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PRESENT STATUS OF THE TEST RF SYSTEM FOR THE KEK PS BOOSTER

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ABSTRACT

Since 1988 we have been constructing a new accelerating system for the KEK PS Booster. The system cancels the beam loading effect[1]. The system test operation result is reported. Our analysis on the beam loading effect is also described.

MECHANISM OF THE LOADING INSTABILITY OF RF SYSTEM

We have studied the of the beam loading instability mechanism of the rf system by the method described in Ref.2). The block diagram of the rf system, which is used for our analysis[3], is shown in Fig. 1. Where the radial beam feedback loop and the cavity phase lock loop are added to the diagram in Ref. 2).

The instability threshold of a rf system having a low Q cavity is shown in Fig. 2, where the horizontal scale is the transient loading angle ϕ_L, the vertical axis is the relative loading $Y = I_B/I_0$, I_B and I_0 are the beam current and drive rf current respectively. The gains of the feedback loops in the system are written in the diagram. We used the word transient loading angle, because a tuning loop in the rf system keeps the angle around $\phi_L \sim 0$. The threshold of the instability is $Y = 2 \sim 3$.

We calculated the values of the cavity transfer functions under a loaded condition.The variation of the cavity transfer function for phase modulation is shown in Fig.3.The values are evaluated at a low phase modulation frequency. For higher beam loading, the cavity transfer function reduces the value. Above a threshold, the value becomes negative. The beam loading instability mechanism is explained by this effect. That is, the loading effect changes a negative feedback loop in the rf system to a positive feedback.

The instability limit in Fig.2 is calculated by the Routh-Hurwitz criterion. Therefore, one must operate the rf system lower than the predicted value.

On the basis of the knowledge of the loading instability mechanism, we ignored the effect of the cross coupling of the loops[2], and calculated the critical damping limit of the beam phase loop. The characteristic equation of the phase loop is given by

$$(s^2 + s\cdot\Omega_p G_{pp}{}^g + \omega_s{}'^2)u_b = 0, \tag{1}$$

where s is the phase modulation frequency, u_b the beam phase, Ω_p the loop gain of the phase loop, $\omega_s' = \omega_s\sqrt{1 + G_{pp}{}^g C_R R}$ the synchrotron frequency shifted by the radial beam feedback, and $G_{pp}{}^g$ the cavity transfer function of phase modulation. If we neglect higher order terms in s, it is written as

$$G_{pp}{}^g = 1 + Y\cdot\cos^2\phi_z(\sin\phi_B - \cos\phi_B\cdot\tan\phi_z), \tag{2}$$

where ϕ_z is the impedance phase angle of the cavity, and ϕ_B the synchronous phase. They are defined in Ref. 2) and 3).

The damping factor of the system of Eq.(1) has to be greater than $1/\sqrt{2}$ for damping. That is, $(\Omega_p G_{pp}{}^g)/(2\omega_s') > 1/\sqrt{2}$. Therefore, we get

$$x\{ 1 + Y\cdot\cos^2\phi_z\cdot(\sin\phi_B - \cos\phi_B\cdot\tan\phi_z)\} > \sqrt{2}, \tag{3}$$

where x is the relative loop gain of the phase loop defined by

$$x = \frac{\Omega_p}{\omega_s'} \simeq \frac{\Omega_p}{\omega_s\sqrt{1 + C_R R}}. \tag{4}$$

The denominator is the synchrotron frequency shifted by the radial feedback[3]. For a normal rf system, where $\phi_L = 0$, we get for the stability,

$$Y < \frac{1}{\cos\phi_B}\left(\frac{x\tan\phi_B}{2\sqrt{2}} + \frac{x^2\tan^2\phi_B}{8} + \frac{x}{2} - 1 \right). \tag{5}$$

In the case of no acceleration $\phi_B = 0$, we get from Eq.(5),

$$Y < \frac{x}{2} - 1. \tag{6}$$

For a system which employs a feedforward compensation[3,4], where impedance phase angle of the cavity ϕ_z is adjusted to zero. Hence from Eq.(3),

$$Y > \frac{\sqrt{2}/x - 1}{\sin\phi_B} \tag{7}$$

The system is critically damped, if $x > \sqrt{2}$. The feedforward compensation is a powerful method. Note,however,that the anode dissipation of the final tube in the power amplifier increases by several factors.

The critical damping limit of the system given by Eq.(3) and is shown in Fig. 4. The critical damping limit is far less than the threshold given by the Routh-Hurwitz criterion (Fig.2).

THE TEST RF SYSTEM FOR THE KEK PS BOOSTER

Our test rf system picks up the wall current upstream of the accelerating cavity and is fed in to the accelerating cavity via the cathodes of the final vacuum tubes installed near the cavity. The current has the opposite polarity to the loading current, therefore, the loading effect at the cavity is cancelled.

The power dissipation at the anodes of the final tubes is the same value as that of feedforward compensation. The current accelerated by the system is determined by the specification of the the final tubes. In our case the final tubes are two 4CW50,000E(Eimac) connected in parallel. The parallel connection is employed, because of its higher maximum current and transconductance. A circulating beam current of 3A will be accelerated by this system.

TEST OPERATION OF CAVITY AND POWER AMPLIFIER

The test operation of the cavity voltage is limited to 4 kV, because of the discharge at the ferrite support mechanism made of FRP.The rf voltage at the accelerating gap and the phase error of the tuning system are shown in Fig. 5. The setup of the system is shown in Fig.6. The bandwidth of the automatic tuning system is ~ 1kHz.

24 ferrite disks with outer diameter of 620 mm are installed in the accelerating cavity, with a permeability of 250. The estimated shunt impedance of the cavity is 1.5 kΩ at an accelerating voltage of 15 kV.

The measured impedance is only 1.2 kΩ at 4kV. The impedance is calculated from the measured cathode current. The quality factor of the ferrite is far less than the expected value. The equivalent circuit of the cavity is shown in Fig.5. The Q-value of a ferrite changes with magnetic flux density in the ferrite.

$$Q = \frac{Q_0}{1 + \eta \cdot B_{rf}} .$$

For our ferrite $\eta \sim 0.027$ [1/gauss], B_{rf} the average flux density in the ferrite, and $Q_0 \simeq 50$ is the value at $B_{rf} \sim 0$. The shunt impedance of the cavity at 15 kV is estimated to be 520 Ω.

If we remove the 200pF capacitance at the gap, the shunt impedance of the cavity at 15 kV will increase to ~800 Ω, which is nearly one half of what is expected. The peak power in the ferrite amounts to 140kW at 15kV.The average power and the power density in the ferrite are ~ 70 kV and 0.56 W/cm³ respectively. The maximum permissible power density is determined by the tensile strength of the ferrite and its thickness. If we assume that the temperature at the surface of the ferrite is 30°C,the maximum temperature in the ferrite is ~50°C. The maximum tensile stress in the ferrite is ~ 1.7 kg/mm². The maximum tensile strength of the ferrite is ~2kg/mm². Therefore, the accelerating voltage of 15kV is a limit for this cavity.

The leakage inductance of anode windings on the ferrite and the gap capacitance resonated at 10 MHz. To remove this resonance from the accelerating frequency range, two 0.01μF capacitors which connect the anodes of the final tubes and the accelerating gap are installed at the accelerating gap.

BEAM CURRENT PICKUP

The gap which picks up the loading beam current is loaded with amorphous core having a large permeability. Because of the large imaginary part of the permeability, it behaves as a 100 Ω resistor for frequencies above ~ 500 kHz. The input impedance of the cathodes of the final tubes is 10 Ω. Therefore, nearly 90 % of the wall current at the pickup gap flow into the tubes.

The cathode circuit diagram including the beam current pickup is shown in Fig.8.In the diagram the drive rf current source and the wall current are connected in parallel. Our test operation was at 4kV which corresponds to a drive rf current of 3 A . This means that the final tubes will also be drive n by the wall current.

THE OTHER ELECTRONICS

We have designed power supplies for the vacuum tube grids[1]. To reduce the power dissipation at the anode,the power supplies for final tube control grids have to switch their output voltage from -400V to -200V within several 10μsec. They have a response of 50μsec. The other power supplies are working without any trouble.

All-pass networks employed in control grid circuits reduce the drive power.

In order to get the desired frequency response,the careful adjustment of the inductances in the networks was necessary.

CONCLUSION

The improvement of the ferrite stacks will be finished within 1990. In order to increase the shunt impedance, the capacitance at the accelerating gap has to be removed. Further experiments are necessary to increase the accelerating voltage.

ACKNOWLEDGEMENTS

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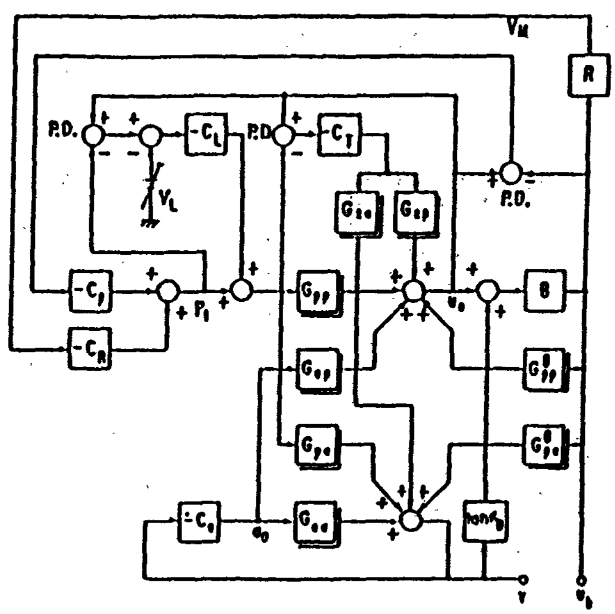


P.D.; Phase Detector

R ; ΔR monitor and circuit. $R = -\frac{N_f X_p s}{\eta \omega_{rf}}$, $V_M = R u_b$

$C_\phi = \Omega_\phi/s$, $C_L = \Omega_L/s$, $C_p = \Omega_p/s$, $C_R = \Omega_R/s$, and $G = \Omega_T/s$

Fig. 1. The Block Diagram of The RF System Used for The Analysis.

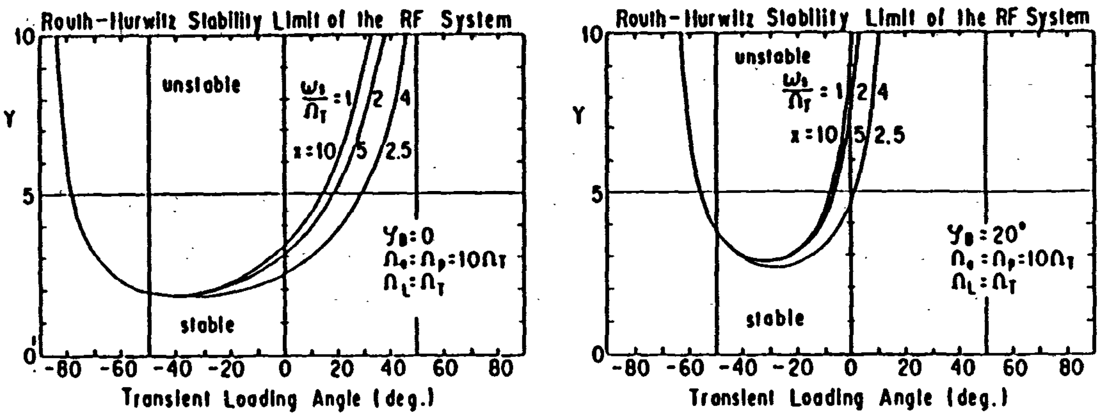


Fig. 2. The Stability Limit of The System Having a Low Q RF Cavity.

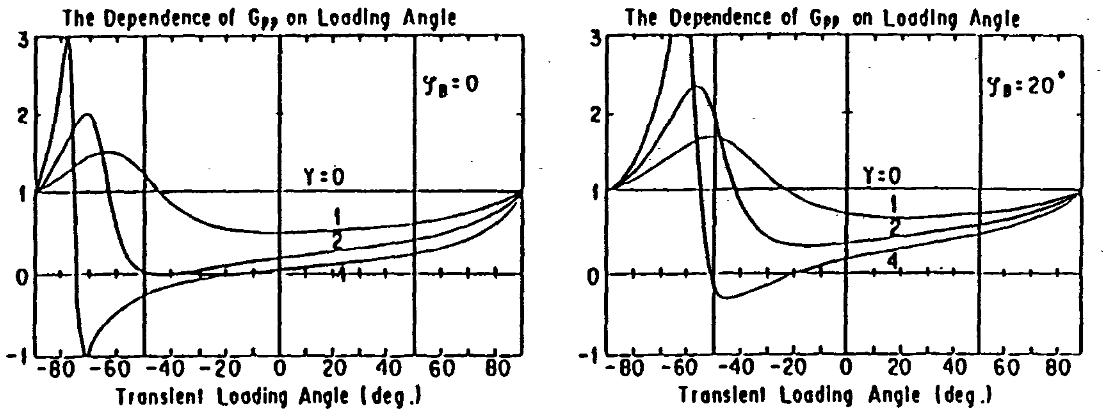


Fig. 3. The Variation of The Cavity Transfer Function for Phase Modulation.

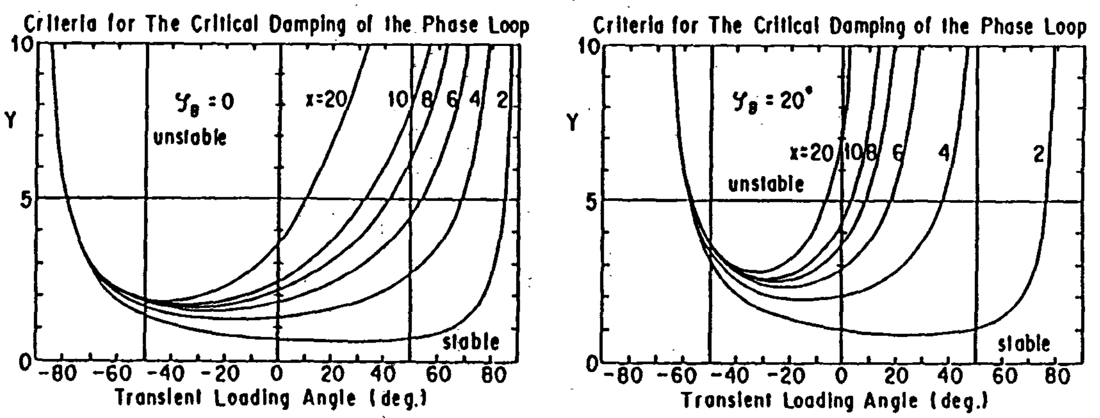
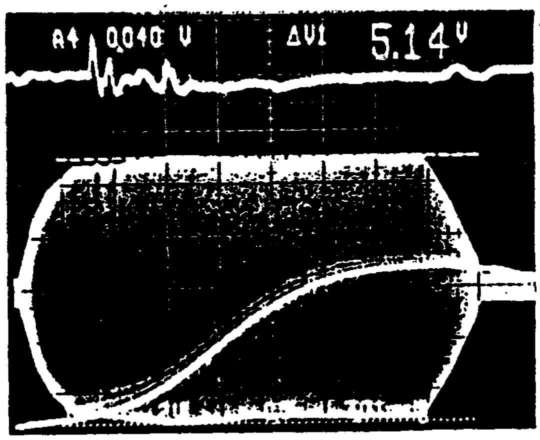


Fig. 4. The Critical Damping Limit of The Phase Loop.

Fig. 5. Upper; Phase Detector Output in Tuning Loop. (20deg/div).
Next; The Gap Voltage (4kV Amplitude).
Lower; The Bias Current. (500A/div).
Horizontal; 3 msec/div.



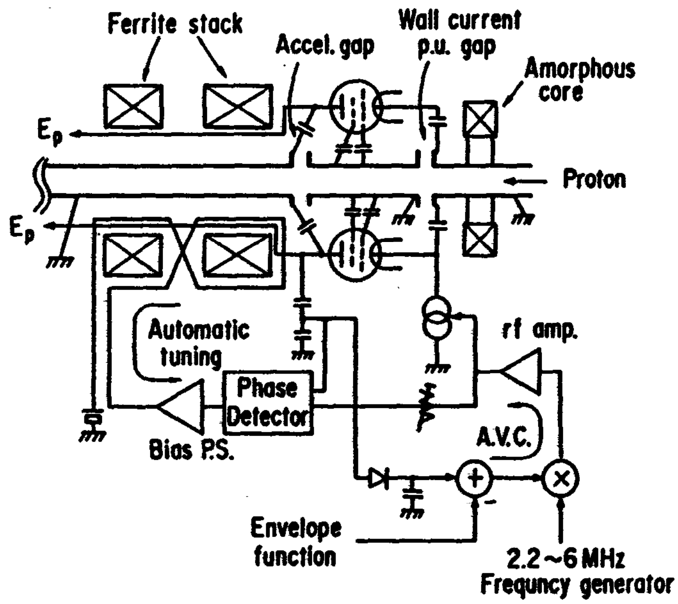


Fig. 6 Block Diagram of The Test System.

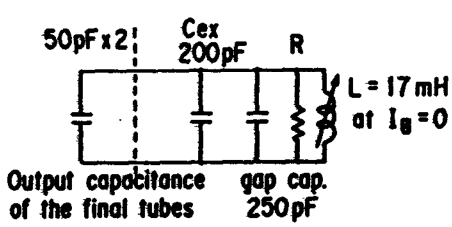


Fig. 7 Equivalent Circuit of Acceleration Gap

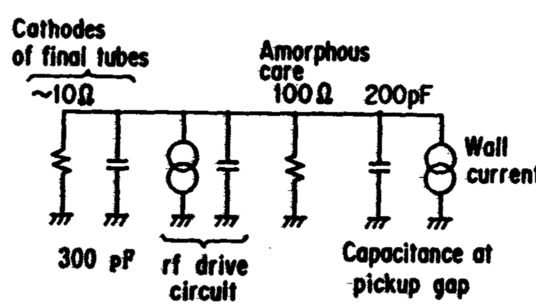


Fig. 8 Equivalent Circuit of Wall Current Pickup.

Q(Y.Mori): What happen in the ferrite situation if you can not assume a homogenity of the ferrite quality?
A(S.Ninomiya): I think that our ferrite is homogeneous.