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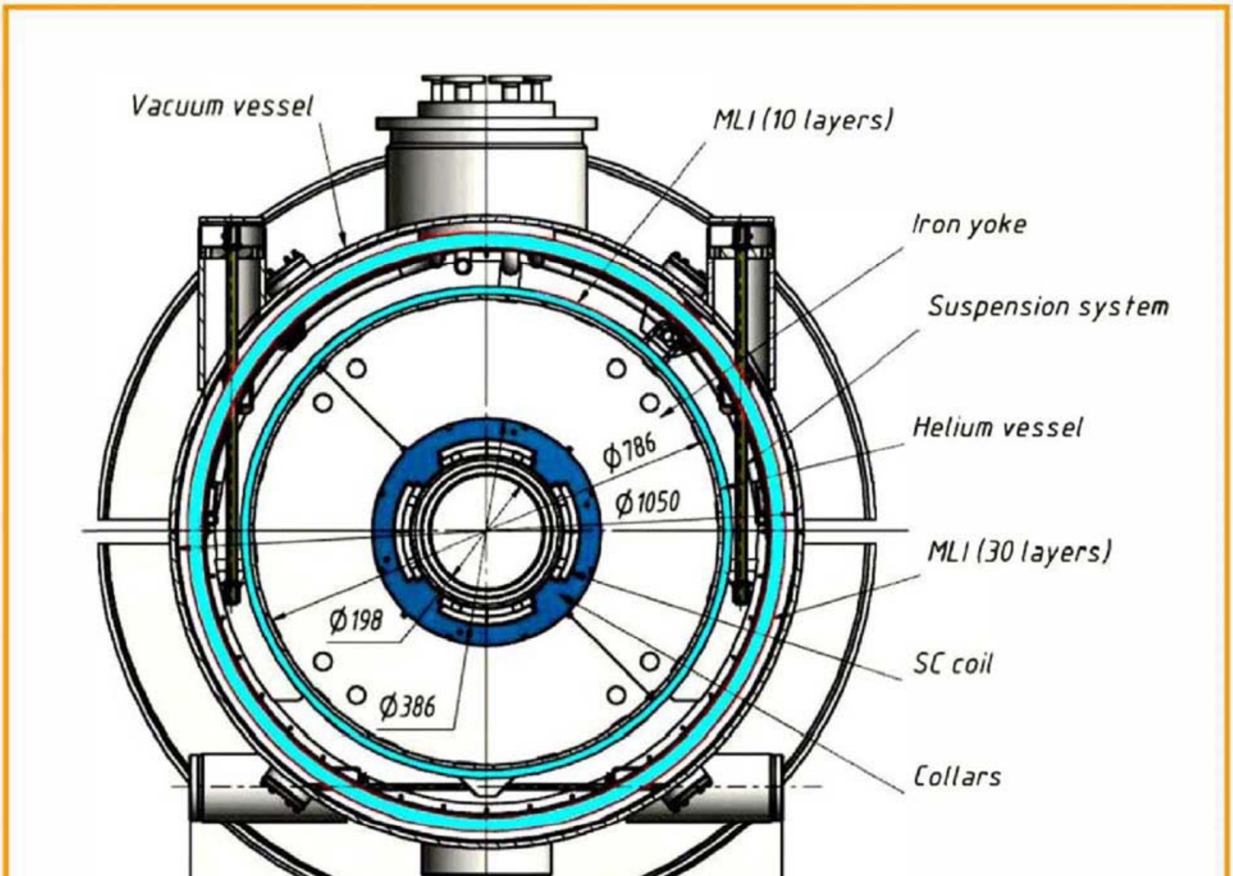
# High Energy Density generated by Heavy Ion and Laser Beams




The HED@FAIR Collaboration - Report 2017

# Stopping power of warm dense electron plasmas*

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Phenomena related to the interaction between beams of charged particles with condensed matter and plasmas have been widely studied using different methods of diagnostics. In addition, beams of heavy fast ions are considered as a perspective driver for the inertial fusion.

The plasma polarizational stopping power of heavy ions projectiles is described by the Lindhard formula [1]:

$$\left[-\frac{dE}{dx}\right]^{pol}=\frac{2(Z_pe)^2}{\pi v^2}\int_0^\infty\frac{dk}{k}\int_0^{kv}\omega^2\left(-\mathrm{Im}\frac{\varepsilon^{-1}(k,\omega)}{\omega}\right)d\omega,\quad (1)$$

whose high-velocity asymptotic form was found by Bohr, Bethe, and Larkin [2-4]:

$$\left[-\frac{dE}{dx}\right]^{pol}_{v\to\infty}\cong\left(\frac{Z_pe\omega_p}{v}\right)^2\mathrm{Ln}\frac{2m_ev^2}{\hbar\omega_p}.\quad (2)$$

The plasma inverse dielectric function (IDF), $\varepsilon^{-1}(k,\omega)$, was determined in [5] within the moment approach [6] complemented by some physical observations which permitted to express it in terms of only two characteristic frequencies, which are the ratios of the frequency power moments of the IDF imaginary part:

$$\varepsilon^{-1}(k,\omega)=1+\frac{\omega_p^2\left(\sqrt{2}\omega_1\omega+i\omega_2^2\right)}{\sqrt{2}\omega_1\omega\left(\omega^2-\omega_2^2\right)+i\omega_2^2\left(\omega^2-\omega_1^2\right)}.\quad (3)$$

The frequencies $\omega_1$ and $\omega_2$ in (3) can be calculated rigorously as soon as we know the static structure factor (SSF) of the system [5, 6]. Here we employ the following interpolation expressions [7,8]:

$$\omega_1^2=\omega_1^2(k)=\omega_p^2\left(1+k^2k_D^{-2}+k^4k_q^{-4}\right),\quad (4)$$

$$\omega_2^2=\omega_2^2(k)=\omega_p^2\left(1+\frac{\langle v_e^2\rangle k^2}{\omega_p^2}-\frac{v_{int}^2k^2}{\omega_p^2}\right).\quad (5)$$

The interpolation and fitting parameters introduced here are the following:

$$v_{int}^2=-\frac{4}{15}\frac{\Gamma^{\frac{3}{2}}}{\beta m_e}\left(\frac{-0.9052}{\sqrt{0.6322+\Gamma}}+\frac{0.27243}{1+\Gamma}\right),$$

and $k_D^{-1}$ is the Debye radius, $\Gamma=\beta e^2/a$, $k_q^4=12r_s/a^4$ $r_S=a/a_B$, $a$ and $a_B$ are the Wigner-Seitz and Bohr radii, $\beta=1/k_BT$, $k_B$ is the Boltzmann constant, and $T$ is the temperature. Under the thermodynamic conditions we deal with here, the system is practically a classical plasma so that all magnitudes can be expressed in terms of the plasma coupling parameter Γ, and we may use for the average electron thermal velocity the Vlasov classical form: $\langle v_e^2\rangle=3k_BT/m_e$.

We have compared the polarizational losses of heavy projectiles in electron gas calculated within the simplified interpolation version of the modified method of moments [5] to the results of the latter and to the PIC simulation data [9] in classical systems, see the Figures 1-4.

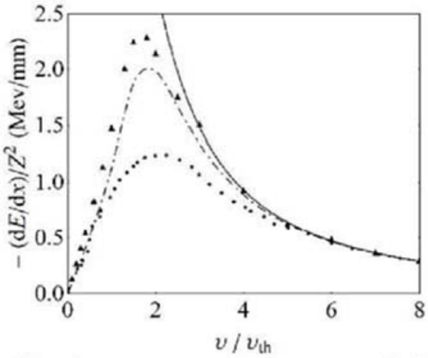


Figure 1: The electron gas stopping power (*-dE/dx*) as a function of the projectile velocity v normalized to the thermal velocity $v_{th}=\sqrt{k_BT/m_e}$ for a positively charged ion and different coupling strengths $Z\Gamma^{3/2}$ ; the circles display the simulation data, the solid line represents the asymptotic form (2), the dash-dotted line stands for the results of the interpolation model, while the triangles correspond to the complete method-of-moments results with the SSF determined in the hyper-netted chain approximation. The plasma conditions and charge state Z are: $k_BT=10$ eV, $n=10^{21}$ cm$^{-3}$, $Z=2$ for $Z\Gamma^{3/2}=0.23$.

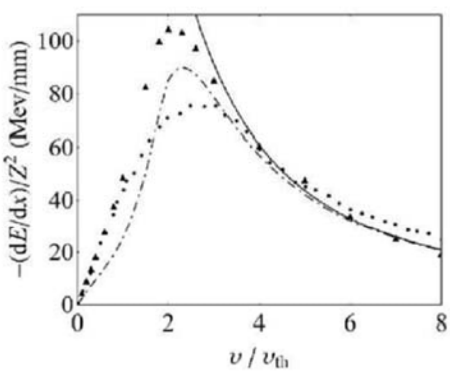


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Figure 2: As in Fig. 1 but for $k_B T = 20$ eV, $n = 2.1 \cdot 10^{23}$ cm$^{-3}$, $Z = 2$ and $Z\Gamma^{3/2} = 1.1$

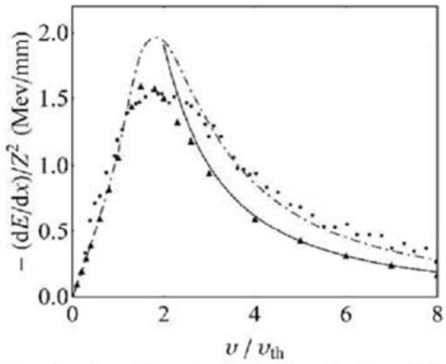


Figure 3: As in Fig. 1 but for $k_B T = 10$ eV, $n = 10^{21}$ cm$^{-3}$, $Z = 1$ and $Z\Gamma^{3/2} = 0.11$

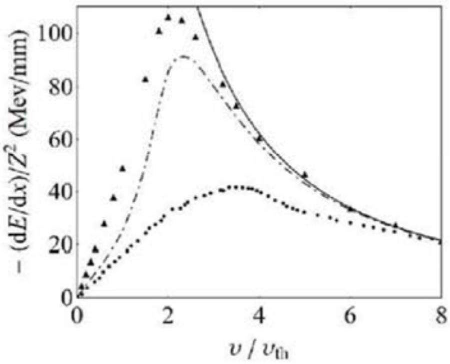


Figure 4: As in Fig. 1 but for $k_B T = 20$ eV, $n = 2.1 \cdot 10^{23}$ cm$^{-3}$, $Z = 8$ and $Z\Gamma^{3/2} = 4.6$

Under the above conditions the interaction contribution $|U(q)|$ to the frequency $\omega_2$ is at least an order of magnitude smaller than the kinetic one, $K(q)$, so that the simplified random-phase interpolation form for the frequency $\omega_1(q)$ is perfectly applicable [10].

We observe that the suggested simplified interpolation approach based on the modified method of moments is capable of describing the energy losses of a charged particle in warm dense effectively classical electron plasmas with a fairly good precision. Notice that no adjustable parameters were used, and the interpolation-model calculation is practically algebraic. Last year the same interpolation approach was applied to describe the stopping power of two-component plasmas, and we are planning to carry out a comparative study. Our results imply the physical applicability both of the interpolation and the complete modified moment approach.

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