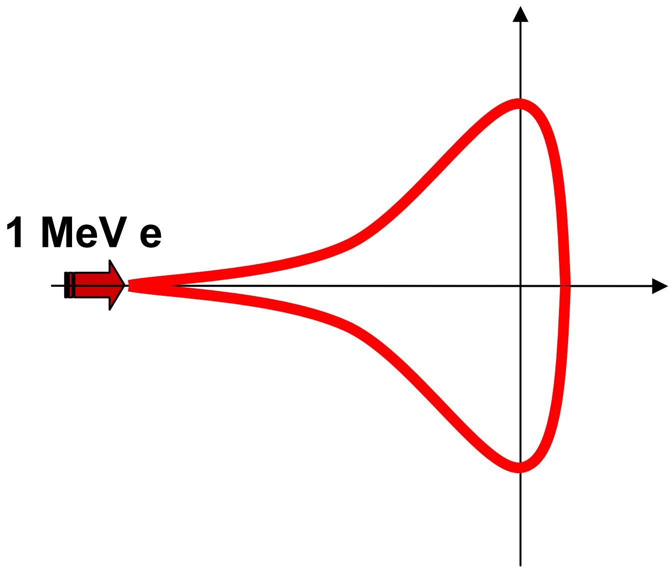
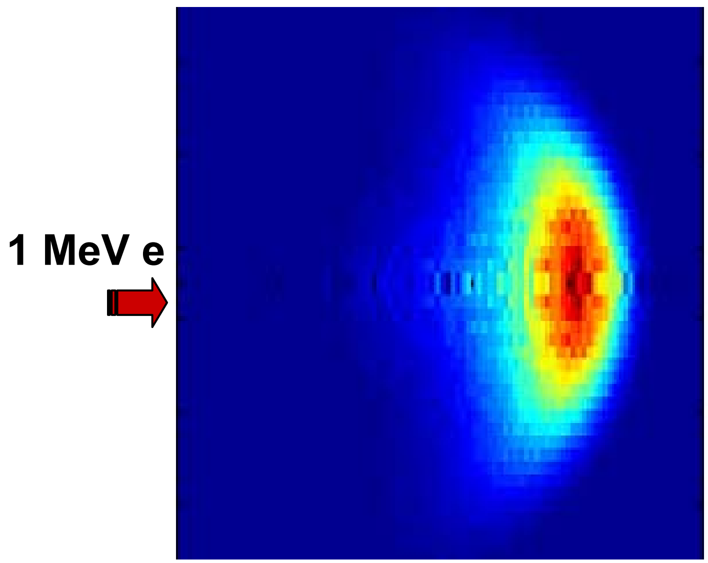
Stopping, blooming, and straggling of directed energetic electrons in hydrogenic and arbitrary-Z plasmas

This model



Monte Carlo



C. K. Li and R. D. Petrasso MIT

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America Physics Society
Division of Plasma Physics
Denver, CO October 24-28, 2005

Motivation

- Stopping in solids … Bohr, Bethe, Molière, Seltzer…
- Fast ignition
  - Electron penetration and straggling
  - Energy deposition profile
  - Beam blooming
- Preheat … to determine tolerable levels
- Astrophysics (*e.g.* relativistic astrophysical jets)

Companion presentations:

- R. Petrasso *et al*., GO1.0005 ….e preheat
- C. Chen *et al*., QP1.00137………simulations

Summary

Fundamental elements of this plasma stopping model

- For hydrogenic plasmas, binary $e \rightarrow e$ and $e \rightarrow i$ scattering are comparable, and must be treated on an equal footing
- Energy loss, penetration, and scattering are inextricably coupled together
- Blooming and straggling effects, a consequence of scattering, lead to a non-uniform, extended region of energy deposition
- Whenever the Debye length is smaller than the gyro radius, binary interactions will dominate penetration, blooming, and straggling effects

Summary

Additional elements of this plasma stopping model

The results:

- **Are insensitive to plasma density and temperature gradients**
- **Depend largely on $\rho<x>$**
- **Have strong Z dependence**
- **Applies to degenerate plasmas**

Outline

- ❑ Introduction
- ❑ Relevance to fast ignition
- ❑ Models
- ❑ Discussions

Electron energy loss along the path (continuous slowing down) does not include the effects of scattering

Binary interaction + plasma oscillation

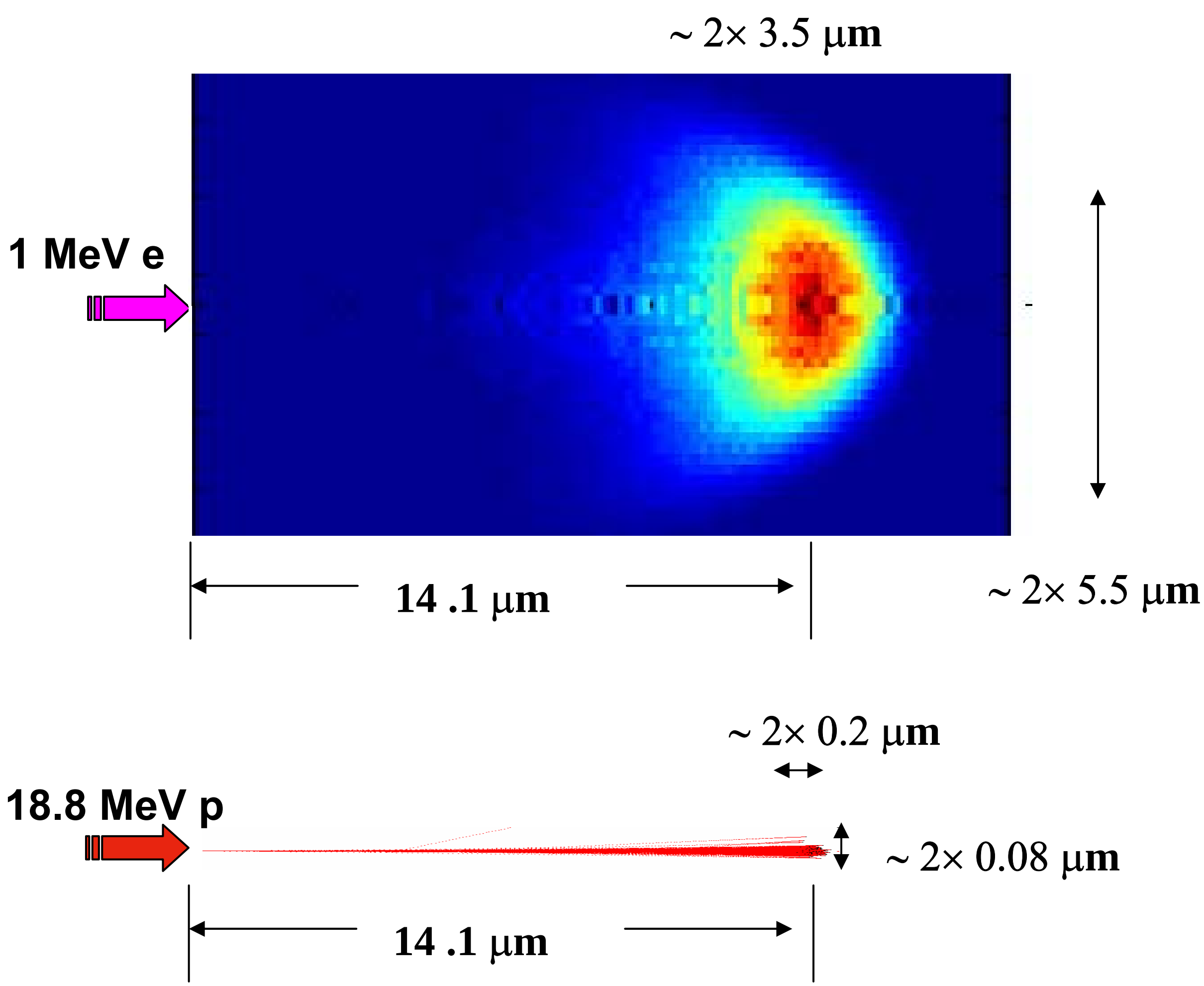
$$\frac{dE}{ds} = \left(\frac{dE}{ds}\right)_{Binary} + \left(\frac{dE}{ds}\right)_{Oscillation}$$

Dielectric response function

$$\frac{dE}{ds} = Ze\int \frac{d^3k}{(2\pi)^3} \frac{i\mathrm{k}\cdot\mathrm{v}}{v} \frac{4\pi Ze}{k^2 \varepsilon_L(k, \mathrm{k}\cdot\mathrm{v})}$$

mathematical equivalence

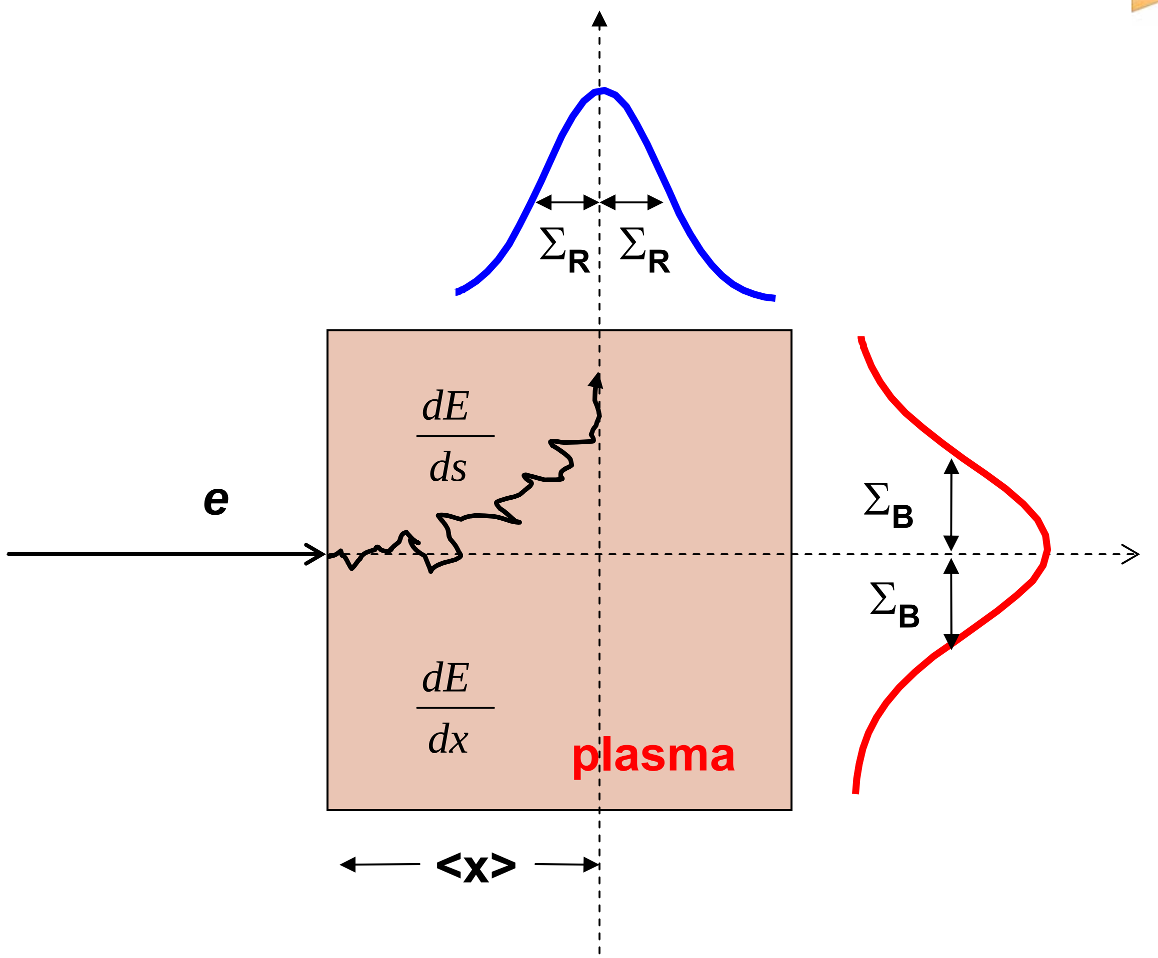
Electron scattering must be included in calculating the energy deposition



$$\frac{\Sigma_B}{\langle x \rangle} \sim 40\%$$

$$\frac{\Sigma_B}{\langle x \rangle} \sim 0.5\%$$

Scattering reduces the electron linear penetration, and it results in longitudinal straggling and beam blooming



Combine all these effects, the energy deposition profile is modified

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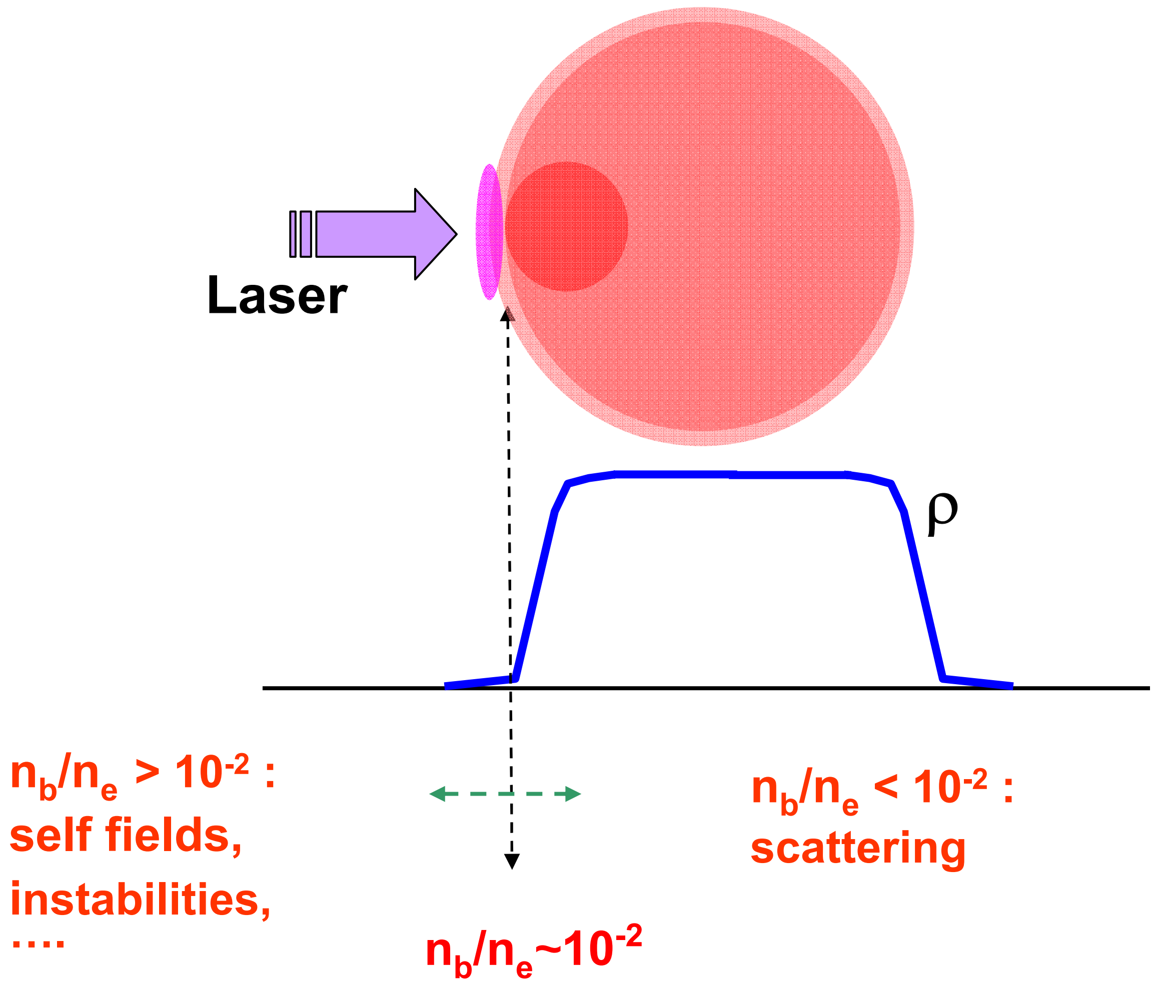
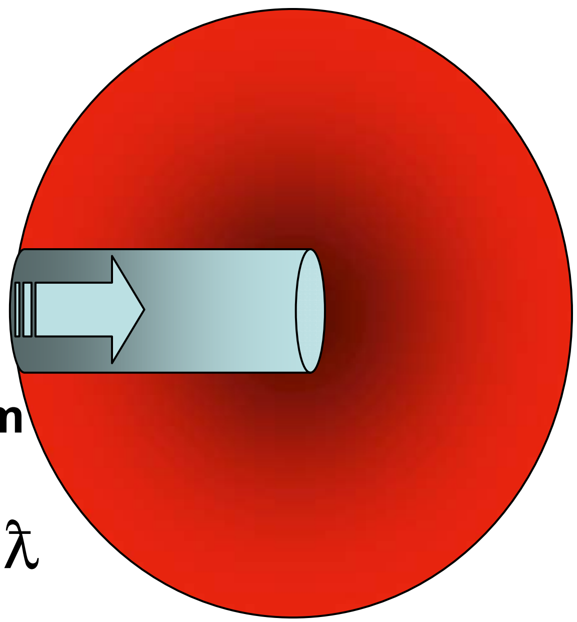
For the interior of a FI capsule, scattering dominates other mechanisms in affecting energy deposition, beam blooming, and straggling



This talk focuses on dense, deeply collisional regimes for which self-field corrections are unimportant

1-MeV e

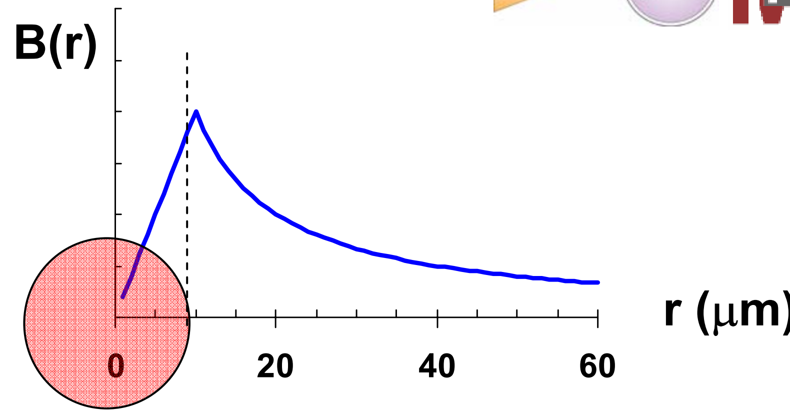
t_p=10ps

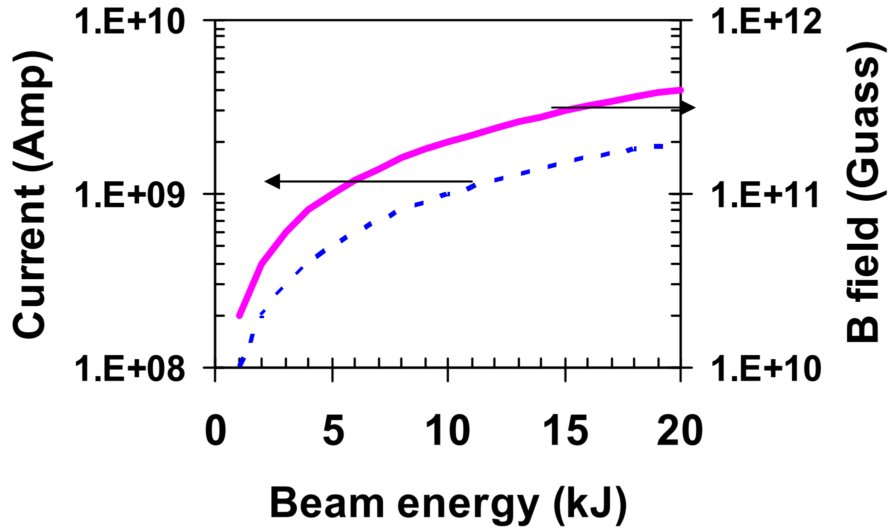


r_b=10 μm

$L_{||} >> \lambdabar$

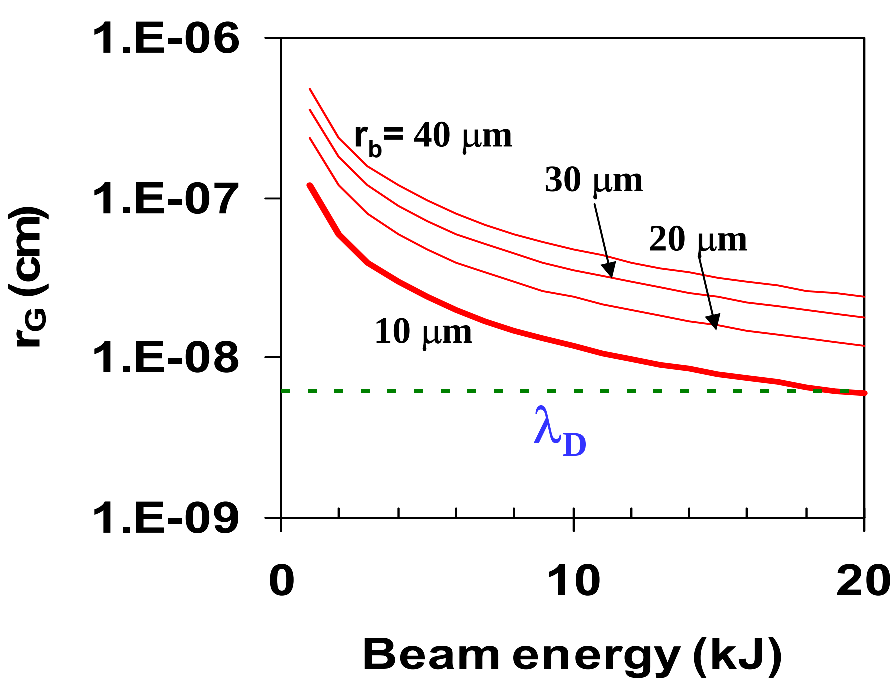
$L_{\perp} >> r_G$

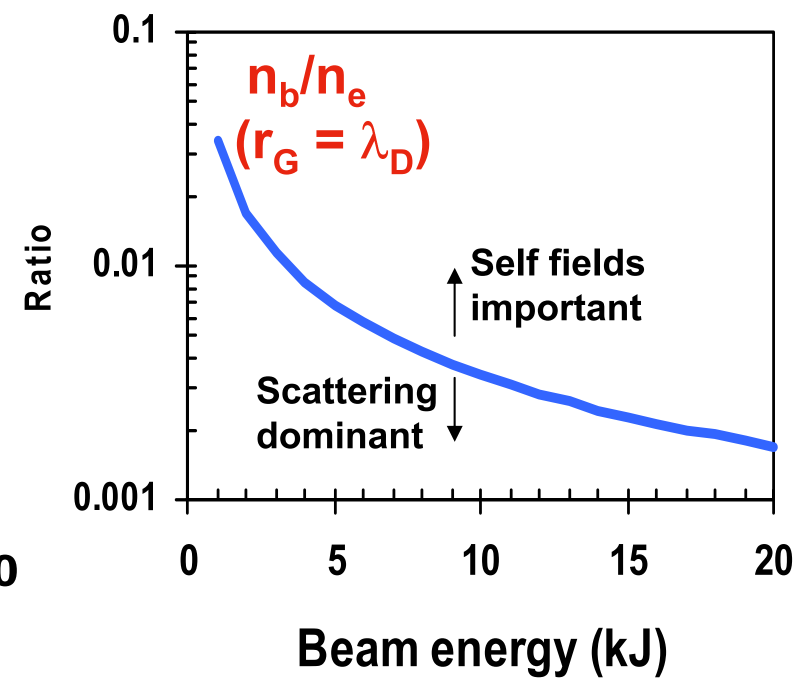




When $\lambda_D < r_G$, blooming, straggling, and penetration are determined by (collisional) binary interactions

T_e=5 keV; ρ=300g/cm^3 DT plasma → $n_e \sim 10^{26}$/cm^3





Only for very small deposition regions (beam size) and very large beam energy does r_G approach λ_D

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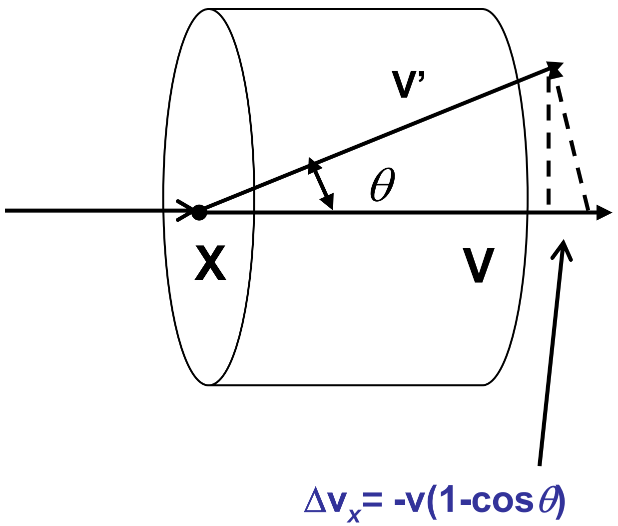
This plasma model includes necessary effects that were previously untreated:

- Couples directly scattering and energy loss
- Includes the effects of longitudinal momentum loss [$\Delta v = v(1-\cos\theta)$] upon energy loss
- Treats the case of full energy loss
- Results in both blooming and straggling

In addition:

This model is insensitive to plasma screening, and applies to degenerate plasmas (e.g. for e preheat)

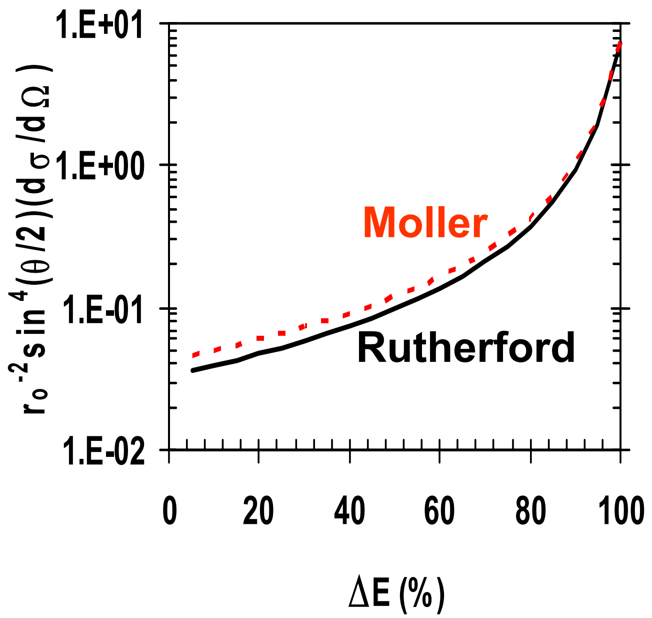
Electron angular and spatial distributions are calculated by solving a diffusion equation



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

- **Angular distribution → mean deflection angle, <cosθ>**
- **Longitudinal distribution → penetration and straggling**
- **Lateral distribution → beam blooming**

The effects of energy loss and scattering must be treated with a unified approach



$$f(\theta,E) = \frac{1}{4\pi}\sum_{\ell=0}^{\infty}(2\ell+1)P_\ell(\cos\theta)\exp\left(-\int_{E_0}^{E} k_\ell(E')\left(\frac{dE}{ds}\right)^{-1} dE'\right)$$

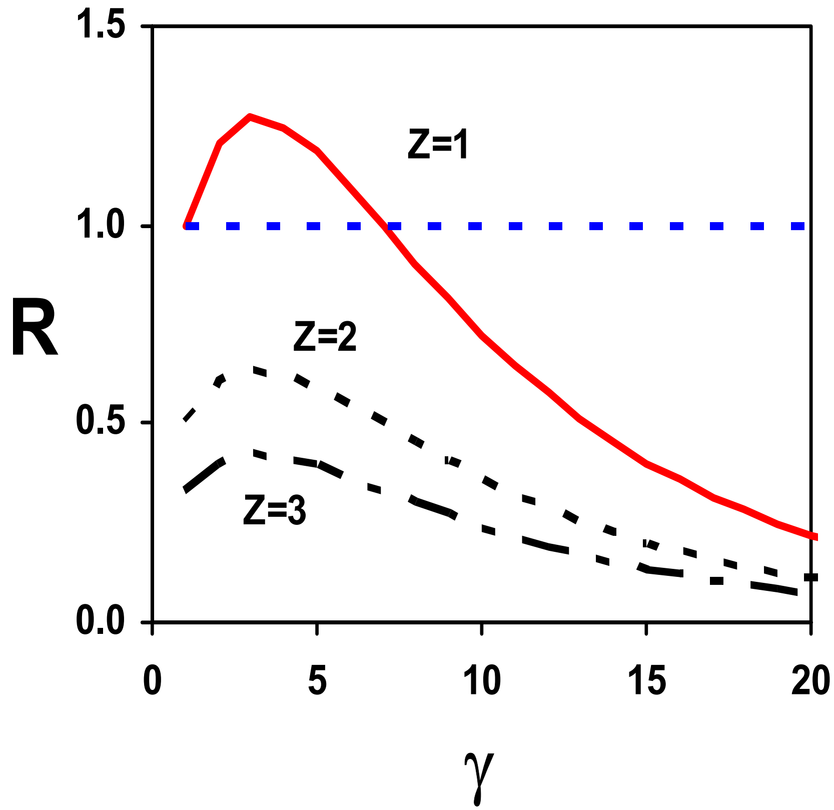
Scattering

Energy loss

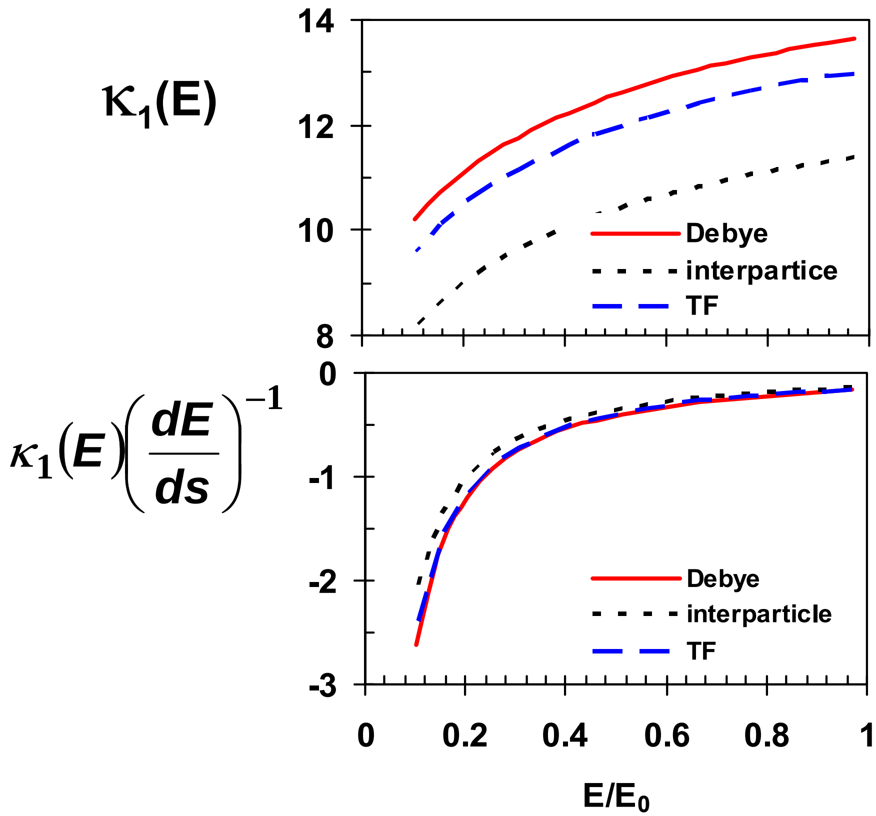
Where: $k_\ell(E) = n_i \int \left(\frac{d\sigma}{d\Omega}\right)\left[1 - P_\ell(\cos\theta)\right] d\Omega$

For hydrogenic plasmas, *e-e* scattering is comparable to *e-i* scattering (for $\gamma \lesssim 10$) and must be included

$$R = \left(\frac{d\sigma}{d\Omega}\right)^{ee} \Bigg/ \left(\frac{d\sigma}{d\Omega}\right)^{ei}$$



Scattering are insensitive to plasma screening models



scattering

Energy loss

$$\kappa_1(E)\left(\frac{dE}{ds}\right)^{-1} \propto \frac{\ln\Lambda^{ei} + \dfrac{4(\gamma+1)^2}{\left(2^{\sqrt{(\gamma+1)/2}}\right)^4}\ln\Lambda^{ee}}{\ln\Lambda}$$

Plasma screening:

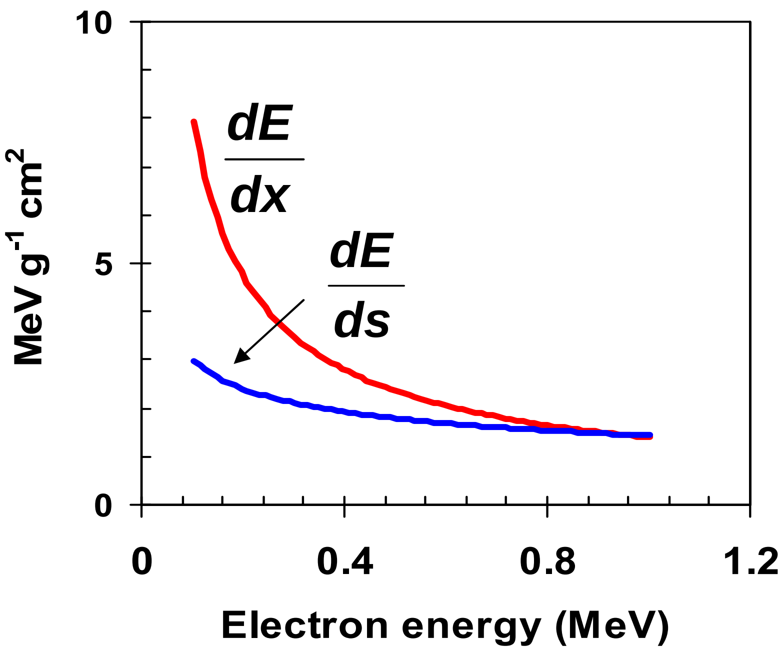
λ_D ---- **Debye length**

λ_d ---- **inter-particle distance**

λ_{TF} ---- **Thomas-Fermi**

ρ = 300 g/cm^3; T_e = 5 keV

Multiple scattering enhances electron linear-energy deposition



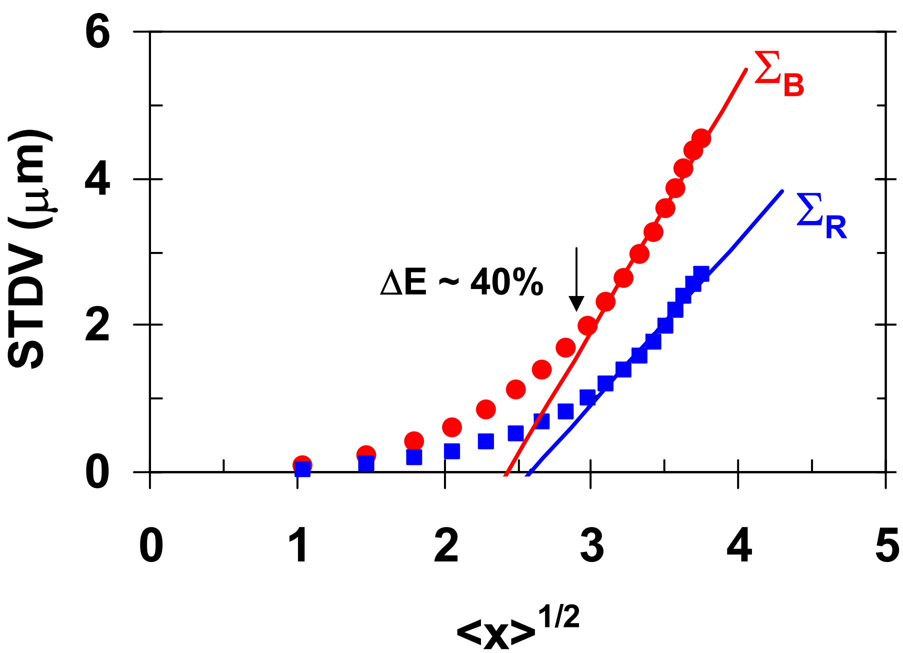
ρ = 300 g/cm^3; T_e = 5 keV

$$\frac{dE}{dx} = <\cos\theta>^{-1} \frac{dE}{ds}$$

where

$$<\cos\theta> = \exp\left(-\int_{E_0}^{E} \kappa_1(E')\left(\frac{dE'}{ds}\right)^{-1} dE'\right)$$

For 1-MeV electrons, straggling and blooming are proportional to $\sqrt{\langle x \rangle}$ when the energy loss > 40%



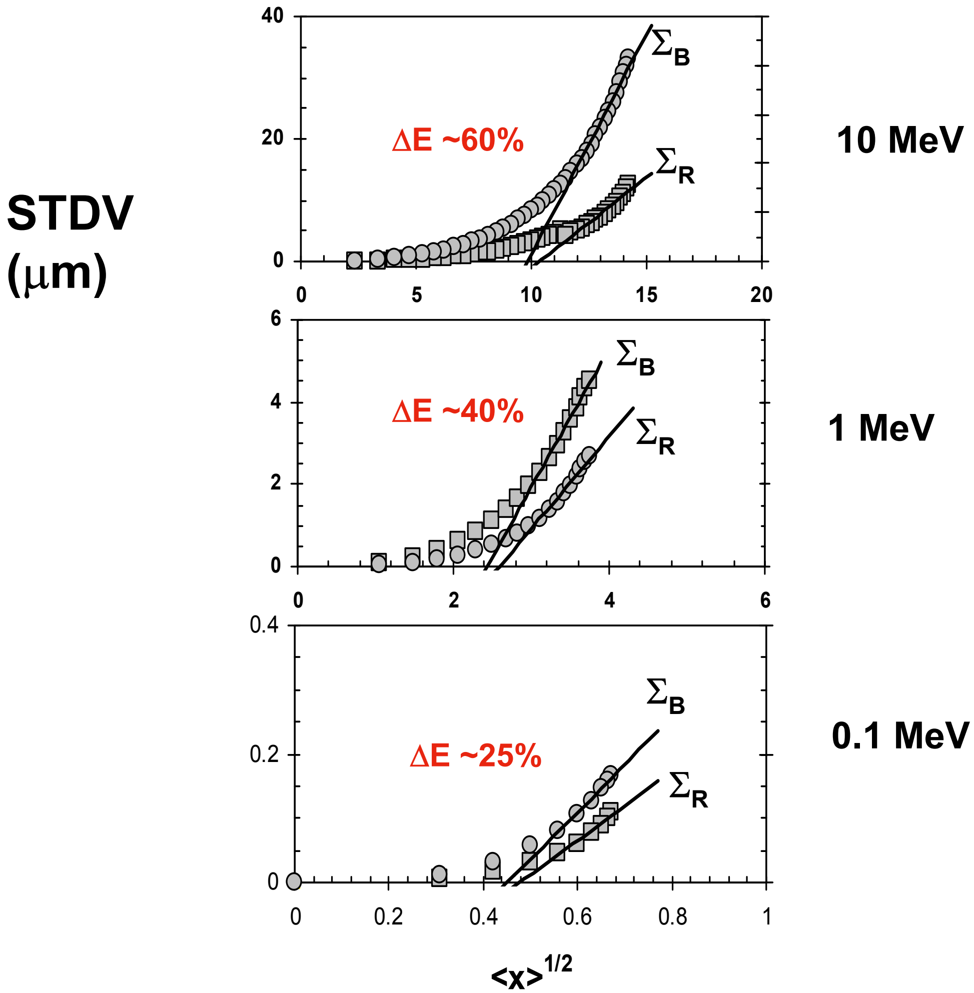
<x>: ~ 14 μm

Σ_B: ~ 5 μm

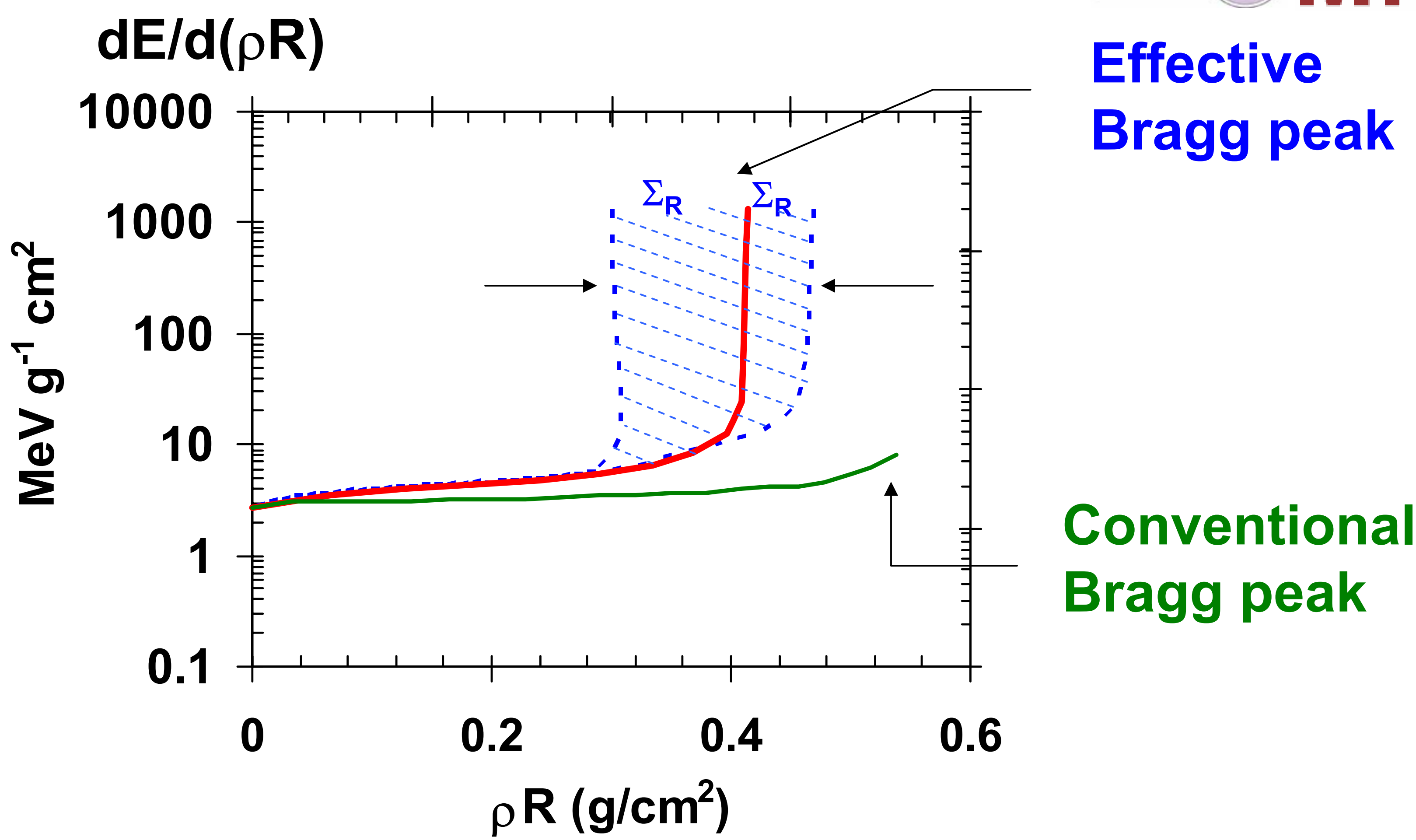
Σ_R: ~ 3 μm

Assumption of uniform energy deposition is reasonable when ΔE < 40%, as little straggling and blooming has occurred

For electrons with low energies, blooming and straggling become important even with little energy loss (ΔE)



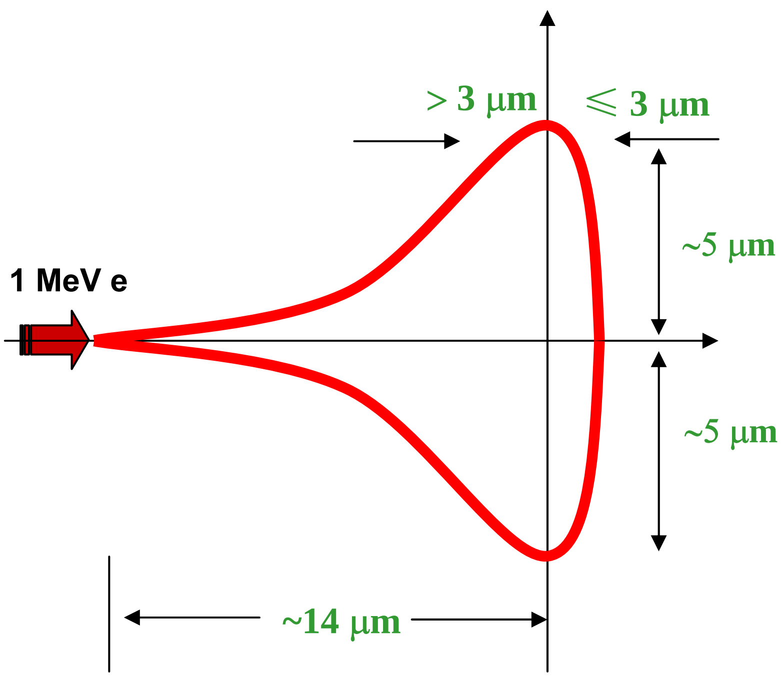
An effective Bragg peak results from the effects of blooming and straggling



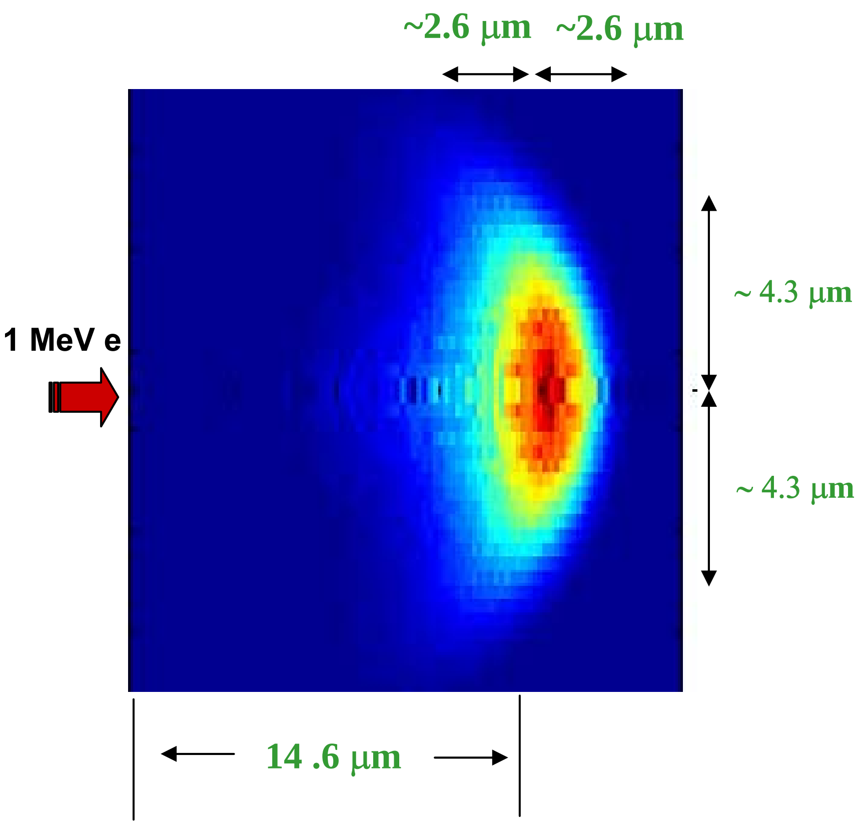
Conventional Bragg peak results from the velocity match

$$\frac{d\sigma}{d\Omega} \sim \frac{1}{\left| v_e - v_{th} \right|^4}$$

The qualitative features of this model --- penetration, blooming and straggling --- are replicated by Monte Carlo calculations for solid DT



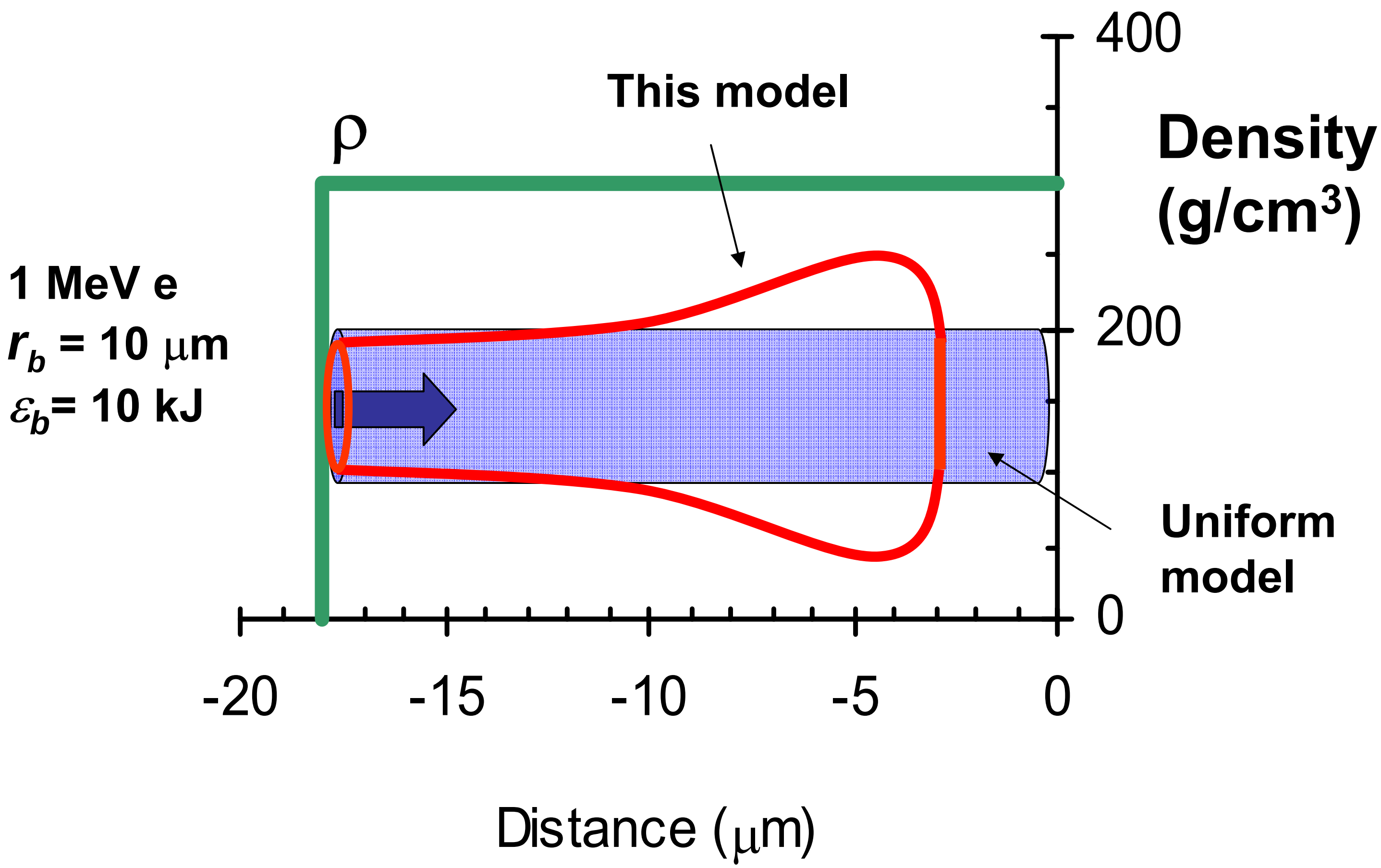
This model



Monte Carlo

Calculated by Cliff Chen

Combine all these effects, electron energy deposition profile is modified



Simultaneous coupling of penetration, blooming and straggling requires a rigorous numerical calculation

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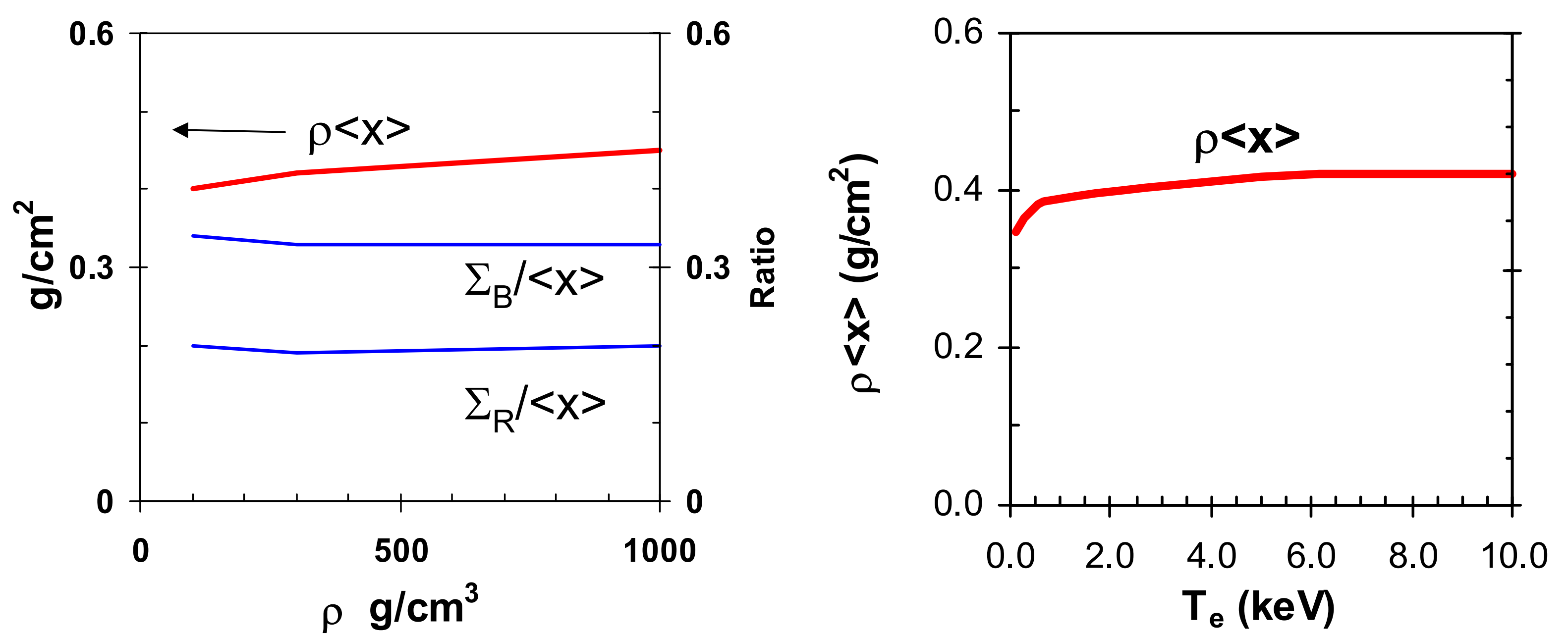
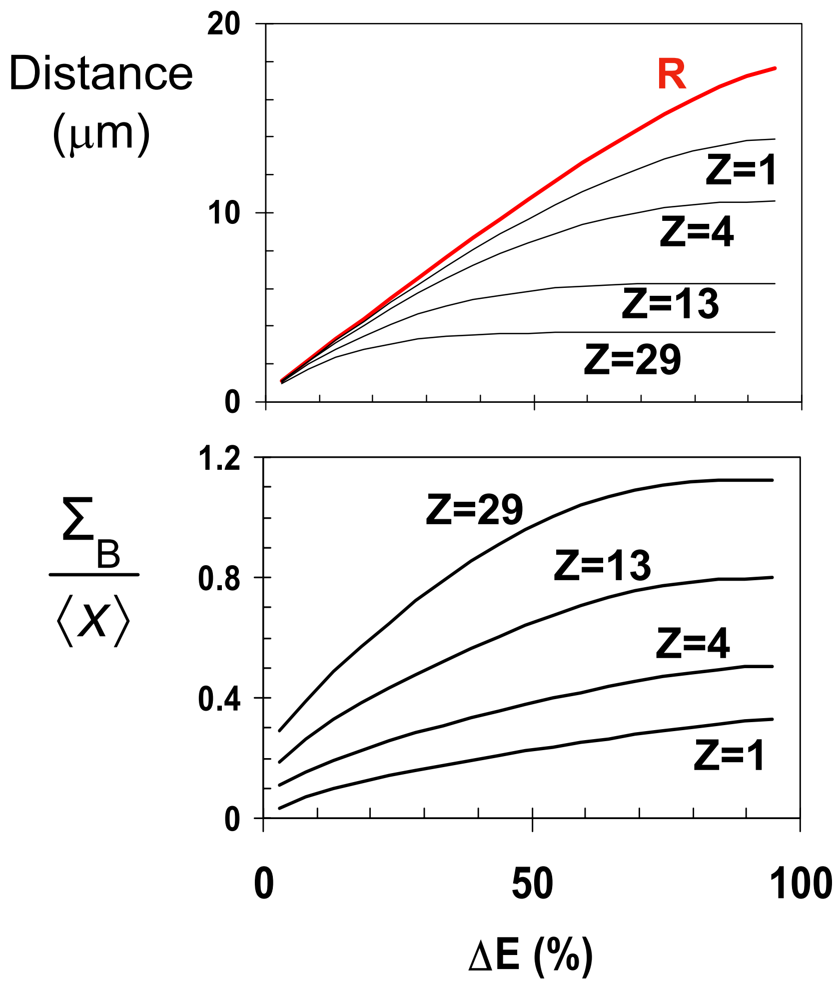
Penetration, blooming and straggling are insensitive to the plasma density and temperature



This insensitivity indicates that density and temperature gradients will not impact these results

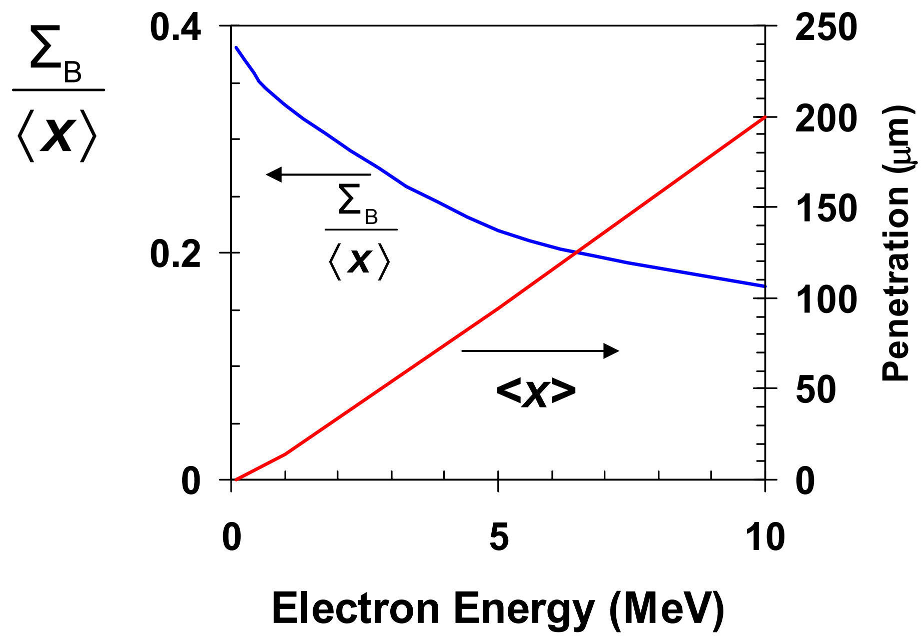
Penetration, blooming and straggling have a strong dependence upon the plasma Z

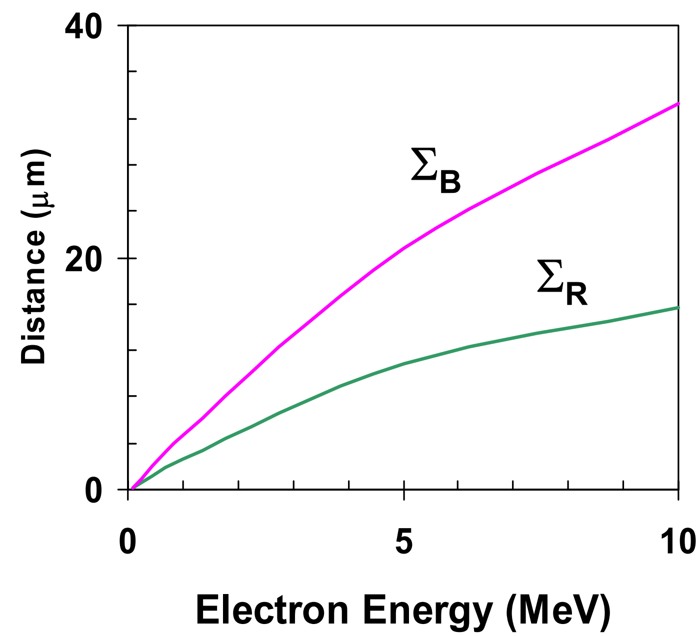


Assuming all elements are fully ionized and have same n_e

→ equal *R* --- the total path length

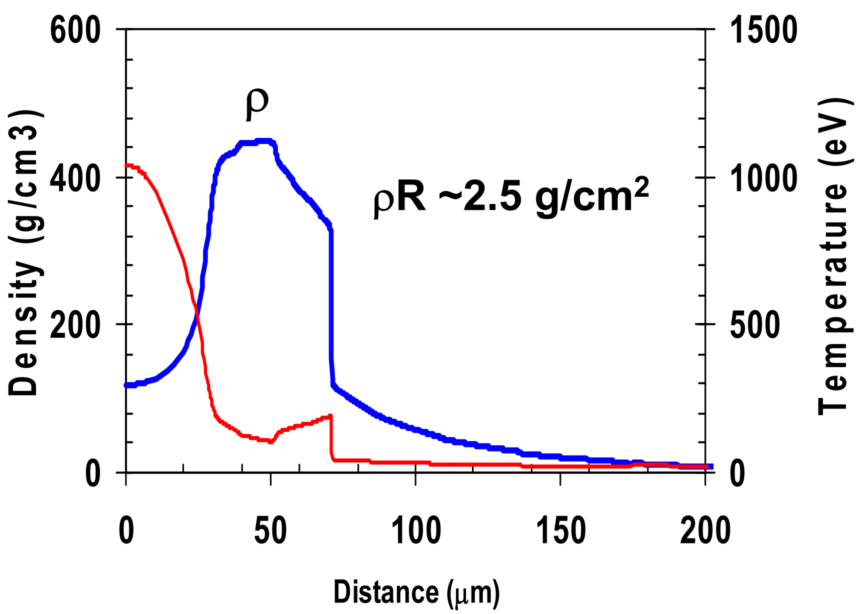
Penetration drops with decreasing electron energy, while blooming and straggling increase

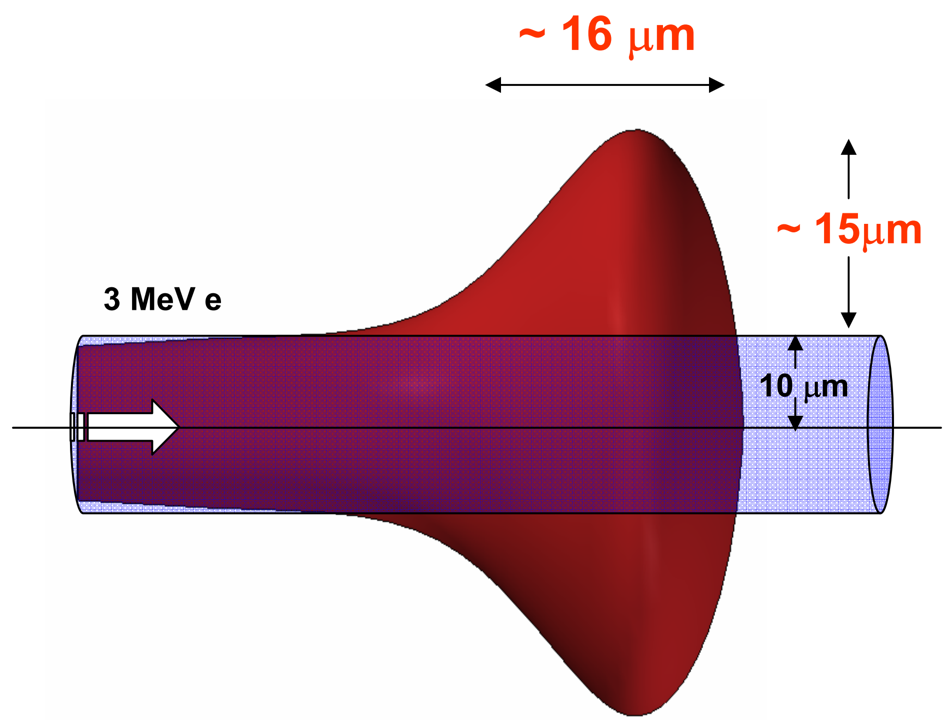




Scattering will be important for setting the requirements of Fast Ignition (E_{ig}, W_{ig} and I_{ig})

Designed by R. Betti





For NIF fast ignition capsules, 2-3 MeV electrons are required

$\langle x \rangle$: ~ 60 μm

Σ_R: ~ 8 μm

Σ_B: ~ 15 μm (> r_b=10 μm)

Summary

Fundamental elements of this plasma stopping model

- For hydrogenic plasmas, binary $e \rightarrow e$ and $e \rightarrow i$ scattering are comparable
- Energy loss, penetration and scattering are inextricably coupled together
- Blooming and straggling effects, a consequence of scattering, lead to a non-uniform, extended region of energy deposition
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