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

$\rho = 300 \text{ g/cm}^3$

$T_e = 5 \text{ keV}$

$\Delta E \sim 40\%$

1 MeV electron

Region of uniform energy deposition

Region of enhanced linear energy deposition

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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 $\Delta E > 40\%$ 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

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

- Angular distribution \(\rightarrow\) mean deflection angle, \(\langle \cos\theta \rangle\)

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

- Longitudinal distribution \(\rightarrow\) penetration and straggling

- Lateral distribution \(\rightarrow\) beam blooming
The penetration is reduced by ~ 30% compared to the range, and energy transfer is enhanced towards the end of the penetration.

\[ \frac{dE}{d\rho R} = \frac{dE}{d\rho R} \cdot \frac{1}{\langle \cos \theta \rangle} = \frac{dE}{ds} \]

1 MeV electrons; \( \rho = 300 \, \text{g/cm}^3; \, T_e = 5 \, \text{keV} \)
With a mean penetration of $\sim 13.8 \, \mu m$, multiple scattering results in longitudinal straggling of $\pm \sim 3 \, \mu m$ and lateral blooming of $\pm \sim 5 \, \mu m$.

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

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1 MeV electrons; $\rho = 300 \, g/cm^3$; $T_e = 5 \, keV$
Straggling smears out the effective Bragg peak

When $\Delta E \sim 90$
- $\langle x \rangle \sim 13.8 \mu m$
- $\Sigma_R \sim 3 \mu m$

Including the effects of blooming would effectively increase (decrease) $\Sigma_R$ for values less (greater) than the mean penetration
When $\Delta E > 40\%$, both straggling and blooming are approximately proportional to the square root of the penetration.

Assumption of uniform energy deposition is approximately justified when $\Delta E < 40\%$, for which little straggling and blooming occurs.

\[
\begin{align*}
\Sigma_B &= 3.39\langle x \rangle^{1/2} - 8.24 \\
\Sigma_R &= 2.25\langle x \rangle^{1/2} - 5.82
\end{align*}
\]
The mutual interaction between energy loss, straggling and blooming leads to a region of enhanced linear energy deposition.

- Reduce penetration $\sim 30\%$
- Cause divergence $\pm \sim 5\ \mu m$
- Increase straggling $\pm \sim 3\ \mu m$
- Change energy deposition profile

Multiple scattering is critical for setting the requirements of Fast Ignition.

$\rho = 300\ \text{g/cm}^3$
$T_e = 5\ \text{keV}$
For fast ignition, multiple scattering must *ultimately* dominate over all other mechanisms in affecting energy deposition and beam divergence.

When \( \frac{n_b}{n_e} > 10^{-2} \): Weibel-like instabilities + ....

When \( \frac{n_b}{n_e} < 10^{-2} \): 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. \( \frac{n_b}{n_e} < 10^{-2} \)
2. \( \Delta E > 40\% \)
For relativistic astrophysical jets, electron energies $\sim 1$ MeV or greater

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

$\rho R \ (\text{FI}) \sim \rho R \ (\text{jet}) \sim 0.4 \text{ g/cm}^2$

- $R \ (\text{FI}) \sim 10 \ \mu\text{m} \sim 10^{-3} \text{ cm}$
- $R \ (\text{Jet}) \sim 10^4 \text{ light years} \sim 10^{22} \text{ cm}$
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