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ECCD Experiments in Heliotron J, TJ-II, CHS and LHD

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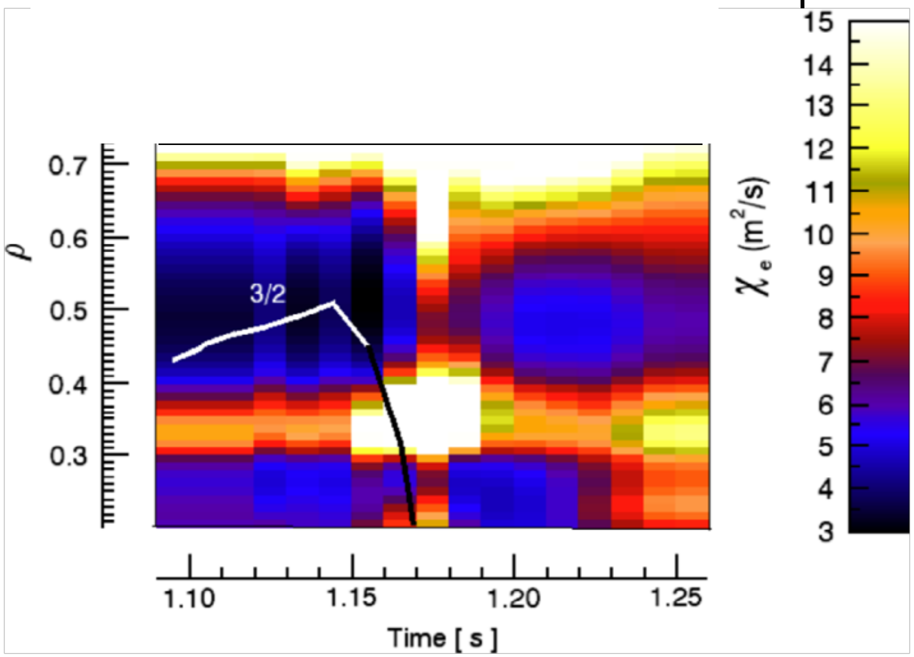
Motivation

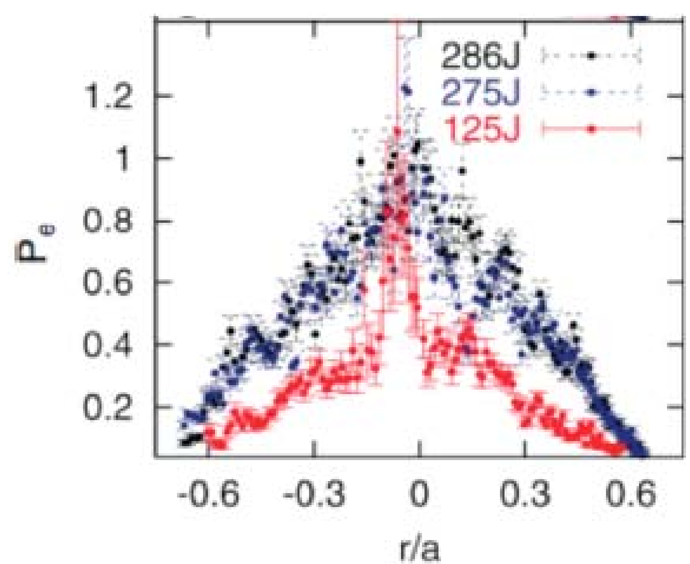
- Study of non-inductive current is one of key issues to control plasma confinement in tokamaks and S/H systems
- In S/H systems, no Ohmic current is required for plasma equilibrium
- However, the bootstrap current is inherently driven due to plasma pressure, affecting MHD equilibrium and stability due 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

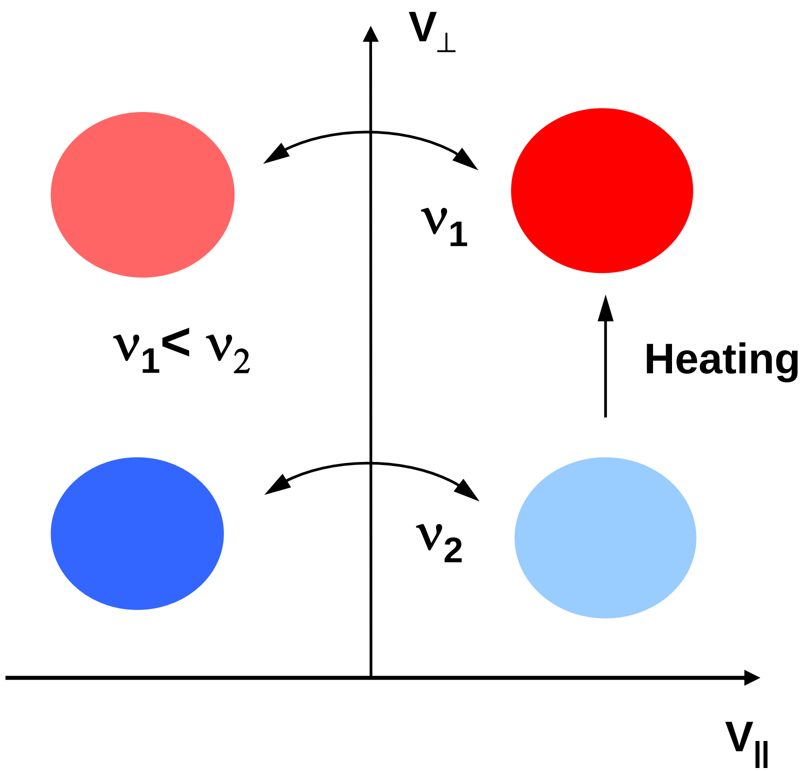
Purposes of ECCD in S/H Systems

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

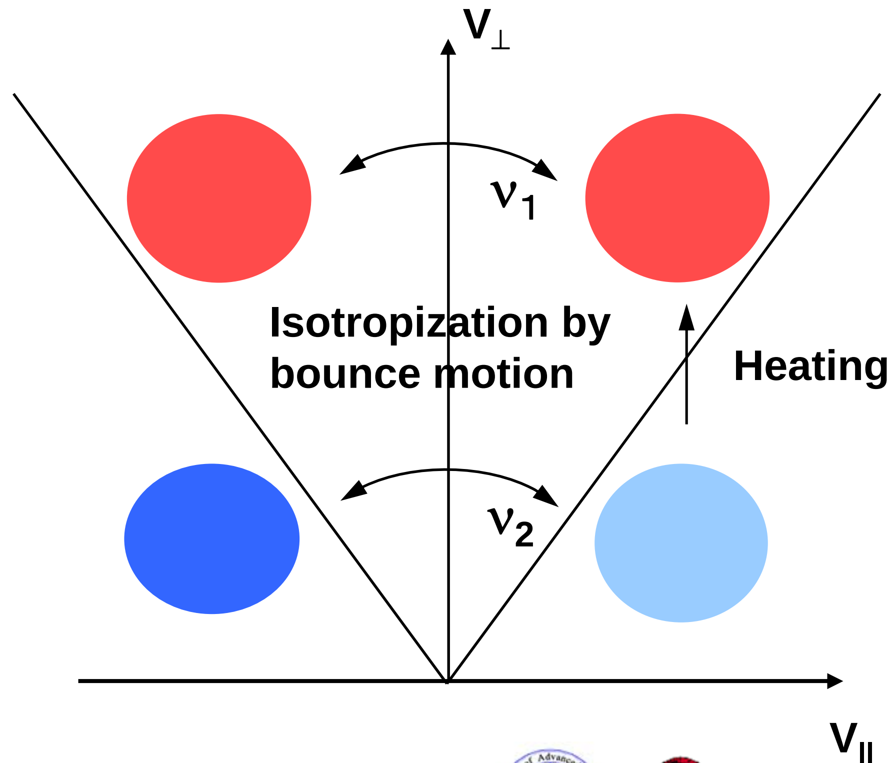
Physical Mechanism of ECCD

- 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

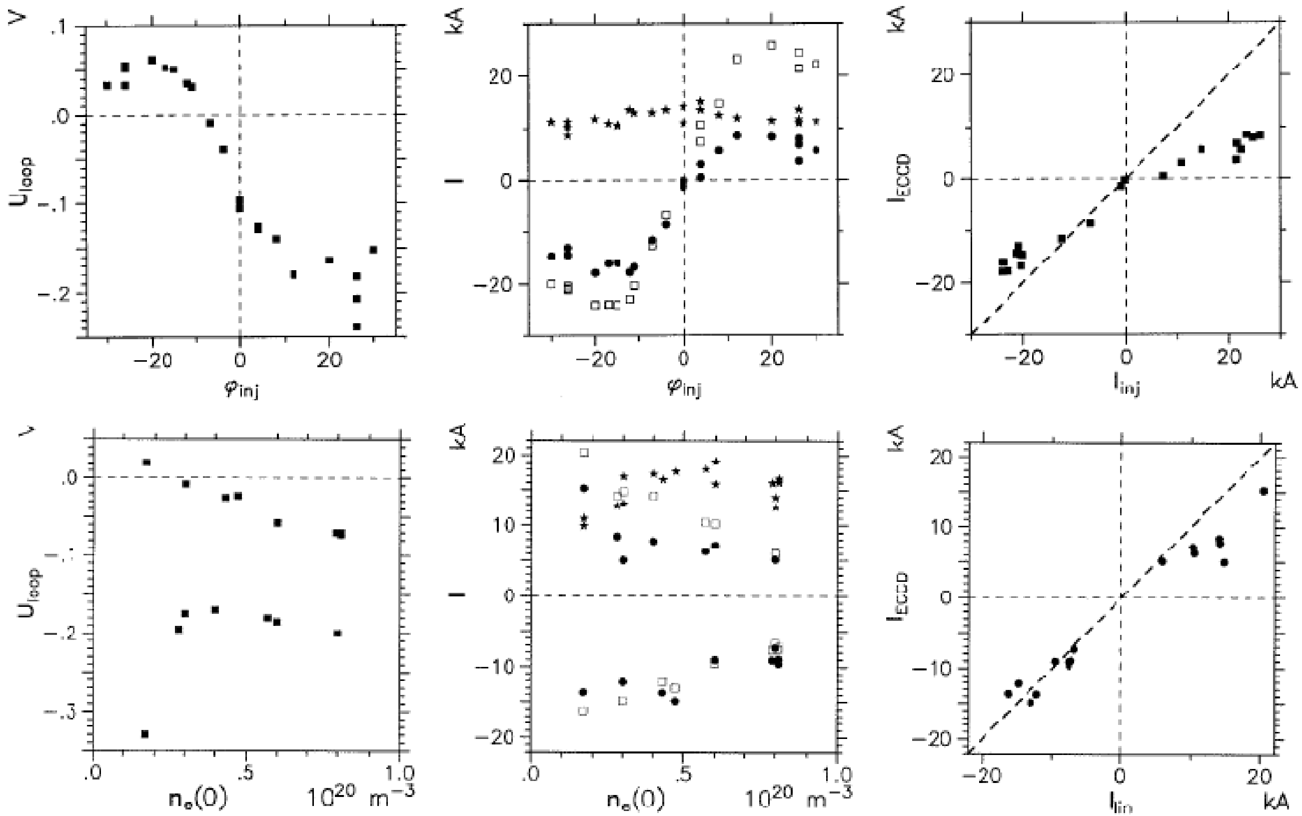


Ohkawa Effect



ECCD Experiment in W7-AS

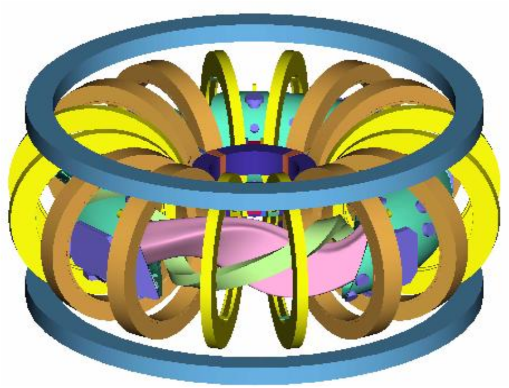
- ECCD was investigated with an ECRH power of up to 1.3 MW at 140 GHz
- Highly localized EC current up to 20 kA were estimated
- The linear prediction is in reasonably agreement with the current balance except for low-density discharges with highly peaked on-axis deposition
- EBW current drive was also demonstrated



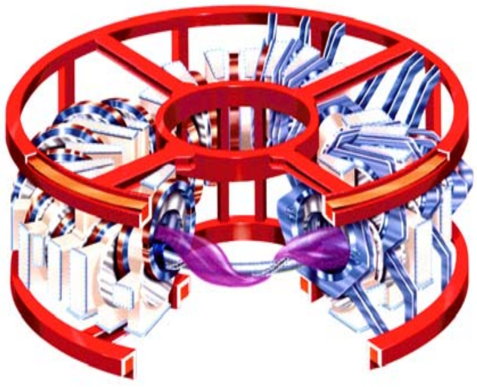
Erckmann NF (2003), Maassberg PPCF (2005)

Schematic Views of Plasma Devices

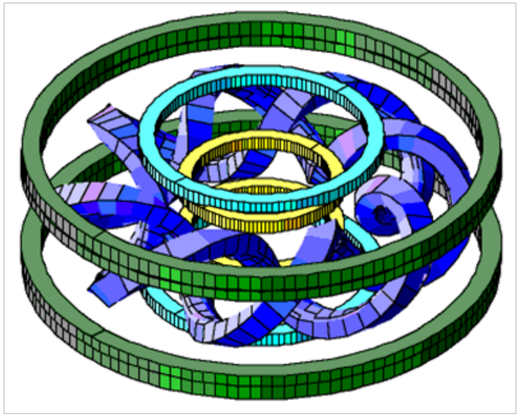
- The device parameters are similar
- The plasma parameters are similar, n_e=0.2-2x10^{19} m^{-3}, T_e=0.3-2 keV



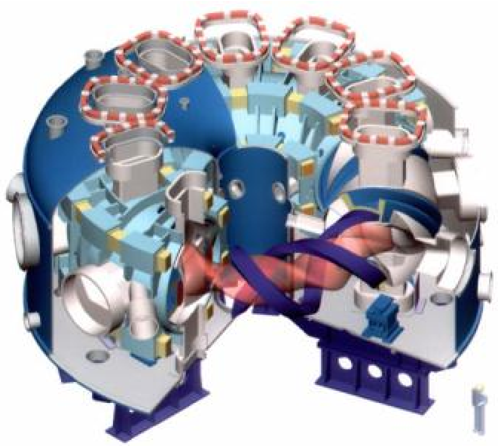
Heliotron J
R= 1 m, a= 0.2 m, L=1, M=4



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

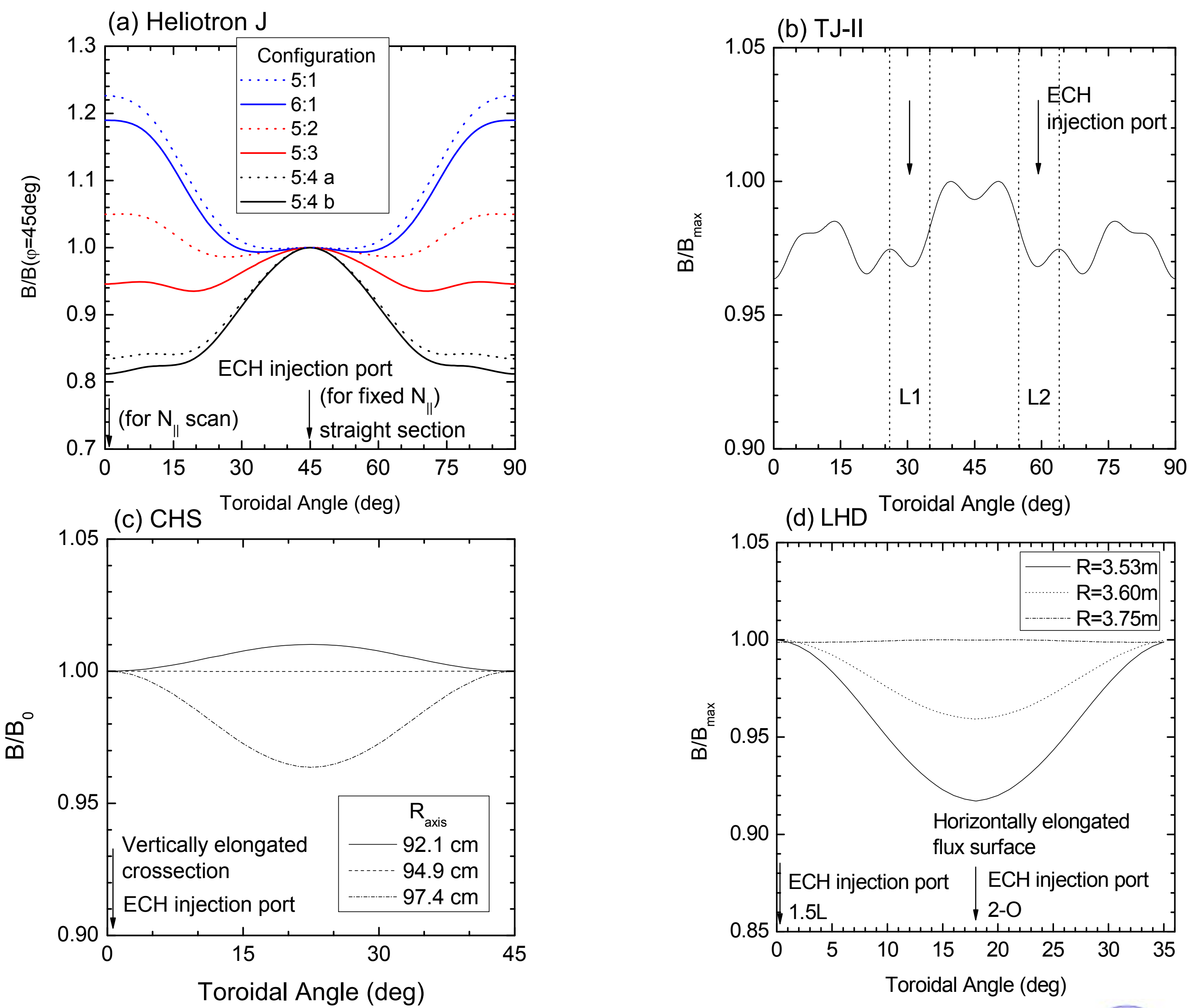


CHS
R= 1 m, a= 0.2 m, L=2, M=8



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

Magnetic Field Structures

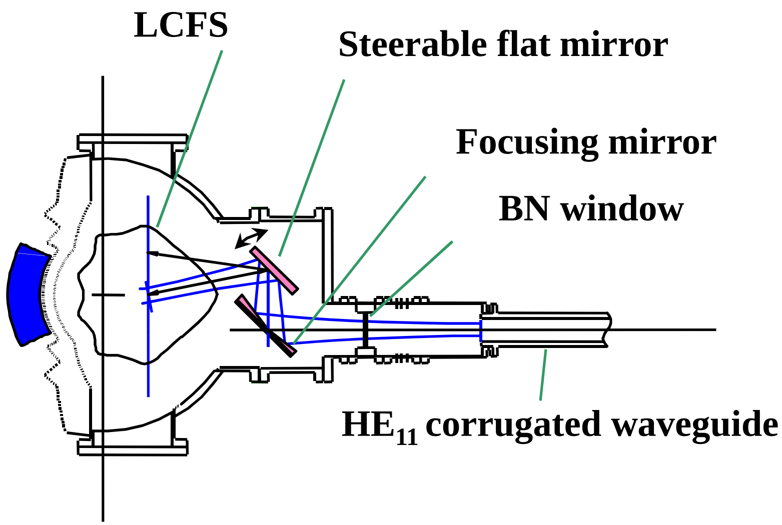


ECH/ECCD Systems

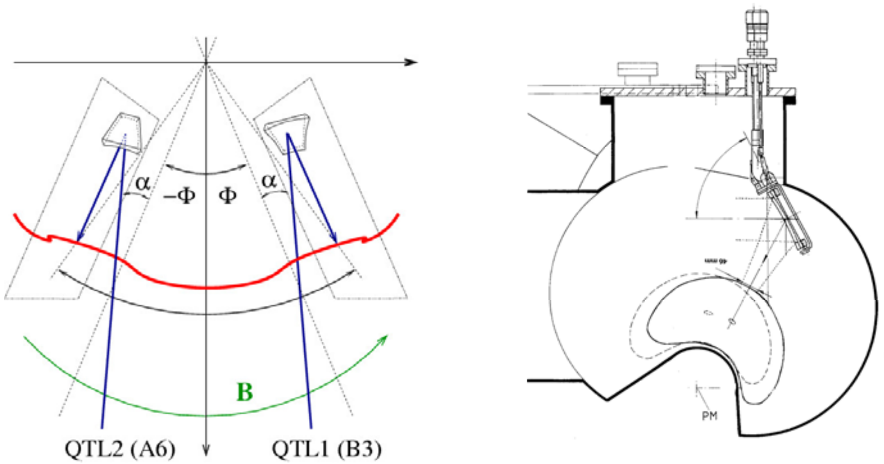
	Heliotron J	TJ-II	CHS	LHD
Frequency	70GHz	53.2GHz	53.2GHz	84GHz
Maximum injection power	0.4MW	0.3MWx2	0.3MW	1.3MW
Maximum pulse length	0.2sec	0.5sec	0.1sec	3sec
Injection mode	Focused/ nonfocused Gaussian	Focused Gaussian	Focused Gaussian	Focused Gaussian
Injection angle	Controllable/ fixed	Controllable	Controllable	Controllable
Polarization	Controllable	Controllable	Controllable	Controllable
Injection mode	2nd X	2nd X	2nd X	1st O/2nd X

ECH/ECCD Systems

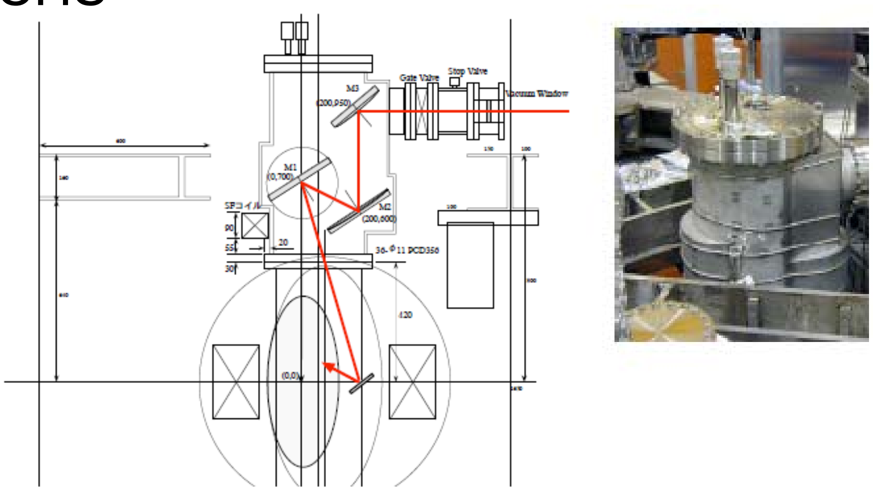
Heliotron J



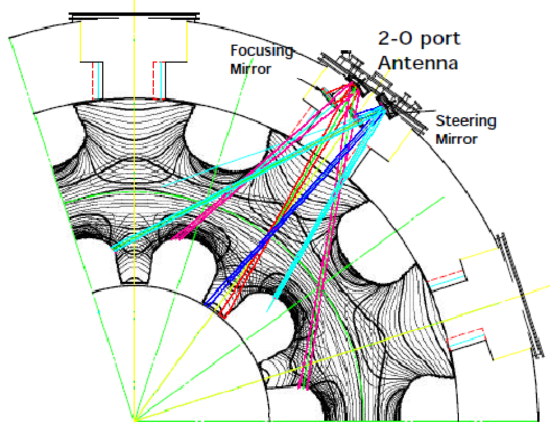
TJ-II



CHS

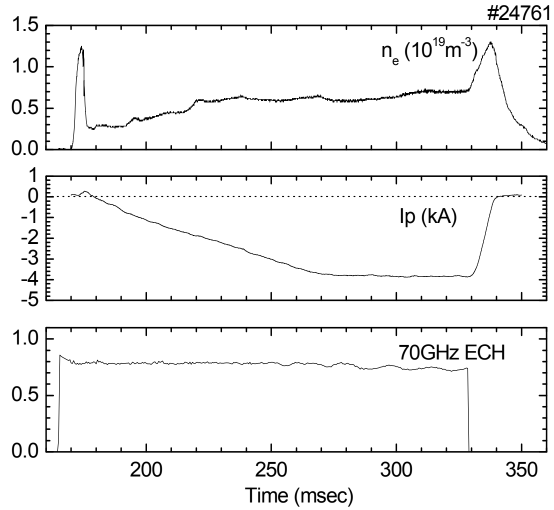


LHD

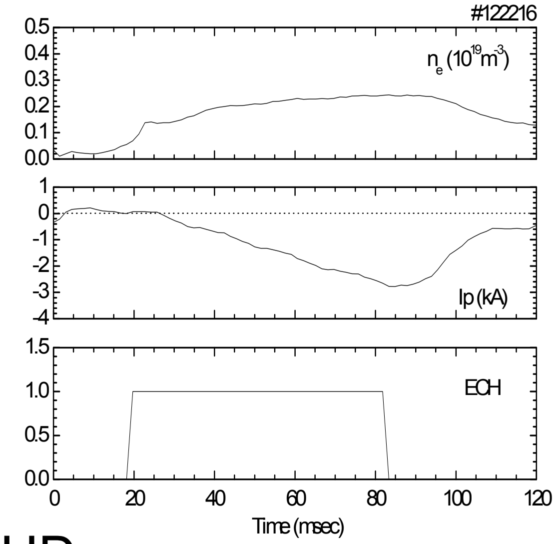


Time Evolution of Plasma Current

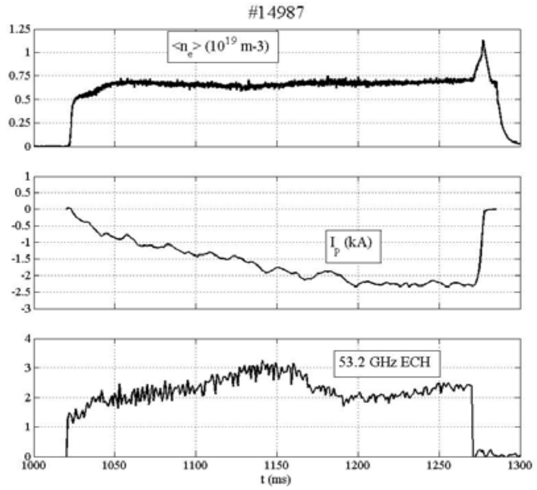
Heliotron J



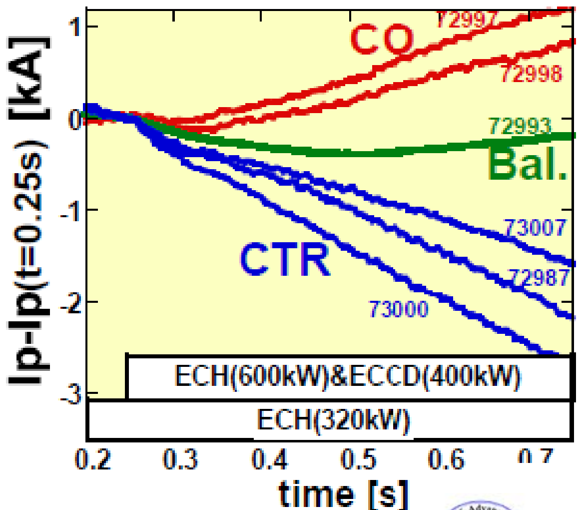
CHS



TJ-II



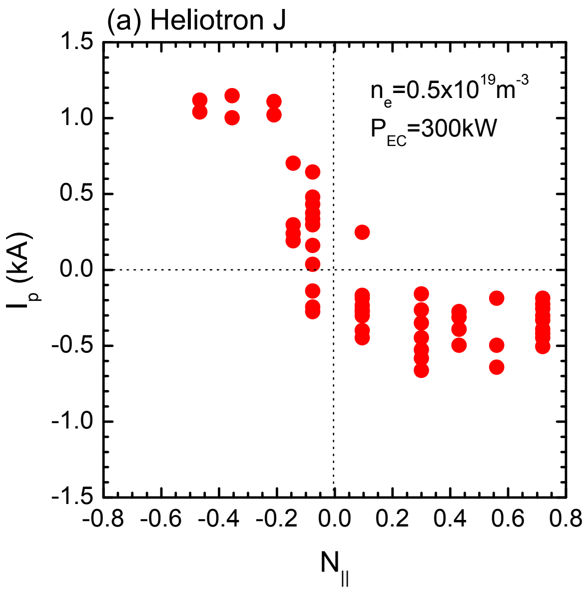
LHD



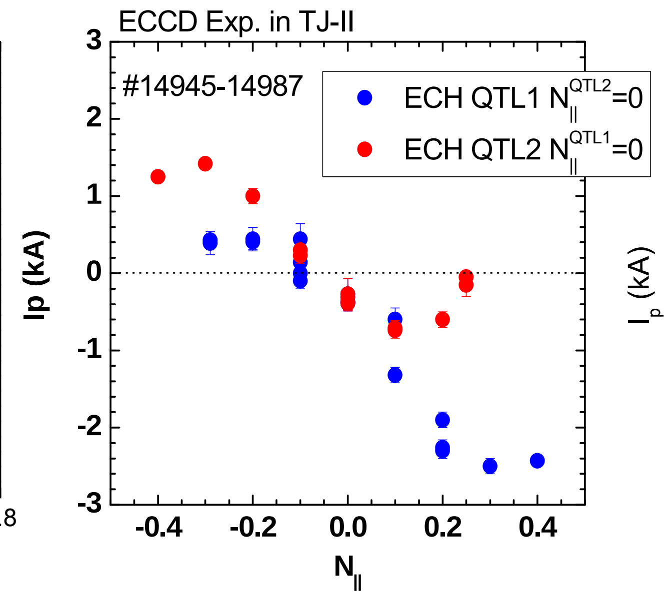
Dependence on Injection Angle

- The EC current depends on the toroidal injection angle
- The EC current is the order of a few kA
- The current direction is determined by the Fisch-Boozer effect at nearly the ripple top power deposition

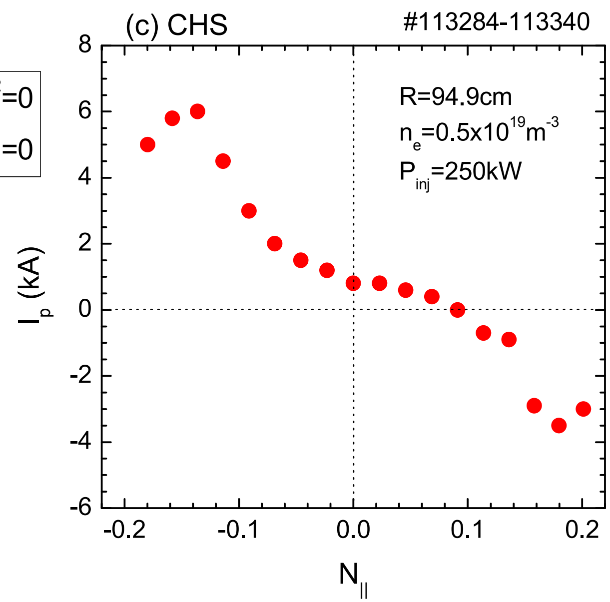
Heliotron J



TJ-II



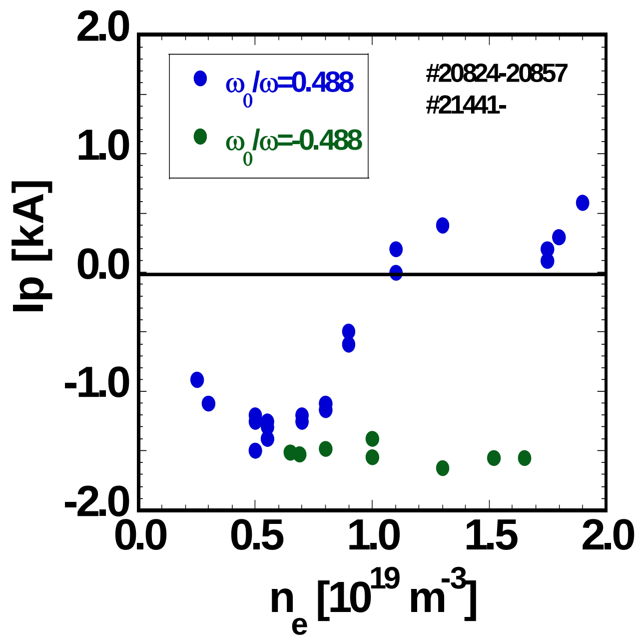
CHS

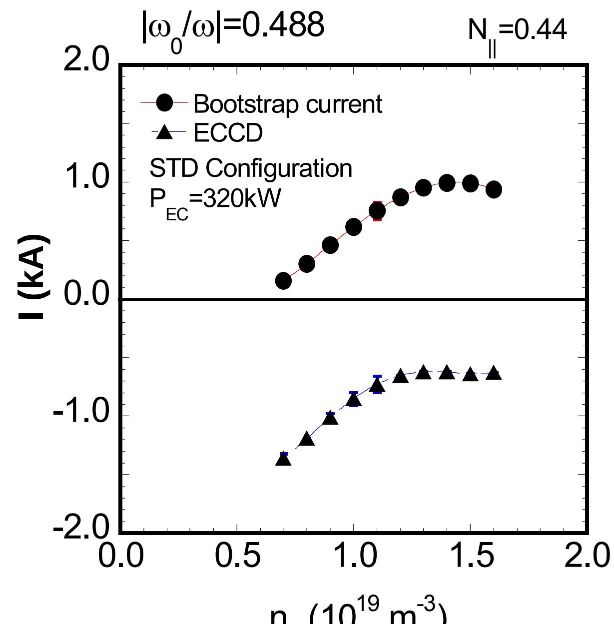


Separation of BS and EC currents

- Theory predicts that the BS current change its flow direction when the magnetic field direction is reversed, while the EC current does not
- The EC and BS currents can be separated by reversing the magnetic field direction in Heliotron J

$$\begin{cases} I_{BS} = \frac{1}{2}\left(I_{\mathrm{P}}^{\mathrm{CW}} - I_{\mathrm{P}}^{\mathrm{CCW}}\right) \\ I_{EC} = \frac{1}{2}\left(I_{\mathrm{P}}^{\mathrm{CW}} + I_{\mathrm{P}}^{\mathrm{CCW}}\right) \end{cases}$$

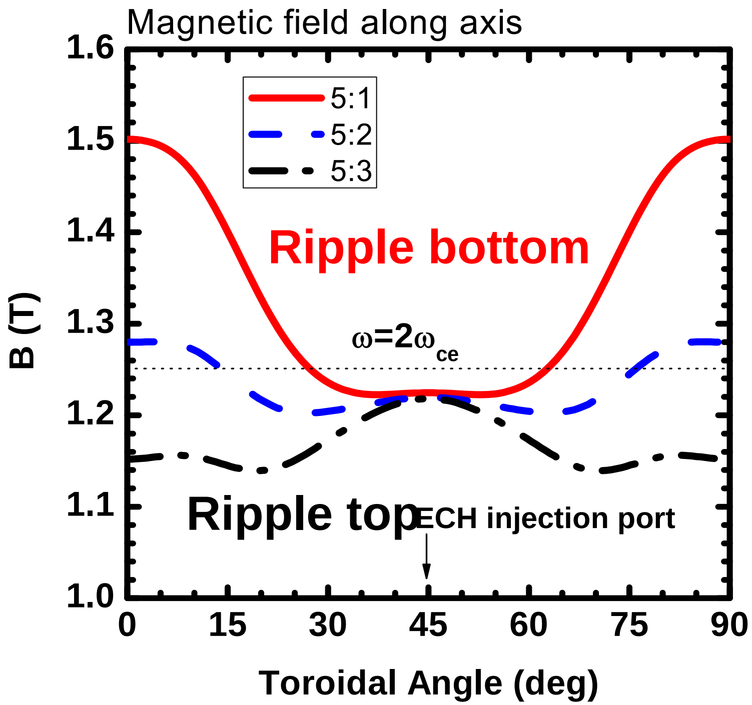


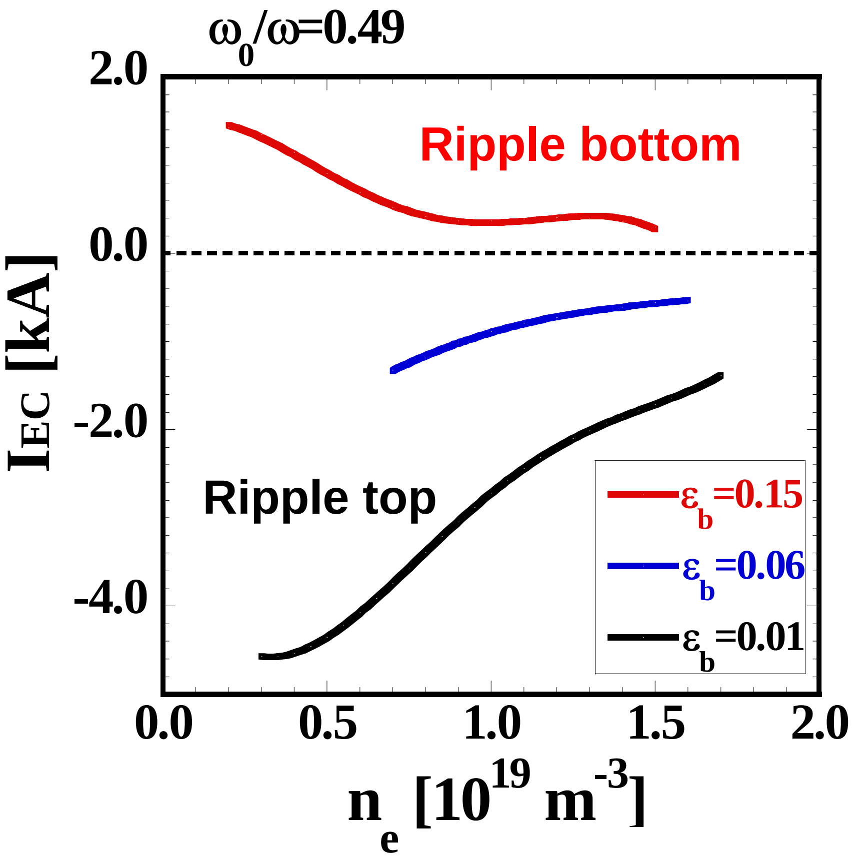


Reversal of EC Current Direction

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

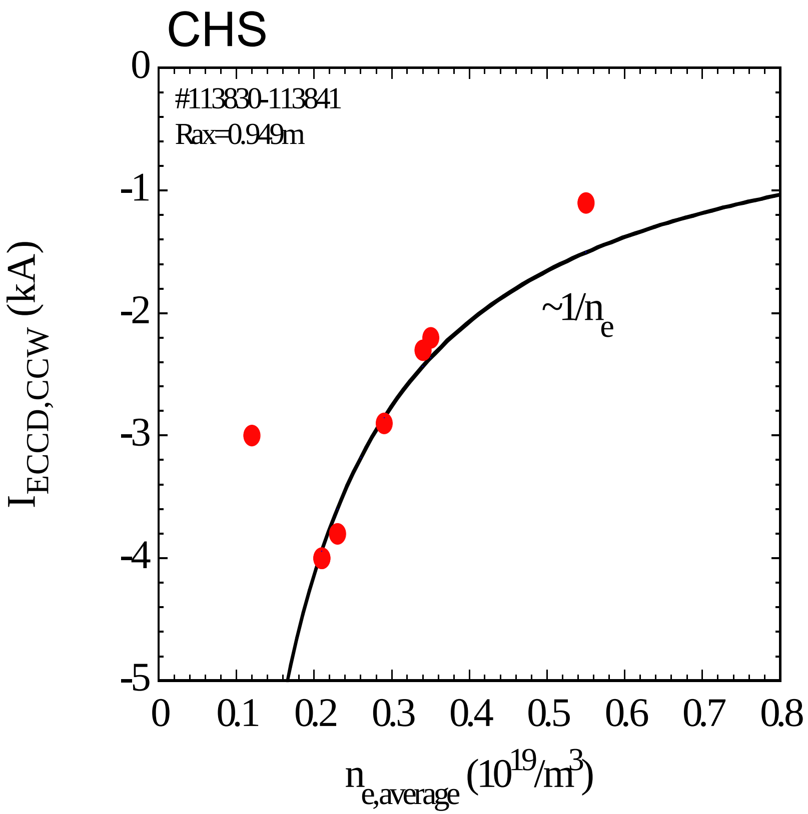
Heliotron J

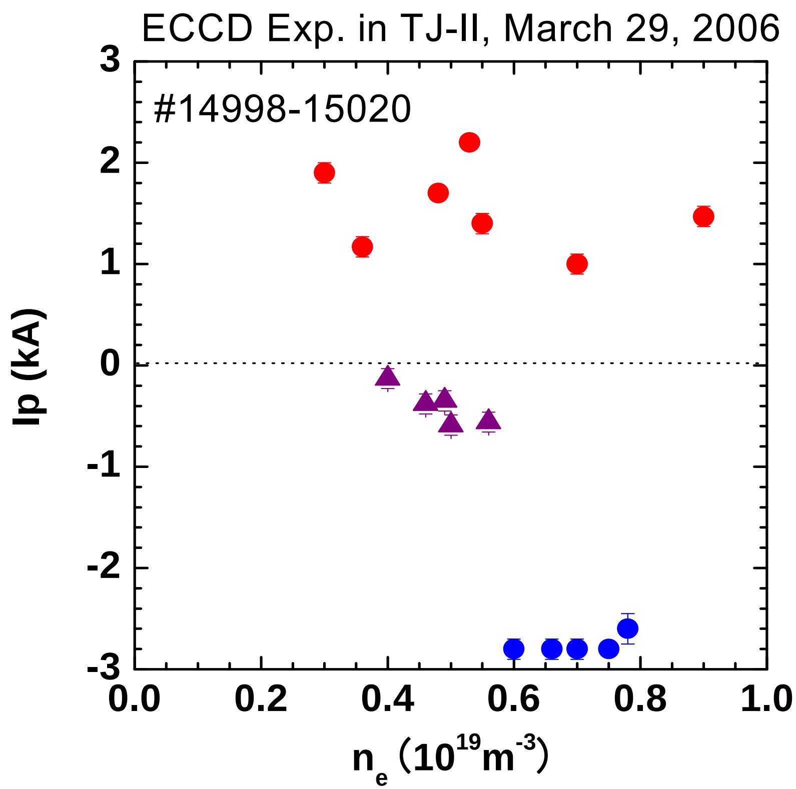




Density Dependence

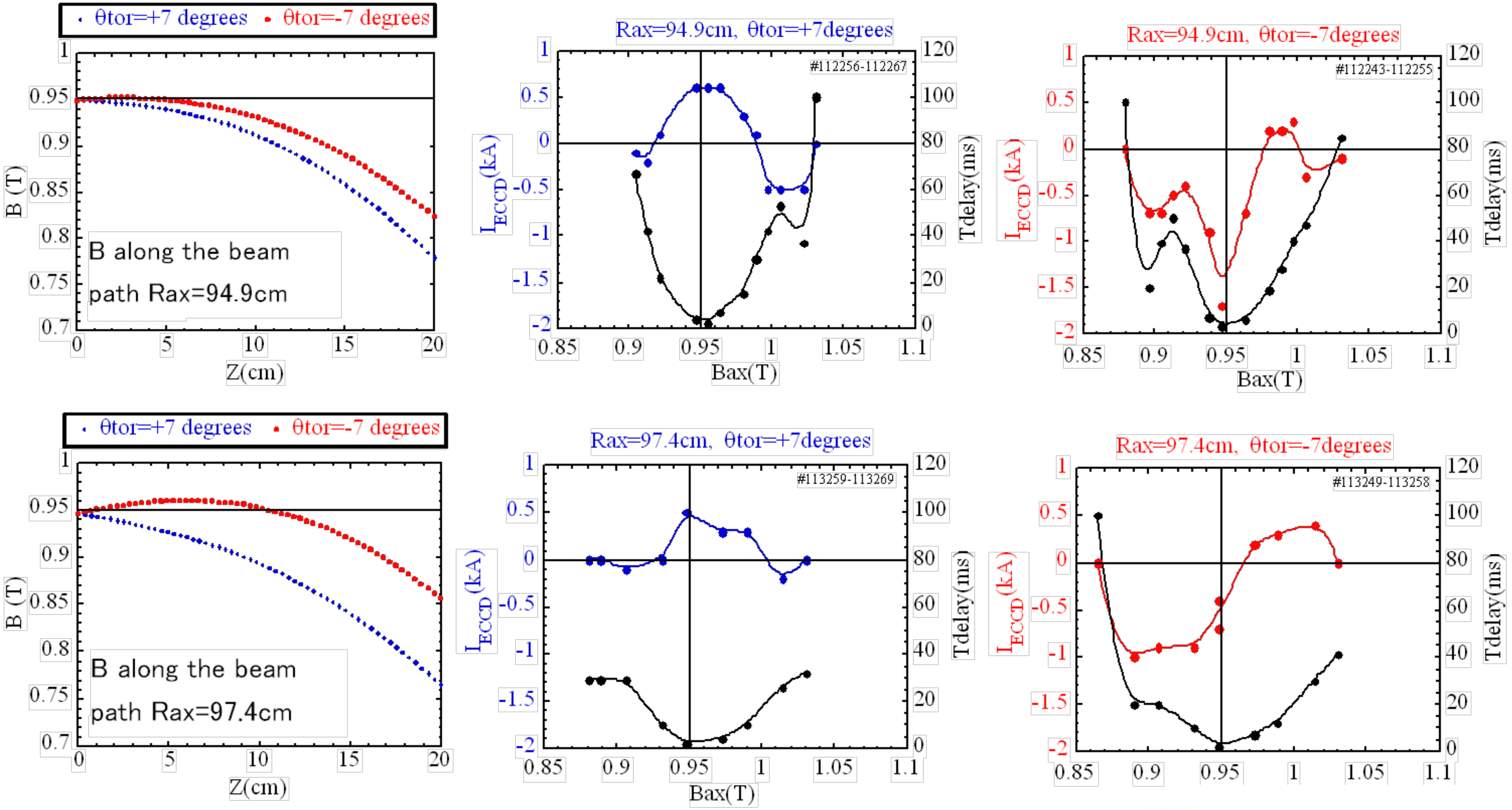
- The EC current decreases with electron density at $n_e<1x10^{19}$ m^{-3} in CHS
- The total current is almost constant in TJ-II probably due to the contribution of bootstrap current





Dependence on Power Absorption Position

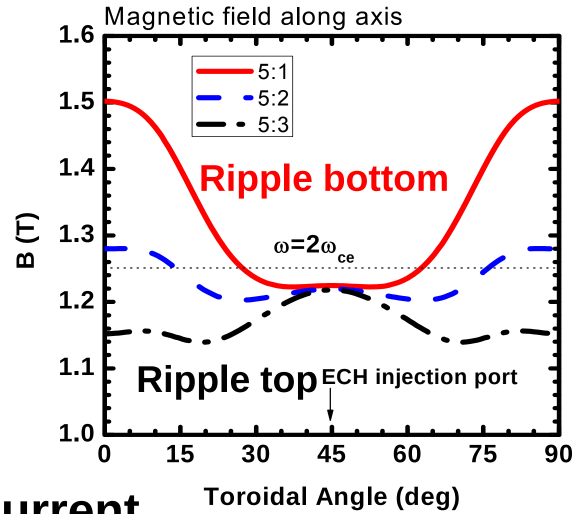
- On-axis power deposition is preferable for high ECCD



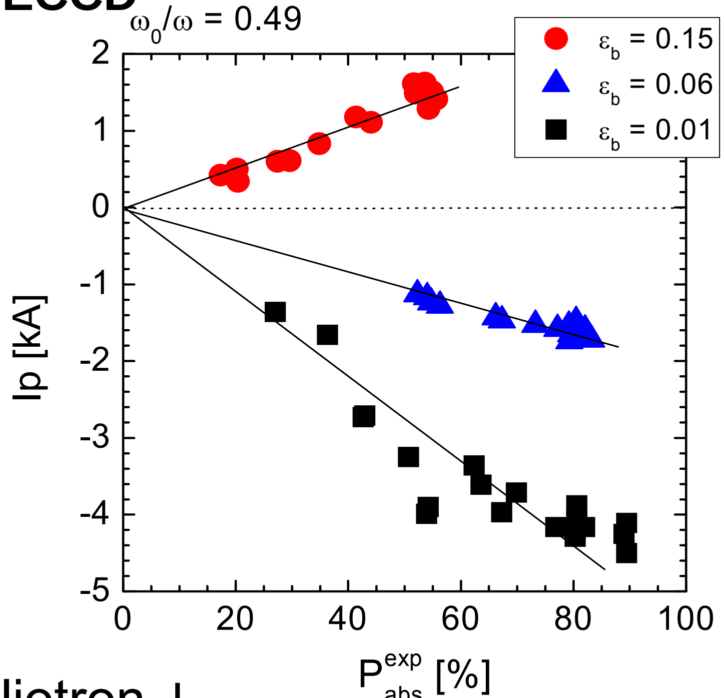
CHS

Role of Single Pass Absorption

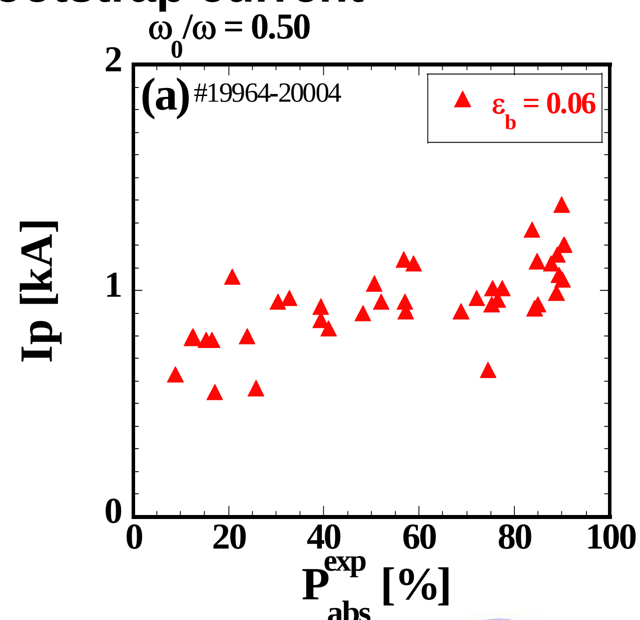
- The X-mode fraction was changed by polarization control angle in order to determine the role of single pass absorption
- EC current decreases when the X-mode fraction is decreased in all three configurations, indicating that the ECCD is driven by single pass absorption



ECCD



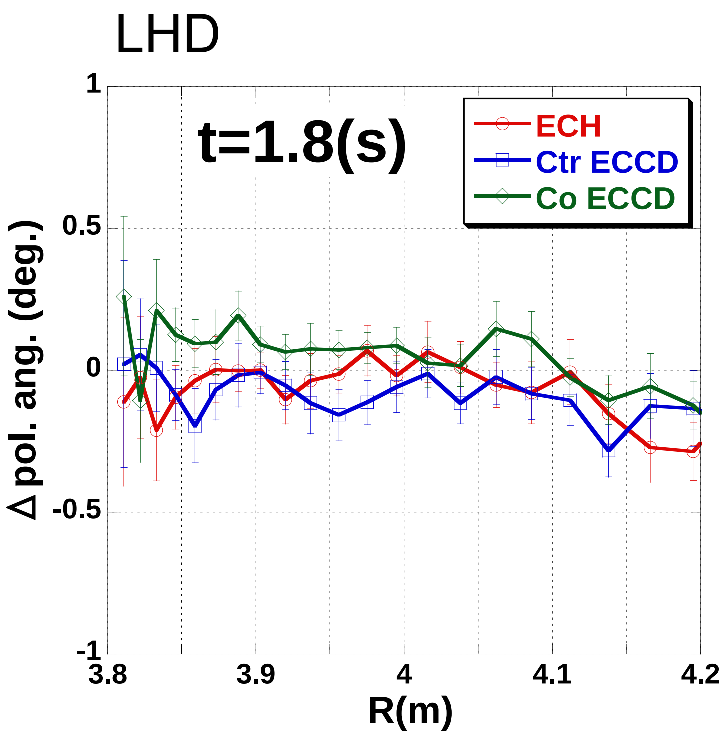
Bootstrap current

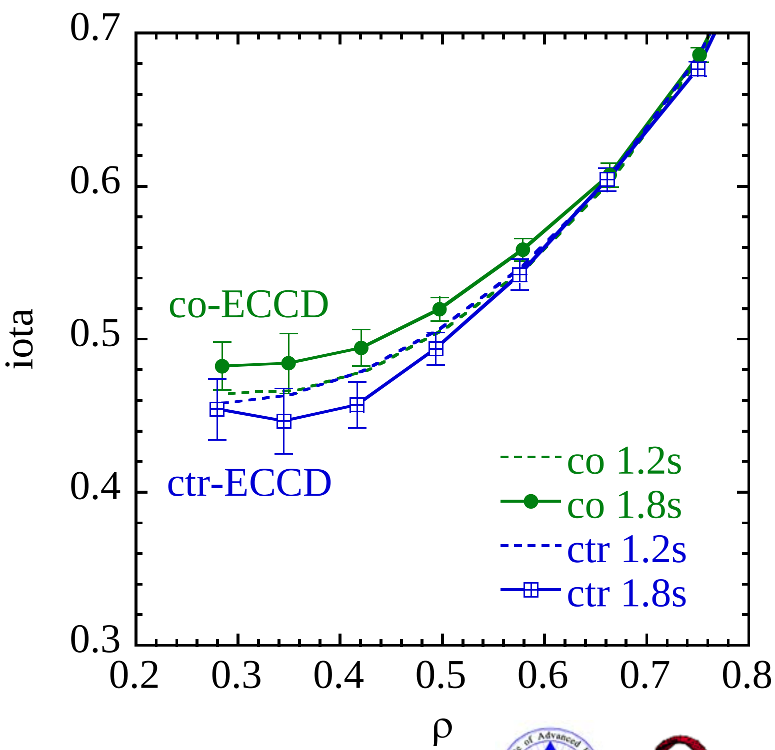


Heliotron J

Effect on Rotational Transform Profile (I)

- Rotational transform profile has been measured in LHD by MSE diagnostic
- Co-ECCD increases the central rotational transform, and vice versa.
- This tendency qualitatively agrees with the direction of poloidal magnetic field generated by the measured EC current

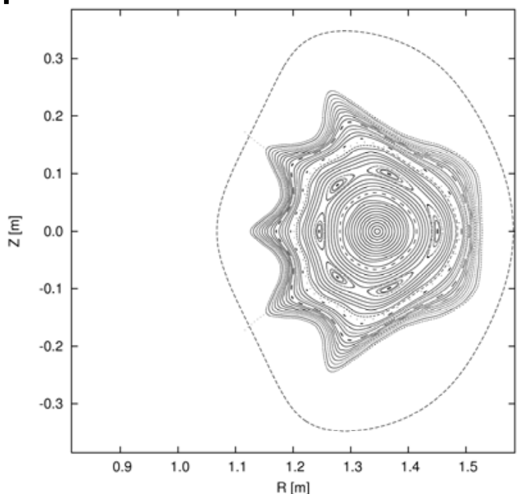




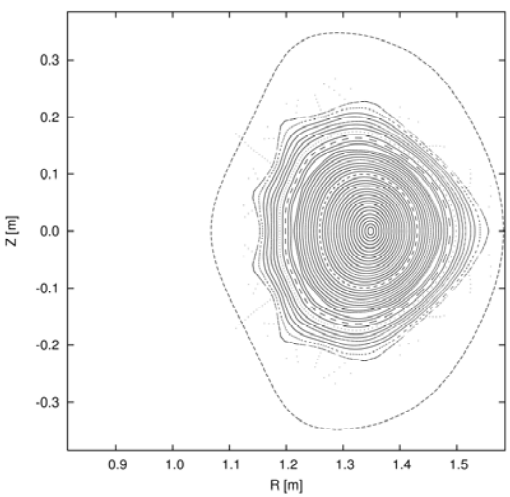
Effect on Rotational Transform Profile (II)

- Rotational transform profile is calculated by HINT2 code

Ip=+5kA $\varepsilon_b = 0.01$

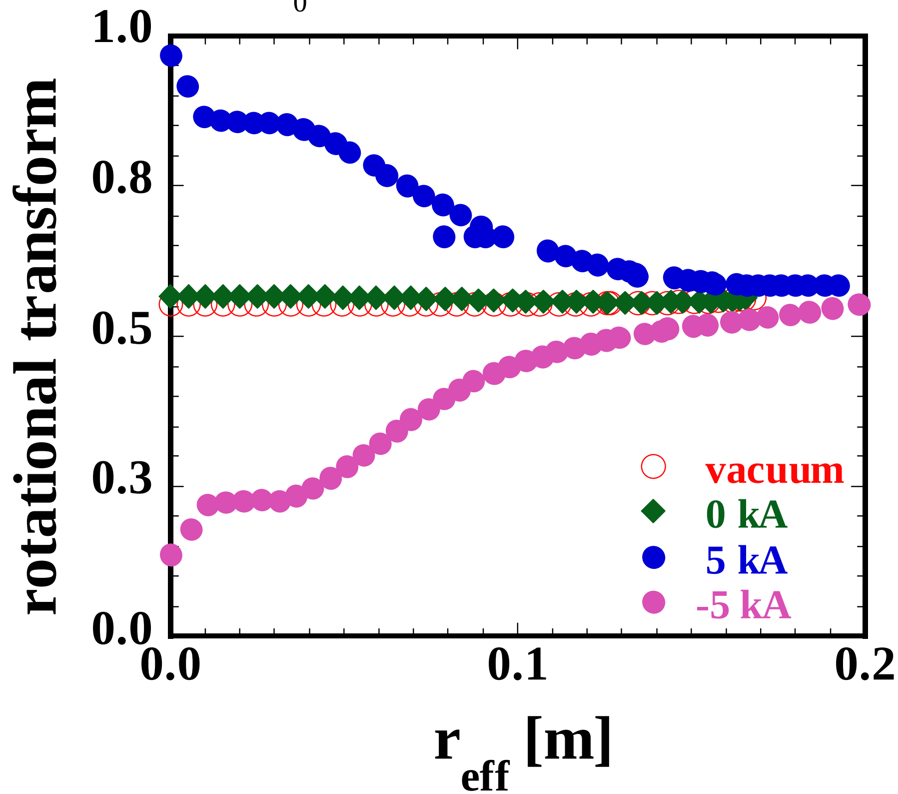


Ip=-5kA



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

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

Estimation of ECCD Efficiency

- ECCD efficiency in linear theory

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

$$= \frac{3em\mathrm{v}_1^{\,2}}{4\pi e^4 n_e \Lambda (5+Z_{eff})}$$

$$\gamma = \frac{I_{EC} n_e R}{P_{EC}} \sim \frac{T_e}{5+Z_{eff}}$$

Fisch, PRL 41 (1980) 720

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

- Dimensionless figure of merit

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

Prater, PoP 11 (2004) 2349

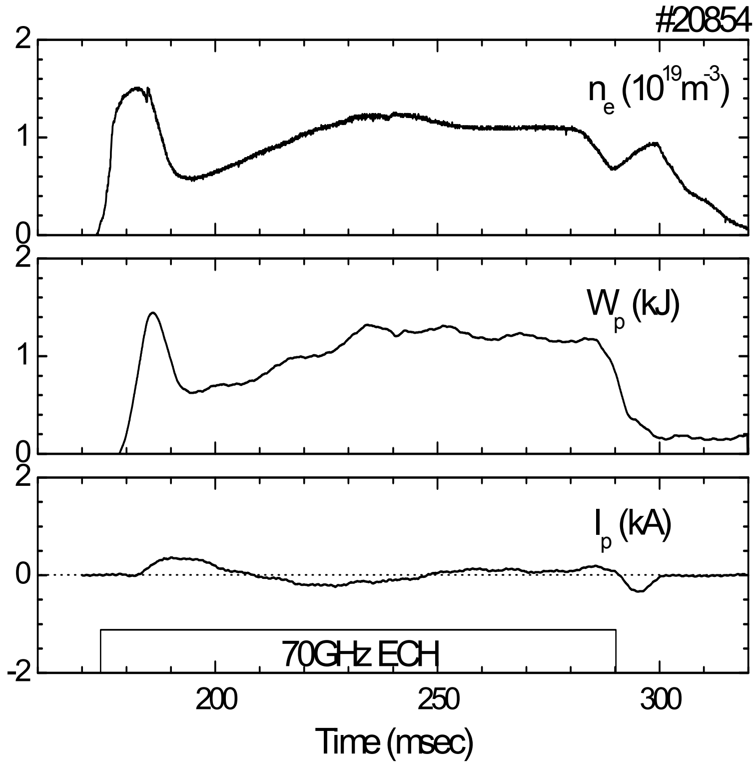
Current Drive Efficiency

	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

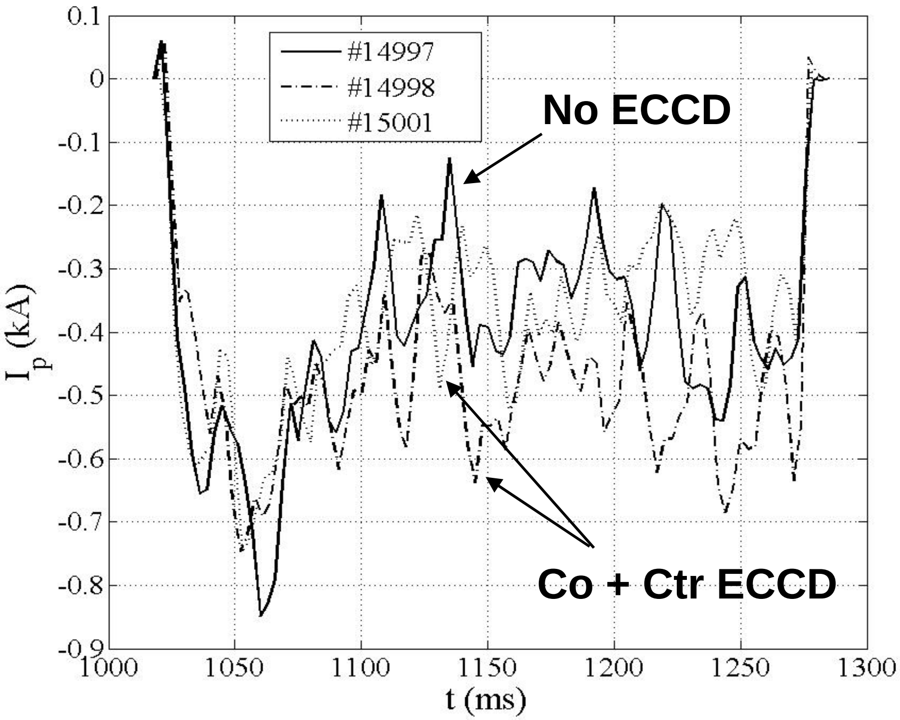
Control of Net Current in ECH Plasmas

- 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



Conclusion

- The ECCD has been studied in Heliotron J (Kyoto Univ), TJ-II (CIEMAT), CHS (NIFS) and LHD (NIFS)
- The EC current is controlled by $N_{||}$, the EC power deposition and magnetic field configuration
- The ECCD is determined by the ripple structure at the EC power deposition due to the balance between the Fisch-Boozer and Ohkawa effects
- The current drive efficiency is similar in Heliotron J, TJ-II and CHS
- The EC current is comparable to the BS current
- Net free current state has been experimentally demonstrated by compensating the bootstrap current with the EC current

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