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ANALYSIS OF SYNCHROTRON RADIATION EMITTED BY RUNAWAY ELECTRONS IN TOKAMAKS

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The synchrotron radiation diagnostics allows a direct observation of the runaway electron beams and an analysis of their parameters. Strong oscillations of the instantaneous curvature radii of electron orbits were a characteristic feature of recent EAST and KSTAR tokamak runaway electron experiments. Incorrect analysis of synchrotron radiation spectra of runaway electrons was carried out by EAST team. In presented paper the detail theoretical analysis of the synchrotron radiation spectra of the runaway electrons which gyrate around their guiding centers in the curved magnetic field is presented for cases when the curvature radius of electron orbit oscillates strongly. Key parameter of the analysis is the ratio of the cyclotron rotation velocity to the velocity of the vertical centrifugal drift. This analysis is applied for correct calculations of synchrotron radiation spectra for EAST and KSTAR runaway electron parameters.
KEYWORDS: synchrotron radiation; runaway electrons; tokamak; curved magnetic field

АНАЛИЗ СИНХРОТРОННОГО ИЗЛУЧЕНИЯ УБЕГАЮЩИХ ЭЛЕКТРОНОВ В ТОКАМАКАХ
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Диагностика, основанная на синхротронном излучении убегающих электронов, позволяет как непосредственное наблюдение, так и анализ параметров этих электронов. Особенностями недавних экспериментов на токамаках EAST и KSTAR с убегающими электронами были сильные осцилляции мгновенного радиуса кривизны орбит электронов. На токамаке EAST выполнен неправильный анализ спектров синхротронного излучения убегающих электронов. В представленной работе проведен детальный теоретический анализ спектров синхротронного излучения убегающих электронов, которые вращаются в кривом магнитном поле, именно для случаев, когда радиус кривизны орбит электронов сильно осциллирует. Ключевым параметром такого анализа является отношение скорости циклотронного вращения к скорости вертикального центробежного дрейфа. Полученные результаты применены для правильного расчета спектров синхротронного излучения убегающих электронов с параметрами экспериментов на токамаках EAST и KSTAR.
КЛЮЧЕВЫЕ СЛОВА: синхротронное излучение; убегающие электроны; токамак; кривое магнитное поле

АНАЛІЗ СИНХРОТРОННОГО ВИПРОМІНЮВАННЯ ВТІКАЮЧИХ ЕЛЕКТРОНІВ У ТОКАМАКАХ
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Діагностика, що базується на синхротронному випромінюванні втікаючих електронів, дозволяє як безпосереднє спостереження, так і аналіз параметрів цих електронів. Особливостями недавніх експериментів на токамаках EAST та KSTAR з утікаючими електронами були сильні осциляції миттєвого радіусу кривизни орбіт електронів. На токамаку EAST виконано неправильний аналіз спектрів синхротронного випромінювання втікаючих електронів. У представленій роботі проведено детальний теоретичний аналіз спектрів синхротронного випромінювання втікаючих електронів, які обертаються у кривому магнітному полі, саме для випадків, коли радіус кривизни орбіт електронів сильно осцилює. Ключовим параметром у цьому аналізі є відношення швидкості циклотронного обертання до швидкості вертикального відцентрового дрейфу. Отримані результати застосовано для правильного розрахунку спектрів синхротронного випромінювання втікаючих електронів з параметрами експериментів на токамаках EAST та KSTAR.
КЛЮЧОВІ СЛОВА: синхротронне випромінювання; втікаючі електрони; токамак; криве магнітне поле

The runaway electrons can cause a serious damage of plasma-facing-component surfaces in large tokamaks like ITER [1]. The strong electric fields induced during the tokamak disruption can generate a lot of these runaways [2]. Therefore an effective monitoring of the runaway electrons is an important task.

The synchrotron radiation is a powerful tool for direct observation and investigation of runaway electrons in large tokamaks. The established methods of runaway electron monitoring (HXR, photoneutron emission) will be difficult to apply at large machines like ITER because of the high gamma and neutron background and the very thick wall (vessel shielding). Only the diagnostic based on the runaway electron synchrotron radiation measurements will be possible at ITER [3]. In [4] a synchrotron radiation diagnostic at ITER was discussed in wavelength range λ = (1-5) μm and it was shown how to deduce the runaway electron parameters, such as energy, pitch angle, number and beam radius.

For the first time this diagnostic was used at the TEXTOR tokamak [5]. The TEXTOR tokamak main parameters are the major radius R = 1.75 m, the minor radius a = 0.46 m, the plasma current I_p = 350 kA and the toroidal magnetic field B_T was changed in the range from 1.3 to 2.9T. The energy of runaway electrons was 25 MeV. It was found during TEXTOR experiments that the runaways have the finite ratio $v_\perp / v_{||} \sim 0.1$ ($v_\perp$ – is the transverse and $v_{||}$ – is the longitudinal velocities with respect to the tokamak confining curved magnetic field).

Recently the investigation of runaway electron generation was started at the EAST and KSTAR tokamaks [6-8] and the synchrotron radiation diagnostic detecting the runaway electrons is used there. The energy of runaway electrons was above 30 MeV in these experiments. The EAST tokamak main parameters are the major radius R = 1.7 m, the minor radius a = 0.4 m, the plasma current I_p = 1 MA and the maximum toroidal magnetic field B_T =3.5 T [6]. The KSTAR tokamak main parameters are R = 1.8 m, a = 0.5 m, I_p = 300 kA and the maximum toroidal magnetic field B_T was 3.5 T [8]. Strong oscillation of the curvature radii of the electron orbits was a feature of these runaway experiments.

The theoretical bases of the analysis of synchrotron radiation spectra of runaway electrons in the curved magnetic field with the finite value of the transverse velocity were considered in [9]. But incorrect calculations of synchrotron radiation spectra of runaway electrons [7] (that were carried out by EAST team) show a necessity of more detailed consideration of the case when the curvature radius of electron orbit oscillates strongly. In the paper an expression for the spectral density of the power emitted by runaways is presented in a form which is more suitable for the correct diagnostic application and the experiment interpretation when the curvature radius of electron orbit oscillate strongly. The theoretical results are applied for synchrotron radiation spectra analysis of runaway electrons in recent EAST and KSTAR experiments [7,8].

Note, asymptotic expressions for the analysis of synchrotron radiation spectra of runaway electrons from the review paper [4] are not applied for experiment interpretations when the curvature radius of electron orbit oscillates strongly. In this paper simple usability conditions of the asymptotes are obtained.

The aim of this paper is to demonstrate correct performing the theoretical analysis of the electron synchrotron radiation spectra, especially for case when the instantaneous curvature radii of electron orbits oscillate strongly.

MONITORING OF RUNAWAY ELECTRONS

In this paragraph the theoretical background of synchrotron radiation spectra of runaway electrons is discussed in details since it is integral part for the experimental analysis. The inaccuracies in [4] will be noted, also.

Recall that highly relativistic particles emit radiation in the direction of their velocity vector [10]. As first step of the analysis, the ratio $v_\perp / v_{||}$ << 1 must be estimated from the shape of the synchrotron radiation spot. The detailed analysis of the synchrotron radiation spot shape in the case of the finite ratio $v_\perp / v_{||}$ << 1 was carried out in [11]. Usually a detector of synchrotron radiation is positioned in equatorial plane of tokamak looking tangentially to the direction of runaway electron flow.

If for the runaway electrons

$$v_\perp / | v_{||} | << r_{beam} / q(r_{beam}) R_0 , \quad (1)$$

the detector records the radiation of electrons from small part of runaways beam poloidal cross section. This results in a narrow pattern (strip) that has the angle β with equator line in the poloidal plane of the discharge (D is a distance from the detector to the observed runaways)

$$tg\beta \approx D / q(r) R_0 . \quad (2)$$

In expression (1) r_{beam} is the radius of electron beam, $q(r)$ is the safety factor, R_0 is the major radius of the magnetic surface.

When

$$v_\perp / | v_{||} | \geq r_{beam} / q(r_{beam}) R_0 , \quad (3)$$

the large (almost circular) spot or like inclined ellipse spot (with angle β (2) between the equatorial plane and the ellipse major axis) is observed by the detector. The expression (2) was applied for analysis of the synchrotron radiation spot in the TEXTOR experiments [12]. Unfortunately, the incorrect expression for angle β is presented in review paper [4] instead of (2).

The theoretical analysis of the synchrotron radiation spectra of runaway electrons was carried out in [9] (relativistic factor $\Gamma >> 1$, $v_{||} >> v_\perp$). The features of the relativistic electron motion in a tokamak (the motion along the tokamak helical magnetic field, cyclotron gyration with frequency $\omega_B = eB/mc\Gamma$ and vertical centrifugal drift with velocity $v_{dr} = v_{\|}^2 / R\omega_B$) were taken into account. Here *e* and *m* are the charge and rest mass of electron, *c* is the ligth velocity.

Only a small part of the electron trajectory in a tokamak is effective to produce the radiation observed in the detector. A key parameter of the radiation analysis is

$$\eta = v_{\perp} / v_{dr} \; . \tag{4}$$

The instantaneous curvature radius of electron orbit depends on the phase of cyclotron gyration and oscillates strongly, when parameter η is the order of a few units ([9])

$$\frac{1}{R_{curv}^2} \approx \frac{1}{R_0^2}[1+\eta^2+2\eta\sin(\vartheta+\alpha)] \, . \tag{5}$$

Hence the emission of a single electron reproduces this dependence also. The spectral density of the synchrotron radiation $P(\lambda,\alpha)$ depends on cyclotron gyration phase α ($\dot{\alpha} \approx -\omega_B$) and oscillates strongly with α (ϑ is the poloidal angle corresponding to the position of the electron guiding center). In tokamaks the radiation of many runaway electrons is observed in the detector simultaneously. In this case it is possible to introduce an averaged spectral density of the emitted power:

$$P(\lambda) = \frac{1}{2\pi}\int_0^{2\pi} d\alpha P(\lambda,\alpha). \tag{6}$$

It is convenient to present the result in the form of contour integral (compare with [9]):

$$\begin{aligned} P(\lambda) = i\frac{2\pi c e^2}{\lambda^3\Gamma^2}\{ \int_C \frac{du}{u}(1-2u^2) I_0\left(\frac{\xi\eta u^3}{1+\eta^2}\right)\exp[-\frac{3}{2}\xi\left(u-\frac{u^3}{3}\right)] - \\ - \frac{4\eta}{1+\eta^2}\int_C du u I_1\left(\frac{\xi\eta u^3}{1+\eta^2}\right)\exp[-\frac{3}{2}\xi\left(u-\frac{u^3}{3}\right)]\}, \end{aligned} \tag{7}$$

where the integration path is taken along the line of steepest descent from a saddle point, $I_{0,1}(z)$ are the modified Bessel functions,

$$\xi = \frac{4\pi}{3}\frac{R_0}{\lambda\Gamma^3}\frac{1}{\sqrt{1+\eta^2}} \, . \tag{8}$$

There is a difference between (7) and Schwinger's result [13]:

$$P_{Sch}(\lambda) = \frac{4\pi c e^2}{\sqrt{3}\lambda^3\Gamma^3}\int_w^{\infty} K_{5/3}(x)dx \, , \tag{9}$$

where

$$w = 4\pi R_{curv} / 3\lambda\Gamma^3 \, . \tag{10}$$

Equation (9) describes the emission of single electron, meanwhile (7) describes the radiation of many runaway electrons whose distribution function is independent on the phase of cyclotron gyration α i.e., distribution function has the form $f(p_{\|}, p_{\perp}, t)$. Another question is: in which way (9) may be used in case of strong oscillations of the instantaneous curvature radius R_{curv} from (5). It is necessary to apply (7) for spectra analysis instead of (9) in this case.

Correct estimation of the ratio $v_{\perp}/v_{||}$ is important part of spectra analysis. Uncertainties during measurement of the ratio $v_{\perp}/v_{||}$ may cause large errors during spectra analysis.

The asymptotic approximation of integral (7) simplifies the spectra analysis. Integral (7) can be easily integrated by saddle point method (see, e.g. [14]) when

$$\xi = (4\pi/3)\left(R_0/\lambda\Gamma^3\right)\left(1/\left(1+\eta^2\right)^{1/2}\right) >> 1 \, . \tag{11}$$

Two limit cases are possible (see [9]). In first case

$$P(\lambda) \approx \pi c e^2 \sqrt{\frac{2\sqrt{1+\eta^2}}{\lambda^5 R_0 \Gamma}}\left[I_0(a) + \frac{4\eta}{1+\eta^2} I_1(a)\right]\exp\left(-\frac{4\pi}{3}\frac{R_0}{\lambda\Gamma^3}\frac{1}{\sqrt{1+\eta^2}}\right), \tag{12}$$

when

$$a = (4\pi/3)\left(R_0/\lambda\Gamma^3\right)\left(\eta/\left(1+\eta^2\right)^{3/2}\right) \lesssim 1 \, , \tag{13}$$

here the saddle point is $u_0 = (1,0)$.

Expression (12) has a maximum at $\lambda = \lambda_m$, where λ_m is a solution of following equation:

$$\lambda = \frac{8\pi}{15}\frac{R_0}{\sqrt{1+\eta^2}}\frac{1}{\Gamma^3}\left[1-\frac{\eta}{1+\eta^2}\frac{\left(1+\eta^2\right)I_0'(a)+4\eta I_1'(a)}{\left(1+\eta^2\right)I_0(a)+4\eta I_1(a)}\right], \quad (14)$$

where $I_{0,1}'\left(a\right)$ are derivatives of modified Bessel functions with respect to an argument.

For $\eta << 1$ or $\eta >> 1$ we have from (14) that

$$\lambda_m \approx \frac{8\pi}{15}\frac{R_0}{\sqrt{1+\eta^2}}\frac{1}{\Gamma^3}. \quad (15)$$

The asymptotic expression (12) for $P(\lambda)$ is valid for

$$\eta >> 2.5 \quad (16)$$

or

$$\eta << 0.4 \quad (17)$$

as it follows from the inequalities (11) and (13). There are not the strong oscillations of R_{curv} in these cases, $R_{curv} \approx R_0 / \sqrt{1+\eta^2}$. Note that the parameter η was large, $\eta >> 1$, in well known TEXTOR experiments [4,5].

In second case

$$P\left(\lambda\right) \approx \frac{\sqrt{3}}{2}\frac{ce^2\Gamma(1+\eta)^2}{\lambda^2 R_0\sqrt{\eta}}\exp\left(-\frac{4\pi}{3}\frac{R_0}{\lambda\Gamma^3}\frac{1}{1+\eta}\right), \quad (18)$$

when

$$a = \left(4\pi/3\right)\left(R_0/\lambda\Gamma^3\right)\left(\eta/\left(1+\eta\right)^3\right) > 1, \quad (19)$$

here the saddle point is $u_0 = (\sqrt{1+\eta^2} \,/\, (1+\eta), 0)$.

Expression (18) has a maximum at

$$\lambda_m = \frac{2\pi}{3}\frac{R_0}{\left(1+\eta\right)\Gamma^3}. \quad (20)$$

When η is the order of several units ($\eta \sim (1-2)$), equation (18) has to be used instead of (12). The analysis of experimental conditions shows that it is just a case of the EAST and KSTAR tokamaks. But the equation (12) is discussed only in the review paper [4].

The application of asymptotic expressions (12) and (18) simplifies the spectrum analysis. Note that presentation of parameter ξ (11) is convenient in following form:

$$\xi(\lambda) = 2.5\left(\lambda_m/\lambda\right) >> 1, \quad (21)$$

for first limit case when λ_m is defined by (15) ($\xi(\lambda_m) = 2.5$). For second limit case

$$\xi(\lambda) = 2\left[\left(1+\eta\right)/\sqrt{1+\eta^2}\right]\left(\lambda_m/\lambda\right) >> 1, \quad (22)$$

when λ_m is defined by (18) ($\max(\xi(\lambda_m)) \approx 2.8$).

Hence the asymptotic expressions (12) and (18) describe correctly the features of the spectrum in the range $\lambda < \lambda_m$ only, where $\xi >> 1$.

The spectrum is shifted toward shorter wavelengths with increasing of parameter η. Recall that the experimental measurement of the spectrum in the region $\lambda < \lambda_m$, where $P(\lambda)$ decreases exponentially fast, is very important because it allows estimating the maximum energy of runaways in the discharge [4].

The integral (7) can be taken numerically without additional simplifications. It has been taken numerically along the contour C (a hyperbola x^2-$y^2/3=1$ passing through the saddle point (x=1, y=0), where x and y are real and imaginary parts of the complex number respectively) in the complex plane to calculate accurately the spectrum near the maximum position. This integration path provides the most rapid convergence of the integral.

APPLICATION OF THEORY IN EAST AND KSTAR EXPERIMENT INTERPRETATIONS

The synchrotron radiation spectra for the same (as in Fig.5 of Ref. [7]) runaway electron parameters of the EAST tokamak are shown in Fig. 1. The spectra have been calculated numerically from (7) and they are different from the data of [7]. A reason of these differences is explained below. Note when parameter $v_\perp/v_{||}$ is constant the spectrum moves to smaller values of wavelength with runaway energy increasing.

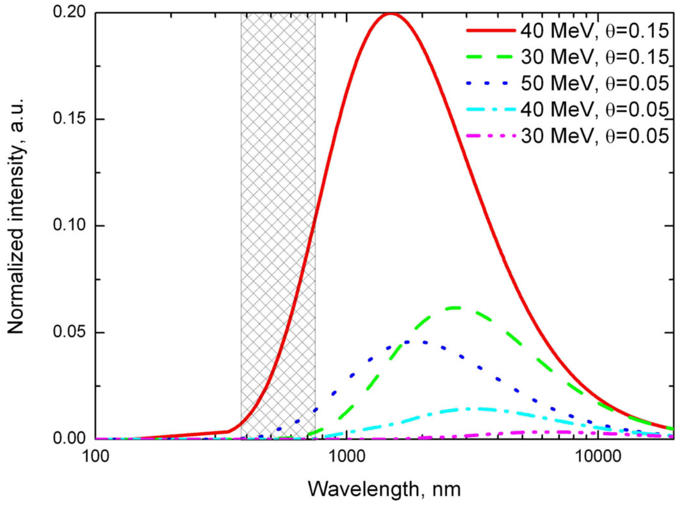

Fig.1. The synchrotron radiation spectra calculated on the base of (7) for experimental parameters of the EAST tokamak presented in [7]. The wavelength range detected by the visible CMOS camera of the EAST tokamak is shaded.

As was claimed in [7] when pitch angle is small $v_{\perp}/v_{||} = 0.05$ the runaway electron energy has to reach 40 MeV to observe synchrotron radiation during EAST experiments as visible light. This conclusion was made on the base of (12). Note parameter η is equal to 1.38 for 40 MeV in case $v_{\perp}/v_{||} = 0.05$.

Data of synchrotron radiation spectra obtained from (7) and its comparison with data of the asymptotic expressions (12) and (18) for the EAST tokamak in case $\eta = 1.38$ is shown in Fig. 2. A visible CMOS camera of the EAST tokamak operates in the narrow (0.38 – 0.75) μm wavelength range [6] which is shaded in Figs.1-3. Note that the value $\eta = 1.38$ is outside of application range (16,17) of asymptotic expression (12). Although the part of the spectrum calculated by asymptotic equation (12) is inside (0.38 – 0.75) μm range but the correctly calculated spectrum is outside of this range. Therefore the runaway electrons with $v_{\perp}/v_{||} = 0.05$ and energy 40 MeV are invisible during EAST experiments.

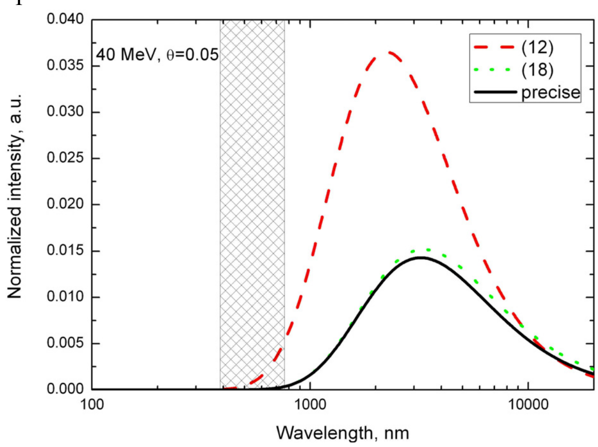

Fig. 2. The comparison of synchrotron radiation spectra calculated on the base of (7) with data of the asymptotic expressions (12) and (18) for the EAST tokamak in case $\eta = 1.38$ (B_T = 2T, 40 MeV, $v_{\perp}/v_{||} = 0.05$).

The wavelength range detected by the visible CMOS camera of the EAST tokamak is shaded.

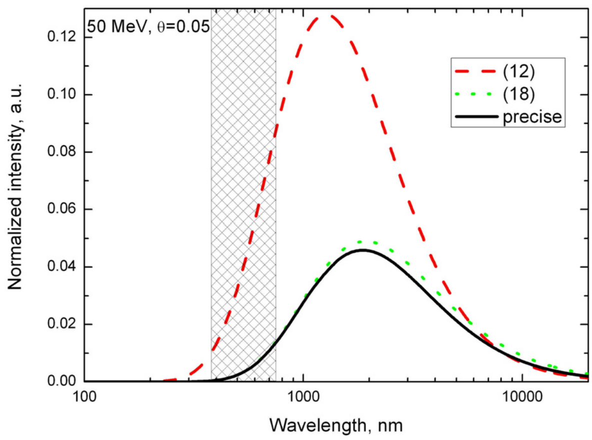

Fig. 3. The comparison of synchrotron radiation spectra calculated on the base of (7) with data of the asymptotic expressions (12) and (18) for the EAST tokamak in case $\eta = 1.11$ (B_T = 2T, 50 MeV, $v_{\perp}/v_{||} = 0.05$).

The wavelength range detected by the visible CMOS camera of the EAST tokamak is shaded.

Data of the similar EAST spectrum calculations for parameters B_T = 2T, 50 MeV, $v_{\perp}/v_{||}$ = 0.05 is presented in Fig. 3. Here $\eta = 1.11$. In this case the part of the correctly calculated spectrum is inside of (0.38 – 0.75) μm range. Runaway electrons with $v_{\perp}/v_{||} = 0.05$ and energy 50 MeV is visible during EAST experiment.

We also present a comparison of synchrotron radiation spectra of runaway electrons calculated numerically from (7) with asymptotic expressions (12) and (18) in figure 4 for the KSTAR tokamak. An IR TV camera of KSTAR tokamak operates in the wavelength range (3 – 5) μm which is shaded in Fig. 4. The expression (18) approximates better the spectrum of (7) even for $\eta = 4.22$ (B_T = 2T, $\Gamma = 50$, $v_\perp / v_{||}$ =0.1) as it can be seen from Fig.4.

The asymptotic expressions for the spectral density allow to define the maximum energy of the runaway electrons [4]. The ratio $P(\lambda_1)/P(\lambda_2)$ is measured in the region $\lambda < \lambda_m$ to determine the runaway energy using two different interference filters in front of the IR or visible camera. In the first case (12)

$$P(\lambda_1)/P(\lambda_2) \propto \exp\left(-\frac{4\pi}{3}\frac{R_0}{\Gamma^3}\frac{1}{\sqrt{1+\eta^2}}(\frac{1}{\lambda_1}-\frac{1}{\lambda_2})\right). \quad (23)$$

In the second case (equation (18))

$$P(\lambda_1)/P(\lambda_2) \propto \exp\left(-\frac{4\pi}{3}\frac{R_0}{\Gamma^3}\frac{1}{1+\eta}(\frac{1}{\lambda_1}-\frac{1}{\lambda_2})\right). \quad (24)$$

For $\eta >> 1$ this ratio depends on toroidal magnetic field value *B*, ratio of $v_\perp / v_{||}$ and Γ only,

$$P(\lambda_1)/P(\lambda_2) \propto \exp\left(-\frac{4\pi}{3}\frac{1}{\Gamma^2}\frac{c^2}{v_\perp \omega_{B0}}(\frac{1}{\lambda_1}-\frac{1}{\lambda_2})\right). \quad (25)$$

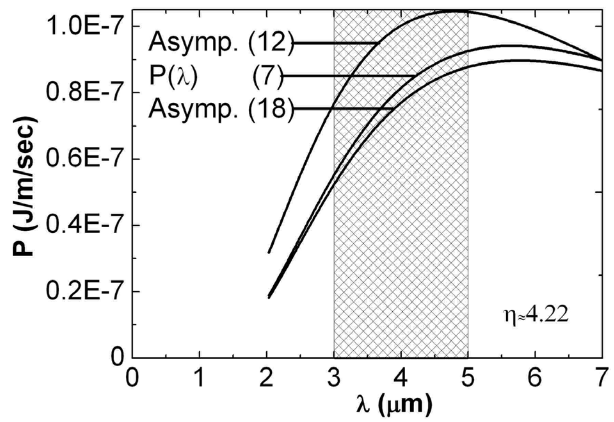

Fig. 4. The comparison of synchrotron radiation spectra calculated on the base of (7) with data of the asymptotic expressions (12) and (18) for the KSTAR tokamak in case of the moderate values of η.
Here $\eta = 4.22$ (B_T = 2T, $\Gamma = 50$, $v_\perp / v_{||} = 0.1$). The asymptote of (18) approximates better the spectrum of (7) in the region $\lambda < \lambda_m$.
The wavelength range detected by the IR camera of the KSTAR tokamak is shaded.

The synchrotron radiation spectra of runaway electrons for typical values of toroidal magnetic field B_T and parameter η are presented in figure 5 for the experimental conditions at the KSTAR tokamak. It was used for estimates of maximum runaway energy in KSTAR experiments [8]. The position of the spectrum maximum is defined not only by the relativistic factor Γ value but also by the parameter η which depends in turn on toroidal magnetic field value, ratio of $v_\perp / v_{||}$ and Γ.

Spectra for magnetic fields 3T and 3.5 T (Fig.5) may be used during runaway experiments on any of the tokamaks with $v_\perp / v_{||}$ = 0.1 and the same magnetic field. Here $\eta >> 1$ and ratio of spectra don't depend on major radius *R* of tokamak in the region $\lambda < \lambda_m$ (25).

CONCLUSIONS

The features of synchrotron radiation spectrum analysis of runaway electrons with the finite value of the transverse velocity (with respect to the curved magnetic field) are discussed for the case when the instantaneous curvature radius of electron orbit oscillates strongly. It takes place, when key parameter η (the ratio of transverse velocity of electron to vertical centrifugal drift velocity)

$$\eta = v_\perp / v_{dr}$$

is the order of several units ($\eta \sim (1-2)$).

The asymptotic expressions for the spectral density of the power emitted by the runaways are presented in the form which is convenient for the interpretation of the experiments. The usability conditions of the spectral density asymptotes are obtained in term of parameter η.

The obtained results are applied for calculations of synchrotron radiation spectra for recent EAST and KSTAR runaway electron experiments.

A peculiarity of the runaway experiments is a fact that an IR or visible camera operates in the narrow (a few *μm*) wavelength range on any of the tokamaks.

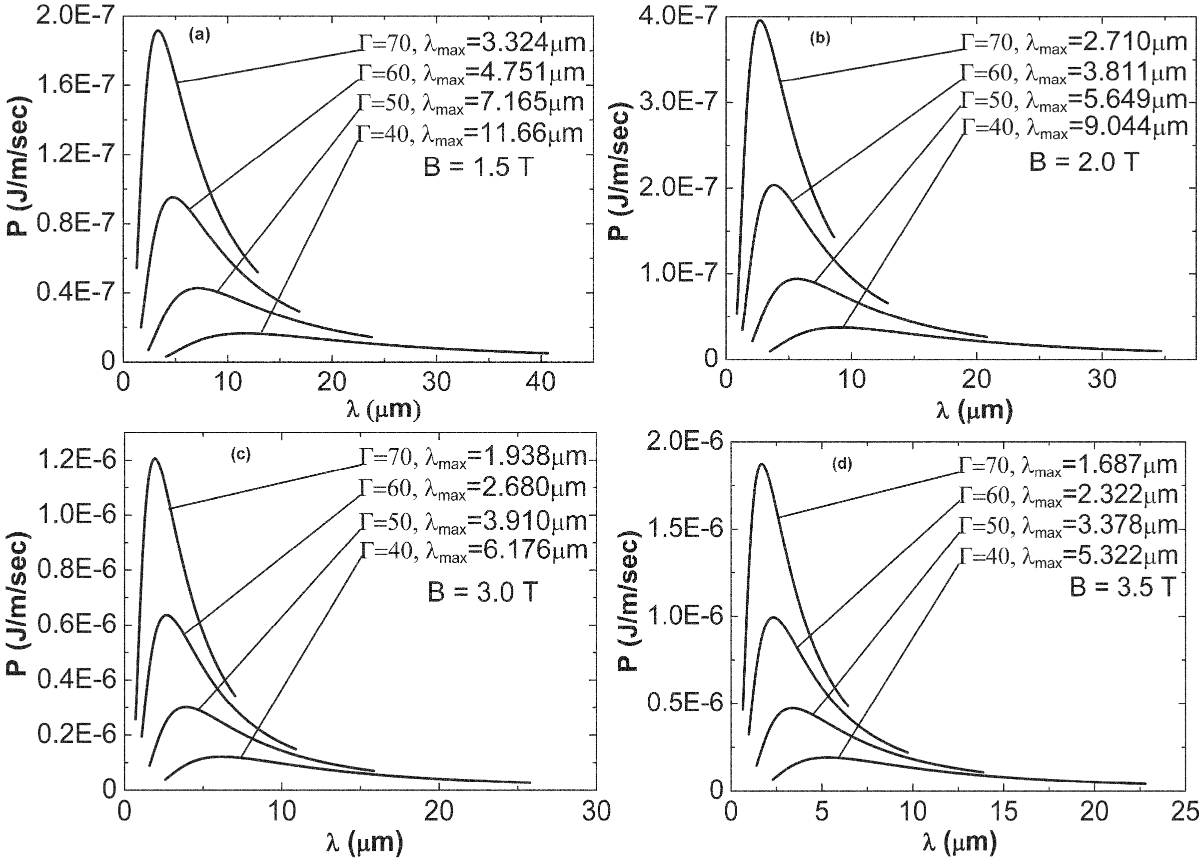

Fig. 5. Synchrotron spectra are calculated for the KSTAR typical magnetic fields: a) 1.5T, b) 2T, c) 3T and d) 3.5 T for the different values of the relativistic factor when $v_{\perp}/v_{||}$ = 0.1. The wave length of the spectrum maximum is indicated for each curve.

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