Title: The basics and not-so-basic physics of beam plasmas

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Abstract:

UCLM
UNIVERSIDAD DE CASTILLA~LA MANCHA

The basics and not-so-basic physics of beam plasmas

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Universidad de Castilla-La Mancha

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

FEEDBACK OVER 44 ORDERS OF MAGNITUDE: FROM GAMMA-RAYS TO THE UNIVERSE

March 14-16, 2016

CASTILLA-LA MANCHA?

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COLLABORATORS

- **Laurent Gremillet** CEA, France
- **Mark Dieckmann** Linköping, Sweden

PHYSICS OF PLASMAS **17**, 120501 (2010)

Multidimensional electron beam-plasma instabilities in the relativistic regime

A. Bret,[1,a)] L. Gremillet,[2,b)] and M. E. Dieckmann[3,c)]
[1]*ETSI Industriales, Universidad de Castilla-La Mancha, 13071 Ciudad Real, Spain and Instituto de Investigaciones Energéticas y Aplicaciones Industriales, Campus Universitario de Ciudad Real, 13071 Ciudad Real, Spain*
[2]*CEA, DAM, DIF, F-91297 Arpajon, France*
[3]*Department of Science and Technology (ITN), VITA, Linköping University, 60174 Norrköping, Sweden*

(Received 16 July 2010; accepted 21 October 2010; published online 28 December 2010)

The interest in relativistic beam-plasma instabilities has been greatly rejuvenated over the past two decades by novel concepts in laboratory and space plasmas. Recent advances in this long-standing field are here reviewed from both theoretical and numerical points of view. The primary focus is on the two-dimensional spectrum of unstable electromagnetic waves growing within relativistic, unmagnetized, and uniform electron beam-plasma systems. Although the goal is to provide a unified

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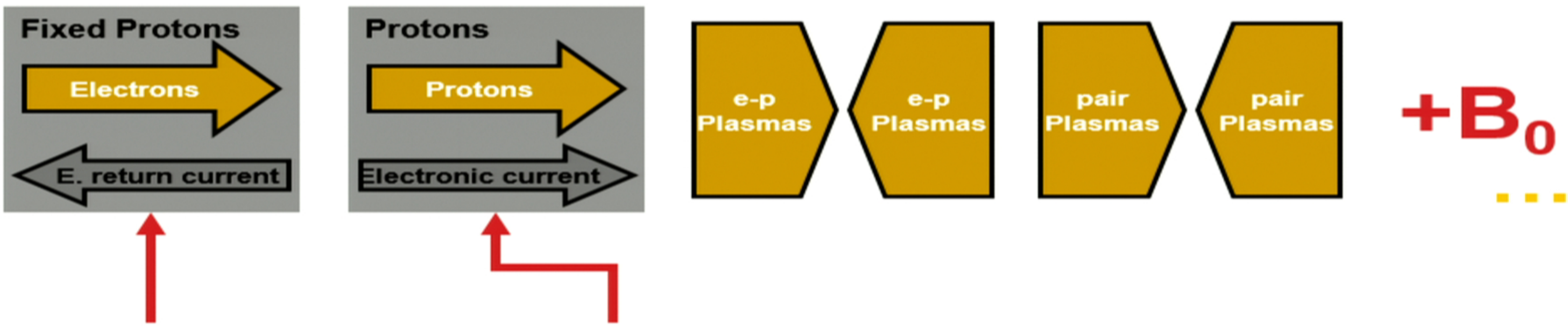
OUTLINE

- How are pair beams from TeV blazars losing their energy? Instabilities with IGM?

- Two-stream, filamentation (Weibel), oblique
- LINEAR (NL: Chang, Schlickheiser, Shalaby)
- Cold regime
- Kinetic regime
- Modes hierarchy
- Fermi (intuitive) calculations

SYSTEM CONSIDERED

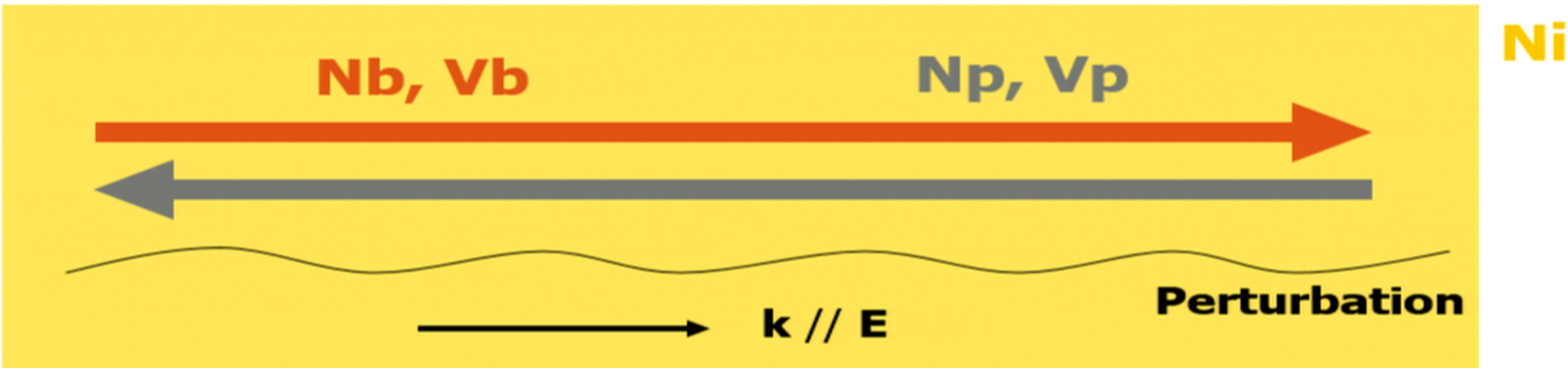
- Beam/plasma system: infinite, homogenous, collisionless, current and charge neutral.
- Settings are numerous:



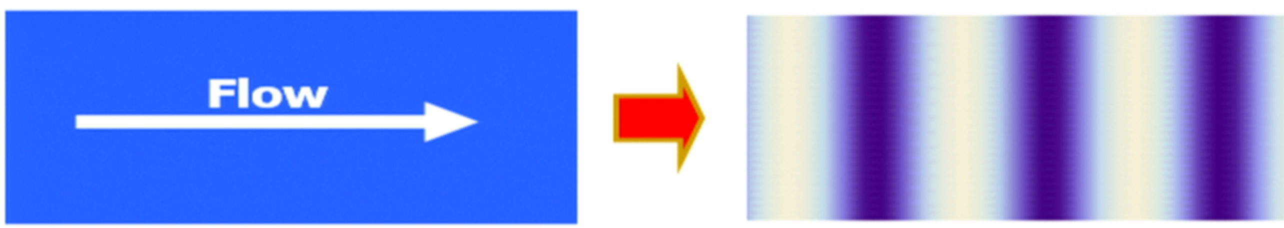
ICF
Fast Ignition

Shock physics
“Bell modes”

TWO-STREAM

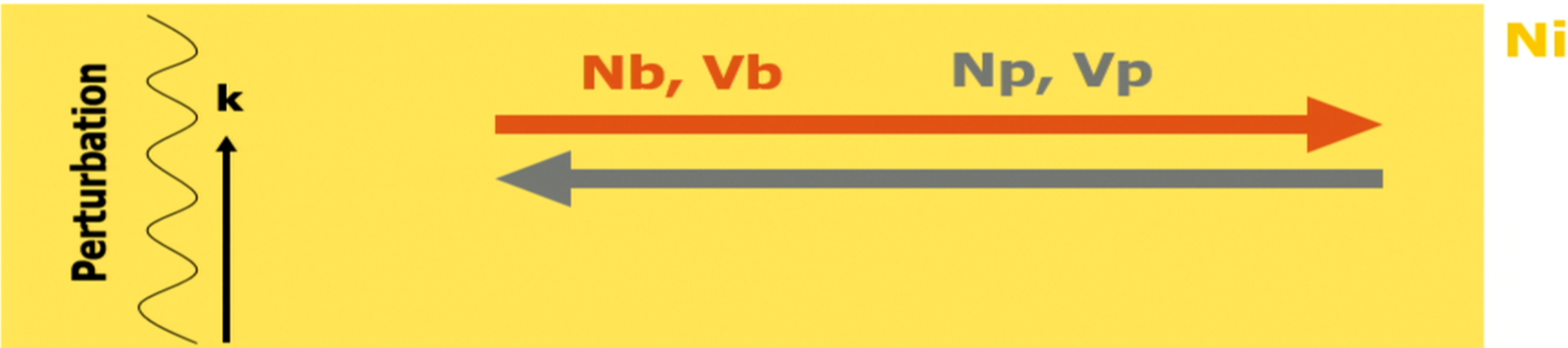


The system is in « static » equilibrium. No net current, no net charge. But unstable



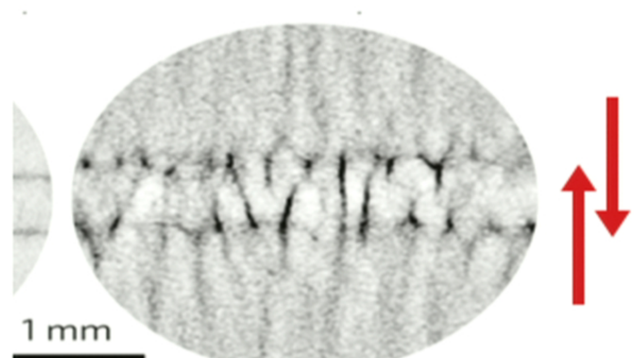
Bohm & Gross, Phys. Rev. **75**, 1851 & 1864 (1949)
Bludman, Watson & Rosenbluth, Phys. Fluids **3**, 747 (1960)

FILAMENTATION (WEIBEL)



- Wave vector is here normal to the beam flow.
- Produces current filaments and B fields.

Why filaments, and not stripes?
Two-stream "lost the race" because of system parameters (relativistic)! **MODES COMPETITION**



Huntington et al, *Nature Physics* **11**, 173–176 (2015)

BASIC FORMALISM

- Relativistic Vlasov system in 3D:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) \cdot \frac{\partial f}{\partial \mathbf{p}} = 0$$

- + Maxwell's.

- Linearization $\rightarrow$ Dielectic tensor $\varepsilon(\mathrm{k},\omega)$ non-diagonal
- Given k, Det $\varepsilon(\mathrm{k},\omega) = 0 \rightarrow \omega(\mathrm{k}) = \omega_r(\mathrm{k}) + i\,\delta(\mathrm{k})$
- E along eigenvectors of $\varepsilon[\mathrm{k}, \omega(\mathrm{k})]$

DEALING WITH THE RELATIVISTIC REGIME

Non relativistic system

$$\varepsilon(\mathbf{k},\omega) = 1 + \frac{4\pi q^2}{k^2}\int \frac{\mathbf{k}\cdot\partial f_0(\mathbf{p})/\partial \mathbf{p}}{\omega - \mathbf{k}\cdot\mathbf{v}} d^3p$$

=0

Because it is **governed by the flow-aligned** instabilities.

Relativistic system

Any part of the spectrum can lead

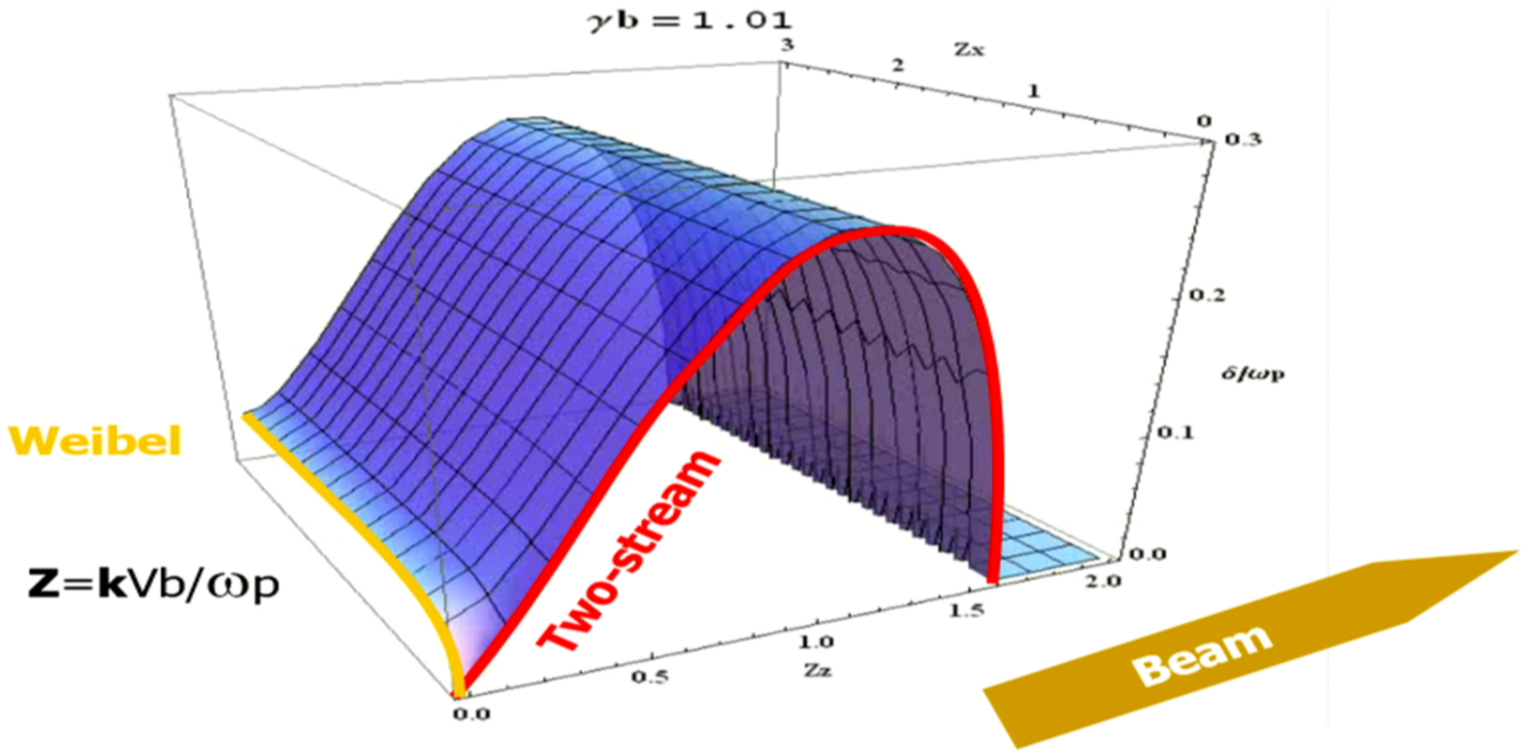
$$\det\left|\frac{\omega^2}{c^2}\varepsilon_{ij} + k_i k_j - k^2\delta_{ij}\right| = 0$$

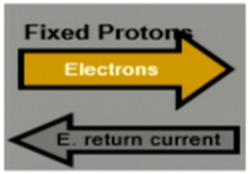
$$\varepsilon_{\alpha\beta} = \delta_{\alpha\beta} + \frac{\omega_{\mathrm{pe}}^2}{n_e\omega^2}\int \frac{p_\alpha}{\gamma}\frac{\partial f_0}{\partial p_\beta} d^3p + \frac{\omega_{\mathrm{pe}}^2}{n_e\omega^2}\int \frac{p_\alpha p_\beta}{\gamma}\frac{\mathbf{k}\cdot\partial f_0/\partial \mathbf{p}}{m_e\gamma\omega - \mathbf{k}\cdot\mathbf{p}} d^3p$$

10

FULL UNSTABLE SPECTRUM – COLD REGIME

- Diluted beam Nb/Np = 0.1, γ_b=1.01





Same Branch

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FULL UNSTABLE SPECTRUM – COLD REGIME

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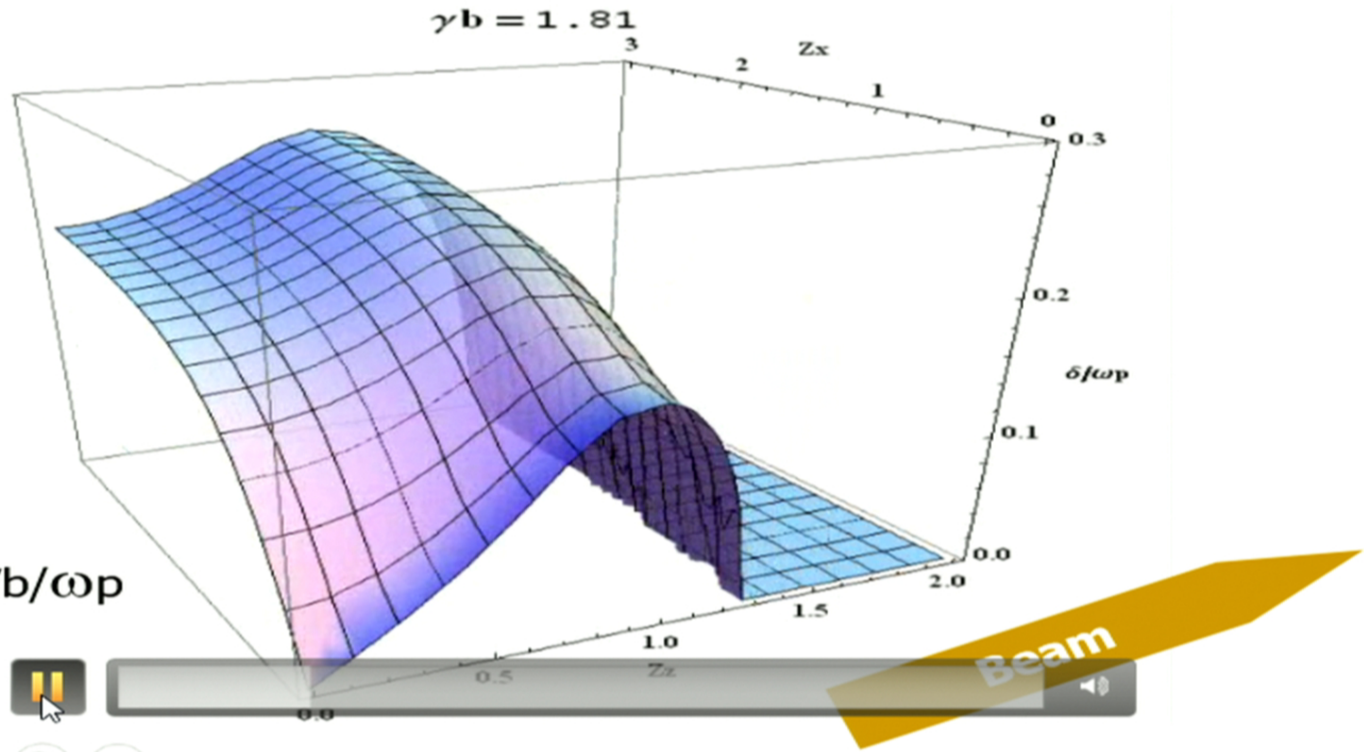
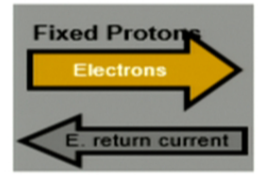


Z=**k**Vb/ωp



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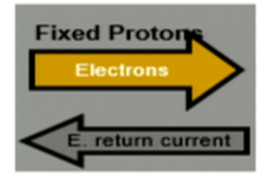
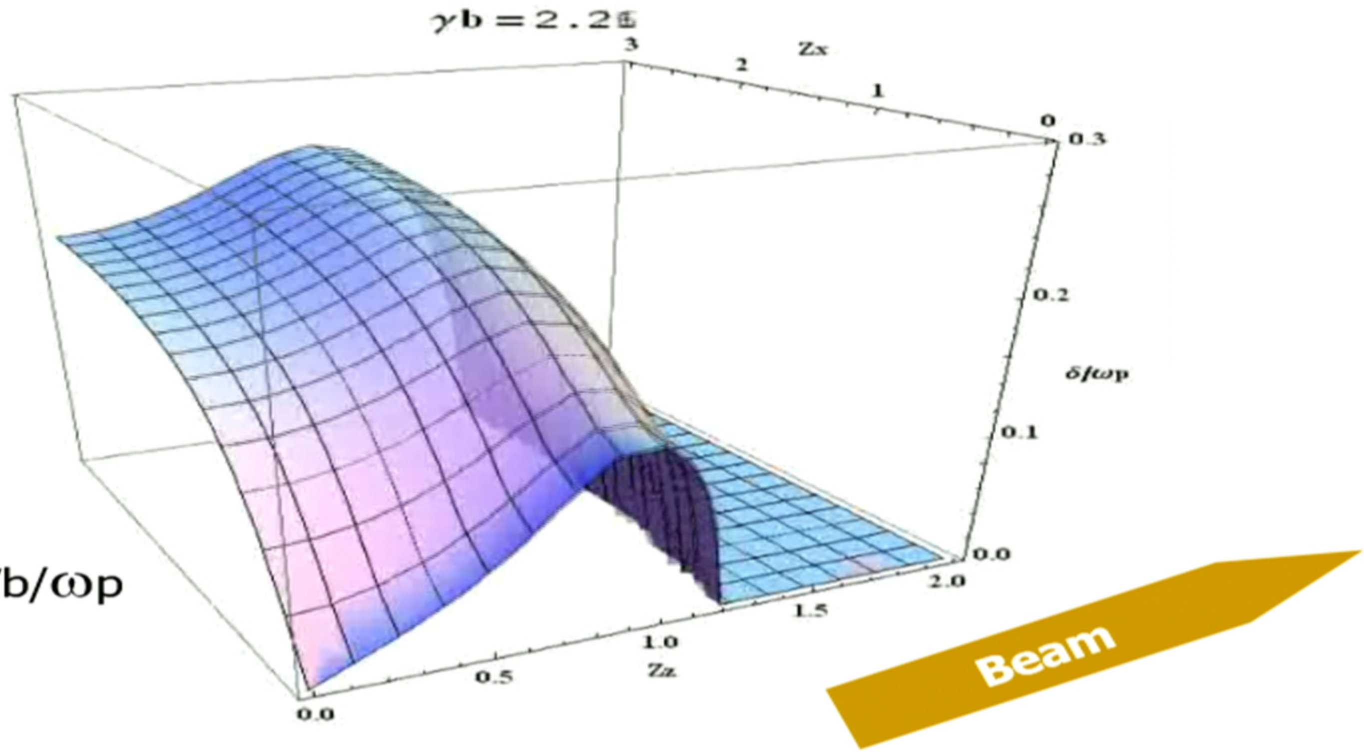




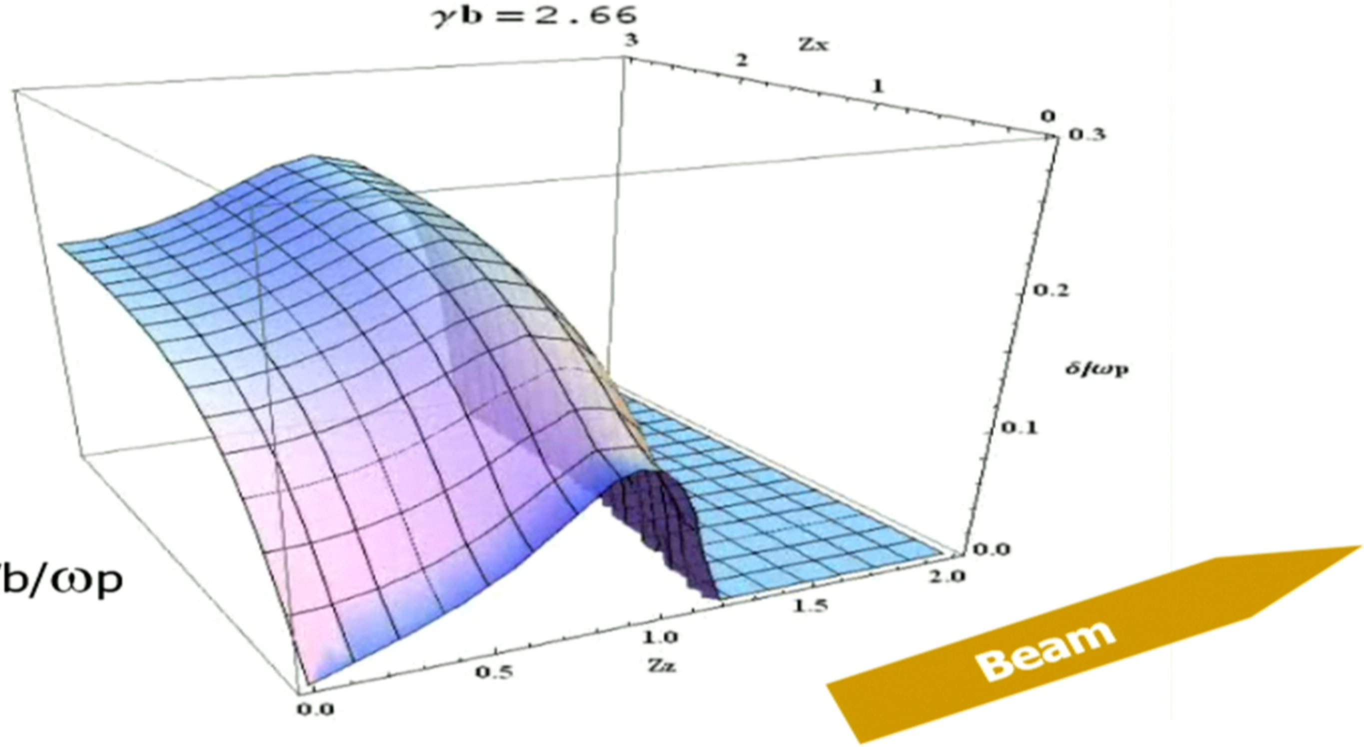
Z=kVb/ωp

Same Branch

12

FULL UNSTABLE SPECTRUM – COLD REGIME

- **Diluted beam Nb/Np = 0.1, γ_b=1.01**



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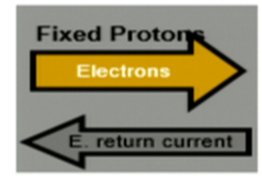

Same Branch

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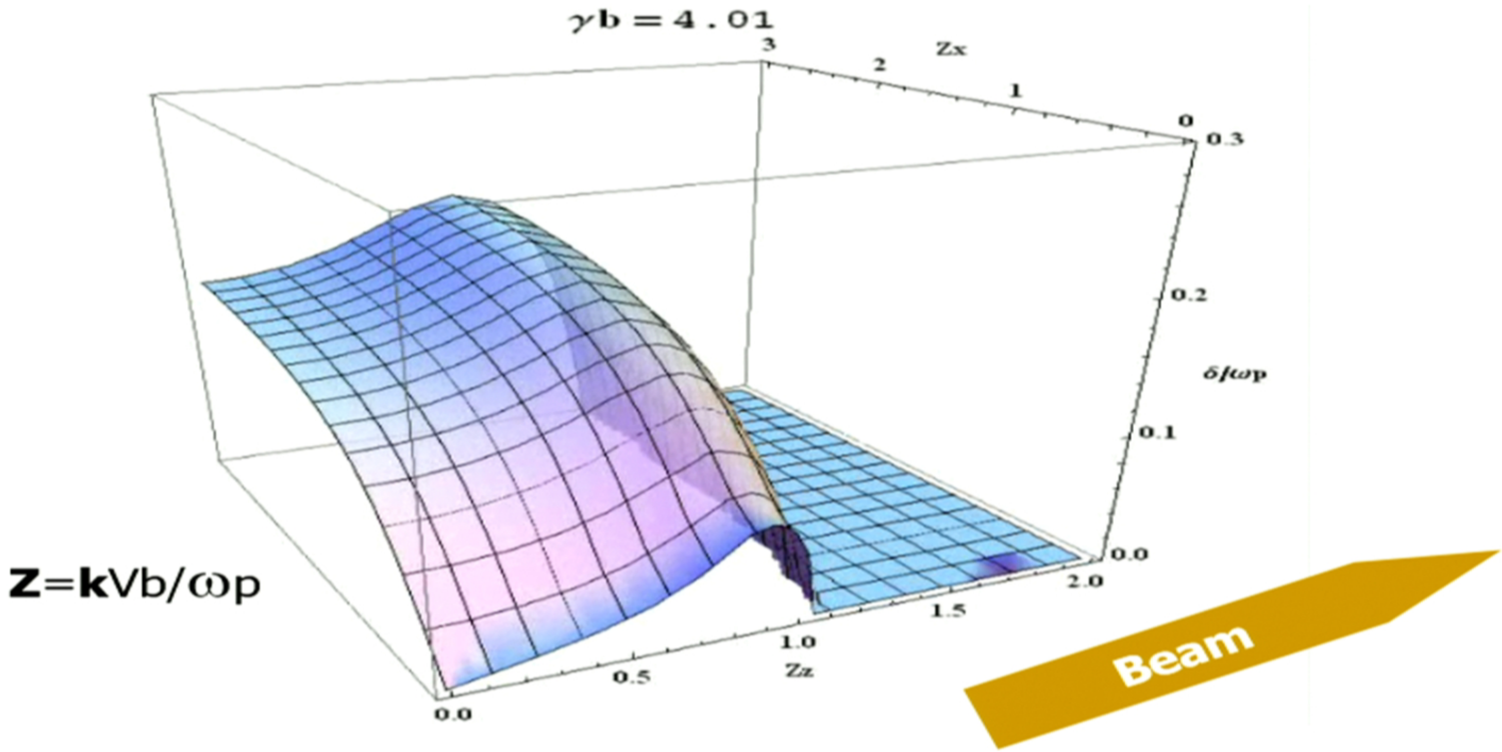

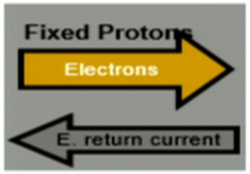

Same Branch

12

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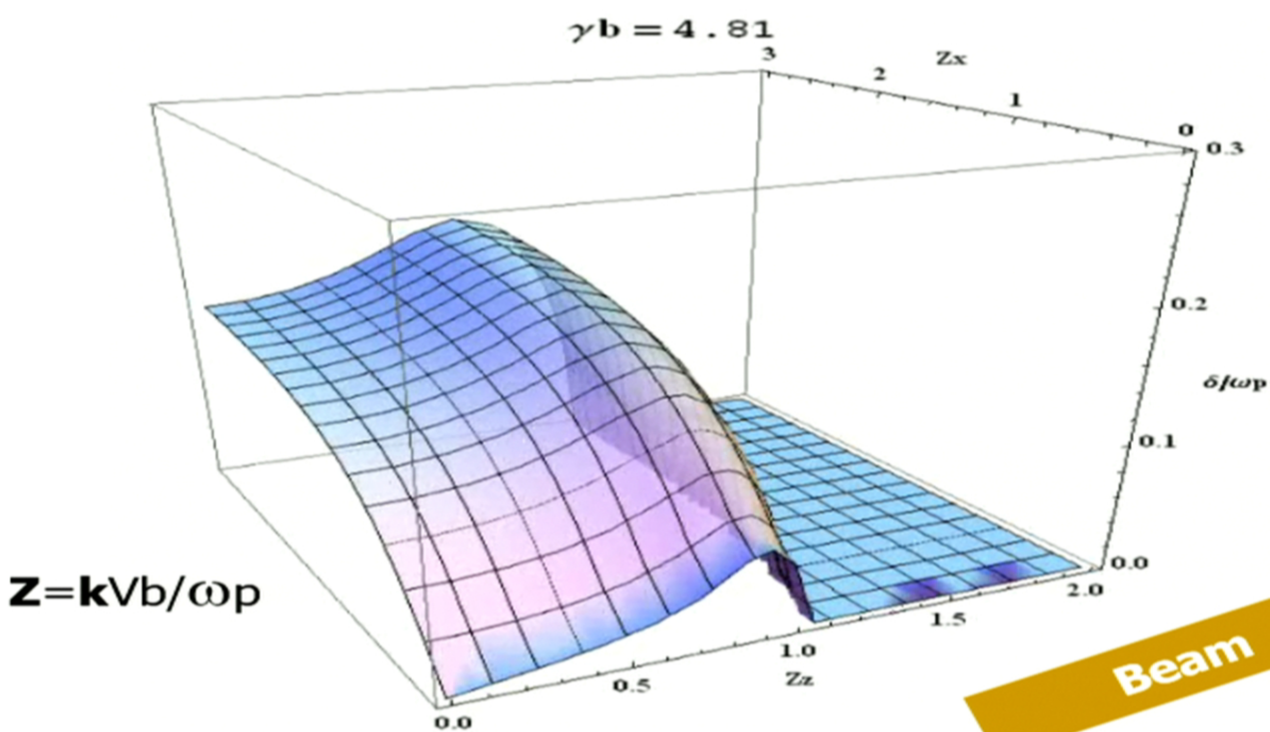

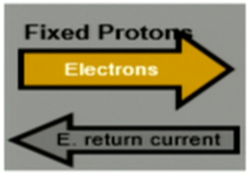

Same Branch

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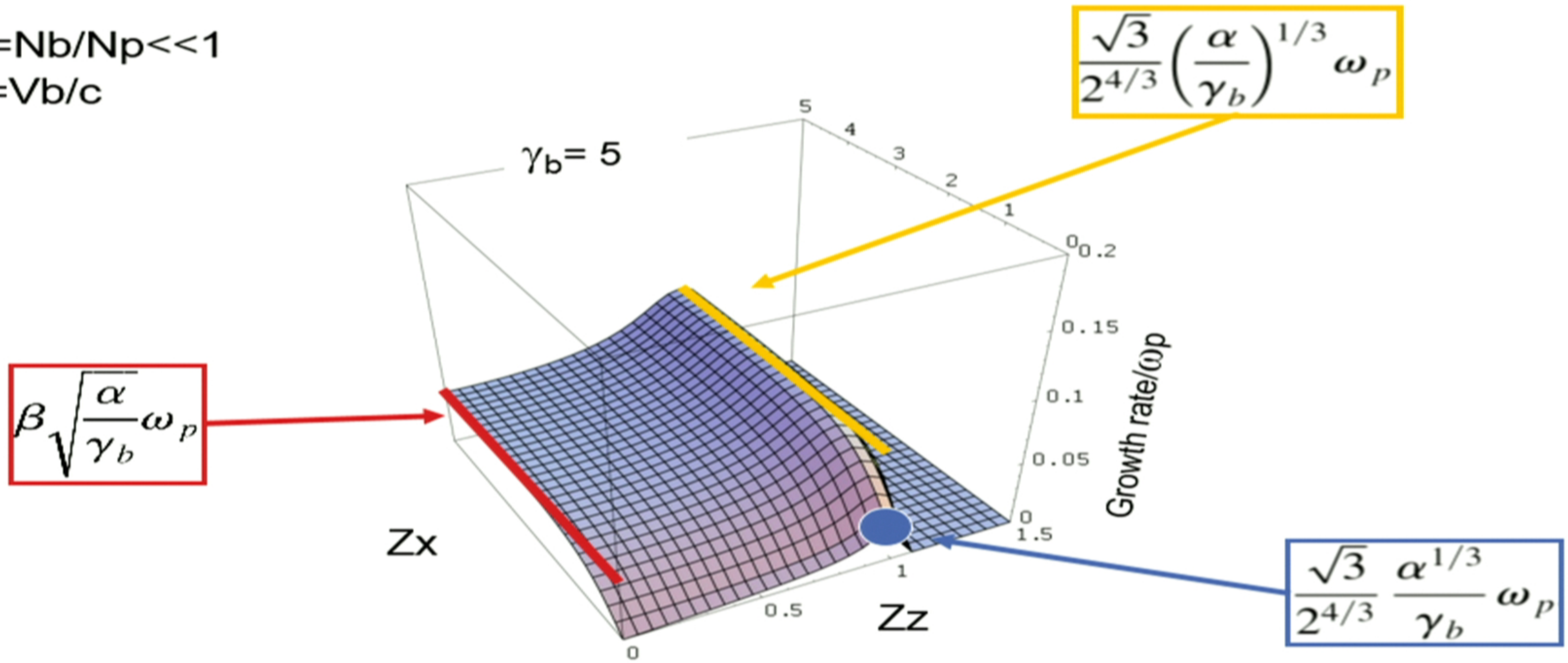
FULL UNSTABLE SPECTRUM – COLD REGIME

α=Nb/Np<<1
β=Vb/c



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NOTHING NEW UNDER THE SUN

THE PHYSICS OF FLUIDS VOLUME 3, NUMBER 5 SEPTEMBER-OCTOBER, 1960

Statistical Mechanics of Relativistic Streams. II

S. A. Bludman and K. M. Watson
University of California, Lawrence Radiation Laboratory, Berkeley, California
and
M. N. Rosenbluth
John Jay Hopkins Laboratory for Pure and Applied Science,
General Atomic Division of General Dynamics Corporation,
San Diego, California
(Received June 1, 1960)

1960

$$\mathrm{Im}\,\omega^{W} \doteq 0.69(\omega_b'\omega_i^2)^{\frac{1}{3}}$$

1/3

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NOTHING NEW UNDER THE SUN

SOVIET PHYSICS JETP VOLUME 30, NUMBER 3 MARCH 1970

NONLINEAR THEORY OF INTERACTION BETWEEN A "MONOCHROMATIC" BEAM OF RELATIVISTIC ELECTRONS AND A PLASMA

Ya. B. FAĬNBERG, V. D. SHAPIRO, and V. I. SHEVCHENKO
Physico-technical Institute, Ukrainian Academy of Sciences

Submitted April 10, 1969
Zh. Eksp. Teor. Fiz. 57, 966–977 (September, 1969)

1970

$$\delta = \frac{\sqrt{3}}{2^{4/3}}\,\omega_p \left(\frac{n_b}{n_p \gamma_0}\right)^{1/3}$$

1/3

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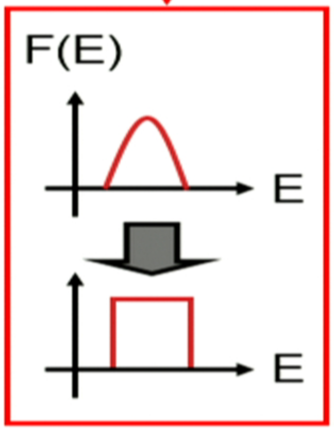
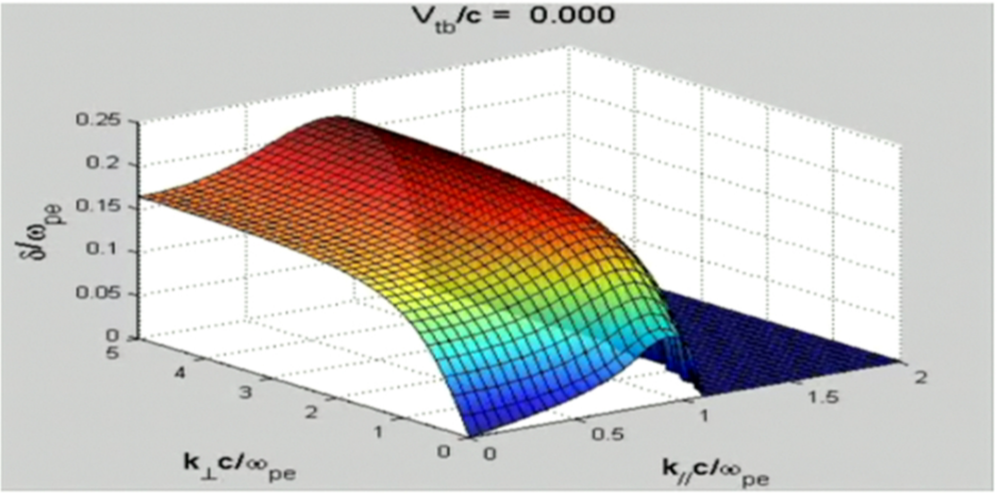
E-BEAM/PLASMA INTERACTION: TEMPERATURE DEPENDANT CALCULATIONS

- **Waterbag calculation (10 s CPU instead of 3 weeks).**
  $N_b/N_p = 0.1$, $\gamma_b = 4$





L.O. Silva et al., Bull. Am. Phys. Soc. 46, 205 (2001)
Bret et al. PRE 2004, 2005 – PRL 2005

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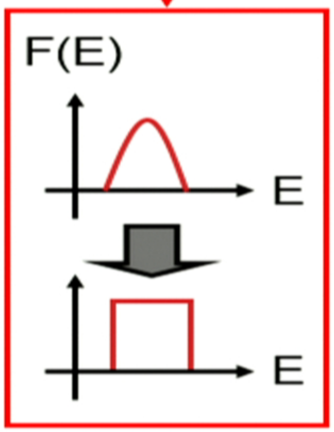

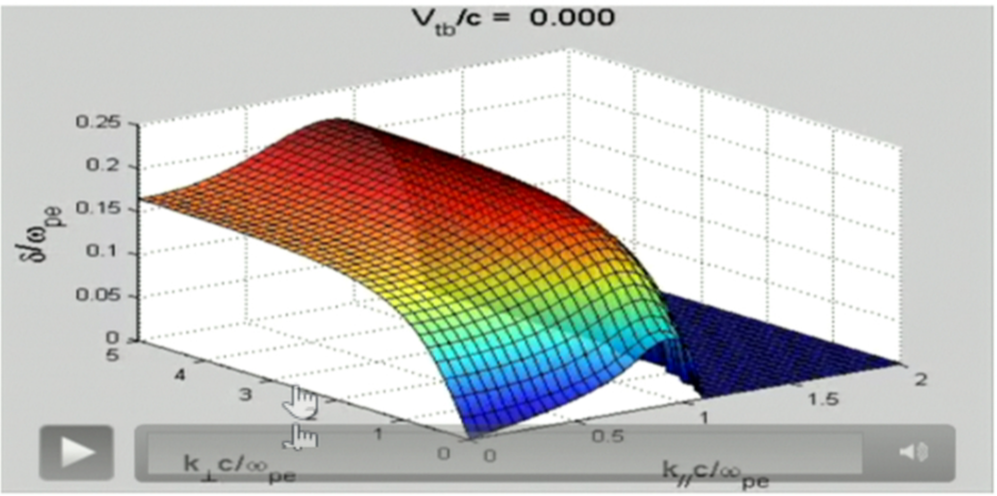

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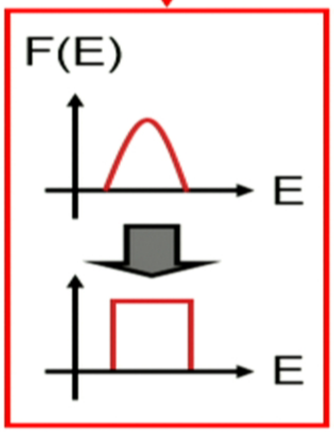

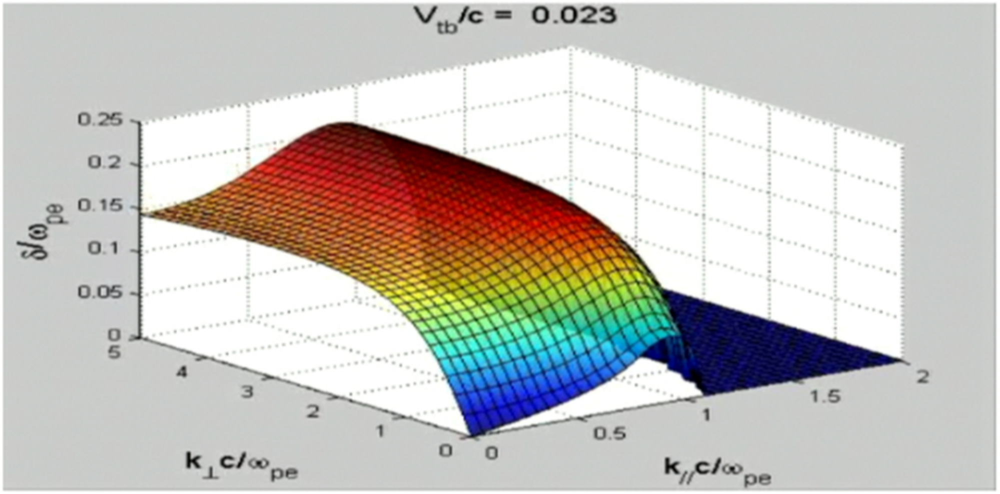

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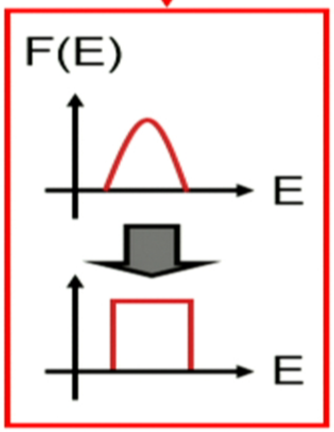

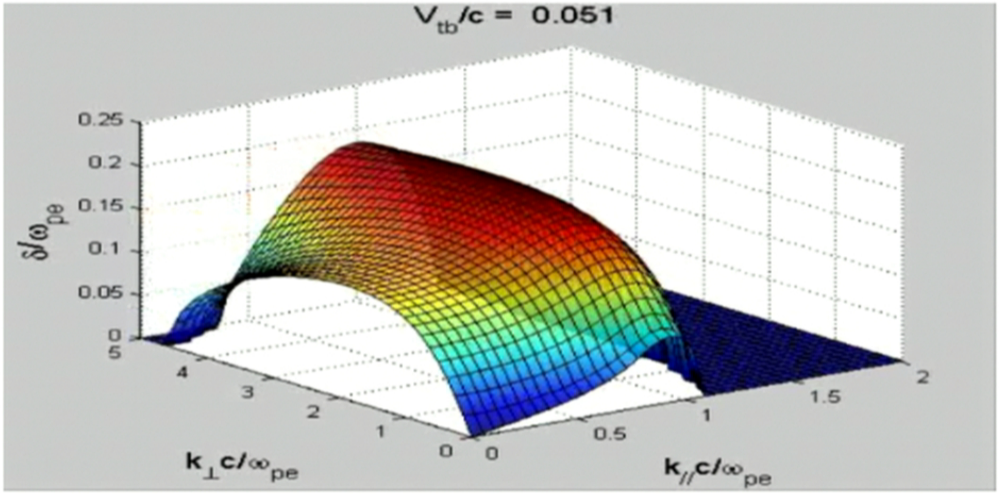

L.O. Silva et al., Bull. Am. Phys. Soc. 46, 205 (2001)
Bret et al. PRE 2004, 2005 – PRL 2005

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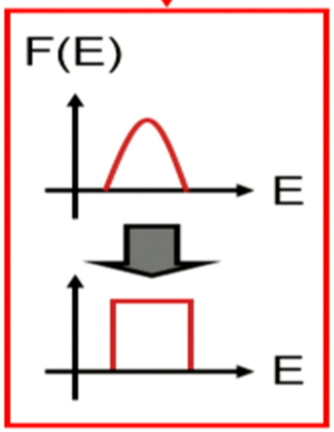

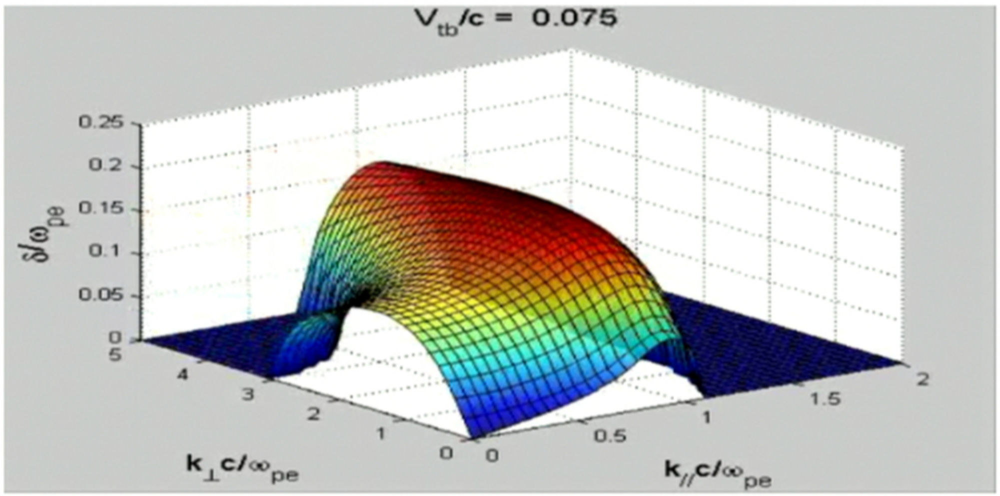

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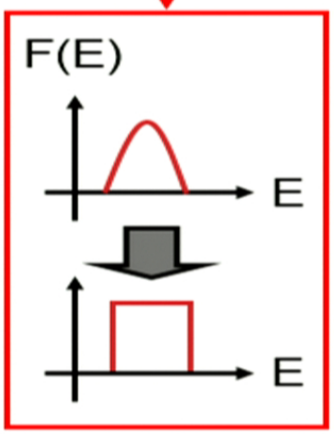

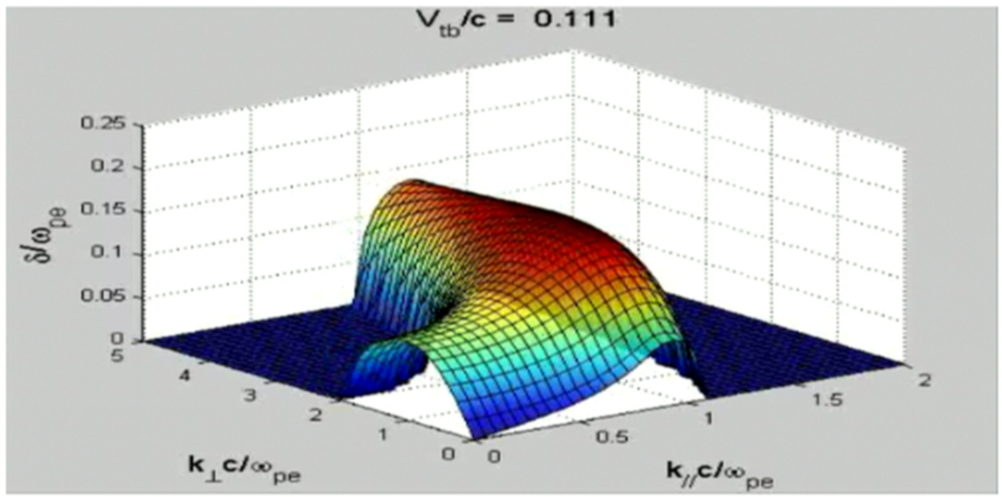

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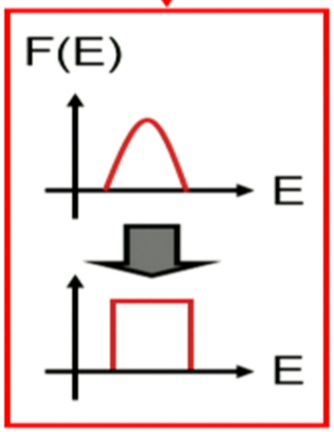

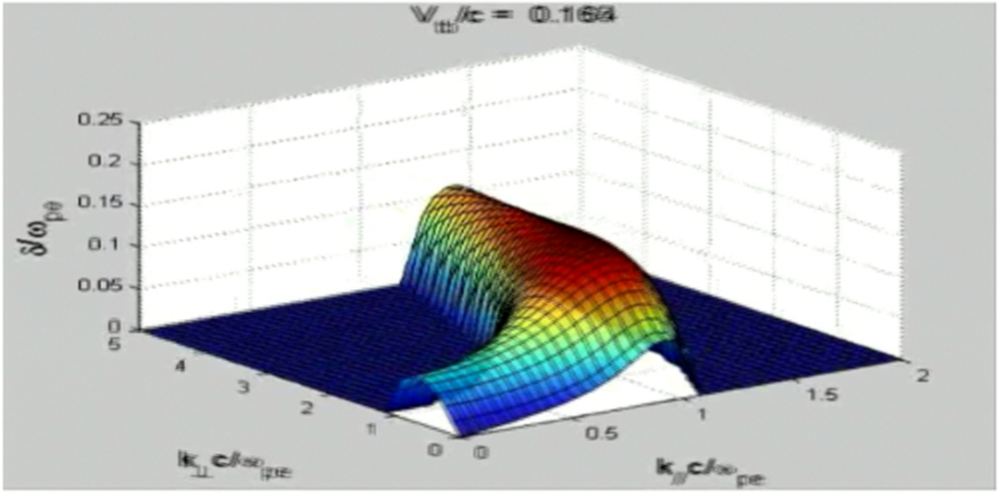

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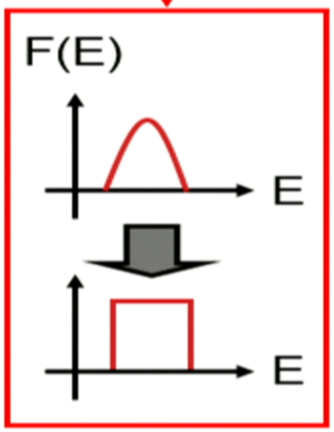

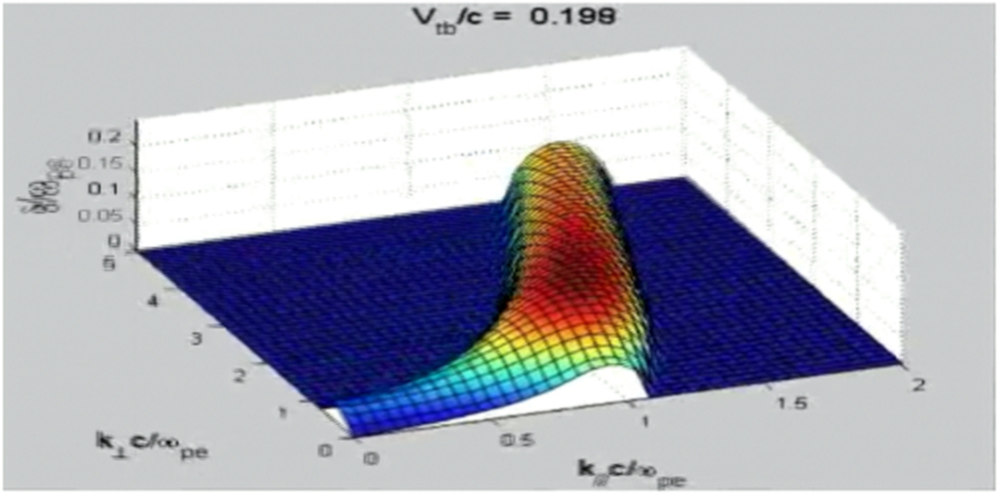

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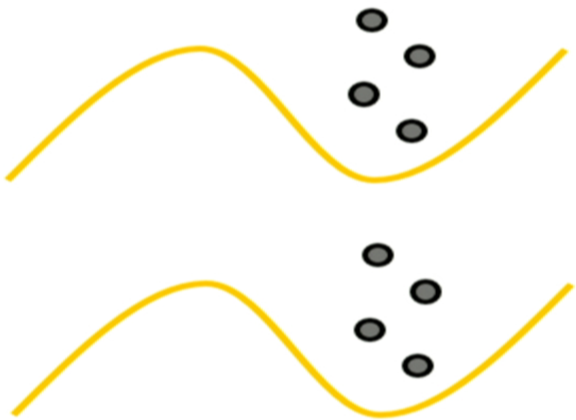
Bret et al. PRE 2004, 2005 – PRL 2005

GENERAL KINETIC RULES

- Why do thermal spread reduces the instability?

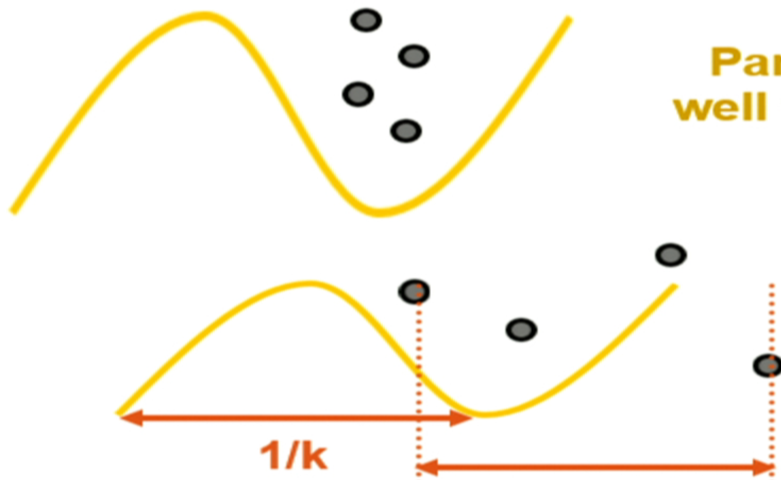


Fainberg, et al, Sov. Phys. JETP 30, 528 (1970).

17

GENERAL KINETIC RULES

- **Why do thermal spread reduces the instability?**



"Cold" if $1/k >> \Delta V_{//k} / \delta(k,\omega)$
Not homogenous on the k spectrum…

Fainberg, et al, Sov. Phys. JETP 30, 528 (1970).

17

GENERAL KINETIC RULES

- Transverse beam spread matters all the more than k is oblique.
- For k // Flow:

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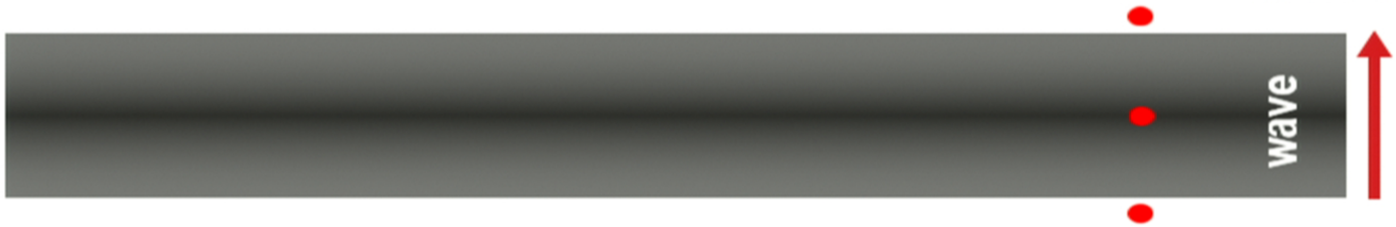
GENERAL KINETIC RULES

- Transverse beam spread matters all the more than k is oblique.
- For k perp. to the Flow:

k ⊥ flow



Particles initially well tuned "detune"

Beam temperature effects: Filamentation > Oblique > Two-Stream

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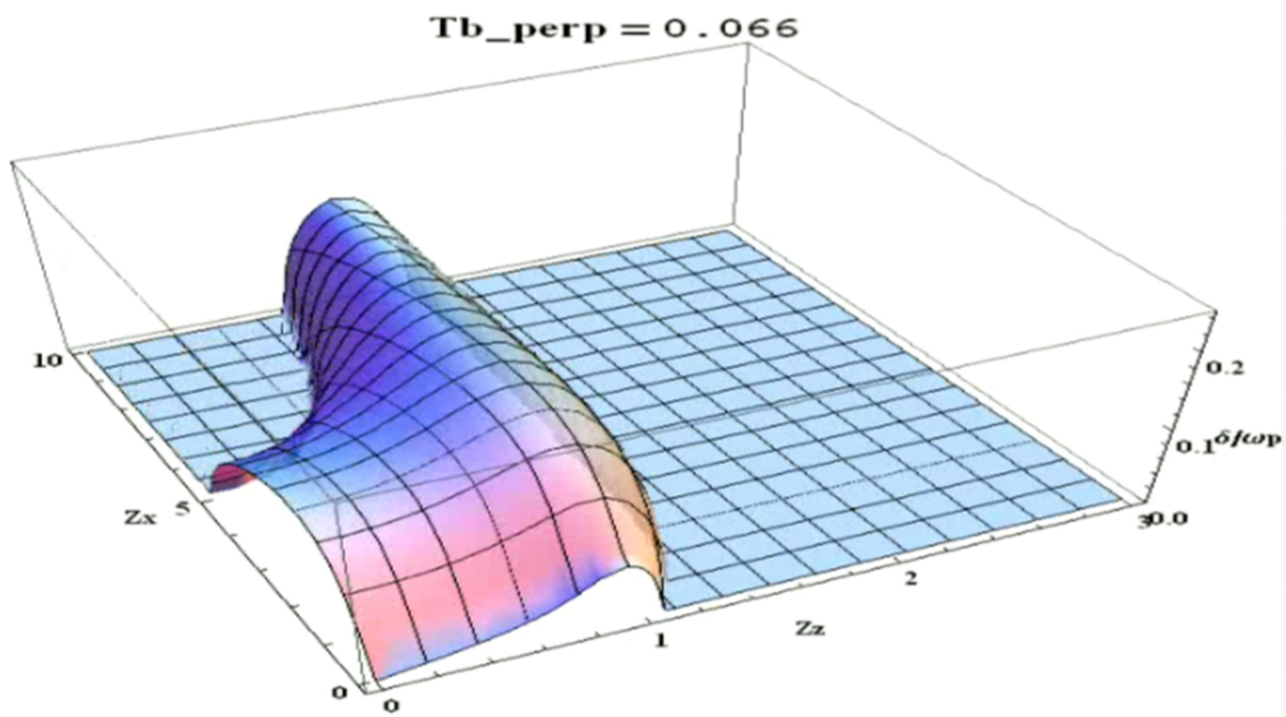
BEAM PERP TEMP (WATERBAG)



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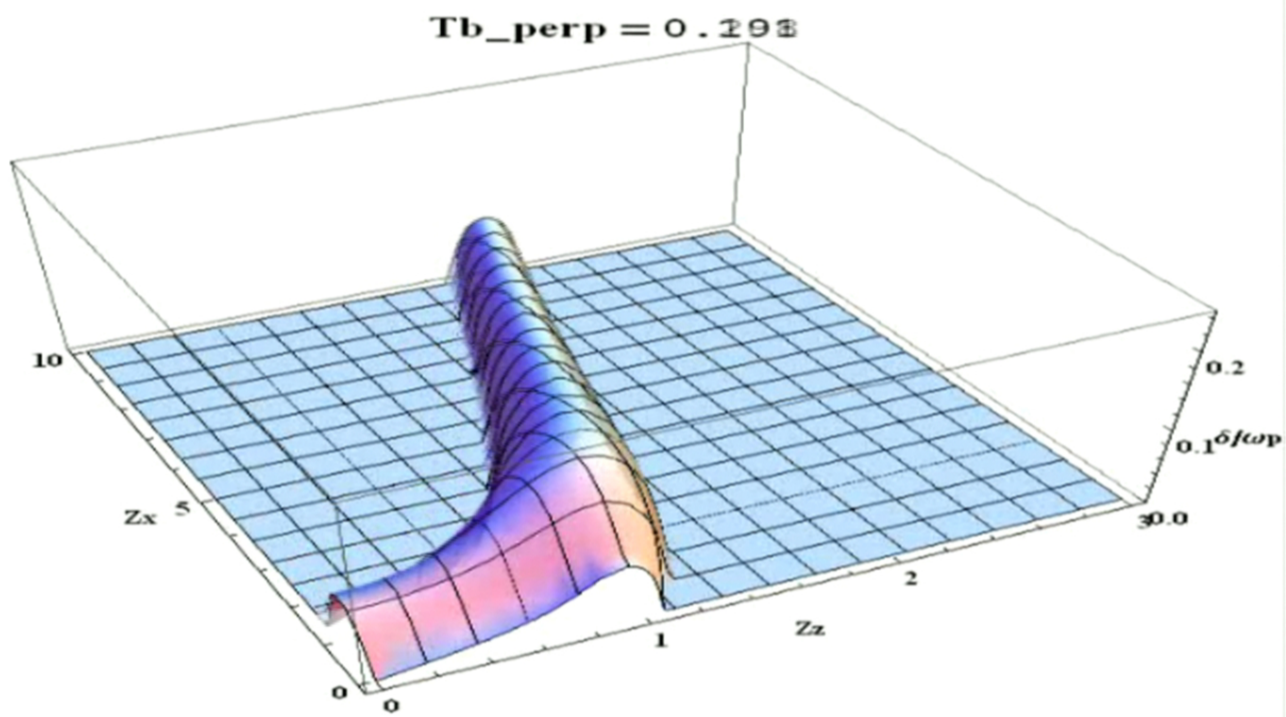
BEAM PERP TEMP (WATERBAG)



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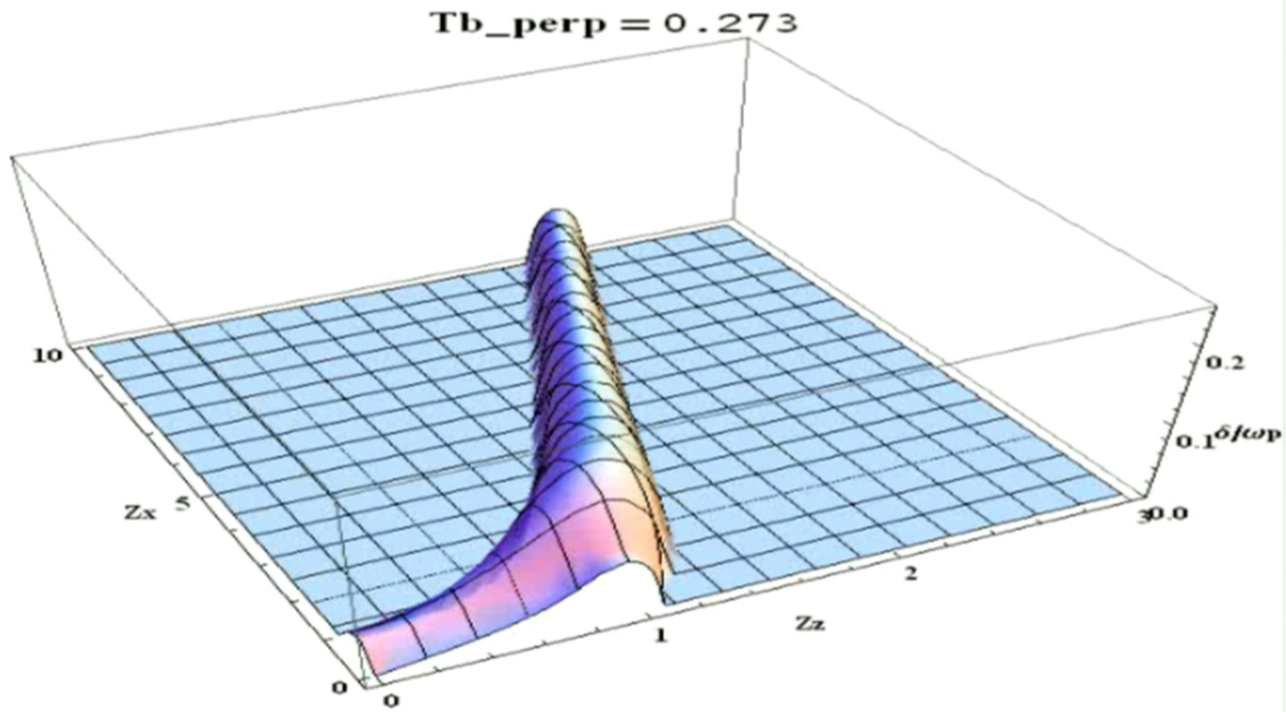
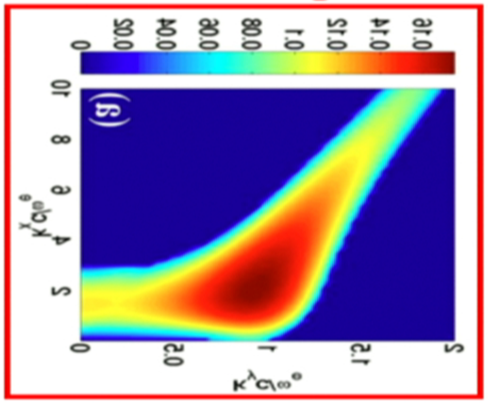
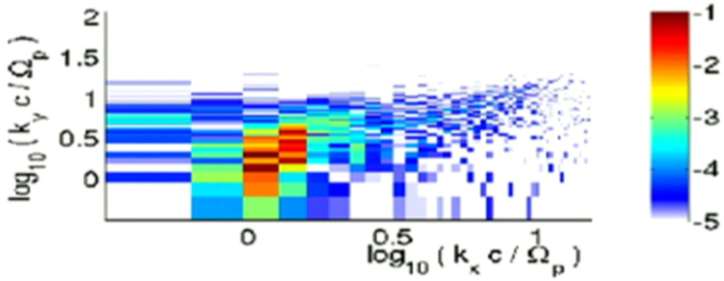


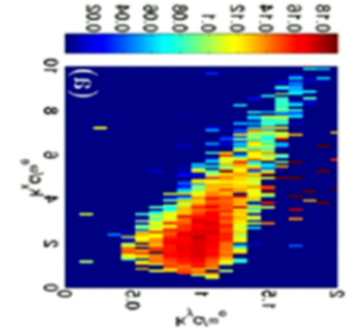
SIMULATIONS VS. THEORY

Theory

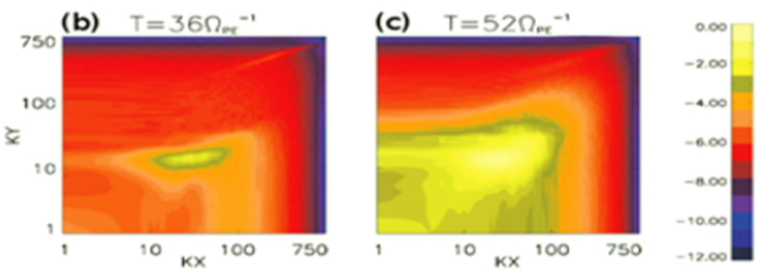




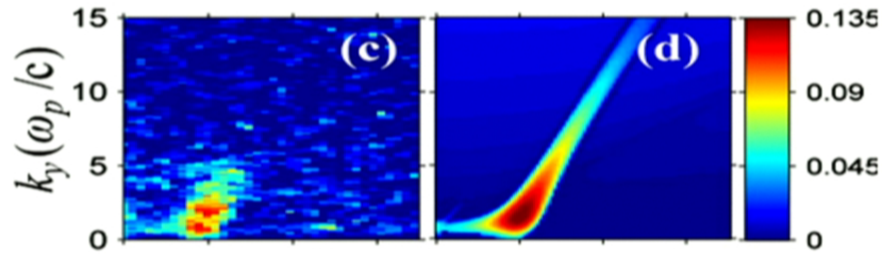
Dieckmann, Phys. Plasmas, 2006



Gremillet, Phys. Plasmas, 2007



Frederiksen, Phys. Plasmas, 2008

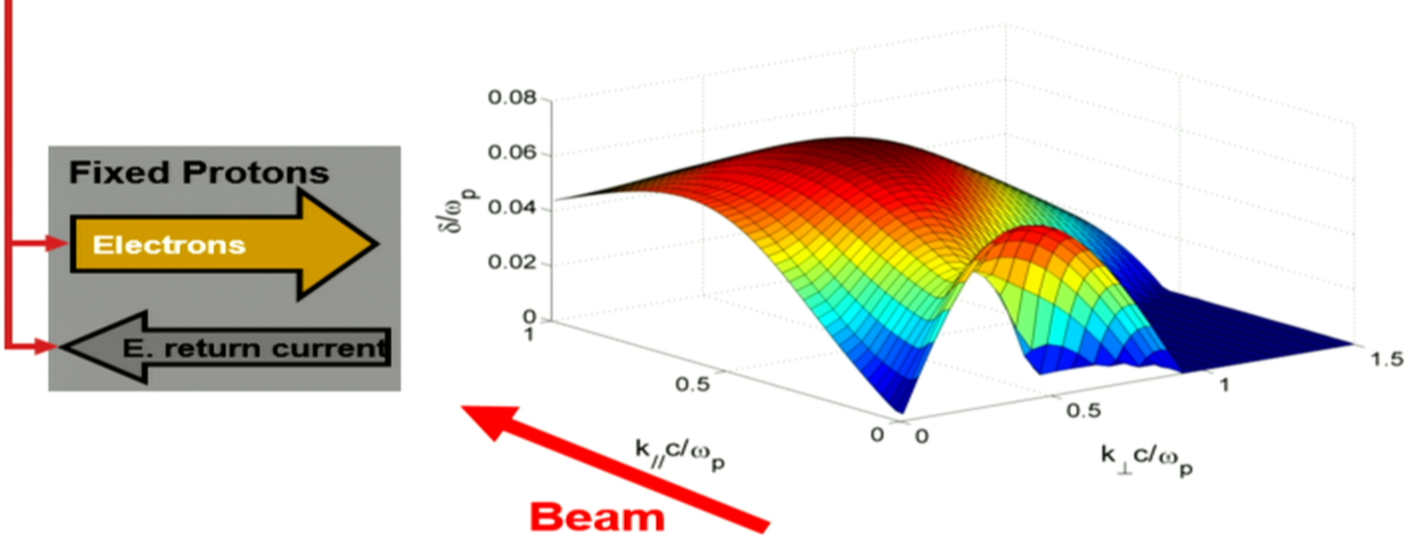


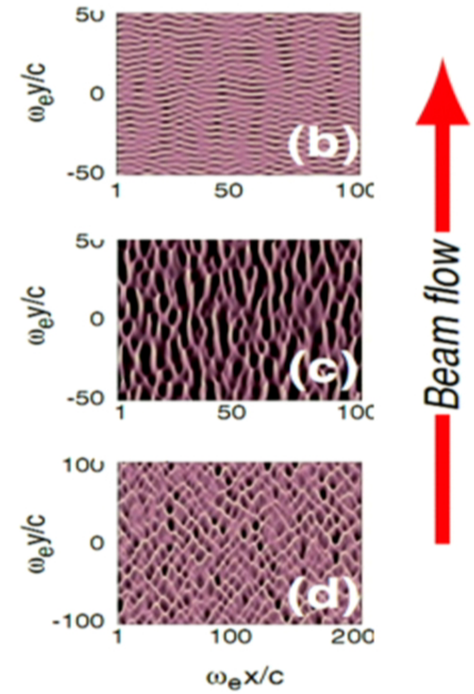
Kong, Phys. Plasmas, 2009

REALISTIC DISTRIBUTION

- **Spectrum and generated patterns**

$$f_\alpha^0(\mathbf{p}) = \frac{\mu_\alpha}{4\pi\gamma_\alpha^2 K_2(\mu_\alpha/\gamma_\alpha)} \exp[-\mu_\alpha(\gamma(\mathbf{p}) - \beta_\alpha p_y)]$$





A. Bret et al., PRL 100, 205008 (2008).

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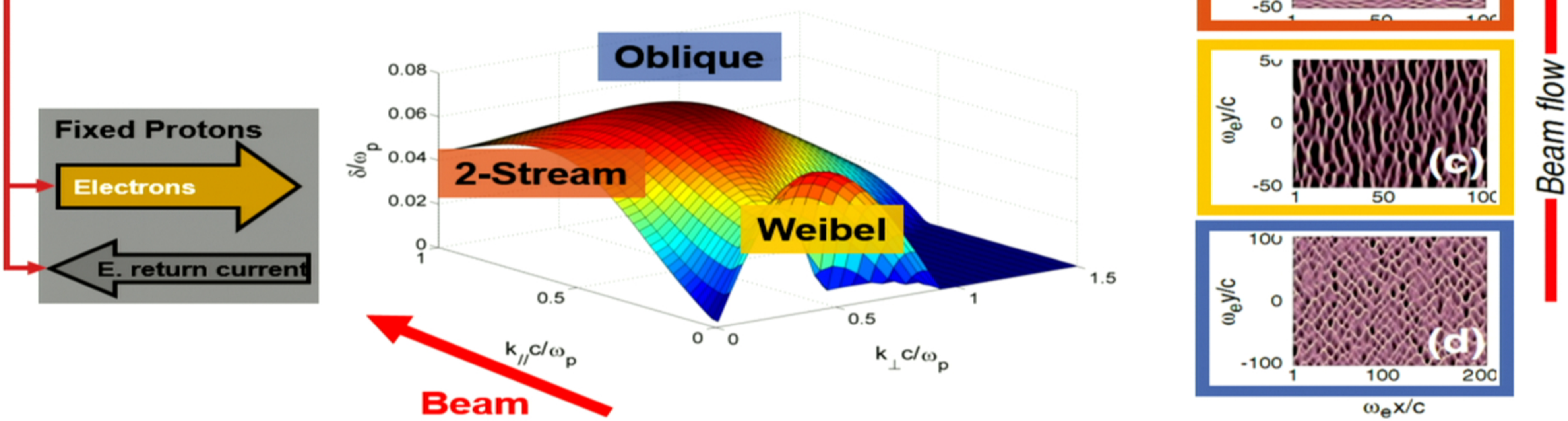
REALISTIC DISTRIBUTION

- Spectrum and generated patterns

$$f_\alpha^0(\mathbf{p}) = \frac{\mu_\alpha}{4\pi\gamma_\alpha^2 K_2(\mu_\alpha/\gamma_\alpha)} \exp[-\mu_\alpha(\gamma(\mathbf{p}) - \beta_\alpha p_y)]$$



A. Bret et al., PRL 100, 205008 (2008).

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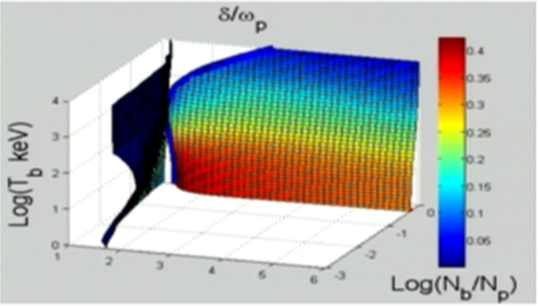
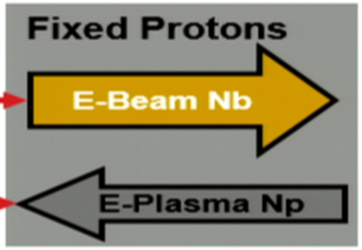
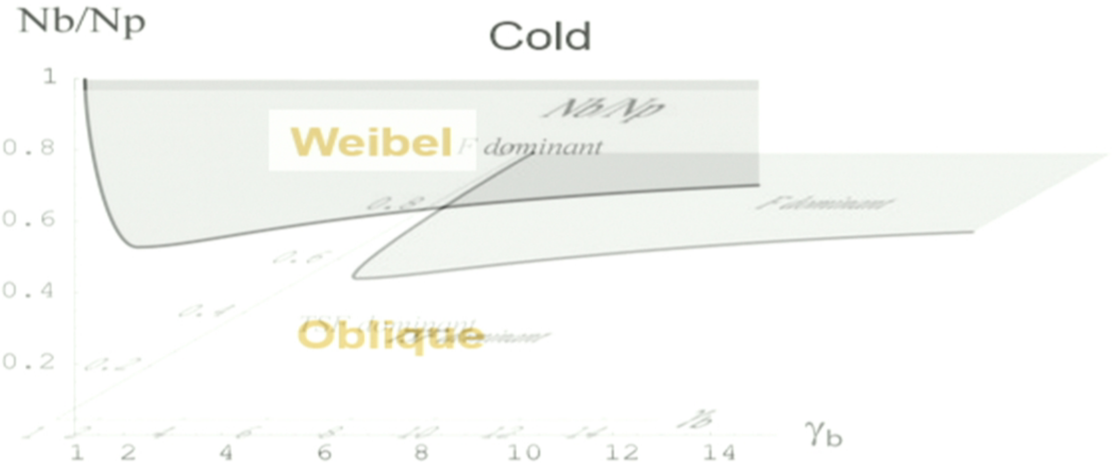
HIERARCHY - HOT



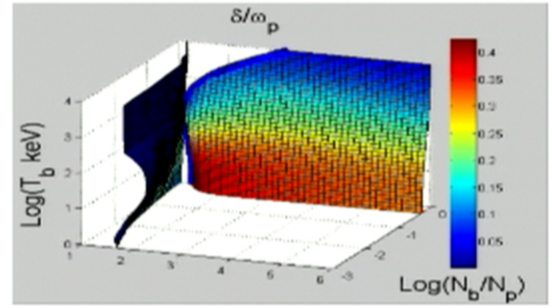
$$f^0_\alpha(\mathbf{p}) = \frac{\mu_\alpha}{4\pi\gamma_\alpha^2 K_2(\mu_\alpha/\gamma_\alpha)} \exp[-\mu_\alpha(\gamma(\mathbf{p}) - \beta_\alpha p_y)]$$





A. Bret et al., PRL 100, 205008 (2008).

HIERARCHY - HOT



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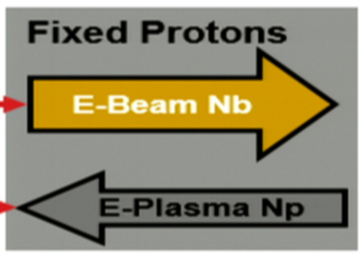
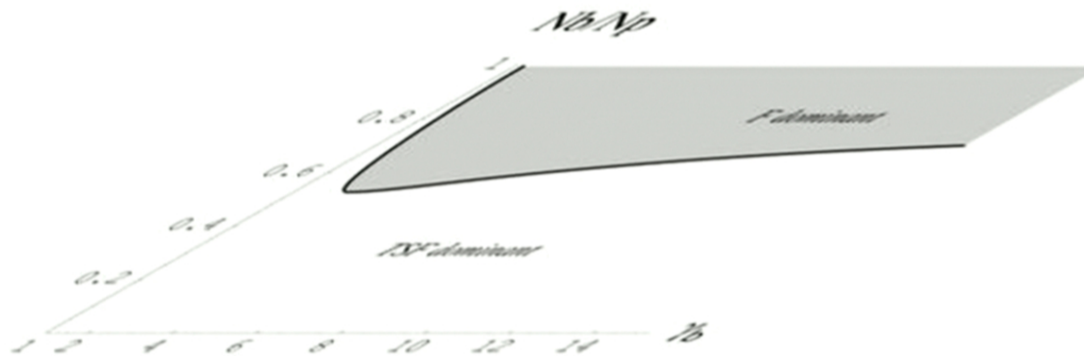
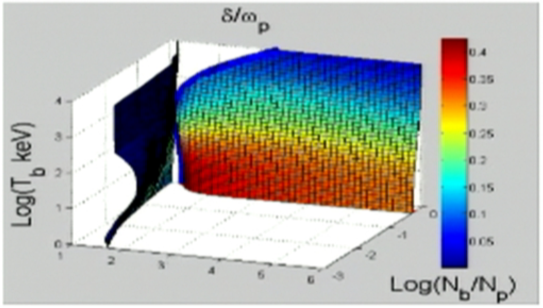




A. Bret et al., PRL 100, 205008 (2008).

HIERARCHY - HOT



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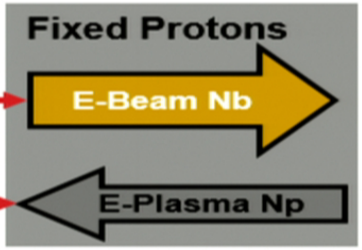
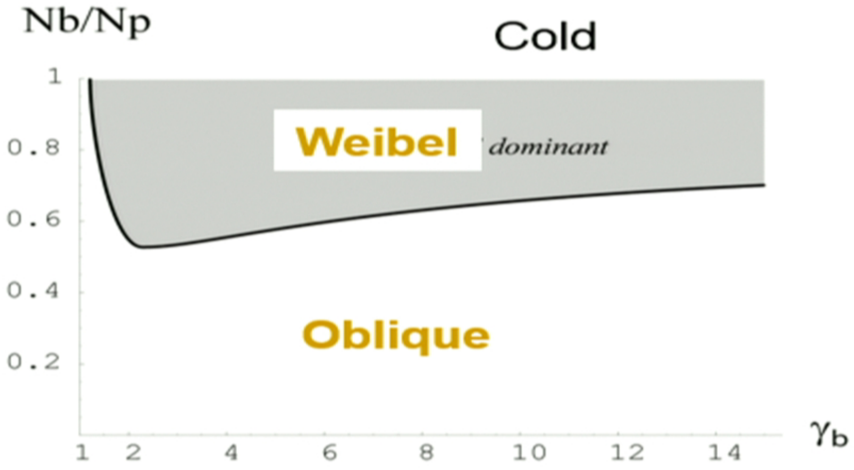
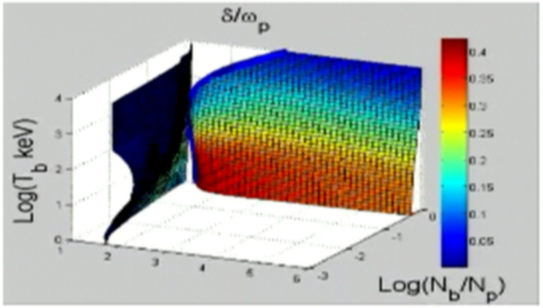




A. Bret et al., PRL 100, 205008 (2008).

HIERARCHY - HOT



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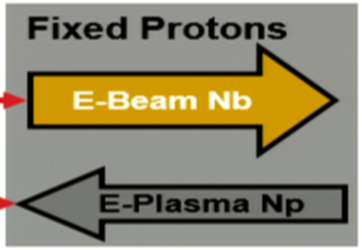
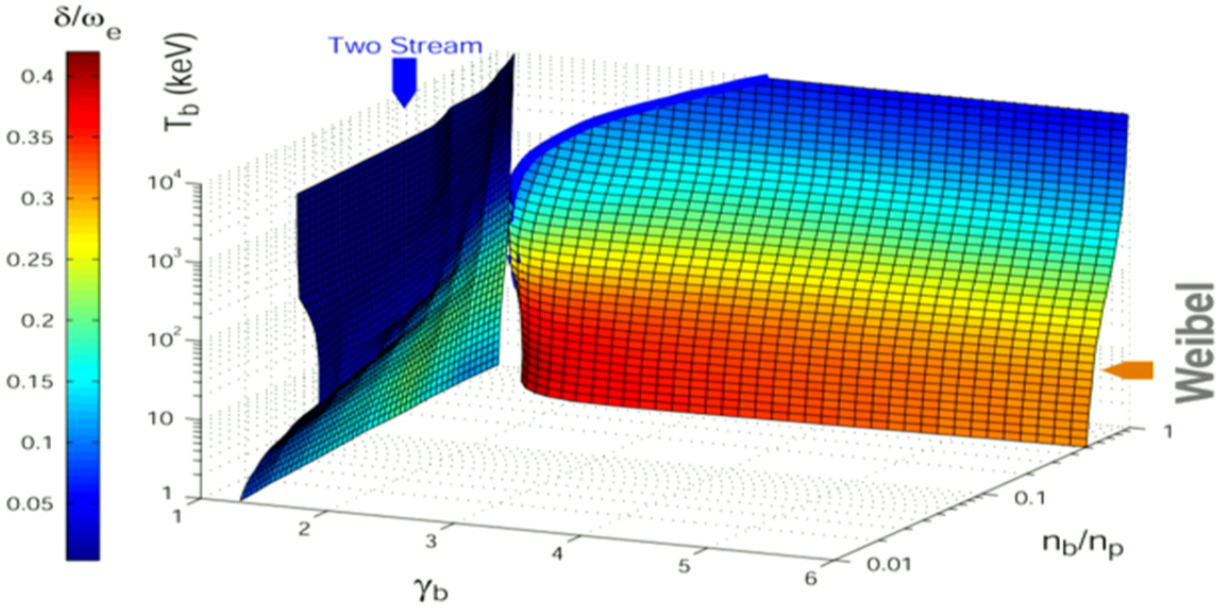
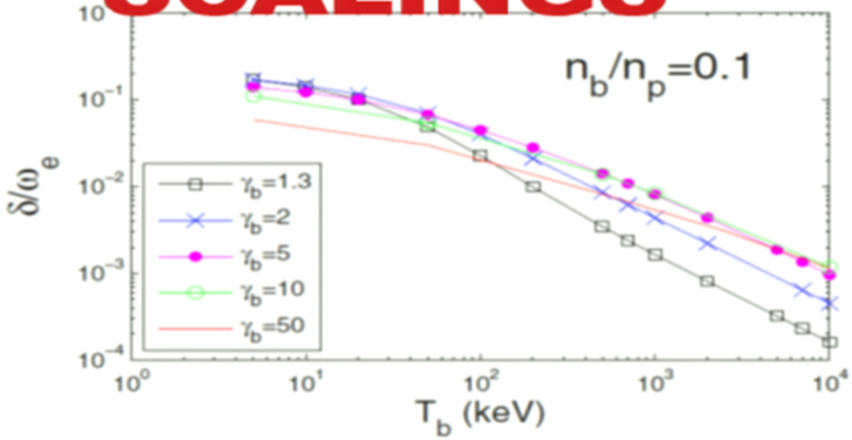


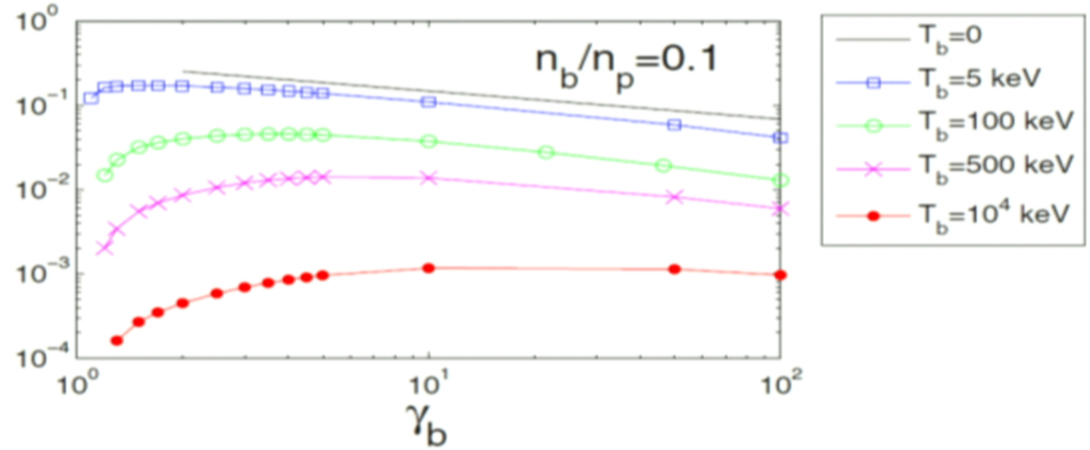


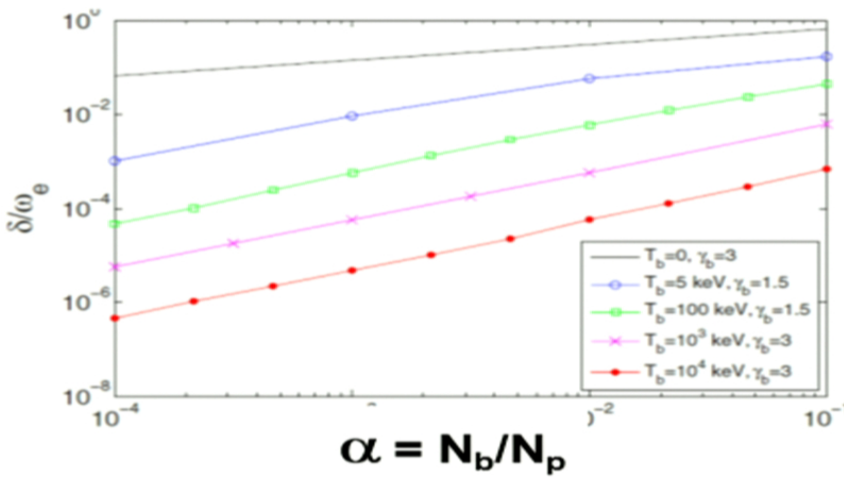
T_plasma: 5 keV
Universal graph

A. Bret et al., PRL 100, 205008 (2008).

OBLIQUE MODES: KINETIC SCALINGS







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OBLIQUE MODES: KINETIC SCALINGS

- **Oblique modes similar to Two-stream ones:**

Parameters	Two-stream	Oblique	
T_b	T_b^{-1}	T_b^{-1}	
γ_b	γ_b^{-1}	$\gamma_b^{-1/3}$	
n_b/n_p, low T_b	$(n_b/n_p)^{1/3}$	$(n_b/n_p)^{1/3}$	→ Fluid
n_b/n_p, large T_b	n_b/n_p	n_b/n_p	→ Kinetic

A. Bret, Gremillet L, Benisti D, Phys. Rev. E, 2010

FERMI CALCULATIONS

- **Filamentation**

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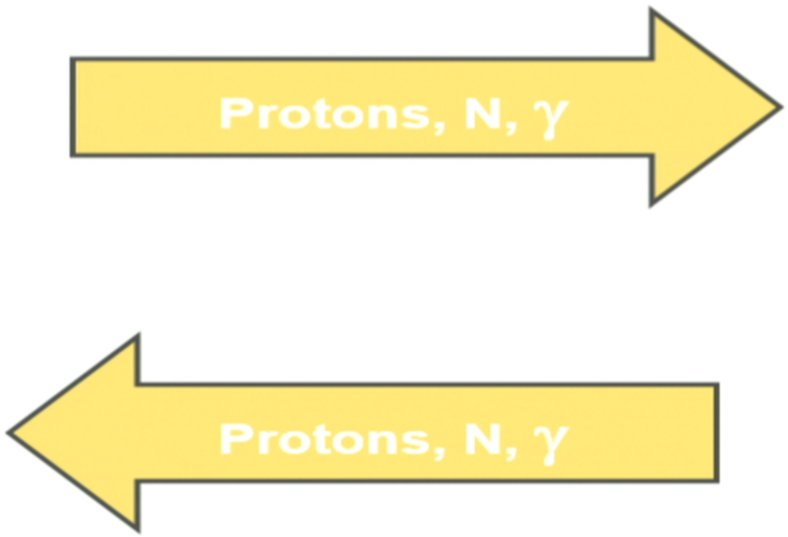
FERMI CALCULATIONS

- **Filamentation**



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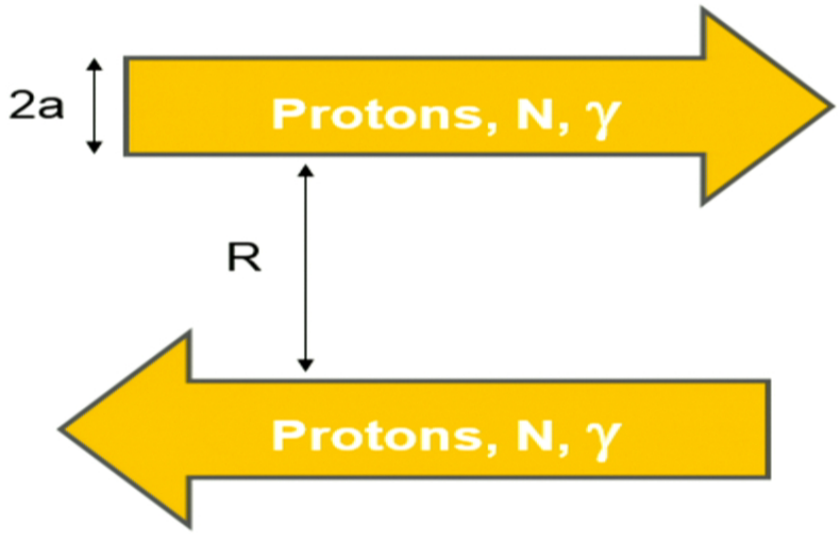
FERMI CALCULATIONS

- **Filamentation**



$$\xi = \frac{R}{a}, \quad \beta = \frac{u}{c}$$

$$\frac{d^2\xi}{dt^2} = \frac{\delta^2}{\xi}, \quad \text{with} \quad \delta = \omega_p \frac{\beta}{\sqrt{2\gamma}}$$

Exact growth rate

Bret, arXiv:1205.6259

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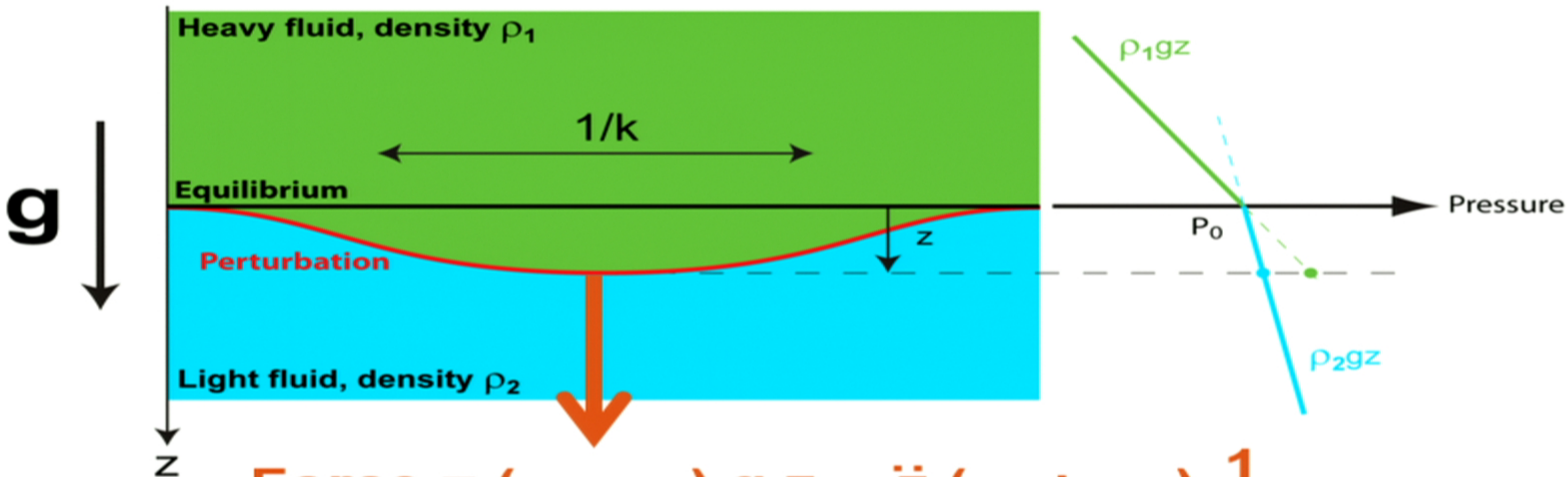
FERMI CALCULATIONS

- **Rayleigh Taylor**

Piriz, *Am. J. Phys.* **74**, 1095, 2006 Bret, *Las. Part. Beams*, **29**, 255, 2011

FERMI CALCULATIONS

- **Rayleigh Taylor**



$$\text{Force} = (\rho_2 - \rho_1)\, g\, z \propto \ddot{z}\, (\rho_2 + \rho_1)\, \frac{1}{k}$$

Piriz, *Am. J. Phys.* **74**, 1095, 2006 Bret, *Las. Part. Beams*, **29**, 255, 2011

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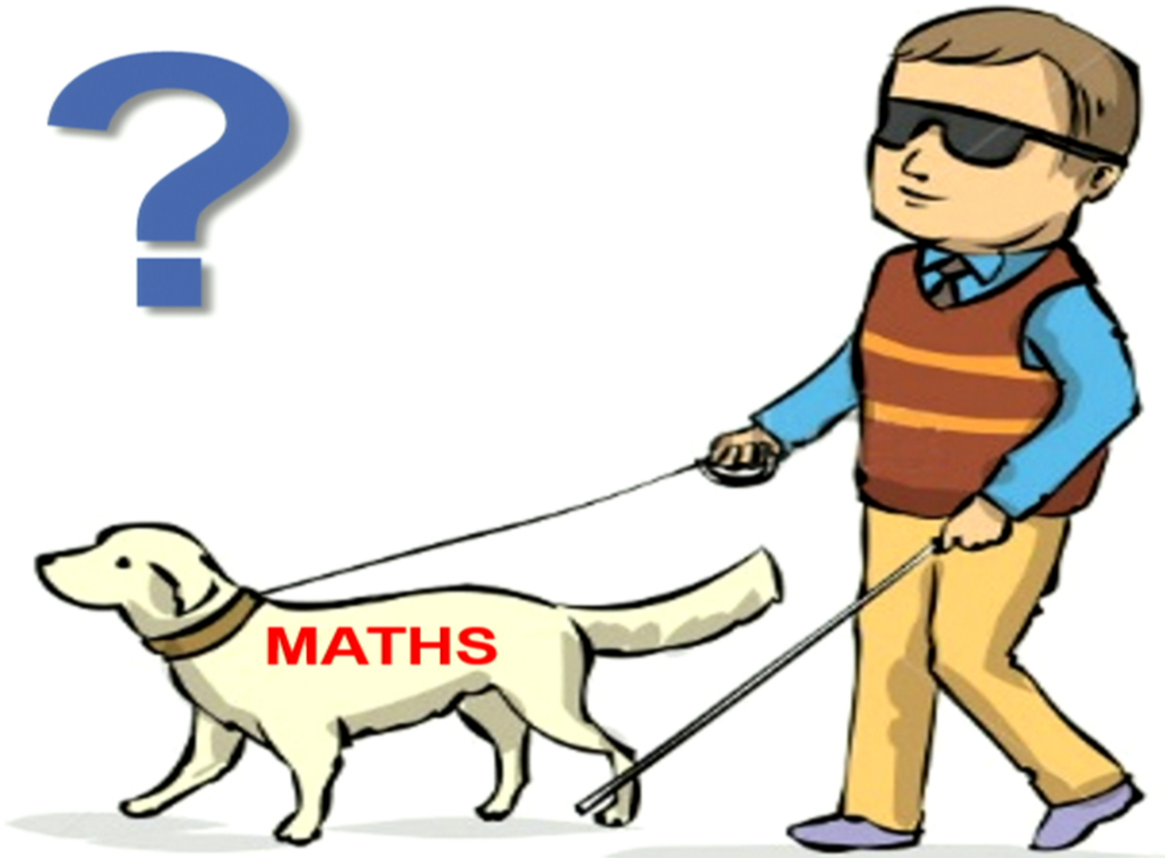
FERMI CALCULATIONS

- Two Stream
- Oblique



CONCLUSION

- A zoo of instabilities, even for a simple system
- Mode competition
- The full linear spectrum has been explored
- Oblique modes govern high γ, Tb & low α limits
- Need for a deeper understanding oblique + TS
- Watch non-linear evolution!

Thank you!