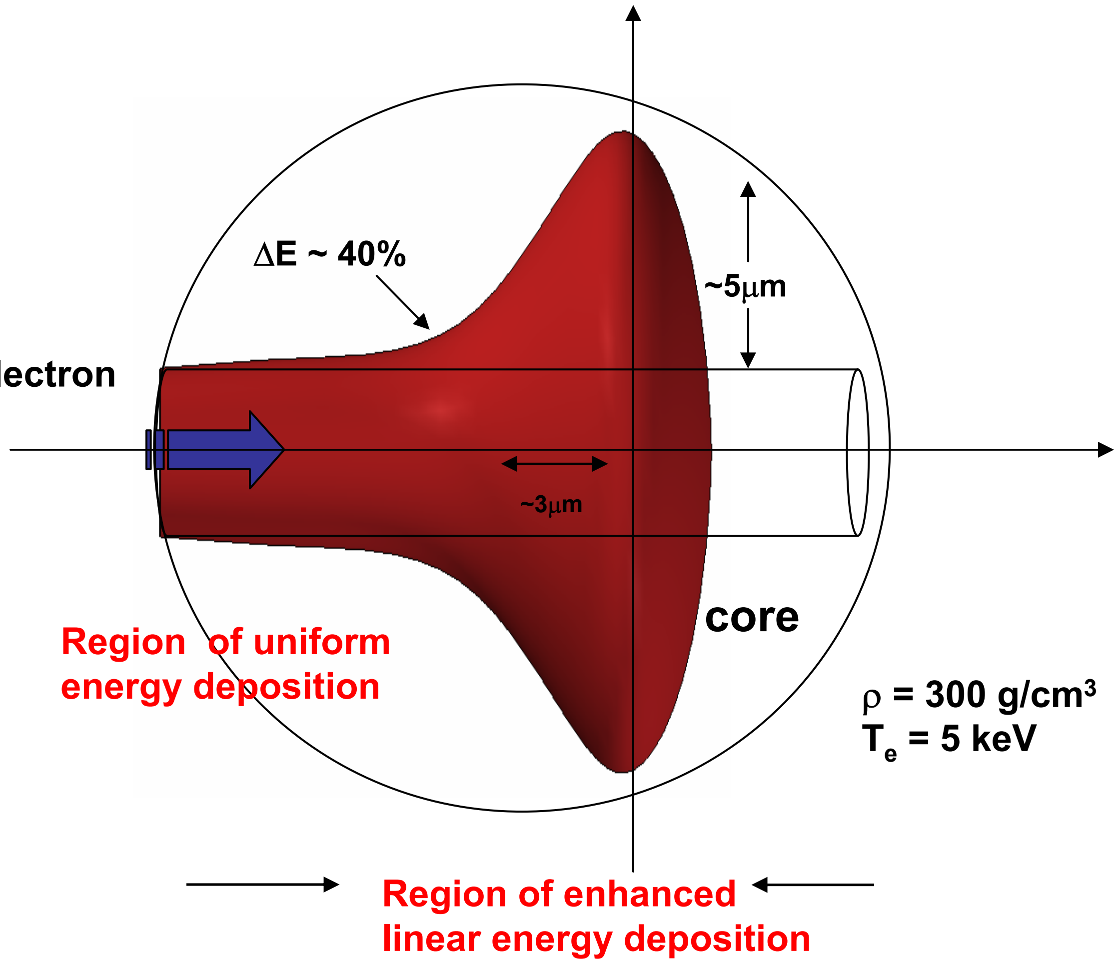
Stopping, Straggling and Blooming of Directed Energetic Electrons in Hydrogenic Plasmas



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Multiple scattering significantly impacts electron energy loss, straggling, and blooming in plasmas

- **Scattering and energy loss are *inextricably* coupled**
- **The mutual interaction among energy loss, straggling and blooming leads to a region of enhanced linear energy deposition**
- **Both straggling and blooming are proportional to the square root of the penetration when ΔE > 40% for 1 MeV electrons**
- **Multiple scattering eventually dominates over all other sources of beam divergence**

Multiple scattering is relevant to physics of current interest

- Fundamental physics
- Fast ignition
  - Electron penetration and straggling
  - Energy deposition profile
  - Beam blooming
- Pre-heat
- Astrophysics
  (*e.g.* relativistic astrophysical jets)

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The angular and spatial distributions are calculated from the integro-differential diffusion equation

$$\frac{\partial f}{\partial s} + \mathbf{v} \cdot \nabla f = N \int \left[f(\mathbf{x}, \mathbf{v}', s) - f(\mathbf{x}, \mathbf{v}, s) \right] \sigma\left(\left| \mathbf{v} - \mathbf{v}' \right| \right) d\mathbf{v}'$$

- **Angular distribution → mean deflection angle, <cosθ>**

$$f(\theta, s) = \frac{1}{4\pi} \sum_{\ell=0}^{\infty} (2\ell + 1) P_\ell(\cos\theta) \exp\left(-\int_0^s \kappa_\ell\left(s'\right) ds' \right)$$

- **Longitudinal distribution → penetration and straggling**

- **Lateral distribution → beam blooming**

The penetration is reduced by ~ 30% compared to the range, and energy transfer is enhanced towards the end of the penetration

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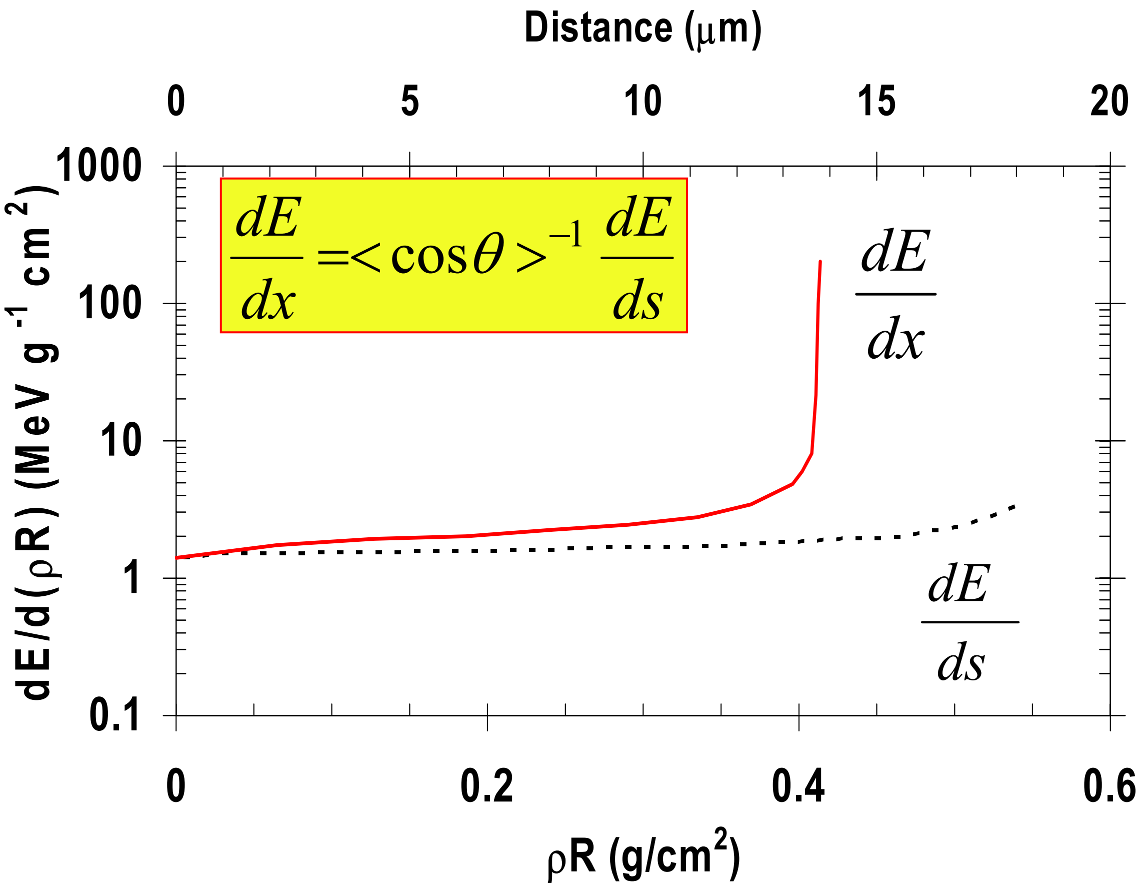


1 MeV electrons; ρ = 300 g/cm^3; T_e = 5 keV

With a mean penetration of ~13.8 μm, multiple scattering results in longitudinal straggling of ± ~3 μm and lateral blooming of ± ~5 μm

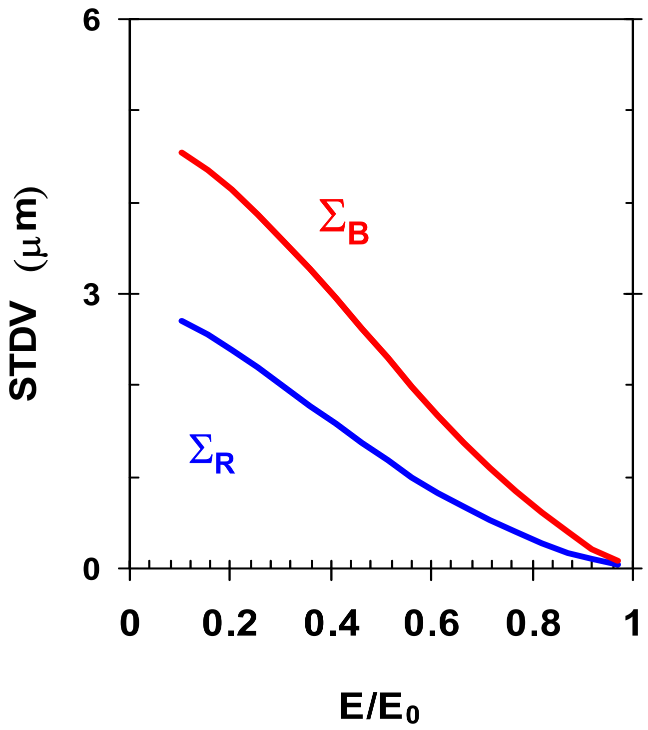
Longitudinal straggling

$$\Sigma_R(E) = \sqrt{\langle x^2 \rangle - \langle x \rangle^2}$$

Lateral blooming

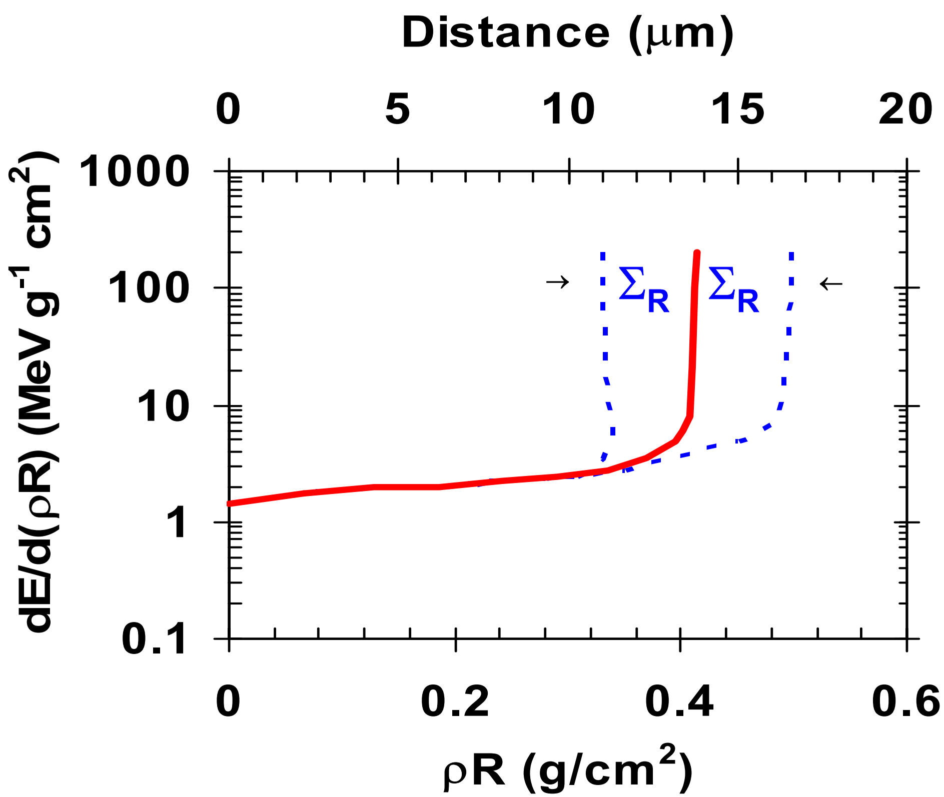
$$\Sigma_B(E) = \sqrt{\langle y^2 \rangle}$$

Where: $\langle y \rangle = \langle z \rangle = 0$



1 MeV electrons; ρ = 300 g/cm^3; T_e = 5 keV

Straggling smears out the effective Bragg peak

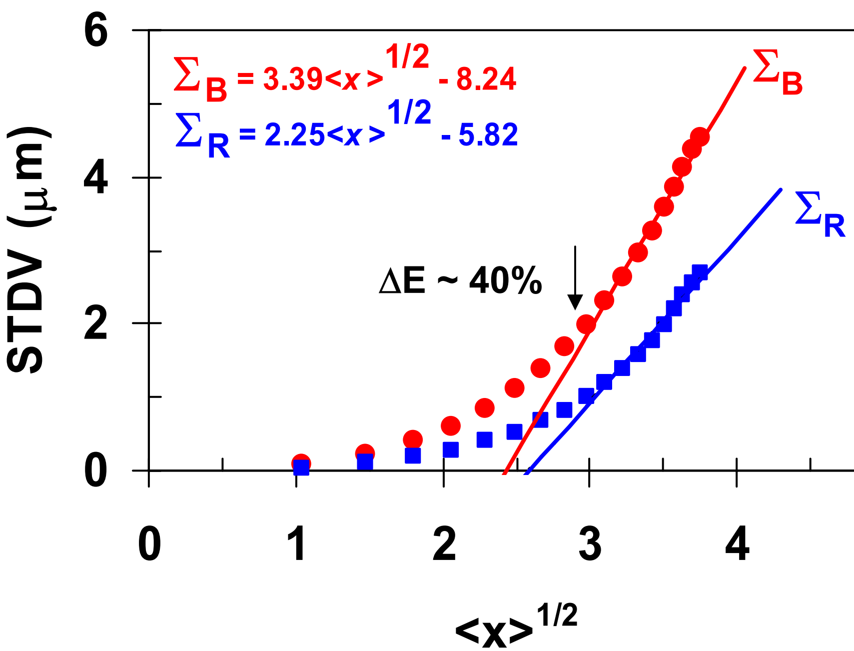


When $\Delta E \sim 90\%$

- $< x > \sim 13.8\ \mu m$
- $\Sigma_R \sim 3\ \mu m$

Including the effects of blooming would effectively increase (decrease) Σ_R for values less (greater) than the mean penetration

When ΔE > 40%, both straggling and blooming are approximately proportional to the square root of the penetration



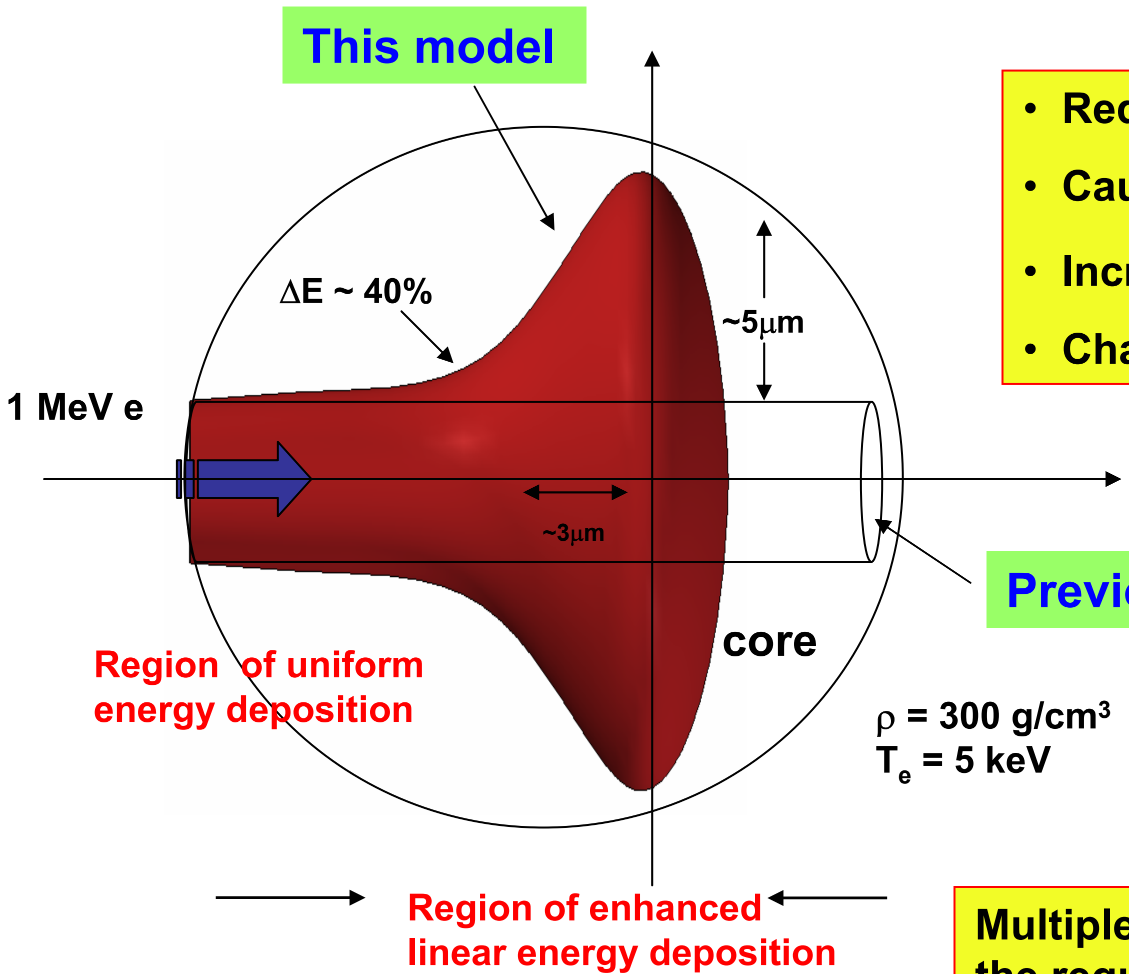
When ΔE > 40%

$$\Sigma_B \propto \sqrt{\langle x\rangle}$$

$$\Sigma_R \propto \sqrt{\langle x\rangle}$$

Assumption of uniform energy deposition is approximately justified when ΔE < 40%, for which little straggling and blooming occurs

The mutual interaction between energy loss, straggling and blooming leads to a region of enhanced linear energy deposition



- Reduce penetration ~30%
- Cause divergence ± ~ 5 μm
- Increase straggling ± ~ 3 μm
- Change energy deposition profile

Multiple scattering is critical for setting the requirements of Fast Ignition

For fast ignition, multiple scattering must *ultimately* dominate over all other mechanisms in affecting energy deposition and beam divergence

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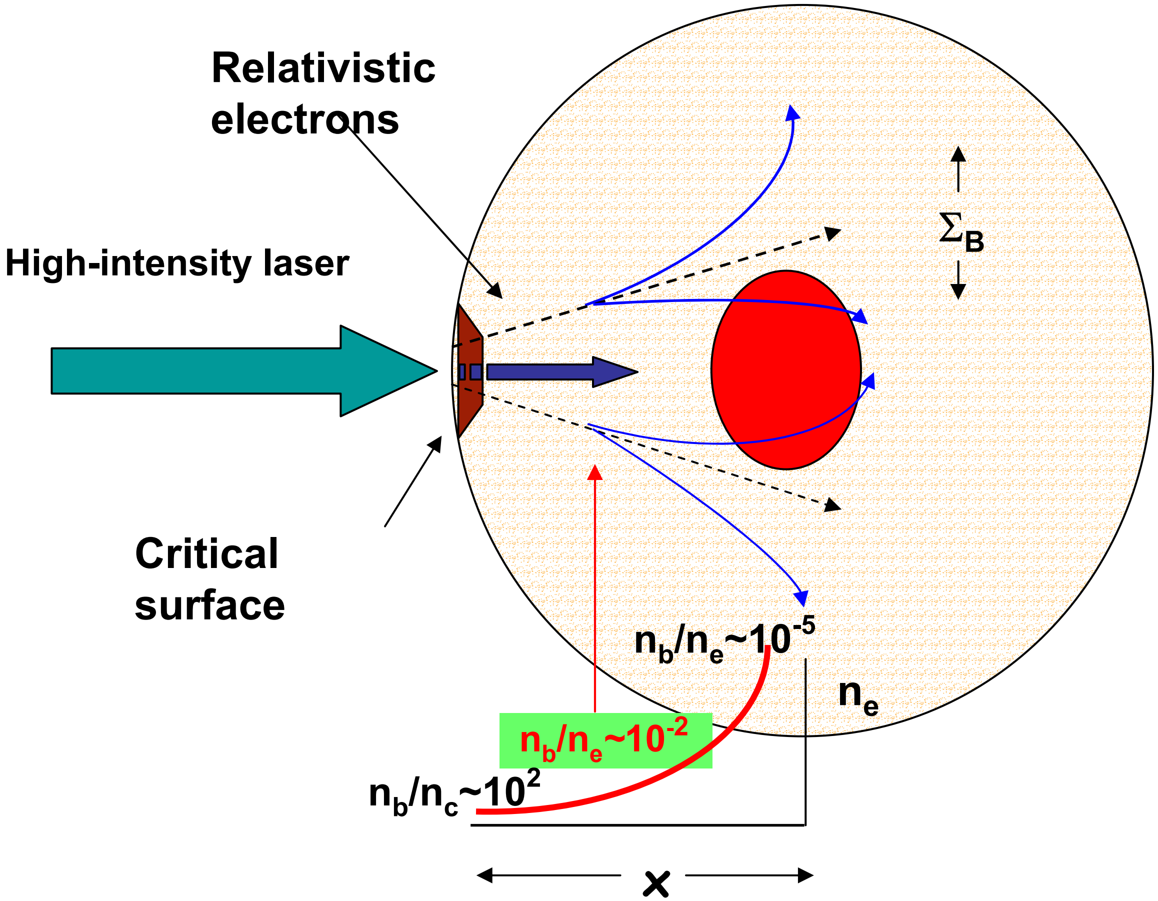
When $n_b/n_e > 10^{-2}$: Weibel-like instabilities + ….
When $n_b/n_e < 10^{-2}$: Multiple scattering
→ the interaction can be envisioned as the linear superposition of individual, isolated electrons interacting with the plasma

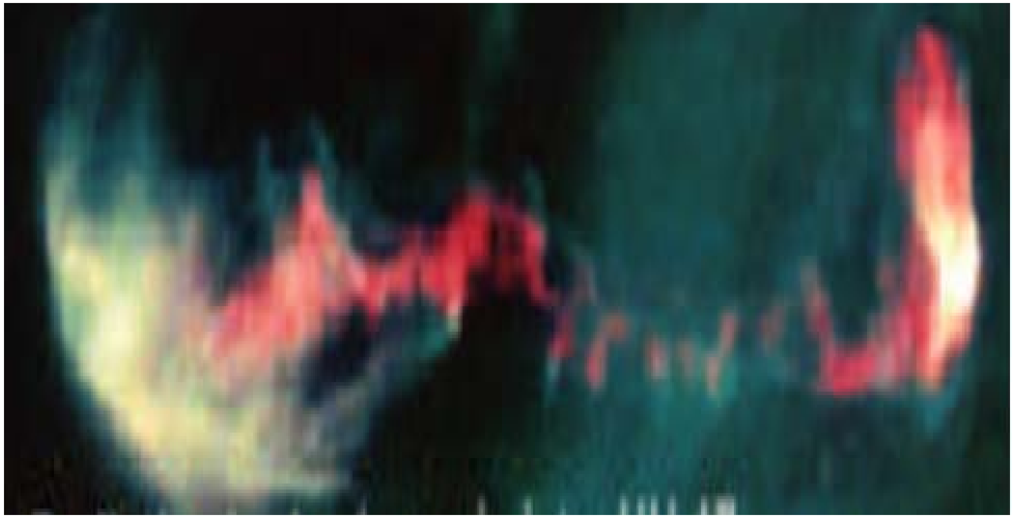


Two conditions for blooming and straggling become significant:

1. $n_b/n_e < 10^{-2}$
2. $\Delta E > 40\%$

These calculations are relevant to other current problems, such as preheat in ICF, or relativistic astrophysical jets

For relativistic astrophysical jets, electron energies ~ 1 MeV or greater



ρR (FI) ~ ρR (jet) ~ 0.4 g/cm^2

- R (FI) ~ 10 μm ~10^{-3} cm
- R (Jet) ~ 10^4 light years ~10^{22} cm

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