Nanosecond high voltage pulses for internal cyclotron

beam deflection

by

H. Beger, M. Giesch and W. Stockdreher

Genève
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ABSTRACT

The projected electrical beam deflection system for the generation of a 40 ns proton beam pulse in the CERN 600 MeV synchrocyclotron is described. A test model of the most critical part of this system, the triggered spark gap, has been constructed and tested carefully. The necessary operation conditions of this gap (electrode distance, gas flow and gas pressure) are described to obtain a deflection pulse of 45 kV, 10 ns rise time and ± 5 ns jitter.
1. **Introduction**

On account of radial betatron oscillations, the particles produced by a proton beam hitting an internal target at the end of the acceleration cycle in the CERN Synchro-cyclotron have to go through about 1000 revolutions before they are fully ejected from the machine. The length of the secondary particle pulse leaving the target is about 200 $\mu$s. It is interesting, however, for certain experiments, e.g. time of flight measurements, to have appreciably shorter pulses. If all the protons accelerated can be deflected on to a target during one revolution the length of the secondary particle pulse can then be expected to be 40 ns. The protons are deflected by an electrostatic-magnetic deflector system, to which a suitably short electric pulse is applied when the proton bunch goes through it. A vertical velocity component is thus applied to the protons which, at the next revolution, hit a target of large vertical and radial dimensions. The present paper chiefly describes an arrangement to obtain the deflection pulse required.

2. **Deflection system**

2.1 **Deflector plates**

The proton beam will be deflected at a mean radius of 220 cm. On this radius, the beam is 11 cm wide and can be assumed to be 2 cm high. The deflector plate system consists of 3 parallel horizontal plates with a curvature in accordance with the path of the particles (Fig. 1, Ref. 1). Owing to lack of space, the arrangement cannot take up more than 30°. The two outer plates are earthed in order to minimize radiation losses, while the deflection pulse is applied to the middle plate through a coaxial cable of 50 Ohm (RG 19-U). To match the impedance of the cable, the plate system also has a $Z$ of 50 ohm, which is obtained when the ratio $\text{distance between plates/width of plates}$ is 0.3.

4529 / p
2.2. **Deflection pulse**

The proton beam is deflected by a travelling wave propagating along the deflector plates which must satisfy several conditions with respect to polarity, direction of motion and pulse form.

With the lay-out of the plates in the machine, the polarity is negative to obtain the required upward beam deflection.

The direction of motion of the deflection pulse must be opposite to that of the proton beam, so that the electromagnetic deflection should reinforce the electrostatic deflection.

During the passage of the beam between the plates, the amplitude of the pulse must be kept as constant as possible so that the deflection remains constant throughout the full length of the proton bunch. The minimum pulse length depends on the velocity and length of the proton bunch and on the length of the plates.

The leading edge of the pulse must have been travelling over the whole length of the plates by the time the proton bunch enters the plate system. The end of the pulse should not reach the plates before the proton bunch has left the system. For a deflection radius \( r = 220 \text{ cm} \), the azimuthal bunch length is about \( 120^\circ \) while the velocity is \( v = 0.78 \text{ c} \) (Fig. 1a). The minimum duration of the peak value is therefore

\[
t_{\text{min}} = \frac{\ell_{\text{plates}}}{c} + \frac{L_{\text{bunch}} + \ell_{\text{plates}}}{v}
\]

(1)

the numerical value being \( t_{\text{min}} = 28 \text{ ns} \).

Rise time and jitter must, however, be included in the actual length of the pulse. The maximum permissible time for rise time and jitter is itself restricted by the time during which the protons travel outside the plates.

4529 / p
\[ t_{\text{max}} \ (\text{rise + jitter}) = \frac{2 \pi m \alpha}{V} \left( \frac{\ell}{\text{bunch}} + \frac{\ell}{\text{plates}} \right) - \frac{\ell}{\text{plates}} \]

The numerical value being \( t_{\text{max}} \ (\text{rise + jitter}) = 30 \text{ ns} \)

The present paper deals with the conditions under which a triggered spark gap satisfies the requirement \( t_{\text{max}} \ (\text{rise + jitter}) \leq 30 \text{ ns} \).

The voltage required for the deflection pulse is calculated as follows. When a proton goes through the deflection system, it is subjected to a force working in the vertical direction

\[ k = eE + e v B \]  

where \( E \) = electric field between the plates

\( B \) = flux density of magnetic field arising from the deflection pulse.

With relations \( B = 1/c E \) and \( \beta = v/c \), one has

\[ k = eE \left( 1 + \beta \right) \]  

This force gives the following acceleration to the proton (of mass \( m_p \))

\[ Z = \frac{k}{m_p} = \frac{1}{m_p} eE \left( 1 + \beta \right) \]

The double integration of Equation 5 gives the height of the deflection at the end of the plates

\[ h = \frac{1}{m_p} E \left( 1 + \beta \right) \frac{\ell \omega}{2v^2} \]

\[ \frac{4529}{p} \]
In addition a restoring force due to the radial component $B_r$ of the cyclotron magnetic field acts on the proton towards the median plane. The proton accordingly goes through a vertical betatron oscillation of amplitude

$$Z = A \sin (\omega_s \sqrt{n} t + \varphi)$$

where $\omega_s = \text{revolution frequency of the protons at } r = 220 \text{ cm};$

$$n = \text{field index } dB/dr = 0.05 \text{ at } r = 220 \text{ cm.}$$

The constants $A$ and $\rho$ are determined by the conditions $t = 0: z = h, \dot{z} = \dot{h}$. With Equation (6), one has

$$Z = \frac{g}{\varepsilon} E (1 + \rho) \frac{1}{v} \sqrt{\frac{1}{\omega_s^2 n} + \frac{\rho^2}{4v^2}} \sin (\omega_s \sqrt{n} t + \varphi)$$

(8)

where $\varphi = \arctg (\frac{1}{v} \omega_s \sqrt{n})$.

At 220 cm, the betatron oscillation reaches its maximum after about one revolution. If the target is placed at the end of the plates, one obtains from Equation (8) for $z = 3.3 \text{ cm}$ a pulse voltage of

$$U = 42.5 \text{ kV}$$

The repetition frequency of the pulse voltage must be the same as the repetition frequency of the cyclotron, viz 55 Hz.
3. **Arrangement for generating pulses**

Fig. 2 is a block diagram of the arrangement for generating pulses. The outer conductor of the coaxial storage cable is connected via a load resistor to a stabilized high voltage supply at a maximum of +100 kV. When the load is on the outer conductor, the inner conductor is practically at earth potential. When the Trigatron is fired by the trigger circuit, the voltage of the inner cable of the coaxial system rises sharply with respect to earth and the storage cable discharges on to the deflector plate system and the matching resistor. In this case, the storage cable works as a generator free from energy losses with resistance equal to the cable impedance. The deflector plate voltage is therefore half the charging voltage of the storage cable, whereas the pulse length is twice the travelling time corresponding to the length of the cable.

In the case considered for a deflection voltage of about 45 kV as required, the storage cable must be charged to 90 kV. The length of the storage cable for the required pulse of 45 ns is therefore

\[ 1 = \frac{t}{2} = \frac{t \cdot c}{2 \sqrt{\varepsilon r}} = 4.5 \text{ m} \]

where \( \varepsilon r \) is the dielectric constant of the cable and \( c \) the velocity of light.

3.1. **Trigatron**

The trigatron works as a controllable high voltage switch with a very short delay and rise-time. Hydrogen thyratrons and other electronic switches available on the market are unsuitable from the point of view of breakdown voltage, currents and rise-time.
The trigertron is a spark gap which produces a high discharge between two electrodes by means of a controlled trigger electrode; it is operating in a pressurized gas which is constantly renewed by a feed system.

A coaxial arrangement of the trigertron would have the advantage of shortening the rise-time of the pulse. On the other hand, it makes triggering difficult. Either the trigger pulse must be allowed to run on to the deflector electrodes, producing thereby an unwanted deflection of the beam before the appropriate time, or a spark gap with three electrodes has to be used which will produce more jitter on account of the connection in series of two gas discharge gaps.

In the case under consideration, the trigertron was not therefore set up as a coaxial arrangement. This has the added advantage that all parts are accessible during an experiment.

As Fig. 3 and 4 show, the two main electrodes of the spark gap are brass hemispheres, 110 mm in diameter. The hemisphere which is at high potential is threaded so that the gap can be varied. In order to protect the most exposed parts of the hemispheres from damage by arcing, molybdenum inserts are screwed into them. The trigger electrode consists of a tungsten wire, 3 mm in diameter, which is accurately positioned in the centre of a channel, 4 mm in diameter, which runs through the middle of the earth electrode. The position of the trigger electrode is adjustable with respect to the earth electrode. The spark gap as a whole is in a pressure vessel which consists of a glass tube with insulating plates at both ends and can withstand up to 4 Atm. The gas inlet is on the inside side of the earth electrode; the gas flows through the trigger electrode channel and goes out through a valve at the side of the high voltage electrode.

* see Annex 1
3.2. **Trigger pulse generator**

The pulse necessary to fire the trigatron is generated by discharging a condenser charged at 20 kV on a 5949 hydrogen thyratron (Fig. 5). The pulse necessary to fire the thyratron is amplified to the required 400 V from an E 130 L. The RC element between the grid of the 5949 and the transformer T1 is necessary in order to protect the grid of the 5949 when it fires. Initial attempts to use a thyratron* instead of an E 130 L proved unsuccessful on account of the time instabilities and time lags which occur. In the arrangement shown on Fig. 5, the time lag is 250 ns.

3.3. **The matching resistor**

The matching resistor absorbs the pulse which reaches the end of the cable, so that the shape of the primary pulse is not distorted by reflection. While the average power loss is about 100 W, the peak power during the pulse is 50 MW, corresponding to 50 kV and 1 kA for a resistance of 50 ohms. Furthermore, the matching resistor makes it possible to obtain an oscillogram of the pulse which is free from reaction and from distortion.

Figure 6 is a drawing of the matching resistor. The 50 ohm special r.f. layer resistor is placed in an aluminium housing filled with oil, whose distance from the resistor decreases roughly exponentially, so that the effect of the inductance of the resistor is eliminated. Measurements of the dielectric constant of the insulating oil have shown that, in a frequency range of 50 c/s - 27 Mc/s and at temperatures between 20° C and 40° C, it remains practically the same. The oscillograph for the measurement of the pulse is connected to a

* as suggested in Ref. 3

4529 / p
capacitive voltage divider insert on the lower end of the 50 ohm resistor *. To avoid arcing, the joint between the cable and the resistor is also surrounded with oil.

4. Measurements

Measurements were made to ascertain the behaviour of the trigatron with respect to various parameters. The object of these measurements was firstly to determine the appropriate working point for the required purpose and, secondly, to find out as precisely as possible how the trigatron behaves. The high voltage pulse produced had an amplitude \( U_p = 45 \text{ kV} \). The repetition frequency was 50 / sec.

The jitter and pulse form of the high voltage pulse were investigated with respect to the following parameters:

- pressure, gas flow, type of gas and position of trigger wire with respect to the main electrodes.

Before making the measurements proper, it is necessary to determine the trigger range. The voltage at the electrodes of the spark gap is constant. Accordingly, the trigger range of the trigatron is the range of inter-electrode gaps at which every trigger pulse causes the trigatron to break down. The trigger range is determined with the help of two electronic counters. One counter counts the pulses of the Mercury relay pulse generator, i.e. the trigger pulses. The second counter counts the high voltage pulses. By making both counters coincide after a certain counting time (in this case, it was 5,000 pulses), one finds the appropriate inter-electrode gap within the trigger range of the trigatron.

* for details, see Annex 2

4529 / p
The high voltage pulses were measured with an oscilloscope to determine jitter, pulse form and time lag. The oscilloscope used had an input voltage of 0.2 - 20 V and a maximum time base of 10 ns/cm, for a rise time of 3.5 ns. For the measurement of the jitter and of the time lag, the oscilloscope is triggered externally from the Mercury pulse generator. For the measurement of the pulse form, it is triggered internally to produce a clear image on the oscilloscope even with large jitter.

The high voltage pulse can easily be measured with a voltage divider in the matching resistor (dividing ratio 1:2500) (see Appendix IIa).

One major difficulty in measuring this extremely short voltage pulse is to provide suitable screening for the oscilloscope. The measurements are distorted in particular by the high frequency energy radiated by the trigatron and by the oscillation of the hydrogen thyratron. The whole device is therefore placed in a Faraday cage. Measuring cables to the oscilloscope and other instruments are screened (see Appendix IIb).

5. Results

5.1. Trigger pulse

The trigger pulse which supplies the output stage of the trigger circuit is a negative pulse of 20 kV peak with a rise time of 40 ns. The time constant of the decay is 400 ns.

It is always the leading edge of the trigger pulse which causes the breakdown of the trigger gap. If the trigger electrode is flush with the surface of the earth electrode, the breakdown occurs between 6 kV at 0 atm and 14 kV at 4 atm. Between 4 l/min and 16 l/min, it was not possible to detect any effect of the gas flow on the breakdown of the trigger gap.

4529 / p
If the trigger wire projects 1 mm above the surface of the earth electrode, the result is the same as when the trigger wire is flush with the earth electrode.

If the trigger electrode is withdrawn 2 mm below the surface of the earth electrode, whatever the pressure, a higher voltage is necessary to break down the trigger gap than for the other positions of the trigger wire. The breakdown occurs in this case between 8 kV at 0 atm and 18 kV at 4 atm. In this case, also any influence of the gas flow is undetectable.

In all the cases considered, the trigger pulse showed no jitter.

The time lag of the pulse between input and output of the trigger circuit is 400 ns. On these 400 ns are superimposed slow fluctuations of ± 10 ns with a frequency of about 1/20 min, which could be shown to be generated by the hydrogen thyratron.

5.2. Trigger range of main pulses

The study of the trigger range gives the following results for a constant voltage \( V = 90 \text{ kV} \) between the main electrodes. When the trigger electrode is flush with the earth electrode, for all pressures from 0 to 4 atm and for a gas flow varying from 4 to 16 \( 1/\text{min} \), there is a gap length for which every trigger pulse causes the main gap to break down. With the electrode 1 mm forward, such a gap can be found only for a pressure of 1 atm. For higher pressures, there is no gap length for which every trigger pulse can cause a breakdown of the thyratron. When the trigger electrode is withdrawn 2 mm behind the surface of the electrode, a trigger range can be found only between 2 atm and 3 atm. Measurements were therefore restricted mostly
to the position where the trigger wire is flush with the earth electrode. Among the gases considered, i.e., nitrogen, air and argon, argon proved unsuitable. The breakdown voltage of argon is very low compared to that of the other two gases. Accordingly, it would be necessary to have a greater gap length which, on account of the larger mismatch, would only lead to unnecessary distortions of the high voltage pulse.

The trigger range is related to the static breakdown gap. The static breakdown gap is the inter-electrode gap at which a breakdown occurs without trigger spark. At a constant electrode voltage, it is dependent on the pressure in the trigatron. Figure 7 shows this dependence for both air and nitrogen. For all air pressures considered, the static breakdown gap is smaller for air than for nitrogen. Both curves, however, show a similar trend, i.e., with increasing pressure the pressure dependence of the static breakdown gap decreases.

Figure 8 shows the trigger range of the trigatron, given as a function of the specific static breakdown, vs pressure. At the beginning of the range, there is no dependence on gas flow. The range is in the neighbourhood of 1. The inter-electrode gap at the beginning of the trigger range is therefore only a little wider than the static breakdown gap for the same pressure. The curve for the beginning of the range has about the same shape both for air and nitrogen, with a minimum between 1.5 and 2 atm.

At the end of the range, there is a strong dependence on the type of gas used. For nitrogen, the value is about $s/s_d = 1.8$ and for air about $s/s_d = 1.2$. The measured values varied considerably, so that the shape of the curve did not appear to follow a distinct trend. This is not surprising, however, as for inter-electrode gaps which are
considerably above the breakdown value many statistical influences such as cosmic rays, the condition of the electrodes, etc., are bound to have some effect.

5.5. Jitter

The tests carried out show that minimum jitter is obtained when the trigger electrode is flush with the surface of the earth electrode (best value 2 ns). When the trigger electrode projects one millimetre above the surface of the earth electrode the best value obtained for jitter is 10 ns; when it is withdrawn 2 mm below the surface this value is 40 ns.

The study of the jitter over the whole trigger range of the trigatron for various pressures and gas flows shows that the jitter is always lowest at the beginning of the range. As the inter-electrode gap is increased to the end of the trigger range the jitter grows from a few ns to some 10 μs, viz. approximately by a factor 10,000. The pattern of the jitter within the trigger range is shown in Fig. 9 for several pressures and gas flows. It can be seen that for a pressure of 2 atm (nitrogen flow 8 l/min) the jitter in the first 40% of the trigger range is below 10 ns. For a pressure of 2.5 to 3 atm this value is held only in the first 20% of the trigger range. For all other pressures the jitter of 10 ns or less is obtained only when the inter-electrode gap does not exceed the initial trigger range gap by more than 0.5 mm. To minimise the jitter a pressure of 2 atm should therefore be chosen as it is the pressure at which the electrode gap is least critical.

The effect of the gas flow can be seen in Fig. 10. The curves show the minimum jitter as a function of nitrogen flow for various pressures. The minimum jitter is the smallest value of the
jitter found by varying the interelectrode gap within the trigger range. It is found each time at the beginning of the trigger range. The curves show that gas flow has no significant effect above 8 l/min. It should also be noted that for every gas flow considered the minimum jitter was obtained for a pressure of 2 atm.

Other measurements were made to study the effect of the type of gas used on jitter. The gas flowing through the trigatron is not recovered and relatively cheap gases were therefore used for the study. In addition to the study done with nitrogen a study was carried out with air. It was found that for flows of 16 to 4 l/min and for all pressures the jitter is greater by a factor 1.5 to 2 than with nitrogen. Since nitrogen also prevents the oxidation of the electrodes it was chosen to fill the trigatron.

To conclude the tests a reliability trial was conducted at the most appropriate working point from the point of view of jitter. For a pressure of 2 atm, a nitrogen flow of 8 l/min and an inter-electrode gap corresponding to the beginning of the trigger range, during sixteen hours continuous operation (about 3 million pulses) the jitter remained constant within 5 ns.

5.4. Pulse form

The pulse form was examined only at the inter-electrode gap corresponding to minimum jitter but for various pressures and gas flows. The trigger wire was nearly flush with the surface of the earth electrode. The gas used was nitrogen. The rise of the leading edge of the pulse was 10–15 ns. Theoretically the design value of the boundary is 8 ns (see appendix 1.) The pulse form does not appear to depend on pressure or gas flow. The pressure dependence that could be expected in the rise time was probably hidden by the distortion of
the pulse and accordingly could not be accurately measured. The peak of the pulse has a ripple of about 12.5%. Figure 11 shows an oscillogram of the pulse for a pressure of 2 atm and a nitrogen flow of 8 l/min. Figure 11a is photographed with internal triggering and Figure 11b with external triggering to show the jitter. The time of exposure was about 2 minutes in both cases.

6. Conclusions

6.1. Best operating conditions

The tests carried out on the device gave the following results, which are satisfactory:

\[ U_{\text{deflect.}} = 45 \text{ kV} \pm 12\% \text{ for } Z = 50 \text{ ohm} \]

Rise time = 10 to 15 ns

Minimum jitter = 5 ns

in \( N_2 \) at a pressure of 2 kg/cm\(^2\) with a gas flow of 8 l/min.

It is essential for the satisfactory operation of the spark gap with minimum jitter to choose these parameters and keep them sufficiently constant so that the tritatron operates always just before the static breakdown.

6.2. Possible arrangements to improve performance.

4529 / p
6.2.1. A shortening of the length of the trigatron and thus of the mismatch in the circuit by a factor of 2 is possible without difficulty. The rise-time of the pulse need not then exceed 5 to 7 ns. Corona discharge phenomena which eventually occur could be overcome by means of present araldite insulation techniques.

6.2.2. The long-term stability of the trigger generator could be substantially improved by replacing the hydrogen trigatron by a special high vacuum tube (Eimac 4 PR 60 A?).
The spark gap is conditioned by the characteristic impedance of the rest of the arrangement (50 ohm). This brings about a distortion of the leading edge of the travelling wave.

The characteristic impedance of the mismatch is

\[ Z = c \cdot L \quad (\sigma r = 0; \quad \mu r = 0) \]

when \( c \) is the velocity of light in vacuum and \( L \) the inductance per unit length represented by the double line, which is formed by the inner conductor and the electrodes of the spark gap.

Neglecting the effect of the insulation and of the glass tube on the relative dielectric constant, one has

\[ L = \frac{\mu_0}{4\pi} \left[ 2 \cdot \ln \frac{a^2}{r_1 r_2} + 1 \right] \]

B)

With \( \mu_0 = 0.4 \pi \cdot 10^{-8} \frac{\text{H}}{\text{cm}} \), \( a = 12 \text{ cm} \), \( r_1 = 0.325 \text{ cm} \), \( r_2 = 5.5 \text{ cm} \)

\[ L = 9.78 \cdot 10^{-9} \frac{\text{H}}{\text{cm}} \]
and the characteristic impedance of the mismatch is

\[ Z^* = 294 \text{ ohm}. \]

The influence of this mismatch is obvious from the following equivalent circuit diagram

When the switch \( S \) is closed a wave of height \( U^* \) travels in the mismatch \( Z^* \).

\[ U^* = E \frac{Z^*}{R + Z^*} \]

At \( K_2 \) this wave is allowed to pass in accordance with the refraction factor \( \beta_2 \) and it is reflected in accordance with the reflection factor \( \rho_2 \).

This reflected wave is reflected at \( K_1 \) according to \( \rho_1 \) and subjected consequently at \( K_2 \) to a refraction and reflection as the outgoing wave etc.

Accordingly a travelling wave builds up by steps in the conductor at \( K_2 \),

\[ U_2 = U^* \beta_2 + U^* \rho_1 \rho_2 \beta_2 + U^* \rho_1 \rho_2 \rho_1 \rho_2 \beta_2 + \ldots \]

\[ U_2 = U^* \beta_2 \left[ 1 + \left( \rho_1 \rho_2 \right) + \left( \rho_1 \rho_2 \right)^2 + \ldots \right]. \]
At step n, where the duration \( t \) of a step is equal to double the transit time of the wave in the mismatch,

\[
F) \quad (t = 2 \cdot \frac{1}{C} = 2 \cdot \frac{30}{10} = 2 \text{ ms}) \text{ the value of } U_2 \text{ is }
\]

\[
U_2 = U^X \cdot \beta_2 \cdot \frac{1 - (\rho_1 \rho_2)^n}{1 - \rho_1 \rho_2}
\]

\[
G) \quad \beta_2 = \frac{2 \cdot R}{R + Z}; \quad \rho_1 = \frac{R - Z^X}{R + Z^X}; \quad \rho_2 = \frac{R - Z^X}{R + Z^X}
\]

\[
U_2 = \frac{E}{2} \left[ 1 - \left( \frac{R - Z^X}{R + Z^X} \right)^{2n} \right]
\]

With \( E = 90 \text{ kV} \), \( R = 50 \text{ ohm} \), \( Z^X = 294 \text{ ohm} \), one has

\[
H) \quad U_2 \ [ \text{ KV}] = 45 \left[ 1 - (0.71)^{2n} \right]
\]

The following are the values of the individual steps

<table>
<thead>
<tr>
<th>Step</th>
<th>( U_2 ) [KV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.3</td>
</tr>
<tr>
<td>2</td>
<td>33.9</td>
</tr>
<tr>
<td>3</td>
<td>39.2</td>
</tr>
<tr>
<td>4</td>
<td>42.1</td>
</tr>
<tr>
<td>5</td>
<td>43.5</td>
</tr>
</tbody>
</table>
From the above graph it is clear that the rectangular leading edge of the wave is distorted by about 8 ns. This is caused by the mismatch of the spark gap.
APPENDIX II

a) Voltage Divider

A voltage divider with a dividing ratio of about 1 : 2500 is used for the measurement of the high voltage pulse. As the voltage is divided in the matching resistor, the pulse voltage decreases linearly along the 48 cm of the resistor layer. One part of this voltage is taken off with a narrow cup-shaped electrode fitting closely on the porcelain tube which gives a further capacitive dividing of the voltage of 1 : 10, as the capacity of the cup electrode is ten times higher. Through a measuring probe plugged into the cup electrode, with an attenuator 1 : 5, the divided voltage is taken to the oscilloscope.

![Diagram of voltage divider](image)

b) Screening

The high-frequency energy radiated by the breakdown of the trigatron distorts measurements so much that one must endeavour to screen off this high frequency effectively.

In order to keep out the distortions from the oscilloscope image, a wave filter is built in as a first arrangement in the connection of oscilloscope to the mains. Thus the distortions can be practically eliminated from an oscilloscope that is not earthed. If the oscilloscope is earthed, high frequency oscillations become visible again. Therefore the oscilloscope was
perfectly surrounded by copper mesh to which all the earth leads including those of the measuring leads were connected. After an additional insulating transformer had been built into the connection to the mains, it became possible to make pulse measurements free from defect. The high frequency radiated also produces distortions in other laboratories so that the final solution chosen was to place the tritron in a Faraday cage. This cage is entirely made of metal, whose damping in the frequency range of about 100 kHz to 1 GHz is more than 100 db. The mains are taken into the cage through a wide-band frequency anti-interference device.

All the equipment is situated in the Faraday cage except for the processing devices (oscilloscope, counters) and the trigger circuit situated before the hydrogen thyatron. The grid pulse is taken to the thyatron via a coaxial cable. To prevent high frequency pick-up all leads going into the cage are surrounded by copper mesh. A filter had to be placed into the trigger lead as an additional arrangement.
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Fig 1a  Position of the deflection system in the Synchrocyclotron

Fig. 1b. Cross-section of deflector plates
Fig 2  Electrical Network
Fig. 5  Trigger circuit
50 kV - Input

RG 19-U cable

Oil-Level
(Esso Standard \( \varepsilon_r = 2.23 \))

Conus-Line \( Z = \text{const} = 50 \Omega \)

Aluminium housing with exponential form

Special RF resistor
50 \( \Omega \) 300W

Capacitive pick-up electrode

10 V Output

FIG 6
Matching resistor for 50 MW peak power
(For details see CERN SST 30399)
Fig. 7  Static breakdown distance of the Trigatron versus pressure of filling-gas

$U = 90\text{ kV}$
Fig. 8. Triggerrange of the Trigatron.

gasflow: 82/lmin, U = 90 kV, trigger electrode level with earthed electrode

$S_d = \text{distance of electrodes at static breakdown voltage}$

$S = \text{distance of electrodes of the triggered trigatron}$
Fig 9. Jitter within the Triggerrange of the Trigatron.

filling gas: Nitrogen, U=90 kV
trigger electrode level with earthed electrode
Fig. 10. Minimal jitter versus nitrogen flow for different pressures

U = 50 kV, trigger electrode flush with earth electrode
Fig. 71  High voltage pulse  $U = 45$ kV
nitrogen flow  8 l/min at 2 atm.