УДК 538.9

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DEVELOPMENT OF HIGH FREQUENCY GYROTRONS AND APPLICATION TO HIGH POWER THz TECHNOLOGIES

Development of high frequency cw gyrotrons (Gyrotron FU CW Series) as high power THz radiation sources was advanced in FIR FU on the basis of the success in the development and application of the previous Gyrotron FU series [1]. In this paper, we would introduce the development of high frequency gyrotrons in FIR FU and applications to high power THz technologies.

Keywords: gyrotrons, high frequency, high power, THz technologies, DNP-NMR, ESR spectroscopy.

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РАЗРАБОТКА ВЫСОКОЧАСТОТНЫХ ГИРОТРОНОВ И ПРИМЕНЕНИЕ В ТГЦ ТЕХНОЛОГИЯХ ВЫСОКИХ МОЩНОСТЕЙ

FIR FU (исследовательский центр исследований в дальней ИК-области частот университета Фукуи, Япония) добился успеха в разработке высокочастотных гиротронов бегущей волны (серия Gyrotron FU CW) в качестве мощных источников ТГц излучения благодаря своим достижениям в разработке и применении предыдущей серии, Gyrotron FU [1]. В этой статье статье описано развитие высокочастотных гиротронов в FIR FU и их применение в ТГц технологиях высоких мощностей.

Ключевые слова: гиротрон, высокие частоты, высокая мощность, терагерцовые технологии, ЯМР, динамическая поляризация ядер, спектроскопия электронного спинового резонанса.

1 Introduction

Our high frequency gyrotrons (present Gyrotron FU CW Series and the previous Gyrotron FU Series) are high power radiation sources covering sub-THz to THz frequency region [2]. The output power of such gyrotrons are much higher, by several orders, than those of conventional radiation sources, for example, BWOs, TWTs, molecular gas lasers, solid state devices, etc.

In the THz region, conventional devices (vacuum devices and solid state devices) lose their output power with frequency increased. On the other hand, free electron lasers and molecular lasers lose the output power with the frequency decreased. As the result, the output powers of these radiation sources are quite low in the frequency range near 1 THz. We call such a situation as “THz gap”. However, recent development of THz pulse gyrotrons and gyrotron FU CW series can improve such a situation. Gyrotrons are much more powerful radiation sources in THz frequency region compared with any other radiation sources. At the present, gyrotrons are the only radiation sources which can bridge on the THz gap.

The gyrotron series are now being applied for development of high power THz technologies in wide research fields [3]. Such a high frequency gyrotron is the only radiation source which will open the high power THz technologies such as DNP-NMR spectroscopy [4–6], X-ray detected magnetic resonance (XDMR) measurement [7], ESR echo measurement in THz region [8], etc.

ISSN 1818-7994. Вестник НГУ. Серия: Физика. 2010. Том 5, выпуск 4
Vestnik Novosibirsk State University. Series: Physics. 2010. Volume 5, issue 4

In the next section, development of high frequency CW gyrotrons (Gyrotron FU CW Series) in FIR FU is summarized, in section 3, the applications of the gyrotrons are presented and in section 4 the summary and the future prospects are presented.

2 Development of high power far infrared radiation sources Gyrotrons

2-1 Submillimeter wave gyrotron FU series

The previous gyrotron FU Series [9] was successfully developed, before FIR FU was established in 1999. Totally nine gyrotrons were constructed and applied for high power, new science and technologies in submillimeter wave region. The series has achieved long-term world record of high frequency operation of gyrotron at 889 GHz, frequency step-tunability in wide range from 70 GHz to 889 GHz, modulation of frequency and amplitude, high stabilization of frequency and amplitude, etc. These gyrotrons were applied for submillimeter wave scattering measurement on plasma, ESR spectroscopy in sub-THz region, etc. Table 1 summarizes the status of the Gyrotron FU Series.

2-2 A pulse gyrotron with a high field pulse magnet achieved the breakthrough of 1 THz

In 2005, our gyrotron with a high field pulse magnet has achieved the breakthrough of 1 THz [10]. This is new world record for high frequency operation of gyrotron at the second harmonic. The pulse operation with a narrow pulse width of several tens micro-second [11]. The highest frequency reached 1005 GHz at the field intensity of 19.0 T. The cavity mode is $TE_{6,11}$. The output power is several hundred watts. The pulse width was extended up to 1 milli-second by adjusting the operation phase at the top flat phase of the magnetic field waveform [12]. In the case, the frequency is increased up to 1014 GHz by use of $TE_{4,12}$ cavity mode.

2-3 Development of CW gyrotron series for application to high power far-infrared technologies

The early gyrotrons developed in FIR FU are pulse gyrotrons operating in sub-THz region. Some of them have already applied for plasma scattering measurement, ESR spectroscopy, etc.

Table 1. The status of Gyrotron FU Series which consists of nine gyrotrons

gyrotrons	Frequency	Items which each gyrotron has achieved
Gyrotron FU I	**38-220 GHz**	**High frequency operation at 100GHz and 9 kW output power**
Gyrotron FU E	**90-300 GHz**	**Radiation source for the first experiment on ESR**
Gyrotron FU IA	**38-215 GHz**	**Radiation source for plasma scattering measurement of WT-3**
Gyrotron FU II	**70-402 GHz**	**Studies on mode competition and mode cooperation,** **Radiation source for plasma scattering measurement of CHS**
Gyrotron FU III	**100-636 GHz**	**3rd harmonic operation in single modes, Amplitude modulation, Frequency step switching**
Gyrotron FU IV	**160-847 GHz**	**Frequency modulation, CW operation for high stability of amplitude and frequency**
Gyrotron FU IVA	**160-889 GHz**	**Higher frequency operations by 3rd harmonics, Highest frequency of gyrotron, Radiation source for ESR experiment**
Gyrotron FU V	**186-222 GHz**	**CW operation for long time using a He free magnet, High stabilizations of frequency and amplitude, High purity mode operation**
Gyrotron FU VI	**64 -137 GHz**	**Gyrotron with a permanent magnet, High harmonic operations up to 5 th, High purity mode operations in TE_{m1} modes at high harmonic**

Table 2. The status of Gyrotron FU CW Series which consists of nine gyrotrons

Gyrotron	Freq. *f* range	Output power	Max. *B*	Applications
FU CW I	300 GHz	2.3kW, CW	12 T	Material processing, New medical technology
FU CW II, CW IIA	110–440 GHz	20–200 W, CW	8 T	DNP-NMR at 600 MHz for protein research at Osaka University, Heating of the Si substrate
FU CW III	130–1,080 GHz	10–220 W, CW	20 T	High power THz Technologies
FU CW IV	131–139 GHz	5–60 W, CW	10 T	DNP-NMR at 200 MHz for material science
FU CW V	203.4 GHz	100–200 W, CW	8 T	Accurate measurement on hyperfine structure of positronium, new medical technology
FU CW VI	393–396 GHz	50–100 W, CW	15 T	DNP-NMR at 600 MHz for protein research at Osaka University
FU CW VII	203.7, 395.3 GHz	200W, 50W, CW	9.2 T	DNP-NMR at 300 MHz and 600 MHz at Warwick University
FU CW VIIA	131.5 GHz 395 GHz	200W, CW	8 T	ESR echo experiment in sub-THz region
FU CW VIII	100-350 GHz	100W, CW	8T	XDMR experiment with high power THz radiation at ESRF

However, continuous wave (CW) gyrotrons are sometime much more convenient for application to many high power THz technologies. For responding to such requirement, we have developed gyrotron FU CW series [2]. Up to the present, nine CW gyrotrons were developed. Each gyrotron has its own objective and was optimized for respective application subject. Table 2 summarizes the status of Gyrotron FU CW series.

Gyrotron FU CW III with a 20 T magnet has achieved the breakthrough of I THz in CW operation. The highest frequency is 1.08 THz. These gyrotrons are being used for many high power THz technologies, such as material processing, new medical technology, DNP enhanced NMR spectroscopy, Accurate measurement on hyperfine structure of positronium, ESR echo experiment in sub-THz region, X-ray detected magnetic resonance (XDMR) measurement, etc. Gyrotrons are only radiation sources in order to develop high power THz technologies in future.

3 Applications of Gyrotrons FU Series and FU CW Series to high power far-infrared technologies

3-1 DNP enhanced NMR spectroscopy at 200, 300 and 600 MHz

For DNP-NMR spectroscopy, a high power sub-THz gyrotron is needed in order to allow transfer of the high magnetization of the electron spins to the nuclear spins. The frequency of the gyrotron should be adjusted to the electron spin resonance (ESR) frequency corresponding to the nuclear magnetic resonance (NMR) frequency (or vice–versa). For 200 MHz, 300 MHz and 600 MHz proton NMR, the corresponding ESR frequencies are 131.5 GHz, 197.3 GHz and 394.6 GHz, respectively. In addition, an irradiation power of several W is required. In order to respond to such a requirement, we designed Gyroptron FU CW II, FU CW IV and FU CW VII operating at around 130 GHz and 200 GHz under the fundamental electron cyclotron resonance and at around 400 GHz for the second harmonic resonance.

In order to realize such operation frequencies, we need a superconducting magnet whose maximum field intensity is higher than 8T. We have prepared an 8T magnet for Gyrotron FU CW II, a 10 T magnet for FU CW IV and a 9.2T magnet for FU CW VII. The diameter of the room temperature bore is 100 mm or 88 mm and the uniformity of the field distribution at the center of the magnet is better than 0.1 percent within the sphere with the diameter of 10 mm. The designed cavity modes are TE_{12}, TE_{42} and TE_{13} for the fundamental operations and TE_{06} and TE_{16} for the second harmonic operations.

The design sheet and the side-view of the gyrotron FU CW VII are shown in Fig. 1 and Photo 1, respectively. The diameter and the length of the cavity are 4.35 mm and 19 mm, respectively. The frequencies of designed modes are 186.97 GHz (TE_{13} mode), 203.75 GHz (TE_{42} mode) and 395.28 GHz (TE_{16} mode). Typical parameters of electron beam are as follows, acceleration voltage V_b=10-15 kV, beam current I_b=200 – 350 mA, duty ratio η=0.1 – 1(CW) and the repetition rate f_m=1-10 Hz.

Gyrotron FU CW VII will allow the high enhancement of NMR sensitivity by Dynamic Nuclear Polarization (DNP). The gyrotron is installed in the NMR Research Group, University of Warwick, UK for 300 MHz and 600 MHz DNP-NMR spectroscopy.

The other gyrotron FU CW II has been installed in Institute of Protein Research, Osaka University, Japan for 600 MHz DNP-NMR spectroscopy. Fig. 2 is the typical result of DNP enhanced NMR spectroscopy. NMR absorption signal is enhanced by the irradiation of 394.5 GHz radiation power from the Gyrotron FU CW II. This is only qualitative result for DNP-NMR spectroscopy.

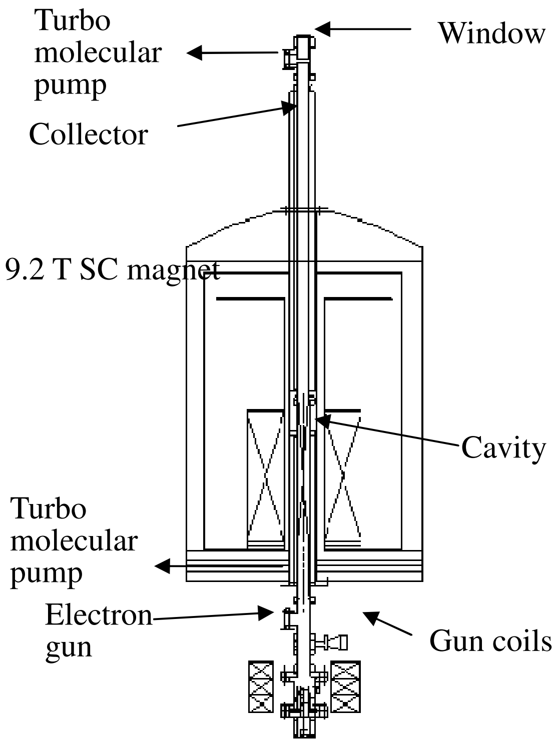

Fig. 1 A cross-section of Gyrotron FU CW VII

Photo 1 Side-view of Gyrotron FU CW VII

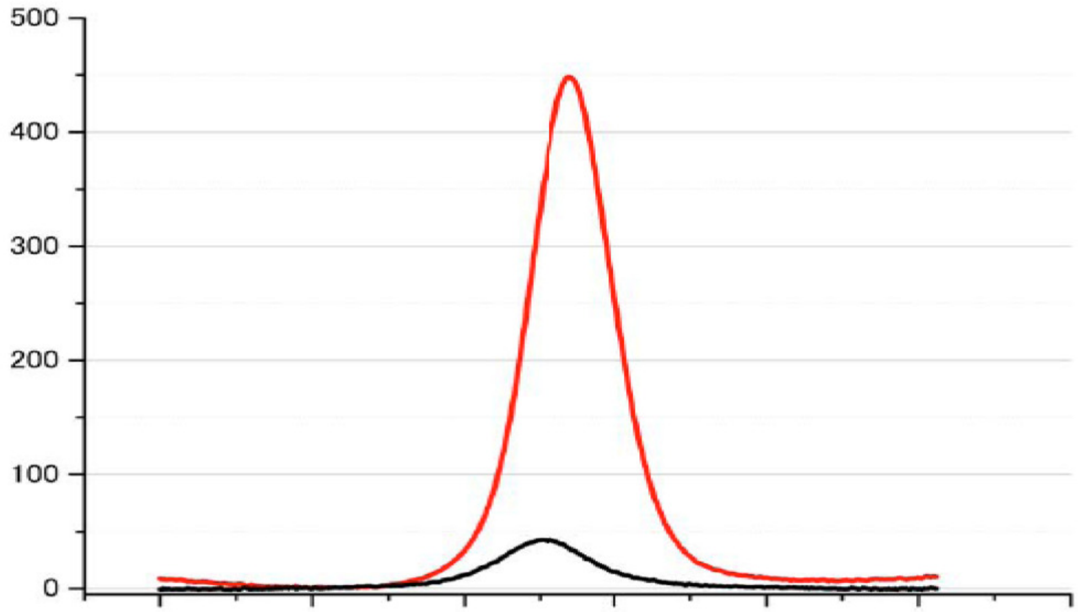

Fig. 2 Enhancement of ^{13}C-NMR absorption signal by irradiation of 394.5 GHz high power from the Gyrotron FU CW II at Osaka University. The enhancement factor is 10.4

Now, we are planning to increase the enhancement factor by one or two orders. For this purpose, we are preparing a new NMR probe optimized for DNP and a new frequency tunable gyrotron [13].

3-2 ESR spectroscopy in sub-THz frequency region

Electron spin resonance (ESR) spectroscopy is a convenient and useful tool for analyzing the properties of materials. Especially, high frequency ESR spectroscopy with high field pulse magnet can open new research areas in material science. In addition, it brings high resolution of the measurement and resolves fine structure of the ESR spectroscopy [14].

We have applied early gyrotrons, Gyrotrons FU II and FU IVA to ESR spectroscopy in sub-THz region. The applied frequency range is 160 to 800 GHz and the output power is ranged from several watts to 100 watts. Corresponding magnetic field intensity is also high. We are using a pulse magnet which covers the field intensity region up to 40 T. Fig. 3 shows the experimental set up (Upper) and typical measurement results (Lower).

The gyrotron output power is transmitted by a circular waveguide system and fed on the sample installed in the center of a pulse magnet. The transmitted signal is picked up by a horn antenna and analyzed by the detection system. The pulse magnet operates by discharging the condenser bank. The pulse width is several milliseconds. During this short time, the transmission signal is analyzed as the function of magnetic field intensity.

In Fig. 3 (Lower), are shown typical measurement results of ESR spectroscopy of the sample $CsFeCl_3$. At the fixed frequency of the spectrometer, the magnetic field intensity is varied under the pulse operation of the magnet. Several resonance absorption peaks appear on the observed transmission power. In the figure, the magnetic field intensities where absorption peaks appear for each fixed frequency are plotted. A red line shows observed magnetization M as a function of the field. A step-like drastic increases in M are observed near double resonance points of electron spin at around 9 T and 33 T. This result suggests that any phase transition in the sample occurs at these magnetic field intensities. The second step-like increase in M at 33 T can be found only by high frequency ESR

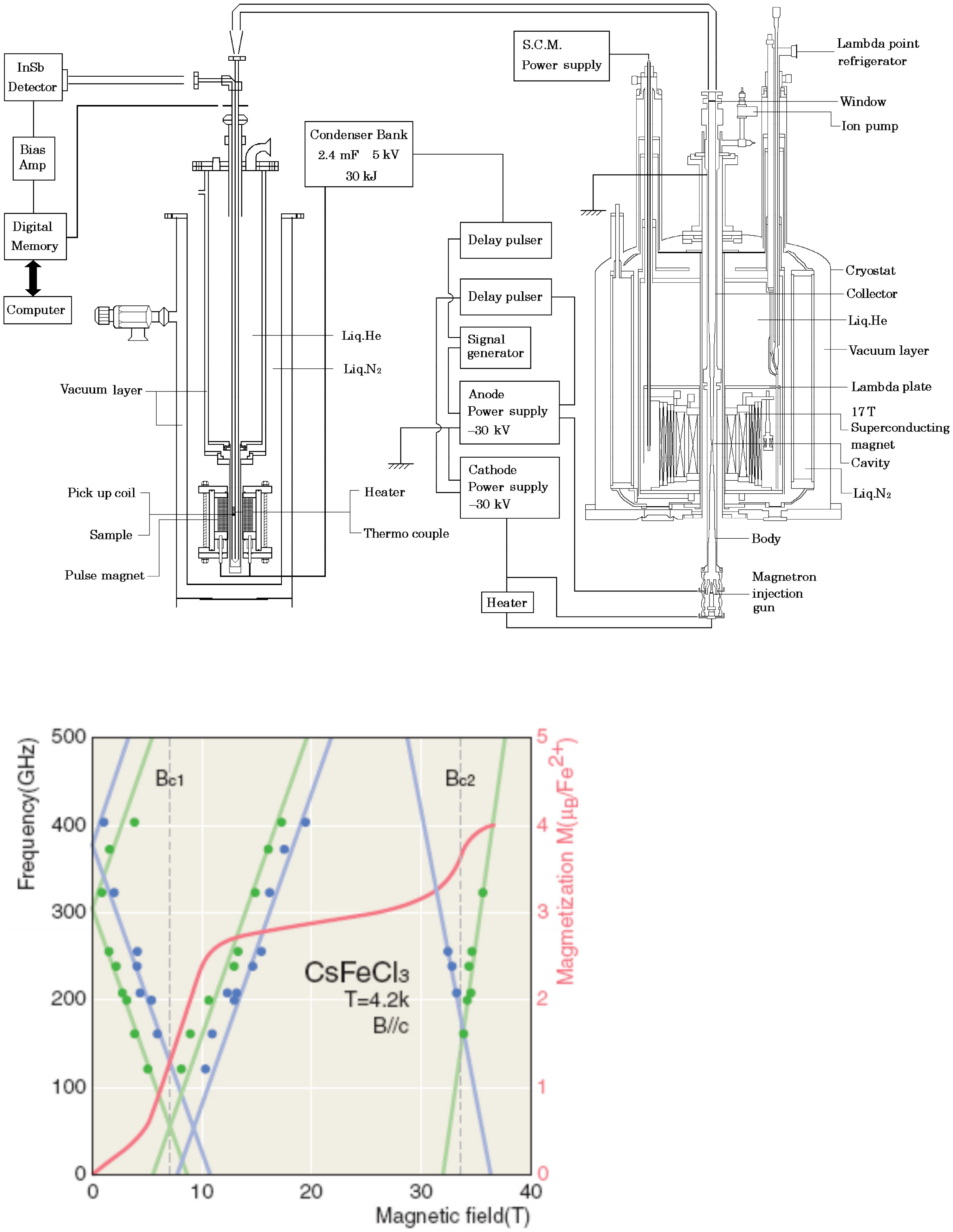

Fig. 3 (Upper) The experimental setup. Gyrotron FU IVA is used as a sub-THz radiation source. The sample is installed in the center of a pulse magnet. The transmission power is picked up by a horn antenna and analyzed by the detection system. (Lower) The typical measurement result of ESR spectroscopy. The sample is $CsFeCl_3$. Circles show the resonant absorption peaks for each frequency. A solid curve shows observed magnetization as a function of the magnetic field intensity

spectroscopy with a sub-THz radiation source and a high field pulse magnet. This ESR spectroscopy system will be used for study on high frequency ESR phenomena and opens the new areas of material science.

4 Summary and the future prospects

In FIR FU, we have developed Gyrotron FU CW Series as high power THz radiation sources. It consists of nine CW gyrotrons covering sub-THz to THz frequency range. The operation mode is complete CW or long pulse. The duty ratio can be changed 0.1 to 100 percent. Some of the gyrotrons included in Gyrotron FU CW Series as well as the previous Gyrotron FU Series have already been applied to high power THz technologies such as submillimeter wave scattering measurement on plasma, DNP enhanced NMR spectroscopy and ESR spectroscopy in sub-THz region. The following results were obtained..

1) Gyrotrons FU CW II, FU CW IV and FU CW VII were applied for DNP enhanced NMR spectroscopy at the frequencies of 600 MHz, 300 MHz and 200 MHz. The sensitivity of NMR spectroscopy is increased drastically by transferring large magnetization of electron spin to nuclear spin. In the calculation, the enhancement factor reaches several thousand. Experimentally obtained enhancement factor is around ten. We are preparing a new NMR probe optimized for DNP, in order to increase the enhancement factor. High sensitive NMR spectroscopy is useful for protein research in future.

2) Gyrotrons FU IVA and FU II were used as radiation sources for development of high frequency ESR spectroscopy covering sub-THz region. We are using a pulse magnet in order to generate high magnetic field up to 35 T which corresponds to the ESR frequencies in sub-THz region. High frequency ESR spectroscopy has advantages, such as high resolution of ESR measurement, finding the new phenomenon in the material science, etc. We have applied the developed system to measurement of $CsFeCl_3$ and found a new phenomenon on the phase transition at the field intensity of around 33 T. We hope that a sub-THz ESR spectroscopy will be a useful tool in the field of material science.

Now, we are preparing to study on many THz technologies opened by high power THz radiation sources - gyrotrons, for example, ESR echo experiment in sub-THz region, X-ray detected magnetic resonance (XDMR) measurement, measurement on hyperfine structure of positronium, etc. Gyrotrons optimized for these studies have already been prepared. We hope these studies will begin in the near future.

Acknowledgements

This work was supported partially by the Special Fund for Education and Research from Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan and by SENTAN Project of Japan Science and Technology Agency (JST).

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15.09.2010