A Wide Band Electronic Phase Shifter for the Phase Control of the Second Harmonic Acceleration Voltage in the CERN Booster Synchrotron

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Abstract

This paper describes a voltage controlled phase shifter which was developed for longitudinal bunch shape control in the CERN 1 GeV Booster (PSB). This is required to improve high intensity beam stability during acceleration and for pulse to pulse modulation of the matching in the longitudinal phase plane between PSB and PS (bunch to bucket or 2 bunches to bucket transfer). A phase variation of up to 2π radians over a wide frequency range (1 to 20 MHz) is achieved with fast field effect transistors. After analysis of the applied all-pass network the complete circuit is described. Measurement results for the circuit are given. The phase space behaviour for acceleration with fundamental and second harmonic in various phases is illustrated.The performance observed on the accelerated beam after implementation of this device is presented.

1. INTRODUCTION

The second harmonic acceleration voltage added to the fundamental one allows to control the longitudinal charge density of the bunches in the PSB [1]. Depending on the phase and amplitude of the 2^{nd} harmonic the bunch shape can be varied corresponding to the deformed potential well. The purpose of this bunch shape control is to minimize space charge detuning at injection, to avoid beam losses during acceleration (damping of modes and bucket maximization) and to minimize the bunch length for a transfer of 2 bunches into 1 RF bucket of another machine.

Due to these reasons and the necessity of pulse to pulse modulation, an electronic phase shifter was built which allows fast control of the 2^{nd} harmonic phase within a range of 2π.

2. PRINCIPLE OF THE PHASE SHIFTER

Figure 1 shows the applied circuit in principle. The basic elements are two cascaded phase bridges, separated by a differential amplifier. The variable elements are two FET-resistances R which are controlled in parallel by the voltage U.

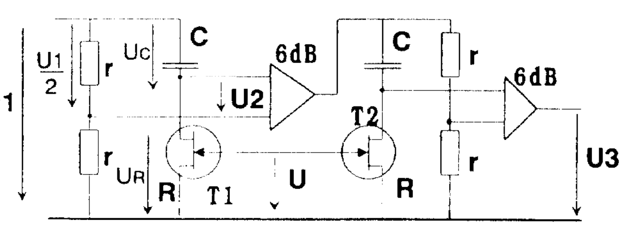

Fig. 1 Schematic Diagram of Phase Shifter.

Each bridge allows a maximum phase variation of 180°, shown by the vector diagram in Figure 2. The input voltage U1 divided by 2 serves as reference for the bridge voltage U2. The voltage vectors U_C and U_R are orthogonal and when added always give U1. Hence the vector U2 lies on a circle and has constant amplitude. The phase ϕ varies between 0° (for R = 0) and 180° (for R = ∞) As the identical second stage adds the same phase, the total controllable phase variation is 360°.

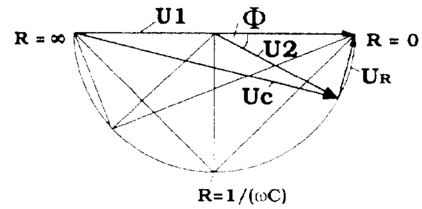

Fig. 2 Vector Diagram of Bridge Voltages.

3. ANALYSIS

The transfer function U2/U1 can be written from inspection of Figure 1 as the difference between the two dividers.

$$F(p,C,R) = \frac{U_2}{U_1} = \frac{r}{2r} - \frac{R}{R + \frac{1}{pC}} \qquad (p = j\omega) \qquad (1)$$

or rearranged

$$F(p,C,R) = \frac{1}{2} \cdot \frac{1 - pCR}{1 + pCR} \qquad (2)$$

which has all-pass characteristics (constant amplitudes for all frequencies and complementary poles and zeros).

The phase angle between U2 and U1 is given by

$$\boxed{\Phi(\omega,R,C) = \mathrm{arctg}\frac{\mathrm{Im}(F)}{\mathrm{Re}(F)} = \mathrm{arctg}\frac{2\omega RC}{(\omega RC)^2 - 1}.} \qquad (3)$$

Plotting Equ.(3) as a 3D plot gives the Figure 3.

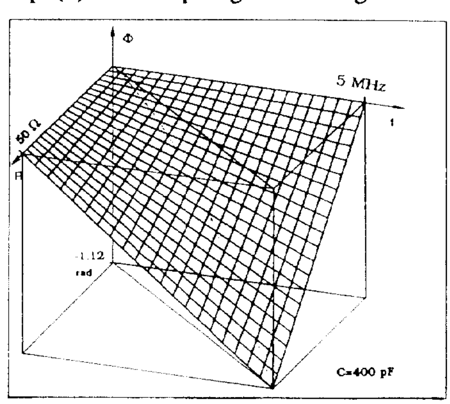

Fig. 3. Phase Angle ϕ vs frequency f and resistance R.

Due to symmetry the projections in the ϕ-R and ϕ-f planes look the same. Only the variables and parameters are different (Figure 4).

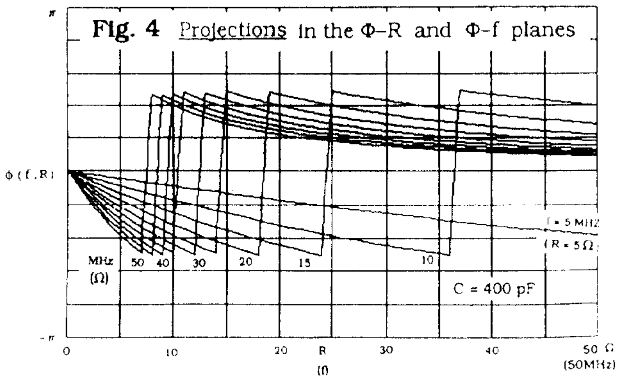

Fig. 4 Projections in the Φ-R and Φ-f planes

4. ELECTRICAL LAYOUT

Figure 5 gives the complete electronic circuit diagram of the phase shifter.

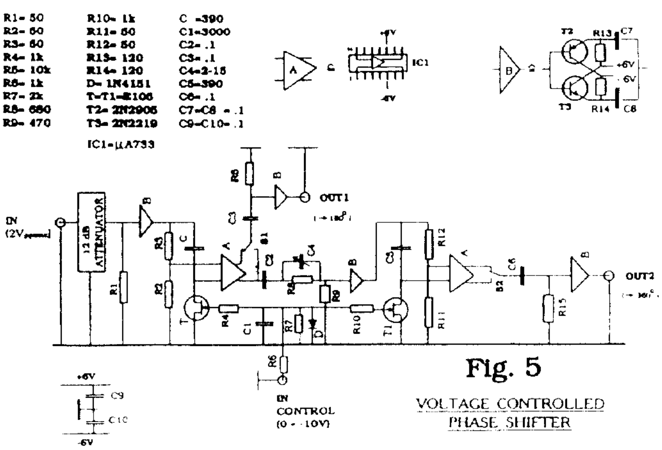

Fig. 5 VOLTAGE CONTROLLED PHASE SHIFTER

The 12 dB input attenuator decreases the amplitude to a convenient level for the first bridge amplifier A and the FET T (E105). The R,C,D network at the control input serves for protection and filtering.

There are two outputs. At OUT1 the maximum phase variation is 180° and at OUT2 360°. The circuit is mounted in a NIM module. More details are given in ref. [2].

5. CHARACTERISTICS (MEASURED)

Figure 6 shows the measured phase angle (lower traces) versus control voltage U for 3 and 8.34 MHz at output OUT 2. For more detailed characteristics see ref. [2].

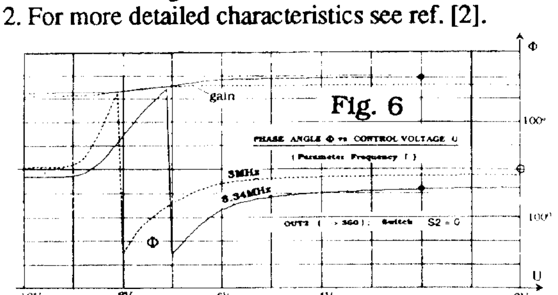

Fig. 6 PHASE ANGLE Φ vs CONTROL VOLTAGE U

6. APPLICATION OF THE PHASE SHIFTER AS SECOND HARMONIC PHASE CONTROLLER

6.1 Acceleration Voltage, Potential Well, RF Bucket, Bunch Shape.

Illustration of the phase influence in acceleration with 2nd harmonic voltage is given in Figures 7 - 9, showing typical operation examples.

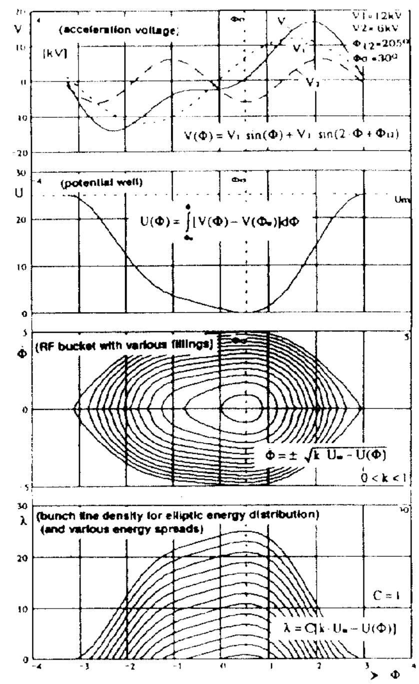

Fig. 7 Shows versus Phase ϕ in :

a) the acceleration voltage V, composed of V1 (12 kV) and V2 (6 kV) and a phase ϕ_{12} = 205°. between them,
b) the corresponding potential well with maxima on same potential energy (no acceleration).
c) a number of trajectories (of particles with various energies) in the longitudinal phase plane $\dot{\phi}$–ϕ,
d) the corresponding bunch line densities λ (for elliptic energy distribution) [3].

For a stable phase ϕ_σ>0 the greatest bucket size is not obtained with a flat topped bunch (smallest space charge) but with a certain top inclination (Figure 7d).

Figure 8 shows the behaviour for ϕ_{12} = 156° and V2 = 10 kV. (Acceptance increases with V2.)

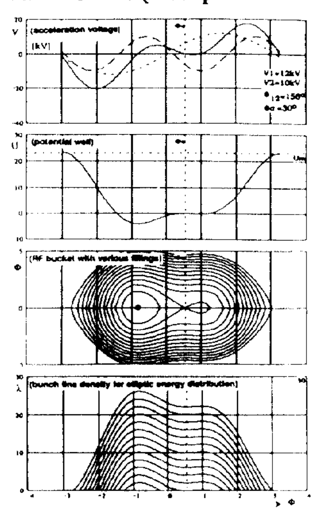

Fig.8 Bucket increases with V2.

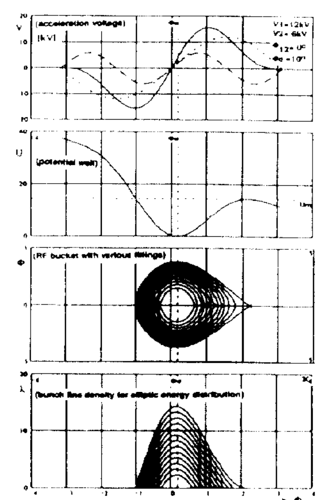

Fig.9 Shortest Bunches for ϕ_{12} = 0.

Figure 10 demonstrates (slightly exaggerated!) the principle how two bunches, coming from two different Booster (PSB) rings, are transferred into one PS RF bucket. (Filamentation neglected). Shorter (black) PSB bunches lead after 1/4 synchrotron period Ts in the PS to a lower space charge ρ_{max} than the longer ones [4], [5].

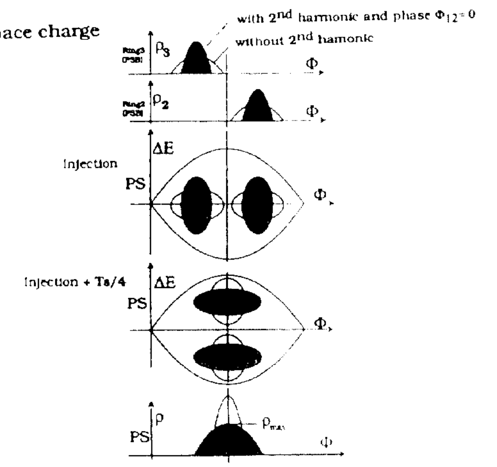

Fig. 10 Transfer of 2 Bunches to 1 RF Bucket.

6.2 *Observed Beam Response*

Figure 11 shows how the bunch shape is changed from a long flat topped bunch to a short and high one by a 180° ϕ_{12} program step (double exposure with 20 ms delay).

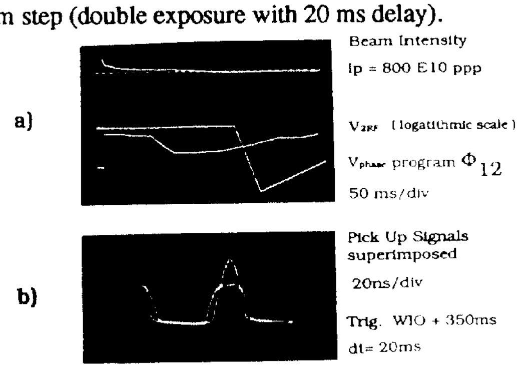

Fig. 11 Bunch Shape Control.

Figure 12 demonstrates on a mountain range display this bunch shape modulation just before ejection (upper trace).

Figure 13 illustrates the stabilisation effect of the 2^{nd} harmonic applied with the right phase. The upper intensity trace in Figure 13a shows sudden losses (after 350 ms) due to coupled bunch mode oscillations. Deforming the potential well by applying a 2^{nd} harmonic voltage peak for a short time with the phase corresponding to Figure 8 causes asymmetrical bunches (Figure 13c). The bucket increase as well as Landau damping help to avoid losses (Figure 13b).

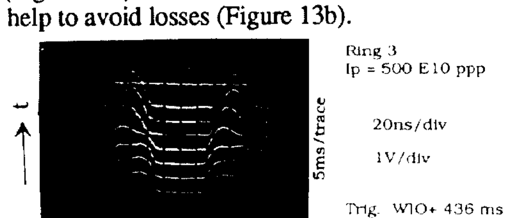

Fig. 12 Bunch Shape Evolution.

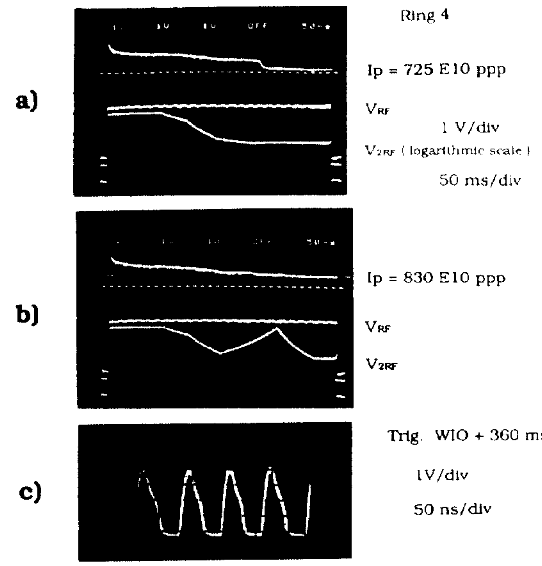

Fig. 13 Stability Improvement by Bucket Deformation.

The mountain range display of Figure 14 shows the bunches during the complete acceleration cycle in the PSB ring 2.

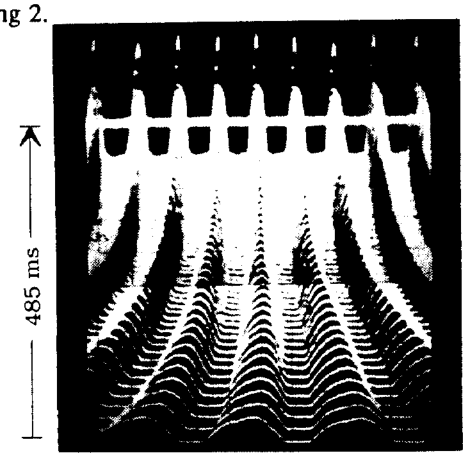

Fig.14 Wall Current Monitor Signal during Booster Cycle

1V/div
100ns/div

The bunch shape at the bottom line is generated with a phase ϕ_{12} of about 200° (Figure 7). The short and high bunches at the top are produced before ejection by ϕ_{12} = 0° with the condition shown in Figure 9. The short bunches from 2 PSB rings offset by ± 80° are then transferred to the PS with the scheme illustrated in Figure 10.

All this bunch shape gymnastics is possible in pulse to pulse modulation due to the presented electronic phase shifter.

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