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Energy Losses in the DØ β Solenoid Cryostat Caused by Current Changes

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Abstract

The proposed D0 β solenoid¹ is a superconducting solenoid mounted inside an aluminum tube which supports the solenoid winding over its full length. This aluminum support tube, also called bobbin, is therefore very tightly coupled to magnetic flux changes caused by solenoid current variations. These current changes in the solenoid, will cause answer currents to flow in the resistive bobbin wall and therefore cause heat losses.

The insertion of an external dump resistor in the solenoid current loop reduces energy dissipation inside the cryostat during a quench and will shorten the discharge time constant.

This note presents a simple electrical model for the coupled bobbin and solenoid and makes it easier to understand the circuit behavior and losses. Estimates for the maximum allowable rate of solenoid current changes, based on the maximum permissible rate of losses can be made using this model.

Electrical Model of the D0 Solenoid

The D0 solenoid can be looked at as a perfectly coupled transformer with a shorted one turn, secondary winding, with resistance R_b which represents the bobbin. The primary winding is made of superconducting wire placed inside the aluminum stabilizer of the superconducting wire assembly. The resistance R_s of the stabilizer is shorted out by the superconductor, except during a quench when the superconducting wire has a small resistance value that increases with temperature. The resulting resistance value of the stabilizer in parallel with the quenched superconductor is R_q .

A basic electrical model of the solenoid, in which inductance L and quench resistance R_q are lumped together, is shown in Fig. 1. Figure 1 is later on developed into Fig. 3 and Fig. 4. These circuit models can be used for heat loss estimates and also as a guide to estimate the quench voltage distribution across the solenoid winding for cases where R_q is constant during a brief timespan.

To understand the quench voltage distribution across the solenoid winding, we must realize that each turn and also the bobbin are coupled to the same flux change. The net voltage appearing across a quenched turn is therefore:

$$V_{qturn} = \frac{d\phi}{dt} - IR_{qturn}$$

This net voltage is simply the induced voltage $d\phi/dt$ for turns with $R_q = 0$. The induced voltage per turn equals the quench resistance voltage drop for cases with an external

short at the solenoid terminals and an equally distributed quench. The net resulting voltage per turn is zero in that case.

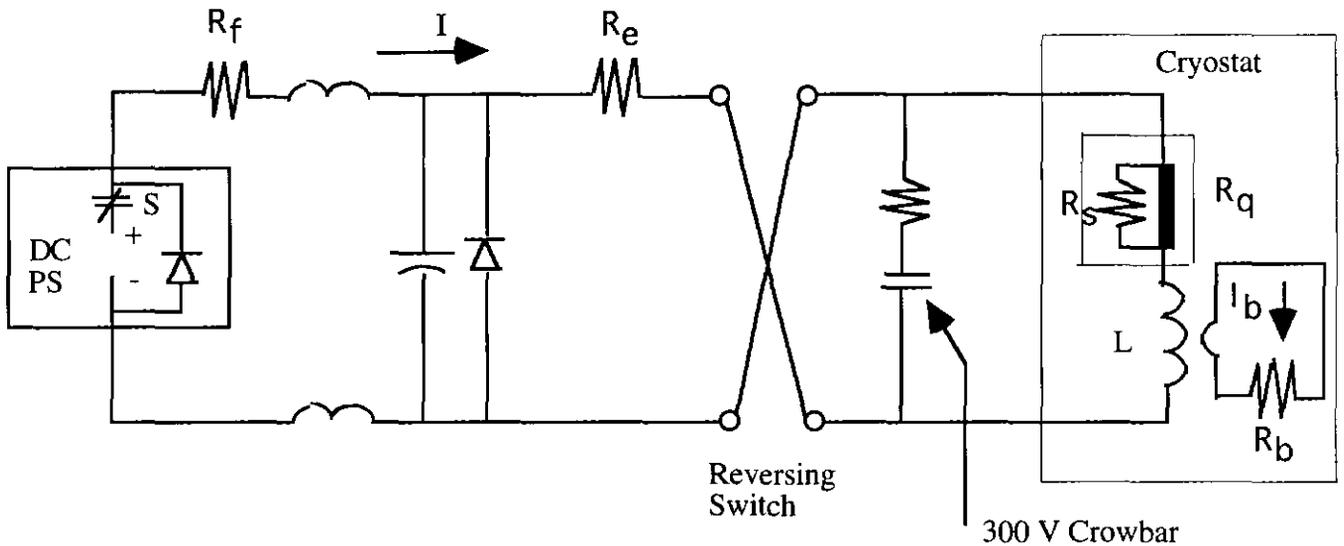


Fig. 1. Solenoid Electrical Circuit Model

Ratings:

- DC PS - 5000A, 18V maximum
- I - 4825A maximum
- Re - external circuit resistance of the solenoid current loop through the freewheeling diodes at the ripple filter
 $R_e = R_h = 0.7 \times 10^{-3} \Omega$ (Assembly Hall)
 $R_e = R_c = 1.5 \times 10^{-3} \Omega$ (Collision Hall)
 $R_e = R_d = 50 \times 10^{-3} \Omega$ (Fast Dump)
- Rf - Filter choke circuit resistance. $R_f = 0.8 \times 10^{-3} \Omega$
- Rs - Aluminum stabilizer resistance of the superconducting wire from which the solenoid is wound.
 $R_s = 2.17 \Omega$
- Rb - Aluminum bobbin, 1 turn
 $R_b = 3.2 \times 10^{-6} \Omega$
- L - 0.48 H, 1010 turns, ~ 122 cm ID x 260 cm long
- $\frac{1}{2} LI^2$ - $5.6 \times 10^6 \text{ J}$

Figure 2 shows the equivalent circuit for a generalized transformer having two windings. Commonly accepted nomenclature is as follows:

- N_p = number of primary turns
- N_s = number of secondary turns

- a = turns ratio N_p/N_s
- C_p = primary equivalent shunt capacitance
- C_s = secondary equivalent shunt capacitance
- E_g = root-mean-square generator voltage
- E_{out} = root-mean-square output voltage
- k = coefficient of coupling
- L_p = primary inductance
- l_p = primary leakage inductance
- l_s = secondary leakage inductance
- R_c = core-loss equivalent shunt resistance
- R_g = generator impedance
- R_l = load impedance
- R_p = primary-winding resistance
- R_s = secondary-winding resistance

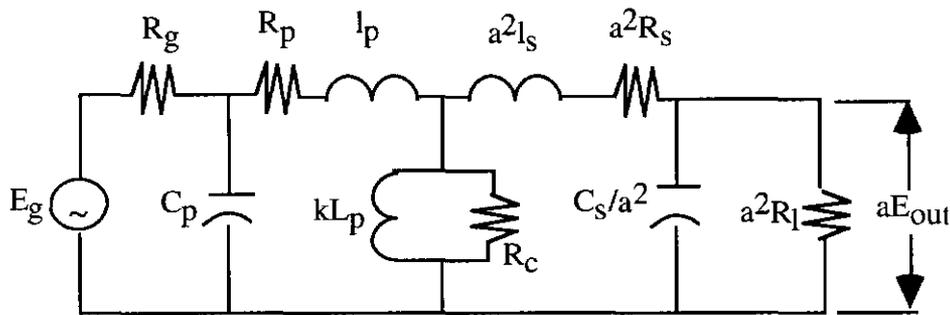


Fig. 2. Equivalent Network of a Transformer

The solenoid can be modeled using the transformer equivalent circuit of Fig. 2. Since the operating frequency of the solenoid is low or zero, we will neglect the shunt capacitances shown in Fig. 2. The leakage inductances may also be taken at zero for perfect coupling ($k = 1$). The superconducting primary winding resistance is zero, except during a quench when it is R_q . R_c in Fig. 2 is infinity because there are no iron losses. The reversing switch and overvoltage crowbar, shown in Fig. 1, are normally not activated and may be deleted for normal circuit operating conditions. With these assumptions Fig. 1 can be drawn as Fig. 3.

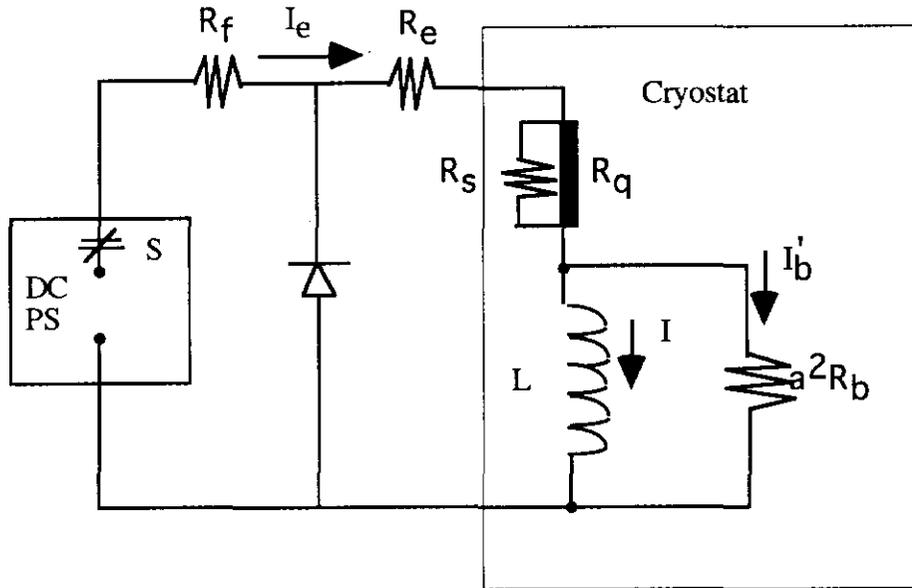


Fig. 3. Solenoid Power Circuit.

I	$=$	4825 A
L	$=$	0.48 H
R_q	$=$	0 (superconducting)
R_s	$=$	2.17Ω (stabilizer)
$a^2 R_b$	$=$	3.26Ω
R_e	$=$	$R_h = 0.7 \times 10^{-3} \Omega$ or $R_c = 1.5 \times 10^{-3} \Omega$ or $R_d = 50 \times 10^{-3} \Omega$
R_f	$=$	$0.8 \times 10^{-3} \Omega$

Imaginary switch S opens when the power supply trips off.

The value of the external circuit resistance R_e depends on whether the solenoid is located in the Assembly Hall (R_h), the Collision Hall (R_c) or is in a fast dump mode (R_d). Current I'_b represents the circulating bobbin current reflected to the primary (solenoid winding) side. The true value of the bobbin current is $I_b = a I'_b$. Current I drives the magnetic flux in the solenoid. $I'_b = 0$ during steady state conditions and external current $I_e = I$ during that time. The losses caused by I'_b or I_b are the same.

$$(I'_b)^2 a^2 R_b = I_b^2 R_b$$

During a dump, Fig. 3 can be drawn as Fig. 4.

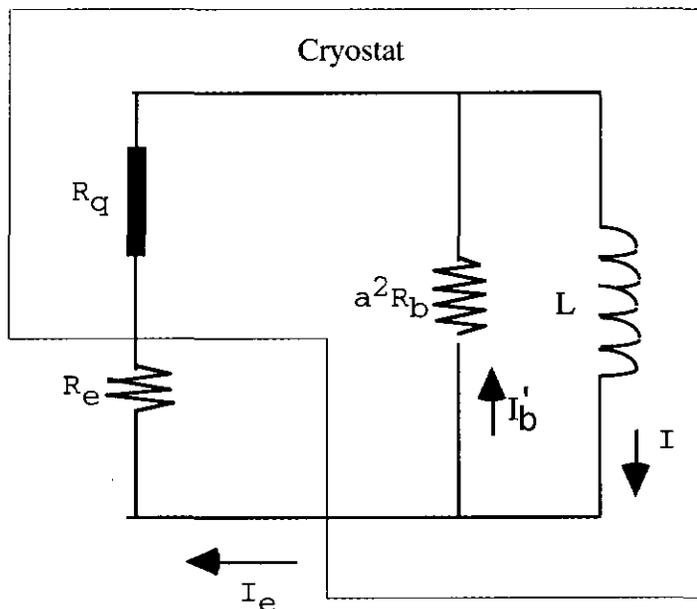


Fig. 4. Solenoid Power Circuit During a Dump

The energy dissipated in $a^2 R_b$ and R_q is dissipated inside the cryostat. Normally $R_q = 0$.

Charging Losses

Charging losses in the bobbin of the solenoid assembly will occur because of circulating bobbin currents caused by the increasing magnetic field. The highest losses occur when the maximum (Fig. 3) power supply voltage of 18 V is switched on instantaneously. The maximum losses would be:

$$P_{\max} = \frac{V^2}{a^2 R_b}$$

$$P_{\max} = \frac{18^2}{3.26} = 99 \text{ Watt}$$

The initial maximum $\frac{dI}{dt}$ with 18V applied is:

$$V = L \frac{dI}{dt}$$

$$\frac{dI}{dt} = \frac{18}{0.48} = 37.5 \text{ A/sec (2250 A/min.)}$$

Bobbin losses of 99 Watt exceed the amount of steady state losses of 45 Watt at which quench back could occur². Bobbin losses of 45 Watt are caused by a charging voltage of 12.1 V, or a current increase of 25.2 A/sec (1514 A/min). As a safety margin it is recommended² to limit the charging voltage at the solenoid terminals to 6 V, which yields a current increase of 12 A/sec (720 A/min) and bobbin losses of 10 Watt. This limit of 720 A/min may be conservative.

The maximum voltage needed to charge the solenoid at 12 A/sec is:

$$V_c = I(R_f + R_e) + L \frac{dI}{dt}$$

$$V_{cmax} = 4825 (0.8 + 1.5) \times 10^{-3} + 6$$

$$V_{cmax} = 17 \text{ V}$$

This is very close to the full load ceiling voltage of the power supply, so that a continuous charge rate of 12 A/sec is feasible. It is however obvious that charging rates >12 A/sec cannot be sustained at high current values, because of the limited amount of available power supply voltage.

The total accumulated charging losses E_b in the bobbin can be estimated and depend on the current charging rate $\frac{dI}{dt}$ as follows:

$$E_b = \frac{V^2}{a^2 R_b} t$$

E_b	=	energy dissipated in the bobbin
V	=	applied voltage across the solenoid terminals
t	=	time duration of the applied voltage

$$E_b = \frac{(L \frac{dI}{dt})^2}{a^2 R_b} \times \frac{I}{\frac{dI}{dt}}$$

or

$$E_b = \frac{0.48^2 \times 4825}{3.26} \frac{dI}{dt}$$

$$E_b = 341 \frac{dI}{dt} \text{ Joules for a full charge to 4825 A.}$$

The accumulated charging losses from 0 to 4825 A with $\frac{dI}{dt} = 12$ A/sec are 4092 Joules. Smaller values of $\frac{dI}{dt}$ reduce the charging losses.

Power Supply Ripple Voltage Heat Losses

Ripple voltage present on the power supply d.c. output voltage will not cause large heat losses in the cryostat. The power supply ripple is predominantly 720 Hz, although there are probably also small amounts of 60 Hz and 360 Hz components in the ripple. The output ripple filter at the power supply will reduce this ripple.

The unfiltered ripple at the power supply output may be estimated to be about 2.7 V peak to peak or about 1 V RMS. The losses inside the cryostat caused by the ripple voltage are the losses dissipated in resistor a^2R_b of Fig. 4. Since $R_e \ll a^2R_b$ and $2\pi fL \gg a^2R_b$ we may assume that all ripple voltage appears across a^2R_b , which represents the bobbin. The output ripple losses in a^2R_b are:

$$P_{\text{ripple}} = \frac{0.35^2 \times V_{\text{ripple p to p}}^2}{a^2R_b}$$

A worst case peak to peak ripple voltage of 3 V, in case of a filter failure, causes therefore estimated losses of:

$$\frac{0.35^2 \times 9}{3.26} = 0.34 \text{ Watt}$$

The power supply will be equipped with a filter that reduces the output ripple at least a factor of 100. Losses inside the cryostat, caused by voltage ripples on the d.c. output of the power supply, even without a ripple filter, are negligible. The main purpose of the filter is to reduce electrical noise.

Dumping Heat Losses and Voltages

The power supply is switched off during a dump and Fig. 4 may be used to calculate the amount of energy dissipated inside the cryostat for various values of R_e while $R_q = 0$, or some other fixed value. $(R_e + R_q)$ is connected in parallel with a^2R_b , which yields a total circuit resistance R_t .

$$R_t = \frac{(R_e + R_q) a^2R_b}{R_e + R_q + a^2R_b}$$

The time constant τ of the solenoid current decay during a dump is:

$$\tau = \frac{L}{R_t}$$

In most cases:

$$\tau = \frac{L}{R_e} \text{ because with a superconducting solenoid } R_q = 0 \text{ while } R_e \ll a^2 R_b$$

The dump voltage V_d , developed in the current loop of the solenoid equals the voltage induced in the solenoid windings due to the current decay and is:

$$V_d = I R_t$$

or

$$V_d \sim I (R_e + R_q) \text{ for cases where } R_e + R_q \ll a^2 R_b$$

The total dump voltage in the current loop consists of two portions. One portion, V_{de} , is the portion developed across the external resistance R_e and the other portion, V_{di} , remains inside the solenoid cryostat.

$$V_d = V_{de} + V_{di}$$

Only portion V_{de} can be measured at the outside power terminals of the solenoid.

$V_{de} = I_e R_e$ and $V_{di} = N \frac{d\phi}{dt} - I_e R_q$. External current I_e equals about solenoid current I when $R_e + R_q \ll a^2 R_b$ (Fig. 4).

The maximum rate of current change (exponential decay) occurs at the start of a dump.

$$\frac{dI}{dt} = \frac{V_d}{L}$$

The total stored energy of the solenoid dissipates partially inside the cryostat and the rest dissipates in the outside circuit. The amount of energy dissipation at various locations depends on the value of R_e , R_q and R_b .

Power losses in a resistor are in general proportional to the square of the voltage across it.

$$P = \frac{V^2}{R} \text{ Watt}$$

The total energy dissipation in a resistor depends on how long the voltage is applied.

$$E = \frac{V^2}{R} t \text{ Joules}$$

The ratio of energy dissipation $\frac{E_1}{E_2}$ in two parallel resistors R_1 and R_2 connected to a common voltage source is thus:

$$\frac{E_1}{E_2} = \frac{R_2}{R_1}$$

This ratio is independent of the applied voltage and time. We can therefore calculate the amount of energy dissipated in each resistor for a fixed amount of stored energy in the charged solenoid using Fig. 4.

$$\frac{1}{2} LI^2 = E_e + E_q + E_b$$

E_e = external energy dissipation

E_q = quenched coil energy dissipation, $R_q \neq 0$

E_b = bobbin energy dissipation.

$$\frac{E_e + E_q}{E_b} = \frac{V^2/R_e + R_q}{V^2/a^2R_b} = \frac{a^2R_b}{R_e + R_q}$$

$$E_b = \frac{R_e + R_q}{a^2R_b} (E_e + E_q)$$

$$\frac{1}{2} LI^2 = (E_e + E_q) \left(1 + \frac{R_e + R_q}{a^2R_b}\right)$$

$$E_e + E_q = \frac{1}{2} LI^2 \frac{a^2R_b}{a^2R_b + R_e + R_q}$$

$$E_e = \frac{R_e}{R_e + R_q} \frac{1}{2} LI^2 \frac{a^2R_b}{a^2R_b + R_e + R_q} \quad (1)$$

$$E_q = \frac{R_q}{R_e + R_q} \frac{1}{2} LI^2 \frac{a^2R_b}{a^2R_b + R_e + R_q} \quad (2)$$

$$E_b = \frac{R_e + R_q}{a^2R_b} \frac{1}{2} LI^2 \frac{a^2R_b}{a^2R_b + R_e + R_q} \quad (3)$$

For a dump with a superconducting solenoid we find:

$$E_e = \frac{1}{2}LI^2 \frac{a^2R_b}{a^2R_b + R_e} \quad (\text{for } R_q = 0) \quad (4)$$

$$E_q = 0 \quad (\text{for } R_q = 0) \quad (5)$$

$$E_b = \frac{1}{2}LI^2 \frac{R_e}{a^2R_b + R_e} \quad (\text{for } R_q = 0) \quad (6)$$

Table 1 can now be made for various values of R_e and R_q using Eq. 1, 2, and 3.

TABLE 1
Energy Dissipation Areas in the Solenoid Current Loop During a Dump

I A	$\frac{1}{2}LI^2$ kJ	V_d V	V_{de} V	R_e 10^{-3} Ω	R_q 10^{-3} Ω	a^2R_b Ω	R_t 10^{-3} Ω	dI/dt Max. A/S	τ sec	E_e kJ	E_q kJ	E_b kJ
4825	5587	3.4	3.4	0.7	0	3.26	0.7	7.1	686	5586	0	1
4825	5587	51.6	3.4	0.7	10	3.26	10.7	108	44.9	364	5205	18
4825	5587	471	3.3	0.7	100	3.26	97.7	981	4.9	38	5482	67
4825	5587	3691	2.6	0.7	1000	3.26	765	7790	0.63	0	4275	1312
4825	5587	7.2	7.2	1.5	0	3.26	1.5	15	320	5584	0	3
4825	5587	55.5	7.2	1.5	10	3.26	11.5	116	42	726	4841	20
4825	5587	474	7	1.5	100	3.26	98.4	988	4.9	81	5337	169
4825	5587	3695	5.5	1.5	1000	3.26	76.6	7698	0.63	6	4315	1266
4825	5587	237	237	50	0	3.26	49.2	494	9.8	5503	0	84
4825	5587	284	237	50	10	3.26	58.9	592	8.1	4572	914	101
4825	5587	692	231	50	100	3.26	143.4	1442	3.3	1780	3561	246
4825	5587	3831	182	50	1000	3.26	794	7981	0.6	201	4025	1361

- ◆ Add diode voltage drop of 1.5 V.
 V_d = total induced dump voltage.
 V_{de} = part of total dump voltage at the solenoid terminals.

NOTE: This table is oversimplified because R_q and a^2R_b are a function of energy deposit and time.

Dump resistor values $> 50 \times 10^{-3} \Omega$ will cause dump voltages in excess of the specified limit of 250 V maximum. Insertion of a dump resistor will shorten the current

decay time constant and the stored energy dissipation outside the cryostat except for $R_q \sim 0$.

Insertion of the dump resistor ($50 \times 10^{-3} \Omega$) will also cause quenchback because $dI/dt = 494 \text{ A/s}$. Quenchback may occur at $dI/dt > 25 \text{ A/s}$.

The total induced dump voltage in Table 1 exceeds the maximum specified limit of 250 V for cases where R_q is in the order of 100 mΩ or larger. The total net voltage at the solenoid terminals is always limited to $I_e R_e$ and cannot exceed 250 V. All turns contribute equally to the net voltage, when R_q is equally distributed across all solenoid turns. Fairly large voltages could develop inside the solenoid, when R_q is not equally distributed across all turns. This could be the case during the early stages of a quench. We could think of the following scenario:

$R_q = 100 \text{ m}\Omega$ is divided equally over 50 turns, shortly after the start of a localized quench. The stabilizer resistance of 50 turns is about 100 mΩ. The other 960 turns of the solenoid are superconducting at that moment.

$$\begin{aligned} I &= 4825 \text{ A} \\ R_e &= 50 \text{ m}\Omega \\ a^2 R_b &= 3.26 \Omega \end{aligned}$$

What is the voltage distribution across the solenoid winding?

Maybe it is not possible to get into this situation, but let us see what happens. Schematically this condition is as shown in Fig. 5.

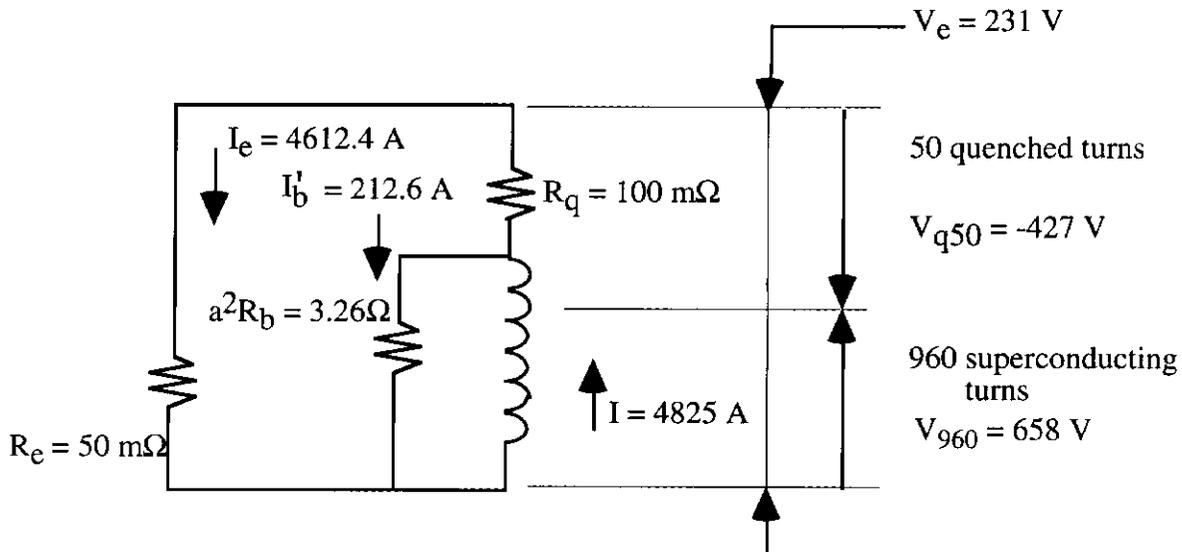


Fig. 5: Voltage and current distribution in the solenoid with a partial quench

The equivalent resistance R_t in parallel with the solenoid (Fig. 5) is:

$$R_t = \frac{0.15 \times 3.26}{0.15 + 3.26} = 0.143 \Omega$$

The net induced solenoid voltage is:

$$IR_t = 692 \text{ V}$$

The induced voltage per turn is:

$$V/\text{turn} = 692/1010$$

$$V/\text{turn} = 0.685 \text{ V}$$

The 960 superconducting turns have no opposing resistance in them and support thus a total induced voltage of:

$$V_{960} = 0.685 \times 960 = 658 \text{ V}$$

Looking at Fig. 5, we see that some of the solenoid current escapes to a^2R_b (the bobbin) and not all current needed to maintain the magnetic flux, flows therefore through the winding turns. The current distribution can be calculated.

$$I_e + I_b' = 4825 \text{ A}$$

$$I_e \times (R_e + R_q) = I_b' \times 3.26$$

$$I_b' = 212.6 \text{ A. The true value of the bobbin current is } 212.6 \times 1010 = 214,726 \text{ A}$$

$$I_e = 4612.4 \text{ A}$$

The 50 quenched turns have a net voltage of:

$$V_{q50} = 50 \times (V/\text{turn} - I_e R_q/\text{turn})$$

$$V_{q50} = 50 \times 0.685 - 4612.4 \times 0.1$$

$$V_{q50} = -427 \text{ V}$$

$$V_q/\text{turn} = -8.54 \text{ V}$$

It can be concluded that high quench voltages can develop inside the solenoid, if the above scenario could happen for a brief moment before a uniform quench has developed. Figure 5 shows the quenched turns at the end of the solenoid winding, but

they can be drawn at any location in the solenoid winding. Relocating the quenched turns will result in different voltage distribution and stresses on the insulation, especially for a two layer winding.

Water Cooling Failures

The DC power bus is watercooled and an interesting question to ask is: "Can the DC power bus dissipate all stored energy during a slow dump, while there is a cooling water failure?"

The free wheeling diodes behind the ripple filter shunt current away from the filter chokes and power supply during a dump. The power supply and filter chokes are not rated to carry the slowly decaying dump current without cooling water flow.

Worst case bus heating would occur during a cooling failure with a slow dump at full current in the Assembly Hall. Practically all stored energy would, in that case, be deposited in 140 ft or 464 kg of DC bus copper. Copper at 25°C has a specific heat of 0.092 cal/g/°C or

$$92 \text{ cal/kg/}^\circ\text{C} \text{ or}$$

$$385 \text{ Joules/kg/}^\circ\text{C}$$

A stored energy of 5587 kJoules would raise the temperature of 464 kg of copper $\frac{5587000}{385 \times 464} = 31^\circ\text{C}$. The average operating temperature of the DC bus at the start of a cooling failure would be 60°C so that the final average temperature would be the acceptable value of 91°C. A dump resistor is thus not needed for thermal protection of the external circuit during a cooling water failure.

Reversing Losses and Times

Users of the β solenoid need dc current reversal several times a week. Current reversal can only be done at zero current, or with very small dc currents in the solenoid, because an inductive circuit cannot be opened under load without producing high voltage spikes. The installed crowbar (Fig. 1) will clip the induced voltage at 300 V in case of accidental reversing under load. Induced voltages, caused by reversal under load, will also be limited by the bobbin because the solenoid current can always escape to the bobbin to maintain the solenoid flux. The maximum load current value I_{rmax} at which reversal can take place without tripping the 300 V crowbar level is:

$$I_{\text{rmax}} = \frac{300}{a^2 R_b}$$

$$I_{\text{rmax}} = \frac{300}{3.26} = 92 \text{ A}$$

The stored energy of the solenoid at 92 A is 2 kJ, which would all be dissipated in the bobbin. It is not recommended to reverse at light load currents, but starting reversing at 10 A will only produce a 30 V spike and cause 24 Joules of losses. The load current does therefore not have to be absolutely zero when reversing starts. Recognizing this can speed up the reversing process by reducing the waiting period before reversing switch operation can start. This may be useful, especially when there are many reversals.

A normal reversing process requires a slow dump discharge and a recharge of the solenoid. The complete reversing process will then cause reversing losses E_{rev} in the cryostat.

$$E_{\text{rev}} = \text{dump losses} + \text{charging losses}$$

At $I = 4825 \text{ A}$ these losses are:

$$E_{\text{rev}} \sim 5.6 \times 10^6 \frac{R_e}{3.26 + R_e} + 341 \frac{dI}{dt}$$

A charging rate $\frac{dI}{dt} = 12 \text{ A/sec}$ (720 A/min) is normally used and the reversing losses inside the cryostat are:

$$E_{\text{rev h}} \sim 1202 + 4092$$

$$E_{\text{rev h}} \sim 5294 \text{ Joules (Assembly Hall)}$$

or:

$$E_{\text{rev c}} \sim 2575 + 4092$$

$$E_{\text{rev c}} \sim 6667 \text{ Joules (Collision Hall)}$$

The time needed for reversing is:

$$T_{\text{rev}} = \text{slow dump decay} + \text{charging time} + \text{reversing switch operation.}$$

The slow dump decay needs about 5 times constants. The charging time depends on $\frac{dI}{dt}$ and is 402 sec at 4825 A with $\frac{dI}{dt} = 12 \text{ A/sec}$. Switch reversing takes only a few seconds and is negligible. Reversing takes about:

$$T_{\text{rev}} = 5\tau + 402$$

or:

$$T_{rev h} = 5 \times 686 + 402$$

$$T_{rev h} = 3832 \text{ sec (63.9 min) (Assembly Hall)}$$

or:

$$T_{rev c} = 5 \times 320 + 402$$

$$T_{rev c} = 2002 \text{ sec (33.4 min) (Collision Hall)}$$

An operating current of 4825 A will decay to $0.00674 \times 4825 = 32.5 \text{ A}$ in 5 time constants. The operating current will in reality decay faster, because the freewheeling diode drop has not been accounted for in the time estimates. Slow dump decay times must initially be measured to set the delay times of the reversing switch.

The time needed for solenoid current reversal could be shortened by starting a fast dump after the initial slow dump has reached a low, say 250 A, solenoid current value. The energy dissipation for reversal inside the solenoid would be higher because of the fast dump process at lower current values.

The expected results for reversing, with a slow dump from 4825 A to 250 A, and a fast dump from 250 to 0 A in the Collision Hall are tabulated below:

Collision Hall Reversing Time with Slow/Fast Dump:

Slow dump current decay from 4825 A to 250 A	-	947 sec
Fast dump decay from 250 A, 5 time constants	-	49 sec
Charging time $\frac{dI}{dt}$, 12 A/sec	-	402 sec
TOTAL REVERSING TIME	-	1398 sec (23.3 min)

Regular slow dump reversal takes about 33.4 minutes. This approach yields therefore about 10 min time savings per reversal in the Collision Hall

Collision Hall Reversing Losses Inside the Cryostat with Slow/Fast Dump:

Slow dump losses from 4825 A to 250 A	-	2564 Joules (16.1 Watt peak)
Fast dump losses from 250 A	-	230 Joules (48 Watt peak)
Charging losses to 4825 A, 12 A/sec	-	4092 Joules (10 Watt peak)
TOTAL REVERSING LOSSES	-	6886 Joules

Regular slow dump reversal losses are 6667 Joules. This approach causes, therefore, only 219 Joules additional reversing losses per reversal in the Collision Hall. The peak losses of 48 Watt, at the start of the 250 A fast dump, are at the limit of 45 Watt steady state losses for quench back and starting a fast dump at higher current values may not be acceptable.

It may be concluded, that starting the fast dump at a current value in the range of 250 A could save time and assure reversal at currents close to zero.

Comments

The solenoid design values, used in this note, may slightly differ from the final design values. Minor final design changes will not have a large impact on the conclusions.

The development stages of a partial quench should be understood, so that realistic voltage distribution estimates, for the insulation system design can be made.

Reference

1. "Design Report of the 2 Tesla Superconducting Solenoid for the Fermilab D0 Detector Upgrade", J. Brzezniak, R.W. Fast, K. Krempetz, A. Kristalinski, A. Lee, D. Markley, A. Mesin, S. Orr, R. Rucinski, S. Sakla, R.L. Schmitt, R.P. Smith, B. Squires, R.P. Stanek, A.M. Stefanik, A. Visser, R. Wands, R. Yamada, August 11, 1993.
2. "Charging and Discharging the D0 β Magnet", R.P. Smith, B. Squires, May 26, 1993.