Invited Review Paper

Modulation and Stabilization of the Output Power and Frequency of FU Series Gyrotrons

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Abstract: Both the modulation and the stabilization of the output power and frequency are very important for many applications of gyrotrons. In this paper we present the review of recent progress in the fast modulation and stabilization of the output power and frequency of the gyrotrons developed at FIR UF.

Keywords: Gyrotron, Power and frequency modulation, Power and frequency stabilization

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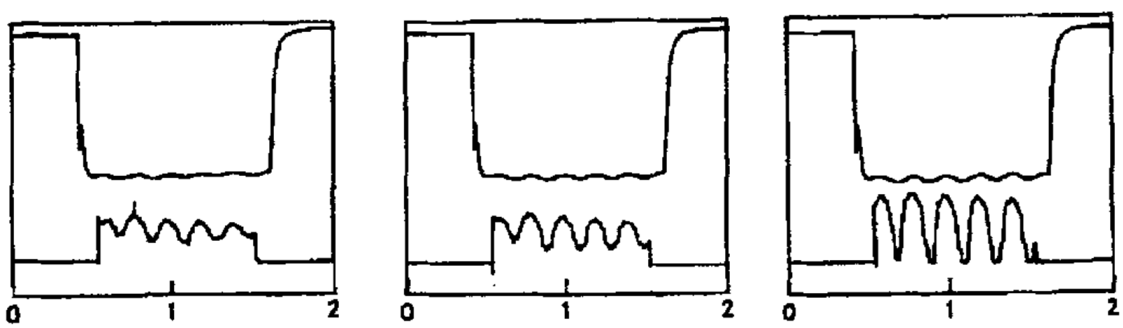
1. Introduction

Gyrotrons are the most powerful sources of coherent radiation in the Sub-THz frequency range up to 1*THz* [1-4]. This makes them unique radiation sources for many novel and perspective applications such as high power THz technologies [4, 5], plasma science and material processing [5-10], advanced spectroscopic techniques [11-15], etc. Many applications of gyrotrons, like remote sensing of the atmosphere, telecommunications, studies on relaxation processes in plasma, propagation of electron cyclotron waves in tokamak plasma and coupling of the radiation, multichannel plasma diagnostics, signal enhancement in NMR spectroscopy through dynamic nuclear polarization (DNP-NMR), and so on, require both a frequency and a power modulation [15-21]. From another hand, for some applications (e.g. DNP-NMR spectroscopy), continuous gyrotron operation (CW regime) during several days with a stable output power and frequency is required in order to keep the DNP gain stable and hence to allow a long-term signal averaging. Despite the fact that the modulation and the stabilization of the output parameters are tasks of contrary types both of them utilize the dependency of the power and the frequency on the voltages of the used power supplies and only their controlling algorithms are different. In this survey, we discuss the recent achievements in the modulation and stabilization of the output power and frequency of the FU series of gyrotrons.

2. Amplitude modulation

Since the output power depends on the magnetic field, heater current, accelerating and anode voltages, its control can be implemented by changing the voltages of the corresponding power supplies. The most intuitive control of the output power can be performed by varying either the cathode heater current I_h (and thus the electron beam current) or the anode voltage V_{an} in a triode magnetron injection gun (MIG), which, however, affects also the beam pitch factor [16, 17, 20-25]. In the case of a fast amplitude modulation, the first option is inappropriate because of the lag between the heater current change and the power response [27, 28]. Therefore in [25] a fast amplitude modulation of the second harmonic 444*GHz* gyrotron FU III through a modulation of the anode voltage has been studied experimentally and numerically. The output power P_o of this gyrotron was 300 *W*. Some power and anode voltage traces from [25] are shown in Fig. 1. The study has shown that:



$\Delta V_{an}/V_{an0}$=0.025 $\Delta V_{an}/V_{an0}$=0.036 $\Delta V_{an}/V_{an0}$=0.055

Fig. 1 (upper trace) Voltage pulse applied to the anode of the gyrotron FU III and (lower trace) modulated output for three modulation levels $\Delta V_{an}/V_{an0}$. Gyrotron operation conditions: cathode voltage -30*kV*, V_{an0}=8.6*kV* and beam current 420*mA*. Modulating signal is of sinusoidal waveform with a frequency of 300*kHz*.

- The level of power modulation $\Delta P_o/P_o$ was proportional to the voltage modulation level $\Delta V_{an}/V_{an0}$, for low modulation levels ($\Delta V_{an}/V_{an0}$<0.02); almost sinusoidal modulation was achieved for low modulation levels ($\Delta V_{an}/V_{an0}$<0.02).
- A high-frequency modulation up to 600 kHz has been achieved.
- The modulation efficiency defined as (($\Delta P_o/P_o$)/(($\Delta V_{an}/V_{an0}$) decreases with increasing the output power, P_o.
- One hundred percent modulation of the gyrotron output has been obtained by less than 10 percent modulation of the anode voltage. This suggests that the gyrotron output may be switched on and off using a square wave modulation of the anode voltage. A modulation of

the gyrotron output like this would be useful for studies of relaxation phenomena in plasma and other materials and for investigation of the propagation of electron cyclotron waves in tokamak plasmas

3. Frequency modulation

Generally, it is difficult to modulate the frequency, especially in low-power gyrotrons, because the tube operates at fixed frequencies determined by the fixed geometry of its high-Q cavity restricting frequency modulation range Δf to values $\Delta f \leq f_0/2Q$. Nevertheless, even such values can be sufficient for achieving sufficient enhancement factors in DNP-NMR spectroscopy [12] as well as for toggling of the combined power between the two outputs of the resonance diplexer [30-32]. A relatively slow change of the gyrotron frequency via cyclotron frequency fc=28nB/(1+Vac/511) variations (i.e. by changing the magnetic field in the cavity) has been demonstrated in several studies [33-40]. However, as it was pointed out in [41, 42], the typical time scale of the variation of the magnetic field is of the order of 0.1 s. Another possibility for modulation of the cyclotron frequency relays on the modulation of the acceleration voltage. Such opportunity was considered theoretically in [41, 42] and realized experimentally in [30-32, 43-46], where much faster frequency changes of the gyrotron output signal were achieved.

3a. Frequency modulation by sinusoidal waveform of the modulation voltage

The beam energy in Gyrotron FU IV [44] and FU CW GVI [15, 46] was modulated by variation of the body potential. The body includes the cavity and is separated electrically from the beam collector (grounded) by a ceramic insulator. The photo of the 460*GHz* second harmonic gyrotron FU CW GVI (called FU CW GOI at Osaka University) and installed at the Institute for Protein Research intended for 700*MHz* DNP-NMR spectroscopy is shown in Fig. 2. The gyrotron consists of a demountable tube, a JAS TEC's 10*T* superconducting magnet with refrigerator for cooling down the magnet to around 3.9*K* and high voltage power supply systems for the electron gun. The gyrotron has an internal mode converter, which forms a well-collimated Gaussian-like beam. In order to modulate the acceleration voltage V_{ac}, the body of the gyrotron (that includes the resonant cavity, the mode converter system, and the output window) is separated by an insulating flange from the collector and the electron gun. The potential of the body can be modulated by both sinusoidal and triangular signals. As a result, the energy of the beam electrons injected into the cavity region is also modulated with the same waveforms. The modulation amplitude of V_{ac} was changed (peak to peak) up to 1*kV*. The modulation speed is increased up to 30*kHz* or a little bit higher.

Fig. 3 shows frequency spectra when the acceleration potential V_{ac} is modulated in sinusoidal mode. In Fig. 3(a), the observed frequency spectrum is shown without the modulation of acceleration voltage (ΔV_{ac} = 0). The half value width Δf_0 is around 0.5*MHz* and is caused mainly by power supply fluctuations. Fig. 3(b) - (d) show the frequency spectrum under a modulation of the acceleration voltage (ΔV_{ac}= 200-1000*V*). A typical shape of the frequency spectrum under sinusoidal modulation is seen in this figure [43]. The half value width for ΔV_{ac} =1000*V* is increased to Δf=54*MHz*. Theoretically obtained spectra using a quasi-static approximation are shown in Fig. 3 e.

Fig. 2 Photo of the gyrotron FU CW GVI (GO-I) installed at Osaka University, Institute of Protein Research for 700*MHz* DNP-NMR spectroscopy.

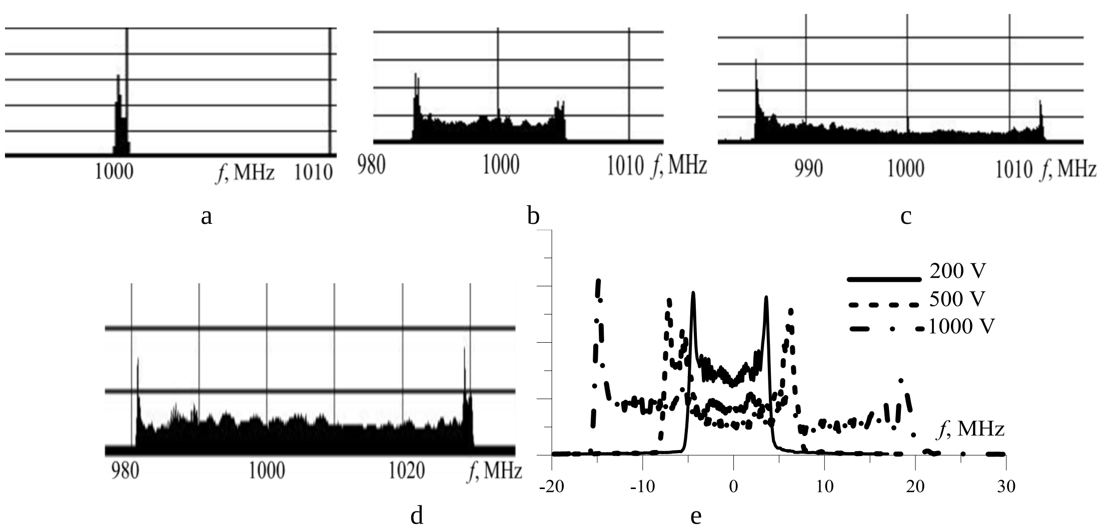
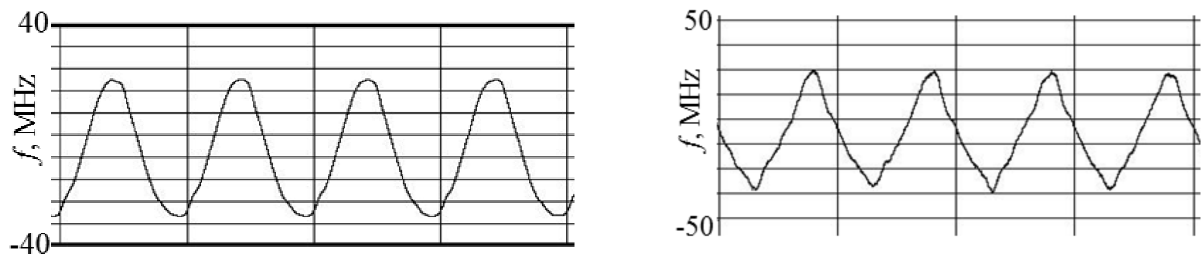


Fig. 3 Frequency spectra for various modulation amplitudes of the acceleration voltage. a) ΔV_{ac}=0;

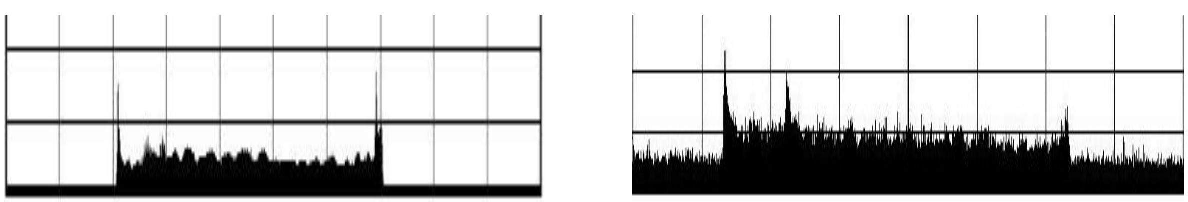
b) ΔV_{ac}=200V; c) ΔV_{ac}=500V; d) ΔV_{ac}=1000V; e) calculated results with zoomed up frequency axis. V_{ac0}=19kV, f_0=460.37GHz.

Fig. 4 (a) and (b) shows the frequency variation for both sinusoidal wave and triangle wave modulations of the acceleration voltage. As can be seen in these figures, sinusoidal- and triangular-like wave modulations of the frequency are observed. In Fig. 5 (a) and (b), the corresponding frequency spectra are demonstrated. The formation of the spectrum is reasonable for both modulations of the acceleration voltage. In addition, the widths of the frequency spectra observed in Fig. 5 (a) and (b) are in good agreement with the peak to peak value of the frequency variation observed in Fig. 4 (a) and (b). These results confirm that the width of the frequency spectrum is a complete measure of the frequency variation shown in Fig. 4 (a) and (b).



a b

Fig. 4 Frequency versus time. Modulation speed f_m=5 kHz, $U_{p\text{-}p}$=1 kV a) sinusoidal; b) triangle



a b

Fig. 5 Frequency spectrum. f_m=5 kHz, $U_{p\text{-}p}$=1 kV a) sinusoidal; b) triangle, 10 MHz/div.

The main reason of the spectrum fluctuations in Fig. 3 and 5 is the dependence of the output power on the acceleration voltage. In fact, the voltage modulation causes also a power modulation which is shown in Fig 6. The acceleration voltages in these two cases are V_{ac0}=19.2 kV and V_{ac0}=17.75 kV, respectively. One can see that the first case involves only fundamental axial mode with 50 MHz frequency modulation and the corresponding power modulation is about 20%. In the second case, the high axial modes are involved with 150 MHz frequency modulation and deeper power modulation.

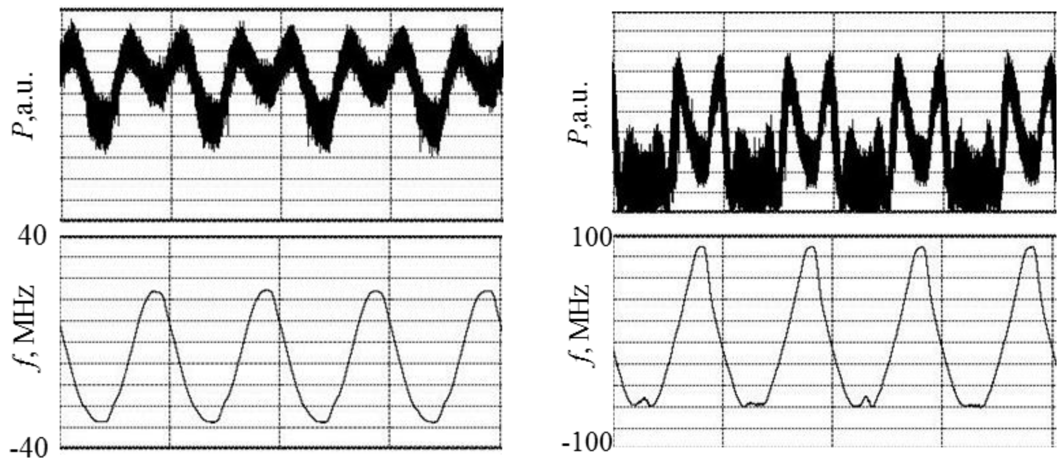


Fig. 6. Frequency modulation through a sinusoidal modulation of the acceleration voltage together with a variation of the amplitude. The operation frequency of the gyrotron f_0= 460.3 *GHz*. Horizontal axis, 0.2 msec/div, f_m = 5 *kHz*. Amplitude of the modulated acceleration voltage: 1000 *V*. Left hand side: V_{ac0}=19.25 *kV*. Right hand side: V_{ac0}=17.75 *kV*.

The half widths of the frequency spectra δf were measured by changing the modulation amplitude ΔV_{ac}. The result is shown in Fig. 7 where the observed values of δf are plotted as a function of the modulation amplitude of the acceleration voltage. The modulation of the acceleration voltage ΔV_{ac} is sinusoidal at f_m = 300*Hz*. It is seen in this figure, that the amplitude δf is almost linearly proportional to ΔV_{ac}. The solid line represents the calculated results obtained by a self-consistent model and assuming a field intensity B=8.5*T*. The numerical and the experimental results are in fairly good agreement. The slope of the estimated line, $\delta f/\Delta V_{ac}$ is 0.05 *MHz/V*. This slope is much smaller than the slope of the cyclotron frequency vs. acceleration voltage, $\Delta 2f_c/\Delta V_{ac}= -2f_{c0}/511$, which is around 0.9 *MHz/V*. Here, the parameters are assumed to be B=8.5*T* and f_{c0} = 238*GHz*, respectively. Such decrease of the slope of the observed value $\delta f/\Delta V_{ac}$ can be explained by the fact that in a resonant cavity with a high quality factor Q the frequency variation is limited in a narrow interval around the resonance frequency. The same tendency is also observed in the experiment on frequency modulation using the Gyrotron FU II [44].

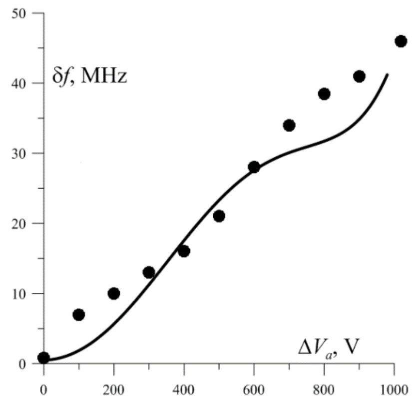


Fig. 7 Frequency modulation as a function of the acceleration voltage modulation

3b. Rapid step frequency switching

Another kind of frequency control is the frequency step switching. The frequency can jump within a fixed cavity mode as well as between two cavity modes whose operating conditions are very close. The square waveform of acceleration voltage is preferable in frequency switching rather that sinusoidal or triangle as for frequency modulation. For example in [45] the following distinct two cases have been tested experimentally: (1) Frequency step switching between two fundamental modes, namely TE_{911} mode at f_1 =260*GHz* and the TE_{521} at f_2 = 257*GHz*. In this case, $(f_1-f_2)/f_1$=0.015; and (2) Frequency step switching between the fundamental mode (TE_{421} at f_1 =223*GHz*) and the second harmonic (TE_{161} at f_2=444*GHz*). In this case, $(f_1 - f_2/2)/f_1$=0.00448. The results for the second case are shown in Fig. 8.

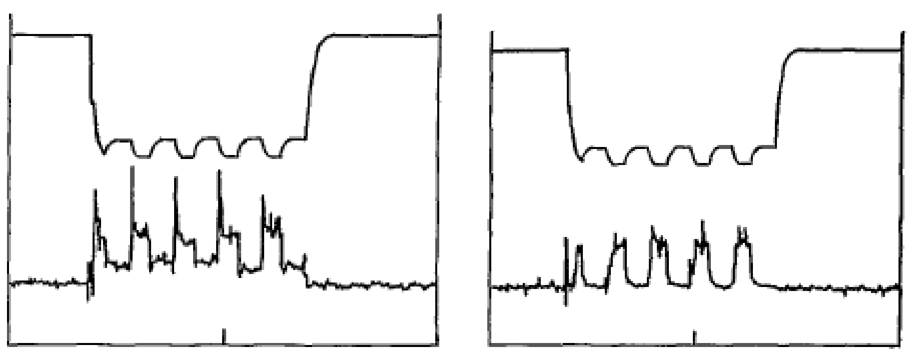


Fig. 8 (upper trace) High voltage pulse of 1*msec* applied to the cathode, modulated by a 5*kHz* square wave. (lower trace) Output power measured by a pyroelectric detector. The magnetic field 8.12*T*. V_{ac1}=28.8*kV*, V_{ac2}=24.2*kV*. (a) The power detector is placed just at the gyrotron output window; (b) Power detector is placed after the Fabry-Perot interferometer which is used as a band-pass filter, whose center frequency is adjusted to pass a signal while $U_{ac} = U_{ac1}$

3c. Other methods of frequency modulation

As it was mentioned above, a relatively slow change of the gyrotron frequency has been performed by varying the external magnetic field. A frequency modulation is possible also by a modulation of the anode voltage [37-39], however, in the latter case the frequency modulation range is narrow and is accompanied by an undesirable deep spurious amplitude modulation. In [47-52] it was suggested to modulate the frequency by using a reflector. The idea of this method is based on the change of the resonator frequency by changing of the external reflector position in the gyrotron with an axial output. In contrast to the voltage modulation, such mechanical modulation is slow and difficult to realize. However, such a method of frequency modulation has an advantage since it is characterized by a reduced spurious amplitude.

4. Stabilization of the gyrotron output power and frequency

In the case of DNP-NMR spectroscopy, for example, a CW gyrotron operation during several days with stable output power and frequency is required in order to keep stable the DNP gain and hence to allow a long-term signal averaging. However, external disturbances such as the instabilities of the power supplies and some intrinsic disturbances in the gyrotron tube operation may cause a deviation of the output power and frequency.

One way to decrease the fluctuation is to stabilize the used power supplies. For example for the gyrotron FU IV CW [53] operation (TE_{03}, mode, f= 301GHz, P = 20W, B_0 = 10.8T, V_{ac} = -16kV, V_{an} = -2.9kV), the output power of CW operation was not stable (- 5 %) due to the fluctuation of the cathode potential (ΔV_{ac} ~40V). The evolution of operational parameters with time is shown in Fig. 9a. The fluctuations of the output power correlate with that of the cathode potential. In order to suppress the fluctuation level of the cathode potential, the high voltage power supply is equipped with smoothing circuits consisting of a resistor, an induction coil and a capacitor (Fig. 10). The fluctuation level of the cathode voltage was decreased (ΔV_{ac} ~0.6V) by introducing the smoothing circuit and accordingly, the fluctuation of the output power was decreased from 4 % to 1% (Fig. 9b).

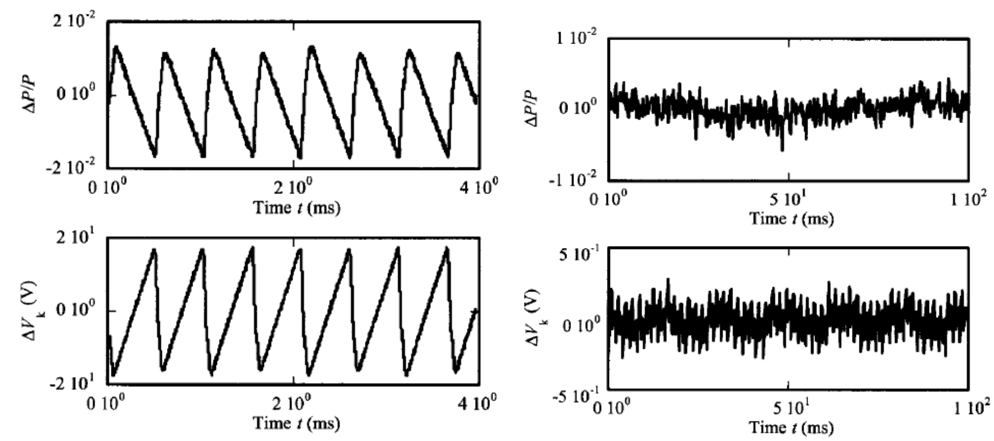


Fig. 9 Time evolution of the fluctuation of the gyrotron output power ΔP and the cathode potential (a) without a smoothing circuit; (b) with a smoothing circuit

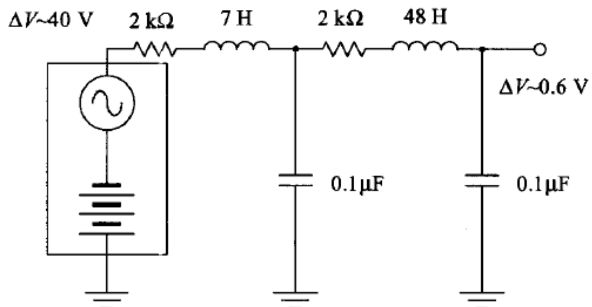
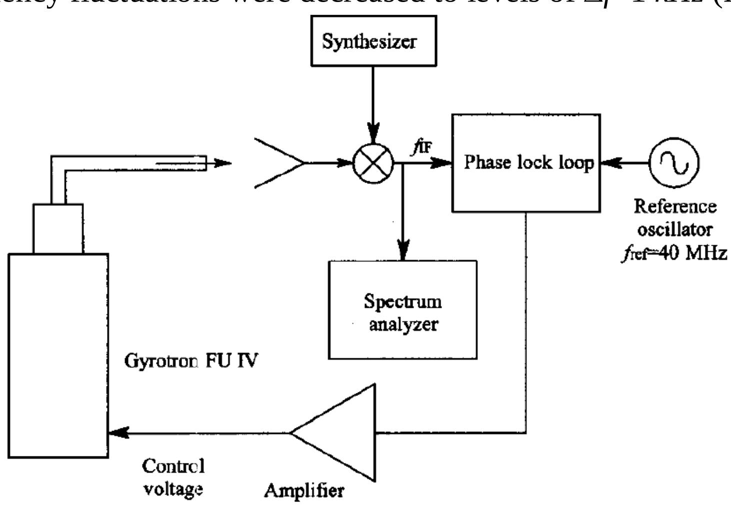


Fig. 10 A smoothing circuit used to suppress the output voltage fluctuations

Since output parameters fluctuations are not only due to fluctuations in power supplies, further stabilization is needed. As in the case of modulation, the stabilization of frequency can be provided by a feedback control of the acceleration voltage, whereas the output power stabilization can be done by a feedback control of the anode voltage [29] or the heater current [29, 54, 55].

The frequency was stabilized by implementing a phase lock loop [53, 56, 57] and using PID algorithm feedback control [58]. For the first case, the block diagram is shown in Fig. 11a. Using this scheme the frequency fluctuations were decreased to levels of Δf~1 *kHz* (Fig. 11b).



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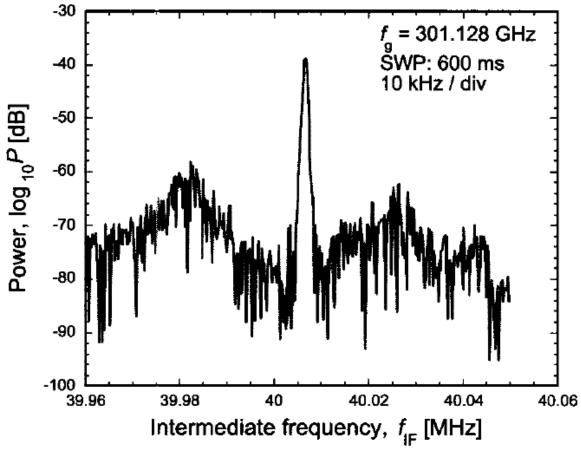

b

Fig. 11 (a) Block diagram of the phase lock system and (b) frequency spectrum of the intermediate frequency signal under phase-locked stabilization

The block diagram of the system for a feedback control of both the output power and the frequency using PID algorithm is shown schematically in Fig. 12. The results of the stabilization obtained using the gyrotron FU GVI [14, 59] are shown in Fig.13 for a long-term (three hours) operation. The observed power deviation is 0.4% and the frequency deviation is less than 10^{-6}. Compared with and the results of separate power or frequency stabilization [29, 58] and with phase lock scheme, these parameters are worse because of an additional amplitude modulation and finite response time of the used DAC and PC Labview set. But they are still satisfactory for the DNP-NMR experiments. Compared with the phase-lock experiment, the PID algorithm is more robust and reliable since it has much wider pull-in and lock-in range and can operate not only in CW but also in a pulsed mode.

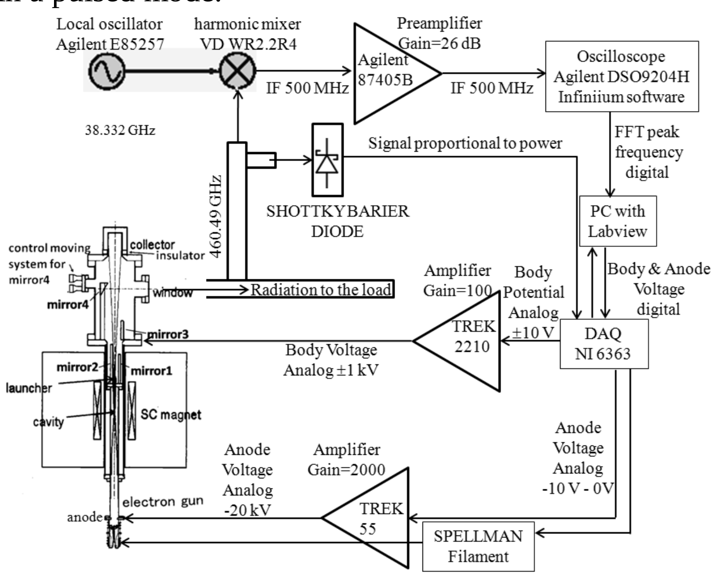

Fig. 12 Block diagram of the system for simultaneous stabilization of the gyrotron output frequency and power by a PID feedback control of the acceleration and the anode voltages

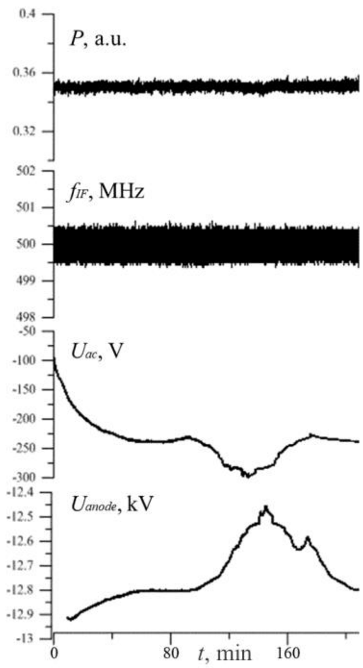

Fig. 13 Simultaneous stabilization of the power and the frequency by a feedback control on both the anode and the acceleration voltages. Power deviation is ±1%, frequency deviation is ±0.4 *MHz*. $f=nf_{LO}+f_{IF;}\ f_{LO}$=38.32 *GHz*, n=12

5. Summary.

Such function as amplitude and frequency modulation may increase the number of gyrotron applications. Simultaneous stabilization of the output power and the frequency is more advantageous for a lot of applications (e.g. DNP-NMR spectroscopy) and satisfies better the preconditions imposed to the radiation sources for various spectroscopic techniques. The efforts being undertaken for the development of frequency tunable gyrotrons [60-62] with a wider frequency tuning range and improved stabilization of both the output power and frequency would result in a higher operational performance of the FU Series of gyrotrons.

Acknowledgements

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