NON-RESONANT ACCELERATING SYSTEM AT THE KEK-PS BOOSTER

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Abstract

The non-resonant accelerating system for the KEK-PS Booster accelerator has been constructed. The system has been operating since October 2003 without trouble. The accelerating gap in the system is loaded with magnetic cores of high permeability. The cores produce high resistive impedance at the gap. The power dissipated in the cores amounts to 50kW at 16kV accelerating voltage. It is removed by forced-air cooling system. At the last operation of the accelerator, with the help of new COD-correction system [1], the average beam intensity of the booster increased to 2.8×10^{12}ppp, which is 40% higher than before. The circulating beam current at this intensity is 2.7A.

A low-pass filter is applied to the anode circuit to extend the operating frequency range. The drive amplifier is class-A push-pull circuit which, with the aid of a grid-bias voltage control, increased the power efficiency to 30%. The superposition of the second-harmonic RF onto this system is also tested.

1. THE ACCELERATING STRUCTURE

We use the dissipative characteristic of a core of very large-μ material as the load resistor of the amplifier [2]. 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 ($L(\omega)$), 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 cut-off frequency of the system is determined by the time constant of R_p and C. The capacitance C is designed using mapping technique to be nearly 30pF by keeping a large inner radius of the core (r_i = 165mm), vacuum tube-radius of 80mm, and a wide accelerating gap width (30mm). If we use FINEMET (FT-3M) produced by Hitachi-metal Ltd as the core, the resistance $R_p(\omega)$ is given by

$$R_P(\omega) \approx 3.7 \times F \;\; [\mathrm{k\Omega\ at\ 1\,MHz}],\ \text{with}\ F = D \times \ln\frac{r_0}{r_i}.$$

where $\mu_r = \mu' - j\cdot\mu''$, ($j= (-1)^{1/2}$), D =7×25mm is the thickness of the core, and r_o =350mm is the outer radius of the core, and F = 0.13m is the form factor of the core. Then, R_P ~ 500Ω can be obtained at 1MHz. The impedance produced by $L(\omega)$ is very large at this frequency range.

The system uses two accelerating structures. One of the accelerating structures is shown in Figure 1. The length of a structure is 52.5cm. The length of the total system is 2×0.525m. While a structure has two air outlets, only lower one is shown in the figure. Between the two structures, there is an empty space with the length of 0.4m; we can install a correction magnet at this space.

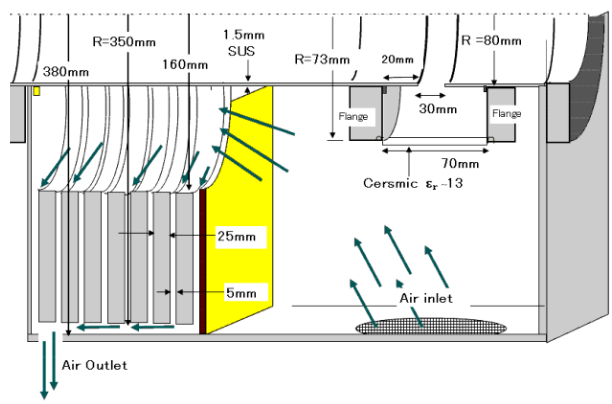


Figure 1: A unit structure of the accelerating system.

The gap impedance is simulated by the circuit shown in Figure 2. The circuit precisely describes the measured impedance at the gap. The maximum impedance is 630Ω.

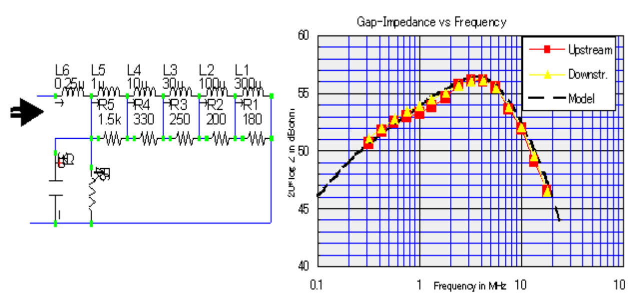


Figure 2: The gap impedance and its equivalent circuit.

Cooling of Cores; The peak power at 20kV is 220kW, and the average power is nearly 74kW for two accelerating structures. The forced-air cooling is used to keep the core temperature less than 90°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 FRP for supporting the cores. Two set of cooling system having 35kW power capability is designed. The volumetric flow rate of air is $1m^3/s$ for each accelerating structures. Water flow which cools air is 40 l/min for each system. Figure 3 shows the cooling system installed in the booster room.

Magnetic Field in the Core; At 10kV rf voltage, the average magnetic field in the core increases to 20A/m. We have tested the stability of the material using a test piece. The test indicated that the impedance has a slightly positive temperature coefficient. The RF group of the JHF has demonstrated that the large-μ magnetic material is possible to use at larger flux density [3].

Figure 3: Cooling system.

2. EXPERIMENTS

At the first experiment, we used the gap resistors to the termination resisters of distribution amplifier [2]. And at the second, the scheme of which is used for the real operation, gaps are connected to the anode via inductors which, in combination with the capacitor at the gaps, form LPF. The LPF is terminated with the gap-resistors, $R_P(\omega)$.

At test experiment, the same power amplifier, which is currently working in Booster, is improved to the distribution amplifier scheme; the amplifier employs four 50kW tetrodes (TH571b). Figure 4 is the photo of the accelerating system under construction at RF experimental hall. The resistive components of the gap impedance changes from 500Ω at 1MHz to 1kΩ at 10MHz. The resistive components of the two gaps are used as the terminators of the delay line. While we had expected the frequency response of 10MHz, the measured frequency response was only 7.5MHz.

Figure 4 Accelerating system under construction.

At high voltage test, we could increase accelerating voltage to 16kV at 4MHz, and the asymmetry of the wave form due to the non-linearity of anode current vs. grid voltage of the tetrode was observed. Figure 5 is its wave form at 4MHz.

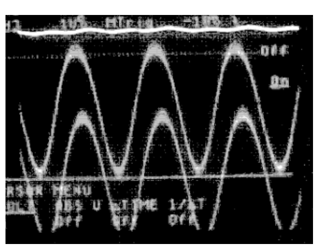


Figure 5: Test operation of non-resonant system with a scheme of the distributed amplifier. Voltage is $14kV_{PP}$.

At the next experiment, we changed the circuit to push-pull amplifier to improve the power efficiency and wave form. The frequency response can be improved by using low-pass filter in which an inductance is used to connect anode and accelerating gap; the inductance and capacitor at the gap resonate at 7MHz to increase the response at 6MHz. This technique is commonly used at the RF system of accelerator for cancer therapy [4].

A simulation shows that the bandwidth is sufficient for our purpose, since the accelerating frequency range of our booster is 2.2MHz to 6.05MHz.

A large size RF power transformer is used at the parallel push-pull circuit. The sizes of the transformer are 425mm (outer diameter), 250mm (inner), and 4×25mm (thickness). To cool the cores, the four cores are stacked to have 5mm slits. A single side of the output of the push-pull amplifier is connected to the gaps via two coils (10μH).

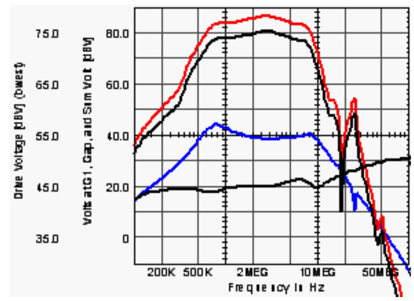


Figure 6: Line at the top is the frequency response of system at 1kW drive, second is that of a single gap, third is grid voltage, and the lowest is the input voltage of the amplifier (10dBV/div)

Figure 7 shows the frequency characteristics of the system, and figure 8 is the photo at the high power test. While, the parallel capacitance inherent in the winding of the RF transformer prevented to reduce the distortion at output voltage, the anode-power efficiency is increased to ~30% by varying voltage of the control grid power supply (Fig. 8).

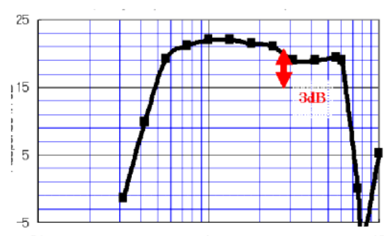


Figure 7: Amplitude transfer function from the input of 1kW transistor amplifier to the output voltage monitor.

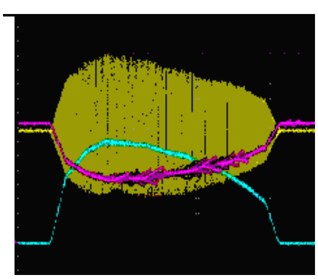


Figure 8: Frequency is swept from 2.2MHz(left) to 6.1MHz. Peak accel. voltage is 16kV. Grid voltage is varied from -120V to –70V (middle line). Lowest line is the control signal of RF envelope.

After the above experiments, we installed the RF system to the position of #1 RF system (Booster has two RF systems), in August 2003. Figure 9 is a photo of oscilloscope display at an early stage of operation; from the top, beam intensity for neutron meson laboratory, the radial position, the intensity for main ring, and the accelerating voltage, which is the vector-sum of two RF voltages. Distortion at the envelope of RF signal is due to (1) a resonance at anode power circuit, and (2) large stray capacitance at the power transformer of the push-pull circuit.

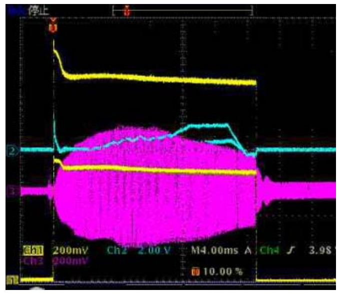
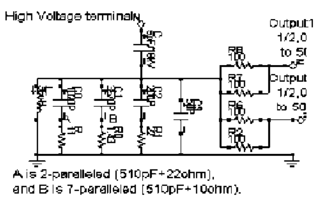
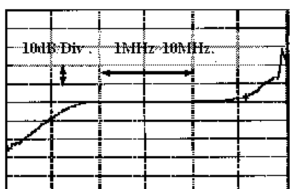
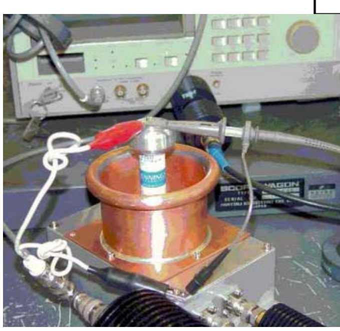


Figure 9

Miscellaneous Technology; (1) In order to maintain a small gap capacitance, we have to develop the low capacitance voltage divider. Figures 10, 11, and 12 are its circuit diagram, the frequency characteristics, and its photo. (2) As already shown in Figure 9, the grid bias







Figures 10, 11, 12: Circuit diagram, Frequency response of the divider, and photo under measurement, where 5pF/18kV capacitor is installed at the center of the guard ring

voltages of tetrodes are varied according to variation of the output voltage. The currents of tubes are reduced to nearly 0.1A after the acceleration; they are increased to nearly 10A at the maximum accelerating voltage. This technique increases the power efficiency at the anodes. This grid power supply has been operating from 1992 in other RF systems at the KEK-PS.

Test Experiment of 2nd Harmonic Superposition; Our Booster employs two RF stations to obtain 32kV-accelerating voltage. Since the counter-phasing technique is used to reduce the effect from beam, two cavity-phases are locked together with controlling the offset phases using phase-lock loop (PLL). Whereas the PLL prevents the superposition of 2nd harmonic RF voltage at sufficient amplitude, we have tried the test experiment. The 2nd harmonic signal is added onto the input of the transistor amplifier of the non-resonating RF system. Figure 13 is the photo of vector sum of the RF voltages of the two accelerating system during the beam capture process. This photo clearly indicates that the voltage of the 2nd harmonic is far lower than the necessary value. Even by this wave form, the beam loss at capture process is reduced from 15% to 10% of the injected beam.

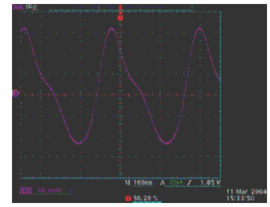


Figure 13: RF wave form during beam capture process. The frequency is near 2.3MHz.

3. DISCUSSIONS

The non-resonant accelerating system having high accelerating voltage has been realized at the KEK-PS Booster synchrotron. This work is a realization of our dream since 1992 [5]. The system has been working steadily without any troubles since Oct. 2003. This system, with the help of COD correction [1], increased the beam intensity of our booster to 95% of its limit intensity imposed by radiation-shielding.

The scheme which is used for the operation is, may be, not the best way; the power efficiency of the distribution amplifier (the first experiment) can also be increased by controlling grid-bias voltage, and the distortion, shown in Fig. 5, can also be improved by superposing harmonics. We had no sufficient time to investigate the characteristics of the scheme.

We are planning to replace the second RF system in the booster. The new system realizes a more symmetric drive, and the distortion of RF wave will be reduced.

Further investigations on the power transformer are necessary to reduce the distortion and to improve the anode power efficiency.

Acknowledgements

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