Design Study on Plasma-Loaded Cyclotron Resonance Maser Utilizing TPD-II Machine in NIFS

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Design study of an experiment for plasma-loaded cyclotron resonance maser (CRM) utilizing TPD-II Machine at NIFS, Japan is described. We derive and analyze numerically an exact linear dispersion relation of radiation from a large orbit electron beam, and found that the relation includes two principles of cyclotron emission with oscillation frequencies above and below the relativistic electron cyclotron frequency. The former is conventional CRM instability, and the latter is named Cherenkov instability in the azimuthal direction (CIAD). In this study, the existence of CIAD is tried to verify experimentally. For plasma density $n > 1.5\times10^{11}$ cm^{-3}, the CRM instability may be suppressed and the CIAD may take turn.

Keywords: Cavity, Cherenkov instability in azimuthal direction, cyclotron resonance maser, fast wave, gyrotron, negative absorption, microwave, slow wave, TPD-II, wiggler.

1. Introduction

The principle of gyrotrons, high-power millimeter microwave sources indispensable for fusion research, is believed cyclotron resonance maser (CRM) instability [1-4]. The CRM was verified in an experiment in which negative absorption was observed for $\omega > \tilde{\Omega}$ [2]. Here, ω and $\tilde{\Omega} = eB_0/\gamma_0 m$ are, respectively, oscillation angular frequency and relativistic electron cyclotron frequency.

However, all the existing linear dispersion relations of CRM instability [3, 4] include unphysical (numerical) modes unstable at infinite values of axial wavenumber k_z in slow wave region, $\omega / k_z < c$, that can never be observed experimentally. To overcome the difficulty, we derive and analyze numerically exact linear dispersion relations of CRM for a large orbit (LO, hereafter) electron beam, for the first time in the history of the CRM research [5-7]. The conventional unphysical modes are replaced by stable modes near the fast cyclotron mode. Here, LO means that all the electrons have an identical location of guiding center on the center axis of waveguide.

Our exact dispersion relations [5-7] include two principles of cyclotron emission with oscillation frequencies above and below the branch of relativistic fast electron cyclotron wave $\omega = \tilde{\Omega} + V_z k_z$. The former is well-known CRM instability $(\omega > \tilde{\Omega})$, and the latter $(\omega < \tilde{\Omega})$ is named Cherenkov instability in the azimuthal direction (CIAD). The reason why the CIAD has not been included in the existing dispersion relations is that the boundary conditions with inevitable finite Larmor radius effect at beam-vacuum interface were not analyzed correctly.

It should be emphasized, however, that the CIAD we found remains only a proposal of possible cause of cyclotron emission, until its physical existence is verified experimentally. To verify the CIAD, we try to extend the CRM experiment in vacuum made by Hirshfield and Wachtel [2] to a plasma environment.

We design and fabricate a plasma-loaded CRM in the TPD-II Machine at National Institute for Fusion Science (NIFS), Japan, utilizing as beam source. With increase in density of plasma in TPD-II, the CRM instability may be suppressed and the CIAD may take turn. In other words, frequency of negative absorption observed in vacuum [2] may change from above to below $\tilde{\Omega}$ with increase in the beam density in the cavity such that $n > 1.5\times10^{11}$ cm^{-3}.

2. Theoretical Study on CRM Instability and CIAD

The CRM instability [1, 2] has been believed to be caused by the faster branch $\omega > \tilde{\Omega} + V_z k_z$ of the fast cyclotron wave $\omega = \tilde{\Omega} + V_z k_z$. It must be emphasized, however, that all the existing linear dispersion relations [3, 4] of the CRM instability include unphysical branches unstable at infinite values of axial wavenumber k_z. Gyrotron researchers have trusted that the growth rate near $k_z = 0$ was still CRM instability. The fact is as follows: Their physical explanation [3, Fig. 1] of CRM instability was correct, but their relation [3, Eq. 1] of CRM was entirely incorrect. Both of them have nothing to do with each other. In order to understand CRM instability physically, one must take into account the logical presence of CIAD that is unavoidable in general whenever a high density beam has a boundary.

We consider a circular waveguide of radius r_{cav} including concentric LO infinitely thin thickness beam. If the beam is neutralized by cold ions, no radial motion of the gyrating electrons is allowed, and they must stay on the original LO circle at any moment. The derivation of our exact dispersion relation for infinitely thin thickness annular beam is described in [5]. Somewhat surprisingly, infinitely thin annular beam does not exhibit CRM instability, but CIAD is obtained. On the other hand, when all the non-relativistic terms in the surface current density are dropped, without legitimacy through approximation $c \to 0$, to exclude the nonrelativistic effect, we obtain the relation identical to conventional linear dispersion relations of CRM obtained by Sprangle and Drobot [3, Eq. 1], and by Chu and Hirshfield [4, Eq. 8] that include unphysical branches in the limit of wavenumber $k_z \to \pm\infty$. These classical relations were still understood to be correct, because the obtained branch of CRM instability with $\omega > \tilde{\Omega}$ at k_z=0 [3, Fig. 1] was qualitatively identical to the experimental fact $\omega > \tilde{\Omega}$ [2, Fig. 2(a)]. However, this superficial coincidence cannot justify to ignore the presence of unphysical branches in their dispersion relations. The unphysical branches are the evidence of inadequate derivation of the linear dispersion relations of CRM. Such unphysical instabilities flat for k_z are observed often in numerical analyses, but have never been observed experimentally. A correct dispersion relation that includes both CIAD and CRM instability is obtained, when one analyzes a finite-thickness LO annular beam that allows radial displacement of the electrons. Our exact dispersion relations [5, 7] are exceptions that have overcome the difficulty in a particular case of LO electron beams for the first time in physics of gyrotrons.

3. Design Study of Plasma-Loaded CRM in TPD-II Machine

For experimental verification of the CIAD, a design and fabrication of plasma-loaded CRM have been conducted. Schematic view of the TPD-II Machine and our constructed apparatus are shown in Fig. 1. In (a), total view of the apparatus is depicted. Plasma is produced by DC helium gas discharge between a hot cathode and grounded anode in TPD-II at the right-side.

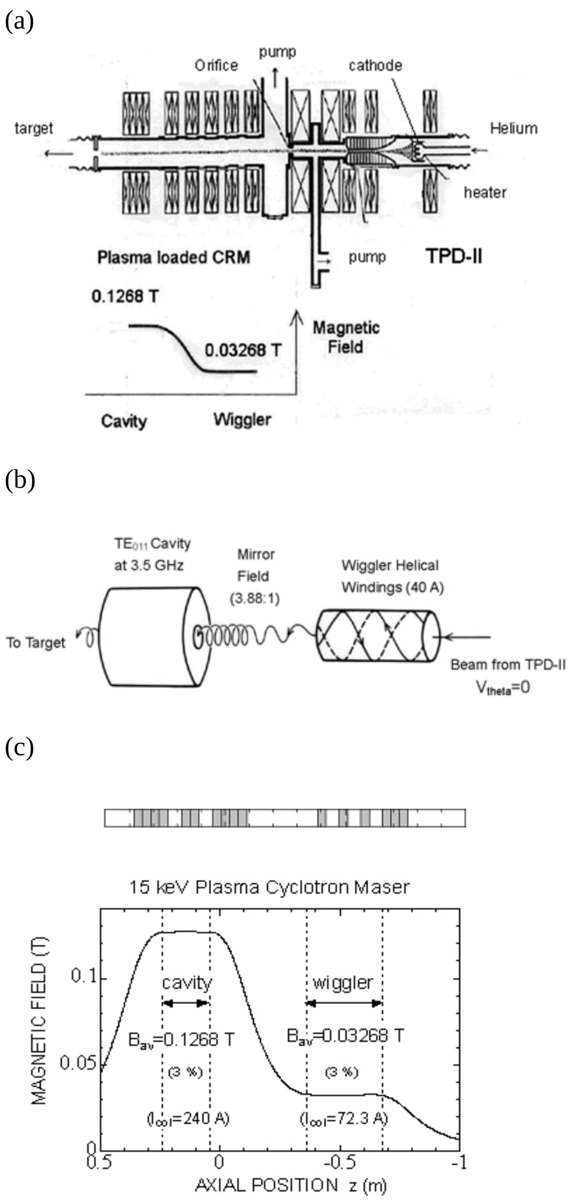

Fig. 1 Plasma-loaded CRM installed inside the TPD-II Machine, NIFS, Japan. (a) Total view. (b) Principle of plasma-loaded CRM. (c) Distribution of axial magnetic field in the wiggler and the cavity. Bar code shows the location of 16 coils.

Plasma is emitted from a small orifice in the anode into left-side plasma container in solenoid coils where the plasma-loaded CRM is located. This portion is evacuated by high speed pumps to remove neutral gases for attaining fully ionized plasma. The plasma column has high density up to 10^{14} cm^{-3}, temperature of a few eV and beam diameter 10 mm.

To detect negative absorption caused by CRM instability or CIAD, a large number of gyrations of the beam inside the cavity are required. The principle of the plasma-loaded CRM is schematically shown in Fig. 1(b). It consists roughly of two different portions: (i) A pair of helical windings called wiggler in this paper for creating transverse velocity in the beam at the right-hand side, and (ii) the TE_{011} mode cylindrical cavity at the left-hand side. The latter is connected to microwave circuits for detecting negative absorption of incident low power microwave near 3.45 GHz. An electron beam from TPD-II Machine is incident from the right-hand side. The beam, however, has no azimuthal velocity component, namely $V_\theta \simeq 0$.

In order to create a large V_θ for gyrations, the beam is introduced on the axis of the wiggler that produces a helical circularly polarized static magnetic field b_t of the order of 10^{-3} (T) near the axis. Here, b_t can be quite small, because it does not give any energy to the beam. In Fig. 1(c), calculated distribution of axial magnetic field on the axis of the plasma-loaded CRM is shown.

If the pitch length λ_w of the right-hand circularly polarized DC magnetic field b_t generated by the wiggler is equal to axial pitch length $2\pi V_z/\tilde{\Omega}$, the electrons are accelerated in azimuthal direction secularly by the Lorentz force $-e\vec{v}_z \times \vec{b}_t$ at the expense of their axial velocity. The designed wiggler is a pair of four turn bifilar conductors with pitch length $\lambda_w = 8.0$ cm, radius $a = 1.775$ cm and total length $L = 32$ cm. The pitch factor $\alpha = V_\theta / V_z \simeq 0.65$ will be obtained at the exit of the wiggler.

The obtained α can be increased further, by transmitting the beam before the incidence on the cavity through the mirror field shown in Fig. 1(c) from B_s=0.03268 T at the wiggler to another axial field B_0=0.1268 T at the cylindrical cavity. The mirror ratio is B_0/B_s=3.88, and α =1.28 will be obtained that enables many gyrations in the cavity.

In Fig. 2, expected electron properties through wiggler and mirror magnetic field are demonstrated by trajectory tracking in order to show an example that helical field b_t enhances perpendicular pitch $\alpha = V_\theta / V_z$. In (a) and (b), the profiles of axial and perpendicular magnetic fields, B_z, B_r and B_θ on the axis, are calculated. In (b), B_r and B_θ with and without b_t=0.0008 T (I_{tot}=40 A) are depicted. In (c), an example of radial position of electron trajectories is followed from z=-1.1 to 0.3 m for both cases b_t=0.0008 T and b_t=0. In (d), changes in perpendicular pitch $\alpha = V_\theta / V_z$ are depicted for both b_t. It is clearly shown in (c) and (d) that the presence of wiggler magnetic field b_t=0.0008 T enhances significantly the spiral motion.

The frequency of incident microwave on the fabricated cylindrical stainless-steel cavity works at TE_{011} mode near 3.5 GHz. Inner diameter of the TE_{011} cavity is 0.1083 m, and the length is varied from 0.17 to 0.21 m by the adjustable shorting disk. Figure 3 shows the calculated curves of positive and negative absorptions as a function of axial magnetic field B_0. The frequency of incident microwave is adjusted at the resonance in empty cavity to observe the minimum $|R_{\max}|^2$. The vertical axis $|R|^2$ is assumed to be proportional to attenuation constant α for round-trip of microwave in the cavity as [1, 2]:

$$\alpha = \frac{\pi G}{Q_e}\left(1 + \frac{2py}{1+y^2}\right), y = \frac{\omega - \omega_1}{2B_1},$$

where ω_1, B_1 and p are given numerical constants to fit the positive and negative absorptions. In Fig. 3, coupling factor s=0.15 and other parameters shown in the figure are assumed. Negative absorption (in fact, decreased positive absorption) arises for $|p| > 1$ [1]. The resonant curve of the CRM instability for p=1.5 is depicted by solid curve, whereas the case of the CIAD for p=-1.5 is shown by dashed curve. Negative absorption of the CRM instability and the CIAD could be observed, respectively, for $\omega > \tilde{\Omega}$ and $\omega < \tilde{\Omega}$ as shown in Fig. 3. In other words, the CRM and the CIAD are expected for low-field and high-field sides of $\omega = \tilde{\Omega}$ that corresponds to the axial magnetic field $B_0 = 0.3106$ T for our 15 keV beam.

According as beam current increases, the region of the negative absorption is expected to move from left-hand side (solid curve) to right-hand side (dashed curve) of $B_0 = 0.1306$ T. Or, probably we may observe both negative absorptions at the same time for the incidence of high density beam such as $n > 1.5 \times 10^{11}$ cm^{-3}, where $n = 1.5 \times 10^{11}$ cm^{-3} corresponds to $\omega = \tilde{\Omega} = \omega_b$.

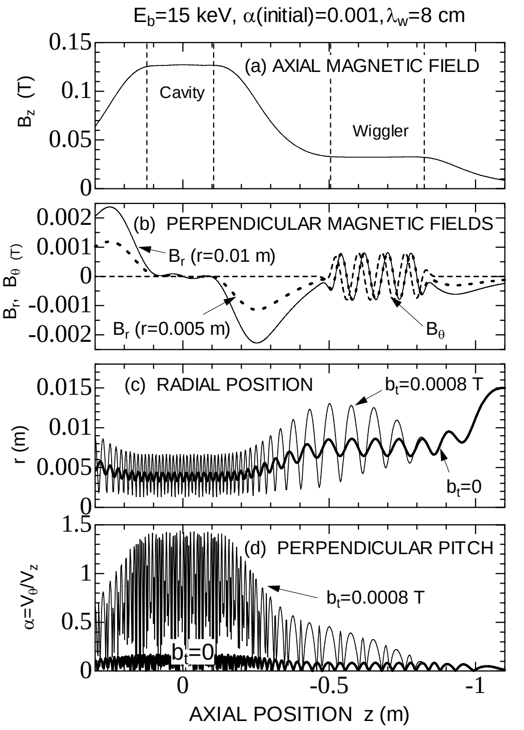

Fig. 2 Electron beam properties obtained by trajectory tracking. Helical field b_t enhances significantly perpendicular pitch $\alpha = V_\theta / V_z$.

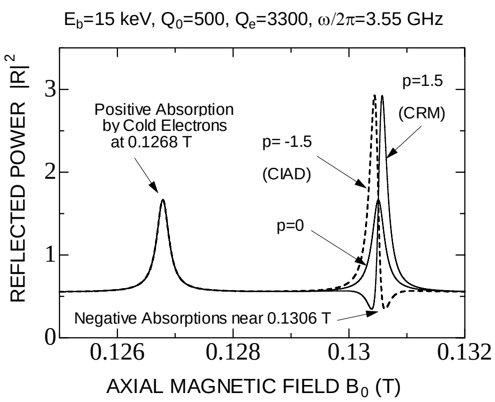

Fig. 3 Curves of absorption expected for CRM (solid curve) and CIAD (dashed curve).

The physical meaning of $|p| > 1.0$ for negative absorption is physically analogous to $N(V_\theta / c)^2 > 1$ that many gyrations in the cavity are required for detecting the resonant curves correctly, where $N \gg 1$ is number of gyrations in the cavity.

Diagram of constructed microwave interferometer including the TE_{011} plasma cavity is shown in Fig. 4. In near future, the measurements of negative absorption caused by the CRM instability and the CIAD will be conducted.

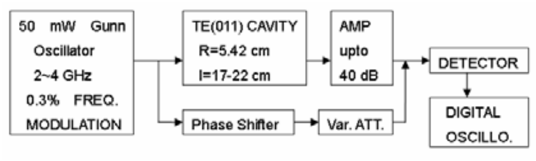

Fig. 4 Constructed microwave interferometer circuits including fabricated TE_{011} mode cylindrical two-port cavity with resonant frequency near 3.45 GHz.

4. Discussion and Conclusion

Currently, it may not be a fashionable subject of research to discuss which oscillation frequency $\omega > \tilde{\Omega}$ or $\omega < \tilde{\Omega}$ is observed in real gyrotrons. This is partly because ω is almost a fixed quantity given by the sizes of a cavity. Moreover, the distinction between $\omega > \tilde{\Omega}$ and $\omega < \tilde{\Omega}$ is practically difficult from experimental point of view, because $\tilde{\Omega}$ is a quantity spatially non-uniform, whereas ω can be measured very precisely. The difference between ω and $\tilde{\Omega}$ can be observed, only when a device to fit the particular purpose of distinction between CRM and CIAD were carefully designed [2].

The CIAD and the CRM instability are probably coexisting mechanisms of cyclotron emission from various gyro-devices incliding the gyrotrons. The CRM instability ($\omega > \tilde{\Omega}$) may not be the exclusive principle of gyrotron oscillation, because there has been no experimental verification to be $\omega > \tilde{\Omega}$ in gyrotrons. It is quite important to distinguish between $\omega > \tilde{\Omega}$ and $\omega < \tilde{\Omega}$ in cyclotron emissions in plasma physics and in gyrotron research, since physical reasons are different. It should be emphasized that, sometimes, physics requires a stringent accuracy for better understandings, even though such accuracy may not be required from engineering point of view.

The gyrotron community over the world is partly spoiled by the defect of unphysical solutions [3,4]. We regret that fundamental understandings of physics of gyrotrons are not very firm yet, although there exist huge amount of research reports for technical and hardware developments. For decades, many of students in universities over the world are left to study the incorrect theory of CRM.

Our constrained gyration model and the resultant CIAD [5] remains only a proposal at this moment, until the physical existence is verified experimentally. It is the purpose of our experimental program to verify a physical cause of cyclotron emission that has not been known up to date. In our plasma-loaded CRM, negative absorption due to the CRM instability may be suppressed in high-density beam such as $\omega_b^2 \gg \tilde{\Omega}^2$, namely density $n > 1.5\times10^{11}$ cm^{-3}, and the CIAD may take turn. In this experimental program, we try to observe the new principle of cyclotron emission different from the CRM instability. The present experimental study contributes to a deeper understanding and a widened future prospect in gyrotron research.

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