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Enhancement of X-ray Generation in a Microwave Discharge

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Abstract

In the present paper we describe the observation of enhancement of X-ray generation in a microwave plasma at a sub-harmonic of the gyro-frequency, where the equality $\omega = \frac{1}{2}\,\omega_H$ is satisfied (here ω is the microwave frequency, ω_H is the gyro-frequency of electrons). Our experiments show, for the first time, that the X-ray flux produced at sub-harmonic resonance is five times higher than that produced at the cyclotron resonance.

Keywords:

sub-harmonic resonance, gyro-frequency, plasma, X-ray, microwave discharge, magnetic trap, electron cyclotron resonance

One of the prospective X-ray plasma sources is based on a microwave discharge in a magnetic trap at low gas pressure, under electron cyclotron resonance (ECR), *i.e.* under conditions when there is a region in the trap where the resonance on the fundamental harmonic $\omega = \omega_H$ is fulfilled (ω_H is the gyro-frequency of electrons). In such a relatively small source a plasma with density of the order 10^{10}–10^{11} cm^{-3} containing « hot » electrons with energies of a few tens of keV is obtained. When these electrons impinge on a solid target, located inside the plasma chamber, X-rays with considerably higher intensity are generated [1]. The use of permanent magnets to produce the mirror magnetic field prevents the axial injection of microwaves, therefore transverse injection of microwaves was used.

Ikegami *et al.* [2] showed that when the microwave power is fed across the magnetic flux lines, the hot electrons are bunched in a closed-shell structure located at the midplane of the magnetic mirror, both during the microwave discharge and in the afterglow of the plasma. Ikegami *et al.* [2] also found a resonant increase of the X-ray emission when the second and third harmonics of the electron cyclotron frequency associated with the magnetic field in the midplane of the magnetic mirror reached the frequency of the heating microwave.

We describe here the observation of the resonant increase of X-ray emission at a sub-harmonic of the gyro-frequency, namely at $\omega = \frac{1}{2}\,\omega_H$, when launching microwaves in a compact X-ray source transverse to the magnetic field lines. It was suggested earlier that the nonlinearity of the equations of electron motion which determines resonant interaction on the sub-harmonic can be related to the non-homogeneity of the microwave pumping [3] as well as with non-homogeneity of the dc magnetic field [4]. We experimentally investigate the

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efficiency of X-ray production in the ECR discharge for different resonance conditions at $\omega = \omega_H$ and $\omega = \frac{1}{2}\omega_H$. The specific feature of our experiment was to keep a fixed frequency of the microwave source (2.45GHz). The transition from sub-harmonic to cyclotron resonance was performed by varying the dc magnetic field in the trap.

The experimental setup is shown on Fig. 1. The microwave source for producing the plasma is a magnetron from a microwave oven with a frequency of 2.45GHz at a power of 1kW, operated in a pulsed mode, with the pulse length 1ms. The linearly polarized microwaves are transferred through a cylindrical waveguide with a diameter of 9.3cm into the vacuum chamber with characteristic dimensions $14\times14\times14\text{cm}^3$. The vacuum chamber was placed in a simple axisymmetric magnetic trap, created by two pulsed solenoids. The curent pulse length was 13ms and the mirror ratio was 3.5. Moveable targets made of different materials were introduced in the midplane of the discharge chamber filled with argon. When working with a magnetic field of 1750Gauss ($\omega = \frac{1}{2}\omega_H$) near the target, the magnetic field value of 875Gauss ($\omega = \omega_H$) was not present in the chamber. A NaI scintillation detector (designed primarily for counting photons) was used to measure the X-ray spectrum, by measuring the amplitude of the 10μs pulses, which is proportional to the photon energy. The spectral resolution of the detector is 28%, the working energy range is 15–150keV. In this experiment the lowest measured photon energy is determined by the Al window of 200μm thickness. For measuring the X-ray dose a calibrated dosimeter DRG-05M was used (minimum energy of the measured photon is 15keV). For the estimation of the plasma density in the discharge, we measured the current with a Langmuir probe, located on the axis outside the magnetic trap at a considerable distance from the magnetic mirror. In addition, one could estimate the plasma electron density by measuring the intensity of the microwave radiation transmitted through the plasma. The absorption coefficient of the microwave signal by the plasma was measured with an antenna and HF diode, located outside the chamber, behind the microwave window.

During the herein described experiments the Bremsstrahlung flux with various targets was studied at fixed microwave frequency (2.45GHz) versus the magnetic field, at different gas pressures. The maximum X-ray flux at the fundamental harmonic of the gyro-frequency $\omega = \omega_H$ was measured for a pressure of 4×10^{-5}Torr (curve *a* on Figure 2), while the maximum at half-harmonic of the gyro-frequency $\omega = \frac{1}{2}\omega_H$ (i.e. $B/B_c = 2$) was measured at a lower pressure, 2×10^{-5}Torr (curve *b* on Figure 2). Both maxima cannot be observed at the same pressure. No other maximum was observed by increasing the magnitude of the magnetic field up to $B/B_c = 6.5$, irrespective the pressure.

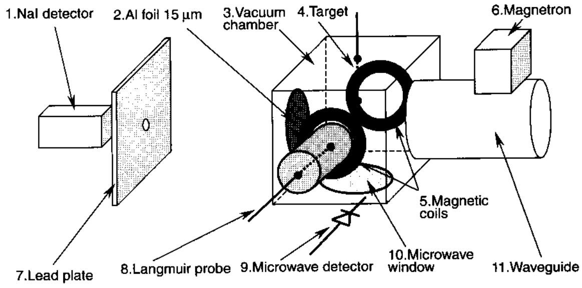

Fig. 1 Schematic presentation of the experimental setup.

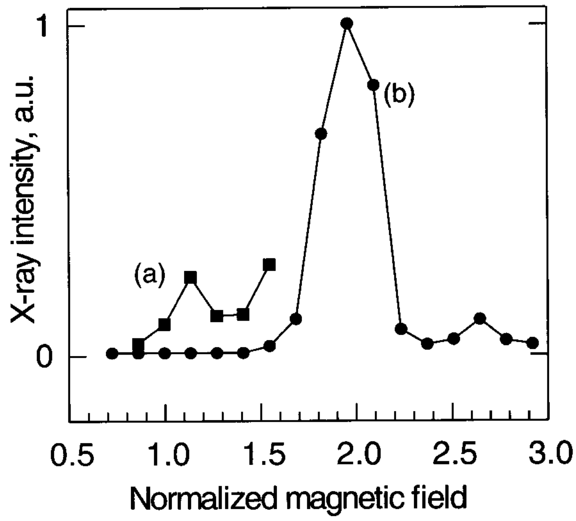

Fig. 2 Integrated X-ray spectrum intensity versus normalized magnetic field B/B_c. Curve *a* corresponds to pumping at the fundamental harmonic, with optimum pressure 4×10^{-5}Torr, curve *b* - to pumping at the half-harmonic, with optimum pressure 2×10^{-5}Torr.

It is important to note that the X-ray flux measured when pumping on the half-harmonic of the gyro-frequency (at lower pressure) exceeds by a factor five the flux obtained when pumping on the fundamental harmonic.

The pressure dependence of the discharge characteristics for the half harmonic of the gyro-frequency is illustrated in Figures 3 and 4. Typical time

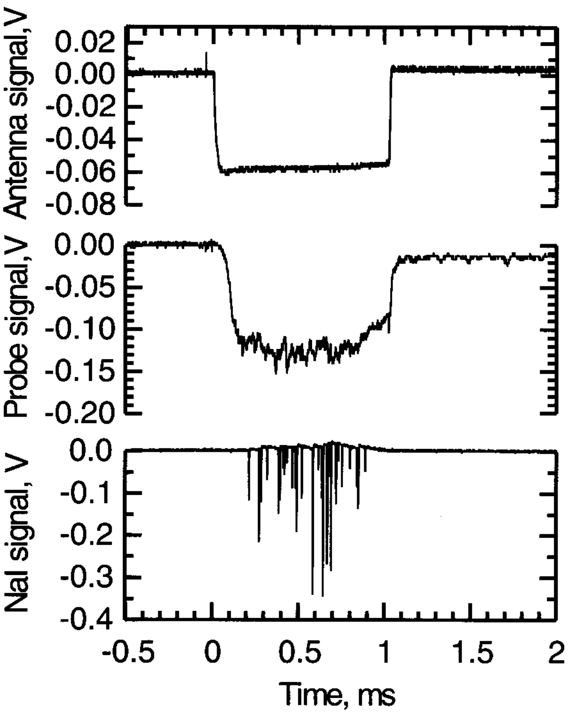

Fig. 3 Oscilloscope traces of (from top to bottom): transmitted microwaves, electron current to the probe, signal of the X-ray detector. Discharge at pressure of 2×10^{-5}Torr.

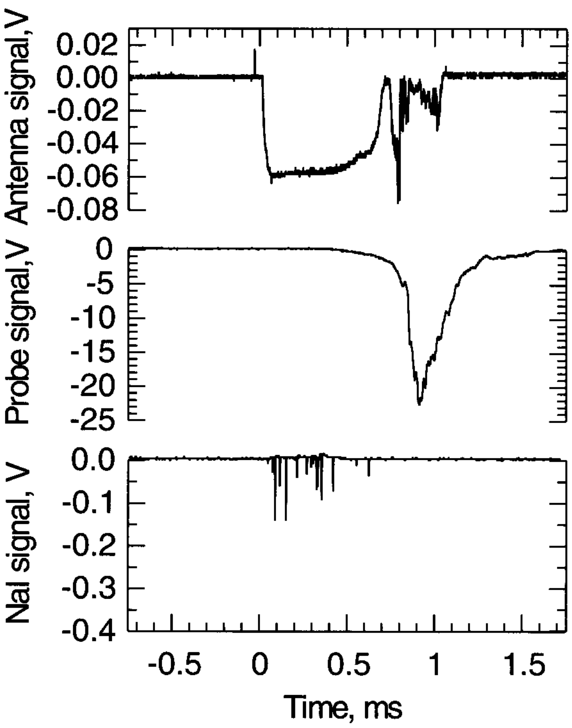

Fig. 4 Oscilloscope traces of (from top to bottom): transmitted microwaves, electron current to the probe, signal of the X-ray detector. Discharge at pressure of 5×10^{-5}Torr.

dependences of the microwave detector signals, from the Langmuir probe and the X-ray detector for two different pressures are displayed. The analysis of these dependences shows the existence of two different discharge modes with different electron densities and temperatures. At low gas pressure (2×10^{-5}Torr, Fig. 3) a discharge with low plasma density is obtained. In this case there is no temporal variation of the transmitted microwave signal (Fig. 3, upper oscillogram), which means that the plasma density is much less than the cut-off value. The Bremsstrahlung recorded by the X-ray detector can be seen from the lowest oscilloscope trace in Figure 3. At higher pressures (5×10^{-5}Torr, Fig. 4) at a certain time the discharge mode is suddenly changing. The signal from the probe placed on the longitudinal axis of the magnetic system increases abruptly (by a factor ten relative to the signal before the change of the discharge mode), while the signal recorded by the microwave diode decreases, and the X-ray radiation disappears. The further increase in the pressure leads to the disappearance of the low-density discharge phase, while the high-electron-density discharge phase starts from the very beginning of the microwave pulse.

The X-ray Bremsstrahlung spectrum recorded when using a light target such as aluminum (showing no characteristic lines in the observed energy range) is shown on Fig. 5. Note that the intensity spectrum decays following an exponential function $\exp(-E/kT_e)$, with kT_e = 30 keV. When heavier targets are used, a substantial contribution to the X-ray intensity is brought by the characteristic lines of the target material (18keV or 64keV, if a molybdenum or a tungsten target is used, respectively).

The total accumulated X-ray dose was measured by two methods: (1) by integrating the measured spectra and (2) by using a dosimeter. Under optimum conditions, the dose at 30cm from the radiation source was determined to be 3.57mGy/s.

In conclusion, we underline our main experimental results : (a) the first observation of an X-ray flux produced under conditions of sub-harmonic resonance, and (b) the significantly higher flux of the latter compared to the X-ray flux produced in the fundamental cyclotron resonance regime under optimum plasma conditions (gas pressure, see Fig. 2). The relatively high intensity of X-ray radiation in the sub-harmonic regime

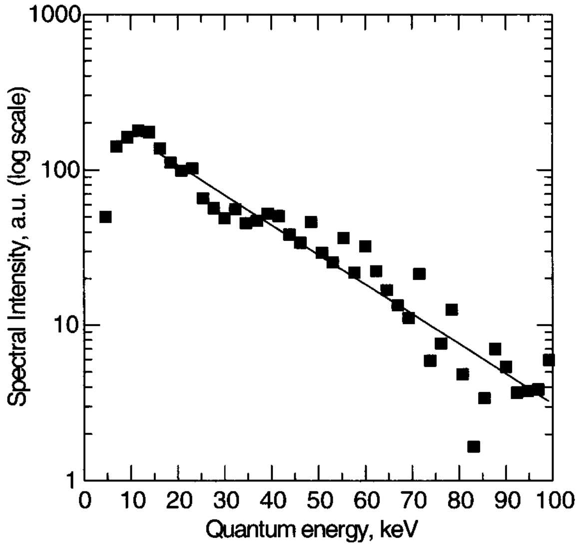

Fig. 5 Spectrum of Brehmsstrahlung with Al target (T_e = 30keV) when pumping at the half-harmonic of the gyro-frequency.

of electron acceleration was recorded in characteristic lines of heavy material targets. This is convincing evidence that under suitable plasma conditions a fraction of electrons are accelerated up to relatively high energies.

The detailed comparative theoretical analysis of X-ray production in these two regimes is a rather exciting and interesting problem, but it lies outside the scope of this paper. We have considered a number of theoretical explanations and made the corresponding calculations. Work is in progress to find the genuine cause of the sub-harmonic resonant enhancement of X-ray generation.

One should also realize that in the sub-harmonic regime the magnitude of the mirror magnetic field is double the magnitude of the latter in the fundamental harmonic regime. This fact points to considerably-improved confinement properties of the magnetic trap for energetic electrons.

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