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ON EFFICIENCY OF COLLISIONAL ENERGY EXCHANGE OF ELECTRONS AND IONS IN RELATIVISTIC PLASMAS

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The collisional coupling of the relativistic electrons and non-relativistic ions in hot plasmas has been analyzed. It was shown that the relativistic effects produce a quite new feature in the collisional transfer of energy from the electrons to ions with different temperatures. While in the non-relativistic limit the condition for absence of the collisional decoupling is $T_e/T_i < 3$, the relativistic effects shift the maximum of the energy-exchange with increasing the temperature to a higher values of T_e/T_i until it finally disappears that makes an appearance of the collisional decoupling impossible.
KEY WORDS: relativistic plasma, kinetics, collisional energy exchange, collisional decoupling

ПРО ЕФЕКТИВНІСТЬ ОБМІНУ ЕНЕРГІЄЮ ПРИ ЗІТКНЕННЯХ ЕЛЕКТРОНІВ ТА ІОНІВ У РЕЛЯТИВІСТСЬКІЙ ПЛАЗМІ

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У статті аналізується швидкість обміну енергією при зіткненнях між релятивістськими електронами та нерелятивістськими іонами у релятивістській плазмі. Показано, що релятивістські ефекти призводять до значних змінень у характері переносу енергії при зіткненнях від електронів до іонів з різними температурами. У той час як у нерелятивістській межі умовою стабільності енергообміну при зіткненнях є $T_e/T_i < 3$, урахування релятивістських ефектів призводить до зміщення максимуму швидкості обміну енергіями у напрямку більших значень T_e/T_i, доки не зникає взагалі, що робить втрату зв'язку при зіткненнях неможливою.
КЛЮЧОВІ СЛОВА: релятивістська плазма, кінетика, обмін енергією при зіткненнях

ОБ ЭФФЕКТИВНОСТИ СТОЛКНОВИТЕЛЬНОГО ЭНЕРГООБМЕНА ЭЛЕКТРОНОВ И ИОНОВ В РЕЛЯТИВИСТСКОЙ ПЛАЗМЕ

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В статье анализируется столкновительный энергообмен между релятивистскими электронами и нерелятивистскими ионами в горячей плазме. Показано, что релятивистские эффекты приводят к заметным изменениям в характере столкновительного переноса энергии от электронов к ионам с разными температурами. Тогда как в нерелятивистском пределе условием стабильности энергообмена является $T_e/T_i < 3$, учет релятивистских эффектов приводит к сдвигу максимума скорости обмена энергиями в сторону больших значений отношения T_e/T_i, пока не исчезает вовсе, что делает невозможным потерю столкновительной связи.
КЛЮЧЕВЫЕ СЛОВА: релятивистская плазма, кинетика, столкновительный обмен энергией

The relativistic effects were recognized as basics in astrophysics long time ago and necessary formalism for description of relativistic plasmas has been developed [1]. For the fusion reactions, sufficiently high temperatures are required [2] and careful consideration of the kinetics in hot plasmas is necessary. Apart from this, the production and heating of plasmas by the high-power laser pulse has been intensively studied [3] and it was shown that for the interpretation of an experimental results the relativistic effects are necessary [4,5].

The relativistic effects in hot plasmas created in a laboratory devices are usually considered as important only with respect to the populations of high-energetic electrons [2] while the macroscopic consequences of the relativistic effects have not been studied well. Only few tasks related to the relativistic effects in hot fusion plasmas were investigated: this is, in particular, solving the relativistic Spitzer problem for the calculation of conductivity [6] and electron cyclotron current drive; see [7] and the references therein.

A quite common opinion about a negligible role of the relativistic effects in plasmas without any non-thermal populations is based on the assumption that those are important only for the relativistic and ultra-relativistic electrons with energies $E \sim m_{e0}c^2$ and higher (for example, running-away electrons in tokamaks [8]), while the bulk electrons are rather non-relativistic even at high temperatures. At the same time, the relativistic effects can appear also due to a macroscopic features of the relativistic thermodynamic equilibrium given by the Jüttner distribution function [1], known also as relativistic Maxwellian [6]. In particular, contrary to the non-relativistic Maxwellian, the shape of the Jüttner-Maxwell distribution function, which is Gaussian only in the non-relativistic limit, $c\to\infty$, depends on the temperature and, as a consequence, the relative «weight» of the bulk electrons is decreasing with the increasing of the temperature. For example, it is known that for the electron temperature T_e even less than 10 keV a use of the relativistic kinetic model gives a non-negligible effect in electron cyclotron current drive (ECCD) [9], while the main contribution in generation of ECCD is coming from the thermal electrons (0.5-2.5 thermal velocities). However, all transport codes (like ASTRA [10]) are still non-relativistic.

In the present work, we focus our attention only at the collisional energy exchange between the relativistic electrons and the ions which are considered as non-relativistic (this is true for almost all fusion temperatures). It is known from the experiment [11] that if the power is launched in the plasma by heating of only the electrons, the collisional decoupling can happen, which means that the increasing of T_e leads to following degradation of collisional coupling between electrons and ions and T_e/T_i is increasing (here, T_i is the ion temperature).

Since the relativistic Coulomb operator is applied [6], an applicability of the results is limited by a validity of a small-angles scattering approach, $T_e/m_{e0}c^2 << (137\ \ln\Lambda)^{1/2}$ [12], while in the opposite case the bremsstrahlung and creation of the Coulomb pairs dominate (here, m_{e0} is the electron rest-mass and $\ln\Lambda$ is the Coulomb logarithm).

GENERAL DEFINITIONS

In fully ionized plasmas, the electrons heated by the external sources collide only with themselves and ions. Since the collisions within the same plasma components conserve the energy, the electron-electron collisions do not lead to any cooling down but only to the thermalization of the power absorbed from the external sources. Collisional energy losses for hot electrons appear only due to an electron-ion friction.

Below, we consider the electrons which can be heated by any external high-power source (for example, megawatt laser pulse or RF-heating) as relativistic, while the ions which obtain the energy predominantly by the collisions with hot electrons are classical. Here, we are going to check the relativistic effects of zeroth order and use the assumption about the thermal equilibrium within each plasma component, i.e. assuming that both electrons and ions have their own Maxwellian with the temperatures defined by the energy balance. The Maxwellian for the ions with density n_i and temperature T_i is taken as a standard one,

$$f_{Mi} = \frac{n_i}{\pi^{3/2} v_{ti}^3} e^{-(v/v_{ti})^2}, \tag{1}$$

where $v_{ti} = (2T_i/m_i)^{1/2}$ is the ion thermal velocity. The electrons with density n_e and temperature T_e are considered as relativistic with the Jüttner-Maxwellian distribution function [1,6],

$$f_{JMe} = C_{JM} \frac{n_e}{\pi^{3/2} u_{te}^3} e^{-\mu_r(\gamma-1)}, \tag{2}$$

where $u_{te} = p_{te}/m_{e0}$ with $p_{te} = (2m_{e0}T_e)^{1/2}$ is the thermal momentum per unit mass, $\mu_r = m_{e0}c^2/T_e$, and $\gamma = (1+u^2/c^2)$ with the momentum per unit mass $u = v\gamma$. Since f_{JMe} is normalized by density,

$$C_{JM} = \sqrt{\frac{\pi}{2\mu_r}} \frac{e^{-\mu_r}}{K_2(\mu_r)} \simeq 1 - \frac{15}{8\mu_r} + ...\ (\mu_r \gg 1). \tag{3}$$

Note also the important difference from the non-relativistic Maxwellian: since $\mu_r(\gamma-1) = 2x^2/(\gamma-1)$ with $x = u/u_{te}$, the "weight" of the tails with $u >> u_{te}$ is increasing together with T_e.

The energy balance equation in the relativistic plasmas can be presented in the same form as the well-known non-relativistic one. In contrast to the linear dependence between temperature and internal energy contained in Maxwell distribution function, $W_e^{(cl)} = \int (m_{e0}v^2/2) f_{Me} d^3v = (3/2)n_e T_e$ (similar definition with arbitrary distribution function of electrons was used by Braginskii [13]), internal energy contained in Jüttner-Maxwellian distribution function, $W_e = \int m_{e0}c^2(\gamma-1) f_{JMe} d^3u$, is the complex function of temperature. It is convenient then to introduce a new quantity T_e^R defined by $W_e = (3/2)n_e T_e^R$, which is a relativistic analogue of a temperature

$$T_e^R = \frac{2}{3n_e}\int m_{e0}c^2(\gamma-1)\, f_{JMe} d^3u = (1+r)T_e, \tag{4}$$

with relativistic correction-term

$$r(\mu_r) = \frac{2\mu_r}{3}\left(\frac{K_3(\mu_r)}{K_2(\mu_r)} - 1\right) - \frac{5}{3} \simeq \frac{5}{4\mu_r} + ...\ (\mu_r \gg 1). \tag{5}$$

Now, weighting the relativistic kinetic equation for electrons [6,12] (not shown here) by the kinetic energy, $m_{e0}c^2(\gamma-1)$, and integrating over the momentum, one can obtain the energy balance equation,

$$\frac{\partial W_e}{\partial t} = \frac{3}{2}\frac{\partial n_e T_e^R}{\partial t} = -P_{ei} + P_{ext} - P_{loss}, \tag{6}$$

where P_{ei} is the rate of energy exchange between the relativistic electrons and classical ions, P_{ext} is the power of the external heating (laser pulse or RF-heating) and P_{loss} is the total energy losses of the electrons (including radiation and transport losses). Below, we consider only the case which is the most desirable for experiments: the heating of electrons is balanced predominantly by the collisional transfer of power to the ions, i.e. $|P_{ei}| >> |P_{loss}|$.

COLLISIONAL ENERGY EXCHANGE IN RELATIVISTIC PLASMAS

Let us consider the collisional energy exchange between relativistic electrons and classical ions. For the electrons and ions with own Maxwellians f_{JMe} and f_{Mi} the rate of energy exchange is

$$P_{ei} = -\int d^3u\, m_{e0}c^2(\gamma-1)C_{ei}[f_{JMe},\ f_{Mi}]. \tag{7}$$

Applying the relativistic collision operator written in the Fokker-Planck form [6,12],

$$C_{ei}[f_{JMe}, f_{Mi}] = \frac{\partial}{\partial u_\alpha}\left(D_{\alpha\beta}^{\ e/i}\frac{\partial f_{JMe}}{\partial u_\beta} - F_\beta^{\ e/i} f_{JMe}\right), \tag{8}$$

where $D^{e/i}_{\alpha\beta}(u)$ and $F^{e/i}_{\beta}(u)$ are the Coulomb diffusion and friction coefficients, respectively, integrating by parts and taking into account the relation $D^{e/i}_{uu} = -(T_i/m_e)(\gamma/u)F^{e/i}_u$, which nullifies for the thermal equilibrium the local phase-space flux, given in the brackets in Eq. (8), one can obtain the rate of energy exchange between the relativistic electrons and ions,

$$P_{ei} = -4\pi m_{e0}\frac{T_e - T_i}{T_e}\int_0^\infty \frac{u^3}{\gamma}F_u^{e/i}(u) f_{JMe}(u)du, \tag{9}$$

where $F^{e/i}_u(u)$ is the Coulomb drag of the relativistic electrons with ions. Since $m_i >> m_e$, the main contribution in the integral in Eq. (7) is coming from the range $u >> v_{ti}$, and for the non-relativistic ions the "high-speed-limit" expression for $F^{e/i}_u(u)$ can be applied [6],

$$F_u^{e/i}(u) \simeq -\nu_{e0}u_{te}^3\frac{n_iZ_i^2}{n_e}\frac{m_e}{m_i}\frac{\gamma^2}{u^2}. \tag{10}$$

The final expression for the rate of energy exchange can be written in the form

$$P_{ei} \simeq P_{ei}^{(cl)}C_{JM}(\mu_r)\left(1 + \frac{2}{\mu_r} + \frac{2}{\mu_r^2}\right), \tag{11}$$

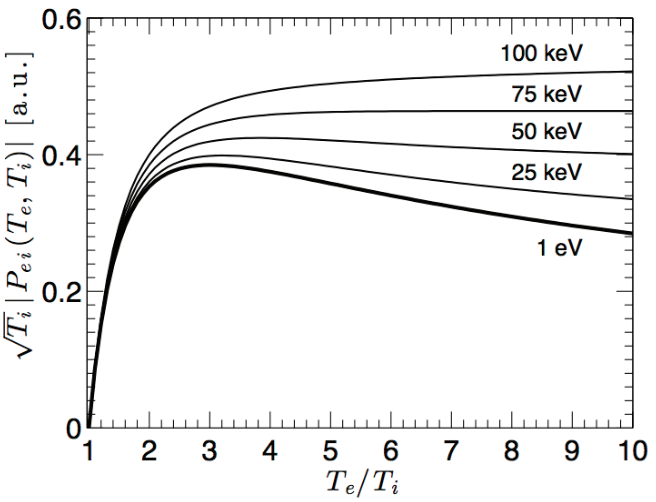


Fig.1. The absolute value of the rate of energy e/i exchange, $|P_{ei}(T_e,T_i)|$ scaled by $(T_i)^{1/2}$, as function of T_e/T_i for the different values of T_i is shown (T_i = 1 eV corresponds to the non-relativistic limit).

where $P_{ei}^{(cl)} = (4/\pi^{1/2})\nu_{e0}n_iZ_i^2(m_e/m_i)(T_e-T_i)$ is the classical (non-relativistic) rate of energy exchange, $\nu_{e0} = 4\pi n_e e^4\ln\Lambda/(m_{e0}^2u_{te}^3)$ is the thermal collision frequency and the relativistic correction in Eq. (11) is equal to unity in the non-relativistic limit.

In Fig. 1, the value $T_i^{1/2}|P_{ei}(T_e,T_i)|$ is plotted as a function of T_e/T_i. The scaling factor $T_i^{1/2}$ was applied only for convenience of graphical presentation and does not introduce any qualitative changes (one can find the weighting of P_{ei} by factor $T_i^{1/2}$, for example, in review of Sivukhin [15]). The results are shown for T_i equal to 1 eV (chosen as non-relativistic case), 25 keV, 50 keV, 75 keV and 100 keV. One can see that with increase of the ion temperature, the maximum of $|P_{ei}|$ is shifting towards the higher values of T_e/T_i.

The expression given in Eq. (11) is limited only by the "high-speed-limit" in e/i collision coefficients and can be used for wide temperature range from non-relativistic to high-energy limit $T_e < mc^2$, while the small-angles scattering approach is still valid.

STABILITY OF COULOMB COUPLING OF RELATIVISTIC ELECTRONS AND IONS

In the simplest case, when T_i is constant in time, one can easily find from the energy-balance equation Eq. (6) that stability of the steady state with respect to the collisional decoupling is defined by the sign of dP_{ei}/dT_e. Indeed, if the set of plasma parameters corresponds to a steady state, $-P_{ei} + P_{ext} - P_{loss} = 0$, the equation for deviation of the electron temperature from the steady state, $\delta T_e = T_e - T_{e0}$, can be written as follows:

$$\frac{3}{2}(1+\alpha)n_e\frac{\partial \delta T_e}{\partial t} = -\frac{dP_{ei}}{dT_e}\delta T_e, \tag{12}$$

where $\alpha = r + T_e(dr/dT_e) << 1$; see Eq. (4). It is evident that any steady state is absolutely stable with respect to collisional decoupling (growth of δT_e together with dropping P_{ei}) only if $dP_{ei}/dT_e > 0$ and unstable for the opposite sign.

It can be shown that the sign of dP_{ei}/dT_e is definitive for stability with respect to the collisional decoupling also for more complicated model. Let us analyze the case, which is of practical interest, namely: the power from the external source, P_{ext}, is absorbed only by electrons (electron cyclotron heating, for example) and ions are heated only due to the collisions with hot electrons. Moreover, we assume a most wanted situation when any losses from electrons are small and the power balance is kept only through the ion channel. The energy balance equations then can be written as follows:

$$\frac{\partial W_e}{\partial t} = P_{ext} - P_{ei}; \qquad \frac{\partial W_i}{\partial t} = P_{ei} - \frac{W_i}{\tau_E}, \tag{13}$$

where $W_e = (3/2)n_e T_e^R$ and $W_i = (3/2)n_i T_i$ are the internal energies for (relativistic) electrons and ions, respectively, and τ_E is the confinement time. Again, considering the deviation from the steady state, $P_{ext} - W_i/\tau_E = 0$, which is realized in the temperature disturbances for both electrons and ions, δT_e and δT_i, one can get the system of coupled equations:

$$\begin{aligned} &\frac{3}{2}(1+\alpha)n_e \frac{\partial \delta T_e}{\partial t} = -\frac{dP_{ei}}{dT_e}\delta T_e - \frac{dP_{ei}}{dT_i}\delta T_i, \\ &\frac{3}{2}n_i \frac{\partial \delta T_i}{\partial t} = \frac{dP_{ei}}{dT_e}\delta T_e + \frac{dP_{ei}}{dT_i}\delta T_i - \frac{3}{2}n_i \frac{\delta T_i}{\tau_E}. \end{aligned} \tag{14}$$

Since dP_{ei}/dT_i is always negative and never turns to zero, it is convenient to abbreviate $\beta = -(2/(3n_e))dP_{ei}/dT_i$ and normalize the Eq. (14) by β (we assume for simplicity that $n_e = n_i$). Finally, the system of equations can be rewritten as follows:

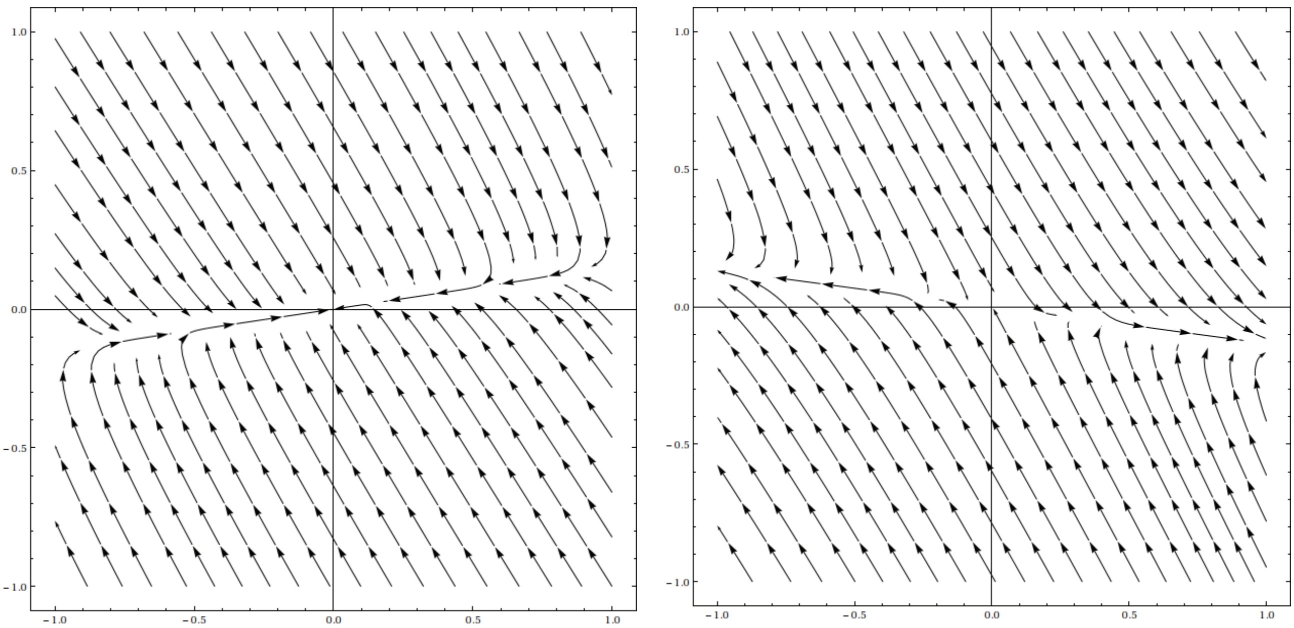
$$\begin{aligned} &\frac{\partial \delta T_e}{\beta \partial t} = +\Omega \frac{\delta T_e}{1+\alpha} + \frac{\delta T_i}{1+\alpha}, \\ &\frac{\partial \delta T_i}{\beta \partial t} = -\Omega \delta T_e - \nu^* \delta T_i, \end{aligned} \tag{15}$$

where $\Omega = -2/(3n_e\beta)\, dP_{ei}/dT_e$ and $\nu^* = 1 + (\tau_E\beta)^{-1}$. Since $\alpha << 1$ and $\nu^* \geq 1$, the single parameter which is responsible for qualitative behaviour of the solution is sign of Ω. If Ω is negative, i.e. $dP_{ei}/dT_e > 0$, the solution is stable with respect to collisional decoupling. If Ω is positive, i.e. $dP_{ei}/dT_e < 0$, – the decoupling is possible.

Below, the system Eq. (15) is examined in the non-relativistic approach for the cases of negative and positive Ω. Since in the non-relativistic limit $\alpha = 0$ and $\Omega = (x-3)/2x$ with $x = T_e/T_i$, the equations are simplified. Introducing convenient new abbreviations $u = \delta T_e/T_{e0}$ and $v = \delta T_i/T_{e0}$, and denoting the operation $d/d(\beta t)$ by the dot, we obtain the equations,

$$\begin{aligned} \dot{u} &= +\Omega u + v, \\ \dot{v} &= -\Omega u - \nu^* v. \end{aligned} \tag{16}$$

Let us consider Eq. (16) for two cases, $\Omega = -0.25$ (stable) and $\Omega = +0.25$ (unstable) with $\nu^* = 1.25$. The phase-portraits of the system Eq. (16) are shown in Fig. 2a and Fig. 2b. In both figures x-axis corresponds to u and y-axis corresponds to v. Axes are given in arbitrary units.



a) b)

Fig.2. The phase-portrait of Eq. (16)
a) $\Omega = -0.25$ and $\nu^* = 1.25$: stable solution, b) $\Omega = +0.25$ and $\nu^* = 1.25$: unstable solution

The phase-portraits of the considered system were obtained by solving Eq. (16) with the initial conditions distributed on the plane (u, v). One can see from Fig. 2a that all the phase-lines returns to zero with $t \to \infty$, independently of the initial conditions for $u(0)$ and $v(0)$. It means that the solution of Eq. (16) calculated with $\Omega = -0.25$ (this value corresponds to $x = 2$, i.e. $T_e = 2T_i$) is absolutely stable. Note that we do not discuss here a feature of the solution but only a tendency. The opposite case, with $\Omega = +0.25$ (i.e. $x = 6$ and $T_e = 6T_i$) is shown in Fig. 2b. In this case, all the phase-lines are going to infinity with $t \to \infty$ practically with any initial conditions (apart from one specific phase-line which corresponds to the exclusive quasi-stable solution). Neither asymptotic solution nor quasi-stable one are not interesting in the context of the considered problem and are not studied here.

INFLUENCE OF RELATIVISTIC EFFECTS ON STABILITY CRITERIA

Physically, the condition for collisional decoupling, $dP_{ei}/dT_e < 0$, means that if the ions are heated only by the drag with hot electrons, i.e. without any auxiliary ion heating, the positive feedback can appear leading to the new steady state with $T_e >> T_i$ stabilized by other factors not considered here. Experimentally, the collisional decoupling was observed predominantly in low density discharges [11,14]. Important remark: this instability takes place *only* in the case if the temperature dependencies of the heating and the loss terms responsible for the steady state are sufficiently weak (for example, if the gradients of plasma parameters are small enough and the diffusive transport is suppressed), otherwise this instability is not mandatory but still potentially danger. The case, when the collisional transfer of energy to the ions is of minor importance and heating of electrons is balanced predominantly by transport or emission, i.e. $|P_{ei}| << |P_{ext}|, |P_{loss}|$, is one of the most unwanted scenarios for experiment.

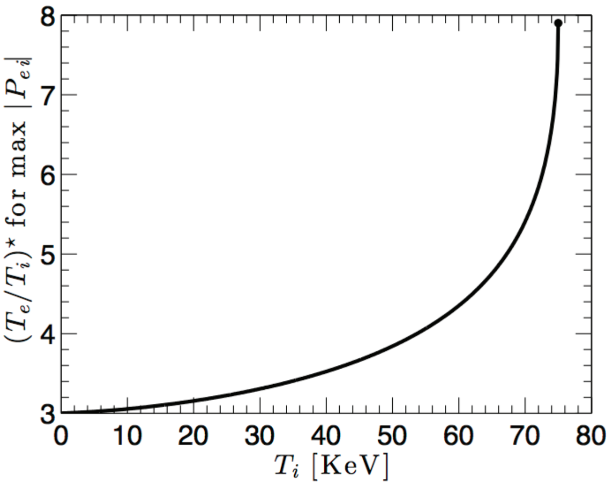


Fig.3. The ratio $(T_e/T_i)^*$, which corresponds to the maximum of $|P_{ei}|$ as the function of the ion temperature T_i. The area under the line corresponds to a stable collisional coupling between the electrons and ions, and vice versa.

Let us analyze the classical (non-relativistic) limit. Since the temperature dependence of $P_{ei}^{(cl)}$ can be written explicitly as $P_{ei}^{(cl)} \propto (T_e - T_i)/T_e^{3/2}$, one can immediately recognize that $dP_{ei}^{(cl)}/dT_e$ changes sign at the point $T_e^* = 3T_i$ (temperature threshold). As consequence, the heating of plasma by electrons is absolutely stable with respect to the collisional decoupling if $T_e < 3T_i$. In the opposite case, any increasing of the electron temperature leads (if any other factors do not prevent this) to a degradation of the collisional energy transfer from electrons to the ions. It is also known that in the ultra-relativistic case, the temperature dependence of $P_{ei}^{(ur)}$ is the monotonic function of temperature, $P_{ei}^{(ur)} \propto (T_e - T_i)/T_e$, and the energy transfer from electrons to ions is absolutely stable with respect to collisional decoupling in this limit. Now, by means of analysis of Eq. (11), one can connect both limits to find out what happens to the temperature threshold when the temperatures are increasing from non-relativistic to sufficiently high values for which the relativistic effect becomes important.

In Fig. 3 the maximum of P_{ei} is plotted as a function of T_e/T_i. One can see that the maximum of P_{ei} disappears for $T_i \approx 75$ keV when P_{ei} becomes a monotonically increasing function of T_e/T_i (see also Fig. 1). In this limit, the collisional energy exchange between electrons and ions becomes absolutely stable and the collisional decoupling becomes impossible at such temperatures.

SUMMARY

It is well known from experiments that the collisional decoupling has the temperature threshold. However, different conditions of the experiments made the threshold sufficiently varying value. In this paper, an exact definition for the threshold defined solely by the feature of the Coulomb interaction is given.

The case when the collisional transfer of power from the hot electrons to ions is the dominant channel for balancing the heating of electrons, which is the most critical from the point of view of possible collisional decoupling, is considered. The opposite case, when the collisions are of minor importance and heating of electrons is balanced by transport and/or emission, is not considered here being one of the most unwanted scenarios for experiment. It was shown that the sign of dP_{ei}/dT_e is definitive for stability of plasma with respect to collisional decoupling.

A specific feature of the rate of energy exchange between the relativistic electrons and non-relativistic ions with own Maxwellians has been studied. It was shown that while in the non-relativistic plasmas the condition for stable collisional coupling is $T_e/T_i < 3$, the relativistic effects lead to a significant improvement of the Coulomb coupling between the electrons and ions and for the sufficiently high temperatures ($T_{e,i} > 75$ keV) the Coulomb coupling becomes absolutely stable with respect to the collisional decoupling. It means that in the scenarios with heating of plasma exclusively by the heating of electrons, the collisional decoupling has the temperature threshold shown in Fig.3, and for higher temperatures the decoupling cannot appear anymore.

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REFERENCES

1. de Groot S.R., van Leewen W.A., van Weert Ch.G. Relativistic Kinetic Theory. – North-Holland Publishing Company, Amsterdam, 1980.
2. Ward D.J. The physics of DEMO // Plasma Phys. Control. Fusion. – 2010. – Vol.52. – P.124033
3. Dunne M. A high-power laser fusion facility for Europe // Nature Physics. – 2006. – Vol.2. – P.2-5.
4. Honda M., Mima K. Relativistic Effects on Transport Coefficients in Collision Dominant Magnetoactive Plasmas // J. Phys. Soc. Jpn. – 1998. – Vol.67. – P.3420-3428.
5. Robiche J., Rax J.M. Relativistic kinetic theory of pitch angle scattering, slowing down, and energy deposition in a plasma // Phys. Rev. E. – 2004. – Vol.70. – P.046405.
6. Braams B.J. and Karney C.F.F. Conductivity of a relativistic plasma // Phys. Fluids B. – Vol.1. – 1989. – P.1355-1368.
7. Marushchenko N.B. et al. Electron cyclotron current drive in low collisionality limit: on parallel momentum conservation. // Phys. Plasmas. – Vol.18. – 2011. – P.032501.
8. Helander P., Eriksson L.G., Andersson F. Runaway acceleration during magnetic reconnection in tokamaks // Plasma Phys. Control. Fusion. – 2002. – Vol.44. – P.B247.
9. Karney C.F.F., Fisch N.J., Reiman A.H. Green's function for RF driven current in a toroidal plasma // AIP Conf. Proc. – 1989. – №190. – P.430.
10. Pereverzev G.V., Yushmanov P.N. ASTRA: Automated System for Transport Analysis in Tokamak. – Max-Planck Institute Report IPP 5/98, 1998.
11. Braun D.G., Emmert G.A. Time evolution of ECRH power deposition in a tandem mirror plasma // Nuclear Fusion. – 1984. – Vol.24. – P.1393-1406.
12. Beliaev S.T., Budker G.I. Relativistic Kinetic Equation // Sov. Phys. Dokl. – 1956. – Vol.107. – P.807-810.
13. Braginskii S.I. Reviews of Plasma Physics/ ed. by M. A. Leontovich. – Consultants Bureau, New York, 1965. – Vol.1. – P.205.
14. Stroth U. et al. Recent Transport Experiments in W7-AS on the Stellarator-Tokamak Comparison // Physica Scripta. – 1995. – Vol.51. – P.655-664.
15. Sivukhin D.V. Reviews of Plasma Physics/ ed. by M. A. Leontovich. – Consultants Bureau, New York, 1966. – Vol.4. – P.93.

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