A SECOND RADIO-FREQUENCY HARMONIC IN THE U-70 BOOSTER

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Introduction

Experimental and theoretical researches carried out at various accelerators have obviously shown that the beam intensity may be limited by the coulomb shift of betatron frequencies. One of the methods to decreases this limitation caused by the beam space charge is to add the second harmonic to the accelerating voltage [1,2]. As a result the beam losses during acceleration decrease, equipment activation reduces and the accelerated beam intensity increases. In this paper we investigated with the aim to decrease the maximal longitudinal charge density at low beam energy the accelerating regime with adding the second radio-frequency harmonic at the beginning of cycle.

Main Performance

At injection the working points in the booster is Q_h=3.90 and Q_v=3.75. For the design intensity of $17\cdot10^{11}$ protons per accelerating cycle incoherent tune shift of vertical betatron oscillations ΔQ_v exceeds 0.3 [3]. The present operating intensity is about $7\cdot10^{11}$ protons per cycle ($10\cdot10^{11}$ at injection), beam losses are about 30%. The main beam losses are observed up to 4 ms after injection (the total accelerating time of 28 ms).

On introducing the second harmonic the basic regime was chosen according to

$$V = V_1\cos\varphi + V_2\cos2(\varphi-\psi),$$

where V_1 and V_2 is the amplitude of the fundamental and second harmonic of the accelerating voltage.

The analysis of phase and amplitude correlations for harmonics showsthat for the bunch shape optimization it is necessary to fulfil condition $V_2 \simeq 0.5V_1$, and moreover the phase shift between the first and second harmonics must change from $\psi=45^o$ at $\cos\varphi_s=0$ up to $\psi=75^o$ at $\cos\varphi_s=0.5$ (φ is the phase of a synchronous particle without the second harmonic). The second harmonic voltage should "slowly" go down, during some synchrotron frequency periods.

Radio-Frequency System

The RF system in the Booster is described in detail elsewhere [4]. It produces a peak accelerating voltage up to 60 kV with the help of 9 ferrite loaded cavities located in the beam orbit at quotient 30° intervals. The fundamental harmonic frequency changes from 0.7 to 2.8 MHz. The frequency program is generated by an integrated $\dot{B}$ signal using 32 sectors in the function converter. Beam phase and position feedback loops are also used. The low level electronics located in the control room generates the RF excition signals for the power amplifiers and programmed analog signals for automatic amplitude (AVC) and cavity tuning control. Nine separate power amplifiers located near the accelerator generate voltage in the accelerating gaps.

The amplifiers ensure peak voltage up to 10 kV in one cavity, and the accelerating may be obtained with 6 operating cavities. Two from nine cavities located at 180° to azimuth apart were used with the second harmonic operating. During first 4-9 ms after injection the second harmonic voltage is applied to them and then slowly decreased up to zero. In these two cavities the tuning rate became higher by power increasing in direct current ferrite magnetizing amplifiers. In all others parameters they are analogous to the others seven accelerating systems and can be used for the operation in the fundamental mode.

Low Level Electronics

Three feedback loops control the cavities operating with the second harmonic: RF feedback loop around the power amplifier, the cavity tuning and AVC (Fig.1). Similar loops are described in detail in ref. [5]. The cavity tuning program is derived from a computer-controlled analog function generator. The signals from the cavity gap and RF power amplifier input are received by the phase discriminator. The control signal is applied to the power amplifier. The maximum current for the ferrite magnetizing is equal 150 A.

In the voltage loop the signal from the gap cavity through a divider is detected, compared with the program generated by a computer-controlled analog function generator and is then applied to the preamplifier modulator. To ensure a large dynamic range RF signal is preliminarily modulated in the low level electronic unit. A wide-band multiplier is used as a modulator.

The RF feedback is realized on traditional circuit [5]. The impedance reduction factor approximately changes from 6 to 20 dB.

The signal of the fundamental mode (0.7-2.8 MHz) from the frequency control oscillator is applied to the quadrature frequency generator, which is controlled by a Phase-Locked Loop (PLL) to ensure 1.4-3.0 MHz band. The phase program is derived from a computer-controlled digital function generator. The phase method of forming a single sideband signal is implied for the change of RF signal phase [6]. A wide-band phase shifter has ±90° band and operates up to the 10 MHz frequency bandwidth. The digital quadrature generator is built on the basis of two DAC and programmable read-only memory. In the experiments this generator had a step of 10° and operating bandwidth from DC up to 5 kHz. Further it is proposed to decrease its step up to 2.5°.

A summed signal from the cavities gaps is applied to the amplitude detector and through a divider by 2 is applied to the phase discriminator. Its output signals are used in the observation system when working with the second harmonic.

Experimental Results

Two operating regimes at the second harmonic were tested: using two accelerating cavities and using one cavity. The second harmonic amplitude V_2 in the regimes, close to the theoretical ones, is shown in Fig.2 together with the first harmonic amplitude V_1. The shift phase programs were experimentally found to differ from theoretical, because one has to compensate own phase shifts in the preamplifiers and driver stages.

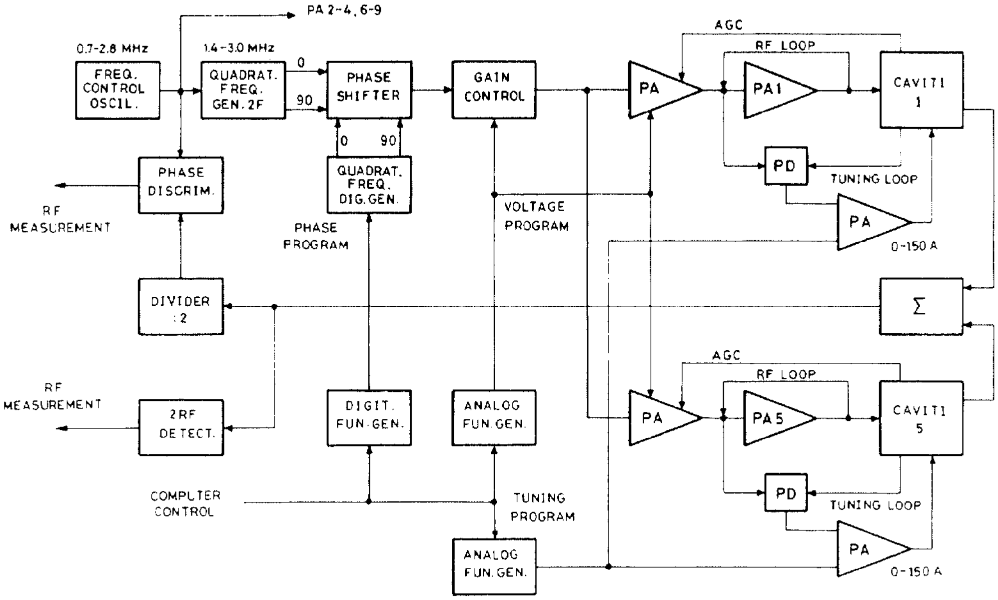

Fig. 1. Block diagram of the accelerating system for operating with the second harmonic.

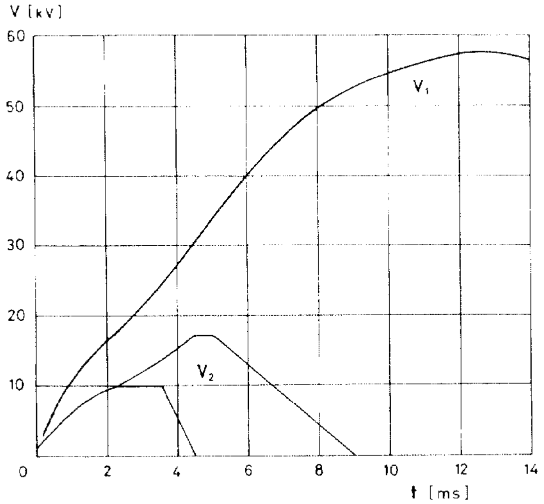

Fig. 2. Amplitude change of the fundamental V_1 and second V_2 harmonics of the accelerating voltage in the booster cycle.

Once in the first regime the beam intensity was increased by 20% by switch on the second harmonic, and record intensity of $9 \cdot 10^{11}$ protons per cycle was achieved. A photograph showing change of the bunch shape on 2 ms after injection by the second harmonic switch on in this regime is shown in Fig.3.

In the second regime efficiency of the accelerator is decreased negligible, but this regime permits to have one accelerating cavity in reserve. A photograph of beam intensity signals for the second regime with the second harmonic switch on and switch off is shown in Fig.4. The increasing of the intensity makes up 15%.

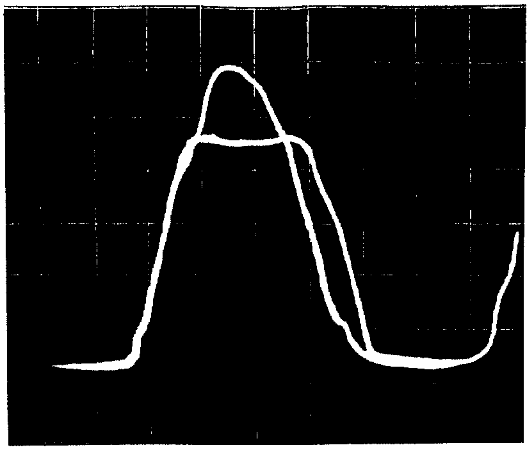

Fig. 3. Current distribution in bunch at 2 ms after injection (horiz. axis: 200 ns/div).

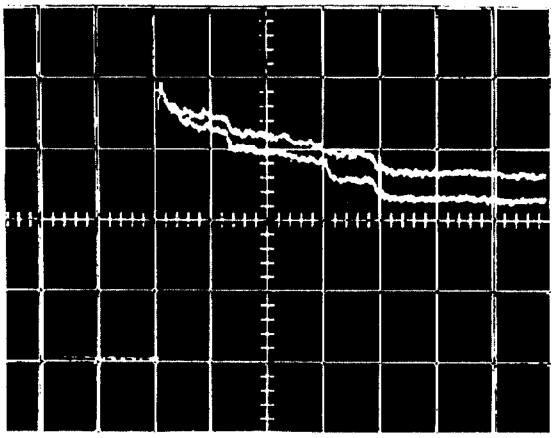

Fig. 4. Beam intensity in the booster (horiz. axis: 1 ms/div).

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