THE REFLEX SWITCH: A HIGH-CURRENT, FAST-OPENING VACUUM SWITCH*
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1. Introduction

The "reflex switch" is a new, ultra-high-power, fast-opening switch suited to pulsed power generation by magnetic energy storage systems. The final, "open" state of the reflex switch can itself serve as a vacuum diode load and generate an intense x-ray pulse; or the opening of the switch can transfer the power pulse to a parallel load.

The basic elements of a magnetic energy storage system using a reflex switch are illustrated in Figure 1. During the "closed" (low-impedance) mode of the reflex switch, the generator builds a current, I, in the storage inductor, Ls. When the current is near its peak value the reflex switch makes a very fast transition to its "open" (high-impedance) mode. The sharp increase of series impedance produces a corresponding increase of voltage across the switch, which can be much greater than the generator voltage. The power of the high-voltage output pulse can exceed the input power (the rate of energy accumulation in the inductor during the low-impedance phase) by approximately the ratio of the low-impedance duration to the output pulse duration.

In contrast to other types of high-power opening switches, the reflex switch operates in vacuum. This is a very important property that allows megavolt power pulses to be generated entirely in vacuum, at or near the load, and eliminates the need for the dielectric vacuum interface to insulate the full output voltage of the system. Thus, the basic limitation on power density, caused by dielectric insulator breakdown, is overcome. Instead, it is possible to use the much higher values of power per unit area that can be achieved with magnetic insulation in vacuum. Energy is transported at relatively low power into the vacuum inductive energy store through a low-voltage insulator, and the current in the vacuum inductor rises over a relatively long period of time. The magnetically stored energy is then converted into a short, high-power output pulse when the switch abruptly opens. The energy density in a vacuum magnetic store can be orders of magnitude greater than is possible for capacitive energy storage, giving magnetic systems great compactness.

2. Reflex Switch Operation

Figure 2 shows the reflex switch configuration used in our experiments. The switch is based on reflex triode physics. It consists of a primary cathode, K1, a thin anode, A, and a secondary cathode, K2, which is electrically floating and serves to reflect electrons back through the anode toward K1, which in turn repels them back through the anode toward K2, etc. The reflexing electrons scatter in the anode and deposit some of their energy in it on each pass. An axial magnetic field is used to minimize radial loss of electrons. Positive ions are accelerated from the anode to the cathode, K1.

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*Work supported by the Defense Nuclear Agency.

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Figure 1. Schematic of a vacuum inductive energy storage system using the reflex switch.

Figure 2. Reflex switch experimental setup.
## The Reflex Switch: A High-Current, Fast-Opening Vacuum Switch

### Abstract

"(closed" switch) to the much higher impedance Langmuir bipolar mode ("open" switch). Reflecting is terminated, in our technique, by allowing the floating electrode, \( K_2 \), to undergo a short-circuit to the anode at the desired time. When the negative potential of \( K_2 \) collapses to anode potential, electrons no longer reflect from \( K_2 \) and instead deposit in it after one pass through \( A-K_1 \). Once reflecting is terminated, the transition of \( A-K_1 \) to the Langmuir bipolar mode is governed by ion and neutral atom dynamics in \( A-K_1 \). These effects play a crucial role in determining the rate at which the impedance of \( A-K_1 \) increases.

The high-current, reflex triode mode of electron and ion flow was first predicted by Ian Smith from theoretical considerations. Further developments of the theory are given in References 2 and 3. The first experimental observation of the high-current mode was made by Prono et al.\(^2\) There is now a considerable amount of experimental evidence indicating that the basic features of the theoretical model are correct. The use of the reflex triode as a switch was first suggested by Creedon.\(^1\)

The potential distribution in the reflex triode, shown in Figure 3, sheds some light on the reason for the high-current mode of operation. Define \( \eta \) as the average number of times an electron encounters the anode prior to stopping in it. In the limit of very low voltage across the \( A-K_1 \) gap, \( \eta = 1 \), and the potential distribution is that of ordinary Langmuir bipolar flow. The current is about 1.9 times the L-C value. The value of \( \eta \) increases with \( A-K_1 \) gap potential, \( V \). For \( \eta \gg 1 \), the potential distribution is distorted by the space charge of the multiply reflected electrons and the corresponding positive ion flow. The greater the value of \( \eta \), the greater is this distortion, until \( \eta \) approaches a critical number, \( \eta_c \), corresponding to a critical gap potential, \( V_R \). For \( \eta \sim \eta_c \), the potential distribution is relatively flat in most of the \( A-K_1 \) gap, and most of the potential difference is concentrated in a thin "sheath" near the anode, as shown in Figure 3. This thin sheath becomes the effective diode gap, instead of the much larger \( A-K_1 \) gap. It is due to this small effective gap that the reflex mode gives very high-current operation relative to ordinary Langmuir bipolar flow.

As \( V \) approaches \( V_R \) and \( \eta \) approaches \( \eta_c \), theory predicts that the gap operates essentially as a constant-voltage device with \( V = V_R \) over a large range of current. Figure 4 shows the I vs. V characteristic of the \( A-K_1 \) gap in the reflex mode. The value of \( V_R \) depends on the energy spectrum of reflexing electrons and on the anode thickness. The energy spectrum determines \( \eta_c \) (Reference 2) which in turn determines the \( V_R \) value required to give electrons enough energy to pass through the anode \( \eta_c \) times, at a given anode thickness. For a given electron energy spectrum, increasing the anode thickness raises \( V_R \). For the reflex triode to serve as a closed switch in a magnetic energy storage system, it is desirable for \( V_R \) to be as low as possible relative to the voltage of the driving power source. This minimizes dissipative losses in the switch and allows maximum current build-up in the storage inductor. We have obtained values of \( V_R \) as low as 15 kV, as compared with the 1-MV power sources that we have used in our studies to date.

As indicated in Figure 4, the external circuit determines the total current in the closed reflex switch, and also the current density, for a given diode geometry. Earlier we indicated that the potential distribution effectively reduces the gap width and allows for high current density. The potential distribution, the current density and \( \eta \) are self-consistently related (along with the electron energy spectrum and the ratio of ion to electron current density).\(^2\) Consequently, the fixing of current density by the external circuit also determines the potential distribution and \( \eta \). The higher the current density, the smaller the anode sheath with the large potential gradient. This is illustrated in Figure 5, which shows the potential distribution and the value of \( \eta \) at various current densities, for a flat electron energy distribution from zero energy up to full diode potential. This distribution is only one of several energy spectra that we have used for modeling purposes.
Figure 5. Theoretical potential distribution in the reflex mode at various values of current density and electron transit number, $n$. $J_e/J_0$ is the ratio of the electron current density in the reflex mode to the Langmuir-Child electron current density computed using the full A-K spacing. Asterisks indicate values of $n$ that are asymptotically close to $n_c$.

The operating characteristics of a reflex switch are illustrated in Figure 6. Figure 6a is a plot of switch current versus switch voltage; Figure 6b is a plot of switch voltage versus time. The three lighter curves in Figure 6a represent the characteristics of the device in various modes of operation. The heavy curve in Figure 6a represents the temporal path of switch operation in the current-voltage plane. The curve marked $I_R$ in Figure 6a represents the low-impedance reflexing mode at the potential $V_R$. The curve marked $I_{BP}$ is the ordinary bipolar mode, with electrons emitted from $K_1$ and ions from $A$, but no reflexing electrons. The curve marked $I_{ER}$ corresponds to the presence of reflexing electrons but no ions. The 1-

Figure 6. Current and voltage behavior during reflex switch operation. In (a), $I_R$ is the reflex mode characteristic, $I_{BP}$ is the Langmuir bipolar mode characteristic, and $I_{ER}$ is electron-only reflex mode (ionless) characteristic.

Figure 7 displays representative experimental results obtained using the CAMEL generator (Pulserad 225W) at Physics International Co. The measured voltage across $A-K_1$, labeled "V-output," shows a reflex switch going through the phases described above. The peak voltage during Phase 1 is 560 kV. The reflexing voltage $V_R$ in Phase 2 is about 100 kV. The peak open-switch accelerating voltage $V_0$ in Phase 3 is 1.8 MV. Switch impedance increases at a rate in excess of 1 ohm/ns during

Figure 7. Diagnostic traces of CAMEL Shot No. 5137.
low-impedance phase of the switch, the inductive store accumulates energy at an average rate of 65 GW. The stored energy is released in the output pulse at a peak power of 360 GW. Peak energy in the inductor is 3.4 kJ. The magnetic energy in the store is converted to REB kinetic energy with essentially 100% efficiency. The X-ray pulse occurs at the same time as the high-voltage pulse across the switch and is due to bremsstrahlung from the stopping of the accelerated REB in $K_2$. The risetime of the X-ray pulse is 8 ns and the pulse duration is 15 ns (FWHM).

Figure 8 shows a case in which $K_2$ was withdrawn so that reflexing never terminated. The constant-voltage operation of the reflex mode is well illustrated. (As mentioned in Part 1, the initial transient spike in the voltage waveform represents a delay for anode emission of ions, as required for the low-impedance mode. Preionization of the anode surface may reduce or eliminate the early voltage peak.)

![Figure 8](image_url)

**Figure 8.** Measured waveforms of reflex switch voltage [(a), 278 kV/div] and current [(b), 32.3 kA/div] with switch kept in "closed," reflex mode for entire pulse. Both waveforms are 20 ns/div.

3. Reflex Switch Opening Model

In the previous section we described the basic operation of the reflex switch. Here we focus on our model of the opening of the switch. Analysis of the opening phase of a reflex switch requires the solution of a complex, two-dimensional, time-dependent space-charge-flow program. In addition, the reflex switch represents a highly time-dependent load that is driven, in our studies, by a relativistic electron beam generator. Thus, the generator, storage inductor, and reflex switch must be treated as a coupled, self-consistent system. We have developed a numerical model which treats the problem in that manner, using equivalent circuits. The modeling of the opening reflex switch begins when reflexing electrons are eliminated and the switch begins a transition to the ordinary bipolar mode of operation. However, this transition is quite complex, with several processes occurring simultaneously:

1. Ion emission from the anode decreases dramatically. Ions from the reflexing phase drift out of the $A-K_1$ gap at finite velocity. The much smaller ion current of bipolar flow ensues.

2. Cathode and anode plasmas can expand into the $A-K_1$ gap.

3. Ionizable charge-exchange neutral atoms generated in the anode plasma can flow into the $A-K_1$ gap both before and during the opening of the switch.

4. The problem is basically two-dimensional. Fringing electric fields and cathode shank emissions cause higher current densities at the cathode edge than at the center. In addition, the net magnetic field vector varies with radius, since the ratio of the azimuthal self-field to the axial applied field is a function of radial position.

As a first step in solving this problem we have adopted the following simple model. The sudden termination of electron reflexing causes an abrupt, large reduction in the ion flux emitted from the anode. However, the high-flux ions which were injected before reflexing terminated require a finite time to clear out of the $A-K_1$ gap. The widening gap between the trailing edge of these ions and the anode is the opening switch in our model. The relation between the voltage and current across this gap of width $x(t)$ is assumed to be that of Langmuir bipolar flow. During the opening phase, it seems likely that the potential of the receding region of high-flux ions does not differ greatly from that of the cathode. Thus, the high-flux ions are not accelerated appreciably and drift out at essentially constant velocity even though the voltage across the widening gap is increasing rapidly. (Note that the potential of the receding high-flux ion region during the opening phase may not be the same as the field-free region of the $A-K_1$ gap during reflexing. Also, preliminary analysis indicates the potential of the receding region, although close to that of the cathode, may not be completely field-free.) If these ideas are correct, the drift velocity of the departing ions, $v_i$, is simply the velocity with which they were injected into the field-free region during reflexing. This velocity governs the rate of opening of the switch:

$$\frac{dx}{dt} = v_i = \sqrt{\frac{2q_i \Delta V}{m_i}}$$

(1)

where $\Delta V$ is the potential difference between the anode and the field-free region during reflexing ($\Delta V \ll V_p$), and $q_i$ and $m_i$ are the charge and mass of the ion, respectively. The value of $\Delta V$ is governed by the electron energy spectrum in $A-K_1$ during reflexing. The example shown in Figure 5 has $\Delta V \approx V_p$, but the difference in potential between the field-free region and the cathode could be considerably larger for other electron energy distributions than assumed for Figure 5. In all of the calculations presented here, we have neglected any difference in potential between the field-free region and the cathode, and have set $\Delta V$ equal to the full reflexing voltage, $V_p$. We have also assumed the ions to be singly ionized carbon. As we shall show, these assumptions give calculated results which compare meaningfully with the experimental data. It is possible, however, that assuming smaller $\Delta V$ and lighter ions (protons) would give equally useful results.
For simplicity, we begin with the initial value \( x = 0 \) when reflexing stops and the opening phase begins. As \( x \) increases, the impedance of \( A-K_1 \) increases according to the familiar formula for space-charge-limited Langmuir bipolar flow. We include fringing effects in our computation of the voltage and current across the opening Langmuir bipolar gap by defining the effective area of the gap as

\[
A = \pi \left( R_C + cx \right)^2
\]

where \( R_C \) is the cathode radius and the term \( cx \) represents the fringing effects. To estimate the value of \( c \), measurements of diode voltage and current were made in an ordinary, nonreflex diode (thick anode) at various \( A-K \) spacings. The value of \( c \) was determined by requiring agreement between these data and the \( I-V \) prediction using Eq. (2). This procedure consistently gave \( c = 0.7 \), which we use in our numerical model.

The theoretical scaling predicted by our inductive storage/reflex switch system model depends in a complex way on many experimental variables. Here we simplify by holding all experimental conditions fixed and varying only the charging voltage of the generator. We assume that the reflex switch is in the "closed" mode for 45 ns and that the reflexing voltage, \( V_{rf} \), is 150 kV (typical values measured). For these conditions our numerical model calculates the peak open-switch voltage and the simultaneous current for various charging voltages, as shown by the curve labelled "scaling curve" in Figure 9. The other four curves through the origin are Langmuir bipolar characteristics for the diode gaps indicated. With the above assumptions, the switch always has opened to approximately the same gap width (2.5 cm) at the time of peak voltage, so the scaling curve falls along the Langmuir bipolar flow characteristic for this gap. The experimental data in Figure 9 are discussed in the next section.

The measured \( I \)-versus-\( V \) trajectory shown in Figure 9 (corresponding to Phases 3 and 4 in Figure 6a) was obtained with an \( A-K_1 \) spacing of 5.3 cm. The crossing of the Langmuir bipolar characteristics by the measured trajectory shows the opening of the switch (Phase 3). These data are in good agreement with the scaling curve predicted by our numerical model; i.e., the point of peak voltage falls on the scaling curve.

However, at smaller values of \( A-K_1 \) spacing, we have observed a considerable discrepancy between the predictions of the model and the experimental results. Figure 10 compares the measured and calculated opening of the switch with an \( A-K_1 \) gap of 3.5 cm. The data are from Figure 7 (\( V \)-output and \( I \)-inductor waveforms). The calculated \( I \)-\( V \) trajectory reaches the \( I_{BP} \) characteristic for a 3.5 cm gap and follows that characteristic in Phase 4, while the measured trajectory in Phase 4 lies along the \( I_{BP} \) characteristic for a gap of only about 1.5 cm. Thus the data are consistent with the attainment of a well-defined...
maximum gap with Langmuir bipolar flow, but indicate an effective final gap width that is appreciably smaller than the A-K₂ spacing, limiting the peak voltage across the switch.

The most plausible explanation for the reduced gap is that not only ions are injected into the A-K₂ gap from the anode plasma during reflexing, but also neutral atoms that subsequently get ionized. As Prono² first pointed out, neutrals at ~10 keV can be created through a charge exchange process between the accelerating ions in the anode sheath and slow neutrals liberated at high densities at the anode surface (by flashover and electron energy deposition). A number of independent observations confirm the influential presence of injected neutral atoms. Greenly⁹ has detected neutrals directly. The most obvious influence of neutrals on diode performance is to cause impedance collapse far more rapidly than can be explained in terms of the usual mechanism, i.e., expansion of anode and cathode plasmas.²,¹⁰ It was the observation of anomalously fast diode closure that first prompted Prono to suggest the charge-exchange mechanism.² The charge-exchange mechanism implies that the flux of neutrals should be proportional to the ion current density. The effect of neutrals is significant only in diodes that generate a copious flux of ions from the anode, as in the reflex triode.

We do not yet understand how the injected neutrals get ionized in A-K₁ and seem to produce a reduced but approximately constant A-K₂ spacing, as our data suggest (e.g., Figure 10). Perhaps, during reflexing, the region of ionized neutrals effectively extends the anode surface into the gap, just as the receding region of ions during the opening phase extends the K₁ surface into the gap, as shown in Figure 11. Two independent observations in our studies indicate that all during the closed phase of the switch, the region of ionized neutrals moves from the anode toward K₂ at a velocity of about 40 cm/μsec: (1) the amount of gap closure (as revealed by plotting the data as in Figure 10) divided by the time spent in the low-impedance mode (the time for the closure to occur) consistently gives velocities of 35 to 45 cm/μsec; (2) the full size of the A-K₂ gap divided by the time of final impedance collapse gives velocities of 30 to 35 cm/μsec.

Obviously, by limiting the opening of the gap, the charge exchange neutrals are detrimental to reflex switch performance. A goal of our present experimental work is to develop a method of circumventing their effect. One possibility is simply to use a larger A-K₂ gap, which would make gap reduction by neutrals relatively less significant. The data of Figure 9 were obtained using a 5.3 cm gap, and the effective maximum gap (as Figure 9 indicates) was about 4 cm. Beyond a certain A-K₂ gap size, the applied electric field becomes too low to properly "light" the anode and cathode for reflexing, and we expect that special techniques for preionizing the anode and cathode become necessary to produce the reflex mode.

A-K₂ Operation

In the previous discussion, we assumed that A-K₂ operates in an ideal mode in which (a) electrons reflect elastically from K₂, and (b) A-K₂ undergoes abrupt impedance collapse, causing abrupt termination of electron reflexing. In practice, we have found that A-K₂ operates in what we term the "reemission mode," which can approach the ideal mode as a limiting case. In the ideal mode, the potential of K₂ is equal either to that of K₁ (causing elastic reflection of electrons) or to that of the anode (preventing reflexing). Several different observations prompted us to consider the possibility that the floating voltage of K₂ can be significantly smaller than that of K₁, and yet not collapsed to anode (ground) potential either. In such a case, all electrons from K₁ would first strike K₂ (losing energy eV_K₁-V_K₂ in doing so), and then reemitted from K₂, reimpinging upon the anode and reentering A-K₁ with reduced energy eV_K₂ (whereas in ideal reflexing, electrons reimpinge upon the anode with no energy loss due to K₂). The energy reduction of electrons reentering A-K₁ can have important effects on reflex switch operation, explaining the otherwise anomalous observations that initially led us to consider the reemission mode of A-K₂. These observations include a dependence of VR on A-K₂ geometry and a correlation of the optimum K₂ diameter with K₁ diameter. The clearest confirmation of the reemission mode has been our observation of a circular damage pattern in the anode with precisely the diameter of K₂ on a few shots which failed to reflex, suggestive of energetic electron emission from K₂.

References


Figure 11. Geometrical model of opening reflex switch.

