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Overcooling of the Hot Spot of Laser Plasma by Electron Conductivity

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A hot spot of laser plasma is surrounded by extensive region of weakly ionized gas and the electron conductivity in background cold plasma is main reason for plasma electrons cooling.

1. Introduction

The possibility of developing a x-ray recombination laser by intense, ultrashort laser pulse has been considered in many papers [1-3]. But a residual energy is determining by above-threshold ionization and inverse-bremsstrahlung heating may be significant. Cooling is usually achieved either by hydrodynamic expansion or by radiative cooling. A hot spot of laser plasma is surrounded by extensive region of weakly ionized gas. Our calculations indicate that the main channel of a plasma electrons cooling of a hot spot is electron conductivity in background cold plasma.

2. Radiative cooling of laser plasma spot

Let us estimate the time of radiative cooling for high residual energy of electrons after laser pulse.

The energy withdraw from the electron component due to bremsstrahlung is expressed as [4]

$$Q_{bs} = 1.54 \times 10^{-32} z^2 T_e^{1/2} N_i N_e \text{ W/cm}^3.$$

The energy loss due to photorecombination is expressed as [5]

$$Q_{pr} = 5 \times 10^{-31} z^4 T_e^{-1/2} N_i N_e \text{ W/cm}^3.$$

The ratio of specific powers of bremsstrahlung and photorecombination radiation is $Q_{bs}/Q_{pr} = T_e/30z^2$. For $z=7$ and $T_e < 1$ keV photorecombination radiation is predominant over bremsstrahlung radiation. At first let us consider a low electron density case

$$N_e < N_{epr} = 3.1 \times 10^{13} T_e^{3.75} / z \text{ cm}^{-3},$$

where photorecombination is predominant collisional ion-electron recombination [6]. For $z=7$ and $N_e = 2 \times 10^{20} \text{ cm}^{-3}$ the electron temperature $T_{epr} = 50$ eV is lower bound of the low electron density case. The time of electron cooling due to photorecombination at initial electron temperature $T_e = 100$ eV is $\tau_{ph,rec} = 3T_e N_e / 2Q_{pr} = 1$ ns, the time cooling from 1 keV is $\tau_{ph,rec} = 30$ ns. Thus the cooling due to bremsstrahlung and photorecombination radiation is not effective to create overcooled plasma with $z \gg 1$.

3. Overcooling by electron conductivity

We shall consider the problem, from which it is possible to determine time dependence of hot spot temperature due electron conductivity in surround weakly ionized gas.

Suppose, that hot spot of plasma is surrounded by cold plasma. Assume, that a cold surrounded plasma has a mean ion charge z_0 , electron temperature $T_0 < T_{max}$, density if ions N_i in hot spot and surround plasma are equal. Let the hot spot of laser plasma has radius r_0 , electron temperature T_{max} , mean ion charge z_{max} . Propagation of heating wave is described by equation

$$\frac{\partial T}{\partial t} = \frac{1}{r^s} \frac{\partial}{\partial r} (r^s \chi \frac{\partial T}{\partial r}),$$

where $s=0, 1, 2$ for plane, cylindrical and spherically symmetric cases. A temperature conductivity coefficient may be writing as $\chi = aT^n$, for the electron conductivity $n=5/2$. Let background electron temperature is $T_0=0$ and instantaneous thermal energy put in point $r=0$ at time $t=0$.

In spherical symmetry case $s=2$ the solution depends from self similar variable $\xi = r/(aQ^n t)^{1/(3n+2)}$ and this solution is $T(\xi) = T_c [1 - (r/r_f)^2]^{1/n}$, where thermal heating front radius is $r_f = \xi_f (aQ^n t)^{1/(3n+2)}$, T_c - temperature at center, constant $\xi_f \approx 1$, a temperature source constant $Q = \int T dV$ [6]. A mean temperature of electrons in volume inside heating wave $r < r_f$ is $T_{pl} = 3Q/4\pi r_f^3$ and one little differents from temperature in center T_c [6]. Therefore for estimation of T_c value we will consider

$$T_c \approx (Q/at)^{2/3} \sim t^{6/19}$$

The validity of this model is restricted by condition $T_0 < T_c < T_{max}$. Here Q is a temperature source constant

$$Q = 4\pi z_{max} N_i r_0^3 T_{max} / 3z_0,$$

a coefficient electron temperature conductivity at $z_0=1$ is $\chi = 2\kappa_e / 3N_e \approx 6.32 T_e \tau_e / m_e$, where κ_e is the thermal electron conductivity, $\tau_e = 3.5 \times 10^{-14} T_e^{3/2} / (\Lambda/10) z_0^2 N_i$ sek is the time between electron collisions, Λ - Coulomb logarithm [7]. When $r_f < r_0$, the self similar solution is not correct. In this case we can use the estimation for r_f as $r_f = r_0 + (\chi t)^{1/2}$. Therefore for T_c value we will consider

$$T_{pl} = 3Q/4\pi(r_f^3 + (z_{max}/z_0 - 1)r_0^3) = z_{max} T_{max} / (r_f^3/r_0^3 + z_{max}/z_0 - 1).$$

In cylindrical symmetry case $s=1$ for T_c estimation we will consider

$$T_c \approx (Q/at)^{1/n+2} \sim t^{2/7},$$

where $Q = \pi r_0^2 z_{max} T_{max} / z_0$. When $r_f < r_0$, we will estimate r_f as $r_f = r_0 + (\chi t)^{1/2}$ and for mean plasma temperature have

$$T_{pl} = Q/\pi(r_f^2 + (z_{max}/z_0 - 1)r_0^2) = z_{max} T_{max} / (r_f^2/r_0^2 + z_{max}/z_0 - 1).$$

Plasma temperature depends from time as $T_c \sim t^{-6/19}$ for spherical symmetry and as $T_c \sim t^{-2/7}$ for cylindrical symmetry case. Space picture of plasma spot may be

very complex in real experiment. Simple formula for $T_c(t)$ allows to estimate a temperature with good accuracy.

Table presents same results of calculation [8]. A hot spot plasma parameters r_0 , T_{max} , z_{max} and surround plasma parameter z_0 are taken from experiments for nitrogen [9], neon [2] and helium [10]. Calculations 1-12 are for nitrogen, 1-8 in spherical symmetry and 9-12 in cylindrical symmetry, the electron density in hot spot is $N_e=2 \times 10^{20} \text{ cm}^{-3}$ and $z_{max}=7$. Calculations 13-18 are for neon in cylindrical, electron density in hot spot is $N_e=10^{20} \text{ cm}^{-3}$, $z_{max}=10$. Calculations 19-23 are for helium in cylindrical symmetry, electron density in hot spot is $N_e=6 \times 10^{19} \text{ cm}^{-3}$, $z_{max}=2$.

Recent studies have extended the validity of the electron conductivity equation in collisionless limit by using non local transport coefficients [11,12]. It makes possible using of the simple self similar solution in a weakly collisional regime.

4. Ionization cooling in heating wave

The velocity of heating wave is rapidly decreased after 30 - 100 μm in our plasma parameters of a hot spot and a background plasma. The ionization of surrounded gas by electron impact is a next possible cause of the hot spot cooling. For example, the time of ionization is $\tau_{ion}=1/\sigma_{ion}N_a v_e \approx 10 \text{ ps}$ and this time corresponds to the time of ionization cooling in heating wave.

5. Conclusion

The results of the estimations and calculation permit to do the following conclusion. The main reason of plasma electrons cooling of a hot spot of laser-produced multicharged ion plasma is electron conductivity in background cold plasma.

6. References

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Table

N	z_0	r_0 μm	T_{max} eV	$T_c(t)$, eV, at time (s)				
				10^{-13}	10^{-12}	10^{-11}	10^{-10}	10^{-9}
1	1	5	100	49	30	17	9	4
2	1	5	1000	121	62	31	15	7
3	5	5	100	91	51	27	13	7
4	5	5	1000	183	94	46	22	11
5	1	20	100	74	53	33	19	10
6	1	20	1000	254	138	71	36	18
7	1	5	100	60	42	26	15	8
8	1	5	1000	200	113	62	33	17
9	5	5	100	86	64	37	20	11
10	5	5	1000	272	146	77	40	21
11	1	20	100	82	64	45	29	17
12	1	20	1000	367	224	128	70	37
13	1	5	200	80	50	29	16	9
14	1	5	2000	218	119	63	33	17
15	8	5	200	141	78	42	22	1,7
16	8	5	2000	307	161	84	44	3
17	1	20	200	123	87	56	33	8
18	1	20	2000	431	246	135	72	38
19	1	2	100	42	24	13	7	4
20	1	2	500	77	41	22	12	6
21	0,1	2	100	26	15	8	5	2,4
22	0,1	2	500	48	26	14	73	4
23	0,1	10	500	07	61	34	18	9