PULSE GENERATORS FOR DELAY LINE DEFLECTORS

by

H. van Breugel, J. Goëni and B. Kuiper

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0. Summary

A design is presented of a standard line type pulser for adjustable pulse duration with a rise and fall time of about 15 nanoseconds. A combination of such standard pulsers can serve in a variety of applications with inflectors, ejectors and fast beam switches. The design is based on operational experience with the pulsers of the CPS fast ejection system. Arguments leading to this engineering approach are given.

1. Introduction

By the trend towards higher energies combined to a general lack of space in circular accelerators, electrostatic deflectors have become marginal or inadequate as inflectors into or ejectors from these machines. For that reason magnetic deflectors have been proposed in most recent designs 1,2,3).

Though several approaches can in principle produce the required rectangular magnetic pulse 4), the delay line deflector 5) has come to the foreground due to its superior pulse shape and inherent flexibility.

Deflection systems of this type have been proposed for use in multipurpose beam transfer systems 6,7) and beam switchyards. As their application in several places of one and the same project is foreseen, a certain standardization of magnet and pulser designs is desirable.

This is possible due to the different modes in which delay line magnets can be excited, i.e. by several pulsers in parallel, in series, or several magnet units by separate pulsers. A practical module can then be formed by a pair of pulse generators on an intermediate impedance level. Such a combination leaves a certain freedom as to the above modes of excitation. Up to 4 or even 6 pulsers can be triggered and monitored from one local control rack. Some parameters like the impedance can within limits be changed by obvious simple modifications so as to optimize these for application in a particular project. The proposed design can thus serve as a
basis for a number of identical modules, that by relevant combination can excite the different delay line deflectors of one project.

In this design advantage is taken of several years of operational experience with the pulse generators exciting the delay line kicker magnet of the CPS fast ejection system 8). Confidence is hence felt that with the chosen parameters reliable long term operation can be attained.

2. Design Philosophy

The major choices to be made in the design of line type pulzers for delay line magnets are in order of their importance: (1) The impedance level, (2) the execution of the pulse forming network, (3) the type of switch and (4) the means of pulse transmission.

2.1. Impedance level

The desired magnet performance and the desire for voltage reduction set a constraint to the impedance level. There is in general some margin to fit the latter level to a commercially available pulse cable or a combination thereof in parallel. In case of multiple utilization in one and the same project the large order for pulse cable may justify the choice of the optimum impedance. However, even in one project it is unlikely that these different applications result in the same optimum. The resulting impedance level will therefore be a compromise anyway and the choice may then be influenced by other considerations than the optimum magnet parameters.

Though there exists no sharp limit toward higher impedances, the concomitant higher voltages for the same current make them less attractive. Very low impedances become increasingly difficult to handle, due to the series inductances in capacitors of the delay line magnets and in the pulse forming networks. For a given switch a lower impedance leads to a longer rise and fall time of the current pulse. Finally very low impedances are more complicated and costly due to the use of more low impedance pulse cable in parallel.

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Impedances between 5 and 15 \( \Omega \) appear in practice to be convenient and most recent designs propose values within this range. The present proposal is made for 10 \( \Omega \) impedance, but obvious modifications may adapt it to any impedance in the above range.

2.2. Pulse shaping

The seemingly simplest execution of the pulse forming network is a charged cable. Another possibility is the use of a lumped element line simulating network.

Advantages of using cable, commonly put forward, are the inherent flat top of the current pulse, the short rise and fall time of the latter and the simplicity of the concept. For short pulses, say up to 0.1 \( \mu s \), these arguments are valid without reserve. For pulses of say 1 \( \mu s \) or longer the cable lengths in question become such that the resistance of the conductor produces a droop of the flat top. At the same time the fall time is increased (cp. fig. 1b) to values impractical for application in inflectors and partial fast ejectors. Calculations \(^9\) show that at least up to 2 \( \mu s \) pulse length this may be improved by using two or more cables of a higher impedance in parallel, with solid (as opposed to stranded) conductors and without semi-conductor screen. Experiments in this sense are being planned. However, reliable high voltage low impedance pulse cable with solid conductors and without semi-conductor screen is not yet commercially available.

To keep the electrical stress in the dielectric within practical values, low impedance cable tends to have a large diameter. This and the solid conductor render it stiff. Reduction of electrical stress and mechanical stiffness are two additional reasons for using two or more cables in parallel. Also, due to the difficulty of producing the long cable stretches in one piece, cable terminations become numerous. These constitute the hardest point in this approach because their particularly severe duty, i.e. the combination of high d.c. and pulse voltages. This latter fact, the number of cables, their lengths and their stiffness render the argument of simplicity doubtful.
Advantages of the lumped element line simulating networks are their reliability, price and simplicity, stemming from long industrial experience in the manufacture of oil impregnated capacitors and lines. Executions up to 120 kV charging voltage and more can be commercially obtained. The pulse from a lumped element line with 6 or more sections can be made flat to within any practical precision. The rise time is mainly determined by the time constant of the first section and can be shortened by increasing the number of sections for a given pulse length. The fall time stems from the same pulse front, but is rounded off by subsequent small phase shifts in each section as the discharge wave travels to the end of the line and back. Thus even in a lossless line the fall time will be a multiple of the rise time. Dividing the line into smaller elements is not very effective, since the initially smaller rise time is partially offset by the traversal of a greater number of sections. Such a procedure increases the losses in the line and makes tuning of it more difficult.

A fast rise (cp. figs. 1c and ld) can conveniently be obtained by use of an adaptor network such as $R_{1}C_{1}L_{1}$ in fig. 2b. As explained, there are fundamental difficulties in realizing a long rectangular current pulse with a steep descent using passive elements. The slowly falling tail can however be cut off (cp. fig. 1e) by short circuiting the line at the required moment. Using these 'tricks' rectangular current pulses can be generated with rise and fall times essentially determined by the characteristics of the switches, independent of the pulse length or of the section size.

These principles are the basis for the present proposal. A superior pulse shape is thus obtained whilst taking advantage of the main qualities of lumped element lines, such as reliable high voltage performance, low price, compact construction and easy handling. The duty of the pulse cables and their terminations is thereby reduced to pulse transmission only, hence to half the charging voltage. Additional advantages are fine adjustment of the pulse length by the delay for the second trigger, and the possibility of relaxing the tolerances on the impedance of the pulse cables. The latter can then be taken as they come and the lines and magnets can be matched to their actual impedance.

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2.3. Switching

For line voltages under 50 kV hydrogen thyratrons are commercially available with current capacities of up to 5000 A, for pulse lengths around 2 µs. Their main advantage is ready availability, wide operating voltage range, negligible jitter, high maximum repetition rate (up to 1000 pps), and great number of operations (10⁷ or more). Drawbacks are their relatively long delay time (up to 1 µs) and slow current rise time (50-100 ns). The necessity for heating, is a constraint in certain circuits. For these reasons several designs still use triggered high pressure sparkgaps even under 50 kV. Designs of the latter have become reliable and sophisticated. Delay times and rise times are of the order of 10 ns and time jitter can be kept smaller than 5 ns. Sparkgaps are 'custom built', so as to suit a particular application, they are simple to operate and to service and their life can be stretched to more than 10⁷ operations (for charges of 20 mC) by using the revolving discharge principle (cp.sec.4), where the sparking point is continuously shifted over a large surface. Hydrogen thyratrons remain the solution where extreme pulse repetition rates are envisaged.

Even if delay and current rise time of the thyratrons are acceptable sparkgaps are generally preferred above 50 kV due to the complications arising from series operation of hydrogen thyratrons. The present proposal uses triggered sparkgaps with automatic pressure regulation.

2.4. Pulse transmission

High voltage coaxial low impedance pulse cable is now commercially available in a range of voltage ratings and impedance levels. Its pulse transmission characteristics for the rise times in question are satisfactory up to distances of around 50 meters. This is adequate for most installations.

The cable connections are manipulated from time to time. They should not be too stiff and hence their diameter should remain limited. For reasonable outer diameters, say up to 50 mm, and pulse voltages up to 50 kV no adequate pulse cable of 10Ω impedance is yet available. The diameter
ratio of the conductors in 50 $\Omega$ cable would give the greatest high voltage reliability and the best tolerance on the impedance. Per unit length and for a given voltage rating the price decreases with increasing impedance up to 50 $\Omega$. Yet, the lowest number of cables in parallel, satisfying requirements of voltage and flexibility is still the lowest priced overall proposition. The present pulse generators are therefore based on pulse-transmission by two 20 $\Omega$ cables in parallel. The voltage ratings can be obtained and the higher tolerance on the impedance can be dealt with (cp. sec.2.2.).

3. The Pulse Forming Network

The circuit diagram of one pulse generator is shown in fig. 2b. The line has 10 $\Omega$ impedance and the pulse has a maximum flat top of 2.1 $\mu$s. The line is laid out for a charging voltage up to 80 kV. It will consist of 10 lumped sections of 10 000 pF capacitance and 1 $\mu$H inductance each. The line is preceded by an adaptor for providing the fast current rise. Approximate values for its elements are: $R_1 = 10\Omega$, $C_1 = 10\ 000\ \text{pF}$ and $L_1 = 1.5\ \mu\text{H}$. They are adjusted empirically so as to produce the desired pulse shape.

If the pulse length is to be changed the utilization of an entirely canned and oil impregnated line is unpractical. Separate capacitor units are therefore used and the inductances are mounted between the bushings. The length of the bushings of the capacitors inevitably introduces some series inductance into the capacitive branches but with the element size chosen and with some care in the connections this is not appreciable.

Coaxially inside the inductances are small pneumatic cylinders, actuating the circuit breakers between line sections. The entire assembly, including the adaptor, is contained in a vessel pressurized to a few atmospheres of nitrogen or air. The dome shaped upper part can easily be lifted off and the assembly is then accessible for inspection and maintenance.

The design of the capacitor bushings must give special attention to the tracking problem which is more severe than in conventional lines due to
the repeated voltage reversals introduced by the short circuiting. The resistor in the adaptor must have adequate pulse ratings, since the energy contained in the cut-off tail of the pulse is dissipated in it under normal operating conditions and the entire energy under fault conditions (early trigger of the short circuit sparkgap). Obvious provisions are made for entry of charging voltage, compressed gas and control signals. The exit terminal of the pulse forming network is a 10Ω coaxial pulse connector on which the main sparkgap is mounted directly. Fig. 2a depicts the rack mounted dual 10Ω pulse generator, with its local controls and triggering units.

4. Main Sparkgap

The main sparkgap is derived from the three electrode swinging cascade gap, combined to the revolving discharge principle. Fig. 3 shows a sectional drawing of the gap.

The trigger pulse arrives through a 50Ω cable and is coupled to the trigger electrode by a capacity of 150 pF. This pulse almost instantaneously breaks down the small gap between trigger electrode and needle, creating its own ionization by field emission. This small discharge creates primary ionization in upper and lower half of the main gap and, charging the center electrode, overvolts and breaks down the upper gap. The center electrode then assumes the potential of the hot electrode and this breaks down the lower gap.

The annular electrodes reduce the influence of erosion by exposing a greater surface. Due to manufacturing tolerances the spark will at first preferentially occur at one spot. This erodes the electrodes there and eventually enlarges the local gap spacing. The sparking point then moves to a less eroded point where the gap spacing is smaller and in prolonged operation it revolves slowly around the ring shaped electrodes until the gap spacings are equalized. The spark then tends to occur at random places, but in the average uniformly around the ring. Experience shows that this
distributes erosion homogeneously around the annular surfaces. Local deformations remain so small, that no influence of erosion can be detected on the performance over several million operations.

Using a 30 kV trigger pulse with a rise time of 20 ns and an exponential decay of 50 ns, the delay of the gap is around 10 ns, the jitter smaller than 5 ns and the rise time of the current pulse in a 10 Ω line around 15 ns, depending on the gas pressure used.

The gap is entirely coaxial and terminated on two sides with 10 Ω coaxial pulse connectors fitting to the pulse forming network on the upper side and to the short circuit gap on the lower side. The gap is shown assembled in fig. 4 and dismounted in fig. 5.

5. Short Circuit Sparkgap

The obvious approach to the short circuit sparkgap is a trigatron with the trigger pin in the earthed electrode of the outer conductor. However, the erosion of the trigger pin by the main discharge requires its too frequent adjustment and renders the trigatron in this application less practical for continuous operation.

A three electrode configuration, like in the main gap, is the next logical proposition. Voltage division is obtained by inter-electrode capacities. The trigger electrode can not directly act on the center electrode, since the induced voltage surge in the latter will prematurely trigger the gap by a discharge to the trigger electrode, which being fed from a low impedance source, remains essentially on earth potential. To avoid this the distance between these two electrodes must be increased, but this introduces delay and jitter, due to lack of premiary ionization, since the field strength becomes too small for field emission.

To deal with these problems a sparkgap was developed specially adapted for this application. It is represented in fig. 6, where an insert gives a simplified diagram. Electrode 4 is a 'floating' trigatron, i.e. with a
high impedance to earth. The trigger pulse produces instantaneous ionization for the whole gap, by the small pin electrode discharge. This overvolts and breaks down the gap 2-4, thus rapidly charging the center electrode. The remainder of the breakdown mechanism is like in the main gap.

The electrical parameters of the gap must fulfill certain conditions to make the scheme work. (1) The inter-electrode capacities must be such that the voltage division corresponds to the relative gap spacing between center and other electrodes. If spacings are designed by the symbol d, this means \( \frac{C_{12}}{C_{23}} \approx \frac{d_{23}}{d_{12}} \). (2) For a constant voltage division during the pulse the time constant for discharge of the center electrode through its leak resistor must be long compared to the length of the line pulse \( T \), hence \( \left( \frac{C_{12} + C_{23}}{C_{34}} \right) R_{24} \gg T \) assuming \( R_{24} \gg R_{43} \). (3) For good triggering of the trigatron we require that \( C_{t4} \ll C_{34} \) and \( R_{43} C_{34} \gg D \), where the subscript \( t \) refers to the trigger pin and \( D \) is the firing delay of the whole gap. The first condition ensures good overvolting of the gap 2-4, the second maintains the trigatron voltage until the gap has broken down. (4) For effective overvoltage and breakdown of gap 2-4 one requires \( C_{24} \ll C_{12} + C_{23} \). (5) To avoid premature triggering by induced voltage on the trigatron electrode we must require \( C_{24} \ll C_{34} \).

The electrodes have been shaped so as to increase the inter-electrode capacitors, thus meeting the above conditions. Resistance values are chosen accordingly. As in the main gap the revolving discharge principle ensures constant performance over prolonged periods. Firing delay, time jitter and current rise time are of the same magnitude as in the main gap, if the same trigger pulse is being used.

6. Pulse transmission

As explained in sec.2.4, the pulses will be transmitted through two BICC 40 P 3 pulse cables of 20 \( \Omega \) impedance in parallel. Transmission distances should be limited since the rise and fall time of the current pulses will be adversely affected.
The 10Ω coaxial conductors of the pulse generators end in cable junctions with two pulse connector sockets. The dielectric of the cable is terminated with coaxial pulse connector plugs of epoxy resin. The conical plugs fit precisely into the female cones of the connector sockets on the cable junctions. They are introduced with a thin layer of silicon grease. The outer conductor of the cable ends in a stress cone. The joint between the polyethylene dielectric and the epoxy plug needs adequate attention as it is the main point of difficulties in pulse transmission over cables. Pulse contacts between the conductors must be shaped so as to avoid sparking due to the high rates of rise of the current.

7. Triggering and Controls

Triggering of each pair of spark gaps is done by a 30 kV dual triggering unit. Such a unit is essentially a master sparkgap that switches a charged capacity to two 50 Ω cables in parallel, leading to the sparkgaps. Triggering cables are long enough to avoid interference between the gaps. The resulting trigger pulse has a peak voltage of 30 kV, a rise time of around 20 ns and an exponential decay of 100 ns time constant. The master gap is preceded by a two stage hard valve pulser that works with a 40 V fast pulse as input.

The local control unit permits to switch on and off, to adjust the voltage and charging speed of the line, the pulse length and the repetition rate. It contains the necessary interlocks for personnel and material safety and permits their monitoring and that of the operating parameters. The control panel is repeated in the remote operating rack. The latter also contains timing devices and a fast synchronization channel to lock the rise of the generated pulse to the RF phase of the machine in question. A fast oscilloscope monitor permits observations of the pulse behaviour in relevant points of the circuit. The monitor makes use of a coaxial channel selector unit in the local controls rack between the lines. This unit also contains an interlocked pulse comparator, that switches off the high voltage
on the lines if the difference between two pulses is repeatedly above a threshold value.

The gas pressure control unit makes the pressure inside the sparkgaps follow a reference signal proportional to the charging voltage of the line. The unit further contains reducers, filters, gas pressure and flow monitors, remote indication transmitters and interlocks.

8. Acknowledgements

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a) 20 section lumped element line of 10 Ohm impedance. Horizontal scale: 0.4 µs/division. Flat top corresponds to 2500 A.

b) Continuous line, i.e. 14 Ohm cable. Fall of current pulse only. Horizontal scale: 0.050 µs/division. Flat top corresponds to 1500 A. (By courtesy of W. Middlekoop, A.R. Division).

c) 20 section lumped element line, adaptor preceding the first section. Horizontal scale: 0.2 µs/division. (Low voltage model of 125 Ohm impedance).

d) Same as c) but on horizontal scale 0.010 µs/division.

e) 20 section lumped element line without adaptor but its tail cut off by a short circuit sparkgap. Impedance 10 Ohm. Horizontal scale: 0.2 µs/division. Flat top corresponds to 2500 A.

Fig. 1. Oscillograms of current pulse shapes
a) Assembled generator

b) Circuit diagram. HV = charging line from high voltage supply; IR = isolating resistor; Lo Co = line elements; S = switches; R1C1L1 = adaptor elements; G = main spark gap; SCG = short circuit sparkgap; T1 = 1st trigger generator; T2 = 2nd trigger generator; D = delay.

Fig. 2. Proposed 10 Ohm dual pulse generator
Fig. 3. Drawing of main sparkgap

- HOT ELECTRODE
- CENTER ELECTRODE
- TRIGGER CABLE
- TRIGGER ELECTRODE
- CONNECTOR TO SHORT CIRCUIT GAP
- TUNGSTEN TIPS
- ADJUSTMENT TRIGGER NEEDLE
- NYLON ROD
- TEFLON INSERT
- TRIGGER NEEDLE
- TEFLON INSERTS
- CERAMIC CAPACITORS
- TRIGGER ELECTRODE
- MALE 10A PULSE CONNECTOR TO PULSE FORMING NETWORK
- WINDOW
- AIR FLOW OUT
- TEFLON INSERT
- CAPACITIVE PICKUP
- STOP RESISTOR
- TEFLON INSERTS
- AIR PRESSURE IN
Fig. 4. Assembled main sparkgap
Fig. 5. Components of main sparkgap

Legend:

1) Upper part of gap
2) Center part of gap
3) Lower part of gap
4) High voltage electrode
5) Center electrode
6) Ground electrode
7) Connector socket for d.c. bias of center electrode
8) Connector on cable coming from voltage divider
9) Stop resistor in connector
10) Connector socket for trigger pulse
11) Connector on trigger cable
12) Knob for adjusting trigger needle
13) Connector socket on capacitive pickup of center electrode voltage
14) Compressed gas inlet
15) Gas outlet
16) Window permitting view of trigger and main discharge
17) Trigger electrode
18) Trigger needle
19) Loaded epoxy resin dielectric
20) Female 10 Ohm pulse connector
21) Male 10 Ohm pulse connector

Fig. 5. Components of main sparkgap
Fig. 6. Drawing of short circuit sparkgap
Legend:

1) Hot electrode  
2) Center electrode  
3) Ground electrode  
4) Floating trigatron  
5) Housing  
6) Compressed gas inlet  
7) Loaded epoxy resin  
8) Teflon insert  
9) Connector on trigger cable  
10) Female 10 Ohm pulse connector  
11) Male 10 Ohm pulse connector

Fig. 7. Short circuit sparkgap