EXPERIMENTAL RESULTS ON A FAST-CYCLING PULSED HV POWER SUPPLY

A. Brückner and A. Plunser

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EXPERIMENTAL RESULTS ON A FAST-CYCLING PULSED HV POWER SUPPLY

A. Brückner and A. Plunser
SUMMARY

This report describes a full-size realization of a fast-cycling power supply for recharging 20 times the one-bunch delay line of the full-aperture kicker (FAK) of the Proton Synchrotron. It will allow the bunch-by-bunch transfer at 10 GeV from the 28 GeV CERN Proton Synchrotron to the 300 GeV CERN Proton Synchrotron.

The power supply is capable of charging a 35 nF capacity up to 60 kV. It represents an improved version of our first proposal, published in September 1970\(^1\) and successfully tested on a model in 1971\(^2\). The new supply offers higher performance (the repetition time is 22 \(\mu\)sec instead of 50 \(\mu\)sec) combined with higher reliability and full timing flexibility, all this at lower cost. It needs only 20\% of the stored energy foreseen in the earlier proposal\(^1\).

This 20-pulse supply consists principally of 10 double-triggered glass-envelope triode-thyatron tubes, each discharging a double capacitor into the primary winding of a premagnetized ferrite-core power pulse transformer. There are no semiconductor diodes on the HV side of the supply, as their reliability remains to be demonstrated.

Performance measurements were made on a 40 kV-CX1154 thyratron.
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1. **INTRODUCTION**

The working principle of single- or multi-pulsing power supplies is described elsewhere\(^1\sim 7\). Supplies with a typical charge time of 5 msec were used by the authors for all 28 PS Booster kickers, and they were also adopted for the FAK project by Flander\(^5\). The new supply described in this report will fulfill the same function 1000 times faster.

Assuming a typical charging time of 5 \(\mu\)sec and a repetition time as small as 20 \(\mu\)sec, the main problem consists in creating proper de-ionization conditions for all thyatrons.

After conduction, the anode voltage of any thyatron stays between 0 and -5 kV during the recovery time (typically 20 \(\mu\)sec). Fast-recovery thyatrons cannot be considered, as they do not offer high enough power pulses.

2. **BASIC CIRCUIT AND WORKING PRINCIPLE**

The circuit diagram (Fig. 1) shows the following principal components:

- a 0-14 kV d.c. power supply to charge all primary capacitors,
- one (of 20) single-pulsing primary pulser(s) (thyatron + capacitor) and, alternatively,
- one (of 10) double-pulsing primary assembly(ies),
- the HV power pulse transformer,
- the premagnetization generator,
- the transformer-recovery diode system,
- a 35 nF HV dummy load with discharge thyatron.

Before the 20-pulse burst starts, all 20 \(C_1\) and \(C_{12}\) capacitors are charged to the primary voltage \(U_{C_1}\), say +10 kV.

An auxiliary 4 msec, 120 A pulse generator, connected to the biasing winding P2, has already premagnetized the pulse transformer core to -2 KG. The first primary thyatron Th 1 may now be fired, discharging the first primary capacitor \(C_1\) from +10 kV to -4 kV into the primary winding P1 of the pulse transformer. The secondary winding S1 now charges the load capacitor \(C_2\) from \(U_2 = 0\) to \(U_2 = 40 \text{ kV}\), via the diode D3.

After a flat top of 1-3 \(\mu\)sec, \(C_2\) will be discharged to \(U_2 = 0\) by the main switching thyatron. After the discharge, the transformer returns to its initial induction within about 20 \(\mu\)sec, and the cycle may be repeated by triggering the second primary thyatron.

A single-pulse primary assembly is discharged completely after one pulse; therefore 20 primary thyatrons are needed. A double-pulse assembly (Fig. 1) is particularly interesting as it allows the primary thyatron to be used twice, and, therefore, reduces the primary equipment by 30%. After the discharge of capacitor \(C_1\) (first to tenth pulse) a half-period oscillation between \(C_{12}\), \(L_1\), and \(C_1\) recharges \(C_1\) to its initial voltage within 220 \(\mu\)sec. The oscillation is interrupted by the diode D1 when \(C_1\) is charged to maximum. Each primary thyatron may thus be retriggered 220 \(\mu\)sec after its first pulse.
Fig. 1 Diagram of the basic circuit
3. **DETAILED DESCRIPTION OF OPERATION AND CIRCUIT ELEMENTS**

3.1 **Primary circuit $C_1$, $C_{12}$, $L_1$, $D_1$**

The circuit must provide identical amplitudes for the first and second pulse of each primary assembly, i.e. the resonant circuit $C_{12}-L_1-C_1$ must recharge $C_1$ for the second pulse to the initial voltage $U_{L_1}$. This gives the equation:

$$\frac{C_{12}}{C_1} e^{-\pi/2Q} = 1,$$

(where Q is the quality factor of the $C_{12}-L_1-C_1$ resonant circuit). To make up for the losses, $C_{12}$ has therefore to be slightly larger than $C_1$. Fine adjustment can be made by additional damping (resistor in parallel with $L_1$). The diode $D_1$ is protected by a resistor capacitor (RC) and conducts during a half sine-wave of ~100 A.

3.2 **Premagnetization circuit**

A 500 μF capacitor, charged to 400 V, is discharged in 4 msec by a thyristor to the decoupling inductance $L_3$ (2 × 1.8 mH), producing the premagnetization of the HV pulse transformer. The decoupling choke is made in two equal parts ($L_{31}, L_{32}$) to obtain a voltage symmetrical to earth across P2 during the 20 fast pulses.

3.3 **HV pulse transformer**

3.3.1 **Windings**

The O-core pulse transformer (Fig. 3) has four independent windings:

i) The main primary winding $P1$ is split into two parallel parts of six turns each (Fig. 4).

ii) The main secondary $S1$ is split into four parallel parts, each having 50 turns (Fig. 5). The HV ends of the four secondary windings are located in the middle of the whole coil, away from the yokes.

iii) An auxiliary primary winding $P2$ is connected to the premagnetization pulse generator.
iv) The auxiliary secondary winding S2 divides the ferrite cross-section into four magnetic parallel parts, thus producing four 1/4-turn windings, electrically connected in parallel and feeding 100 diodes D2, each one in series with a resistor Rs, to limit the reverse voltage during the transformer recovery to a safe level (10 to 18 kV on the diode D3, thyratron FX297) (Fig. 6).

3.3.3 Other transformer data

Ferrite cross-section : 100 cm²
Working range of magnetic induction : \( B = -2 \text{ kG} - +3 \text{ kG} \)
Max. secondary flux swing : \( \Delta \psi_{\text{pp}} = 250 \text{ mV sec} \)
Leakage inductance : seen at primary \( L_0 = 3.3 \text{ µH} \)
seen at secondary \( L''_0 = 230 \text{ µH} \)
Main inductance : seen at primary \( L_m = 110 \text{ µH} \)
seen at secondary \( L''_m = 7.5 \text{ mH} \).

Fig. 3 Ferrite core and winding P2
Fig. 4 Primary winding P1
Fig. 5 Transformer with secondary winding S1
Fig. 6 Transformer yoke with \( R_s-D_2 \) combination
3.4 Recovery system

After the charging pulse, i.e. during the flat top and the recovery time of the transformer, the inverse diode thyatron D3 (see Fig. 7) blocks the reverse secondary current and allows the transformer to recover without submitting the HV load capacitor C3 to an important negative voltage. The recovery is done by a reverse voltage of -10 kV to -20 kV. The diode need not withstand the full forward charge voltage, and a classical glass-envelope thyatron FX297 is therefore used, which in this application offers more reliability than a series of semiconductor diodes. The combination of fast reverse voltage rise, high peak current (up to 700 A), and the necessity of a short recovery time would complicate the use of semiconductor diodes.

The elements R31, R32, and C3 improve the shape of the recovery voltage; the diode D2 conducts during transformer recovery and the energy, stored in the ferrite core, is mainly dissipated in the resistor R3.

3.5 Despiking of reverse voltage at the primary thyatrons

During the flat top of each charging pulse, the reverse voltage on the primary thyatrons would be

$$U_{a}(T) = U_{c}(T) - \frac{U_{r}(T)}{r}.$$  

Under normal conditions we get

$$U_{c}(T) = -4 \text{ kV}$$
$$U_{r}(T) = 40 \text{ kV}$$
$$U_{a}(T) = -9 \text{ kV},$$

with $r$ = the ratio of the turns = 8.3.

This might lead to backfiring in the primary thyatrons.

The saturating choke $L_2$ (flux swing $\Delta\phi_{pp} = 16$ mV sec) prevents an important reverse current from flowing before saturation (see Fig. 7). The small reverse current flows mainly into the combination $R_3$-$C_3$ and the primary thyatron anode voltage will not exceed -4 kV.

3.6 Overvoltage protections

Both ends of the secondary winding $S1$ are protected by spark gaps in series with energy dump resistors.

![Fig. 7 High-voltage rack with inverse diode D3, pulse transformer, and the chokes L31 and L2](image)
4. FORMULAE FOR CALCULATION OF CHARGE TRANSFER, DESIGN FIGURES OF THE CIRCUIT, AND EXAMPLES OF DIFFERENT WORKING CONDITIONS

The most interesting formulae are reproduced below without giving their mathematical derivation. Figures 8 and 9 help towards an easier understanding of the calculated results and in defining the symbols.

Table 1 gives the formulae for calculations. Table 2 shows calculated values at four different working points. Table 3 indicates experimental results at different working points.

Other symbols used are:

- Load ratio: \( \rho = C_2 r^2 / C_1 \)
- Quality factor of the \( C_1 - L_0 - C_2 \) circuit: Q
- Ratio of two consecutive amplitudes with different polarity: \( \alpha \)
- Ratio of transformer turns: \( r \)
- Fixed values of circuit elements: \( L_0 = 3.3 \, \mu\text{H} \), \( r = 8.3 \)
  \( c_1 = 1 \, \mu\text{F} \), \( c_{12} = 1.12 \, \mu\text{F} \)
  \( Q = 15 \), \( \alpha = 0.90 \)

![Equivalent circuit reduced to primary](image1)

**Fig. 8** Equivalent circuit reduced to primary

![Charge transfer from primary capacitor \( C_1 \) to secondary capacitor \( C_2 \)](image2)

**Fig. 9** Charge transfer from primary capacitor \( C_1 \) to secondary capacitor \( C_2 \)
### TABLE 1
Formulae for calculation of charge transfer

| Ratio of two consecutive amplitudes with different polarity | \( \alpha = e^{-\pi/2Q} \approx 1 - \frac{\pi}{2Q} \) |
| Charging time \( T \) | \( T = \frac{\pi}{I_{q} c_{1} \rho} \frac{1 + \rho}{1 + \rho} \) |
| Secondary charging voltage | \( U_{2}(T) = r U_{1}(0) \frac{1 + \alpha}{1 + \rho} \) |
| Necessary primary voltage | \( U_{1}(0) = \frac{U_{2}(T)}{r} \frac{1 + \rho}{1 + \alpha} \) |
| Primary voltage after charging | \( U_{1}(T) = U_{1}(0) \frac{1 - \alpha \rho}{1 + \rho} \) |
| Characteristic primary impedance | \( Z_{p} = \sqrt{\frac{L_{q}(1 + \rho)}{C_{1} \rho}} \) |
| Peak primary current | \( \hat{I}_{1} = \frac{U_{1}(0)}{Z_{0}} \) |
| Peak secondary current | \( \hat{I}_{2} = \frac{I_{1}}{r} \) |
| Secondary flux swing | \( \Delta \psi = \left( \frac{1}{2} + T_{2} \right) U_{2}(T) \) |

### TABLE 2
Calculated values under different working conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Nominal condition</th>
<th>Second example</th>
<th>Third example</th>
<th>Fourth example</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{2} )</td>
<td>nF</td>
<td>35</td>
<td>35</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>( U_{2}(T) )</td>
<td>kV</td>
<td>40</td>
<td>60</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>( \rho )</td>
<td></td>
<td>2.4</td>
<td>2.4</td>
<td>2.1</td>
<td>1.7</td>
</tr>
<tr>
<td>( U_{1}(0) )</td>
<td>kV</td>
<td>8.6</td>
<td>13</td>
<td>13.7</td>
<td>13.7</td>
</tr>
<tr>
<td>( U_{1}(T) )</td>
<td>kV</td>
<td>-3.4</td>
<td>-5.1</td>
<td>-4.0</td>
<td>-2.8</td>
</tr>
<tr>
<td>( T )</td>
<td>usec</td>
<td>4.8</td>
<td>4.8</td>
<td>4.7</td>
<td>4.6</td>
</tr>
<tr>
<td>( Z_{0} )</td>
<td>( \Omega )</td>
<td>2.15</td>
<td>2.15</td>
<td>2.2</td>
<td>2.25</td>
</tr>
<tr>
<td>( \hat{I}_{1} )</td>
<td>A</td>
<td>4000</td>
<td>6000</td>
<td>6250</td>
<td>6100</td>
</tr>
<tr>
<td>( \hat{I}_{2} )</td>
<td>A</td>
<td>480</td>
<td>720</td>
<td>750</td>
<td>730</td>
</tr>
<tr>
<td>( \int I_{2}^2 , dt )</td>
<td>A² sec</td>
<td>38</td>
<td>86</td>
<td>92</td>
<td>87</td>
</tr>
<tr>
<td>( \Delta \psi(T_{2} = 1 , \mu\text{sec}) )</td>
<td>mV sec</td>
<td>140</td>
<td>210</td>
<td>245 (max)</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta \psi(T_{2} = 0.5 , \mu\text{sec}) )</td>
<td>mV sec</td>
<td>120</td>
<td>180</td>
<td>210</td>
<td>240 (max)</td>
</tr>
</tbody>
</table>
**TABLE 3**

Experimental results at different working points of the power supply

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nF</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>(C_2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(U_2(T))</td>
<td>kV</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>(U_1(0))</td>
<td>kV</td>
<td>8.4</td>
<td>10.6</td>
</tr>
<tr>
<td>Observed minimum cycle time</td>
<td>usec</td>
<td>18</td>
<td>26</td>
</tr>
<tr>
<td>Safe cycle time a)</td>
<td>usec</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Used discharge thyatron</td>
<td></td>
<td>CX1154</td>
<td></td>
</tr>
</tbody>
</table>

a) The safe cycle time is limited by the discharge thyatron.

5. **OBSERVED PERFORMANCE OF THE DISCHARGE THYRATRON CX1154**

For rise-time measurements of the discharge thyatron dummy load, the \(C_2-R_4-L_4\) pulse-forming network was improved by an additional RC circuit across the tube (not shown in Fig. 1).

The current rise was measured by a current transformer. We observed that the following four parameters could not be set to a maximum simultaneously:

i) reservoir voltage (when high, this causes high gas pressure and short rise-time),
ii) anode voltage (near the tube rating),
iii) repetition rate,
iv) number of pulses.

If one of the first three parameters is pushed to the limit, erratic breakdown, appearing first in the last pulses of the burst, is observed.

A cumulative effect exists (probably due to the heating up of the electrodes of the thyatron), reducing the instantaneous performance during many pulses. Table 4 gives conditions for operation with ten successive pulses without erratic breakdown.
TABLE 4
Observed performance of the discharge thyratron

<table>
<thead>
<tr>
<th>Reservoir voltage</th>
<th>$V_{rms}$</th>
<th>6.0</th>
<th>6.5</th>
<th>7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise-time 10%-90%</td>
<td>nsec</td>
<td>18</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Anode voltage</td>
<td>kV</td>
<td>30</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Peak current</td>
<td>kA</td>
<td>1</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Rate of current rise</td>
<td>A/nsec</td>
<td>55</td>
<td>65</td>
<td>75</td>
</tr>
<tr>
<td>Minimum cycle time</td>
<td>µsec</td>
<td>21</td>
<td>25</td>
<td>29</td>
</tr>
<tr>
<td>Network impedance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6. OSCILLOGRAMS

Figure 10 shows the input and output voltages at the HV pulse transformer. All five voltages are synchronized.

Figure 11 gives the anode voltage shape of a single-pulsing primary thyratron before, during, and after its working cycle.

Figure 12 shows three synchronized traces: the anode voltage of a double-pulsing primary thyratron, the strip-line voltage, and the load voltage. (The 2 × 5 missing pulses will be added during stage 2 of construction, when the primary circuit will be completed by another five double-pulsing groups.)

In Fig. 13, the third trace shows the shape of the HV transformer flux, synchronized with the load and recovery voltages in traces 1 and 2.

Figure 14 shows again the transformer flux on a larger time base, as well as the pre-magnetization current and the load voltage.

The despiking effect of the saturating choke $L_2$ on the primary anode voltage is explained in Fig. 15: trace 2 shows the voltage shape when $L_2$ is applied; trace 3, for comparison, when $L_2$ is taken out of the circuit. The most dangerous spike appears during the flat top of the load voltage. Both traces are synchronized with the load voltage (trace 1).

Figure 16 shows a charging pulse with short cycle time (19 µsec) at 35 kV load voltage.

A typical discharge current rise into a 30 Ω network is shown in Fig. 17. The current rises up to 1350 A within 15 nsec (10%-90%).
Fig. 10  Repetitive charging of a 35 nF load to 38 kV

Fig. 11  Anode voltage of third primary single pulsing thyratron
Fig. 12 Charging of a 35 nF load to 38 kV

Fig. 13 Flux of transformer core
Fig. 14 Premagnetization of transformer core

Fig. 15 Influence of saturating choke on primary anode voltage spikes
Fig. 16  Fast pulse repetition (35 nF, 35 kV)

Fig. 17  Discharge current (CX1154)
REFERENCES

1) A. Brückner, A proposal for 20 × 1 or 10 × 2 bunch ejection from the CPS to the 300 GeV machine based on a new fast-charging system, CERN Internal Note MPS-SI/Note 300/INJ/2 (1970).

2) D. Grier, A fast charging pulse generator for 20 × 1 bunch ejection from the PS to the 300 GeV machine, CERN Internal Note MPS/SR/Note 71-26 (1971).

3) A. Brückner and J.F. Labeye, A resonant charging pulsed high-voltage power supply, CERN Internal Report SI/Int. MAE/68-6 (1968).

4) J. Cupéras, A fast-charging power supply for the delay lines of the kicker magnet pulser, CERN Internal Report PS/FES/Int. 68-5 (1968).


6) A. Brückner, A resonant charging pulsed high-voltage power supply, Paper presented at the 3rd Int. Conf. on Magnet Technology, Hamburg, 1970.

7) P. Pearce and D. Fiander, A proposal for a pulse generator for bunch by bunch transfer from the CPS to the SPS, CERN Internal Note MPS/SR/Note 71-37 (1971).
### A.1. EXPENSES FOR DEVELOPMENT AND CONSTRUCTION

<table>
<thead>
<tr>
<th>Cost (in thousands of Sw.Frs.)</th>
<th>Stage 1 (10 pulses)</th>
<th>Stage 2 (20 pulses)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Components</td>
<td>Labour</td>
</tr>
<tr>
<td>14 kV/0.5 A d.c. supply</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Premagnetization system</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>HV pulse transformer</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Saturating choke L₂</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Five primary double-pulse assemblies, equipped with 5949 A</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Special rack and stripline</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Recovery diode assembly (FX297)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Metal mounting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 trigger units 1.5 kW/15 A</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>1.5 kW d.c. supply</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timing facility</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Voltage stabilizer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A.2. LAYOUT OF THE INSTALLATION

Figures 18 and 19 show the general layout of the whole power supply installation.

![Fig. 18 Low inductive strip-line construction](image1)

![Fig. 19 The complete power supply installation, equipped with five primary assemblies](image2)