

Experimental Results of a PLL-Stabilized MW-Class 140 GHz Gyrotron at W7-X

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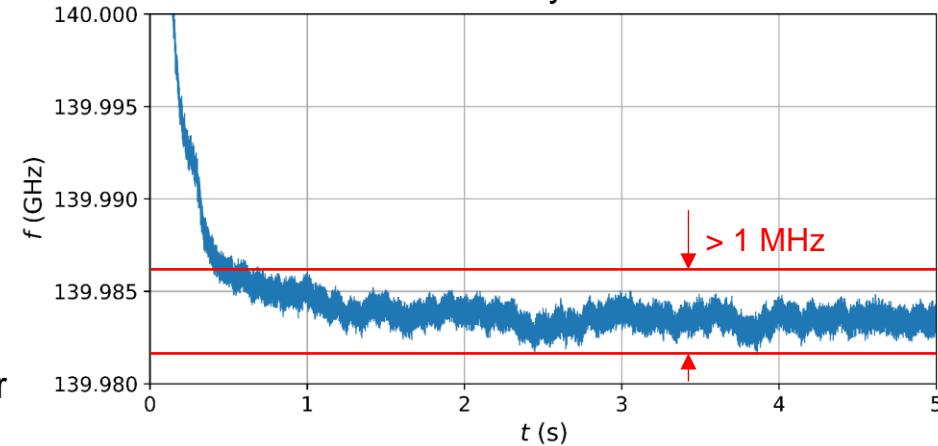
EUROfusion

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Introduction (1/2)

- Until now: gyrotrons are free running oscillators
- Unwanted frequency variations from
 - Cavity temperature (expansion)
 - Power supply noise
 - Vacuum conditions
- Applications of frequency stabilized high-power gyrotrons:
 - Collective Thomson Scattering (CTS) diagnostic
 - Fast Directional Switch (FaDiS) for high-power millimeter-wave beams
 - Direct ion heating at the ion cyclotron resonance frequency with beat waves at the electron cyclotron frequency

Free-Running Frequency of Megawatt-Class W7-X Gyrotron



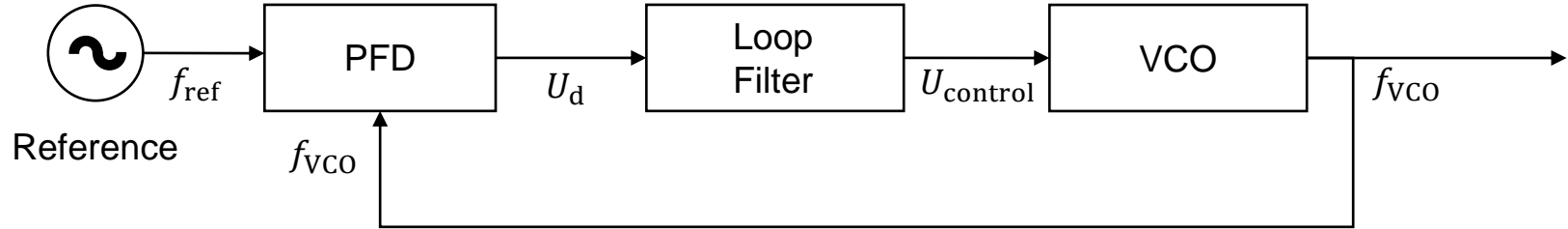
Introduction (2/2)

- Two methods to frequency stabilize a gyrotron:
 - Injection locking
 - External control circuit
- No need to change the gyrotron design with an external control circuit
- Phase-Locked Loop (PLL) is a well known method for phase and frequency stabilization of free-running oscillators
- Demonstration of PLL stabilization (gyrotrons with triode-type MIG)
 - 100 W, 263 GHz gyrotron: line width as narrow as 1 Hz [1]
 - 25 kW, 170 GHz gyrotron: line width as narrow as 1.5 Hz [2]

[1] A. Fokin *et al*, *Scientific Reports* **8**, 4317 (2018)

[2] G.G. Denisov *et al*, *22nd IVEC 2021* (27-30 April 2021)

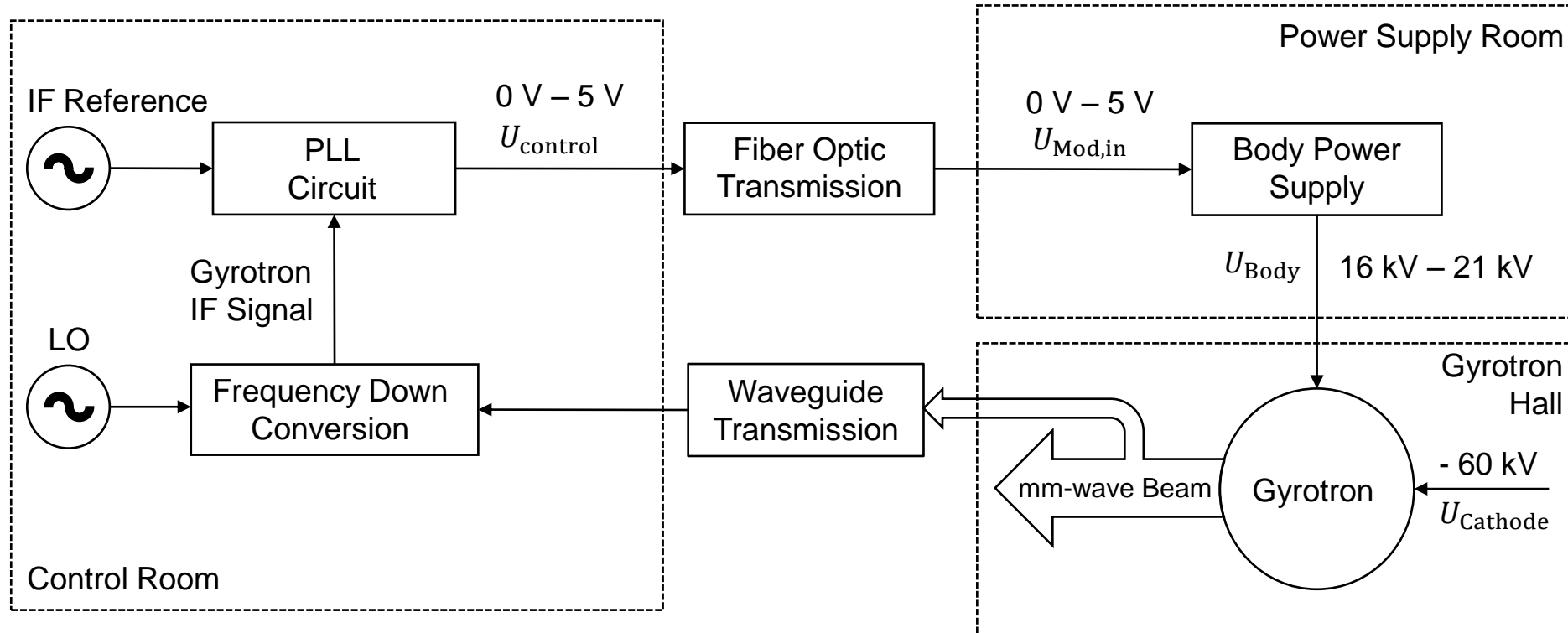
PLL Block Diagram



- **Phase Frequency Detector (PFD):** compares the phase and frequency of two signals and develops an output signal U_d , which is proportional to the phase or frequency error
- **Loop Filter:** filters appropriately the output signal of the PFD for the VCO and determines the dynamics and stability of the control loop
- **Voltage Controlled Oscillator (VCO):** generates an output signal with a frequency depending on the input voltage

$$f_{\text{VCO}} = f_0 + K_{\text{VCO}} U_{\text{control}}$$

Experimental Setup (Diode-Type MIG)



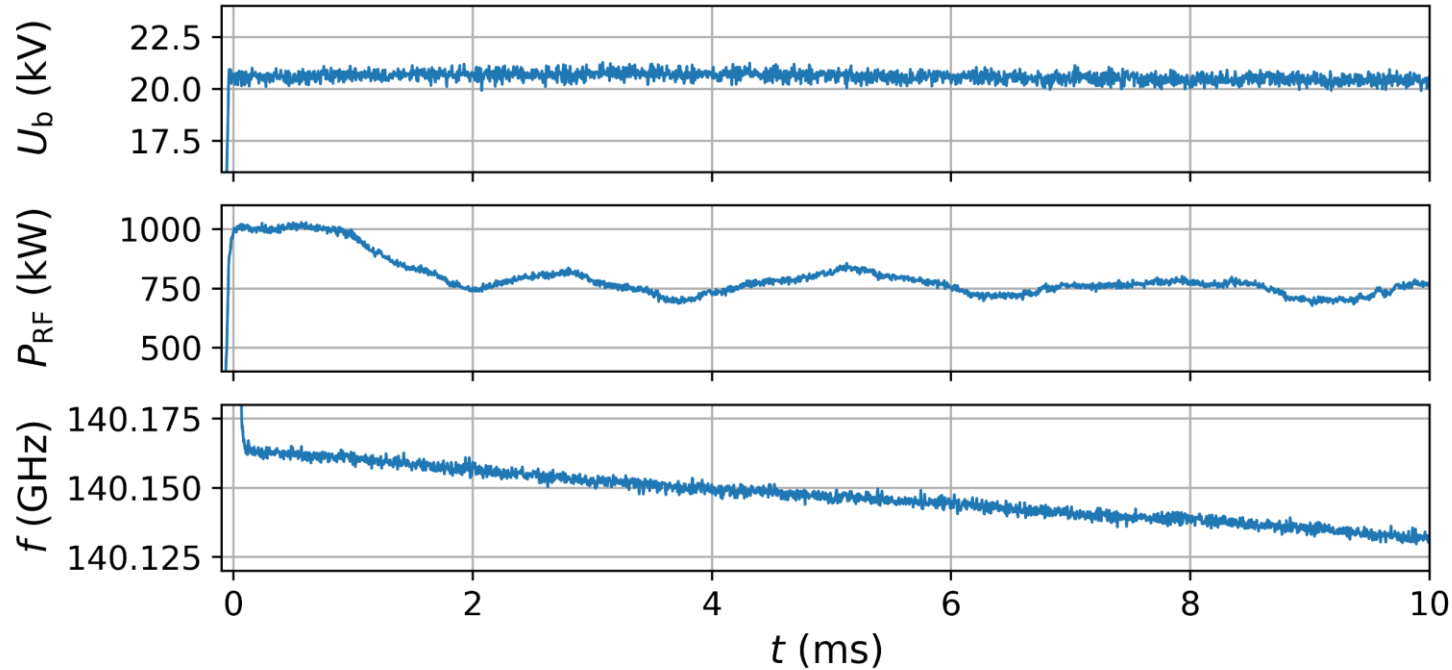
Gyrotron Experimental Parameters

- Experiments with W7-X ECRH gyrotron from manufacturer CPI
- Gyrotron Parameters:
 - $U_{\text{cathode}} = -60 \text{ kV}$
 - $U_{\text{body}} = 16 \text{ kV} - 21 \text{ kV}$
 - $I_{\text{beam}} = 38 \text{ A}$
- Stabilization to an IF frequency of 45 MHz
- Short and long pulse shots

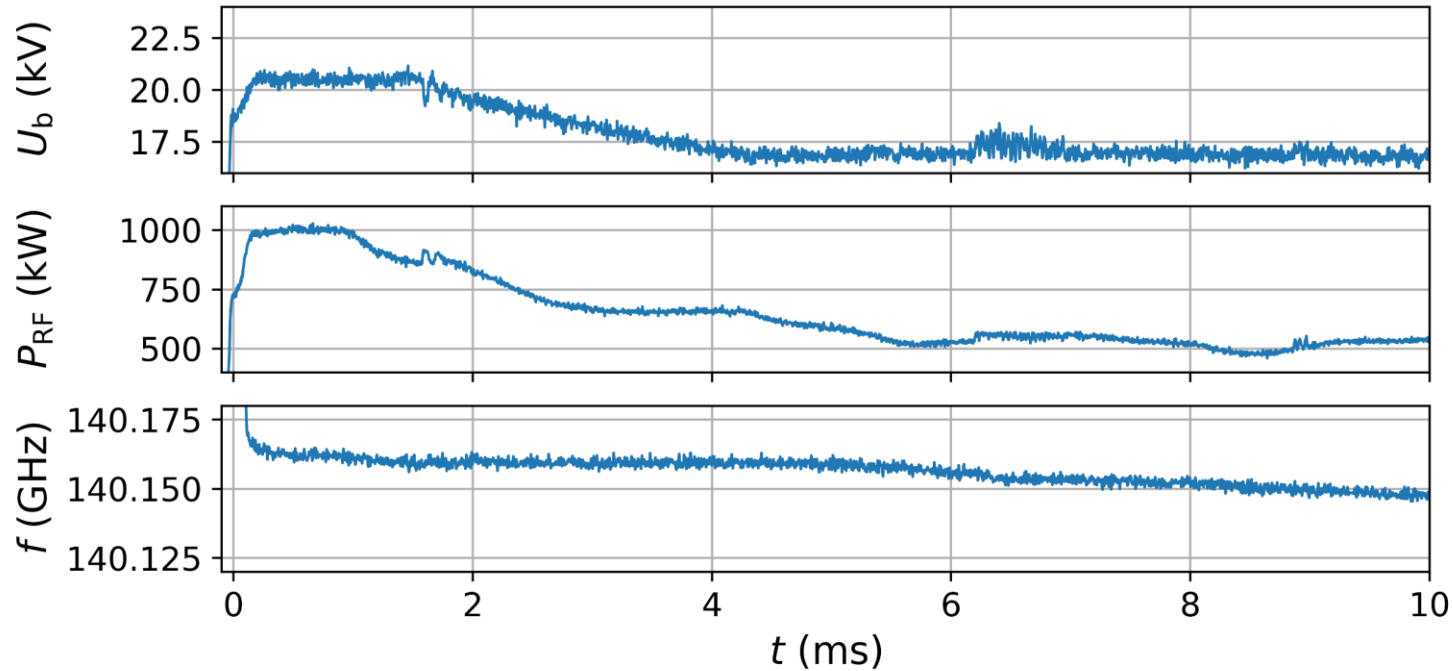
Short Pulse Experiments

- Collective Thomson Scattering diagnostic at W7-X requires short pulses in the 2-5 ms range
- **Problem:**
Frequency drop at the beginning due to electron beam space charge neutralization and cavity expansion from heating
- Counter frequency drop with large change in body voltage

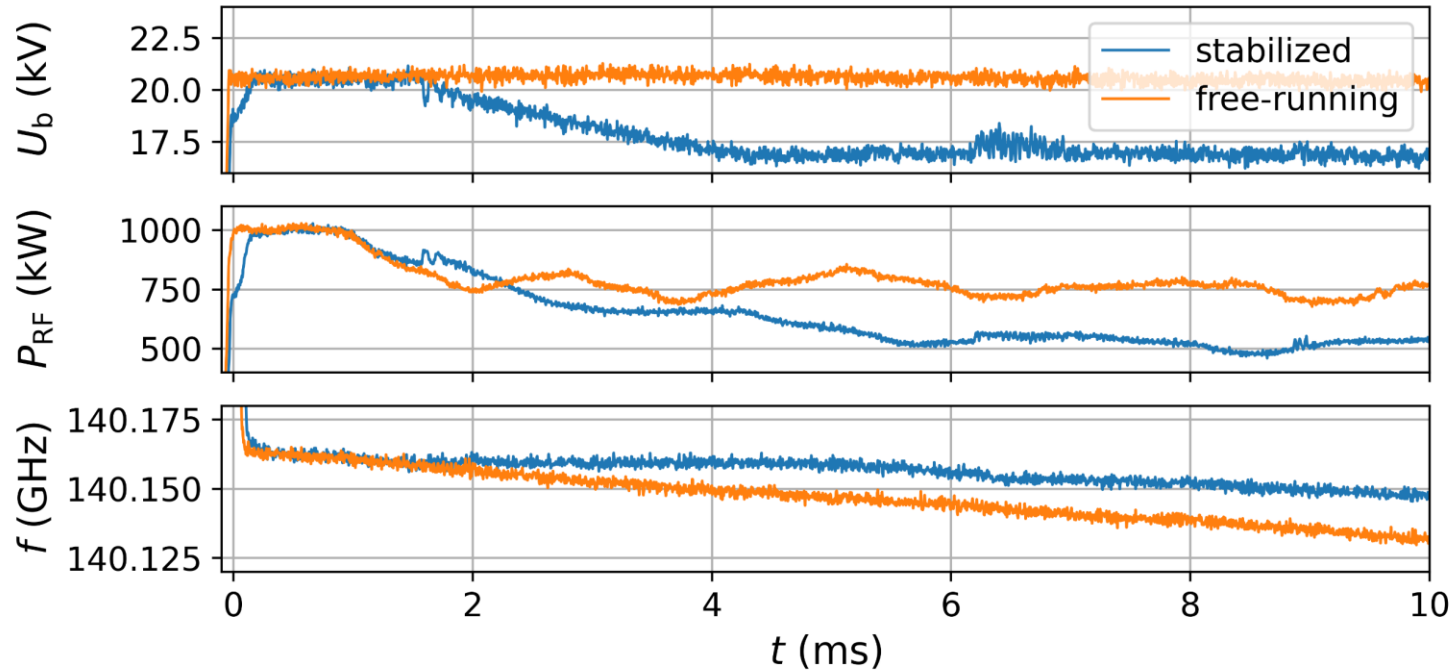
10 ms Short Pulse Free-Running



10 ms Short Pulse Stabilization to 140.160 GHz



10 ms Comparison Free-Running - Stabilized

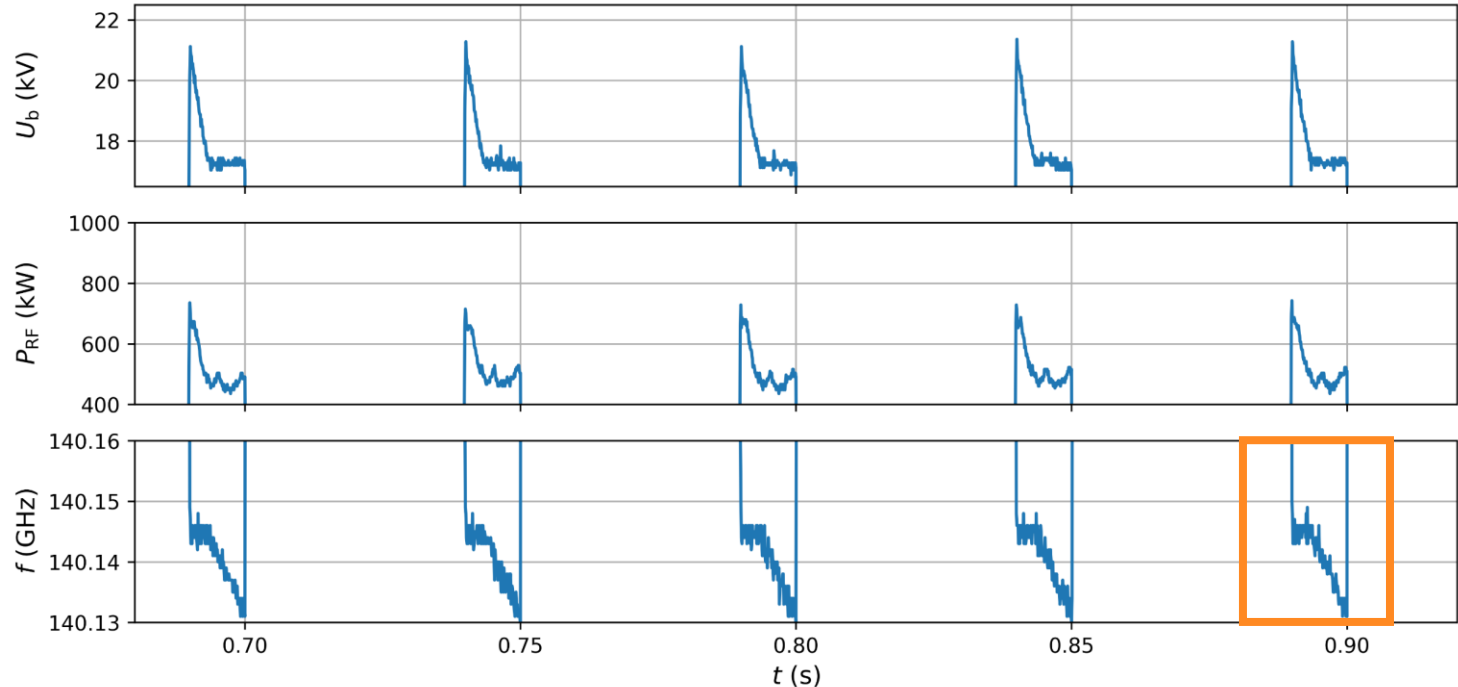


Multiple Short Pulses – 5 Last Pulses from 20

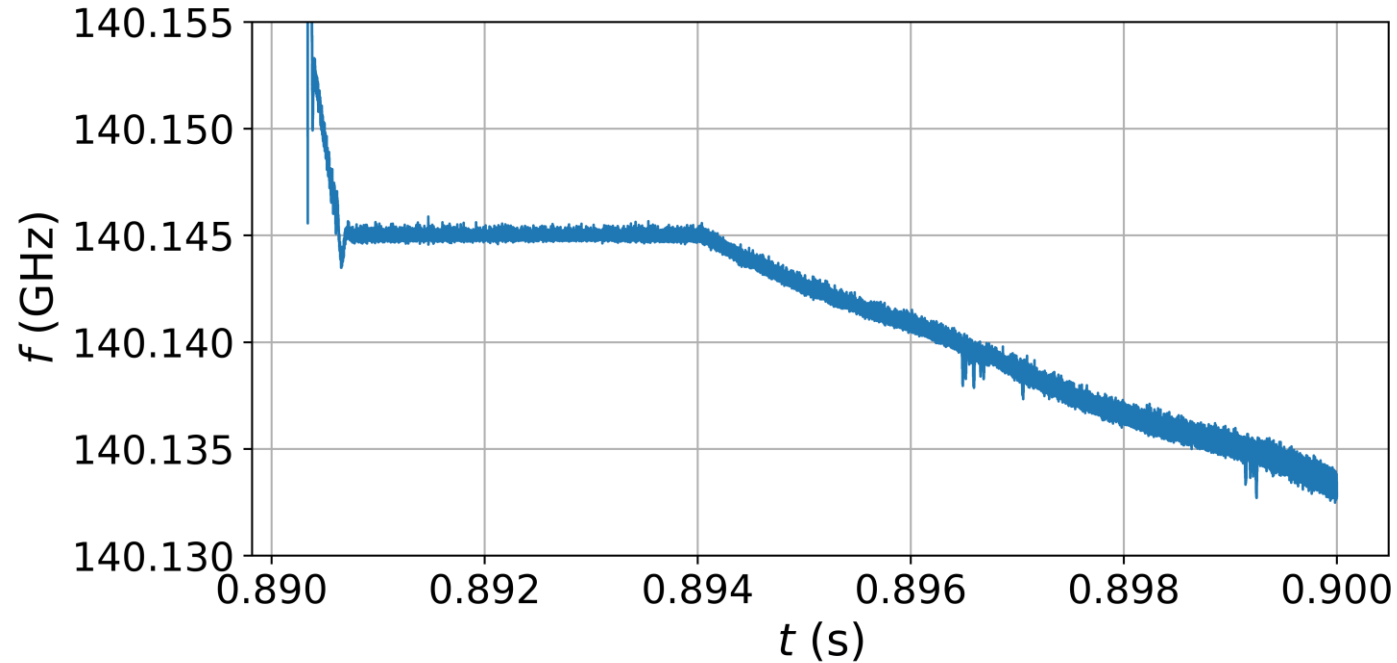
Pulse
Duration:
10 ms

Repetition
Period:
50 ms

Stabilized
Frequency:
140.145 GHz



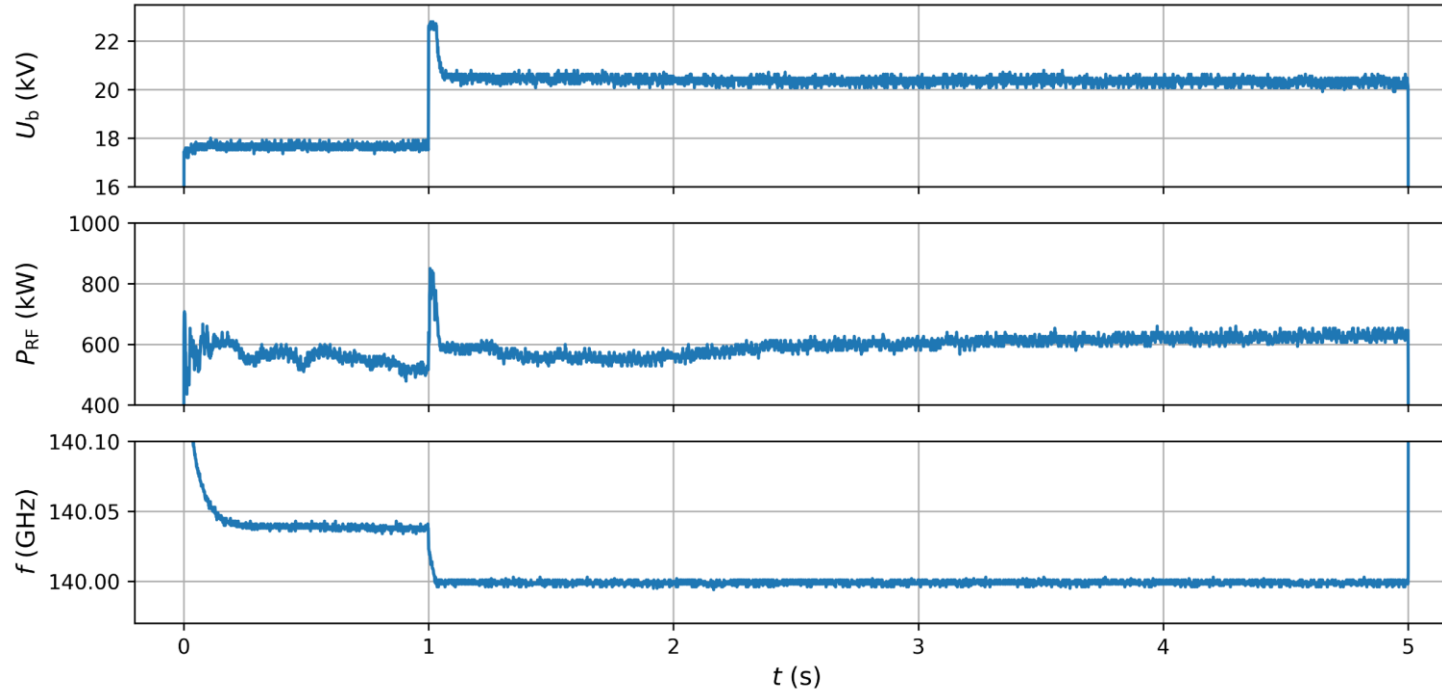
Multiple Short Pulses – Last Pulse



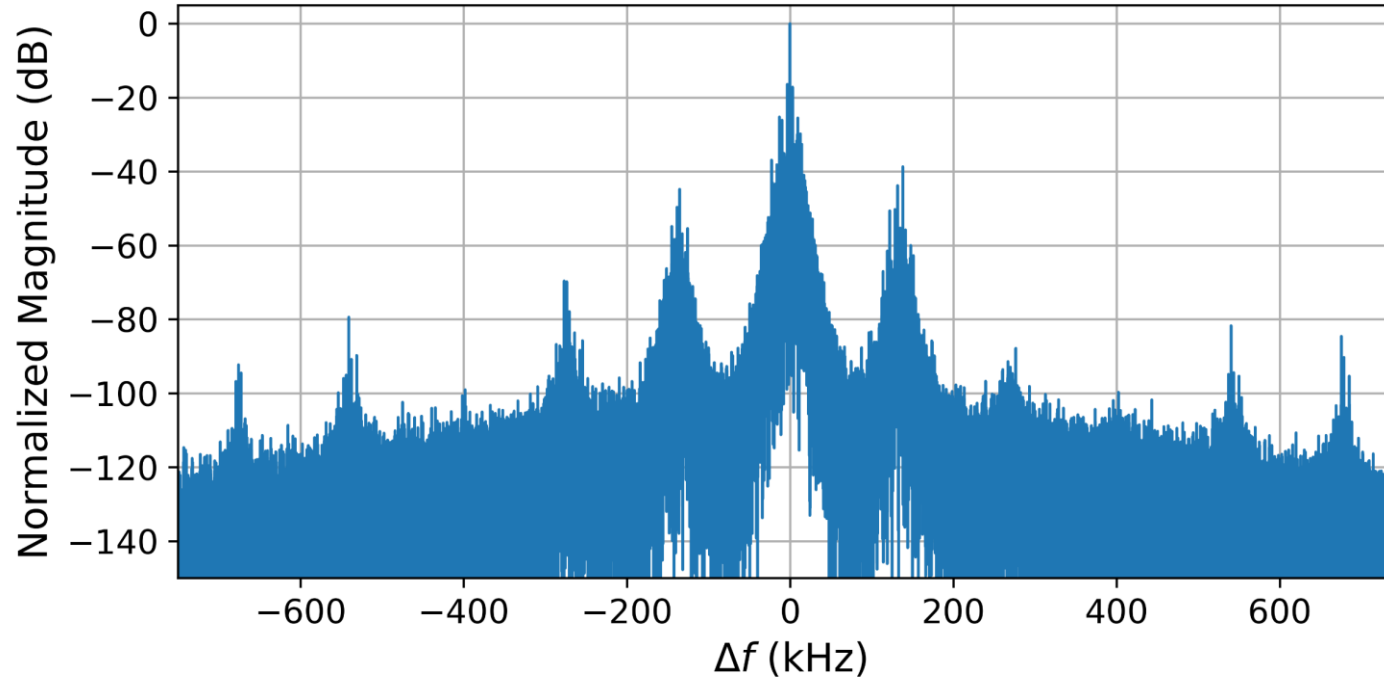
Long Pulse Experiments

- Frequency stabilization after initial frequency drop
- Free-running frequency only changes in the MHz range
 - ➡ Small corrections in body voltage required to stabilize the frequency (below 1 kV)
- Control circuit enabled after 1 s from the start of the pulse
- Frequency is kept stable until the end of the pulse

Frequency Stabilized Gyrotron at 140.000 GHz

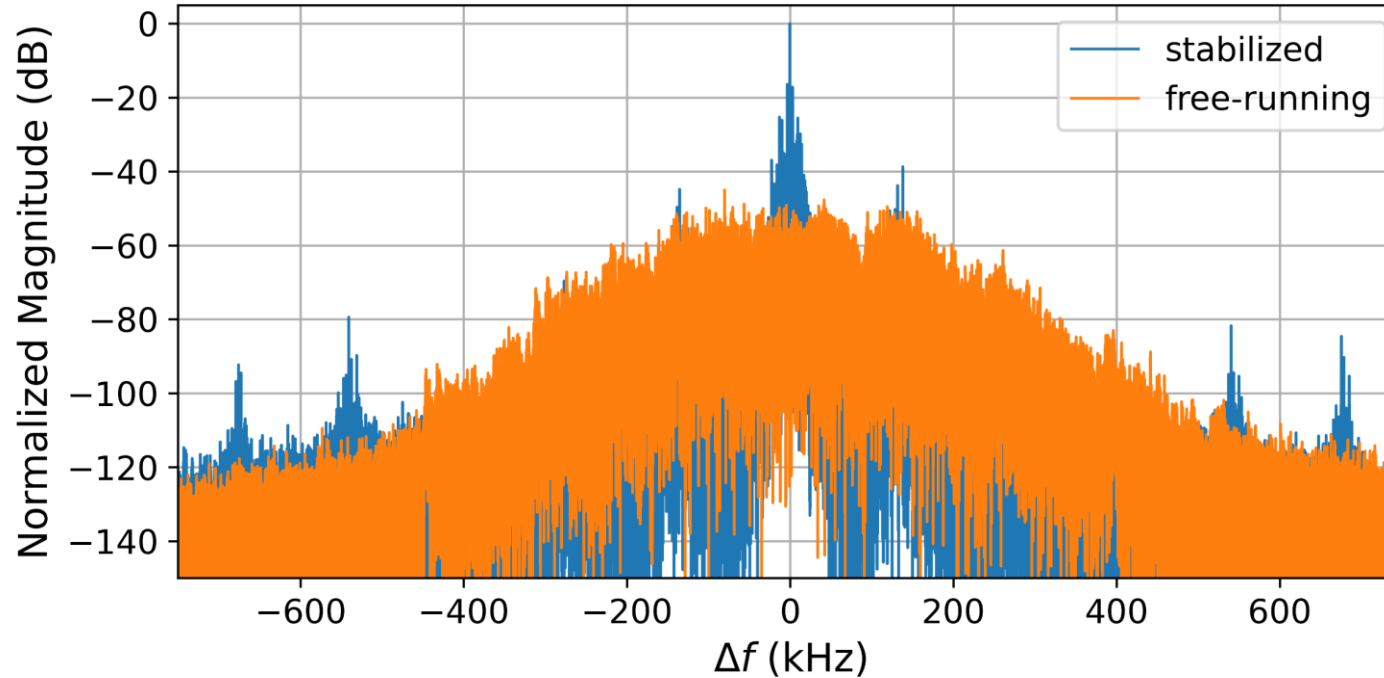


Frequency Stabilized Gyrotron at 140.000 GHz



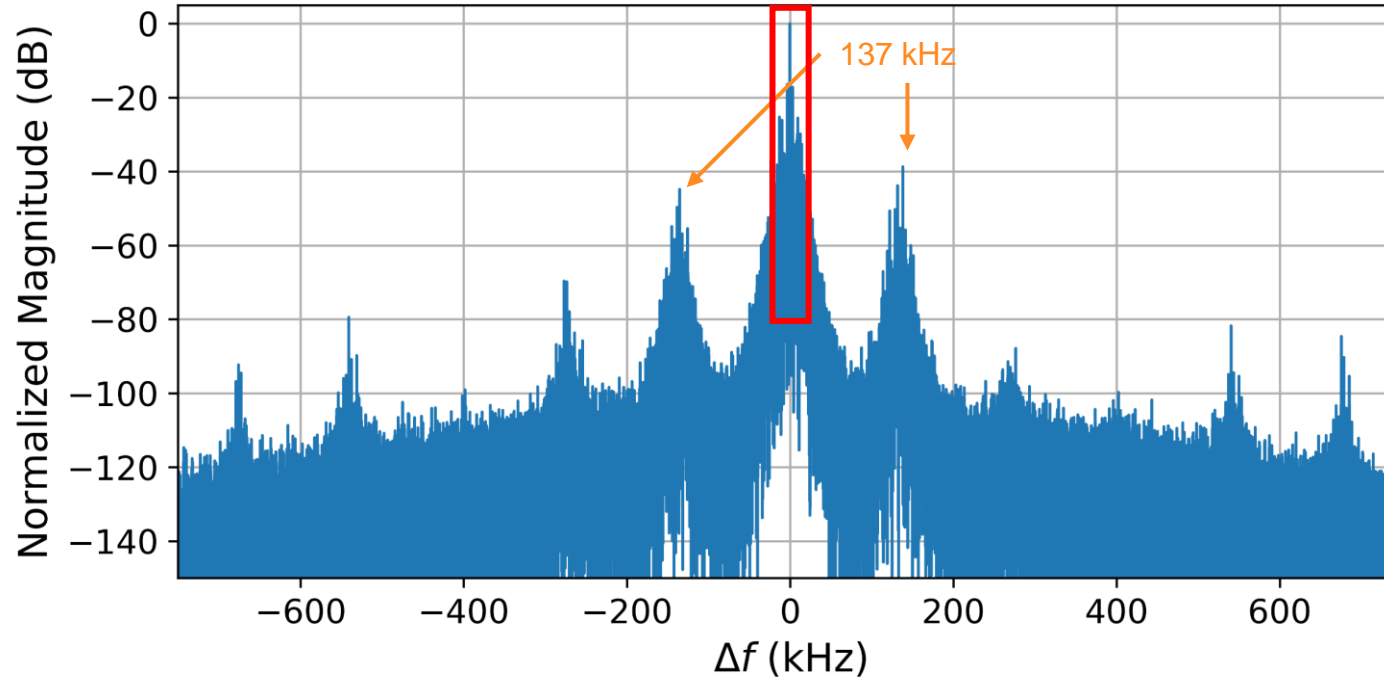
$$f = 140.000 \text{ GHz} + \Delta f$$

Comparison Free-Running and Stabilized Spectrum



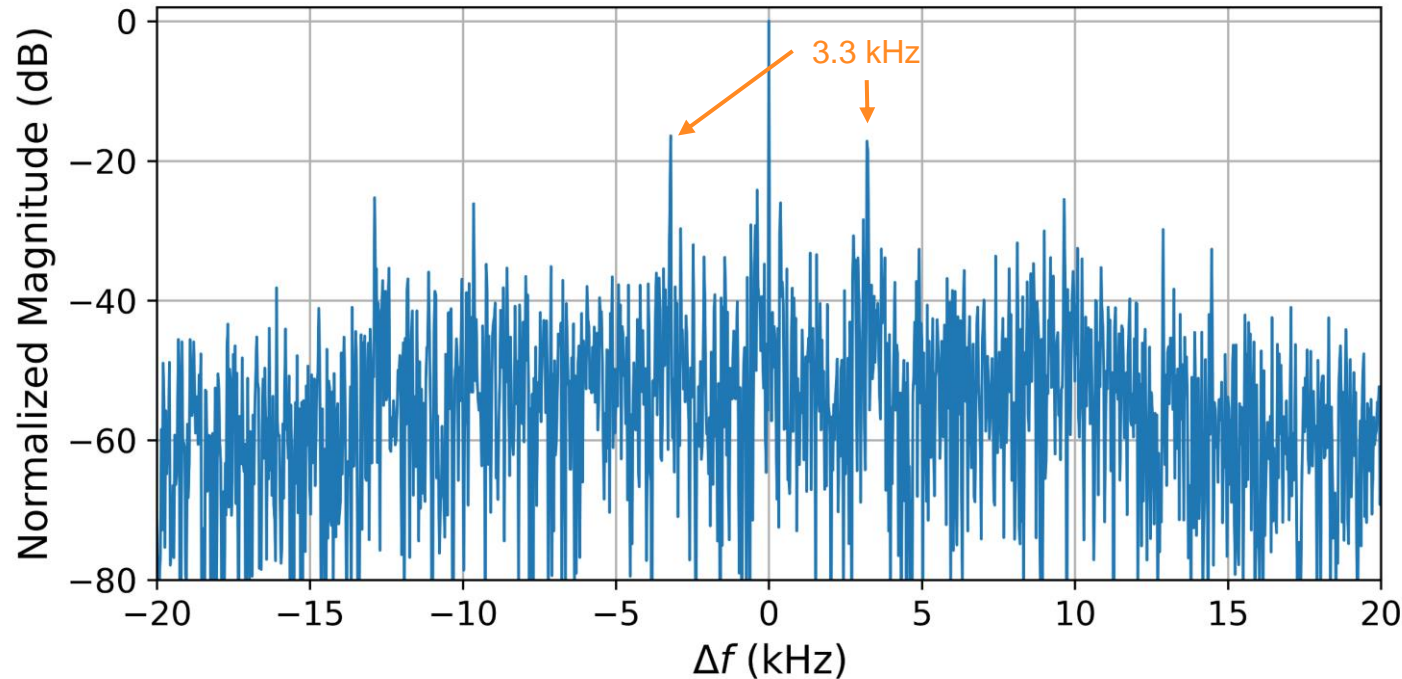
$$f = 140.000 \text{ GHz} + \Delta f$$

Frequency Stabilized Gyrotron at 140.000 GHz



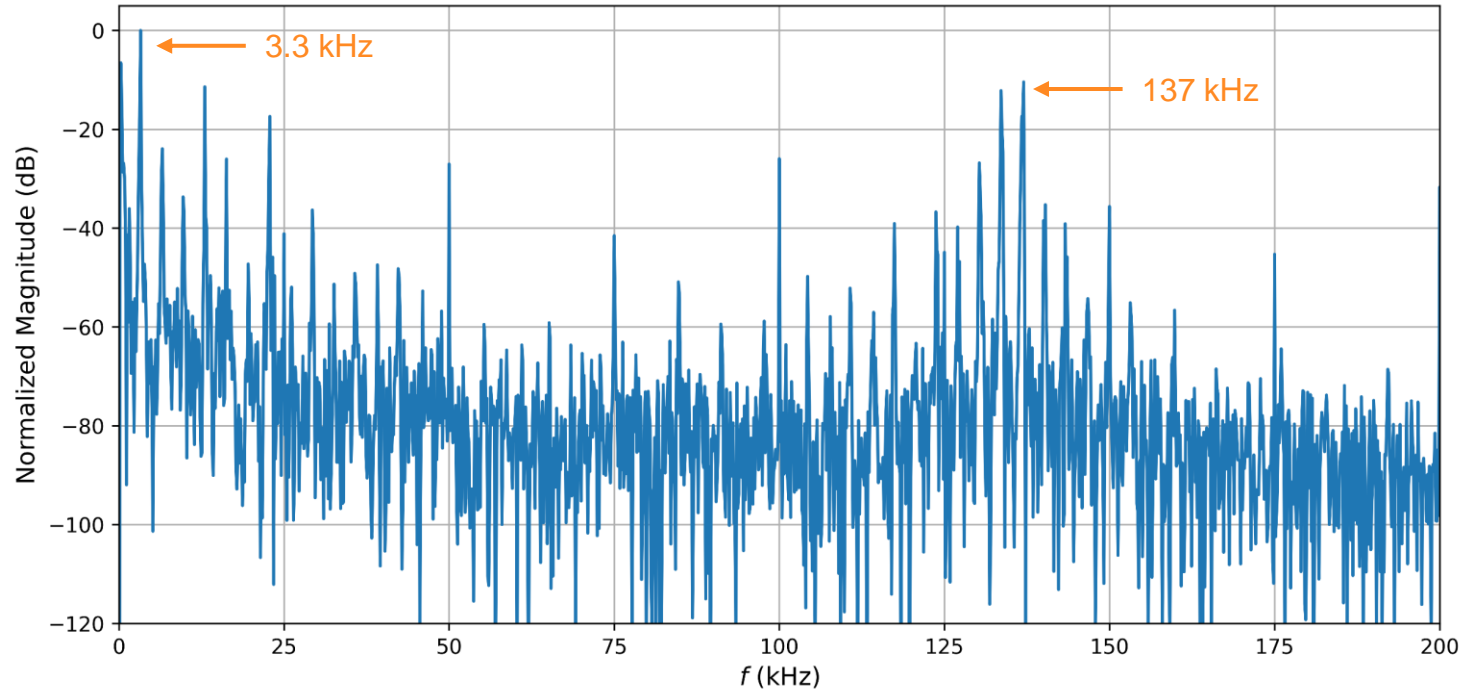
$$f = 140.000 \text{ GHz} + \Delta f$$

Frequency Stabilized Gyrotron at 140.000 GHz (Zoomed In)



$$f = 140.000 \text{ GHz} + \Delta f$$

Noise Spectrum of Cathode Power Supply



Conclusion and Outlook

- Experiments show the potential to stabilize the frequency of a high power gyrotron with diode-type MIG and single-stage depressed collector via the body voltage
 - Possibility to set a desired frequency
 - In spectrum, single gyrotron line with a full -15 dB bandwidth of < 500 Hz
- Investigation of side-bands in the stabilized spectrum, which are coming from the power supplies (3.3 kHz and 137 kHz lines)
- Implementation of PLL circuit at W7-X gyrotron for
 - Collective Thomson Scattering diagnostic at 175 GHz
 - Experiments to explore the possibility of direct ion heating at the ion cyclotron resonance frequency with beat waves at the electron cyclotron frequency