SSC-N-298

February 6, 1987

To: M. Tigner

From: J. D. Jackson

Subject: Specification of Copper Plating of Beam Tube

The following is a sequence of logical or semi-logical points narrowing down the properties.

1. The very low frequency longitudinal impedance of the beam tube is proportional to $(RRRt_1)^{-1}$, where t_1 is the thickness of the copper layer, and RRR is the residual resistance ratio at the operating field B and temperature T. In the CDR, $t_1 = 0.1$ mm, RRR = 30 and $Z_{||}(\omega \approx 0) = 4.4$ ohms. Hence

$$Z_{||}(\omega \approx 0) = \frac{13.2}{RRRt_1} \text{ ohms}$$

with t_1 in mm.

Discussions with Alex Chao lead to the conclusion that $Z_{||}(\omega \approx 0)$ values more than twice that of the CDR, while not impossible to handle, rapidly become undesirable. Hence we demand

$$RRRt_1 > 1.5 \text{ mm}$$

2. From considering the necessary beam tube wall thickness to withstand gas pressure of up to 100 atm, we conclude that a maximum Lorentz force of $A = f_{max} = 250$ psi during a quench is the upper limit (My calculations imply the need for a wall thickness of 2.0 mm for A = 250 psi and P = 200 atm.). If we demand performance at 8.0 tesla, where $(B|\dot{B}|)_{max}$ is estimated to be 325 T^2s^{-1}, and A < 250 psi, then RRR(6.1 T) $t_1 < 5.5$. (At the time of maximum $B|\dot{B}|$, the field value of 0.76 x 8 = 6.1 T is close enough to 6.6 T that we can take the RRR values as the same.) We now have a range,

$$1.5 < RRR\,(6.6T, 4.3\text{ K})\, t_1\,(\text{mm}) < 5.5$$

From the point of view of the mechanical aspects, a choice close to the lower end is clearly desirable.

3. The magnetic resistance effect limits the range of RRR values possible at 6.6 tesla. For zero field values ranging from 100 to 10^3, RRR (6.6 T, 4 K) = 34 to 50. For $RRRt_1 = 1.5$, these imply $t_1 = 4.4 \times 10^{-2}$ mm (1.7 mils) to 3.0×10^{-2} mm (1.2 mils). At the upper end of the range, the thicknesses are 3.7 times larger.

A thickness of $t_1 = 5 \times 10^{-2}$ mm (2 mils) seems sensible. With RRR = 50 (RRR(0) $\approx 10^3$) this thickness gives A = 113 psi for an 8.0 tesla quench.

4. With $t_1 = 5 \times 10^{-2}$ mm, RRR > 30 is required to meet the Chao criterion of $Z_{||}(\omega \approx 0) \leq 2$(CDR value). This requires the zero-field value of RRR to be greater than 75. In setting a specification, a zero-field value of greater than 100 is desirable, perhaps even 150. Extreme purity is not at a premium, however. RRR(B = 0) in the range 150 to 500 seems allowable.

5. Bane and Chao examined the effects of surface finish on the impedance with a model of a corrugated beam tube with annular corrugations whose depth and separation are a typical peak to valley for the surface. The impedance at low frequencies ($Z_{||}/n$) is linearly proportional to the scale parameter in this model. At 5 μm, the contribution is ~30% of the estimated impedance for the whole ring. If this estimate is reasonable, less than 10 μm seems desirable. Bintinger states that the platings obtained by BNL from their commercial plater had a peak to valley scale of less than 5 μm. Hence 5 μm is easily achievable and desirable for the rms surface finish.

6. Bintinger has the following observations:

   a) 2 mil plating is acceptable from the point of view of photodesorption, as demonstrated with the 5 m sample tubes obtained by BNL.

   b) Those tubes have plating with the 5 μm peak to valley surface finish. The finish is clean, without discoloration, and dull or matte. He believes these qualities should be requirements. We do not want anything done to the surface to make it shiny, for example, provided the rms surface finish is acceptable.

   c) Outgassing after one hour of pumping should be less than 5×10^{-9} torr-liters/cm^2/s. David says that the BNL samples meet this condition.

   d) While he feels that the existing plating samples meet the photodesorption requirements, he thinks it prudent to impose an eletrodesorption requirement on the plating. The Accelerator Systems Division is developing the exact specification, but it will not be available for several weeks.

   e) David says that Skaritka has specs on strength, etc. (peeling, flexing, fatigue).

   f) In the tubing samples seen so far, the nominal 2 μm plating varied from 2 to 3 mils in thickness. That is a ± 20% variation around 2.5 mils. I have no information on the spatial distribution of the variation. Such a variation in thickness seems excessive.

7. "<u>Specifications</u>"

   1) Copper plating thickness: 2 mils, with ± 10% tolerance, continuous

   2) RMS surface finish: ≤ 5 μm

   3) Surface: clean, dull, free from discoloration

   4) Copper purity: Such that $\rho = 1.6 \times 10^{-6}\ \Omega$-cm at room temperature and RRR at 4 K and B = 0 in the range, 150 to 500. (No premium on the highest possible value.)

   5) Outgassing: less than 5×10^{-9} torr-liters/cm^2/s after one hour of pumping

   6) Electrodesorption test: (Details to come.)

   7) Mechanical properties: (Skaritka/BNL to supply.)

Appended to this memorandum are Exhibits A, B and C from Jackson, Bintinger and Chao (with handwritten notes by JDJ). These provided backup for the arguments.

Revisiting Beam tube stresses

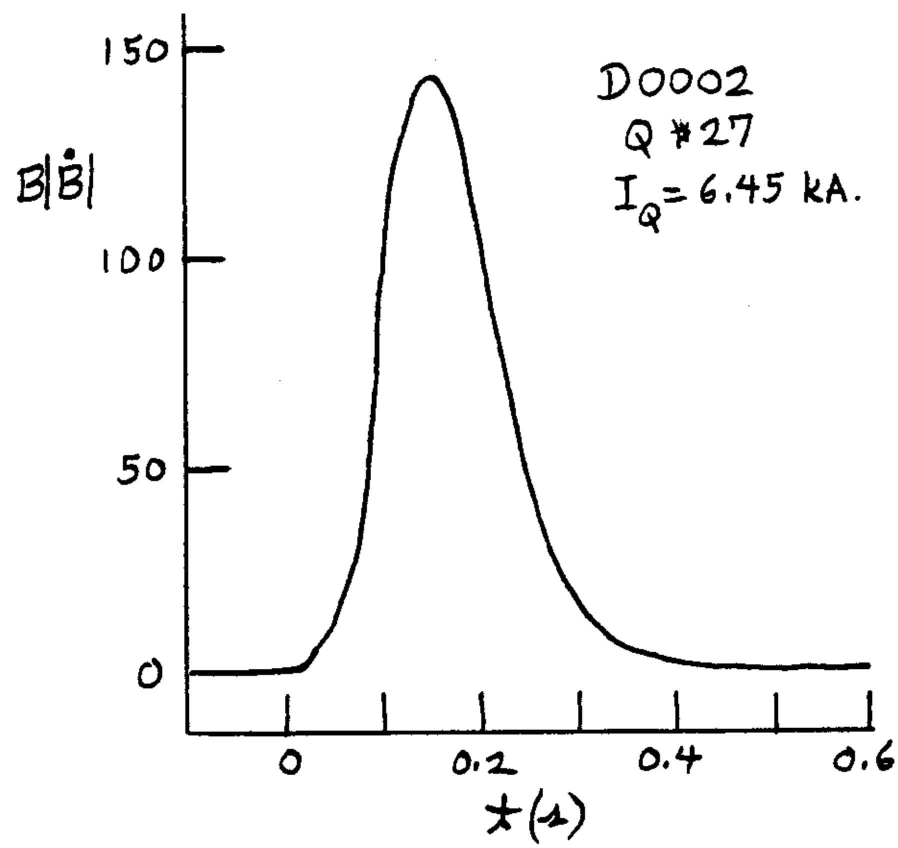
Max. Horizontal Lorentz force per unit area

$f_{max} = A = B|\dot{B}|b\,(t_1/\rho_1)$, where $b = 1.65$ cm is beam tube radius, t_1 = thickness of copper layer, ρ_1 = resistivity of copper layer. With $B|\dot{B}|$ in $T^2 s^{-1}$, b in cm, t_1 in mm, ρ_1 in micro-ohm-cm, then

$$A = 0.145\,(B|\dot{B}|)\,b\,t_1/\rho_1 \quad \text{psi}.$$

We assume $\rho_1 = 1.72\times10^{-6}\ \Omega\text{-cm}/RRR$

$b = 1.65$ cm



Typical quench at high current

Data are actually smoothed $I|\dot{I}|$ in $(kA)^2 s^{-1}$

Transfer function is close enough to 1.0 to call it $B|\dot{B}|$.

Data on D0002

Quench	I_Q (kA)	$(B\|\dot{B}\|)_{max}$	T_{max} (s)
1	5.224	70	0.24
14	5.603	89	0.21
15	5.899	108	0.19
11	5.603	88	0.20
25	6.033	115	0.18
26	6.362	148	0.18
27	6.450	148	0.15
28	6.447	149	0.15
30	6.185	123	0.18
6	5.726	97	0.19+

Log-log plot of $(B|\dot{B}|)_{max}$ vs. I gives $I^{3.58}$ as power law.
B value at Tmax is approx. 0.76 B_0, where B_0 is peak field at the quench.

$$B|\dot{B}| = 0.188\ I^{3.58}\ T^2 s^{-1} = 0.188\ B_0^{3.58}\ T^2 s^{-1}$$

RRR values are needed at 0.76 B_0. Shutt's formula,

$$RRR = \frac{R(0)}{1 + 3\times10^{-3} B\,R(0)}$$

becomes

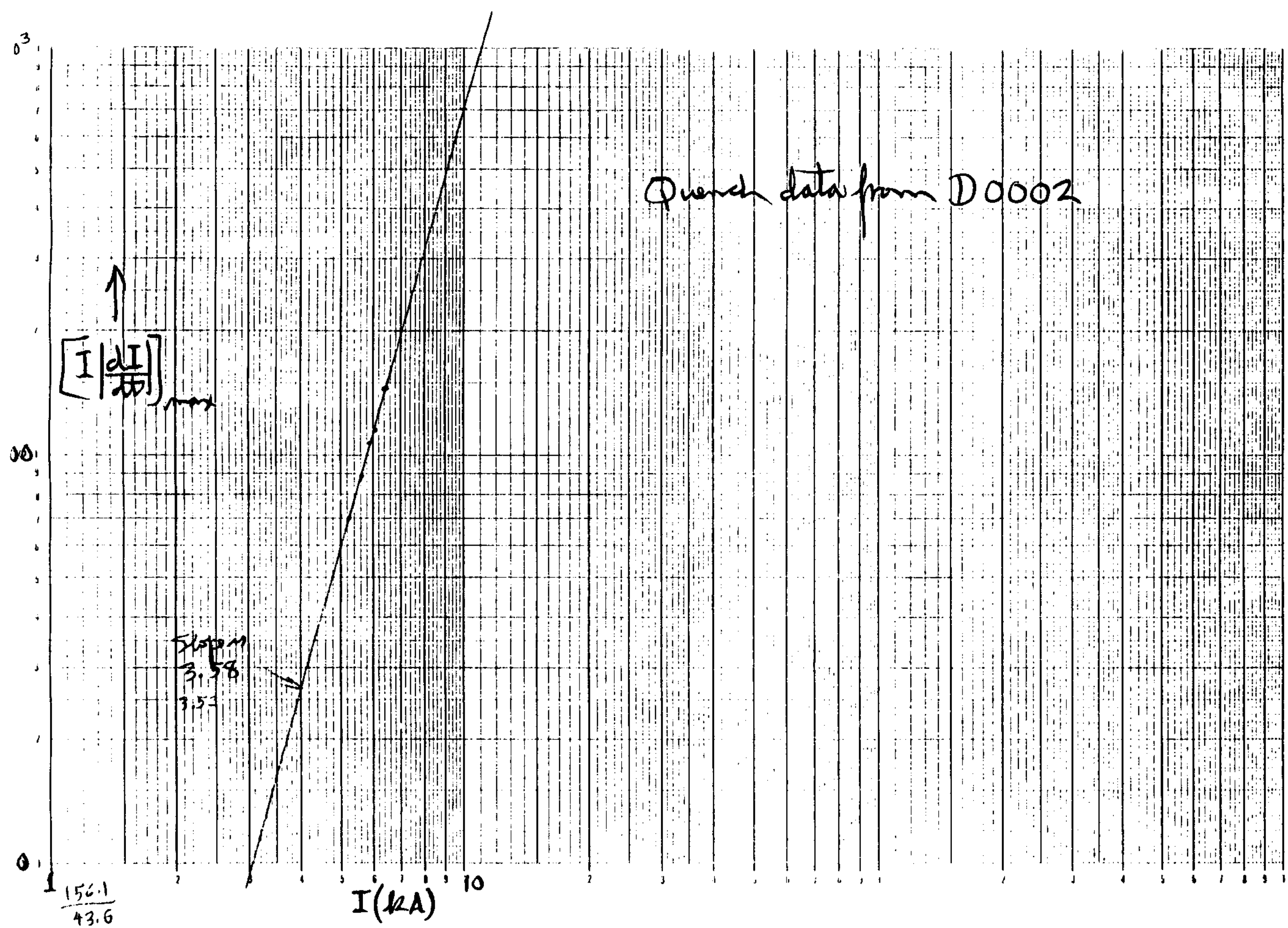
$$RRR = \frac{R(0)}{1 + 2.28\times10^{-3} B_0 R(0)}$$

With $t_1 = 5\times10^{-2}$ mm (2 mils), we have

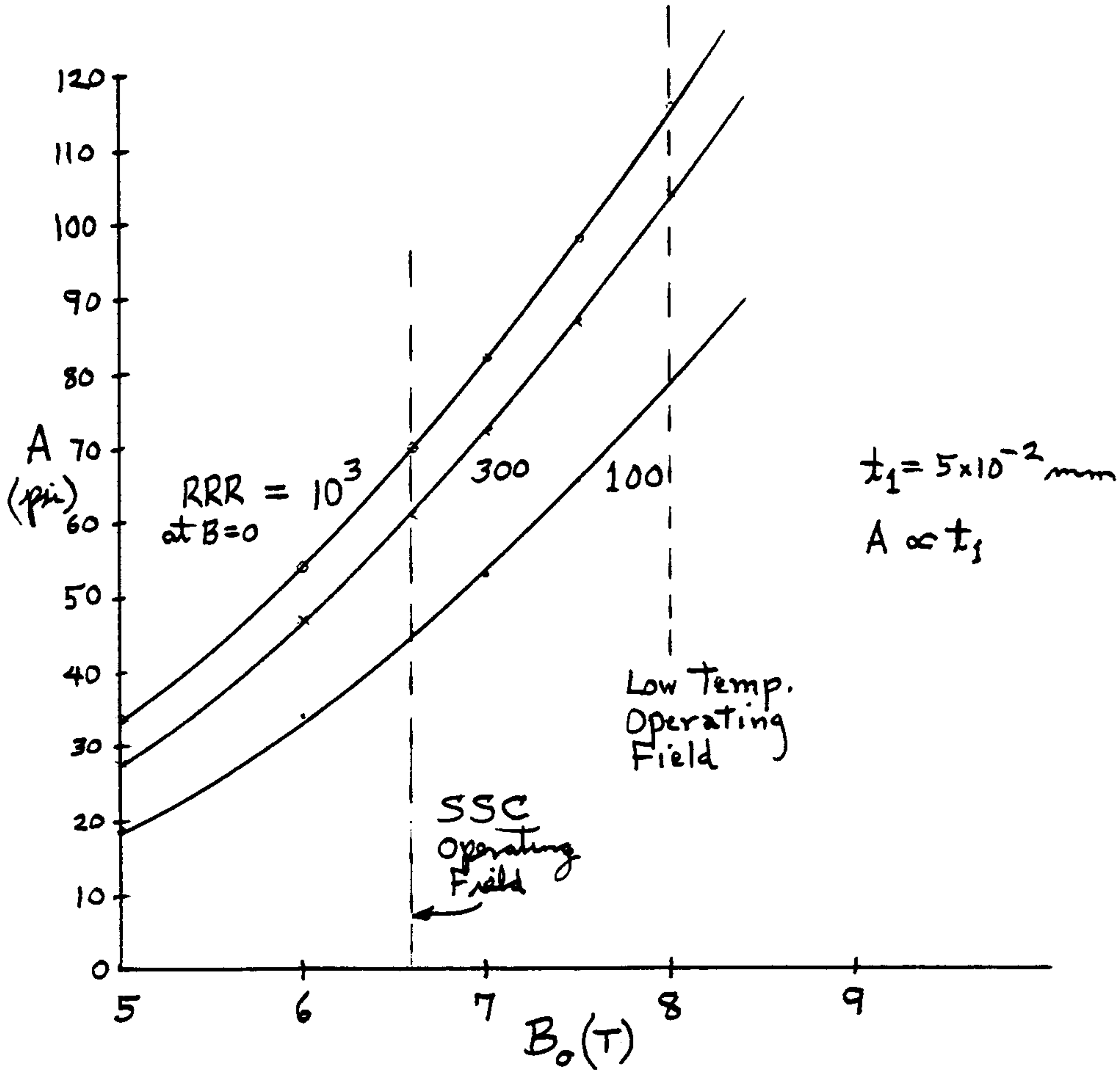
$$A = 1.308\times10^{-3} \frac{B_0^{3.58} R(0)}{1 + 2.28\times10^{-3} B_0 R(0)} \quad \text{psi}$$

LBL "LOREN"

STO R(0) in 00
Key B_0



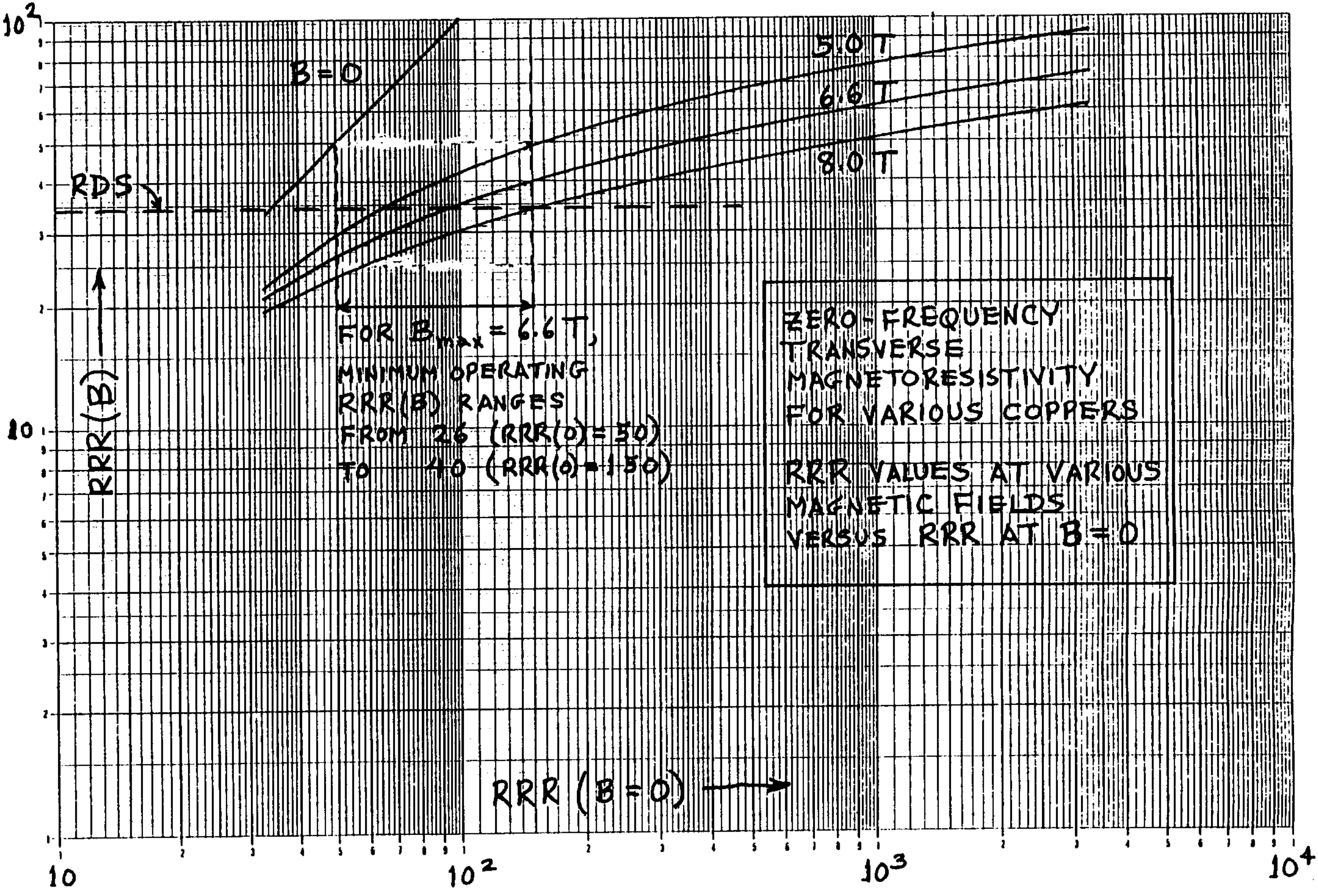
Quench data from D0002
[I|dI/dt]max
Slope ≈ 3.58
3.53
I (kA)
10
156.1
43.6



Empirically, $\frac{A(B_2)}{A(B_1)} \simeq \left(\frac{B_2}{B_1}\right)^{2.58 + \frac{40}{R(0)}}$

For reference, Shutt's formula gives RRR values at 6.6 T as follows:

R(0)	100	200	300	500	1000	50
RRR	33.6	40.3	43.2	45.9	48.1	25.1
(My values from my graph (See next page)) →	(35)	(44)	(48)	(54)	(61)	(26+)



B = 0
5.0 T
6.6 T
8.0 T
RDS
RRR (B)
RRR (B = 0)
FOR B_{max} = 6.6 T,
MINIMUM OPERATING
RRR(B) RANGES
FROM 26 (RRR(0) = 50)
TO 40 (RRR(0) = 150)
ZERO-FREQUENCY
TRANSVERSE
MAGNETORESISTIVITY
FOR VARIOUS COPPERS
RRR VALUES AT VARIOUS
MAGNETIC FIELDS
VERSUS RRR AT B = 0
10
10^2
10^3
10^4

If we restrict RRR(0) between 10^2 and 10^3, we have RRR(6.6T) between 34 and 50. With $t_1 = 5\times10^{-2}$ mm,

$Z_{\parallel}(\Omega)$ ranges from 7.8 to 5.3

$Z_{\parallel}(1-i)\sqrt{\omega}$ " " 14 to 12 Ω

Parasitic heating 67 to 55 watts/beam

Max. quench force ranges from 45 psi (6.6T, $R(0)=10^2$)
to 116 psi (8.0T, $R(0)=10^3$)

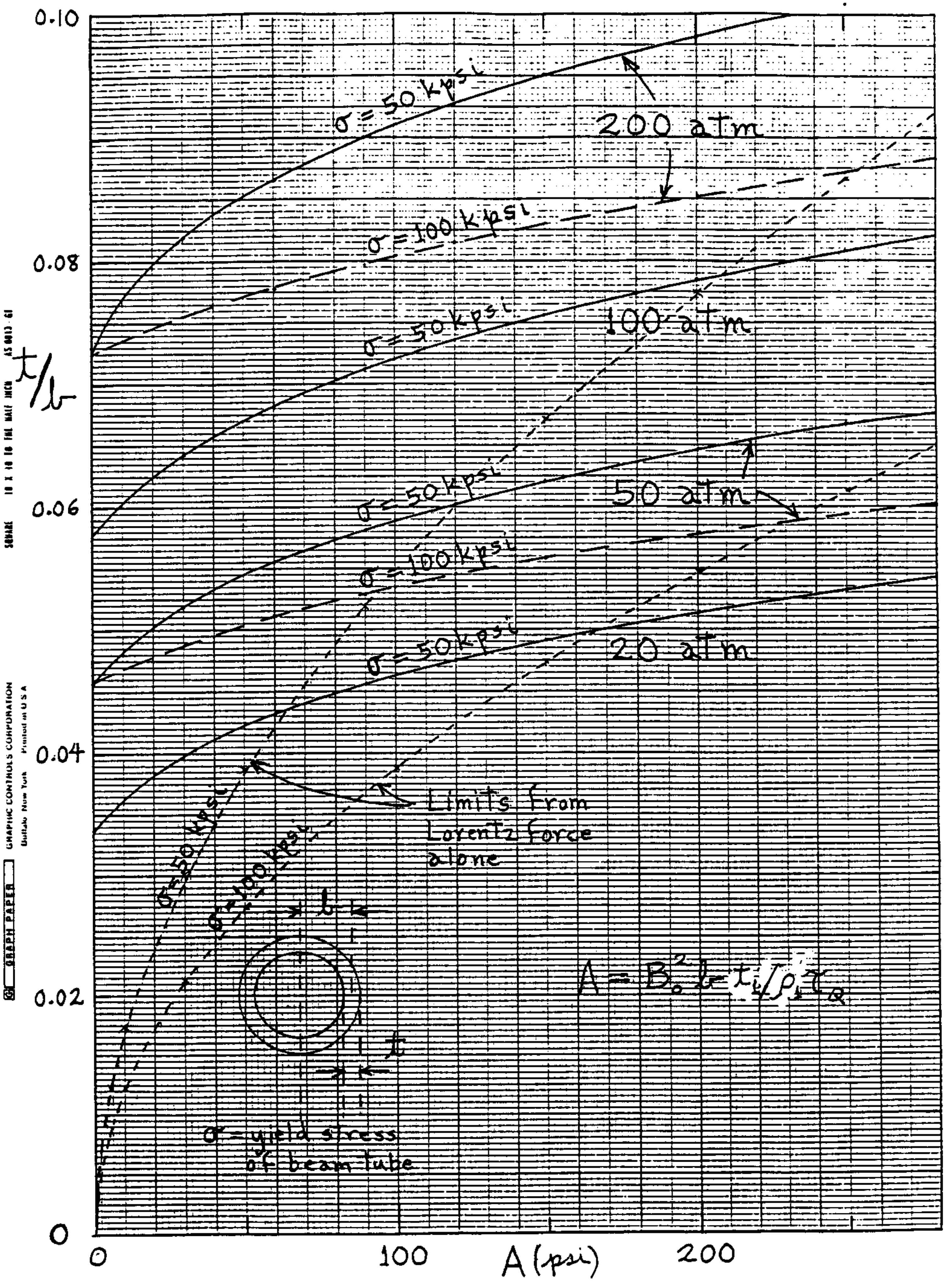
If I examine my graph that computes the stresses with an <u>unsupported</u> beam tube (the conservative case) and the Timoshenko treatment of the effects of gas pressure, I find that for $\sigma_{max} = 50$ kpsi (roughly the value for stainless, conservative for Nitronic 40) the min. values of t_2 (mm) are ($b = 1.65$ cm)

A (psi) \ P(atm)	0	50	100	200
50	0.64	0.90	1.11	1.41
100	0.90	0.97	1.19	1.50
120	1.00	1.00	1.21	1.53
150	1.11	1.11	1.25	1.57
200	1.28	1.28	1.30	1.62

For 6.6T operation, $A \lesssim 100$, $P \lesssim 100$ ∴ $t_2 > 1.2$ mm

For 8.0T operation, $A \lesssim 150$, $P \lesssim 200$ ∴ $t_2 \gtrsim 1.5$ mm

If pressures are known to be less than 50 atmospheres, a tube wall of 1.0 mm, supported, should be adequate.



0.10
0.08
0.06
0.04
0.02
0
t/b
0
100
200
A (psi)
σ = 50 kpsi
200 atm
σ = 100 kpsi
σ = 50 kpsi
100 atm
σ = 50 kpsi
50 atm
σ = 100 kpsi
σ = 50 kpsi
20 atm
Limits from
Lorentz force
alone
σ = 50 kpsi
σ = 100 kpsi
b
t
A = B₀² b τᵢ/ρᵢ τ_Q
σ - yield stress
of beam tube
GRAPH PAPER
GRAPHIC CONTROLS CORPORATION
Buffalo, New York Printed in U.S.A.
SQUARE 10 X 10 TO THE HALF INCH

EXHIBIT B

Feb 3, 1987
David Bintinger

Specification on Copper Plating

1. <u>RRR and plating thickness.</u> Experimentally RRR's have been measured at 6T from 46 to 108. The CDR assumes an RRR of 30 for 4 mils thick plating. We therefore reduced the thickness of plating to 2 mils in the 5m long test platings of SCA. (These are the platings that were used in the photodesorption experiment and are acceptable from the photodesorption point of view) The actual plating was from 2 mils to 3 mils in thickness. (.0025 ± .0005 inches)

2. <u>Surface Finish</u> The peak to valley grain of the plating was 5 micro-meters. The finish was clean, and without discoloration and matt. All these qualities should be requirements.

3. Outgassing. In an outgassing test, after 1 hour of pumping, the copper surface should outgas at a rate less than 5×10^{-9} Torr-liters/sec/cm². (The present plating meets this requirement)

4. Desorption. The present plating meets photodesorption requirements although there are still some test to do. A quick photodesorption test is not feasible, but a quick electrodesorption test is. Therefore we should require that the plating pass an electrodesorption test for total desorption rate and the absence of any oils or high mass number molecules in the desorbed gases. (The specification for electrodesorption rate is being developed at this time. I think we can just require a test at this time.)

5. Strength Test John Sieritree has the data on peel test, flex test, and fatigue test. Eric should get this information from John.

EXHIBIT C

to : Maury Tigner
from . Alex Chao 1/19/87
re : impedance issues concernig copper coating

This memo is to propose the specs and tolerances, from the impedance point of view, for:

- copper coating thickness t_1
- copper RRR value
- coating grain size g — What about surface impedance
- circumferential breaks

I assume the following are known:

- stainless steel thickness t_2 = 1mm
- stainless steel conductivity $\sigma_2 = 2.0\times10^6\ (\Omega\text{-m})^{-1}$
- pipe radius b = 1.65 cm
- copper conductivity = $1.8\times10^9\ (\Omega\text{-m})^{-1}$ for RRR=30
- max. B-dot during quench = 6.6T / 0.2sec
- rms bunch length = 7 cm
- number of particles per bunch = 7.3×10^9
- ring circumference = 83 km

1. RRR and t_1 Specs

Below is a table illustrating the various effects due to the variations in RRR and t_1:

	CDR case	case 1	case 2	case 3	case 4		
RRR	30	60	40	60	40	30	50
t_1 [mm]	0.1	0.06	0.04	0.04	0.06	0.05	0.05
low freq. $Z_{\parallel}$ [Ω]	4.4	3.7	8.2	5.5	5.5	8.8✓	5.3
high freq. $Z_{\parallel}$ [$(1-i)\sqrt{\omega}$ Ω] (ω in MHz)	15	11	13	11	13	15	12
transition freq. ω_t [MHz]	0.084	0.12	0.39	0.26	0.18		
parasitic heating [watt/beam]	71	50	61	50	51	71	55
trans. multi-bunch growth time -narrow band [s]	0.009	0.010	0.005	0.007	0.007		
-wide band [s]	14	17	7	11	11		
eddy curr. pinch during quench [psi]	100	120	53	80	80	← Force during ramping at 6.6T x 5000.	

All cases 1 to 4 are within acceptable tolerance. Conclusion: RRR=50±10, t_1=(0.05±0.01)mm can be accepted as current specs.

.02x5000

RRR = 40 at 6.6T → RRR = 150 at B = 0
60 → 850
35 → 100

RRR(0)		RRR(6.6T)	
100	150	35	40
200		43.5	
300		48.2	
400		52	
500		54	

2. Circumferential Breaks Specs

This is being studied by Meller and Ng. Their final report is due in a month. Quoted below are only the tentative results. If the final report is different, I will let you know as soon as possible. for RRR = 60

Assume a one-inch break in copper coating every 15 feet. The low frequency impedance increases by 50%. The high frequency impedance increases by 16%. Parasitic heating increases by 16%. Transverse instability effects are worsened by no more than 50% and most likely by only 16%. Eddy current effects are in general reduced. Such circumferential breaks are acceptable from the impedance point of view. This, however, is not meant to say we recommend to have circumferential breaks.

? 25 %

$\frac{\sigma_{cu} t_{cu}}{\sigma_{ss} t_{ss}} \times \frac{1}{12\times 15}$

3. Coating Grain Size

A report, yet to be documented, is being written by Karl Bane and me. Assuming grain size of 5 µm, results so far are:

- A pessimistic estimate gives $Z_{||}/n$ due to grainy wall to be 0.06 Ω, which is about 30% of the estimated longitudinal impedance for the whole ring.

- Grainy wall contribution to $Z_{\perp}$ is 6 MΩ/m, which is about 15% of the total ring value.

- Parasitic loss due to grainy wall is 1.6 watt per beam, which is very small.

Conclusion: 5 µm grain size is acceptable from the impedance point of view. Substantially larger grain size is to be avoided.

cc Vic Karpenko
Peter Limon