

THE MAGNETRON-TYPE VARACTOR FOR FAST CONTROL IN ACCELERATOR RF SYSTEMS

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ABSTRACT

The RF test of the magnetron-type varactors have shown [1] the proof of principle of this device. A comparison with the other power rf tunable devices, such as ferrite tuners, shows, that the varactor has a response time a few orders of magnitude shorter. In the experiments this time was estimated to be in the order of 10^{-6} sec for operating frequency ≈ 66 MHz. This feature of the varactor opens new applications of the varactor for a fast modulation (in order of few tens of the working rf period) of the amplitude and the phase of the accelerating voltage in the the rf cavities. Basing on results of numerical simulation, different applications of the device for fast control and improvements in the design to reduce response time are considered.

I. INTRODUCTION

During the development of rf systems for kaon factories a magnetron type varactor was proposed [4] as a tuner for accelerating cavities in synchrotron rings. The Test&Development program was carried out as a collaboration between TRIUMF and INR resulting in the proof of principle of this device.

Varactor may be used as the narrow range tuner for accelerating cavities with moderate or high accelerating voltage [1], but main advantage of the magnetron type varactor is its short time of reaction. It stimulates us in consideration of this device as the instrument of fast control in RF systems.

II. VARACTOR. DESIGN, OPTION OF OPERATION, LIMITATIONS

A schematic sketch of the varactor is presented in Fig. 1. The varactor is a coaxial system consisting of outer conductor (1), inner conductor (2), cathode (3) and reflector (4). The ceramic insulator (5) mechanically supports the construction and provides a dc isolation. The magnetic field B is directed along the z axis, the dc control voltage U_{cc} (with respect to outer conductor) and the rf voltage U_{rf} are applied between the conductors, providing electric fields E_{cc} and E_{rf} in a radial direction. The outer conductor with radius r_a is fixed at ground potential.

The simple theory of the device is described in [2]. Under conditions above the motion of electrons in interaction space between inner and outer conductors may be subdivided in three parts:

- fast cyclotron rotation with the frequency $\omega_h = \left| \frac{eB}{m} \right|$;
- drift of the center of Larmor orbit in azimuth direction with velocity $V \sim (E_{cc} + E_{rf} + E_o)/B$, where E_o is the own electric field of the electron cloud;
- motion along z axis.

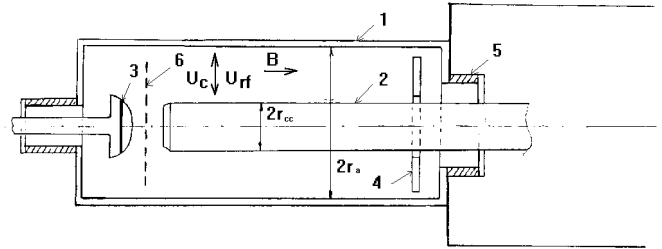


Figure 1. Schematic sketch of the varactor. 1 - outer conductor, 2 - inner conductor, 3 - cathode, 4 - reflector, 5 - insulator, 6 - control grid

It may be shown [2], that presence of the electron cloud or electron beam in the interaction space results in an increase of the effective permittivity:

$$\epsilon = 1 + \frac{ne^2}{m(\omega_h^2 - \omega^2)} \approx 1 + \frac{ne^2}{m\omega_h^2} \quad (1)$$

where n is density of electrons, $\omega = 2\pi f$, f is the self rf frequency of the system. This effect depends on both the charge density and the position of the electron cloud. Treatment of results obtained in experiments [2] have confirmed, that the influence of the charge density is match more stronger, especially if ratio r_a/r_{cc} is not large.

Several reasons:

- a - to have the controllable motion of electrons;
- b - to reduce a absorption of the RF energy;
- c - to reduce radius of cyclotron rotation, and, hence, radial dimension of the beam - lead to the condition $\omega \ll \omega_h$.

Two different options may be realized in the operation of the varactor.

The simplest case is a beam regime, when electron pass varactor one time from the cathode to the reflector (this case reflector really is an absorber). Only heat loading to the reflector limits the range of tuning. Both estimations and the results of numerical simulation shows for the reasonable heat deposition (less than 1 kWt, cooling is necessary) the range $\Delta\epsilon \sim 5\%$ as achievable. A transit time for electron from the cathode to the absorber may be one order less than RF period. Experiments performed

in 1992 have shown this option as realistic [3], but reflector must be specially adapted.

Second option of operation - an accumulation of electron cloud, was investigated in more details [2] in 1993. Providing magnetic mirrors near the cathode and the reflector and probably adding it with reflective potentials at these electrodes we establish a trap for electrons in interaction space. Electron will pass interaction space several times. It leads to sufficient reduction in the emission current and more uniform distribution of losses in the surface of the device. By providing a good magnetic trap one can get narrow band tuning ($\Delta\epsilon = 0 \div 5\%$ for $U_{cc} = 0 \div -20$ kV,) at low RF level practically without any drop in Q - factor of the system with very small value of emission current ($I_{hc} = 18$ mA) [2], [1]. Critical points in this option of operation are regions near reflector and near cathode. In these regions density of electrons is match more higher than average density in interaction space (here electrons change sign of axial velocity). If any instabilities take place in the cloud, they arise in these return points. Moreover, main part of an energy extraction from RF field takes place under injection and near reflector. After investigation the results of experiments we have developed the proposals for improvements in injection and the reflector design to reduce RF energy absorption and for damping instabilities. Specific time for this mode of operation is life-time of electron in the cloud. From a treatment of experimental data we estimate this time in range $1 \div 10$ RF periods, depending on the regime of the varactor (see [2]).

For both options of the varactor operations the response time of the varactor as the controllable device will strongly depend on delay time in a control circuit. Differing from previous versions [4], [3], [1], we consider a now device with constant high DC voltage at the central conductor. Changing of the cloud density will be by modulation of the injection current with low control voltage applied between the cathode and the control grid (Fig. 1). All problems, connected with the forming of current pulses in such injection system are good investigated in the development and design of high frequency powerful electron tubes.

The results of numerical simulation have confirmed previous estimations [1] for reasonable parameters of the device at different levels of the rf voltage and have clarified reasons of disadvantages.

The reason of nonlinearity in the varactor is the coaxial design. It leads to the nonuniformity of the electric fields E_{cc} and E_{rf} (the r^{-1} dependence). At low rf voltage level $U_{rf} \approx 500$ V \ll U_{cc} the displacement of electrons under rf field action is small and the nonlinearity mainly depends on ratio r_a/r_{cc} . At moderate rf voltage level (1 kV $\leq U_{rf} < U_{cc}$) additional factor arises. If the density of the cloud is comparable with the Brillouin density $n_b = \frac{m\epsilon_0\omega^2}{e^2}$ (it is needed for $\Delta\epsilon/\epsilon_{min} \approx 30\%$ or more), own electric field of the cloud E_o is comparable with E_{cc} and E_{rf} . The displacement of electrons under rf field action is not small and together with high density leads to significant redistribution of electrons in the cloud. This effect grows fast with the increasing of the cloud density ($\sim n^2$) and very fast with r_a/r_{cc} increasing. To keep nonlinearity in reasonable limits at moderate rf voltage level we need in restriction $r_a/r_{cc} < 1.5$.

It is known, that all controllable reactive devices are nonlinear. The smallest value of nonlinearity was observed for perpen-

dicular biased ferrite-tuned cavities [5]. But in these cavities rf magnetic field is two order less than external control one. For the varactor we are interesting in $U_{rf} \sim U_{cc}$ and a nonlinearity don't looks as the especial problem of this device.

For high rf voltage level $U_{rf} \geq U_{cc}$ direct numerical simulation of electron motion in the interaction space shows interesting but very complicated picture, especially for high density of the cloud. The dependence of the E_o on radius differs from E_{cc} and E_{rf} dependencies - E_o grows in absolute value with a radius increasing. The total electric field inside the cloud changes with time during rf period $E_t = E_{cc} + E_{rf} \sin(\omega t) + E_o$. The cloud becomes subdivided with cylindrical surface $r = const$ in two parts, differing in a direction of the azimuthal rotation. As it is known well, such configuration is unstable. But a boundary between parts moves enough fast in radius due to $E_{rf} \sin(\omega t)$ changing. It provides a very complicated mixture in motion of electron. As it also known well, such effects are very efficient in instabilities damping. The ability of stable operation for varactor at high rf voltage level $U_{rf} \geq U_{cc}$ have to be proved in experiments.

An application of the varactor looks more comfortable at low frequencies. The scaling relationship for the varactor regimes ($U_{rf} \sim U_{cc} \sim B^2 \sim \omega_h^2$) is valid. To meet requirement $\omega_h^2 \gg \omega^2$, with increasing of operating frequency one have to increase magnetic field and control voltage (but will have increase in rf voltage). Another problem is the forming of control pulse at the control grid at high frequency.

III. POSSIBLE APPLICATIONS OF THE VARACTOR FOR FAST CONTROL

Experimentally it was shown that the varactor may be used as a controllable reactive device with an rf voltage amplitude at least close to the control voltage value U_{cc} . Taking into account all improvements proposed, we consider now the tuning range $\Delta C/C_{min} \approx 30\%$ with high Q factor as a reasonable limit at moderate rf voltage level.

With partial connection (through a small dividing capacitor), one may use the varactor for higher values of rf voltage, but with respective reduction in the tuning range.

One can consider the varactor as a part of transmission line with controllable wave-resistance or as a capacitor with controllable capacitance. A lot of applications in rf systems are possible, for example phase regulator and so on. Let consider possible applications for fast control of the frequency, and the phase of the accelerating voltage in the the rf cavities.

1. Suppose the varactor is included into a transmission line between an rf amplifier and a cavity. If one will change the capacitance of the varactor as $C = C_0 + C_1 \sin(\omega_1 t)$, it will results in amplitude modulation with frequency ω_1 for transmission coefficient of the line. A rf spectrum for a signal after the varactor will contain frequency components $\omega - \omega_1$, ω and $\omega + \omega_1$. It will be the spectrum of amplitude modulated signal. The cavity will accept this signal if a bandwidth $2\omega_1$ is less than a width of a resonant curve of the cavity $\Delta\omega = \omega/Q_l$ and rf voltage in the cavity will be modulated in amplitude. Continuing this proposal, one can change the capacitance in more complicated law $C = C_0 + C_1 \sin(\omega_1 t) + \dots + C_m \sin(\omega_m t)$. Combin-

ing $C_1 \dots C_m$ in a relation defined one can provide for the cavity rf spectrum for modulation in frequency (but with a reduction in band, because for modulation in frequency $\omega/Q_l \geq 2m\omega_1$). So, using the varactor inserted into transmission line, one can get in the cavity signal with modulation in amplitude or in frequency, or more complicated signal. The bandwidth of the modulation will be defined by passband of the cavity. The depth of the modulation depends on the range of capacitance change and can not exceed it. This case seems not a difficult problem. The length of the interaction space of the varactor is related with a wavelength at an operating frequency (it is nonefficient take length $\geq \lambda/4$). Specific time for the cloud is also related with operating frequency. For the cavity with reasonable high Q_l factor frequency of the modulation is low enough. There will be no difficulties in forming of a pulse on control grid of the varactor.

2. Suppose the varactor is coupled to the cavity by a loop or a probe. One can use the varactor as a delicate fast additional instrument in frequency control system. It may be interesting for accelerating systems with heavy heat loading, for example, linear accelerators in cw mode of operation. A traditional frequency control by cooling liquid may be enough inertial. If a traditional system will eliminate slow main part of the detuning, the varactor can eliminate a small residual detuning in Q_l rf periods. Our calculations, using the coupled circuit method, shows the varactor be able to detune in narrow band tuning range $\Delta\omega/\omega \approx 5 \cdot 10^{-5}$ enough big cavities, like RFQ or short IH and DTL tanks.

In both cases considered above typical frequency of the modulation is determined by cavity Q_l factor. It is more or less evident result, because cavity is mostly inertial chain in the circuit. To provide more fast modulation, one need actively modify parameters of the cavity.

3. Much more interesting results may be obtained when the varactor is directly included in the cavity. Suppose the cavity is good described with lumped parameters, an equivalent capacitance is concentrated near accelerating gap, the varactor is connected in parallel to accelerating gap. If one will change the capacitance of the varactor as $C = C_0 + C_1 \sin(\omega_1 t)$, it will results in changing of total capacitance of the cavity. Using analogy with LRC-circuits, we have LRC chain with floating parameters. Theoretical analysis of such circuit is very complicated and may be done using methods of a theory of nonlinear oscillations. Numerical simulations shows additional peaks at the resonant curve of such system. The position of peaks at a frequency scale depends on the modulation depth of total capacitance, ratio ω_1/ω and may be far from the main resonant peak. It means, that the cavity can accept broadband signal and modulation will be faster (really in order of several tens of the working rf period for high Q_l cavity). But we consider this conclusion as preliminary. Very careful analysis have to be continued, because such systems (as it is known from theory of oscillations) may exhibit undesirable effects (instability, parasitic oscillations, jumps in phase and amplitude...).

IV. CONCLUSION

The magnetron-type varactor now is not the device with specified parameters. It looks now more like principle of operation for new type of controllable reactive RF devices. Our experiments

have shown proof of this principle. It is impossible in one paper describe all possible versions and applications. Different particular requirements will lead to different realizations, will need in detailed development and experimental verification. Varactor will not replace ferrite-based devices for broad-band applications, but as the instrument for the fast control it has promising perspectives.

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