## PROTECTION OF NEUTRAL-BEAM-ACCELERATOR ELECTRODES FROM SPARK DISCHARGES*

W. F. Praeg
Argonne National Laboratory
Argonne, Illinois 60439

### Summary

The high-voltage (HV) electrodes of neutral beam sources (NBS's) must be protected from occasional sparks to ground. Spark currents can be limited with special transformers and reactors which introduce time delays that are long enough to quench the spark or to disconnect the energy source. A saturated time delay transformer (STDT) connected in series with the HV power supply detects spark faults and limits the current supplied by the power supply and its capacitance to ground; it also initiates spark quenching. Nonsaturated, longitudinal reactors limit the discharge current supplied by the energy stored in the circuit capacitance of the NBS filament and arc power supplies long enough to discharge this capacitance into a resistor. The design principles of these protective circuits are presented in this paper.

### Introduction

Some electrodes of a NBS operate at voltages of up to 200 kV and must be protected from damage by occasional sparks to ground. Sparks are sustained by the HV power supply and by the energy stored in the circuit capacitance to ground.

If a high series impedance is designed into the HV power supply, a shunt regulator can limit the spark current supplied from the power source.[1] However, this makes the power source much more expensive and does not reduce by much the spark current due to circuit capacitance. As an alternative, conventional HV power supplies can be used in conjunction with fast switch tubes connected in series with the NBS. Figure 1 illustrates such a circuit arrangement. The switch tube limits the spark current and interrupts it within a few microseconds. Unfortunately, at very high potentials, switch tubes may themselves be subject to damage from sparking. When this happens, the spark current, which may also damage the NBS, will be sustained until the crowbar shorts the power source.

Destructive sparks can also be sustained by the energies stored in the circuit capacitance. These are shown as $C_1$, $C_2'$, $C_2''$, and $C_3$ in Fig. 1. The current magnitudes of these capacitor discharges are limited only by the impedance of the discharge paths.

It has been proposed[1] to absorb the capacitively stored energy with eddy-current losses in magnetic cores. For this purpose, the HV leads going to the NBS are threaded through the holes of toroidal ferromagnetic cores. The resistance introduced by core losses of this one-turn inductor is connected in series with the NBS. The number of cores and their electromagnetic properties are selected empirically to match the NBS. This method of arc attenuation is inefficient because magnetic core materials are formulated to keep eddy-current losses small. It also is not very practical, especially at high energies and voltages, where the core dimensions can become unwieldy. The eddy-current losses should limit the capacitive spark current to a nondestructive magnitude. For example, for a NBS operating at 120 kV and 65 A it would be desirable to limit the spark current to $\leq$ 200 A. This would call for a resistance value, generated by core losses, of $\geq 600\,\Omega$. With a circuit capacitance of 4.5 nF (~32 J), the discharge time constant would be 2.7 μs and the spark would be quenched after approximately 3 time constants (~8 μs). It may be impractical to build a magnetic-core assembly capable of generating eddy-current losses equivalent to $\geq 600\,\Omega$ for 8 μs when a step voltage of 120 kV is applied to its one-turn winding. During these 8 μs the inductance of this core assembly must also be large enough to limit the inductive current to a small fraction of 200 A.

So far, tests to dissipate capacitively stored energies by this method have been made at relatively low voltages ($\leq$ 40 kV) and with energies of $\leq$ 1.4 J.[2,3] This energy is not much greater than the energy limit of 1J above which spark damage has been observed on a 40 kV NBS.[2] Therefore, it is difficult to extrapolate from the tests data for the design of core assemblies for applications where energies of $\leq$ 40 J, at < 200 kV, must be dissipated. Initially the toroidal cores were to protect only the arc and filament circuits,[3] and the proposed circuit did not provide a core reset winding; the cores were operating on a minor hysteresis loop with correspondingly smaller eddy-current losses. Later,[2] the HV cable to the NBS was also threaded through the toroidal cores and a reset winding was added to compensate for magnetization by the normal NBS current. However, this reset winding was in the form of an air choke wound over the o.d. of the core stack. It produced a magnetic field which was at right angle with the field caused by the NBS current and, therefore, could not compensate for the magnetization by the NBS current.

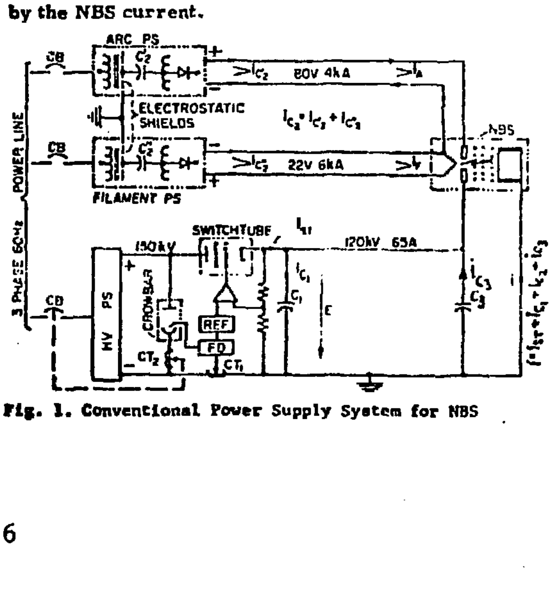



Fig. 1. Conventional Power Supply System for NBS

*Work supported by the U.S. Dept. of Energy.

This paper describes circuits that limit NBS spark currents to tolerable values for the duration of magnetic time delays. The circuits initiate disconnection of the power source and provide means to efficiently discharge the capacitively stored energy into HV resistors. This eliminates most of the problems mentioned above and permits a relatively simple design of the HV power supply.

## Protection from HV Power Source

In the simplified circuit of Fig. 1, capacitor $C_3$ represents the capacitance of the HV terminal of the NBS. It may have a typical value of 100 pF, which, at $E = 120$ kV, corresponds to a stored energy of 0.72 J. The capacitance of the HV cable and switch tube is approximately $C_1 \approx 3$ nF ($\approx 22$ J). In case of a spark in the NBS, capacitors $C_1$ and $C_3$ discharge through and damage the NBS. The switch tube limits the fault current from the HV power supply to values that are about 1.3 times the normal current. This fault current is interrupted by the switch tube within a few microseconds. In case the switch tube sparks over, the fault detector (FD) energizes the crowbar. The crowbar short circuits the power source and opens the circuit breaker (CB) of the commerical power line via current transformer $CT_2$. An NBS can be protected from overcurrent supplied by the HV power supply and by the charge on capacitor $C_1$ with an STDT.[4,5] The primary winding $n_1$ is connected in series with the load, as illustrated in Fig. 2. A secondary winding $n_2$ carries a dc bias current $i_2$, which magnetizes the core to saturation. This is shown in Fig. 3 by point

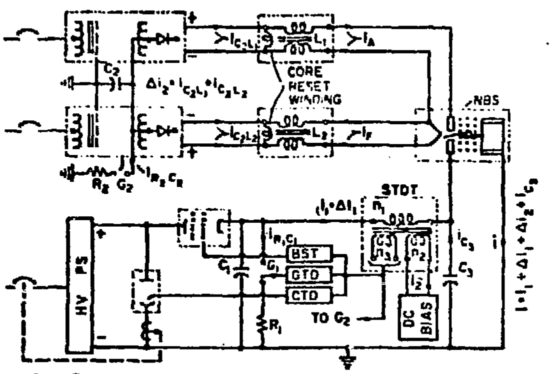



Fig. 2. NBS Protected Against Spark Damage by STDT, Reactors, and Discharge Circuits

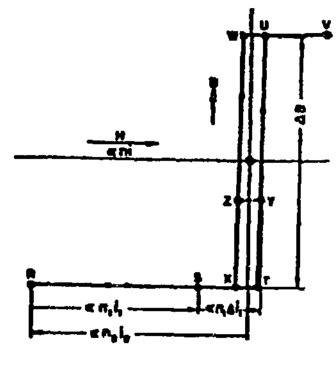


Fig. 3. Simplified B-H Curve for the STDT Core Material

R. The normal NBS current $i_1$ reduces the core saturation to point S, which is still in saturation but near the knee of the B-H curve. A spark causes the primary current to increase, bringing the core out of saturation. When this occurs, the magnetizing inductance L of the primary winding limits the rate of current increase to $di/dt \leq E/L$ while the magnetization shown in Fig. 3 changes from point T to U. The associated flux change induces in the transformer windings a voltage that is used to initiate remedial action. The time in seconds required for the flux to change from point T to point U of Fig. 3 is given by

$$\Delta t_1 = \frac{n_1 A \Delta B}{E} 10^{-8}, \quad (1)$$

where

$A$ = effective core cross section, in $cm^2$,

$\Delta B$ = change in flux density between points T and U, in G, and

$E$ = voltage applied to $n_1$.

During the time interval $\Delta t_1$, the spark current increases by $\Delta i_1$, as shown in Fig. 3. The STDT can be designed to limit this increase to be a fraction of the normal NBS operating current $i_1$.

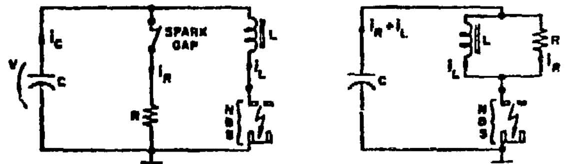
In the circuit of Fig. 2, when the NBS sparks, the voltage induced in auxiliary winding $n_3$ blocks the switch tube (BST). After the switch tube has interrupted the current from the power supply, spark gap $G_1$ is triggered via a gap-time-delay (GTD) circuit. Capacitor $C_1$ discharges through resistor $R_1$ and through the inductance of the STDT.

With $C_1$ discharged the spark is quenched and the voltage across the transformer primary is zero. The core of the STDT resets to point S of Fig. 3 via points Y, Z, and X.

With the spark current limited by the STDT to a value only slightly larger than the normal NBS current, the switch tube should be able to interrupt the spark current reliably. However, if the tube fails to interrupt the current, a crowbar time-delay (CTD) circuit energizes the crowbar before the time delay $\Delta t_1$ of the STDT has elapsed. This action removes the power source while the fault current is still limited.

## Equivalent Discharge Circuit

The discharge currents of $C_1$ are analyzed with reference to the equivalent circuit shown in Fig. 4a.




a) Spark gap with discharge resistor b) Transformer coupled discharge resistor

Fig. 4. Equivalent circuits for the capacitor discharge

With capacitor C charged to voltage V and for oscillatory circuit conditions, the currents are

$$i_R = \frac{V}{R} \epsilon^{-\alpha t} \left(\cos \omega t - \frac{\alpha}{\omega} \sin \omega t\right) , \tag{2}$$

$$i_L = \frac{V}{\omega L} \epsilon^{-\alpha t} \sin \omega t , \tag{3}$$

and

$$i_C = i_R + i_L = \frac{V}{R} \epsilon^{-\alpha t} \left(\cos \omega t + \frac{R - \alpha L}{\omega L} \sin \omega t\right) \tag{4}$$

where

$$\alpha = \frac{1}{2RC} , \quad \omega = \left(\frac{1}{LC} - \alpha^2\right)^{1/2} .$$

The peak current through the inductor is reached at the point of zero slope for the current described by Eq. 3. To solve for the time $t_p$ of maximum current, we differentiate Eq. 3 and set the result to zero:

$$\frac{di_L}{dt} = \frac{V}{\omega L} \epsilon^{-\alpha t_p} \left(\omega \cos \omega t_p - \alpha \sin \omega t_p\right) = 0 . \tag{5}$$

Solving Eq. 5 for the time $t_p$ results in

$$t_p = \frac{1}{\omega} \tan^{-1} \frac{\omega}{\alpha} . \tag{6}$$

This multivalued function gives the various times corresponding to both the maximum and minimum points. The current reaches its maximum at a point before $\omega t = \pi/2$.

With $\alpha^2 > \frac{1}{LC}$ , the resistor overdamps the circuit, and the above equations become

$$i_R = \frac{V}{R} \epsilon^{-\alpha t} \left(\cosh \beta t - \frac{\alpha}{\beta} \sinh \beta t\right) , \tag{7}$$

$$i_L = \frac{V}{\beta L} \epsilon^{-\alpha t} \sinh \beta t , \tag{8}$$

$$i_C = i_R + i_L = \frac{V}{R} \epsilon^{-\alpha t} \left(\cosh \beta t + \frac{R - \alpha L}{\beta L} \sinh \beta t\right) , \tag{9}$$

and

$$t_p = \frac{1}{\beta} \tanh^{-1} \frac{\beta}{\alpha} \tag{10}$$

where

$$\beta = \left(\alpha^2 - \frac{1}{LC}\right)^{1/2} .$$

The circuit is critically damped when $\omega = \beta = 0$. This is the case for

$$R = 0.5(L/C)^{1/2} . \tag{11}$$

## Pulse Permeability of Core Material

The B-H curve of Fig. 3 is a dc hysteresis loop. It can be realized with grain-oriented 50% nickel-iron core material, e.g. Deltamax. However, less expensive grain-oriented silicon steel, e.g. Silectron, is satisfactory for most applications.

The STDT must provide both a time delay $\Delta t_1$ (Eq. 1), and an inductance L that limits the current $i_L$ (Eqs. 3 or 8) to tolerable values.

When a step voltage is applied to the STDT, eddy-currents will be generated in the core laminations. They will prevent magnetic flux from penetrating the whole core area right away. In time the eddy-currents decay and the area containing flux increases. For this reason the value of $\Delta t_1$ will be smaller than is calculated from Eq. 1. It is customary to express this reduction in useful cross section for the flux by means of an effective pulse permeability

$$\mu_p = B/H \, \mu_0 \tag{12}$$

where

B = induction in G,

H = magnetizing force, A $cm^{-1}$, and

$\mu_0$ = permeability of space, $4\pi \times 10^{-9}$ H $cm^{-1}$ .

The solid lines in Fig. 5 show published magnetization curves for 2 mil Silectron laminations. Similar data has not been published for Deltamax laminations. Therefore, the B-H curves shown for 1 mil Deltamax have been derived from the Silectron curves as described below.

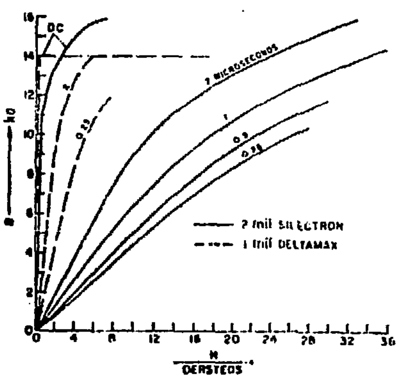



Fig. 5. Pulse Magnetization Curves for 2 mil Silectron and 1 mil Deltamax.

The peak dc permeability of Deltamax laminations is about 7 times larger than that of Silectron. When these materials are pulsed under conditions where the flux distribution over their cross sections is identical, then the pulse permeability of Deltamax should also be 7 times larger ($\mu_{pD} = 7 \mu_{pS}$).

The depth where the magnetic field has a value of $\epsilon^{-1}$ of the field on the surface of a core lamination is

$$\sigma = \left(\frac{\rho}{\pi f \mu}\right)^{1/2} \tag{13}$$

where $\rho$ = resistivity, μΩ cm,

$f$ = frequency, $s^{-1}$.

To achieve the same flux distribution in laminations of Deltamax and Silectron their respective ratios of lamination thickness d to skin depth $\sigma$ must be the same,

$$\frac{d_D}{\sigma_D} = \frac{d_S}{\sigma_S} \tag{14}$$

The resistivities of Deltamax and Silectron are $\rho_D = 45$ μΩ cm and $\rho_S = 50$ μΩ cm. Finally, from Eqs. 13 and 14 we find the lamination thickness of Deltamax $d_D$ which has a pulse permeability 7 times that of 2 mil Silectron.

$$d_D = d_S \frac{\sigma_D}{\sigma_S} = d_S \left(\frac{\rho_D\ \mu_{pS}}{\rho_S\ \mu_{pD}}\right)^{1/2}$$

$$= 2 \text{ mil } \frac{45}{7 \times 50}^{1/2} = 0.72 \text{ mil} .$$

By dividing the H-values of the 2 mil Silectron curves in Fig. 5 by a factor 7, we obtain H-values applicable to Deltamax laminations 0.72 mil thick for $B \leq 14$ kG. To correct for the additional eddy currents in 1 mil as compared to 0.72 mil Deltamax laminations, a factor of 7 x 0.72 = 5 was used to obtain the curves for 1 mil Deltamax shown in Fig. 5.

From the curves of Fig. 5 we can calculate $\mu_p$ and with it the inductance of the primary winding $n_1$ of the STDT from

$$L = \frac{n_1^2\ \mu_0\ A}{l_g + l_{Fe}/\mu_p} \tag{15}$$

where

$l_{Fe}$ = length of flux path in iron, cm

$l_g$ = length of flux path in air, cm.

## Protection from Capacitive Stored Energy of Arc and Filament Power Supplies

Figure 1 shows the capacitive discharge currents $i_{C_2'}$ and $i_{C_2''}$ of the arc and filament power supplies. They are superimposed on the circulating arc current $i_A$ and filament current $i_F$ as shown. In most cases, capacitors $C_2'$ and $C_2''$ are effectively connected in parallel. This is illustrated by combining them to one capacitor, $C_2 \approx 1.5$ nF (~ 10 J) in the circuit of Fig. 2.

To limit the capacitive discharge current when the NBS sparks, longitudinal reactors $L_1$ and $L_2$ have been added to the circuit. A dc bias winding resets the core of these reactors to a point similar to point X of Fig. 3. The reactor windings are wound bifilar to have negligible inductance in the metallic circuits of the load currents $i_A$ and $i_F$. The longitudinal circuits, which are completed through capacitance $C_2$ and ground, carry capacitor discharge currents $i_{C_2L_1}$ and $i_{C_2L_2}$. These currents are limited by the magnetizing impedance of the reactors. The reactors are designed for a time delay $\Delta t_2$ that is larger than the time required to discharge $C_2$.

When the NBS sparks, a signal from the STDT initiates triggering of spark gap $G_2$ causing $C_2$ to discharge into $R_2$ and through $L_1$ and $L_2$. $L_1$ and $L_2$ are dimensioned to keep these discharge currents within the rating of the NBS.

## Arc Current Due to $C_3$

Locating the STDT and the reactors as close as practicable to the NBS terminals holds the value of $C_3$ to a minimum. The electrodes of the NBS should be designed to withstand the discharge of $C_3$ ($\leq$ 1 J). Relatively small ferrite cores could be added to the NBS terminals to inductively limit the peak current of this discharge.

## Design Considerations

### The STDT Circuit

With a typical duty cycle of 1/30 for the HV power supply the rms current of the NBS in the circuit of Fig. 1 is only 12 A. The primary of the STDT can be wound with relatively small wire and with a relatively large number of turns. Therefore, we can use the lower permeability Silectron core material which is less expensive and less sensitive to strain and temperature than Deltamax. To fully realize the magnetic capabilities of a given material requires a core geometry having a minimum air gap, such as tape-wound toroids. Gapped structures reduce the unsaturated core permeability. This is illustrated by the dc B-H curves of the Silectron core assembly, with and without a gap, as shown in Fig. 6. The low pulse permeability of Silectron of $\mu_p \approx 600$ makes the core assembly insensitive to small air gaps. A gapped core is preferred because it permits using low-cost coil-winding techniques.

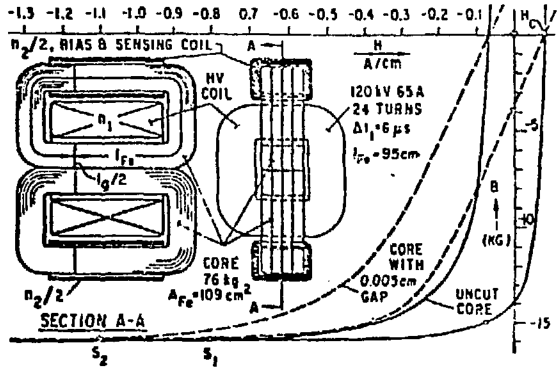



Fig. 6. Conceptual Design for an STDT and DC Hysteresis Curves for Silectron Cores

Figure 6 shows the conceptual design for an STDT for a 120 kV, 65 A load. The core cross section of 109 $cm^2$ is made up from eight C-cores each wound from 1 in wide and 2 mil thick Silectron tape. The switch tube interrupts fault currents in less than 3 µs. In order to keep $\Delta t_1$ small we discharge $C_1$ in about 1 µs. This requires a discharge resistor of about $R_1 \le 1$ µs/3 x 1 nF $\le 111\ \Omega$. The time delay of the STDT should be about 6 µs. From Eq. 1 and with $\Delta B \approx 28 \times 10^3$ Vs $cm^{-2}$ we require

$$n_1 \ge \frac{\Delta t_1\ E\ 10^8}{A\ \Delta B} = \frac{6\ \mu s\ 120\ kV\ 10^8}{109\ cm^2\ 28\ k\ Vs\ cm^{-2}} = 24\ \text{turns}.$$

With a pulse permeability of $\mu_p \approx 600$ the inductance L of this winding is from Eq. 15

$$L = \frac{24^2 \times 1.26 \times 10^{-8}\ H\ cm^{-1}\ 109\ cm^2}{(0.005 + 95/600)cm} = 4.84\ mH\ .$$

Since $R_1 = 111\ \Omega < 0.5\ (4.84\ mH/3nF)^{1/2} = 635\ \Omega$, the circuit is overdamped. From Eq. 7 the discharge current through resistor $R_1$ is

$$i_R = 1081\ A\ e^{-1.5 \times 10^6 t}\ (\cosh 1.48 \times 10^6\ t - 1.016 \sinh 1.48 \times 10^6\ t)\ .$$

The discharge current of $C_1$ which flows through the STDT and the NBS is, from Eq. 8,

$$i_L = 16.8\ A\ e^{-1.5 \times 10^6\ t} \sinh 1.48 \times 10^6\ t\ .$$

Its maximum occurs, from Eq. 10, at time $t_p = 0.881$ µs with a value of 4.8 A.

### The Longitudinal Reactors

The arc and filament currents are large, requiring large conductor cross sections. Therefore, a one-turn design as shown in Fig. 7 is recommended for most applications. In order to keep the core area small, the higher permeability Deltamax core material should be used without an air gap. In addition, the discharge of $C_2$ should be as fast a practicable. For example, we could discharge $C_2 \approx 1.5$ nF in about 0.5 µs with a resistor of $R_2 \le 0.5$ µs/3 x 1.5 nF $\le 111\ \Omega$. The delay time $\Delta t_2$ of the reactor should then be $\ge 1$ µs. From Eq. 1 this requires a core area of $A \ge 42.9\ cm^2$. This area could be realized by stacking 17 cores of 20 cm I.D. and 40 cm O.D. which are wound from 1 in wide 1 mil Deltamax tape.

With a flux path length of about 94 cm and a pulse permeability $\mu_p \approx 3000$, the one-turn reactor has an inductance of

$$L = 1.26 \times 10^{-8}\ H\ cm^{-1}\ \frac{429\ cm^2}{94\ cm/3000} = 173\ \mu H\ .$$

The capacitive discharge current through resistor $R_2$ is, from Eq. 7

$$i_R = 1081\ A\ e^{-3 \times 10^6\ t}\ (\cosh 2.27 \times 10^6\ t - 1.32 \sinh 2.27 \times 10^6\ t)\ .$$

The current through the reactor and through the NBS is, from Eq. 8,

$$i_L = 306\ e^{-3 \times 10^6\ t} \sinh 2.27 \times 10^6\ t\ .$$

Its maximum occurs at time $t_p = 0.40$ µs with a value of 75.5 A. This is well below the limit of 200 A which the NBS can tolerate.

When the NBS sparks, the one-turn windings of the reactor are exposed to a 120 kV step voltage. To keep this potential from the reset bias power supply, an inductor $L_B$, rated 120 kV, and a low voltage (LV) capacitor $C_B$ are part of the bias circuit.

### Combining the STDT and Longitudinal Reactor on One Magnet Core

In the circuits of Figs. 2 and 7, capacitor $C_2$ was discharged in the shortest time practicable. The discharge of $C_1$ was delayed until the switch tube had interrupted the fault current fed from the power supply. This time sequence permits an optimal design of the time delay for the reactor 1. ($\Delta t_2$) and for the STDT ($\Delta t_1 > \Delta t_2$).

For applications where the switch tube can interrupt current and block HV in $\le 1$ µs, it may be economical to combine the functions of the reactor and the STDT on one core. In this case, all windings would have the same number of turns, e.g. one. The switch tube would interrupt in $\le 1$ µs the HV power supply current. Approximately 0.5 µs later, the spark gaps would discharge capacitors $C_1$ and $C_2$ into resistors $R_1$ and $R_2$, respectively. For a total time delay of 2.5 µs and one turn windings, the core area for Deltamax cores would be $A \ge 1070\ cm^2$. Since all windings are coupled, the discharge time constants should be the same $R_1 C_1 = R_2 C_2$.

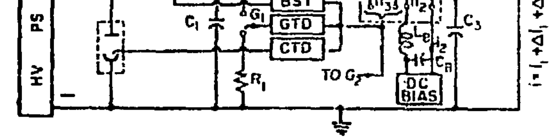



**Fig. 7.** Spark Protection of NBS with and STDT, a One-Turn Reactor and Discharge Circuits.

### Eliminating Spark Gaps $G_1$ and $G_2$

For NBS's operating at relatively lower potentials and with less stored energy to be dissipated, the spark gaps of the circuit of Fig. 7 can be eliminated. This is done by coupling resistors $R_1$ and $R_2$ into the discharge path by transformer action as shown in the circuit of Fig. 8. Here the bias winding $n_2$ of the STDT serves also as a signal winding for the switch tube and crowbar control circuits. A secondary winding $n_S$ couples discharge resistor $R_1'$ into the circuit. The STDT serves as a pulse transformer discharging $C_1$ into $R_1'$.

The turns ratio $n_1/n_S$ permits circuit optimization. In fact, if the STDT is made up of a number of smaller cores, the resistor $R_1'$ could consist of several lower-voltage resistors, each being coupled into the circuit by one of the smaller cores.

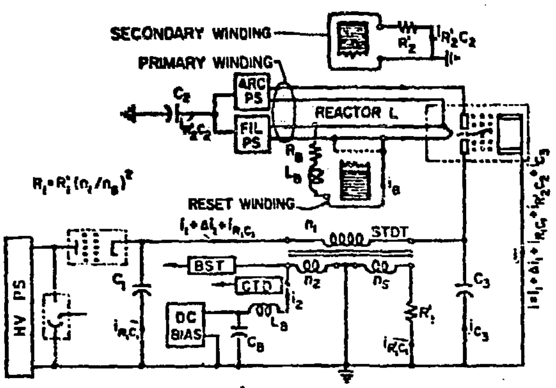



Fig. 8. Spark Protection with and STDT, a Reactor and Transformer Coupled Discharge Resistors.

A one-turn secondary added to the longitudinal reactor of Fig. 7 converts it into a 1:1 pulse transformer with a load resistor $R_2'$ as shown in Fig. 8. Again, if the core cross section of reactor L is made up of a number of small cores, then discharge resistor $R_2$ could be made up of several lower-voltage resistors, each coupled by transformer action into the discharge circuit by these separate cores.

The reset bias supply of Fig. 7 has been eliminated by connecting the bias winding to the dc filament power supply. Resistor $R_B$ is required to set the correct bias current. Inductor $L_B$ absorbs the 120 kV step voltage when the NBS sparks. This bias circuit must be connected as shown by the solid lines. If it were connected across the terminals of the filament supply, as shown by the dashed line, 120 kV would appear across the LV power-supply terminals.

The transformer-coupled discharge circuit of Fig. 8 eliminates spark gaps and associated trigger circuitry, thereby improving circuit reliability and speed of response. Discharge resistors $R_1'$ and $R_2'$ are automatically applied as soon as the NBS sparks. However, in this circuit all the discharge currents of $C_1$ and $C_2$ pass through the NBS. This is illustrated by the equivalent circuit of Fig. 4b.

### References


1. W. R. Baker, et al., "Saturable Reactor-Controlled Power Supply System for TCT/TFTR Neutral Beam Sources," Proceedings of the Sixth Symposium of Engineering Problems of Fusion Research, San Diego, CA. p. 440-444 (November 18-21, 1975).

2. W. R. Baker, "Stor Energy and the LBL Neutral Beam Source," Lawrence Berkeley Laboratory, Internal Memo, May 1976.

3. J. H. Fink, et al., "Analysis and Application of a Transformer Core Which Acts as a Snubber," Lawrence Livermore Laboratory, paper submitted to IEEE Transactions on Plasma Science (1977).

4. W. F. Praeg, "A Saturated Time-Delay Transformer for Overcurrent Protection of DC Accelerators," ANL/CTR/TM-59, Argonne National Laboratory, Argonne, IL (December 1975).

5. W. F. Praeg, "A Time Delay Transformer for Overcurrent Protection," IEEE Power Electronics Specialists Conference, PESC 76 Record, Cleveland, p. 297-302 (June 1976).