JA-KO Joint Workshop on RF Heating and Current Drive in Fusion Plasmas
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ECCD Experiments in Heliotron J

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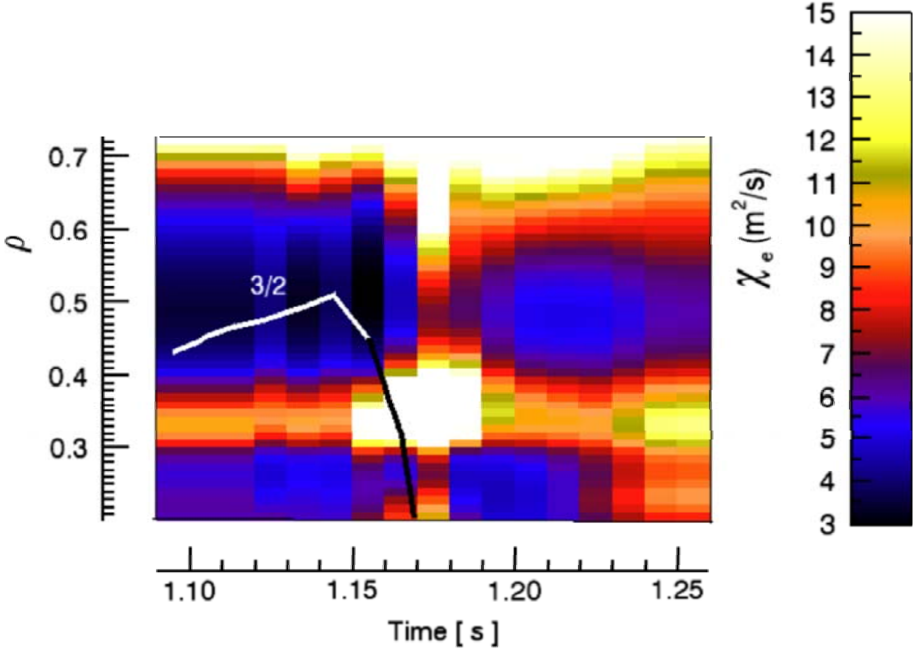
Motivation

- Study of non-inductive current is a key issue to control plasma confinement in tokamaks and helical systems
- In helical systems, no Ohmic current is required for plasma equilibrium
- However, the bootstrap current is inherently driven due to plasma pressure, affecting MHD equilibrium and stability due to the change in rotational transform
- Electron cyclotron current drive (ECCD) is recognized as a useful scheme for the suppression of MHD modes, high performance and/or full non-inductive operations
- ECCD is considered to suppress the bootstrap current in order to avoid the MHD instabilities or to make local strong magnetic shear

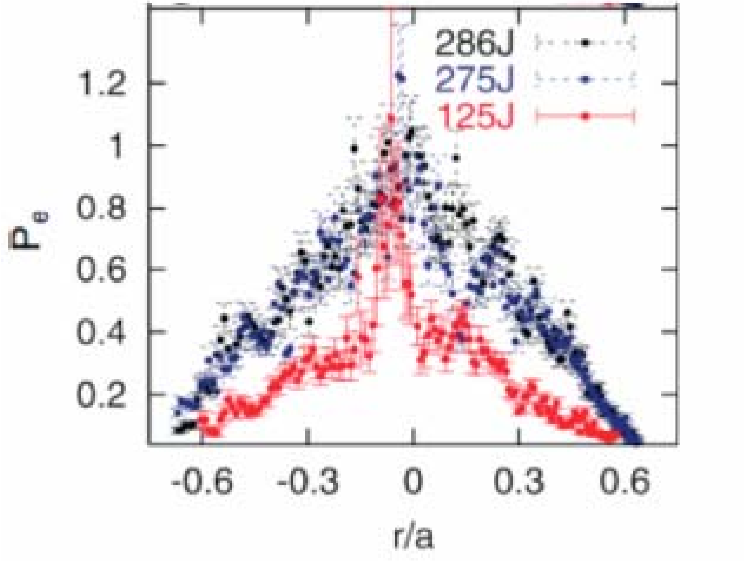
Degraded confinement due to low order resonances at low β, no shear: TJ-II

ECH discharge with induced OH current

- time evolution of effective *Xe* (obtained from power balance calculations). Te profiles from ECE diagnostic
- estimated time evolution of iota (assuming total current due to OH transformer): it is forced to flatten so that 3/2 occupies part of the plasma with no shear.



3/2 does not deteriorate transport until 1160-80 ms



Transient flattening of the pressure profile

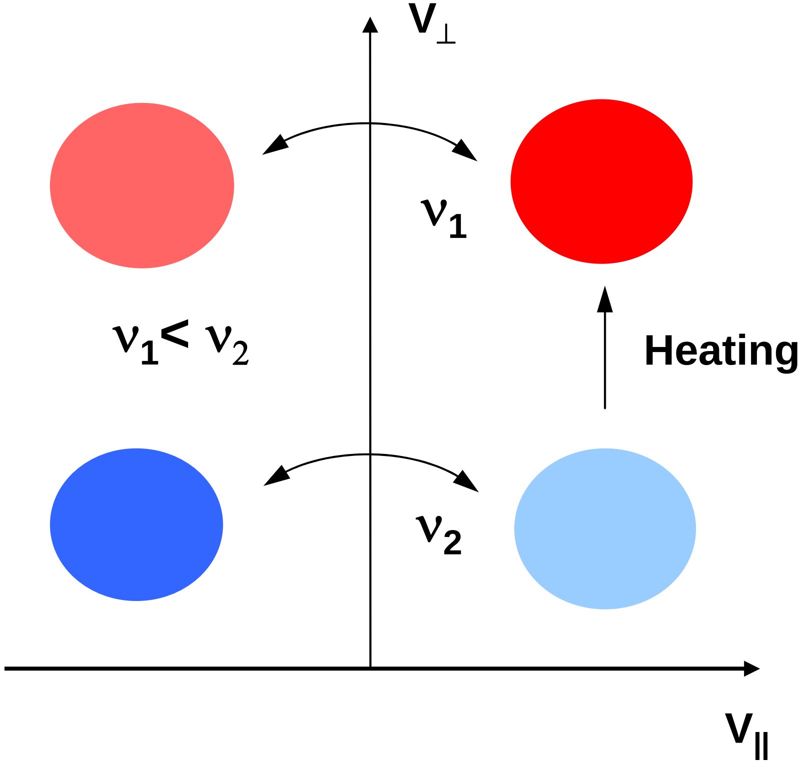
Purposes of ECCD in Helical Systems

1. Control of rotational transform
    - Avoidance of magnetic island at rational surfaces
    - Suppression of bootstrap current
2. Understanding of ECCD physics
    - Accurate measurement of 0.1 kA order
    - No synergetic effect of $E_{||}$
    - Effect of trapped electrons due to magnetic ripples
        - Ohkawa effect

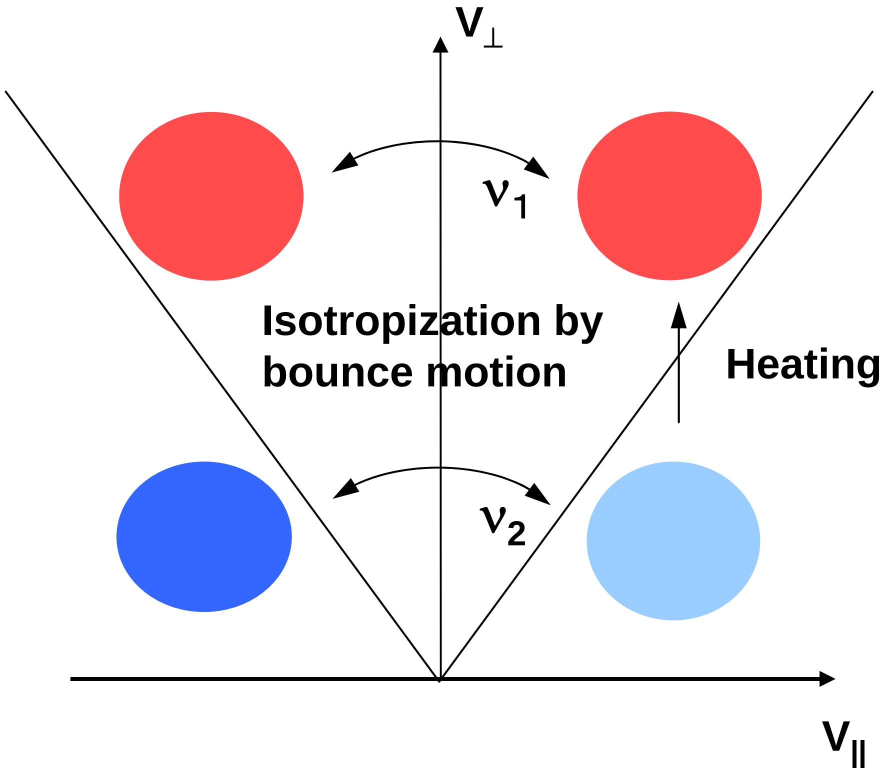
Physical Mechanism of ECCD

- Simply considering, electron cyclotron waves accelerate electrons only perpendicularly, resulting that they do not give toroidal momentum
- However, the anisotropy in velocity space due to the EC waves with finite $N_{||}$ produces electron parallel momentum

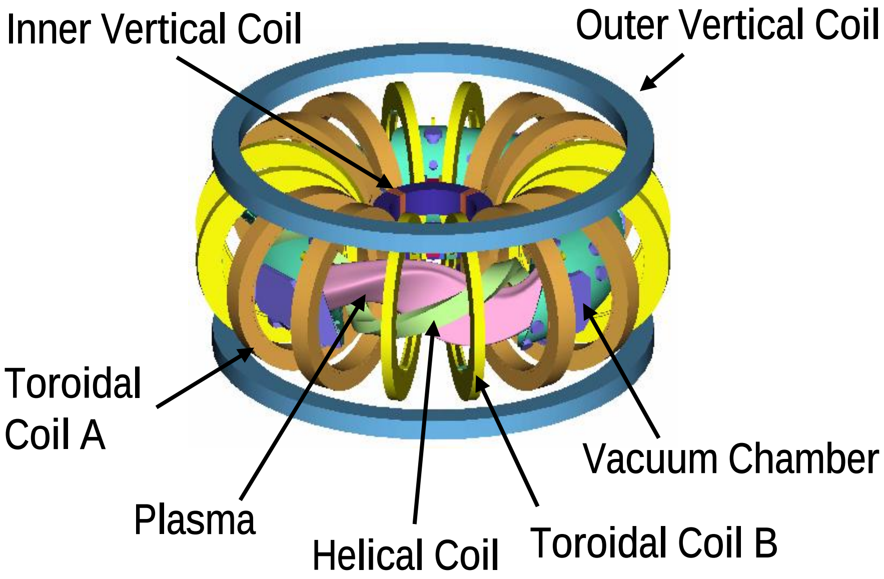
Fisch-Boozer Effect

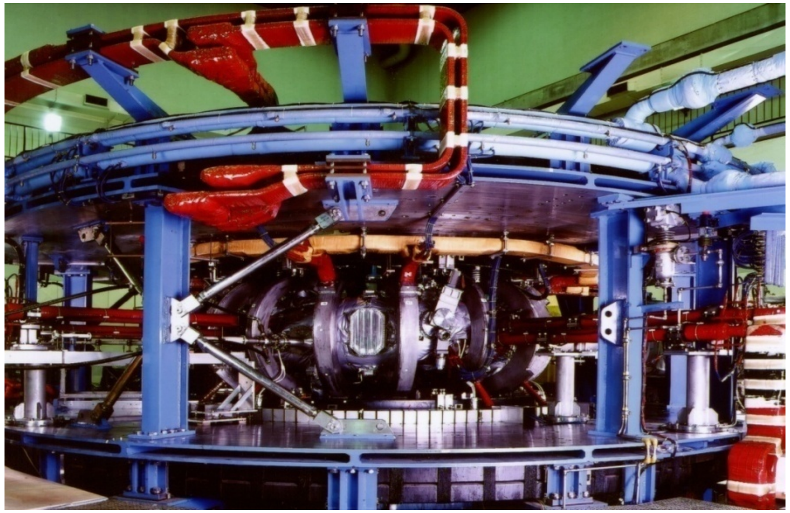


Ohkawa Effect



Heliotron J Device





Coil System

L=1/M=4 helical coil	0.96MAT
Toroidal coil A	0.6MAT
Toroidal coil B	0.218MAT
Main vertical coil	0.84MAT
Inner vertical coil	0.48MAT

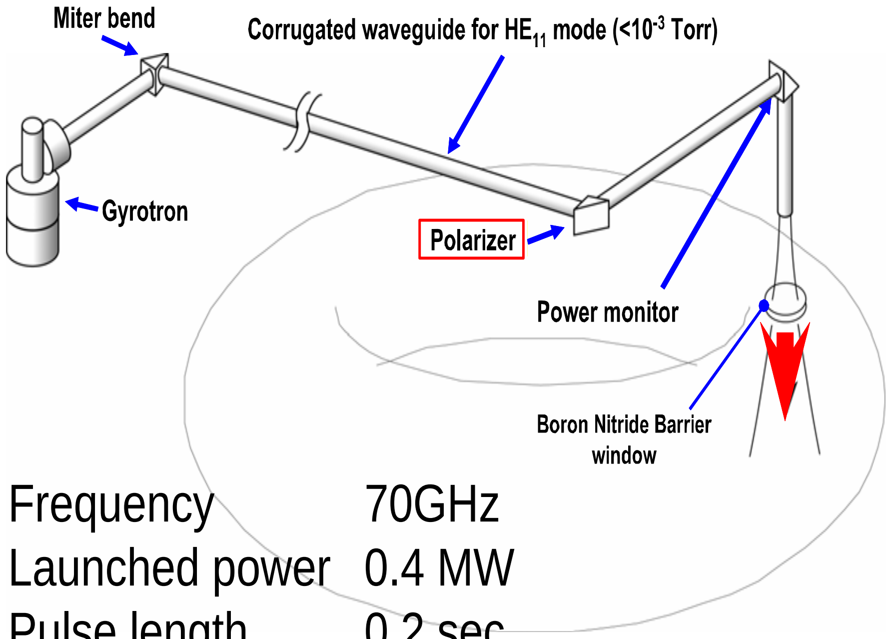
Major radius	1.2m
Plasma minor radius	0.15-0.2m
Plasma volume	0.82 m^3
Rotational transform	$\iota/2\pi$= 0.3-0.8
Aspect ratio	7
Port	65

Low magnetic shear

The magnetic well is formed in the whole confinement region

Magnetic Field	1.5T
Pulse length	0.5sec

70GHz ECH/ECCD System for Heliotron J

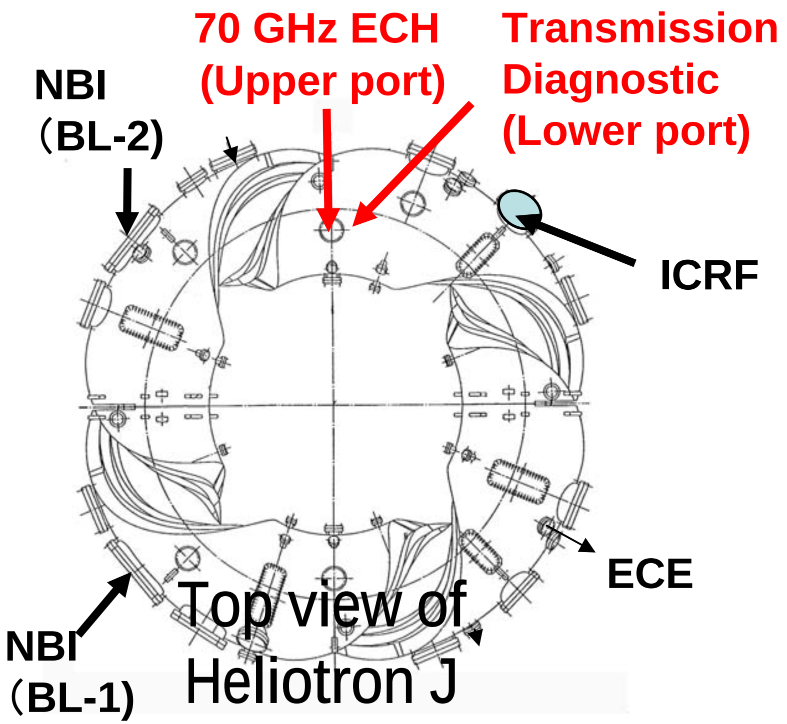


Frequency	70GHz
Launched power	0.4 MW
Pulse length	0.2 sec

HE$_{11}$ mode transmission line

Transmission efficiency

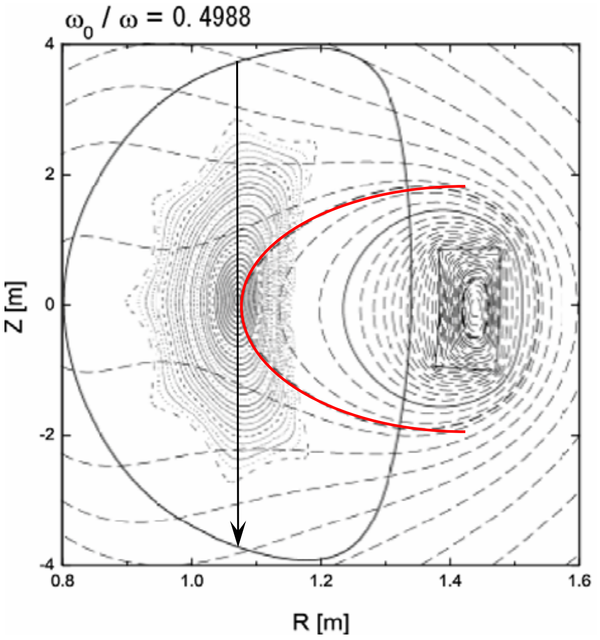
MOU: 90%, Waveguide: 92 %



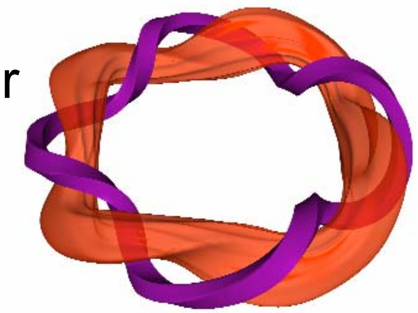
- Non-focused Gaussian beam is launched from the top port at the straight section
- Wave polarization is controlled by a polarizer installed on a miter bend

Magnetic Field Structure at ECH/ECCD Port

- The launched EC wave vector is oblique to the magnetic field due to the 3-D field structure of Heliotron J

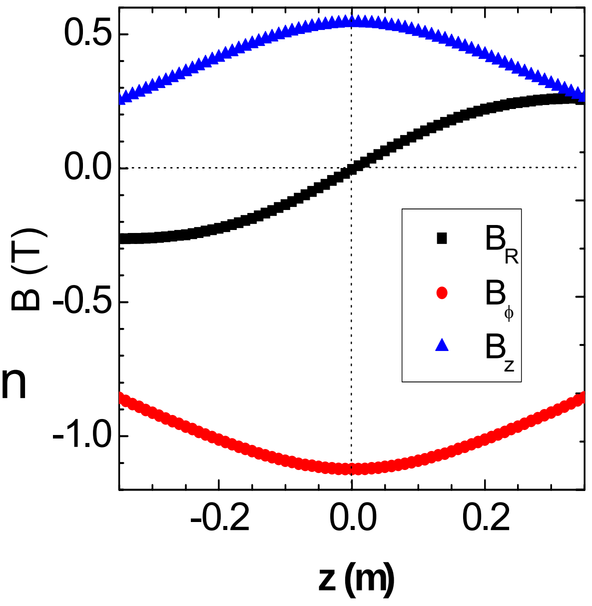


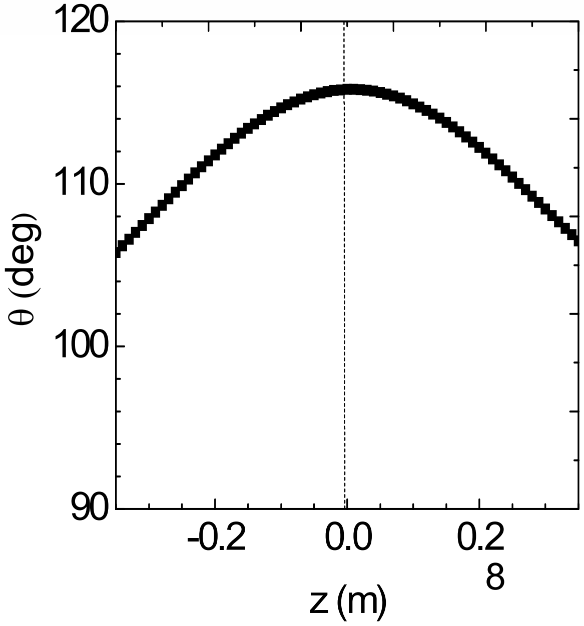
Saddle type resonance layer
Beam shape flux surface



$N_{||}$=0.44 (in vacuum)

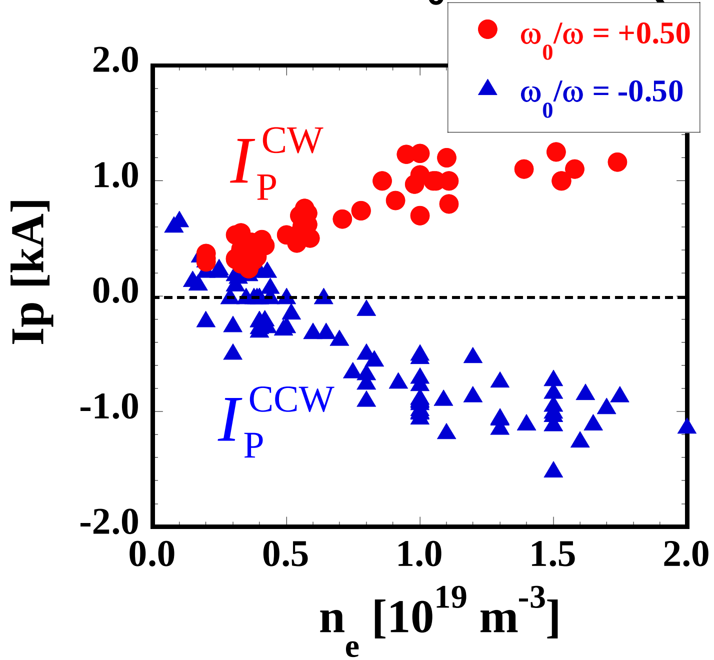
The magnetic configuration is “standard configuration”

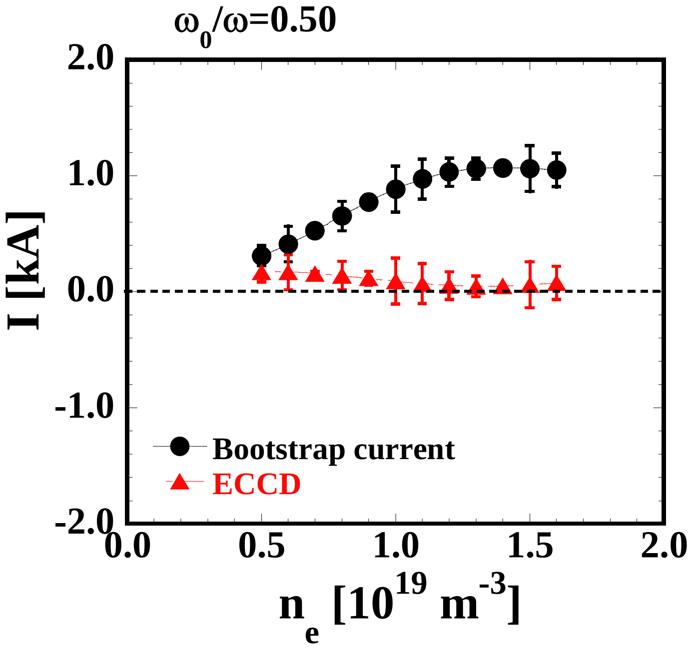




Separation of Bootstrap Current and EC current

ω_0/ω=0.50 (off-axis deposition, *r/a*~0.2)





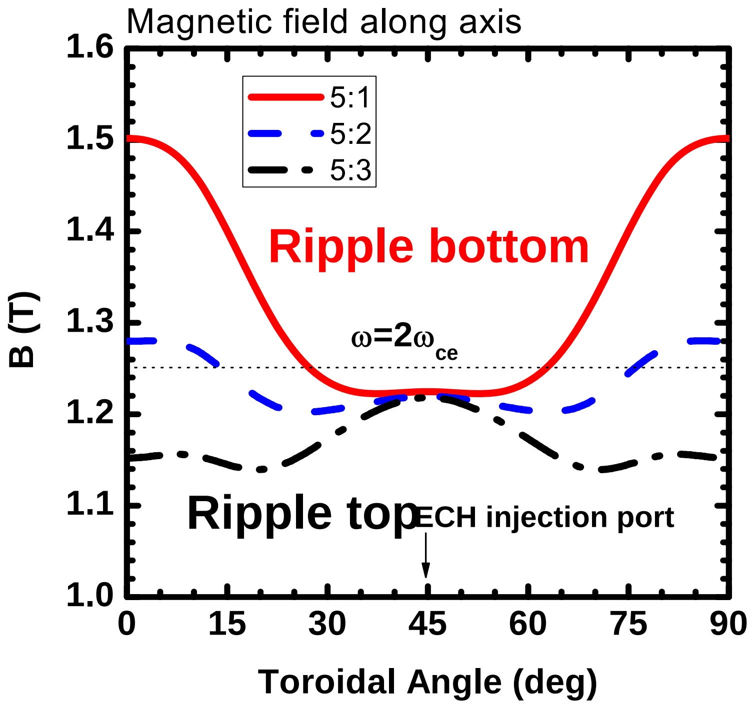
$$\begin{cases} I_{BOOT} = \dfrac{I_P^{CW} - I_P^{CCW}}{2} \\ I_{ECCD} = \dfrac{I_P^{CW} + I_P^{CCW}}{2} \end{cases}$$

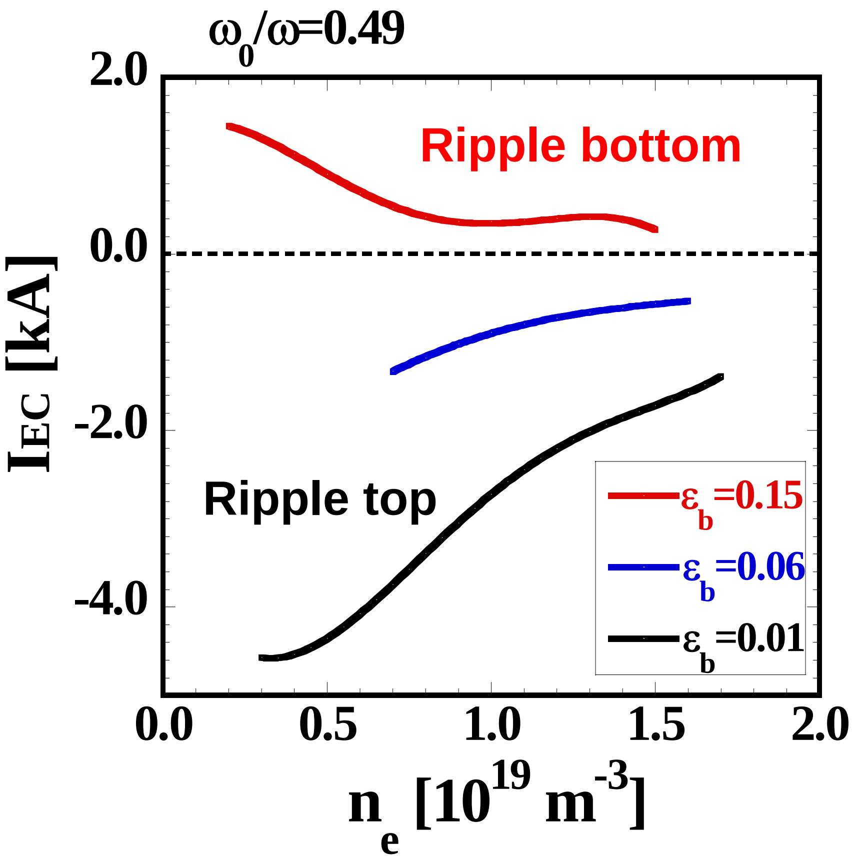
- The bootstrap current and the EC current are separated by reversed field experiments
- The direction of the bootstrap current is changed by B × ∇*B*, while EC current is not changed
- The bootstrap current increases with the electron density due to the increase in plasma pressure

Reversal of EC Current Direction

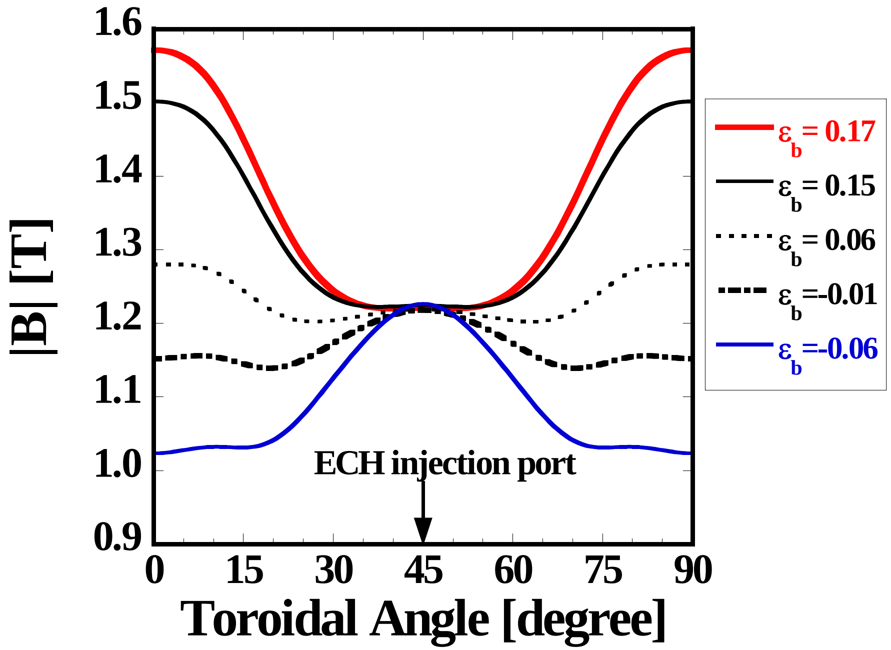
- ECCD is driven much at low n_e/high Te, ripple top heating
- The EC current is reversed at ripple bottom heating

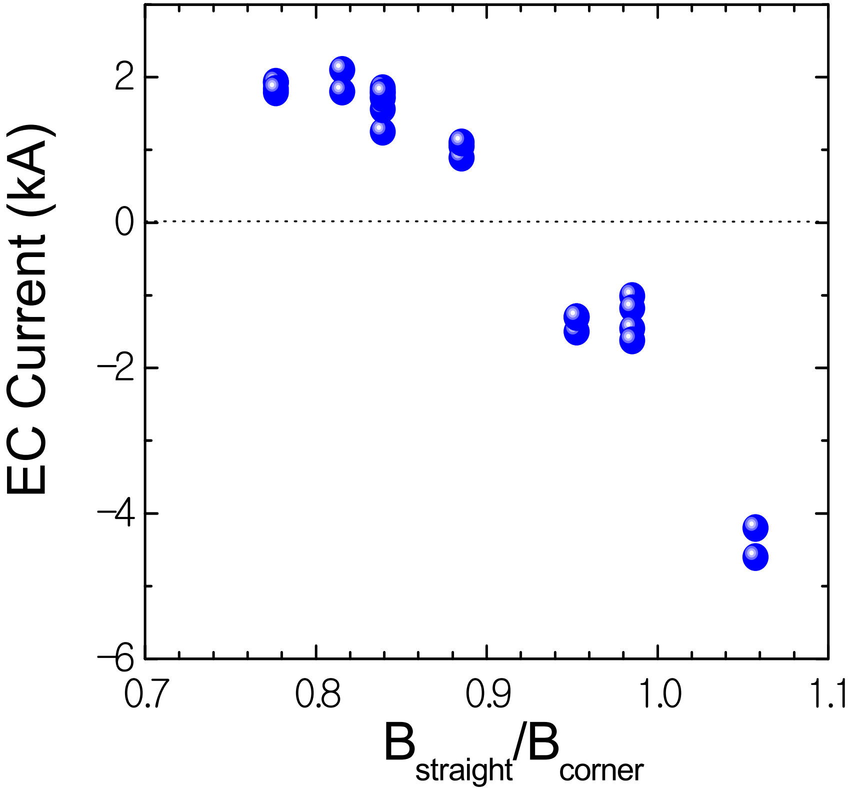
Heliotron J





Dependence on Magnetic Ripple



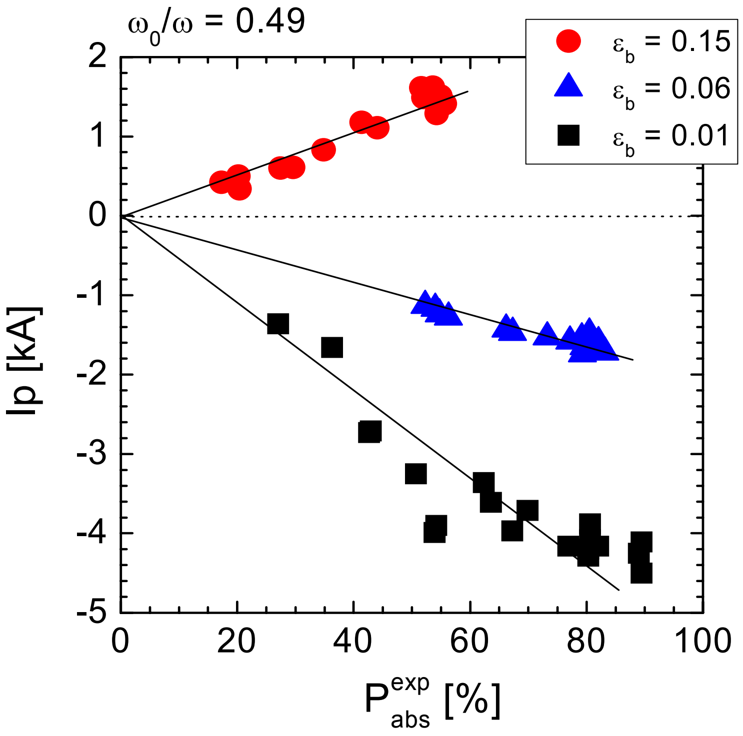


- The bumpiness control causes the change in ripple structure
- The toroidal current changes its flowing direction depending on the ripple structure
- The current direction is explained by the balance between the Fisch-Boozer effect and the Ohkawa effect

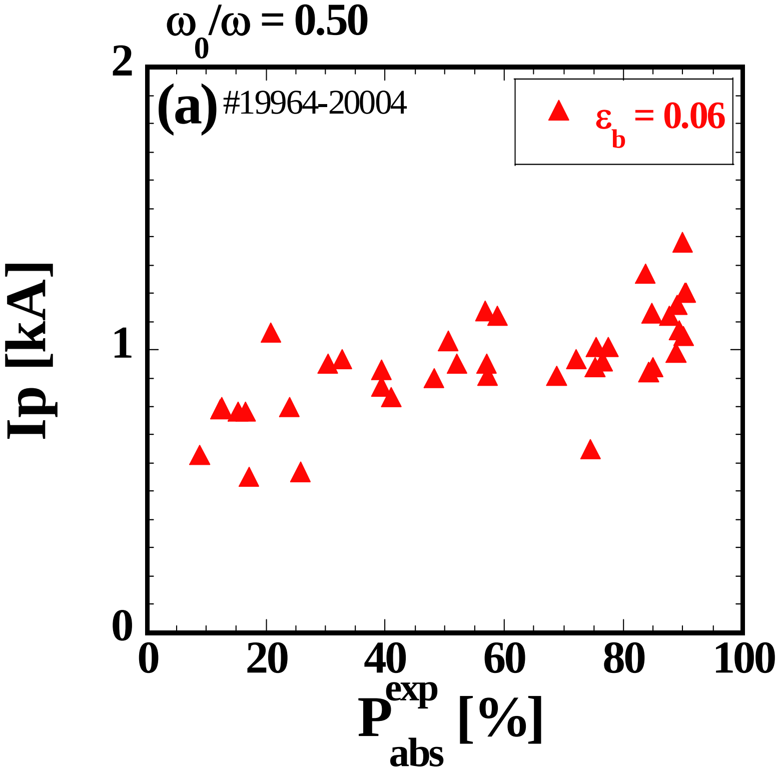
Role of Single Pass Absorption

- The X-mode fraction was changed by polarization control angle in order to determine the role of single pass absorption
- EC current decreases when the X-mode fraction is decreased in all three configurations, indicating that the ECCD is driven by single pass absorption

ECCD

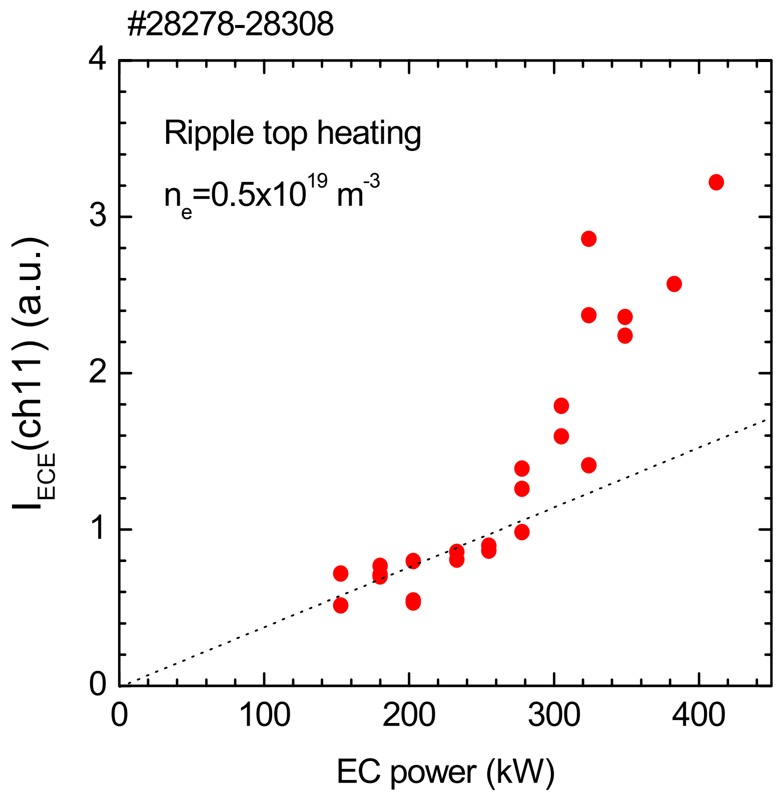


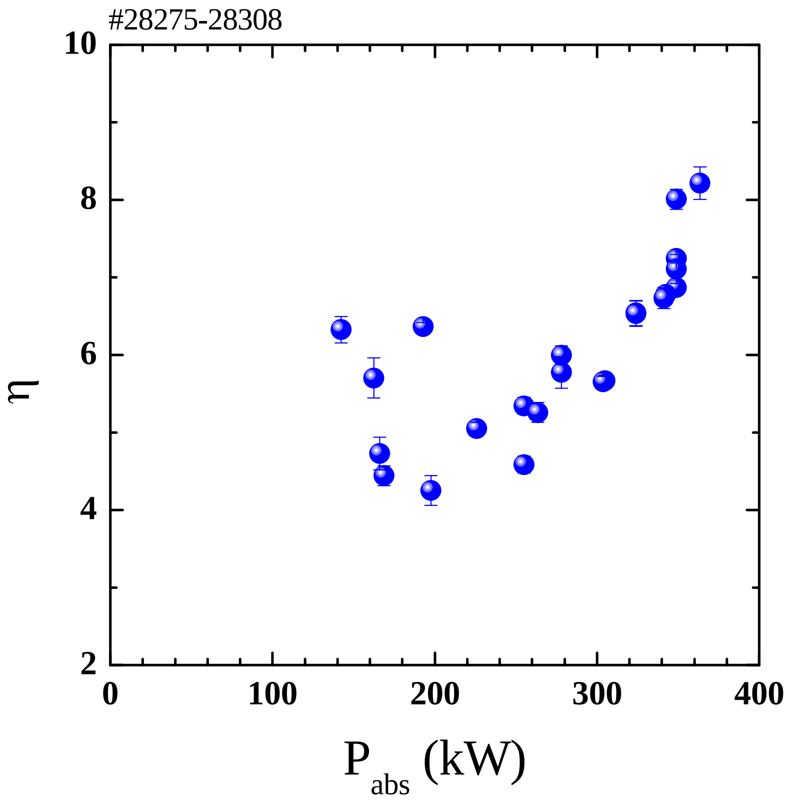
Bootstrap current



Effect of High Energy Electrons

- The ECE intensity is enhanced as the EC power is larger
- High energy electrons possibly has a large contribution to ECCD





Electron Energy Distribution at Ripple Top Heating

5:3 configuration
PHA spectrum

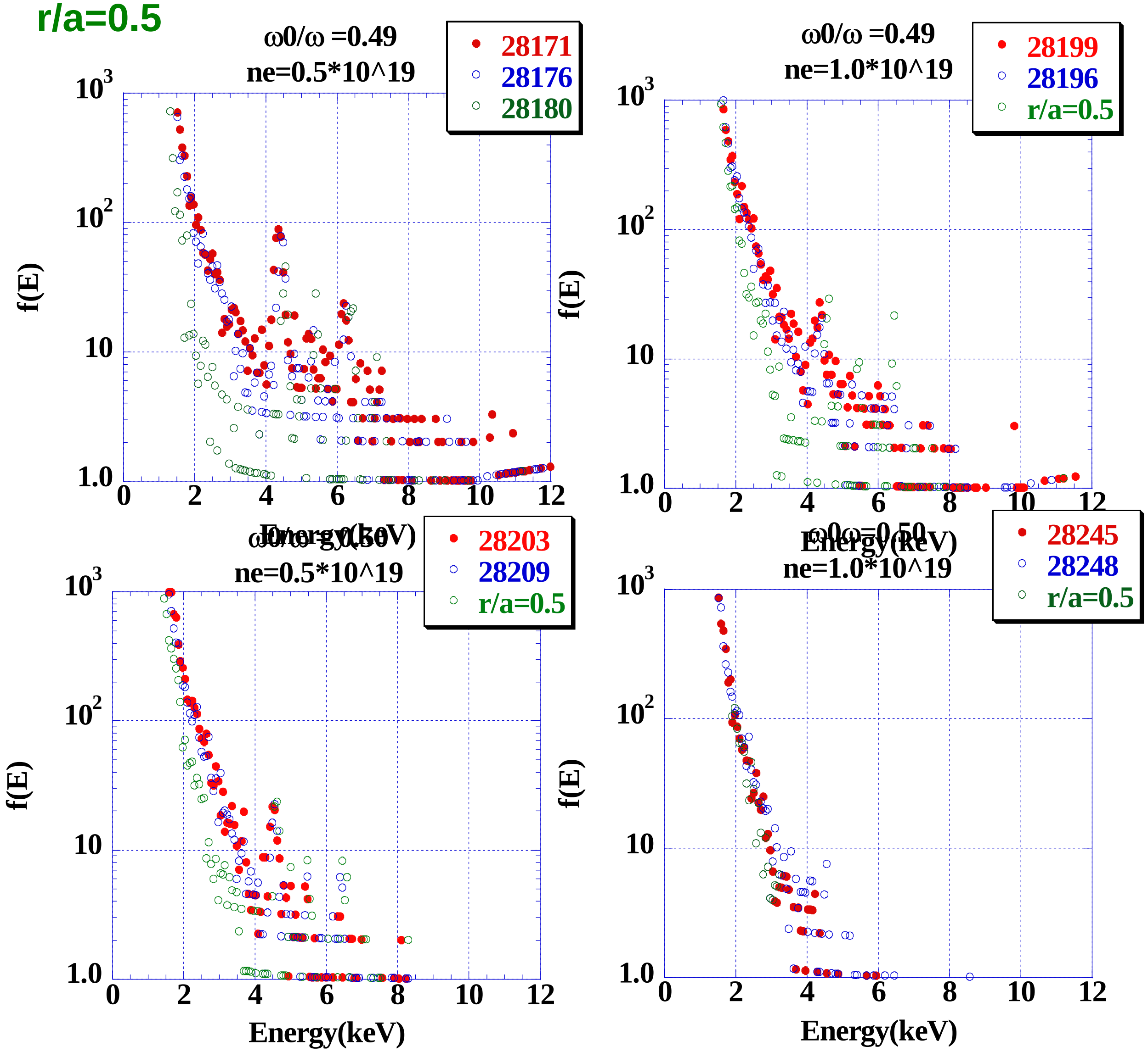
r/a=0
r/a=0.25
r/a=0.5

$\tilde{n}_e \approx 0.5\times10^{19}\,m^{-3}$

$\tilde{n}_e \approx 1.0\times10^{19}\,m^{-3}$

ω_0/ω=0.49

ω_0/ω=0.50



Estimation of ECCD Efficiency

- ECCD efficiency in linear theory

$$\eta = \frac{j_{EC}}{P_{EC}} = \frac{4}{5+Z_{eff}} \frac{\mathbf{s}\cdot\nabla\left(v_{\parallel}/v_{th}\left(v/v_{th}\right)^{3}\right)}{\mathbf{s}\cdot\nabla\left(v/v_{th}\right)^{2}}$$

$$= \frac{3emv_{1}^{2}}{4\pi e^{4} n_{e} \Lambda (5+Z_{eff})}$$

$$\gamma = \frac{I_{EC} n_{e} R}{P_{EC}} \propto \frac{T_{e}}{5+Z_{eff}}$$

Fisch, PRL 41 (1980) 720

ECCD is a factor of 3/4 as efficient as LHCD

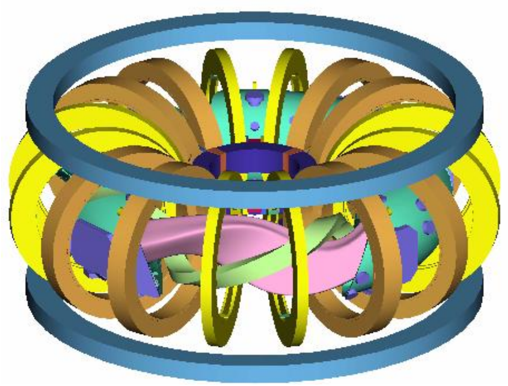
- Dimensionless figure of merit

$$\zeta = \frac{I_{EC} n_{\mathrm{e}} R}{T_{\mathrm{e}} P_{EC}}$$

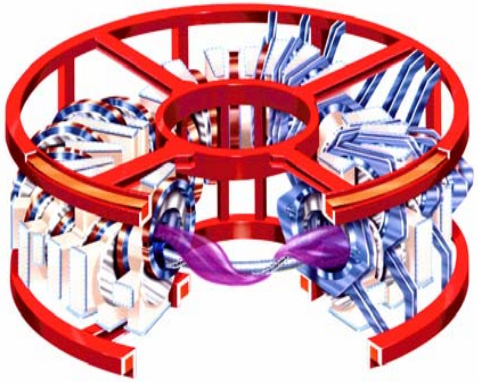
Prater, PoP 11 (2004) 2349

Schematic Views of Plasma Devices

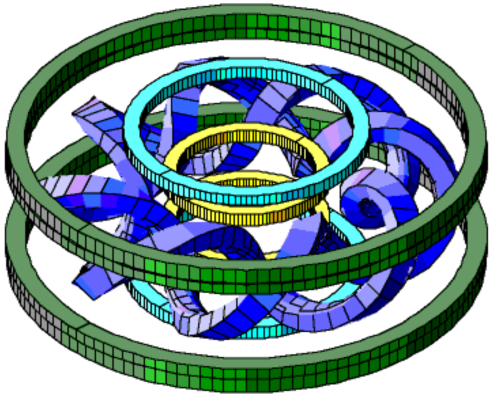
- The device parameters are similar
- The plasma parameters are similar, n_e=0.2-2x10^{19} m^{-3}, T_e=0.3-2 keV



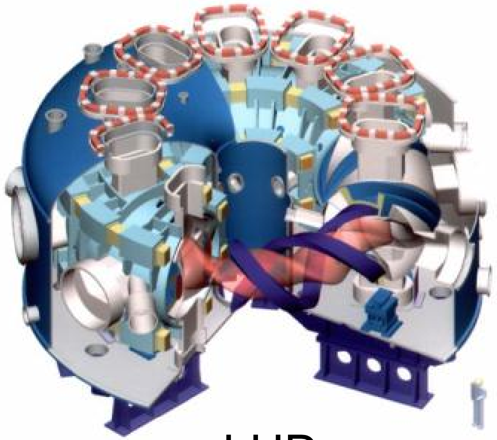
Heliotron J
R= 1 m, a= 0.2 m, L=1, M=4



TJ-II
R= 1.5 m, a= 0.2 m, L=1, M=4



CHS
R= 1 m, a= 0.2 m, L=2, M=8

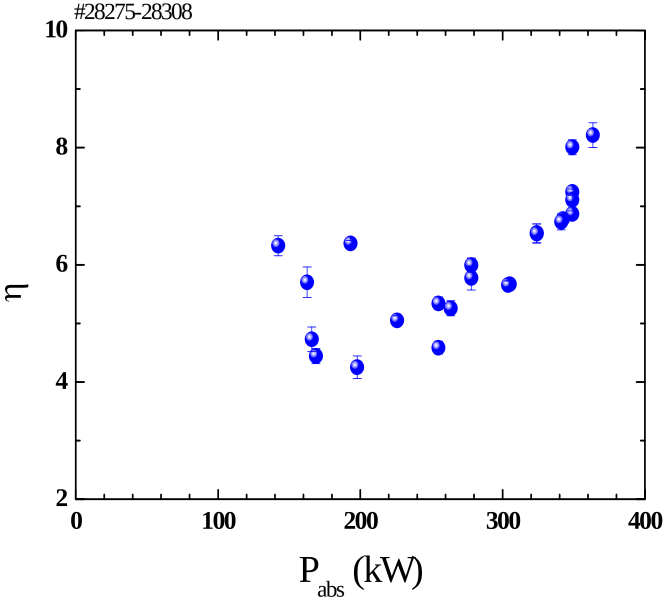


LHD
R= 3.75 m, a= 0.6 m, L=2, M=10

Current Drive Efficiency

	Heliotron J	TJ-II	CHS
Mode	2nd X	2nd X	2nd X
EC Power	320 kW	200+200 kW	300 kW
Max I_{EC}	4.6 kA	2 kA	6 kA
$\eta=I_{EC}/P_{EC}$	14 A/kW	10-15 A/kW	35 A/kW
$\gamma=n_e I_{EC} R/P_{EC}$	~ 8×10^{16} A/Wm^2	~ 9×10^{16} A/Wm^2	~16×10^{16} A/Wm^2
$\zeta=32.7 n_{20} I_A R_m / P_W T_{keV}$	~ 0.05	~0.03	~0.04

Power Dependence of Current Drive Efficiency



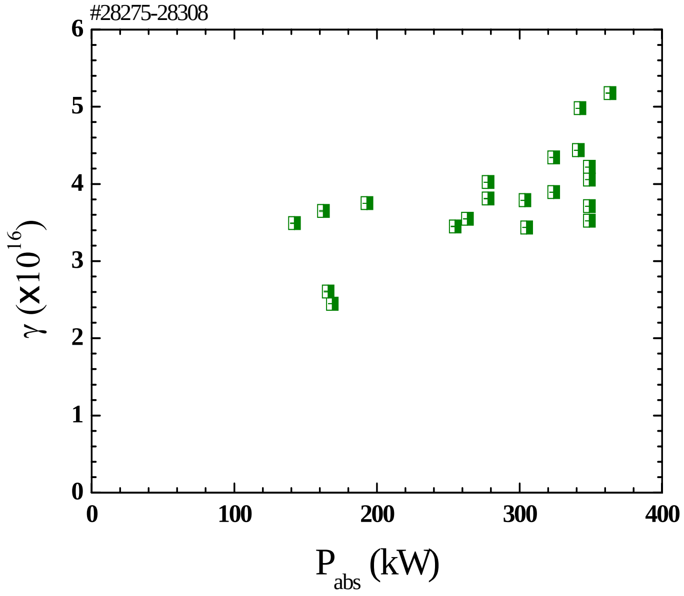
Power Scan at 5:3 configuration, $\omega_0/\omega = 0.491$

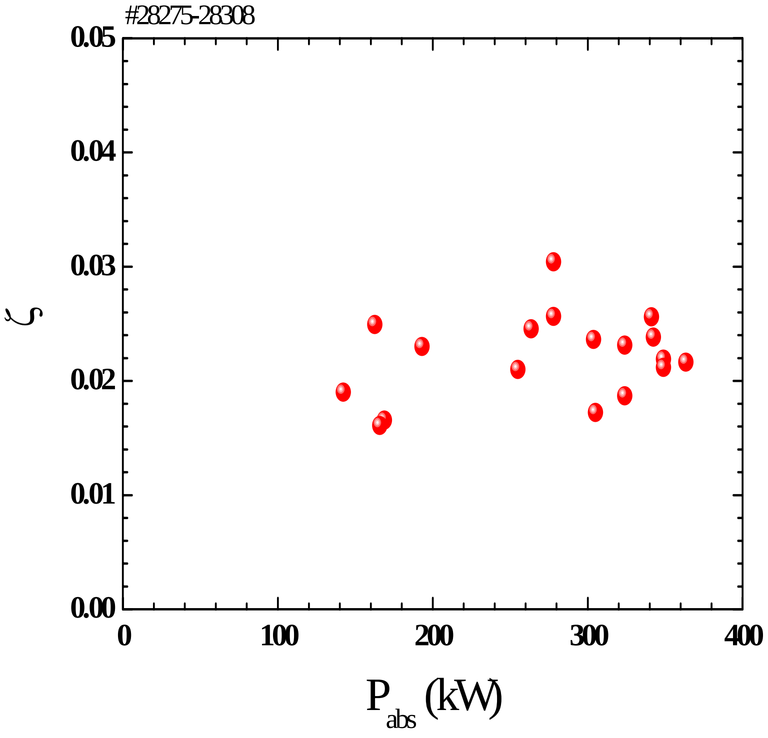
$n_e = 0.4 - 0.6\times10^{19}\ \mathrm{m}^{-3}$

$$\eta = I_{EC} / P_{EC} \quad (\mathrm{A/kW})$$

$$\gamma = n_e R I_{EC} / P_{EC} \quad (\mathrm{A/Wm^2})$$

$$\zeta = 32.7 n_e I_{EC} R / P_{EC} T_e$$

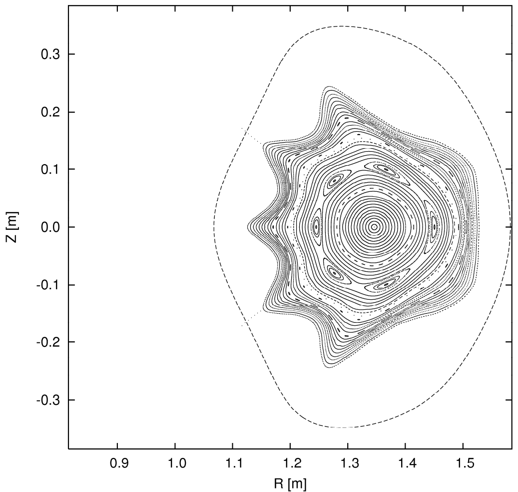




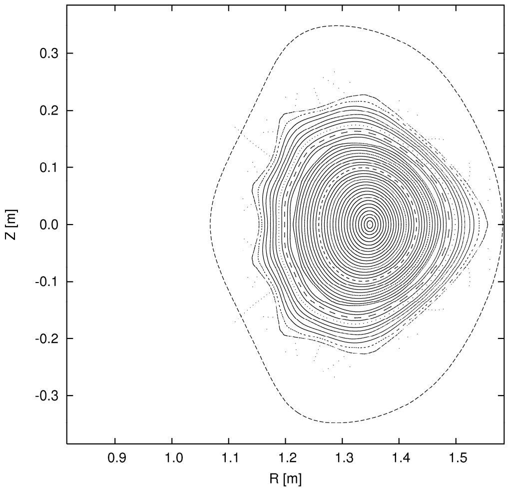
Effect on Rotational Transform Profile

- Rotational transform profile is calculated by HINT2 code

Ip=+5kA $\varepsilon_b = 0.01$

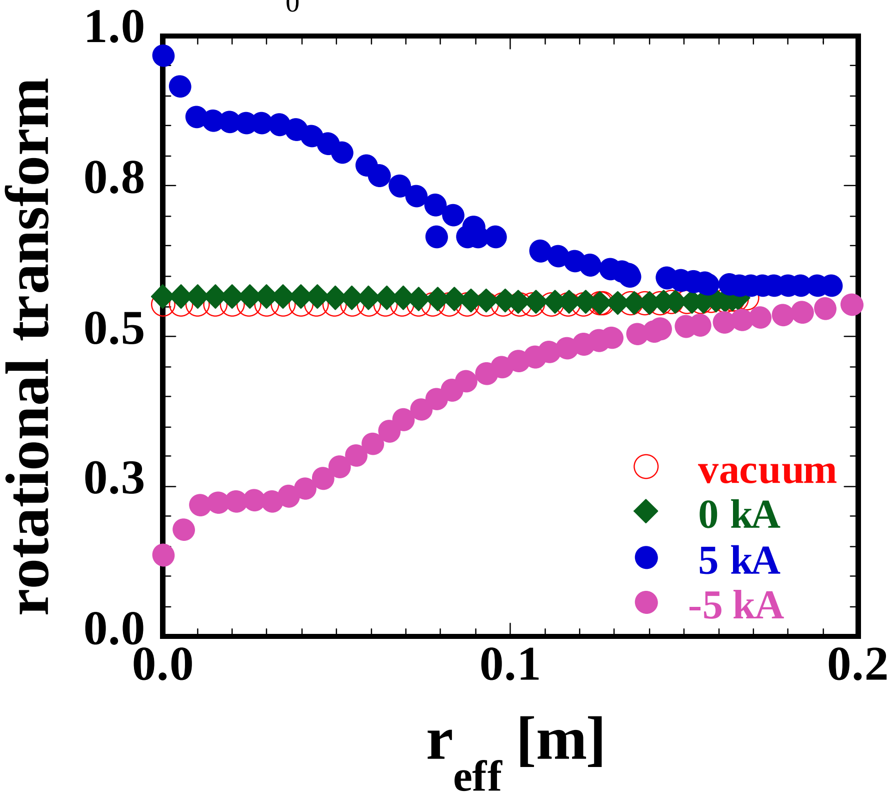


Ip=-5kA



$j = j_0(1-s)^{10}$

Ref. Y. Suzuki. et al, *Nucl. Fusion* 46 (2006) L19

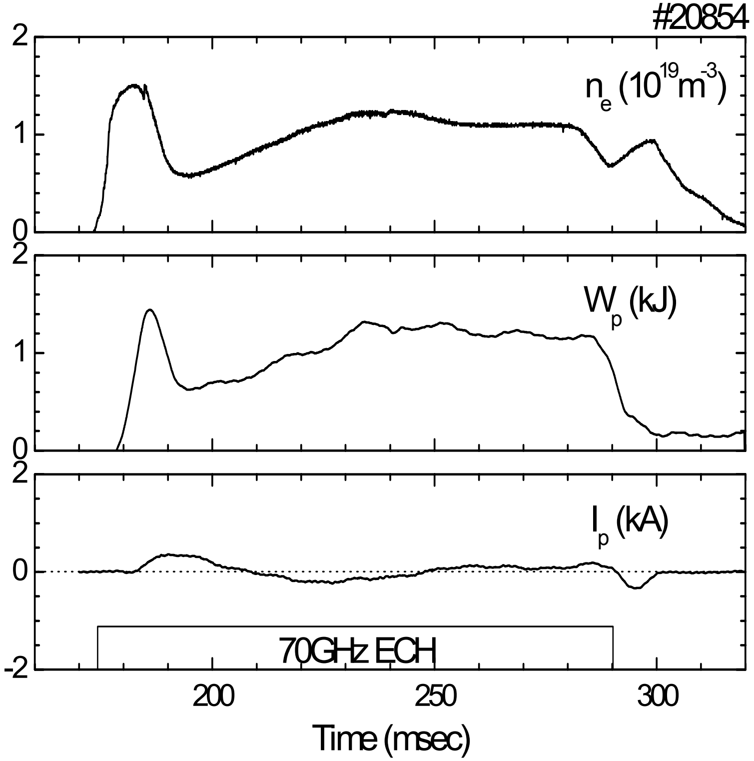


- Localized toroidal current changes rotational transform
- No significant degradation of plasma confinement due to the change in rotational transform has been observed

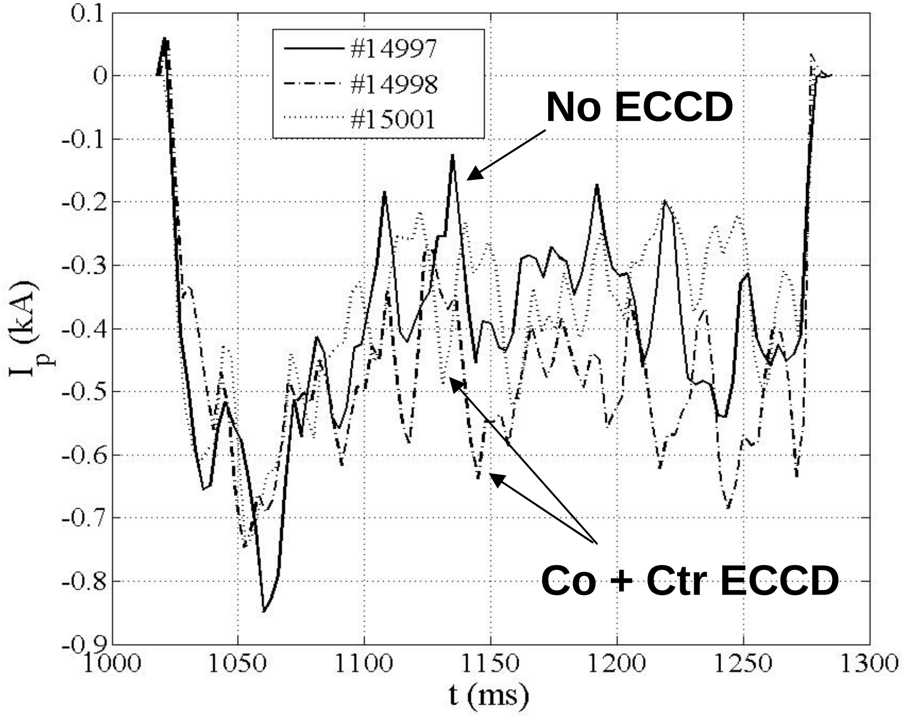
Control of Net Current in ECH Plasmas

- Net current free plasma is realized by compensating the bootstrap current by the EC current in Heliotron J
- Co- and counter-ECCD compensate total EC current in TJ-II

Heliotron J



TJ-II



No ECCD

Co + Ctr ECCD

Conclusion

- The ECCD experiment has been performed in Heliotron J
- The contribution of bootstrap current was eliminated by the magnet field reversal experiment
- The EC current is strongly dependent on the magnetic ripple structure where the EC power is deposited
- The direction of EC current is reversed at ripple bottom heating
- The magnetic field ripple scan shows that the EC current is determined by the competition between the Fisch-Boozer current and the Ohkawa current
- The normalized ECCD efficiency is independent of EC power
- The EC current may be closely connected to high energy electron population

Future Plan

- Application of ECCD to plasma confinement improvement
  - Modification of rotational transform profile
  - Demonstration of MHD suppression by ECCD
- Is local cancellation of BS current required?
- Enhancement of ECCD efficiency
- Extension of ECCD databases
  - ECCD efficiency
  - Dependence on ripple structure
- Nonlinear interaction between BS current and EC current
- Comparison with tokamak experiment and theory