Possible new astrophysics-relevant experiments with high-energy-density plasmas*

D.D. Ryutov

Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

Presented at the Exploratory Workshop on Laboratory Astrophysics, Paris Observatory, September 22-24, 2008

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
Laboratory experiments can be interesting for astrophysics for at least three reasons:

- Provide “tabular” data (e.g., cross-sections, EOS, opacities)
- Allow benchmarking of astrophysical codes under scaled conditions
- Help in the understanding of astrophysical objects in the course of developing scaled laboratory experiments
In this presentation I will briefly discuss five examples:

1) *In situ* measurements of thermal conduction of warm dense matter.

2) Rayleigh-Taylor instability of a photoionization front for non-normal irradiation.

3) Using an array of plasma jets to obtain a differentially-rotating plasma disc.

4) Identifying effect of a large Reynolds number on the global dynamics of the turbulent flow.

5) Experimental comparison of two potent instabilities affecting a variety of collisionless processes in astrophysics: electromagnetic filamentation instability and (mostly) electrostatic beam-plasma instability.


In situ measurements of thermal conduction of warm dense matter
The Rayleigh-Taylor instability (RT instability) is an instability driven by the release of the gravitational energy of the fluid in the course of displacing the fluid element.

Step-wise density profile

Smooth density profile

NB: In the case when wavelength of perturbations is small or comparable to the length-scale of the steady-state density distribution, the instability is sometimes called “Convective Instability.”
DESTABILIZING EFFECT OF THERMAL CONDUCTIVITY

• It is usually thought that dissipative processes (heat conduction, viscous friction) lead to reduction of the growth rate of the RT instability.

• However, this is not universally correct, especially with respect to the heat conduction.

• Specifically, thermal conduction can destabilize the system if the composition of the matter varies with height.
In this analysis, thermal conductivity is assumed to be a dominant dissipative process

- The Prandtl Number (the ratio of kinematic viscosity to thermal diffusivity, \( P = \frac{\nu}{\chi} \)) is typically small in HEDP experiments; small Prandtl numbers are typical for Warm Dense Matter. It is roughly

\[ P \sim \frac{10^{-2}}{\sqrt{A}} \]

- We neglect also mutual diffusion of the components in the material with spatially varying composition (\( P_m \sim P << 1 \))
Unperturbed state: smoothly varying parameters, vertical length-scale $L \equiv |\rho/\rho'|$

$$\frac{dp}{dz} = -\rho g \quad L \sim \frac{s^2}{g}$$

Here $s$ is the sound speed and $C$ characterizes the composition (a molecular fraction of one of the two components).

We use general equation of state, $p = p(\rho, T, C)$, and general equation for the internal energy, $\varepsilon = \varepsilon(\rho, T, C)$ (per unit volume).
For the zero thermal conductivity, the system is unstable if

\[
\frac{\rho'}{\rho} + \frac{g}{s_{ad}^2} > 0,
\]

The growth rate is

\[
\Gamma_{ad}^2 = g \left( \frac{\rho'}{\rho} + \frac{g}{s_{ad}^2} \right) \sim \frac{g}{L}.
\]
Thermal conductivity is insignificant for the global scale $L$

\[
\frac{L^2}{\chi} \gg \sqrt{\frac{L}{g}}
\]

Heat diffusion time over the global scale

RT growth time

\[
\varepsilon \equiv \frac{\chi}{g^{1/2}L^{3/2}}
\]

<table>
<thead>
<tr>
<th></th>
<th>$g$, cm/s$^2$</th>
<th>$L$, cm</th>
<th>$\chi$, cm$^2$/s</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN</td>
<td>$4 \cdot 10^3$</td>
<td>$10^{11}$</td>
<td>$7 \cdot 10^{12}$</td>
<td>$4 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>Exp. on warm dense matter</td>
<td>$10^{13}$</td>
<td>$2 \cdot 10^{-3}$</td>
<td>0.4</td>
<td>$2 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

Thermal conductivity is fast for

\[
\hat{\lambda} < \hat{\lambda}^* \equiv \frac{\chi^{1/2}L^{1/4}}{g^{1/4}} \equiv \varepsilon^{1/2}L
\]
For short wavelengths, $\lambda < \lambda^*$, the stability criterion changes completely.

For such perturbations, thermal conductivity is important ($T_i= T_e$, $i = \text{internal}$, $e = \text{external}$)

\[ p_{i2} = p_{e2}, \quad T_{i2} = T_{e2}, \quad C_{i2} = C_{i1} = C_{e1} \]

\[ \delta \rho_i - \delta \rho_e = \frac{p_C}{\rho s_{iso}^2} C'' \xi \]

Unstable if $\delta \rho_i - \delta \rho_e < 0$, i.e., if $p_C \mid_{\rho, T} C' < 0$,

(not if $\rho_0' / \rho_0 + g / s_{ad}^2 > 0$)

\[ \Gamma_{iso}^2 = -gC' \frac{p_C}{\rho s_{iso}^2} \]

The growth rate:
For short wavelengths, $\lambda<\lambda^*$, the stability criterion changes completely. For such perturbations, thermal conductivity is important ($T_i=T_e$, $i=\text{internal}$, $e=\text{external}$)

An ideal gas:

$p=\rho T/\mu$;

The system is unstable if $\mu'>0$

The growth rate:

Unstable if $\delta\rho_i - \delta\rho_e < 0$, i.e., if $p_C \big|_{\rho,T} C' < 0$,

(not if $p_0'/p_0 + g/s_{ad}^2 > 0$)

$$\Gamma_{iso}^2 = -g C' \frac{p_C \big|_{\rho,T}}{\rho s_{iso}^2}$$
Instability in the adiabatically stable domain \( (\frac{\rho'}{\rho} + g/s_{ad}^2 < 0) \) can exist even for small thermal conductivity (large wavelengths)

Overstability (instability of oscillatory growth) exists at steep-enough variation of the composition and temperature

\[
-\frac{g}{s_{ad}^2} (\gamma - 1) + \frac{\mu'}{\mu} < \frac{T'}{T} < -\frac{g}{s_{ad}^2} (\gamma - 1)
\]

(for the ideal gas)
Thermal conductivity makes plasma more unstable

In the absence of thermal conductivity, the instability is present only in the orange region. When thermal conductivity is finite, the yellow and pink regions become unstable, too. The white region is universally stable.

Two important ingredients:
- finite thermal conductivity
- variation of the composition
The growth rate is significant even for long-wavelength perturbations

Yellow domain on the stability diagram

Pink domain on the stability diagram; solid lines: growth rate; dashed lines: frequency
**Measuring thermal conductivity**

1. Make a planar slab with a desired composition distribution, L~50 µm

2. In the course of manufacturing, impose a perturbation and a tracer at the desired depth

3. Adjust a drive so as to create a desired temperature distribution by the initial shock; this stage should be followed by the stage of an approximately constant acceleration

The experiment does not seem to require anything that goes beyond the present state of art

\[ L \approx 2 \cdot 10^{-3} \text{ cm}, \ g \approx 10^{13} \text{ cm/s}^2, \ \lambda \approx 2 \cdot 2\pi \lambda^* \approx 15 \mu \text{m} \text{ (for } \chi \approx 0.4 \text{ cm}^2/\text{s}), \ t = 50 \text{ ns} \]

The expected growth rate is \( \Gamma \approx 5 \cdot 10^7 \text{ s}^{-1}, \ \Gamma t \approx 2.5 \)

To obtain a 30% accuracy in the estimate of the thermal diffusivity, one has to provide 10 to 20 % of accuracy (depending on the mode) in the measurements of the growth rate.

Control experiments include: 1) evolution of the stable configuration; 2) dependence of the growth-rate on the wavelength; 3) observing the overstable mode
Summary

The destabilizing effect of thermal conductivity

- May cause an instability in the situations where it is not expected

- May be used as a way for *in situ* measurements of thermal conductivity and thermodynamic parameters of the non-ideal matter
Rayleigh-Taylor instability of a photoionization front for non-normal irradiation
TILTED RADIATION (TR) INSTABILITY

Instability of the ablation front is strongly modified in the case of a non-normal incidence of the radiation.

The origin of the effect is a reaction of the ablation pressure to the perturbation of the surface (for a normal incidence, this is a second-order effect and does not affect the linear stability).

\[ \delta I = I_0 \tan \alpha \frac{\partial \xi}{\partial x} \]

There is no linear perturbation of ablation pressure at \( \alpha = 0 \)

Interesting new features of the instability

1. The growth rate becomes anisotropic, with the maximum and the minimum values corresponding to the mutually perpendicular directions of the wave vector; the orientation of these “principal axes” is determined by the angular distribution of the incident radiation.

2. For the optimum orientation, the growth rate is greater than $(gk)^{1/2}$.

3. Unlike the case of a canonical R-T instability, unstable perturbations have finite phase velocity along the surface.

4. Because of a higher growth rate, the instability is less sensitive to the ablative stabilization.
The “Tilted Radiation” instability can be conveniently studied in a standard indirect drive setting, provided there is a significant asymmetry in the radiation flux.

A possible experiment: deliberately non-uniform irradiation of the hohlraum.

An alternative: use a hole in a hohlraum wall and place the sample outside, with the surface tilted to the beam axis.

At the nonlinear stage of the TR instability, formation of detached “blobs” moving along the surface is possible (Ryutov et al, Plasma Phys. Contr. Fus., 45, 769, 2003).
Compare the Eagle Nebula, and a potential experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Eagle Nebula</th>
<th>Potential lab. experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$, cm</td>
<td>$10^{18}$</td>
<td>$6 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\ell_{abs}$, cm</td>
<td>$2 \cdot 10^{13}$</td>
<td>$4 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$p_{abl}$, dyn/cm$^2$</td>
<td>$5 \cdot 10^{-9}$</td>
<td>$10^{13}$</td>
</tr>
<tr>
<td>$\rho$, g/cm$^3$</td>
<td>$1.5 \cdot 10^{-19}$</td>
<td>$1.3$</td>
</tr>
<tr>
<td>$\rho_{abl}$, g/cm$^3$</td>
<td>$3 \cdot 10^{-21}$</td>
<td>$0.07$</td>
</tr>
<tr>
<td>$\tau$, s</td>
<td>$6 \cdot 10^{12}$</td>
<td>$2.4 \cdot 10^{-9}$</td>
</tr>
</tbody>
</table>

*J. Hester et al., AJ, 111, 2349 (1996)*
*B. Remington et al., PhysFluids, B5, 2590 (1993)*
Using of an array of plasma jets to obtain a differentially-rotating plasma disc
Galactic and extragalactic jets are among the most spectacular astrophysical phenomena

J. Wiseman, J. Biretta. “What can we learn about extragalactic jets from galactic jets?” New Astronomy Reviews, 46, 411, 2002
There have been numerous HEDP-based studies of astrophysical jets carried out during the last decade:


Scalability issues have been considered in:


“Magnetic tower jets” were studied with the MAGPIE Z-pinch facility (London, UK)

An array of plasma jets of the type described by Witherspoon et al* would allow one to imitate the formation of a differentially rotating disc of the size ~10 cm

---

**Expected plasma parameters for an array of 12 jets forming a 20 cm diameter disc**

Plasma parameters in the disc:

\[ n = 3 \times 10^{15} \text{ cm}^{-3}; \ T = 10 \text{ eV}; \text{ disc radius } r = 10 \text{ cm}; \text{ rotation velocity at the periphery } v_{\text{rot}} = 5 \times 10^6 \text{ cm/s} \]

Plasma parameters in the outflow:

\[ n_{\text{jet}} = 3 \times 10^{15} \text{ cm}^{-3}; \ T_{\text{jet}} = 10 \text{ eV}; \text{ minimum radius } r_{\text{jet}} = 5 \text{ cm}; \text{ vertical velocity } v_{\text{jet}} = 5 \times 10^6 \text{ cm/s} \]

Derived parameters:

Plasma kinematic viscosity \( \nu \sim 2 \times 10^5 \text{ cm}^2/\text{s} \); Reynolds number \( Re \equiv r v_{\text{rot}}/\nu \sim 250 \)

In astrophysical case, the plasma is collisional due to very large length-scale (~ parsec for Young Stellar Outflows). Plasma parameters in the typical Herbig-Haro object: \( r_{\text{jet}} = 3 \times 10^{17} \text{ cm} \); \( v_{\text{jet}} = 2 \times 10^7 \text{ cm/s} \); \( T_{\text{jet}} \sim 20 \text{ eV} \); \( n_{\text{jet}} = 10-100 \text{ cm}^{-3} \); \( Re \equiv r_{\text{jet}} v_{\text{jet}}/\nu \sim 10^3 – 3 \times 10^4 \)
Impose a weak cusp magnetic field to see a conversion of the poloidal field into toroidal field by the differential rotation.

Magnetic diffusivity for the aforementioned plasma parameters:

\[ D_{\text{magn}} \sim 10^5 \text{ cm}^2/\text{s} \]

Magnetic Reynolds number:

\[ Re_m = v_{\text{rot}}/D_{\text{magn}} \sim 500 \]
How could the experimental information be used?

1. Benchmark 3D astrophysical codes in the relevant range of dimensionless parameters

2. Vary the parameters and geometry at will; collect large statistics (in particular, vary the ratio of the ambient plasma density to that in the jet; use gas-puffs? add higher-Z impurities to enhance radiative losses?)

3. Generate internal slow shocks in the outflow

4. Obtain morphologically relevant pictures; show the ability to modify them by controlling the parameters and orientation of jets
Identifying effect of a large Reynolds number on the global dynamics of the turbulent flow
**Background**

In experiments simulating astrophysical systems the Reynolds number $Re$ is large, in the range $\sim 10^6$ and higher; it is typically even higher in the simulated astrophysical systems.

Therefore, the global scale motion in both cases can be described by the ideal hydrodynamics which *does not* contain the Reynolds number as a parameter.

The Euler scaling covers magnetohydrodynamics of inviscid polytropic gases (with *shocks* and spatial variations of the polytrope index *allowed*).

---

The ideal hydrodynamics applies for an early stage of shear-flow turbulence (a few eddy turn-over times $L/v$).

It takes time $\tau_{\text{cascade}} \sim (L/v)\ln Re$ to generate vortices by cascading down to the dissipation scale, $\lambda_{\text{diss}} \sim L/Re^{3/4}$.

This time-scale may be sufficient to answer the most important questions (e.g., will the large-scale spikes poke through the surface of a SN?)
What if, however, the dissipative-scale motions do appear within the time-scale of interest?

Then the large-scale motion may be affected by the presence of dissipative vortices and, therefore, by the Reynolds number.

It is practically impossible to create conditions where the Reynolds number in the laboratory experiment would be the same as in its astrophysical counterpart.

A question then arises: Will two systems with very large but different Reynolds number (say, $10^6$ and $10^7$) behave differently on the global scale? {Important not only for astrophysics but for any hydrodynamic system.}
Three difficulties in the experimental assessment of this question:

1. The EOS in the regimes typical for HED hydrodynamic experiments can be uncertain.

2. Information about transport coefficients in HED, non-ideal, dense plasmas is very crude, if available at all.

3. Small-scale vortices cannot be resolved.
Equations of ideal hydrodynamic (magnetohydrodynamic) of a fluid with varying composition

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0
\]

\[
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p - \frac{1}{4\pi} \mathbf{B} \times \nabla \times \mathbf{B}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{v} \times \mathbf{B}
\]

\[
\frac{\partial \epsilon}{\partial t} + \mathbf{v} \cdot \nabla \epsilon = -\left( \epsilon + p \right) \nabla \cdot \mathbf{v}
\]

\[\epsilon = \epsilon(p, \rho, C)\]

\[
\frac{\partial C}{\partial t} + \mathbf{v} \cdot \nabla C = 0
\]

\(\epsilon = \epsilon(p, \rho, C)\) is the internal energy per unit volume (no assumptions regarding equation of state!)

\(C\) characterizes a fluid with a varying composition (for a more than two-component system, one can introduce several such parameters)

The rest of notation is standard
The “perfect similarity” transformation

\[ r' = Ar, \quad t' = At \]

\[ v' = v, \quad B' = B, \quad \rho' = \rho, \quad p' = p, \quad C' = C \]

This transformation holds

- For an arbitrary equation of state;
- For an arbitrary varying composition;
- In the presence of shocks
This similarity holds if dissipation is negligible

Dissipative processes can be characterized by familiar dimensionless parameters:

\[ \text{Re} = \frac{Lv}{\nu} \text{ (Reynolds number)}, \]
\[ \text{Pe} = \frac{Lv}{\chi} \text{ (Peclet number)}, \]
\[ \text{Pe}_m = \frac{Lv}{D} \text{ (Peclet mass number, characterizes the inter-species diffusion)}, \]
\[ \text{Re}_M = \frac{Lv}{D_M} \text{ (Magnetic Reynolds number)}, \]

where \( L \) is the global spatial scale, and \( v \) is the characteristic velocity.

Dissipative processes (except for the dissipation in shocks) are small for the global-scale motion if all these parameters are very large.
In two systems related by the “perfect similarity” transformation both the equations of state and transport coefficients are identical in the corresponding points.

Accordingly, any differences in the evolution of the two systems will be related only to the difference in the Reynolds number.

This opens up a possibility of experimental isolating this subtle effect even in the situation where the EOS and transport coefficients are poorly known, and the small-scale (dissipative) vortices are not resolved.

1 From here on we concentrate on the systems where the viscous effects are dominant among the dissipative processes.
Energy scaling for the “perfect similarity” transformation

As spatial scales are increased by a factor $A$, with fluid parameters remaining unchanged, the energy required for driving a scaled experiment is\(^1\)

$$W' = A^3 W$$

The power required to drive the scaled experiment is

$$P' = A^2 P$$

The power density (the flux) remains unchanged:

$$q' = q$$

A possible experiment for isolating the effect of the Reynolds number: driving a strongly nonlinear stage of the RT instability

The same bubble in a “perfectly similar” large-scale experiment (say, Re= 10^6). The outcome 1) corresponds to an independence of the global-scale motion on the Reynolds number; the outcome 2) corresponds to the presence of non-negligible Reynolds number effects.
Other candidate experimental configurations include pulsed jets\(^1\), flows past the body\(^2\), and turbulent mix experiments\(^3\).


\(^3\)Drake RP. Design of flyer-plate-driven compressible turbulent mix experiments using Z. Phys. Plasmas. 9, 3545, 2002
CONCLUSION

• The “perfect similarity” approach allows evaluating effect of the Reynolds number on the global scale motion in HED experiments

• This can be done despite substantial uncertainties with EOS and transport coefficients, and our inability to resolve small-scale vortices, provided the geometrical scales of large-scale features are measured with a sufficient accuracy

• The experiment discussed would serve as a direct discovery tool, not just a tool for code benchmarking: we do not know at present (and will hardly know in a few years to come) what dependence on the Reynolds number comes out of such an experiment (but this only adds fun and suspense to the whole undertaking!)
Comparison of the electromagnetic filamentation instability and (mostly) electrostatic beam-plasma instability
Formulation of the problem

1. Ultrarelativistic, $\gamma \gg 1$, electrons are injected into a uniform plasma

2. Beam density is much less than the plasma density, $n_b << n$

3. Plasma is dense enough to neutralize the beam charge and current, so that the regular electric and magnetic fields are negligible

4. Linear theory

When analyzing the stability of this system, we initially neglect the nonuniformity of the unperturbed state, and account for this nonuniformity later in the study
Beam without angular spread

The dispersion relation that describes both beam instability and filamentation instability reads as

\[
\left( \frac{\omega^2 - \omega_{pe}^2}{c^2} - k^2 \right) \frac{\omega^2 - \omega_{pe}^2}{c^2} = -\frac{\gamma n_b}{n} \frac{\omega_{pe}^2}{c^2} \frac{k^2_{\perp} \omega_{pe}^2}{(\omega - k_{\parallel} v)^2}
\]

where \( v \approx c \) is the beam velocity. One can identify the filamentation (Weibel type) instability by setting \( k_{\parallel} \) small, \( k_{\parallel} \ll \omega_{pe}/c \). One then finds the following growth-rate:

\[
\text{Im} \omega \approx \omega_{pe} \sqrt{\frac{k_{\perp}^2 c^2}{\omega_{pe}^2 + k_{\perp}^2 c^2} \frac{n_b}{\gamma n}}
\]

This mode is characterized by a significant magnetic field perturbation. Identification and interpretation of this mode can be traced back to the papers by Weibel and Fried (E.S. Weibel. Phys. Rev. Lett., 2, 83, 1959; B.D. Fried. Phys. Fluids, 2, 337, 1959).
Beam without angular spread (continued)

If one takes $k_{||}$ approaching $\omega_{pe}/c$, one finds a beam instability, where the electric field is almost vortex-free:

$$\text{Im} \omega \approx \frac{k_{\perp} c}{\sqrt{(1 + k_{\perp}^2 c^2 / \omega_{pe}^2)(1 - k_{||}^2 c^2 / \omega_{pe}^2)}} \sqrt{n_b} \left(1 + k_{\perp}^2 c^2 / \omega_{pe}^2 \right) \left(1 - k_{||}^2 c^2 / \omega_{pe}^2 \right) \sqrt{\gamma n}$$

This expression is valid if $k_{||}$ is not too close to $\omega_{pe}/c$. When it becomes close to $\omega_{pe}/c$, the growth rate reaches its maximum value,

$$\text{Im} \omega \approx \left( \frac{3}{2} \right)^{1/2} \left( \frac{k_{\perp}^2 c^2}{\omega_{pe}^2 + k_{\perp}^2 c^2} \right)^{1/3} n_b$$

Generally speaking, both instabilities are present, but the beam instability has larger growth rate.
Effect of the angular spread

Effect of the energy spread can be easily accounted for if the electrons remain relativistic; this can be done by introducing an average $\gamma$. Accounting for the angular spread is somewhat more complex (see, e.g., A.A. Vedenov, D.D. Ryutov, in: Reviews of Plasma Physics, M.A. Leontovich, Ed., v. 6, p.p. 1 – 76, Consultants Bureau, NY-London, 1975).

For the beam with a relatively large angular spread, the growth rate is:

$$\text{Im}\omega(k, \theta') = \frac{n_b \omega_p^2}{2 k^2 c^2} \int_{\theta_1}^{\theta_2} \frac{\left(\cos \theta - \frac{k c}{\omega_p} \cos \theta'\right) \frac{dg}{d\theta} - 2g \sin \theta}{\sqrt{(\cos \theta_2 - \cos \theta)(\cos \theta - \cos \theta_1)}} d\theta; \quad g = \int_0^\infty fp dp;$$

$$1 = 2\pi \int_0^\infty \int_0^\pi f p^2 \sin \theta d\theta dp$$

By the order of magnitude,

$$\text{Im}\omega \sim \omega_p \frac{n_b}{\gamma n \Delta \theta^2}$$

The beam remains unstable even for the angular spread $\sim 1$, albeit at a smaller growth rate.
Effect of the angular spread (continued)

The electromagnetic mode is more sensitive to the angular spread and ceases to exist if

\[ \Delta \theta > \sqrt{\frac{\omega_{pe}^2 n_b}{\omega_{pe}^2 + k_{\perp}^2 c^2 \gamma n}} \]

As the beam energy deposition into the plasma is accompanied by the scattering, one can expect that the electromagnetic instability will not lead to a significant energy loss of the beam.

Conversely, the quasi-electrostatic beam instability can lead to a significant beam energy loss. This has been confirmed in very detailed experiments by several groups.*

**Effect of the plasma inhomogeneity and finite size of the beam.**

Electromagnetic perturbations with small $k_{\parallel}$ manifest an absolute instability; the finite size of the beam $a$, as well as the plasma inhomogeneity, do not have any significant effect on them.

Quasi-electrostatic perturbations are more sensitive to the instability due to their resonant character.* The constraints on the parallel ($L$) and perpendicular ($a$) length scales

$$a > \frac{c}{\omega_{pe}} \frac{\gamma n}{\Delta \phi^2 n_b}$$

$$L > \frac{c}{\omega_{pe}} \frac{\gamma n}{n_b}$$

If scales are smaller than the ones determined by these equations, the instability is quenched.

**Effect of electron-ion collisions (collision frequency \( \nu \))**

Electron-ion collisions have a very weak effect on the electromagnetic instability.

They have a significant effect on the beam instability of the beam with large angular spread.* The beam instability is quenched if

\[ \nu > \omega_p \frac{n_b}{\gamma n \Delta \vartheta^2} \]

If this condition holds, the beam can release only part of its energy:

\[ \frac{\Delta E}{E} < \frac{n_b \omega_{pe}}{\gamma n \nu} \]

The domain for the beam instability can be conveniently described in terms of dimensionless parameters $n_b/\gamma n$, $c/L\omega_{pe}$, and $\nu/\omega_{pe}$.

\[ \frac{c}{\nu L} < 1 \quad \text{unstable} \]

\[ \Delta \theta^2 = \left( \frac{\omega_{pe}}{\nu} \right) \left( \frac{n_b}{\gamma n} \right) \]

\[ \frac{c}{\nu L} > 1 \quad \text{unstable} \]

\[ \Delta \theta^2 = \left( \frac{\omega_{pe}}{\nu} \right) \left( \frac{n_b}{\gamma n} \right) \]
Similar plot can be made for the electromagnetic instability

\[
\Delta \theta^2 = \frac{n_b}{\gamma n}
\]

The effect of collisions and plasma non-uniformity is relatively insignificant, but the instability exists only for small angular spread.
Possible experimental setting for assessing the role of collisionality and nonuniformity

Here the proton experiment is shown; in the electron experiment the plasma volume should be in contact with the foil.
Summary

• For a strongly relativistic electron beam of a small density, its interaction with the background plasma is dominated by electrostatic modes, except for the initial stage of a small angular spread (contrary to a wide-spread view).

• The electromagnetic (Weibel-type) instability is stabilized at a relatively small angular spread and does not give rise to a significant beam energy release. On the other hand, it is much more robust with respect to possible quenching by plasma non-uniformity and electron-ion collision in the bulk plasma.

• Relative importance of the two instabilities can be assessed on the basis of a few dimensionless parameters.

• Analysis of quasi-electrostatic beam instability in astrophysical settings is needed to get a complete picture of such phenomena as gamma-ray bursts.

• Future work will include a quantitative assessment of the effect of angular spread on both instabilities.

• A dedicated experiment could be performed by injecting the beam into a gas bag, as in M.S. Wei et al, Phys. Rev. E, 70, 056412 (2004)
Laboratory experiments can be interesting for astrophysics for at least three reasons:

- Provide “tabular” data (e.g., cross-sections, EOS, opacities)
- Allow benchmarking of astrophysical codes under scaled conditions
- Help in the understanding of real objects in the course of developing scaled laboratory experiments