SSC DETECTOR SOLENOID DESIGN NOTE #35

TITLE: Backup Calculations for Parameters in Design Note #34

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SUMMARY: This note contains calculations, references, and remarks backing up the numbers cited in Design Note #34, "Large Detector Solenoid Parameters".

COIL

1. Active length of coil module

   l_{2m} = 1812 mm, from Jim Krebs

2. Calculated excitation per module for 1.7 T

   From Bob Wands, module current density

   $J_{coil} = 7.312$ MA/m^2 for B(0,0) = 1.7 T

   NI(calc, 2 m, 1.7 T) = $J_{coil}\, l_{2m}\, \Delta R$ = (7.312 MA/m^2)(1.812 m)(0.212 m) = 2.81 MAturns

3. Maximum operating current

   If the as-wound coils all contain the number of turns specified below, the calculated excitation will be attained with 4.56 kA. The power supply will be capable of 5 kA and therefore ~10% extra amp-turns. All conductor, stability and quench issues will be calculated at 5 kA.

4. Turns, turns per layer, layers

   Total of 616 turns, 88 turns/layer x 7 layers, to provide the calculated excitation at 4.56 kA.

5. Excitation available per coil module

   NI(available) = 616 turns x 5 kA = 3.08 MAturns

6. Total self inductance

   L(16 m) = $2E/I^2$ = (2)(1400 MJ)/(5 kA)^2 = 112 H. Because all eight, 2-m coils are in series electrically, the current is always the same in all modules and I ignored the various mutual inductances.

7. Turn-to-turn insulation

   Thickness = (1/87)[1812 mm - (88 x 18 mm)] = 2.62 mm = 0.103 in

8. Layer-to-layer insulation

   Thickness = (1/6)[212 mm - (7 x 26 mm)] = 5.0 mm = 0.197 in

9. Length of conductor in module

   Length (2m) ~ [π (9.5 m/turn)](616 turns) =18.4 km

10. Total length of conductor required
Assuming eight, 2-m modules, i.e. no spares, and no cutting loss, Length (16m) = 8 x 18.4 km = 147 km = 92 miles

CONDUCTOR

11. Overall conductor dimensions
Keep the same conductor as before, but fewer turns per layer and correspondingly thicker turn-to-turn insulation.

12. Peak field at the conductor
Bob Wands has found that the highest fields occur at the coil I.D. at the longitudinal mid-point of the modules, where the field has only an axial component. The total field at the outside-longitudinal--inside-radial corner is about 1.3 T.

13. Short sample conductor specification
The superconductor current density of 3×10^9 A/m^2 came from Al McInturff in 1988. An Outokumpu brochure gives 4×10^9 A/m^2 at 3 T and 4.2 K. The choice of 10 kA at 2 T is sort of arbitrary, based partly on the requirement for the CDF conductor (10.4 kA @ 1.5 T).

14. Cu:SC area ratio

$$A_{SC} = 10 \times 10^3 \text{ A}/3 \times 10^9 \text{ A/m}^2 = 3.33 \times 10^{-6} \text{ m}^2$$

$$A_T = 0.018 \times 0.126 \text{ m}^2 = 4.68 \times 10^{-4} \text{ m}^2$$

$$A_{Cu} = 4.65 \times 10^{-4} \text{ m}^2$$

$$A_{Cu}/A_{SC} = 4.65 \times 10^{-4}/3.33 \times 10^{-6} = 141$$

15. Conductor-copper current density
= 5000 A/4.68×10^{-4} m^2 = 1.07×10^7 A/m^2 =1070 A/cm^2 ~ 11 A/mm^2. It is interesting to note that AWG 16 (ϕ = 0.0508" = 1.29 mm) copper wire is rated for 10 A in household use, a current density of 7.6 A/mm^2.

16. Copper RRR
Although the RRR of typical superconductors can reach 250 in the drawing process, the spooling and winding strain will reduce that. The magnetoresistance effect will increase the resistivity, and decrease the RRR, by about a factor of two at 2 T.

17. Copper resistivity
I used the value at 273 K from the Superconducting Machinery Handbook at an RRR = 100, 1.55×10^{-10} Ω-m. An ORNL reference gives $\rho = 1.48 \times 10^{-10}$ at 2 T for annealed OFHC copper.

18. Full surface heat flux
Heat flux = $I^2\rho/2(ab)(a + b)$ [Design Note #18]. I used I=5000 A, $\rho = 1.55 \times 10^{-10}$ Ω-m, a = 1.8 cm, b = 2.6 cm. The heat flux is so low that the wetted fraction does not matter very much.

19. Critical current margin

I adopted the General Dynamics definition of this, found in their MFTF report GDC-LLNL-84-001, p. 11-14:

$$\text{Crit.C.M.} = [(I_c - I_{op})/I_{op}]_{Bop}.$$

I constructed the B-I short sample curve (Fig. 1) on either side of the 10 kA/2 T point using the Outokumpu data sheet (Fig. 2).

$$\text{Crit.C.M.} = [(10.5 - 5\ \text{kA})/5\ \text{kA}]_{1.8T} = 1.1 = 110\%$$

20. Critical field margin

The GDC definition:

$$\text{Crit.F.M.} = [(B_c - B_{op})/B_{op}]_{Iop} = [(5.3 - 1.8\ \text{T})/1.8\ \text{T}]_{5kA} = 1.94$$

21. Cryostable current margin

Again the GDC definition: $\text{Cryo.C.M.} = [(I_s - I_{op})/I_{op}]_{Bop}.$

GDC defines the cryostable current I_s (page 9-290 as the current which gives a surface heat flux equal to the minimum film boiling recovery flux. Van Sciver, "Helium Cryogenics", p. 219, gives the MFBF = 0.3 W/cm^2. For the 18 x 26 mm conductor at 5 kA, the heat flux is ~ 0.01 W/cm^2. Then

$$I_s^2 = (0.3/0.01)\ I_{op}^2 = 30\ I_{op}^2 \text{ and } I_s = 5.48\ I_{op} = 27.4\ \text{kA}.$$

$$\text{Cryo.C.M.} = [(27.4 - 5\ \text{kA})/5\ \text{kA}]_{1.8T} = 4.48$$

These three margins were 0.10 (10%) for the MFTF solenoids.

22. Fraction of short sample on load line

The operating point (5 kA, 1.8 T) is 0.611 (61.1%) of the way along the B_{max} load line, which intercepts the short sample curve at (8.3 kA, 2.9 T).

23. Temperature margin

On the B_{max} load line the point (8.3 kA, 2.9 T) is at 4.2 K, the point (0,0) is at 10 K. I assumed a linear decrease of (I,B) along the load line. The operating point is 0.389 (38.9%) of the way from 4.2 to 10 K. The maximum temperature at which the coil will remain superconducting at the operating point is 4.2 + 0.389(10 - 4.2) K = 4.2 + 2.26 K = 6.46 K. The temperature margin is 2.26 K.

QUENCHING

24. Fast discharge resistor

The value of the FDR was chosen to give an initial terminal voltage of 500 V during a fast, non quenching discharge from 5 kA. The coil is center tapped to ground (Design Note #31) so the maximum terminal voltage to ground is 250 V.

25. Nominal fast discharge time constant

The value is simply the coil inductance divided by the FDR, $\tau_{FD} = 112\ \text{H}/0.1\ \Omega = 1120$ s. This will be the time constant for a fast, but non-quenching discharge. The time constant for a quenching discharge will doubtless be less than this over most of the discharge because eddy current heating in the coil will cause the resistance to grow quickly enough that the coil resistance, $R_Q(t)$, enters into the equation for the time constant, $\tau = L/[R_D + R_Q(t)]$.

26. $U(\theta_m) = {}_0\int^{\infty} J^2(t)\ dt$

Reference: Wilson, "Superconducting Magnets", p. 201, 219

The value calculated from $U(\theta_m) = (0.5)J^2\tau_{FD} = (0.5)(1.07 \times 10^7)^2(1120) = 6.41 \times 10^{16}\ A^2\text{-s-m}^{-4}$ is a maximum since the quenching time constant will be less than 1120 s.

27. ${}_0\int^{\infty} I^2(t)\ dt$ -- MIITS

This is simply $A_{Cu}U(\theta_m)$

28. Maximum adiabatic hot spot temperature, θ_m

From Wilson, "Superconducting Magnets", Fig. 9.1, p. 202:

$U(\theta_m)$	ρ_0 (Ω-m)	θ_m (K)
6.5×10^{16}	1×10^{-10}	85
"	5×10^{-10}	120
"	1.55×10^{-10}	90

The value at 1.55×10^{-10} Ω-m is a linear interpolation between the other two points.

29. Initial/maximum eddy current heating in conductor during fast discharge

Reference: Design Note #25

$P(t)\{\text{conductor, 2-m module}\} = (N/R_C)(A_{eff}\ dB/dt)^2$

With $N = 616$, $R_C = 1.55\ (6.4\ \mu\Omega) = 9.92\ \mu\Omega$, $A_{eff} = 0.78\ m^2$

$P(t)\{\text{conductor, 2-m module}\} = 37.8 \times 10^6\ (dB/dt)^2$

$P_m\{\text{cond, 2-m}\}$ = maximum power in the conductor of a 2-m module

$= P_0\{\text{cond, 2-m module}\} = (N\ A_{eff}^2/R_C)(dB/dt)_0^2$

$= 37.8 \times 10^6\ (B_0/\tau)^2 = 87.1$ W and

$P_m\{\text{conductor, eight 2-m modules}\} = 697$ W

$E\{\text{cond, 8 x 2-m}\}$ = energy deposited in conductor during fast discharge

$= (\tau/2)P_m = 390$ kJ

30. Initial/maximum eddy current heating in helium vessel during fast discharge

Reference: Design Notes # 20 and 25

During any discharge

$P(t)\{\text{He vessel}\} = (M\ dI/dt)^2/R\{\text{He vessel}\}$

During a fast, non-quenching discharge, the maximum power occurs at t_0

$P_0\{\text{He vessel}\} = (MI_0/\tau_{FD})^2/R\{\text{He vessel}\}$

For an 8-m He vessel $M = 0.028$ H, $I_0 = 5000$ A, $\tau_{FD} = 1120$ s, R{8-m He vessel} = 21.1 μΩ

$P_m\{\text{8-m He vessel}\} = 740.5$ W, $P_m\{2 \times \text{8-m He vessel}\} = 1481$ W

$E\{2, \text{8-m He vessels}\} = (\tau_{FD}/2)P_m = 829$ kJ

31. Total energy deposited into coils and He vessels during a fast discharge
$E\{total\} = 390 + 829$ kJ $= 1219$ kJ

32. Liquid helium boiled during fast discharge
A simple-minded calculation is to apply the energy deposited into the cold mass to boiling LHe at one atmosphere, dividing the energy by the heat of vaporization, 1219 kJ/ 2.56 kJ/liquid liter = 475 liquid liters. If the gas from this quantity of boiloff liquid is removed from the magnet system to the refrigerator without raising the pressure/temperature, then this method and value is correct. If this is not the case, then part of the energy goes into raising the internal energy (temperature) at constant volume. The rate at which liquid is boiled is actually an exponential function of time. Furthermore, a fast discharge will almost surely initiate a quench, in which case the rate at which heat is added to the helium and cold mass will obviously be greater than for a non-quenching fast discharge. I have not attempted to do the comprehensive calculation of the pressure in the helium vessel as a function of time after initiation of a fast discharge or a quench or the rate of venting of helium after the reliefs open.

33. Quenching after initiation of a fast discharge
To investigate whether a quench will be initiated by the eddy current heating in the conductor, I considered the heat flux from the surface of the conductor in a 2-m module, at the time of maximum eddy current heating,
$Q/A = 87.1\ \text{W}/2(1.8 + 2.6\ \text{cm})(18.4 \times 10^5\ \text{cm}) = 5\ \mu\text{W/cm}^2$,
which is in the nucleate boiling regime and a normal spot will collapse rather than propogate. However, the heat flux to a 2-m helium vessel (185 W) will either boil away or blow out the liquid helium surrounding the coil and it will probably quench--I'm guessing that the gas remaining within the coil won't sustain even this low heat flux.

CHARGING AND SLOW DISCHARGE

34. Power supply voltage and current
A charging voltage of 100 V (50 V to ground) gives a linear charge time of about 1.5 hours. In order to provide a linear charge to the operating current of 5 kA, the power supply will be capable of 6 kA which it will deliver just as the coil reaches the operating current (5 kA through the coil and 1 kA through the fast discharge resistor). The supply will be rated at 600 kW. The steady state power would probably be a few volts at 5 kA.

35. Charge rate at constant voltage
$V = L\ (dI/dt)$; $dI/dt = V/L = 100\ \text{V}/112\ \text{H} = 0.893\ \text{A/s}$

36. Charge time with constant voltage
Charge time = 5000 A/0.893 A/s = 5600 s = 93.3 min

37. Slow discharge resistor
A slow discharge consists of two time segments. During the initial, exponential portion the terminal voltage drops exponentially from an initial value to

75 V, the maximum reverse voltage possible from the 100-V power supply (reference: John Stoffel). The coil current is also decaying exponentially from 5000 A during this time. The SDR was chosen so the intial discharge voltage would be the same as the charging voltage, so SDR = 100 V/5000 A = 0.02 Ω. During the exponential portion of the slow discharge the coil current decays from 5000 to 3750 A (75%I_0).

The second portion of the slow discharge is linear at a constant voltage of 75 V. At some low current the reverse power supply voltage will droop, but I have ignored this and assumed a linear discharge from 3750 to 0 A.

38. Slow discharge time constant

$$\tau_{SD} = L/SDR = 112 \text{ H}/ 0.02 \ \Omega = 5600 \text{ s}.$$

39. Exponential slow discharge time, 100 to 75 V, 5000 to 3750 A

In general $I(t) = I_0 \exp(-t/\tau_{SD})$. At $t = t_1$, $I(t)/I_0 = 0.75$, so

$$-(t_1/5600) = \ln(0.75) \text{ and } t_1 = 1611 \text{ s}.$$

40. Linear slow discharge time, 3750 to 0 A

From t_1, $I_1 = 3750$ A to t_2, $I_2 = 0$

$$dI(t)/dt = V(t)/L = 75/112 = 0.67 \text{ A/s and } (t_2 - t_1) = 3750/0.67 = 5600 \text{ s}$$

41. Total slow discharge time, from 5 kA

$$t_2 = t_1 + (t_2 - t_1) = 1611 + 5600 \text{ s} = 7211 \text{ s} = 2 \text{ h}$$

42. Eddy current heating--general

Power

$$P(t)\{8\text{-m He vessel}\} = [M\ dI(t)/dt]^2/R\{8\text{-m He vessel}\}$$
$$=[M\ V(t)/L]^2/R\{8\text{-m He vessel}\} = [(0.028/112)^2/21.1 \times 10^{-6}]\ V^2(t)$$
$$=(0.00296 \text{ W/V}^2)\ V^2(t)$$

$$P(t)\{2,\ 8\text{-m He vessels}\} = (0.00592)\ V^2(t)$$

$$P(t)\{2\text{-m coil}\} = 37.8 \times 10^6\ (dB/dt)^2$$
$$= 37.8 \times 10^6\ [(1.7 \text{ T}/5000 \text{ A})\ dI/dt]^2$$
$$= (37.8 \times 10^6)(0.1156 \times 10^{-6})[V(t)/L]^2$$
$$= [(37.8)(0.1156)/(112)^2]\ V^2(t)$$

$$= (0.000348 \text{ W/V}^2)\ V^2(t)$$

$$P(t)\{8,\ 2\text{-m coils}\} = (0.00279)\ V^2(t)$$

$$P(t)\{\text{total}\} = (0.00871)\ V^2(t)$$

Energy

$$E = \int P(t)\ dt$$

43. Eddy current heating during constant 100-V charge

$$P\{2,\ 8\text{-m He vessels}\} = 59.2 \text{ W}$$
$$P\{8,\ 2\text{-m coils}\} = 27.9 \text{ W}$$
$$P\{\text{total}\} = 87.1 \text{ W}$$

$$E\{total\} = (87.1\ W)(5000\ A/0.893\ A/s) = 488\ kJ = 190\ L\ LHe$$

44. Eddy current heating during slow discharge

Exponential portion, $t_0 = 0$ to $t_1 = 1611$ s; $V_0 = 100$ to $V_1 = 75$ V

$P_0\{2,\ 8\text{-m He vessels}\} = 59.2$ W
$P_0\{8,\ 2\text{-m coils}\} = 27.9$ W

$P_1\{2,\ 8\text{-m He vessels}\} = (0.00592)(75)^2 = 33.3$ W
$P_1\{8,\ 2\text{-m coils}\} = 15.7$ W

$$E_{0,1}\{total\} = {}_0\int^1 P(t)\ dt = (0.00871)\ {}_0\int^1 V^2(t)\ dt$$
$$= (0.00871)\ {}_0\int^1 V_0^{\ 2} \exp(-2\ t_1/\tau)\ dt$$
$$= (0.00871)V_0^{\ 2}\ (-\tau/2)\ [\exp(-2t_1/\tau) - \exp(-2t_0/\tau)]$$
$$= (0.00871)(10000)(5600/2)[1 - \exp(-2 \times 1611/5600)$$
$$= 244\ kJ\ [1 - \exp(-0.572)]$$
$$= 244\ kJ\ (1 - 0.563) = 107\ kJ$$

Linear portion

$P_{1,2}\ \{total\} = 33.3 + 15.7\ W = 49$ W

$E_{1,2}\{total\} = (49\ W)(5600\ s) = 274$ kJ

Entire discharge

$P_m\{total\} = P_0\{total\} = 59.2 + 27.9\ W = 87.1$ W

$E_{0,2}\{total\} = 107 + 274\ kJ = 381\ kJ = 149$ L LHe

45. Summary of eddy current heating

	Charge	Fast Discharge	Slow Discharge	
V_{max}	100. (const)	500. (exp)	100. (exp)	75. (const)
P_m\{2, 8-m vessels\}--W	59.2 (const)	1481. (exp)	59.2 (exp)	33.3 (const)
P_m\{8, 2-m coils\}--W	27.9 (const)	697. (exp)	27.9 (exp)	15.7 (const)
P_m\{total\}--W	87.1 (const)	2178. (exp)	87.1 (exp)	49.0 (const)
Energy--kJ	488.	1219.	107.	274.
			381.	
LHe boiled--L	190.	475.	149.	

(const) and (exp) indicate constant or exponentially decaying values

LIQUID NITROGEN CRYOGENIC SYSTEM

46. Cooling mode

Reference: Design Note #10. The LIN cooling system is basically a copy of that planned for the SSC ring magnet system, in which the LIN supply is 77-K, 6-ata subcooled liquid and the return 89 K and 4.7 ata. Flow is maintained by liquid circulators (pumps) with a pressure ratio 6/4.7 = 1.28.

47. Average fluid temperature

$= (77 + 89)/2 = 83$ K

48. Total flow rate

Reference: NBS Technical Note 129

h(77 K, 6 ata) = 29.000 J/g   h(83 K, 4.7 ata) = 41.228 J/g

Assuming a heat load of 5 kW for the magnet system,
flow rate = 5000 J/s /(41.228 - 29.000) J/g = 409 g/s

49. Number of nitrogen cooling circuits

On each 8-m assembly: (1) inner radiation shield, (2) outer radiation shield, (3 & 4) end radiation shield and radial support intercepts, (5) axial support intercepts. The LHe dewar might have its own circuit (6).

50. Expected heat load

Reference: Design Note 31, paper at IISSC-89.

A value of 50 W is given for the 16-m magnet system in this design note, substantiating calculations are not available.

LIQUID HELIUM CRYOGENIC SYSTEM

51. Cooling mode

We chose a thermosiphon as was used for the MFTF solenoids and the Aleph solenoid at CERN/LEP.

52. Number of circuits

On each 8-m assembly: (1 -4) coil modules, (5) axial support intercepts, (6 & 7) radial support intercepts.

53. Module flow rate/gas fraction

Reference: Design Note #24, paper at ICEC-12; also DN #26 (ASC) and DN #31 (IISSC). These are the only reference documents on this subject. DN #24 gives 23 g/s with <1% by weight, DN #26 and 31 give 25 g/s with <1%

54. Support intercepts flow rate/gas fraction

Design Note #24 gives 50 g/s at <7% gas by weight, DN #26 and 31 give only the 7%.

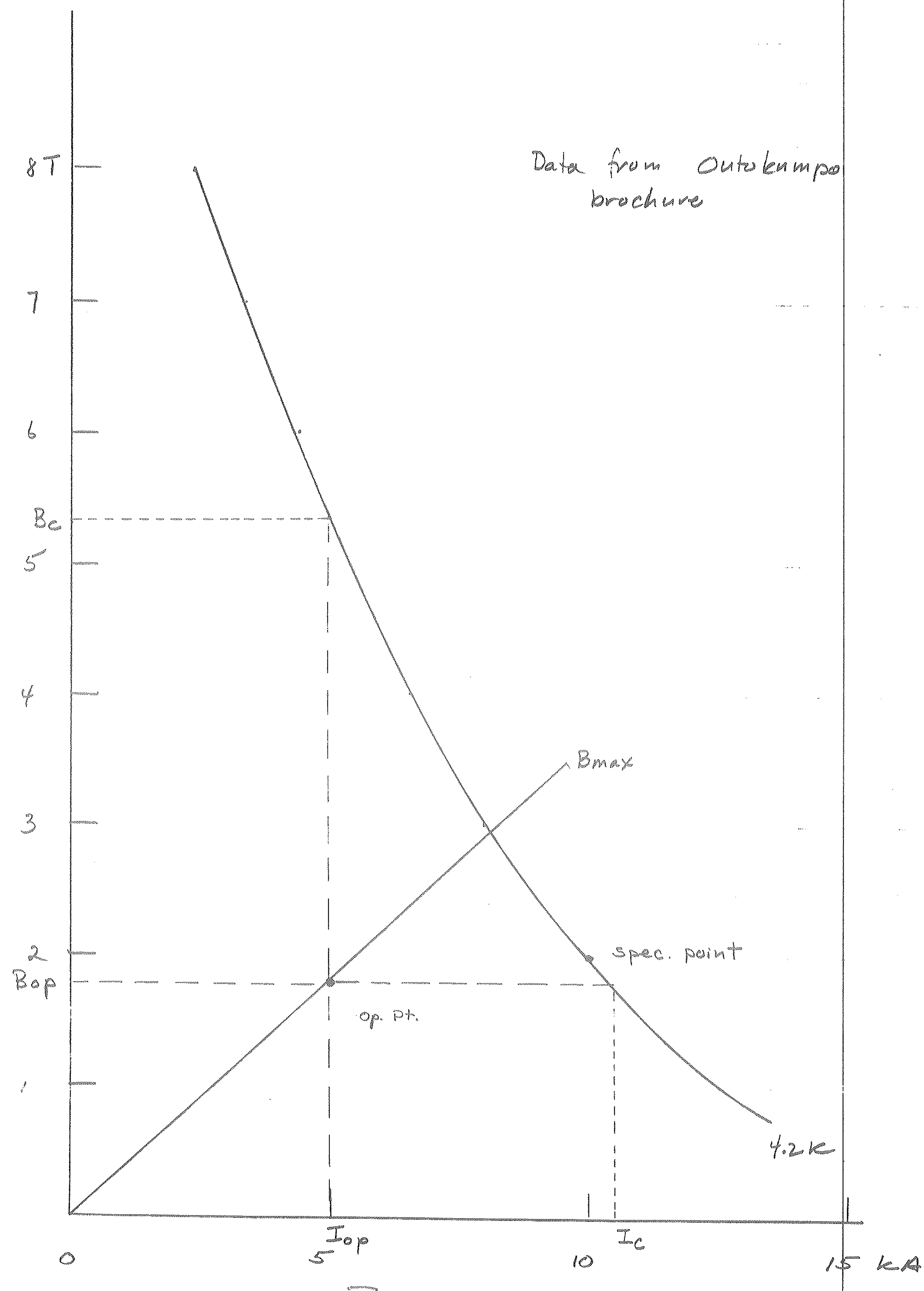
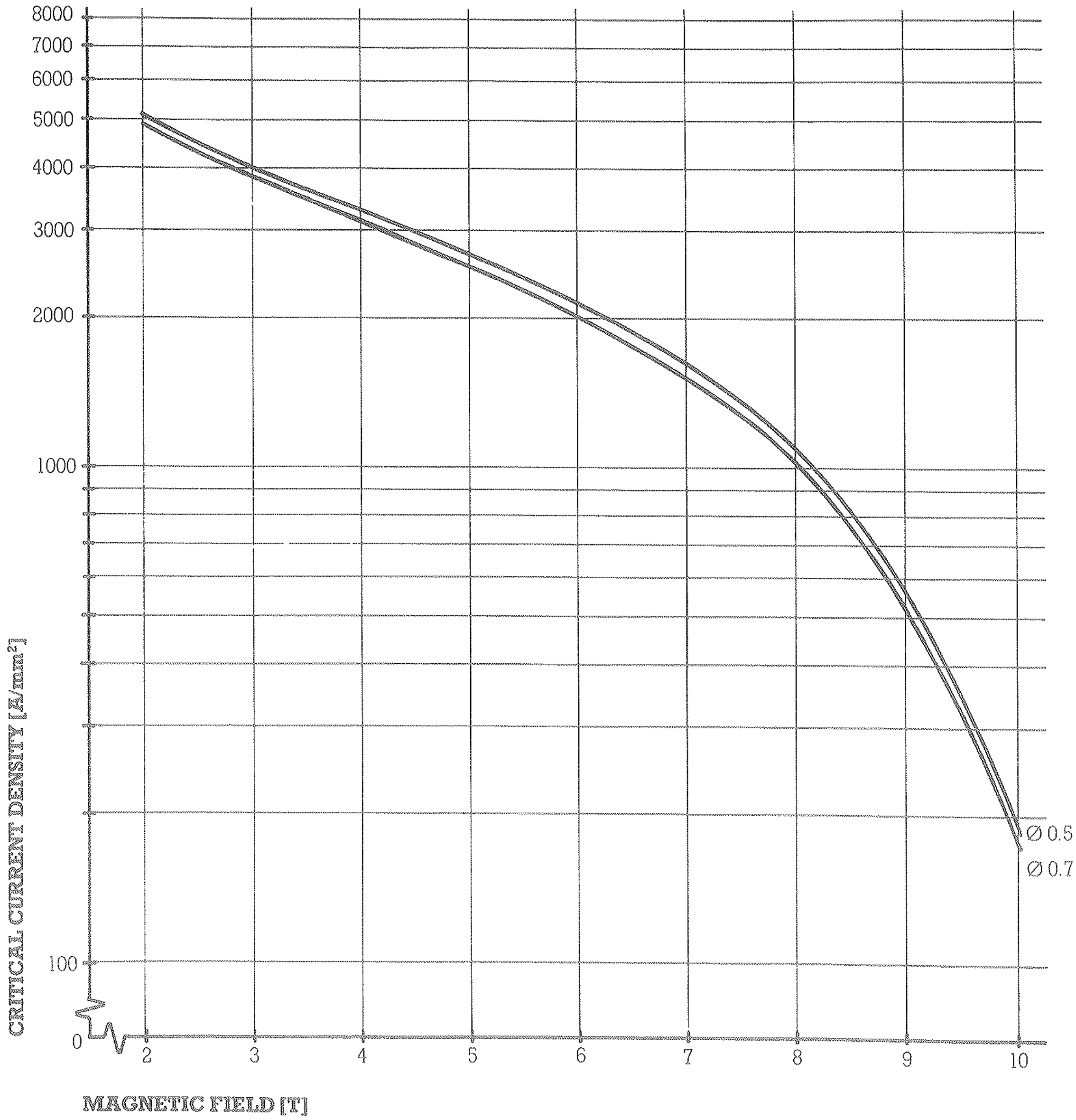

Data from Outokumpo brochure
8T
7
6
Bc
5
4
3
2
Bop
1
Bmax
spec. point
op. pt.
4.2K
Iop
Ic
0
5
10
15 kA

Fig 1.

FACTS AND FIGURES



Guaranteed critical current densities v.s. magnetic field at 4.2 K using a criterion of 10^{-14} Ω m for multi-filament Cu/NbTi wires. Upper curve for Ø 0.5 mm and lower curve for Ø 0.7 mm SCOK 20 – SCOK 60 wire types.

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