NON-RESONANT RF ACCELERATING SYSTEM

S. Ninomiya, K. Endo, K. Muto, and M. Toda, KEK, Tsukuba, 305-0801 JAPAN

Abstract

An accelerating cavity loaded with a very large-μ magnetic material (μ_r~10^5) has large real impedance for frequencies above several-100kHz. Non-resonant accelerating system using an amorphous core was designed in 1992 [1]. Based on this idea, the system having an rf voltage of 1kV with frequency range from 1MHz to 10MHz was realized for an accelerator dedicated for cancer therapy [2]. The frequency range of such a system is limited by the capacitance of the accelerating gap. Because of the large output capacitance of vacuum tube, the performance of the high voltage system is restricted.

The principle of the distributed amplifier extends both bandwidth and applied voltage of the non-resonant rf system. The system, which has an accelerating voltage of 20kV with a frequency range from 500kHz to 20MHz, is designed for Table Top Proton Synchrotron (TTPS) [3].[*)]

1 THE ACCELERATING STRUCTURE

If we load a core of a very large-μ material in the rf cavity, the gap impedance is an inductance having a large loss at high frequency. The impedance at the gap is described by a parallel circuit of large inductance (L(ω)), resistance ($R_p(\omega)$) and capacitance (C) at the gap. At the frequency above several 100kHz, the effect of the resistance dominates over that of the inductance. The higher cutoff frequency of the system is determined by the time constant of R_p and C. The capacitance C is designed to be nearly 10pF by keeping a large inner radius of the core (r_i) and a wide accelerating gap width. The resistance $R_p(\omega)$ is given by

$$R_P(\omega) = f\mu_o \frac{\mu_r^2}{\mu''} D \ln\left(\frac{r_o}{r_i}\right) \quad [\Omega],$$

where $\mu_r = \mu' - j\mu''$, ($j = (-1)^{1/2}$), D the length of the core, and r_o the outer radius of the core. The core made of large permeability metal film formed as a toroid, the value ($f\mu_o\mu_r^2/\mu''$) is nearly 3.0[kΩ/m] at 1MHz. This value is

$$R_p(\omega) \approx 3.0 \cdot D \cdot \ln\frac{r_o}{r_i} \ [\mathrm{k\Omega\ at\ 1\,MHz}].$$

calculated from data of an amorphous core [1] having μ_r ~ 4×10^4 (if we select FINEMET produced by Hitachi-metal Ltd, a more large value can be obtained). Then, Dependence of $R_p(\omega)$ on frequency is approximately given by $f^{0.25}$. If we put r_i=0.1m, r_o=0.3m, and D=6×0.032m, the impedance at 1MHz is 630Ω. The length of this structure can be made to less than 0.5m. As shown in Fig.1, by connecting a passive compensating network (2kΩ, and 100pF +1kΩ), the resistance at the gap (R_T) can be made to 425Ω. Thus the gap can be made to have a bandwidth of 0.2MHz to 30MHz. In Fig. 1, $X_L(\omega) = \omega L(\omega)$, $R_p(\omega)$, and impedance of 10pF, are plotted.

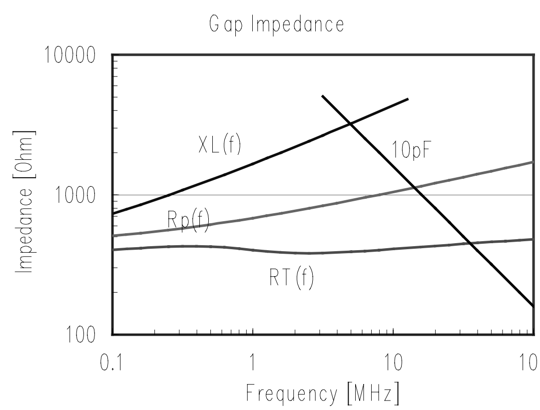

Figure 1: The components of the gap impedance

The system uses two accelerating structures (Fig. 2). The gaps are connected with four series inductors which, in combination with the output capacitors of power tubes, form a delay line. The both ends of the delay line are terminated with the gap-resistors, R_T. The length of the system can be made within 1m.

In the case of TTPS, two accelerating structures are installed at separate positions. While the separation of the accelerating gaps produces ~5% loss in sum voltage at low frequency, at high frequency the voltage at gap 2 dominates over that of gap 1.

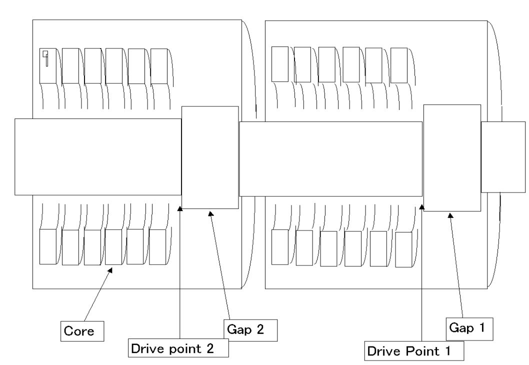

Figure 2: Structure of the accelerating system

*) shigeshi.ninomiya@kek.jp

Cooling of The Core. The peak power at 20kV is 240kW, and nearly 1/3 of the power is dissipated at the resistors of the compensating network. Since, in the application to TTPS [3], where the duty factor of rf operation is very small, the average power dissipated in the core at repetition of less than 10Hz is smaller than 10kW; In this case forced-air cooling [1] is the easiest way to keep the core temperature lower than 100°C; This value is not the limit of the core itself (Curie temperature of the FINEMET is ~600°C). The temperature enables us to use fiber reinforced plastic for supporting the cores.

For an application where the average power in the core is greater than 10kW, the water-cooling system must be employed.

Magnetic Flux Density. At high rf voltage, magnetic flux density in the magnetic material increases greater than 100gauss. But RF group of the Japan Hadron Facility demonstrated that the large-μ magnetic material is possible to use at high flux density [4].

2 POWER AMPLIFIER

If we apply the distribution amplifier scheme to drive the gaps, the limitations imposed by the capacitance at the gaps and that of the power tubes can be disregarded. In this amplifier, the anode circuit forms a delay line. The resistors at the two accelerating gaps are used as the terminators of the delay line. Thus several power tubes can be used in parallel to drive the gaps.

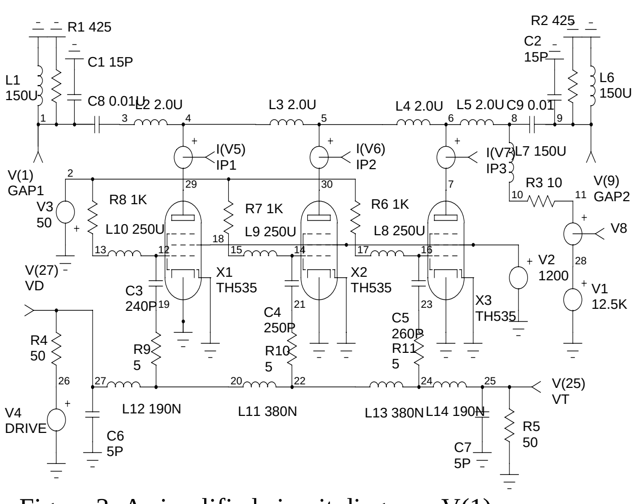

Figure 3: A simplified circuit diagram. V(1) and V(9) are the voltages of gap 1 and gap 2

The circuit which was used at the early stage of our simulation is shown in Fig. 3. The impedance at the accelerating gap is simplified by using the parallel circuit of 150μH, 425Ω(R_T) and 15pF($C_0/2$). Where 5pF is added for trimming of the gap capacitance, or it can be used for the rf voltage divider, with which we measure the voltages at the accelerating gaps.

The delay line can be thought as a series of constant-k low-pass filer with L_0(= 2μH; L2~L5 in Fig.3), and C_0. The characteristic impedance, $Z_0 = (L_0/C_0)^{1/2}$, is 258Ω. The unit delay (τ) is given by $(L_0C_0)^{1/2}$ =7.75ns. The output capacitance of the power tube, TH535 (Thomson CFS, 100kW), is 30pF(=C_0). The cutoff frequency of this transmission line is given by $1/(2\pi\tau)$ = 21MHz. Note that, in order to obtain a large rf voltage, we terminated the delay line with the resistor R_T, which is larger than characteristic impedance of the line, Z_0.

The delay line of the grid circuit must be made to have the same unit delay as that of the anode circuit. In order to make the characteristic impedance of the line to be 50Ω, the input capacitance of the control grid (340pF+ 1.2pF×(Voltage Gain) ≈ 440pF) is reduced to 160pF by using the series coupling capacitors of 250pF(C3~C5). This gives the inductance of the grid delay line, (L11, L13 = 0.38μH).

The generic pentode model in ICAP/4-library is used to simulate the power tube(TH535).

While not shown explicitly in Fig. 3, parallel capacitors (2~5pF) of coils are also included in the model.

The peak current of the anode power supply must be greater than 50A at 12.5kV. The screen grid voltage is set to 1.2kV in our simulation. While the bias voltage of control grids is fixed to –50V in the simulation, this voltage must be decreased to –100V for decelerating period to avoid large power dissipation at the anodes.

Figure 4 shows the dependence of output voltages on frequency at 1kW drive power. While an excellent response at gap 2 can be obtained, the vector sum of the two gap-voltages decreases -10dB at 20MHz. The accelerating voltage at 2MHz is ~15kV. Therefore, if we increase the drive power to 2kW, the accelerating voltage can be increased to 20kV for frequencies from 0.5MHz to 5MHz. At 20MHz, the voltage is reduced to ~1/3 of its maximum due to the limitation of the anode current of tubes (~30A).

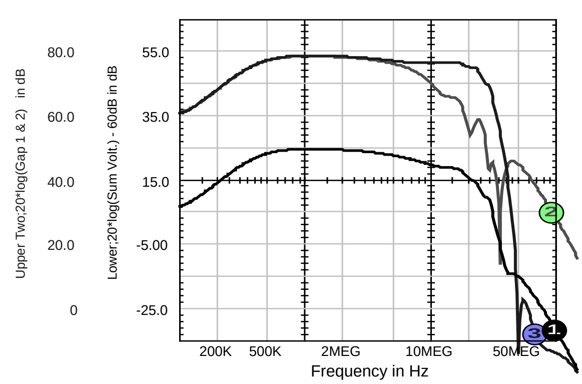

Figure 4: Frequency response at 1kW drive power

The model also gives the impedance seen by the beam by applying 1A-current source onto the two gaps at a constant anode current (in this case we set ~7A). Fig. 5

shows the result. The impedance above 35MHz is given by the gap capacitance (15pF). Note, however, that this circuit model cannot describe the impedance of a real system above 30MHz.

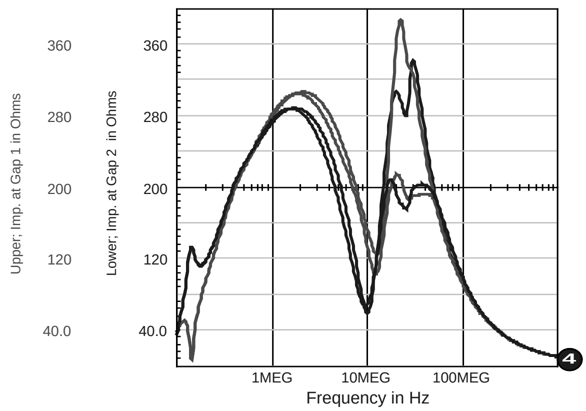

Figure 5: Impedances at the two gaps by 1A current sources. Lower curves at 20~30MHz are the result of compensation with LCR.

The voltages at gaps under the influence of the beam having a circulating beam current of ~2A with 9A-peaked half sine distribution at zero synchronous phase are shown in Fig. 6. The direction of protons is assumed to be from gap 1 to gap2. The beam current is nearly 10-times larger than the expected current of TTPS(0.2A).

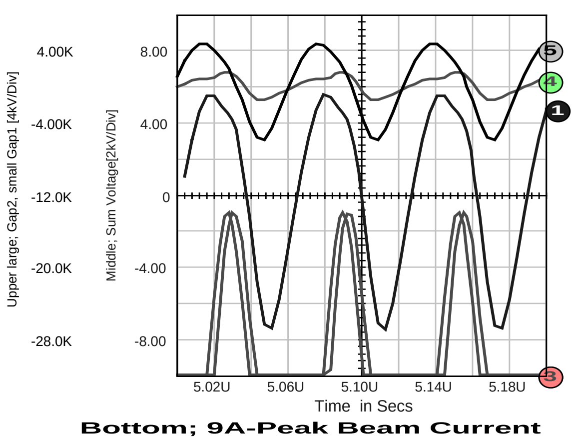

Figure 6: Voltages under the influence of beam current at 16MHz.(Upper wo traces are the voltages at gap 1(large amplitude) and gap 2 (small amplitude), and middle trace is sum of the two voltages).

Distortion of the rf wave form is due to (1) the beam loading, (2) the non-linearity of the vacuum tube, and (3) reflection near the cutoff frequency. While the loading beam current produces the decelerating voltage, which will be compensated by a radial beam-position feedback.

Remarks on Manufacturing. (1) In order to reduce its stray capacitance and to avoid the saturation, the inductor (L7 in Fig. 3) which feeds current to anodes must be made by a series of a large number of small inductors which are made with a few turns of coil wound onto a core having a large AT-product. (2) In order to avoid distortion due to control grid current, the operation of power tubes must be kept within the area of negative control grid voltage. High power tube, which has a large anode current at zero grid voltage, must be selected.

3 DISCUSSIONS

(1) While the system is designed for the rf system of TTPS [3], the system can also be applied to a heavy-ion accelerator.
(2) While the momentum aperture of TTPS is only ±1.5%, the bucket height at beam injection is nearly 5% at 20kV. We can superpose the rf harmonics onto the accelerating voltage simultaneously to decrease the bucket height. With the superposition of 2nd and 3rd rf harmonics, the beam capture efficiency can be increased to nearly 3-times more than in the case without harmonics.
(3) Note that the influence of the beam is different from that of the resonating rf cavity; As shown in Fig. 6, the beam current directly deforms the rf bucket.
(4) For an application to high intensity beam acceleration, cancellation of influence of the beam current using feed-forward technique is easier than the rf system using a resonating rf cavity.
(5) Whereas the peak impedance at 20~30MHz cannot be cancelled by any loop in which the power amplifier is included, the peak can be reduced to ~1/2 by a network with L, C, and R (see also an example of the compensation shown in Fig. 5). A more desirable compensation technique must be studied.
(6) An excellent frequency characteristics can be obtained, if we use only gap 2 with a resistor for gap 1. This does not change the accelerating field (20kV/m; the voltage divided by the length of the system), though it reduces the accelerating voltage and the power efficiency of the system to 1/2,

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REFERENCES

[1] S. Ninomiya, “Conceptual Design of a Non-Resonant Accel. System”, KEK Report 92-2, April 1992.
[2] Y. Mikita et al, “A Non-Resonant RF Cavity”, Proc. of PAC1999, p.848, 1999.
[3] K. Endo et al, this conference.
[4] JHF ACCELERATOR DESIGN STUDY REPORT, KEK Report 97-16.