Sensitivity Study of Stopping Power Models in ICF Targets

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Abstract

Accurate treatment of fusion product charged particle transport (in particular the 3.5 MeV alpha particles) is very important for the accurate simulation of ICF ignition, bootstrap heating and burn. Many models have been proposed that focus on various aspects plasma conditions (collisionality, wave interaction, Fermi-degeneracy) which have various limitations. Here we present a comparison of several stopping power models, including the models of Trubnikov; Li and Petrasso; Brown, Preston and Singleton; Brysk; and Skupsky. Particular attention is given to regions of validity as they relate to ignition conditions. We present results that highlight the limitations of existing models to semi-Fermi-degenerate plasmas and models with explicit Coulomb logarithms. We also present initial results treating collisional effects in a semi-Fermi-degenerate plasma.

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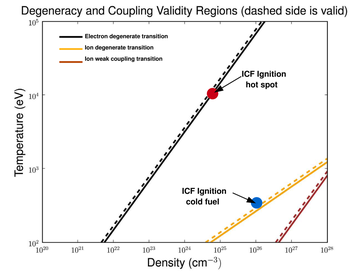
Stopping power models have theoretical constraints that limit their applicability

Coupling (the BBGKY sense)

Maxwell-Boltzmann vs Fermi-Dirac statistics

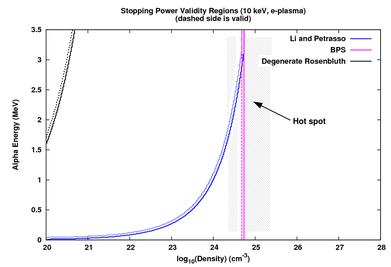
Field vs Particle interaction dominance



There are few valid models at hot spot conditions

Brysk, Skupsky models indicate validity over entire range

MB Rosenbluth model never valid (too small Coulomb log)



A degenerate BPS model is needed to describe alpha stopping near ignition

Different models model different physics (short range vs long range physics)

We need a model that consistently incorporates both

The BPS model does this for Maxwellian plasmas at all alpha particle energies

We should extend the BPS model with a semi-degenerate distribution function (like the degenerate Rosenbluth model)

Summary of Results

Developed stopping power library `deeks`

- **Implementations of models by MB Rosenbluth; (Fermi) degenerate Rosenbluth; Li and Petrasso; Brysk; Skupsky; Brown, Preston and Singleton (BPS); Jackson; Meyer-ter-Vehn; Spitzer**
- **Extensive validity checks**

Demonstrated need for stopping power for Fermi-degenerate plasmas with energetic particles

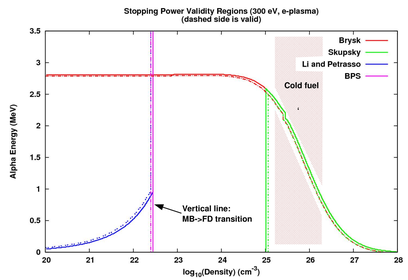
Demonstrated mutually v alid stopping powers are frequently inconsistent

Derived simple Boltzmann model for Fermi-degenerate plasma (degenerate Rosenbluth)

Cold fuel lacks a valid stopping power for unslowed alpha particles

Degeneracy effects important (excludes MB Rosenbluth, LP and BPS models)

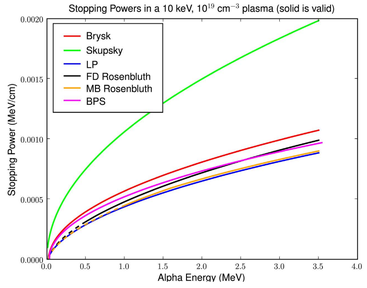
MB/degenerate Rosenbluth model never valid (Coulomb log too small)



Mutually valid models give inconsistent answers

Valid does not imply a complete description of the needed physics

While all models have similar behavior, there are still significant differences



Degenerate Rosenbluth model

Calculation of usual Rosenbluth, MacDonald and Judd stopping power, but with semi-Degenerate distribution function

$$\frac{dE}{dx} = -\frac{LM}{v}\left(\frac{M+m}{m}vH' + H\right)$$

$$vH' = \frac{n}{4\pi v} - \frac{AT}{m}y^{-1/2}\frac{\sqrt{\pi}}{2}\mathscr{F}(\eta, y) \qquad y = \frac{mv^2}{2T}$$

$$H = -vH' - \frac{AT}{m}\ln\left(1 + e^{\eta - y}\right) \qquad A = \frac{1}{4}\left(\frac{m}{\pi\hbar}\right)^3$$

$$n = A\int \frac{4\pi x^2}{1 + \exp\left(\frac{mx^2}{2T} - \eta\right)}dx$$

$$\mathscr{F}(\eta, y) = \frac{2}{\sqrt{\pi}}\int_y^\infty \frac{t^{1/2}}{1 + e^{t-\eta}}dt$$

Future Work

Extend BPS stopping power to Fermi-Dirac distribution functions

Develop charged particle Monte Carlo code to apply `deeks` to transport problems

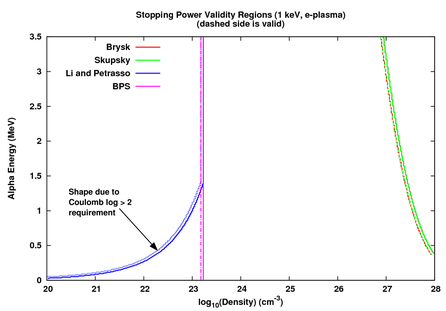
Incorporate stopping power library into an ICF radiation-hydrodynamics code

Add magnetic perturbation to BPS

Li and Petrasso-like extension to degenerate Rosenbluth stopping power (primarily for comparison and benchmarking purposes)

At intermediate temperatures MB distribution functions are very constraining

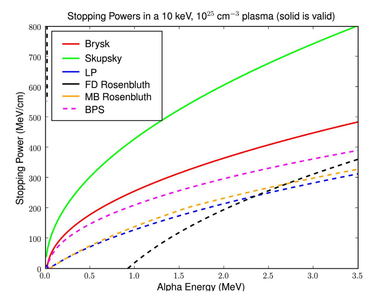
MB Rosenbluth, FD Rosenbluth models never valid (Coulomb log too small)



At more ICF-like conditions there is even disagreement between models

Conditions represent small, but significant degeneracy

Consistent difference between field and collisional models



Acknowledgments

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