On forced RF generation of CW magnetrons for superconducting accelerators

High power CW magnetrons, designed and optimized for industrial RF heaters, were suggested to power Superconducting RF cavities due to their higher efficiency and lower cost of RF power per Watt comparing to klystrons, IOTs or solid-state amplifiers.

RF amplifiers driven by a master oscillator serve as controllable coherent RF sources. CW magnetrons are regenerative RF generators with a huge regenerative gain. Very large regenerative gain causes instability with large noise when a magnetron operates with the anode voltage higher than the threshold of self-excitation. Traditionally for stabilization of magnetrons is used injection locking by a quite small signal. In this case the CW magnetrons do not provide correlation of the magnetron startup with the injected locking signal. Thus, the magnetron except the injection locked oscillations may generate large noise. This may preclude the required suppression of microphonics and will increase emittance of the beam in SRF accelerators.

Required Field Control to meet accelerator performance:

– Proton/ion Accelerators/Rings: 0.5° and 0.5%
– Nuclear Physics Accelerators: 0.1° and 0.05%
– Light Source: 0.01° and 0.01%

[C. Hovater, TUBF1131_TALK, EIC 14, 2014]

This may make it necessary to suppress parasitic modulation of the phase and power of the accelerating field in various SRF accelerator projects.

G. Kazakevich, Muons, Inc.-FNAL collaboration, LINAC2024
On probability of the injection locking

We considered operation of a CW magnetron as it is traditionally assumed, in a self-excitation mode, at a free run or low injection-locked signal with power $P_{\text{Lock}}$. The effective bandwidth of injection-locking, $\Delta f$ at the locking signal with power $P_{\text{Lock}}$ is expressed by the following equation: $\Delta f = \frac{f_0}{2Q_L} \sqrt{\frac{P_{\text{Lock}}}{P_{\text{Mag}}}}$.


For the free running 2.45 GHz, CW magnetron type 2M137-IL the spectra with span of 5.63 MHz are:

[R.J. Paskuinelli, RF Sources, PIPII XMAS, Feb. 26, 2014].

For 2.45 GHz CW tube one estimates as: $w_{\text{Lock}} \sim \frac{\Delta f}{\Delta f_{\text{FR}}}$, and $w_{\text{FR}} \sim \frac{\Delta f_{\text{FR}} - \Delta f}{\Delta f_{\text{FR}}}$.

The probabilities estimated values vs. $P_{\text{Lock}}$ are shown in the Table.

<table>
<thead>
<tr>
<th>$P_{\text{Lock}}$</th>
<th>$\Delta f$</th>
<th>$w_{\text{Lock}}$</th>
<th>$w_{\text{FR}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10 dB</td>
<td>3.87 MHz</td>
<td>~0.86</td>
<td>~0.14</td>
</tr>
<tr>
<td>-20 dB</td>
<td>1.22 MHz</td>
<td>~0.27</td>
<td>~0.73</td>
</tr>
<tr>
<td>-30 dB</td>
<td>0.39 MHz</td>
<td>~0.09</td>
<td>~0.91</td>
</tr>
</tbody>
</table>

Probability of the injection-locked RF generation of such RF source may be notably less than probability of the free running generation caused by noise.

[G. Kazakevich et al, FERMILAB-PUB-23-663-TD-V]

This was tested by measuring the spectral density of the noise power.

[G. Kazakevich et al, PRAB, 21, 062001 (2018)]
The spectral density of noise power relatively $f_c$ of the magnetron 2M137-IL at the output power of 1 kW, at the locking signal of 100, 30, and 10 W, traces A, B, and C, respectively. Traces D are the spectral density of noise power of the injection-locking signal ($P_{\text{Lock}} = 100$ W), when the magnetron feeding voltage is off.

The plots show increase of the spectral density of noise power by $\approx 20 \text{ dB}_C$ at $P_{\text{Lock}} = 10$ W.

G. Kazakevich, Muons, Inc.-FNAL collaboration, LINAC2024
Smoothed by adjacent averaging method the offset of carrier frequency of the 2M137-IL magnetron at the tube output power of 100 W vs. power of the injection-locking signal, $P_{\text{Lock}}$.

[G. Kazakevich et al, NIM A 1039 (2022) 167086.]

**Stimulated generation mode for CW magnetrons**

Ranges of the anode voltage, $U_{\text{Mag}}$, and magnetron current, $I_{\text{Mag}}$, in the Stimulated generation mode for the magnetron type 2M219G vs. $P_{\text{Lock}}$, pulse operation.

[G. Kazakevich et al, NIM A 980 (2020) 164366].

4 kHz trains of 147 ms pulses (duty factor of ≈59%). Traces 1 and 2 - the resonant injected and the magnetron output RF signals with powers of 125 W and 803 W, respectively; trace 3 - the magnetron pulsed current (right scale); trace 4 - the magnetron 2M219G cathode voltage (-3.37 kV), [Ibid.]

13 μs 20 kHz train when the magnetron operates in the Stimulated generation mode. Traces 3 and 4 are the tube output RF signals in dependence on the power of driving signals, traces 1 and 2, respectively. [Ibid.].
Conversion efficiency in the Stimulated generation mode

\[ \eta \approx \frac{P_{RF}}{U_{Mag} \cdot I_{Mag} + P_{Lock}} \]

Dependence of conversion efficiency of the 2M219G magnetron on power of injected signal \( P_{Lock} \). Conversion efficiency of the magnetron operating in free run mode at nominal power is \( \approx 54\% \). [Ibid.]

Bandwidth of control, \( BW_C \) in the Stimulated generation mode

\[ BW_C \] of 2.45 GHz CW magnetrons measured by transfer function phase and magnitude characteristics.

G. Kazakevich et al, arXiv:2404.16249

Summary

- Recently developed and tested by CW magnetrons the Stimulated generation mode provides highly-stable coherent generation of the tubes fed below the Hartree voltage and being driven by the forcing signal of \( \sim -10 \text{ dB}_C \).
- The quasi-continuous noise in this mode is practically suppressed.
- Pulse operation of CW magnetrons with 100% pulse modulation of the forcing signal results in 100% pulse modulation of the tube output power without HV pulse modulators.
- Bandwidth of phase and power control of CW magnetrons operating in the Stimulated generation mode is most wide and suitable for various SRF accelerators.
- Lower the magnetrons anode voltage and reduced the electron back-stream in the Stimulated generation mode along with improved tubes vacuum will increase the magnetrons lifetime.