MATERIALS.
TECHNOLOGIES.
DESIGN

УДК 533.9, 621.039.6
P.A.C.S. 52.25.Xz, 52.65.-y, 52.77.-j
DOI 10.54708/26587572_2023_5515140

INFLUENCE OF BREMSSTRAHLUNG ON THE HEAT BALANCE OF HIGH-TEMPERATURE PLASMA

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ABSTRACT

The bremsstrahlung in the heat balance of a high-temperature plasma is soft X-ray, which cannot be directly converted into electricity, as is possible in the case of charged particle energy or cyclotron radiation. Bremsstrahlung is the main radiation mechanism at temperatures of several keV. For the operating temperatures of alternative fuel reactors, calculations of relativistic electron bremsstrahlung have been performed and approximating formulas have been obtained. The radiation losses are given depending on the plasma radius and the temperature.

KEYWORDS

Bremsstrahlung; fusion; plasma; radiation.

ВЛИЯНИЕ ТОРМОЗНОГО ИЗЛУЧЕНИЯ НА ТЕПЛОВОЙ БАЛАНС ВЫСОКОТЕМПЕРАТУРНОЙ ПЛАЗМЫ

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АННОТАЦИЯ

Тормозным излучением в тепловом балансе высокотемпературной плазмы является мягкое рентгеновское излучение, которое не может быть непосредственно преобразовано в электричество, как это возможно в случае энергии заряженных частиц или циклотронного излучения. Тормозное излучение является основным механизмом излучения при температурах в несколько кэВ. Для рабочих температур реакторов на альтернативном топливе были выполнены расчеты тормозного излучения релятивистских электронов и получены аппроксимирующие формулы. Потери на излучение приведены в зависимости от радиуса плазмы и температуры.

КЛЮЧЕВЫЕ СЛОВА

Рентген; плазма; излучение.

Introduction

When the plasmoid is compressed by a plasma/solid liner or beams/jets and heated almost adiabatically to the conditions of thermonuclear combustion, the magnetic field is compressed too, increasing its values to the level of megagauss [1, 2]. Compression is considered almost adiabatic due to the presence of a megagauss magnetic field, which restrains electronic and thermal conduction, reduces losses by several orders of magnitude; the plasma density at the center remains relatively low, so the losses due to bremsstrahlung are low.

As a result of considering the processes occurring in a system with plasma jets to calculate the main parameters included in the power balance and making the main contribution to energy and physics, it was concluded that the characteristics of the magnetic configuration can significantly affect the confinement of the plasma core and, accordingly, the energy data of the system. And one of the main specific losses in the heat balance of the plasma core are radiation losses P_{rad}.

1. Considering reactions

Braking losses are soft X-rays that cannot be directly converted into electricity, as is possible in the case of charged particle energy or cyclotron radiation. Bremsstrahlung is the main radiation mechanism at temperatures of several kiloelectron volts (keV) and can be estimated with good accuracy for both epithermal particles and nonthermal electrons [3–7].

The following thermonuclear reactions are considered, which have radioactive elements neither among the fuel nor among the fusion products:

$$ {}^{2}_{1}D + {}^{3}_{2}He \rightarrow {}^{1}_{1}p + {}^{4}_{2}He + 18.3\ \text{MeV}, $$

$$ p + {}^{6}Li \rightarrow {}^{4}He\ (1.7\ \text{MeV}) + {}^{3}He\ (2.3\ \text{MeV}). $$

In addition to the fact that the last reaction proceeds with the release of 4.02 MeV energy, it can also result in the production of the helium isotope (^{3}He) under terrestrial conditions.

2. Power balance

The power balance of the plasma core can be represented by the statement

$$ P_{fus} + P_{in} = P_q + P_n + P_b + P_s, $$

where P_f is the fusion power, P_{in} is the injection (additional heating), P_q is the energy loss of charged particles due to diffusion, P_n is the neutron power, P_b is the bremsstrahlung radiation and P_s is the cyclotron radiation losses.

The specific value (per unit volume) of the fusion power corresponding to thermonuclear energy release can be written as

$$ P_{fus} = (\beta \cdot B^2/2\mu_0)^2 \cdot <\sigma v> \cdot E_f/(T^2 \cdot Z^2), $$

where $\beta(r) = p(r)/(B_e^2/2\mu_0)$ is the ratio of internal magnetic field to external field, B is the magnetic induction, $\mu_0=4\pi(10^{-7})=1{,}26\cdot 10^{-6}$ H/m is the magnetic constant (permeability), $<\sigma v>$ is the thermonuclear reaction rate, E_f is the energy of a particular fusion reaction.

The specific bremsstrahlung (radiation during electron deceleration on other particles), taking into account the relativistic correction, was equally defined as [8]

$$ p_b = $$

$$ = 0.00536 n_e^2 \sqrt{T_e} \begin{bmatrix} z_{eff} + \left(0.00155 z_{eff} + 0.00414\right) T_e \\ + 7.15(10^{-6}) z_{eff} T_e^2 + 0.071 z_{2eff} / \sqrt{T_e} \end{bmatrix}. $$

Radiation losses are the sum of bremsstrahlung and cyclotron radiation, respectively

$$ P_{rad} = P_b + P_s. $$

Fig. 1 illustrates the radiation loss as a function of the radius of a shrinking magnetized plasma for a magnetic trap, specifically a compact torus. Temperature and concentration increase as the plasmoid is compressed, as shown in Ref. 7, $T = T_0(V_0/V)^{\gamma-1}$ and $n = n_0(V_0/V)$, where T_0, n_0 and V_0 are the initial temperature, concentration and volume of the plasma configuration. In the particular case of no energy loss from the plasma, the pressures of the gas and magnetic components change according to the adiabatic law with the adiabatic exponents: for gas $\gamma = 5/3$ and magnetic field $\gamma = 4/3$ (the case of isotropic spherical compression) [8, 9]. The bremsstrahlung power is shown in Fig. 2.

Losses due to cyclotron radiation are negligible compared to the rest, especially for systems with high beta (the ratio of plasma pressure to the pressure of an external magnetic field), which is typical for compact systems such as a torus or a mirror cell. Therefore, this type of energy is taken equal to 0, i.e. $P_{rad} = P_{br}$.

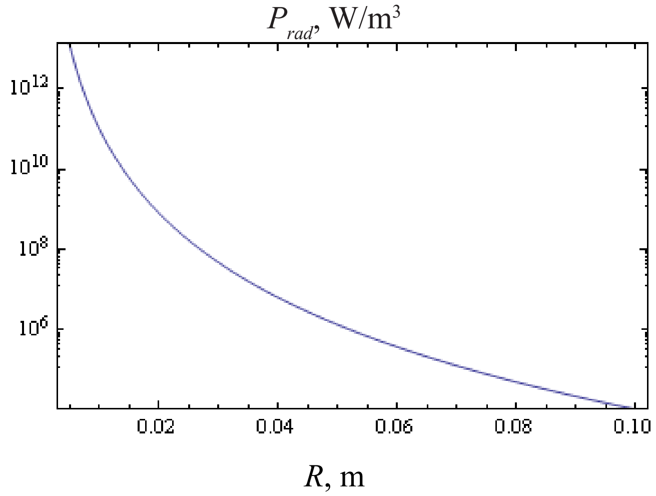

Fig. 1. Radiation losses depending on the compact torus plasma radius R. Initial plasma parameters $T_0 = 2$ eV, $n_0 = 10^{21}$ m^{-3}

Рис. 1. Потери излучения в зависимости от радиуса плазмы компактного тора R. Исходные параметры плазмы $T_0 = 2$ эВ, $n_0 = 10^{21}$ м$^{-3}$

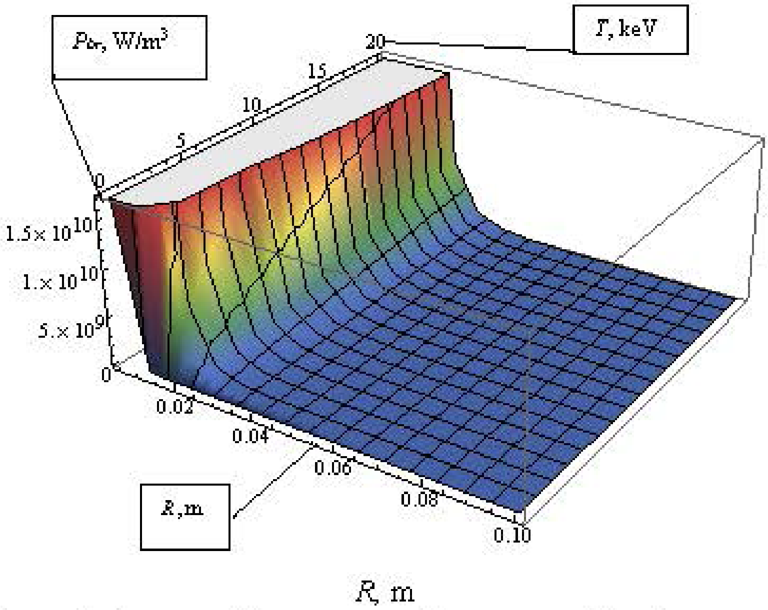

Fig. 2. Volumetric bremsstrahlung power of a compressible plasma as a function of the plasma radius and temperature of the magnetized plasma

Рис. 2. Объемная мощность тормозного излучения сжимаемой плазмы в зависимости от радиуса плазмы и температуры намагниченной плазмы

The absorption coefficient of laser radiation is determined using the mechanism of continuum absorption, which is inverse to the mechanism of electron bremsstrahlung under conditions of local thermodynamic equilibrium [10]:

$$\chi_\omega = \frac{4{,}97 g Z_i n_i n_e}{n_c^2 \lambda^2 \left(kT_e\right)^{3/2}} \frac{1}{\sqrt{1-n_e/n_c}},$$

where λ is the laser radiation wavelength (μm), n_e, n_i are the concentration of electrons and ions (cm^{-3}), kT_e is the electron temperature (keV), $n_c = 10^{21} \times \lambda^{-2}$ is the critical electron concentration (cm^{-3}), $g = \frac{\sqrt{3}}{\pi} n\left(\frac{4kT_e}{e^2\left(n_e\right)^{1/3}}\right)$ is the Gaunt factor [11], which distinguishes the quantum expression for the absorption coefficient of laser radiation from the classical relation. The above expression for the absorption coefficient is valid in the region in which the electron concentration of the substance $n_e^\Sigma = Z\frac{\rho}{M_\Sigma}$, $M_\Sigma = A \cdot m_p$ does not exceed the critical electron concentration $n_c = \frac{m_e}{4\pi e^2}\left(\frac{2\pi c}{\lambda}\right)^2$. In this case, it is generally accepted that radiation reaching a point in space in which $n = n_c$ is reflected and does not pass further into the target, which is sometimes modeled by the complete absorption of radiation [12]:

$$\chi_\omega = \begin{cases} \frac{4{,}97 g Z_{\grave{u}}^2 n^\Sigma n^\Sigma}{n_c^2 \lambda^2 \left(kT_e\right)^{3/2}} \frac{1}{\sqrt{1-n_e^\Sigma/n_c}}, n_e^\Sigma < n_c \\ \infty, n_e^\Sigma \geq n_c \end{cases}.$$

3. Main results

Below are comparative characteristics for D-^{3}He plasma (thick lines) and D-^{3}He-^{6}Li cycle (thin lines). Two extreme cases are specially selected: the minimum and maximum (from the considered range) values of the magnetic field B and beta.

As follows from Figs. 3–5, D-^{3}He plasma has a large energy release compared to the D-^{3}He-^{6}Li mixture, and the last cycle has large radiation losses. In any case, from the energy point of view, the D-^{3}He thermonuclear cycle is more promising. But in order to conclude about the advantage of one or another fuel, it is necessary to consider a reactor model with all costs and a full assessment of its energy efficiency.

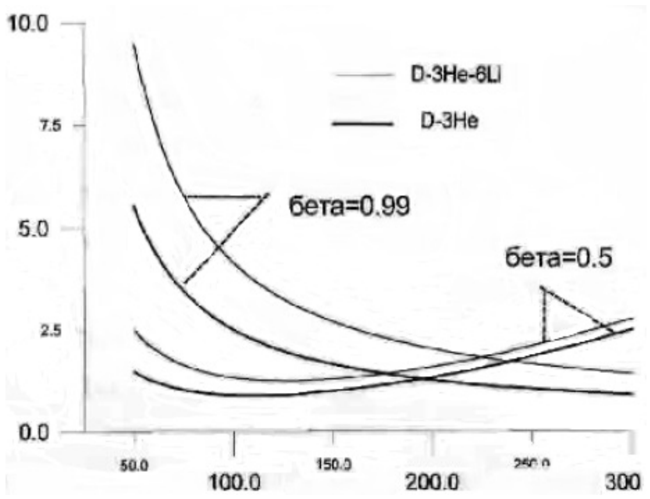

Fig. 3. Losses due to bremsstrahlung and cyclotron radiation (MW/m^3) as a function of plasma temperature (keV)

Рис. 3. Потери из-за тормозного излучения и циклотронного излучения (МВт/м^3) в зависимости от температуры плазмы (кэВ)

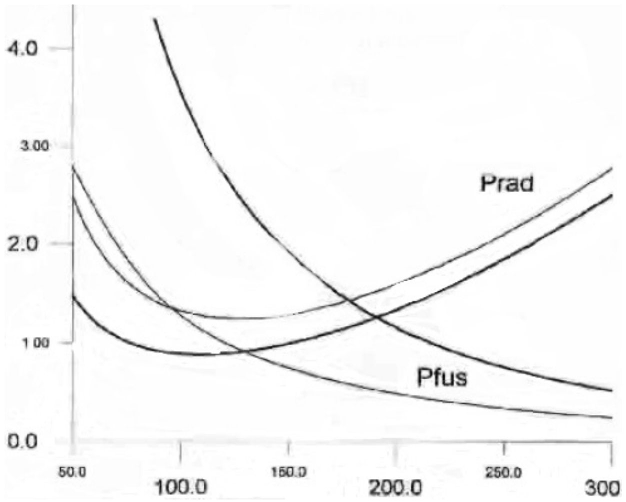

Fig. 4. Comparison of specific energy release P_{fus} and radiation losses P_{rad} (MW/m^3) for B = 5 T and beta = 0.5 for D-^{3}He and D-^{3}He-^{6}Li plasma

Рис. 4. Сравнение удельного энерговыделения P_{fus} и потерь на излучение P_{rad} (МВт/м^3) для B = 5 Тл и beta = 0,5 для D-^{3}He и D-^{3}He-^{6}Li реакций

It can be seen from Fig. 4 that both for D-^{3}He plasma and for the D-^{3}He-^{6}Li complex there are regions where the value of $\xi = P_{rad}/P_{fus} < 1$. For D-^{3}He this range is up to 190 keV, and with ^{6}Li – up to 90 keV. Therefore, theoretically, it is possible to ignite the reaction cycle D, ^{3}He, ^{6}Li and use it in thermonuclear fusion [13–16].

Conclusions

The bremsstrahlung power depends on the temperature and electron concentration and does not depend on the shape and size of the plasma formation, in contrast to cyclotron losses, which are also determined by the values of the magnetic field, which is essential for the magneto-inertial regime [17–20]. But taking into account the current level of development of science and technology, it is believed that cyclotron radiation almost completely returns to the plasma, since average absorption of radiation by plasma during multiple reflections from walls ~0.9. Or in other words, the coefficient of reflection from the walls is ~0.9, i.e. the power of cyclotron losses can be neglected.

The D-T reaction dominates fusion research because has the highest reaction rate. However, D-3He and p-11B reduce neutron production and are environmentally friendly fusion reactions. The main characteristics of installations/projects on low-radioactive D–3He fuel in terms of radiative heat transfer, and first of all, bremsstrahlung, are presented in Figs. 1 and 2. Interest in them is shown by venture capital companies and start-ups financed from private sources. P-11B fuel has no restrictions, but at a temperature corresponding to the maximum energy release rate (~300 keV), the plasma is characterized by huge energy losses due to bremsstrahlung, making it impossible to maintain the reaction.

For the operating temperatures of alternative fuel reactors, calculations of relativistic electron bremsstrahlung have been performed and approximating formulas have been obtained [21–24]. The stellarator and compact torus have the highest plasma temperatures and the lowest bremsstrahlung fraction.

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