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Development of high-power, long-pulse gyrotrons and its application for high electron temperature, EBWH and ECCD experiments on LHD

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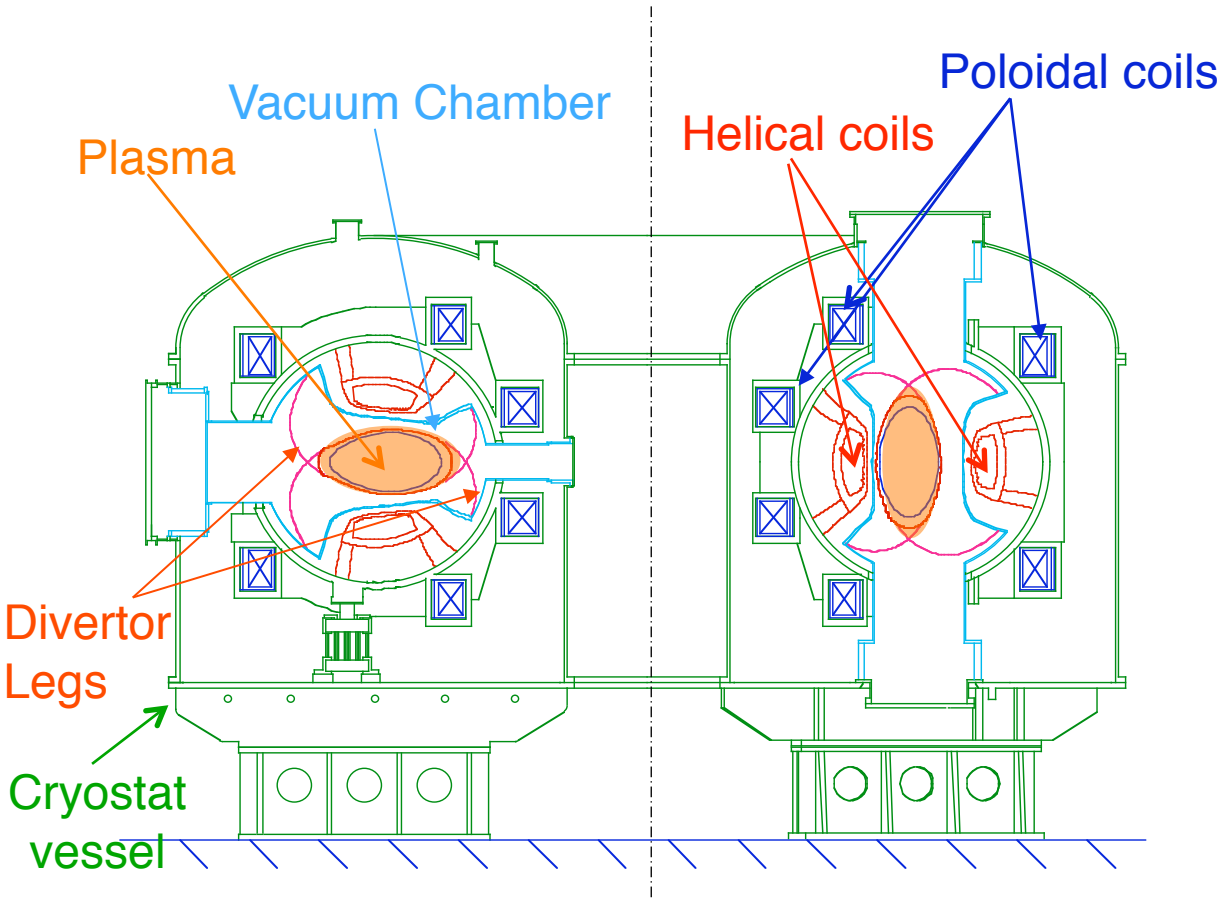
> Summary

Large Helical Device (2010, 14th exp. campaign)
Upgrade of Heating systems



Total Weight 1,500ton
World Largest Superconducting Device

> LHD Specifications

-Plasma Major radius
3.4 ~ 4.1m

-Plasma Minor radius
~ 0.63m (at R_{ax}=3.6m)

-Plasma Volume
~ 30m^3 (at R_{ax}=3.6m)

-Magnetic field on axis
< 2.85T (at R_{ax}=3.6m)

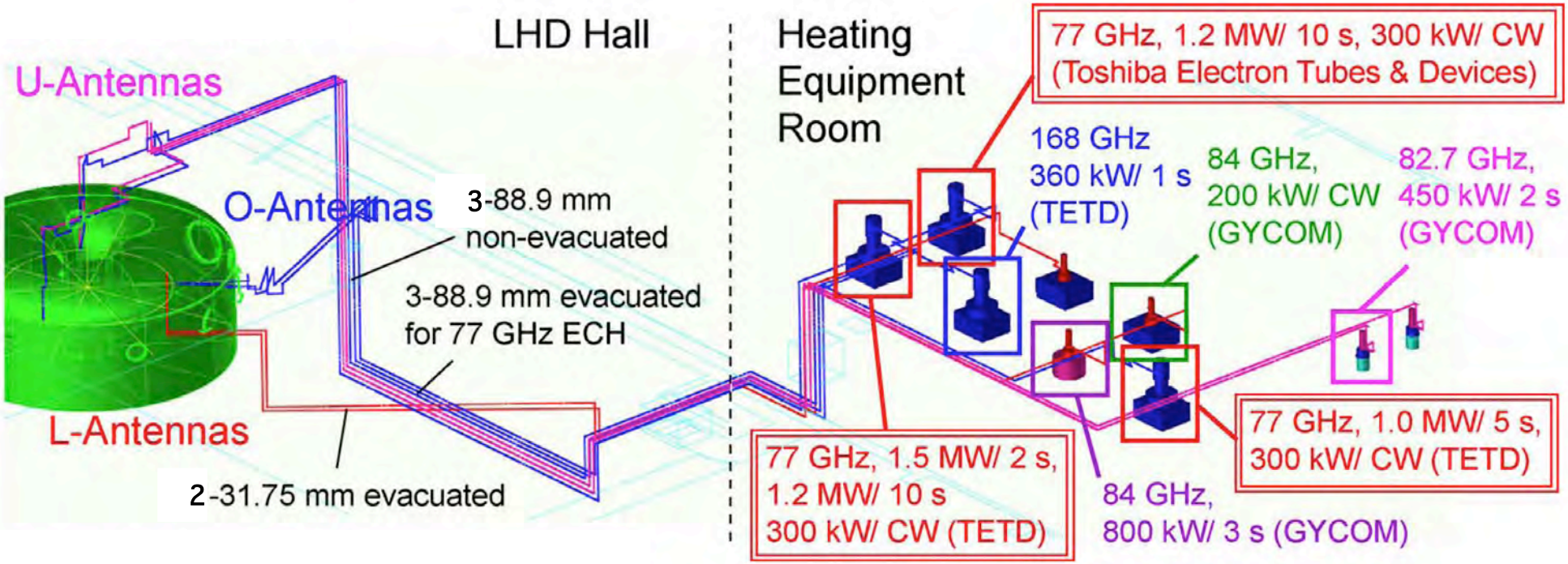
> Heating power

-ECH
(77/82.7/84/168GHz)
3.5MW 0.4MW/CW
-> 3.7MW 0.6MW/CW

-NBI (Neg.x3, Pos.x2)
21MW 0.5MW/10min
-> 27MW 0.5MW/10min

-ICRF (25-100MHz)
0 MW
-> 1.5MW 1MW/CW

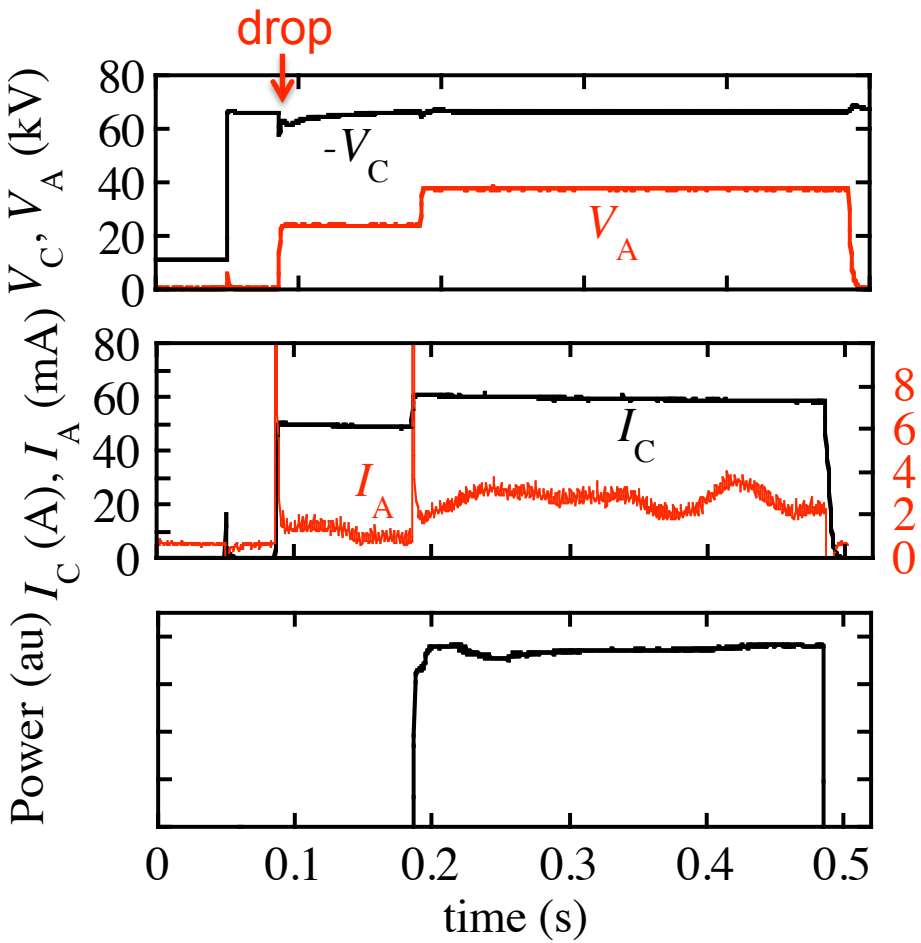
State of ECH System on LHD

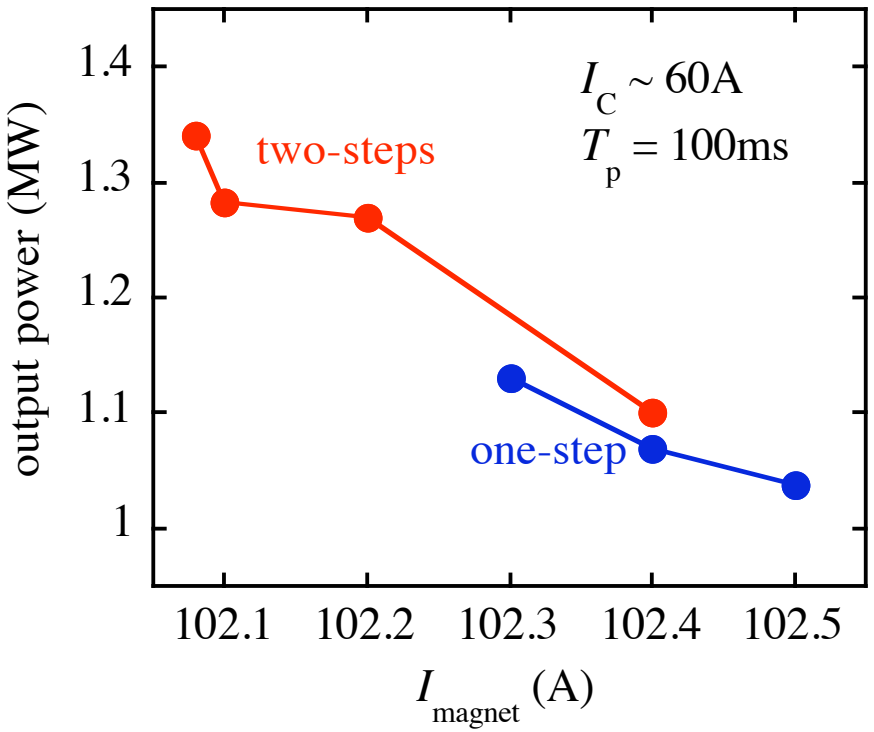


> New high-power, long-pulse 77GHz gyrotrons (#1 started working on 2007, #2: on 2008 and #3: on 2009)
> 7 working gyrotrons (77G x3, 82.7G x1, 84G x2, 168G x1)
> 8 transmission lines (evacuated x5, non-evacuated x3)
> Max. total injection power to LHD simultaneously was 3.7MW last experimental campaign

Modification of Anode Voltage Control Works Well for Improved Operation of Gyrotrons

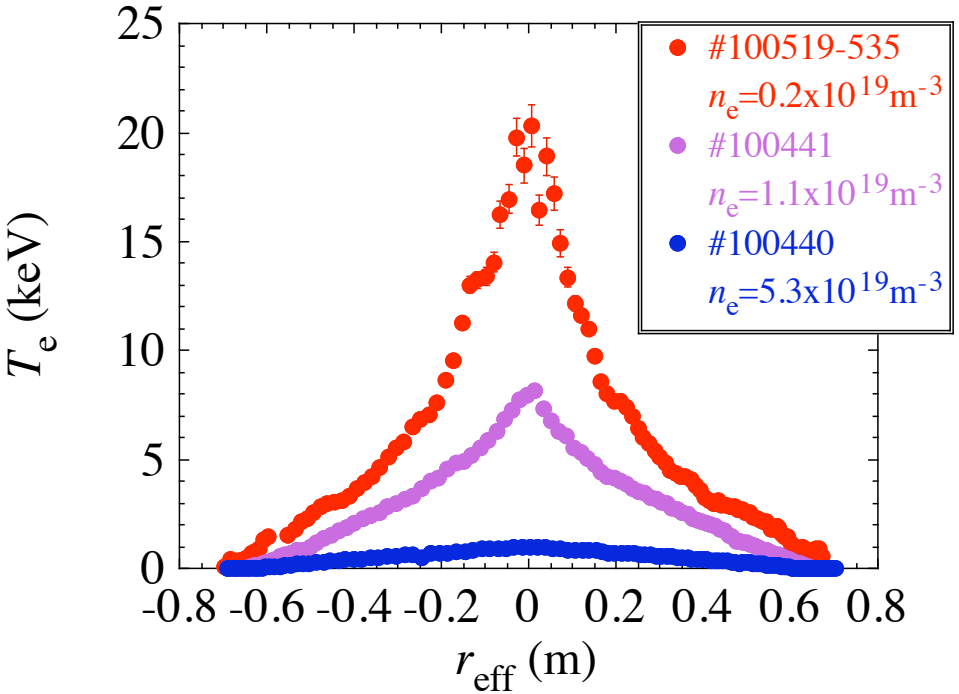
> Large drop of V_C at the rise time of I_C causes large I_A and failure of operation
> Anode PS was modified to be an amplifier for external signal
> Two-steps operation of V_A (moderate V_A at the 1st step) using function generator suppresses I_A and widens operation parameter region for power-up

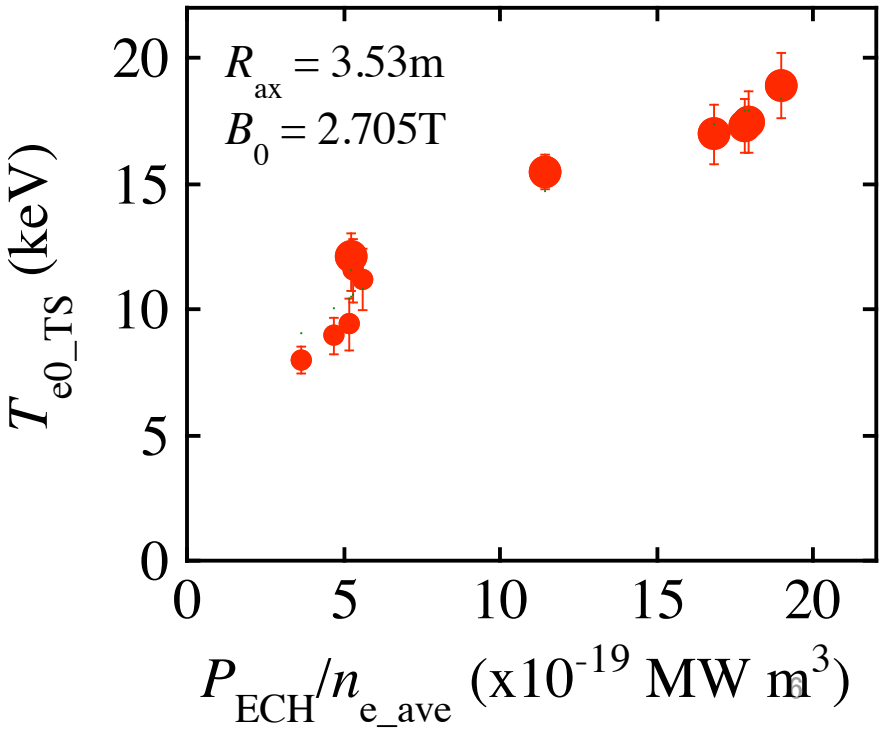




High-Power, Center-Focused ECH Contributes to Extend LHD Plasma Parameter Region: T_{e0} up to 20keV

> High T_{e0} up to 20keV was successfully achieved with improved ECH system (77GHz power = 3.3MW) for $n_e = 0.2\times10^{19}\mathrm{m}^{-3}$
> LHD plasma parameter region was extended to low-collisional side
> T_{e0} = 8.7keV for $n_e = 1.1\times10^{19}\mathrm{m}^{-3}$, T_{e0} = 1.0keV for $n_e = 5.3\times10^{19}\mathrm{m}^{-3}$
> More power will extend the region to high T_e and higher n_e side



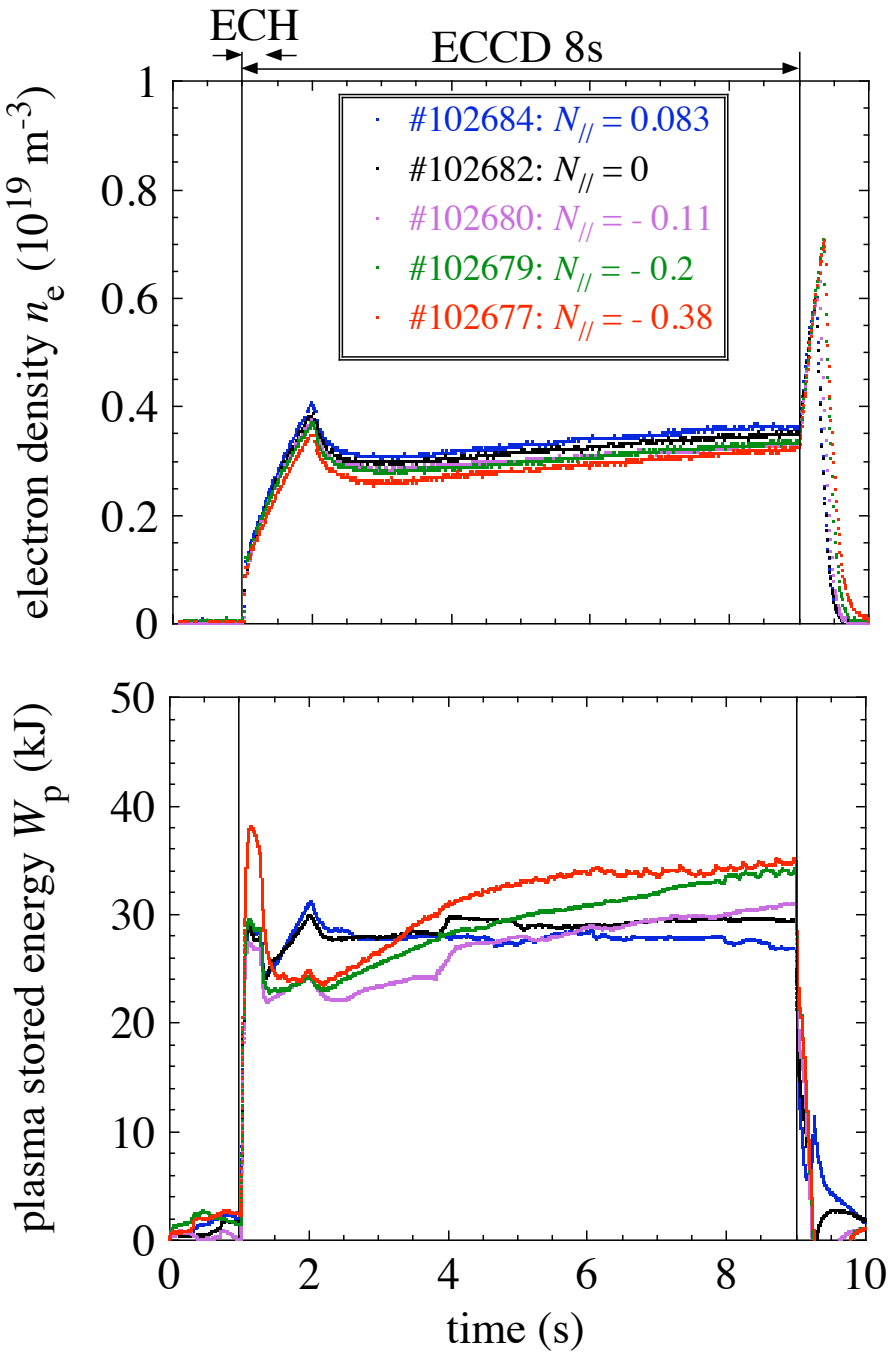


Progress in ECCD in LHD

> Previous ECCD exp. has been performed with 84GHz/200kW/CW ECH system considering long current diffusion time of LHD plasmas

> A high-power, long-pulse 77GHz ECH system with EC-wave beam injection mirror antenna system at a horizontal port which has wide range of beam injection angle effectively works for ECCD

> Goal: improvement of plasma performance with ECCD by controlling current and rotational transform (ι) profiles, especially by removing $\iota/2\pi$=0.5 surface to suppress 2/1 MHD mode



Waveforms in a Series of ECCD Discharges

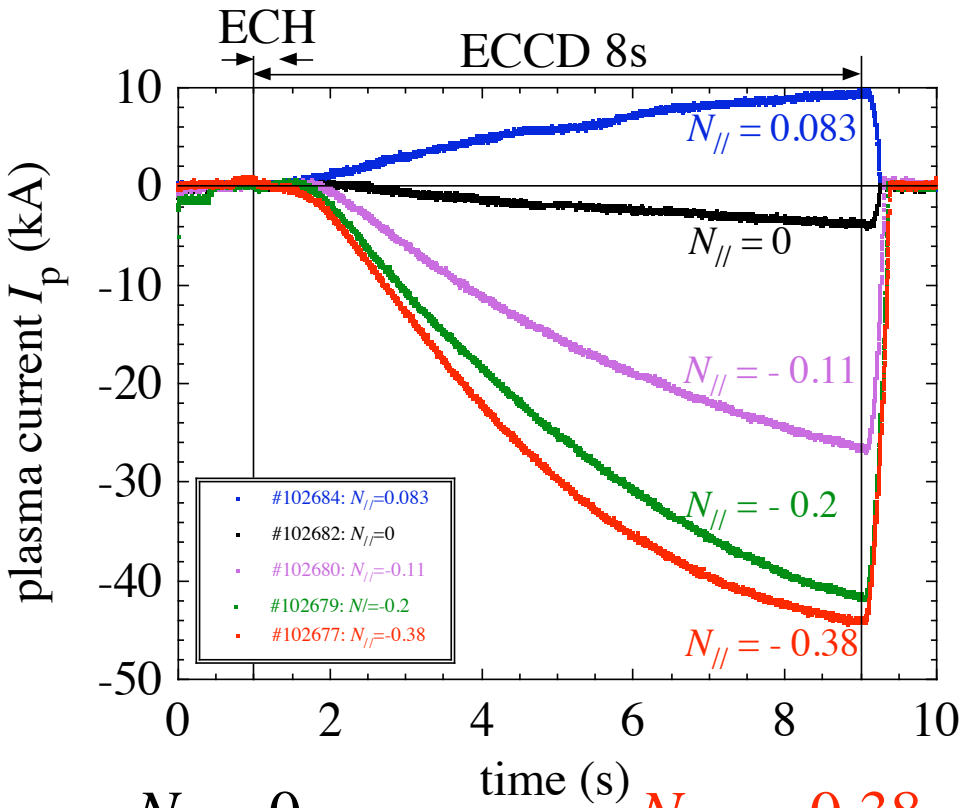
> Stable long-pulse, high-power operation of 77GHz ECH system became possible

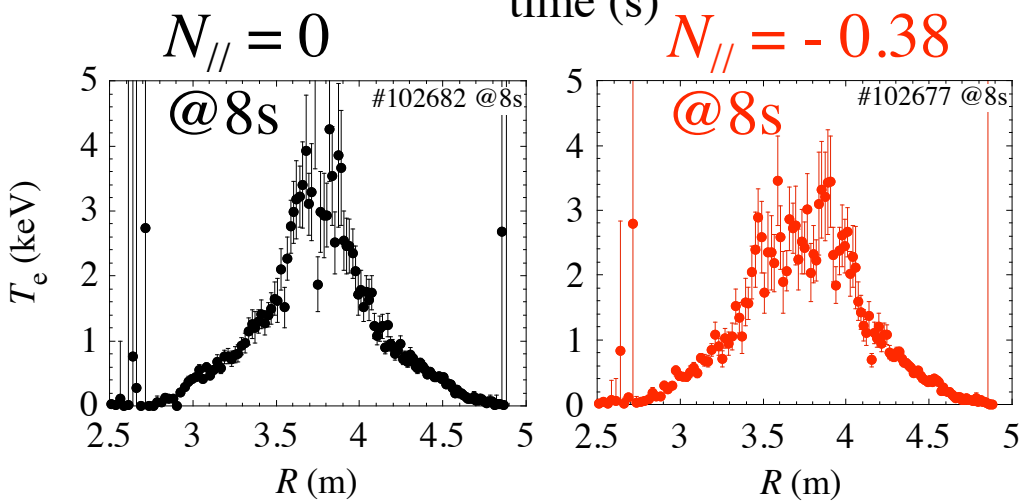
> 2nd harm. ECCD experiment using the 77GHz/775kW EC-wave was performed

> Plasmas with line-averaged electron density n_e of ~ $0.35 \times 10^{19} m^{-3}$ was sustained only with EC-waves in various injection angles defined by $N_{//}$

> n_e and plasma stored energy W_p are nearly the same for discharges instead of wide variation of $N_{//}$

Large EC-Driven Current Generated with 77GHz Wave





> Beam direction $N_{//}$ was scanned in toroidal direction aiming at magnetic axis

> Right-hand circular pol. was set for non-zero $N_{//}$ and linear X-mode for $N_{//}$=0

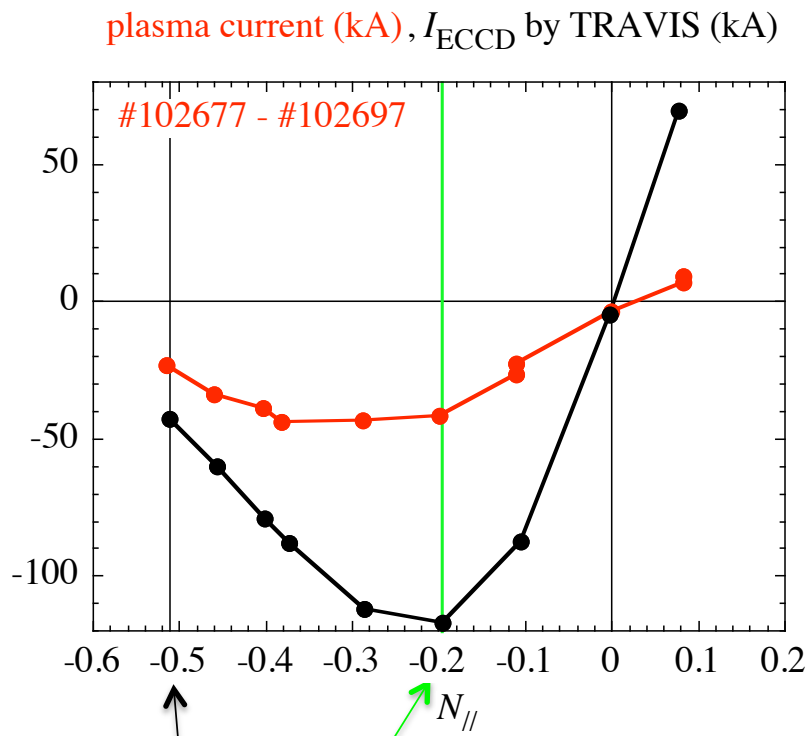
> I_p reverses its direction by the change of the sign of $N_{//}$

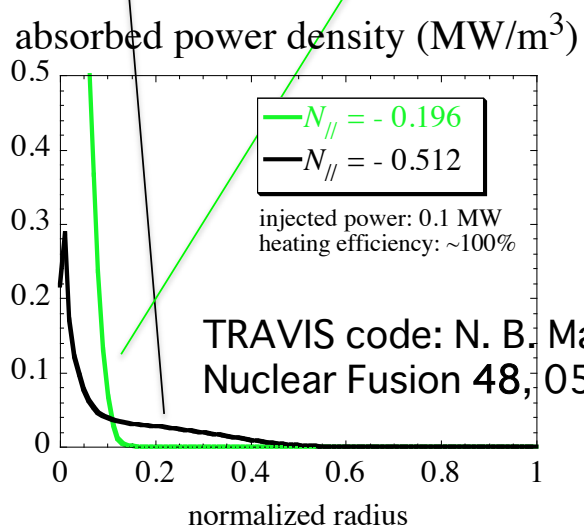
> Direction of I_p agrees with the Fisch-Boozer theory

> Max. ECCD efficiency $\eta = n_e * R_{ax} * I_{ECCD} / P_{EC}$ ~6.4x10^{17} A/Wm^2: 1.6 times higher than the previous record in LHD

> T_e profile becomes broader with $|N_{//}|$, suggesting Doppler-shifted broader power deposition

Optimization of EC-Wave Beam Direction for ECCD





TRAVIS code: N. B. Marushchenko et al., Nuclear Fusion **48**, 054002 (2008)

> EC-wave beam direction $N_{//}$ was scanned in the range of -0.51 ~ 0.08

> Optimum $N_{//}$ for effective ECCD was confirmed as ~ -0.3 experimentally

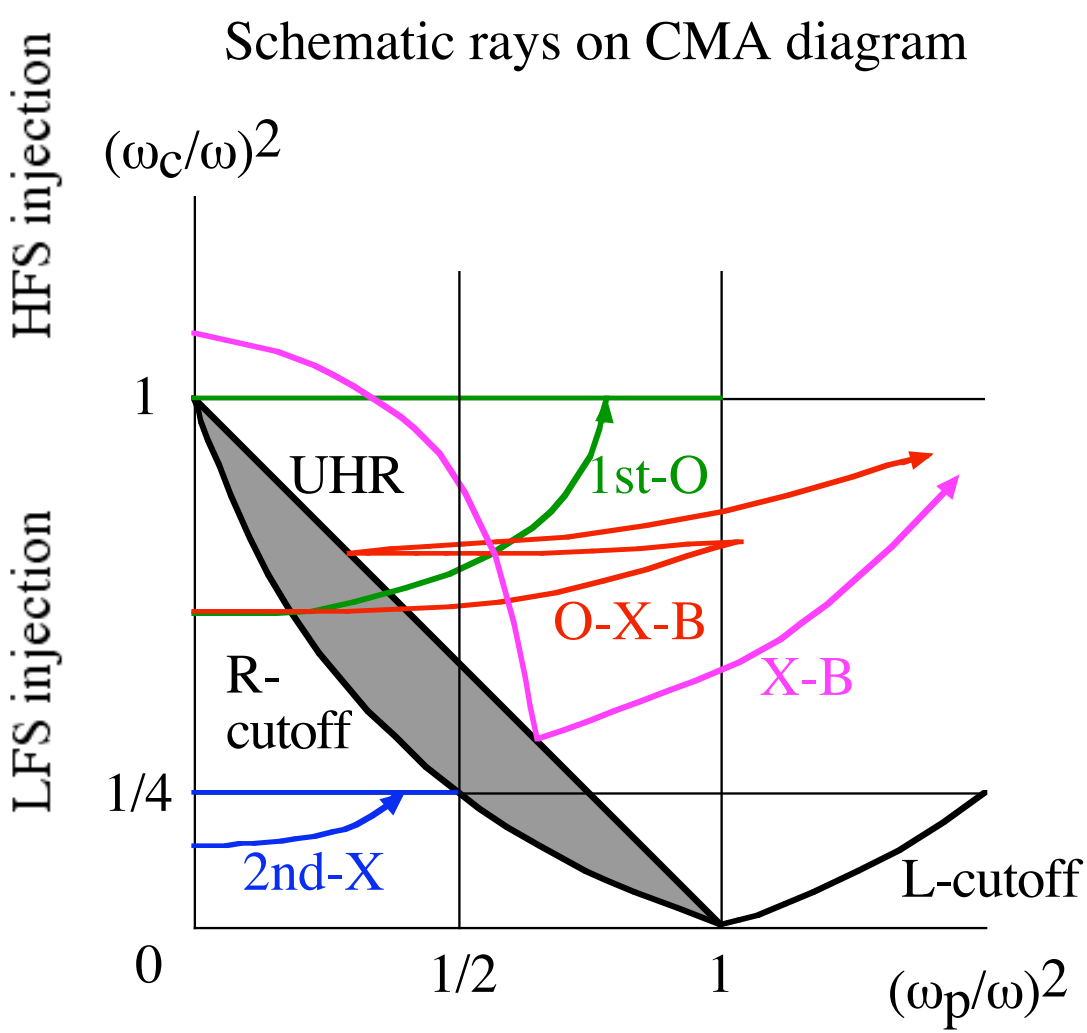
> With larger $|N_{//}|$, the power deposition becomes off-axis where magnetic ripple is larger than that at near-axis: the decrease in driven current at $N_{//} < -0.4$ would be attributed to the ripple effect

> Dependence of I_{ECCD} on $N_{//}$ calculated with TRAVIS code qualitatively explain that of measured I_p in experiment, except for the absolute value

Electron Bernstein Wave Heating in LHD

> Recent progress in LHD plasma parameters, especially in achieving high central electron density over $1 \times 10^{21} m^{-3}$ named super-dense-core plasma, highly requires EBWH

Two EBWH Schemes in LHD: Slow X-B and O-X-B



> Conventional 2nd-X and 1st-O waves have density limits while EBW doesn't

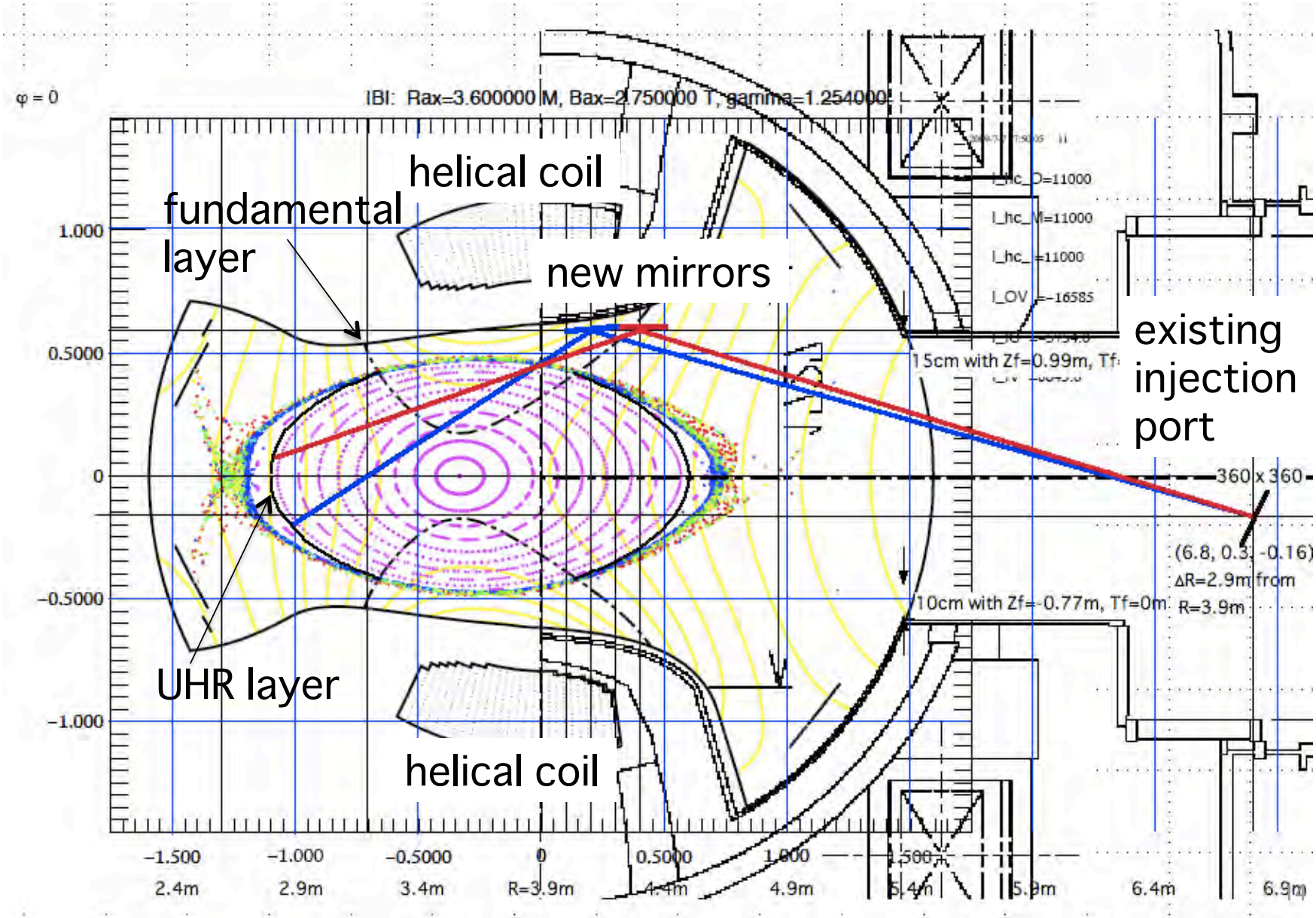
> Recent developments of plasma parameters require EBW heating worldwide

> slow X-B: X-wave is injected from the High-Field-Side, then converted to B-wave at UHR layer

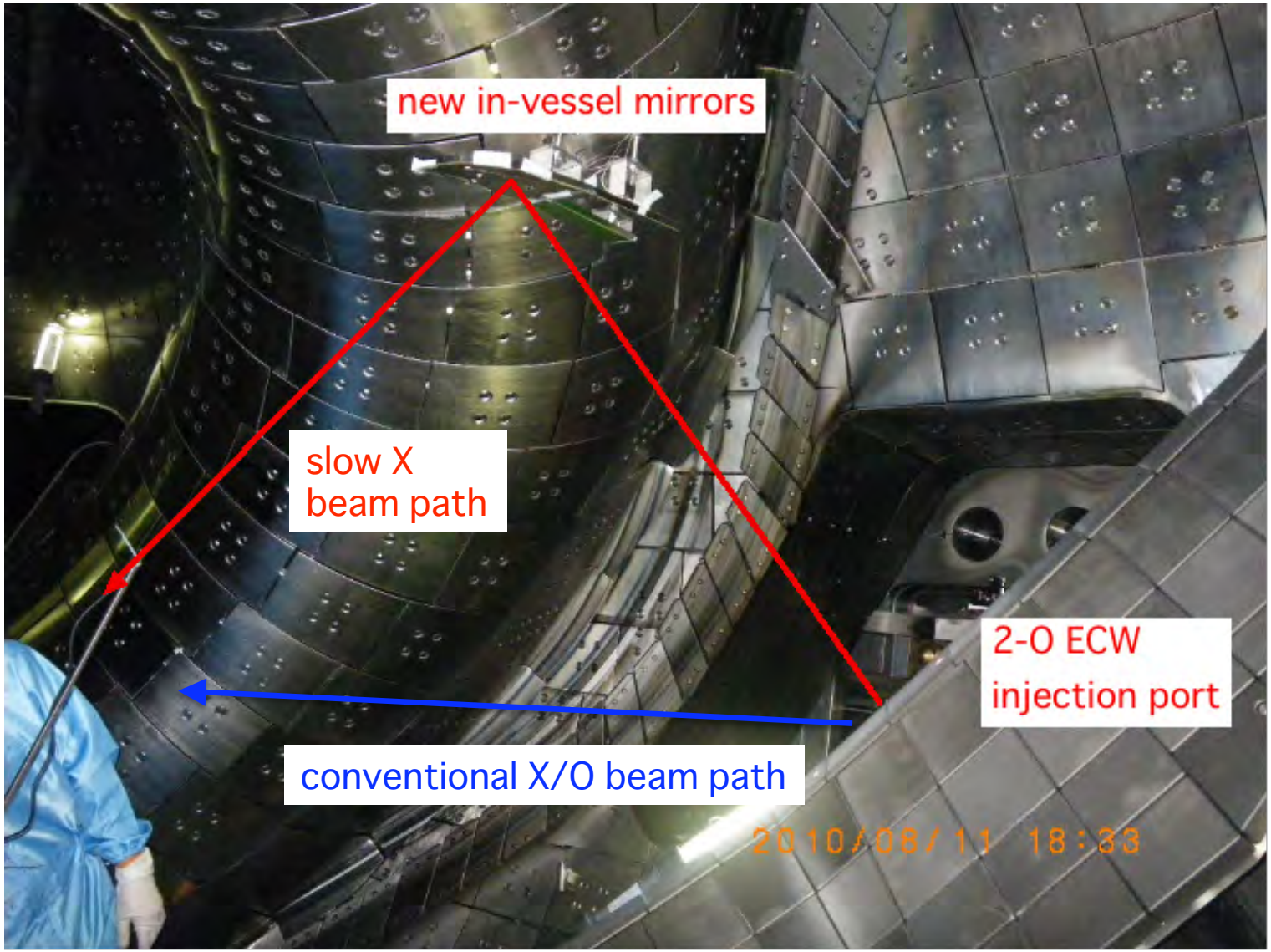
> O-X-B: O-wave is obliquely injected from the Low-Field-Side, then converted to X-wave at plasma cutoff layer, and then converted to B-wave at Upper-Hybrid-Resonance layer

EBWH by Slow X-B Scheme

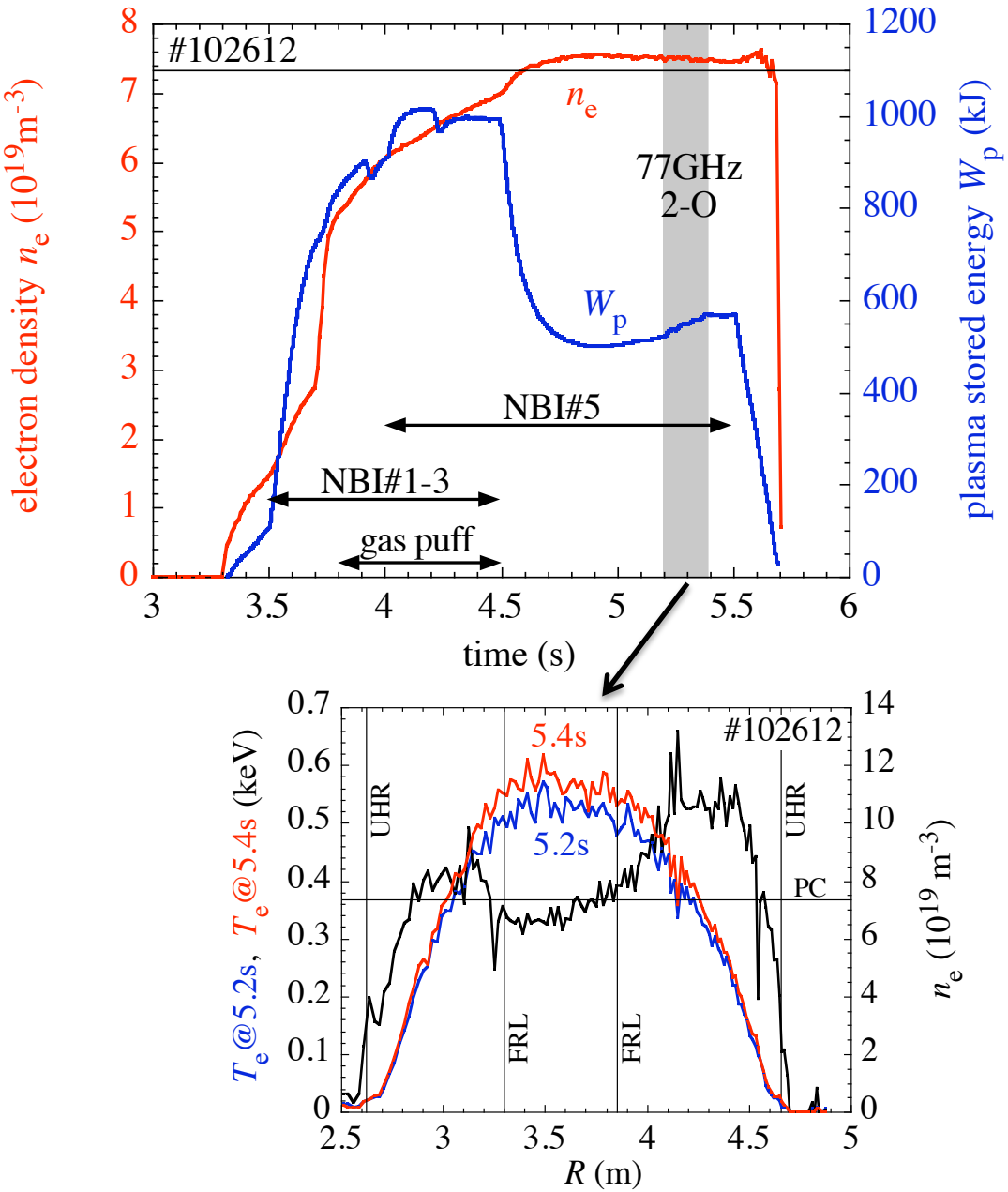
Slow X-B Heating by Use of New in-Vessel Mirrors



Slow X-B Heating by Use of New in-Vessel Mirrors



Successful Heating of Over-Dense Plasmas by HFS X Inj. (1)



> Plasma cutoff density for 77GHz wave is 7.35×10^{19}m^{-3}

> Target over-dense plasmas were sustained with 5MW NBI: much higher than ECH power of 775kW

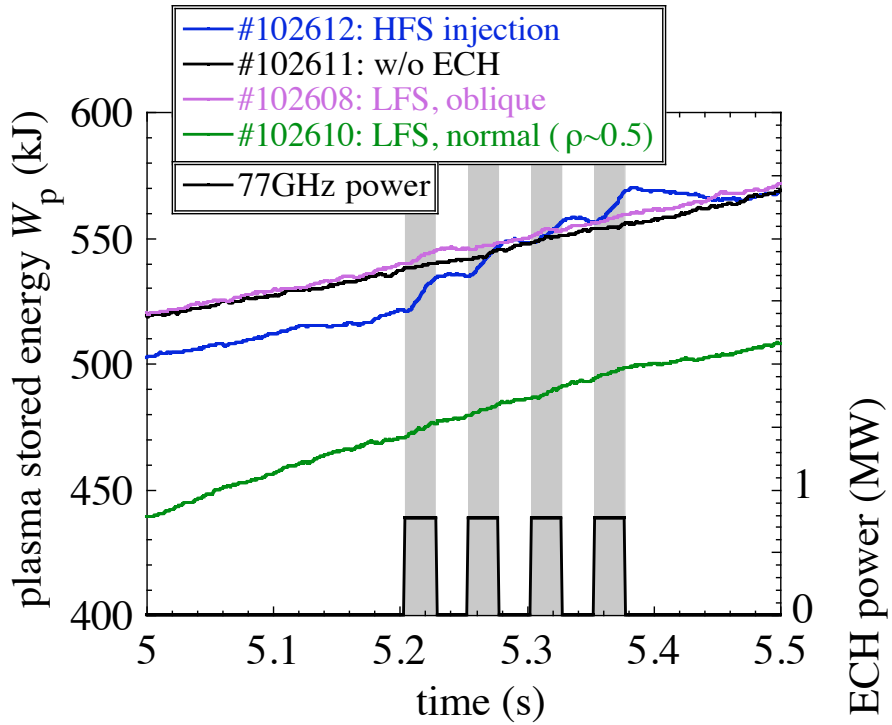
> 20Hz-modulated EC-waves were injected in X-mode from HFS

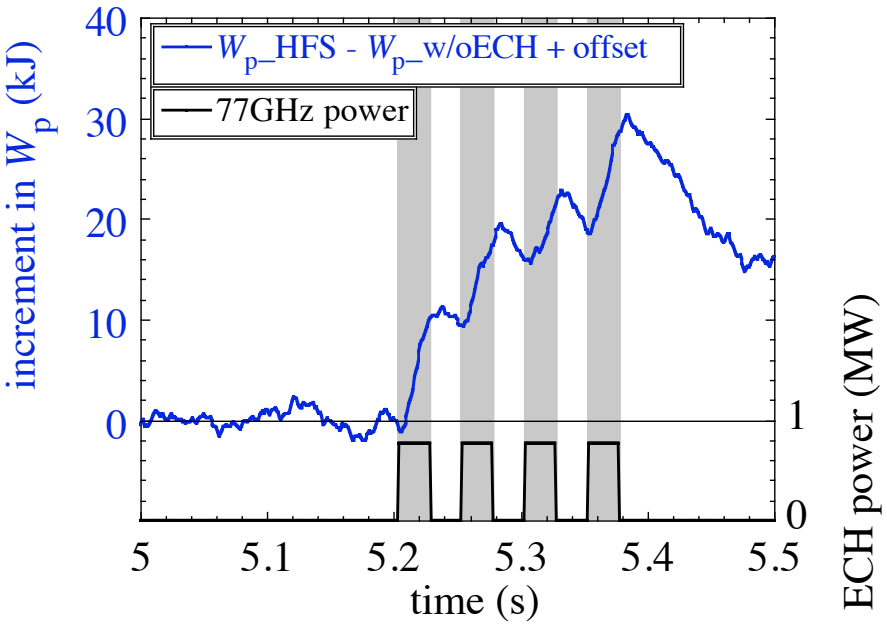
> Line-averaged n_e at the timing of EC-wave injection is higher than 7.5×10^{19}m^{-3}

> Fundamental resonance layer on the beam path is surrounded by over-dense region for O-mode, but it is not the case for slow X-mode (cutoff: 14.7×10^{19}m^{-3})

> Clear increases in T_e at the core and W_p were observed

Successful Heating of Over-Dense Plasmas by X-Mode Injection from HFS (2)





> W_p increases with the slow X-mode injection, adding to the increasing trend caused by NBI

> τ_E is evaluated as ~140ms

> Heating efficiency evaluated from the changes in W_p is ~70%

> On the other hand, usual ways of O-mode injection from low-field-side have no effect on W_p

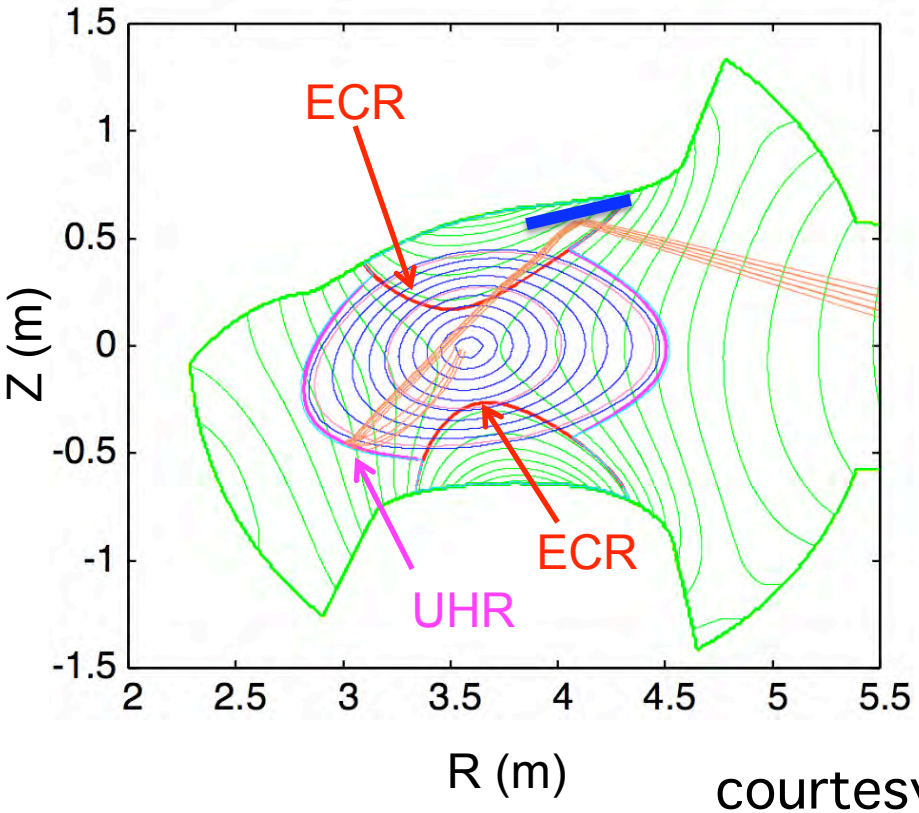
> Thus, effective heating of high-density plasmas over plasma cutoff by slow X-B, and/or fundamental X was successfully demonstrated

> Following experiments will distinguish the heating effects by slow X-B and fundamental X

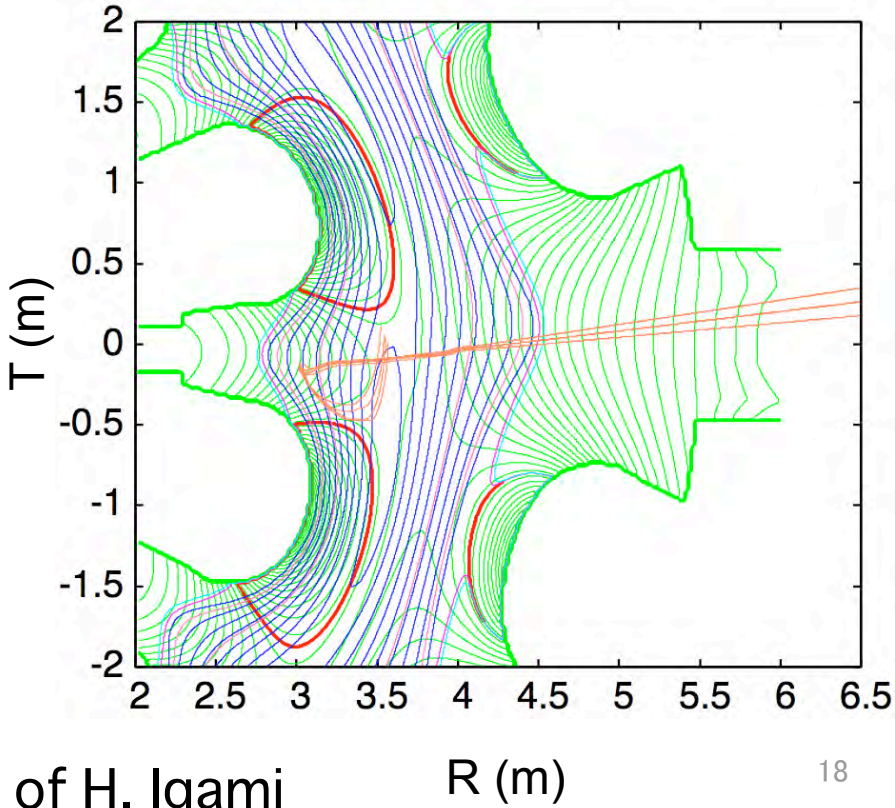
Ray Trajectory and Power Deposition in X-Mode Injection from HFS (1)

> Ray-trace calculation shows that the injected X-mode wave is mode-converted to a Bernstein wave at the UHR layer in the peripheral region, and the B-wave goes back to the plasma core

poloidal cross section



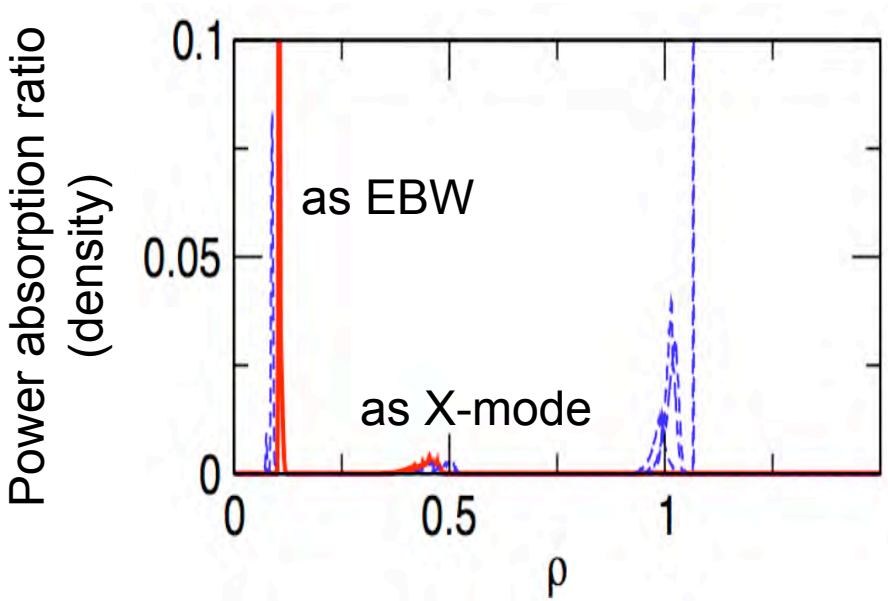
toroidal cross section

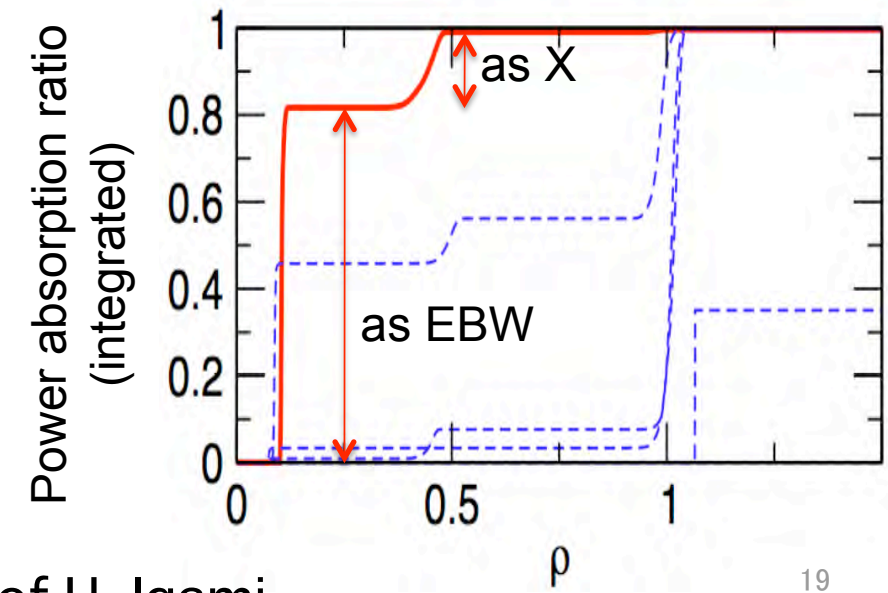


courtesy of H. Igami

Ray Trajectory and Power Deposition in X-Mode Injection from HFS (2)

> Ray-trace calculation shows that the power of the center-beam line plotted in red is partially (~20%) absorbed as X-mode wave when it passes the fundamental resonance layer at ρ ~0.5, and mostly (~80%) absorbed as EBW at the plasma core region





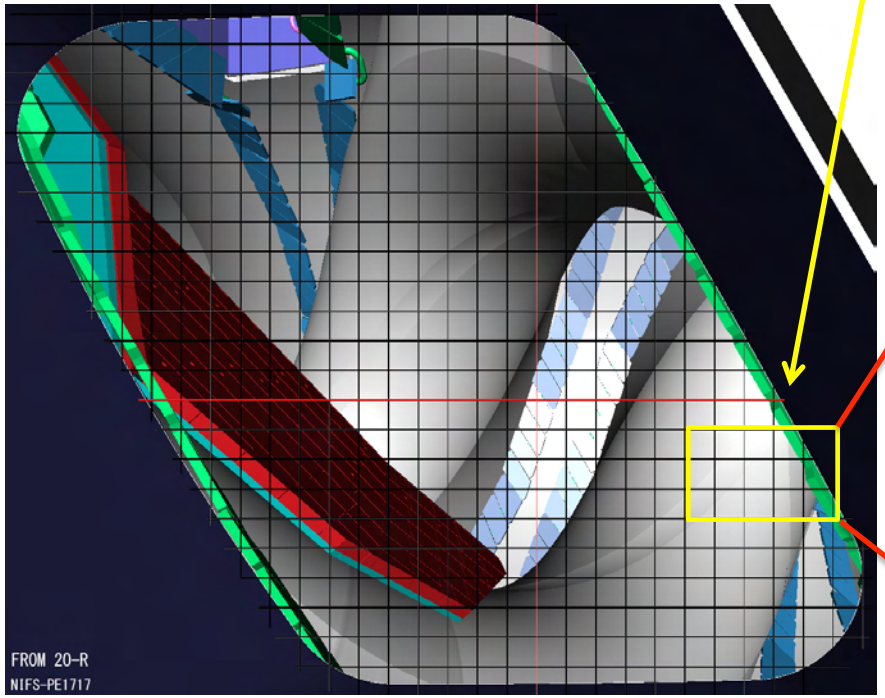
courtesy of H. Igami

EBWH by O-X-B Scheme

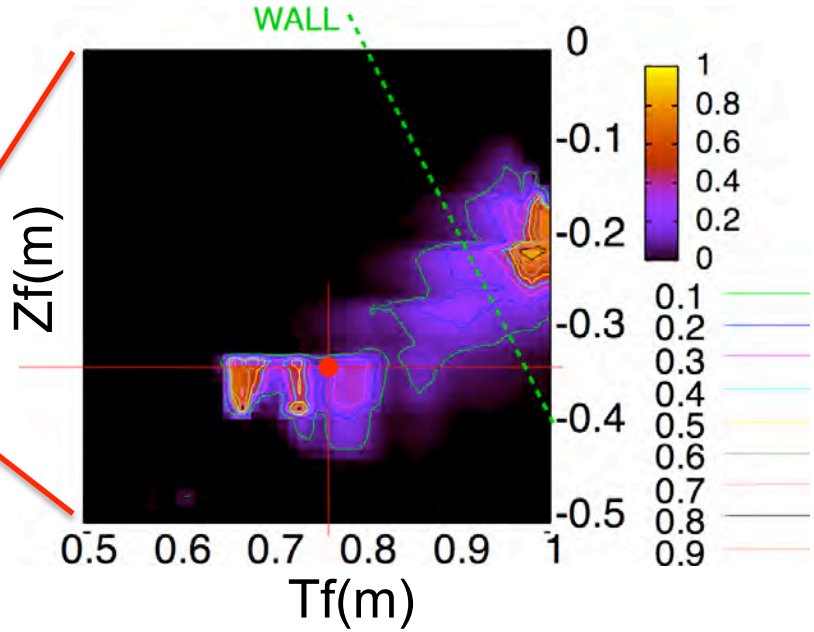
Estimation of the O-X-B Mode Conversion Efficiency

View from the horizontal port

Surveyed region



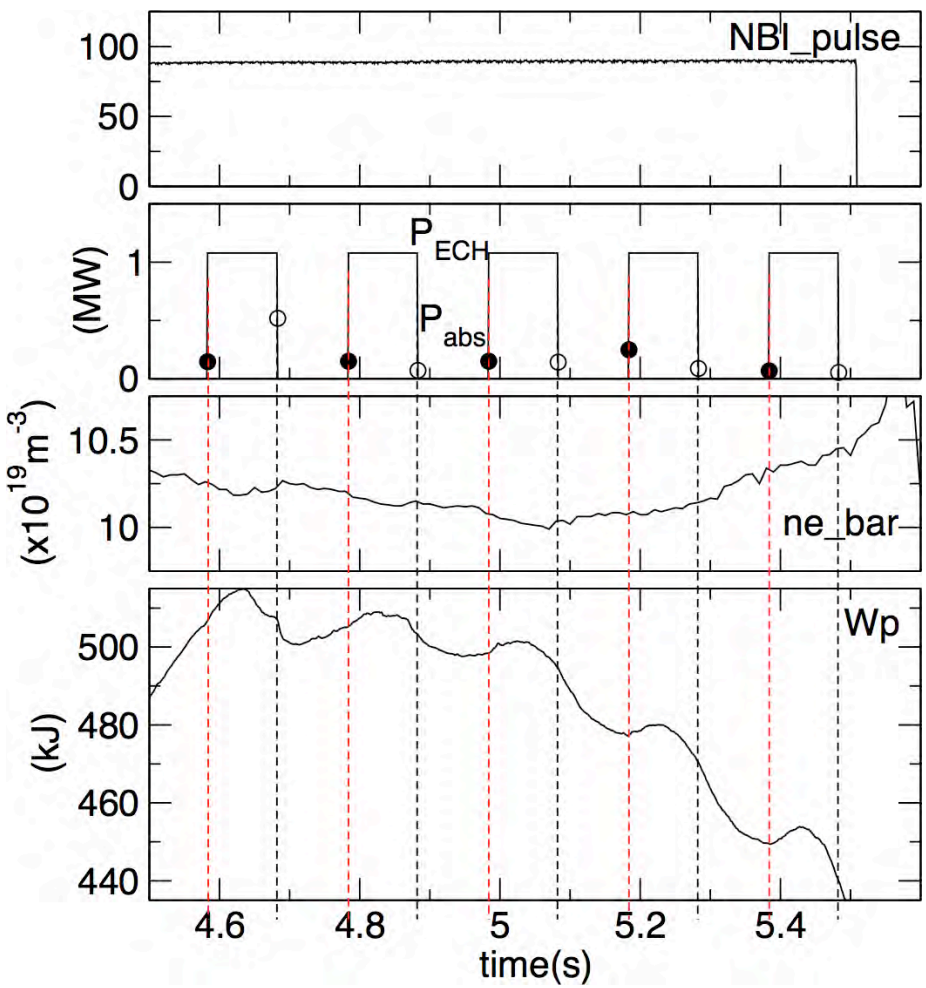
OXB mode-conversion efficiency



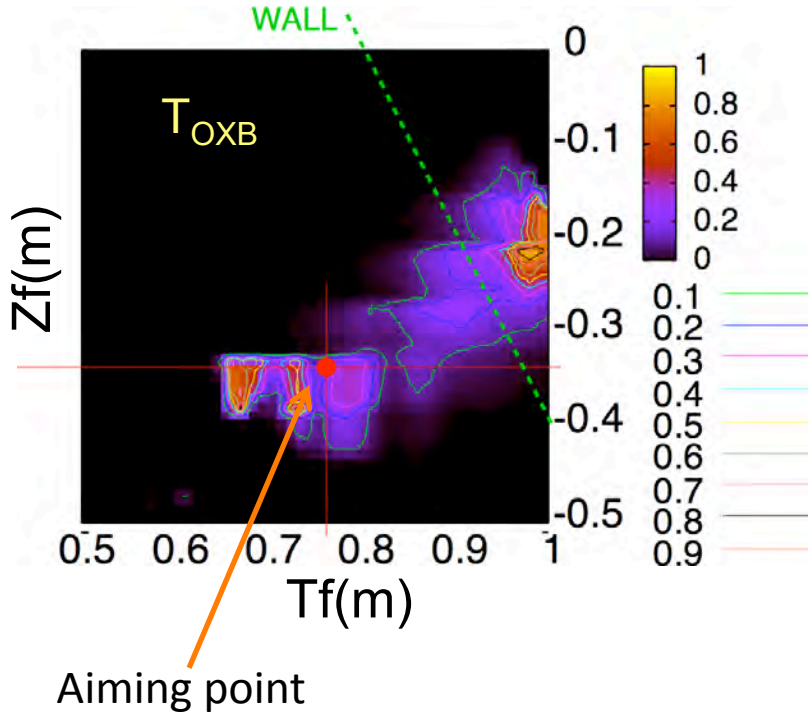
Increase in W_p was Observed for Over-Dense Plasmas with Left-Hand Circular Polarization (nearly O-mode) Injection

#103209

(Ra, Bt, g, Bq)=(3.75m, -2.2T, 1.2538, 100%)



OXB mode-conversion efficiency



> With right-hand circular polarization (~X-mode), the increase in W_p disappears

Summary

> ECH system on LHD has been upgraded by applying high-power, long-pulse 77GHz gyrotrons

> With the high-power 77GHz ECW, T_{e0}=20keV/n_e=0.2x10^{19}m^{-3}, 8.7keV/1.1x10^{19}m^{-3} and 1.0keV/5.3x10^{19}m^{-3} were achieved

> With 775kW, 8s 77GHz EC-wave injected in optimum toroidal angle, significant EC-driven current over 40 kA was successfully generated

> Control of current and rotational transform profiles with the high-current ECCD will improve LHD plasma performance

> Both of EBWH schemes for over-dense plasmas: slow X-B and/or fundamental X by use of in-vessel mirror for high-field-side injection, and O-X-B by EC-wave beam injection to mode conversion window were successfully demonstrated

> Effective EBWH will contribute to achievements of higher electron density and higher plasma stored energy in LHD even for over-dense plasmas