Magnet – Quench Detection limitations

Hall D Solenoid Magnet

Reference - JLab_HALL D

(Superconducting Magnet Solenoid)

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Probir K Ghoshal & Renuka Rajput-Ghoshal

Engineering Division, Jlab

National®Brand 42-381 50 SHEETS EYE-EASE® - 5 SQUARES 42-382 100 SHEETS EYE-EASE® - 5 SQUARES 42-389 200 SHEETS EYE-EASE® - 5 SQUARES

A TYPICAL SCENARIO OF A QUENCH -

① MAGNET IS SUPERCONDUCTING AT A STATE $I = I_{op}$

② A QUENCH (Q) OCCURS AT SOME LOCATION IN THE MAGNET.

③ THE NORMAL ZONE PROPAGETES, A RESISTIVE VOLTAGE IS GENERATED ACROSS THE COIL (NORMAL SECTION) @$t = 0^+$

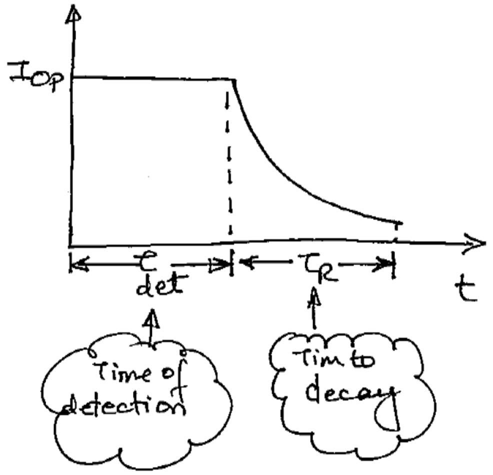
④ THE DETECTION SYSTEM ONLY DETECTS ONCE THE SET VOLTAGE THRESOLD IS REACHED. THE EXISTENCE OF A QUENCH ONCE SUFFICIENT VOLTAGE HAS DEVELOPED.

⑤ THE CURRENT IN THE MAGNET BEGINS TO DECAY WITH A TIME CONSTANT $\tau_R = L/R$

WHERE, R = SUM OF ALL RESISTANCE IN THE CURRENT CARRYING LOOP (CLOSED CIRCUIT), eg. NORMAL ZONE RESISTANCE & ANY EXTERNAL DUMP RESISTOR CONNECTED.

L = TOTAL INDUCTANCE OF THE LOOP/SYSTEM INDUCTANCE.

$$E = \left(\frac{1}{2}\right) * L I^2$$



SIMPLE REPRESENTATION

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VOLTAGE SCENARIO DURING A QUENCH

- IN THE EVENT OF A QUENCH, THE NORMAL ZONE GROWTH RESULTS IN A RISING/VARYING RESISTANCE, NORMALLY – CHALLENGED WHERE THE VOLTAGE COMES FROM?
    - FROM POWER SUPPLY
    - INDUCTANCE OF THE COIL (BACK EMF)

① @ $t = 0$, $I = I_{op}$

$t = 0^+$, POWERSUPPLY WILL TRY TO MAINTAIN CURRENT UNTIL THE VOLTAGE LIMIT (TRIGGER OR SUPPLY) HAS REACHED.

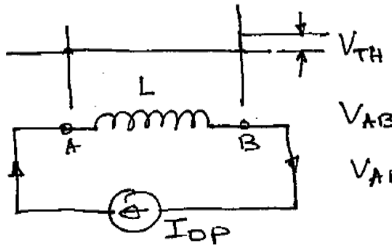
② A VOLTAGE THRESHOLD ON THE PSU IS USED TO DIAGNOSE A TYPICAL QUENCH (EASY) AND THE PSU IS SHUTOFF.

③ ONCE THE PSU IS SHUT, CURRENT BEGINS TO DECAY AND VOLTAGE DOES NOT COME FROM PSU ANY MORE BUT IS DEVELOPED/GENERATED BY THE MAGNET INDUCTANCE

(CURRENT IN AN INDUCTOR DO NOT CHANGE INSTANTANEOUSLY)

SCHEMATIC REPRESENTATION

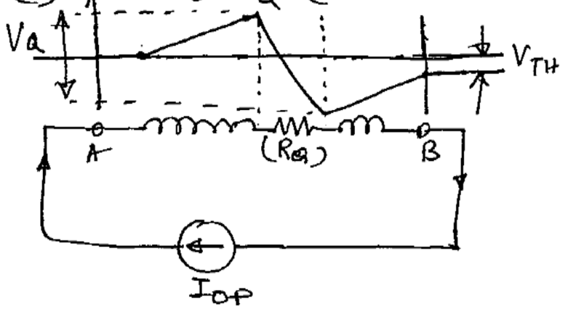
(1) $I = I_0$ (NO QUENCH)



$V_{AB} = 0$

$V_{AB} < V_{TH}$

(2) $I = I_0 = I_Q$ ($t = 0^+$ QUENCH)



$V_{AB} = V_{TH}$ (JUST DETECTED)

* BUT THE VOLTAGE ACROSS NORMAL ZONE (R_Q) IS SIGNIFICANT.

$V_{RQ} \gg V_{TH}$ (OR V_{AB})

V_{TH} = THRESHOLD/(DETECTION)

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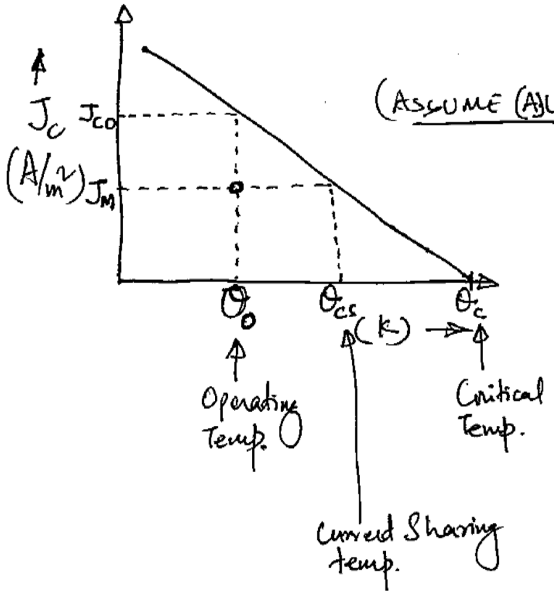
* J_c FALLS WITH TEMPERATURE.

(A MAGNET OPERATING VERY CLOSE TO ITS CRITICAL CURRENT WILL BE DRIVEN INTO THE NORMAL STATE BY THE SLIGHTEST INCREASE IN TEMPERATURE.)

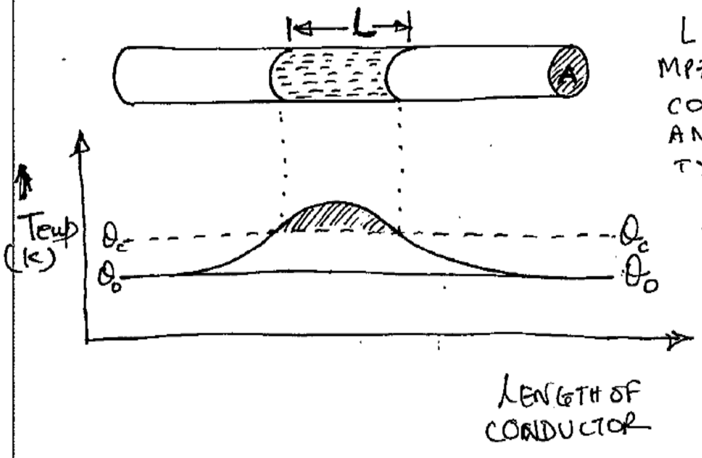
(A MARGIN OF SECURITY CAN BE PROVIDED BY RUNNING THE MAGNET AT SUB-CRITICAL CURRENT OR TEMPERATURE)



(ASSUME (A) LINEAR DEPENDENCY)

→ Shows a conductor which is carrying current density J_M, OHMIC HEATING, HEAT GENERATION WILL BEGIN WHEN TEMP. HAS RISEN TO θ_{cs}.

IMPORTANT TO NOTE AND UNDERSTAND



L = MPZ Length.
MPZ (L) IS A PROPERTY OF THE CONDUCTOR THAT IS BEEN ANALYSE AND USED TO CHARACTERISE THE TYPE OF DISTURBANCE.

* NOTE: A NORMAL ZONE LONGER THAN 'L' WILL CONTINUE TO GROW (QUENCH), WHERE AS

A NORMAL ZONE SHORTER THAN 'L' WILL COLLAPSE.

SOLUTION: SINCE WE HAVE A LIMITED OPTION / GOVERNED BY CONDUCTOR ITSELF, THEREFORE INCREASING 'L' IS THE WAY GOING AHEAD WITHOUT LOOSING J_c, IS TO HAVE INCREASE K/ρ MEANS COMPOSITE CONDUCTOR (MORE STABILIZER) — $\boxed{\text{CRYOSTABLE}}$

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* SUGGESTION

- FROM EARLIER NOTES (PAGE - 1-3), THIS IS CLEAR THAT VOLTAGE DETECTION AT THE QUENCH LEVEL $t=0^+$ IS LIMITED AND DIFFICULT WITH CRYOSTABLE CONDUCTOR (PAGE#3)
- ALSO SEEN THAT DETECTION OF V_Q (PAGE#2) IS ALSO DIFFRULT AND NOT PRACTICAL TO MEASURE, THEREFORE V_{TH} (THRESHOLD VOLTAGE) IS SET ~ 200 mV (DEPENDING ON THE TYPE OF MEAS. & DETECTION SYSTEM).

*

CONCLUSION:

* ONCE THE QUENCH HAPPENED, THE RECOVERY IS NOT POSSIBLE TO MAKE IT SUPERCON AGAIN, INSTEAD IS ADVISED TO PROPAGATE THE Q- FASTER IN ORDER TO LIMIT THE VOLTAGE &/OR TEMP.

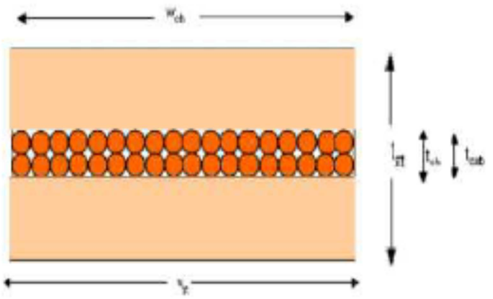
* TEMP. LIMIT IS IMPORTANT ALONG WITH MAX. VOLTAGE LIMIT TO HAVE THE MAGNET SAFE TO OPERATE.

AC loss Calculation needs to be followed through the SYSTEM HeatLoad.

Coil #1A (Alone) ~ Attached.

Conductor Loss Estimates - Hall D Solenoid

Probir Kumar Ghoshal and Renuka Rajput-Ghoshal
April 2013_Copper Channel as built



Stabilizer width	$w_{st} := 7.62\mathrm{mm}$	
Stabilizer thickness	$t_{st} := 2.197\mathrm{mm}$	
Channel width	$w_{ch} := w_{st} = 7.62 \times 10^{-3}\,\mathrm{m}$	
Chanel thickness	$t_{ch} := 0.9398\mathrm{mm}$	
	$RRR_m := 100$ $\quad RRR_{st} := 120$	RRR value for the matrix=100 RRR value for Stabilizer=120
Total conductor area including copper channel Acon		
$A_{con} := 2 w_{st} \cdot t_{st} + w_{ch} \cdot t_{ch}$	$A_{con} = 4.064 \times 10^{-5}\,\mathrm{m}^2$	
Wire diameter	$d_w := 0.127\mathrm{mm}$	This is NbTi wire diameter
Number of wires	$N_w := 87$	Number of NbTi wire in conductor
Material in the conductor	$mat := 4$	This is matrix to superconductor ratio
Wire Area	$A_w := N_w \cdot \left(\frac{\pi}{4}\right) \cdot {d_w}^2 = 1.102 \times 10^{-6}\,\mathrm{m}^2$	No of starnds
Channel occupied by cable	$A_{ch} := w_{ch} \cdot t_{ch} = 7.161 \times 10^{-6}\,\mathrm{m}^2$	$N_s := \mathrm{round}\left(\frac{A_{ch}}{A_w}\right) = 6$
Wire copper area	$A_{wcu} := N_s \cdot A_w \cdot \frac{mat}{1 + mat} = 5.29 \times 10^{-6}\,\mathrm{m}^2$	
Wire NbTi Area	$A_{nt} := N_s \cdot A_w \cdot \frac{1}{1 + mat} = 1.323 \times 10^{-6}\,\mathrm{m}^2$	
Solder area	$A_{vo} := A_{ch} - 6 \cdot A_w = 5.487 \times 10^{-7}\,\mathrm{m}^2$	
Insulation radial thickness	$t_i := \frac{1.02}{2}\mathrm{mm}$	
Inter pancake insulation	$t_{ip} := 2.34\mathrm{mm}$	
Ground plane insulation	$t_{ig} := 5\mathrm{mm}$	

C:\Users\ghoshal\Desktop\Hall D\ 1 of 6 6/11/2013

Width unit cell $w_u := w_{st} + 2\cdot t_i = 8.64\times 10^{-3}\,m$

Unit cell thickness $t_u := 2t_{st} + t_{ch} + 2\cdot t_i = 6.354\times 10^{-3}\,m$

Unit cell area $A_u := w_u\cdot t_u = 5.49\times 10^{-5}\,m^2$

Insulation area $A_i := A_u - A_{con} = 1.425\times 10^{-5}\,m^2$

Stabalizer area $A_{st} := A_{con} - A_{ch} = 3.348\times 10^{-5}\,m^2$

Insulation area is (unit cell area -conductor area) and stabilizer area is (conductor area-channel area)

Total Copper area $A_{Cut} := A_{st} + 6\cdot A_{wcu} = 6.522\times 10^{-5}\,m^2$

Over Unit cell

$$\lambda_{st} := \frac{A_{st}}{A_u} = 0.61 \qquad \lambda_{wcu} := \frac{A_{wcu}}{A_u} = 0.096$$

$$\lambda_{cu} := \lambda_{st} + \lambda_{wcu} = 0.706 \qquad \lambda_{vo} := \frac{A_{vo}}{A_u} = 9.996\times 10^{-3}$$

$$\lambda_{nt} := \frac{A_{nt}}{A_u} = 0.024 \qquad \lambda_i := \frac{A_i}{A_u} = 0.26$$

Cu to Sc ratio $CuSc\_R := \frac{\lambda_{cu}}{\lambda_{nt}} = 29.317$

check if all the ratio are correct $\lambda_{cu} + \lambda_{nt} + \lambda_{vo} + \lambda_i = 1$

Winding Composition

The following materials make up the conductor:

Area of NbTi: $A_{NbTi} := A_{nt}$ $A_{NbTi} = 1.323\cdot mm^2$

Area of Copper: $A_{Cu} := A_{wcu}$ $A_{Cu} = 5.29\cdot mm^2$

Area of Copper channel: $A_{CuCh} := A_{st} = 3.348\times 10^{-5}\,m^2$

Area of solder $A_{vo} = 5.487\times 10^{-7}\,m^2$

Area of insulation $A_i = 1.425\times 10^{-5}\,m^2$

Coil dimensions:

The coil block dimensions for the smallest coil in present solenoid design are:

$R_1 := 1018\cdot mm$ $\Delta R := 151\cdot mm$

$R_2 := R_1 + \Delta R$ $R_2 = 1.169\,m$

$Z_1 := 0mm$ $\Delta Z := 117.14mm$

$Z_2 := Z_1 + \Delta Z$ $Z_2 = 0.117\,m$

$L_{pinner} := 2\pi\cdot R_1$ $L_{pouter} := 2\pi\cdot R_2$

$L_{pinner} = 6.396\,m$ $L_{pouter} = 7.345\,m$

$L_{paverage} := \frac{(L_{pinner} + L_{pouter})}{2}$ $L_{paverage} = 6.871\,\mathrm{m}$

Coil dimensions: Layer to layer: $H_L := R_2 - R_1$ $H_L = 151 \cdot \mathrm{mm}$

Turn to turn: $W_T := Z_2 - Z_1$ $W_T = 117.14 \cdot \mathrm{mm}$

Numbers of turns and layers:

$N_T := \mathrm{round}\left(\frac{W_T}{w_{st} + t_{ip}}\right)$ $N_T = 12$

$N_L := \mathrm{round}\left(\frac{H_L}{2t_{st} + t_{ch} + 2t_i}\right)$ $N_L = 24$

$N_C := N_T \cdot N_L = 288$ $AT := 432000 \cdot A$

$L_p := L_{paverage} = 6.871\,\mathrm{m}$

The coil unit cell area is then $A_c := A_u$ $A_c = 54.897 \cdot \mathrm{mm}^2$

$\lambda_{NbTi} := \frac{A_{NbTi}}{A_c}$ $\lambda_{Cu} := \frac{A_{wcu}}{A_c}$ $\lambda_{CuCh} := \frac{A_{st}}{A_c}$

$\lambda_{NbTi} = 0.024$ $\lambda_{Cu} = 0.096$ $\lambda_{CuCh} = 0.61$ $\lambda_{vo} = 9.996 \times 10^{-3}$

$V_{ct} := \pi \cdot \left[2 \cdot \left(R_2^{\,2} - R_1^{\,2}\right) \cdot W_T\right]$ $V_{ct} = 0.243 \cdot \mathrm{m}^3$ $L_{sincoil} := N_T \cdot N_L \cdot L_p = 1.98 \cdot \mathrm{km}$

Operating Conditions:

All the highlighted values in this section needs to be changed for the operting condition of the coil.

Operating current: $I_0 := \frac{AT}{N_C} = 1.5 \times 10^3 \cdot A$

$J_0 := \frac{I_0}{A_c}$ $J_0 = 27.324 \cdot A \cdot \mathrm{mm}^{-2}$

Charge time: $T_{ch} := 1.15 \cdot \mathrm{hr}$

Maximum coil field: $B_{max} := 2.97 \cdot T$ Maximum field value

Operating temperature: $\theta_0 := 4.603 \cdot K$ Operating temperature of the magnet

Effective total inductance acting on the quenching coil:

$L_{tot} := 0.51 \cdot H$

Stored energy: $E_{st} := \frac{1}{2} \cdot L_{tot} \cdot I_0^{\,2}$ $\quad E_{st} = 5.737 \times 10^{5} \cdot J$

Eddy Current Losses

$\rho_{RT} := 1.678 \cdot 10^{-8} \Omega \cdot m$

Cu magnetoresistance factor $\quad m_B := 4 \cdot 10^{-11} \cdot \frac{\Omega \cdot m}{T}$

$\rho_{ow} := \frac{\rho_{RT}}{RRR_m} = 1.678 \times 10^{-10} \cdot \Omega \cdot m$ $\quad \rho_{cBw} := \rho_{ow} + m_B \cdot B_{max} = 2.866 \times 10^{-10} \cdot \Omega \cdot m$

$\rho_{och} := \frac{\rho_{RT}}{RRR_{st}} = 1.398 \times 10^{-10} \cdot \Omega \cdot m$ $\quad \rho_{cBs} := \rho_{och} + m_B \cdot B_{max} = 2.586 \times 10^{-10} \cdot \Omega \cdot m$

Average over copper resistivity for Cu Matrix and Cu Channel:

$$\rho_{cB} := \left(\frac{A_{st}}{\rho_{cBs}} + \frac{A_{wcu}}{\rho_{cBw}} \right)^{-1} \cdot A_{Cut} = 4.409 \times 10^{-10} \cdot \Omega \cdot m$$

NbTi fraction: $\lambda := \lambda_{NbTi} = 0.024$

$\rho_t := \rho_{cB} \cdot \frac{1 + \lambda_{NbTi}}{1 - \lambda_{NbTi}}$ transverse composite core resistivity.

$\rho_t = 4.627 \times 10^{-10} \cdot \Omega \cdot m$

$L_t := 610 \cdot mm$ filament twist pitch.

$D_{Cu} := d_w \cdot 0.9$ core wire diameter (assume 90% of bare conductor diameter)

Check the material cross sections and adjust λ_{NbTi} to get agreement with parameter list:

Composite: $A_{comp} := A_u = 54.897 \cdot mm^2$

NbTi: $A_{NbTi} = 1.323 \cdot mm^2$

Cu: $A_{Cu} = 5.29 \cdot mm^2$

$a := 0.9 \cdot \frac{D_{Cu}}{2}$ filament bundle radius

$w := \frac{d_w}{2} - a$ conductor sheath effective thickness

$$\rho_{et} := \left[\frac{1}{\rho_t} + \frac{w}{a \cdot \rho_{cB}} + \frac{a \cdot w}{\rho_{cB}} \cdot \left(\frac{2 \cdot \pi}{L_t} \right)^2 \right]^{-1}$$ Equation 8.47

$$\tau := \frac{\mu_0}{2 \cdot \rho_{et}} \cdot \left(\frac{L_t}{2 \cdot \pi}\right)^2 \qquad \mu_0 = 4 \cdot \pi \cdot 10^{-7} H \cdot m^{-1}$$ Equation 8.50

$\tau = 15.949\,s$ Time constant for coupling current decay.

Charge rate: $\frac{B_{max}}{T_{ch}} = 0.043 \cdot T \cdot min^{-1}$

but the minimum field is about zero, and the losses are proportional to the square of the field so we use the RMS field:

$$B_{rms} := \frac{B_{max}}{\sqrt{2}} \qquad B_{rms} = 2.1\,T$$

The coupling current loss is then: $Q_c := \frac{B_{rms}^2}{2 \cdot \mu_0} \cdot \frac{8 \cdot \tau}{T_{ch}} \cdot V_{ct}$ for a whole cycle, i.e a ramp up and a ramp down. equation 8.53

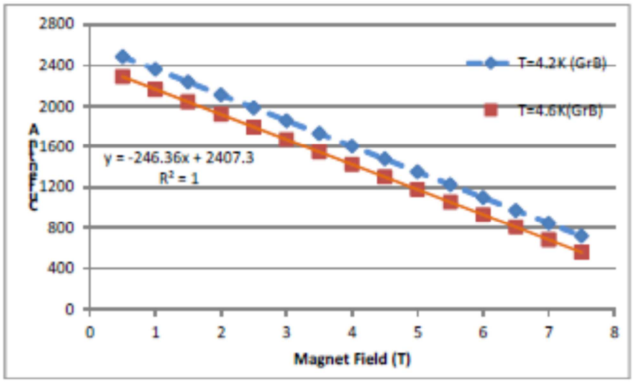
$$Q_c = 1.315 \times 10^4 \cdot J \quad W_c := \frac{Q_c}{T_{ch}} = 3.175\,W$$

Hysteresis Losses

Number of filaments: $N_f := 87$

Filament radius: $a_f := 0.127 \cdot mm$

$$I_{c0} := 2407.3 \cdot A \qquad k := -246.36 \cdot A \cdot T^{-1} \qquad I_c(B) := I_{c0} + k \cdot B$$

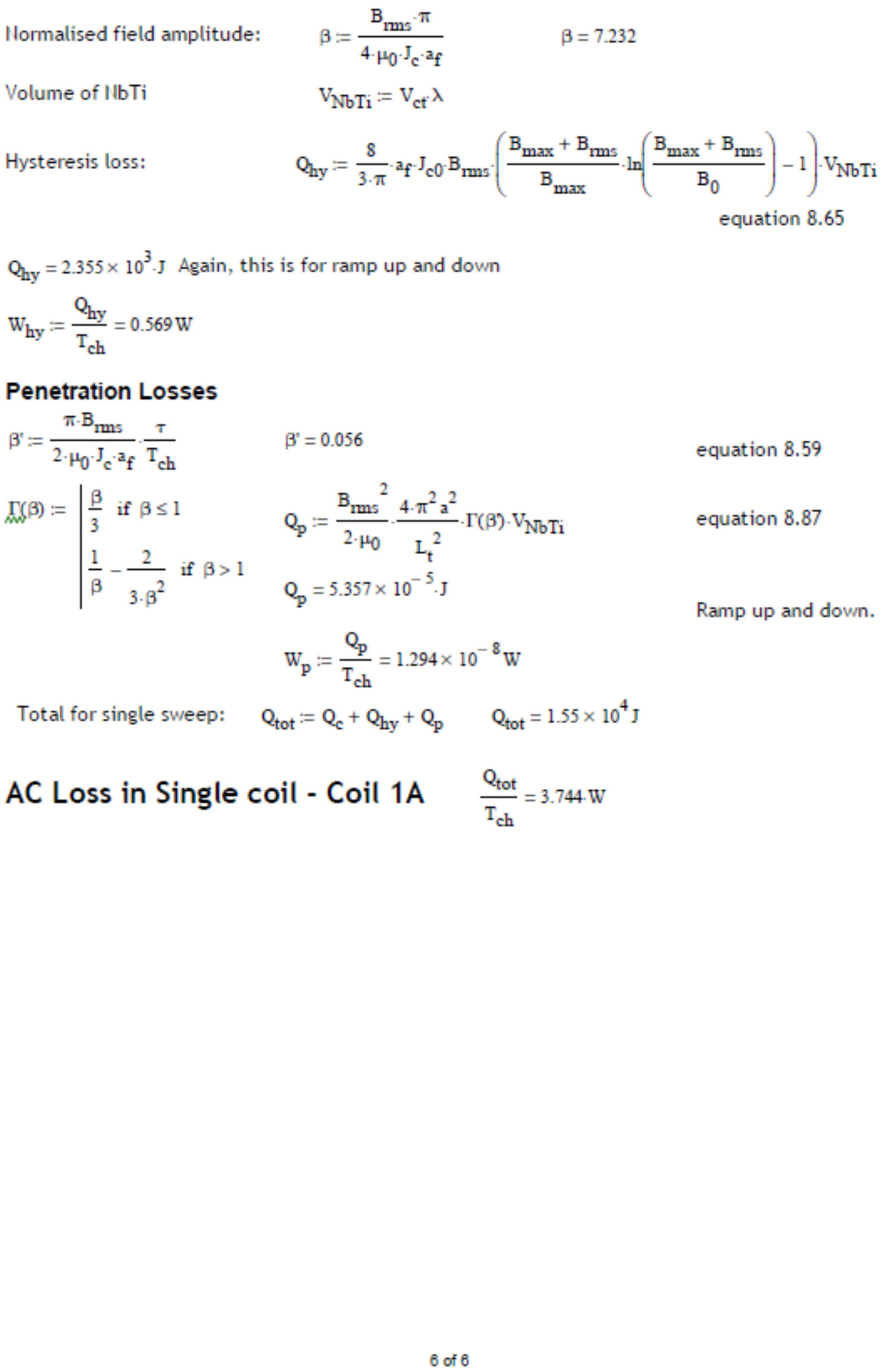


Current is about 1670 A (approx)

$$B_0 := B_{rms} = 2.1\,T$$

$$J_{c0} := 3.52 \cdot 10^9 \cdot \frac{A}{m^2} \qquad I_c(B_{rms}) = 1.89 \times 10^3\,A$$

$$J_c := \frac{I_c(B_{rms})}{A_{NbTi}} \qquad J_c = 1.429 \times 10^9 \frac{A}{m^2}$$



Normalised field amplitude: $\beta := \frac{B_{rms} \cdot \pi}{4 \cdot \mu_0 \cdot J_c \cdot a_f}$ $\beta = 7.232$

Volume of NbTi $V_{NbTi} := V_{cf} \cdot \lambda$

Hysteresis loss: $Q_{hy} := \frac{8}{3 \cdot \pi} \cdot a_f \cdot J_{c0} \cdot B_{rms} \cdot \left(\frac{B_{max} + B_{rms}}{B_{max}} \cdot \ln\left(\frac{B_{max} + B_{rms}}{B_0} \right) - 1 \right) \cdot V_{NbTi}$

equation 8.65

$Q_{hy} = 2.355 \times 10^{3} \cdot J$ Again, this is for ramp up and down

$W_{hy} := \frac{Q_{hy}}{T_{ch}} = 0.569\,W$

Penetration Losses

$\beta' := \frac{\pi \cdot B_{rms}}{2 \cdot \mu_0 \cdot J_c \cdot a_f} \cdot \frac{\tau}{T_{ch}}$ $\beta' = 0.056$ equation 8.59

$$\Gamma(\beta) := \begin{cases} \frac{\beta}{3} & \text{if } \beta \le 1 \\ \frac{1}{\beta} - \frac{2}{3 \cdot \beta^2} & \text{if } \beta > 1 \end{cases}$$

$Q_p := \frac{B_{rms}{}^2}{2 \cdot \mu_0} \cdot \frac{4 \cdot \pi^2 a^2}{L_t{}^2} \cdot \Gamma(\beta') \cdot V_{NbTi}$ equation 8.87

$Q_p = 5.357 \times 10^{-5} \cdot J$

Ramp up and down.

$W_p := \frac{Q_p}{T_{ch}} = 1.294 \times 10^{-8}\,W$

Total for single sweep: $Q_{tot} := Q_c + Q_{hy} + Q_p$ $Q_{tot} = 1.55 \times 10^{4}\,J$

AC Loss in Single coil - Coil 1A

$\frac{Q_{tot}}{T_{ch}} = 3.744 \cdot W$

6 of 6