Overcurrent Protection for the TFTR Neutral Beam Sources During Spark Down*

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Summary

The accelerating grid of a neutral beam source (NBS) of the Tokamak Fusion Test Reactor (TFTR) operates at 120 kV and 65 A. The capacitance to ground between the switch tube (ST) and the NBS is $C_1 \sim 5$ nF (~ 36 J). The arc and filament power supplies for the NBS float at 120 kV and have a capacitance to ground of $C_2 \sim 2$ nF (~ 14 J). When the NBS sparks to ground, C_2 begins to discharge immediately. The ST impedance limits the fault current from the high voltage (HV) power supply to ~ 100 A until it disconnects the power source < 2 μs after spark down. In case the ST fails, a crowbar removes the power source ~ 4 μs after spark down and C_1 begins to discharge. During spark down, fault currents are limited with a saturated time-delay transformer (STDT) connected between the ST and the NBS and with a snubber, which is in the arc and filament power leads, in connection with a spark gap. Alternatively, STDT's can be used for the HV and for the arc and filament power leads. This paper presents design details and experimental results of the overcurrent protection circuits.

Introduction

The accelerating and the gradient grid of an NBS operate at very high voltages and must be protected from damage by occasional sparks to ground. In the summer of 1975 I proposed an STDT to limit the fault current during spark down.[1,2] The STDT is connected in series with the HV source. W. R. Baker of the Lawrence Berkeley Laboratory[3] reported in 1976 that toroidal 50-50 NiFe tape cores can be used as one-turn "snubbers" to limit fault currents. In 1977 I proposed that spark gaps and resistors in conjunction with an STDT and reactors be used to shunt most of the discharge energy away from the NBS.[4] On the basis of this proposal two prototype circuits are being developed to protect the NBS's of the TFTR.

In the circuit of Fig. 1 an STDT limits the current to the acceleration (accel.) and gradient grids of the NBS. During normal operation the ST will open the power circuit in < 2 μs, thereafter capacitor C_1 discharges. In case the ST fails, a crowbar short circuits the power source ~ 4 μs after the NBS sparked to ground. The energy stored in C_2 is dissipated in the Deltamax cores and in resistor R_2 which is connected in parallel to the Deltamax cores when spark gap G is triggered by the STDT.

In the circuit of Fig. 2 the one-turn Deltamax core has been replaced by multi-turn Silectron cores. Silectron cores are less efficient but also very much less expensive than Deltamax cores. With Silectron cores and multi-turn windings, the time delay and circuit impedance can be increased economically, thereby eliminating the need for the spark gap circuit.

<ins>Fault-Current Limits.</ins> The 12 NBS's for the TFTR are each rated 120 kV 65 A. From the specifications[5] for the NBS a few of the many requirements are stated as follows:

Turn-off time after fault	< 10 μs
Interrupt duration after fault	5 to 50 ms,

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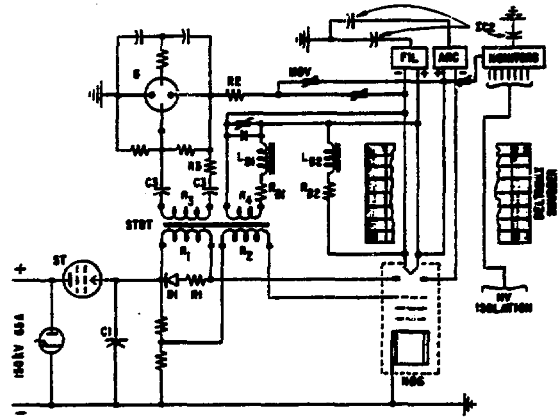


Fig. 1. NBS Protected by STDT, Snubber and Spark Gap.

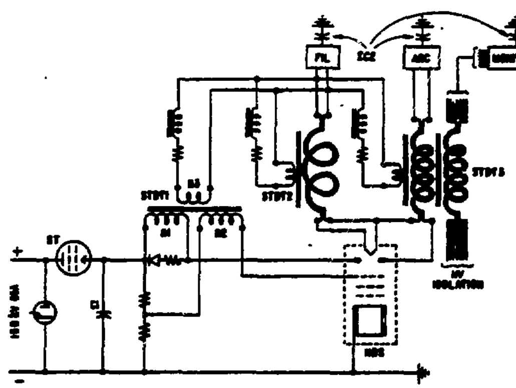


Fig. 2. NBS Protected by STDT's.

Maximum 1/2 CV^2 energy allowed on NBS side of protection circuit	3 J,
Maximum 1/2 CV^2 energy allowed on power supply side of protection circuit	15 J
Maximum fault current permitted by protection circuit over and above operating current	200 A

The above limits the discharge to $\int i dt \leq 265$ A x 10 μs $= \leq 2.65$ m As and the capacitance of 2.1 nF. The specifications do not mention $\int i^2 dt$ values. For the NBS of the TFTR we have $C_1 = 5$ nF (36 J) and $C_2 = 2$ nF (14.4 J) which exceeds the desired value of 15 J by a factor of 3.36. However, there should be no limit set to the 1/2 CV^2 allowed on the power supply side of the protection circuit as long as the protection circuit holds the fault current to safe values.

Failure Modes. The failure mode of the arc and filament circuit is always the same. When the NBS, sparks, the capacitance to ground, C_2, of the arc and filament transformer assembly begins to discharge. The grid circuits can have three failure modes. First, during normal operation of the protective circuits, a spark down causes the ST to disconnect the HV supply within 2 μs, thereafter capacitor C_1 discharges. Second, the ST does not open the circuit but keeps limiting the current. In this case the crowbar is activated within 4 μs. This removes the HV source and capacitor C_1 begins to discharge. The worst fault condition exists if the ST sparks over when the NBS sparks to ground. The ST no longer limits current and causes capacitor C_1 to be charged to 150 kV for 4 μs until the crowbar shorts the HV source.

$\int idt$ versus $\int i^2dt$. In the past only the peak values of charge (As), energy (J) and current (A) have been specified during fault conditions. For a given spark down resistance of a NBS, the energy dissipated is proportional to $\int i^2dt$. Therefore, discharging a given amount of coulombs through as large an impedance, connected in series with the NBS, as practicable will cause the least amount of energy to be dissipated in the NBS. For example discharging 2 nF, charged to 120 kV into a 200 Ω resistor results, with RC = τ = 0.4 μs, in a discharge current of

$$i = I_p \exp(-t/\tau) = 600\ \mathrm{A} \exp(-t/0.4\ \mu s) \quad (1)$$

The total discharge is

$$\int_0^\infty idt = I_p\tau = 600\ \mathrm{A} \times 0.4\ \mu s = 240 \times 10^{-6}\ \mathrm{As}, (2)$$

and for i^2t, we have

$$\int_0^\infty i^2dt = I_p^2\ \tau/2 = 600^2\ A^2 \times 0.4\ \mu s/2$$
$$= 72\ \mathrm{mA^2s}. \quad (3)$$

If we now increase the resistance by a factor 10, $\int idt$ does not change, but the discharge will have a 4 μs time constant and a peak current of only 60 A resulting in a 10 times smaller $\int i^2dt$ of

$$\int_0^\infty i^2dt = 60^2 \times 4\ \mu s/2 = 7.2\ \mathrm{mA^2s}.$$

Of course the energy dissipated is 14.4 J in either case. However, the heat dissipation is 10 times smaller. It is recommended that the specifications for fault currents include values for $\int i^2dt$.

The Snubber Design

The Initial Current Step in Deltamax

Without spark gap G and resistor R_2 the discharge circuit for capacitor C_2 is the snubber circuit first proposed by W. Baker.[3] It uses eddy-current losses in Deltamax cores to limit the current. The equivalent circuit is included in Fig. 4. The circuit is based on a paper by Winter et al.[6] Part of that paper reports on initial current step measurements on toroidal cores of 50-50 NiFe tape with the result that

$$H = 5.65\ \xi^{1/2}, \quad (4)$$

where H = initial step in magnetic field at the surface of a wrap of tape, in Oe,
ξ = gradient of the initial step voltage around the same wrap of tape, in V/cm.

The authors found that most of the good cores tested were within 50% of the value given by Eq. (4). Converting Oe into A/cm we can write

$$H = \frac{5.65}{0.4\pi}\xi^{1/2} = 4.5\ \xi^{1/2} = \frac{i_r n}{\ell_{Fe}} \quad (5)$$

where i_r = initial step in excitation current, in A,
n = number of turns on the excitation coil,

and

ℓ_{Fe} = length of magnetic flux path, in cm.

From Eq. (5) we obtain the initial step current

$$i_r = 4.5\ \frac{\ell_{Fe}}{n}\ \xi^{1/2}. \quad (6)$$

The average initial voltage gradient on the laminations of a tape wound core is

$$\xi = \frac{E}{2wNn}. \quad (7)$$

where E = step voltage applied to the excitation coil, in V,
w = width of the core laminations, in cm,

and

N = total number of laminations

Combining Eqs. (6 and 7) results in

$$i_r = 3.18\ \ell_{Fe}\left(\frac{E}{wNn^3}\right)^{1/2}. \quad (8)$$

The resistance value of the core, equivalent to the initial step response, is

$$R_r = \frac{E}{i_r} = \frac{0.314}{\ell_{Fe}}(EwNn^3)^{1/2}. \quad (9)$$

The resistance, equivalent to eddy-current losses, changes with time.

The Initial Current Step in Silectron

Al Schofield of Los Alamos Scientific Laboratory took experimental data on the step response of 1-mil Silectron. From these measurements a value of

$$H = 14.8\ \xi^{1/2} \quad (10)$$

in A/cm was determined by Vincent Cheng of Gulton Industries, Inc. This agrees with measurements taken at Argonne National Laboratory (ANL) with 2 and 4-mil cores. Therefore, for Silectron, the equations for i_r and R_r become

$$i_r = 14.8\ \frac{\ell_{Fe}}{n}\ \xi^{1/2} = 10.5\ \ell_{Fe}\left(\frac{E}{wNn^3}\right)^{1/2} \quad (11)$$

and

$$R_r = \frac{0.095}{\ell_{Fe}}(EwNn^3)^{1/2}. \quad (12)$$

Discharge Equations

Experiments at ANL have shown that the time responses of the initial current can be grouped as follows:

a. The current decays approximately in a straight line (Fig. 9a)
b. At higher energies the current decays with a 1+cos ωt shape (Fig. 8a)
c. The current rises much above its initial value (Fig. 9c).

The last of these is not in agreement to limit the current to close to its initial step and, therefore, not considered any further.

The Current Decays Linearly. At relatively low energies, the current decay can be approximated with a straight line

$$i(t) = i_r\,(1 - \frac{t}{T_1}), \qquad (13)$$

where T_1 = time when current is zero.

The capacitor voltage is given by

$$e_C(t) = E_o - \frac{1}{C}\int_0^t i\,dt = E_o - \frac{i_r}{C}\,t(1 - \frac{t}{2T_1}), \qquad (14)$$

where E_o = voltage on capacitor C at t = 0.
From Eq. (14) the discharge time, t = T_1, is, for e_C = 0,

$$T_1 = \frac{2\,C\,E_o}{i_r}. \qquad (15)$$

The voltseconds (Vs) the snubber must support are

$$\phi(t) = \int_0^t e_C\,dt = E_o\,t - \frac{i_r t^2}{2C}\,(1 - \frac{t}{3T_1}), \qquad (16)$$

which, at time t = T_1 becomes

$$\phi_{T_1} = \int_0^{T_1} e_C\,dt = E_o\,T_1 - \frac{i_r T_1^2}{3C}. \qquad (17)$$

The heat generated is proportional to

$$\int_0^t i^2 t = i_r^2\int_0^t (1 - \frac{t}{T_1})^2 = i_r^2\,t\,(1 - \frac{t}{T_1} + \frac{t^2}{3T_1^2}), \qquad (18)$$

and at the end of the pulse we have

$$\int_0^{T_1} i^2 t = i_r^2\,\frac{T_1}{3}. \qquad (19)$$

The above equations are plotted on a per unit basis in Fig. 3.

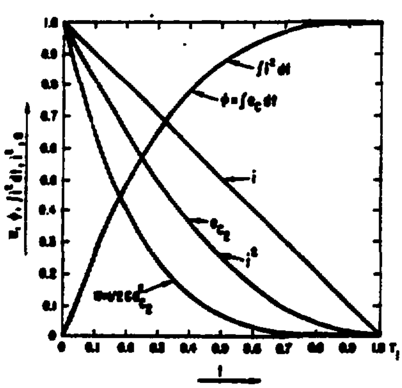


Fig. 3. Linear Current Decay.

The Current Decay Follows (1 + cos ωt). For a current shape described by

$$i(t) = 0.5\,i_r\,(1 + \cos\omega t), \qquad (20)$$

the capacitor voltage becomes

$$e_C(t) = E_o - \frac{1}{C}\int_0^t i\,dt = E_o - \frac{i_r}{2C}\,(t + \frac{1}{\omega}\sin\omega t), \qquad (21)$$

and with e_C = 0 for t = $T_1 = \frac{\pi}{\omega}$, we find

$$T_1 = \frac{2CE_o}{i_r}$$

which is the same as Eq. (15).
For the flux we have

$$\phi(t) = \int_0^t e_C\,(t)dt = E_o t - \frac{i_r}{2C}\left[\frac{t^2}{2} + \frac{1}{\omega^2}\,(1 - \cos\omega t)\right] \qquad (22)$$

which, at $t = T_1 = \frac{\pi}{\omega}$, is

$$\phi_{T_1} = E_oT_1 - \frac{i_r}{2C}\left(\frac{T_1^2}{2} + \frac{2T_1^2}{\pi^2}\right) = E_oT_1 - \frac{0.35\,i_r T_1^2}{C} \qquad (23)$$

Finally, we find

$$\int_0^t i^2 dt = \frac{i_r^2}{4}\left[\frac{3t}{2} + \frac{1}{\omega}\,(2\sin\omega t + \frac{1}{4}\sin 2\,\omega t)\right] \qquad (24)$$

which at $t = T_1 = \frac{\pi}{\omega}$ becomes

$$\int_0^{T_1} i^2 dt = \frac{3}{8}\,i_r^2 T_1 \qquad (25)$$

The above equations are plotted in Fig. 4.

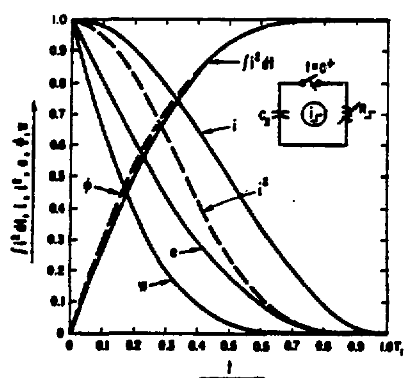


Fig. 4. Current Decay Follows (1 + cos ωt).

The TFTR Deltamax Snubber and Spark Gap Circuit

The Deltamax Circuit. As shown in Fig. 1, the heavy buses of the arc and filament circuits, together with the cables of the monitoring circuits, form a one-turn excitation coil for the Deltamax snubber. The snubber is biased to -0.2 Oe with a one-turn winding. When the NBS sparks to ground, the 120 kV on capacitor C_2 = 2 nF excites the snubber cores. Snubber details are given in Table I.

Table I: For 120-kV Snubber Core Assembly

No. Deltamax cores	36
OD	25.0 cm
ID	14.5 cm
Buildup	b = 5.24 cm
Tape width	w = 1.27 cm
Tape thickness	d = 2.54 x 10^{-3} cm
Stacking factor	s = 0.75
No. wraps in assembly N = 36 bw/d	= 5.57 x 10^4
Average voltage gradient on wraps	ξ = 0.848 V/cm
Voltage between wraps	2.15 V
Median length of flux path	l_{Fe} = 61.8 cm
Cross area of assembly	A = 180 cm^2
Cost of 36 cores @ $310/core	$11,160

The tapes are deburred and double-coated. Each core is in a nylon case and cushioned with dielectric gel XF-13-523 of the Dow Corning Corp. From Eq. (8) the initial current step is i_F = 256 A. From Eq. (15), the discharge time is, T_1 = 1.88 us. From Eq. (23) the core assembly must support a total flux of ϕ_{T_1} = 0.067 Vs. The average voltage during the discharge is V = ϕ_{T_1}/T_1 = 0.067 Vs/1.88 us = 35.8 kV. With a flux density change of ΔB = 28 x 10^3 G the cores will support 35.8 kV for

$$\Delta t = \frac{nA(\Delta B)}{V \times 10^8} \qquad (26)$$

$$= \frac{180 \times 28 \times 10^3}{35.8 \times 10^3 \times 10^8} = 1.40 \text{ us.}$$

This falls 25% short of T_1 = 1.88 us. However, as is shown later, the spark gap will shunt most of the discharge away from the NBS and into R_2 in less than 100 ns after the NBS has sparked down.

We see from Fig. 4 that after 100 ns (0.05 T_1) not much energy has passed through the NBS. Because of the quick response of the spark-gap circuit, we can reduce the amount of core material. For example, by cutting the tape width in half, we would keep the same volts/wrap. The gradient ξ would double, causing i_F to increase by 41.4% to 362 A. With half the area, the volt-second rating of the core assembly would be cut in half to 25 ms, which still provides a large safety margin.

The Bias Circuit. During normal operation a dc bias current of 12 A generates 0.2 Oe on the outer wrap of the snubber cores. This current also causes a dc flux of 5 kG in the cores of bias choke L_{B2}. A short time after the NBS sparks to ground, this bias circuit is by transformer action, connected in parallel to the snubber impedance. Choke L_{B2} is dimensioned to keep this additional fault current small and to absorb the voltage across C_2. The voltage divider made by L_{B2}, R_{B2}, and the parallel connection of a diode and a metal oxide varistor protects the bias supply from transient voltages.

Table II: Details for 120-kV Bias Choke

Eight Silectron cores AL-1463 with	d = 5.08 x 10^{-3} cm
N = 8 bs/d	N = 4.45 x 10^3
Width of Lamination	w = 3.81 cm
No. of turns	n = 13
Volts/turn = 120-kV/13	= 9230 V
Volts/lamination = 9230/N	= 2.07 V
Voltage gradient on lamination	ξ = 0.271 V/cm
Length of flux path in iron	ℓ_{Fe} = 55.6 cm
Length of flux path in air gap	ℓ_g = 0.02 cm
DC induction	B_{dc} = 5000 G

Under worst conditions (perfect coupling between the primary and secondary turns) we would have a current step in the bias circuit when the NBS sparks down. From Eq. (11) the current step is i_F= 33.2 A. This current adds to the 12 A bias current. However, the pulse permeability of Silectron[7] is very much smaller than the dc permeability. This causes the flux density to increase slow enough to stay well below saturation during the discharge pulse. The cores were selected on the basis that the volts/lamination be ≈ 2 V. This voltage requires double coating of the laminations (a carlite coat followed by a magnesium methalyte coat). The turns were wound with RG-17 cable with the braid removed, and the coil assembly was vacuum impregnated with epoxy resin.

Test Results

The Deltamax snubber was tested in the circuit of Fig. 5. The arrangement of the circuit components is shown in Fig. 6.

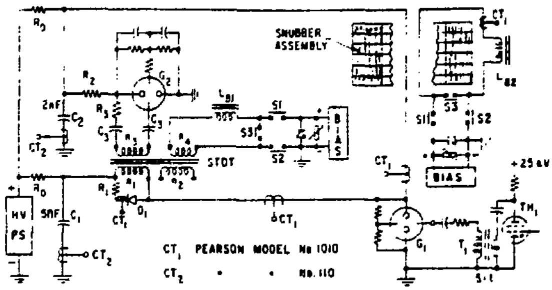


Fig. 5. Test Circuit.

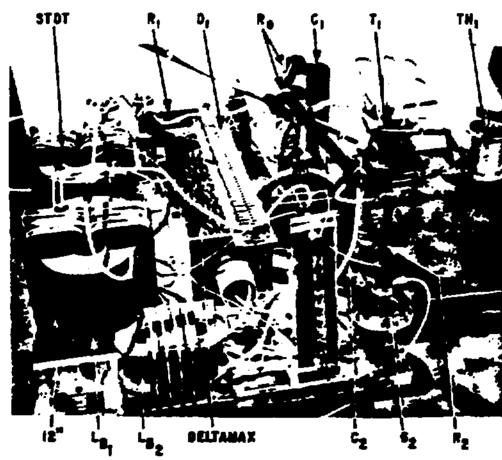
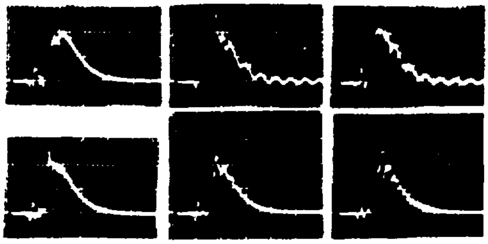


Fig. 6 Test Circuit Components.

Tests Without Spark Gap G2. With the STDT disconnected, the 2 nF capacitor C_2 was discharged through the snubber when spark gap G_1 was triggered via thyratron TH_1. The trigger pulse to thyratron TH_1 was also used to trigger the time sweep of the oscilloscope used to monitor the output of the current transformers (CT's). The spark gap, especially at low voltages, does not always break over at the same time after TH_1 is triggered. This time jitter causes the time delay seen in some of the pictures at the start of the discharge pulses. By means of switches S_1, S_2, and S_3, the effect of bias circuit parameters was investigated.

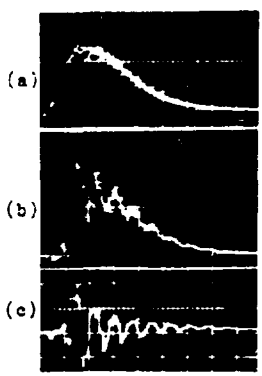
A discharge from 70 kV (4.9 J) with all switches open, after the snubber cores had been reset, is shown in Figs. 7a. The "NBS" fault current is measured by CT_1. The capacitor current is measured by CT_2. Closing switch S_3 after the core had been reset resulted in current pulses as shown in Fig. 7b; the LC of the bias circuit rings at 3.3 MHz. Future operating conditions are simulated by closing switch S_3 after core reset and connecting the bias winding to the primary winding. These conditions are shown in Fig. 7c. With 84 kV on C_2 we expect a peak current of 214 A. As shown in

Fig. 8a the current measured with CT_2 is in reasonable agreement; this picture was taken with all switches open after the core had been reset. Figure 8b was taken with S_1 and S_2 closed. The current through the grounded bias circuit, oscillating at 5.6 MHz, is superimposed to the current shown in Fig. 8a. The current through the bias circuit is shown in Fig. 8c. The changes in current shape and magnitude for various levels of energy are illustrated in Fig. 9, which shows the discharge of a 7 nF capacitor charged to 30, 60, and 85 kV.



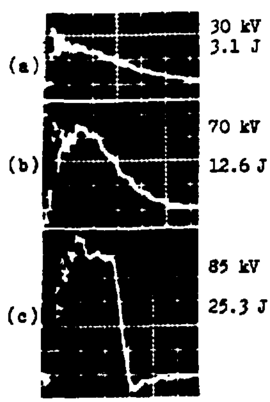
(a) 100 A/div (b) 0.5 µs/div (c)

Fig. 7. Discharges of 2 nF at 70 kV.



100 A/div, 200 ns/div

Fig. 8. Discharges of 2 nF at 84 kV.



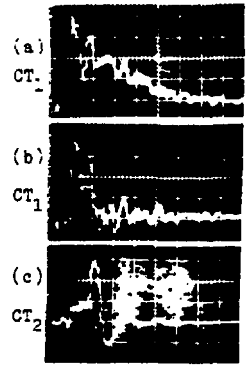
100 A/div, 200 ns/div

Fig. 9. Discharges of 7 nF.

Tests With Snubber and Spark Gap. For reference, Fig. 10a shows the snubber current with G_2 disconnected. With the circuit of Fig. 5, resistor R_2 is parallel with the snubber when G_2 is triggered by the STDT. As illustrated by Fig. 10b, this happened approximately 170 ns after C_2 began to discharge. The capacitor current is shown in Fig. 10c; it shows the current step when G_2 turns on. The pictures in Fig. 11 illustrate how the time to trigger G_2 from the STDT decreases as the operating voltage increases. This is also shown in Table III.

Table III: Voltage and Trigger Delay of G_2 with 40 psi of N_2

E_o	60	70	75	84	kV
Δt	360	170	120	100	$\times 10^{-9}$ s



CT_2 500 A/div
CT_1 100 A/div, 200 ns/div

Fig. 10. Discharges of 2 nF at 70 kV.

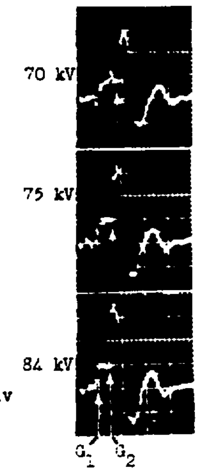


Fig. 11. Discharge Currents of 2 nF Measured on CT_2.

500 A/div

200 ns/div

The STDT Design

In contrast to a snubber, an STDT limits fault currents with its magnetizing inductance. Eddy-current losses, utilized by a snubber, are undesirable in an STDT. An STDT can be designed to provide time delays of tens of microseconds or longer, which is impractical for a snubber. An equivalent circuit for the STDT portion of the circuit of Fig. 1 is shown in Fig. 12. In this circuit, it is assumed that the ST has arced over and that 4 µs will elapse before the crowbar removes the power source. For simplicity, only the primary winding to the accel. grid (n_1) and the secondary winding of the bias current (n_4) of the circuit in Fig. 1 are being shown. All primed components represent circuit values of the secondary of the STDT transformed to the primary.

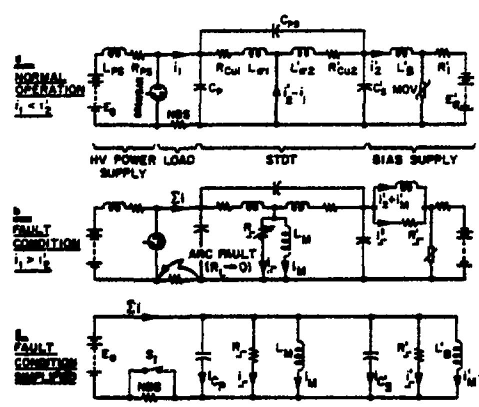


Fig. 12. Equivalent circuits for an STDT.

During normal operation, the bias current i_2' is larger than the load current i_1; this saturates the core ($\mu_{dc} \sim 200$). The power-supply voltage appears across the load. When the NBS sparks to ground, the STDT comes out of saturation and magnetizing impedance L_M and the eddy current resistance R_e appear in the circuit; R_e' appears in the bias choke circuit. Voltage E_o is now absorbed by the STDT. The copper losses and the leakage inductances of the STDT are small when compared with R_e and L_M and can, therefore, be neglected. This results in the simplified circuit of

Fig. 12c. The NBS is exposed to the sum of the currents shown in Fig. 12c, however, we will neglect the capacitive currents i_{Cp} and i'_{C3}. The total fault current can now be written

$$\sum i(t) = \sum i_{STDT}(t) + \sum i'_{3}(t) = i_{\Gamma}(t) + i_{M}(t)$$

$$+ i'_2 + i'_{\Gamma}(t) + i'_{M}(t), \qquad (27$$

Because of the spark gap circuit, there is one more step-current for the STDT shown in Fig. 1. This current $i_{\Gamma G}$ must be added to the above currents. Under worst-fault conditions, 150 kV will be applied to the circuit. We will now calculate the fault current for this case.

<u>Fault Current $\sum i_{STDT}(t) + \sum i_{\Gamma G}(t)$.</u> Table IV gives details of the STDT built for the circuit shown in Fig. 1.

Table IV: Details for 150-kV STDT

Four Silectron cores AL-1268 with	$d = 5.08 \times 10^{-3}$ cm
No. of lamination $N = 4\ bs/d$	$N = 3560$
Width of laminations	$w = 8.89$ cm
No. of primary turns	$n_1 = 28$
No. of secondary turns	$n_2 = n_3 = 28,\ n_4 = 14$
Volts/turn	5357 V
Volts/lamination	1.5 V
Voltage gradient on laminations	$\xi = 0.085$ V/cm
Length of flux path in iron	$\ell_{Fe} = 98.6$ cm
Length of flux path in air gap	$\ell_g = 5 \times 10^{-3}$ cm
Core area	$A = 160\ cm^2$
NBS operating current	$i_1 = 65$ A
Peak bias current for 5 Oe	$i_B = 163$ A
RMS bias current for 5 Oe, $i_B\sqrt{0.133}$	= 59.4 A

From Eq. (11) and data of Table IV, the initial current step is $i_{\Gamma} = 15.2$ A when the NBS sparks down. A short time later, current step $i_{\Gamma G}$ occurs when spark gap G triggers. With $n_1 = n_3$, this current follows the expression

$$i'_{\Gamma G}(t) = \frac{E_o}{R_3} \exp(-2t/R_3C_3) = 60 \text{ A} \exp(-t/0.2\ \mu s).$$

The magnetizing current i_M is calculated from the pulse magnetization curves of the core material.[7] In our case we have, after $\Delta t = 4\ \mu s$, a flux change of

$$\Delta B = \frac{\Delta t \times V\, 10^8}{n_1 A} = \frac{4\ \mu s \times 150\ kV \times 10^8}{28 \times 160\ cm^2} = 13.4\ kG$$

which is less than half of the 30 kG available from the cores. Extrapolating from manufacturer's curves,[7] we find for $\Delta B = 13.4$ kG a $\Delta H = 7.8$ A/cm. The magnetization current required by the STDT can be calculated from

$$i_M = \left(\Delta H_{Fe} \times \ell_{Fe} + \frac{\Delta B}{0.4\ \pi}\ell_g\right)/n_1 \qquad (28)$$

as

$$i_M = \left(7.8 \times 98.6 + \frac{13400}{0.4\ \pi} \times 0.005\right)/28 = 29.4 \text{ A}.$$

<u>Fault Current $\sum i'_3(t)$.</u> For the STDT to come out of saturation, the fault current must exceed the bias current i'_2. Transformed to the primary, the bias current is

$$i'_2 = i_2\, n_4/n_1 = 163 \text{ A } 14/28 = 81.5 \text{ A}.$$

Currents $i'_{\Gamma}(t)$ and $i'_M(t)$ are determined by the step voltage across the bias choke, which is $V_B = E_o\, n_4/n_1 = 150$ kV 14/28 = 75 kV, and by the choke parameters given in Table V.

Table V: Details for the 75-kV Bias Choke L_{B1}

Four Silectron cores with the dimensions of the AL-1268 cores but wound with tape of thickness	$d = 10.16 \times 10^{-3}$ cm
No. of laminations	$N = 1800$
Core Area	$A = 162\ cm^2$
No. of turns	$n = 78$
Volts/turn	961 V
Volts/lamination	0.53 V
Voltage gradient on laminations	$\xi = 0.030$ V/cm
Length of air gap	$\ell_g = 1.7$ cm
DC magnetization	$B_{dc} = 8.8$ kG

The initial current step from Eq. (11) is $i_{\Gamma} = 3.25$ A, which, transformed to the primary amounts to $i'_{\Gamma} = 0.5\ i_{\Gamma} = 1.63$ A. During the fault duration of $\Delta t = 4\ \mu s$, the change in induction in the choke is

$$\Delta B = \frac{4\ \mu s \times 75\ kV \times 10^8}{78 \times 162\ cm} = 2.37\ kG$$

This corresponds to $\Delta H = 1.43$ A/cm. The magnetization current for $\ell_{Fe} = 98.6$ cm and $\ell_g = 1.7$ cm is, from Eq. (28), $i_M = 42.9$ A. This value transformed to the primary becomes $i'_M = 0.5\ i_M = 21.4$ A.

<u>Maximum Values of Fault Current.</u> The step currents will decay to insignificant values within 1 or 2 µs while the magnetizing currents, starting from zero, will be at their peak after 4 µs. The current shape, therefore, has two peaks. One occurs at the time the NBS sparks to ground. Its value of

$$\hat{i}_{t=0+} = i'_2 + i_{\Gamma} + i'_{\Gamma} + i'_{\Gamma G}, \qquad (29)$$

is in our case

$$\hat{i}_{t=0^+} = 81.5 + 15.2 + 1.6 + 60 = 158 \text{ A}.$$

The second peak occurs at the time when the HV source is crowbarred. Its value of

$$\hat{i}_{t=4\,\mu s} = i_2' + i_M + i_M' , \qquad (30)$$

is for our application

$$\hat{i}_{t=4\,\mu s} = 31.5 + 29.4 + 21.4 = 132.3\ \text{A}.$$

With the HV source removed, the magnetizing currents i_M and i_M' will go to zero. Their decay is determined by the L/R time constant of the network.

The above worst conditions of 150 kV, when the ST sparks over, should not occur often. Normally, when the NBS sparks down, only 120 kV is applied for 2 µs. After that time, the ST disconnects the HV source from C_1. The oscillatory discharge current of C_1 is limited by the magnetizing inductance of the STDT as described above. When C_1 has discharged, the circuit energy is stored in the STDT and in the bias choke L_{B1}. Diode D_1 prevents C_1 from taking a negative charge and cuts off the fault current through the NBS. The inductively stored energies are dissipated in R_1 and R_{B1}.

Test Results. In the circuit of Fig. 5, capacitor C_1 was discharged by triggering spark gap G_1. During those tests we had $R_1 = 20\ \Omega$, $R_2 = 1\ \text{k}\Omega$, and $C_3 = 350$ pF. As shown in Fig. 13a, a current of about 11.5 A flows for 26 µs; this amounts to 300 µAs which agrees with the charge on C_1 of 60 kV x 5 nF = 300 µAs. The same agreement is found in Fig. 14, where C_1 is discharged from 84 kV; 84 kV x 5 nF = 15.6 A x 27 µs = 420 µAs. The currents of 11.5 and 15.6 A are proportional to the voltages of 60 and 84 kV. $[i = E_o (C/L)^{1/2}]$. Figures 13c and d show the circulating current through diode D_1, which discharges the STDT in 800 µs. At 60 kV, the initial current spike of $\hat{i} \approx i_F + i_{RG}$ was expected to be $\hat{i} \approx 15.2$ A $(60/150)^{1/2}$ + 60 kV/1 kΩ = 69.6 A. Figure 13b shows an oscillatory peak of 190 A. These large initial oscillations last for about 500 ns and are attributed to the capacitance between windings n_1 and n_4. With n_4 grounded, the interwinding capacitance is charged to 60 kV and discharges with little series inductance when G_1 is triggered. In the TFTR circuit (Fig. 1), both n_1 and n_4 are at the same potential when the NBS sparks down; this should eliminate the initial large oscillations.

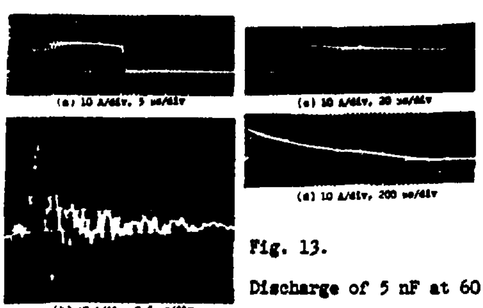


Fig. 13.

Discharge of 5 nF at 60 kV.

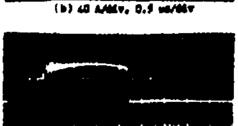


Fig. 14.

Discharge of 5 nF at 84 kV.

STDT's For the Arc and Filament Circuits. The filaments of the NBS operate at 6 kA. With a duty factor of 0.133, the rms current is 2.2 kA. For the arc supply, the peak current is 3 kA, the duty factor 0.033, and the rms current 545 A. It appears to be more economical and more reliable to replace the Deltamax snubber and the spark-gap circuit of Fig. 1 with two STDT's, as shown in Fig. 2. We are presently investigating this possibility. Data for a preliminary design for STDT2 are given in Table VI.

Table VI: Details for the 120-kV STDT2

10 Silectron cores AL-1145 with	$d = 5.08 \times 10^{-3}$ cm
No. of laminations	N = 15,000
Width of laminations	w = 6.99 cm
No. of bifilar turns	n = 4
Volts per turn	30 kV
Volts per lamination	2.0 V
Length of flux path in iron	$\ell_{Fe} = 121.4$ cm
Length of flux path in air	$\ell_g = 5 \times 10^{-3}$ cm
Core area 10 x 9.28 x 6.45 x 0.89	$A = 573\ \text{cm}^2$
$\phi = nA\,\Delta B \times 10^{-8}$	= 0.69 Vs
Initial current step	$i_F = 170$ A
Coil resistance	≈102 µΩ
Heat dissipation	≈500 W
Cost of core material	$5760

For the arc leads and the coaxial monitoring cables, another smaller core assembly is visualized for STDT 3.

REFERENCES

1. 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).
2. W. F. Praeg, "Saturating Time-Delay Transformer for Overcurrent Protection," U. S. Patent No. 4,054,933, October 18, 1977. Filed December 18, 1975.
3. W. R. Baker, "Stored Energy and the LBL Neutral Beam Source," Lawrence Berkeley Laboratory, Internal Memo UCID-3871 (May 1976).
4. W. F. Praeg, "Protection of Neutral-Beam Accelerator Electrodes From Spark Discharges," Proceedings of the 7th Symposium on Engineerging Problems of Fusion Research, Oct. 25-28, 1977, Knoxville, TN.
5. W. R. Baker et al., "120 kV/65 A Neutral Beam Source Specifications and Electrical Requirements," Lawrence Berkeley Laboratory, UCID-8069 (Oct. 1978).
6. S. T. Winter, R. W. Kuenning, G. G. Berg, "Pulse Properties of Large 50-50 Ni Fe Tape Cores," IEEE Transactions on Magnetics, Vol. MAG-6, No. 1, (March 1970).
7. The Arnold Engineering Co. publication TC-101B "Tape Wound Cores."