LOW-THRESHOLD ABSOLUTE PARAMETRIC DECAY INSTABILITY IN X2-MODE ECRH EXPERIMENTS AND THE MISSING POWER EFFECT

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Electron cyclotron resonance heating (ECRH) and current drive have been widely used in toroidal devices for plasma confinement and are considered for local heating and neoclassical tearing mode control in ITER. Recently a decision has been taken on abrupt increase of the ITER ECRH power from 20 MW up to 67 MW. According to the predictions of the theory developed in 80s, nonlinear effects and first of all parametric decay instabilities (PDIs), which can accompany the ECRH experiments, were believed to be deeply suppressed by huge energy loss of daughter waves from the decay region [1].

However, during the last 15 years many experiments have demonstrated excitation of the anomalous nonlinear phenomena in the 1 MW power level ECRH experiments. These include anomalous emission at a frequency shifted by about the lower hybrid frequency relative to the gyrotron one, firstly observed at TEXTOR and then at ASDEX-Upgrade and W7-X [2-4], and plasma emission at half-integer harmonics of the pump wave frequency reported at ASDEX-Upgrade and TCV [3,5], which indicate the nonlinear behavior of sub-megawatt microwave beams. A discrepancy between the launched and actually absorbed microwave power, as well as between the predicted and actually measured power deposition profiles at L-2M, TJ-II, T-10, TEXTOR [6-11] could be as well attributed to the nonlinear phenomena becoming important already at modest pump power level. It should be noted that the physical phenomena reported in [2-7] were observed when a pump microwave beam passed through a plasma region with a non-monotonic density profile. As predicted by the PDI model [12], in this case the low-threshold excitation of the most dangerous absolute PDI (APDI) becomes possible. The latter manifests itself in the temporal growth of daughter waves, at least one of which is localized in the decay region due to the non-monotonic density profile and finite width of the microwave beam. This model allows providing a detailed quantitative explanation of anomalous phenomena observed in the ECRH experiments, as shown, for example, in [12-14].

However, it should be noted that the broadening of the power deposition profile and the missing microwave power effect were found not only at the hollow density profile [6,7], but also in discharges where the density and electron temperature profiles were monotonic, as in T-10, TEXTOR and DIII-D [8-11]. Several possible explanations of this phenomenon were proposed. The first one is based on the generation of non-Maxwellian electron distribution function under the high-power electron cyclotron plasma heating, which is accompanied by reduction of the pump wave absorption, enhanced radial electron transport and EC emission [15]. The second explanation utilises the hypothesis of so-called non-local electron transport - strong anomalous electron thermo-diffusion initiated by the ECR heating, which complicates the interpretation of the power deposition [8,16]. The broadening of the power deposition profile could also be a consequence of the microwave heating beams distortions caused by the edge plasma turbulence [17]. However, all of them are not specific for the extraordinary polarization of the pump wave whereas the missing power effect was only reported in the X2-mode ECRH experiments at T-10 and was never observed at the O1-mode ECRH [10]. This indicates the need for an alternative interpretation of the discovered effect, which is proposed in the present paper.

Here we focus on theoretical investigation of a possibility of low-threshold absolute PDI excitation in cases when localization or trapping of daughter waves is not possible in X2 ECRH experiments. Namely, we study the PDIs driven by the pump beam of extraordinary microwaves propagating along a monotonous density profile and leading to the excitation of a couple of electron Bernstein (EB) or upper hybrid (UH) daughter waves. As we demonstrate, the decay conditions for such a two-plasmon decays in many toroidal devices could be satisfied in a couple of spatial points thus making possible the daughter wave energy circulation between them and, as a consequence, the onset of the absolute PDI predicted by M. Rosenbluth [18]. In the present paper this scenario of absolute PDI is analyzed numerically accounting for the finite width of the pump wave beam. The approximate expression for the absolute PDI threshold dependence on the daughter waves convective losses along the plasma inhomogeneity direction and diffractive losses across the pump beam is obtained. It is shown that the instability power threshold was exceeded under conditions of on-axis X2-mode ECRH experiments at T-10 and TEXTOR, in which the missing power effect was observed [9, 10]. The microwave pump power is also above the absolute PDI threshold in the X2-mode ECRH experiments at DIII-D, in which a substantial broadening of the power deposition profile was reported [11]. It is shown that the considered PDI is also possible in the X2-mode ECRH experiments on the EAST tokamak, whose goal is to control the magnetic island.

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REFERENCES

[1] PRATER, R., Physics of Plasmas **11** (2004) 2349.
[2] WESTERHOF, E., NIELSEN, S.K., OOSTERBEEK, J.W., SALEWSKI, M., DE BAAR, M.R., BONGERS, W.A., BÜRGER, A., HENNEN, B.A., KORSHOLM, S.B., LEIPOLD, F., MOSEEV, D., STEJNER, M., THOEN, D.J., Phys. Rev. Lett. **103** (2009) 125001.
[3] HANSEN, S.K., NIELSEN, S.K., STOBER, J., RASMUSSEN, J., STEJNER, M., HOELZL, M., JENSEN, T., Nucl. Fusion **60** (2020) 106008.
[4] TANCETTI, A., NIELSEN, S.K., RASMUSSEN, J., GUSAKOV, E.Z., POPOV, A.Y., MOSEEV, D., STANGE, T., SENSTIUS, M.G., KILLER, C., VECSEI, M., JENSEN, T., ZANINI, M., ABRAMOVIC, I., STEJNER, M., ANDA, G., DUNAI, D., ZOLETNIK, S., LAQUA, H., Nuclear Fusion **62** (2022) 074003.
[5] CLOD, A., SENSTIUS, M.G., NIELSEN, A.H., RAGONA, R., THRYSØE, A. S., KUMAR, U., S. CODA, NIELSEN, S.K., Physical Review Letters **132** (2024) 135101.
[6] GUSAKOV, E.Z., POPOV, A.Y., MESHCHERYAKOV, A.I., GRISHINA, I.A., TERESHCHENKO, M. A., Phys. Plasmas **30** (2023) 122112.
[7] EGUILIOR, S., CASTEJÓN, F., DE LA LUNA, E., CAPPA, A., LIKIN, K., FERNÁNDEZ, A., TJ-II TEAM, Plasma Phys. Control. Fusion **45** (2003) 105.
[8] ANDREEV, V.F., DNESTROVSKIJ, YU.N., OSSIPENKO, M.V., RAZUMOVA, K.A., SUSHKOV, A.V., Plasma Phys. Control. Fusion **46** (2004) 319.
[9] KANTOR, M.YU., BERTSCHINGER, G., BOHM, P., BUERGER, A., DONNÉ, A.J.H., JASPERS, R., KRÄMER-FLECKEN, A., MANN, S., SOLDATOV, S., QING, ZANG., the TEXTOR Team, Proc. of 36th EPS Conference on Plasma Phys., Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-1.184 (2009).
[10] DNESTROVSKIJ,Y.N., MELNIKOV, A.V., LOPEZ-BRUNA, D., DNESTROVSKIJ, A.Y., CHERKASOV, S.V., DANILOV, A.V., ELISEEV, L.G., KHABANOV, F.O., LYSENKO, S.E., SYCHUGOV, D.Y., Plasma Phys. Control. Fusion **65** (2023) 015011.
[11] SLIEF, J.H., VAN KAMPEN, R.J.R. , BROOKMAN, M.W., VAN DIJK, J., WESTERHOF, E., VAN BERKEL, M., Nucl. Fusion **63** (2023) 026029.
[12] [10] GUSAKOV, E.Z., POPOV, A.Y., Phys. Usp. **63** (2020) 365.
[13] GUSAKOV, E.Z., POPOV, A.Y., Physics of Plasmas **23** (2016) 082503.
[14] GUSAKOV, E.Z., POPOV, A.Y., Plasma Physics Reports **49** (2023) 949.
[15] SHALASHOV, A.G., SUVOROV, E.V. Plasma Phys. Control. Fusion **45** (2003) 1779.
[16] ANGIONI, C., PEETERS, A., GARBET, X., MANINI, A., RYTER, F., ASDEX Upgrade Team, Nuclear Fusion **44** (2004) 827.
[17] TRETINNIKOV, P.V., GUSAKOV, E.Z., HEURAUX, S., Plasma Phys. Control. Fusion **63** (2021) 085003.
[18] ROSENBLUTH, M.N., Phys. Rev. Lett. **29** (1972) 565.