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PROGRESS IN ELECTRONIC FREQUENCY CONTROL OF SUPERCONDUCTING HELIX RESONATORS

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Abstract

This paper describes a series of improvements for the frequency control system of superconducting helix accelerating structures. The improvements are such, that costs and reliability of the control equipment to suppress the mechanically induced eigenfrequency vibration become competitive with those of mechanically more stable structures like the split-ring. In this manner the main limitation of the practical use of the helix are overcome. Consequently, the merits of the helix, i.e. its simple fabrication, can be fully exploited and the helix becomes a serious candidate for heavy ion and proton accelerators.

I. Introduction

The problems concerned with the mechanical weakness of the helix accompany its development since the times it was proposed for superconducting accelerators.[1] The first period (1969-71) was characterized by the analysis of the mechanical vibrations, especially the instability caused by the so-called ponderomotive forces. This instability had been first observed and analyzed with normalconducting structures [2]. After the stability analysis was elaborated for the superconducting case [3,4] and the results entered into the design of amplitude and phase control[5,6] the development of frequency regulation systems based on PIN-diodes was started in 1971 [7,9]. An eigenfrequency regulation system was necessary, because the mechanically induced frequency excursions of the helix exceeded the bandwidth substantially. The operation of the resonator on a common master oscillator to allow phase synchronous particle acceleration was thus impossible. The properties of this so-called VCX (voltage controlled reactance) system were investigated in detail [8-10] and it worked sufficiently well at moderate rf fields. Later on, however, when the system was prepared for design field operation, heavy ponderomotive instability was again encountered [11,12]. Through the use of an elegant electronical countermeasure, namely the feedback of the VCX-signal onto the amplitude modulator, theoretically already investigated [4] in 1971, stability was restored. While in the beginning this measure was merely a means to achieve stability, it became with increasing insight an active method to decrease frequency vibrations by damping [13]. This method of employing the ponderomotive forces to overcome the mechanical weakness of the helix is the first improvement to be presented analytically. The second improvement concerns a substantial reduction of the size of the VCX (tuner).

II. Ponderomotive Damping

Fig. 1 shows a small signal block diagram of the electronic damping feedback in connection with the presently used rf-control device consisting of an amplitude and a phase (or frequency, or VCX) control loop. External forces cause a mechanical displacement of the helix wires and consequently an eigenfrequency deviation $\delta\omega$ due to the work done against the field. By means of the VCX, controlled by the phase difference between helix and master oscillator, this frequency perturbation is eliminated. For sufficiently high loop gain at the mechanical mode frequency Ω, that is $|F_\phi(j\Omega)|>>\Omega$, the VCX induced frequency deviation approaches the mechanically induced frequency perturbation: $\delta\omega_T \simeq \delta\omega$. The VCX-signal $\delta\omega_T$ is fed back via an arbitrary transfer function F(s) to the generator amplitude δa_g. Given a high loop gain the following equation holds for the resonator amplitude $\delta a \simeq \delta a_g/F_a(s)$. δa gives rise to the ponderomotive forces superimposing the external forces and thus closing the

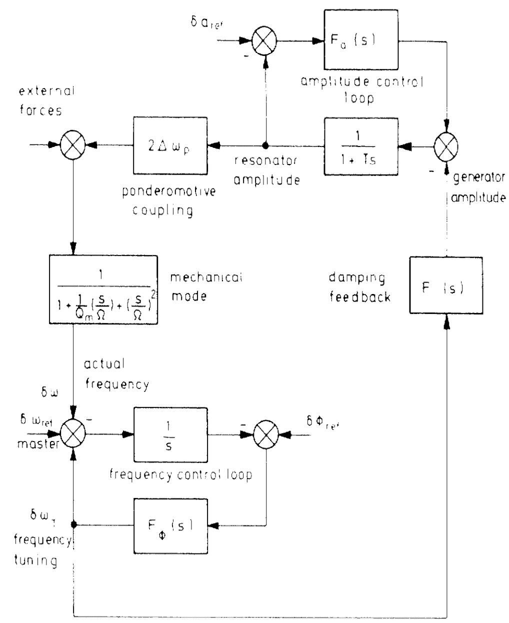

Fig. 1: Block diagram of electronic damping

feedback loop. The coupling factor $\Delta\omega_p$ is identical with the static ponderomotive frequency shift, a chracteristic measurable quantity, which is observed in all helix structures. The factor of 2 arises from the small signal approximation and the fact that field forces and amplitude are quadratically related. Given the assumptions mentioned above, we may rewrite the feedback equation as follows:

$$\delta\omega[(\frac{s}{\Omega})^2 + \frac{1}{Q_m}\frac{s}{\Omega} + 1] = \delta f_{ex} + \delta f_p$$

$$\delta f_p = -2\Delta\omega_p F(s)/F_a(s).$$

When $\delta f_p \propto - s\delta\omega$ is chosen, we can see immediatly, that the feedback force δf_p clearly is a damping force. The effect of the feedback damping can also be interpreted through the reduction of the mechanical Q-value Q_m:

$$\frac{1}{Q_{eff}} = \frac{1}{Q_m} + 2\Delta\omega_p \cdot \mathrm{Im}[F(j\Omega)/F_a(j\Omega)].$$

Evidently, the optimum damping effect at a given feedback gain occurs for a phase shift of 90^o: $\measuredangle[F(j\Omega)/F_a(j\Omega)] = +90^o$. The most simple case, namely proportional feedback F(s) = const., requires then an amplitude feedback $F_a(s)$ = const./s that is integral behaviour within the band of the relevant mechanical eigenfrequencies Ω. This was fulfilled with a PI-controller. The resulting damping effect for a 90 MHz helix unit containing 5 coupled $\lambda/2$ helix resonators is shown in fig. 2. The lower trace demonstrates that all relevant modes are damped by a factor of at least 5. The average frequency jitter $\delta\hat{\Omega}$ was suppressed from 2 kHz to below 400 Hz. Moreover, the helix became so stable, that even heavy knocks on the cryostat shell did not cause frequency excursions above 1.5 kHz, thus staying within the VCX control window (see. fig. 3). Fig. 3 proves that the damping mechanism acts also in a nonresonant manner. Consequently, no special isolation measures for the cryostat are needed at all. The importance of the insensitivity of the resonators to severe disturbances, a fundamental aspect of a practical super-

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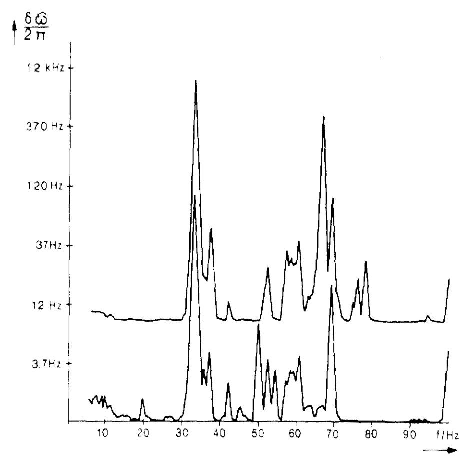

Fig. 2: Frequency deviation spectra of a helix without (upper trace) and with electronic damping (lower trace).

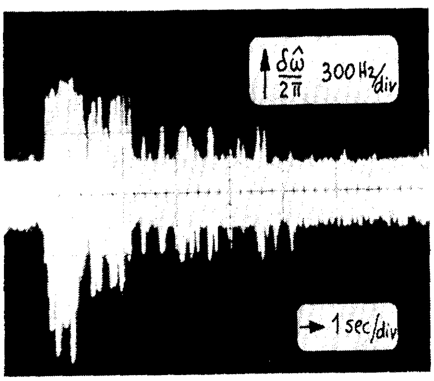

Fig. 3: Polaroid foto of helix frequency excursion after severe shock excitation in the presence of maximum electronic damping.

conducting accelerator, seems not to have been adequatly recognized in the discussion until now. Even mechanically more stable structures may in the presence of severe shock excitation run out of control and become unsynchronized.

III. Improved Frequency Tuning

The PIN-diode tuner developed by G. Hochschild [8] consists of 12 (or 6) parallel branching coaxial transmission lines of length $>\lambda/4$. At the operation frequency of 90 MHz the tuner has therefore the considerable length of nearly 1 m. An obvious solution in attempting to shorten this length was converting the coaxial lines into lumped reactances. Spiral inductances proved to be very useful having the additional advantage that their inductance is continuously variable by a simpel screw as a short circuit between two wires. Thus, the frequency control window can be increased by a factor up to 2. Fig. 4 shows the equivalent circuit of the new tuner. The resonator is coupled via a capacitive pin to a coaxial line of length ℓ_1 to the tuner consisting of n branches of spiral coils each in series with a PIN-diode (drawn n=3). In order to achieve both capacitive and inductive detuning of the resonator (symmetrical rf current) another adjustable spiral coil working as a parallel resonance circuit is provided. Fig. 5 shows a laboratory model of the new tuner operating with 6 PIN-diodes. The obvious advantage of this solution for the VCX is a drastic reduction in size. This is clearly demonstrated in fig. 6.

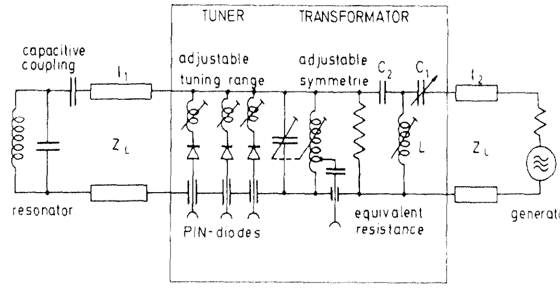

Fig. 4: Equivalent circuit of PIN-diode tuning and power feeding of a helix

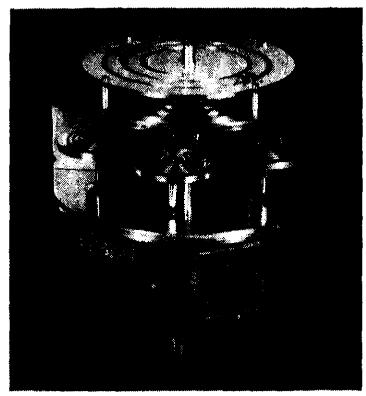

Fig. 5: PIN-diode tuner with spiral coils (outer wall removed)

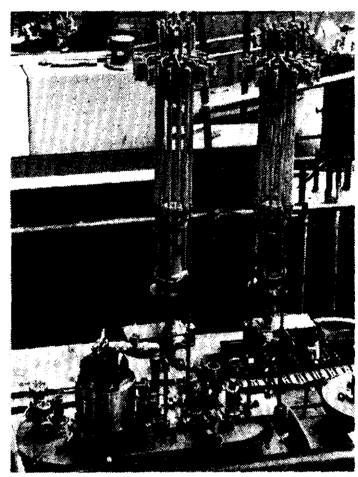

Fig. 6: Top view of the Karlsruhe Proton Linac [14] with two coaxial line tuners and the new tuner (upper left)

The easy tuning capability of the spirals can be used for the compensation of either individual machining tolerances of the spirals or variations of the coupling factor to the resonator.

The lab model was successfully operated at 90% of the design field level with the Karlsruhe linac in Dec. 1978 and reached a reactive power tuning capability of ± 5 kVA maximum. It proved to be easier to assemble than the earlier model, resulting in further cost reduction as well as better maintanance.

Its high inherent flexibility was demonstrated in Febr. 1979, when it was possible to readjust the completed tuner within 2 days from 90 MHz to 108 MHz in order to run it at CEN/Saclay. There the superconducting prototype of a heavy ion post accelerator is operated for demonstration purposes [15]. In Saclay the power comsumption of the two tuner models was compared directly. At a reactive power in the helix of 10^8 VA (corresponding to a voltage gain of 0.3 MV), an external Q of 10^5 and a tuning range of 1.3 kHz both models had the same power dissipation of 65 W (within the range of measuring error). Through further optimization it seems possible to reduce the dissipated power to 30 W.

A further improvement was introduced by directly feeding the generator power into the tuner. This made one of the two power coupling lines used up to now superfluous. Because only half the number of cold windows are now necessary, the cryogenic losses are decreased and the reliability of the accelerator is increased. At the coupling plane of the tuner (see fig. 4) a network, which transforms the equivalent resistance of the tuner into $Z_L = 50\Omega$, must be inserted.

For the transformer a Collins filter has been selected. C_1 and C_2 in fig. 4 can be adjusted so that in first order approximation only L has to be varied. The equivalent resistance was measured to vary from 0.8 kΩ to 1.25 kΩ depending on the number of switched diodes (tuner position). The 3 reactances of the transformer could be adjusted (within a transformation ratio of 1 : 4 to 1 : 5) so that matching at arbitrary tuner position was possible.

Further improvements concern the trombone phase shifter for adjustment of ℓ_1 to $\lambda/4 + m. \lambda/2$ and the digital control circuit. The combined effect of the improvements presented above reduces the additional expense for the VCX. Taking into consideration the amount of control circuitry already needed with mechanically more stable or normal conducting structures, the remaining additional expense is small compared to the overall low level rf control costs.

IV. Conclusion

Looking back 10 years to the beginning of the work on phase control of the helix, we can say that the method chosen to eliminate the mechanical weakness of the helix by electronic means proved to be successful. Good results have also been obtained by introducing mechanically more stable structures.[16-18] However, to remedy the mechanical defect of the helix on a purely electronic basis has not only a charm of its own, but has also been demonstrated to be reliabel and inexpensiv. Moreover, through the aid of the once troublesome ponderomotive forces the formerly sensitive helix becomes markedly resistant to mechanical noise. Therefore, arguments[19,20] which state that phase control of the helix is more difficult than for other structures might be misleading.

Acknowledgements

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