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High-power magnetron transmitter as an RF source for superconducting linear accelerators

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ABSTRACT

A concept of a high-power transmitter utilizing the Continuous Wave (CW) magnetrons, injection-locked by phase-modulated signals, and intended to operate within a wideband control feedback loop in phase and amplitude, is presented. This transmitter is proposed to drive Superconducting RF (SRF) cavities for intensity-frontier GeV-scale proton/ion linacs, such as the projected Fermilab proton linacs or linacs for Accelerator Driven System (ADS). The transmitter consists of two 2-cascade injection-locked magnetrons with outputs combined by a 3-dB hybrid. The transmitter performance was modelled using CW, S-Band, 1 kW magnetrons. A wideband dynamic control of magnetrons, required for the superconducting linacs, was realized using the magnetrons, injection-locked by the phase-modulated signals. The capabilities of the magnetrons injection-locked by the phase-modulated signals and adequateness for feeding of SRF cavities have been verified by measurements of the magnetrons phase performance, by measurements of the transfer function magnitude characteristics of single and 2-cascade magnetrons in the phase modulation domain, and by measurements of spectra of carrier frequency of the magnetron. At the ratio of power of locking signal to output power of ≥ -13 dB (in 2-cascade scheme per magnetron) a phase modulation bandwidth is over 1.0 MHz for injection-locked CW single magnetrons and a 2-cascade setup. The carrier frequency spectra (width of $\sim$1 Hz at the level of -60 dBc) measured with the magnetron, injection-locked by a phase-modulated signal, did not demonstrate broadening at wide range of magnitude and frequency of the phase modulation. The wideband dynamic management of output power of the transmitter model has been first experimentally demonstrated using combined in power magnetrons, injection-locked by the phase-modulated signals. Experiments with the injection-locked magnetrons adequately emulated the wideband dynamic control with a feedback control system, which will allow to suppress all known parasitic modulation of the accelerating field in the SRF cavities. The magnetron transmitter concept, tests of the transmitter models and injection-locking of magnetrons by phase-modulated signals are discussed in this work.

1. Introduction

State of the art intensity frontier GeV-scale proton or ion superconducting linacs require CW RF sources to power SRF cavities, keeping the accelerating voltage phase and amplitude deviations to less than 1° and 1% of nominal, respectively. The average RF power to feed, for example, an ILC-type SRF cavity, providing an energy gain of $\sim$20 MeV/cavity for a 1–10 mA average beam current, is a few tens to a few hundreds of kW.

The investment costs for an RF power system for large-scale projects (e.g. ADS facilities, etc.) are a significant fraction of the overall costs, if traditional RF sources as klystrons, Inductive Output Tubes (IOTs) or solid-state amplifiers are used. Utilization of MW-scale CW klystrons to power groups of the cavities can save costs to some extent, but in turn only allows control of the vector sum of the accelerating voltage in the group. Accelerating voltage vector sum control has not been tested for driving SRF cavities for non-relativistic or weakly relativistic particles; it may be unacceptable for low-velocity particles since non-optimized values of phase and amplitude of the accelerating field in individual SRF

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cavities can cause emittance growth [1] and may lead to beam losses.

The CW magnetrons based on commercial prototypes are more efficient and potentially less expensive than the above-mentioned RF sources [2]; thus utilization of the magnetron RF sources in the large-scale accelerator projects will provide significant reduction of capital and maintenance costs, especially since the CW magnetrons with power up to 100–120 kW are well within current manufacturing capabilities.

The magnetron RF sources intended to feed the room-temperature accelerating structures, can be frequency and phase locked [3] (if there are no transient processes disturbing phase-locking of the magnetrons) to be stable in frequency and phase. The concept assumes that in this case the accelerating field in the structures will be also stable in the frequency and phase. However, the traditional concept is not acceptable for feeding of SRF cavities, since some parasitic modulations inherent in operation of the cavities are not associated with instability of RF sources. E.g. the mechanical noises, including "microphonics" and Lorenrz-force noise, the phase modulations, caused by dynamic tuning errors and beam loading, exist even in the RF sources, feeding the SRF cavities, are ideally stable. Thus, instead of phase-locking of magnetrons, we propose to power the SRF cavities of the superconducting linacs by transmitters based on the magnetrons, injection (frequency)-locked by the wide-band phase-modulated signal [4]. As it is demonstrated in the presented work, the frequency-locking of magnetrons by the phase-modulated signal realizes a wideband dynamic phase control of the magnetrons. Associated with a closed feedback loop, the dynamic control will eliminate all the known low-frequency parasitic modulations of the accelerating field in the SRF cavities.

As the manufactured SRF cavities are not identical in mechanical and RF properties, the parasitic modulations change from cavity to cavity. Thus the concept most applicable for superconducting accelerators is the powering of each SRF cavity by an individual vector controlled RF source providing the dynamic control of phase and of power.

The dynamic control of magnetrons formally is not considered by Adler approach [5], assuming injection-locking of an LC tube generator by an external signal, stable in frequency, phase and power, i.e. assuming the locked oscillator in steady-state.

Basis of the dynamic control of magnetrons, we have proposed and realized, is an approach considering transient processes in magnetrons.

A proof-of-principle of the dynamic phase control of a magnetron, injection-locked by a frequency (phase)-modulated signal first has been demonstrated modelling a transient process in the 2.5 MW, 2.8 GHz pulsed magnetron type MI-456A, forced (injection-locked) by a signal with varied frequency [6–8]. The transient process model was verified with very good accuracy by the measurements of the magnetron frequency (phase) response [6–8]. Unlike the approach, developed by Adler and then applied to magnetrons and described in numerous works, the techniques modelling the transient process allow computation of the magnetron frequency and phase response on the injection-locking signal, modulated in frequency/phase, in time domain. That is the transient process approach allows a dynamic control consideration. The analysis of the computed and measured response of the magnetron on the frequency and phase-modulated locking signal [9] demonstrated an acceptable linearity and small phase errors in the response.

Measurements of the magnitude transfer characteristic and the phase performance of CW, S-band, 1 kW magnetrons, injection-locked by the phase-modulated signal, described in the presented work, demonstrated a wide bandwidth of the dynamic phase control. Performed measurements demonstrate that the injection-locking by the phase-modulated signal at the wide range of magnitude and frequency of the phase modulation does not broaden the very narrow ($\sim$1 Hz at $-$60 dBc level) spectrum of the magnetron carrier frequency, coinciding at high accuracy with carrier frequency of the locking signal. Thus, the magnetrons injection-locked by the phase-modulated signal are adequate RF sources for SRF cavities. The measurements and the presented analysis indicate that a wideband control of magnetrons by injection-locking phase-modulated signal will appropriately satisfy the requirements of intensity-frontier superconducting linacs.

Estimations and numerical modelling based on measurements of the magnetron transfer function magnitude characteristic demonstrate that power line related phase modulation sidebands of the injection-locked magnetrons associated with low-frequency phase pushing may be almost completely eliminated by closed loop feedback of the phase term in the Low Level RF (LLRF) controller. This closed loop also will suppress phase perturbations from cavity beam loading, cavity dynamic tuning errors and perturbations of the magnetron magnetic field induced by magnetron filament AC circuitry, which were observed in the presented work.

A dynamic power control of magnetrons injection-locked by the phase-modulated signal in the setup with power combining, first realized in this work, demonstrates the capability of the magnetrons for the wideband vector control of the accelerating field in SRF cavities.

The experimental tests, measurements, and numerical modelling performed with injection-locked magnetrons demonstrate proof-of-principles of the proposed concepts of the magnetron transmitter and of the dynamic vector control by the phase-modulated injection-locking signals. The control will allow to suppress all known low-frequency parasitic modulation in SRF cavities. The modelling and tests are discussed in this paper.

2. A concept of the magnetron transmitter controlled in phase and power

The proposed concept of the high-power magnetron transmitter based on the injection- locked 2-cascade magnetrons [10] is presented in Fig. 1.

The transmitter consists of two identical channels (A and B) of cascaded injection-locked magnetrons with outputs combined by a 3-dB hybrid. For phase management the phases at inputs of both 2-cascade magnetrons are controlled simultaneously and equally, while the power management is provided by a control of phase difference at the inputs of the 2-cascade magnetrons. The 2-cascade injection-locked magnetrons composed from low-power and high-power magnetrons with series connection via circulators were proposed to use lower locking power ($-$35 to $-$25 dB,

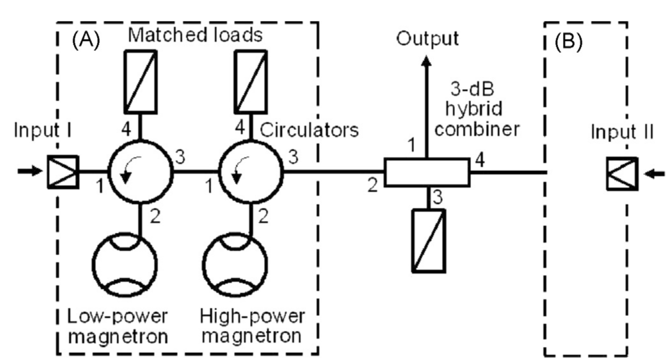

Fig. 1. Conceptual scheme of the magnetron transmitter available for a wideband dynamic control in phase and power.