20th IAEA Fusion Energy Conference,
Nov. 1-6, 2004, Vilamoura, Portugal

Stabilization of Neoclassical Tearing Mode by Electron Cyclotron Current Drive and Its Evolution Simulation on JT-60U Tokamak

K. Nagasaki 1), A. Isayama 2), N. Hayashi 2),
T. Ozeki 2), M. Takechi 2), N. Oyama 2), S. Ide 2),
S. Yamamoto 1) and JT-60 Team

1) Institute of Advanced Energy, Kyoto University
2) Japan Atomic Energy Research Institute

Introduction

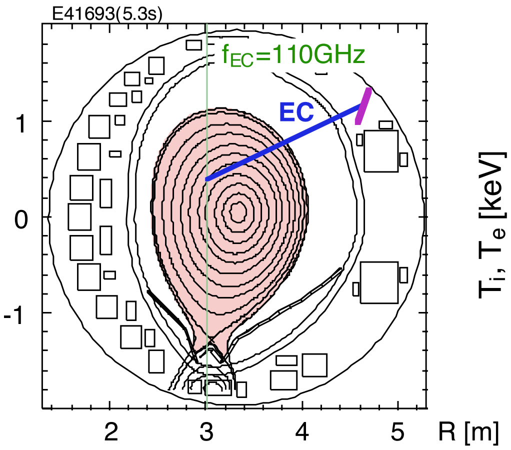
- Electron cyclotron current drive (ECCD) is considered to be one of attractive methods to stabilize the neoclassical tearing mode (NTM), which compensates the missing bootstrap current in the magnetic island.
- The necessary EC power for complete stabilization is estimated as high as 30MW in ITER. The reduction of EC power and the determination of EC conditions will help more reliable operation of high β plasmas without NTM.
- The nonlinear NTM physics is still yet understood well. It is necessary to understand the NTM physics such as the excitation and the disappearance.

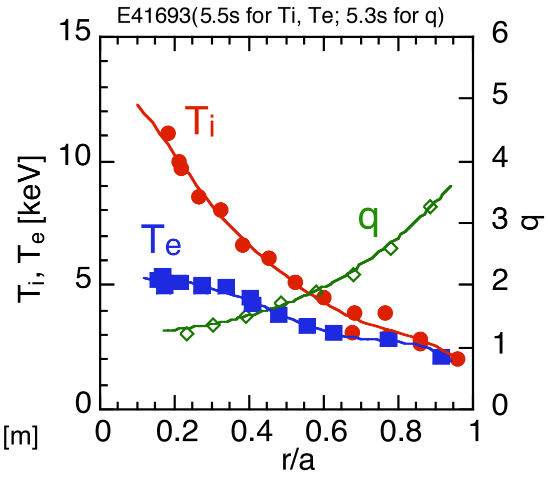
Contents

1. Introduction
2. NTM stabilization experiment by ECCD in JT-60U
    - Dependence of 3/2 NTM on EC injection timing
    - Stabilization at high β_N plasma using 2nd harmonic ECCD
3. Simulation of 3/2 NTM stabilization
    - Modified Rutherford equation (MRE) coupled with 1.5D transport code and EC code.
    - Determination of coefficients in MRE
    - Comparison with early and late ECCD experiment
4. Conclusion

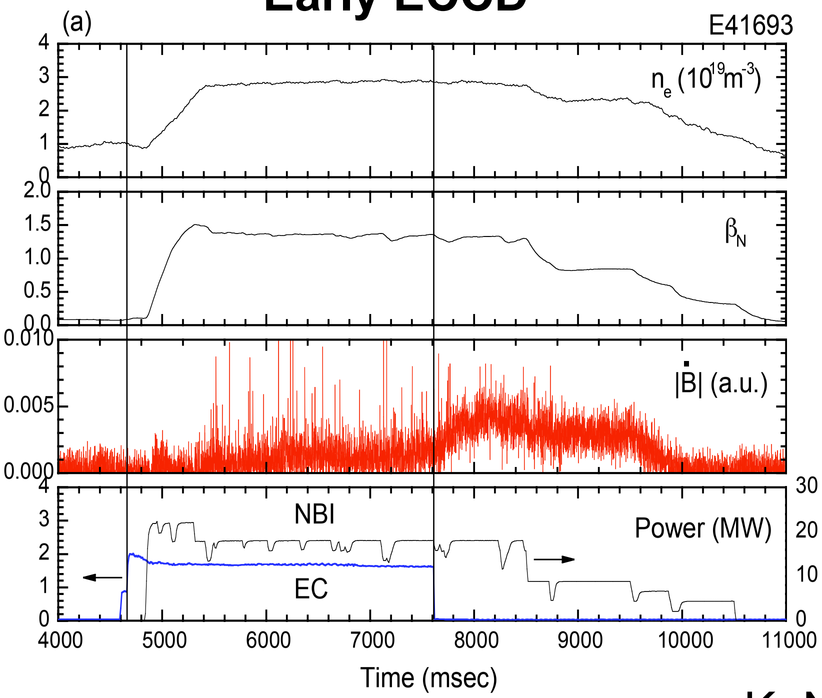
Early ECCD is more effective to suppress 3/2 NTM.

- High β_p ELMy H-mode plasma
- I_p=1.5MA, B_t=3.66T, q_{95}=3.8, P_{NB}=20MW
- Only the m/n=3/2 mode is excited.
- P_{EC}=0-2.7MW
- I_{EC}: 25kA/MW, 0.17MA/m^2 at q=3/2
- Rotation frequency: 10-12kHz

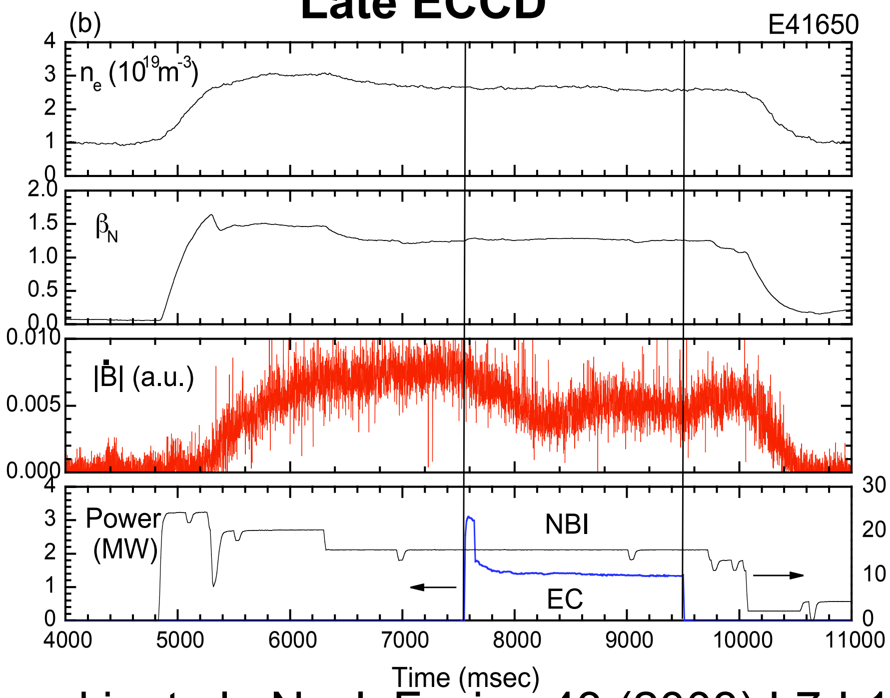




Early ECCD



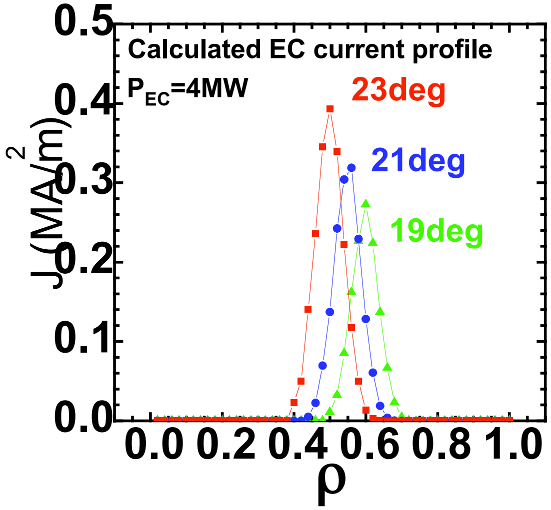
Late ECCD



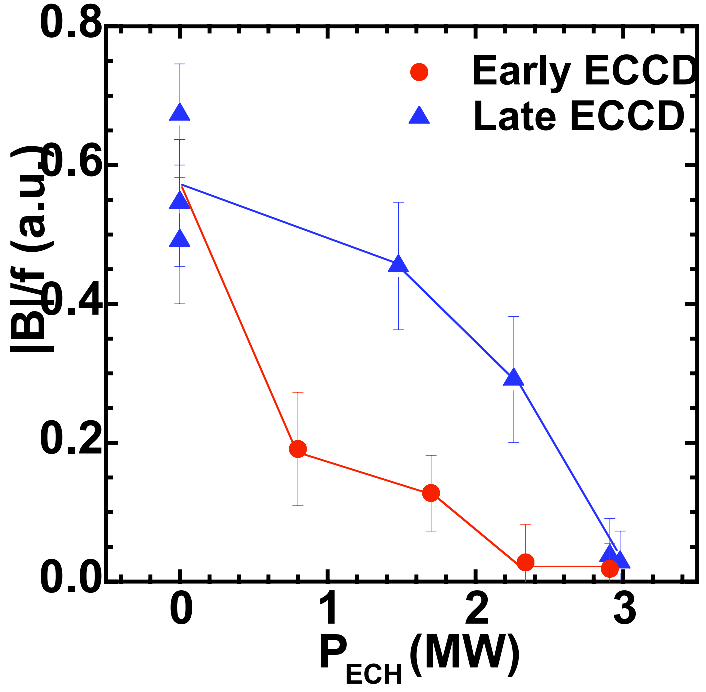
K. Nagasaki, et al., Nucl. Fusion 43 (2003) L7-L10

The EC power for 3/2 NTM suppression is lower in early ECCD.

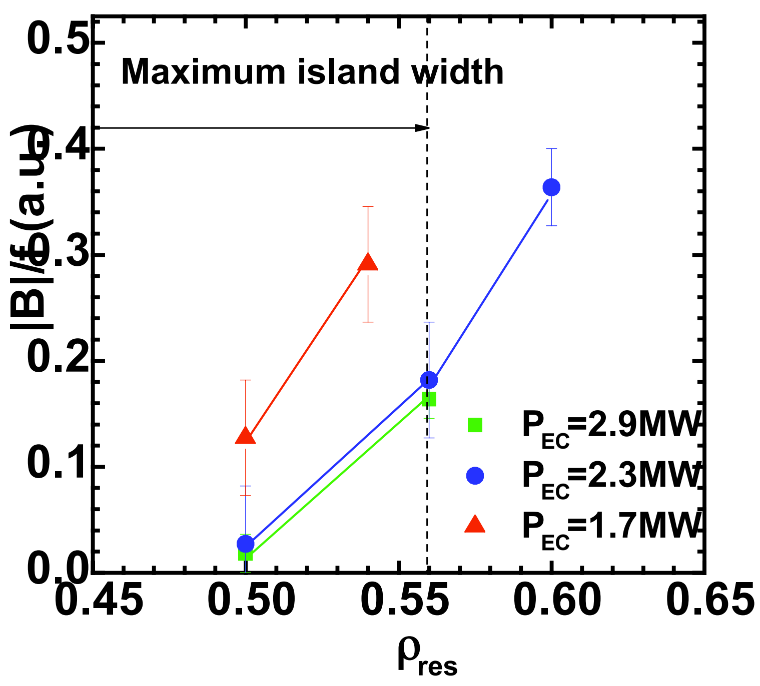
- The EC power for the complete suppression of the m/n=3/2 mode is lower than in the late ECCD.
- The stabilization effect becomes weak when the current location is deviated by about half of the maximum magnetic island width.



Dependence on EC power

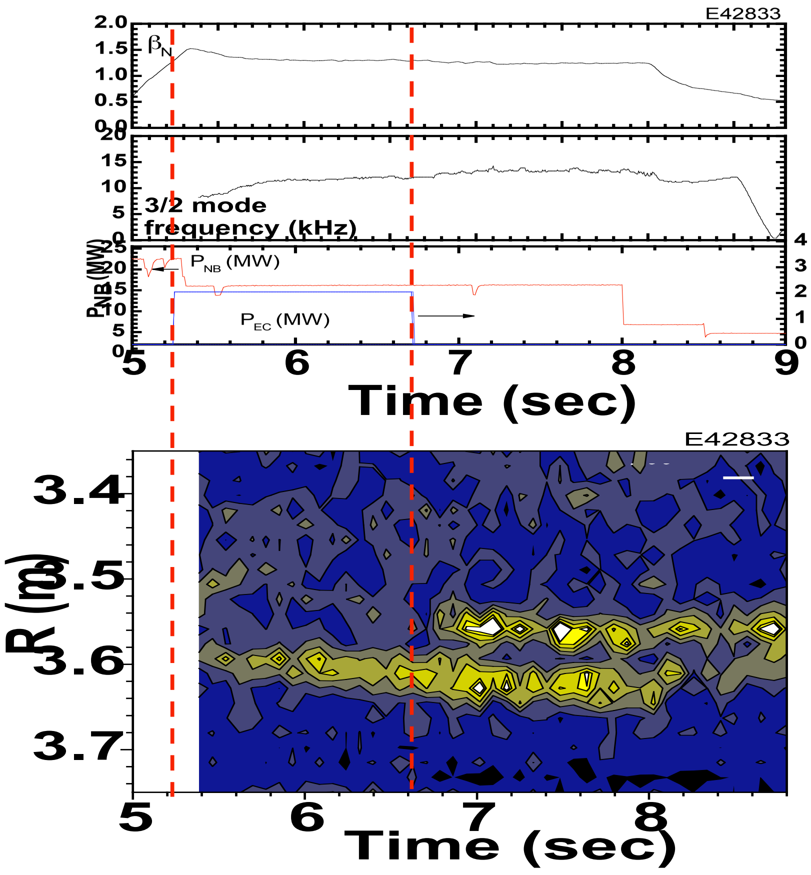


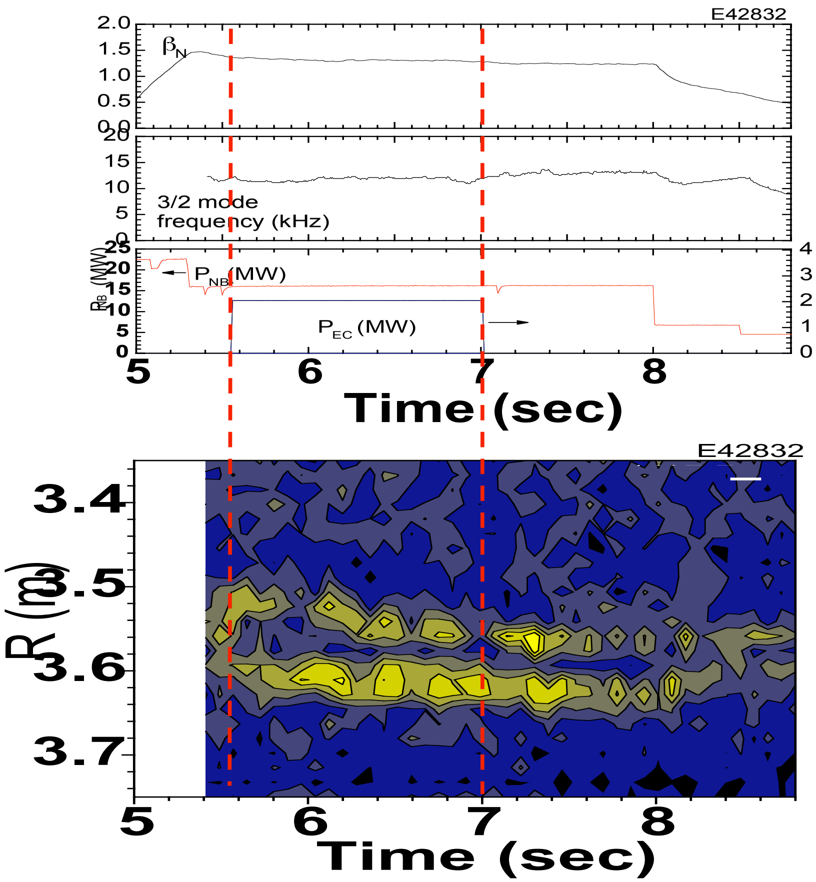
Dependence on EC position



Dependence on injection timing

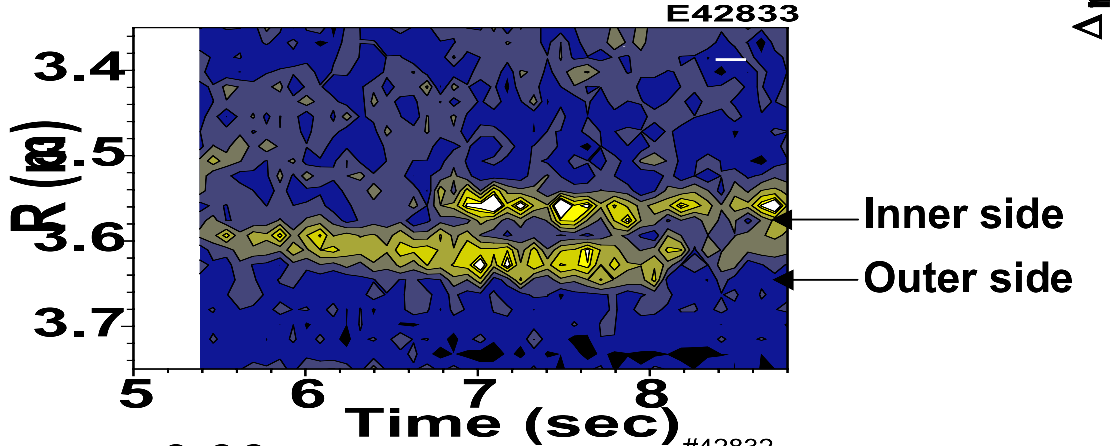
- The T_e perturbation measured with ECE is more suppressed as the EC power is injected earlier.
- The T_e perturbation decreases asymmetrically in the radial direction. The magnetic island looks to decay from the smaller radius position.

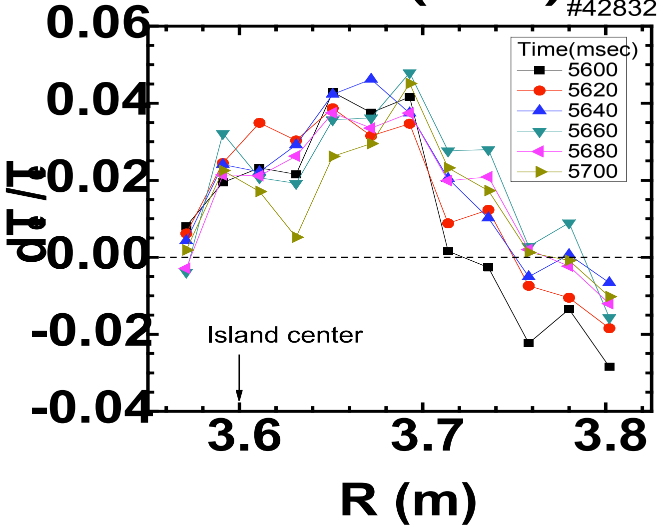


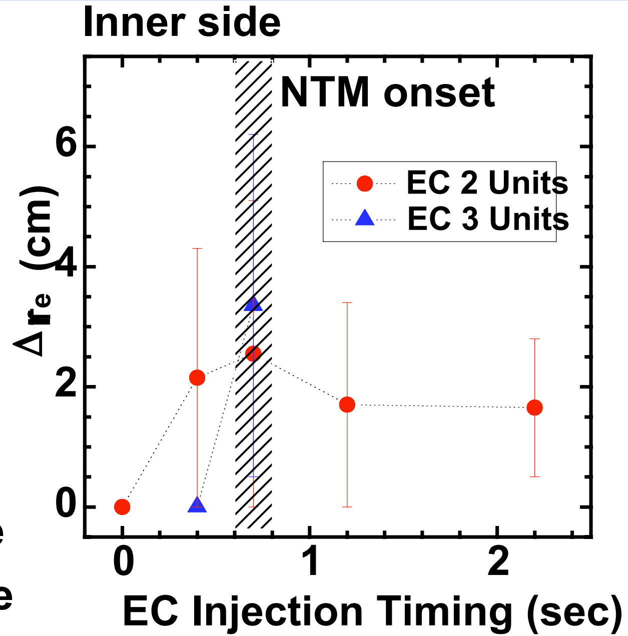


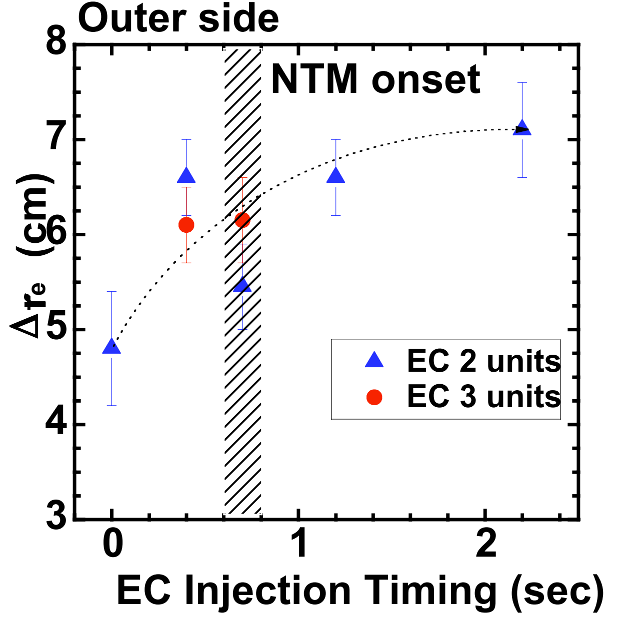
Dependence on injection timing

- **When the ECCD is applied before the onset of NTM, the T_e perturbation is more suppressed.**
- **The critical EC timing for effective ECCD is associated with the NTM onset phase.**



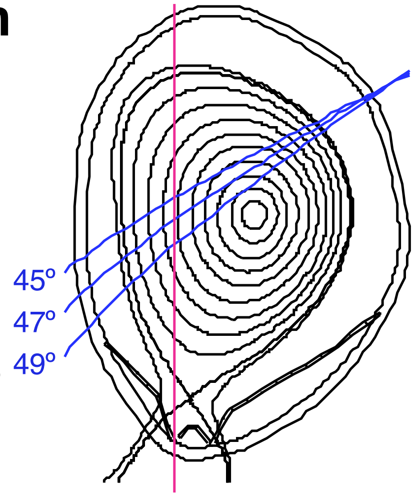




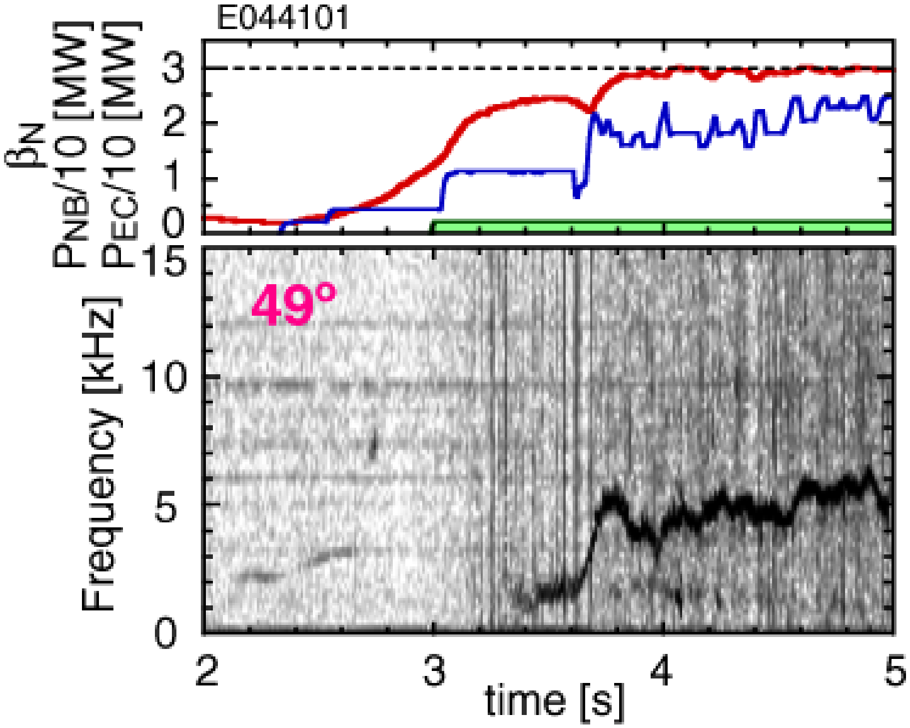


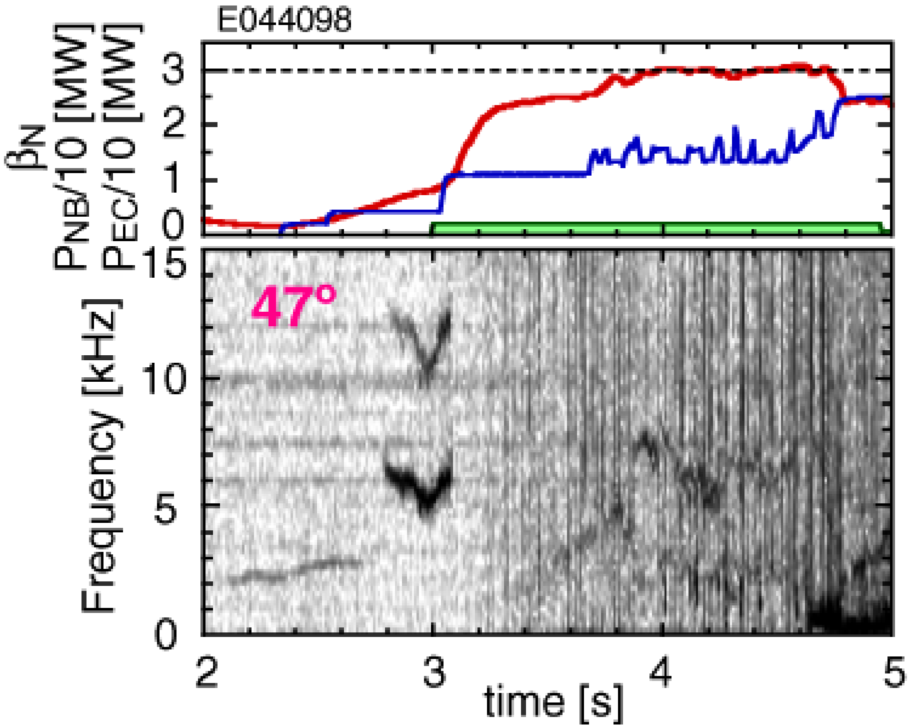
2nd harmonic ECCD at high β_N ELMy H-mode plasma

- **The early ECCD is also effective in a high performance plasma of β_p~1.7, H_{89PL}~1.8, β_N~3.0 and $H_{89PL}\beta_N \geq 5$.**
- **The NB power for keeping β_N is lower when the 3/2 NTM is suppressed.**
- **The stabilization effect is sensitive to the EC current position as well as the fundamental early ECCD.**

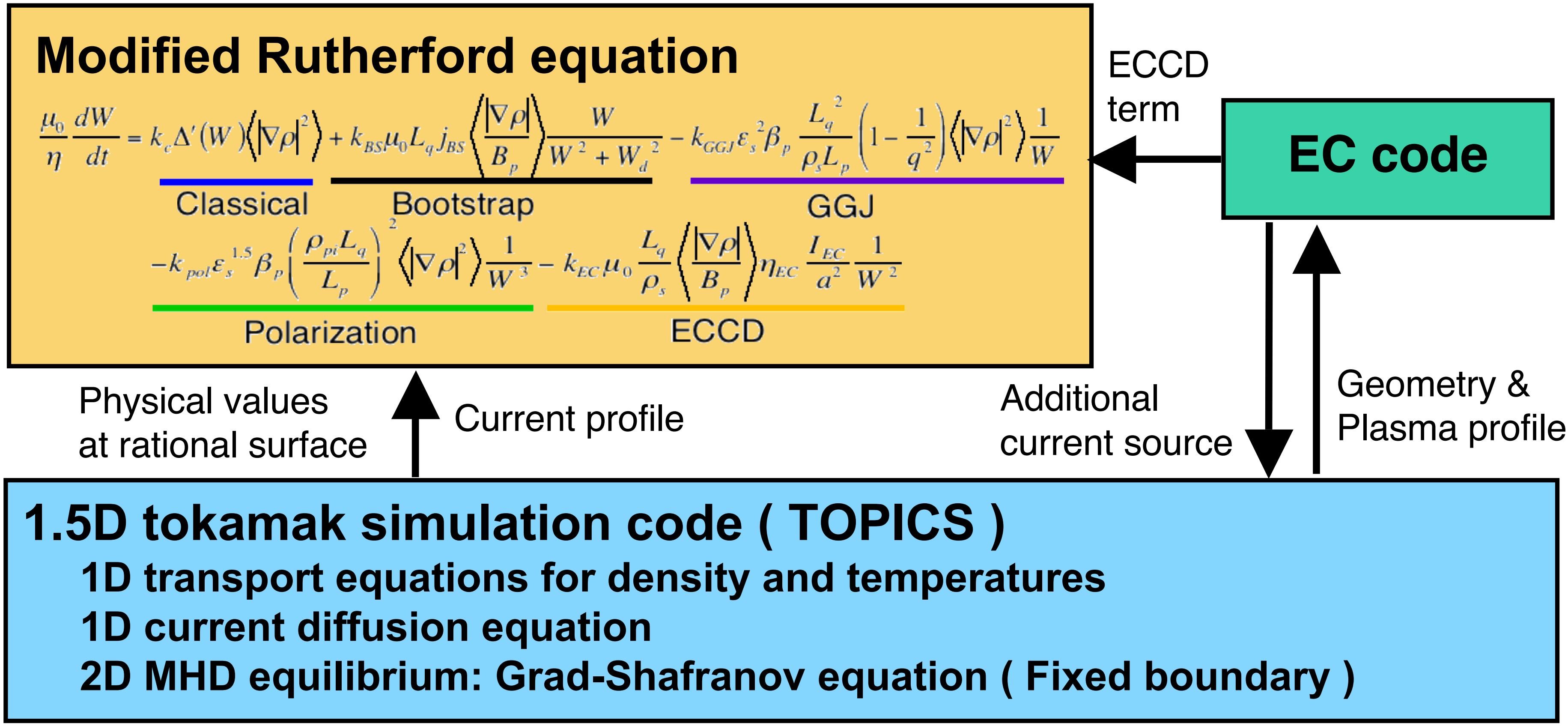


I_p = 0.85 MA,
B_t =1.7 T, q_{95} =3.5
P_{EC}=2MW
J_{EC}=0.3-0.4MW/m^2
ρ_{EC}=0.42-0.50





Numerical model



Modified Rutherford equation

$$\frac{\mu_0}{\eta}\frac{dW}{dt} = \underbrace{k_c \Delta'(W)\left\langle |\nabla\rho|^2 \right\rangle}_{\text{Classical}} + \underbrace{k_{BS}\mu_0 L_q j_{BS}\left\langle \frac{|\nabla\rho|}{B_p} \right\rangle \frac{W}{W^2 + W_d^2}}_{\text{Bootstrap}} - \underbrace{k_{GGJ}\varepsilon_s^2 \beta_p \frac{L_q^2}{\rho_s L_p}\left(1 - \frac{1}{q^2}\right)\left\langle |\nabla\rho|^2 \right\rangle \frac{1}{W}}_{\text{GGJ}}$$

$$\underbrace{-k_{pol}\varepsilon_s^{1.5}\beta_p \left(\frac{\rho_{pi} L_q}{L_p}\right)^2 \left\langle |\nabla\rho|^2 \right\rangle \frac{1}{W^3}}_{\text{Polarization}} - \underbrace{k_{EC}\mu_0 \frac{L_q}{\rho_s}\left\langle \frac{|\nabla\rho|}{B_p} \right\rangle \eta_{EC} \frac{I_{EC}}{a^2}\frac{1}{W^2}}_{\text{ECCD}}$$

ECCD term

EC code

Physical values at rational surface

Current profile

Additional current source

Geometry & Plasma profiles

1.5D tokamak simulation code (TOPICS)

- **1D transport equations for density and temperatures**
- **1D current diffusion equation**
- **2D MHD equilibrium: Grad-Shafranov equation (Fixed boundary)**

Parameters of k_{BS}, k_{GGJ}, k_{pol}, k_{EC} are constant.

Value of W_d depends on theoretical models to limit the parallel heat transport).

(k_{BS}, k_{GGJ}, k_{pol}, k_{EC}, W_d) should be estimated by fitting to experiments.

N. Hayashi, et al., Nucl. Fusion 44 (2004) 477

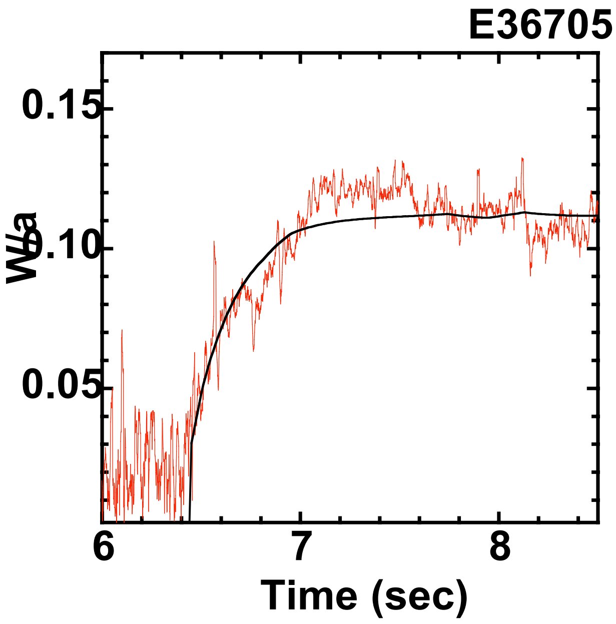
Parameter fitting at NTM growing and stabilizing phases

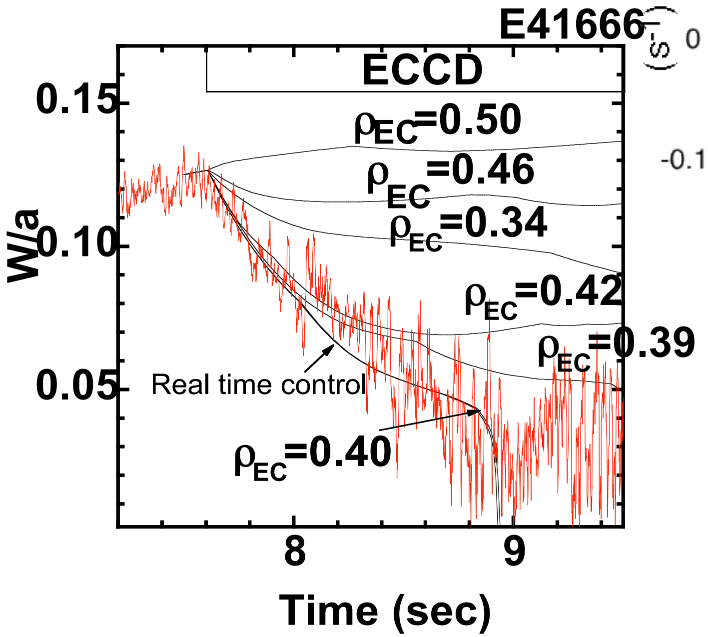
Growth phase

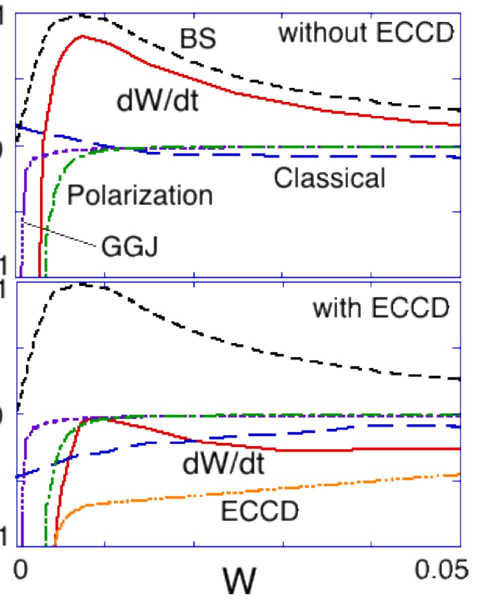
$k_c = 1.2$, $k_{BS} \sim 5$,
$k_{GGJ} < 10$ (not important),
$k_{pol} < 3$,
$W_d = 0.008$
(~ flux-limit model)

Stabilization phase

$k_c = 1.2$, $k_{BS} = 4.5$,
$k_{GGJ} = 1$, $k_{pol} = 1$,
$W_d = 0.02$
(~ flux-limit model)
$k_{EC} \sim 3\text{-}4$, $\Delta\rho_{EC} = 0.025$





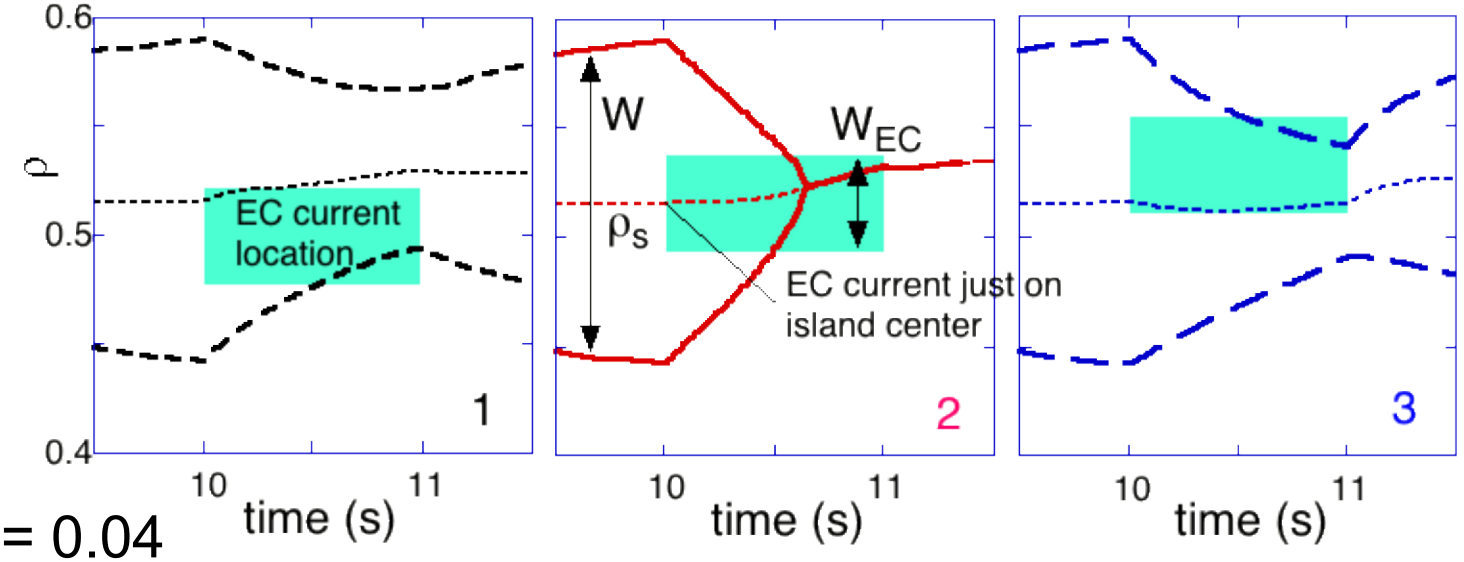


Estimated coefficients are consistent between the growing and stabilizing phases.

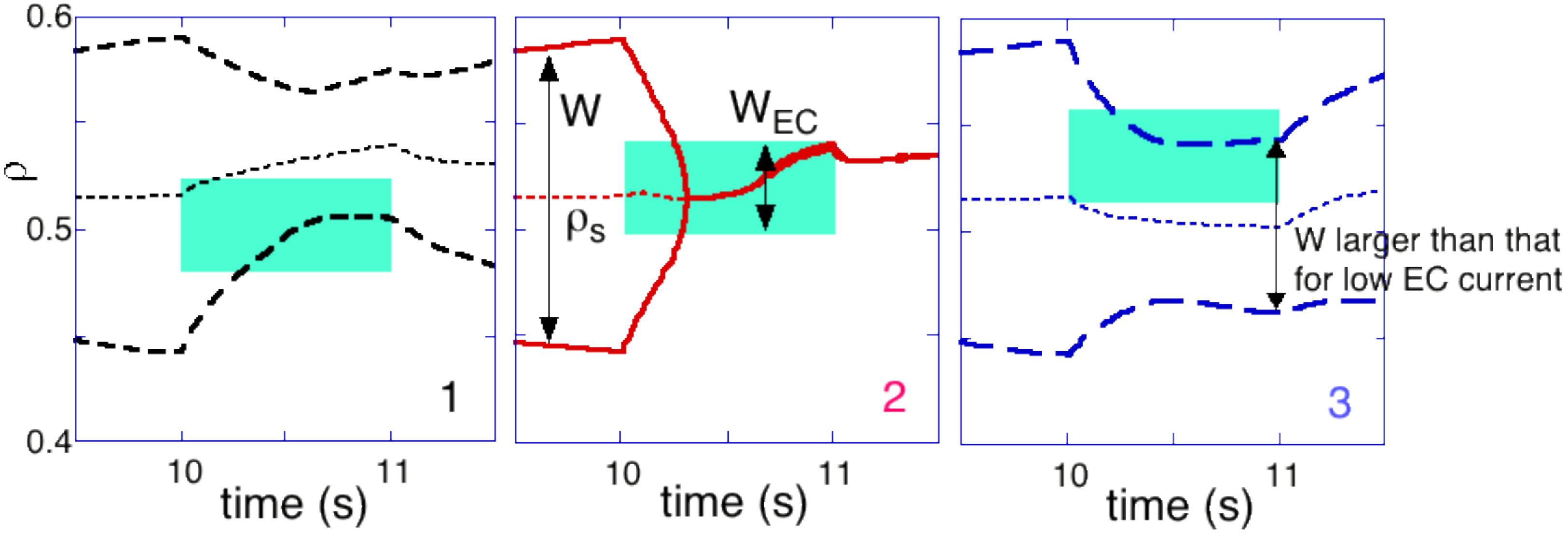
The rational surface is moved by EC current, resulting that the stabilizing effect is reduced.

- **Higher EC current induces larger movement of the 3/2 surface.**

$I_{EC} / I_p = 0.02$

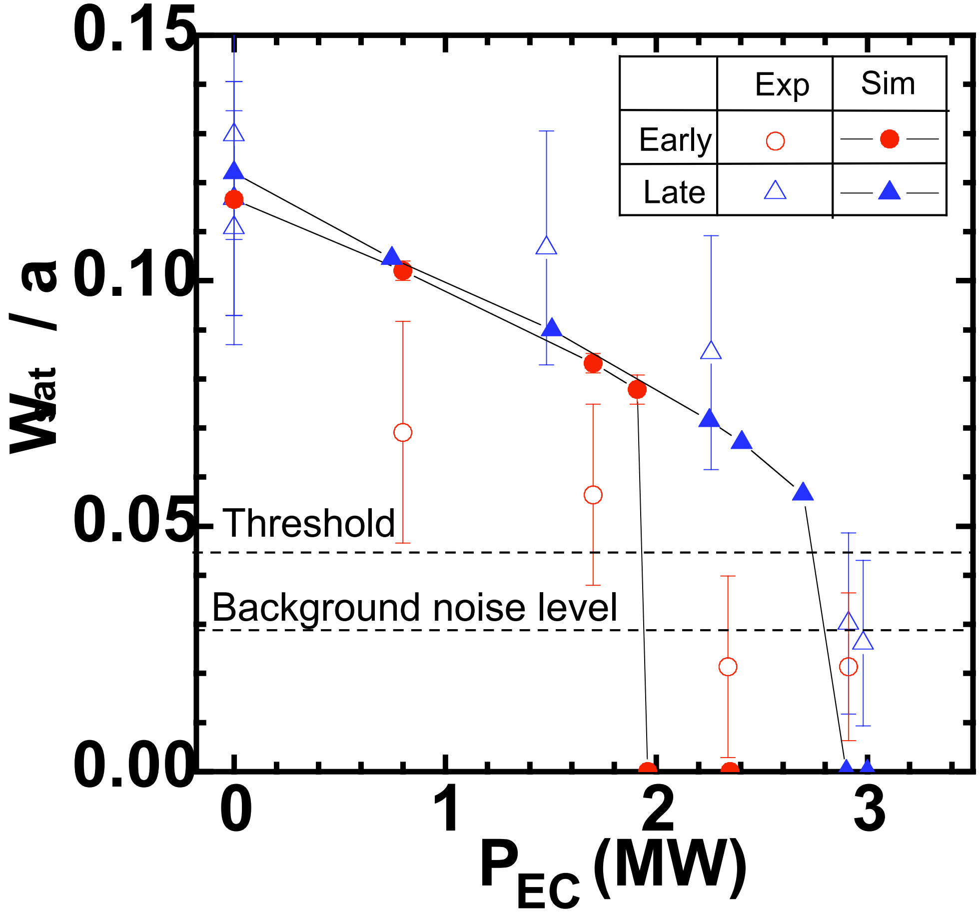


$I_{EC} / I_p = 0.04$



Comparison with Experiment

- **The power dependence in late ECCD agrees with the simulation.**
- **The EC power reduction for complete stabilization can be explained by the simulation. The NTM starts to grow with larger seed island width.**



- **The decrease of the bootstrap current term and/or the increase of classical tearing parameter term may contribute to the smaller island width in early ECCD.**

	Bootstrap current term (Destabilizing term)	Classical tearing term (Stabilizing term)
P_{EC}=0.8 MW (I_{EC}=20 kA)	-37%	+117%
P_{EC}=1.7 MW (I_{EC}=43 kA)	-23%	+71%

Conclusion

- The stabilization of m=3/n=2 NTM has been studied experimentally and theoretically in high β_p ELMy H-mode plasmas on the JT-60U tokamak.
- The early ECCD is more effective than the late ECCD, and the critical EC timing is associated with the mode onset phase.
- The 3/2 NTM has been suppressed in a high β_p ELMy H-mode plasma of β_N=3.0 by the second harmonic early ECCD. The dependence on the EC current position is similar to the fundamental ECCD stabilization.
- The simulation on the basis of the modified Rutherford equation with 1.5D transport code and EC code well reproduce the time evolution of the 3/2 NTM experimentally observed both at the growing and stabilizing phases.
- The mode evolution can be explained by the simulation in late ECCD case. The EC power reduction for complete stabilization in early ECCD agrees with the simulation result.