Invited Paper

Development of terahertz gyrotrons for spectroscopy at MIT

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Abstract: Gyrotron oscillators are vacuum electron devices that have delivered megawatt average power levels at millimeter wavelengths. The lack of other sources that are able to match these power levels at high frequency, with the exception of much bulkier free-electron lasers, makes the gyrotron the oscillator of choice in many applications such as plasma heating, materials processing, and plasma diagnostics. Although the main attractiveness of the gyrotron resides in its high power capability, the ability to extend the frequency of operation into the terahertz frequency band is another attractive feature of the gyrotron. In addition, some applications would also benefit from having a frequency-tunable generator. For instance, the operation of a nuclear magnetic resonance (NMR) spectrometer enhanced by dynamic nuclear polarization (DNP) would be greatly simplified by utilizing a continuously tunable continuous-wave (CW) gyrotron. This paper describes the development and application of terahertz frequency gyrotron oscillators and sub-terahertz gyrotron amplifiers for the program of research on DNP/NMR. It will also describe the development of ancillary components such as low-loss waveguide for transmission of the terahertz radiation.

Keywords: Gyrotron, NMR, Terahertz spectroscopy, Terahertz waveguide

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1. Introduction

A primary motivation for the development of terahertz gyrotrons for spectroscopy is the desire to enhance signal intensities in NMR experiments. Using CW Dynamic Nuclear Polarization (DNP) techniques, it is now routinely possible to record 1D and 2D spectra with enhancement factors (ε) that vary from ε = 50-400 depending on the details of the experiment. The experiments utilize magic angle spinning (MAS), are applicable to many proteins, and employ biradical polarizing agents. An example of a DNP/NMR system is shown in Fig. 1. Most present day experiments utilize CW based polarization transfer mechanisms. These are less efficient at the high fields used in contemporary NMR experiments. The advent of high frequency microwave amplifiers will permit the development of polarization transfer methods based on coherent processes -- the integrated solid effect, the dressed state solid effect, electron-nuclear Hartmann-Hahn cross polarization, etc. -- which are more favorable at high magnetic fields. Gyroamplifiers are essential for the implementation of these time domain experiments since the microwave amplitude, phase and frequency are best modulated at low power levels and translated to high power levels with amplifiers.

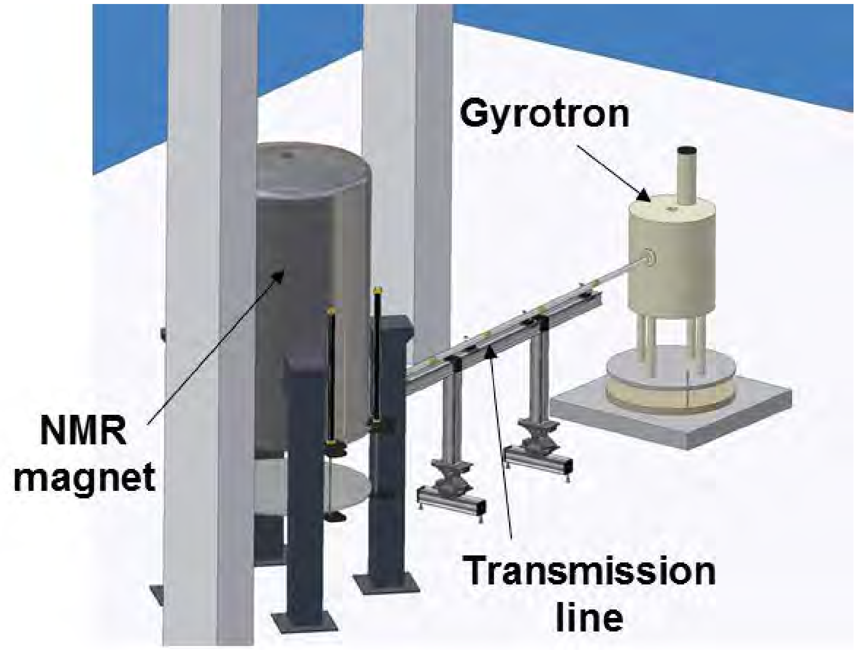

Fig. 1 Schematic of a DNP / NMR experiment showing the gyrotron source, the NMR magnet that holds the sample and the transmission line.

2. Gyrotron oscillators

The source of the millimeter wave / terahertz radiation required for DNP/NMR is typically a gyrotron. The basic requirements for the gyrotron are listed in Table 1.

Tab. 1 Requirements for the gyrotron source for DNP/NMR

Frequency	140-600 *GHz*
Tuning range	~ 1 to 2 *GHz*
Power	10 – 100 *W* (CW)
Power stability	1% for 24 hours
Freq. stability	± 1 *MHz*

An example of an early gyrotron system used for DNP/NMR at 140 *GHz* is shown in Fig. 2. This system was used in the first gyrotron-based DNP/NMR experiment and is still in use today at MIT [1]. The parameters of the gyrotron oscillator are shown in Table 2.

Fig. 2 A 140 *GHz* gyrotron oscillator used for DNP/NMR

Tab. 2 Parameters of the 140 *GHz* gyrotron shown in Fig. 2

Operation Voltage, (*kV*)	12
Beam Current, I_0 (*mA*)	25
Operating Mode	TE_{031}
Magnetic Field B_0(*T*)	5.1
Output Power (*W*)	14

Since the development of this 140 *GHz* system, gyrotrons have been developed at 250, 330 and 460 *GHz* at MIT. The 250 *GHz* system is shown in Fig. 3. This system was reported in ref. [7]. The gyrotrons at 140 *GHz* and 250 *GHz* were operated in the fundamental harmonic of gyro-resonance, where $\omega \cong \omega_c$. When gyrotrons were developed at higher frequency, it was decided to operate the gyrotron at a harmonic of the gyrofrequency in order to reduce the magnetic field requirement of the gyrotron magnet. For example, in second harmonic operation, $\omega \cong 2\omega_c$, the magnetic field of the gyrotron magnet is reduced by a factor of two. However, from a physics point of view, the gyrotron development is much more difficult at harmonics. The reason is that the gain of the gyrotron is lower at the second harmonic, relative to the first, by a factor of $(v_p/c)^2$ where v_p is the electron transverse velocity and c the speed of light. For parameters used in the MIT gyrotrons, this factor is about 0.04, that is, a reduction in gain by a factor of 25. Careful design of the harmonic gyrotrons was successful, with both the 330 *GHz* gyrotron and the 460 *GHz* gyrotron operated successfully at second harmonic.

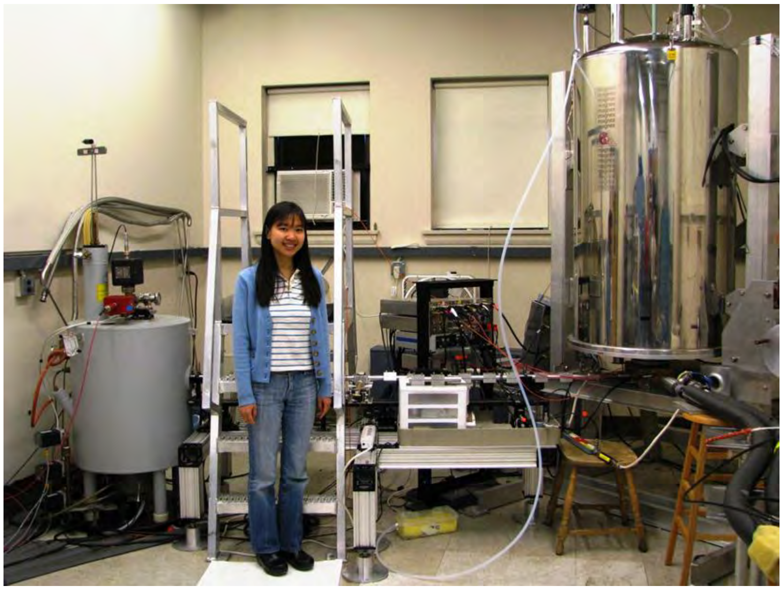

Fig. 3 The 250 *GHz* gyrotron, shown at left, and the 380 *MHz* NMR system shown at right.

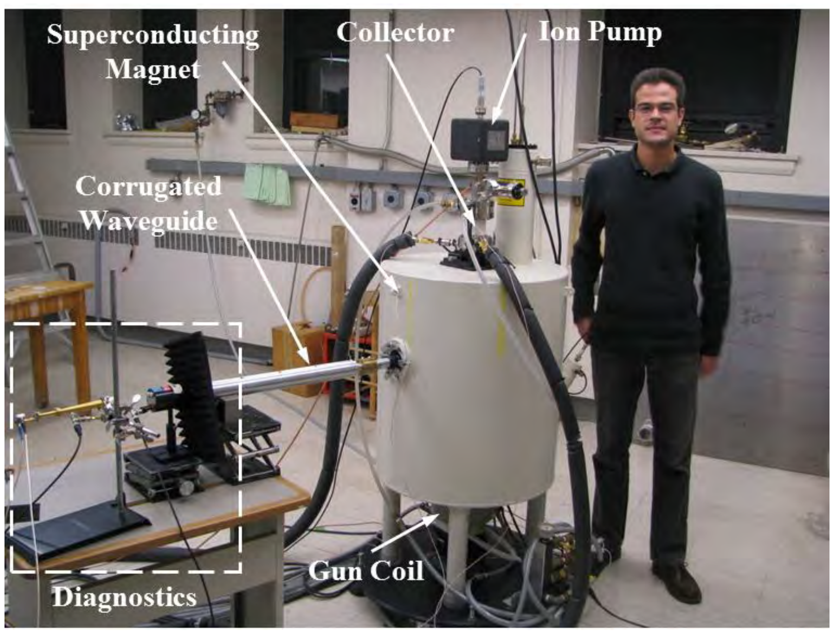

Fig. 4 The 330 *GHz* gyrotron under test

Fig. 4 shows the 330 *GHz* gyrotron under test at MIT. The design and the operation of a frequency-tunable continuous-wave (CW) 330 *GHz* gyrotron oscillator operating at the second harmonic of the electron cyclotron frequency are described in [8]. The gyrotron has generated 18 *W* of power from a 10.1 *kV*, 190 *mA* electron beam working in a $TE_{-4,3}$ cylindrical mode, corresponding to an efficiency of 0.9%. The measured start oscillation current over a range of magnetic field values is in good agreement with theoretical start currents obtained from linear theory for successive high-order axial modes $TE_{-4,3,q}$, where q = 1–6. The minimum start current was measured to be 33 *mA*. A continuous tuning range of 1.2 *GHz* was experimentally observed via a combination of magnetic, voltage, and thermal tuning. Results on the operation of this gyrotron may be compared with results from a 460 *GHz* gyrotron oscillator [9, 10].

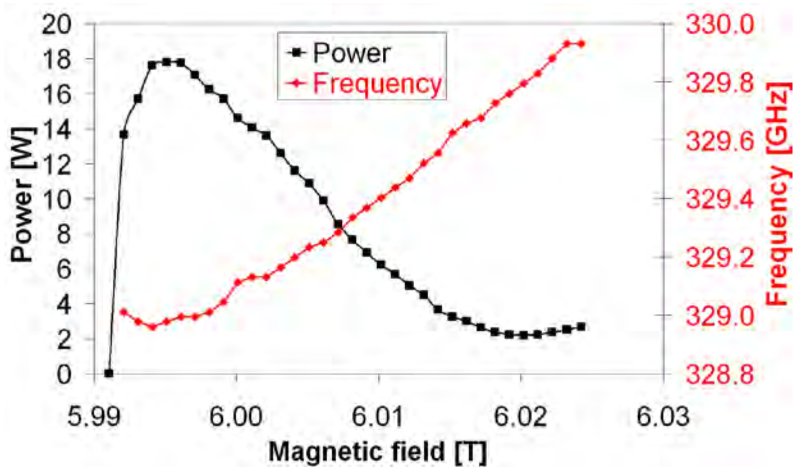

Fig. 5 Tuning of the 330 *GHz* gyrotron vs. magnetic field. Results were taken at a voltage of 10.1 *kV* and a current of 190 *mA*.

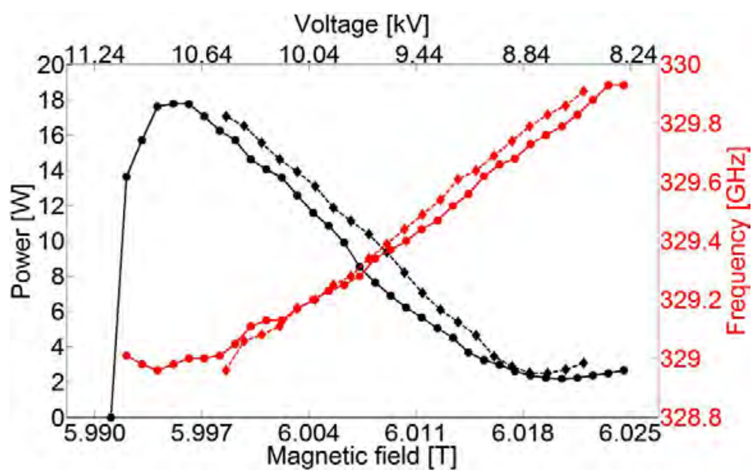

Fig. 6 Comparison of magnetic field tuning and voltage tuning in the 330 *GHz* gyrotron. The voltage tuning was studied at a magnetic field value of 6.003 *T*.

Fig. 5 shows the magnetic field tuning results for the 330 *GHz* gyrotron. Fig. 6 compares the magnetic field tuning with voltage tuning. Comparable results are obtained with the two tuning methods.

For DNP/NMR, it is also necessary to obtain good transmission of the generated terahertz radiation from the gyrotron to the sample. The low loss transmission has been reported in [11, 12]. Studies of the coupling of the terahertz radiation to the sample have been reported in [13].

3. Gyrotron amplifiers

The advantages of time-domain techniques for DNP/NMR have been reported in [3, 14]. We have developed two gyroamplifiers for application in time domain spectrometers at MIT, one operating at 140 *GHz* and one at 250 *GHz*. The 140 *GHz* gyroamplifier is shown in Fig. 7.

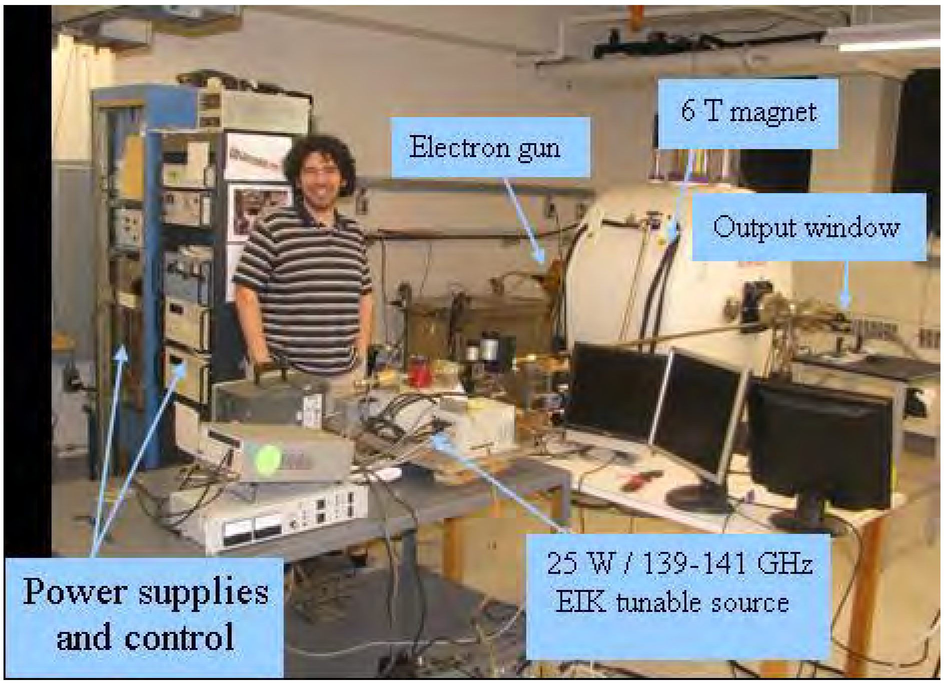

Fig. 7 The 140 *GHz* gyroamplifier.

The 140 *GHz* gyroamplifier has operates in the HE_{06} mode of an overmoded quasi-optical waveguide. At 37.7 *kV* and 2.7 *A* beam current, the gyroamplifier has produced over 820 *W* of peak power with a −3-*dB* bandwidth of 0.8 *GHz* and a linear gain of 34 *dB* at 34.7 *kV*. In addition, the amplifier produced a 3-*dB* bandwidth of over 1.5 *GHz* (1.1%) with a peak power of 570 *W* from a 38.5-*kV* 2.5-*A* electron beam. The electron beam is estimated to have a pitch factor of 0.55–0.6, a radius of 1.9 *mm*, and a calculated perpendicular momentum spread of approximately 9%. The gyro-amplifier was nominally operated at a pulse length of 2 μs but was tested to amplify pulses as short as 4 *ns* with no noticeable pulse broadening. Internal reflections in the amplifier were identified using these short pulses by time-domain reflectometry. The demonstrated performance of this amplifier shows that it can be applied to dynamic nuclear polarization and electron paramagnetic resonance spectroscopy [15]. In recent years, the gyroamplifier has been used to amplify pulses as short as 0.5 *ns* = 500 *ps* [16].

We have also carried out the design and experimental demonstration of a gyrotron traveling-wave-tube (TWT) amplifier at 250 *GHz* that uses a photonic band gap (PBG) interaction circuit [17]. The gyrotron amplifier achieved a peak small signal gain of 38 *dB* and 45 *W* output power at 247.7 *GHz* with an instantaneous -3 *dB* bandwidth of 0.4 *GHz*. The amplifier can be tuned for operation from 245-256 *GHz*. The widest instantaneous -3 *dB* bandwidth of 4.5 *GHz* centered at 253.3 *GHz* was observed with a gain of 24 *dB*. The PBG circuit provides stability from oscillations by supporting the propagation of TE modes in a narrow range of frequencies, allowing for the confinement of the operating TE03–like mode while rejecting the excitation of oscillations at nearby frequencies. This experiment achieved the highest frequency of operation for a gyrotron amplifier. The gyroamplifier is shown in Fig. 8.

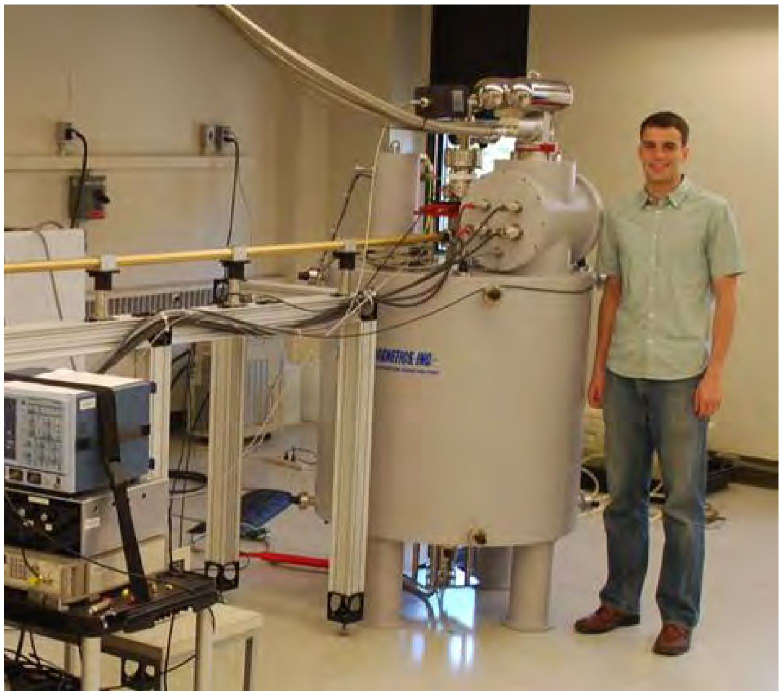

Fig. 8 The 250 *GHz* gyroamplifier.

4. Discussion and conclusions

This paper has described gyrotron oscillators and amplifiers developed for DNP/NMR at MIT. The first DNP/NMR spectrometer using a gyrotron operated at 5 *T* and 140 *GHz* for the electron Larmor frequency, 210 *MHz* proton NMR frequency at MIT [1]. That spectrometer is still in daily use at MIT. However, in the last twenty years, the field of DNP/NMR has seen rapid growth internationally. DNP/NMR spectrometers are now available commercially. The future challenge will be to move on to time domain techniques for DNP/NMR using gyrotron amplifiers. The present paper has been restricted to be a survey of developments at MIT. However, the field of DNP/NMR is now being pursued at many laboratories around the world with important developments occurring in many areas. To provide a full overview of the field would require an extensive review paper.

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