GENERATION OF A HIGH VOLTAGE TRAPEZOIDAL WAVE FORM FOR A μS-PULSED BEAM SYSTEM AT S.I.N.

P. Lanz, H.P. Leber, R. Häussler, M. Märki, N. Schmid, U. Schryber

S.I.N. - Swiss Institute for Nuclear Research, 5234 Villigen, Switzerland

Summary

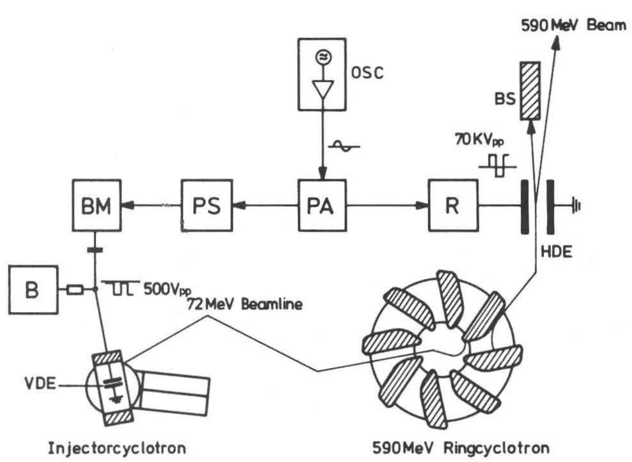
For the pulsed mode of the 590 MeV proton beam at SIN an extremely high current suppression is required. This is achieved by deflecting the beam electrostatically into a stopper block with a repetition rate of 200, 400 or 600 kHz. Trapezoidal deflection voltages of 70 kV are required.

Various possibilities to generate the deflection voltage are compared. The best solution is a network of lumped elements where the wave form is generated by the superposition of odd harmonics (1 to 9). The power amplifier and the harmonic generator are described.

1. Introduction

During the last two years, the S.I.N. accelerator facility[1)] has been operated for approximately 30 % of the high energy beam time in the so called "pulsed beam" mode. In this mode of operation the 590 MeV proton beam is periodically chopped with a frequency of some hundreds of kHz.

The experimental technique of the pulsed beam was proposed by Czapek et al.[2)] for the study of delayed processes at high current accelerators. A typical experiment is the search for very rare muon decays (μ→e-conversion in nuclei). During the beam-on-time stopped muons are accumulated in a target. During the beam-off-time the decaying muons can be observed essentially free of background. The beam-on and off-times must therefore be similar to the lifetime of the muons captured in the target nuclei. (The average lifetime of muons captured in sulphur nuclei is ∿0.6 μs). The particular experiment mentioned above requires a current suppression factor $i_{off}/i_{on} < 10^{-7}$, i_{off} and i_{on} being the beam current during the off-time and on-time respectively. It is very important that the specified current suppression be reached in a time as short as possible. 0.2 μs should not be exceeded.



OSC: Oscillator for 200, 400, or 600 KHz operational frequencies.
PA: Power amplifier for square wave signals
R: Resonator network for odd harmonics (incl. fundamental)
HDE: Horizontal deflection electrodes
BS: Beam stopper
PS: Phase shifter
BM: Bistable multivibrator
VDE: Vertical deflection electrodes
B: Bias voltage supply

Fig. 1 Concept of the pulsed beam system

The concept of the beam pulser is shown in fig. 1. The beam extracted from the 590 MeV ring cyclotron is deflected by an electric RF field into a copper block (BS) during the beam-off-time. The deflection field is produced by a pair of electrodes (HDE) 1.7 m long connected to an RF power amplifier. A square wave voltage of approximately 70 kV_{pp} is produced by the superposition of odd harmonic frequencies. The fundamental frequency is either 200 kHz, 400 kHz or 600 kHz.

In order to keep the beam losses on the beam stopper and in the proton channel as low as possible, the beam is suppressed during the beam-off-time in the center region of the injector cyclotron. This is achieved by vertically deflecting the beam on the first three orbits with a pair of electrodes. The applied deflection voltage of 500 V_{pp} is generated with a bistable multivibrator (BM).

The time structure of the beam pulses extracted from the injector cyclotron does not fulfill the specified conditions. The switching time (10 % to 90 %) was measured to be as large as 0.4 μs. This can be explained by the transit time of the protons through the deflection electrodes and by the multiturn extraction system of the injector cyclotron.

The phase relation between the deflection voltages in the injector cyclotron and in the 590 MeV deflection system is given by the pulse repetition time and the transit time of the protons through both accelerators. In practice, the phase is found empirically such that the beam losses on the stopper are minimised.

This paper concentrates on the generation of the trapezoidal deflection voltage applied to the deflection system in the 590 MeV beam line. The specifications can be summarized as follows (see also fig. 2):

0018-9499/79/0400-2190$00.75

max. ripple	$w=\Delta u/u_{pp} \leq 0.1$
rise-falltime	$T_f \sim T_r \leq 0.1\ T_1$
repetition rate	$T_1 = 1/f_1$
fundamental frequency	f_1

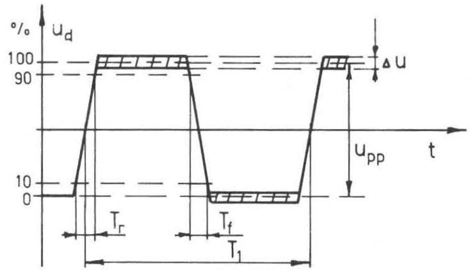


Fig. 2 Required deflection voltage response

2. Possible methods for generating high voltage trapezoidal wave forms

2.1 Voltage switching (floating deck modulator)

The simplest concept is the use of a commutating switch. At high voltage level and high frequency, this has to be done using high power electron tubes which are able to carry high voltage and current levels. Considerable amounts of energy are stored in the load capacitor which is discharged twice on each cycle, the energy being dissipated in the anode. The capacity is estimated to be about 1000 pF. The dissipated power is:

$$P = 2 \cdot W \cdot f = C \cdot u_p^2 \cdot f = 490 \text{ kW}$$

with $u_p = 35$ kV, $C = 1000$ pF, $f = 400$ kHz

Taking into account the internal losses of the tube during the charging cycle of the capacitor, dc-power of the order of 1000 kW is necessary.

2.2 Superposition of odd harmonics (Fourier synthesis)

A symmetrical pulse shape will be produced by the superposition of a fundamental wave and its odd harmonics. By using resonant circuits the stored energy oscillates between the capacitive and inductive elements. Resistance power loss is very small compared to the power dissipation in the previously mentioned arrangement.

2.2.1 Superposition of odd harmonics in a line resonator

A line resonator works according to the principle mentioned above. It consists of a line of length l, shortcircuited at one end. The input impedance $\bar{Z}$ of such a line resonator can be expressed as

$$\bar{Z} = jX = j\ Z_o \cdot \tan 2\pi l/\lambda$$

λ : wavelength
l : line length
Z_o: characteristic impedance of the line

This function has poles at odd harmonics and zero roots at even harmonics as shown in fig. 3.

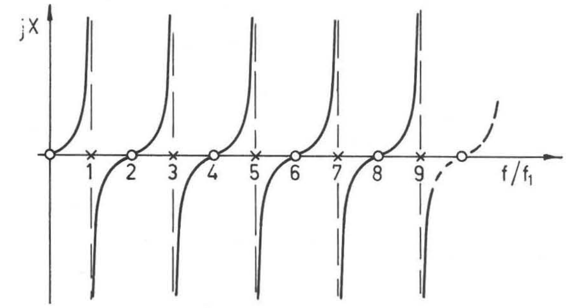


Fig. 3 Impedance response vs frequency

However, a line 187.5 m long ($\lambda/4$ at 400 kHz) takes up too much space. Even with a shortening factor of approx. 3, attained using a helical inner conductor, such an installation is still too large. Separate generation of harmonic waves as well as reaction free addition on the line resonator is complex and requires a dc-power level of approx. 100 kW 3) 4).

2.2.2 Superposition of odd harmonics in a network of lumped elements

A similar impedance behaviour (fig. 3) can be achieved by using a network of lumped elements. The load capacity (deflection electrodes) can be integrated into the network without showing the drawbacks described under 2.1. Resistance losses are very small and, due to the trapezoidal wave form of the anode voltage, tube efficiency is excellent. All odd harmonics needed are generated automatically by one common amplifier. Total dc-power is approx. 18 kW.

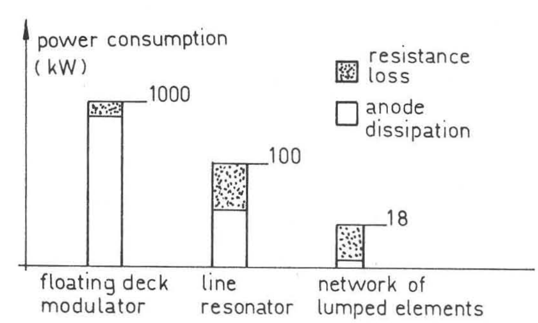


Fig. 4 Power requirements for generating a 70 kV_{pp} trapezoidal deflection voltage using different methods.

The above arguments lead to the conclusion that a system built from lumped elements would be the most suitable for our purpose.

3. Circuit description and operation of the lumped element network

3.1 Impedance response

The trapezoidal wave form is produced by the superposition of odd harmonic voltages on a fundamental wave. To generate the required rise- and falltimes, it is necessary to superimpose the harmonics of order 1, 3, 5, 7 and 9[8]. If the amplitudes and phases are properly chosen, the requirements on preshoot, overshoot and ringing can be satisfied.

To get parallel resonance at these 5 frequencies, such a network has to generate 5 poles. A two port network is characterised by its impedance or admittance as a function of frequency. For a two port network with given frequency response the synthesis of its circuit configuration and elements is possible. With the impedance response of fig. 3 this unknown network contains only loss free elements. Due to the high Q-values of coils, resistive components are negligible for a rough calculation of the reactive elements. To get the required impedance function, Foster's reactance theorem can be applied

$$\bar{Z}_{(p)} = \frac{p\ (p^2+\omega_2^2)\ (p^2+\omega_4^2)\ (p^2+\omega_6^2)\ (p^2+\omega_8^2)\ K}{(p^2+\omega_1^2)\ (p^2+\omega_3^2)\ (p^2+\omega_5^2)\ (p^2+\omega_7^2)\ (p^2+\omega_9^2)}$$

with $p = j\omega$

Inversion of $\bar{Z}(p)$ and partial fraction expansion yields the susceptance

$$jB_{(p)} = pC_L + \frac{1}{pL_1} + \sum_n \frac{p \cdot C_n}{(p^2+\omega_n^2)}$$

with n = 2, 4, 6, 8.

This results in a circuit useful for our purpose wherein the parallel load capacity C_L can be integrated. The last expression of the equation describes the 4 different series resonance circuits (fig. 5).

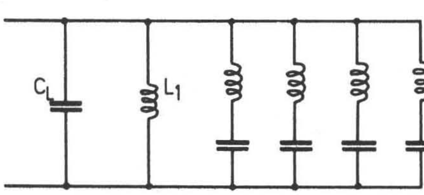


Fig. 5 Simplified circuit diagram

For the 5 odd harmonics p=1, 3, 5, 7 and 9, $B_{(p)}$ becomes equal to zero and the set of 5 equations is defined and can be solved for the component values L_1 and C_n. Corresponding L_n values are then defined by the series resonance condition for each circuit

$$L_n = 1/\omega_n^2 C_n$$

3.2 Design optimisation of the circuit

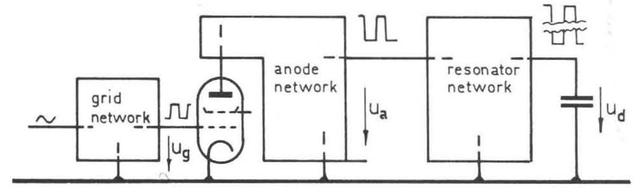


Fig. 6 Block diagram

3.2.1 Resonator network

The circuit of fig. 5 satisfies the impedance response requirement. Each capacitor has to carry voltages considerably higher than the output voltage and therefore high voltage type capacitors are necessary. Studies of equivalent networks have been performed[5] and the most suitable one is shown in fig. 7.

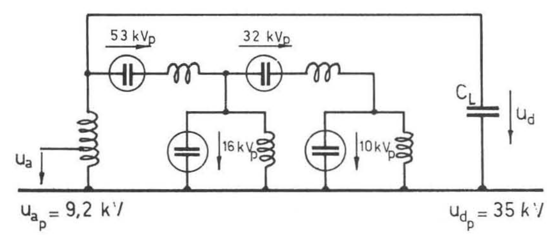


Fig. 7 Resonator network

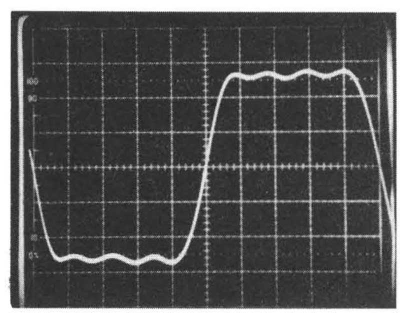


Fig. 8 Deflection voltage u_d

The resistance at resonance must have the same value for all 5 odd harmonics. This can be achieved by matched series coil resistances [5]. Impedance matching is achieved with an autotransformer and results in a constant anode load resistance R_L of 5 kΩ (fig. 9).

3.2.2 Anode network

High anode stray capacity would have a negative influence at high frequencies. Therefore the anode circuit is laid out in a manner similar to the resonator circuit. Design optimisation results in two series resonant circuits combined to a network of 4 elements (fig. 9). Therefore, only 2 high voltage capacitors are necessary. Resonance resistance is made very high and its power consumption is approx. 5 % of the total RF power dissipation.

0018-9499/79/0400-2192$00.75 ©1979 IEEE

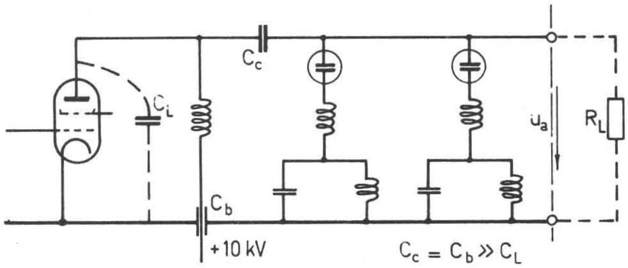


Fig. 9 Anode resonance network

Linear transformation forces the anode voltage to have a similar trapezoidal wave form. With a given constant load resistor R_L and the transconductance S of the tube the control voltage is given by

$$u_g = S \cdot i_a = S\, u_a / R_L .$$

Due to the nonlinear nature of tube characteristics, graphical methods are usually most convenient and rapid (fig. 10).

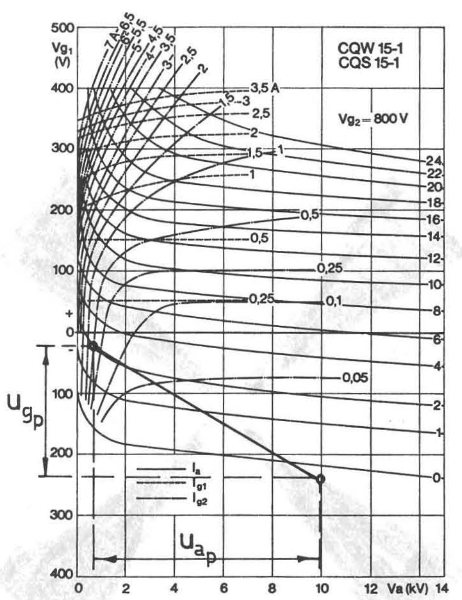


Fig. 10 Characteristic curves of the CQW-15-1 (Tube Handbook[7])

3.2.3 Grid network

The grid control voltage of ± 230 V is generated in a separate network (fig. 11) by direct conversion of a sinusoidal wave form[6])

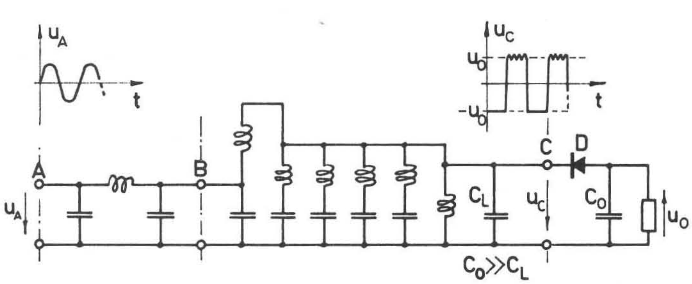


Fig. 11 Grid resonance network

This special network has two functions. For the fundamental wave it represents two π-sections. They transform the voltage u_A and match the load impedance to the impedance of the 50 Ω incoming cable at port A.

For the harmonic waves, however, impedance response, looking into port C, is the same as in fig. 3. Current harmonic components are generated by a clipping diode D. Even harmonic components will produce no voltage at port C as the network impedance $\bar{Z}$ is equal to zero. A superposition of the odd harmonic voltages takes place and automatically produces the trapezoidal wave form (fig. 12) essential to control the tube.

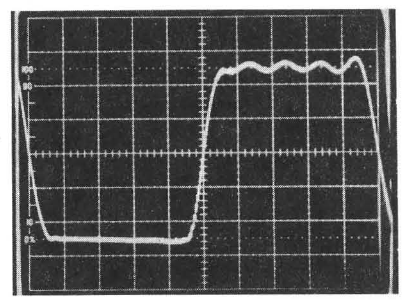


Fig. 12 Grid control voltage

The advantages of this pulse generating method in the grid network are the high stability of the pulse form and the low control power level (150 W) required. This power is furnished by a solid state wideband amplifier 9).

3.3 Change of operating frequency

The networks described above are designed for three different operational frequencies (200, 400 and 600 kHz fundamental). In order to change from one frequency to another, network elements have to be switched and the network must be retuned. This procedure is executed by remote control.

References

1. H.A. Willax
   Proc. 7th Int. Conf. on Cycl. and their Appl. 1975, (Birkhäuser Basel CH), p. 33
2. G. Czapek et al.
   Nucl. Instr. and Meth. 105 (1972), p. 609
3. P. Lanz, M. Dubs,
   Technical report TM-04-29, S.I.N.
4. M. Märki,
   Technical report TM-04-31, S.I.N.
5. R. Häussler, M. Märki,
   Technical report TM-04-32, S.I.N.
6. M. Märki,
   Erzeugung grosser Spannungen mit annähernd rechteckförmigen Verlauf bei hohen Frequenzen,
   SEV Bulletin, 6, p. 262-267, March 1978
7. BBC, Baden
   Electron Tube Handbook, 1975,
   data sheet CQW-15-1
8. H.J. Bartsch,
   Mathematische Formeln, 4. Auflage,
   Leipzig VEB Fachbuchverlag 1962
9. N. Schmid,
   Technical report TM-04-36, S.I.N.