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COMPENSATION OF BEAM LOADING IN THE ISR RF CAVITIES

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Summary

The RF cavities employed for stacking in the ISR are equipped with a powerful feedback system, which compensates for most of the beam-induced voltage. This system is, however, limited - mainly by the current in the final amplifier tube - to injected beam intensities of about 5×10^{12} protons at most. Higher intensities are now available from the PS. Additional beam-load compensation has, therefore, been added to the existing cavities and feedback amplifiers. This beam-load compensation consists of a pick-up, a one-turn delay cable, a wide-band amplifier chain and a final amplifier, directly connected to the accelerating gap. This system injects into the cavity a current approximately equal and opposite to the beam current.

The RF Cavities in the ISR

For stacking the beam in the ISR, each ring is equipped with seven RF cavities. The maximum RF voltage at 9.5 MHz (30th harmonic of ISR revolution frequency) is 21 kV (peak) per turn, 3 kV per cavity. During the stacking process the frequency swing is 0.1% only whereas for the different operating energies of the ISR, between 11 and 31 GeV, the change in RF frequency is 0.3%. No tuning is needed, the Q-factor being about 200. The resonant shunt impedance of each cavity as seen by the RF power amplifier is 3 kΩ. However, the maximum impedance presented to the beam is only 45Ω per cavity. Hence, the RF system's contribution to $|Z|/n$, the total longitudinal coupling impedance[1,2] over the mode number, is about 10Ω which is just about tolerable for longitudinal and transverse beam stability.

In order to achieve this low coupling impedance the RF power amplifiers, which are linear over a wide dynamic range, have always been equipped with a strong wide-band feedback system[3] (Fig. 1), compensating most of the beam-induced voltage. This system is limited, however, mainly by the maximum available RF current in the final stage of the power amplifier, to injected beam intensities of about 5×10^{12} per pulse.

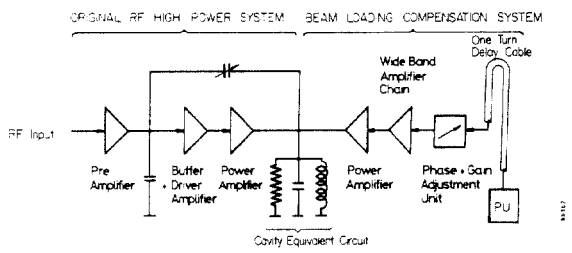

Fig. 1. Schematic circuit diagram of the RF power amplifier with cavity and beam loading compensation system.

With the PS Booster injector, the ultimate PS performance will approach 2×10^{13} protons per pulse. As this would overload the RF amplifiers, the cavities would no longer present a low impedance to the beam and instabilities would occur. The RF system was therefore modified to handle the increased beam load.

The Beam Load Compensation System

The principle of this system for beam load compensation (BLC) is to inject, by means of a second power amplifier, current pulses, which are equal and opposite to the bunched beam current. This is done separately for each cavity. The compensating current is derived from the beam signal by a pick-up station and fed to the cavity gap one revolution later. The power amplifier is inserted in the easily removable upper half of each cavity (Figs. 2 and 3). The interference with ISR operations was thus kept to a minimum and the additional power amplifiers could be installed one by one in different shutdowns.

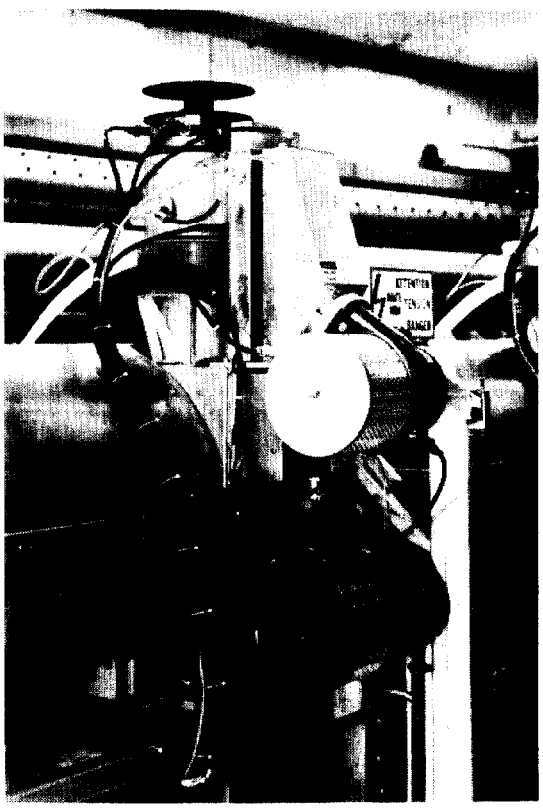

Fig. 2. RF power amplifier for compensation of the beam loading, installed on top of the RF cavity.

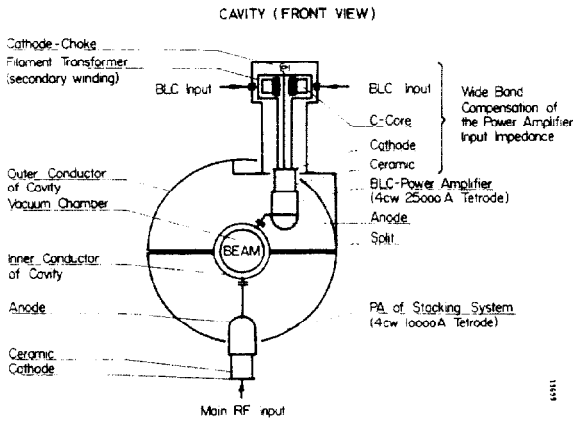

Fig. 3. Insertion of the beam load compensation power amplifier in the upper half of the cavity (schematic).

The main components of the BLC system are a pick-up station, an adjustment device for phase and gain, a one-turn delay cable, a wide-band amplifier chain and the final power amplifier, which is connected via high-voltage ceramic capacitors to the accelerating gap. The amplifier chain consists of a wide-band distributed amplifier as predriver (with a bandwidth from 10 kHz to 100 MHz) and a 200 W distributed driver amplifier with ten 4CX350F tetrodes in parallel (100 kHz to 70 MHz). The output impedance of the driver, which has a tapered anode line, is 25Ω, corresponding to the input impedance of the grounded-grid final amplifier stage. The input of this final tube, which is a linear water-cooled 25 kW power tetrode, is wide-band compensated. The bandwidth of the whole system, 100 kHz to 60 MHz, is essentially determined by the input capacity of this tube and the coupling to the cavity gap. The frequency spectrum of the bunch signal contains frequencies higher than 60 MHz. The experimental results with the installed beam load compensation amplifiers showed, however, that with this limited bandwidth a very satisfactory compensation of the induced voltage can be obtained.

Special measures were needed for the filament supply of the final tube. A 50 Hz supply could not be used since this might excite the coherent phase oscillations, the frequency of which is around 50 Hz, in the ISR. A dc supply would have needed a large RF choke in the filament line since the low end cut-off frequency of the amplifier's operating range is as low as a hundred kHz. Therefore a heater supply working at 800 Hz was chosen. At this frequency the 1.2 kVA filament transformer (located on top of the input compensation circuitry - see Fig. 3), which provides the decoupling between cathode and filament line, does not become too heavy.

The one-turn delay of the compensation signal is adjusted to within an accuracy of ±1 ns. For the different operating energies of the ISR this delay needs to be readjusted since between 11 and 31 GeV the difference in revolution time is 9 ns. These adjustments are done automatically by the computer by switching in different cable lengths.

The mechanical construction of the amplifiers and their power supplies, interlock system and adjustment units, is based on a modular concept. In case of failure the modules concerned can be replaced very rapidly and the repair work can be executed in the lab.

Experimental Results

The Beam Load Compensation System described here is completed, and installed in all 14 cavities of the ISR. So far, our main effort has been devoted to obtaining as complete a compensation of the beam-induced voltage as possible. Figure 4 shows the result.

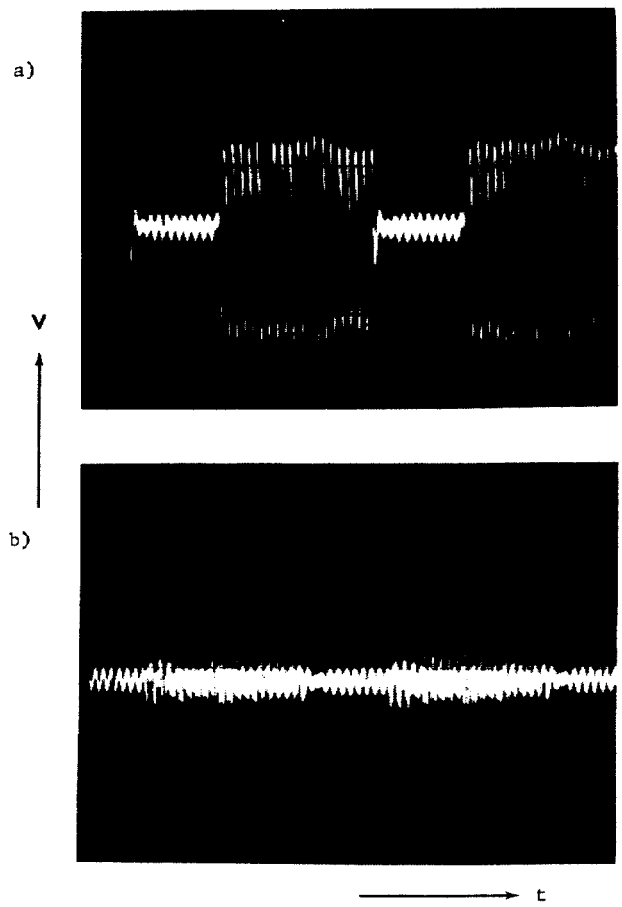

Fig. 4. Bunched-beam-induced voltage across the cavity gap.
a) without compensation
b) with compensation
(20 filled and 10 empty buckets)

About 90% of the induced voltage can be compensated. At the time of writing, the maximum intensity tried was 5.8×10^{12} protons per pulse where, without compensation, overload of the original power amplifiers only begins to be noticeable. With compensation, an increase of stack density by 15% was observed.

Another application of the BLC is acceleration by phase displacement where, at the highest achievable beam density, overload occurs due to the modulation of longitudinal charge density by the empty RF buckets. In an experiment a beam current of 30 A with a density of 0.6 A per millimetre of radial aperture could be

used. For this application the bias of the BLC amplifier must be set to class A operation, since negative current pulses have to be injected to compensate the beam-induced voltage caused by empty RF buckets.

Acknowledgements

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