RF FEEDBACK APPLIED TO A MULTICELL SUPERCONDUCTING CAVITY

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Introduction

In the CERN SPS a superconducting (s.c.) cavity (LEP s.c. cavity prototype), has been installed to investigate its behaviour in a real accelerator environment and to obtain some additional voltage for e^+e^- acceleration when the SPS is working as LEP injector [1]. In the SPS supercycle, (14.4 s long) low intensity e^+e^- beams (0.5 mA DC) and high intensity proton beams are accelerated alternately. During the lepton cycles, the s.c. cavity produces the highest possible voltage for e^+e^- acceleration (8.5 MV total for the nominal field of 5 MV/m at 352 MHz [2]). On the other hand, during the high intensity proton cycle the cavity impedance must be reduced drastically to avoid beam instabilities. This can be achieved by active beam compensation where the amplifier driven by a feedback system feeds a current into the cavity which just cancels the current of the beam. In this way the cavity voltage can be made negligibly small even in the presence of the strong proton beam current (0.2A DC).

Principle of operation

In the neighbourhood of its operating frequency, the impedance of an RF cavity can be reduced considerably by RF feedback [3]. The principle is to monitor the RF voltage seen by the beam when passing through the cavity and to reinject this signal back into the RF power amplifier (Fig. 1). The unavoidable delay T of the entire feedback loop limits the maximum gain and, hence the minimum impedance that can be obtained with RF feedback. If we take a reasonable stability margin (± 45° phase at unity gain) one obtains [3]:

$$R_{min} = 4\, f_o\, T\, R/Q \tag{1}$$

where f_o is the resonant frequency of the cavity (modelled as a lossless LC circuit) and R/Q the usual geometric parameter. The bandwidth of the feedback (distance between the two points where the open loop gain is unity) is simply $2\delta f = 1/4T$.

These results are valid for a single, isolated resonance; this is the case of a single cell cavity, for instance. However, for multicell cavities, like the four cell superconducting cavities proposed for LEP, one finds a cluster of resonances in the vicinity of the operating frequency (four resonances for four cells). Although these other resonances may be harmless to the beam, they can nevertheless render the RF feedback completely unstable. At each resonance the open loop gain is quasi infinite; it is therefore necessary to design the feedback loop in such a way as to ensure stability for all modes of the cluster.

One obvious way is to adjust the open loop gain and phase independently for each resonance. This can be done by channelling separately each resonance with a battery of filters (Fig.1). It is better to use filters with zeros to reject the unwanted resonances, at fixed locations, rather than band pass filters which would introduce more delays in the feedback path. Such a technique is used for the modes at 347 and 349 MHz in the s.c. cavity. However, if the distance between two resonances becomes too small, channelling only works in a small frequency band around each resonance (possibly much smaller than $2\delta f$) and R_{min} may not be reached.

For equally spaced resonances, or if only two have to be considered, one can also make use of the overall loop delay T to rotate in the complex plane the resonances of the open loop transfer function, in such a way as to achieve stability. In the LEP s.c. cavity the main RF coupler and the measuring RF probe are located in the two opposite beam tubes, on each side of the cavity. In this way there is no direct coupling between the two ports, and consequently the RF probe accurately measures the RF voltage seen by the beam (even far from resonance). With this arrangement the cavity transfer function changes sign at each resonance.

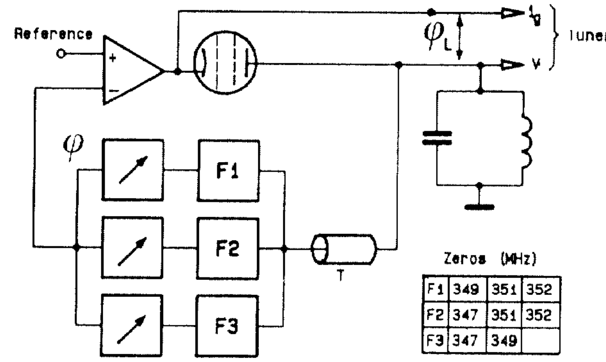

Fig.1 Schematics of cavity with RF feedback

Considering only the last two modes of the LEP s.c. cavity (351 and 352 MHz), the overall transfer function GZ can be synthesized by making the difference (because of this change of sign) of two LC circuits transfer functions:

$$GZ = G\,\frac{R}{Q}\left[\frac{1}{2jx} - \frac{1}{2j(x-x_o)}\right] \tag{2}$$

where x is the relative frequency deviation and $x_o = \delta f/f_o$ the relative distance between the two modes. If the overall delay T of the loop is chosen such as to provide a π phase shift between the two resonances, each of them will occupy the same half complex plane. This is obviously the best condition from the stability point of view. The open loop transfer function now becomes:

$$GZ = G\,\frac{R}{Q}\left[\frac{1}{2jx} - \frac{1}{2j(x-x_o)}\right]\exp\left(-j\pi\,\frac{x}{x_o}\right) \tag{3}$$

It crosses the negative real axis at the point $-2G(R/Q)\,(1/x_o)$, for $x/x_o = 1/2$. To stay reasonably away from the stability limit (-1) we take for instance: $-2G(R/Q)\ (1/x_o) = -1/2$ and obtain the maximum value of G and hence:

$$R_{min} = 4 f_o\,\frac{1}{\delta_f}\,\frac{R}{Q} \tag{4}$$

This is twice the optimum value given by eq.(1), for a single resonance, as here $T = 1/2\delta f$. For the LEP s.c. cavity with δf = 1 MHz, T = 500 ns, f_o = 352 MHz and R/Q = 230 Ω one finds R_{min} = 323 kΩ which is perfectly acceptable for the high intensity proton operation of the SPS.

The higher order modes of the cavity (mostly longitudinal) are damped passively with the standard higher order modes coupler [4]. However a better damping at lower frequencies (~ 600 MHz) where most of the proton beam spectrum lies was obtained by a slight modification of the original design, optimized for e^+e^- beams only.

Design of the low level circuitry

Feedback loop

The overall stability of the feedback loop is obtained using a combination of selective channeling for the two lowest modes (347 and 349 MHz) and by adjusting the overall loop delay T = 500 ns for the other two modes (351 and 352 MHz). All narrow band filtering, phase and amplitude controls take place more conveniently at an intermediate frequency around 50 MHz. This technique also permits an easy tracking of the four zeros of the filters during cooling down and warming up of the cavity, by fine adjustment of the local oscillator frequency.

In each channel, the unwanted frequencies are rejected by two or three notch filters. A zero in the transfer function is obtained by a parallel RLC circuit grounded on one side and in series with the secondary of an RF transformer. This circuit is little sensitive on parasitic elements and shows a frequency response very close to calculations. The variable phase shifters needed to bring each resonance in the left half plane of the transfer function are realized with 90° hybrids loaded with tunable series LC circuits. The overall gain of the electronic chain from the cavity probe to the cathode of the tetrode is larger than 100 dB at optimum. With this extremely high gain, great care must be taken to avoid parasitic couplings in the system. In particular, filtering of the unwanted signals (higher order modes in the cavity, image frequencies) is absolutely necessary; it must however not introduce too much delay in the feedback loop.

For e^+e^- acceleration, the field in the cavity is obtained by injecting a reference RF voltage on the opposite input of the differential loop amplifier (Fig.1). In this way the feedback automatically generates the RF drive to obtain the requested voltage in the cavity. However the reference voltage is never a pure sine wave. Even with the best signal generator, its RF phase noise amplified by the very high electronic gain, may easily saturate the drive amplifier or induce multipactor effects in the vacuum RF window. In this case, a lower gain (-20 dB) is employed, which is perfectly acceptable for the low intensity lepton beams.

<u>Servo tuner</u>

With RF feedback, the role of the cavity servo tuner is only to mimimize the generator current; the amplitude and phase of the field in the cavity are controlled by the feedback irrespective of the tune of the cavity (within limits!). With a s.c. cavity and its extremely high Q (no circulator in our case) the generator current varies by very large amounts; it is almost negligible when the cavity is exactly on tune. If beam loading is considered the drive current can even vanish and change sign. For this situation, a conventional tuner circuitry measuring the phase difference between cavity field and generator current would fail.

The solution was given by Pedersen [5]. Instead of the phase one measures the normalized reactive power $P'/P_0 = Ri_g \sin\varphi_L/V$ (Fig.1) which is a well behaved function, even in the presence of beam loading. The $\sin\varphi_L$ function is provided by an RF mixer and the normalization i_g/V with two coupled AGC amplifiers working at a 10.7 MHz intermediate frequency. A large dynamic range for the normalizer (>50 dB) is very useful for the proper tuner lock in, which has to occur every SPS cycle.

During the proton cycle the current of the magnetostrictive fine tuner [1] is held at its previous value with a sample and hold circuitry.

<u>Coupling the cavity to the amplifier</u> [6]

The amplifier is connected to the cavity input coupler with a piece of transmission line, represented on the equivalent circuit of Fig. 2. Applying the transmission line equation we obtain the forward and reflected powers (P_f, P_r) on the line:

$$P_f\ ,\ P_r = \frac{V^2}{8Z_oK_c^2}\left[(1 \pm Z_oK_c^2\ G)^2 + (Z_oK_c^2\ Y)^2\right] \tag{5}$$

$$P_f\ ,\ P_r = \frac{I^2\ Z_o\ K_c^2}{8}\ \frac{\left(1/(K_c^2\ Z_o) \pm G\right)^2 + Y^2}{G^2 + Y^2} \tag{6}$$

Z_0 being the characteristic impedance of the line, G and Y the real and imaginary parts of the cavity admittance (including beam loading) and K_c the transformation factor between cavity voltage V and input coupler.

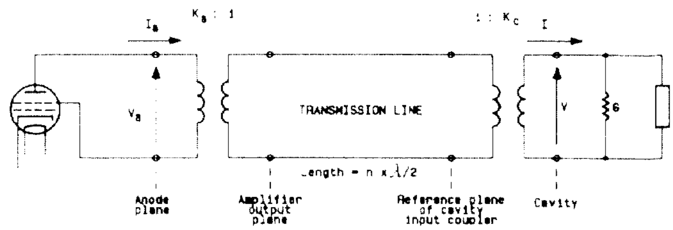

Fig. 2 Simplified equivalent circuit for the amplifier-cavity connection

Let us consider two special cases:

a) <u>High field in the cavity</u>, no beam loading, cavity superconducting and correctly tuned, i.e. G = 0; Y = 0 (open circuit). From eq. (5) we obtain: $P_f = P_r = V^2/(8K_c^2\ Z_o)$.

b) <u>Proton beam compensation</u> ($I = -I_{bp}$), no accelerating voltage (V = 0), i.e. G = ∞ ; Y = ∞ (short circuit). From eq.(6) we obtain: $P_f = P_r = (I_{bp}^2/8).K_c^2\ Z_o$.

In both cases the forward power is fully reflected ($P_f = P_r$). If a circulator were to be used, as is usually the case with a s.c. cavity, the power would be wasted in its dummy load. Much less power is required without a circulator, because only the losses of the forward and reflected waves on the transmission line must be provided. Since a klystron does not permit stable operation at high reflection rates, a gridded tube is better suited for this type of operation.

Optimum use of the transmission line, part of it being the cavity input coupler and its RF window, is achieved if forward powers are equal in both cases, resulting in:

$$K_c\text{opt} = \sqrt{V/(I_{bp}\ Z_o)}\ ;\ P_f = VI_{bp}/8 \tag{7}$$

In eq.(7), I_{bp} represents the RF component of the proton beam current at the cavity frequency, i.e. 352 MHz. This component is rather small, because in the SPS, the accelerating frequency for protons is 200 MHz. Only the non-uniform filling of the buckets gives a non-zero beam spectrum outside the RF harmonics. Over a frequency band much larger than the SPS revolution frequency (43 kHz), the proton beam spectrum looks very much like a white noise (random fluctuations of the bucket to bucket population) [7]. Within the bandwidth of the feedback (1MHz), its r.m.s. value amounts to a few mA for the highest proton beam intensity ($3.5\ 10^{13}$ protons per pulse). A comfortably safe design value of I_{bp} = 10 mA has been chosen, giving $K_c$opt = 4472 and P_f = 12.5 kW for V = 10 MV and Z_o = 50 Ω.

As a matter of fact, it was decided to use a cavity to line coupling stronger than the optimum ($K_c \simeq 0.5K_c$opt), in order to permit passive damping of the cavity in case of amplifier failure [8]. The power on the line increases but is still acceptable by the RF window.

The reference plane of the cavity input coupler is chosen at a place where the high cavity impedance at resonance transforms into a maximum impedance on the line. With this convention the length of the line separating amplifier and cavity is a multiple of the half wavelength (n x λ/2 ≃ 2m) resulting in a 1:1 transformation. In reality a coax-waveguide transition (containing the ceramic input window to separate the cavity vacuum and air), a waveguide section plus elbow and bellows and a waveguide-coax transition are inserted in the 50 Ω coaxial line. The length of the waveguide must be correctly adjusted to realize the 1:1 transformation.

Design of the amplifier

Voltage and current at the line input are transformed within the amplifier (Fig.3), to the anode of the tetrode (transformation factor = K_a):

$$V_a = V\,K_a/K_c \;;\; I_a = I\,K_c/K_a \qquad (8)$$

to values permitting safe and efficient operation. A max RF anode voltage amplitude of 8.5 kV has been chosen for high cavity field operation resulting consequently in a max RF anode current amplitude of 11.8A for proton beam compensation. This seems to be a good compromise for a grounded grid 50kW tetrode operating at 352MHz concerning efficiency, drive power and reliability. Beam loading during e^+e^- acceleration can easily be handled by the amplifier since the beam current is much smaller than for protons.

The amplifier works in class AB, grounded screen grid mode as a compromise between low drive power and high efficiency. The required drive power is about 800W for proton beam compensation and about 50 W for e^+e^- acceleration.

The tetrode assembly is installed close to the cavity in the SPS tunnel, whereas the driver and low level electronics are located in a radiation shielded area some 25 metres away (total round trip delay < 500ns). The RF driver was realized by combining 16 existing 100W transistorized units with Wilkinson couplers, especially designed for that application.

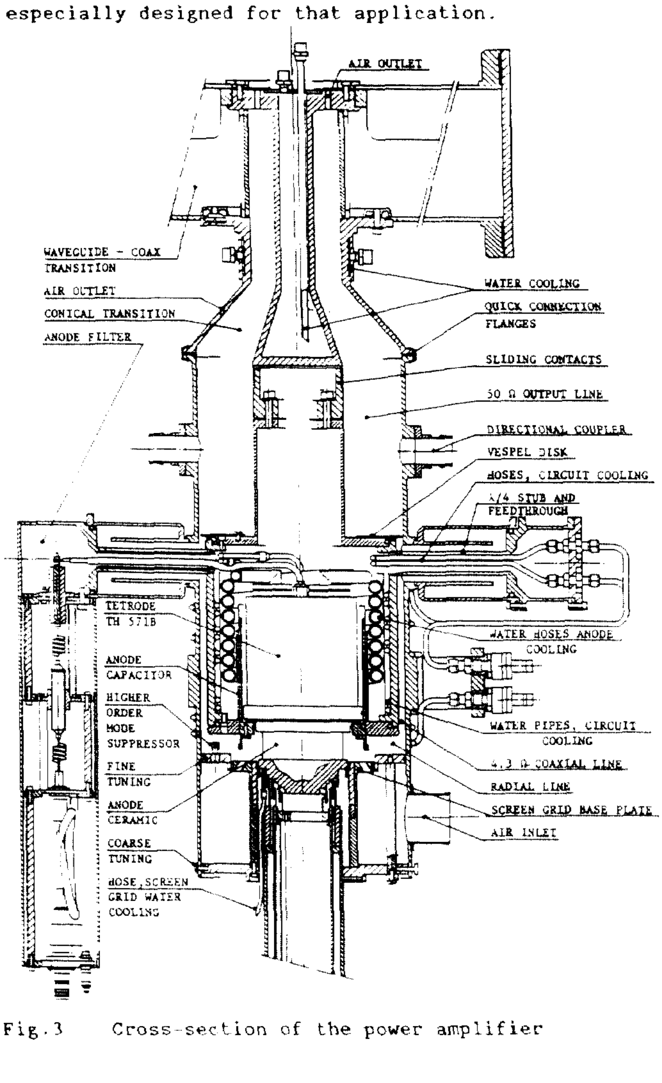

Fig.3 Cross-section of the power amplifier

The amplifier anode circuit was designed with a transformation factor K_a = 3.8 between 50 Ω line and anode corresponding to $K_c = K_c$opt. In principle, an ideal transformation can be realized with two λ/4 transmission lines. The voltage transformation factor is Z_2/Z_1 with Z_2 and Z_1 being the characteristic impedances of the λ/4 lines. In reality the transformation is more complicated,as can be seen in Fig.3. Whereas Z_1 is still a homogeneous coaxial line,Z_2 is a combination of complex transmission line sections outside and inside the tube. These have been approximated by coaxial and radial transmission lines, for analytical calculations. Optimization is possible by varying the diameter of the inner conductor for the λ/4 coaxial line (which mainly determines the transformation ratio) and the height of the radial line (which acts mainly on the tuning). As a result of these calculations a 4.3Ω coaxial line and a 35.4mm high radial line have been chosen.

Four coaxial λ/4 stubs (2 pairs 90° apart) are provided to keep the inner conductor of the 4.3 Ω line in place (Fig.3). The stubs are folded back to save space. Their inner conductor is hollow, which allows auxiliaries to pass through the 4.3 Ω line, well screened from the output power.

A coaxial 2:1 transformer is inserted in the amplifier output in order to achieve the required value of K_a with the K_c value chosen. It is very important to connect the transformer at the right plane, i.e. at the place where a 1:1 transformation of the reference plane of the input coupler appears. A deviation from that plane requires a higher forward power at the amplifier output.

After proper filtering of its long DC feeder lines, the amplifier was perfectly stable in operation when driving the very high s.c. cavity impedance ($Q_{ext} = 2 \cdot 10^7$).

Conclusion

It has been demonstrated that operation of a s.c. cavity without circulator is possible with a tetrode power amplifier and that RF feedback can reduce the impedance of a s.c. cavity by many orders of magnitude. RF feedback provides in addition an extremely precise control of the RF field in the cavity (~ 10^{-4} in our initial measurements).

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