Microturbulence within the front of a quasi-perpendicular supercritical shock

B. Lembège(1) and Muschietti L.(1, 2)

(1): LATMOS, UVSQ, Guyancourt, France; (2): SSL, UC Berkeley, USA

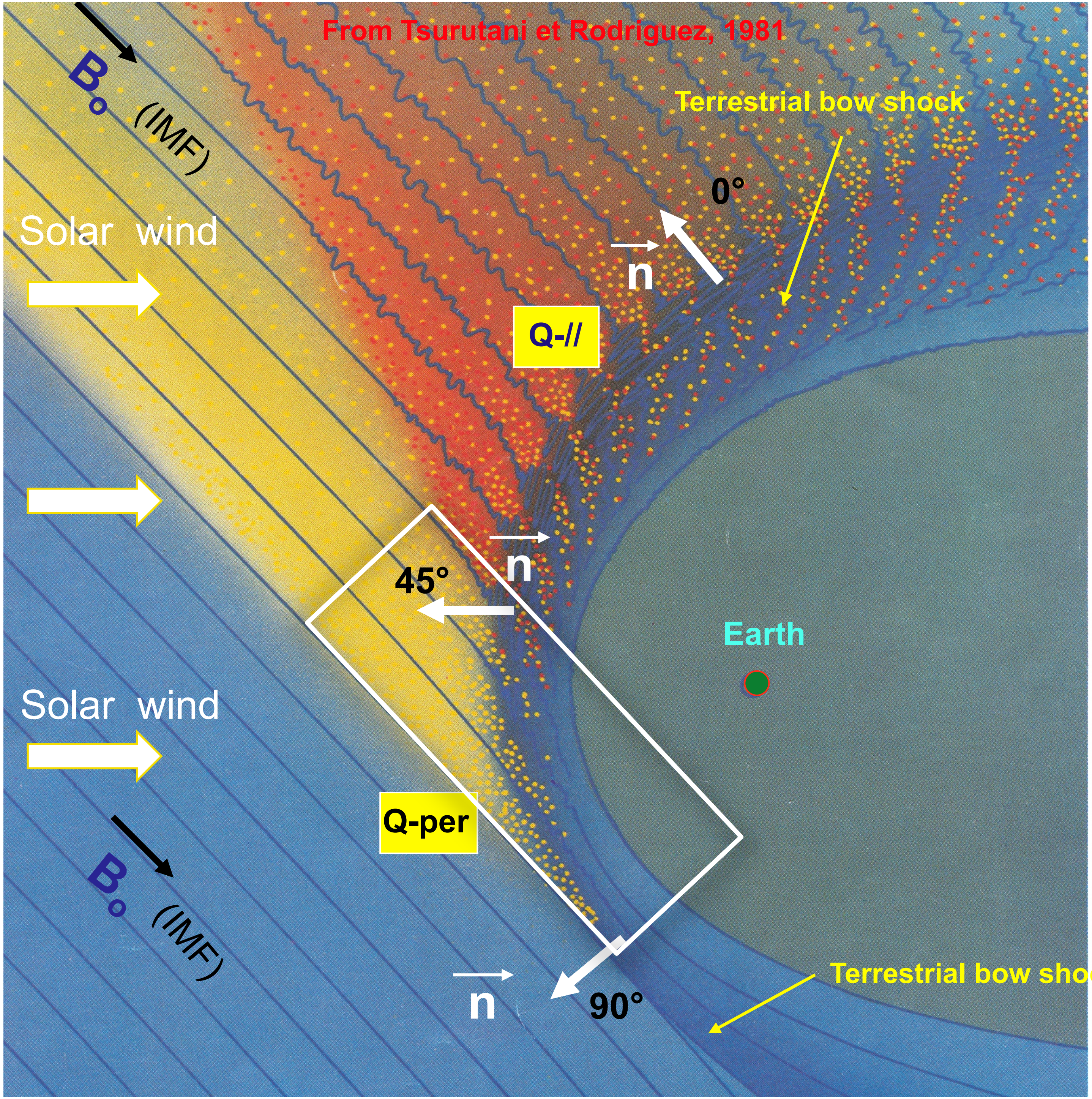
Motivations:

* To focuss on wave activity within a shock front, in particular
  -> in foot region
  -> within Ω_{ce} range

* What main source mechanisms ?

* To analyze in details their linear and nonlinear features ?

* Impact of microturbulence on preheating in the foot ?


From Tsurutani et Rodriguez, 1981

$\theta_{B\nu} = (\vec{n}, \vec{B}_o)$

$\vec{n}$ = shock front normal

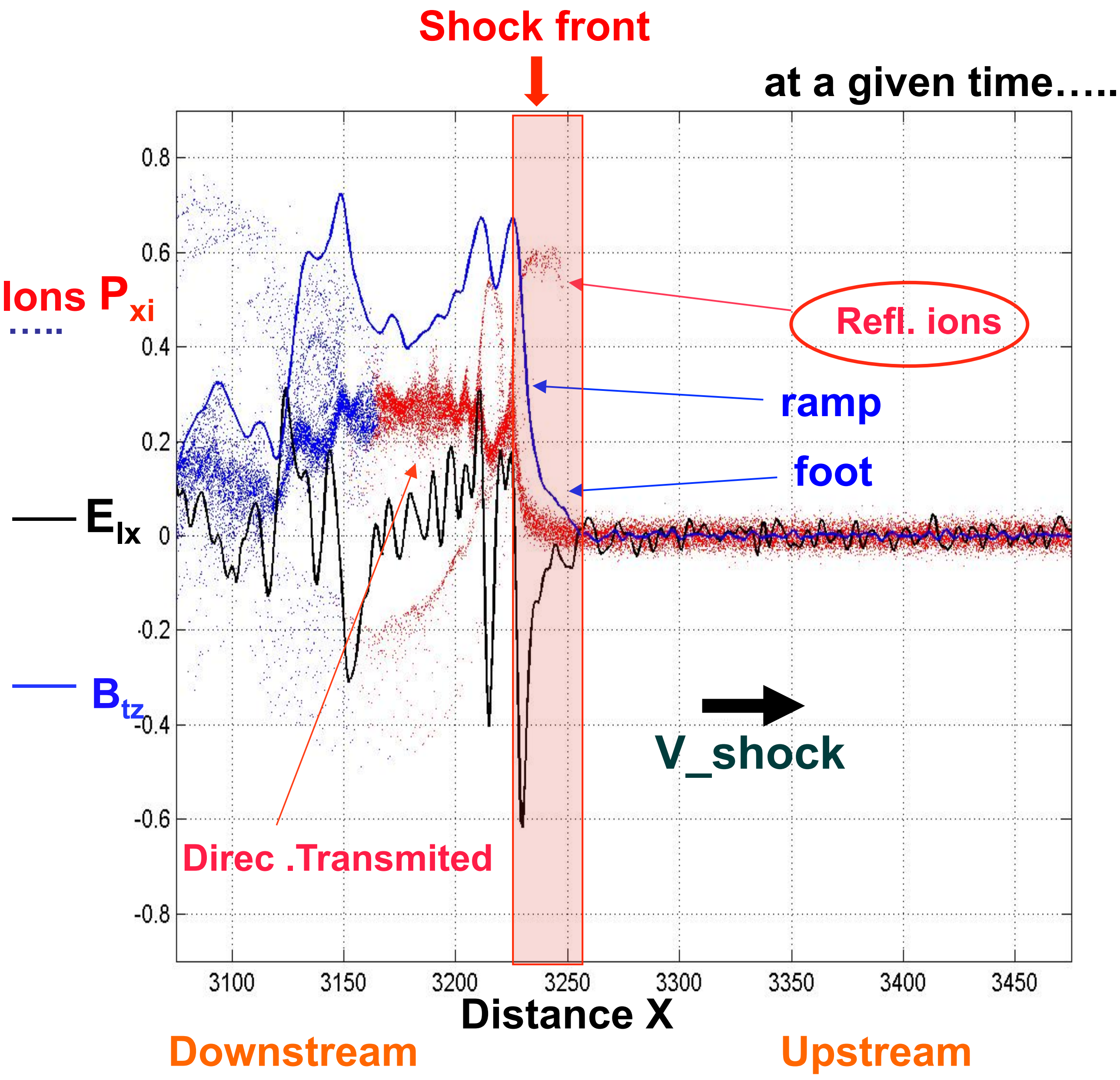
$\vec{B}_o$= interplanetary magnetic field (IMF)

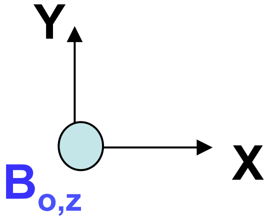
1D PIC simulation of shock: 90°, Ma= 4.3 , βi= 0.022

Supercritical shock

at a given time…..

E x B effect



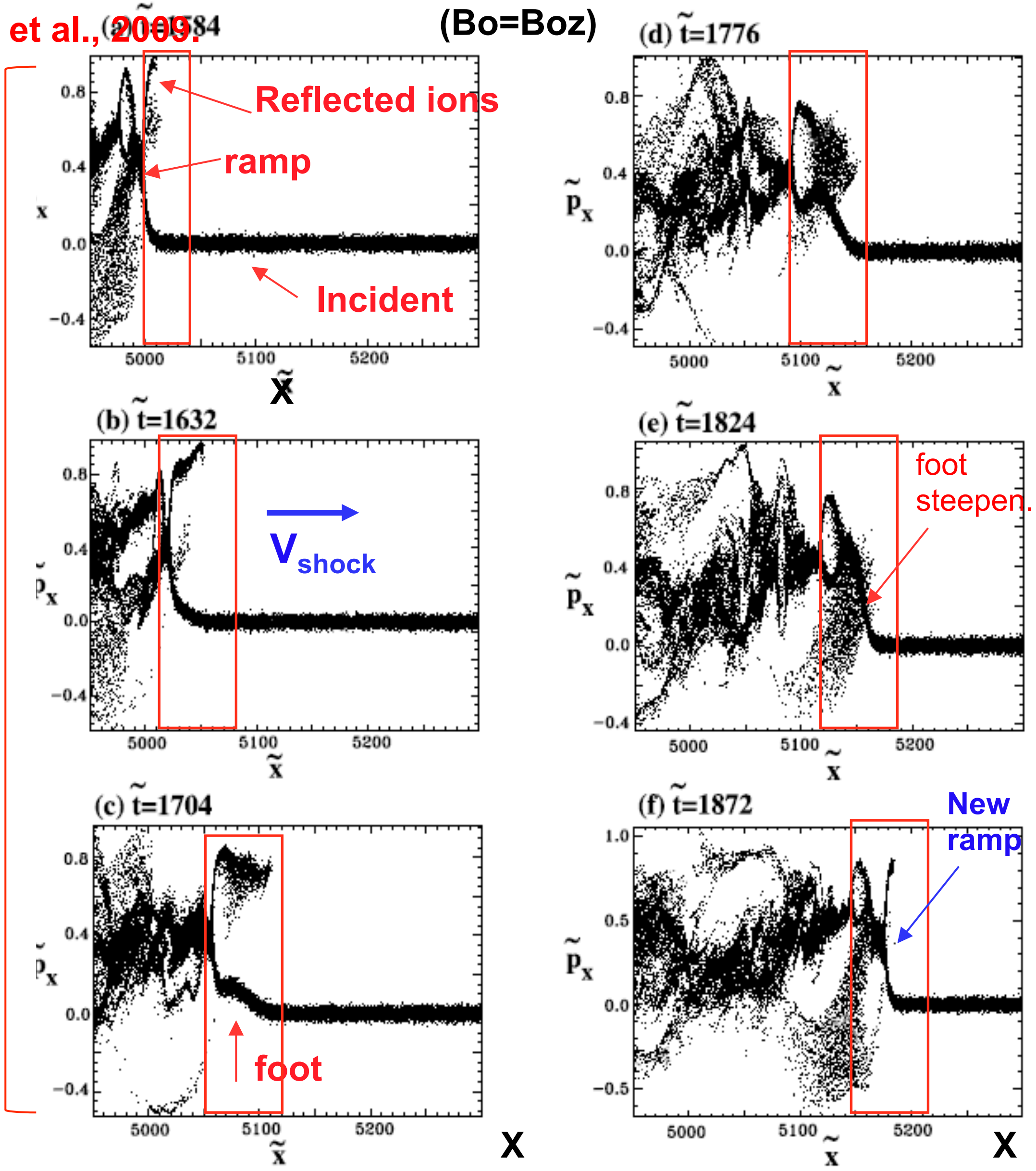


The shock front self-reformation: an example of front nonstationarity

PIC simul.: Biskamp et Welter, 1972; Lembege et Dawson, 1987; Lembege et Savoini, 1992; Schmitz etal., 2002; Lee et Chapman, 2005

Hybrid simul: Hellinger et al. 2002, Lembege et al., 2005.

« Self –reformation» of the shock front



(Bo=Boz)

Reflected ions

ramp

Incident

V_{shock}

foot

foot steepen.

New ramp

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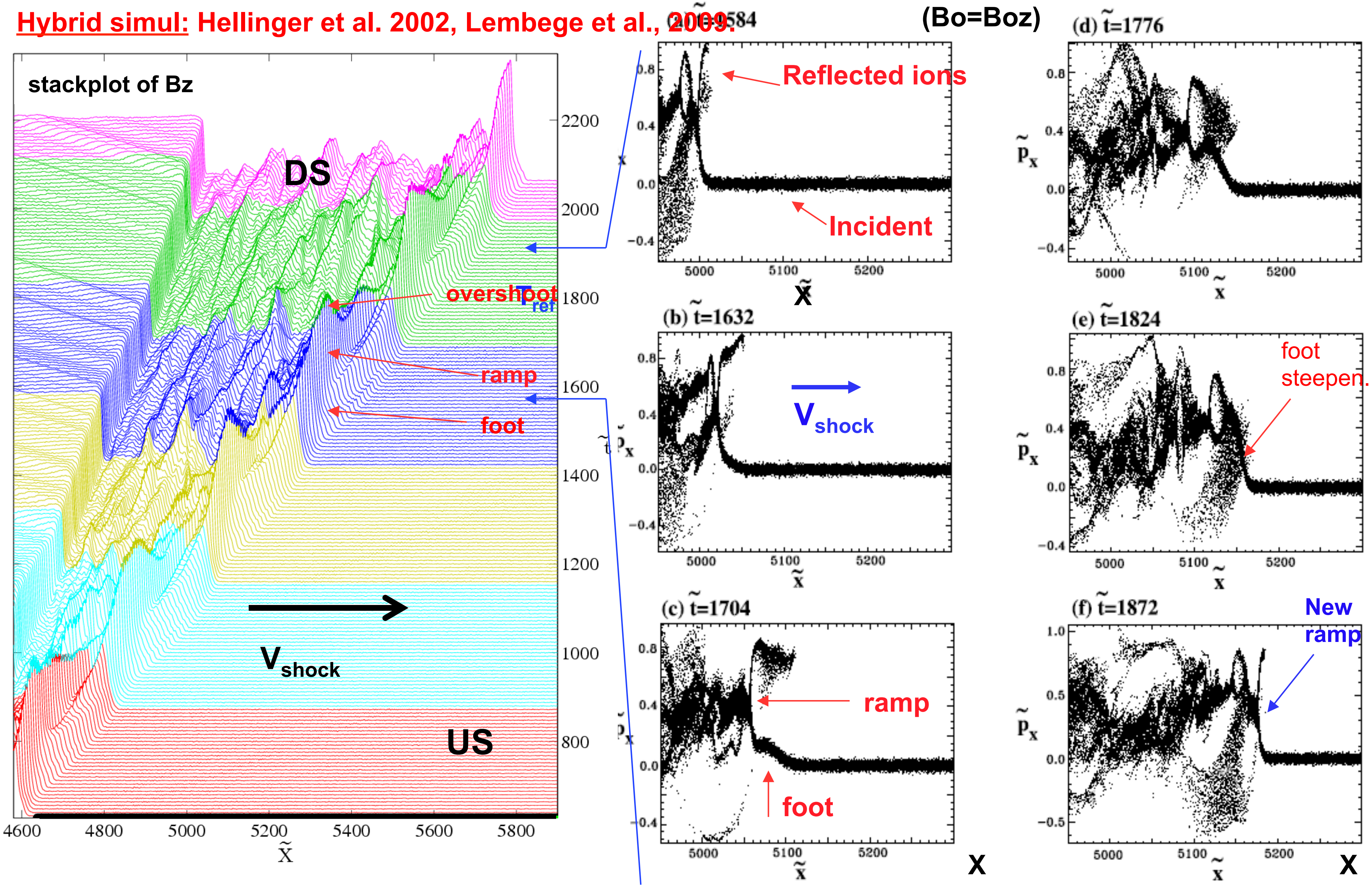

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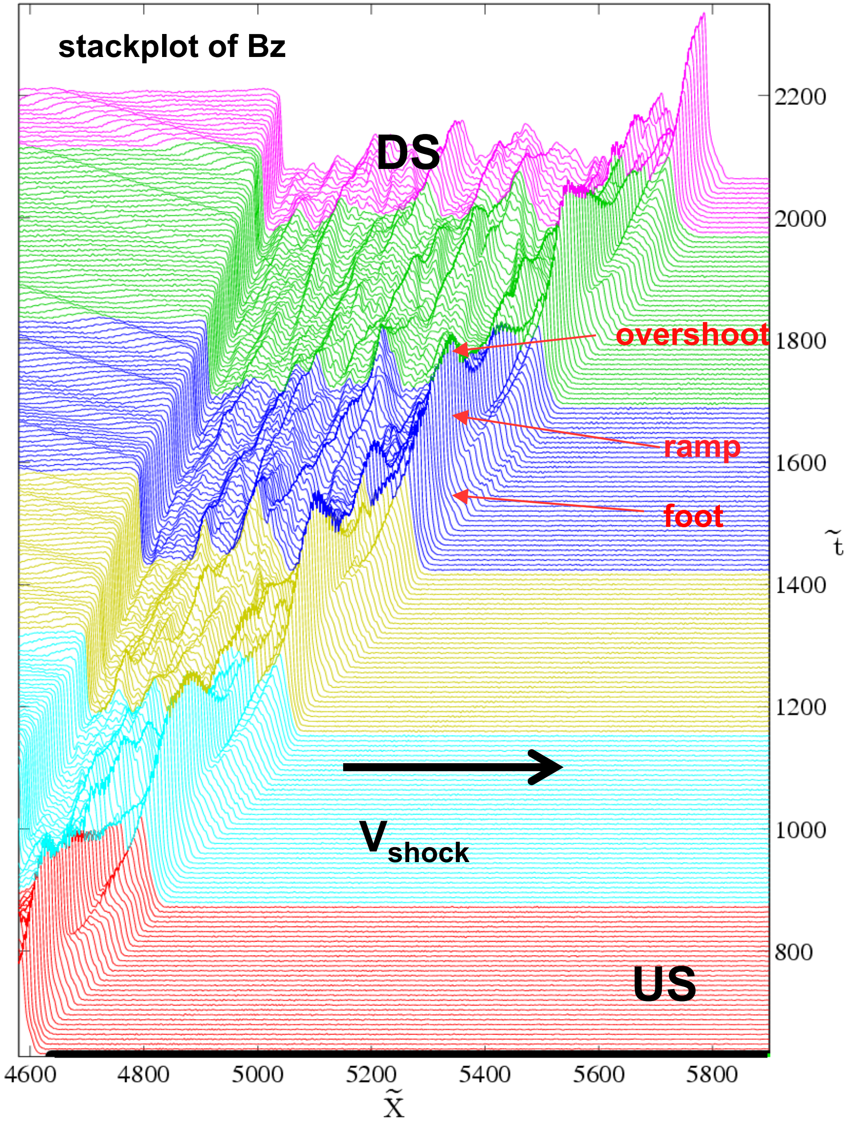


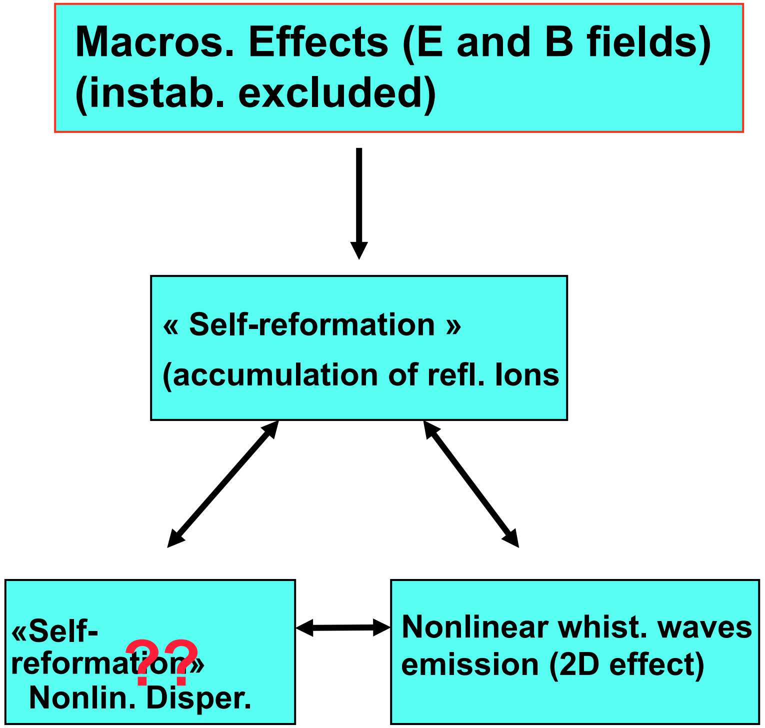
i) This self-reformation process persists

- in 1D/ 2D/ 3D
- with hybrid / PIC simul.

ii) Self reform time period: 0.3 $\tau_{ci,us}$

→ 2-3 cycles within one $\tau_{ci,us}$

Sources of nonstationarity (Q-perp Shock)



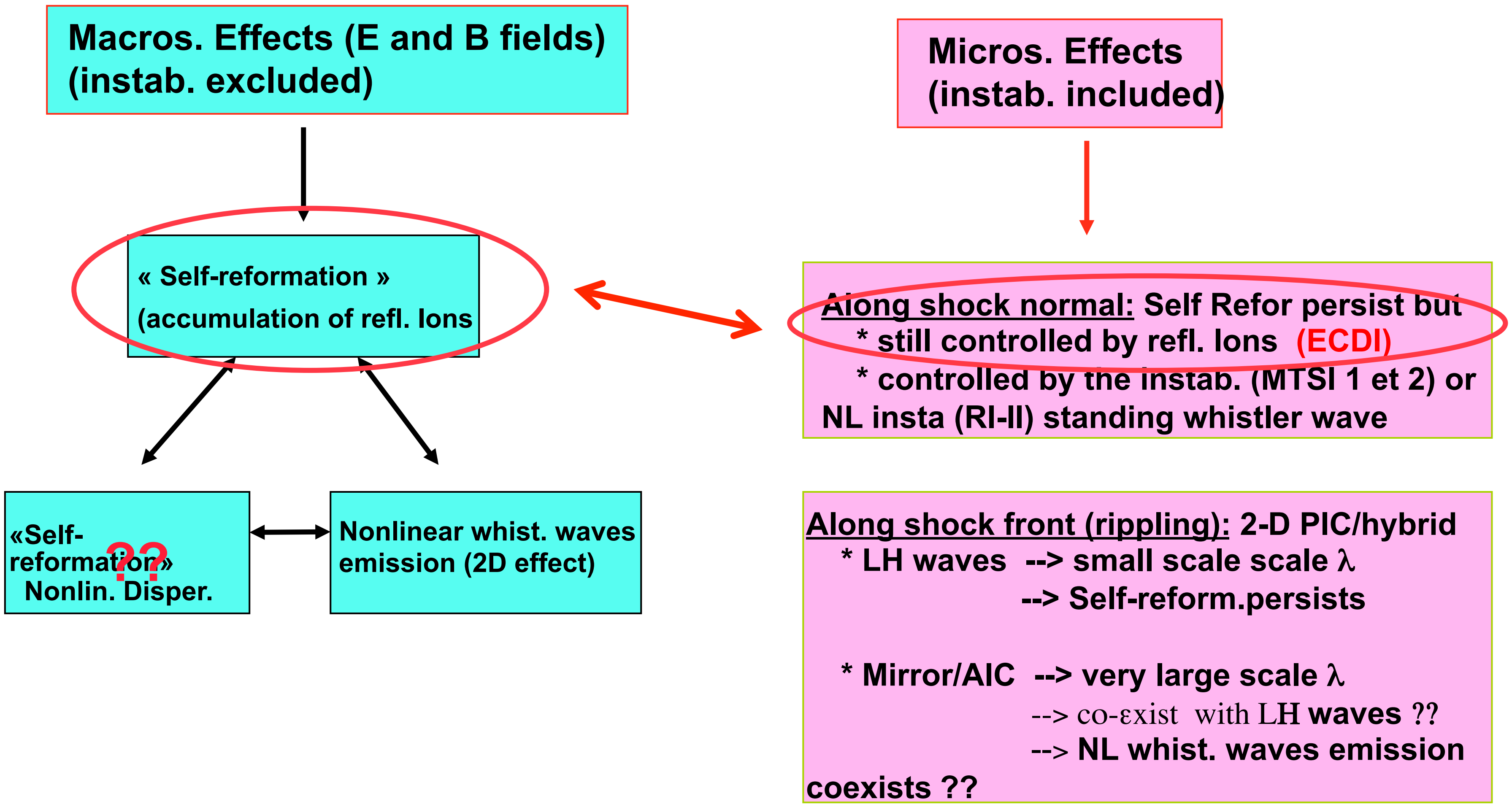
Macros. Effects (E and B fields)
(instab. excluded)

« Self-reformation »
(accumulation of refl. Ions

«Self-reformation» ??
Nonlin. Disper.

Nonlinear whist. waves emission (2D effect)

Sources of nonstationarity (Q-perp Shock)



Macros. Effects (E and B fields)
(instab. excluded)

« Self-reformation »
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«Self-reformation» ??
Nonlin. Disper.

Nonlinear whist. waves emission (2D effect)

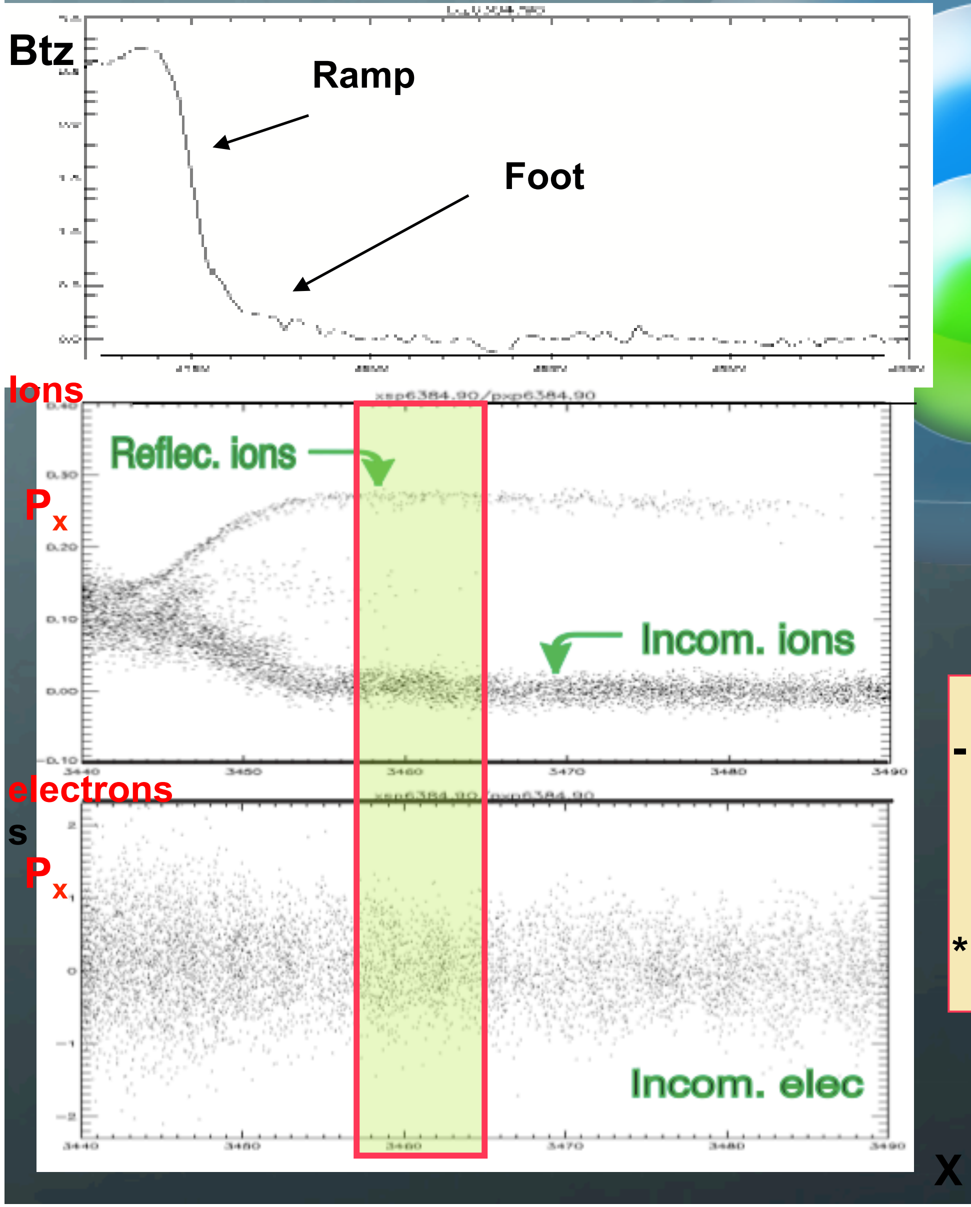
Micros. Effects
(instab. included)

<u>Along shock normal:</u> Self Refor persist but
* still controlled by refl. Ions (ECDI)
* controlled by the instab. (MTSI 1 et 2) or NL insta (RI-II) standing whistler wave

<u>Along shock front (rippling):</u> 2-D PIC/hybrid
* LH waves --> small scale scale λ
  --> Self-reform.persists
* Mirror/AIC --> very large scale λ
  --> co-εxist with LH waves ??
  --> NL whist. waves emission coexists ??

does self-reformation persist in presence of ECDI ?

Basic ingredients for microturbulence in the foot



3 diff popul. (re. drift) --> Micro-instabi.

- MicroInst. --> add diffusion -> local heating
--> impact of this diffusion on
the self-reformation ?

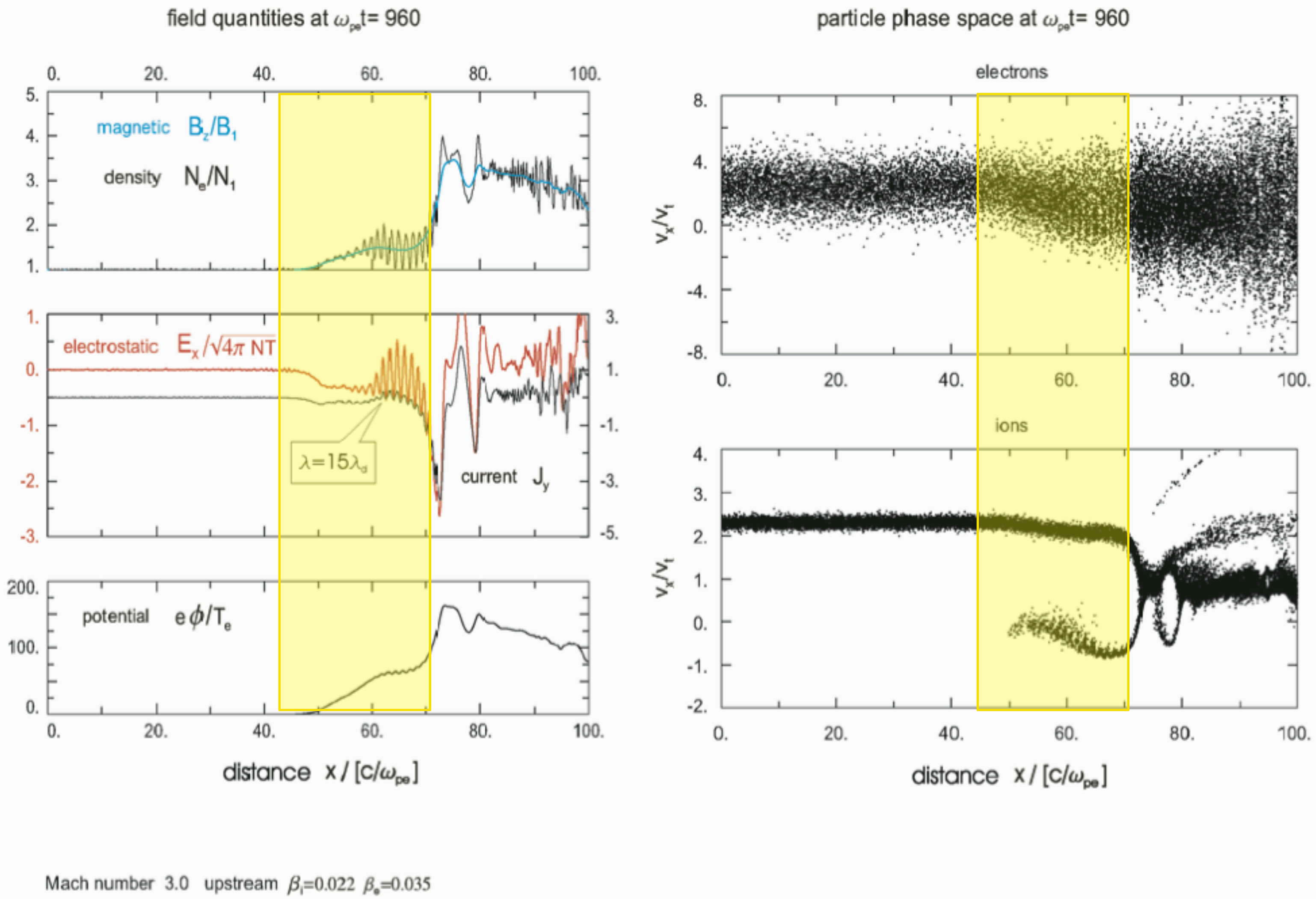
*** Different types of micro-inst may be identified**

	Shimada et Hoshino (2002)	Schmitz et al. (2002, a,b)	Muschietti et Lembege (2005) 2013	Scholer et al. (2003, 2004)	Scholer et Burgess (2005).
Instabilit	Buneman	Buneman	El. Cycl Drift.	MTS	NonLinear whistler
Shock angle	90°	90°	90°	Oblique (87°)	Oblique (70°)
source	Refl. ions / elec.	Refl. ions / elec.	Refl. ions / elec.	Refl. ions/ elec.	Refl. ions/ Ions.
Ma	10.5	10.5	3	6	11
Mi / me	20 (low)	20 (low)	100 (256, 400)	1836 (real)	1836 (real)
ωpe/ωce	20 (high)	20 (high)	2	2 (low)	2 (low)
	SR persists	SR persists	SR persists	SR...differs Self Ref. control by the instab.	SR...differs Self Ref. control. by the instab.

ECD Micro-inst. (Muschietti et Lembege , 2005)

(θ = 90°, Ma = 3, Rmass=100, β_e= 0.035) $\omega_{pe}/\omega_{ce}=2$

PIC simulations: composite snapshot

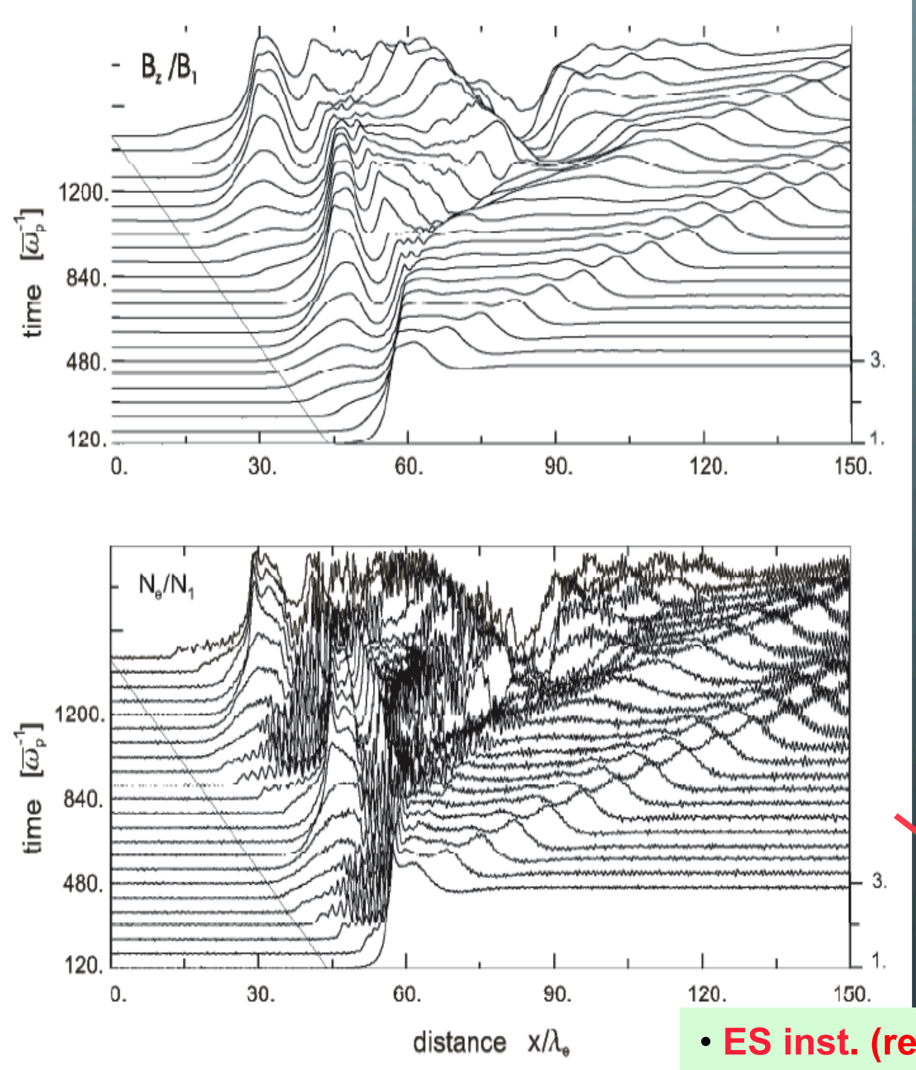


--→ ECDI is observed provided that the grid resolution is high enough

Does the ECDI suppress the self-reformation or not ??

Sources of nonstationarity (Q-perp Shock)

ECDI (Muschietti et Lembège, 2006), Θ= 90°



• ES inst. (refle ions & elec.): coupl. of ion beam & Berstein waves
* Very rapid growth rate
* S.Ref. still driven by the accumul. of refl. Ions
• accessib. to a few 10 λ_{De} fluctuations within the foot

Main questions :

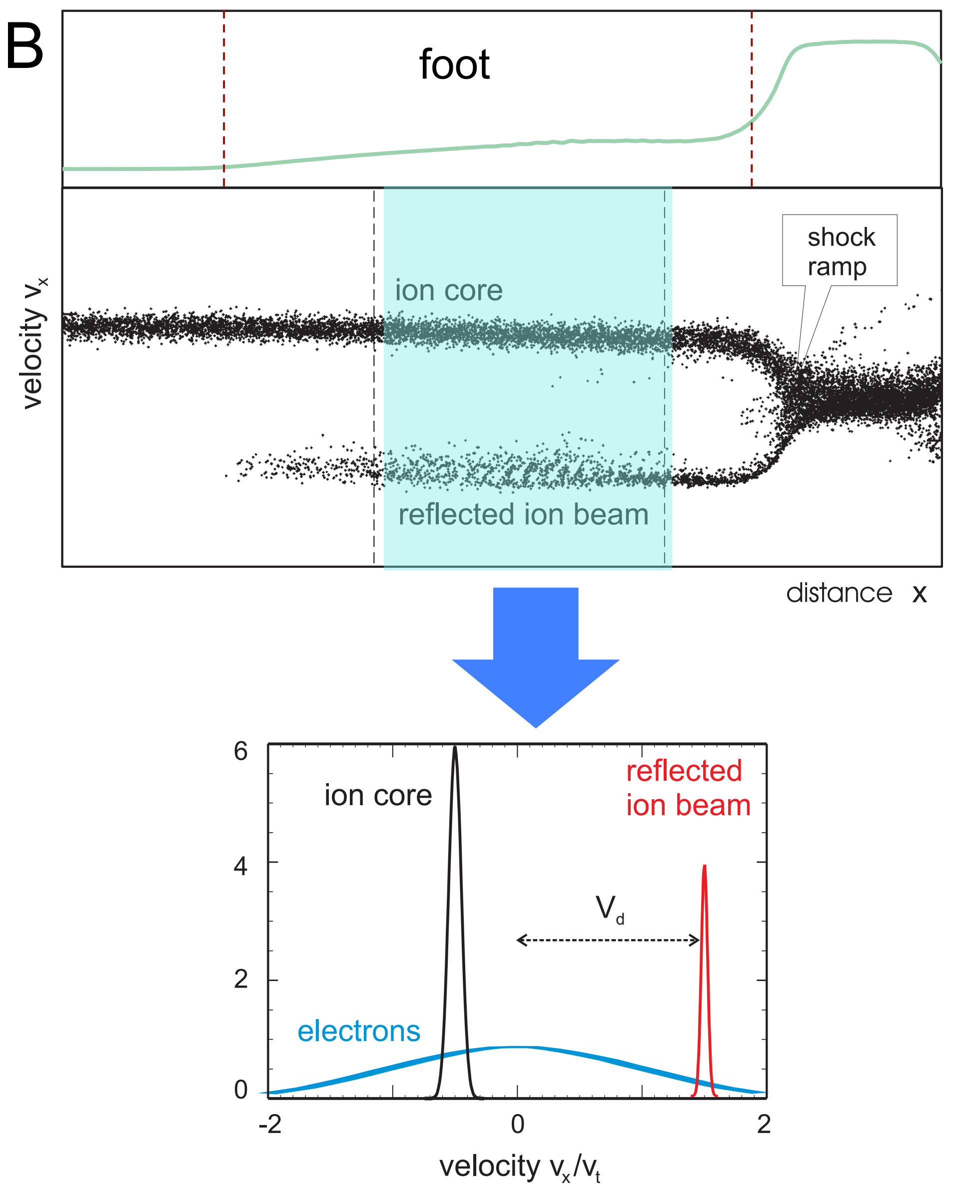
* does self-reformation persist in presence of ECDI ? -→ YES

* To account for wave activity within a shock front -> foot region
  - ECDI candidate OK ?
  - features of ECDI in L and NL stages ?
  - Do one recover signatures of ECDI in space experimental data ?

First approach (linear):
dispersion relation

Second approach:
PIC Numerical simulations

Basic ingredients for microturbulence in the foot



Muschietti et Lembege, 2013

Parameter choice

Symbol	Value
ω_{pe}/Ω_{ce}	10
M/m	400
T_c/T_e	1.
T_b/T_e	0.25
V_d/V_A	6

Elements of the dispersion tensor

- Electrons as hot and magnetized

$$Q_{\mathrm{xx,e}} = \frac{4\pi\imath}{\omega}\sigma_{\mathrm{xx,e}} = -\frac{1}{k^2\lambda_{\mathrm{d}}^2}\left[-1+\Lambda_0(\eta)+2\sum_{\mathrm{n}=1}^{\infty}\Lambda_{\mathrm{n}}(\eta)\frac{\omega^2}{\omega^2-\mathrm{n}^2\Omega_{\mathrm{ce}}^2}\right]$$

where $\eta \equiv (k\rho_e)^2 = (\omega_{\mathrm{pe}}/\Omega_{\mathrm{ce}})^2(k\lambda_{\mathrm{d}})^2$
$\Lambda_{\mathrm{n}}(\eta) \equiv I_{\mathrm{n}}(\eta)\exp(-\eta)$, modified Bessel function

- Ions as unmagnetized

$$Q_{\mathrm{xx,i}} = \frac{4\pi\imath}{\omega}\sigma_{\mathrm{xx,i}} = -\frac{\alpha}{k^2\lambda_{\mathrm{d}}^2}\frac{\mathrm{T_e}}{2\mathrm{T_b}}Z'\left(\frac{\omega-k\mathrm{V_d}}{\sqrt{2}k\mathrm{v_{tb}}}\right)-\frac{1-\alpha}{k^2\lambda_{\mathrm{d}}^2}\frac{\mathrm{T_e}}{2\mathrm{T_c}}Z'\left(\frac{\omega-k\mathrm{V_c}}{\sqrt{2}k\mathrm{v_{tc}}}\right)$$

beam: drift $\mathrm{V_d}$, thermal spread $\mathrm{v_{tb}}$ and relative density α
core: drift $\mathrm{V_c} = \mathrm{V_d}\,\alpha/(\alpha-1)$

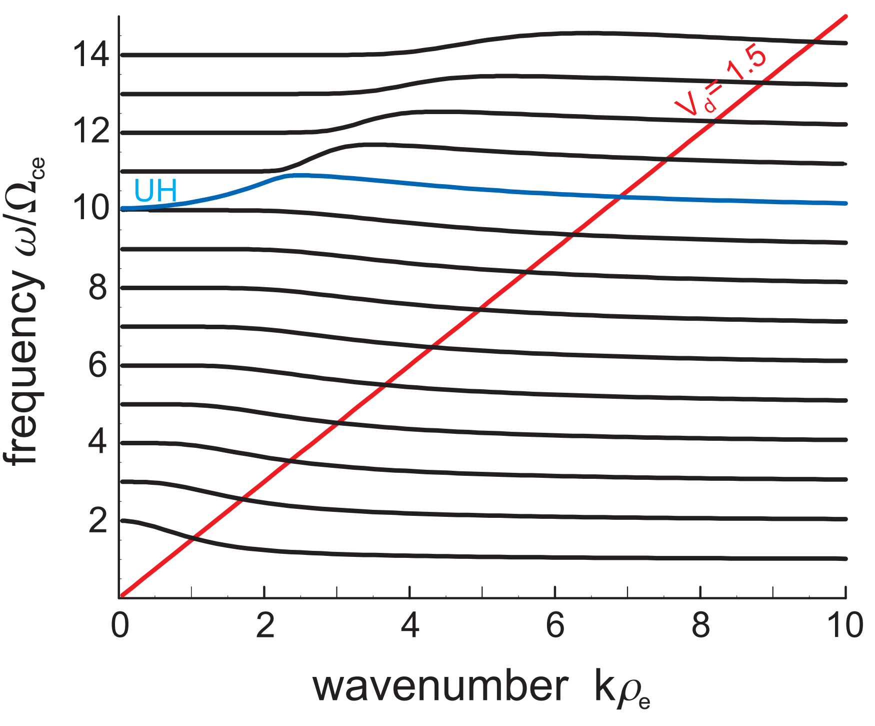
- Perpendicular geometry here, electrostatic dispersion is simply

$$1 + Q_{\mathrm{xx,e}} + Q_{\mathrm{xx,i}} = 0.$$

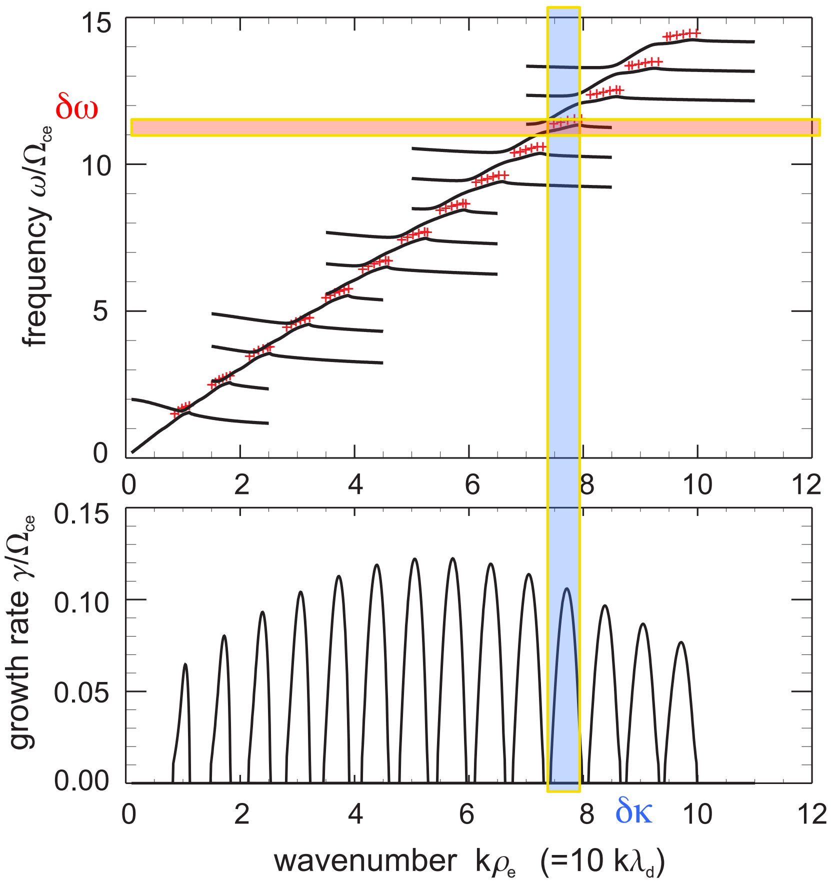
ECDI : due to the relative drift between reflected ions and incoming electrons
(coupling between ion beam and electron Berstein waves

Electron Cyclotron Drift Instability

Before coupling

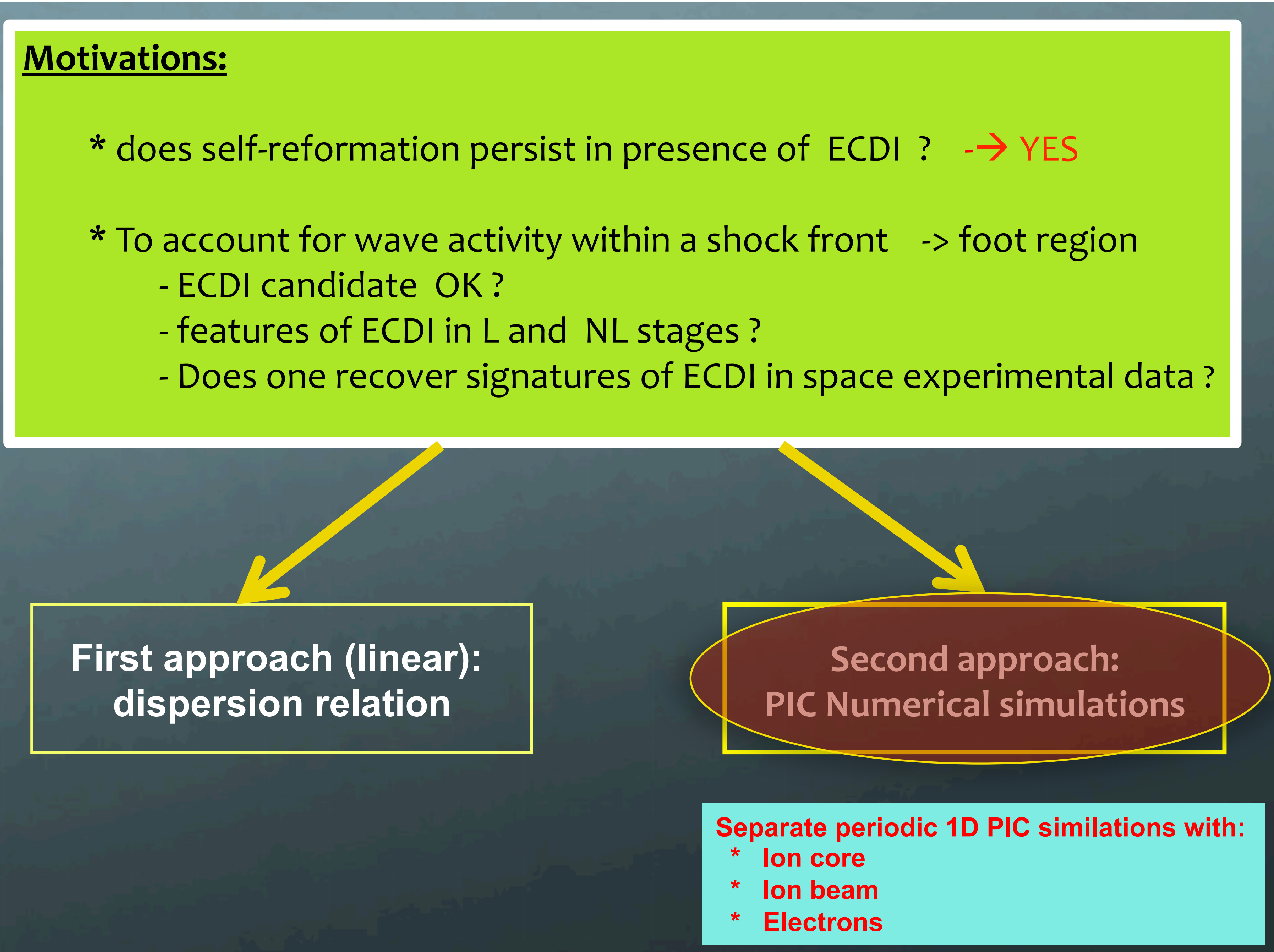


After coupling



* Discrete bands in spectrum

* Peaked envelope → high k excited first, lower k excited later…..



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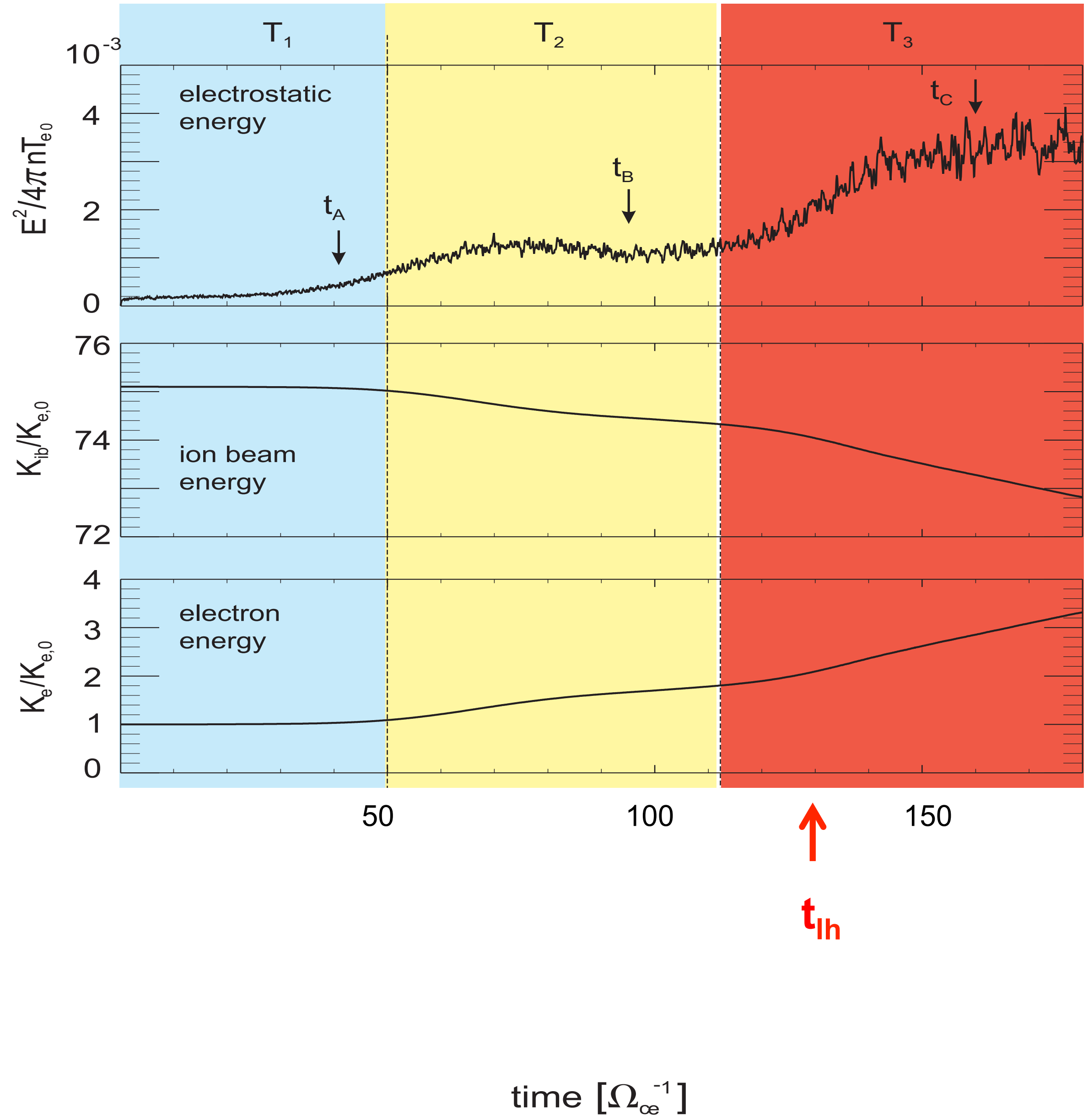
First approach (linear): dispersion relation

Second approach: PIC Numerical simulations

Separate periodic 1D PIC similations with:
- **Ion core**
- **Ion beam**
- **Electrons**

→ To analyze in details the L / NL stages of the ECDI

Evolution of Electron Cyclotron Drift Instability



Main results

a) 3 stages :

*** Linear T1**

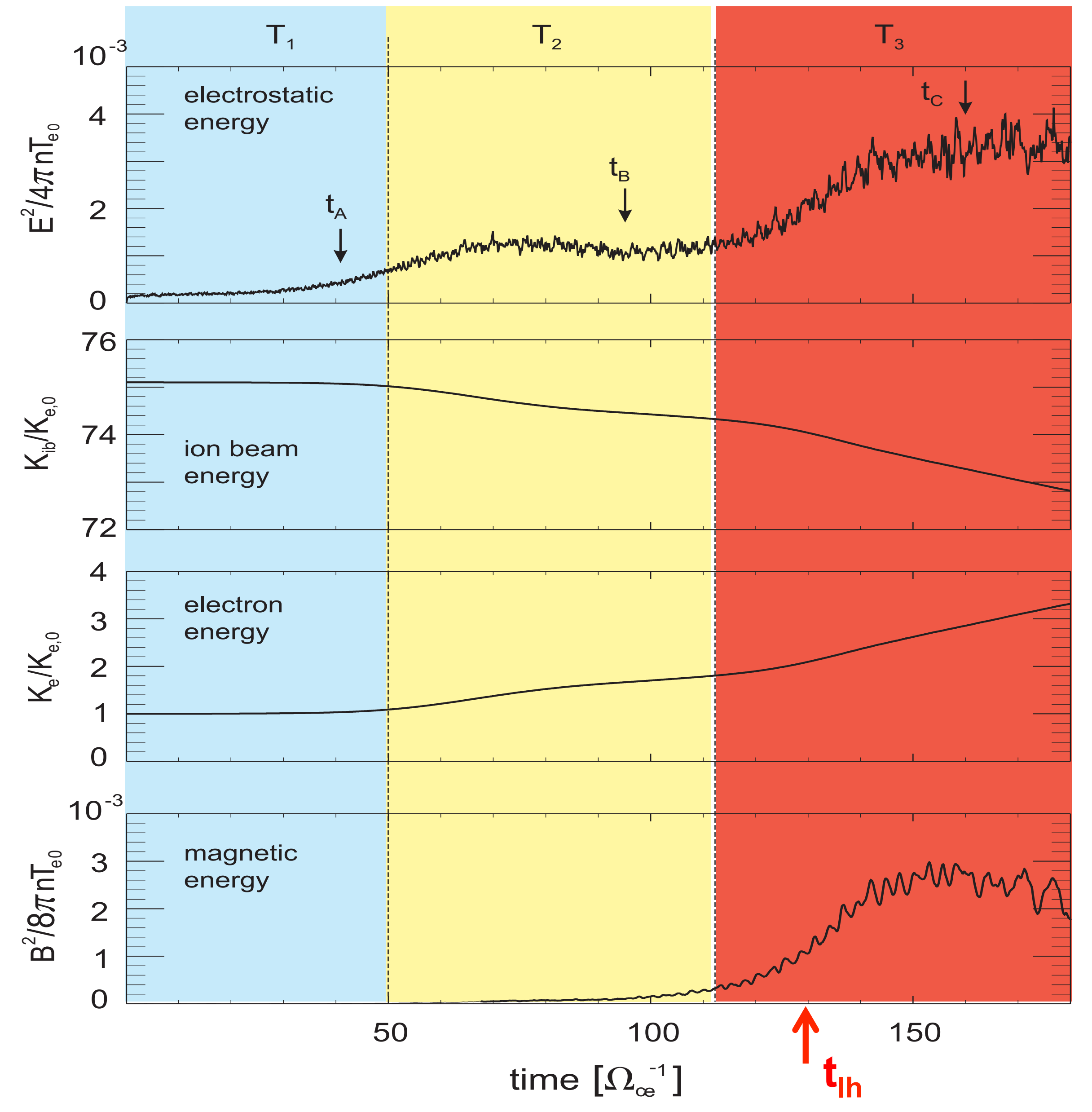
*** Nonlinear: T2 and T3**

(redistribut to lower k modes)

b) transfert of ion beam energy
-> to electrons
→ Ion beam only loses a few %

c) Rapid growth and NL stage ($t < T_{lh}$) ….. << $T_{ref} < T_{ci}$

Evolution of Electron Cyclotron Drift Instability



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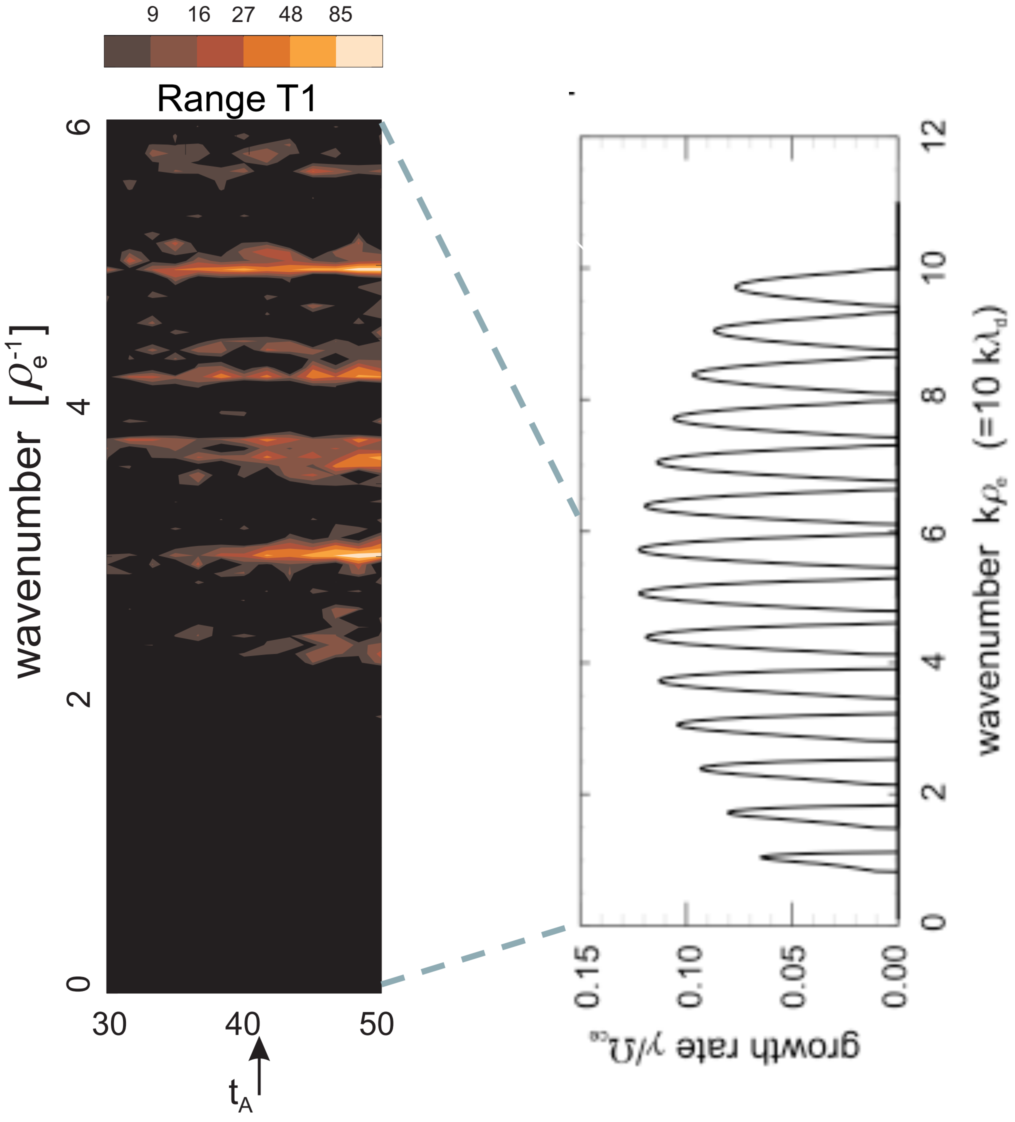
c) Rapid growth and NL stage ($t < T_{lh}$) ….. $<< T_{ref} < T_{ci}$

d) **Magnetic component during stage T3..!!**

Time history of the electrostatic spectrum



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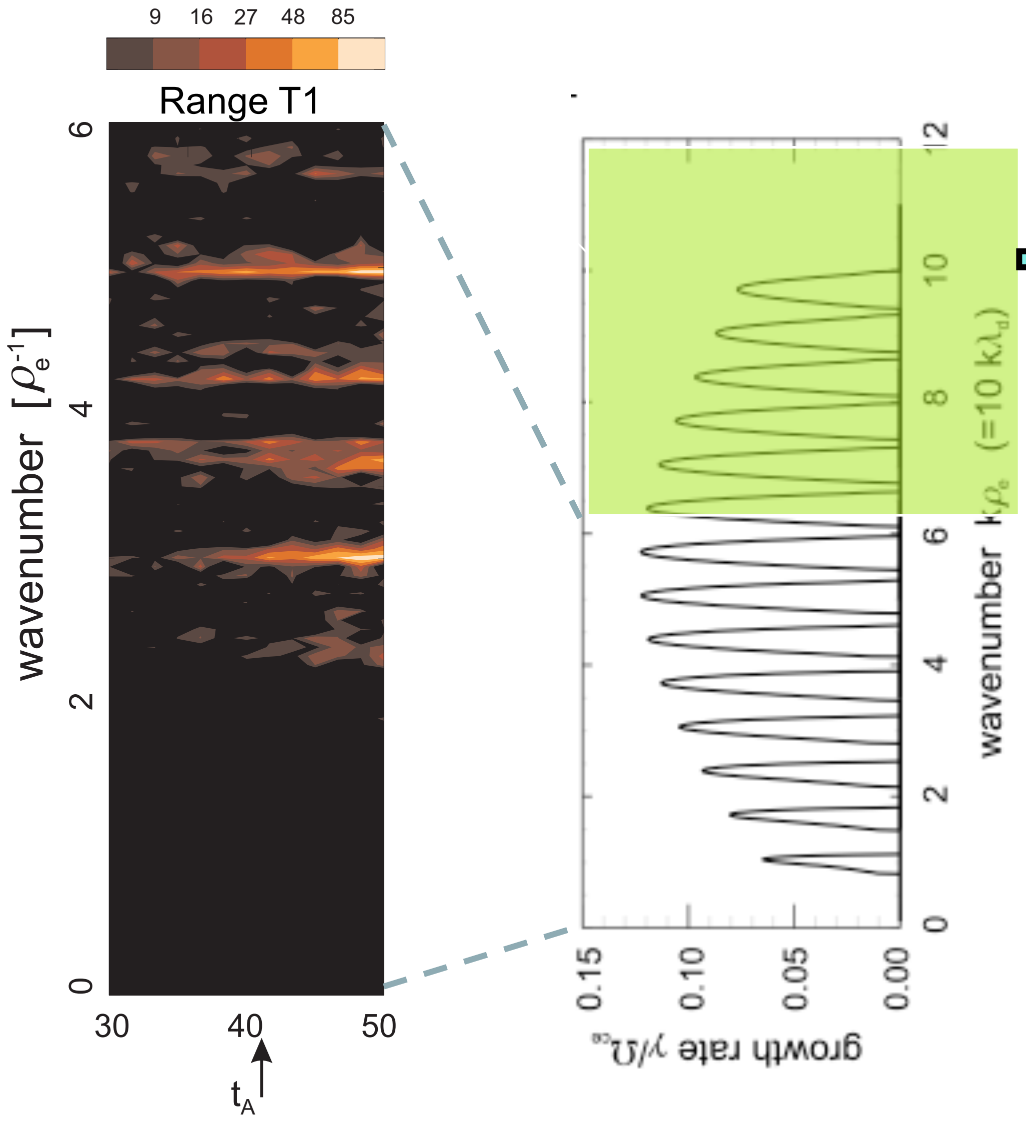
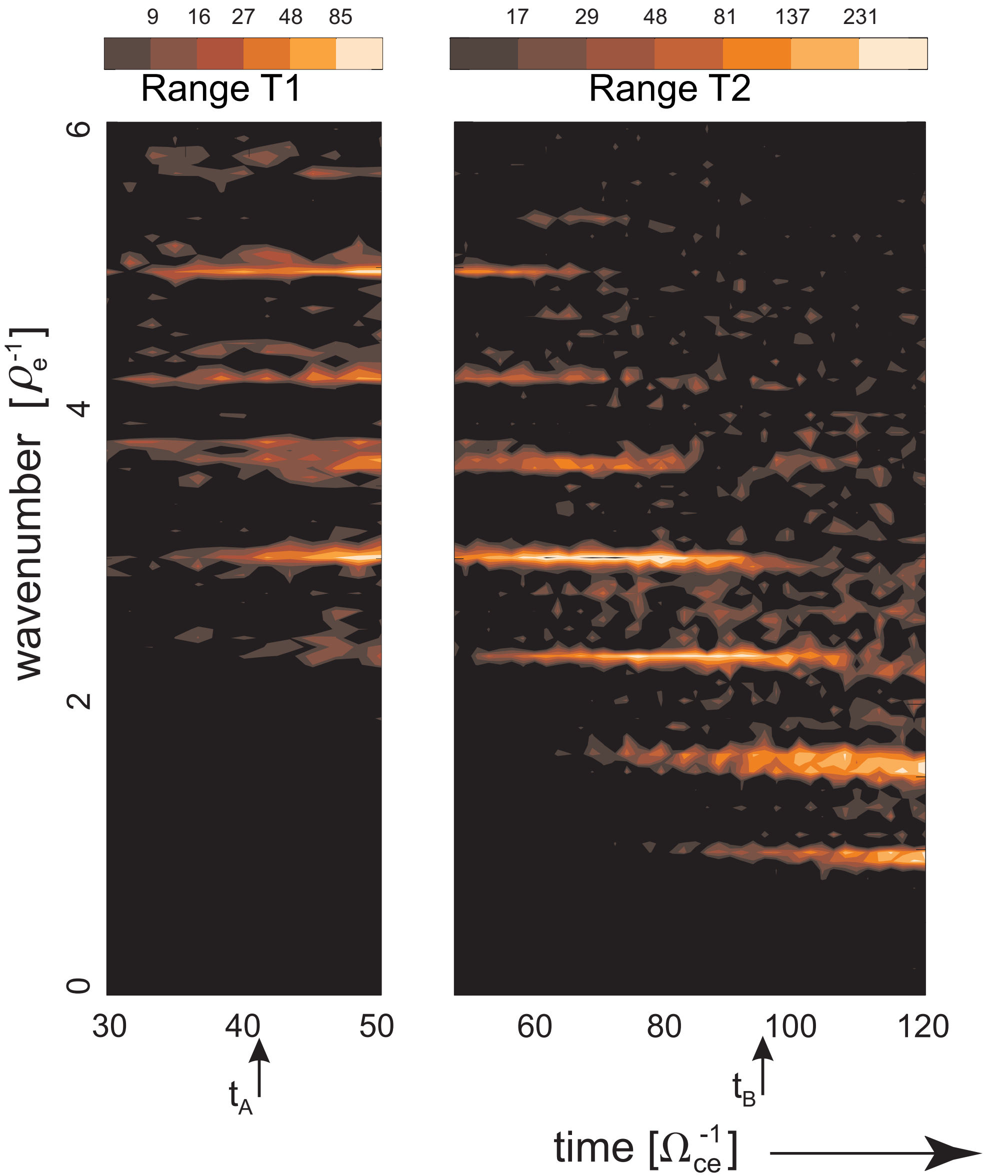


Hardly visible
why ??

Time history of the electrostatic spectrum



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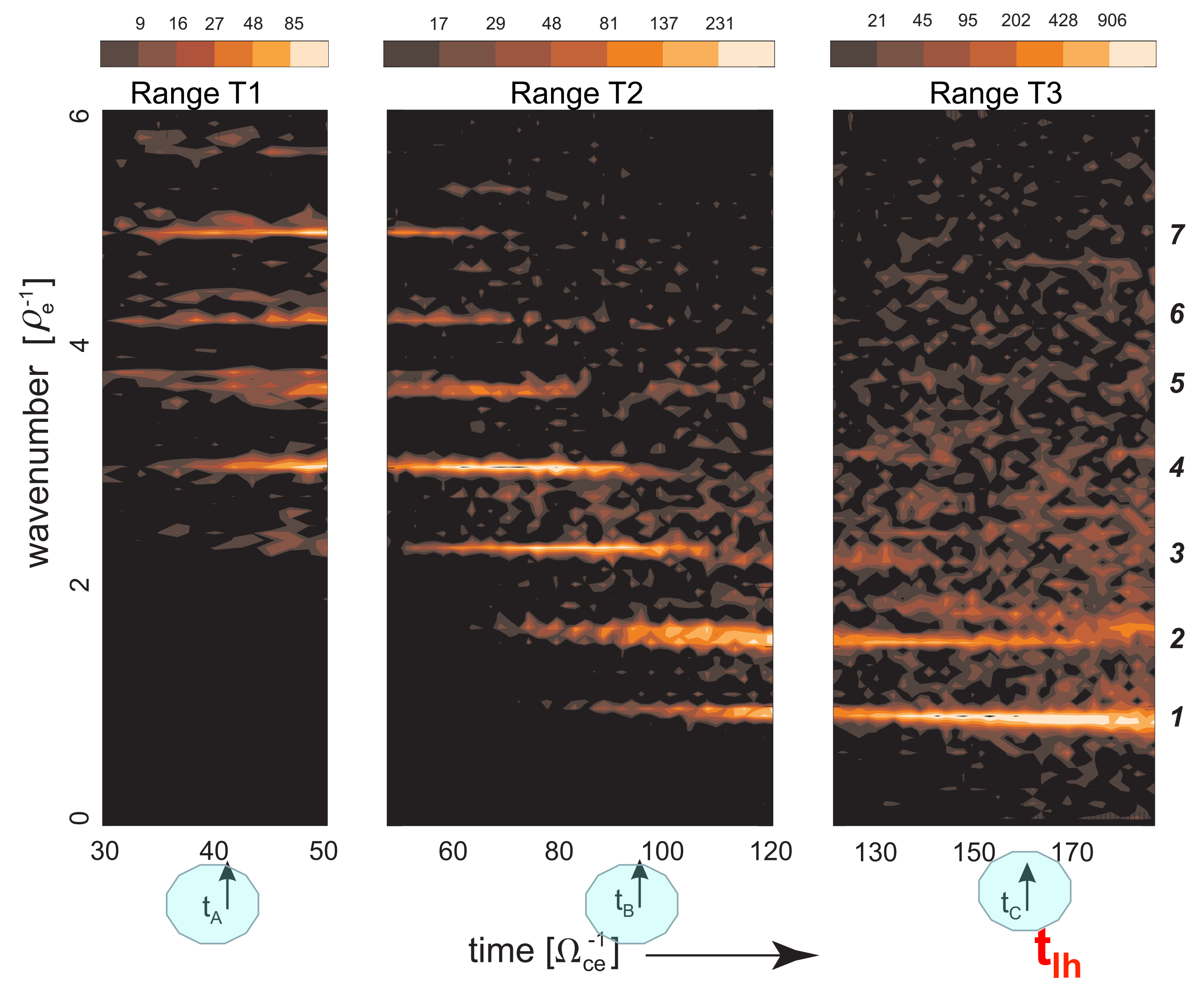
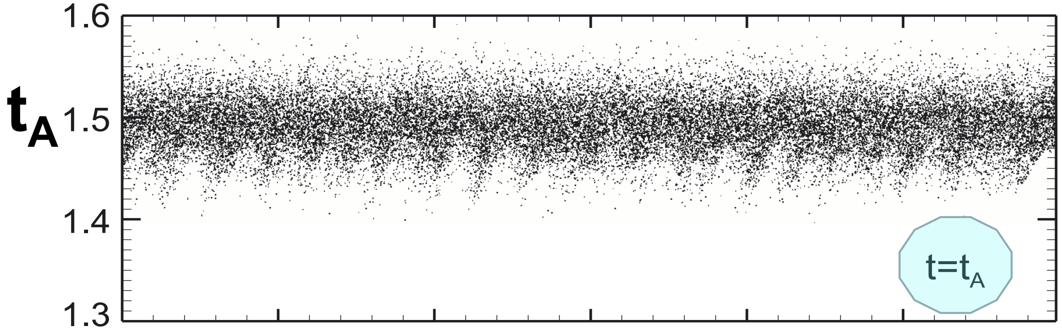


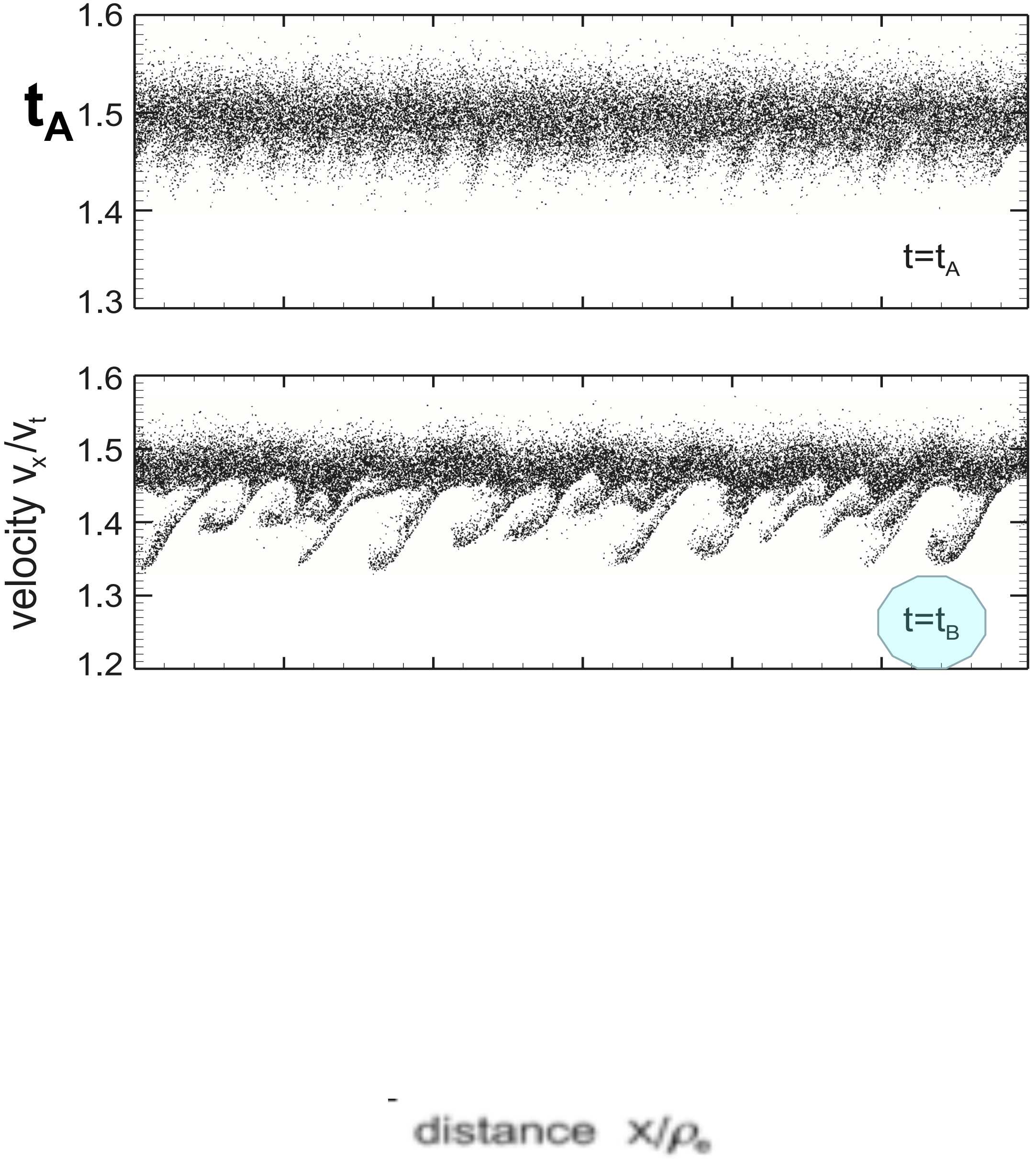
Evolution of the Ion Beam



Ion deceleration

distance x/ρ_e

Evolution of the Ion Beam



Ion deceleration

Bounce frequency:

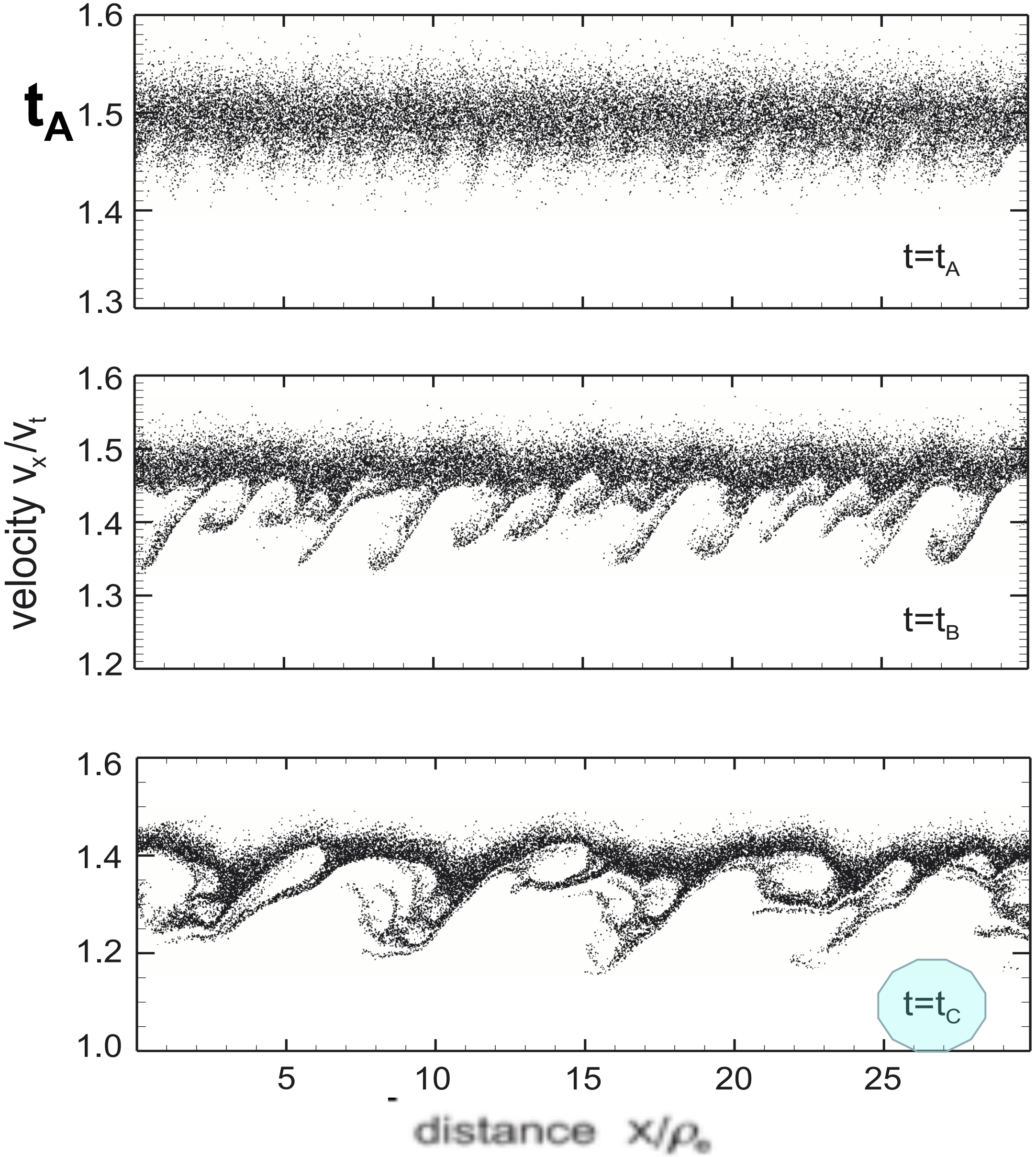
$$\sqrt{\frac{eE}{M}k}$$

trapping begins earlier

for high-k modes

When trapping at low-k begins high harmonics loose coherence

Evolution of the Ion Beam



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Bounce frequency:

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When trapping at low-k begins high harmonics loose coherence

↓

Waves spectrum at high harmonics is reabsorbed

Harmonic 1 at Ω_{ce} grows and dominates the spectrum

Why high-k modes disappear at very late times ?
(….i.e. why only fundamental harmonic ω_{ce} survives ?

Signature of « inverse cascade » process ?

Why high-k modes « die out » at very late times ?
(….i.e. why only fundamental harmonic ω_{ce} survives ?

Signature of « inverse cascade » process ?

NO

Two effects contribute ….:
“Resonance broadening” vs “ion trapping”

Resonance Broadening

[Dum and Dupree, 1970; Lampe et al., 1972]

Electron orbits in ambient magnetic field $(0, 0, B_0)$

- Linear orbit: In plane $[x, y]$ gyrocenter, gyroradius, gyrophase well defined
- Orbit in turbulent medium: Brownian motion of gyrocenter, random changes in gyroradius and phase angle
  $\longrightarrow$ limits wave-electron interaction time to τ_D
  $\longrightarrow$ broadens resonance in dispersion relation

$$Q_{\mathrm{xx,e}} = -\frac{\omega_{\mathrm{pe}}^2}{k^2}\int d^3v\left[1-\sum_{\mathrm{n}=-\infty}^{\infty}\frac{\omega J_n^2(kv_\perp/\Omega_{\mathrm{ce}})}{\omega-\mathrm{n}\Omega_{\mathrm{ce}}+\imath\Delta\omega_k}\right]\frac{1}{v_\perp}\frac{\partial f_e}{\partial v_\perp}$$

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Broadening $\Delta\omega_k \equiv \mathrm{D}k^2$ with $\mathrm{D} \sim \sum_{k'} \frac{|E_{k'}|^2}{4\pi n \mathrm{T_e}}$ diffusion coefficient of electrons.

Effect is stronger for high wavenumbers →loss of coherency in gyromotion

For high $k\rho_e$ $(k\rho_e \gg 1)$ demagnetization of electrons when

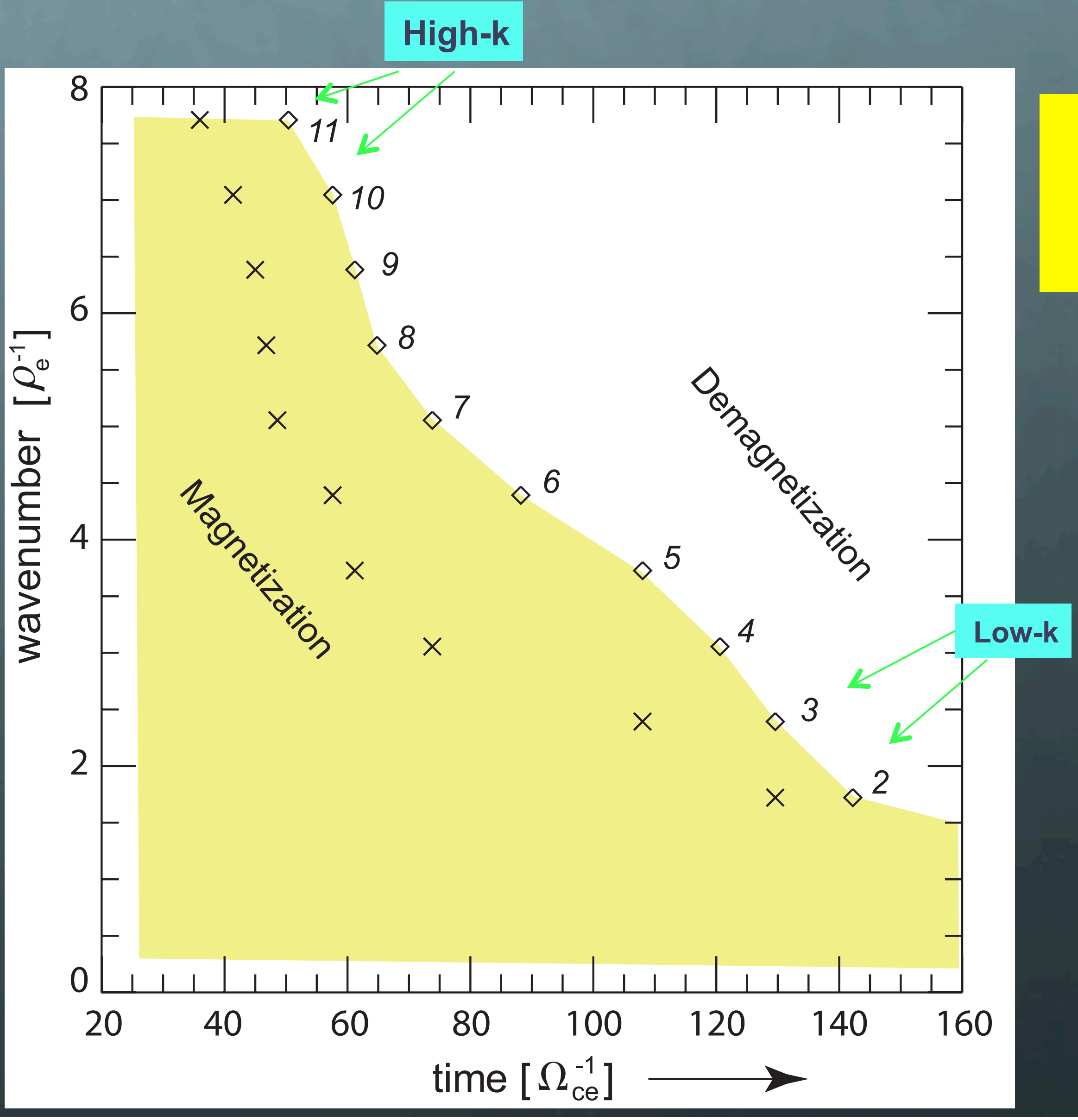
τ_D $(= <\Delta\omega_k>^{-1}) < (\Pi / \Omega_{ce})$

$<\ldots>$: average over F_e

→ Interplay with ampl. of turb ($E_{k'}{}^2$) and k order.

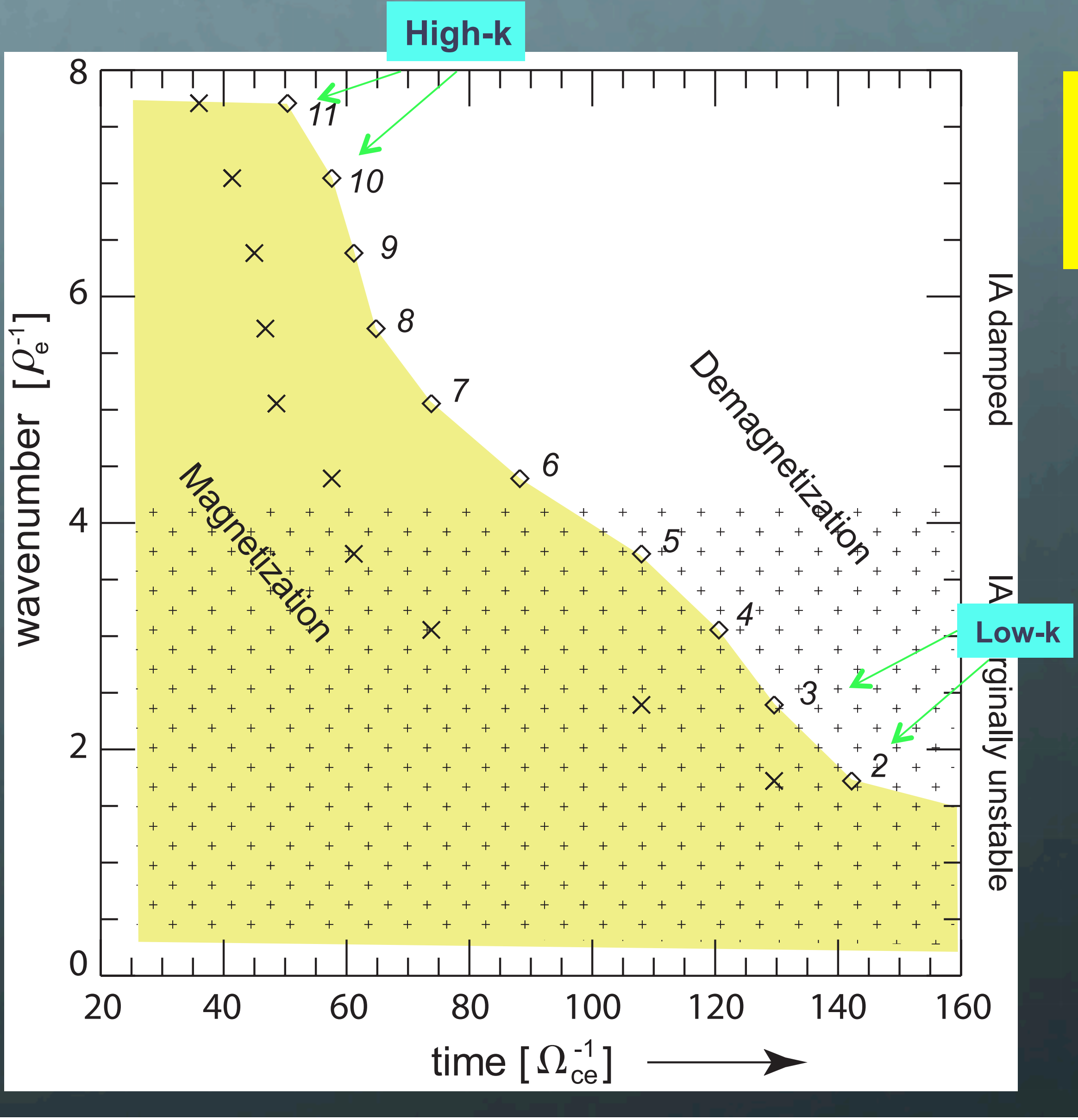
Stabilization by Resonance Broadening

Muschietti et lembège, 2013



As time increases, demagnetization proceeds from high-k to low-k

Stabilization by Resonance Broadening

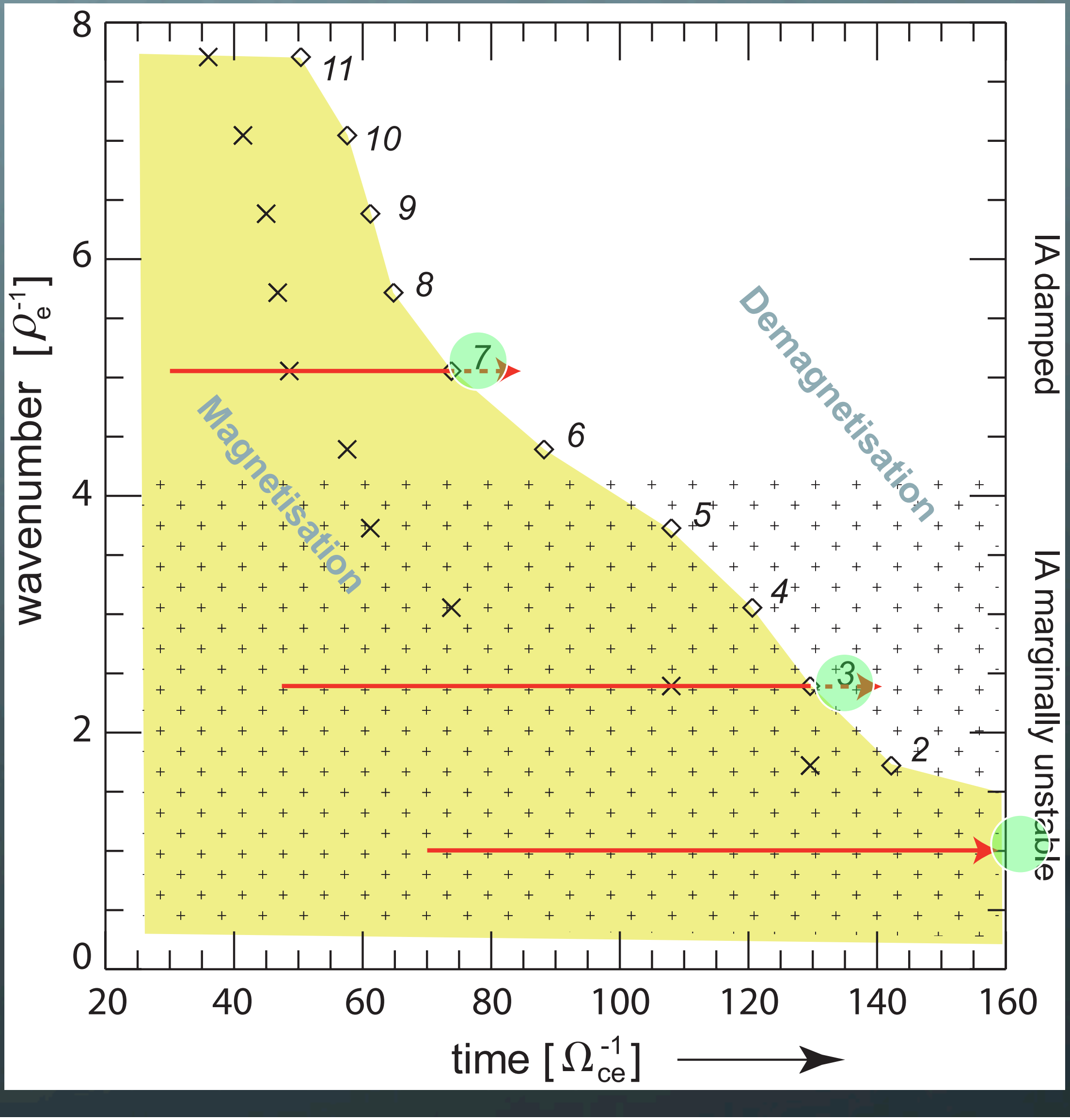


As time increases, demagnetization proceeds from high-k to low-k

Magnetized dispersion disallowed…
No ECD
(Ion acoustic ?)

Stabilization by Resonance Broadening

As time evolves , turbu. level increases



As time increases, demagnetization proceeds from high-k to low-k

Magnetized dispersion disallowed…
No ECD

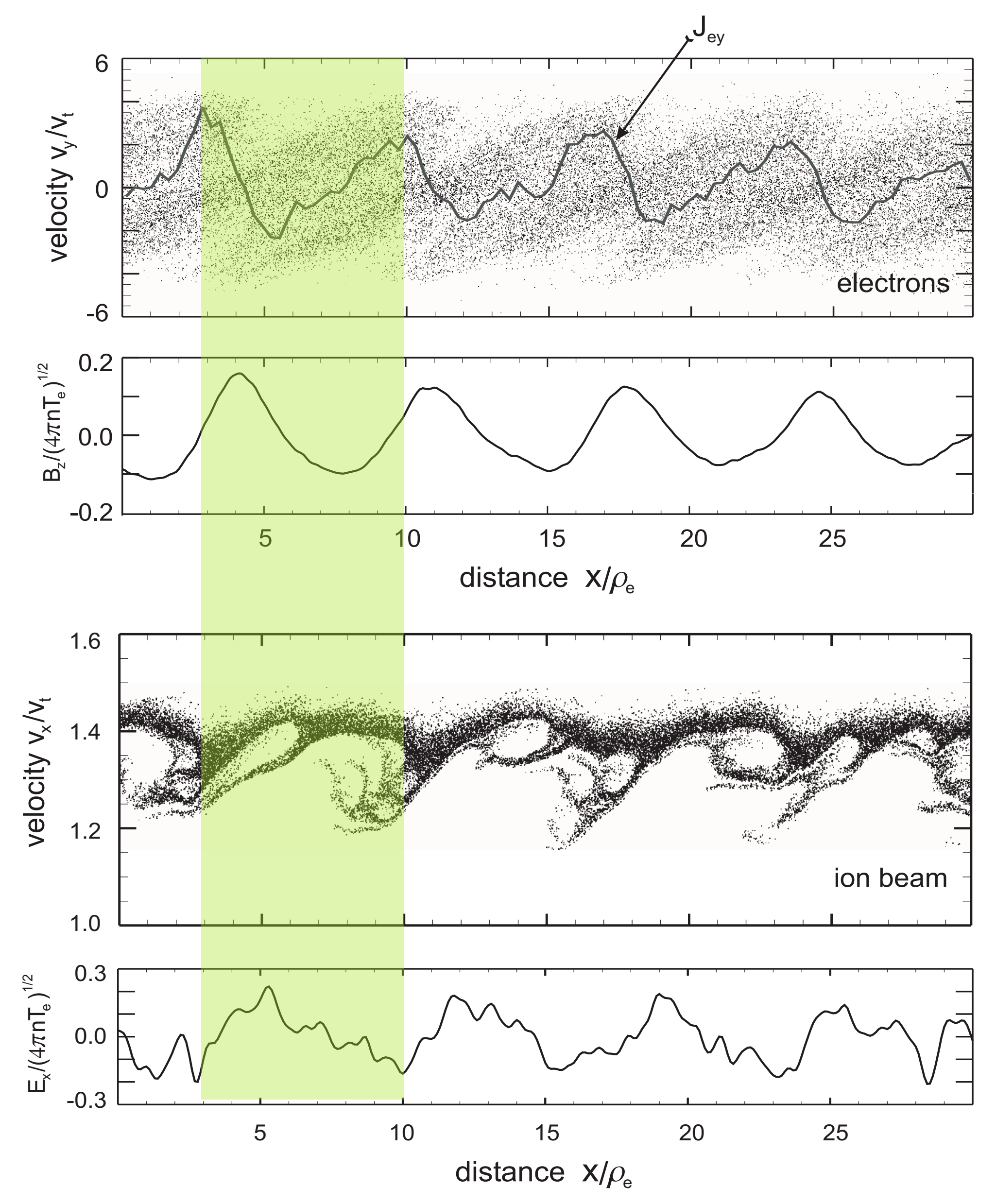
Ion acoustic?

ECD survives only for harmonic 1 at Ω_{ce}

Origin of the magnetic field growth in nonlinear T3 stage

→ Electron current ?

Magnetic signatures of the waves: nonlinear stage T3



* "enlarged" snapshot at $t = t_c$ (stage T3)

* cross-field forces on electrons

$$(B_{0z} \times E_x)$$

* Create current J_{ey} (by integrating electrons)

* Most electrons in the range ($2 < v_y < 4$) contribute to J_{ey}

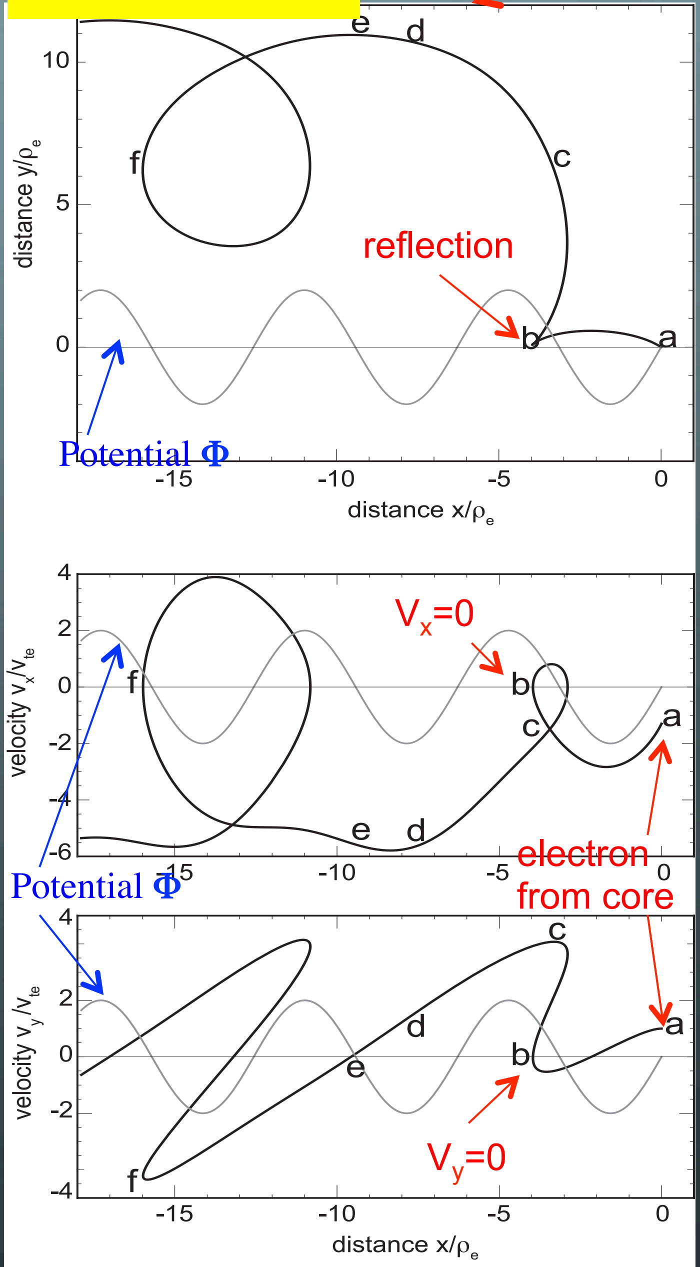
* J_{ey} fluctuations fits with largest scale (in ion beam) which dominates at late time

* Spread electrons in $[v_x,v_y]$ space

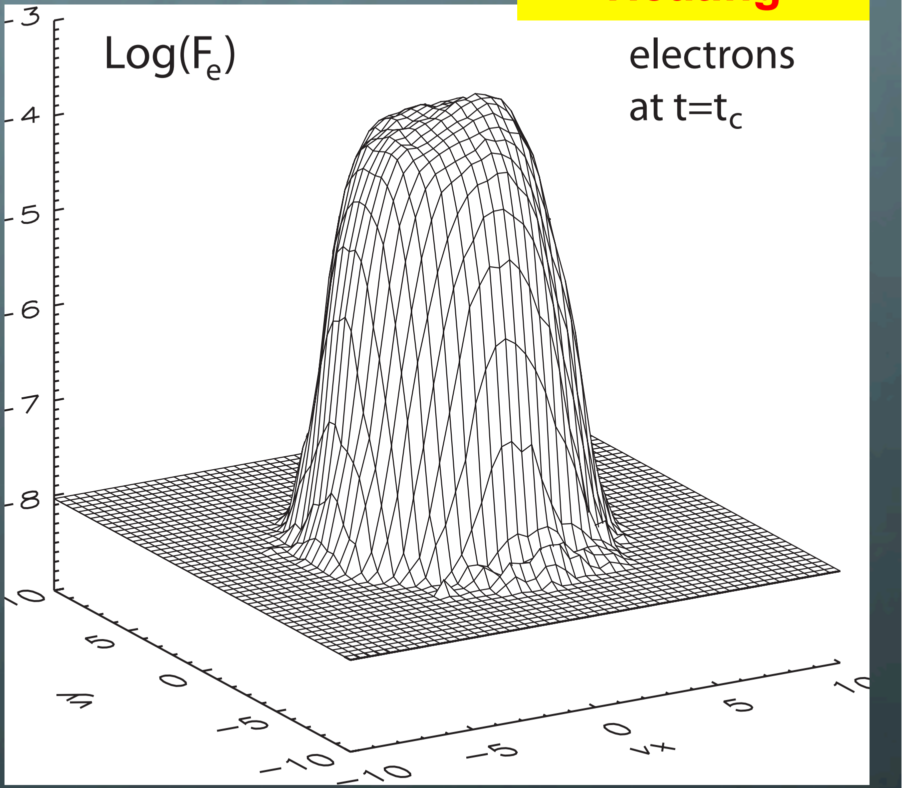
-> heating

electron dynamics in a Berstein wave (with $\omega = 1.3\ \omega_{ce}$)

Acceleration



Heating



t_c ~ lower-hybrid period << T_{MTSI} , τ_{ref}

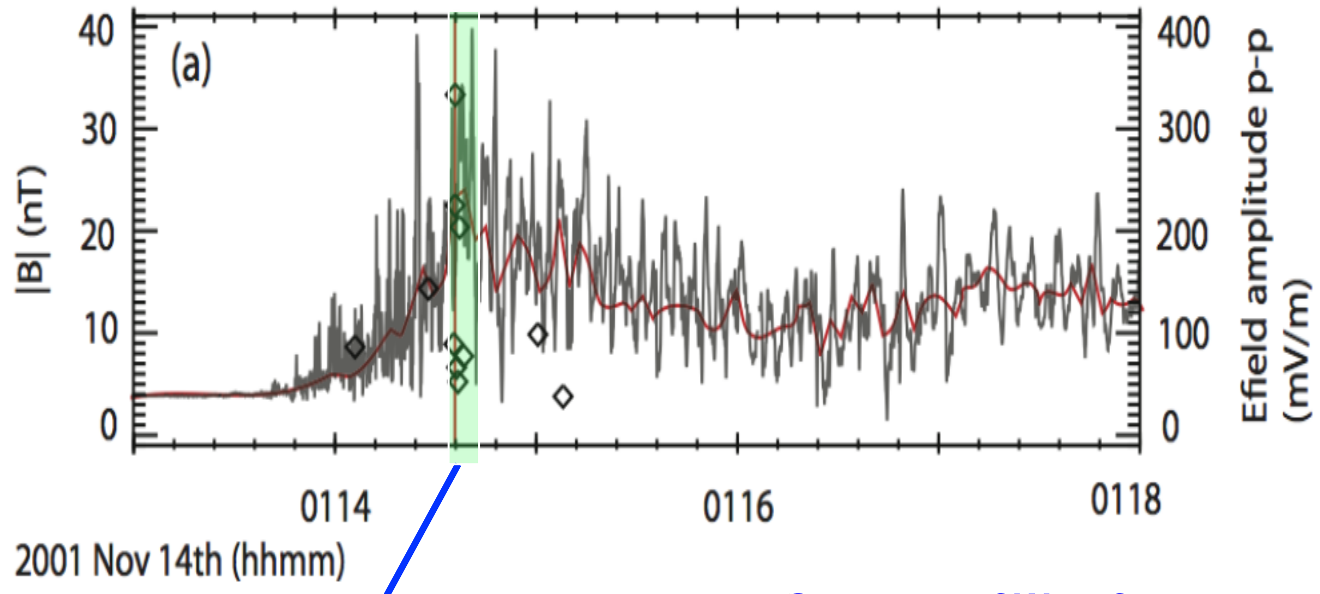
*** electron preheating**

*** Distribution gets rapidly “flat top” shape**

Is ECDI microturbulence observed in exp. data ??

YES !!

WIND Observations (Breneman and al.; 2013), bow shock crossings

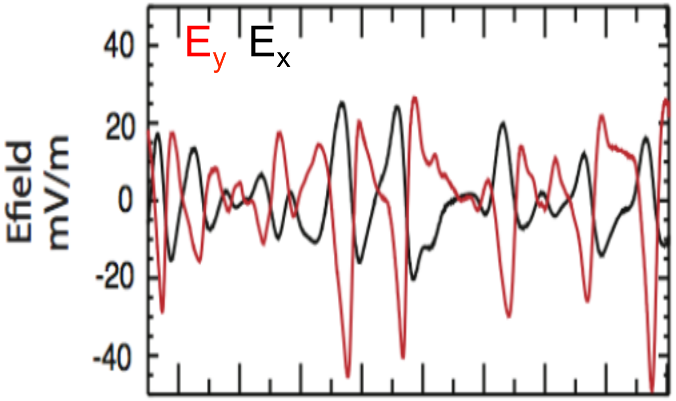


- Peaks around the nΩ_{ce}
- No harmonics along Bo

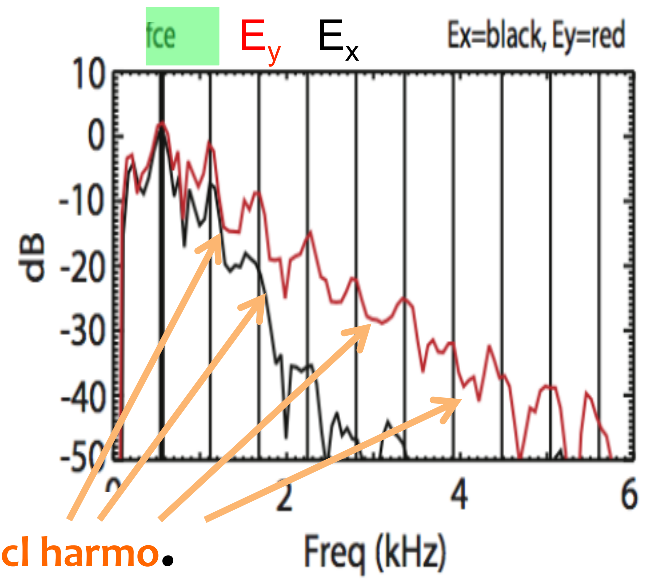
*Emission decays as order n decreases

With a strongest emission at fondam. Ω_{ce}

Waveform capture (for E field)



Spectrum of Waveform capture



Elec. Cycl harmo.

Conclusions:

i) ECDI: Strong and quick emission in the electron cyclotron range → discrete energy spectrum (no continuum) → signature of Berstein waves … ..**within t_{lh} << t_{ref}**

ii) Electrostatic spectrum → temporal accumul of energy on the fundamental (ω_{ce}) («NO inverse cascade» process). Two effects contribute:

a) « ion trapping» takes place but applies at diff times on diff. K modes (from high to low K modes)

b) «resonance broadening» applies to high (early time) and to low K (later time) → electrons demagnetisation.

iii) Energy transfert from ion beam → electrons (flat-top distri function) → «Electron preheating » in the foot (Te/Ti diff . versus US conditions)

iv) Magnetic component in NL regime (due strong E x B to electrons peaked Jy → induces Btz)

v) **In course**.. comparative analysis between….

ECDI ….90° and slightly oblique

MTSI ….oblique

.. extension to MMS data ..