SELF-CONSISTENT SIMULATION OF FREQUENCY STABILIZATION IN A GYROTRON WITH DELAYED REFLECTION

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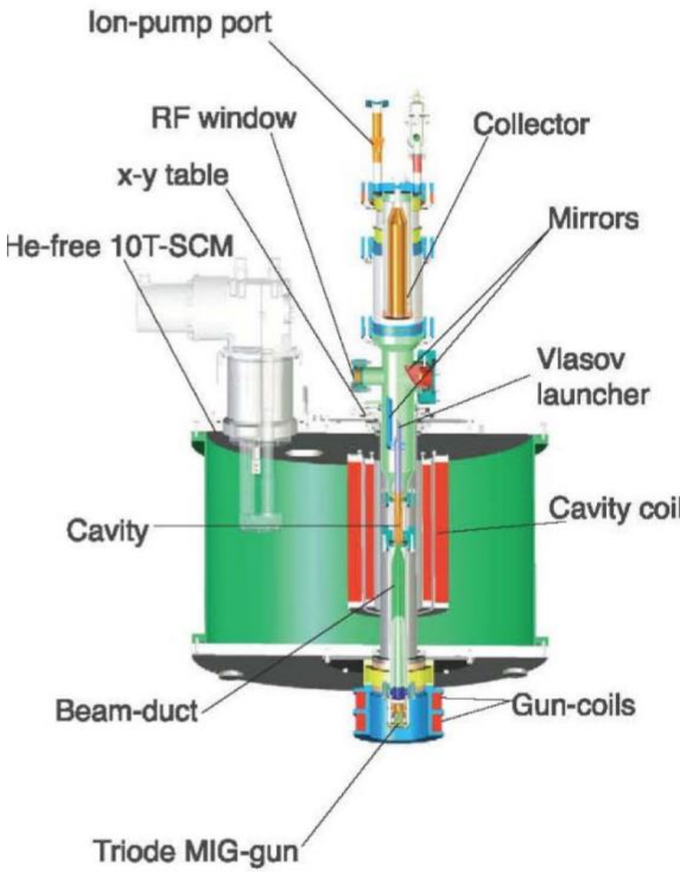
MOTIVATION

Gyrotrons are the most powerful radiation sources in subterahertz and terahertz (THz) frequency ranges, which are widely used for various scientific applications:

- plasma heating;
- THz spectroscopy;
- material processing;
- stand-off detection of radioactive materials;
- medical applications and etc.



For many of such applications, e.g. for THz spectroscopy, high **frequency stability** and tunability within **1-2 GHz frequency range** is typically required.

Motivation

The effect of window reflection on gyrotron operation has been a subject of active studies since 1990-ies:

- T.M. Antonsen, S.Y. Cai, and G.S. Nusinovich, "Effect of window reflection on gyrotron operation," Phys. Plasmas **4**, 4131–4139, 1992.
- O. Dumbrajs, M.Y. Glyavin, V.E. Zapevalov, and N.A. Zavolsky, "Influence of reflections on mode competition in gyrotrons," IEEE Trans. Plasma Sci. **28**, 588–596, Jun. 2000.
- O. Dumbrajs, "Influence of possible reflections on the operation of European ITER gyrotrons," J. Infr. Millim. Terahertz Waves **31**, 892–898, 2010.

In spite of a large number of studies on reflection effect on gyrotron operation, the opportunity of increase frequency stability has not been considered until

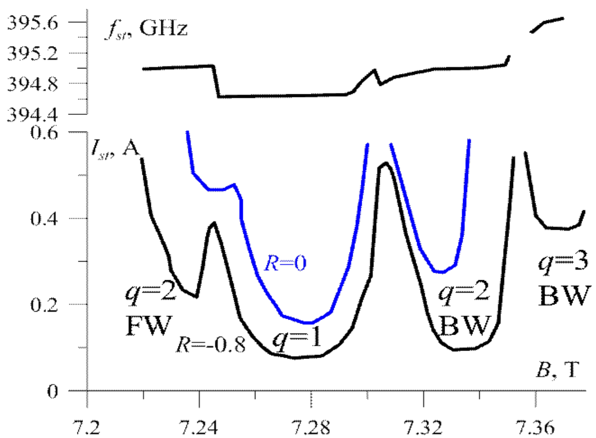
- **M.Y. Glyavin, G.G. Denisov, M.L. Kulygin, and Y.V. Novozhilova, "Stabilization of gyrotron frequency by reflection from nonresonant and resonant loads," Tech. Phys. Lett. 41, pp. 628–631, 2015.**

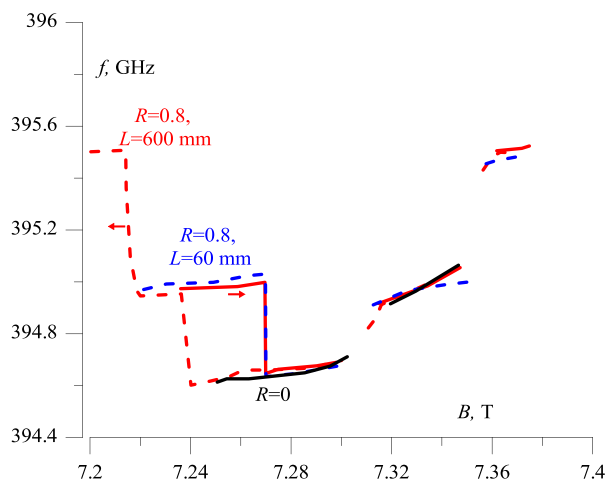
The possibility of self-injection locking by the signal reflected from a resonant or non-resonant load has been demonstrated by numerical simulations as well as in experiments:

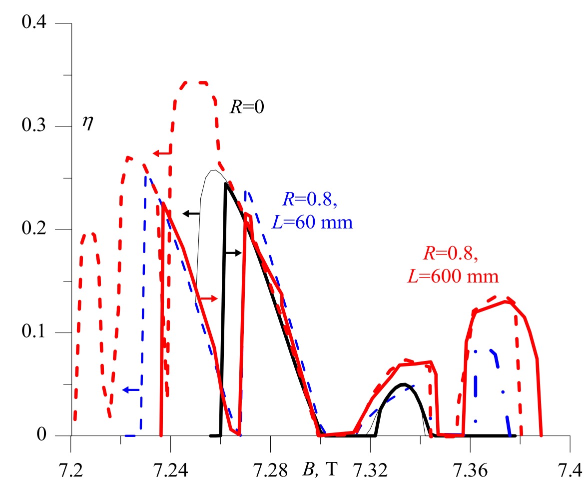
- M.M. Melnikova, A.G. Rozhnev, N.M. Ryskin, A.V. Tyshkun, M.Y. Glyavin, and Y.V. Novozhilova, "Frequency stabilization of a 0.67-THz gyrotron by self-injection locking," IEEE Trans. Electron Dev. **63**, 1288-1293, 2016.
- M.Y. Glyavin, I. Ogawa, I.V. Zotova, N.S. Ginzburg, A.P. Fokin, A.S. Sergeev, R.M. Rozental, V.P. Tarakanov, A.A. Bogdashov, T.O. Krapivnitskaia, V.N. Manuilov, and T. Idehara, "Frequency stabilization in a sub-terahertz gyrotron with delayed reflections of output radiation," IEEE Trans. Plasma Sci. **46**, 2465-2469, 2018.
- A.A. Bogdashov, A.P. Fokin, M.Yu. Glyavin, Yu.V. Novozhilova, A.S. Sedov, "Experimental study of the influence of reflections from a non-resonant load on the gyrotron operation regime," J. Infrared Millim. Terahertz Waves **41**, 164–170, 2020.

INFLUENCE OF REFLECTIONS IN THE SECOND-HARMONIC THZ GYROTRON: EXPERIMENTAL RESULTS

Khutoryan E.M., Idehara T., Melnikova M.M., Ryskin N.M., Dumbrajs O. Influence of reflections on frequency tunability and mode competition in the second-harmonic THz gyrotron // Journal of Infrared, Millimeter, and Terahertz Waves. 2017. Vol. 38. No. 7. P. 824–837.







Thus, using the delayed **reflection** is a promising technique for **frequency stabilization** since it is much simpler and faster than the existing techniques, such as PID feedback control.

BASIC EQUATIONS

Self-consistent single-mode numerical model

Excitation equation and equations of particle motion:

$$\frac{\partial^2 F(\xi,\tau)}{\partial \xi^2} - j s \frac{\partial F(\xi,\tau)}{\partial \tau} + s(\delta - j d) F(\xi,\tau) = I_0 J(\xi,\tau),$$

$$\frac{dp(\xi,\tau)}{d\xi} + j\left(\Delta + |p(\xi,\tau)|^2 - 1\right) p(\xi,\tau) = jF(\xi,\tau)\left(p(\xi,\tau)^*\right)^{s-1}, \qquad (1)$$

$$J(\xi,\tau) = \frac{1}{2\pi}\int_0^{2\pi} p(\xi,\tau)^s \, d\varphi_0. \qquad (2)$$

Boundary conditions: $p(\xi_1,\tau) = e^{j\varphi_0}, \qquad 0 \le \varphi_0 < 2\pi$

$$\left[\frac{\partial F(\xi,\tau)}{\partial \xi} + j\kappa_0 F(\xi,\tau) + \frac{n}{2\kappa_0}\frac{\partial F(\xi,\tau)}{\partial \tau}\right]_{\zeta_{out},\tau} =$$

$$= -\Gamma\left[\frac{\partial F(\xi,\tau)}{\partial \xi} - j\kappa_0 F(z,\tau) - \frac{n}{2\kappa_0}\frac{\partial F(z,\tau)}{\partial \tau}\right]_{\xi_{out},\tau-\tau_d} \qquad (3)$$

$F(\xi,\tau)$ - normalized complex amplitude, $\tau_d = \left(\beta_{\perp 0}^4 / 8\beta_{\parallel 0}^2\right)\omega_H T_d$ - normalized delay time,

$\Delta = \frac{2}{\beta_{\perp 0}^2}\frac{\omega_0 - n\omega_H}{\omega_0}$ - cyclotron resonance mismatch,

$I_0 = 64\frac{e_0}{m_0 c} I_b \frac{\mu_0}{4\pi}\frac{\beta_{\parallel,0}\beta_{\perp,0}^{2(n-4)}}{\gamma_0} n^3 \left(\frac{n^n}{2^n n!}\right)^2 \frac{J_{m\mp s}^2(\nu_{mn} R_b/R_0)}{(\nu_{mn}^2 - m^2) J_m^2(\nu_{mn})}$ - dimensionless current.

The Second-Harmonic 394 GHz Gyrotron (FU CW IIB)

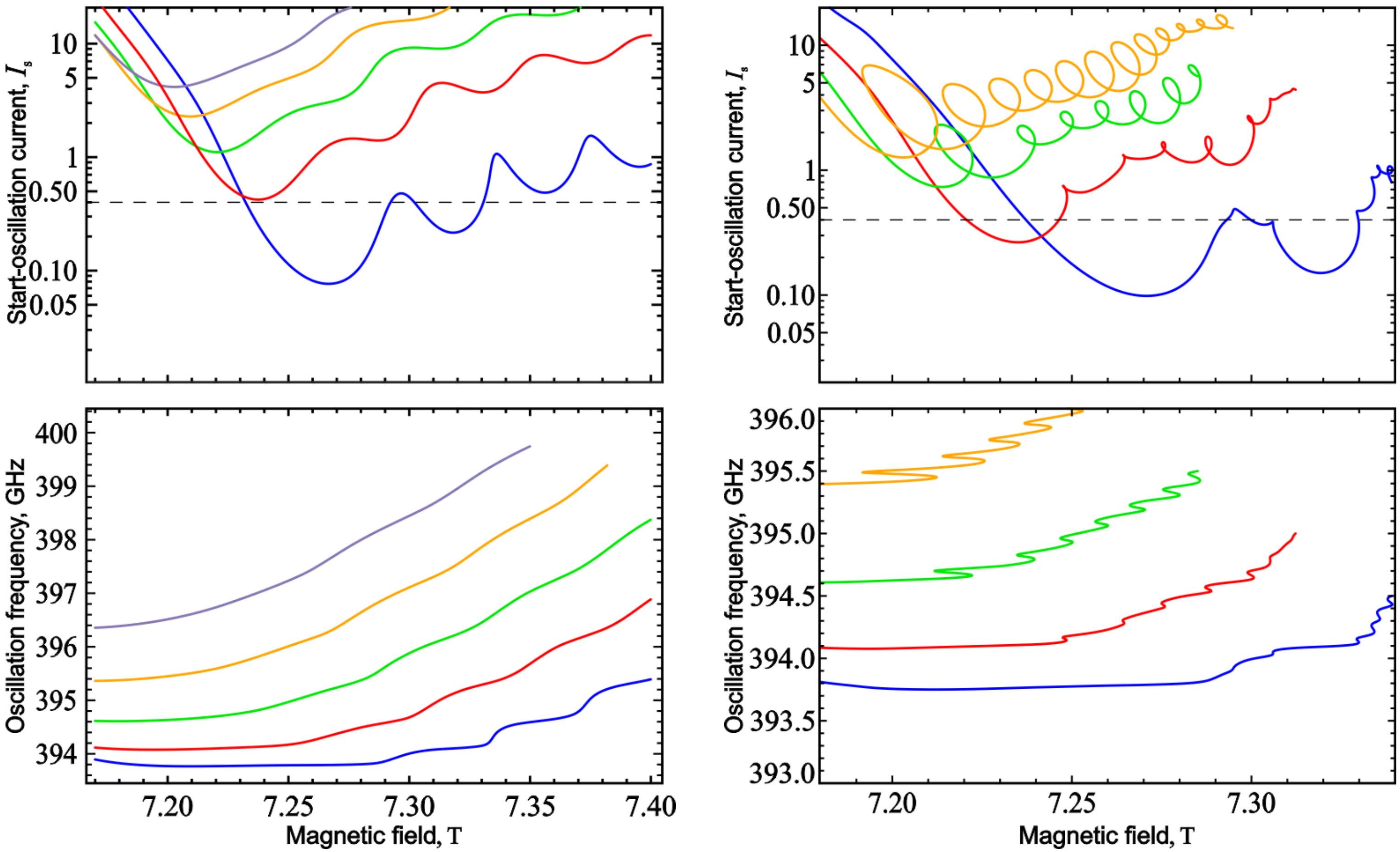
Operation parameters	
U_b	19 kV
B	7.25-7.3 T
R_{cav}	2.365 mm
R_b	0.63 mm
I_b	0.4 A
t_{delay}	3 ns
L	10.2846
I_{s}	0.00173018
Length of the input taper/middle section/output taper	4/15/4 mm
Down-taper/ up-taper angles	2.5°/6°
Operating mode	second-harmonic $TE_{-2,6}$
Frequency	394 GHz

The appearance of FU CW IIB gyrotron

T. Idehara, I. Ogawa, La Agusu, T. Kanemaki, S. Mitsudo, T. Saito, T. Fujiwara, and H. Takahashi, "Development of 394.6 GHz CW Gyrotron (Gyrotron FU CW II) for DNP/Proton-NMR at 600 MHz", Int. J. Infrared Millim. Waves, vol. 28, no. 6, pp. 433–442, 2007

NUMERICAL SIMULATION:

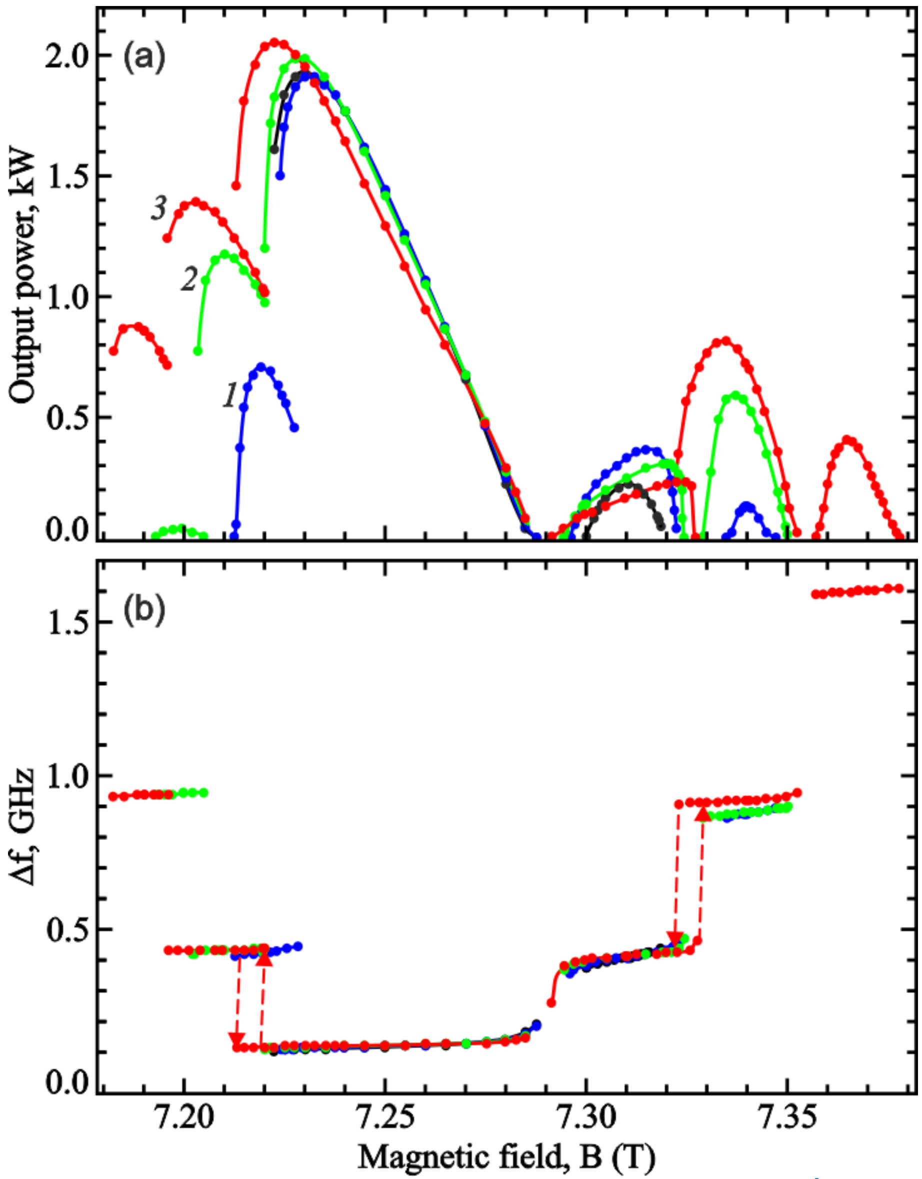
Influence of reflections on the start-oscillation currents and the start-oscillation frequencies



$\Gamma = 0.0$ $\Gamma = 0.2$

With the increase of the reflections, strong deformation of the oscillation zones and frequency-tuning curves due to the “long-line” effect was observed.

NUMERICAL SIMULATION:
Influence of reflections



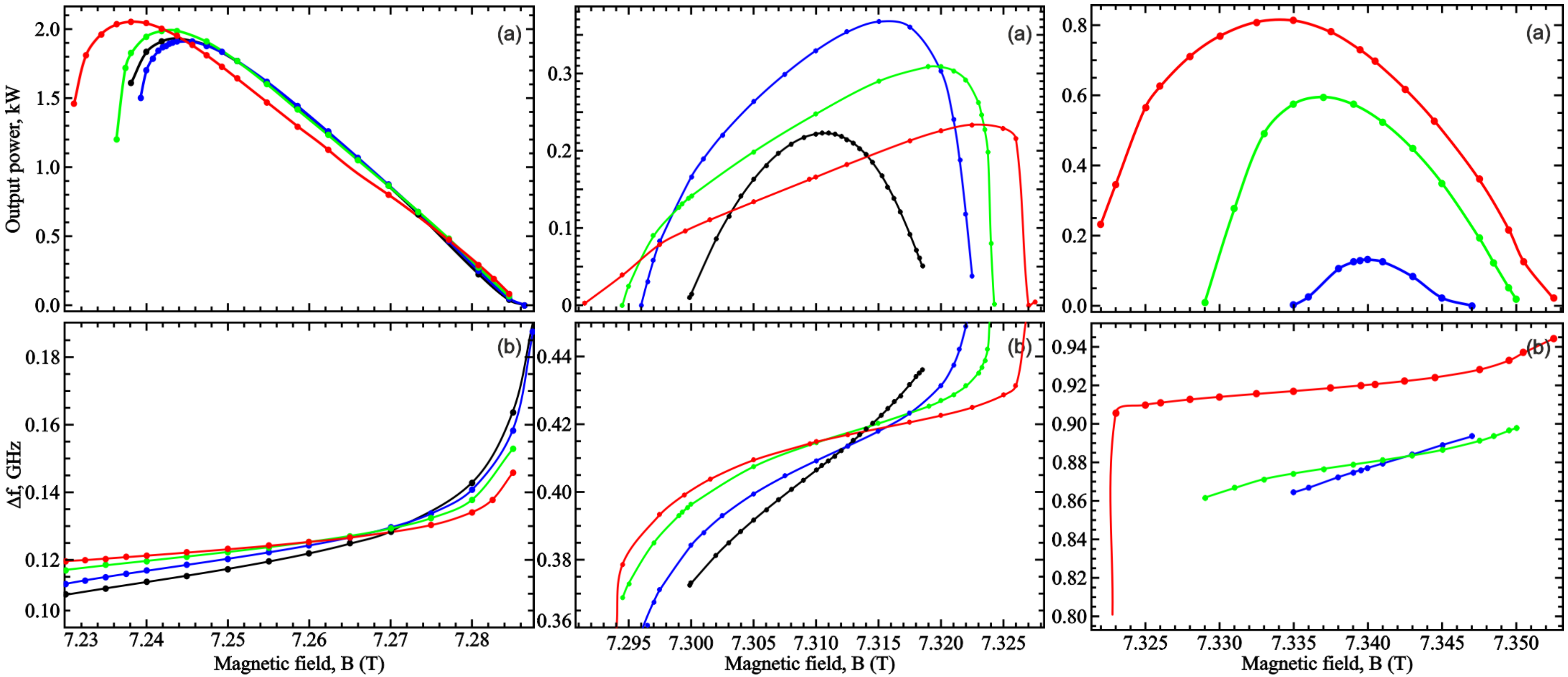
Calculated output power (a) and the frequency shift (b) vs the magnetic field in the case of no reflections (black) and in presence of reflections:

$\Gamma = 0.2$(blue), $\Gamma = 0.4$(green), $\Gamma = 0.6$(red).

The domains of hysteresis for the case of large reflections $\Gamma = 0.6$ are shown with dashed lines on Fig. (b).

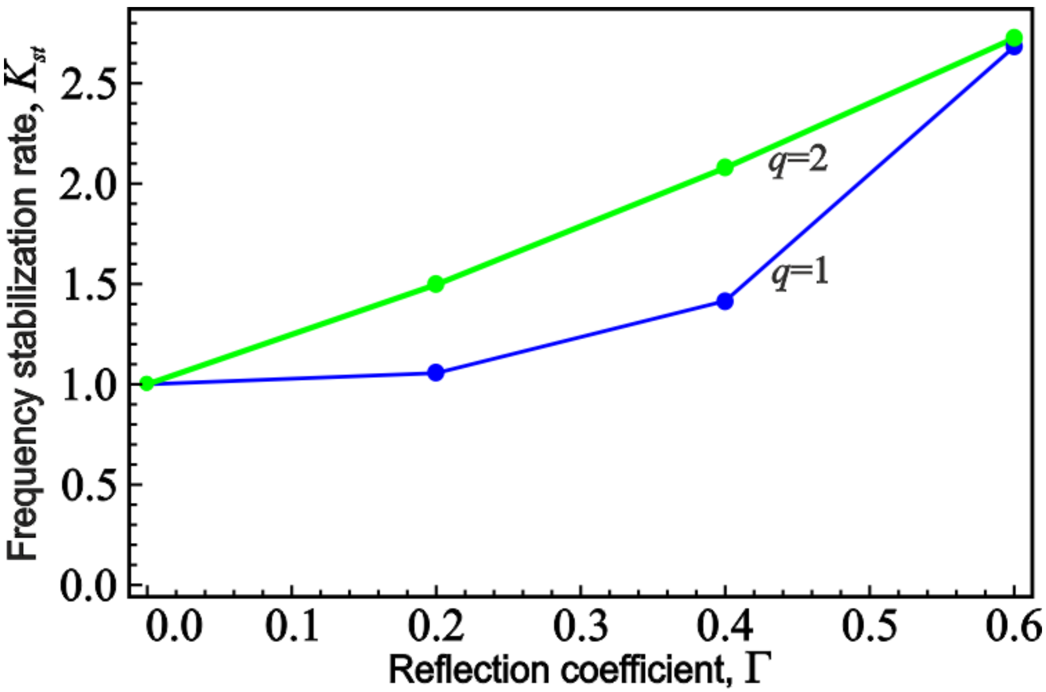
NUMERICAL SIMULATION:
Influence of reflections on the frequency stability

The enlarged parts (see prev. slide) of the calculated output power (a) and frequency (b) vs magnetic field, which are shown separately for each axial mode



q=1 *q*=2 *q*=3

NUMERICAL SIMULATION:
Influence of reflections on the frequency stability

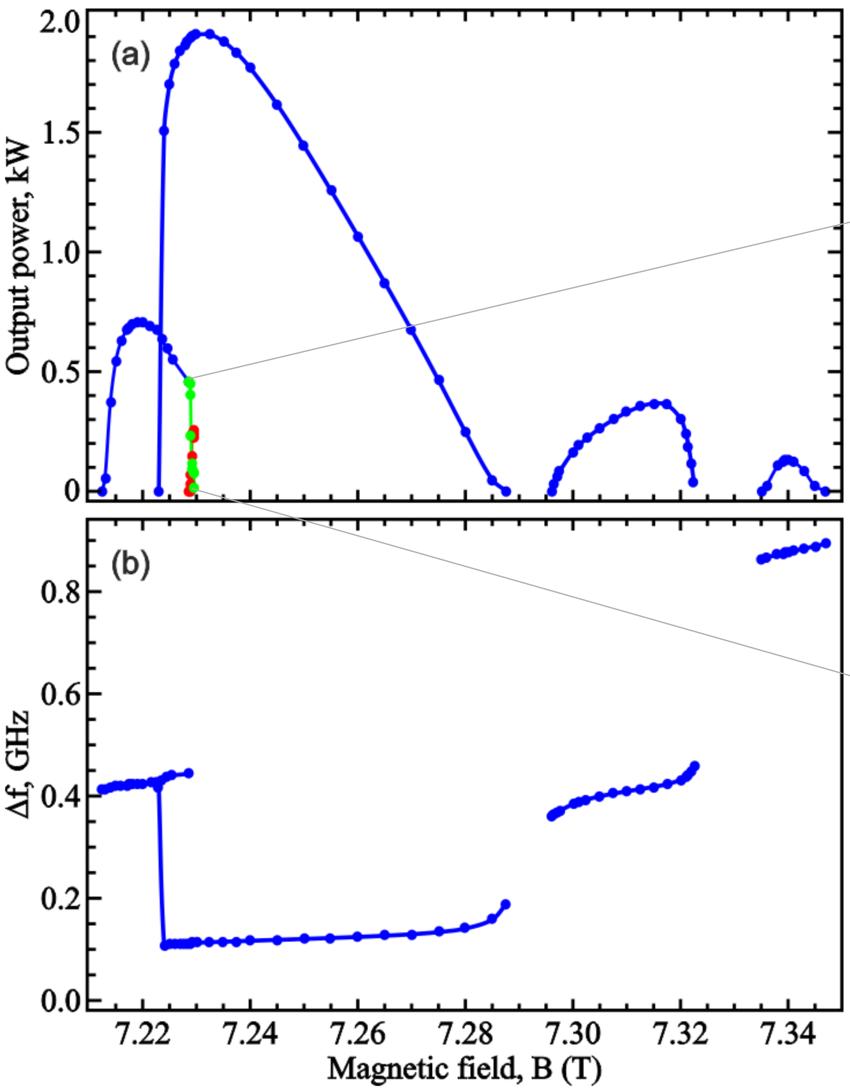


$$K_{st} = \frac{(\Delta f / \Delta B)_{\Gamma}}{(\Delta f / \Delta B)_{\Gamma=0}}$$

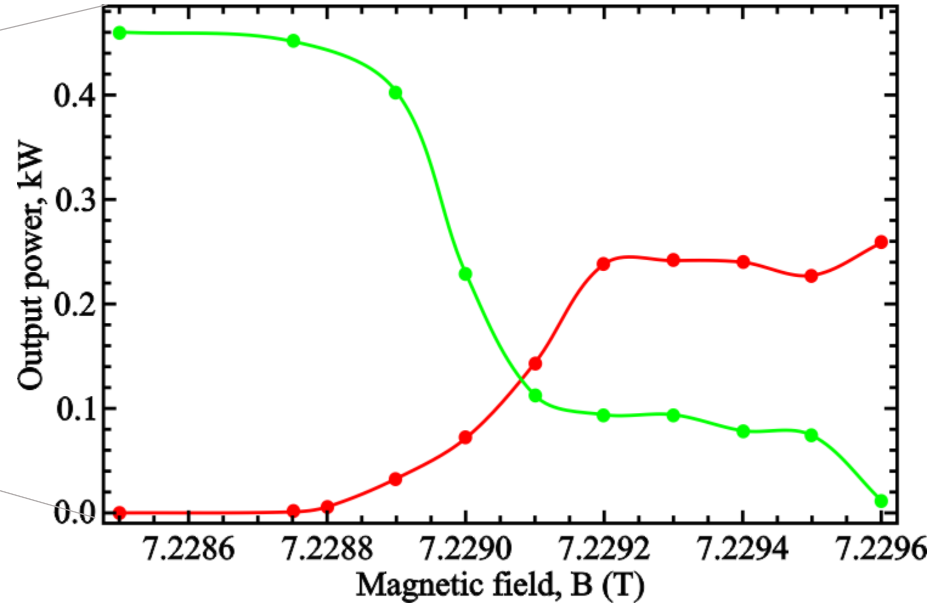
The frequency stabilization increases with the increase of reflection factor and the delay time

- M.M. Melnikova, A.G. Rozhnev, N.M. Ryskin, A.V. Tyshkun, M.Y. Glyavin, and Y.V. Novozhilova, "Frequency stabilization of a 0.67-THz gyrotron by self-injection locking," IEEE Trans. Electron Dev. **63**, 1288-1293, 2016.

Numerical simulation

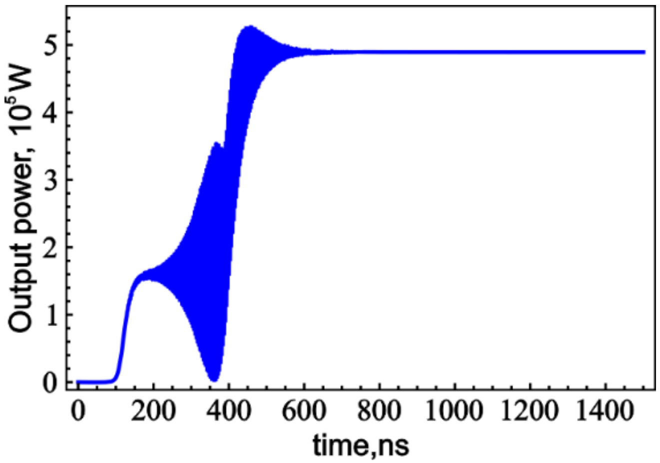


The enlarged part of the multistability domain:



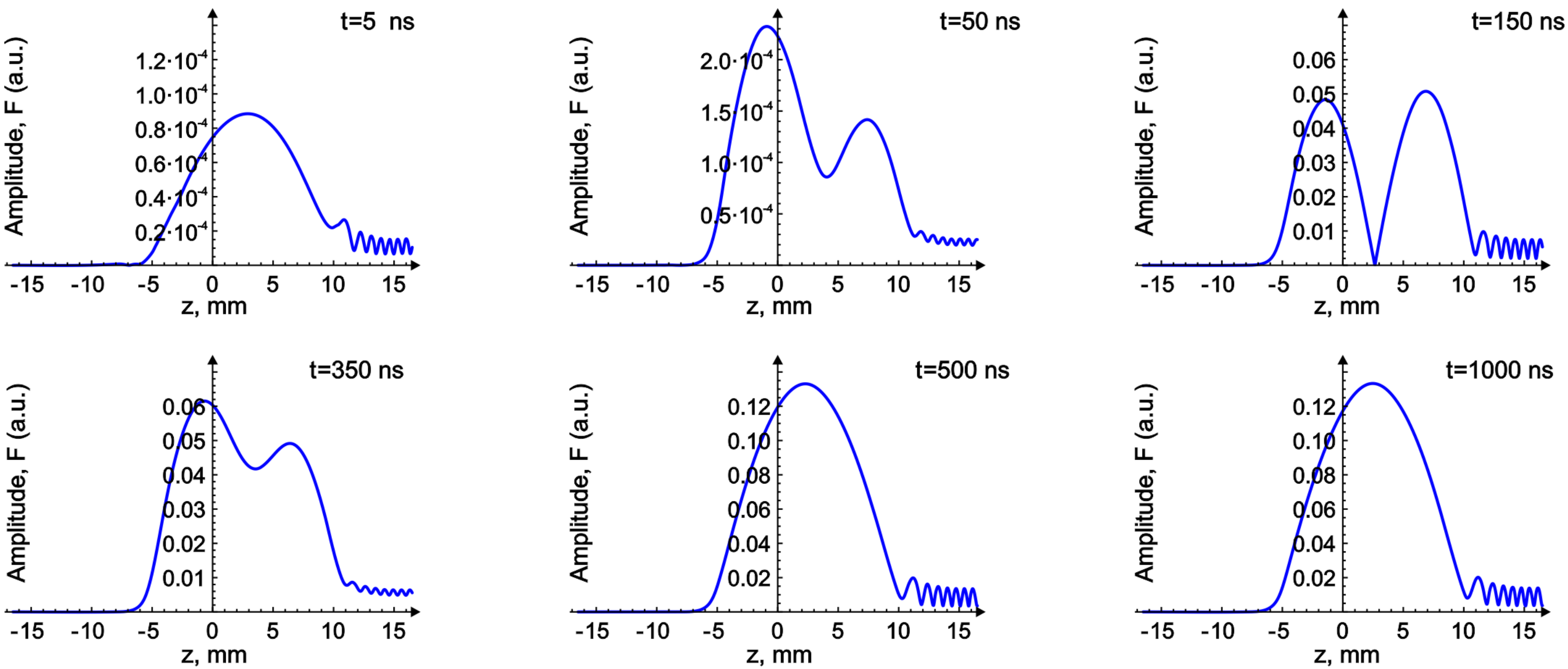
At lower magnetic field, the competition between the fundamental mode and the forward-wave HOAMs is investigated. The effects of the multistability and the hysteresis are observed.

NUMERICAL SIMULATION



The output power vs time at *B*=7.235 T in gyrotron with large reflections Γ=0.6.

Axial profiles of the normalized electric field magnitude at the different times, the mode competition processes are observed



SUMMARY

We present the results of time-domain self-consistent simulation of the second-harmonic 0.4-THz gyrotron with delayed reflection. The reflections lead to decreasing of start-oscillation current, especially for the high-order axial modes (HOAMs). Consequently, due to exciting of the HOAMs, the frequency step-tunability range expands up to 1.5 GHz.

At lower magnetic field, the competition between the fundamental mode and the forward-wave HOAMs is investigated. The effects of the multistability and the hysteresis are observed.

The increase of the frequency stability with the reflection coefficient is also demonstrated.

Influence of the reflection on start-oscillation current and oscillation frequency is studied. With the increase of the reflections, strong deformation of the oscillation zones and frequency-tuning curves due to the "long-line" effect is observed. This indicates the appearance of multistability. To avoid the multistability, one should decrease the delay time.

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Thank you for your attention!