RF Tests of the Magnetron-Type Varactors

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Abstract

During the development of rf systems for kaon factories a magnetron type varactor was proposed [1] as a fast tuner for accelerating cavities in synchrotron rings. A test and development program was carried out as a collaboration between TRIUMF and INR. Two modifications of the varactor with a specially designed test cavity attached to the power amplifier part of the TRIUMF KAON Booster prototype test facility were tested. At low rf voltage amplitude ($U_{rf} \leq 1$ kV), a 19% relative frequency tuning range ($\Delta f/f_{max}$) (corresponding to 63% relative varactor capacity changing range $\Delta C/\Delta C_{min}$) was obtained with a Q-factor from 700 to 250 (for a $\Delta f/f_{max}$ from 0% to 19%). At moderate rf voltage levels (1 kV $\leq U_{rf} \leq 25$ kV) a nonlinearity was observed, causing a reduction of the tuning range. An approximate capacitive range of 5% was obtained with a quality factor Q not less than 500. The results of the experiments have provided the proof-of-principle of the device's operation. The possibilities of using the varactor as a tuner, of implementing improvements to decrease its nonlinearity, of increasing the Q-factor and of increasing the tuning range, are discussed.

1 INTRODUCTION

The first stage of the experiments with a varactor attached to a cavity performed at TRIUMF in 1992, showed up to a 3.5% tuning range at low rf power level. After analyzing the obtained results a specially designed test cavity and two modifications of the varactor, differing in the dimensions of the electrodes and in some particular aspects of the performance and of the operation, were manufactured. The main purposes of the experiments, carried out in 1993, were to show proof-of-principle of the device working at high voltage levels and to clarify the real possibilities and the limitations of the varactor as a fast powerful reactive rf device. This paper describes the main results of the experiments. More details may be found in [2].

2 VARACTOR DESIGN

Let us consider a motion of an electron beam inside a coaxial system, consisting of an internal conductor with a radius r_i and an external one with a radius r_e. The magnetic field B is directed along the z axis, the dc control voltage U_{cc} and the rf voltage U_{rf} are applied to the conductors, providing electric fields E_c and E_{rf} in a radial direction. One can show that the radial displacement r_{rf} of the beam as a whole, under the rf field action, is:

$$r_{rf} = \frac{eE_{rf}}{m(\omega_h^2 - \omega^2)} \approx \frac{eE_{rf}}{m\omega_h^2}, \qquad (1)$$

where $\omega_h = \left| \frac{eB}{m} \right|$ is the Larmor frequency, $\omega = 2\pi f$, f is the self rf frequency of the system, m is the mass of the electron and $\omega_h \gg \omega$. Consider the interaction of the electron beam, having a density ρ, with the electromagnetic field. After the transformation of Maxwell equations, one finds:

$$\Delta E_{rf} + \omega^2 E_{rf}\mu_0(\epsilon_0 + \frac{e\rho}{m(\omega_h^2 - \omega^2)}) = 0. \qquad (2)$$

The presence of the electron cloud in the interaction space results in an increase of the effective permittivity, leading to a capacitance growth. This effect depends on both the charge density and the position of the cloud. The influence of the charge density is stronger.

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), hot cathode (3) and reflector (4). The ceramic insulator (5) mechanically supports the construction and provides a dc isolation. The hot cathode is in the form of a cylindrical stem with a hemispherical thickening and is also isolated from the outer conductor by an insulator (6). The emitting part of the cathode is made from LnB_6 as a thickening in the form of a circular ring with a radius r_{hc}.

The outer conductor with radius r_a is fixed at ground potential. The mode of operation will be designated direct if the inner conductor with radius r_{cc} has a negative control potential ($U_{cc} < 0$) with respect to the outer conductor and a reverse, if the potential $U_{cc} > 0$. The potential of the hot cathode to the ground and the emission current will be designated as U_{hc} and I_{hc} respectively.

The first of both varactors was designed mainly for the direct mode of operation; the second was optimized for the reverse mode of operation.

A feature common for both varactors is the possibility of using secondary emission (SE) from the electrodes as an additional source of electrons to the cloud.
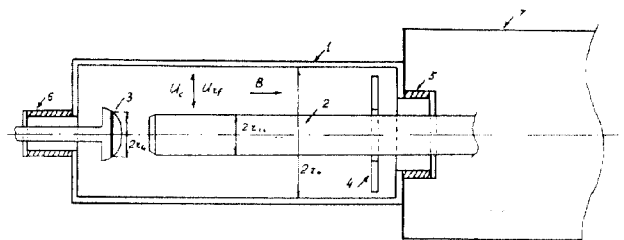

Fig. 1. Schematic sketch of the varactor: outer conductor (1), inner conductor(2), cathode (3), reflector (4), ceramic insulators (5,6), rf cavity (7).

3 EXPERIMENTAL SETUP AND PROCEDURE

The rf test cavity, together with the varactor, represents a coaxial $\lambda/4$ rf system. The central conductor of the test cavity, directly connected to the inner conductor of the varactor, forms the central conductor of the system. Because a high dc voltage U_{cc} must be applied to it, the central conductor of the cavity was dc isolated from the walls by using a set of 250 pF capacitors, limiting U_{cc} to 25 kV dc.

The measured Q-factor of the rf system was 1200 for the rf assembly with the first varactor and 1000 with the second one. To measure the varactors' rf voltage, rf loops calibrated according to the method described in [3], have been used.

The relation between the relative frequency shift of the system and the relative capacitance change of the varactor was $\Delta C/C_{min} = -3.45\Delta f/f_{max}$ for the rf assembly with the first varactor and $\Delta C/C_{min} = -2.75\Delta f/f_{max}$ for the second one.

The experiments [2] include a procedure for dc conditioning of varactors, rf conditioning while pumping the assembled resonator and dc tuning. The criteria for the dc tuning was to have an operating regime of the varactor, which allows maximum possible rf tuning range by changing U_{cc} from 0 to 20 kV with a reasonably small drop in the Q factor and with a nonlinearity as small as possible.

The dc tuning is step by step optimization of the magnetic field distribution and the injection voltage U_{hc}.

4 RESULTS OF THE EXPERIMENTS

The scaling relationship for the varactor regimes ($U_{rf} \sim U_{cc} \sim B^2$) allows all the obtained results to be divided in three groups, according to the rf voltage level.

At low rf voltage levels $U_{rf} \approx 500$ V $\ll U_{cc}$ a large variety of regimes with different characteristics were found. In the experiments with the first varactor ($r_a/r_{cc} = 3.38, r_{hc} = r_{cc}$) a relative capacitance change range $\Delta C/C_{min} = 65\%$ has been achieved (in reverse mode) for $U_{cc} = 0 \div 14.5$ kV with Q-factor reducing from $Q \approx 850$ at $\Delta C/C_{min} \leq 8\%$ to $Q \approx 200$ at $\Delta C/C_{min} = 65\%$. The main reason for the Q factor reduction is the increased rf losses due to the increased number of electrons reaching the central conductor. The current I_{cc} always increased with increase $\Delta C/C_{min}$ and all regimes with high Q-factors were regimes with low $I_{cc} \ll I_{hc}$. By providing a good magnetic trap with mirrors at the ends of the interaction space one can get narrow band tuning in direct or reverse mode practically without any drop in Q. For example, $\Delta C/C_{min} = 0 \div 5\%$ for $U_{cc} = 0 \div -20$ kV, ($U_{hc} = -20$ kV, $I_{hc} = 18$ mA, $U_{rf} \approx 1$ kV) (Fig. 2). Experiments with this varactor have shown either a large tuning range with a reduction in the Q factor, or a high Q factor with a narrow tuning range.

The experiments with the second varactor ($r_a/r_{cc} = 2.5$, only in reverse mode) have shown a moderate tuning range $\Delta C/C_{min} = 0 \div 22\%$ for $U_{cc} = 0 \div 16$ kV. The Q-factor of the system drops to 500 when the hot cathode is switched on and slightly reduces to 400 with the increase of the capacity tuning range $\Delta C/C_{min}$.

At moderate rf voltage levels (1 kV $\leq U_{rf} < U_{cc}$) the resonance curve of the system becomes nonsymmetrical, leading to a reduction of the effective tuning. The main reason for this phenomena is the nonuniformity of the rf field (the r^{-1} dependence). For the first varactor the nonlinearity was strong, the relative frequency tuning range was only 1.5% for $U_{rf} \approx 12$ kV, $U_{cc} = 20$ kV The direct mode has shown a smaller degree of nonlinearity, than the reverse one.

In the second varactor, due to a decreased value of r_a/r_{cc}, the nonlinearity was smaller. The relative decrease of $\Delta C/C_{min}$ was $\approx 15\%$ for $U_{rf} = 0.5U_{cc}$ and 35% for $U_{rf} = U_{cc}$ compared to the case of low rf voltage levels; the Q-factor was practically the same.

At high rf voltage levels $U_{rf} \geq U_{cc}$ an amplitude modulation occurs in the rf voltage pulse envelope (Fig. 3). The frequency of this modulation was ≈ 220 kHz for the first varactor and ≈ 360 kHz for the second one. The amplitude of the modulation may be as high as $0.5U_{rf}$ if $U_{rf} \geq U_{cc}$. The modulation takes place due to an oscillation process arising in the rf system. The reasons for this modulation are now under study with numerical simulations.
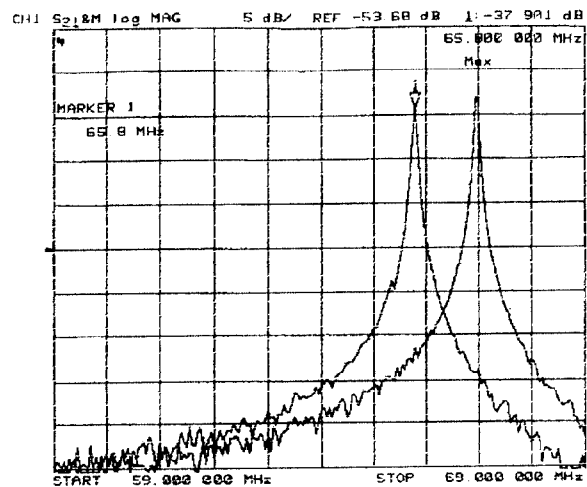
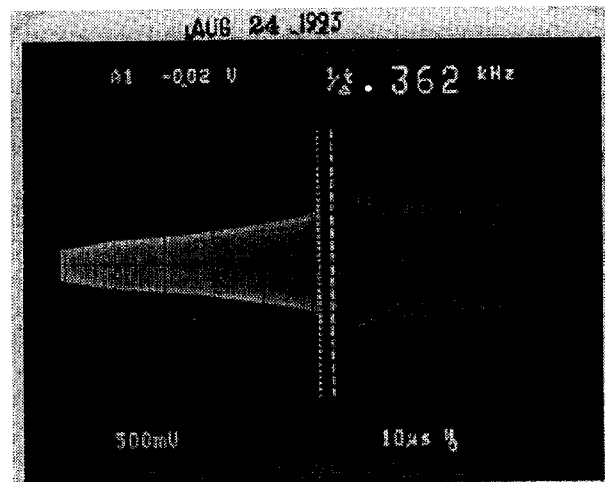Fig. 2. Resonance frequency shift caused by the varactor.

Fig. 3. Amplitude modulation by increasing the rf voltage.

At $U_{cc} = 20$ kV the rf voltage amplitude achieved without modulation was $U_{rf} \approx 18$ kV. The maximum achieved amplitude with a modulation at the crest of the envelope was $U_{rf} \approx 25$ kV.

5 DISCUSSION AND CONCLUSION

The experiments have confirmed the basic theory of this device and proof of principle of its operation. Experimentally it was shown that the varactor may be used as a controllable reactive device with an rf voltage amplitude at least approaching the control voltage value U_{cc}.

The comparison of the results obtained by testing both varactor types allows improvements in the design to be proposed.

The injection system has to be redesigned to exclude the transverse interaction of the electrons with the rf field during the injection. The magnetic trap has to be strong enough to prevent large losses of electrons, but soft enough to pass the electrons with an enhanced energy.

At low rf voltage levels the SE from the electrodes (except from the cold cathode) may be used as an additional source of electrons to the cloud.

The maximal stable stored cloud density is given by Brillouin, $\rho_b = \frac{m \epsilon_0 \omega_A^2}{e}$. Supposing the electron cloud occupies the whole space of interaction and has a Brillouin density, the estimations show that the maximum relative change in the capacitance of the interaction space may be ≈ 2. To reduce the rf losses the cloud must be kept at some distance from the electrodes. Moreover, the real cloud cannot have sharp boundaries and with a Gaussian type distribution only a part of the interaction space may be filled by a cloud with a high density. The requirements of a high electron density to increase the tuning range and a high-Q factor to lower the electron losses at the electrodes are contradictory. The reverse mode is preferred because it provides higher density in the cloud, but to realize an increase in the tuning range, a bigger r_a/r_{hc} ratio is needed, which leads to an increase of the nonlinearity. The nonlinearity depends on the relation between the electrode dimensions and the operational mode of the varactor. It may be decreased by decreasing the ratio r_a/r_{cc}.

The simplest way to decrease the nonlinearity and to shift the modulation threshold to higher voltage is to increase the control voltage with a corresponding increase of the magnetic field. Other solutions are now under consideration with numerical simulations. The parameters of the varactor have to be chosen as a compromise between the contradictory requirements.

At low rf power levels the nonlinearity is not a problem. Preliminary estimations show that a tuning range $\Delta C/C_{min} \approx 80\%$ with a varactor quality factor $Q \geq 1000$ is achievable.

At moderate rf power levels, when $U_{rf} \sim U_{cc}$, a compromise to reduce the nonlinearity leads to a reduction in the tuning range and we now consider $\Delta C/C_{min} \approx 30\%$ with high Q factor as a reasonable limit.

To achieve high rf voltage levels, $U_{rf} \geq U_{cc}$, one needs to avoid the amplitude modulation. Possible changes in the varactor design are now under consideration. We have

observed the amplitude modulation as a parasitic effect, but it allows us to estimate experimentally the speed of the varactor's reaction, because the period of this process is at least twice as long as the recombination time of the electron cloud. For the varactors under test this time is of the order of 10^{-6}sec.

For concrete applications of the varactor as a reactive device in a rf system, this system has to be optimized taking into account the particular aspects of the varactor. Because the varactor is a capacitative tuner, the accelerating cavity has to have its own capacitance as low as possible. If the accelerating cavity voltage U_{acc} is approximately equal to the varactor voltage U_{rf}, from the above mentioned relation $U_{cc} \approx U_{rf}$ a capacitive range $\Delta C/C_{min} \approx 30\%$ with a frequency range $\Delta f/f_{max} \approx 10\%$ are determined. It means, that for a moderate control voltage $U_{cc} \approx 30$ kV the perpendicularly biased ferrite tuned cavity [4] will be superior to the varactor tuned cavity. By connecting the varactor to the cavity partially (through a small dividing capacitor), one may provide the needed relation U_{acc}/U_{rf}, reducing the frequency tuning range by U_{acc}^2/U_{rf}^2. For much higher accelerating voltages ($U_{acc} \approx 150$ kV) a narrow band varactor providing $\Delta f/f_{max} \approx 0.5\%$ may be used as a tuner with a moderate control voltage.

The main advantage of the magnetron type varactor in comparison with the ferrite modulated tuners is its short time of reaction and the absence of induced eddy currents. Now under consideration are possible applications of the varactor for fast cavity detuning to dump the microwave instability and for narrow band tuning range $\delta f/f \approx 10^{-4}$ in frequency control systems for accelerators.

7 REFERENCES

[1] V.A. Konovalov, M.I. Kuznetsov, B.P. Murin, V.V. Paramonov, Yu.V. Senichev. The Perspectives of Application of the Fast-Acting Varactor with Low Losses in High-Current Cyclic and Linear Accelerators. Proc. of the 1992 EPAC Conference, Berlin, v.2, p. 1242, 1990

[2] I.B. Enchevich et al., TRIUMF Design Note TRI-DN-94-16 (internal note), 1994.

[3] M. Cole et al., High Field Conditioning of Cryogenic RF Cavities. Proc. of the 1993 IEEE Particle Accelerator Conference, v.2, p.821-823, 1994

[4] R.L. Poirier, Perpendicular Biased Ferrite-Tuned Cavities, Proc. of the 1993 IEEE Particle Accelerator Conference, v.2, p.753-757, 1994