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SC-CAVITY OPERATION VIA WG-TRANSFORMER

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Abstract

Varying beam currents in storage rings like PETRA and HERA strongly change the match condition of the generator-cavity system. To maintain optimum energy transfer variable input coupling is needed. A variable waveguide transformer was developed which covers transformation ratios of 0.2 to 5. Additionally this device allows to change the cavity phase independently. The parameters of a system consisting of generator, transformer and superconducting cavity under operation in a storage ring will be discussed.

Influence on Cavity Impedance

Superconducting cavities have very low losses. Use of these cavities for beam acceleration in storage rings causes beam losses which normally are much higher than the wall losses. So superconducting acceleration structures which are normally driven in CW operation offer the possibility to transfer nearly all of the transmitter power to the particle beam. But condition for this is: The cavity input impedance must match the transmission line impedance.

How constant is the cavity input impedance?

Low wall losses and high power transfer to the particle beam are features of highly beam loaded cavities. Consequently the loaded Q-values depend on beam intensity and acceleration gradient. The acceleration gradient itself changes with generator power and with the synchronous rf phase to which the particle bunches are shifted by beam dynamical mechanisms of the accelerator or storage ring.

Acceleration gradient, beam intensity and generator power can vary very much. Due to rf phase the gradient may change within a factor of 2 or 3 at same peak field in the cavity. Beam intensity can change by nearly a factor of infinity. Cavity power transfer to the beam - the transmitted part of generator power - is about the product of gradient and beam intensity. But the ratio of both is determining loaded Q-value, impedance and hence power reflection of the cavity.

So even under normal operation conditions of an accelerator the input impedance of a superconducting structure will change very much.

This is much different from the operation of normal conducting acceleration cavities, where the wall losses are dominating and even limiting the

achievable gradients. Here only at very high beam loads the operation situation is getting to be comparable to the situation described above.
Matching of accelerating cavities needs the external Q-value of the high power coupler to equal the loaded Q of the cavity. This condition equals the requirement of impedance match at a plane between cavity and feeding line. A fixed external Q of the main coupler can provide match only for one operation situation. In all other situations there are more or less high amounts of reflected rf power - up to full reflection - to be expected and it will not be possible to transfer all of the transmitter power to the beam. This results in reduced acceleration gradients and in wasting the non transferable part of generator power to the reflection absorbers.

Match of Variable Impedance

In order to avoid those disadvantages of fixed coupling there is an urgent need for variable coupling of high rf power to acceleration structures with high beam load. There are principally two possibilities to realize variable coupling. It can be done either mechanically by change of the main coupler antenna or loop position in the cavity or by microwave electrical transformations in the rf feed line of the cavity (Fig. 1[1], Fig. 2).

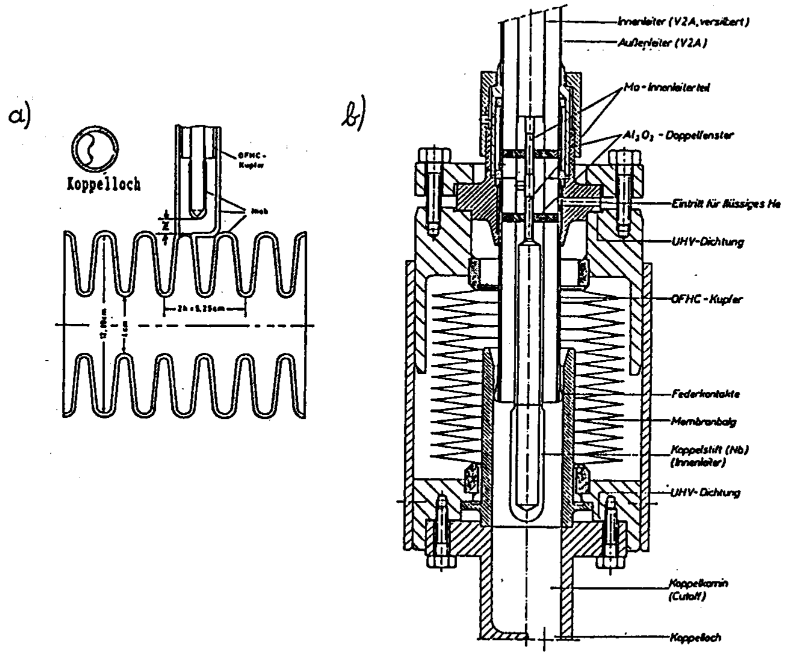

Fig. 1 Example of variable coupler for low power

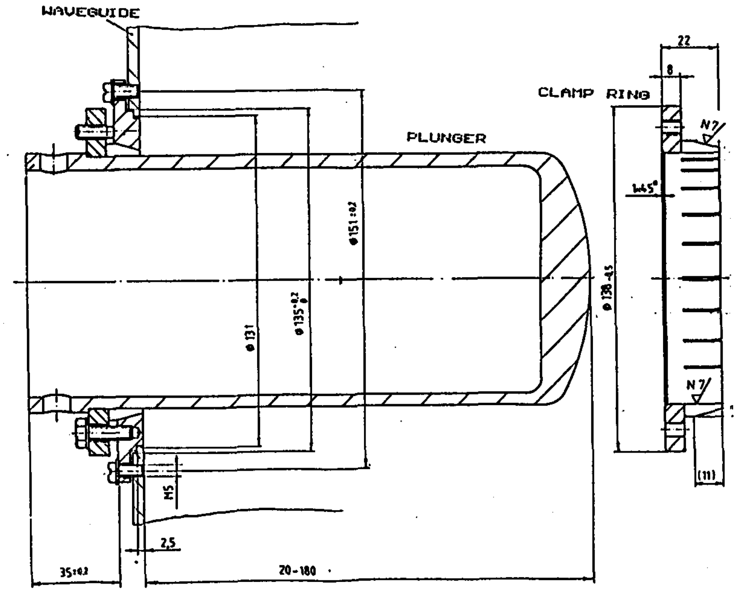

Fig. 2 Tunable plunger for waveguide transformer

Both solutions have advantages and disadvantages. An advantage of mechanical antenna motion is that its range of external Q change can be very high without any standing waves on the feeding line after finding matched position. A big disadvantage is its very critical construction especially in the environment of a superconducting cavity and under the need for very high power transfer. At the other hand transformers in the feeding line between cavity and high power transmitter are much simpler in construction. But rf transformation techniques are based on standing wave handling (Fig. 3).

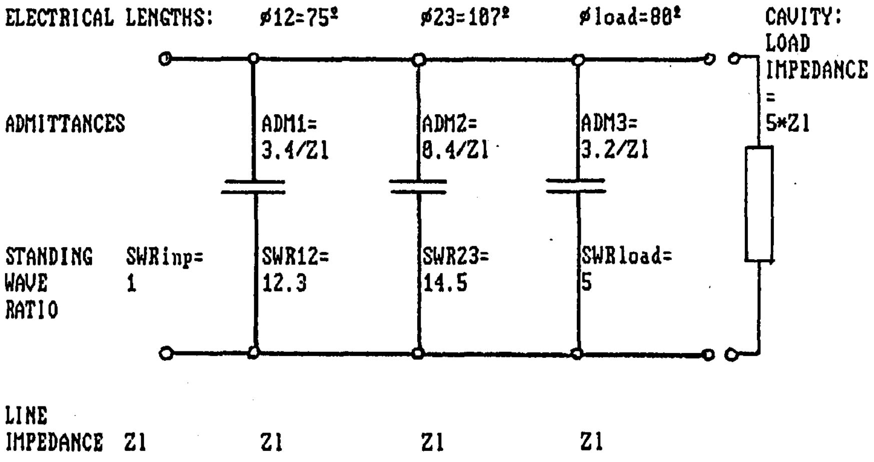

Fig. 3 Example of matching a load of 5 * line impedance by 3 capacitive devices inside a waveguide

There are standing waves inside the transformer and on the section between cavity and transformer in order to realize a match situation towards the transmitter at the input plane of the transformer.

Physically the standing waves are necessary because the input coupler of the cavity will be set to a preselected constant external Q-value. The excitation of standing waves between transformer and input coupler results in an increase of forward power at the coupler and consequently also of input power to the cavity. In the matched case the transformation ratio is chosen just so that the cavity input power equals the generator forward power at the transformer input.

The standing wave ratio gives raise to additional losses in the transformer and on the section between transformer and cavity. These increase with the transformation ratio. It turns out that the maximum transformation ratio is limited by the maximum tolerable losses inside the standing wave area including the high power coupler. Another limitation of high transformation ratios are increasing mechanical precision requirements of the transformer.

For the HERA superconducting cavities the waveguide (WG) transformer is chosen to solve the problem of variable coupling. The transformers consist mainly of a partition of WR 1800 waveguide cavity feed line with several cylindrical plungers inside[2] (Fig. 4, Fig. 5).

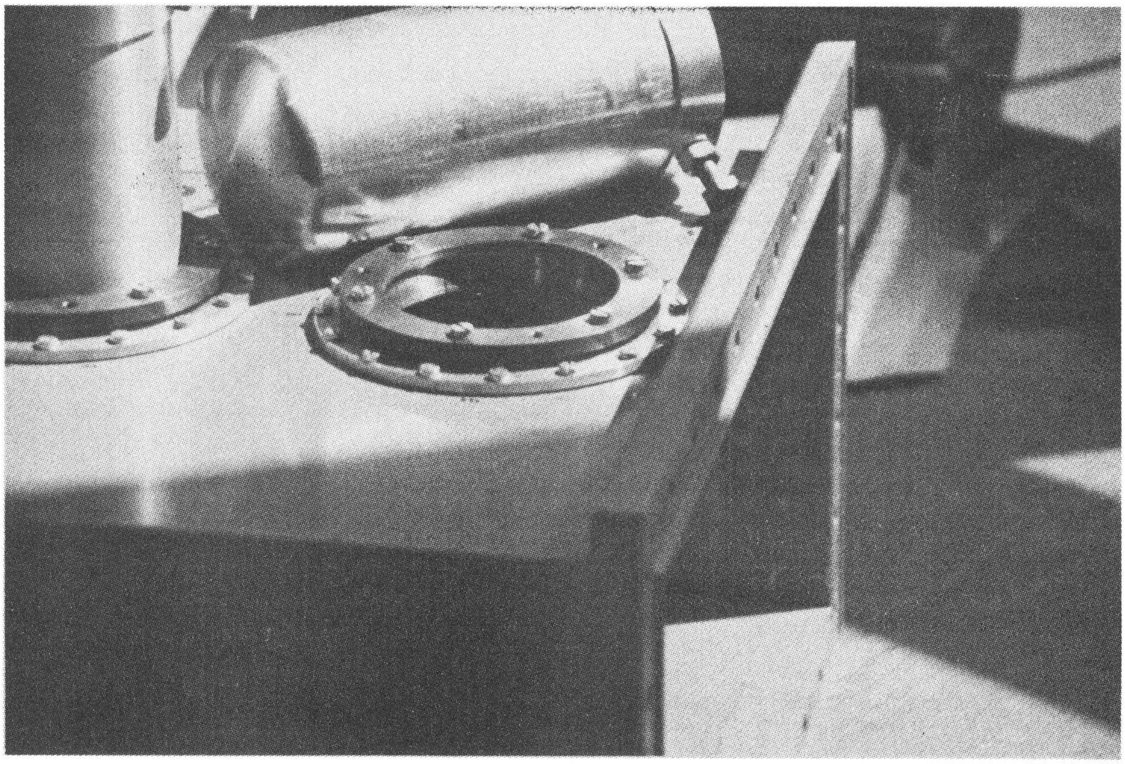

Fig. 4 Variable waveguide transformer, plunger and clamp ring

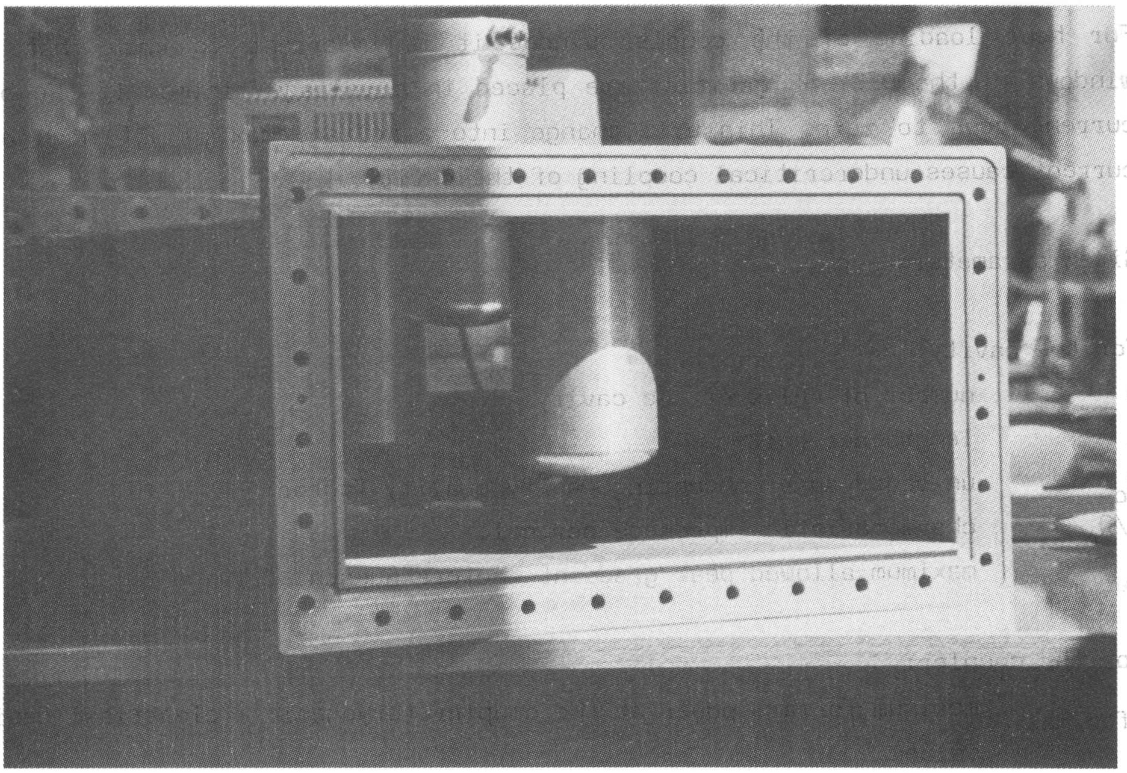

Fig. 5 Variable waveguide transformer

Operating Superconducting Cavities via Waveguide Transformers

After selecting waveguide transformers for matching the variable impedance of the superconducting cavities to the constant impedance of the high rf power feeding line several questions arise. The most important questions are:
What external Q-value has to be selected for the superconducting cavity?
What are the limitations for operation?
Following considerations and computations will answer these questions. Fig. 6 shows the basic circuit diagram of the set up.

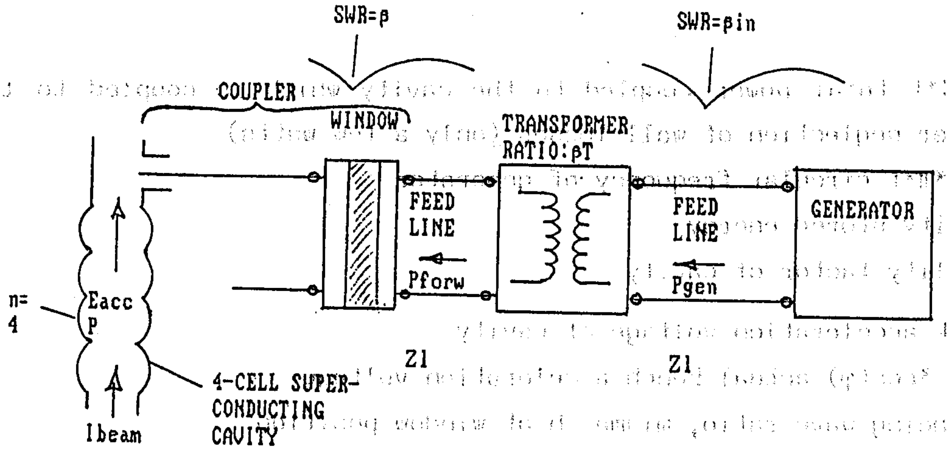

Fig. 6 Basic set-up of cavity driven by transformer

For heat loading of the coupler window it is important to know that the windows of the DESY SC cavities are placed in a voltage minimum if the beam current goes to zero. This will change into a voltage maximum if high beam current causes undercritical coupling of the cavity.

Given parameters are

for the cavity:

n	number of cells of the cavity
L	length per cell
Q_o	unloaded superconducting cavity quality factor
R/Q_o	characteristic impedance per cell
E_{accmax}	maximum allowed peak gradient (before quench)

for the coupler:

$P_{forwmax}$	maximum forward power at the coupler (cryogenic + electrical design value)
P_{norm}	$= U_{norm}{}^2 / Zl$ unreflected maximum forward power at the window as a reference for the maximum voltage U_{norm}

for the transformer:

β_{Tmax}	maximum impedance transformation ratio of the transformer
β_{Tmin}	minimum impedance transformation ratio

for the machine current:

I	average current of the bunches
φ	bunch passage phase after cavity voltage maximum (synchroneous phase angle)

Variables:

P	$= U*I$ total power coupled to the cavity which is coupled to the beam under neglection of wall losses (only a few watts)
ω	$= 2*\pi*f$ circular frequency of generator
W	cavity stored energy
Q_o	Quality factor of cavity
$\hat{U}$	peak acceleration voltage of cavity
U	$= \hat{U} *\cos(\varphi)$ actual bunch acceleration voltage
β	standing wave ratio, mismatch at window position

Z_l line impedance
U_f window voltage
β_{in} transformer input VSWR

In the following procedure an external Q-value of the cavity will be determined by selecting a given beam current I_o and a power transfer P_o to the beam as match condition. Based on this external Q-value it will be tried to find as a function of beam current all important operation parameters like:
Power transfer to cavity, peak acceleration field, normalized window voltage, window VSWR, coupler forward power, transformation ratio, maximum allowed or possible generator power.
At the same time important limitations like quench field of the cavity, maximum window voltage, maximum forward coupler power, maximum and minimum transformation ratio should not be exceeded.
With

$$Q = \frac{\omega \cdot W}{P} = \frac{Q_0 \cdot P_{wall}}{P} = \frac{Q_0}{P} \cdot \frac{(\hat{U}/n)^2}{(R/Q_0) \cdot Q_0} \cdot n$$

$$= \frac{\hat{U}^2}{n \cdot (R/Q_0) \cdot P} = \frac{(P/I \cdot \cos\varphi)^2}{n \cdot (R/Q_0) \cdot P}$$

(1) $$Q = \frac{P}{I^2} \cdot \frac{1}{n \cdot (R/Q_0) \cdot \cos^2\varphi} = \frac{U}{I} \cdot \frac{1}{n \cdot (R/Q_0) \cdot \cos^2\varphi}$$

the external Q of the coupler is

(2) $$Q_{ext} = \frac{P}{I_0^2} \cdot \frac{1}{n \cdot (R/Q_0) \cdot \cos^2\varphi}$$

It can be shown that after selection of Q_{ext} the window voltage is dependent only on the beam current.
From known relations

(3) $$P = P_{forw} \cdot \frac{4\beta}{(1+\beta)^2} \quad ; \quad U_F = \sqrt{P_{forw} \cdot Z_L} \cdot \frac{2\beta}{1+\beta}$$

we get

(3a) $$U_F = \sqrt{Z_L \cdot \beta \cdot P} \quad ; \quad \frac{U_F}{U_{norm}} = \frac{\sqrt{Z_L \cdot \beta \cdot P}}{\sqrt{Z_L \cdot U_{norm}^2 / Z_L}} = \sqrt{\frac{\beta \cdot P}{P_0}} \Big/ \sqrt{\frac{P_{norm}}{P_0}}$$

With (8) the result at beam current I_1 is

(4) $$\frac{U_F}{U_{norm}} = \frac{I_1}{I_0} \Big/ \sqrt{\frac{P_{norm}}{P_0}}$$

The window voltage U_f is independant of cavity/beam power P_1 and cannot be reduced by reduction of generator power.

The maximum cavity power is

(5) $$P_1 = P_{gen\,max}$$

and the corresponding peak field is

(6) $$E_{acc1} = \frac{P_1}{I_1 \cdot \cos\varphi \cdot n \cdot L}$$

If this field is too high, then

(7) $$P_1 = E_{acc1} \cdot I_1 \cdot \cos\varphi \cdot n \cdot L \quad ; \quad E_{acc1} = E_{acc\,max}$$

From (1) and the minimum voltage position of the window at low currents the window standing wave ratio results to be

(8) $$\beta_1 = \frac{1}{(Q_1/Q_{ext})} = \frac{P_0}{P_1} \cdot \frac{I_1^2}{I_0^2}$$

This equation shows, that match will not change if

(8a) $$P_1 = P_0 \cdot \frac{I_1^2}{I_0^2}$$

Corresponding to (3) this yields the coupler forward power

(9) $$P_{forw} = P_1 \cdot \frac{(1+\beta_1)^2}{4\beta_1}$$

If this power is too high, then P_1 has to be recomputed with the maximum allowed value $P_{forwmax}$. This can be done by (3), replacing P by P_1, β by β_1 and solving for P_1:

(10) $$P_1 = 2 \cdot \frac{I_1}{I_0} \cdot \sqrt{P_{forw\,max} \cdot P_0} - P_0 \cdot \frac{I_1^2}{I_0^2}$$

After this E_{accl} and β_1 corresponding to (6), (8) have to be recomputed. Within the limits of β_{Tmax}, β_{Tmin}

(11) $$\beta_{T1} = \beta_1$$ is valid.

Otherwise β_{T1} is limited to be

(11a) $$\beta_{T1} = \beta_{Tmax} \quad \text{or} \quad \beta_{T1} = \beta_{Tmin}$$

This means that the transformer ratio within given limitations compensates for mismatch β_1. From (3) and Fig. 6 it is clear that

$$P_{gen\,1} = P_1 \cdot \frac{(1+\beta_{in})^2}{4\beta_{in}}$$ is valid.

Now β_{in} has to be determined.
If one takes for example voltage minima u_1 (current i_1) at the input side and u_2 (current i_2) at the cavity side of the transformer, then in the matched case

$$u_2^2 \Big/ \begin{matrix}\text{cavity impedance}\\ \text{at window}\end{matrix} = \frac{u_1^2}{Z_L}$$

The device between positions of u_1, i_1 and u_2, i_2 is a linear 4-pole and it behaves like an ideal transformer of voltage transformation ratio $\sqrt{\beta_{T1}}$. Its current transformation ratio is $1/\sqrt{\beta_{T1}}$. With an impedance β_1 we get (Fig. 6)

$$\frac{u_1}{i_1} / Z_L = \beta_{in} = \frac{u_2/\sqrt{\beta_{T1}}}{i_2 \cdot \sqrt{\beta_{T1}}} / Z_L = \beta_1/\beta_{T1}$$

(Rem.: Application of a wave parameter model computation leads to the same result.)

This yields under the preceding conditions the generator power

$$P_{gen1} = P_1 \cdot \frac{(1+\beta_1/\beta_{T1})^2}{4\beta_1/\beta_{T1}} \tag{12}$$

Operating HERA Superconducting Cavities via Transformers

Equations (1) to (12) allow a description of the system behaviour like shown in Fig. 7 ... 14.

Here the equations are evaluated for the HERA case:

The external Q of the main coupler is chosen to be 2 E5. This decides the ratio of beam transfer power and the corresponding square of beam current (r/Q0=115 Ohms per cell, n=4, synchronous phase angle = 39 degrees). Under specification of a maximum available generator power of 100 kW Fig. 7 and Fig. 13 show that at low currents, up to 30 mA the generator power has to be limited for 2 reasons.

The specified peak acceleration field should not be exceeded (Fig. 8) in order to avoid quenches. In addition the maximum forward power of the coupler should not be higher than 120 kW at high reflections (Fig. 11, 10) because the cryogenic part of the coupler is limited in power dissipation.

The window SWR (Fig. 10) has to be compensated by the transformation ratio of Fig. 12. But the transformation ratio is limited to 0.2 as lowest and 5 as highest value.

Fig. 7 shows the peak gradients which are limited by the available rf power at higher currents. For real acceleration the synchronous phase angle of (here) 39 degrees has to be taken into account.

Fig. 9 shows the normalized window voltage. The square of it is proportional to the heating of the ceramic window by dielectric losses.

It was shown by computation that the input standing wave and the power flow into the cavity are compensating in such a way that the window voltage is only dependent on beam current and external Q-value setting. Hence limitation of heat load of the window is only possible by limiting the beam current.

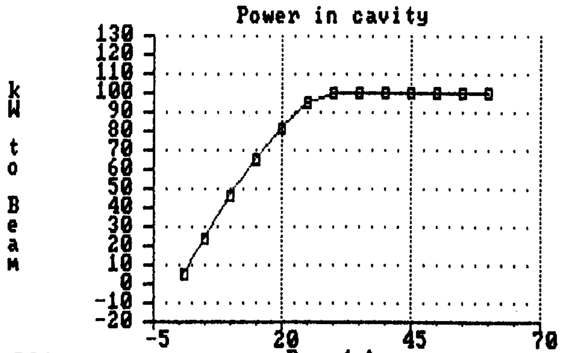

FIG.7

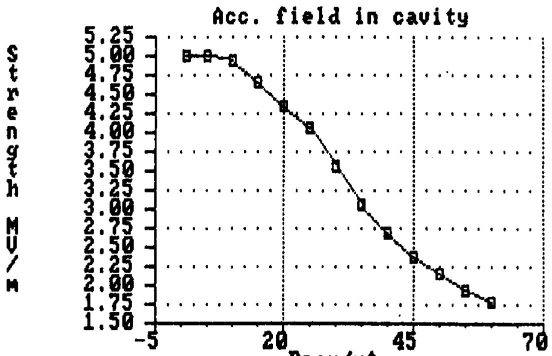

FIG.8

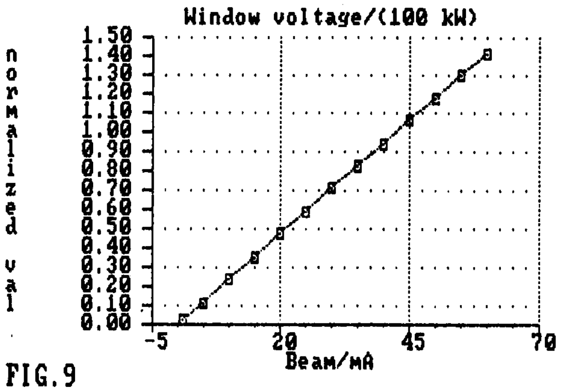

FIG.9

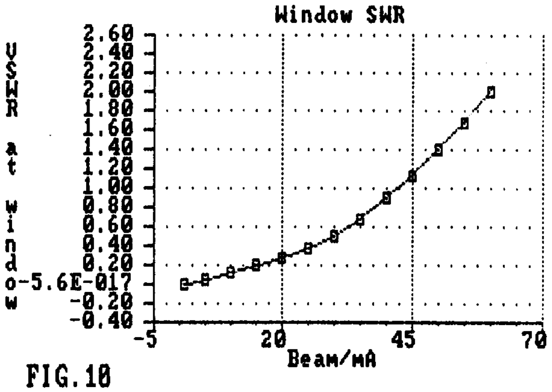

FIG.10

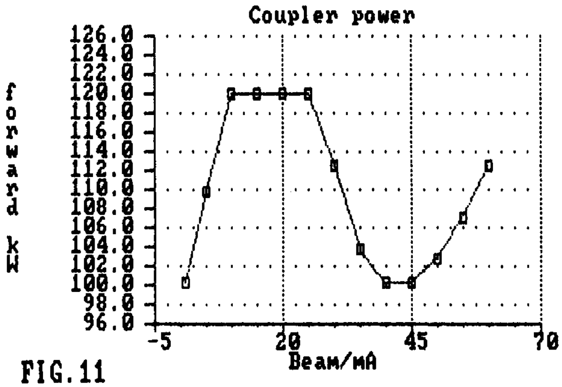

FIG.11

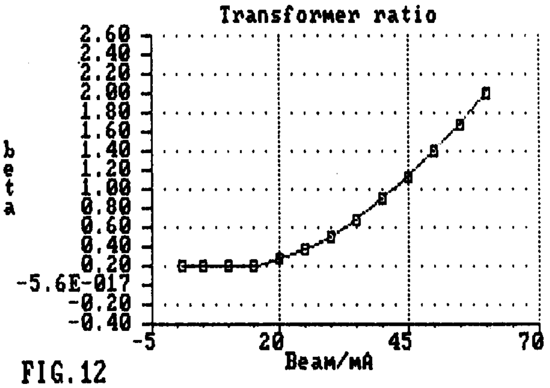

FIG.12

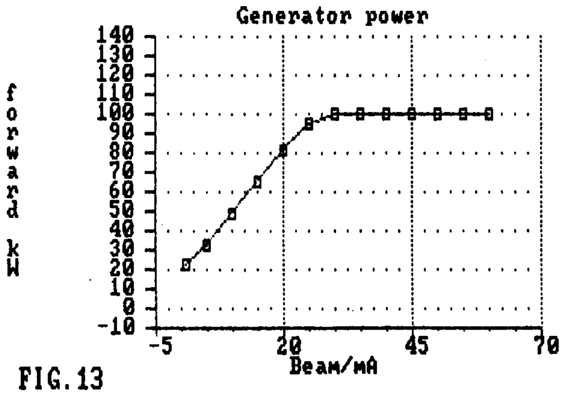

FIG.13

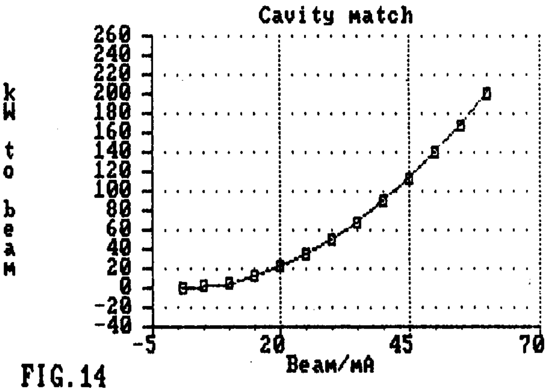

FIG.14

Fig. 14 shows the powers which would be required to match the cavity to the line at given external Q and beam load.

Conclusions

The special match problem of high rf input power for superconducting cavities was described. It can be solved by application of variable WG transformers. The operation parameters of an rf system with use of transformers are computed under neglection of the cavity wall losses and applied to the HERA situation. Comparison of Fig. 7, 14 shows that match can be realized by the transformers over a wide range of beam current. An important precondition is proper choice of external Q.

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