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Effect of Toroidicity and Temperature Profiles on Synchrotron Losses in a Tokamak Plasma

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1. Introduction

In system studies, the calculation of the global loss due to synchrotron radiation in a tokamak plasma is still generally performed using the Trubnikov's fit [1], derived for a homogeneous plasma cylinder with circular cross section, and including the effect of the toroidal inhomogeneity of the magnetic field. Analytical corrections have been later proposed by Fidone-Meyer [2] taking into account the ellipticity of the plasma cross section and the inhomogeneity of density and temperature, described with generalized parabolic profiles.

In this paper, we analyze the qualitative and quantitative effects of formulating the transfer of synchrotron radiation in a toroidal geometry, and modeling the electron temperature with an advanced profile with respect to a generalized parabolic one, using the exact method for the calculation of the absorption coefficient.

2. General formulation of global synchrotron losses

With no reflecting walls, the solution of the equation of transfer of radiation over a ray path of length *s* is given by [3],

$$J_\omega(s) = \frac{\omega^2}{8\pi^3 c^2} k \int_0^s T_e(\sigma)\, \alpha_\omega(\sigma)\, e^{-\int_\sigma^s \alpha_\omega(\sigma')\ d\sigma'} d\sigma$$

where J_ω is the specific intensity of synchrotron radiation, σ is the ray path coordinate, ω is the frequency, T_e is the electron temperature, α_ω is the absorption coefficient, and *c* is the speed of light.

Integrating the specific intensity over all harmonics and over a plasma with toroidal geometry, arbitrary aspect ratio, elliptical cross section, and arbitrary density and temperature profiles, we obtain a general formulation of synchrotron losses appropriate for realistic tokamak plasmas. The description of the plasma emission and self-absorption processes includes the inhomogeneity of the magnetic field, the toroidal calculation of the ray path length, and the spatial variation of $N_{||}$.

As a consequence of the inhomogeneity of the magnetic field in a poloidal section, the electron cyclotron frequency is no longer constant along a ray line. Low frequency waves propagating towards the plasma region of high magnetic field can then reach the cut-off frequency, which we normalize to the electron cyclotron frequency ($\nu_{\text{cut-off}}$). In such a situation, occurring mainly in very low aspect ratio plasmas ($A < 2$), we assume that these waves are reflected and finally absorbed by the plasma itself. In spite of this assumption, the total synchrotron losses in this case are not substantially different with respect to the other extreme case, where the wave is neither reflected nor absorbed by the plasma, for plasmas with $\nu_{cut\text{-}off} < 1.5$. The reason for this lack of sensitivity is that plasmas with appreciable total synchrotron losses (the interesting case) emit mainly in the frequency range above three or four times the electron cyclotron frequency.

The absorption coefficient is calculated from the complete kinetic theory taking a Maxwellian distribution for the electrons, by using the compact representation of the anti-Hermitian part of the relativistic hot-plasma dielectric tensor [4], which has been generalized for all plasma conditions. The resulting exact method for the calculation of the absorption coefficient has been checked at high frequencies to give identical results as the asymptotic saddle-point method used by Trubnikov.

3. Aspect ratio dependence

The aspect ratio effect in a plasma with toroidal geometry is shown in Fig. 1 for the nominal parameters of the European Commercial Reactor [5]. A generalized parabolic model is considered for density and temperature profiles. The global synchrotron losses numerically calculated are compared to the cylindrical geometry approach and to the Fidone-Meyer formula.

At constant plasma volume, the synchrotron losses increase steadily with high aspect ratios (A = R/a) since the plasma becomes thinner and thinner as A increases. Thus, the optical depth of the emitted radiation in the plasma center decreases. As a first confirmation, for high aspect ratios the numerical calculations in toroidal geometry tend toward the ones of the cylindrical approach. On the contrary, as the aspect ratio gets lower the magnetic field increases in the inner part of the plasma cross section, and synchrotron losses grow despite a slight attenuation due to the toroidal correction for the ray path length that is not explained by the approximate formulas.

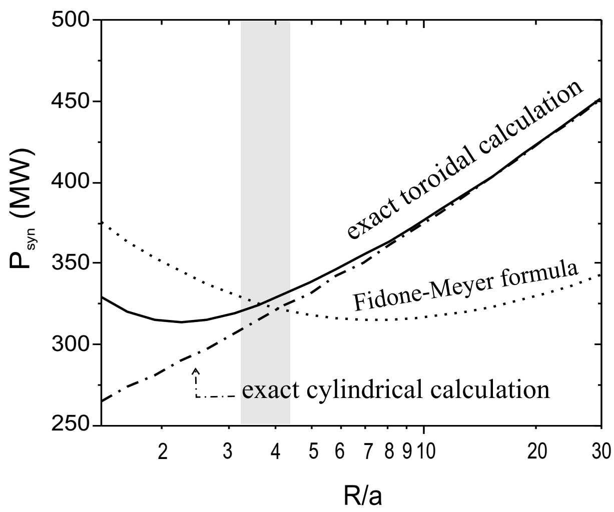

Fig. 1. Global synchrotron loss versus aspect ratio at constant plasma volume. Solid line plots the exact results in a toroidal geometry; the dot line, results from the Fidone-Meyer formula; and the dash-dot line, the cylindrical approach.

We can see that the numerical results from the complete formulation agree well with the approximate formula for aspect ratios in the range 3.2 < A < 4.2 but they differ substantially for larger or smaller aspect ratios, which can be of interest for a commercial reactor.

4. Effect of temperature profiles

In the Fidone-Meyer formula, the density and temperature profiles are described by a generalized parabolic model. But temperature profiles in H-mode or internal transport barrier regimes predicted for next step tokamaks, cannot be described accurately with such a model.

In order to quantify the effect of arbitrary profiles for the electron temperature on the global synchrotron losses, we compare the results considering two different models for the electron temperature profile. The first one is a simple model for an "advanced" temperature profile typical of scenarios with internal transport barrier (ITB), which is characterized by the ITB position ρ_{ITB} expressed in normalized radius (see Fig. 2). The temperature value at the magnetic axis is taken to be T_{e0} = 40 keV, and the temperature value at the plasma edge is taken to be T_{edge} = 1 keV. In this model, the slopes inside the ITB and in the outer part of the plasma cross-section are fixed, as well as the temperature at the inside boundary of the ITB.

The second model for the electron temperature profile is a generalized parabolic model $T_e(\rho) = T_{e_0}\left(1-\rho^2\right)^{\alpha_T}$, where ρ is the normalized radius and α_T is the best peaking parameter fitting the "advanced" model for the same value of the temperature at the magnetic axis (40 keV). The volume average temperatures and the energy contents are not significantly different considering the first or the second model for the temperature profile.

We take the European Reactor nominal parameters with a fixed density profile given by a generalized parabolic profile ($n_0 = 1.5\times10^{20}$, $\alpha_n = 0.5$). On Fig. 2 we can see the substantial differences between global synchrotron losses computed with the "advanced" model and the generalized parabolic one, around 20-40%. The absolute value of the power loss decreases for more central barrier positions due to a lower plasma energy contents. On the other hand, the relative differences between the two temperature models increase when the ITB position is more central. As a result, the power loss due to synchrotron radiation computed with the "advanced" model become more important in the thermal plasma power balance.

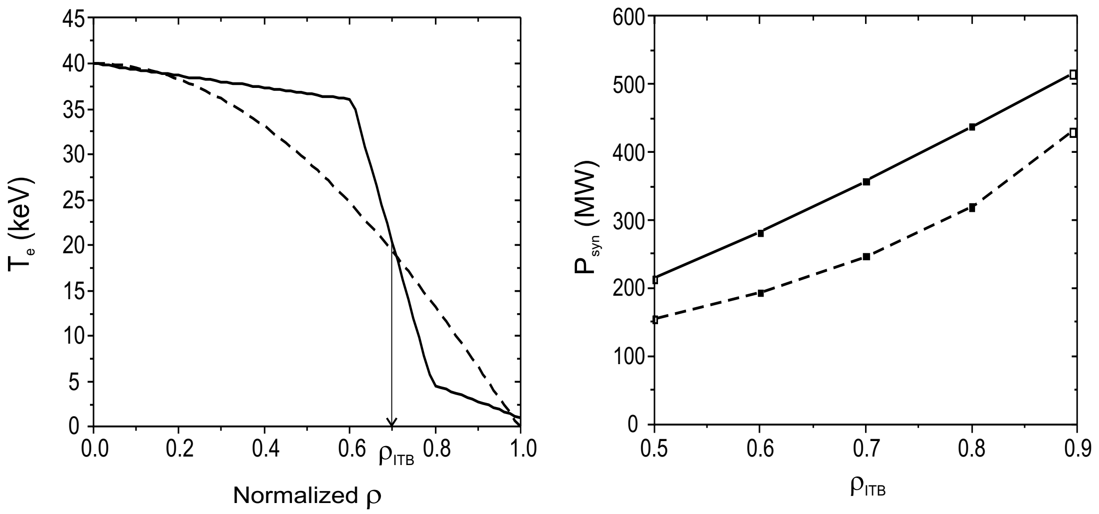

Fig. 2. On the left, the electron temperature profile given by the advanced model (solid curve) with an ITB at 0.7 normalized radius, and the best fitted generalized parabolic profile, $\alpha_T \cong 1.1$ (dashed curve). On the right side, global synchrotron losses at different positions of the internal transport barrier, for both temperature models.

A useful tool to understand the role of the shape of the temperature profile on synchrotron losses is the analysis of the emitted synchrotron profile; i.e., the study of power per unit of plasma volume crossing the last magnetic surface due to the synchrotron emission of this plasma volume (characterized by ρ). Indeed, the spatial distribution of emitted synchrotron radiation losses shows the plasma region that participates the most to the global synchrotron loss, for a set of plasma parameters and a given temperature profile.

The explicit expression of synchrotron power loss per unit volume is derived for an inhomogeneous plasma with cylindrical geometry and elliptical cross-section. For plasmas with a flat electron temperature the emission profile is displaced towards external magnetic surfaces, as seen in Fig. 3, because the synchrotron radiation emitted on the plasma center is reabsorbed before reaching the plasma edge. On the contrary, for peaked temperature profiles (the current case) the emission is strongly peaked near the plasma center. This explains why the synchrotron loss is essentially a function of the central temperature in the latter case. Finally, the inhomogeneity of the magnetic field makes the synchrotron emission slightly increase in an intermediate region of the profile.

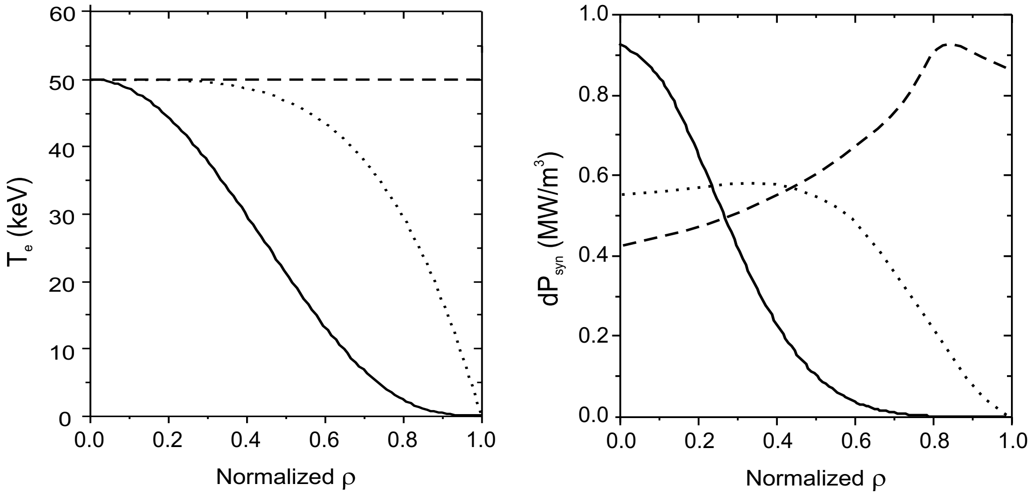

Fig. 3. Three different shapes of electron temperature profile on the left, and the corresponding profile of emitted synchrotron losses on the right. Tokamak parameters are taken from the European Commercial Reactor.

5. Conclusion

A complete formulation of synchrotron radiation losses has been performed for realistic conditions of toroidal geometry and arbitrary shapes of density and temperature profiles, where the plasma self-absorption is calculated exactly. For generalized parabolic profiles, the numerical results from the above formulation agree well with the approximate formulas for aspect ratios close to 3.5, but they differ significantly for larger or smaller aspect ratios due to the inclusion of all the toroidal effects. On the other hand, the temperature profiles in H-mode or internal transport barrier regimes predicted for next step tokamaks, cannot be described with generalized parabolic profiles. We see a strong enhancement of synchrotron radiation losses in the case of an advanced profile with respect to the best generalized parabolic one, resulting in synchrotron losses to be responsible of up to one half of the total plasma losses.

References

[1] B.A. Trubnikov, in *Reviews of Plasma Physics*, edited by M.A. Leontovich (Consultants Bureau, New York, 1979), Vol. 7, p. 345.
[2] I. Fidone, R.L. Meyer, G. Giruzzi, and G. Granata, in Phys. Fluids B **4**, 4051 (1992).
[3] G. Bekefi, *Radiation Processes in plasmas*. (John Wiley and Sons, New York 1966).
[4] G. Granata, and I., Fidone, J. Plasma Phys. **45**, 361 (1991).
[5] I. Cook, P. Knight, N. Taylor, and D. Ward, *Definition of parameters for initial blanket and divertor studies*. (PPA/3.1/UKAEA/2 1999).