RF CONTROL OF SUPERCONDUCTING HELICALLY LOADED CAVITIES

by

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I. INTRODUCTION

In addition to the well-known problems of amplitude and phase control of rf cavities, with superconducting helically loaded cavities[1] three problems become of primary importance. All of them are closely connected to the low mechanical rigidity of the structure:

1) The eigenfrequency excursion caused by external noise sources is much larger than the bandwidth.
2) Radiation pressure induced strain results in eigenfrequency shifts up to 1% at the required field levels.
3) At large field levels transfer of electrical into mechanical energy[2] becomes significant, leading to self-excitation (ponderomotive instability).

All of the three effects are interdependent. Thus, any attempt to control one of them influences the other two. We have therefore developed a series of test experiments in order to study each effect and the related counter measures as clearly as possible.

The main part of our effort is dedicated to the solution of the rf problems. Success in mechanical isolation of the helix against acoustical noise sources or in increasing the mechanical rigidity would be very helpful, but would not change our concept to attack the control problems rigorously. The concept of test experiments is composed of four consistent steps:

1) Investigation of a single $\lambda/2$ helix at maximum field level. In order to bypass the problem of large eigenfrequency excursion, the generator frequency was matched to the momentary eigenfrequency by means of a frequency control loop (see left-hand side of Fig. 1). Detailed study of the ponderomotive effects as a function of the parameters of the helix as well as of the control loop.
2) Investigation of a helix section containing five $\lambda/2$ strongly electrically coupled helices. Determination of the frequency excursion under normal conditions in the accelerator building. Test of the effect of an additional frequency amplitude coupling (F/A coupling) predicted by theoretical considerations.[3]
3) First attempt to operate two sections together. In order to save time the first section is operated as in step 2. The second section is loaded by electrical overcoupling to the extent that the frequency modulation is smaller than the bandwidth. Investigation of the turn-on behavior of two sections. Test of an amplitude control loop, which is of fundamental importance in this context.
4) Implementation of a fast eigenfrequency control system replacing the load operation of the second section. Comparison of performance, cost, and reliability for both operation modes and final decision which to select.

All following steps for completion of the rf part of the accelerator are routine work, if step 4 has been successfully concluded. Steps 1 and 2 are completed; the latest results will be reported. Steps 3 and 4 are in preparation; fundamental considerations as well as progress in the study of single components will be given.

II. NEW MEASUREMENTS ON THE SINGLE HELIX

The influence of a frequency control loop to ponderomotive instability has been reported elsewhere.[4] In the quoted paper the excitation and damping of mechanical modes have been studied through measurement of the rise and decade time. Recently, complementary measurements of the loop response to a sinusoidal input have been performed.[5] For this purpose a sinus of variable frequency is added to the VCO input of the generator (see Fig. 1) and the ratio of the signal amplitude before and after the summing point is determined. Of course, measurements can only be made on the stable part of the resonance curve, i.e., for our parameters on the lower flank.

A typical curve for a superconducting test helix is shown in Fig. 2. The bandwidth was 10 Hz, the nominal phase shift, $+20^{\circ}$, and the field level corresponds to a static frequency shift of 60 kHz. The two peaks at 45 Hz and 85 Hz are due to mechanical modes that couple to the ponderomotive forces. The solid curve was computed on the basis of the theory worked out in Ref. 3.

All parameters necessary for the computation can be determined by measurement, except the individual contributions of the mechanical modes to the integral static frequency shift. A fit of the theoretical curve to the measured points allows determination of these contributions. In our case the 45 Hz mode contributes 20 kHz and the 85 Hz mode, 40 kHz to the integral shift of 60 kHz. This method can be regarded as a step forward in the analysis of the ponderomotive effect.

The broken line in Fig. 2 is due to the gain without ponderomotive coupling. Above 500 Hz there is no significant difference between the gain curve with and without ponderomotive coupling. In this region the gain slopes down with 40 dB/decade, because of a dynamical correction in the feedback loop. Near unity gain frequency, here 20 kHz, the slope turns back to 20 dB/decade in order to get the loop stable. The correction has been introduced in order to increase the static stability margin. In our example we have a margin of 40 dB. Zero dB corresponds to the static stability threshold.

III. RESULTS FROM THE OPERATION OF THE FIRST HELIX SECTION

The resonator tank consisting of five coupled $\lambda/2$ helices[6] has been operated with the same frequency control loop as the single helix earlier (see Fig. 1). The static frequency shift was of the order expected from measurements and calculation[3] on the single helix, namely, 690 kHz at a reactive power of 10^8 VA corresponding to a stored energy of 0.18 J. The eigenfrequency modulation of the tank was 3 kHz under most favorable conditions, whereas peak values up to 100 kHz could also be observed.

No definite indication of the existence of collective ponderomotive effects could be found. This result is not very surprising considering the strong electrical and weak mechanical coupling between the $\lambda/2$ helices.

The ponderomotive stability performance in particular came up to what was known from the single helix so that all hitherto known and employed stabilizing methods could be applied directly. Among these methods the previously mentioned F/A coupling (see Fig. 1 dotted line) was studied in greater detail. This coupling corresponds exactly to the frequency feedback operation on the slope of the resonance curve, which is useful in the damping[4] of mechanical vibrations.

The advantages of the F/A coupling are evident. In the first place stable operation of the resonator in resonance or even on the upper flank now becomes possible. Secondly, the coupling constant κ (= amplitude modulation index/phase modulation in radian) can easily be increased without losing rf power by mismatching. Enlarging the F/A coupling has practically the same effect as enlarging the ponderomotive coupling constant, that is, the static frequency shift. Consequently, as can be seen in Fig. 2, the gain of the frequency control loop is decreased. Static stable operation requires a gain greater than unity, thus immediately setting an upper limit for the coupling constant.

The strong decrease of the loop gain can be avoided by making use of AC coupling; however, in this case the limit of stability is reached at the same order of magnitude of κ. The instability now appears in the form of an exponentially increasing oscillation with a frequency about half the bandwidth.

A good way to inspect the stability of the system is to study the Nyquist diagram. For comparison Figs. 3a and 3b show the Nyquist plots for the lower and upper flank operation without F/A coupling at a static frequency shift of 690 kHz. One can clearly see that stability is obtained for the lower flank ($\phi = +45^{o}$) and instability for the upper flank ($\phi = -45^{o}$), because in the latter case the critical point (0 dB, -180^{o}) lies to the right of the frequency locus of the complex open loop gain. The dotted lines refer to the case of missing ponderomotive coupling. Figure 3c shows the Nyquist plot of an ac coupled F/A loop with $\kappa = 100$ and a cutoff frequency $f_{ac} = 10$ Hz. The resonator's bandwidth was also 10 Hz. Here again the critical point lies to the right of the curve indicating instability.

In fact, using this strong F/A coupling we observed experimentally an exponentially increasing oscillation of 4 Hz. This result was also verified through simulation with an analog computer. By means of this F/A coupling the eigenfrequency modulation was damped down to the previously mentioned value of 3 kHz. It also became possible to compensate for a strong ponderomotive coupling through the 20 Hz mode (fundamental mode) which is not well understood at present. The ponderomotive coupling was possibly reinforced by the existence of a strong 20 Hz component in the external noise spectrum. Stable operation was obtained up to reactive powers of 1.5×10^{8} VA corresponding to a frequency shift of 1 MHz.

IV. LOAD OPERATION AND AMPLITUDE CONTROL

As pointed out in step 3, the most simple extension of the accelerator to two sections is the following: Section 1 is operated as before as reference oscillator, whereas section 2 is strongly coupled to the driving powers amplifier.

The loaded bandwidth should be greater than or equal to the maximum frequency excursion. In order to match the power transmitter to the different operating states of the cavity (field on/off, beam on/off), a rather elaborate matching network is needed. It is still under construction.

This operation mode (shortly "load operation") would make no sense for a heavy ion accelerator because of the small beam power consumption. However, for the heavily beam loaded cavities of a proton accelerator the beam power on the order of 1 kW is comparable with the reactive power change of 6 kVA due to the eigenfrequency modulation of 3 kHz.

The corresponding modulation of amplitude and phase of the accelerating voltage of the second section has to be kept constant by appropriate feedback loops (see Fig. 1).

Since there is no frequency control for the second section, ponderomotive stability in the static sense, i.e., elimination of the hysteresis in the resonance curve, can only be achieved through an amplitude control loop of sufficient gain, in our case larger than 60 dB. As can be seen from Fig. 4, the phase resonance curve will then tend to assume the same shape as without ponderomotive coupling. Thus, one more problem can immediately be recognized. Even a very small drift of the reference amplitude A_2 results in a considerably increased need of reactive power of the second section.

An accuracy of 5×10^{-4} is required, if an additional reactive power of maximum 200 VA, the fifth part of the loss power, is tolerated assuming a static frequency shift of 300 kHz. We are still working on a solution to fulfill these stringent requirements on accuracy and loop gain.

V. SLOW TUNING AND TURN-ON OF HELIX SECTIONS

The individual helix sections have different static frequency shifts. If it were possible to tune at room temperature all helix sections so that they would have the same resonance frequency at the designed field strength, a slow frequency tuning system would not be necessary.

In practice, a frequency gap will always remain. Realistically, it will be of the order of 1% or 100 kHz. Assuming a static frequency shift of 300 kHz would lead to a field error of -20% and consequently to a loss in total energy gain. The total energy gain is kept constant only if a part of the section can be operated above the designed field level.

Since there is a tendency to consume any margin, use of a slow tuner is reasonable. A concept for the superconducting helix has been developed at Karlsruhe by C. M. Jones.[7] Use of slow tuner has basically the advantage of keeping the field profile constant. Tuning on the order of 100 kHz causes only field enhancement up to 10%, whereas quality factor and flatness are almost unaffected.[7]

In any case, a final decision whether or not to use slow tuners can only be made after detailed studies.

There are two ways to turn on a chain of helix sections:

1) Fixed master oscillator frequency. All sections have to be matched to the common frequency by slow tuners.

2) Variable master oscillator frequency. The turn-on procedure would be: Starting with a master oscillator frequency at the largest eigenfrequency, slowly sweeping down the oscillator frequency and simultaneously turning on the amplitude A_2 (or A_n) so that each cavity is operated at a certain phase ϕ_2 (or ϕ_n) on the stable flank.

The latter procedure will be studied in our laboratory in the near future. Within the same experiment we will examine whether automation of this process by a ponderomotive tuning loop (indicated by a dotted line in Fig. 1) is feasible.

VI. FAST FREQUENCY TUNING BY PIN DIODES

The fundamental quantity for step 4 is found to be the reactive power modulation of the resonator of 6 kVA as discussed earlier. A series of pretests have shown that, among all known principles of frequency tuning, good results can be expected almost only from PIN diodes.

The losses of the PIN diode, setting a limit to its use in high power operation, are not only proportional to the reactive power, but also to the switching frequency. A typical diode studied in our laboratory exceeded the loss power limit of 20 W at a switching frequency of 20 kHz and a reactive power of 1 kVA.

The tuning concept developed at Cal Tech[8] uses only one diode capable of switching a power of 200 VA with a rate of 100 kHz.

The switching frequency, as will be explained later, cannot be lowered in order to gain reactive power capability. More than one year ago we decided to follow another line, namely, to distribute the whole power among several, say n diodes.[9] Figure 5 shows the block diagram of our fast tuning principle.

The tuner consists of a symmetric arrangement of 12 shorted coaxial lines with a length variable by a PIN diode switch at point C. At point B the susceptances of all lines are summed up. Only those lines shorted by PIN diodes contribute to the total susceptance, because the susceptances of the lines with the full length of $l_{BD} = \lambda/4$ is zero.

The total susceptance at point B is transformed via the coupling line of length l_{AB} to the coupling plane A. Since the eigenfrequency of the helix is a function of this susceptance, the eigenfrequency is variable by switching the PIN diodes in discrete steps.

The basic idea in selecting a symmetric arrangement consists in the fact that the eigenfrequency is determined by the number of switched diodes only, regardless which diode has been switched. The counter makes sure that the diodes are driven in a definite order.

Thus, two advantages are achieved: first, all diodes are equally loaded and second, the switching frequency of the individual diodes is only the n-th part of the clock frequency. Since the loss power P_d of the diode is approximately proportional to the switching frequency, the final reduction is $P_d \propto 1/n^2$ compared to the concept using a single diode.

For the quoted parameters the loss power of each of the 12 diodes is reduced to 5 W. Thus, in addition to a considerable power margin, a high reliability has been gained.

The diodes are switched within $t < 0.5$ µsec between open and shorted state by driver amplifiers, which are triggered by the previously mentioned counter. Together with the analog/digital converter, the overall characteristic of the tuner from analog input to the resulting change of the eigenfrequency has the shape of a staircase function. The remaining part, phase detector and servo amplifier, is similar to that of the VCO control loop.

The coaxial line arrangement has been partially completed, but not yet tested. In order to study the control loop without the complex rf setup the tuner including driver amplifiers has been replaced by a digital/analog converter.

As shown in Fig. 6 the frequency perturbation can be simulated by summing a voltage of a signal source to the output voltage of the digital-analog-converter corresponding to the eigenfrequency of the resonator determined by the tuner. The frequency to phase transfer function of the resonator is given by an RC-circuit.

A resonator bandwidth of 1 kHz corresponding to the beam power consumption of 1 kW has been simulated, the frequency modulation being 3 kHz and the clock frequency 100 kHz.

Due to its stair characteristic the tuner occupies that stage at which the frequency error is minimal. Because of 12 stages the resulting frequency error is found to be $\leq$ 1/12 x 3 kHz leading to a phase error of about 30°. In closed loop operation, however, the tuner does not remain at the stage with minimum frequency error, but it approximates minimum phase error by switching between two stages applying variable duty cycle. Thus, the maximum frequency error is doubled, but the phase error which only is of interest for particle acceleration is considerably reduced because of lag.

The polaroid photographs of Fig. 7 clearly demonstrate this situation. The frequency error signal 7c and 7d (time base extended by a factor of 10) contains two essential fourier components, the fundamental frequency and the clock frequency. Applying the maximum useful loop gain which was limited by noise, the phase error produced by the fundamental frequency was $\Delta\phi_p < 0.3^{\circ}$. The phase ripple due to clock frequency is estimated to be $\Delta\phi_{clock} \simeq 500$ Hz/100 kHz $\hat{=}\ 0.3^{\circ}$. Maximum phase error thus becomes lower than 0.6°.

This success enables us to be optimistic about solving the most striking rf problems by the middle of next year.

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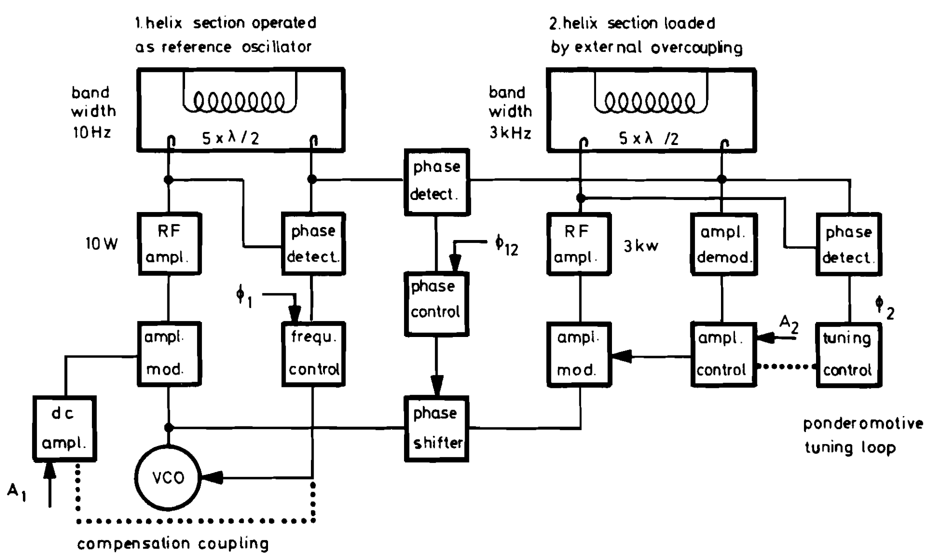

Fig. 1. Schematic diagram of the control system of two helix sections.

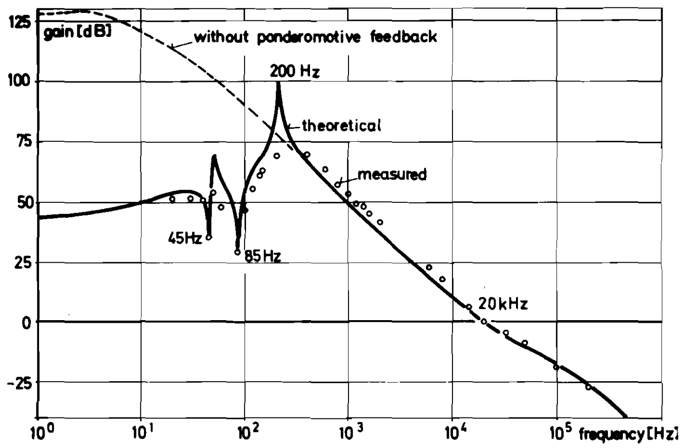

Fig. 2. Bode plot of the gain of a VCO loop with ponderomotive feedback.

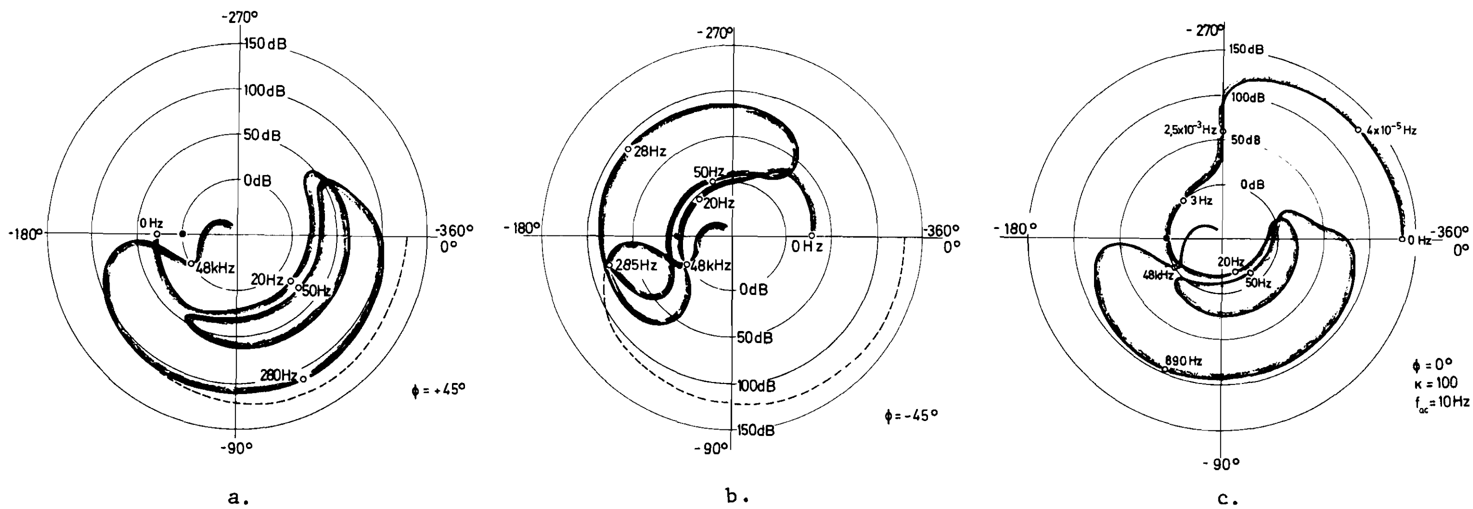

Fig. 3. Nyquist diagram for a VCO loop; a) at $\Phi \doteq +45^{o}$ (lower flank), b) at $\Phi = -45^{o}$ (upper flank), and c) with F/A coupling.

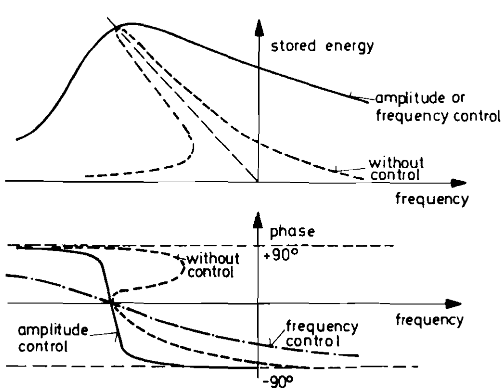

Fig. 4. "Effective" resonance curves for different types of controls.

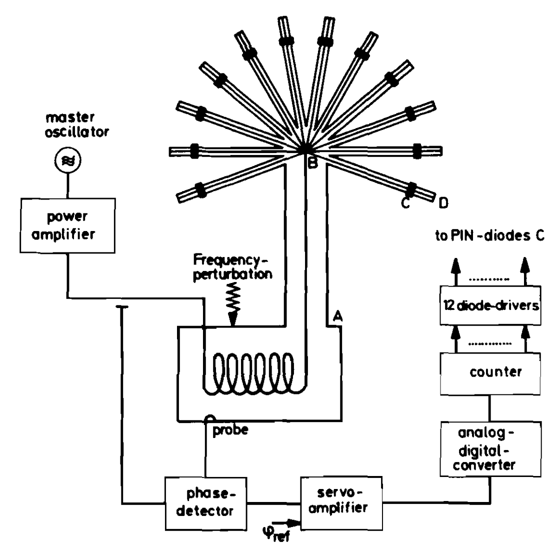

Fig. 5. Block diagram of a fast tuning loop using PIN diodes.

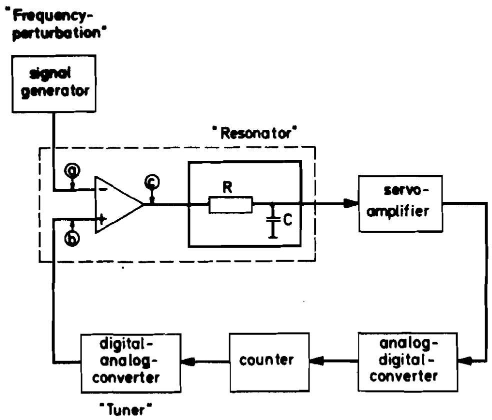

Fig. 6. Equivalent fast tuning loop.

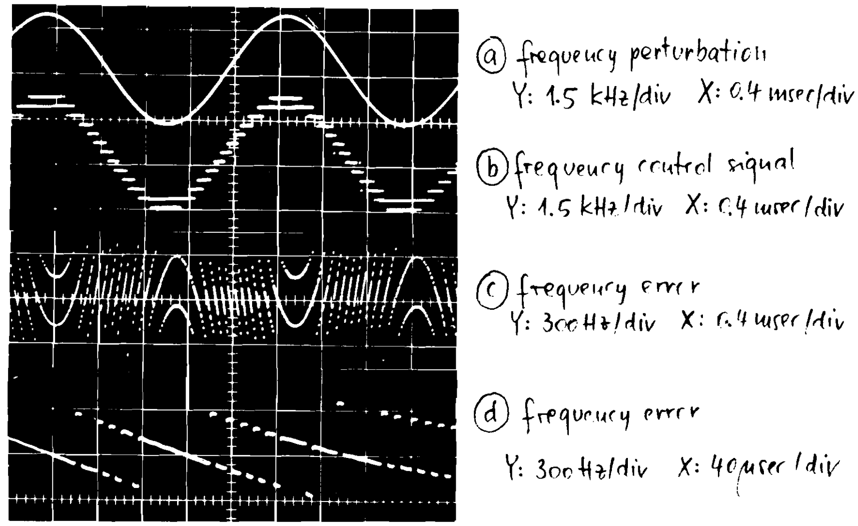

Fig. 7. Photographs of frequency signals according to Fig. 6.

DISCUSSION

T. Khoe, Argonne: What is the mechanical Q of the 5 half-wavelength section at low temperature?

Schulze: In our first measurements of single helices we measured the mechanical Q and observed a decay time of 160 sec. That must correspond to a mechanical Q of the order of 2×10^4.

Khoe: Did the mechanical Q enter into your Nyquist diagram?

Schulze: Yes, it does. In Fig. 3a the circle just below the center of the diagram corresponds to a mechanical mode, and if the mechanical Q is very large then the upper line goes very nearly through the middle of the diagram.

Khoe: A month ago or more we did try the feedback system you describe, and with a mechanical Q of 30,000 we did not have stability.

Schulze: There are several ways to stabilize. One way is to operate on a flank. A second way is to put another coupling into the system. I am sure these methods would give you stability.

Khoe: Yes, these techniques give us stability, but the feedback system you described with a mechanical Q of 30,000 puts the curve to the left of the origin.

Schulze: The effect is due to an ac coupling. It was ac-coupled as an eddy current coupling, and because of it, gives rise with a large coupling strength to another type of instability. What was the frequency you observed?

Khoe: It was 60 Hz and when we coupled it, 120 Hz appeared.