

## Tangent injection of microwave radiation for the purpose of the tearing mode stabilization

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**Introduction** It is known that tearing instability in tokamaks can be stabilized both by temperature profile modification using additional local heating and by current profile modification by means of non-inductive current drive. Both of these two methods (see [1] and the literature cited therein) impose strict limitations on spatial size of the energy release zone (which is about several centimeters for ITER scales). One of the possible ways of solving this problem consists of using the scheme of the tangent injection of RF radiation, where the beam propagates at a tangent to the chosen magnetic surface in the EC absorption region. The results of numerical simulation of RF radiation propagation and absorption at the tangent injection for the ITER parameters [2] on the base of the subrelativistic geometrical-optics code are given in the present work. Weakly relativistic tensor of dielectrical permittivity is represented in terms of a family of functions with half-integer index  $q$  first introduced by I. Shkarofsky [3].

The effective radius  $\rho = 1 - \Psi/\Psi_c$  is used as the “mark” of the surface of constant flux  $\Psi$  (magnetic, or flux surface). Here  $\Psi$  is the flux of the poloidal magnetic field through a circular contour perpendicular to the torus axis of symmetry; on the magnetic axis,  $\Psi_c \simeq 9.62$ . Temperature and density distributions [2] are also determined as functions of the effective radius  $\rho$ .

The efficiency of the considered scheme has been estimated for magnetic surface with the safety factor  $q = 2$ , in the vicinity of which the tearing mode playing a critical role in collapses may be localized. The results of the calculations demonstrated acceptable efficiency of the tangent injection scheme — on this magnetic surface one can provide energy release width about several centimeters which completely satisfies the requirements of a possible tearing mode stabilization experiment.

1. Details of the code description, on the base of which the calculation is done, may be found in (see also [5,6]). To characterize the absorbed power spatial distribution, we use the quantity

$$U(\rho) = \partial \exp(-\tau) / \partial \rho, \quad \tau = \int 2 (\text{Im } \mathbf{k} \cdot d\mathbf{s}), \quad (1)$$

where  $\tau$  is the plasma optical width from the entry point to the plasma column till the current point  $s$  ( $\mathbf{s}$  is the coordinate along the beam trajectory) and the imaginary part of

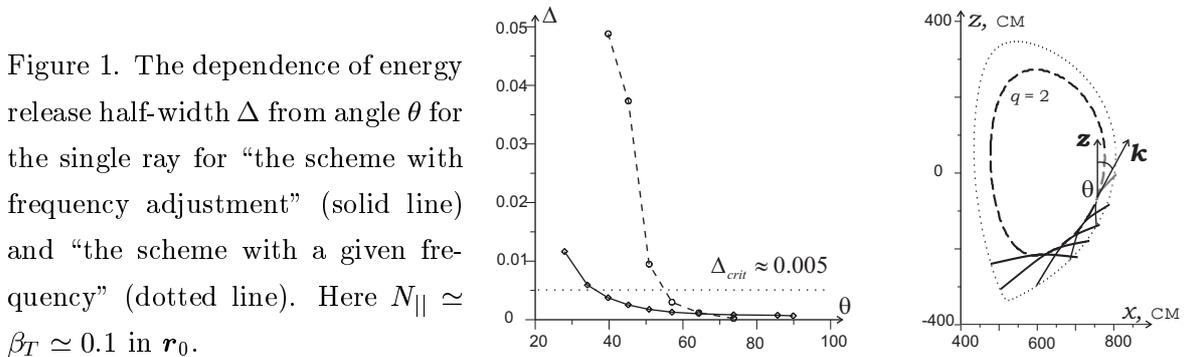
the refraction index  $N_c$  is determined by the standard expression in the weak absorption region [4]:  $N_c = X_c(N_r)/2N_r$ . We will determine the characteristic half-width of the function  $U(\rho)$  in the ordinary way:

$$\Delta = \sqrt{(\rho - \bar{\rho})^2} = \sqrt{\rho^2 - \bar{\rho}^2}, \quad \text{where} \quad \bar{\rho}^k = \int \rho^k U(\rho) d\rho / \int U(\rho) d\rho. \quad (2)$$

The optimization of the ray entrance direction aimed to minimize the heated plasma slab volume is done in the following way. The first stage is to choose the point of the relativistic ‘‘cut off’’ of the cyclotron resonance  $\mathbf{r}_0$  inside the plasma volume (which is also the point where the ray is tangent to the magnetic surface  $\Psi = \Psi_0$ ). At this point, one find the initial values of the wave vector  $\mathbf{k}_0$  by solving the set of nonlinear equations. The former equation  $H(\mathbf{r}_0, \mathbf{k}_0) = 0$  means that its solution  $\mathbf{k}(\mathbf{r})$  coincides with dependence  $\mathcal{R}e \mathbf{k}(\mathbf{r})$  at dispersion equation solving. Second relation  $(\partial H / \partial \mathbf{k}_0 \cdot \mathbf{N}_\Psi) = 0$  states that the ray propagates at a tangent to the magnetic surface  $\Psi_0$  at the point  $\mathbf{r}_0$  ( $\mathbf{N}_\Psi$  is perpendicular to the chosen magnetic surface  $\Psi_0$  in  $\mathbf{r}_0$ ). The last equation  $N_{||}^2/2 = 1 - n\Omega_c/\omega$  is the condition of the relativistic resonance cut off in warm approximation.

It must be emphasized that the cut off condition sets the connection between the parameters  $\omega$  and  $N_{||}$ . So, there are two variants of the scheme with tangent injection realization: by choosing the initial point  $\mathbf{r}_0$  one can alter the radiation frequency  $\omega$ , so that cut off condition is satisfied for the value of  $N_{||}$  determined beforehand, and, vice versa, initially unknown values of  $N_{||}$  (now determined by the choice of the point  $\mathbf{r}_0$  and the value of  $\mathbf{k}_0$ ) correspond to a given frequency  $\omega = \omega_0$ . Further we will term the first variant as ‘‘the scheme with frequency adjustment’’ and the second one as ‘‘the scheme with a given frequency’’.

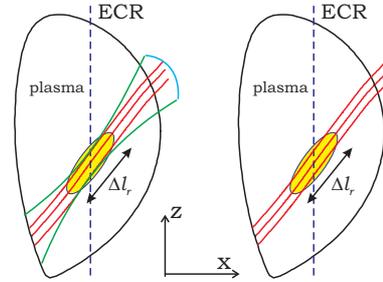
**3.** We shall use a kind of criteria (upper limit) for  $\Delta$  (see (2)) values. At exceeding of this limit one can consider the corresponding energy release half-width like ‘‘wide’’. Value  $\Delta_{crit} = 0.005$  corresponds to calculated in [1] maximum of half-width of energy release profile at which the tearing mode stabilization by temperature profile modification using additional local EC heating of surfaces with  $q = 2$  is yet possible.



Let us consider how parameter  $\Delta$  depends on the choice of the “point of contact”  $\mathbf{r}_0$ . One can use the angle  $\theta = \arccos(k_z/|k|)$  between axis  $OZ$  and ray trajectory in  $\mathbf{r}_0$  in capacity of characteristic of where  $\mathbf{r}_0$  is chosen (see Fig.1 (right)). So,  $\theta = 90^\circ$  means that ray trajectory in  $\mathbf{r}_0$  is close to horizontal line;  $\theta = 0^\circ$  corresponds to merely vertical line. Results of this calculation for the single ray is presented on Fig. 1 (left) both for “the scheme with frequency adjustment” (full line) and “the scheme with a given frequency” (dotted line). Calculations show that  $\Delta$  is minimal on “horizontal” trajectories (with  $\theta \rightarrow 90^\circ$ ).

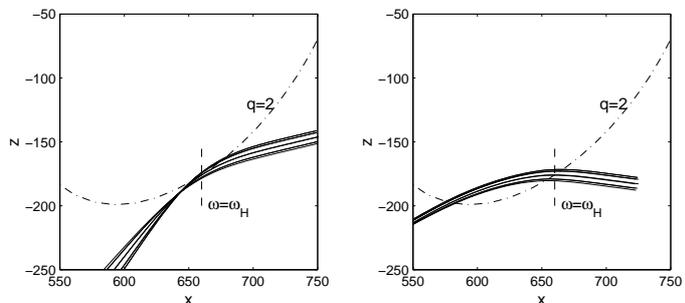
4. Let us now pass on from the modeling case of the single ray to more actual case of the beam with the finite aperture. The beam is modeling by the system of parallel rays with gaussian power distribution in dependence on the distance from the beam axis. Note, that in real experiment one should consider a broad beam focused in vicinity of the “point of contact” (see Fig. 2). Let us use the next “vacuum” relations for the evolution

Figure 2. To estimation of the role of diffraction: real focused beam (on left) and “modeling” beam (on right).



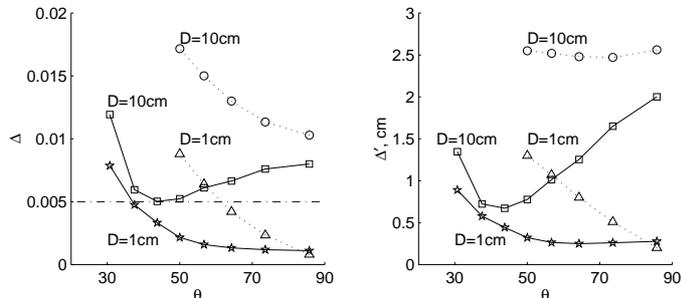
of the gaussian beam width  $D(z) = D = D_0 \sqrt{1 + 4z^2/k^2 D_0^4}$ . To estimate the effect let us limit ourselves by approximation of flat-parallel GO beam with relatively small diameter in resonance region. Such beam will correspond to behaviour of the real focused beam (on Fig. 2 it is the region inside the oval contour). In this case the condition of applicability of GO description consists in that the beam should not diverge sufficiently at least on length of absorption ( $z \approx \Delta l_r$ ), i.e.  $\Delta l_r \lesssim k D_0^2/2$ . According to our evaluations the absorption length  $\Delta l_r$  is 5...8.5 cm, so for wave number  $k \approx 30 \text{ cm}^{-1}$  and beam of diameter in the narrowest place about  $D_0 \approx 1 \text{ cm}$  condition  $\Delta l_r \lesssim 15 \text{ cm}$  is quite appropriate.

Figure 3. Tangent injection of the beam of 10 cm in diameter (left) and corresponding beam at the horizontal injection (right) .



Results of comparison of the tangent and horizontal injection (see Fig. 3) are presented on Fig. 4. It is clearly seen, that the tangent injection provides more efficient localization of the energy release zone even for the beam with 10 cm in diameter, that may be important for the real experiment conditions.

Figure 4. Half-width  $\Delta$  in  $\rho$ -units (left) for the case of tangent injection (solid lines) and horizontal injection (dotted lines) for two beams: 1 cm and 10 cm in diameter. Corresponding dimensional estimations  $\Delta' \approx \Delta/|\nabla\rho|$  (right).



**Conclusion.** On the basis of numerical simulation the possibilities of the energy release width minimization in the scheme with tangent injection of radiation launch are demonstrated. For parameters of large scale toroidal installation (case of warm plasma) calculations show that at such radiation launch one can provide quite localized energy release, which is appropriate both for possible experiments on tearing mode stabilization by non-inductive current generation and for even more hard requirements of the tearing mode stabilization using EC heating of chosen region of plasma volume. Naturally, this derivation may be fulfilled with far more precision after successive account of diffraction and microwave beam dispersion.

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