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An efficient magnetron transmitter for superconducting accelerators

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ABSTRACT

A concept of a highly-efficient high-power magnetron transmitter allowing wide-band phase and the mid-frequency power control at the frequency of the locking signal is proposed. The proposal is aimed for powering Superconducting RF (SRF) cavities of intensity-frontier accelerators. The transmitter is intended to operate with phase and amplitude control feedback loops allowing suppression of microphonics and beam loading in the SRF cavities. The concept utilizes injection-locked magnetrons controlled in phase by the locking signal supplied by a feedback system. The injection-locking signal pre-excites the magnetron and allows its operation below the critical voltage in free run. This realizes control of the magnetron power in an extended range (up to 10 dB) by control of the magnetron current. Experimental studies were carried out with 2.45 GHz, 1 kW, CW magnetrons. They demonstrated stable operation of the magnetrons and the required range of power control at a low noise level. An analysis of the kinetics of the drifting charge within the framework of the presented model of phase focusing in magnetrons substantiates the concept and the experimental results.

1. Introduction

Modern high-intensity superconducting accelerators need RF sources with an average power of tens to hundreds of kilowatts capable of supporting the phase and amplitude instability of the SRF cavity accelerating field to much less than about 1° and 1%, respectively. Typically compensation of the harmful effects of microphonics and beam loading is provided by the phase and power feedbacks which support accelerating field stability at the required level. Successful implementation of such feedbacks requires sufficiently wide bandwidth of the RF transmitter.

The traditional RF sources such as klystrons, Inductive Output Tubes (IOTs) and solid-state amplifiers are expensive and their cost represents a significant fraction of the project cost. The usage of MW-scale klystrons feeding groups of cavities allows one considerable cost reduction. However such a choice only provides control of the vector sum of the accelerating voltage for the group of cavities, which is usually insufficient for proton or ion accelerators if the beam energy is below about 1 GeV [1]. Therefore RF sources dynamically controlled in phase and power around the carrier frequency and feeding individually each SRF cavity are necessary for large-scale intensity-frontier proton and ion accelerators.

Magnetrons are more efficient and less expensive than the above-mentioned traditional RF sources [2]. Thus utilization of magnetron RF sources in large-scale accelerator projects can significantly reduce the RF system cost. As formulated and demonstrated in Ref. [3] magnetron RF sources are suitable for dynamic phase and power control required for stabilization of the accelerating field in SRF cavities. The low cost of magnetron power allows for powering a single cavity which greatly improves the stability of each cavity's voltage and phase.

The magnetron phase is controlled by the phase modulation of the injection-locking signal. The bandwidth of phase control depends on the magnitude of the injection-locking signal and may reach 0.1% of the magnetron frequency [3]. In particular it is at least 3 MHz for the 2.45 GHz, 1 kW, CW magnetrons used in our experiments.

Recently two methods of power control in magnetron based transmitters utilizing the wide-band phase control were suggested and studied experimentally. In the first method the output power is combined from the outputs of two magnetrons by a 3 dB hybrid combiner [3,4]. An independent control of both magnetrons phases yields control of their vector sum and, consequently, the phase and power of the output signal at any impedance of the load. The second method suggested in Ref. [5] is suitable for voltage control in high Q-factor cavities only ($Q_{Load} \sim 10^7$ or more). In this case the signal which controls the magnetron phase has an additional wideband control of depth of the phase modulation at a frequency

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much larger than the cavity bandwidth. The cavity voltage control is provided by redistribution of RF power between the fundamental frequency and the sidebands for which power is determined by the depth of phase modulation. Both methods provide practically the same power efficiency of ~50% at power control in the range of 5–10 dB. Although the second method requires less high power hardware and is less expensive, its usage is limited to sufficiently high Q-factor cavities, because the phase modulation induces a parasitic amplitude modulation of the cavity voltage at harmonics of the phase modulation frequency. The amplitude modulation is increased with reduction of loaded Q-factor.

The two-channel magnetron transmitter with power combining allows a very wide range of power control, certainly sufficient to control the microphonics and beam loading in SRF cavities. However a novel method with a wide-band phase control, but a narrower range of power control at a narrower bandwidth (in the range of a few kHz) may be sufficient for many accelerators. The novel concept of magnetron power control based on the wide-range current regulation in an injection-locked magnetron is considered in this paper. The concept is based on proposed and studied the kinetic model of phase focusing in magnetron by the injection-locking signal. The developed method provides the highest efficiency at the given range of power control. Analytical substantiation and experimental verification of the model and concept are also discussed.

2. Power control in pre-excited magnetrons

Here we consider how a resonant pre-excitation of magnetrons affects the range of current variation based on a simple model utilizing the drift approximation and perturbation theory. For simplicity, the presented kinetic approach does not consider Larmor's motion of electrons and variations of radius of the Larmor's orbit which is significant at the resonant interaction of the moving charge with a synchronous wave excited in an operating magnetron, [6]. The approach is more acceptable for qualitative consideration of the processes in magnetrons and explanation of our concept than for quantitative calculations, nevertheless it can be used for estimations. We will follow the analytical theory of free running magnetrons developed by Kapitza [6]. As in Ref. [6] we will neglect the beam space charge effects, especially because we consider the CW tubes operating without very high currents.

Let us consider a conventional N-cavities magnetron powered somewhat below the critical voltage, with a static constant magnetic field, H, above the critical magnetic field. In this consideration, we assume that the magnetron is loaded by a matched load, so that any wave coming to the magnetron is considered to be excited by an external source. In the absence of generation, the motion of electrons in the crossed magnetic and static electric fields is described by a superposition of two circular motions: rotation of the electron at the angular cyclotron (Larmor's) velocity, $\omega = eH/(mc)$ and motion of the center of this circle around the coordinate frame center at the angular velocity Ω, so that $\omega > \Omega$ [6]. The former motion has a comparatively minor effect on the magnetron operation and can be neglected in the first approximation. The latter motion represents a drift of the transported charge averaged over ω. Under these conditions, the drift equations for a non-generating magnetron in cylindrical coordinates are [7]:

$$\begin{cases} \dot{r} = -\dfrac{c}{Hr}\dfrac{\partial\Phi^0}{\partial\phi} = 0 \\ \dot{\phi} = \dfrac{c}{Hr}\dfrac{U}{\ln(r_2/r_1)r} = \dfrac{c}{Hr}\dfrac{\partial\Phi^0}{\partial r} \end{cases} \tag{1}$$

here Φ° is a potential of the static electric field, so that $E_r = \mathrm{grad}\Phi^\circ$, $\Phi^0 = U\ln(r/r_1)/\ln(r_2/r_1)$, $E_\phi(r) = 0$, U is the magnetron feeding voltage, r_1 and r_2 are the magnetron cathode and anode radii, respectively. As one can see from the first equation the radial velocity is equal to zero, and the azimuthal drift is only present, *i.e.*, the magnetron represents a closed diode with a magnetic isolation.

Now we consider the magnetron operating in a nominal regime in the π-mode. The necessary condition for operation of the magnetron is the presence of a synchronous wave whose frequency, ω, coincides with a harmonic of the charge rotation frequency, Ω, *i.e.*, $\omega = n\Omega$, where $n = N/2$. Taking into account that the magnetron operating frequency is much smaller than the frequencies of modes related to the magnetron interaction space (c/r_1, $c/r_2 \gg \omega/\pi$) the quasi-static approximation can be used. Then, the potential of the rotating wave can be presented in the following well-known form:

$$\Phi = \sum_{k=-\infty}^{\infty} \frac{\tilde{E}_k \cdot r_1}{2k}\left[\left(\frac{r}{r_1}\right)^k - \left(\frac{r_1}{r}\right)^k\right]\sin(k\phi + \omega t), \tag{2}$$

where $\tilde{E}_k$ is the amplitude of k-th harmonic of radial RF electric field at $r = r_1$. Note that the form of the potential was chosen so that the azimuthal electric field at the cathode is zero. The coefficients $\tilde{E}_k$ are determined by requirement to have zero azimuthal electric field at the anode everywhere except the gaps of the cavities. The term in the sum of Eq. (2) with $k = n$ has a resonant interaction with the azimuthal motion of charge and therefore makes the major contribution. In the further considerations we will retain only this term.

Adding the potential of the rotating wave into Eq. (1) due to the perturbation theory one obtains:

$$\begin{cases} \dot{r} = -\dfrac{c}{Hr}\dfrac{\partial}{\partial\phi}(\Phi) \\ \dot{\phi} = \dfrac{c}{Hr}\dfrac{\partial}{\partial r}\left(\Phi^0 + \Phi\right) \end{cases}. \tag{3}$$

Rewriting the above equation in the coordinate frame rotating with the synchronous wave (angular frequency of $\Omega = \omega/n$), and assuming that $\phi' = \phi + \omega \cdot t/n$ one obtains [7]:

$$\begin{cases} \dot{r} = -\dfrac{c}{Hr}\dfrac{\partial}{\partial\phi'}\Phi' \\ \dot{\phi}' = \dfrac{c}{Hr}\dfrac{\partial}{\partial r}\Phi' \end{cases}, \tag{4}$$

where

$$\Phi' = U\frac{\ln(r/r_1)}{\ln(r_2/r_1)} + \frac{\omega H}{2nc}r^2 + \frac{\tilde{E}_n r_1}{2n}\left[\left(\frac{r}{r_1}\right)^n - \left(\frac{r_1}{r}\right)^n\right]\sin(n\phi')$$

is an effective potential. The first two terms determine the azimuthal drift. They are related to the static electric field and azimuthal drift with angular frequency of the synchronous wave frame, $-\omega/n$. The third term determines the azimuthal and radial drifts caused by the RF field of the synchronous wave. Substituting this potential in Eq. (4) one obtains [7]: