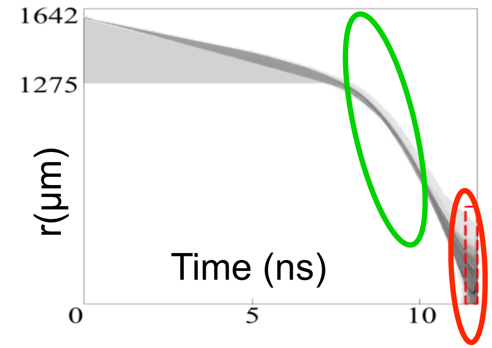
Self-generated magnetic fields and Rayleigh-Taylor Instability in the context of ICF

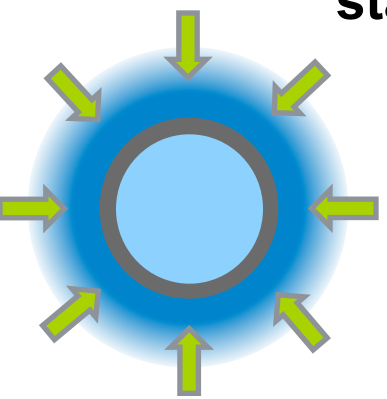
Y.Levy, B. Canaud

CEA, DAM, DIF, F-91297 Arpajon, France

Magnetic fields can be generated during RTI in ICF process.



- **Ablative Rayleigh-Taylor instability (aRTI) develops in acceleration and deceleration stages of ICF process**



- **Pioneering works have evidenced existence of self-generated magnetic fields during ICF process:**

  J.R. Rygg et al., Science, 319(5867):1223, 2008
  C.A. Cecchetti et al., PoP, 16(4):043102, 2009
  F.H. Séguin et al., PoP, 19(1):012701, 2012

- **We focus here on magnetic fields self-generated in a magnetohydro-dynamic way:**

$$\partial_t B = \nabla \times (u \times B) - \nabla \times \overline{\overline{\eta}} \cdot J - \nabla \times \left(\frac{1}{e n_e} J \times B \right) - \nabla \times \left(\frac{k_B}{e} \overline{\overline{\beta}} \cdot \nabla T_e \right) + \boxed{\frac{k_B}{e} \nabla T_e \times \nabla \ln(n_e)}$$

→ no non-local heat flux,
→ No kinetic effects

Outline

- **aIRT in the acceleration phase**

  - ➢ DNS set up
  - ➢ behavior without magnetic field
  - ➢ turning on magnetic fields self-generation

    *B-fields quantification
    *dispersion relations
    *effects evaluation through Masse model

- **aIRT in the deceleration phase**

  - ➢ DNS set up
  - ➢ Comparison between with or without B-fields

Outline

- **aIRT in the acceleration phase**

    - DNS set up
    - behavior without magnetic field
    - turning on magnetic fields self-generation

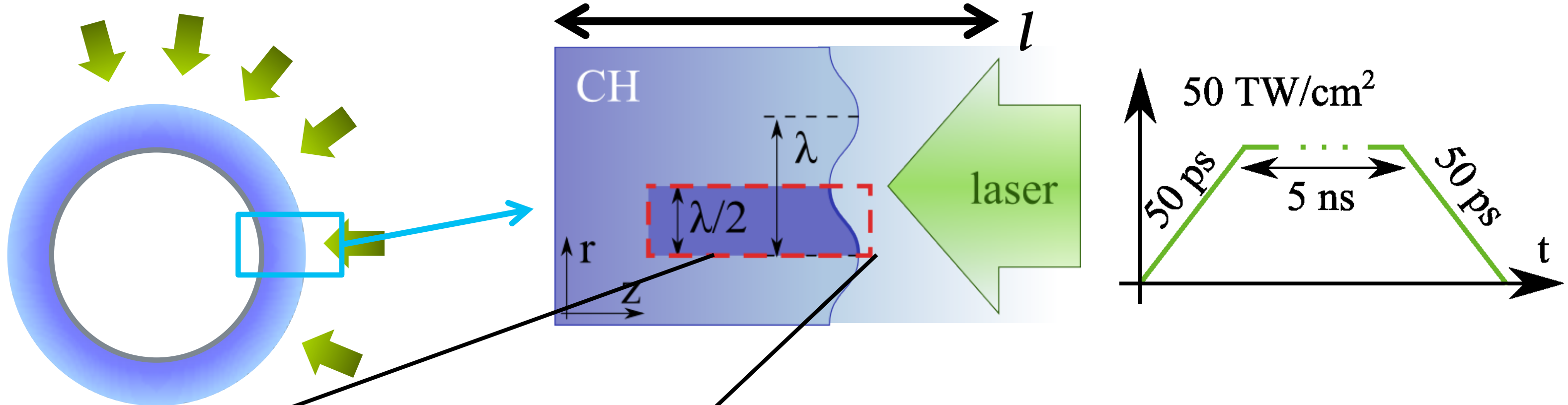
        *B-fields quantification
        *dispersion relations
        *effects evaluation through Masse model

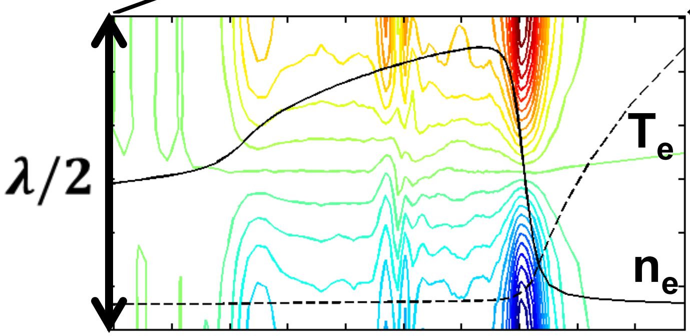
- aIRT in the deceleration phase

    - DNS set up
    - Comparison between with or without B-fields

We restrict ourselves to planar geometry by simulating planar ablator slab.

- **We performed 2D simulations (`FCI2`) of ablator slabs with single mode density perturbation**





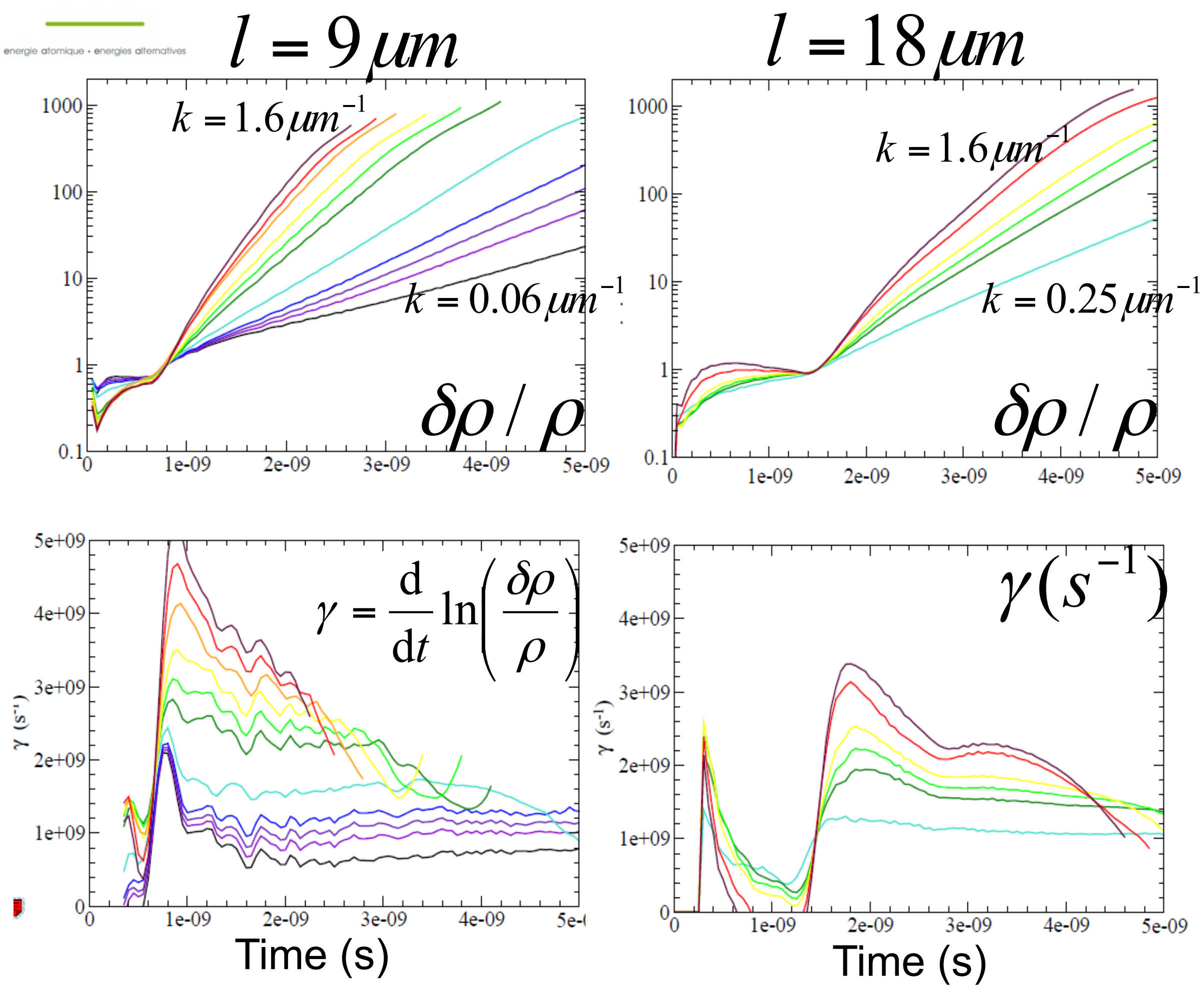
Example of $\delta\rho/\rho$ map at 2ns in the ablation region

- **We only simulate a half wavelength.**
- **2 slab lengths → 2 accelerations**

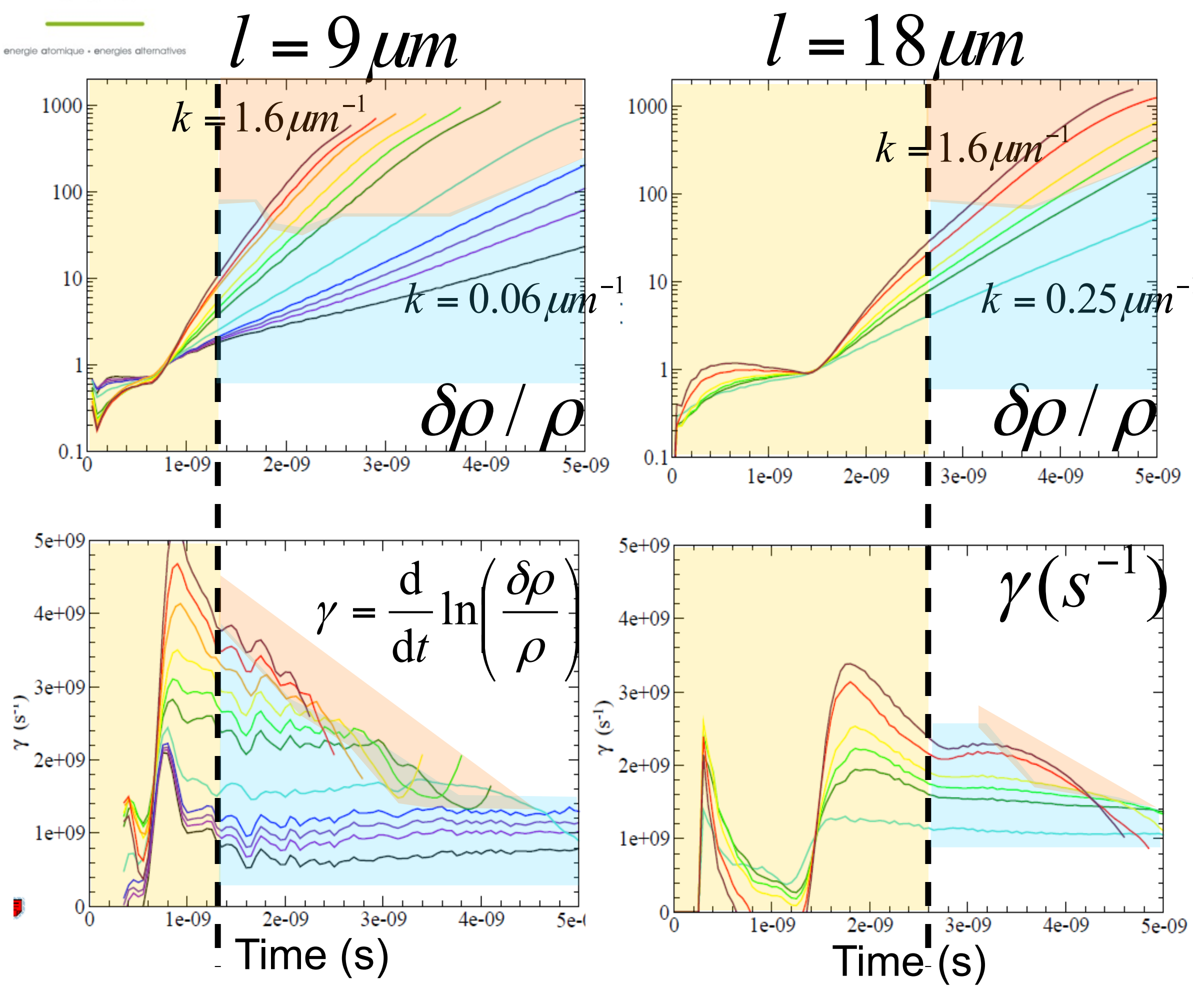
$$l = 9\mu m,\ \ v_a = 0.3\mu m/ns,\ \ g = 18\ \ \mu m/ns^2$$
$$l = 18\mu m,\ \ v_a = 0.3\mu m/ns,\ \ g = 7.7\mu m/ns^2$$

- **We study evolution of $\delta\rho/\rho$ at the ablation front z_a chosen at the location of the minimum gradient scale length**

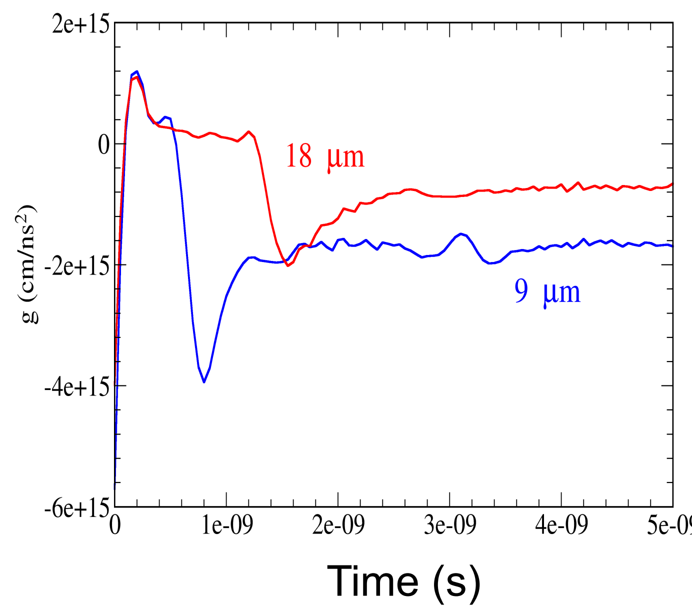
Perturbations (without B-field) at the ablation front experience three different regimes.



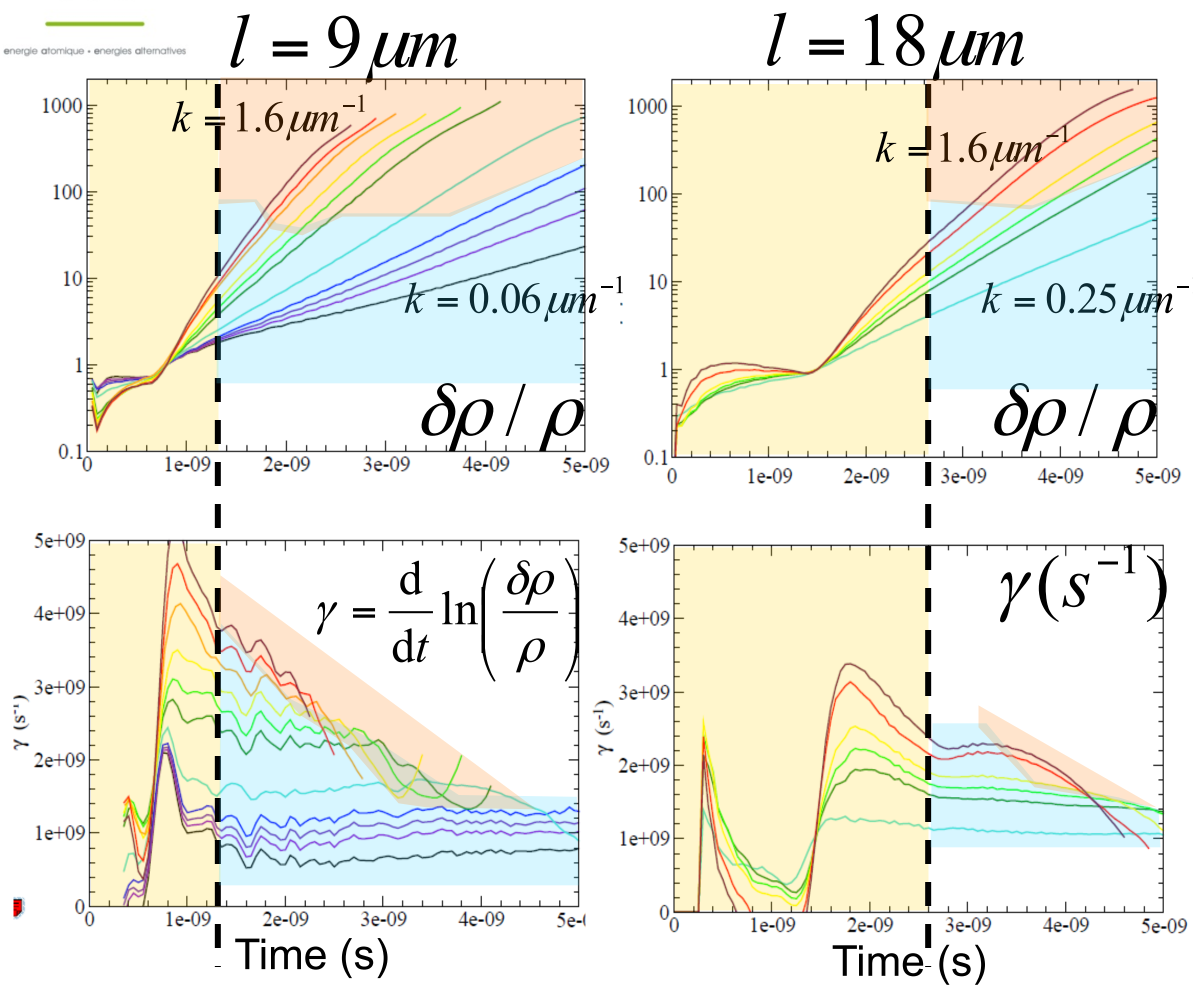
Perturbations (without B-field) at the ablation front experience three different regimes.



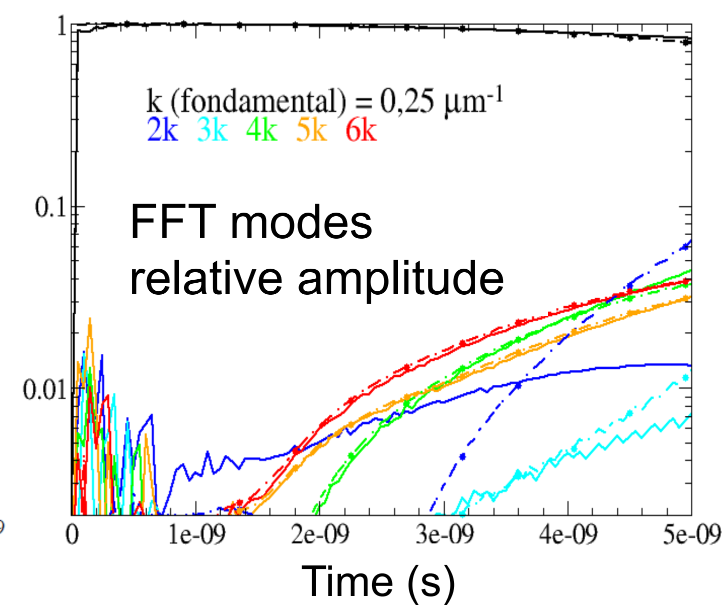
- **Transient regime driven by hydrodynamics**
- **Linear regime**
- **Non linear regime**



Perturbations (without B-field) at the ablation front experience three different regimes.



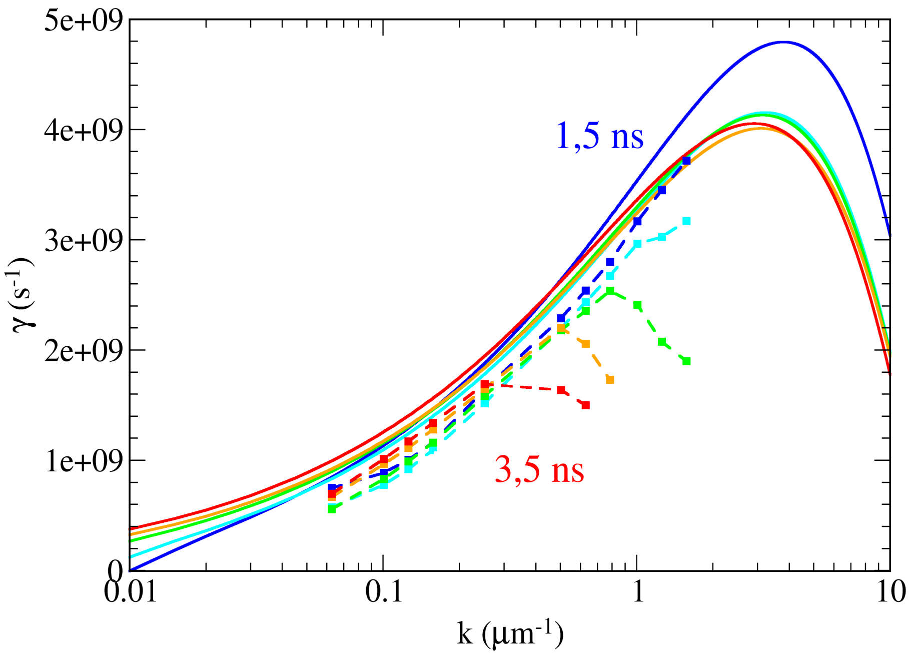
- **Transient regime driven by hydrodynamics**
- **Linear regime**
- **Non linear regime**



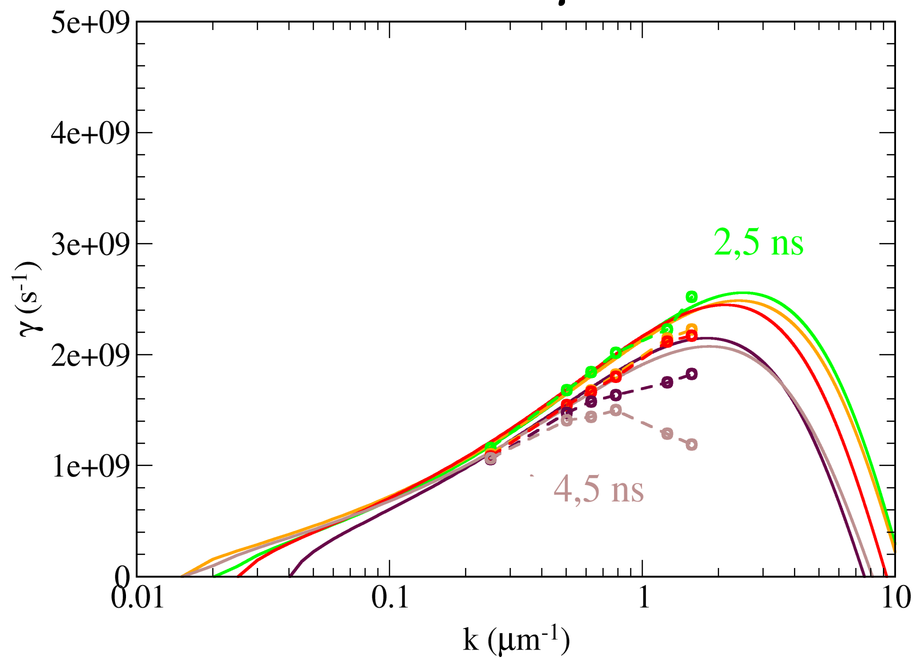
Perturbations (without B-field) at the ablation front experience three different regimes.

- **Growth rapidly enters non linear regime and rates deviate from Goncharov-Betti's model**

$$l = 9\,\mu m$$



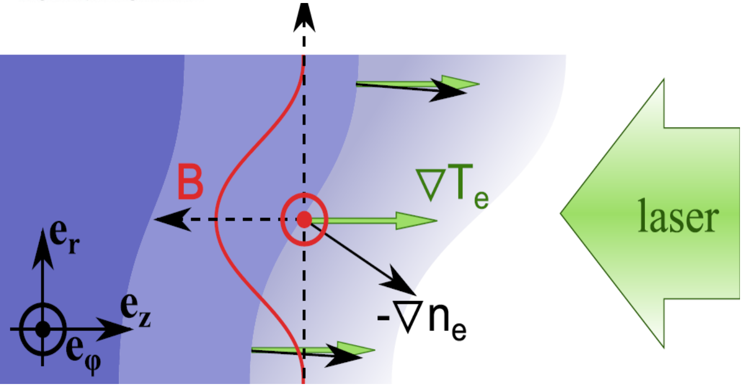
$$l = 18\,\mu m$$



- **We did not reach high wave number because of non linear behaviour and mesh distortion**

Self-generated magnetic field can reach about 1 T at the ablation front.

- **The perturbations enable self-generation of magnetic field:**



$$\partial_t B_{self} \sim -\frac{1}{n_e}\nabla n_e \times \nabla T_e$$

Assuming sinusoidal perturbation and exponential spatial decay, one has at the ablation front:

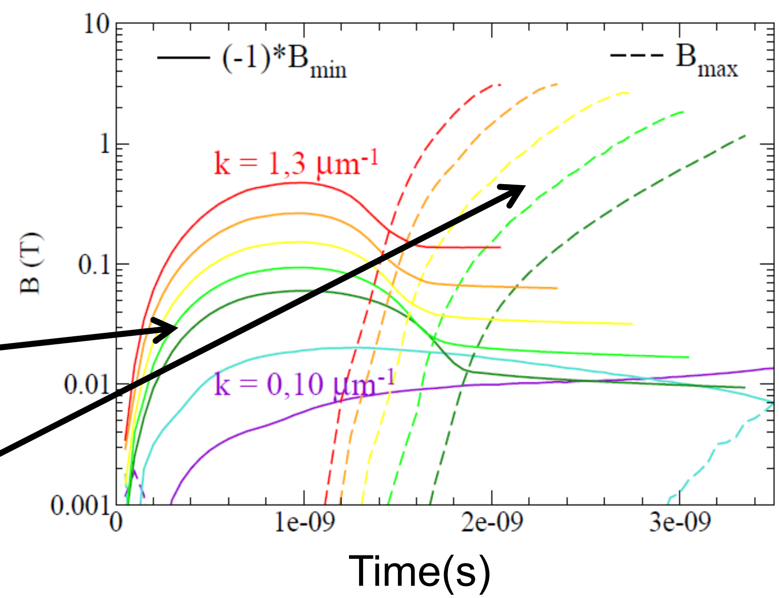
$$\partial_t B_{self} \sim -\left(\frac{\delta\rho}{\rho}\right)_t k\ e^{-k|z-z_a|}\sin(kr)\,\partial_z T_e\big|_a$$

$\left(\frac{\delta\rho}{\rho}\right)_t$ **increases as the aRTI develops**

→ B_{self} **increases**

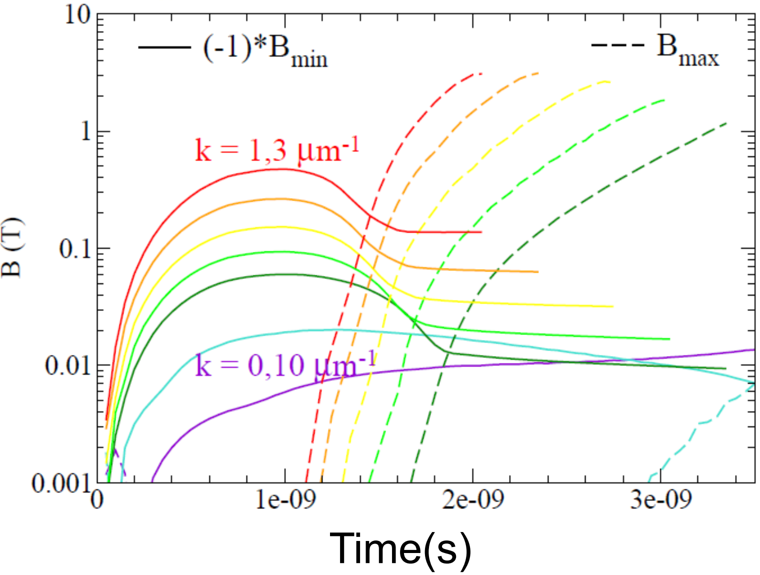
negative magnetic fields during early stage

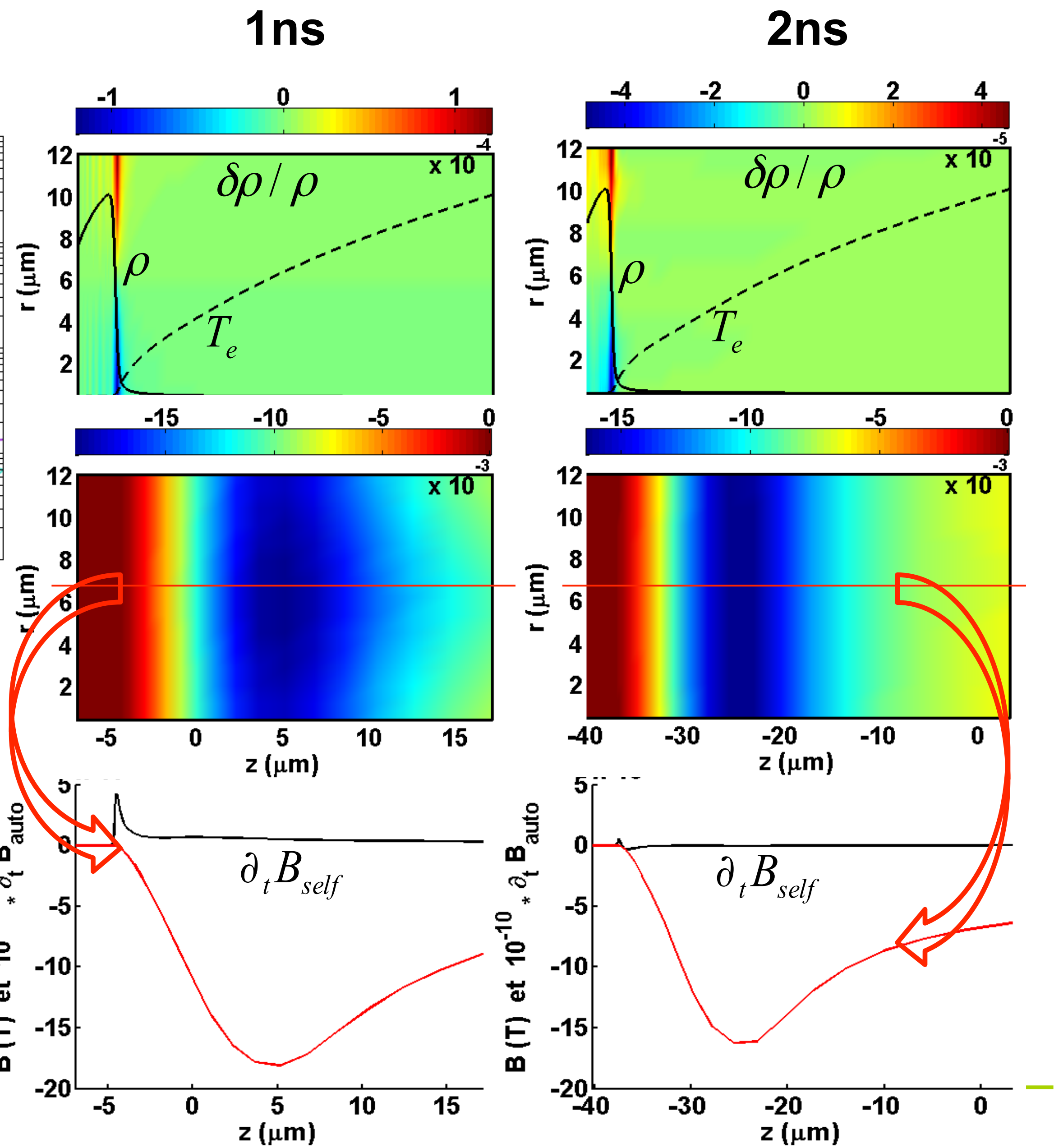
positive magnetic fields at the ablation front associated with self generation by aRTI development



Self-generated magnetic field can reach about 1 T at the ablation front.

$l = 9\,\mu m$



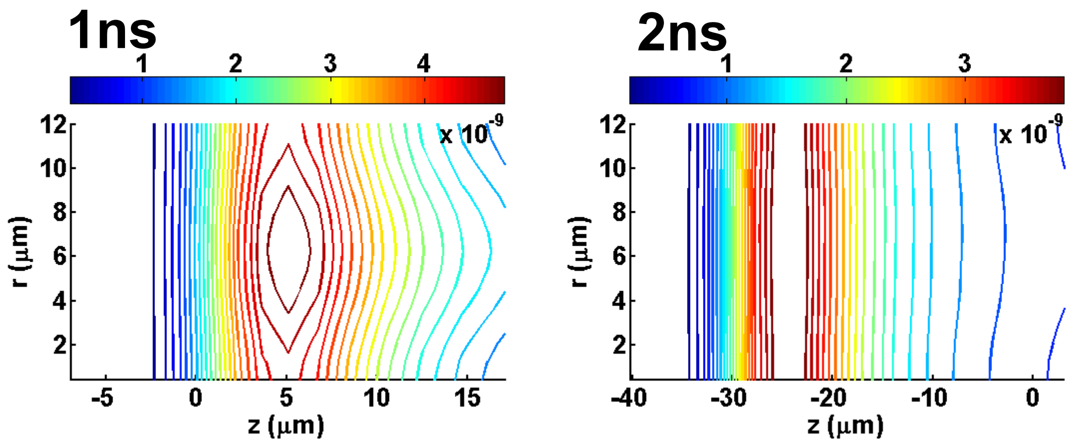


- **Single mode simulations:**
  - *maximum of generation rate at the ablation front
  - *negative magnetic fields during early stage

Self-generated magnetic fields are not high enough to influence hydrodynamics.

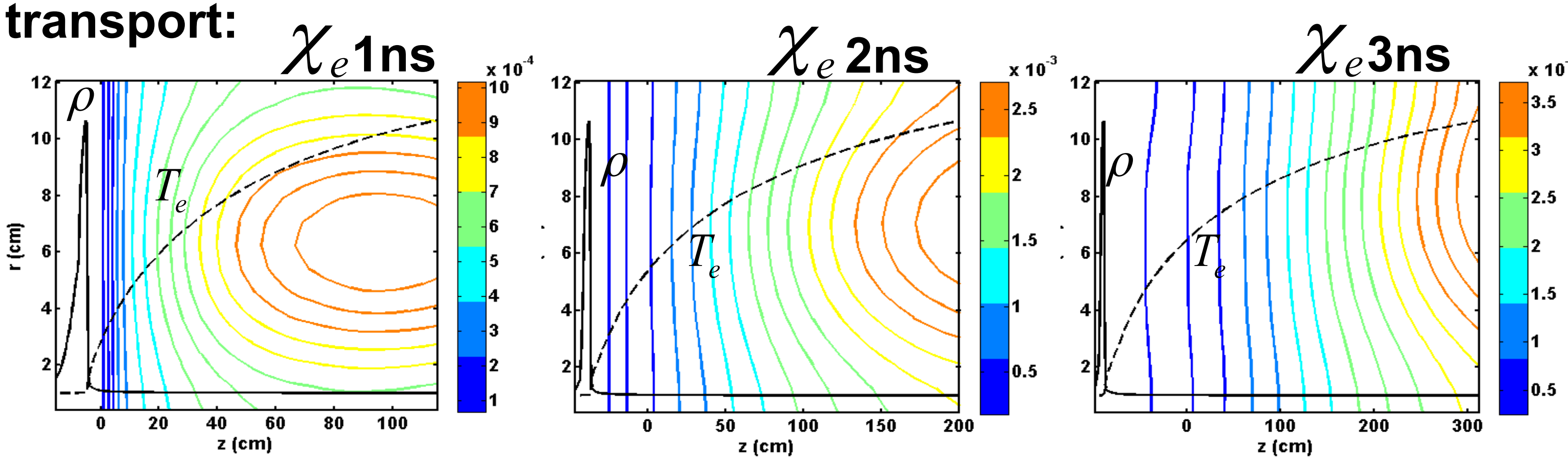
- **The plasma is not magnetised:**

$$l = 9\,\mu m$$



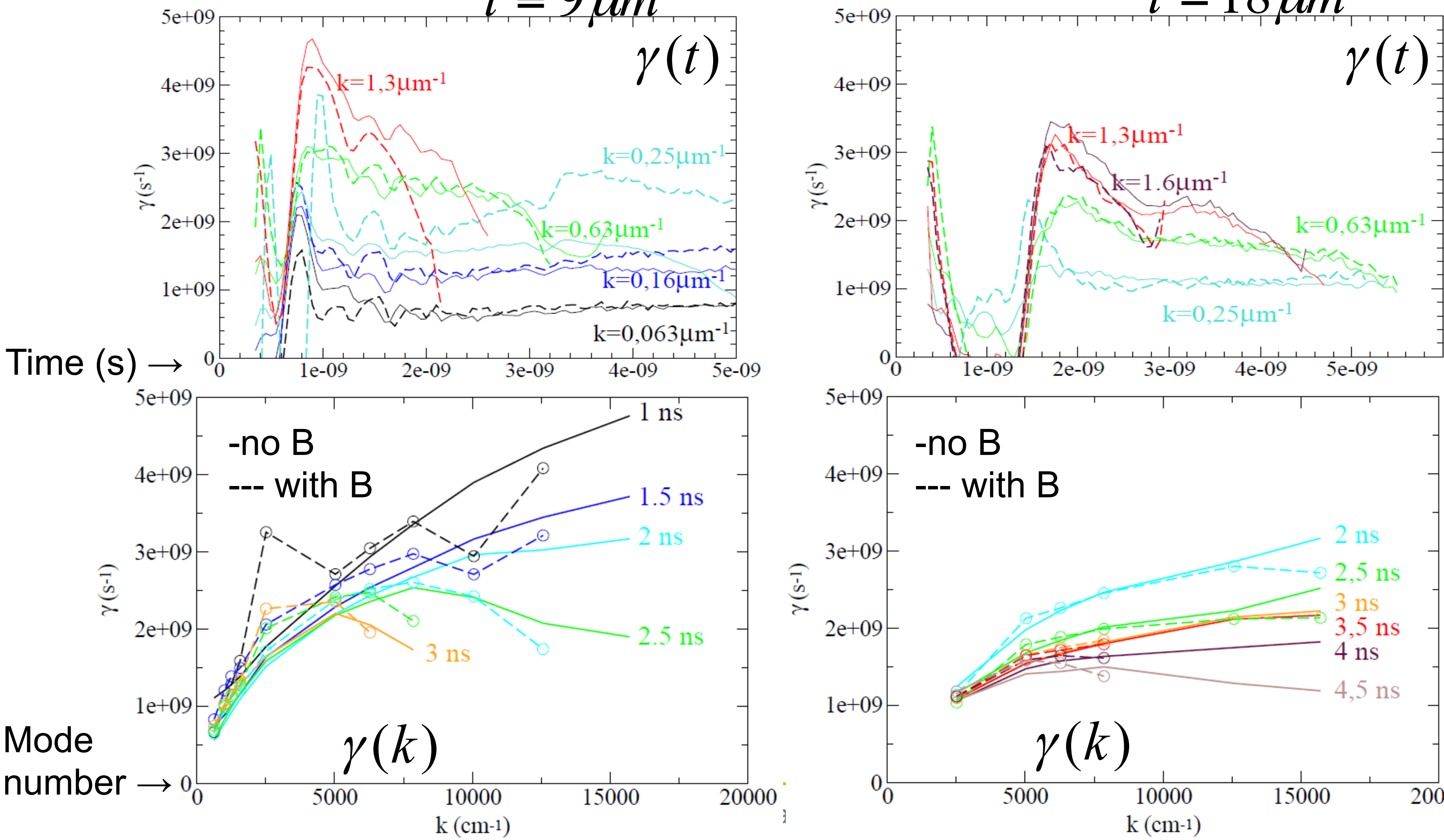
$$\frac{1}{\beta} = \frac{B^2}{2\mu_0 p}$$

- **Hall Parameter $\chi_e = \omega_{ce}\tau_{ei}$ is too small to expect effects on transport:**



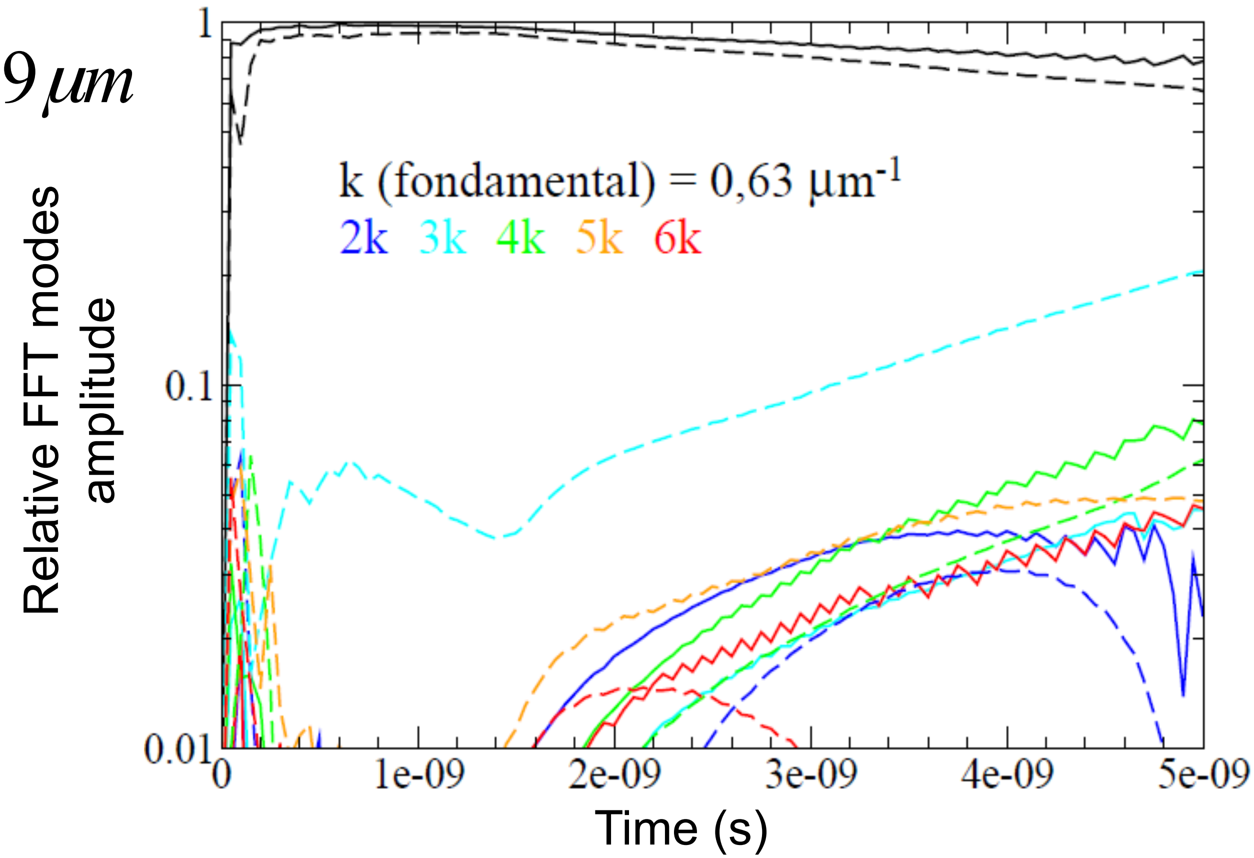
We observe discrepancies in the dispersion relation though when B-field generation is on…

- **Differences are enhanced for long times and high mode wave numbers.**



…especially faster growth of third harmonic.

$l = 9\,\mu m$

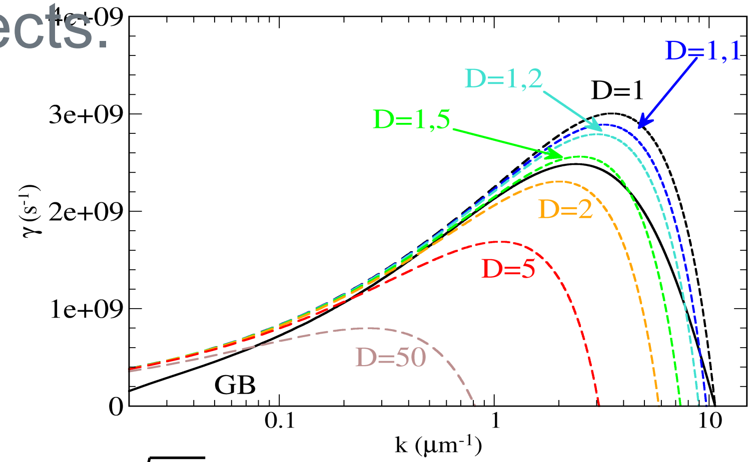


- **High enhancement of third harmonic with self-generation of magnetic field**

We used a model of aRTI with anisotropic thermal conduction* to model B-fields effects:

- **Masse derived dispersion relation using a conduction anisotropy coefficient:**

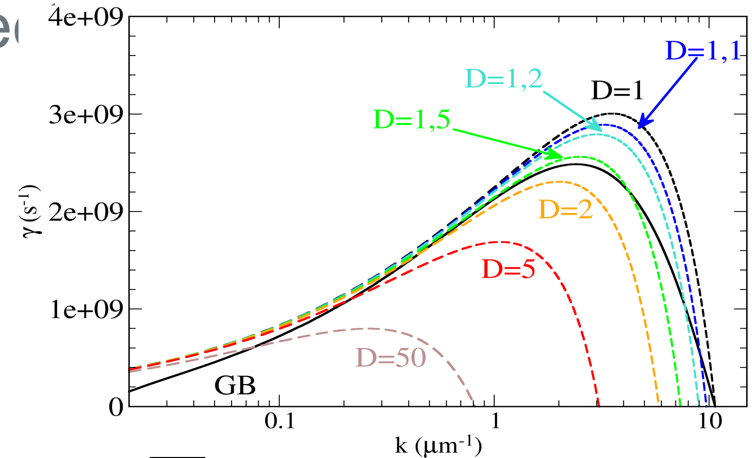
$$D = \frac{\kappa_{transverse}}{\kappa_{along\,\nabla T_e}}$$



$$\gamma^2 + 2(\sqrt{D}+1)kv_a\gamma + a(2\sqrt{D}-1)k^2v_a^2 - kg = 0$$

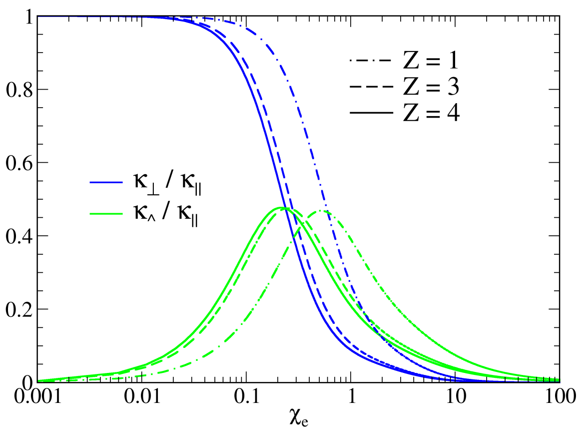
*L. Masse, PRL,98(24):245001, 2007

We used a model of aRTI with anisotropic thermal conduction* to model B-fields effe



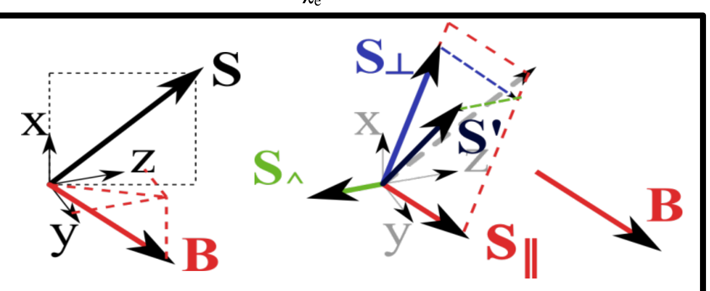
- **Masse derived dispersion relation using a conduction anisotropy coefficient:**

$$D = \frac{\kappa_{transverse}}{\kappa_{along\,\nabla T_e}}$$



$$\gamma^2 + 2(\sqrt{D}+1)kv_a\gamma + a(2\sqrt{D}-1)k^2v_a^2 - kg = 0$$

- **Considering th. flux anisotropy induced by the field according to Braginskii** we propose:**



$$D = 1 + \frac{\kappa_\times}{\kappa_\perp}$$ with

$$\kappa_\times = \frac{n_e T_e \tau_{ei}}{m_e}\frac{\chi_e(\gamma_0'' + \gamma_1''\chi_e^2)}{\Delta}$$

$$\kappa_\perp = \frac{n_e T_e \tau_{ei}}{m_e}\frac{(\gamma_0' + \gamma_1'\chi_e^2)}{\Delta}$$

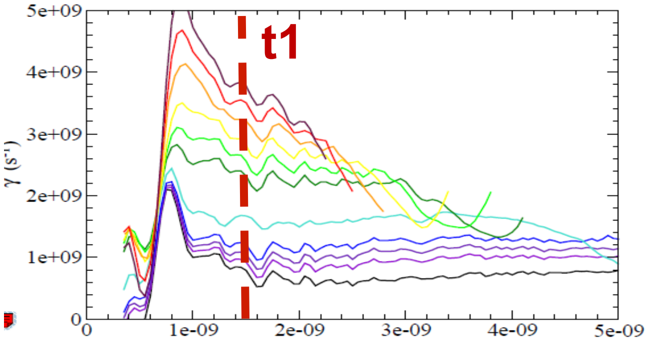
$$\Delta = \delta_0 + \delta_1\chi_e^2 + \chi_e^4$$

- **Since we have small B-fields:** $D = 1 + \frac{\kappa_\times}{\kappa_\perp} \sim 1 + \chi_e \frac{\gamma_0''}{\gamma_0'}$

***L. Masse, PRL,98(24):245001, 2007** ****S.I. Braginskii, Rev. Plasma Phys.,1:205, 1965**

We used a model of aRTI with anisotropic thermal conduction to model B-fields effects.

- **We then make strong assumptions:**



* only self-generated magnetic fields (no convection, no Nernst effect,…) from aRTI growth

* $\partial_z T_e\big|_a \sim \mathrm{cst}$ in time

* we know B and density perturbations amplitude at ablation at time **t1**, when the linear regime starts

$$\gamma = \frac{\mathrm{d}}{\mathrm{d}t}\ln\left(\frac{\delta\rho}{\rho}\right)$$

- **Self-generated magnetic field rate can then be easily integrated…**

$$B(t,k) - B(t_1,k) \sim \int_{t_1}^{t} -\frac{k_B}{e}\frac{\delta\rho}{\rho}(t)\, k\, \partial_z T_e\big|_a \,\mathrm{d}t$$

- **and we link *D* to B and growth rate by integrating B-field evolution equation:**

$$B(t,k) \sim B_1 + \widetilde{B}\frac{k}{\gamma}\left(e^{\gamma(t-t_1)} - 1\right)$$

$$\chi_e(t,k) \sim \widetilde{\chi}B(t,k) \sim \widetilde{\chi}B_1 + \widetilde{\chi}\widetilde{B}\frac{k}{\gamma}\left(e^{\gamma(t-t_1)} - 1\right)$$

with

$$\begin{cases} \widetilde{B} = \dfrac{k_B}{e}\partial_z T_e\big|_a \left(\dfrac{\delta\rho}{\rho}\right)_{t_1} \\ B_1 = B(t_1,k) \\ \widetilde{\chi} = \dfrac{3\varepsilon_0^2 (2\pi k_B T_e)^{3/2}}{\sqrt{m_e n_e}\,\ln\Lambda\, Z e^3} \end{cases}$$

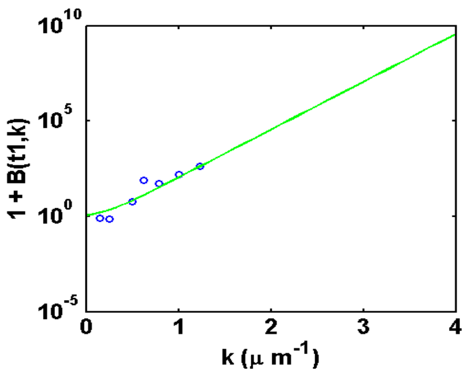
A self consistent closure is still missing though.

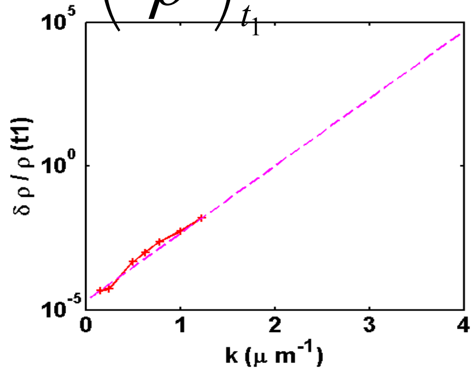
- **We obtained the following non linear dispersion relation:**

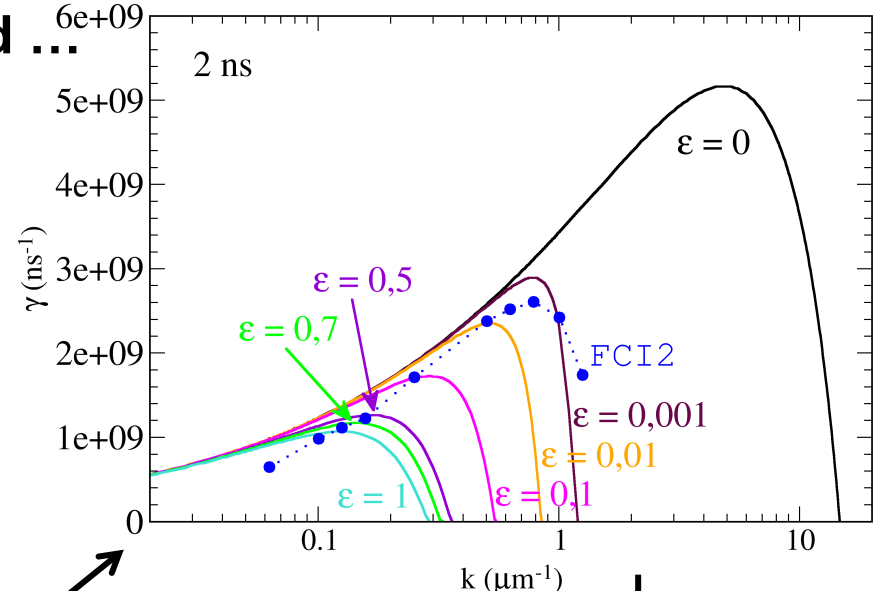
$$\gamma^3+\left(4+\frac{\gamma_0''}{\gamma_0'}\tilde{\chi}B_1\right)kv_a\gamma^2+\left(ak^2v_a^2\left(1+\frac{\gamma_0''}{\gamma_0'}\tilde{\chi}B_1\right)-k^2v_a\frac{\gamma_0''}{\gamma_0'}\tilde{\chi}\tilde{B}-kg\right)\gamma-ak^3v_a^2\frac{\gamma_0''}{\gamma_0'}\tilde{\chi}\tilde{B}$$

$$=-\frac{\gamma_0''}{\gamma_0'}\tilde{\chi}\tilde{B}k^2v_a\left(\gamma+akv_a\right)e^{\gamma(t-t_1)}$$

- **A closure for B_1 and $\left(\frac{\delta\rho}{\rho}\right)_{t_1}$ is needed …**







Fitting their value as a function of k and introducing a multiplicative factor ε to easily estimate discrepancies one obtain

$$B(t,k)\rightarrow\varepsilon\left(B_1+\tilde{B}\frac{k}{\gamma}\left(e^{\gamma(t-t_1)}-1\right)\right)$$

over-estimation of effects since no diffusion, no convection… taken into account

Outline

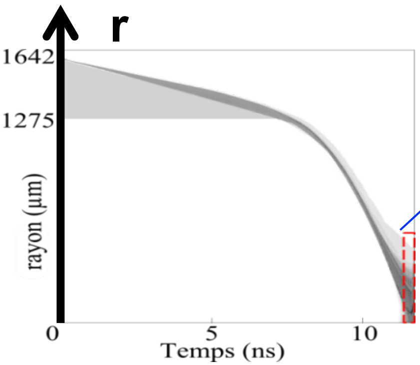
- aIRT in the acceleration phase:
  - DNS set up;
  - behavior without magnetic field;
  - turning on magnetic fields self-generation:

    *B-fields quantification;
    *dispersion relations;
    *effects evaluation through Masse model.

- **aIRT in the deceleration phase:**
  - DNS set up;
  - Comparison between with or without B-fields.

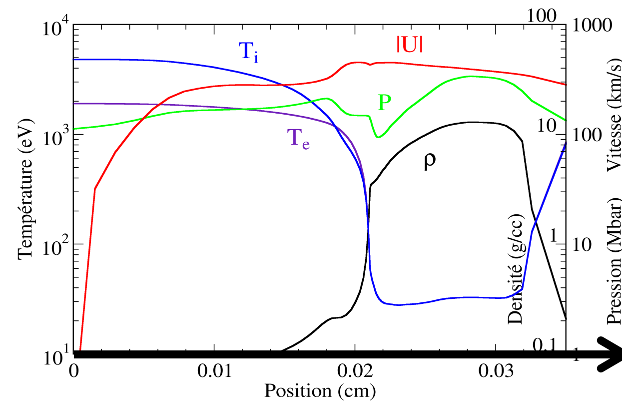
We also investigate B-fields in the deceleration stage by numerical simulations.

- **Numerical simulations that take self-generated magnetic fields into account are performed in 2D in cylindrical geometry:**



t = 0 → HADES → t = 600ps

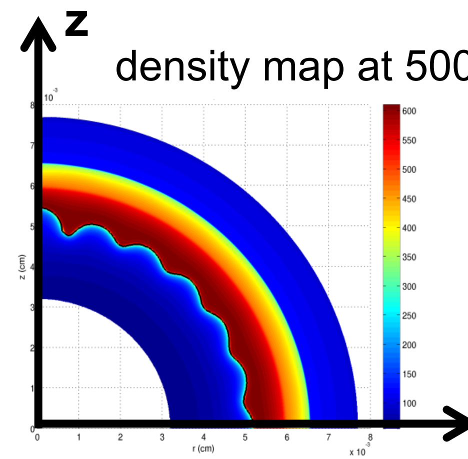
Initialization radial profiles are given by 1D code **FCI***



Symmetrization from 1D radial profile + Legendre single mode perturbation l_0

Deceleration is calculated by HADES:**
- resistive MHD
- perfect gas EOS
- lagrangian with projection
- 2D cylindrical geometry
- no fusion reactions

density map at 500ps

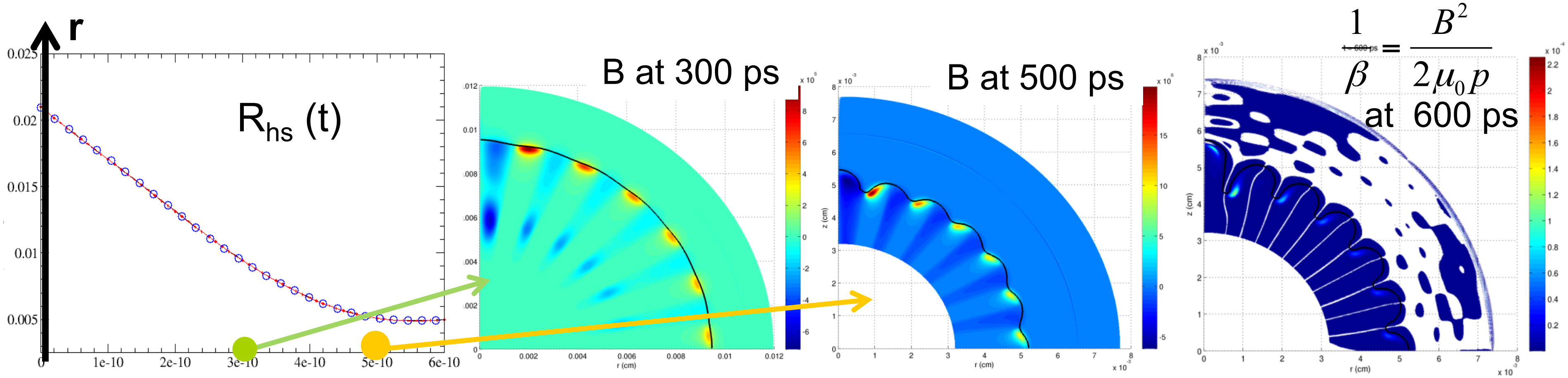


***Canaud & al., Nuc. Fus., 44(10):1118, 2004 **M. Wolff, PhD, 2011**

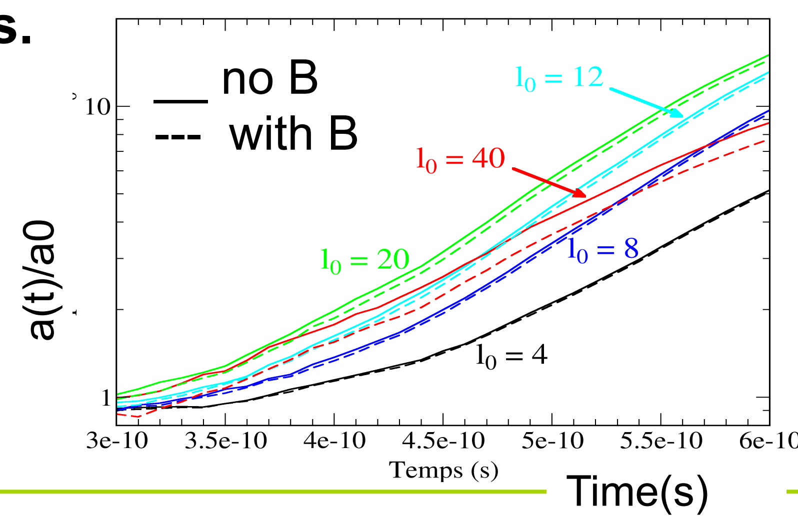
Self-generated B-fields of ~1000 T can be generated at the end of the deceleration phase without influencing aRTI.

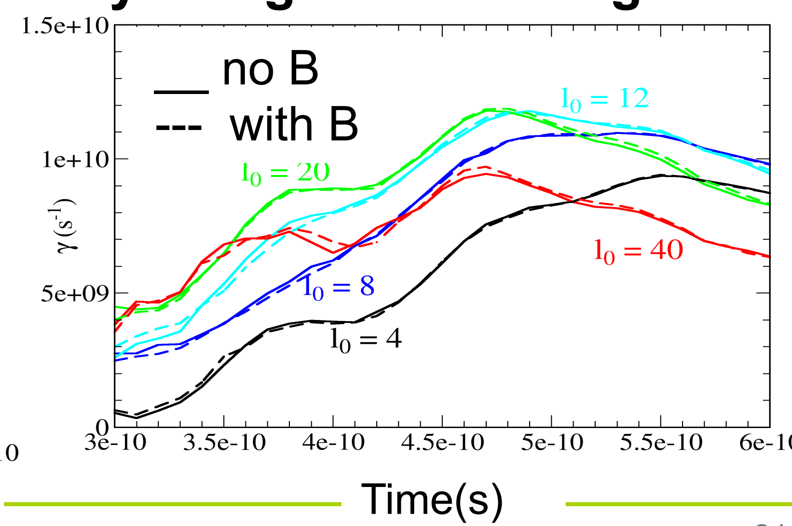
cea
energie atomique • energies alternatives

- **Magnetic fields generated are very localized. Their amplitude is coherent with Hata & al.* cannot balance high hot spot pressure.**



- **Growth rates are not influenced either by self-generated magnetic fields.**

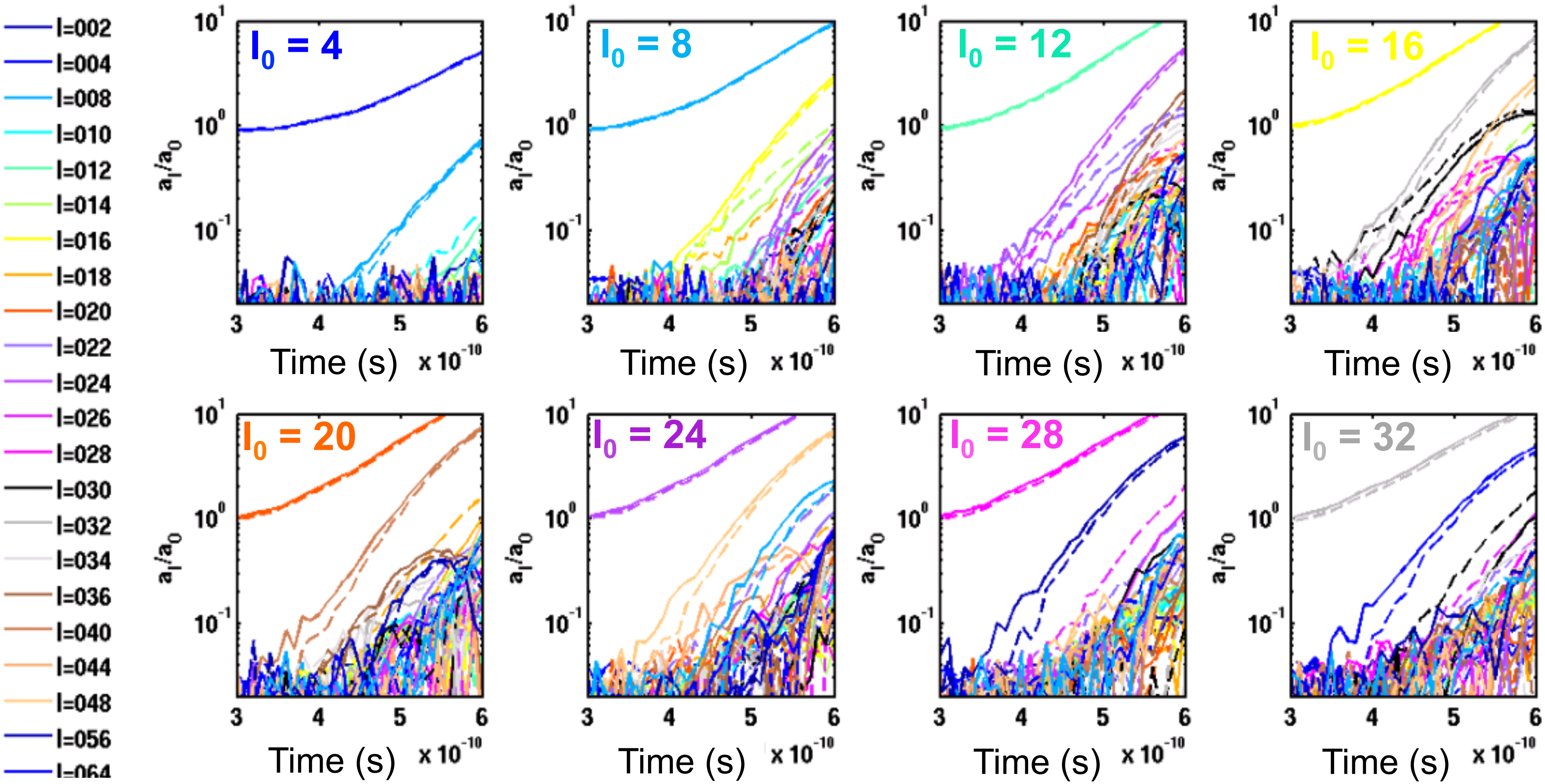




*Hata & al., Plasma Fus. Res., 1:20, 2006

Harmonics do not « feel » self-generated magnetic field.

- **We performed Legendre polynomial decomposition to analyze hot spot contour for different initial mode numbers l_0:**



Conclusions

- **In the acceleration stage:**

  ➢ we found rapid transition to non linear regime.

  ➢ The effect of self-generated magnetic fields is small:

  * enhanced for small wavelength,
  * enhanced at late times,
  * non linear development of aRTI is enhanced especially for third harmonic → transits faster in to non linear growth.

  ➢ we tried to estimate effects on the growth rate by taking anisotropy induced by B-field into account but we also need look at other effects, with a proper closure.

- **Concerning deceleration stage:**

  ➢ no effect on aIRT has been observed because of the too high constraint of this stage where growth is driven by hydrodynamics.