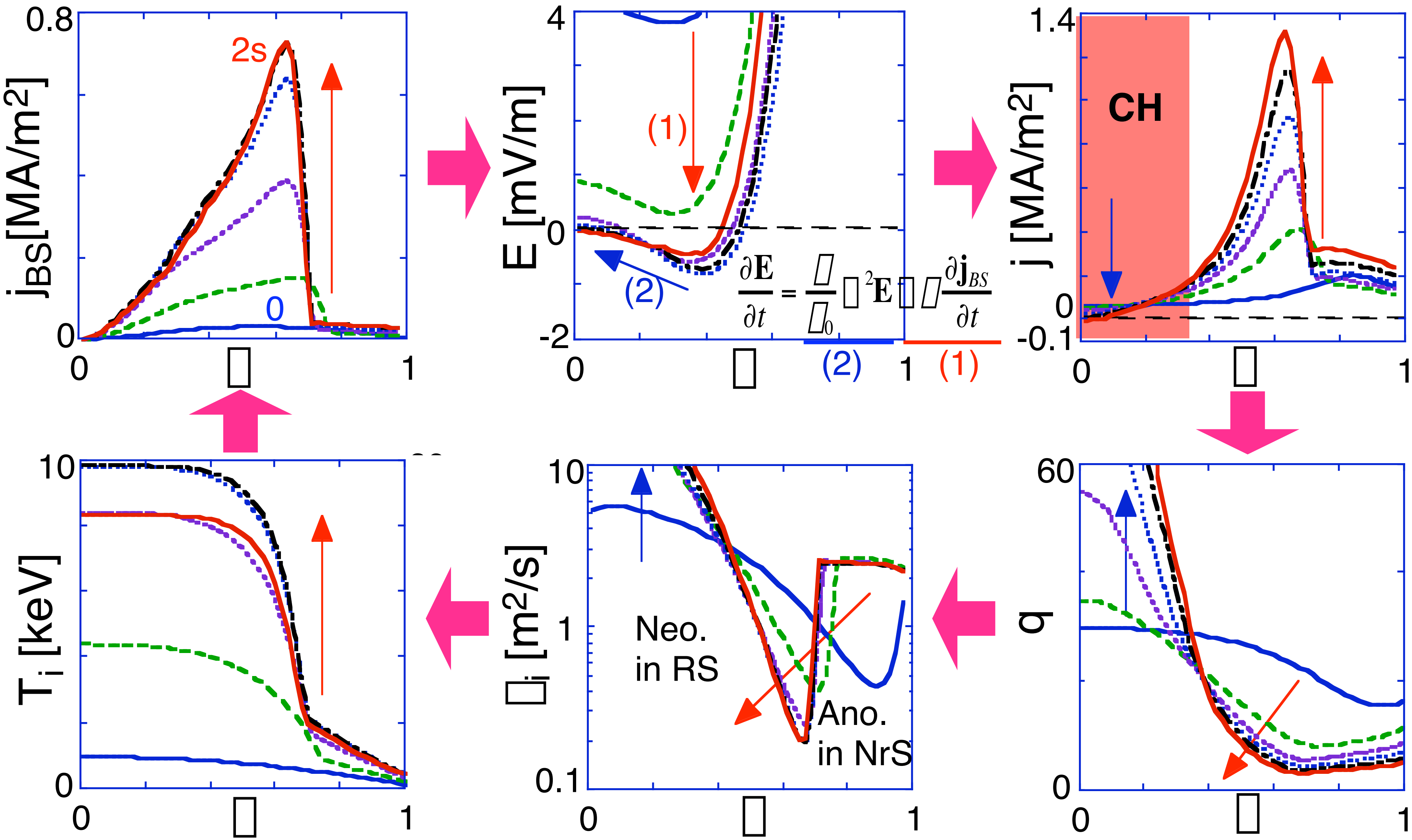
Parameters set to simulate the experiment : $k = 0,\ \chi_0 = 2.6\ \mathrm{m^2/s},\ C_D = 1$





Autonomous formation of CH plasma

Pressure profile and current profile strongly interact with each other through large bootstrap current and current hole is formed.



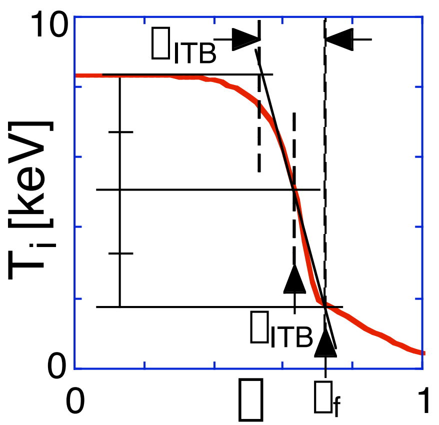
Comparison with JT-60U Scalings for

ITB Structure

Energy Confinement inside ITB

23 simulation runs for JT-60U parameters

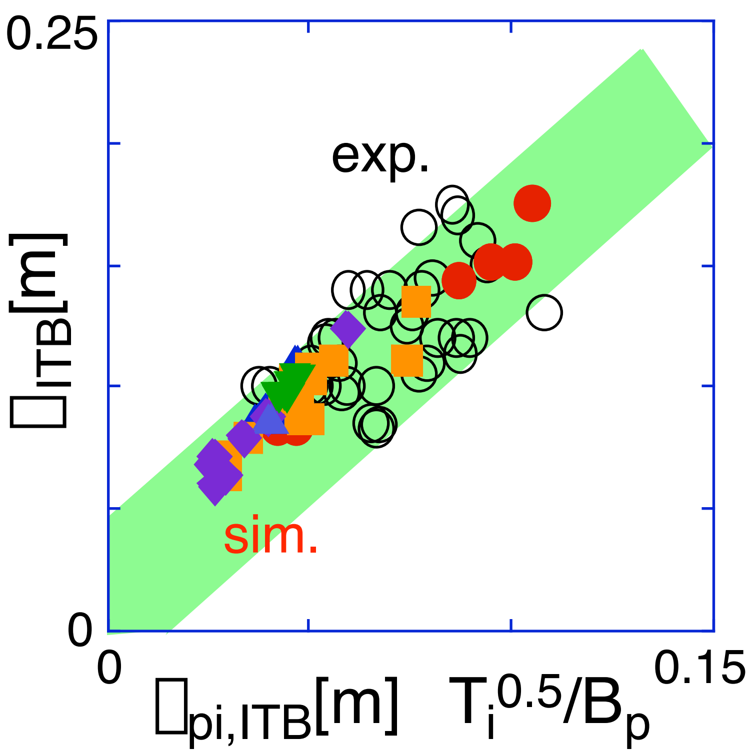
ITB widths determined by the neoclassical-level transport agree with those measured in JT-60U.

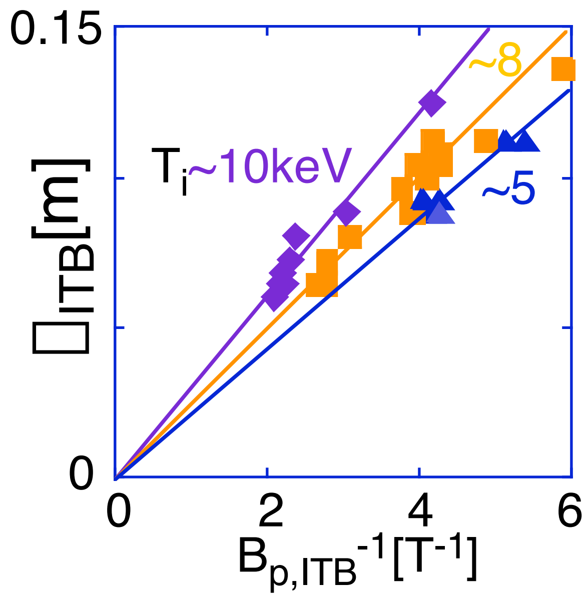


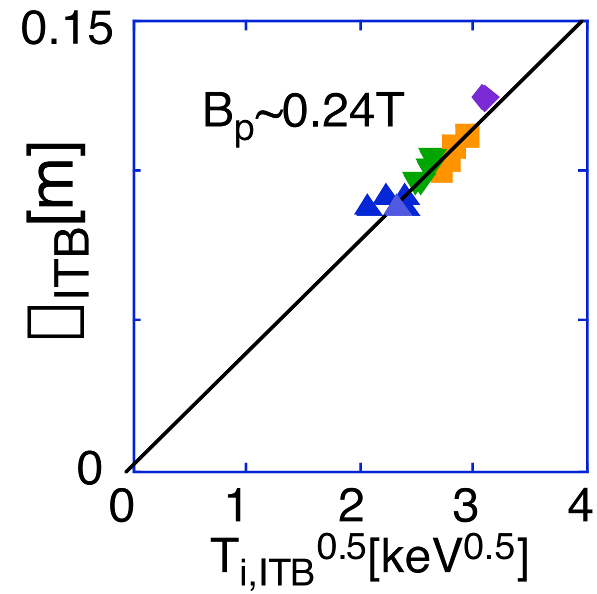
Strong ITB width was found to be proportional to the ion poloidal gyroradius at the ITB centre in JT-60U.

(Y. Sakamoto, NF 2001.)

ITB width in the simulation is clearly proportional to the ion poloidal gyroradius : $□_{ITB}$~1.5 $□_{p,ITB}$







Autonomous Limitation of Energy Confinement in CH plasmas

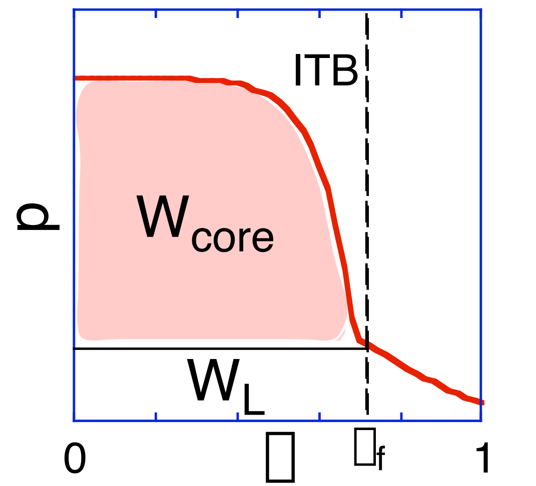
Energy confinement inside the ITB agrees with the JT-60U scaling.

$$W_{scale} = C_0 \varepsilon_f^{-1} B_{p,f}^2 V_{core}$$ (T.Takizuka, PPCF 2002.)

ε_f : inverse aspect ratio at ITB foot

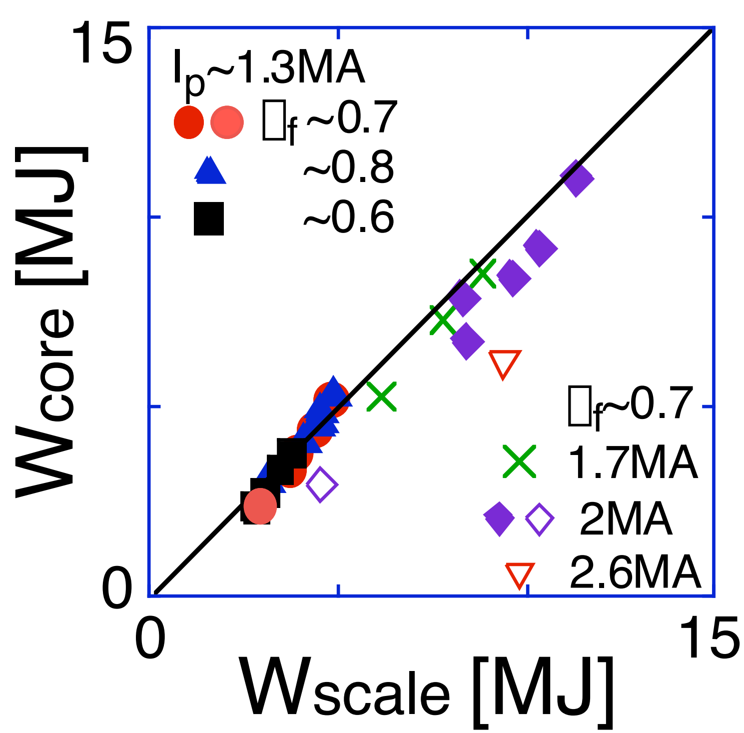
$B_{p,f}$: poloidal magnetic field at outer midplane ITB foot

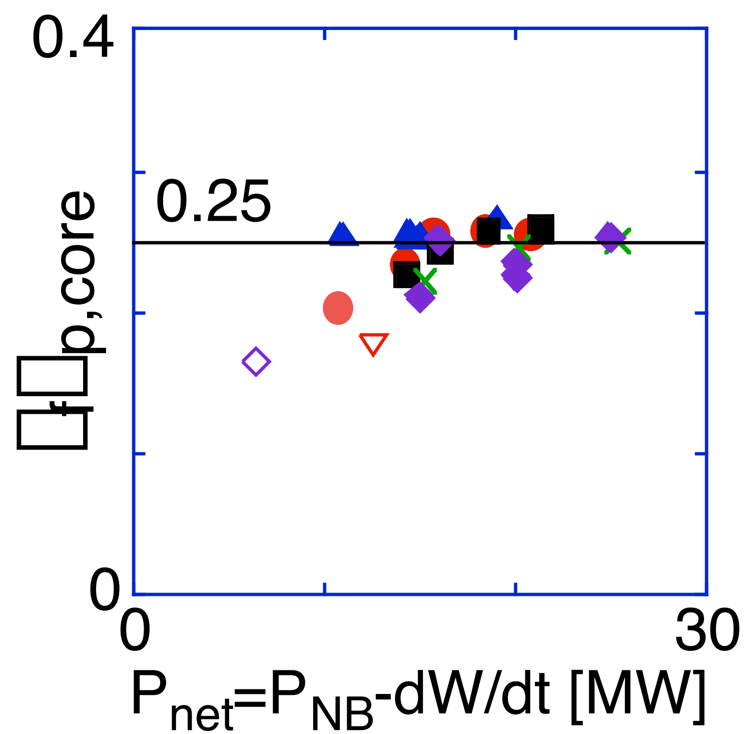
V_{core} : core volume inside ITB foot



The above scaling is equivalently written in the following form.

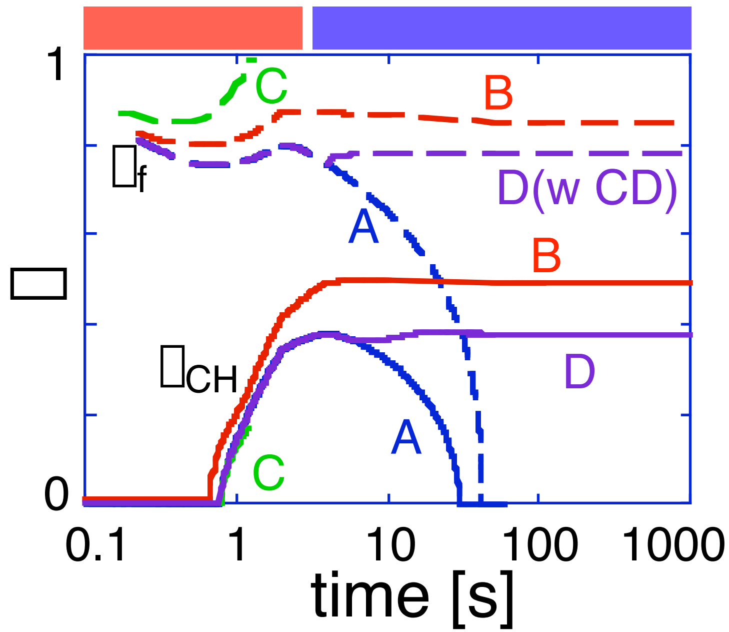
$$\varepsilon_f \beta_{p,core} = C_1 (\simeq 0.25)$$ $\beta_{p,core}$: core poloidal beta inside ITB





Sustainment and Control of Autonomous Current-Hole Plasma by External Current Drive

Sustainment of CH plasmas by external CD



During the CH formation phase (t < 2 s),
CH radius (ρ_{CH}) and ITB foot radius (ρ_f) can be expanded by increasing the heating power.

After the formation phase,

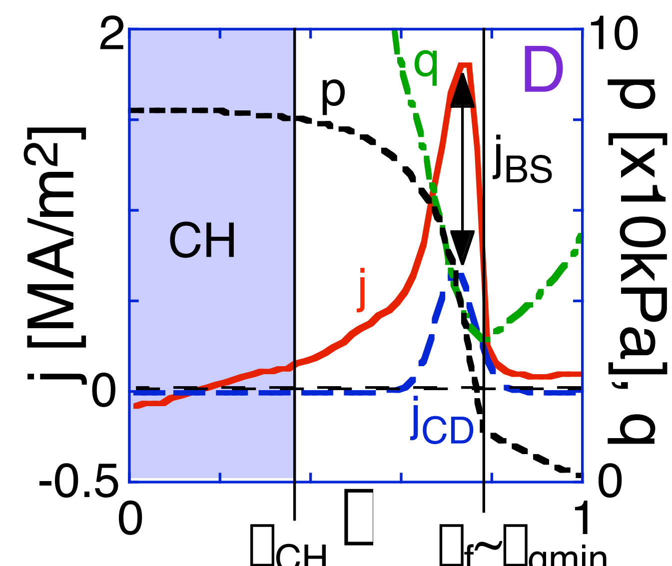
Plasmas with small ρ_{CH} and f_{BS}<1 shrinks due to the penetration of inductive current (case A, P_{NB}=12 MW).

Plasmas with large ρ_{CH} is sustained with f_{BS}~1 (case B, P_{NB}=18 MW).

Condition of $\rho_f \sim \rho_{qmin}$ is important for the sustainment.

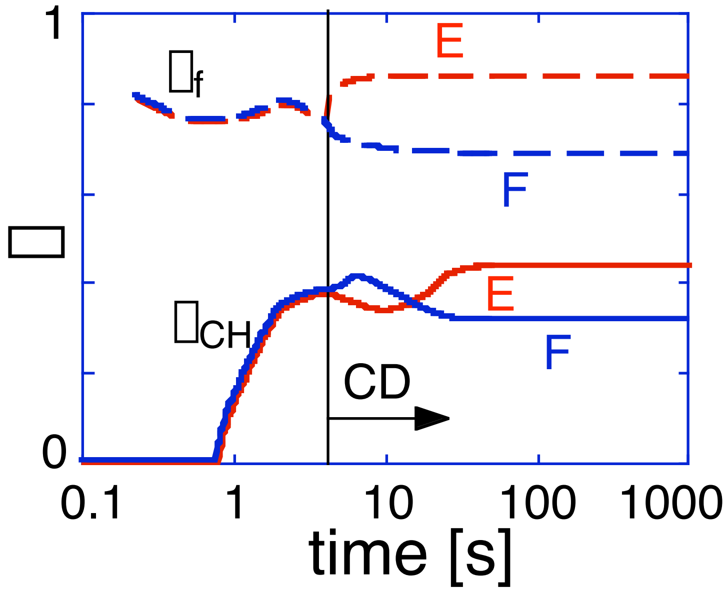
If $\rho_f > \rho_{qmin}$ (k~1), the ITB radius expands continuously (case C). This contradicts experiments.

External CD (ex. EC) can prevent shrinkage of case A by adding at the current peak with $f_{BS}+f_{CD}$~1 (case D).



Controllability of CH plasmas by external CD

CH radius and ITB position can be controlled by an appropriate CD.

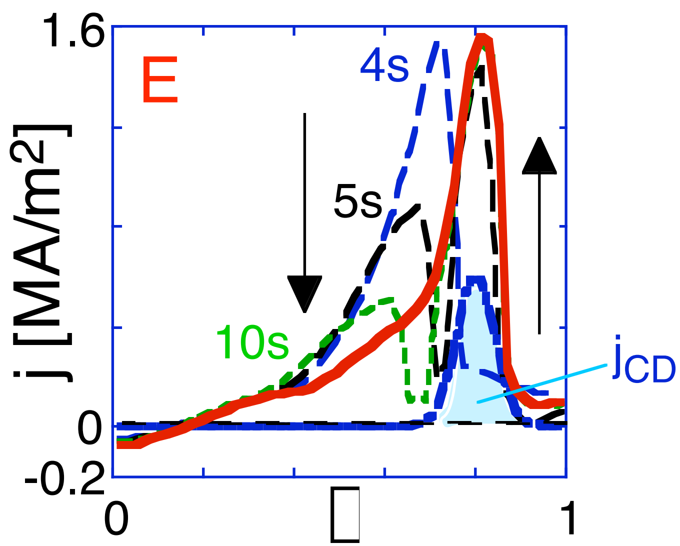


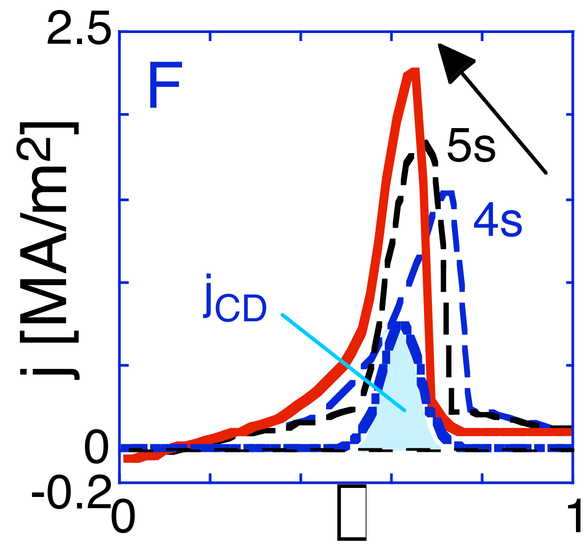
f_{CD}~1 - f_{BS} at CD start

CH radius and ITB foot radius can be expanded by adding CD outside the current peak (case E).

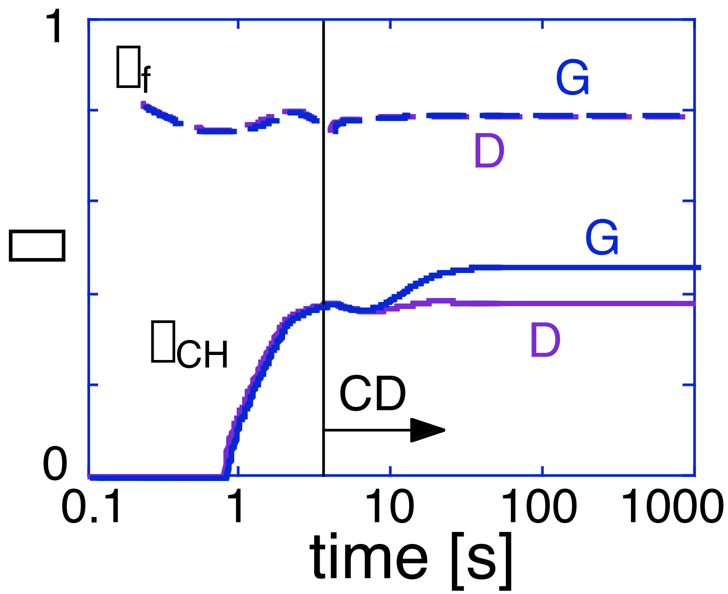
CH radius and ITB foot radius can be reduced by adding CD inside the current peak (case F).

Outer CD ➡ **Outward shift** **Inner CD** ➡ **Inward shift**





Autonomous response of CH plasmas to external CD

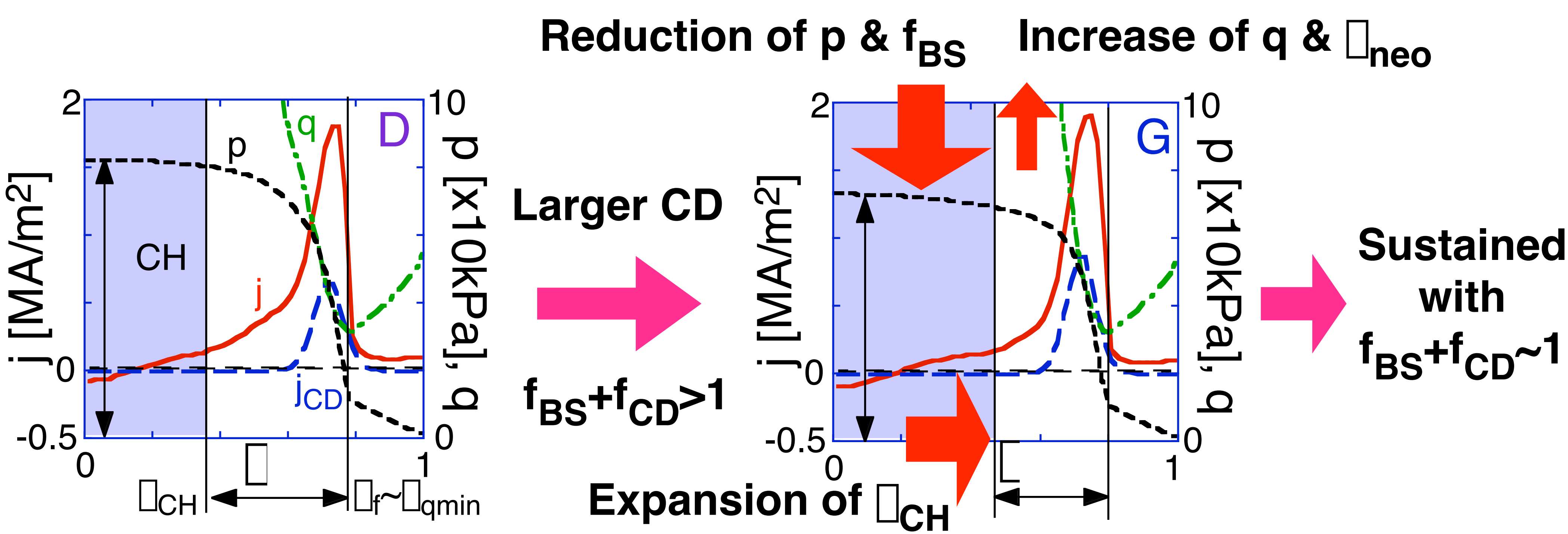


Shrinkage is prevented by adding CD with f_{CD}~1 - f_{BS} (case D).

Larger amount of driven current with f_{CD}>1-f_{BS} expands the CH radius (case G).

Increase of q enhances the neoclassical transport.

Energy confinement and bootstrap current fraction are reduced and $f_{BS}+f_{CD}$~1 is recovered.



Conclusions

- Sharp reduction of anomalous transport in RS region can reproduce the JT-60U experiment.
  - Transport becomes neoclassical-level in RS region, which results in the autonomous formation of ITB and current hole through large bootstrap current.
- ITB widths determined by the neoclassical-level transport agree with those measured in JT-60U : $\Delta_{ITB} \sim 1.5\ \rho_{pi,ITB}$.
- Energy confinement inside the ITB agrees with JT-60U scaling : $\varepsilon_f \beta_{p,core} \sim 0.25$.
- Plasmas with large current hole are sustained with full current drive by bootstrap current.
- Plasmas with small current hole and small bootstrap current fraction shrink due to the penetration of inductive current.
  - This shrink is prevented and CH size can be controlled by the appropriate external CD.
- CH plasmas are found to respond autonomically to the external CD.