Lower Hybrid Wave Principles: Physics Overview

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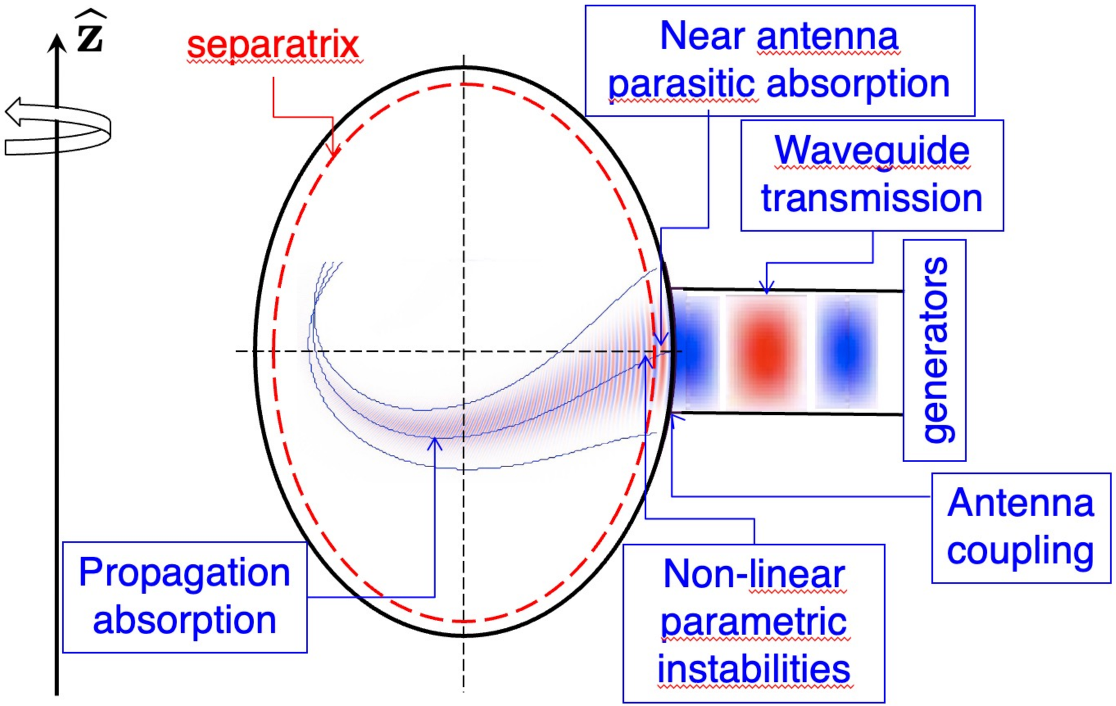
Introduction

- The lower hybrid wave (LHW) is the wave with a frequency between ion cyclotron frequency and electron cyclotron frequency.
- LHW has the attractive property of driving electrons at high parallel phase velocities relative to the electron thermal speed, so it can noninductively drive plasma current efficiently.
- LHCD have been verified in many experiments and has the best ever achieved CD efficiency whatever the non-inductive methods, however, it faces big challenges in reactor-level plasma. Moreover, the LHCD efficiency is still too low for sustaining all plasma current with an acceptable recycled power in fusion reactor. Therefore, the LH wave might be a useful tool for off-axis current profile control in future reactor.
- The LHW dynamics strongly depends on the profiles of density and temperature, and, at the same time it contributes to the profiles through current drive and heating, therefore the theory and simulation must be considered in an integrated tokamak modelling frame.

LHW in tokamak plasma



Y. Peysson, 2009

OUTLINE

- Concept of LHW and its linear dispersion relation
- Propagation, accessibility and absorption in toroidal geometry
- Principles of LHCD
- Representive experimental results
- Challenges at high density
- On helicon wave (LH fast waves)

Frequency range of LH waves

- **Between ion cyclotron frequency and electron cyclotron frequency or near the lower hybrid frequency**

$$\omega_{\mathrm{ci}} \ll \omega \sim \omega_{\mathrm{LH}} = \left(\frac{\omega_{\mathrm{pi}}^2}{1+\omega_{\mathrm{pe}}^2/\omega_{\mathrm{ce}}^2}\right)^{1/2} \ll \omega_{\mathrm{ce}}$$

- **Typical value： at** B=1-10 T， n=10^{18}-10^{20} m^{-3}，

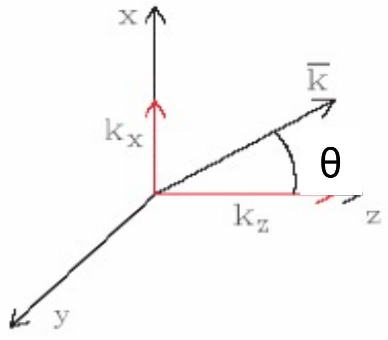
$$\mathrm{f_{LH}} = \frac{\omega_{LH}}{2\pi} = 0.5\text{-}5 \text{ G Hz}$$

$$\lambda_{\mathrm{LH},\boldsymbol{vac}} = \frac{\omega_{LH}}{2\pi} = 60\text{-}6 \text{ cm}$$

e.g. 2.45/4.6 G @EAST, 3.7 G@HL-3 and WEST, 4.6G @ C-mod, 5G @ITER

- **Both ion and electron dynamics included, therefore rich in physics**

Dispersion relation in cold plasma at LHRF



$$\begin{pmatrix} S-n_z^2 & -iD & n_z n_x \\ iD & S-n^2 & 0 \\ n_z n_x & 0 & P-n_x^2 \end{pmatrix} \cdot \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0$$

$$S = \frac{R+L}{2} = 1 - \sum_\alpha \frac{\omega_{p\alpha}^2}{\omega^2 - \omega_{c\alpha}^2} \Longrightarrow S = 1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2}$$

$$D = \frac{R-L}{2} = \sum_\alpha \frac{\omega_{c\alpha}\omega_{p\alpha}^2}{\omega(\omega^2 - \omega_{c\alpha}^2)} \Longrightarrow D = -\frac{\omega_{pe}^2}{\omega\omega_{ce}}$$

$$P = 1 - \sum_\alpha \frac{\omega_{p\alpha}^2}{\omega^2} \Longrightarrow P = 1 - \frac{\omega_{pe}^2}{\omega^2}$$

At B=5T, n=10^{20} m^{-3} ,

P= -321, D= -11.5, S= 1.41

$|P| \gg |D| \gg |S| \sim 1$

except for the edge

$$D \equiv AN_\perp^4 + BN_\perp^2 + C = 0$$

$A = S,$

$B = (S - n_z^2)(S + P) - D^2,$

$C = P\left[(S - n_z^2)^2 - D^2\right].$

$\Rightarrow$

$$n_{\perp F}^2 \approx -\frac{C}{B} \approx -\frac{(n_{||}^2 - S)^2 - D^2}{n_{||}^2}$$

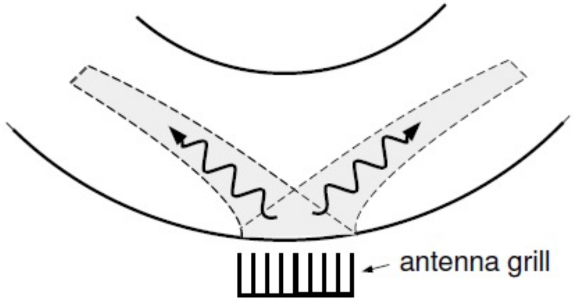
$$n_{\perp s}^2 \approx -\frac{B}{A} \approx -\frac{Pn_{||}^2}{S}$$

Slow wave: nearly parallel propagation

$$n_{\perp s}^2 \approx -\frac{B}{A} \approx -\frac{P n_{||}^2}{S}$$

$$\omega^2 = \frac{\omega_{pi}^2}{1 + \omega_{pe}^2/\omega_{ce}^2 + n_{||}^2/N_{\perp}^2}\left(1 + \frac{m_i}{m_e}\frac{n_{||}^2}{n_{\perp}^2}\right) \approx \omega_{LH}^2\left(1 + \frac{m_i}{m_e}\frac{n_{||}^2}{n_{\perp}^2}\right)$$

$$\frac{n_{||}^2}{n_{\perp}^2} = \frac{v_{p\perp}^2}{v_{p||}^2} \ll 1 \qquad \frac{v_{g\perp}}{v_{g||}} \sim \frac{n_{||}}{n_{\perp}} \ll 1 \qquad v_p v_g < 0$$



Hartmann, 2004

The LH wave is a backward wave with nearly parallel propagation except for the edge

Slow wave: Quasi-electrostatic mode

$$n_{\perp s}^2 \approx -\frac{B}{A} \approx -\frac{Pn_{||}^2}{S}$$

$$\omega^2 = \frac{\omega_{pi}^2}{1+\omega_{pe}^2/\omega_{ce}^2 + n_{||}^2/N_{\perp}^2}\left(1+\frac{m_i}{m_e}\frac{n_{||}^2}{n_{\perp}^2}\right) \approx \omega_{LH}^2\left(1+\frac{m_i}{m_e}\frac{n_{||}^2}{n_{\perp}^2}\right)$$

Resonance: $\omega = \omega_{LH}$

Cutoff: $\omega \sim \omega_{LH} = \omega_{pe}$ $\Longrightarrow$ Can not propagate in vacuum and low density region, i.e. a critical density $n_{min\ S}$

$$\left|\frac{E_y}{E_x}\right| = \left|\frac{-iD}{S-n^2}\right| \ll 1$$

$$\left|\frac{E_z}{E_x}\right| = \left|\frac{-n_{||}n_{\perp}}{P-n_{\perp}^2}\right| \sim \frac{n_{||}}{n_{\perp}} \sim \sqrt{\frac{m_e}{m_i}}$$

Wave field nearly perpendicular to B
but with an acceptable parallel component;
Quasi-electrostatic wave is a fairly accurate approximation

$(E_z/E_x \sim n_{||}/n_{\perp})$

Fast wave

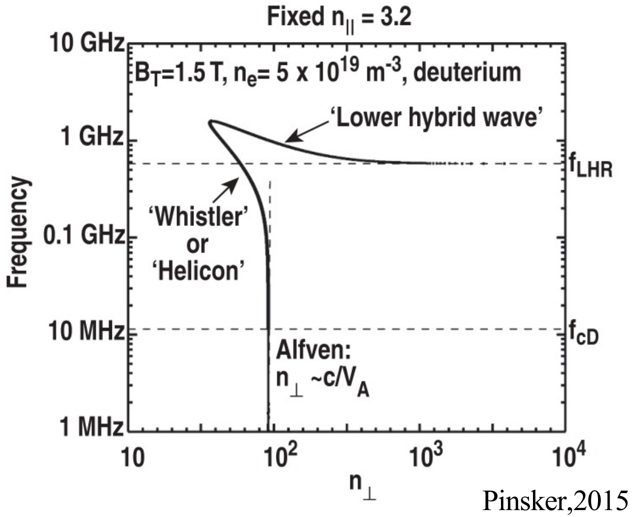
$$n_{\perp F}^2 \approx -\frac{C}{B} \approx -\frac{\left(n_{||}^2 - S\right)^2 - D^2}{n_{||}^2}$$

Also $\frac{n_{||}^2}{n_\perp^2} \ll 1$ but $\mathbf{n}_\perp$ and $\boldsymbol{\omega}$ smaller than SW

$$\left|\frac{E_y}{E_x}\right| = \left|\frac{-iD}{S - n^2}\right| \sim 1$$

Roughly a right-handed circularly polarized wave with little parallel component

$$\left|\frac{E_z}{E_x}\right| = \left|\frac{-n_{||}n_\perp}{P - n_\perp^2}\right| \sim \frac{m_e}{m_i}$$



No Resonance

Cutoff: $n_{||}^2 - S = D$

$\Longrightarrow$ $n_{\min F} > n_{\min S}$

Pinsker,2015

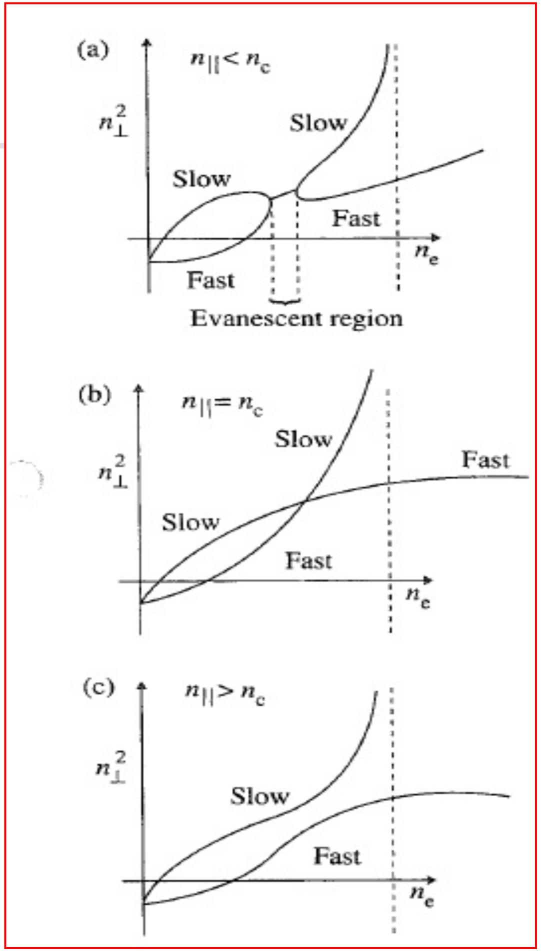
Accessibility condition (linear)

	Accessibility at edgy	Accessibility at core	Wave field
Fast wave	wide cutoff layer	No limit	EM Little $E_{\|\|}$
Slow wave	narrow cutoff layer	LH resonant layer	Quasi-ES Acceptable $E_{\|\|}$

$$A = S > 0 \Rightarrow \omega^2 > \omega_{LH}^2(r)$$ for slow wave

$$B^2 - 4AC > 0$$

$$\Rightarrow n_{||}^2 > n_{||c}^2 = 1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} = 1 + \frac{4\pi n m_e c^2}{B^2}$$

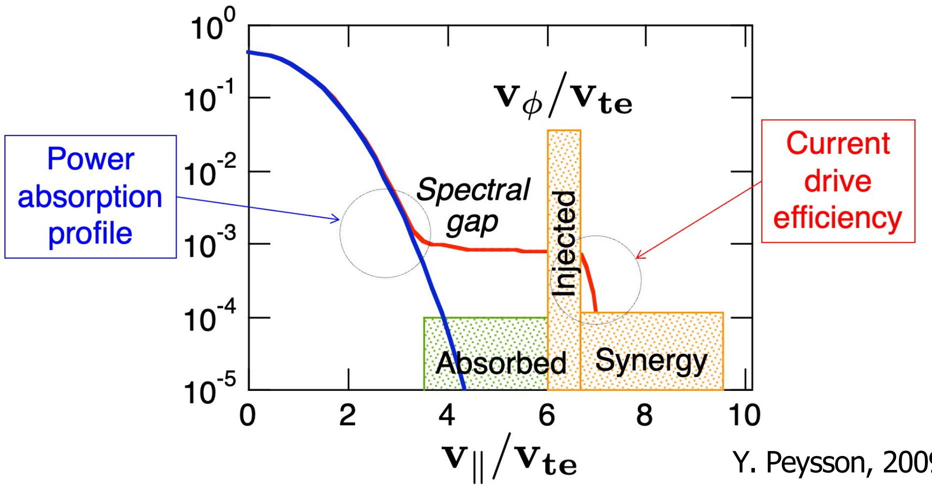


Wesson 2004

Spectral Gap of LHCD

- But, $n_{//}$ too large → low phase velocity → current drive efficiency decrease (discussed later)

  Also, $n_{//}$ >1 → $n_\perp^2 = 1 - n_{||}^2 < 0$ → edge evanescent layer
- Typical $n_{//}$ ~1.5-3.0， $v_{//}/c$ ~0.33-0.67 , corresponding to resonant electron energies 31~175 keV
- For Te = 3-10keV， v_{te}/c~0.07-0.14, so $v_{//}$ ~ 5 -10 v_{te}, nearly no electron for a Maxwellian distribution (plasma is transparent)



Y. Peysson, 2009

Many mechanisms may contribute to bridge the spectral gap

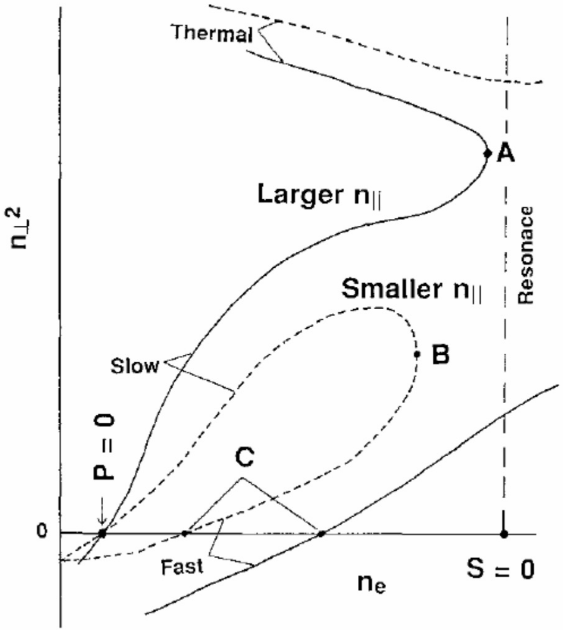
Thermal Plasma Effect

$$Tn_\perp^6 + An_\perp^4 + Bn_\perp^2 + C = 0$$

$$T = -\frac{3}{2}\frac{\omega_{pe}^2}{\omega^2}\frac{v_{ti}^2}{c^2} - \frac{3}{8}\frac{\omega^2\omega_{pe}^2}{\omega_{ce}^4}\frac{v_{te}^2}{c^2}$$

- **For slow wave, a thermal mode (ion Bernstein mode) solution near resonant.**

- **For the purpose of CD, it is usually chosen to minimize the ion absorption.**



Ushigusa 1999

Absorption with kinetic effects

$$D(\omega,\boldsymbol{k}) = D_r(\omega,\boldsymbol{k}) + iD_i\ (\omega,\boldsymbol{k}) = 0$$

In the weak damping limit
$$\gamma = \frac{D_i}{\partial D_r/\partial\omega_r} \qquad \frac{dU}{dt} = 2\gamma U$$

or using the spatial damping
$$k_{\perp i} = \frac{D_i}{\partial D_r/\partial k_{\perp r}} = -\frac{\gamma}{v_{g\perp}} \qquad \frac{dU}{dx} = -2k_{\perp i}U$$

- **Damping from ion/electron collisional/collisionless mechanism, mainly from electron Landau damping**

$$\frac{ck_{\perp i}}{\omega_{pj}} = \pi^{1/2}\frac{\left|E_{//}^2\right|}{E_0^2}\frac{\omega_{pj}}{k_{//}v_{Tj}}e^{-b}I_0(b)\left(\frac{\omega}{k_{//}v_{Tj}}\right)^2\exp\left[-\left(\frac{\omega}{k_{//}v_{Tj}}\right)^2\right]$$

- ✓ Maximum damping for $v_p \sim 1.2 v_{te}$
- ✓ ~1/10 maximum damping for $v_p \sim 2.5 v_{te}$

Propagation in toroidal geometry

- Geometric optics (WKB) approximation: $\lambda \ll L_n$ (wavelength much smaller than density scale length)

$\lambda_{\mathrm{LH},\boldsymbol{vac}}$ = 6 cm for 5G Hz

- Hamiltonian ray equations:

$$\frac{d\boldsymbol{r}}{dt} = \frac{\partial D/\partial \boldsymbol{k}}{\partial D/\partial \omega} \qquad \frac{d\boldsymbol{k}}{dt} = -\frac{\partial D/\partial \boldsymbol{r}}{\partial D/\partial \omega}$$

- Some popular codes: C3PO (France), GENRAY (USA) [except for TORLH(USA, full wave)]
- Outputs: ray trajectories, power deposition profiles

$n_{||}$ upshift due to toroidal effect

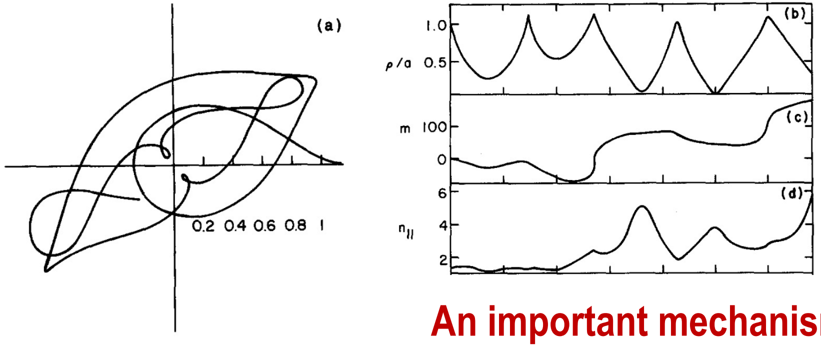
- In tokamaks, the parallel (field) direction is not the same as the toroidal direction, but is changing as the wave pass across the flux surface

$$\boldsymbol{k}_{||} = \frac{B_\theta}{B}\,\boldsymbol{k}_{\boldsymbol{\theta}} + \frac{B_\phi}{B}\,\boldsymbol{k}_{\boldsymbol{\phi}}$$

$$\frac{dk_\phi}{dt} = -\frac{1}{R}\frac{\partial D/\partial\phi}{\partial D/\partial\omega} = 0$$

$$\frac{dk_\theta}{dt} = -\frac{1}{r}\frac{\partial D/\partial\theta}{\partial D/\partial\omega} \neq 0$$

  - The toroidal wave number is a constant of the ray motion (axisymmetric)
  - The poloidal wave number evolved along the ray path because of the poloidal asymmetry of the magnetic equilibrium → upshift/downshift of $k_{||}$

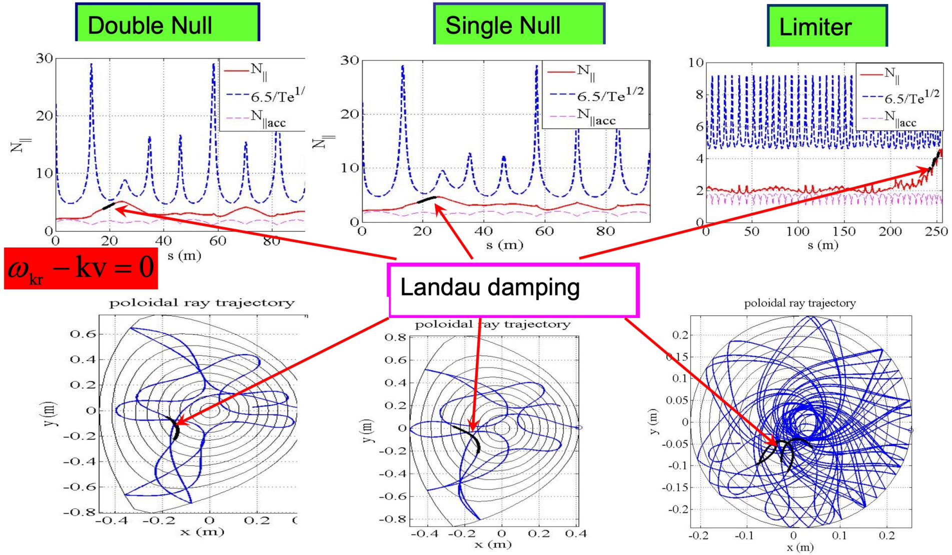


PT Bonoli, 1986

An important mechanism to bridge the spectral gap

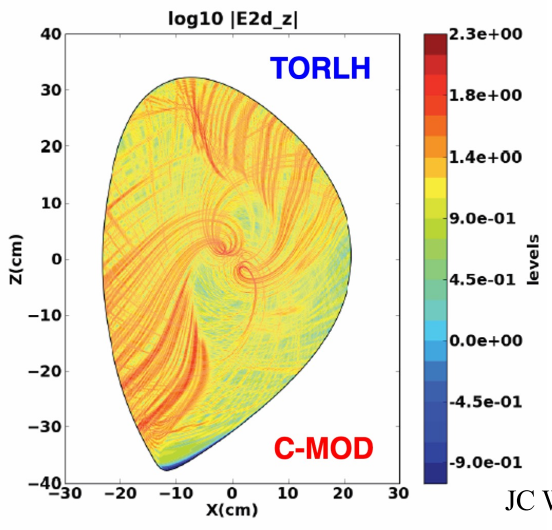
Multi-pass with weak damping

- Multi-pass bounded by cut-off, accessibility, caustics (k_ρ=0), and strong damping
- Help to evolve successive passes into the damping window
- More opportunities for abnormal loss due to collision, scattering and PDI at edge/SOL
- Very sensitive to field geometry and initial conditions (stochasticity chaos?)

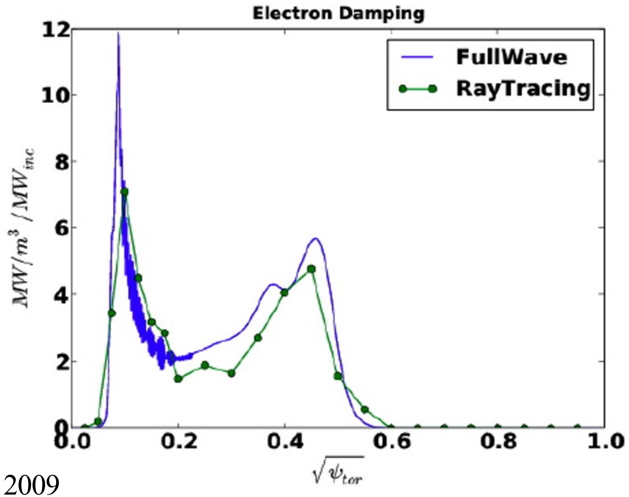


BJ Ding 2011

Full wave description

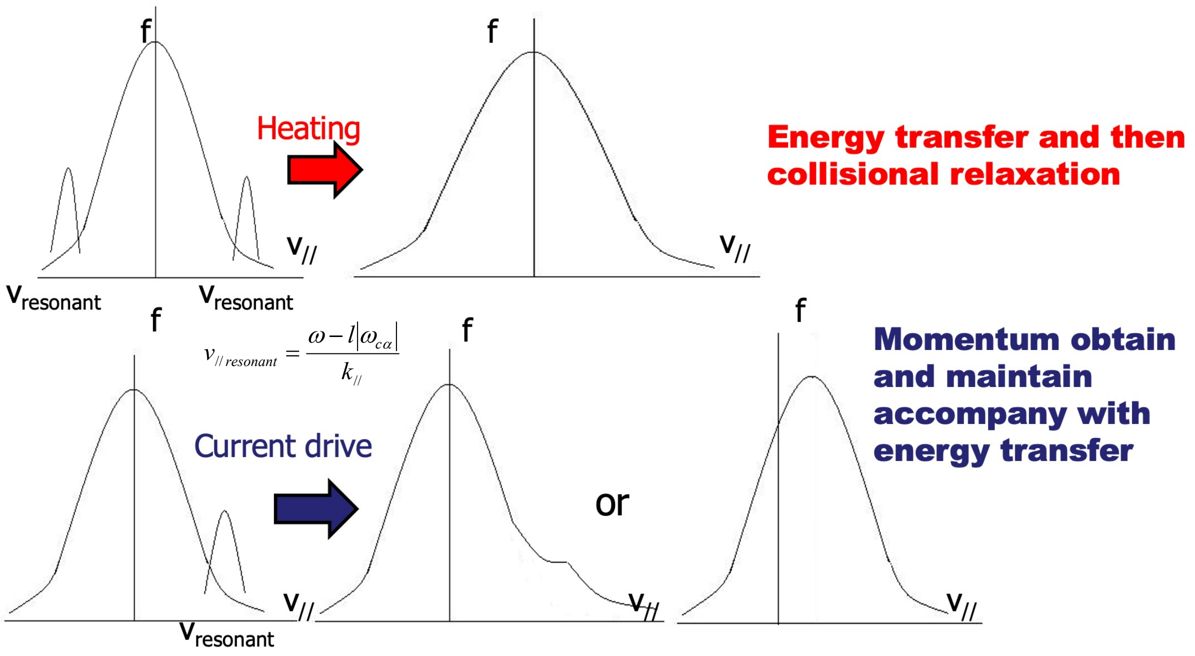


JC Wright, 2009



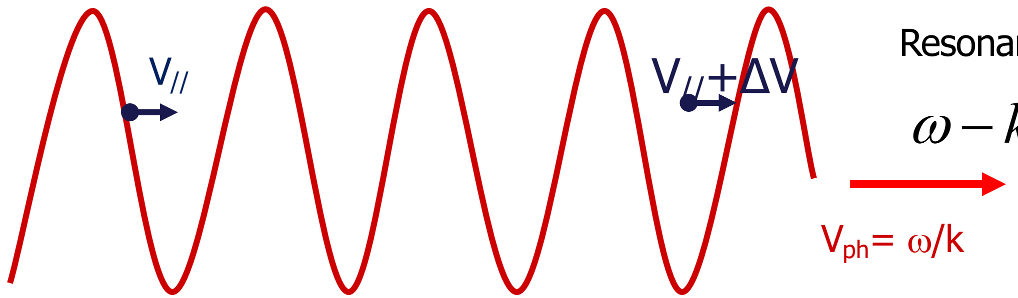
- Ray tracing may breaks down near caustics, cutoffs, strong gradients, and strong scattering, then, full-wave is required. Full-wave interference, diffraction, and finite-wavelength effects can broaden the effective spectrum.
- However, full-wave calculations consistent with Ray tracing calculation in typical scenarios

Picture of heating and current drive



- For current drive, asymmetric $n_{||}$ required for net directional momentum input

A simplest physics: Direct pushing electrons



Resonance condition

$$\omega - k_{//} v_{//} = 0$$

$$\mathrm{v}_{//} \rightarrow \mathrm{v}_{//} + \Delta \mathrm{v}$$

$$J = en\Delta \mathrm{v}$$

Collision relax the plasma toward a currentless status, therefore, a rf power to be reinforced continuously

$$\frac{J}{P_{\mathrm{D}}} = \frac{e}{m\mathrm{v}_{//}\nu_c(\mathrm{v})}$$

$$\Delta W = mn\mathrm{v}_{//}\Delta \mathrm{v}$$

$$P_{\mathrm{D}} = \nu_c \Delta W \qquad \nu_c(\mathrm{v}) \approx \mathrm{v}^{-3}$$

Fisch,1978

Direct pushing electrons: two high effective regimes

- Low phase velocity

$$v_{//} \to 0$$

$$\nu_c(v) \approx v_t^{-3} = const$$

$$J/P_D \propto 1/v_{//}$$

Key point: easy to push

$$\Delta W = mn v_{//} \Delta v$$

but trapping effect comes

Alfven wave CD

by Wort, 1971

$$\frac{J}{P_D} = \frac{e}{m v_{//} \nu_c(v)}$$

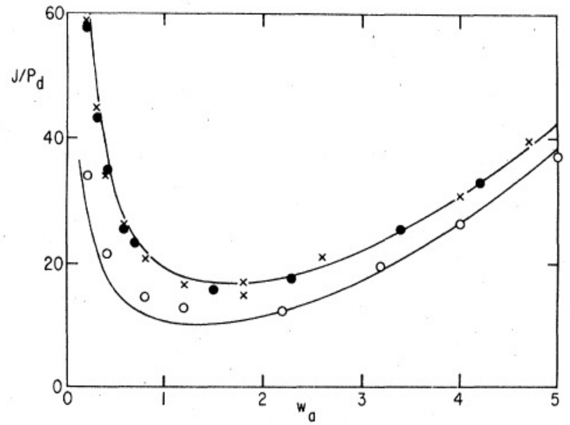


FIG. 21. Normalized J/P_d vs average normalized parallel-phase velocity w_a: ○, Landau damping; ×, magnetic pumping; ●, Alfvén waves in the limit $D_{QL} \to 0$. The solid curves are rough semianalytic fits to the data (Fisch and Karney, 1981).

- High phase velocity

$$v_{//} \to \infty$$

$$\nu_c(v) \approx v_{//}^{-3}$$

$$J/P_D \propto v_{//}^2$$

- Key point: less collisions for fast electrons, momentum is well kept

Low hybrid CD

by Fisch 1978

Quasi-linear diffusion in LHCD

- **A strong quasi-linear plateau is predicted**

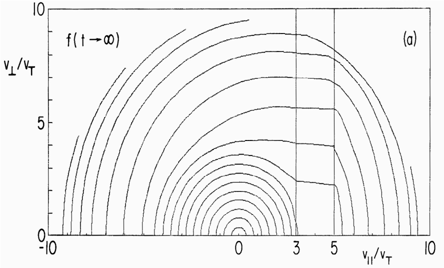
$$\frac{\partial f}{\partial t} = \left(\frac{\partial f}{\partial t}\right)_c + \frac{\partial}{\partial v_{||}}\left[D_{QL}(v_{||})\frac{\partial f}{\partial v_{||}}\right] + \frac{1}{r}\frac{\partial}{\partial v_{||}}\left[rD_r(r)\frac{\partial f}{\partial r}\right]$$

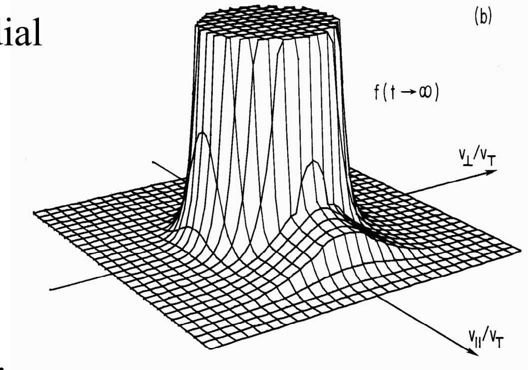
Collisional term

$$D_{QL} \sim \sum_k \left|E_{||}(k)\right|^2 \delta(\omega - k_{||}v_{||})$$

quasi-linear wave drive term

Fast electron radial transport term





$$\frac{J}{P_D} = -e\frac{\nu_1/v_1 - \nu_2/v_2}{E_1 - E_2} = -e\frac{\nu - v_{||}\,\partial\nu/\partial v}{\nu^2\,\partial E/\partial v}$$

$$\propto v_{||}^{-1}\left(v_{||}^2 + v_\perp^2\right)^{3/2} + 3v_{||}\left(v_{||}^2 + v_\perp^2\right)^{1/2}$$

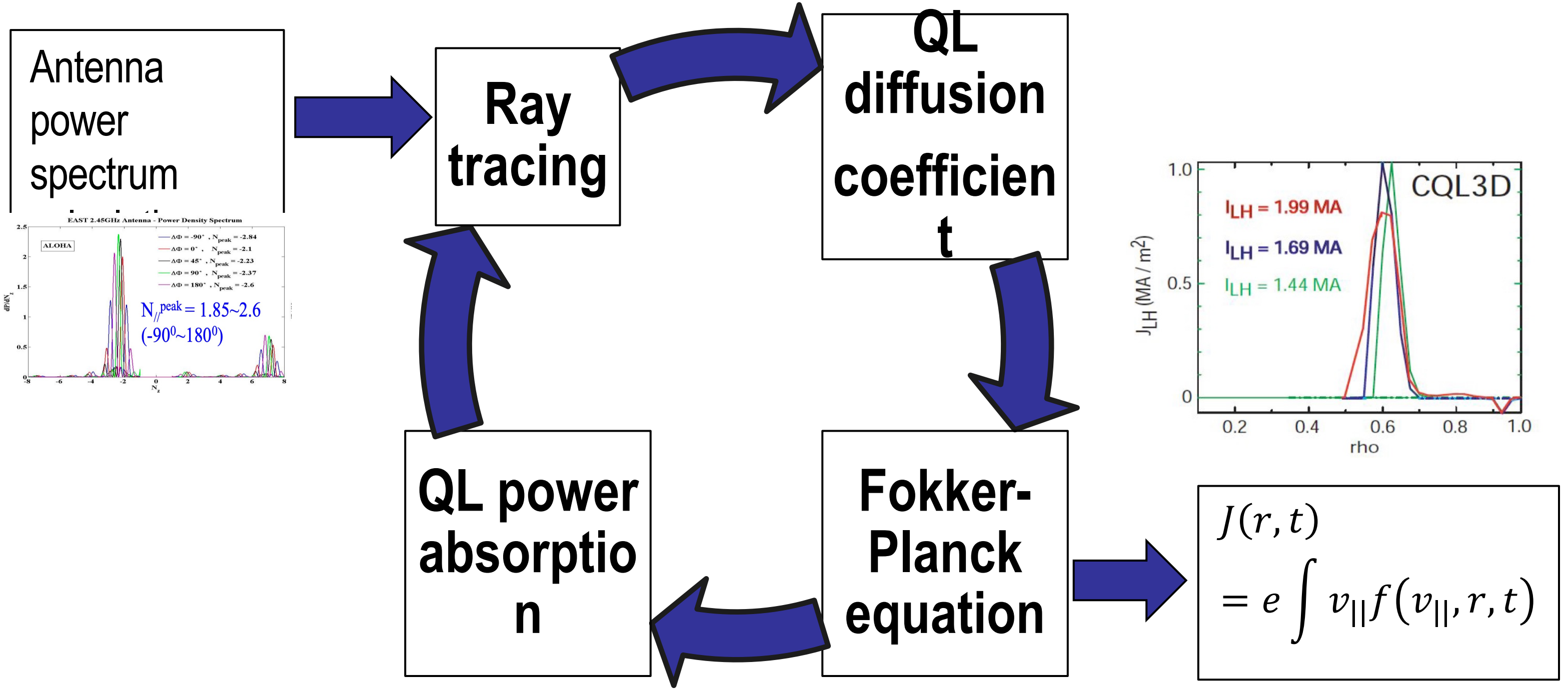
Energy term with asymmetric conductivity

$$\sim \frac{e v_{te}}{\nu m v_{te}^2}\frac{v_p^2}{v_{te}^2}$$

Karney and Fisch, 1979

Definition of LHCD efficiency in experiments $\frac{I}{P} = \frac{JA}{P_D 2\pi R A}$ $\eta_{CD} \equiv \frac{I n_e R}{P}$

Self-consistent quasi-linear calculation



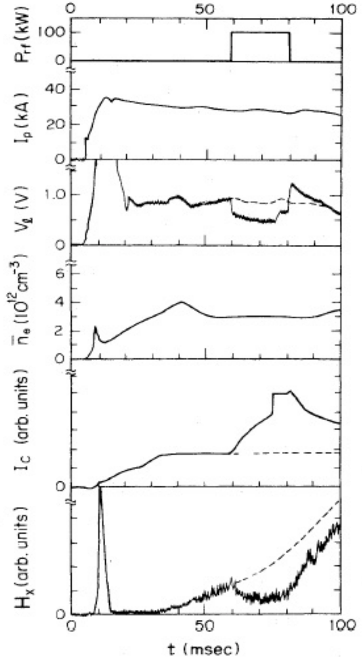
Summary of the first part

- The slow and fast LHW are two roots of the cold-plasma dispersion relation. Slow-wave LHCD has larger E‖ and stronger electron Landau damping.
- Accessibility is a linear-dispersion constraint.
- The spectral-gap problem motivates the need for spectral-broadening mechanisms.
- Toroidal propagation can induce n|| upshift, although sometimes it is not enough and sometimes it needs too longer trajectory.
- LHCD has a high efficiency due to less collisions for fast electrons
- Quasi-linear calculation gives the driven current profile

OUTLINE

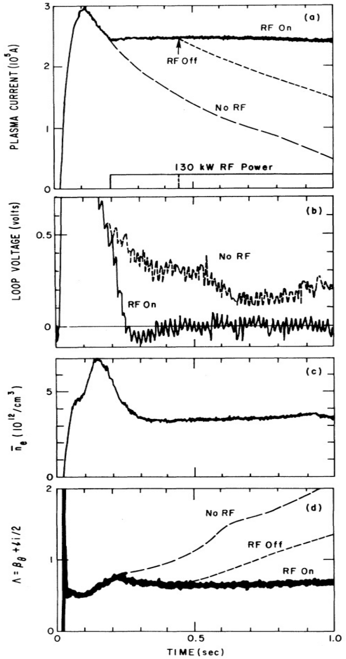
- Concept of LHW and its linear dispersion relation
- Accessibility and absorption in toroidal geometry
- Principles of LHCD
- Representative experimental results
- Challenges at high density
- On helicon wave (LH fast waves)

Early Experiments of LHCD



First LHCD experiment on JFT-2

Yamamoto 1980



LHCD discharge without Ohmic fields on PLT

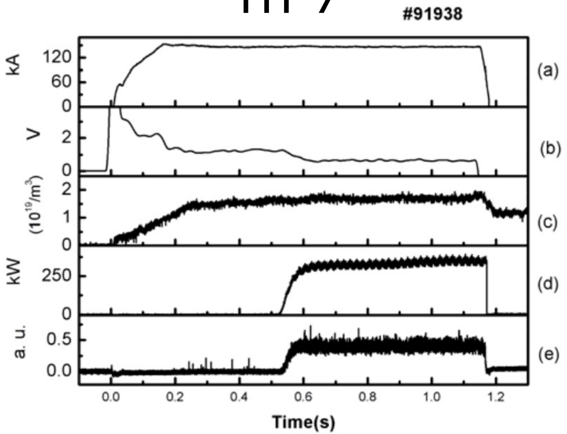
Bernabei 1982

$$V_l = -d/dt(L_{pl} I_p) - \Omega_p (I_p - I_{non\text{-}ind}) + d/dt(\Psi_{pl\text{-}loop})$$

Typical experimental evidences of LHCD

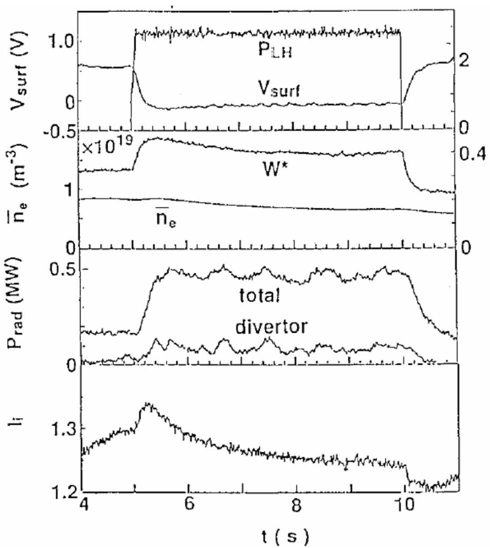
- Loop voltage ↓
- Internal inductance ↓
- Hard X-ray ↑

HT-7



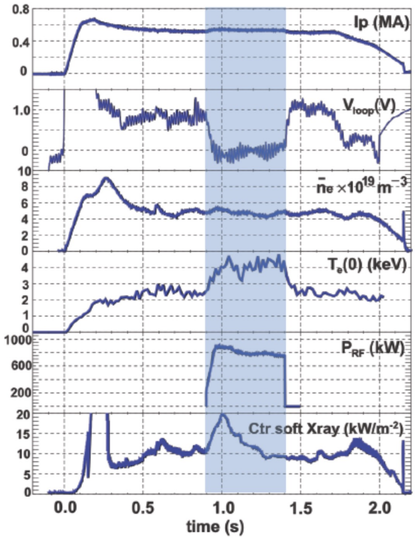
Wan 2010

JT-60U



Ushigusa 1999

C-mod



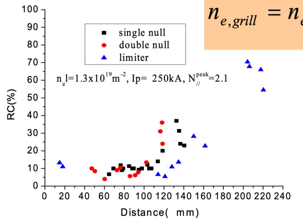
Long distance coupling

- **Decided by plasma density near the grill**
- **Gas puffing can improve the coupling**

Coupling at 3 configurations (EAST)

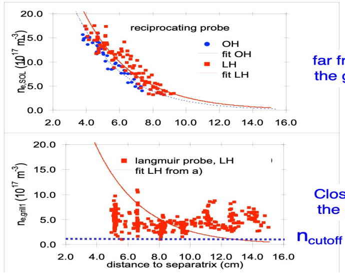
$$n_{e,grill} = n_{e,LCFS} \cdot \exp(-\frac{d}{\lambda_{SOL}})$$

$\lambda_{SOL} \propto L_{//}^{0.5}$



Wan 2010

L-mode operation in Tore Supra



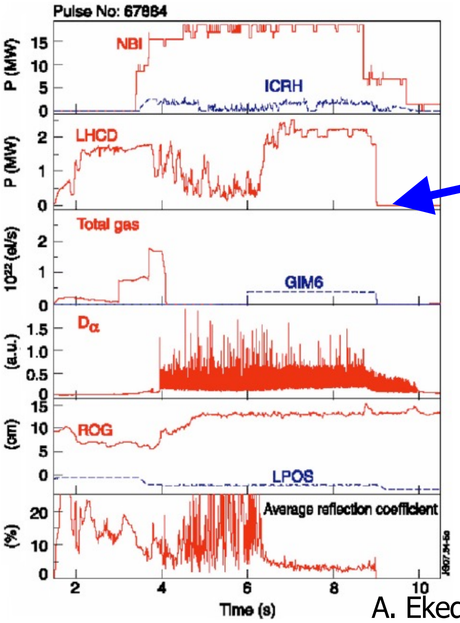
far from the grill

Close to the grill

n_{cutoff}

Y. Peysson, 2009

ELMy H-mode in JET



D_2 gas puffing

A. Ekedahl, 2009

Estimation of current driven efficiency

- LHCD efficiency can be estimated from the relative change of loop voltage
- Due to the presence of asymmetric resistivity (thermal conductivity), the LH-driven current cannot be directly calculated under non-zero loop voltage conditions.

$$J_{tot} = J_{OH} + J_{RF} + \sigma_1 E$$

$$-\frac{\Delta V}{V_{OH}} = \frac{(\eta_0 + \eta_1) P_{norm}}{1 + \eta_1 P_{norm}}$$

$\boldsymbol{\eta_0}$: LHCD efficiency at zero loop voltage

$\boldsymbol{\eta_1}$: contribution from thermal conductivity

$$\eta_1 = \sigma_1 / (P_{norm} \sigma_{sp})$$

$P_{norm} = P_{LH} / \bar{n}_e I_p R$ from the experiments

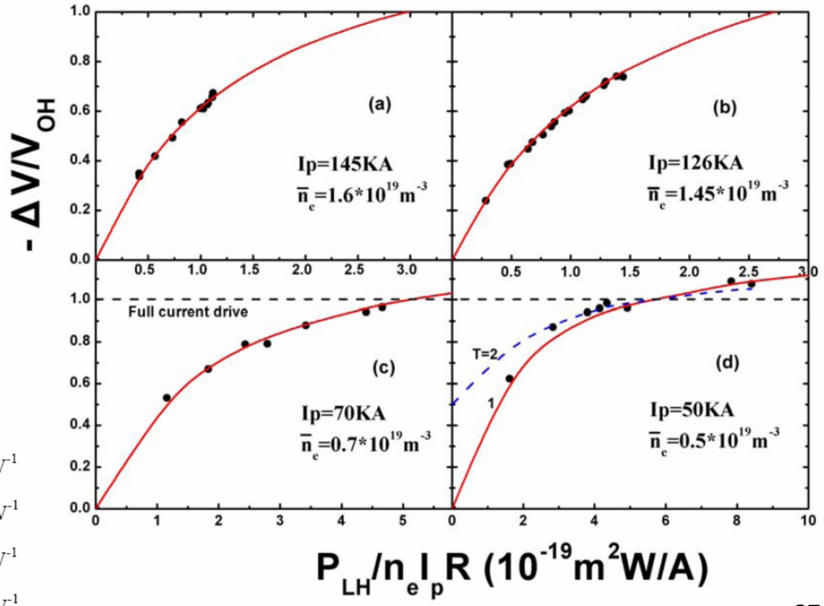
$= 1/\eta_0$ only at zero loop voltage

(a) $\eta_0 = 0.342 \pm 0.061 \times 10^{19} Am^{-2}W^{-1}$, $\eta_1 = 0.713 \pm 0.026 \times 10^{19} Am^{-2}W^{-1}$

(b) $\eta_0 = 0.364 \pm 0.007 \times 10^{19} Am^{-2}W^{-1}$, $\eta_1 = 0.652 \pm 0.019 \times 10^{19} Am^{-2}W^{-1}$

(c) $\eta_0 = 0.196 \pm 0.015 \times 10^{19} Am^{-2}W^{-1}$, $\eta_1 = 0.388 \pm 0.027 \times 10^{19} Am^{-2}W^{-1}$

(d) $\eta_0 = 0.183 \pm 0.012 \times 10^{19} Am^{-2}W^{-1}$, $\eta_1 = 0.615 \pm 0.071 \times 10^{19} Am^{-2}W^{-1}$



Chen 2005, Wan 2010

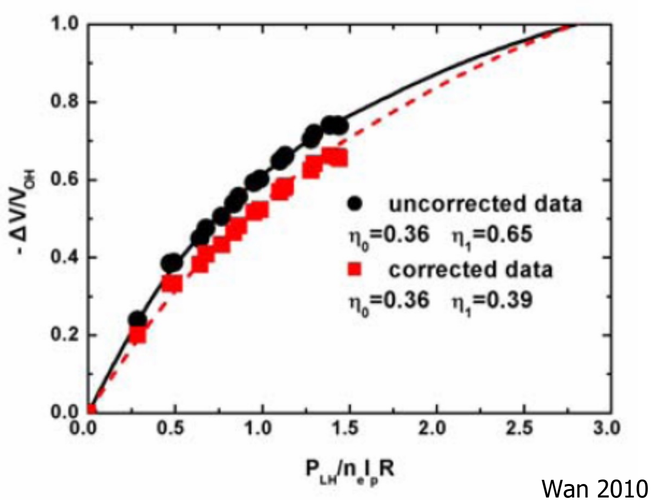
Estimation of current driven efficiency

Correction from the LH heating effect

$$\rho = (R_{sp})_{LH} / (R_{sp})_{OH} = (Z_{LH} / Z_{OH})(T_{e,LH} / T_{e,OH})^{-3/2}$$

$$-\frac{\Delta V}{V_{OH}}' = \rho[(-\frac{\Delta V}{V_{OH}}) - (1 - \frac{1}{\rho})]$$

$$-\frac{\Delta \mathrm{V}}{\mathrm{V}_{\mathrm{OH}}} = \frac{(\rho - 1) + (\eta_0 + \rho\eta_1)P_{norm}}{\rho(1 + \eta_1 P_{norm})}$$



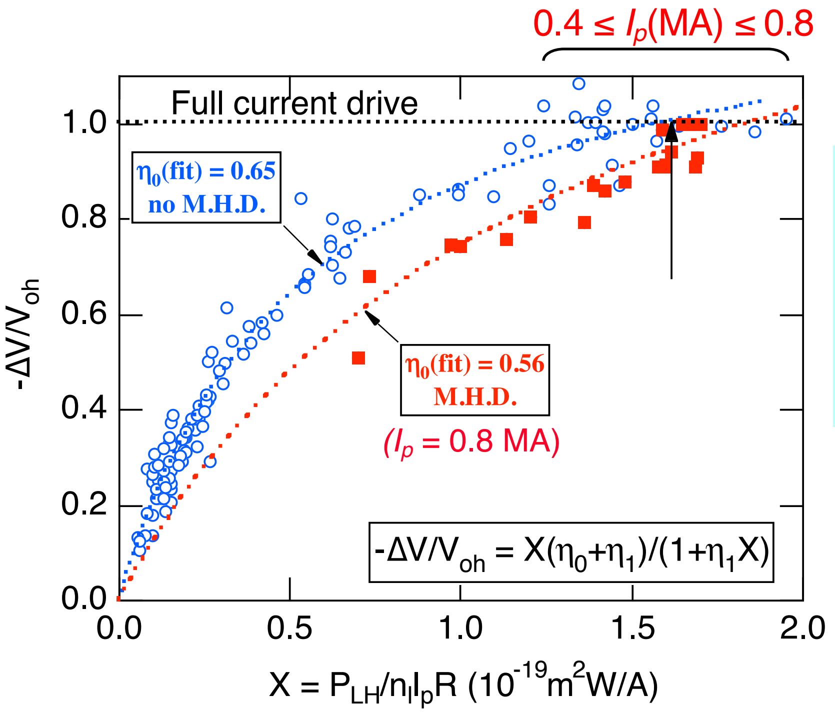
Wan 2010

Correction from the BS current contribution

$$-\frac{\Delta \mathrm{V}}{\mathrm{V}_{\mathrm{OH}}} = \frac{(\rho - \frac{1-\alpha}{1-\beta}) + (\frac{\eta_0}{1-\beta} + \rho\eta_1)P_{norm}}{\rho(1 + \eta_1 P_{norm})}$$

$\alpha, \beta = I_{bs}/I_p$ for the LHCD and Ohmic stage respectively

LHCD efficiency degraded by MHD due to loss of more energetic electrons



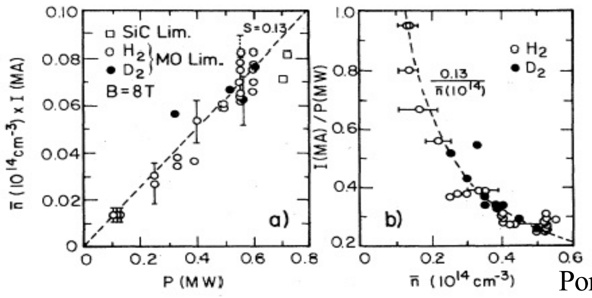
Tore Supra

At V_{loop} = 0 V: **$0.55 \le \eta_0 \le 0.85$**
Almost no dependence of $n_{\parallel 0}$
Decrease with Z_{eff}
M.H.D. activity : $m = 2/n = 1$ tearing mode

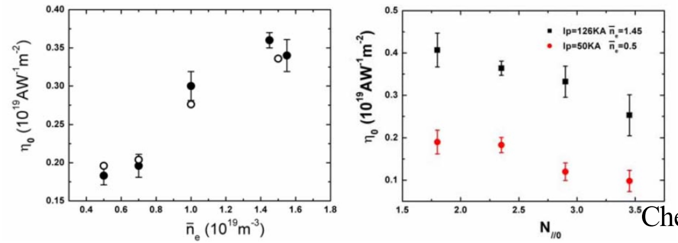
B_t = 3.9 T, 143 discharges
$0.4 \le I_p(\mathrm{MA}) \le 1.2$
$1.3 \le n_l\ (10^{+19}\ m^{-3}) \le 4.5$

Y. Peysson, 2001, 2009

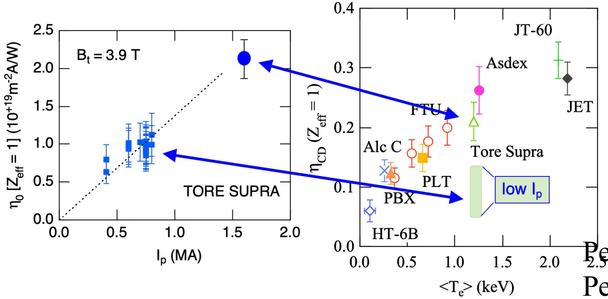
LHCD efficiency scaling



Porkolab et al, 1984



Chen 2005



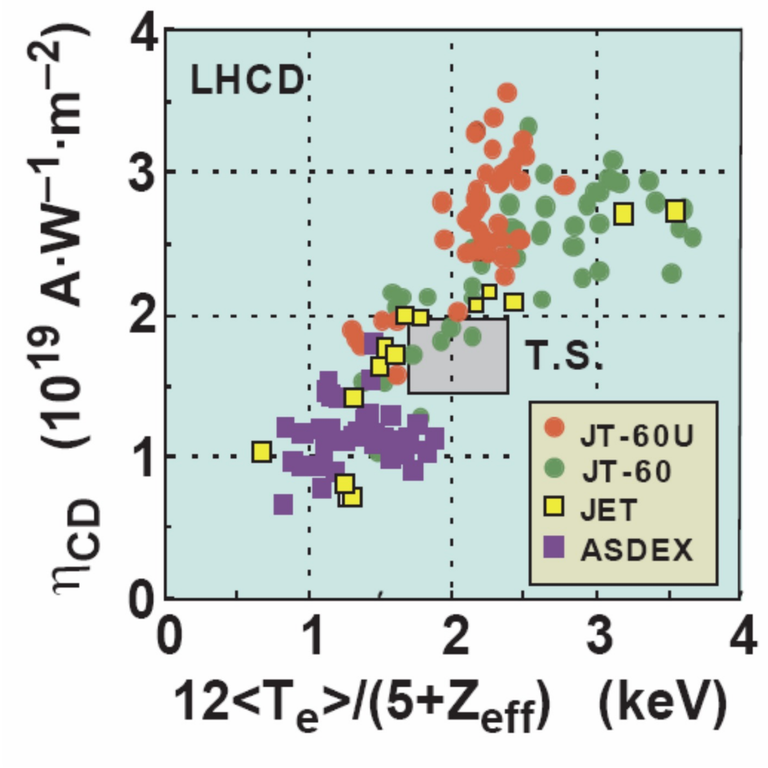
Pericoli-Ridolfini 1999

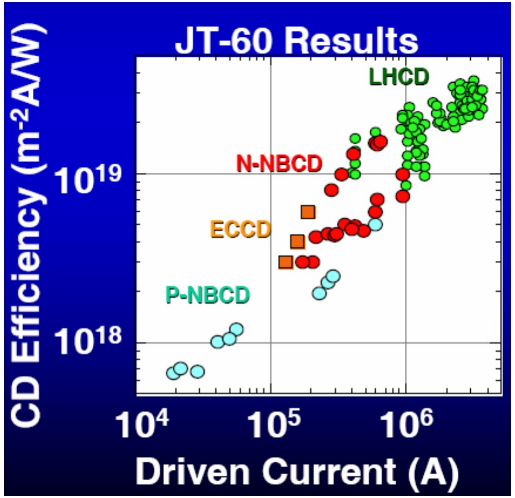
Peysson, 2009

$$\eta_{CD} \equiv \frac{I n_e R}{P} \sim \frac{n}{2\pi} \frac{e v_{te}}{\nu m v_{te}^2} \frac{v_p^2}{v_{te}^2}$$

- **On Alcator C, I/P ~ n^{-1} scaling (η_{CD}~const.) identified. On EAST η_{CD} increases with n_e at very low density regime and then deceases at high density regime.**
- **η_{CD} degraded with an increasing $n_{||0}$ in EAST, but shows almost no dependence of $n_{||0}$ in Tore Supra**
- **η_{CD} improves at higher I_p as well as at higher Te**

LHCD is the most efficient among several noninductive CD methods





Ushigusa 2011

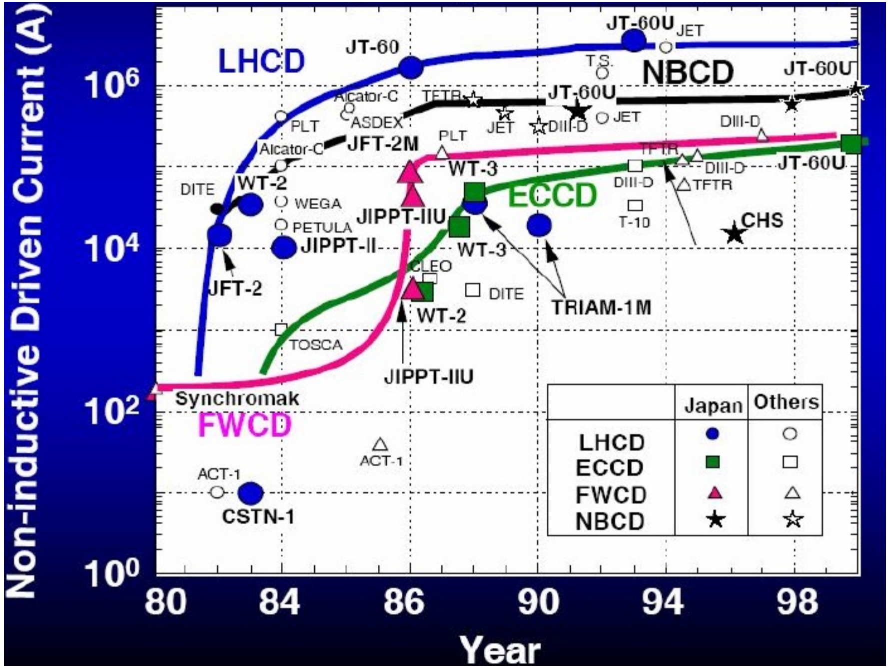
η_{LHCD} ~ 3-4 × 10^{19} (m^{-2}MA/MW)

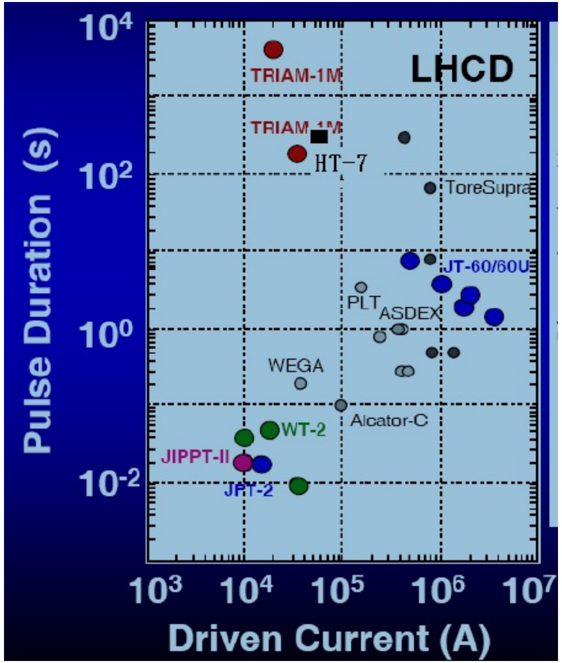
η_{FWCD} ~ 0.45 × 10^{19}

η_{IBWD} ~ 0.7 × 10^{19}

η_{ECCD} ~ 0.42 × 10^{19}

Record by LHCD in total drive current and achieved pulse duration

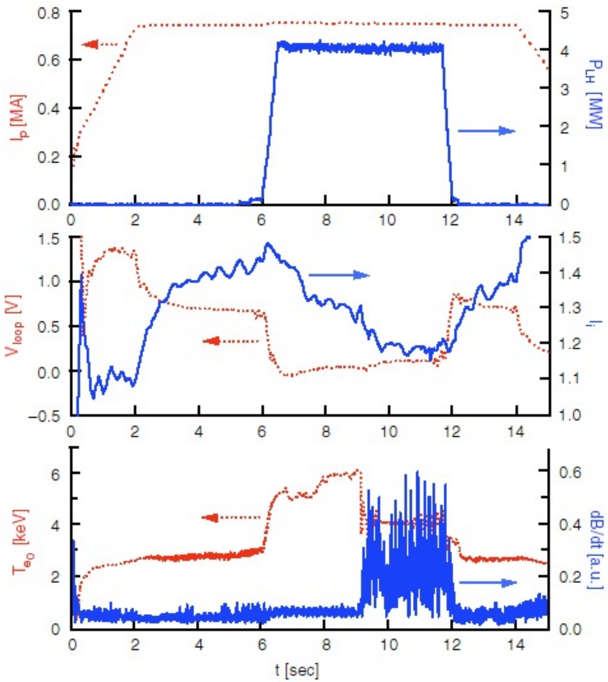




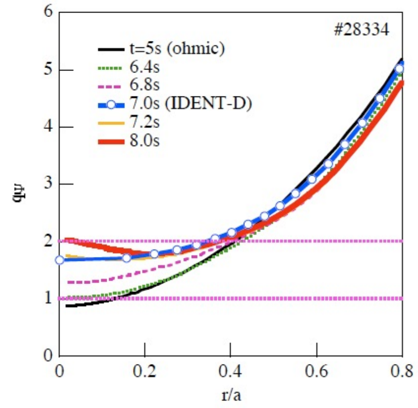
Ushigusa 2011

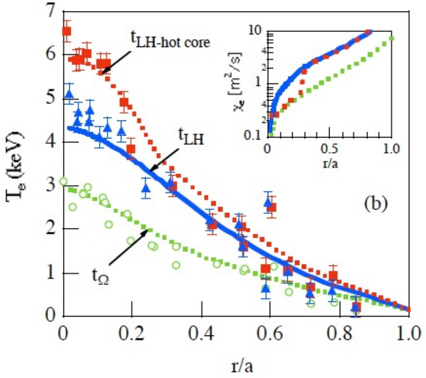
JT-60U:3.6MA, JET:3MA, TS:0.8MA 2mins, EAST 0.34MA 1000s

Current profile control to improve the confinement



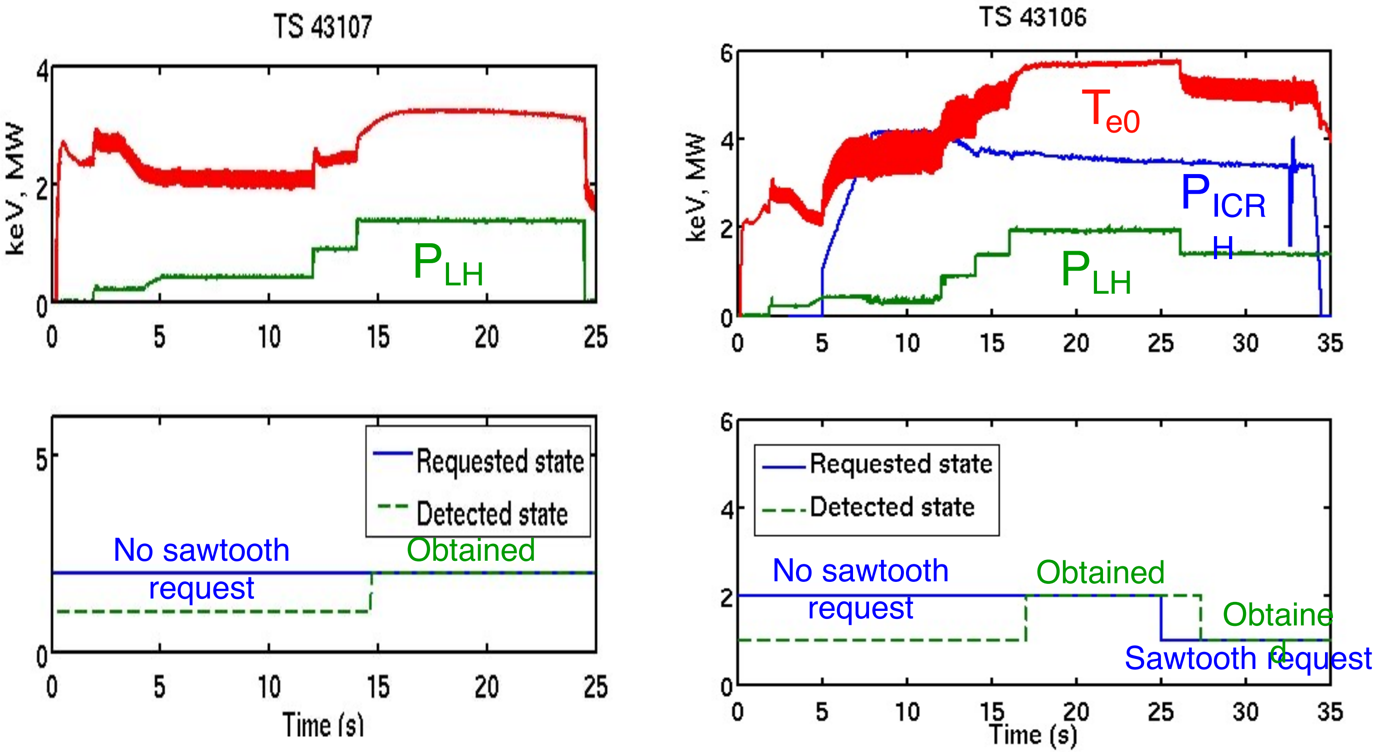
Tore Supra, #28334, $\langle n_{||0} \rangle = 2.00$*





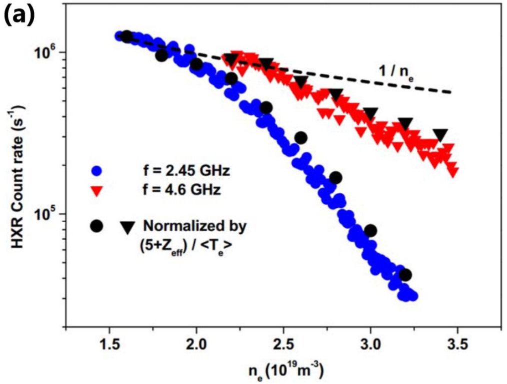
Y. Peysson, 2001, 2009

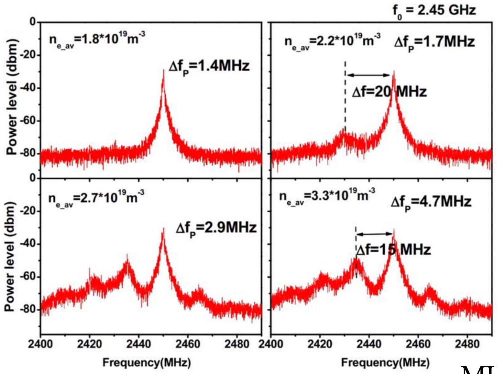
Control of sawtooth activities by modifying q-profile

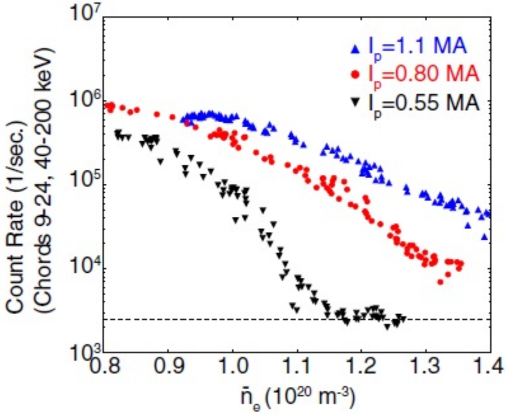


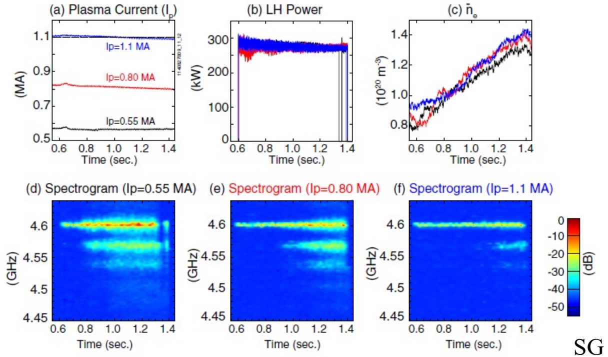
F.Imbeaux 2011, Y. Peysson, 2009

LHCD degradation at high density





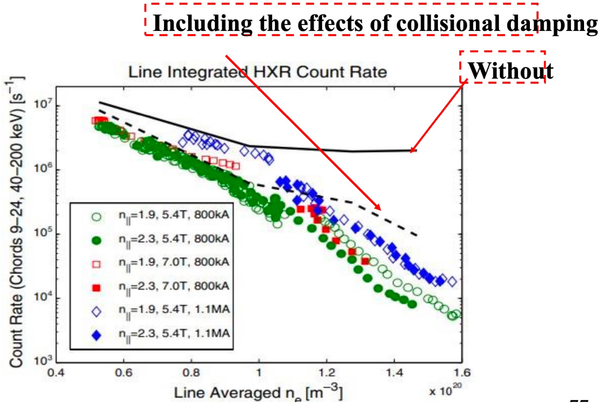




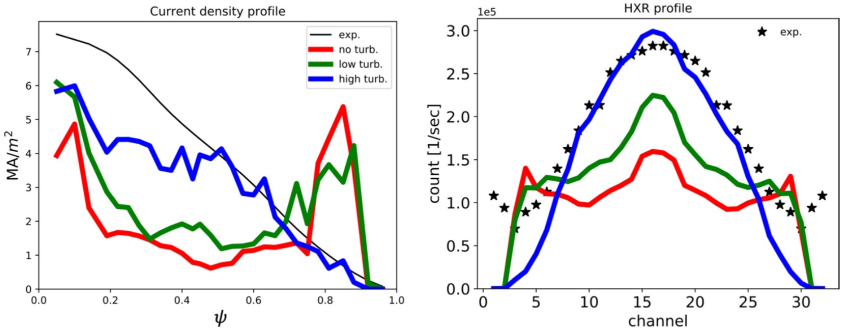
MH Li, 2019

SG Baek 2015

Two possible reasons: collision absorption and density fluctuation



Wallace 2010

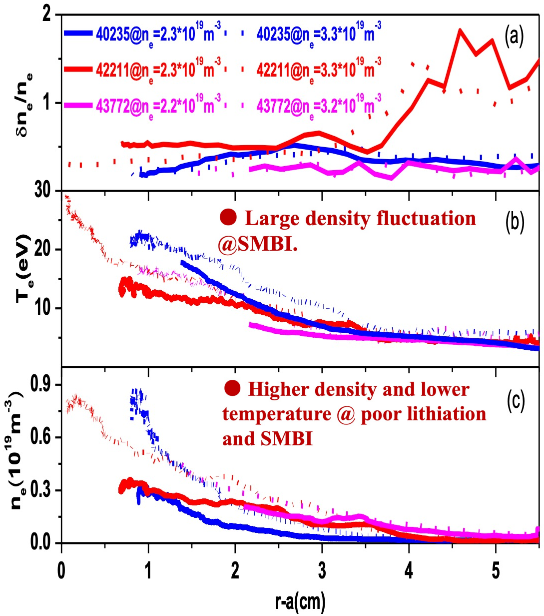


Biswas 2023

The collision absorption at the edge is one of the reasons for the decrease in LHCD efficiency at high-density.

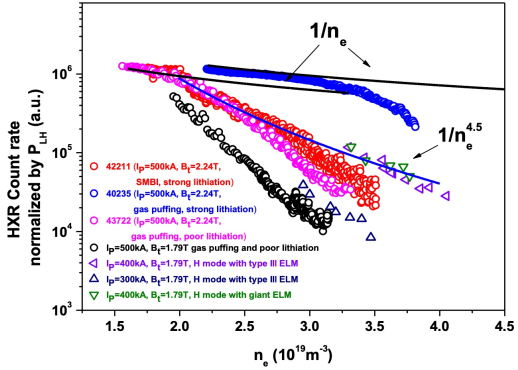
Scattering by large density fluctuation in edge region is one possible candidate

A more general and dominant mechanism: Parametric decay instabilities



42035 (Gas puffing/strong Li.)
42211 (SMBI/strong Li.)
43772(Gas puffing/poor Li.)

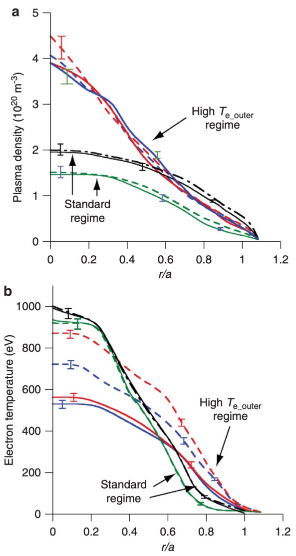
Comparison: 1. Strong and poor lithiation (gas puffing)
2. Density feedback by gas puffing and SMBI (strong)

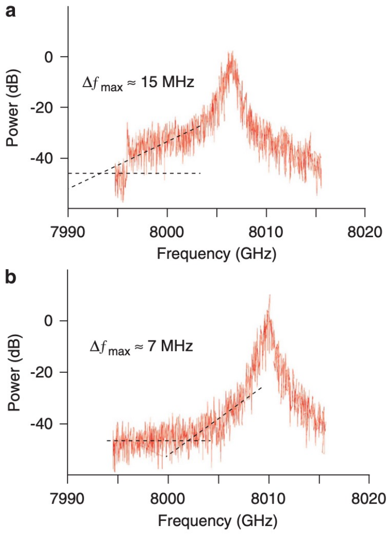


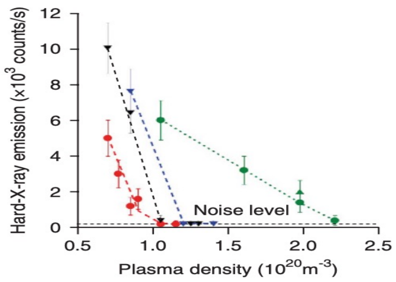
1. Strong lithiation is better than poor lithium coating.
2. Gas puffing is better than SMBI.

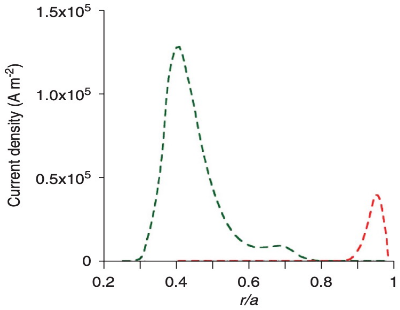
Ding 2023

LHCD at high density with the suppression of PDIs





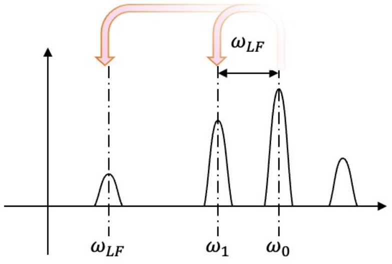




On FTU, when the edge plasma electron temperature is high, nonlinear PDI interactions diminish, then the coupled radio frequency power can penetrate into high-density plasmas.

Cesrio 2010

LHW can decay to sideband and ISQM/ICQM at high density and low temperature

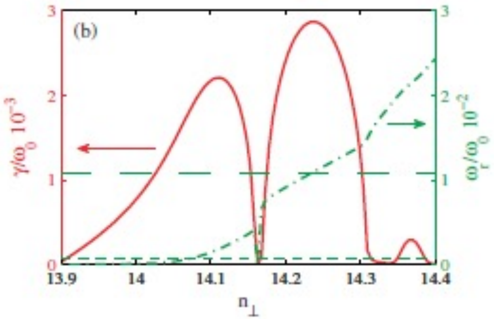


PDI is a common and important nonlinear wave-wave interaction.

$$\begin{bmatrix} \boldsymbol{D}_{\mathrm{LF}} & \tilde{\boldsymbol{\sigma}}^{(1)}_{\mathrm{LF}\leftarrow 1} \\ \tilde{\boldsymbol{\sigma}}^{(1)}_{1\leftarrow \mathrm{LF}} & \boldsymbol{D}_1 + \tilde{\boldsymbol{\sigma}}^{(2)}_{1\leftarrow \mathrm{LF}\leftarrow 1} \end{bmatrix} \begin{bmatrix} \boldsymbol{E}_{\mathrm{LF}} \\ \boldsymbol{E}_1 \end{bmatrix} = \boldsymbol{0}$$

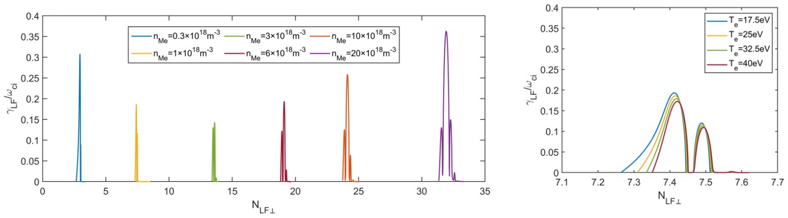
$$\Downarrow$$

$$\begin{vmatrix} \varepsilon_{\mathrm{LF}} & \chi^{(1)}_{\mathrm{LF}\leftarrow 1} \\ \chi^{(1)}_{1\leftarrow \mathrm{LF}} & \varepsilon_1 + \chi^{(2)}_{1\leftarrow \mathrm{LF}\leftarrow 1} \end{vmatrix} = 0$$



two decay channels: ISQM and ICQM

Zhao 2013

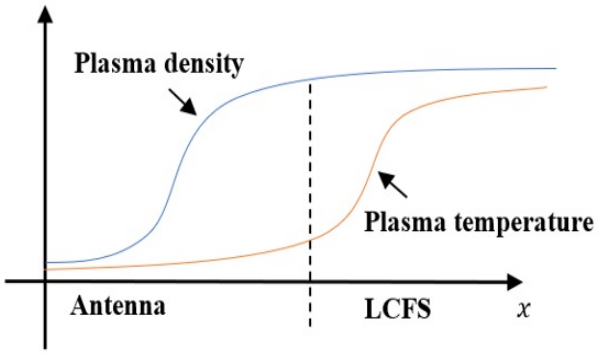


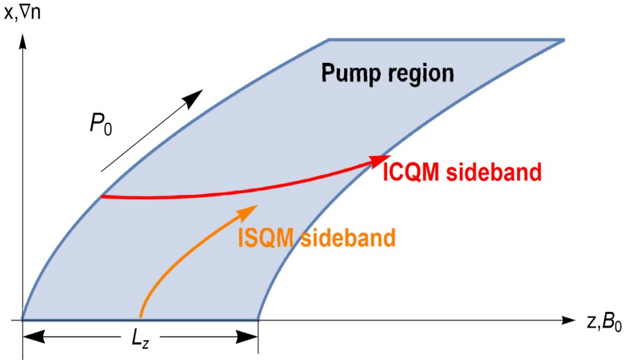
ISQM and ICQM behaviors with density and temperature

Gao 2025

The coupling is mainly ES and fluid, provided that the kinetic effect in the linear response and the EM effect in the linear dispersion relation of the pump is kept.

PDI saturation due to finite pump width and plasma inhomogeneity





Near the antenna, both density and temperature are low, the ISQM type PDI is excited and in the cool and dense SOL plasma, the ICQM PDI is excited.

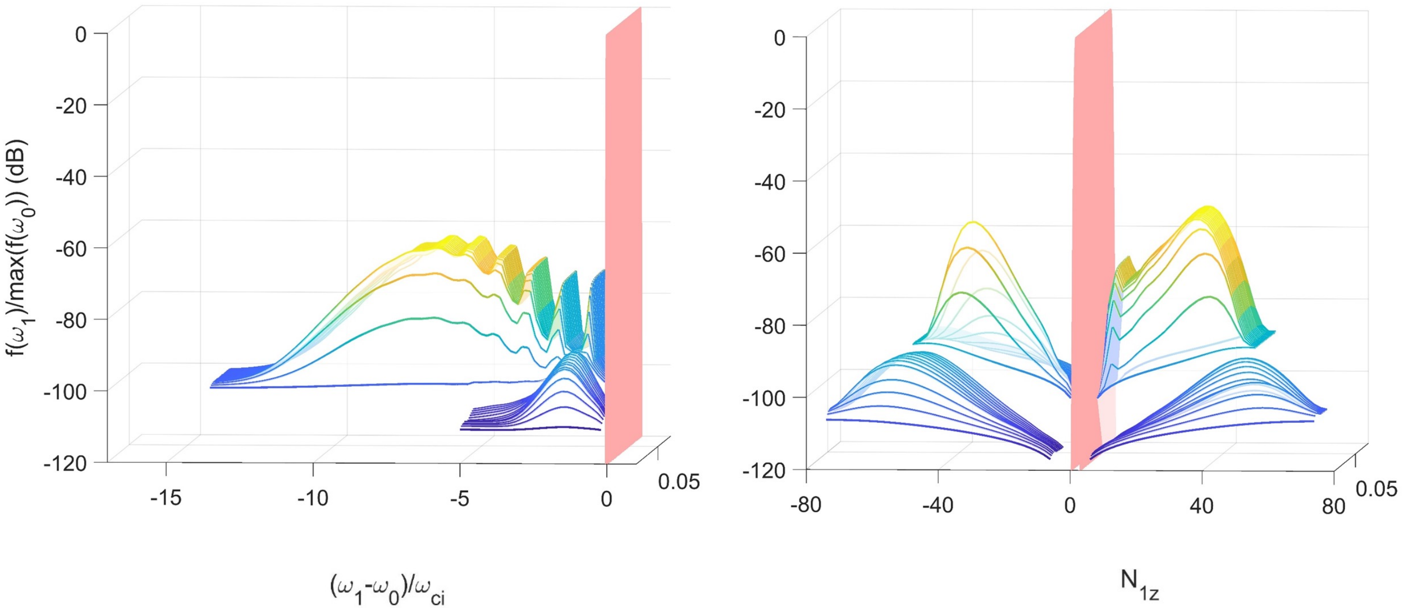
$$A \approx \int \frac{dx}{v_{1gx}} \gamma_0 = \int dt\, \gamma_0$$

Finite pump width, actually finite trajectory length

plasma inhomogeneity (saturation when $\gamma_0 = 0$)

Chen 2025 and Huang 2026

Spectrum evolution and power transfer due to PDIs

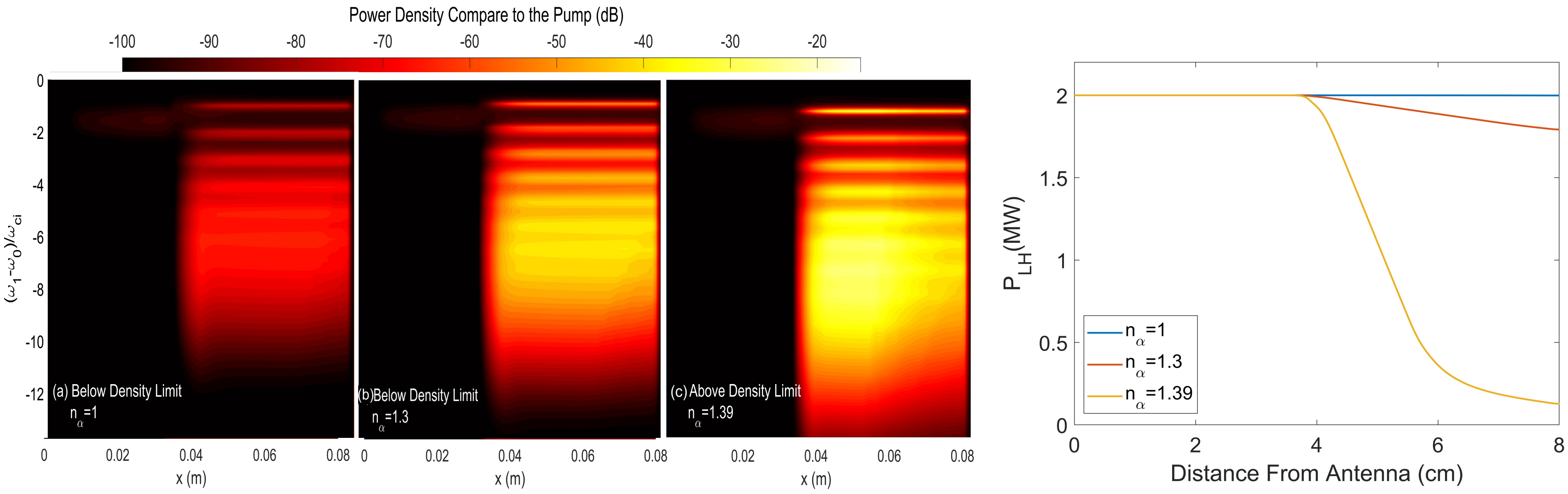


PIPERS： a ray tracing code with the PDI effect included

Frequency sidebands and wavenumber broadening appears but no significant power transfer occurs since PDI is weak

Huang 2026

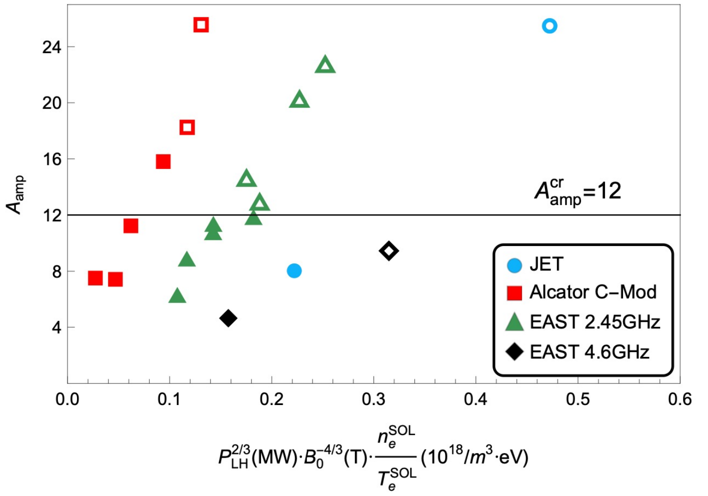
The density limit observed in simulation



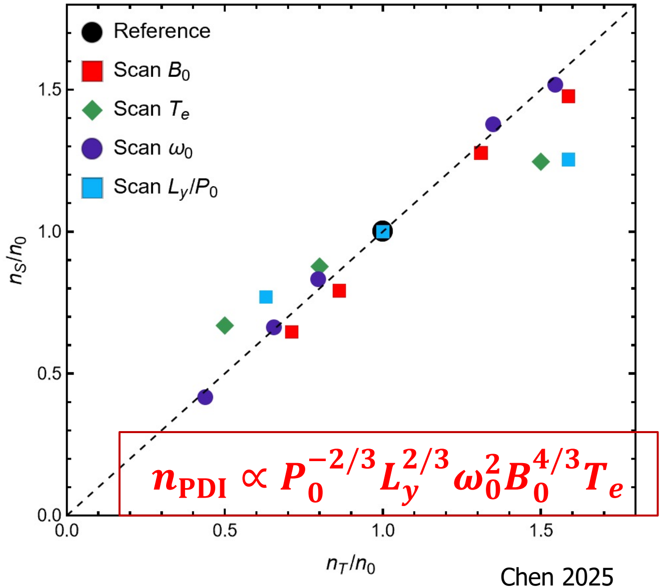
When the density increases above a limit, PDI becomes stronger and the pump is exhausted due to significant power transferring to sidebands

Chen 2025， Huang 2026

A theoretical scaling relation of the density limit



*The hollow points indicate significant degradation of LHCD efficiency

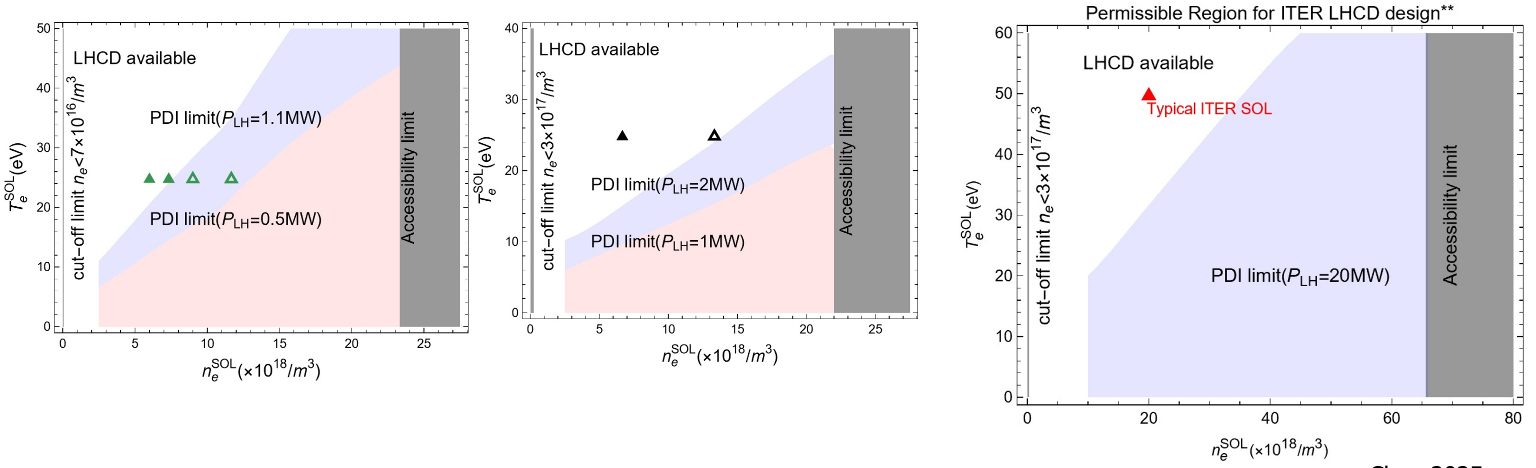


Chen 2025

- When the convective amplification factor is above a certain value, the PDI become strong enough to exhaust the pump
- The simulation results agree quite well with the theoretical scaling relation

PDIs offer a nonlinear density limit

- Agrees with experiments on EAST with 2.45G and 4.6G LHW
- Using the ITER SOL parameters to simulate, **the density is far from the density limit on ITER due to the high SOL temperature, high B and high LHW frequency**
- It may indicate that LHCD on ITER is still effective……

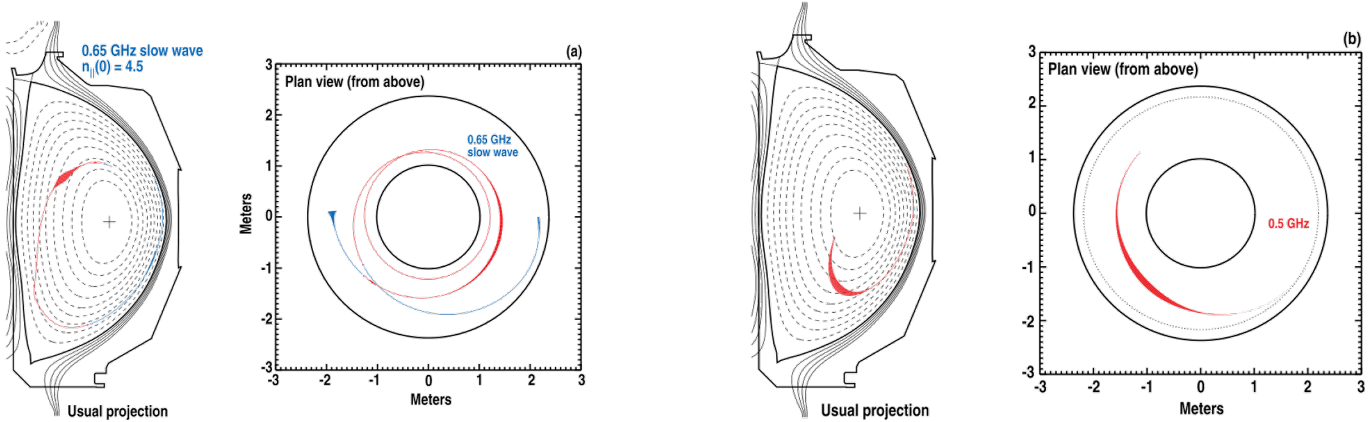


Chen 2025

Helicon wave (LH fast wave) proposed a new CD method in high density plasma

Disadvantage:
- worse coupling at the edge;
- very low Ez for drive electron

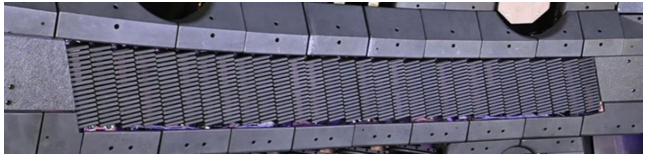
Advantage:
- Good accessibility in the core (no high density resonance; single pass)
- possible weaker PDIs due to low Ez

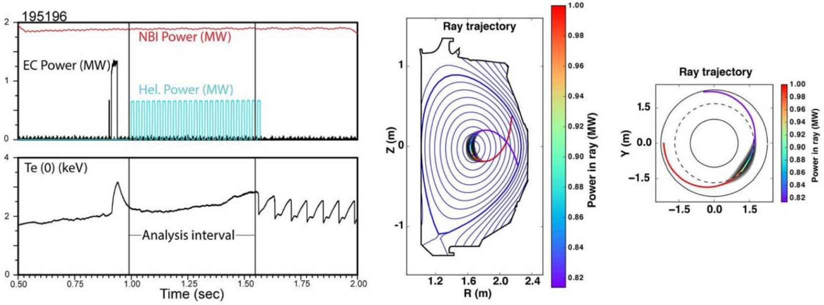


Pinsker,2015

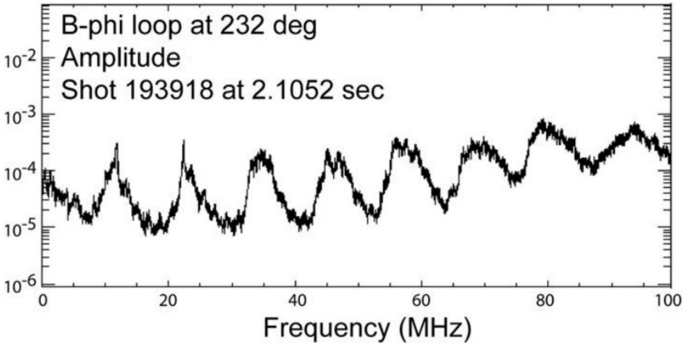
Helicon wave experiment on DIII-D

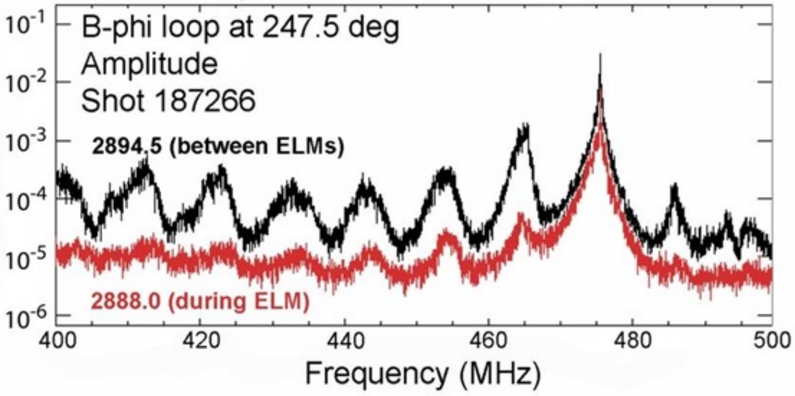
Only on the DIII-D device Helicon waves has successfully achieved power coupling.





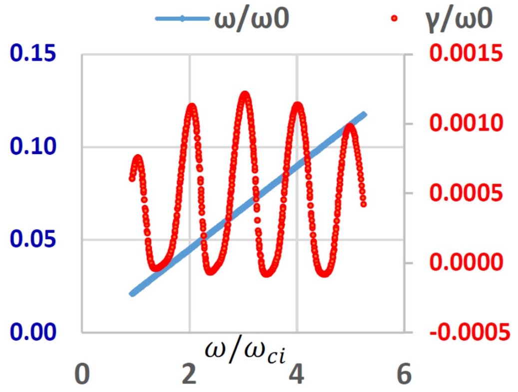
(a) (b) (c)



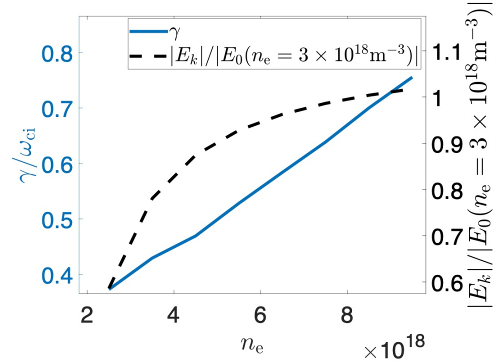


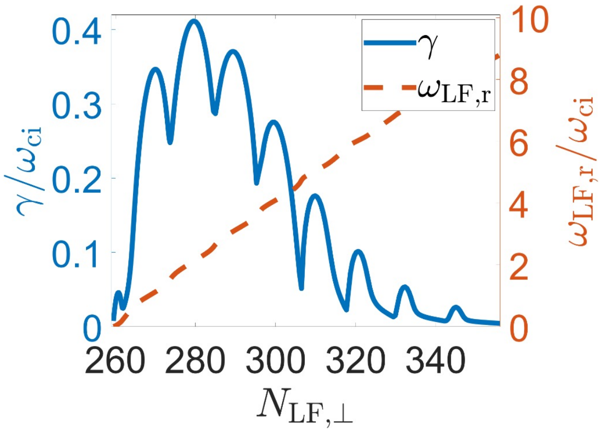
Pinsker 2024

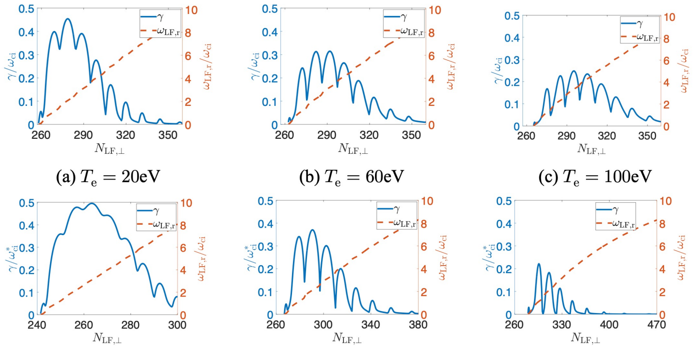
PDIs still to be considered for helicon wave



Porkolab 2023







(a) $T_e = 20$eV (b) $T_e = 60$eV (c) $T_e = 100$eV

(a) $B = 1.0$ T (b) $B = 1.5$ T (c) $B = 2.0$ T

Yang 2026

Final Summary

- The slow and fast LHW are two roots of the cold-plasma dispersion relation at LH frequency range. Slow-wave LHCD with larger E‖ is successfully confirmed in theory, simulation and experiment. It has a high efficiency due to less collisions for fast electrons. The fast wave application is still on the way.
- Accessibility is usually a linear-dispersion constraint. The long coupling problem may be solved by gas puffing and advanced antenna design. However, nonlinear process such as PDI will change the case.
- The spectral-gap problem motivates the need for spectral-broadening mechanisms. Toroidal effect (with multi-pass), scattering, full-wave effect and PDI can induce spectral broadening. It depends on plasma parameters. However, precise calculation of spectral evolution is still a big problem.
- Large progresses have been made concerning simulations of the LHCD. Ray-tracing is rather well validated and wave equation + QL Fokker-Planck self-consistent calculations works in most scenarios. It is lucky that there is good agreement between theory and experiment for single pass case (ITER case)
- LHCD has been performed in many devices. PDI cannot prevent LHCD still being effective on ITER. However, targeted LHCD at high density reactor-like plasma are still necessary.

Acknowledgments

This lecture note only used for IIS 2026.
Many materials in this lecture are from the following publications or lectures.
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- N. J. Fisch, Controlling Plasma with Plasma Waves, 47th Annual Meeting of the Division of Plasma Physics, Denver,2005
- N. J Fisch, Maxwell Prize Talk at APS/DPP 2005
- Y. Peysson, The Lower hybrid wave, the 5th Korea Fusion summer school, Daejon, 2009
- J. Wesson, *Tokamak*, Clarendon Press, Oxford, 2004
- J. P. Freidberg, *Plasma physics and fusion energy* , Cambridge University Press, Cambridge, 2007.
- D. Hartmann, in *Proc. Munich Summer University for Plasma Physics*, (edited by A. Konies and K Krieger),2004
- Baonian Wan，Lower hybrid wave heating and current drive: Theory and experiment, CSSPP2010，Shanghai （in Chinese）
- Bojiang Ding，Lower hybrid wave heating and current drive，CSSPP2023，Suzhou （in Chinese）
- And many related references in these talks.