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On the Influence of Synchrotron Radiation on the Confinement Properties of Field Reversed Configuration in a D-^{3}He Fusion Reactor

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Abstract

The possible influence of synchrotron radiation on confinement properties of Field Reversed Configuration (FRC) with reactor relevant parameters has analysed.

The numerical calculation of synchrotron radiation parameters for FRC with reactor relevant parameters for D-^{3}He fuel was performed self-consistently with plasma particle and energy transport processes. It was supposed that last one is determined by plasma diffusion under Lower Hybrid Drift (LHD) instability development.

It is shown that such type radiation losses do not influence essentially on temperature and plasma pressure spatial distribution in FRC and, as a result, on energy and particle life-time at variation of fusion parameters in the range $n\tau T = 10^{23} - 10^{24}$ m^{-3}·s·keV.

Keywords:

Field Reversed Configuration, D-^{3}He fuel, synchrotron radiation, particle and energy transport

1. Introduction

Fusion reactor with D-^{3}He fuel is very attractive from the viewpoint of the satisfaction of ecological aspects of fusion power generation. Main components of such fuel are nonradioactive and d(^{3}He,α)p fusion reaction is aneutronic. But the needed level of both plasma temperature ($T_i \approx 50$–100keV) and confinement parameter ($n\tau \geq 10^{21}$ m^{-3}s) is high in this case. It results in the necessity to use magnetic field up to $B \approx 40$ T to confine plasma with such parameters in magnetic configuration with low β (e.g. in tokamak). Intensity of synchrotron radiation is proportional to n^2T^2/β and it is very high under these conditions. Positive energy balance can be achieved in the system with low β only in the case of effective utilisation of synchrotron radiation power, that seems at present as unreal problem. That is why D-^{3}He reactor on the base of magnetic configuration with low β has a lot of technological complexities.

In the case of using magnetic configurations with high β, the power of synchrotron radiation losses falls down and for some type of configurations, for example for Field Reversed Configuration (FRC), one can neglect them in the energy balance. First estimations [1] show that these losses in FRC with reactor relevant parameters are little in comparison with bremstrahlung radiation. Main cause of this fact is connected with β distribution in FRC. Nevertheless the level of this radiation power has a finite value. For typical β distribution only narrow area, which situated between magnetic axis and separatrix, can radiate effectively. But these estimations were rough enough and did not take into account influence of these losses on plasma

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transport. The last is dramatically important for FRC-based reactor, because strongly influences on economical factors. So, for PULSATOR concept of quasi-stationary maintaining of magneto-plasma configuration with periodical injection and merging of FRCs [2], the main FRC plasma confinement falling-off results in the necessity to increase the frequency of FRCs injection. That is why the main goal of this work is to make more accurate calculation of FRC synchrotron radiation losses self consistently with plasma particle and energy transport.

2. Calculation Model

Power of synchrotron radiation Q_r is proportional to B^2nT_e (B-magnetic field; n, T_e-plasma density and electron temperature). Taking into account relations: $B^2 = B_e^2(1-\beta)$ and $n(T_e+T_i) = B_e^2\beta/2\mu_o$ (here B_e-external magnetic field) one can see that $Q_r = Q_{rmax}$ for $\beta = 1/2$. It means that, if synchrotron radiation influences on plasma parameters, only area near the separatrix will be cooled for typical FRC β-distribution. But the processes in this area are most important from the viewpoint of confinement properties of FRC. To estimate the conditions, when influence of synchrotron radiation is essential, we propose, following the analysis of Ref. [3], that particle and energy lifetime are determined by plasma diffusion due to Lower-Hybrid Drift (LHD) instability development. Under such proposals energy transport depends mainly on plasma diffusion and energy balance equation can be written as:

$$3n_m\langle\beta\rangle \, dT/du = Q_r\tau_N \qquad (1)$$

here: n_m-plasma density on the magnetic axis; τ_N-particle lifetime; $u = (r/R)^2 - 1$; R-magnetic axis radius. As far as $Q_r = C\alpha_{\varpi}B^2nT$, where $\alpha_{\varpi}(\omega,\beta)$ – radiation absorption factor, equation (1) takes the form:

$$d(\ln T)/du = C_1\alpha_\omega\tau_N n_m T_m\langle\beta\rangle(1-\beta)n/n_m \qquad (2)$$

Equation (2) shows that temperature gradient is determined mainly by fusion parameter $n_m\tau_NT_m$. Estimations show that right part of Eq. (2) is about unit when $n_m\tau_NT_m \approx 10^{23}$ m^{-3}s keV. This value of fusion parameter lies in the area of reactor parameters and one can expect that plasma temperature near the separatrix will be lower then on the magnetic axis. Taking into account that anomalous resistivity determined by LHD depends strongly on temperature, one can suppose that synchrotron radiation can influence on particle lifetime. Thus we need to solve problems of synchrotron radiation and plasma diffusion selfconsistently.

The used model of particle transport is approximately the same as Tuszevski and Linford's one [4], but we did not propose that temperature is constant inside of separatrix surface, because above mentioned estimates show that temperature can fall down. We supposed that $dT/du = 0$ on the separatrix, because power of synchrotron radiation near the separatrix is about zero. Parameter β_s is free in our model, but relative separatrix radius x_s is calculated using relation $\langle\beta\rangle = 1 - x_s^2/2$ for equilibrium state. Taking it into account, density diffusion equation takes the form:

$$d(\ln n)/du = \alpha(1-nT)^{1/2}T^{-2/3}n^{-1/3}(u+1)^{-2/3} \qquad (3)$$

$$\alpha = n_1^{1/3}T_1^{2/3}(1-n_1T_1)^{-1/2}d(\ln\beta_s)/du \qquad (4)$$

$$n_1 = n\big|_{u=1} \qquad T_1 = T\big|_{u=1}$$

here n and T-density and temperature normalised to the density and temperature on the magnetic axis.

Energy transport equation is the same as (1), but τ_N is calculated from the expression:

$$\tau_N = 0.25\langle\beta\rangle b_s^3\beta_s^{-1}[d(\ln\beta_s)du]^{-3}; \qquad (5)$$

here $b_s = B/B_e$;

To calculate Q_r it needs to use equation for radiation transport. As far as absorption coefficient (α_ω) depends

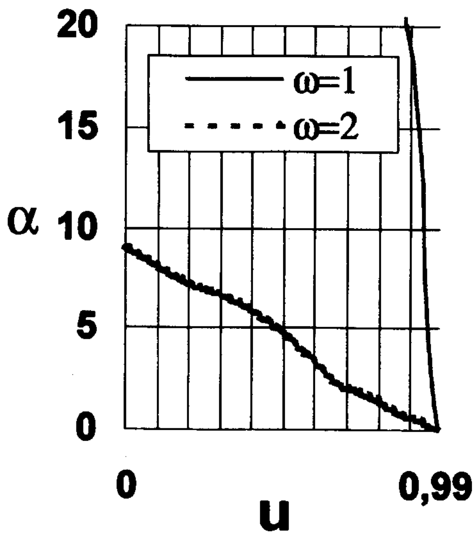

Fig. 1 Spatial distribution of absorption coefficient α for two values of normalised frequency $\varpi = \varpi_c/\varpi_{c0}$.

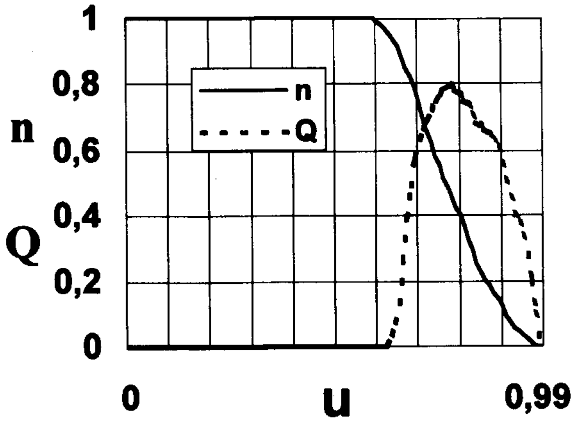

Fig. 2 Spatial distribution of normalised plasma density ***n*** and synchrotron radiation power ***Q***.

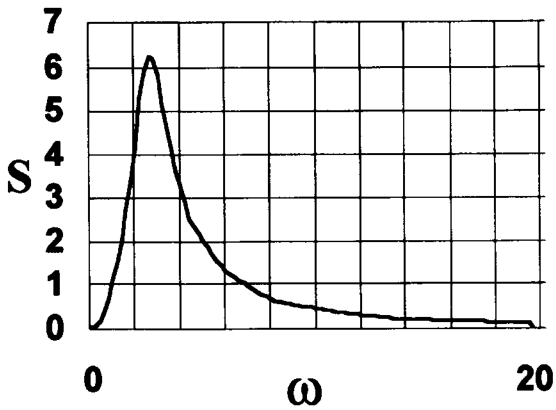

Fig. 3 Spectral distribution of synchrotron radiation intensity ***S*** on the separatrix.

strongly on frequency of radiation and β, equation of radiation transport for each frequency has solved:

$$\mathrm{d}[(u+1)^{1/2} S_\omega]/\mathrm{d}u = R\alpha_\omega (S_{\omega b} - S_\omega)/2\,; \qquad (6)$$

here S_ω and $S_{\omega b}$ are spectral density of radiation intensity and blackbody radiation correspondingly. Absorption coefficient α_ω is calculated on the base of Hirshfield, Baldwin, Brown's model [5].

Space distribution of absorption coefficient for two frequencies is presented on Fig.1. This picture shows that plasma is optically thick for $\omega \approx \omega_{c0}$ and optically thin for $\omega > 3\omega_{c0}$, here ω_{c0}- cyclotron frequency on the separatrix.

Thus, system of equation (1)–(6) give us the model for selfconsistent description of energy and radiation transport in LHD-dominated FRC plasmas.

3. Calculation Results and Conclusions

Numerical solution shows that power of synchrotron radiation losses in FRC is closed to Trubnikov's estimation with absorption factor $\alpha_{\varpi} \approx 0.07$. Space distribution of Q_r is presented on the Fig. 2. It is seen that maximum of radiation intensity Q_r corresponds to the area where $\beta \approx 0.5$, and it means that previous analytical estimations were accurate enough. On Fig. 3 it is shown spectral distribution of intensity of radiation on the separatrix. Maximum of intensity corresponds to the value of frequency $\omega \approx 3\omega_{c0}$.

Taking into account that $Q_r = Q_{rmax}$ in the area, where $\beta \approx 0.5$, one can suppose that $\omega_{max} \approx 5\omega_c$, where ω_c-local cyclotron frequency. It also corresponds previous estimations.

Final observation about numerical solution for the energy transport with consideration of finite level of energy losses due to synchrotron radiation is shown that there is no essential influence of such losses on main FRC plasma parameters and their spatial distribution. Fusion parameter $n\tau T$ was varied up to value $n\tau T = 10^{24}$ keV·m^{-3}·s and plasma temperature on the separatrix is $T_s > 0.8T_m$ for all variants. It is not found also any influence of radiation losses on $P(\psi)$ distribution (here P-plasma pressure, ψ-magnetic flux).

Thus, numerical calculation results support previous analytical estimations and confirm that influence of synchrotron radiation losses on confinement properties of LHD-dominated FRC plasma can be neglected.

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