Experiments with combined Electron Cyclotron and Lower Hybrid Current Drive on Tore Supra

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Why to combine LH and EC waves ?

LH waves:

- best CD efficiency
- limited control capability (multi-junction launcher)

EC waves:

- much lower CD efficiency (waiting for reactor T_e)
- good control capability (localized absorption)

Combination of the two suggested since the early '80s

*I. Fidone et al., Phys. Fluids **27** (1984) 2468*

Successful current ramp-up experiments with LH+EC

WT-2: *A. Ando et al., Phys. Rev. Lett. **56** (1986) 2180*

JFT-2M: *T. Yamamoto et al., Phys. Rev. Lett. **58** (1987) 2220*

WT-3: *T. Maekawa et al., Phys. Rev. Lett. **70** (1993) 2561*

Kinetic calculations point out a possible synergy

*I. Fidone et al., Nuclear Fusion **27** (1987) 579*

What is the synergy ?

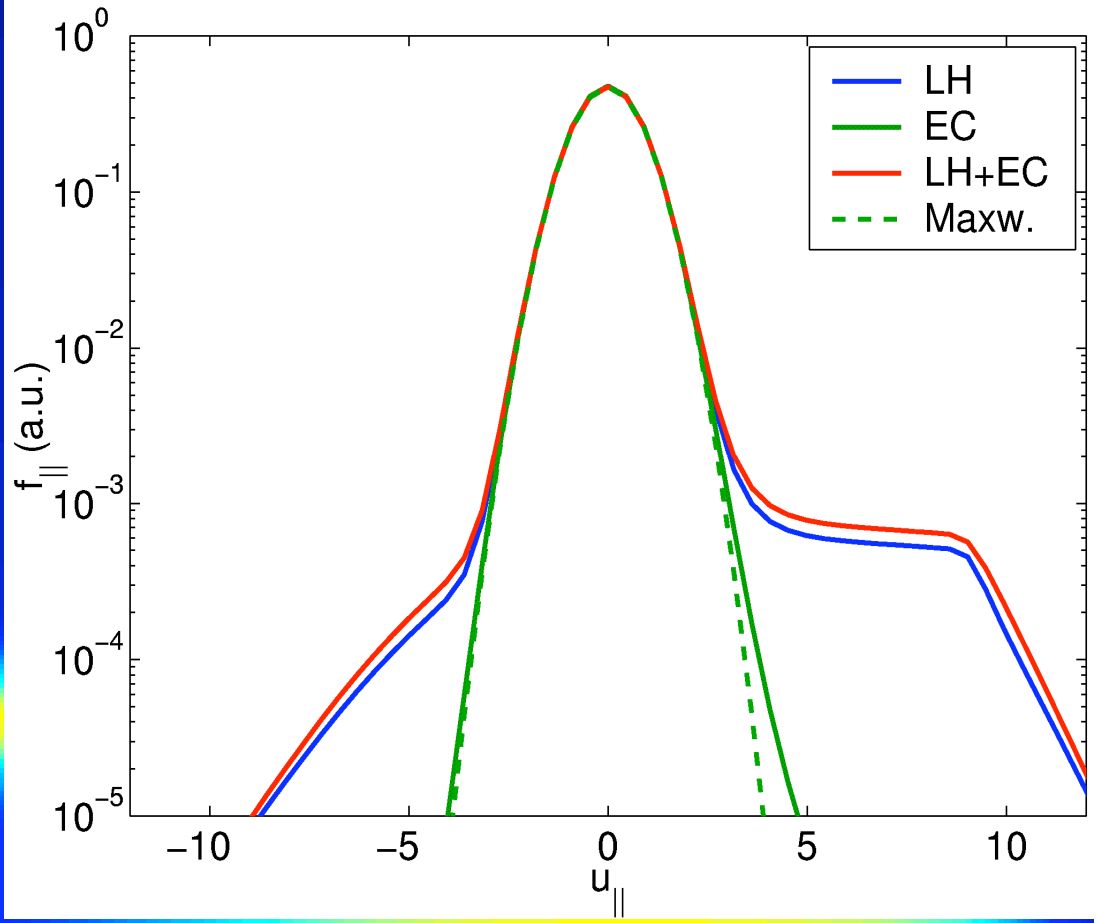
A definition: $I_{LH+EC} > I_{LH} + I_{EC}$

Simple physical picture:

1) EC waves heat electrons at the lower end of the LH tail (~ $3v_{th}$)
2) LH waves push them to high parallel energies
3) As a result, $v_{||} >> 3v_{th} \Rightarrow$ CD efficiency improved

LH controls the efficiency
EC controls the j profile

parallel distribution



Attempts to demonstrate synergy

WT-3 and JFT-2M ramp-up experiments:

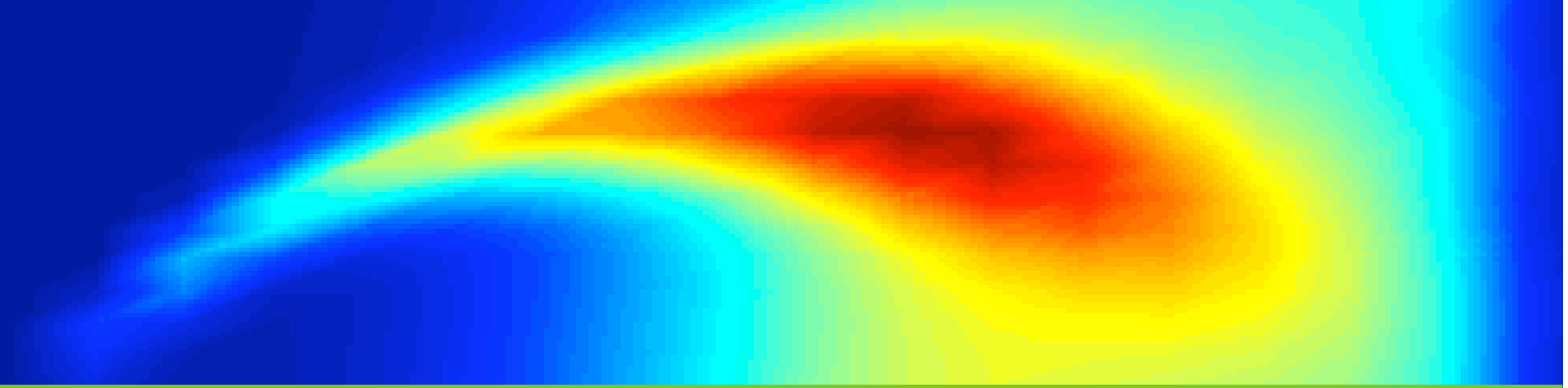
- effect of $E_{||}$ and hot conductivity
- transient regimes
- fast electron confinement issue

⇒ synergy cannot be assessed or quantified

Steady CD experiments:

- Versator- II *(Colborn et al., Nucl. Fusion 38 (1998) 783)*
- TdeV *(Côté et al., 25th EPS Conf. 22C (1998) 1336)*
- *FTU (Granucci et al., Proc. EC12 (2002) 341)*

⇒ inconclusive results



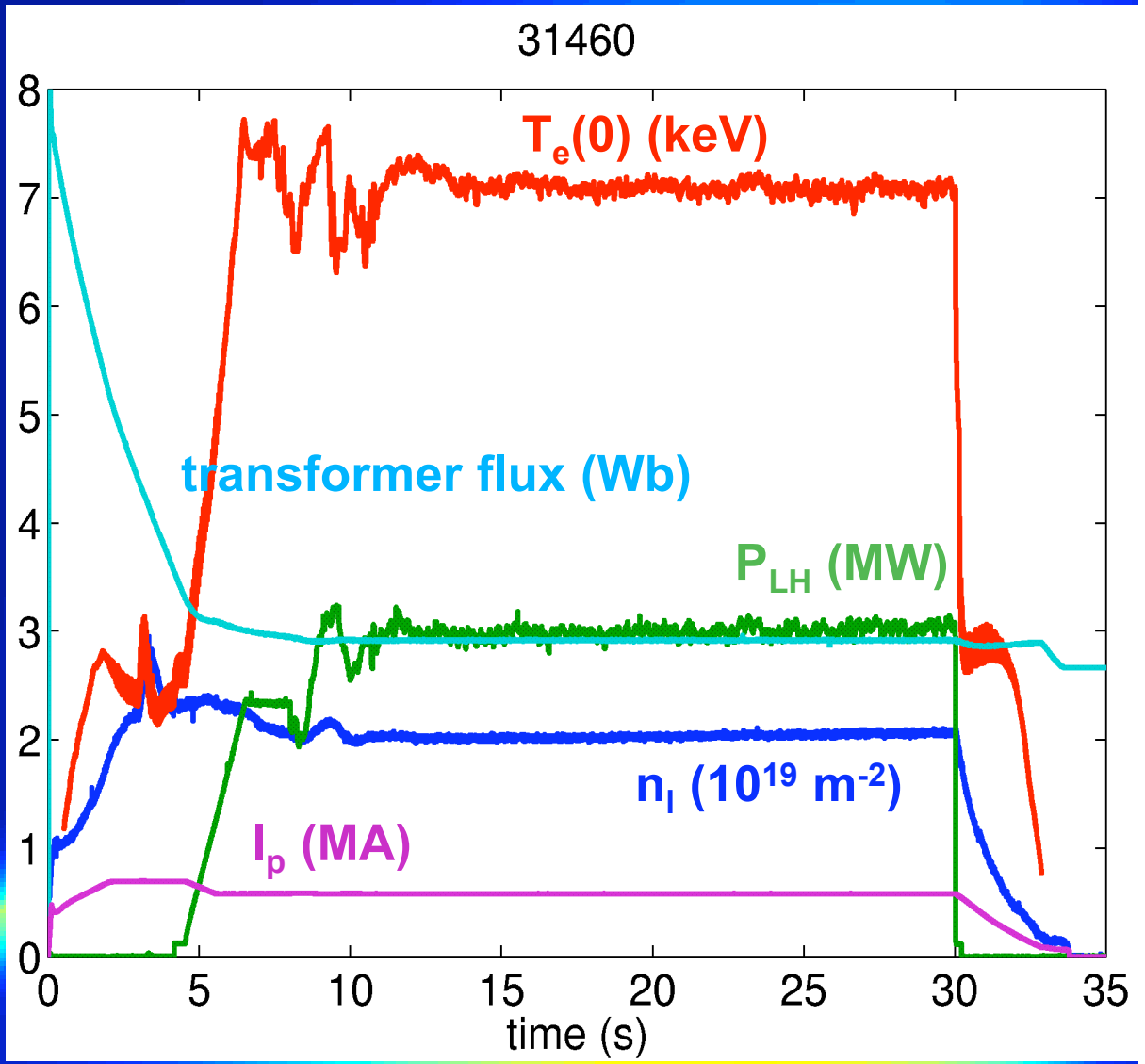
Exploiting long shots on TS

LHCD plasma target:

V_{loop} = 0
(transf. flux kept constant)

I_p kept constant
(feedback by LH power)

density kept constant
(feedback by gas puff)

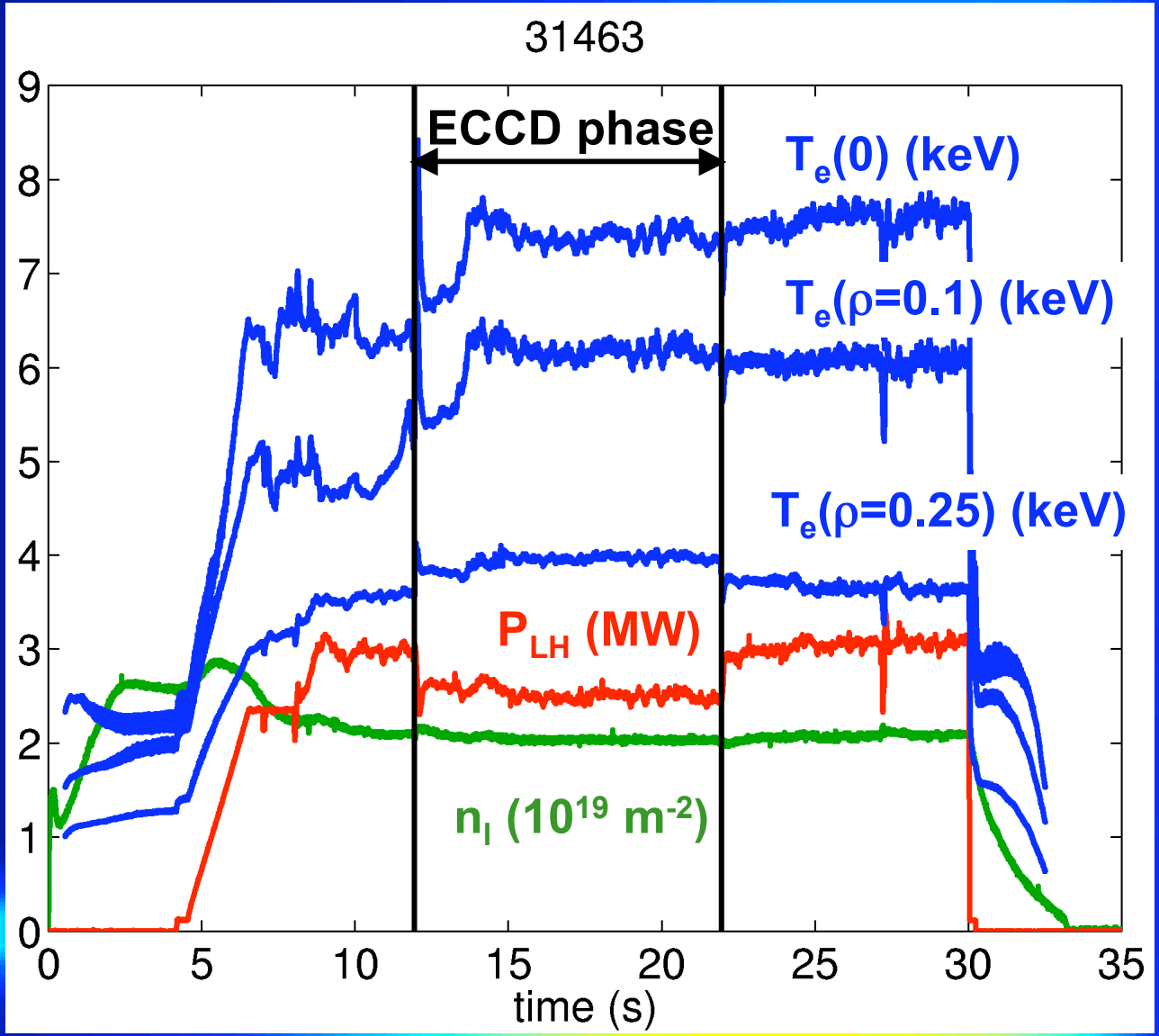


P_{LH} decreases during ECCD phase

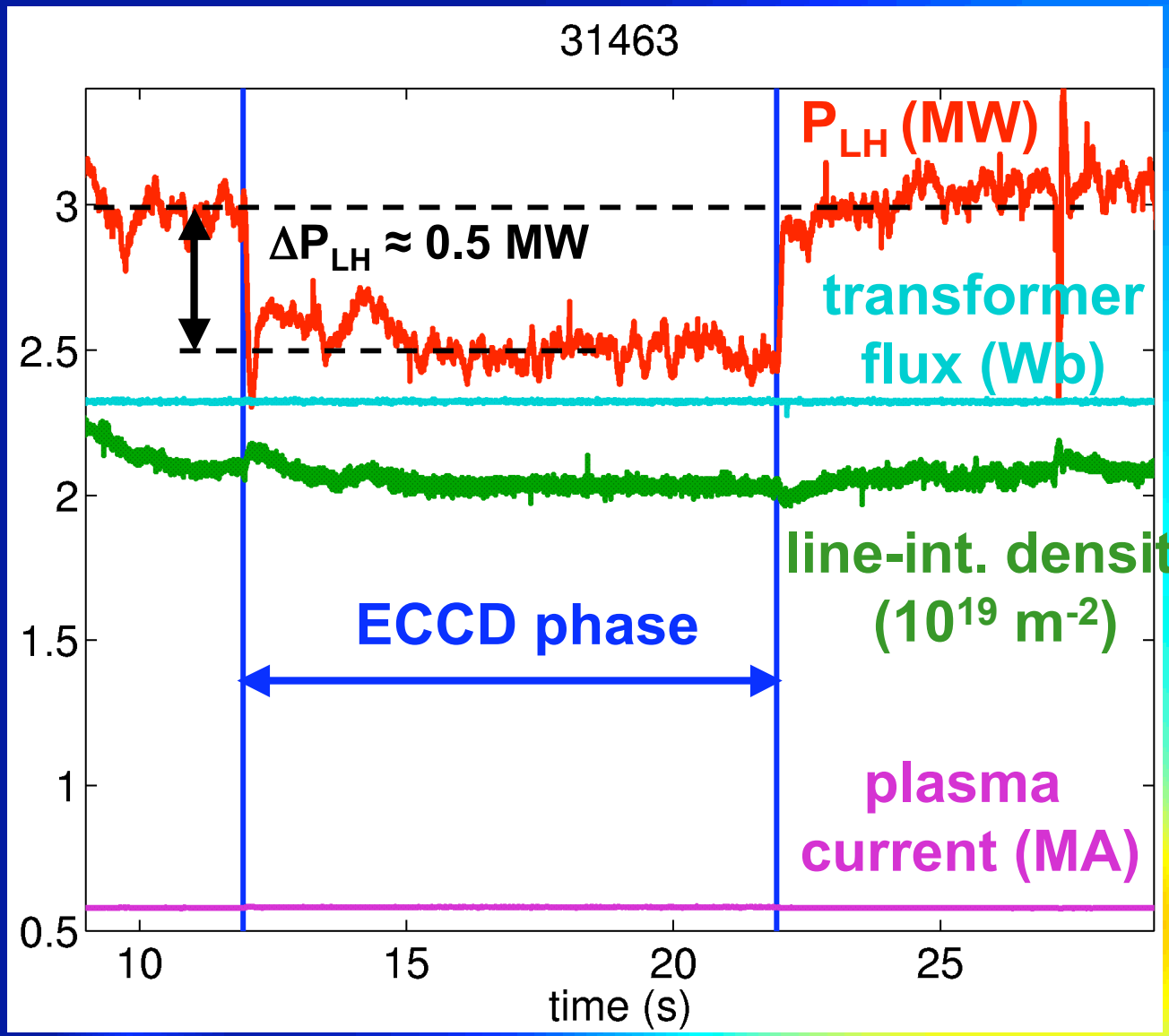
P_{EC} = 0.7 MW (two gyrotrons), toroidal angle +24°

LH and EC waves absorbed at same location

2 improvements:
- core confinement
- ECCD efficiency



P_{LH}=0.5 MW replaced by P_{EC}=0.7 MW



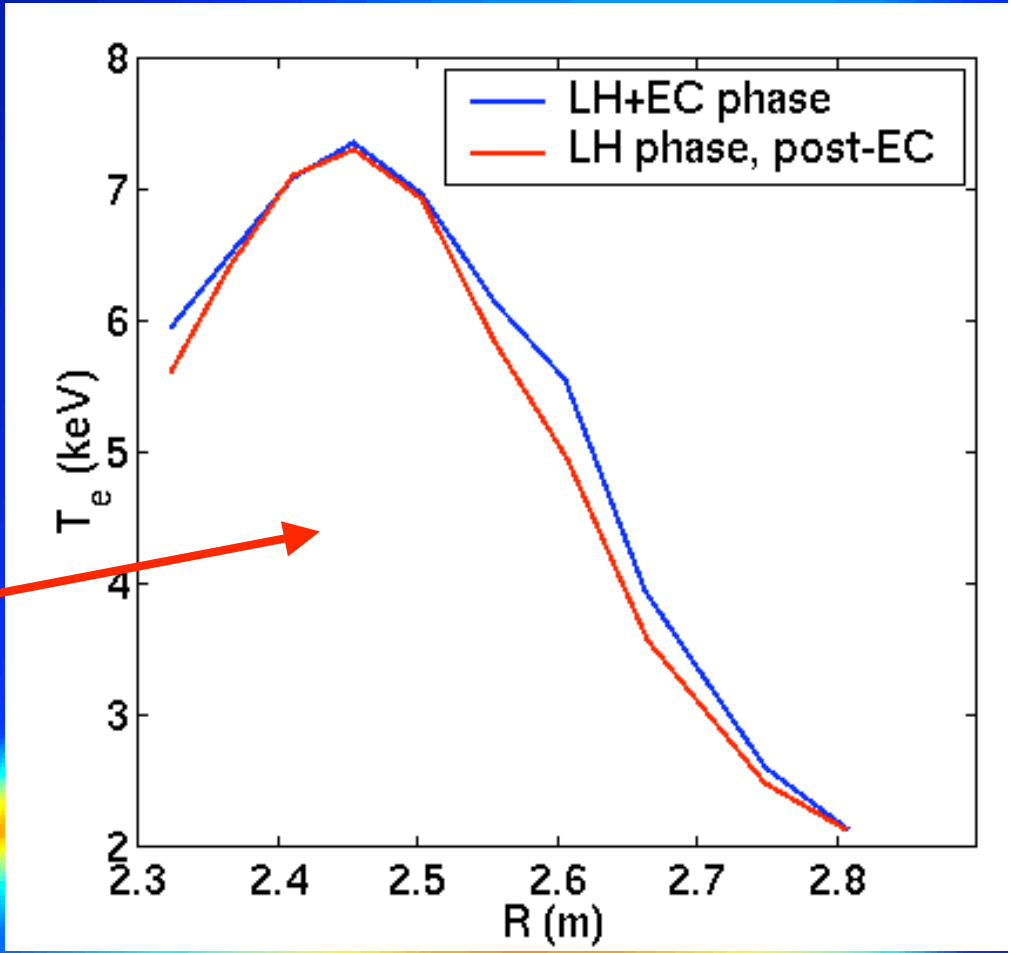
Proof of synergy effect

$\Delta I = (I_p - I_{bs})\Delta P_{LH} / P_{LH}$
predicted I_{EC} = 24 kA.

ΔP_{LH} = 0.5 MW $\Rightarrow \Delta I \approx$ 90 kA

Enhancement of LHCD efficiency η_{LH}. Possible effects:

- η_{LH} increases with I_p.
  Here, I_p constant
- η_{LH} increases with $\langle T_e \rangle$.
  Here, $\langle T_e \rangle$ in the EC phase increases by 5 % only with respect to the phase after EC
- enhancement of I_{bs}.
  NCLASS computations yield negligible difference



Variations of EC power deposition

Variations of:

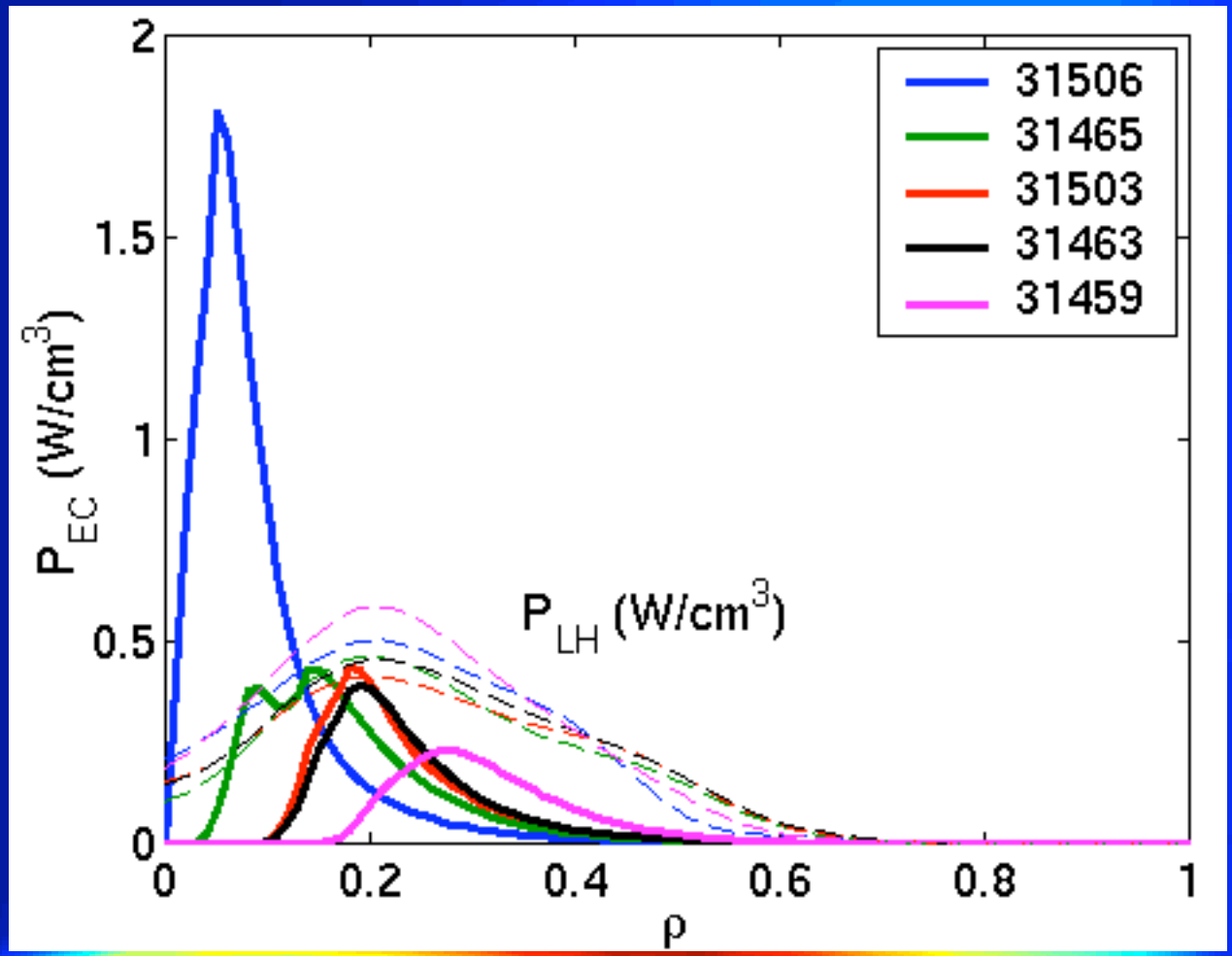
- toroidal angles
- poloidal angles

Result in variations of:

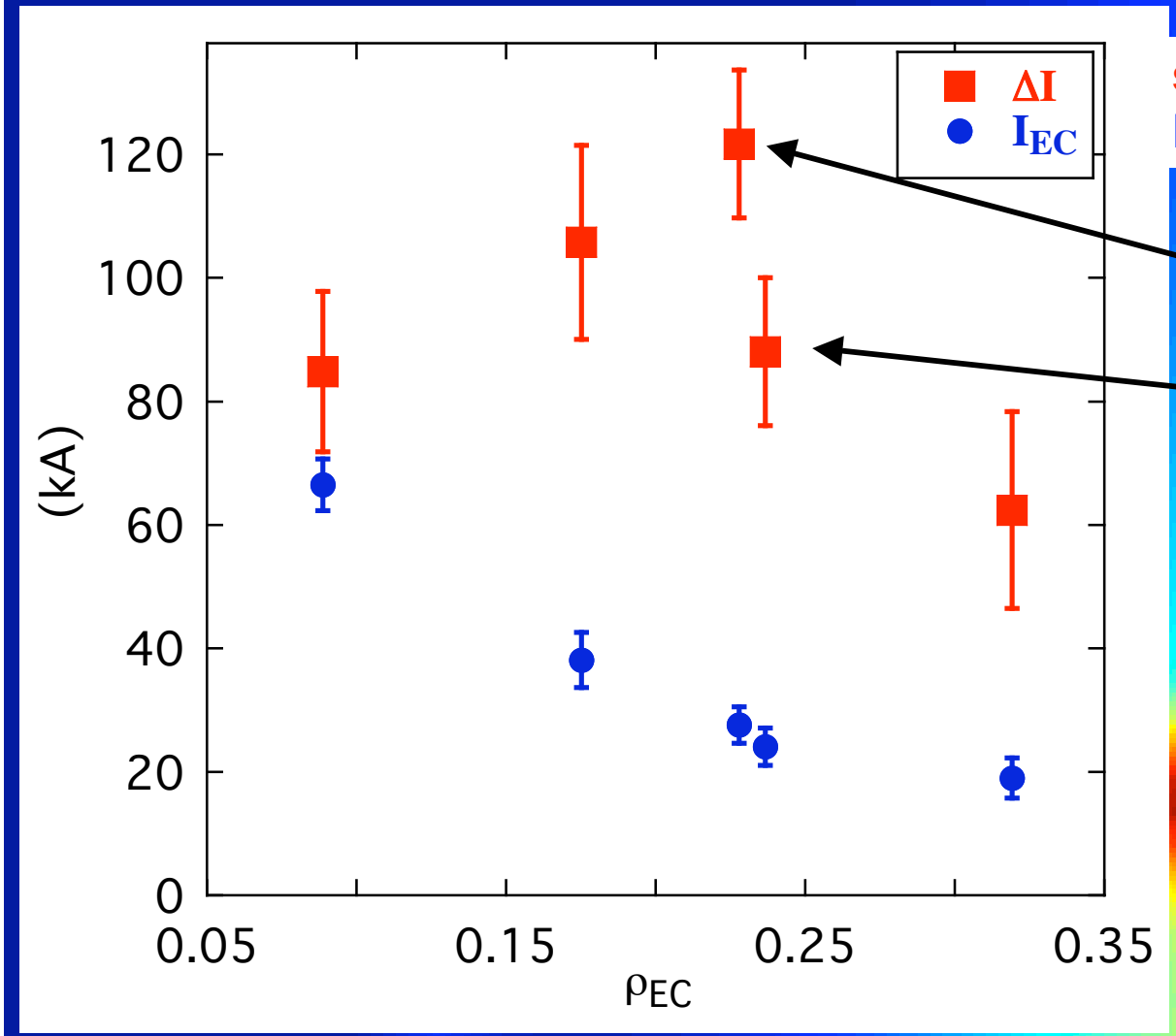
- $\rho_{EC} = r_{EC}/a$

  (EC power deposition location)
- $\langle T_e \rangle$

  (T_e averaged over EC power deposition)



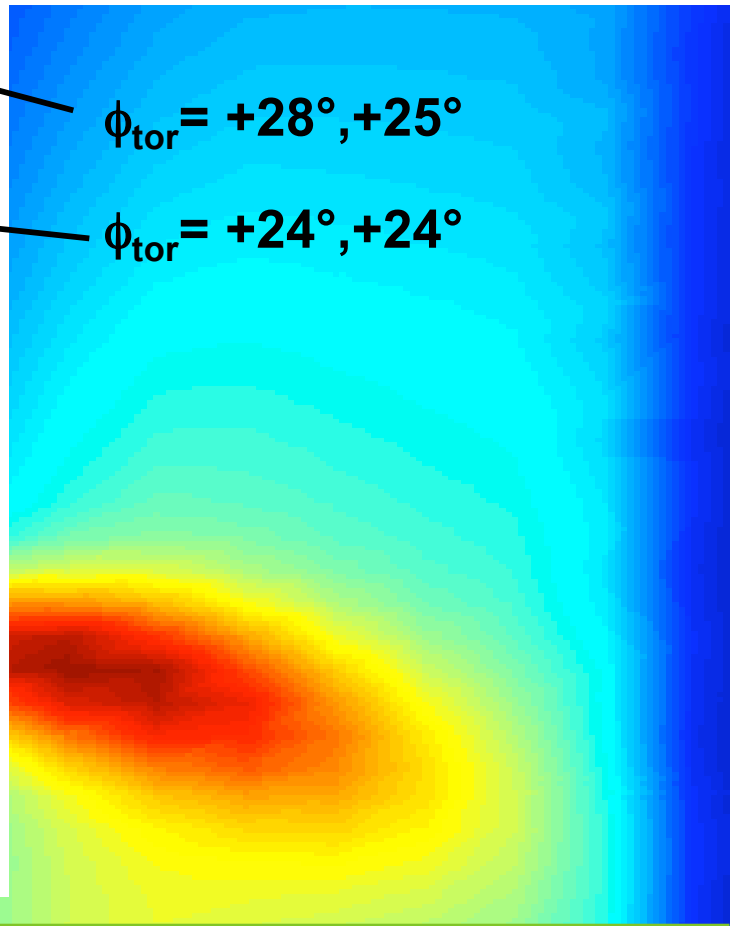
ΔI well beyond computed I_{EC}



synergy current (measured)
linear current (computed)

ϕ_{tor}= +28°,+25°

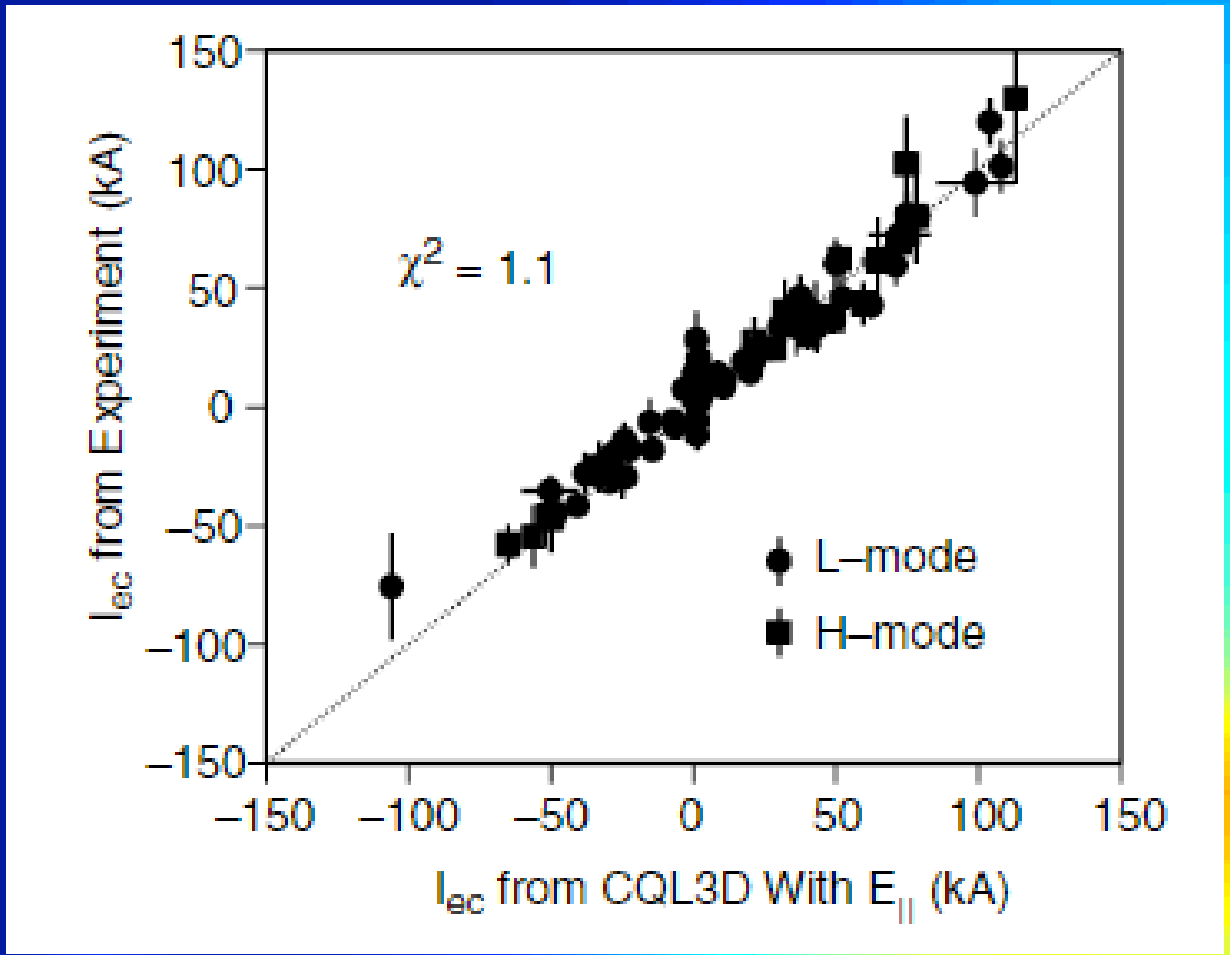
ϕ_{tor}= +24°,+24°



ECCD theory is reliable

ECCD theory in excellent agreement with DIII-D experiments

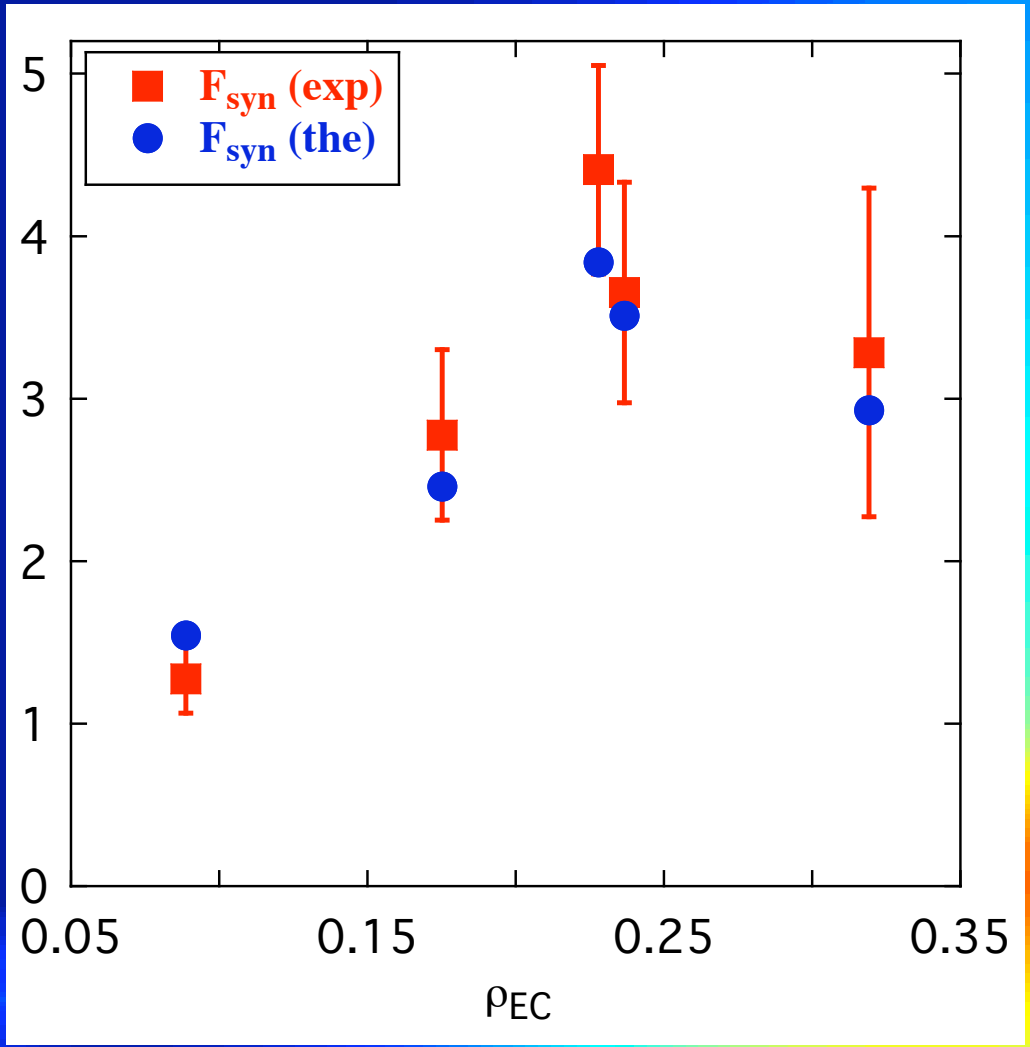
(Petty et al., Nucl. Fus. **42** (2002) 1366)



Synergy factor: $F_{syn} = \Delta I / I_{EC}$

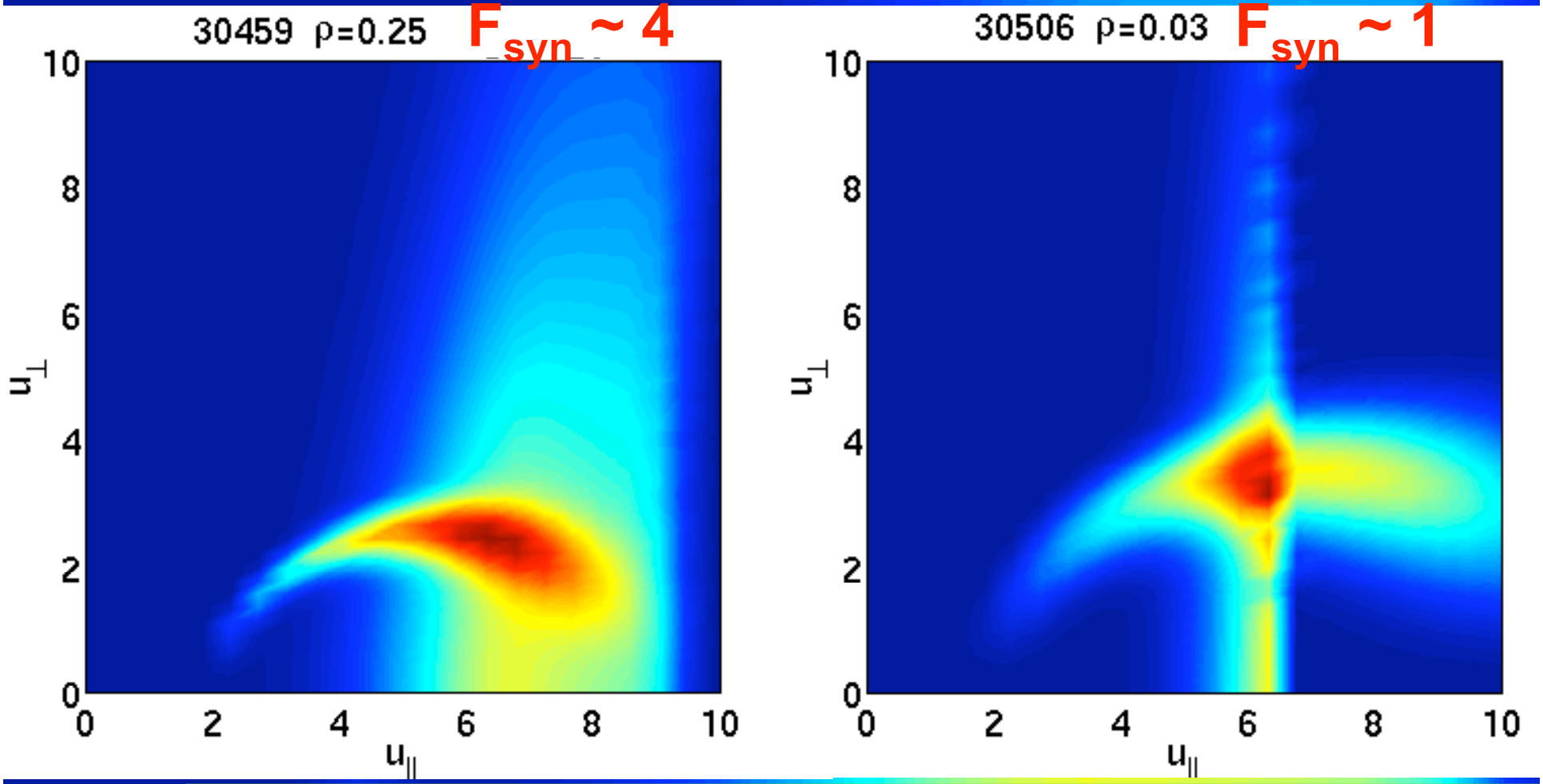
Comparison with kinetic theory

(3-D Fokker-Planck code → *G. Giruzzi, PPCF **35** (1993) A123*



$D_{LH}+D_{EC}$ in the $u_{||}$-$u_{\perp}$ plane

Synergy factor is determined by the overlap of the two interactions in both real and momentum space



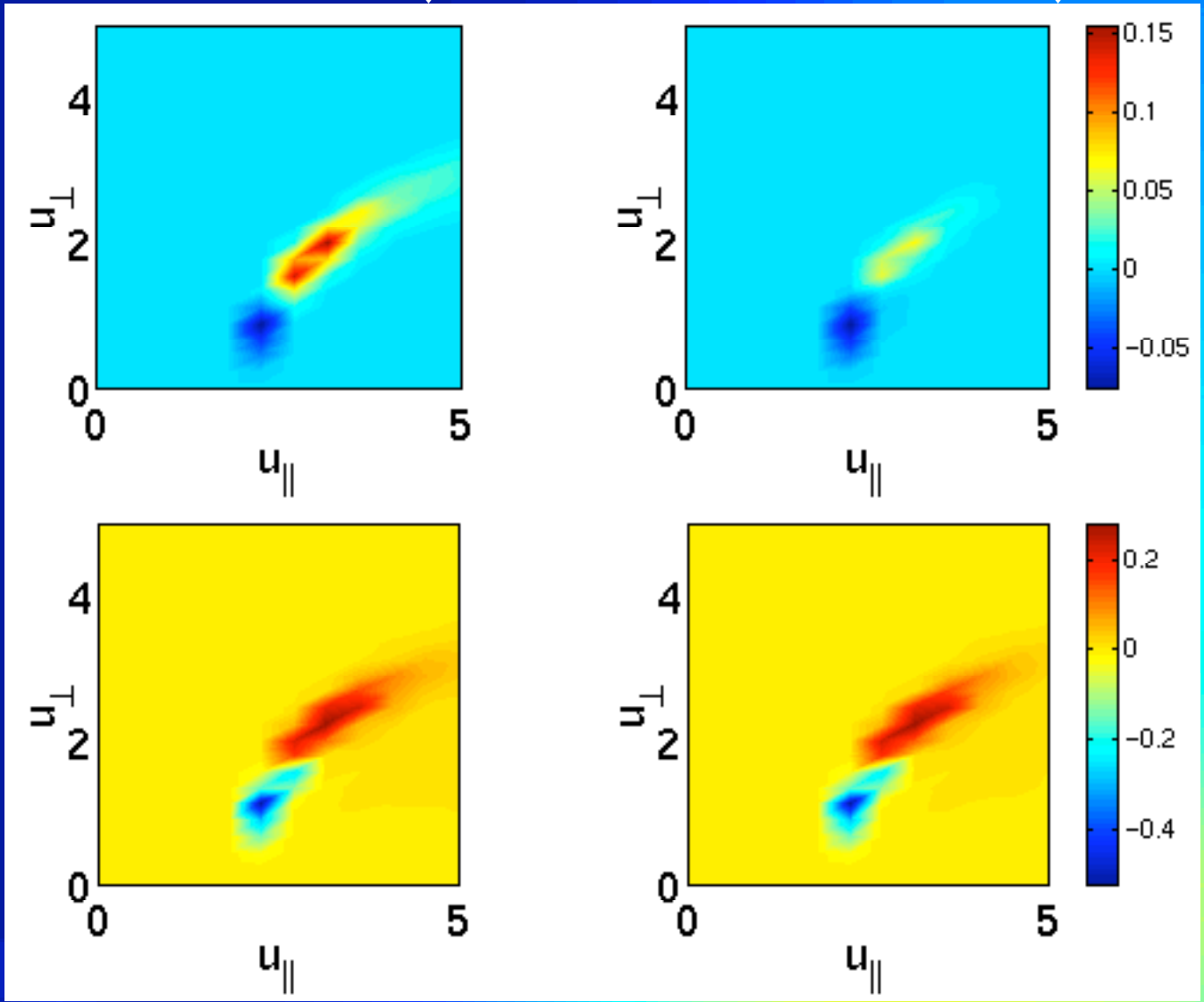
EC absorbed power in $u_{||}$-$u_{\perp}$ space

with LH

without LH

$F_{syn} \approx 4$

$F_{syn} \approx 1$



Conclusions

- LH power replaced by EC power of the same order: an experimental fact
- Improvement of CD efficiency difficult to explain by other effects than synergy
- Kinetic calculations of the synergy factor in good agreement with experiments
- Dependence of the synergy factor on physical parameters still to be explored and understood
- Possible applications to ITER (NTM stabilization ?)