# High-voltage switching for in-flight capture of keV antiprotons in a Penning trap

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The recently observed in-flight capture of keV antiprotons and protons in a Penning trap requires that the $-3$-kV potentials on electrodes of a Penning trap near 4.2 K be switched on and off with switching times less than 20 ns. These rapidly switched potentials are applied via transmission lines which are not terminated at the trap, thereby avoiding unacceptable heat load on the helium Dewar. Simple high-voltage switching circuits are constructed using krytrons and reed relays. A krytron provides the rapid switching and stays on just long enough for a reed relay to kick in and maintain the switched state indefinitely.

Both antiprotons[1] and protons,[2] with kinetic energies below 3 keV, have been captured in flight in a crude Penning trap. This kinetic energy is several orders of magnitude higher than the electron volt or lower energies typically associated with traps. In a departure from simpler procedures for loading traps with low-energy ions, it is necessary to capture the kilovolt antiprotons in flight, by rapidly applying a kilovolt potential to a previously grounded trap electrode.

Figure 1 is a simplified diagram of the trap electrodes and the idealized high-voltage switches which are used. In practice, the switch symbols $S_1$ and $S_3$ represent electronic circuits (discussed below) which are capable of switching times less than 20 ns. A pulse of antiprotons travels along the axis of the three cylinder electrodes from the left. A strong homogeneous magnetic field (6 T) is directed along this axis over the whole length of the electrodes. This magnetic field confines the charged particles in the two transverse dimensions to a field line. As the antiprotons approach, the high-voltage switches are set as shown in the figure. The left cylinder (load endcap) and the central cylinder (ring) are thus grounded while the right cylinder (dump endcap) is at $-3$ kV. As antiprotons with kinetic energies below 3 keV approach the negative dump endcap, they turn around on their magnetic field lines and head back toward the entrance of the trap. Approximately 300 ns later, before the particles can escape through the entrance, the load switch $S_1$ is closed, lowering the potential of the entrance endcap suddenly to $-3$ kV and trapping particles within the trap. The antiprotons are held as long as desired by opening switch $S_2$. Then, the dump switch is closed to quickly raise the potential on the exit endcap from $-3$ kV to 0 V, releasing the antiprotons from the trap. The antiprotons leave the trap toward the right and are detected.

A crucial feature of the high-voltage switching is the transmission lines which connect the switching circuits to the trap electrodes. One function of the transmission line is to thermally isolate the switching units at room temperature from the trap electrodes which are cooled to near 4.2 K. This is easily accomplished with a small diameter 50-Ω coaxial cable of adequate length, made of stainless steel and Teflon. Also, the transmission lines are not resistively terminated at the trap end. Thus, there is no heat generated at the cold end of the transmission lines.

The capacitance to ground of each endcap electrode is very small, of the order of 20 pF or less. For the time scales we are interested in, switching times less than 20 ns, the trap end of each transmission line is thus essentially open. The theory of open transmission lines is well known.[3] Consider the load switch first, operating at negative potential $-V_0 = -3$ kV. With an open switch $S_1$ and a closed $S_2$, as in Fig. 1, the 470-kΩ resistor pulls the potential of the load endcap to ground potential. The 0.02-$\mu$F capacitor is, meanwhile, charged up to $-V_0$ through the 35-MΩ isolation resistor. When the switch $S_1$ is closed, the switch end of the transmission line immediately goes to $-V_0/2$ because the voltage across the capacitor is divided across the 50-Ω resistor and the effective 50-Ω impedance of the transmission line. This line appears to be of infinite length until enough time has elapsed for the disturbance to travel to the trap, reflect off the essentially open end of the line, and return to the switch end of the transmission line. However, the potential $-V_0/2$ is doubled back to $-V_0$ at the trap in order that the boundary conditions for an open transmission line be satisfied. One transmission line transit time $\tau$ after the switch $S_1$ is closed, the potential at the trap electrode thus suddenly changes from 0 to $-V_0$. At $2\tau$, the reflected wave returns to the switch end of the transmission line so that the potential at this switch end changes from $-V_0/2$ to $-V_0$. For a long cable, we clearly observe this step pattern. The 50-Ω resistor

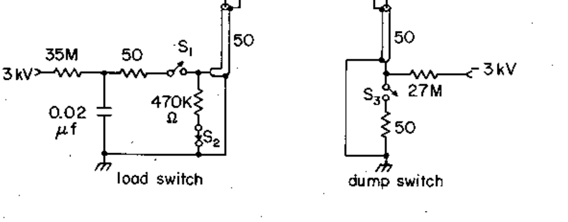

FIG. 1. Simplified outline of the Penning trap electrodes and the idealized high-voltage switches used to capture antiprotons in flight. Schematic diagrams of the actual electronic high-voltage switches are shown in later figures. A strong homogeneous magnetic field is directed along the axis of the three cylindrical electrodes over the length of the trap.

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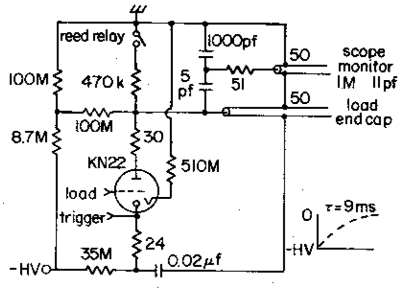
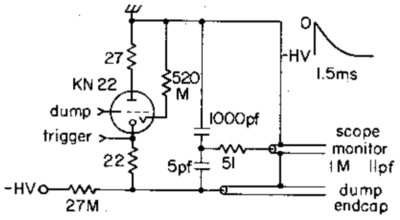


(a) Antiproton load switch

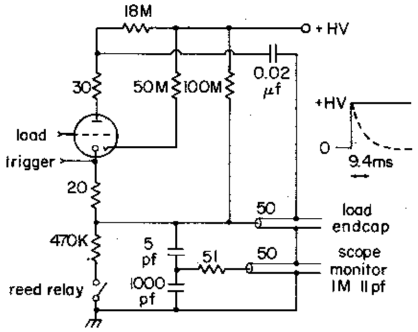


(b) Antiproton dump pulser

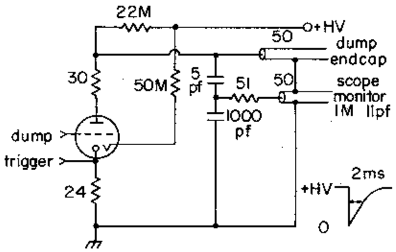
FIG. 2. Circuit used to capture antiprotons in flight. The trigger circuit and the relay driver circuit are shown in Fig. 4.

terminates the wave traveling back from the trap so that no further reflection occurs. On a much longer time scale, the 0.02-$\mu$F capacitor discharges through the 470-k$\Omega$ resistor with a time constant of 9 ms. This is adequate time for switch $S_2$, a reed relay in practice, to be opened in order to stop the decay in the potential. If this is done quickly enough, the load endcap potential will remain near $-V_0$ indefinitely.

Analogous arguments pertain to the more simple dump switch on the right of Fig. 1. When the switch is closed, the dump endcap potential changes from $-V_0$ to 0 at one cable transit time $\tau$ later. No second switch is needed. When the dump switch is opened, the dump endcap capacitance to ground and the cable capacitance is slowly charged up through the 27-M$\Omega$ isolation resistor. For the cable we used, this time constant was typically 7 ms.



(a) Proton load switch



(b) Proton dump pulser

FIG. 3. Circuit used to capture protons in flight. The trigger circuit and the relay driver circuit are shown in Fig. 4.

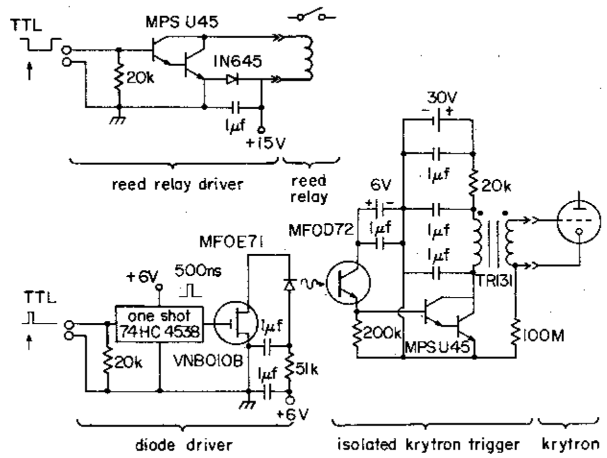


FIG. 4. Driver circuit for the reed relay and the isolated krytron trigger circuit. The optical coupling is actually through an optical fiber.[7]

The fast high-voltage switching is done with KN22 krytron tubes.[4] These small and versatile tubes are well known for other applications.[5] A krytron is filled with hydrogen gas and normally offers a very large resistance between the anode and the cathode. A small discharge is maintained continuously between the extra "keep alive" electrode and the cathode to prepare the tube for firing. When a voltage spike of greater than 750 V, with a rise time less than 1 $\mu$s, is applied between the grid and cathode, the tube discharges and the resistance between the anode and cathode becomes very low. When the discharge current falls below 10 mA for longer than 100 $\mu$s, the discharge stops.

The actual high-voltage switching circuits used to capture antiprotons in flight are shown in Fig. 2. Analogous circuits for proton capture are shown in Fig. 3. The krytron in Fig. 2(a) is the switch $S_1$ of Fig. 1. The reed relay is switch $S_2$. The reed relay we used[6] opened with a switching time and jitter of order 1 $\mu$s. The closing time delay and jitter was much worse but was not important for these circuits. The waveform shown to the right of each circuit indicates the ideal behavior of the potential at the essentially open end of the transmission line at a trap endcap. The measured waveforms closely approximate these waveforms in each case. The dashed waveform in Figs. 2(a) and 3(a) indicate the consequence of leaving the reed relay closed. Several extra resistors are added to the antiproton load switch to ensure that the anode remains more positive than the grid and cathode to keep the krytron from back firing. This slightly changes the potentials applied to the load endcap from $-V_0$ and 0, but not a significant amount with the values chosen.

Each switched potential is monitored at the switching units with identical capacitive monitors, as shown. The properties of such a monitor is well known,[3] even though at first glance it may seem strange that the oscilloscope input impedance must be high. This is done so that the scope end of the monitor cable is virtually an open circuit. The capacitive divider divides the high voltage $-V_0$ down to a reasonable level which can be handled on most scopes

$$V_m = -V_0 \frac{C_1}{C_1 + C_2} \approx -\frac{V_0}{200},$$

where here $C_1 = 5$ pF and $C_2 = 1000$ pF. On time scales short compared to the transit time in the monitor cable $\tau$, the potential at the switch end of the monitor cable is $V_m/2$. When the disturbance gets to the open end of the transmission line at time $\tau$, the open circuit boundary condition forces the doubling of the potential so that $V_m$ is actually measured at the scope. For times larger than $2\tau$, both ends of the monitor cable are at $V_m$. The 50-Ω resistor terminates the reflected wave so that there are no further reflections. We have verified that the monitor works reliably out to the very large times at which the 1000-pF capacitor is discharged through the scope input resistance, at a time of approximately 1 ms in our case.

Figure 4 shows the reed relay control circuit used for the load circuits. This is not at all critical but works very well with the relay and solenoid which is used.[6] Figure 4 also shows the krytron trigger circuit which is used in each of the four switching circuits. The diode driver on the left converts the rising edge of a TTL pulse into a light pulse sent into an optical fiber, which isolates the control circuit from the floating trigger circuit. The battery powered trigger circuit uses a fast 1:40 transformer to generate the high-voltage spike needed to trigger the krytron. The delay time from TTL input to the high-voltage switching is approximately 500 ns at $V_0 = 3$ kV. For the load circuits shown, a TTL falling edge was applied to the input of the reed relay driver at the same time as a rising TTL edge was applied to the diode driver. The high voltage was then applied to the load endcap with a switching time of less than 20 ns and yet remained applied as long as the input to the reed relay driver remained low.

In conclusion, the circuits described here make it possible to change the potential of a Penning trap electrode by 3 kV in less than 20 ns and maintain it indefinitely. The circuits were successfully used to capture both antiprotons and protons in flight. A possible improvement is to use a krytron KN22B which is rated at 8 kV or to use two KN22 krytrons in series to double the switching potential. Similar circuits could also be constructed with a thyratron or with a high-frequency radio transmitter tube.

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[6] DRVT-10-658 reed relay with the Guardian Electric Series 200 relay solenoid.

[7] Archer 276-228.