Discrete Frequency Hopping in Long-Pulse High-Power Gyrotrons

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***Abstract*—Careful investigation of the RF oscillation frequency generated by MW class long-pulse 140 GHz gyrotrons for the Wendelstein 7-X (W7-X) stellarator found discrete frequency hopping in steps of 5-10 MHz during the initial frequency down-tuning as well as in long-pulse "quasi" steady-state operation. The classical explanation for this behavior, such as electron beam acceleration voltage ripple and the classical long-line effect of the load, are reviewed, and are found not to match the experimental observations. As alternative hypotheses we propose a long-line effect involving multiple internal reflections, or small discrete changes in the effective cavity radius, caused by discontinuous thermo-mechanical expansion.**

I. INTRODUCTION

GYROTRONS are high power millimeter wave oscillators, capable of delivering coherent continuous-wave (CW) power in the megawatt range. The major application is electron cyclotron heating and current drive (ECH&CD) in thermonuclear fusion plasma experiments. In this paper, first the relevant effects concerning gyrotron frequency stability are discussed and then experimental observations during long-pulse 500 kW operation of 140 GHz gyrotrons for the new stellarator W7-X at IPP Greifswald, Germany, are presented.

II. FREQUENCY VARIATION EFFECTS

During long-pulse operation of high-power gyrotrons two internal phenomena cause a downward shift of the oscillation frequency by a few hundred MHz: Thermal cavity expansion and electron beam space charge neutralization [1].

In comparison to this downward shift, the possible electron beam voltage-dependent frequency variations are rather small: For the gyrotron tetrode power supply at KIT with a specified voltage ripple of ± 300 V, only an absolute maximum of about ± 2.1 MHz of possible periodic frequency variation can be expected.

There also exists the so-called long-line effect. It is caused by power reflection from the output window or an external distant load. As a consequence, load-pulling can result in dynamically altered oscillation frequency and power level [2]. The key figure for this classical long-line effect is the round-trip time delay $\tau_{\mathrm{M}} = 2L/v_{gr}$ of the mm-wave waves on the line length L between the gyrotron cavity and the location of reflection. Here v_{gr} is the group velocity in the medium of propagation. For W7-X gyrotrons, the closest possible point of reflection is the end of the quasi-optical launcher which yields $\tau_{\mathrm{M}} \sim 4$ ns, corresponding to a characteristic modulation frequency of $f_{\mathrm{M}} = 1/\tau_{\mathrm{M}} \sim 250$ MHz. Reflections from the output window would lead to a corresponding frequency of $f_{\mathrm{M}} \sim 100$ MHz. The last component in the transmission line is the calorimetric dummy load, where a round-trip delay of $\tau = 50$ ns corresponds to $f_{\mathrm{M}} \sim 20$ MHz.

This classical long-line effect was mostly investigated in the context of window and load reflections at gyrotrons with axial waveguide output coupling [2]. In the case of gyrotrons with transverse quasi-optical output coupling and slightly tilted output window disk it is of minor relevance, since here reflected waves do not propagate back into the cavity as easily.

III. MEASUREMENT SYSTEM

Recently, a high resolution Pulse Spectrum Analysis (PSA) system was developed at KIT which allows the investigation of millimeter waves in the frequency range from 100-170 GHz (extended D-band) with 6 GHz instantaneous bandwidth combined with unambiguous RF identification [3]. Modification of the system, involving a reduction of the sampling rate to 0.2 GS/s, extends the maximum continuous pulse-duration acquisition length to 1.4 s. A scheme of the experimental setup is plotted in Fig. 1.

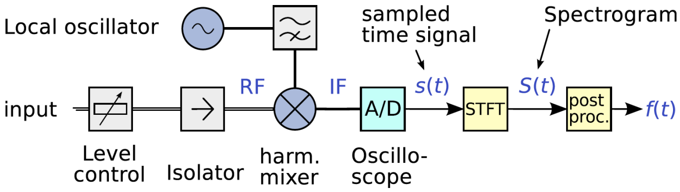

Fig. 1: Hardware setup and data processing system in modified Pulse Spectrum Analysis (PSA) setup for extended data acquisition time (1.4 s).

IV. EXPERIMENTAL RESULTS

A. *Initial frequency tuning*

The measured total initial frequency down tuning due to cavity expansion at 500 kW operation is below 200 MHz as displayed in Fig. 2. While the logarithmic time axis (right) yields a clearer impression of the process, also the linear scale (left) is shown for easier comparison with former publications. For this figure a frequency resolution of 50 kHz was chosen, giving a physical time resolution of approximately 200 µs. The frequency drop settles after approximately 500 ms, however, the frequency tuning is not entirely continuous, but is interrupted by clear instantaneous frequency jumps at irregular time intervals. Histogram analyses of the frequency jump heights measured in several pulses showed an equal distribution in the range from 1 to 10 MHz.

B. *Frequency stability during steady state operation*

A 500 kW pulse with 30 min duration was investigated by taking successive measurements of one second duration. Data transfer speed and other technical limitations allowed approximately one such measurement per minute. Fig. 3 shows eight example spectrograms, each concentrated on the main

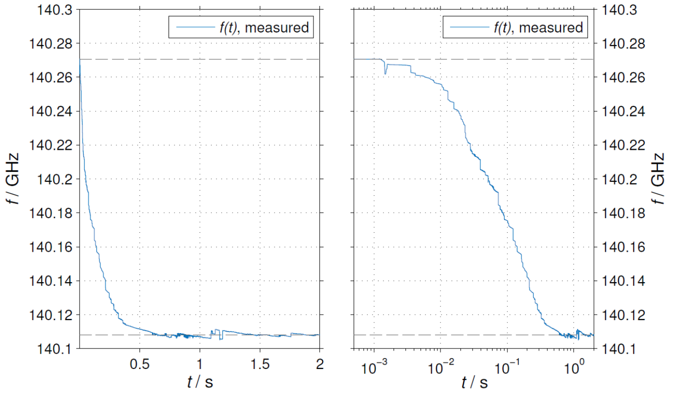

Fig. 2: Initial frequency down tuning due to cavity expansion during several 500 kW pulses with identical parameters; the frequency resolution is 50 kHz.

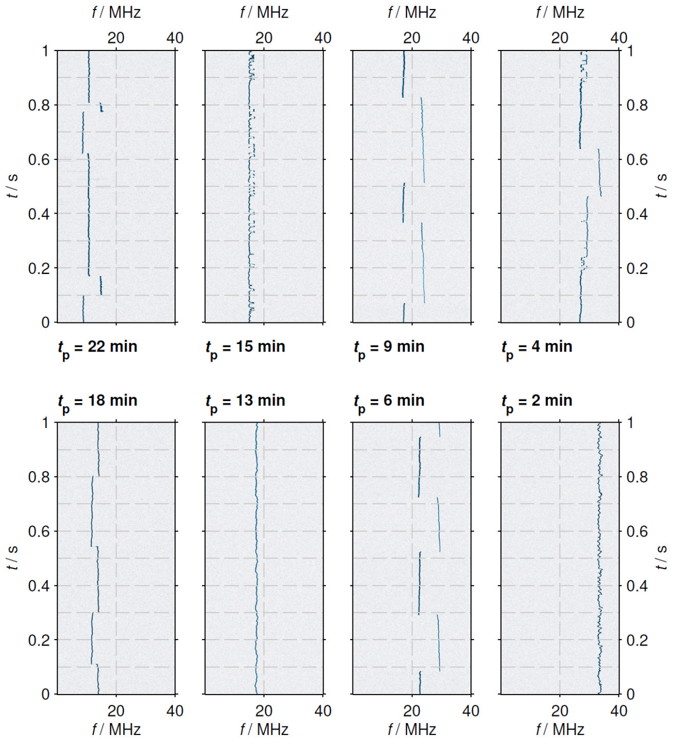

Fig. 3: Spectrograms of irregular frequency jumps during 500 kW steady-state long-pulse operation of a W7-X gyrotron. The frequency axis indicators are relative to the absolute frequency of 140.05 GHz.

line at the given pulse time index t_p. Following the average frequency in each of the eight spectrograms, it becomes clear that no true steady state is reached during the pulse, since a total gradual frequency downshift of more than 20 MHz can be found. The explanation for this is most probably again thermal expansion, since the coolant temperatures increase slightly during the whole duration of the pulse. The associated slow frequency drift is approximately 1.5 MHz/min, and thus not of much concern for ECH&CD applications.

Inspecting and comparing the individual spectrograms reveals different effects: small scale frequency instability (at t_p = 2 min and 13 min), irregular discrete frequency jumps and fast, "glitch-like" frequency staggering (at t_p = 4 min), frequency jumps of around 10 MHz (at t_p = 6 min and 9 min), frequency jumps of approximately 4 MHz (at t_p = 18 min), irregular jumps of 4 to 10 MHz (at t_p = 22 min) and frequency staggering (at t_p = 15 min).

V. DISCUSSION

Both the initial frequency down tuning and the steady state operation show small-scale frequency jumps of 4 – 10 MHz which are not relevant for ECH&CD applications. They cannot be explained by power supply voltage ripple or classical long-line effect. The only possible explanations for this frequency hopping are as follows.

A. *Multiple reflections inside the gyrotron*

During the operation of W7-X gyrotrons at IPP Greifswald discrete frequency hopping with typically 3.4 MHz, but up to 15 MHz, was observed also [4] and attributed to a long-line effect due to high-order multiple reflections of stray radiation inside the tube causing a number of longitudinal eigenmodes. with non-equidistant spectrum. Changing system parameters cause bifurcational jumps between modes of different eigenfrequencies. For slowly and weakly changing parameters, the time interval between two successive frequency jumps becomes longer. However, the total internal stray radiation is only in the order of 2 % of the output power [5], and only coherent radiation which is coupled back into launcher and cavity in the correctly rotating cavity mode (here $TE_{28,8}$) can influence the oscillation in the cavity.

B. *Discontinuous thermal expansion of cavity*

It could be that the cavity, influenced by its external boundary conditions, itself does not expand entirely smoothly on the microscopic scale, but exhibits intervals of continuous tuning between which built-up internal stresses cause slipping of grain boundaries or abrupt changes of micro-rupture patterns in the structure material. Bi-stable resonator operation could be possible. For frequency jumps of around 5 MHz a radius slip of approximately 700 nm is necessary. This hypothesis is not unrealistic since the cavity of W7-X gyrotrons is fabricated of dispersion strengthened copper (GlidCop) which exhibits mechanical anisotropy [6] and has locally non-uniform ductility, caused by the alumina embedded in its crystal structure.

VI. SUMMARY

Irregular discrete frequency hopping in steps of 4-10 MHz in 500 kW long-pulse operation of 140 GHz W7-X gyrotrons only can be explained by time-dependent high-order multiple reflections inside the gyrotron or by discontinuous cavity expansion due to mechanical stress and reversible changes in the metal structure. Both effects are hard to verify.

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