DESIGN STUDY OF NON-RESONANT ACCELERATING SYSTEM FOR THE KEK PS BOOSTER

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Abstract

The scheme of non-resonant accelerating system [1] was investigated on the KEK-Booster RF-system. By improvement of the accelerating system and other instruments, the KEK-Booster increased its intensity to 2×10^{12}ppp. In order to increase the beam intensity further, we must reduce the space charge tune-shift [2]. The straightforward way to reduce the tune-shift is to reduce charge density by extending the bunch-width with superposing higher harmonics of the accelerating voltage. At an early stage of accelerating period, this system enables the superposition of harmonics up to 3rd without introducing separate RF-system.

The accelerating voltage of 20kV for frequency from 1MHz to 10MHz can be obtained by this system without employing tuning system. The accelerating structure is 1m in length, which is 70cm shorter than that of the present RF-system. The RF source is the distributed amplifier employing four tetrodes (TH571B), which are working in our RF-system.

Since the shunt impedance of the system is small, the beam loading effect can be disregarded up to the present intensity. Compensations will be necessary to accelerate higher intensity.

The accelerating voltage divided by the length of the cavity (accelerating field) of this system is compared with existing and planning wideband RF systems in Fig. 1. The specifications of the system are summarized in the table attached in Fig. 4.

1 ACCELERATING STRUCTURE

As shown in Fig. 2, the unit accelerating structure is similar to that of the ferrite loaded cavity. Magnetic material having a very large permeability is installed instead of the ferrite. Two units are used as a set.

The material that has a relative permeability of 10^4 becomes resistive at frequencies above 100kHz. A parallel circuit of resistor $R_p(\omega)$ and reactor $X_p(\omega)$ represents the impedance produced by the magnetic material.

The values $R_p(\omega)$ and $X_p(\omega)$ are calculated by the following experimental equations for FT-3M [4],

$$R_P(F) = 4.9 \cdot F^{0.26} \cdot \Gamma \ [k\Omega], \ (F \ in \ MHz.)$$

$$X_L(F) = 8.2 \cdot F^{0.24} \cdot \Gamma \ [k\Omega]. \tag{1}$$

The value Γ is the form factor of core;

$$\Gamma = D \cdot \ln\left(\frac{R_o}{R_i}\right) = 0.1351 \ [m]. \tag{2}$$

Where R_o (0.35m) is the outer diameter, R_i (0.18m) the inner one, and D (8×0.025 m) the thickness of the core. In order to decrease the capacitance at the gap, we must make the core diameter large.

Impedance given by equation (1) is compared with our data measured using a small test piece in Fig. 3.

The frequency dependence of the impedance can be compensated to be 550Ω (see amplifier section) at a cutoff frequency (12 MHz) of the amplifier by connecting networks which are two set of series circuits (C12, R5, and C13, R6 in Fig. 4).
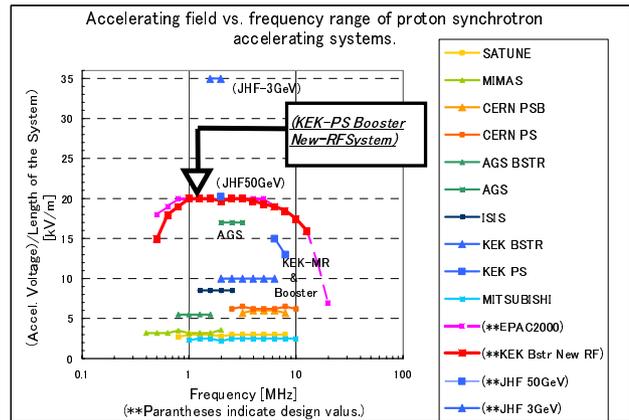

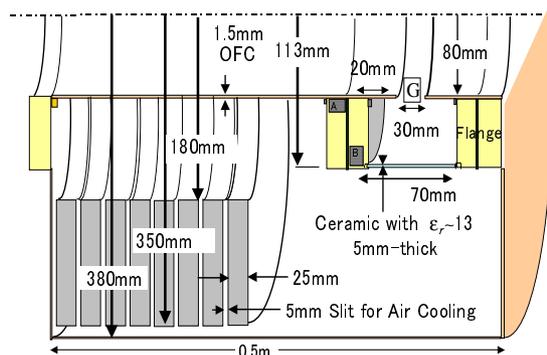Figure 1. Comparison of accelerating fields of various systems.

Figure 2. Schematic illustration of the non-resonant accelerating structure.
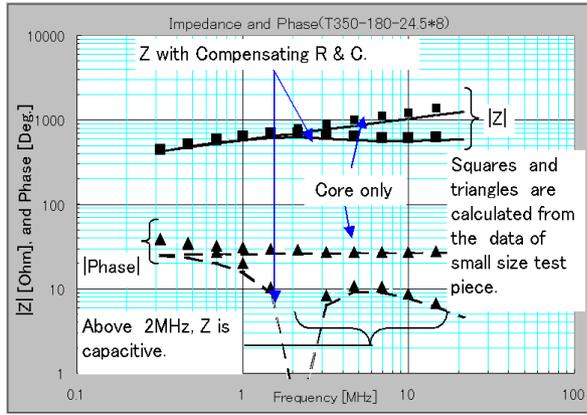
Figure 3. Comparison of gap impedance calculated with Eqs. (1) and test piece measurements.

2 FORCED-AIR COOLING

The core impedance at 4MHz, which is the average operating frequency of our Booster, is

$$R_P = 949 \ [\Omega], \quad X_L = 1.54 \ [k\Omega].$$

The average power dissipated at the core is estimated to 27kW for a single cavity at a voltage of 20kV with 50 %-duty operation.

Cooling air is guided from the inner bore to the outer of the core-stacks through the 5 mm-width slits between the cores. For the power of 27 kW, the temperature of forced-air at the outlet is estimated to be 60°C at airflow of 0.84m^3/sec and at inlet temperature of 30°C [3]. The flow is turbulent, and the maximum surface temperature of the cores is 73°C. The temperature at the core centre is 74°C, which is far less than the recommended maximum operating temperature (100°C~150°C) of the core [4]. Nearly 20 kW power is dissipated at R5 and R6 in Fig. 4. The resistors must be cooled with water.

The characteristics of the core under an rf magnetic field up to 18 A/m are measured using a small test piece. The impedance seems to have a slightly positive

temperature coefficient; the positive temperature coefficient of the core impedance prevents the system from the thermal runaway.

3 DISTRIBUTED AMPLIFIER

The circuit diagram is shown in Fig. 4. Two sets of R-L networks at the upper part in the figure represent the impedances of two core-stacks.

In the circuit simulation ICap/4 is used. The power tetrode (TH571B) is simulated with modifying its model of pentode.

The anode circuit forms a delay circuit. The Π- type equivalent circuit for the delay line is adapted to the anode circuit, while the T- type for grid circuit.

The circuit have the delay time of the unit circuit (τ_0). The output capacitors of the tetrodes play role of those in the delay circuit. Both ends of the line must be terminated with its characteristic impedance Z_0. Thus we can connect tubes in parallel without reducing bandwidth.

Let the cut-off frequency be ω_C, then

$$Z_0 = \sqrt{L/C}, \quad \tau_0 = \sqrt{L \cdot C},$$
$$\text{and} \quad \omega_C = \frac{2}{\tau_0}. \tag{3}$$

Since we use four tetrodes (TH571B) which have the maximum anode current of 80 A, in order to obtain the accelerating voltage of 20kV, the termination resistor (Z_0) of the delay line must be greater than 500Ω. We select 550Ω for Z_0. For anode circuit, C/2 = 21pF(output capacitance (C_{A-G2}) of TH571B). We get L (L6~8) = 12.7μH and τ_0 = 23ns. The capacitances at the two accelerating gaps also take part in the delay circuit.

The capacitances at the accelerating gaps (C1, C2) are calculated using the mapping method [5]. The calculated gap-capacitances are ~25pF(C1, C2). We added 5pF(C14, C15; monitor of the sum of two gap voltages (VT)) and

Figure 4. Circuit diagram, and pecifications of the system;

Frequency Range ;   1 ~ 12MHz
(Acc. Freq. Range; 2.2 ~ 6.0MHz)
Max. Acc. Voltage;   20kV
Peak Output Power ;   180kW
Average Power;   ~90kW
Anode Voltage;   12.5kV
Total Anode Current;   80A
Length of Acc. system;   1m
Diameter of Acc. System; 0.8m
Weight;   900kg
Drive power;   ~1kW
Impedance;   ~550Ω/gap
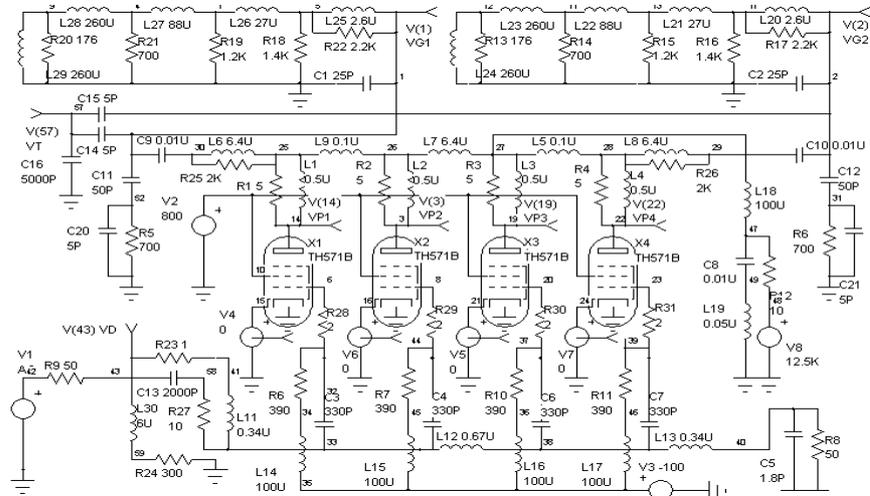
5pF(C20, C21; parallel capacitors of the power resistors, R5, R6) to the gaps. While the total capacitance is far greater than C/2 (21pF), it does not appreciably affect on the characteristic of the amplifier.

For grid circuit, the delay of the unit circuit (τ_0) must be the same value as that of the anode circuit, and let Z_0 be 50Ω. We obtain L (L12, 2×L11, 2×L13) = 1.15μH and C = 460pF. Since we use two tetrodes in parallel, the input capacitance of the tetrode (~400pF) is reduced to 230pF using series capacitor (C3, 4, 6, 7). And the network connected at the input of grid drive circuit compensates the variation of the input impedance at high frequency.

In order to increase the response at frequencies above 10MHz, the parameters in Fig. 4 are changed from the calculated values (Fig. 5(a)).
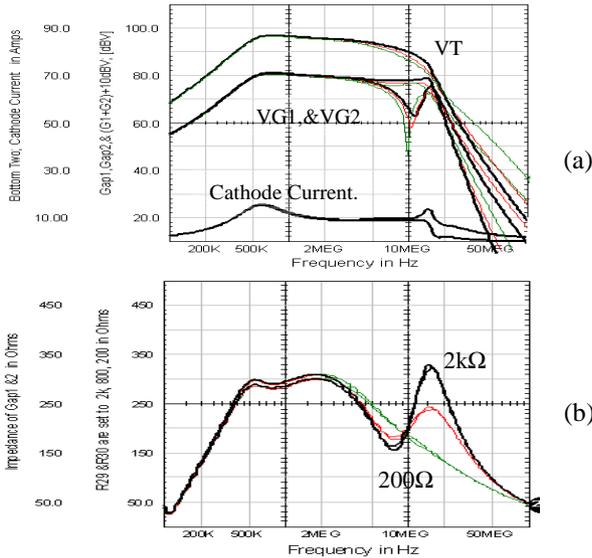

Figure 5. (a) Output voltages and cathode currents at 530W drive power, and (b) Gap Impedance seen by the beam. The damping resistors (R25, R26) are changed 2kΩ(black), 800Ω(red), and 200Ω(green).
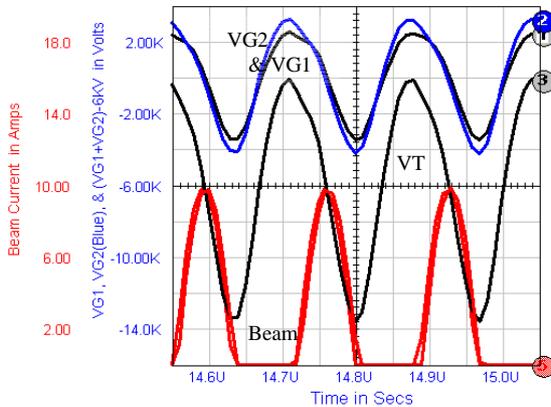

Figure 6. Output voltages under the influence of 3A-beam current at 6MHz. (R25, R26=800Ω)

As shown in Fig. 5(b), the damping resistors (R25, R26) connected parallel to L6 and L8 reduce the peak impedance at 15MHz. The reduction of the peak is more effective than that shown in Ref. [1]. If we increase the values of C11, C12, and limit the maximum voltage to 10kV, a more flat response can be obtained. The maximum current of the tubes limits the lower-frequency response of the system to 1MHz.

4 DISCUSSIONS

By superposing harmonics up to 3rd, the bunching factor at an early stage of acceleration cycle can be increased from 0.4 to a value larger than 0.5, which reduces charge density and the tune-shift. Thus the beam intensity of our Booster can be increased to ~3×10^{12}ppp.

The accelerating frequency generator having the output of harmonics up to 3rd is already operating. The system employs three Direct Digital Synthesizers (DDS) to avoid the drift. The operating clock of this system is 1MHz, which minimizes frequency step error, and also minimizes the phase-lag of beam feedback signal due to anti-aliasing filter at the input of AD converter.

The deformation of rf-wave due to the beam loading at the intensity of 3×10^{12}ppp is shown in Fig. 6. Since the bucket distortion becomes large, in order to accelerate the beam higher than this intensity, the loading beam current must be cancelled by feeding inverse beam signal to the input of the drive amplifier.

We have also developed a variable delay system that can be used to adjust the phase of cancelling signal. This delay has the signal bandwidth of 100MHz and 100kHz-bandwidth for the delay-time variation.

The other non-resonant RF system using a triode is also studied. Since the system consumes enormous power to drive the tube, it is omitted from our project. Since the triode has an output impedance of less than 100Ω, it may be suitable for accelerators having beam intensities higher than our machine.

ACKNOWLEDGEMENTS

REFERENCES

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[5] see for example W. H. HAYT JR "Engineering Electromagnetics", McGRAW-HILL.