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CALCULATIONS FOR A BRIDGE THERMALLY SHORT-CIRCUITING THE STOCHASTIC COOLING PICK-UPS FOR THE CERN ANTIPROTON COLLECTOR

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Introduction

Stochastic cooling requires wide-band and low-noise signal acquisition and processing. For this purpose, the CERN Antiproton Collector is equipped with six beam pick-up stations operating at cryogenic temperature (see figure 4). Each station consists of a high-vacuum vessel housing arrays of pick-up electrodes, actually cooled to about 100 K by radiation to a surrounding thermal shield, and two pre-amplifiers kept below 20 K. Refrigeration is provided by a pair of two-stage Gifford-McMahon helium cryogenerators, thermally linked to the pre-amplifiers and to the thermal shield. The cryogenerators also cool activated charcoal cryopanels, in order to maintain a residual pressure in the vessel below 10^{-8} mbar. The choice of such cryogenic options is dictated by performance (steady-state and cool-down), simplicity of operation and maintenance, and high reliability.

Each pick-up stationconsists of a cylindrical high-vacuum vessel, 0.5m in diameter, 2.3 m in length, made of AISI 304L stainless steel, housing two mobile arrays of pick-up electrodes supported by 2.2 meters long aluminium alloy beams facing each other inside the vessel. In order to mantain a sufficient signal level, the electrode-supporting beams vertically translate by about 45mm each in order to follow the decrease in transverse dimensions of the particle beam envelope during the stochastic cooling process (about 1 s). This translation is achieved by means of two rigid actuating shafts supporting and accurately positioning the beams.

In order to obtain better signals, it would be desirable to reach lower temperatures for the pick-up electrode beams.

A possible solution can be represented by simply short-circuiting the beams with the thermal screen by means of a metallic connection between them. This would transfer heat by means of conduction instead of radiation. It would also affect, unfortunately, dynamics of the system, with relative vibration and fatigue problems.

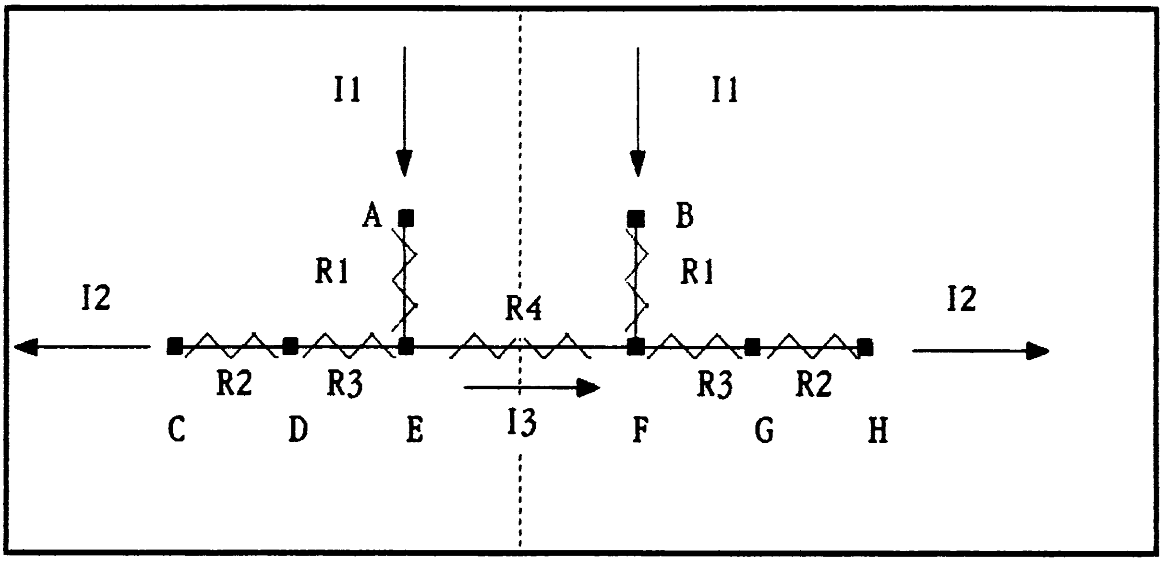
Heat Transfer Model

The thermal scheme could be represented by an electric circuit analogy:

La référence attribuée à cette note
était erronée. Il s'agit en fait de
la Tech. Note 88-11.

merci,

La Secrétaire



The element D-E-F-G represents the pick-up electrode beam.
The elements A-E and B-F stay for the cantilever spring pivots suspending the beam.
The elements C-D and G-H represent the metallic short-circuit.
These last elements might consist of n parallel prebent and relieved silver-bearing oxygen-free copper (Cu-OFS) sheets. They are connected by welding or brazing to two Cu-OFHC plates of large thermal conductivity. These plates would then be fixed to the pick-up electrode beam and the thermal screen respectively.
The physical quantities I (current), V (voltage) and R (resistance) are equivalent to the thermal parameters according to the following:

V	⇒	T	temperature
I	⇒	$dQ/dt = Q'$	rate of heat transfer
R	⇒	$L/A/k_{aveAB}$	thermal resistance

where

Q	=	exchanged heat
L	=	element length
S	=	element surface
k_{aveAB}	=	average thermal conductivity between temperatures A and B

The analogy is completed with the physical relationships between the previous quantities, i.e. law of heat conduction

$$Q' = S * k_{aveAB} / L * \Delta T = S / L * \int_A^B k \, dT$$

equivalent to Ohm's law, $\Delta V = I * R$.

Naturally we can now apply Kirchoff's law to nodes E and F:

point E $\quad I_1 = I_2 + I_3$
point F $\quad I_1 = I_2 - I_3$

therefore $I_3 = 0$
The model can be mathematically represented by the following system of equations

a)	Q'_{AE}	=	Q'_{ED}
b)	Q'_{ED}	=	Q'_{DC}
c)	Q'_{AE}	=	$S_{AE} / L_{AE} * \int_{TE}^{TA} k\, dT$
d)	Q'_{ED}	=	$S_{ED} / L_{ED} * \int_{TD}^{TE} k\, dT$
e)	Q'_{DC}	=	$S_{DC} / L_{DC} * \int_{TC}^{TD} k\, dT$

We can calculate S_{AE} / L_{AE} by noting that: the cantilever spring pivots are made of Ti-6Al-4V alloy, between 300 K and 100 K they actually deliver (CERN LEP-MA/85-29, CERN PS/85-47 (ML), table 2) 1.8 W each (Q') . For Ti-6Al-4V alloy, from CRYOGENIC MATERIALS DATA HANDBOOK, Volume I, Fred R. Schwartzberg et al, Martin Marietta Corporation, Denver, Colarado, USA, July 1970, is

$$\int_{100}^{300} k\, dT = k_{ave100-300} * \Delta T$$

$$= \{[(4.44+2.56)/2] \text{ BTU/ft hr °F} * (0.0173734908 \text{ W/cm K} /(\text{BTU/ft hr °F})\} (300-100) \text{ K}$$

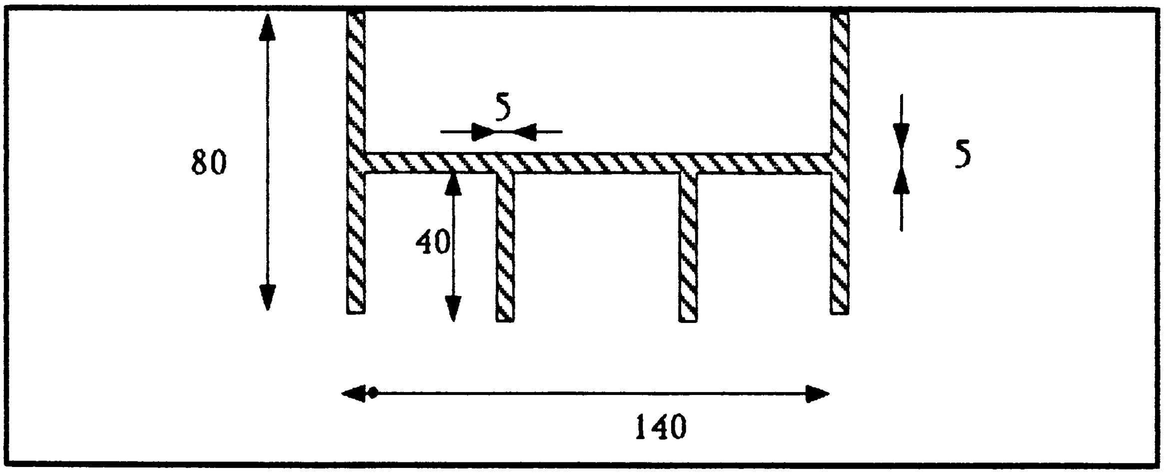
$$= 12.12 \text{ W cm}^{-1}$$

$$\Rightarrow \quad \mathbf{S_{AE} / L_{AE}} = (1.8)/(12.12)$$

$$= \mathbf{0.149\ cm}$$

TA is room temperature, **TA = 300 K**.

S_{ED} is measurable directly from the pick-up electrode beam cross section



$$\mathbf{S_{ED}} = 2(5)(80) + (5)(140) + 2(5)(40)$$

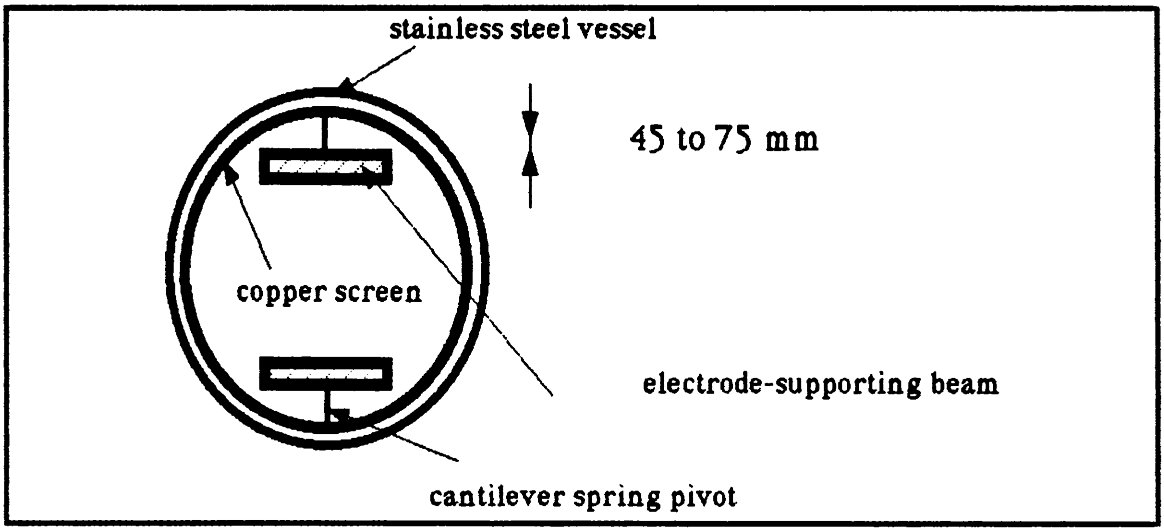
$$= 1900 \text{ mm}^2 \qquad = \mathbf{19\ cm^2}$$

L_{ED} can be measured from the tank:

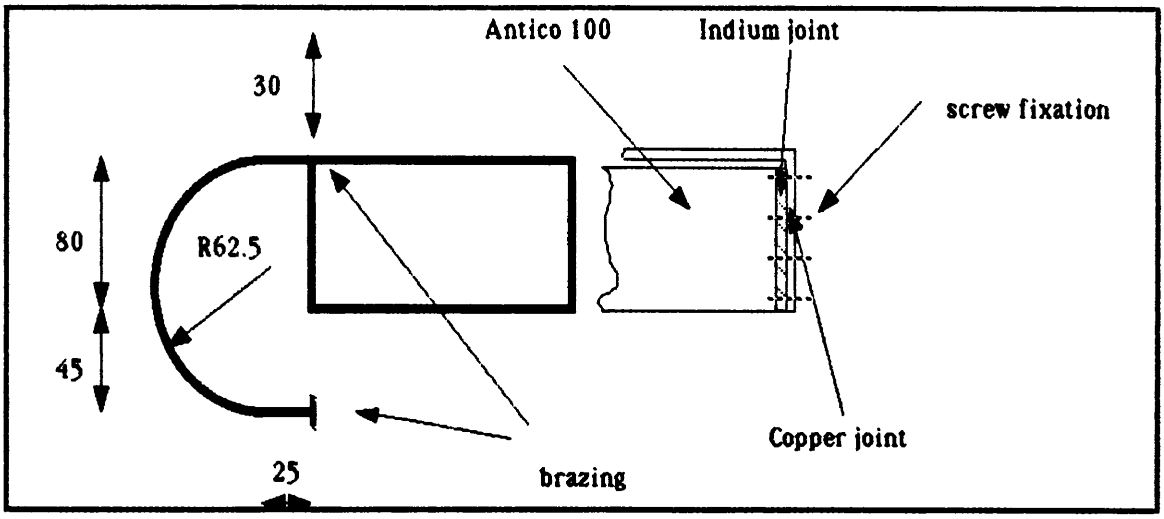
$$\mathbf{L_{ED}} = 350 \text{ mm} \qquad = \mathbf{35\ cm}$$

To reduce the rigidity of the short-circuit it should be as wide and thin as possible. The minimum thickness available on sheet is 0.15mm. We assume as reasonable a 200 mm width. We can think of brazing the sheets to the inner part of the pick-up electrodes, so that they describe a semicirconference at the most inner stroke point.
The distances between beam and screen vary as

	point D	point E
min	45 mm	65 mm
max	75 mm	85 mm



The length required for the sheets is minimum when demanding to reach the 45 mm stroke plus the 80 mm height of the beam, that is



The length required for the sheets is maximum instead when demanding to reach the 85 mm stroke plus the 80 mm height of the beam, that is

$$L_{DC} = \pi * (80+85) / 2 = 259 \text{ mm} = \mathbf{25.9 \text{ cm}}$$

$$S_{DC} = n\,(200)\,(0.15) = 30\, n \text{ mm}^2 = \mathbf{0.3\, n \text{ cm}^2}$$

were n is the number of sheets in parallel.

Thermal conductivity for Cu-OFS can be retraced from data by CIDEC, Geneva, 1983

T	k
73.15 K	1.25 cal/cm/s/K
90.15 K	1.13 cal/cm/s/K
173.15 K	1.04 cal/cm/s/K

Fitting with a parabolic curve, we have $k = sT^2 + tT + v$, where

$a = 5.974486\ 10^{-5}$; $b = -1.681514\ 10^{-2}$; $c = 2.160337$.

TC can be assumed, from recent measurements (June 14th, 1988), around **TC = 48 K**.

Q', n, TD and TE are the unknowns of the problem

We can start the problem by assuming TD - TC = 6 K.
Solving the above system of equations by iteration and assuming TE = 48K we find:

<u>1st iteration</u>

$$Q' = S_{AE} / L_{AE} * \int_{48}^{300} k\,dT$$

$$= S_{AE} / L_{AE} * k_{ave48-300} * \Delta T$$

$$= (0.149)\ cm\ \{[(4.44+1.42)/2]\ BTU/ft\ hr\ ^\circ F * (0.0173734908\ W/cm\ K\ /(BTU/ft\ hr\ ^\circ F)\}\ (300-48)\ K$$

$$= 1.90\ W$$

$$Q' = 1.90\ W$$

$$= S_{DC} / L_{DC} * \int_{48}^{54} k\,dT$$

$$= S_{DC} / L_{DC} * k_{ave48-54} * \Delta T$$

$$= (0.3\ n) / (25.9) * (1.46 * 4.186) * (6)$$

$$= 0.424\ n\ W$$

$$n = (1.90) / 0.424)$$

$$= 4.5\ \text{sheets} \rightarrow 6\ \text{sheets}$$

$$Q' = S_{ED} / L_{ED} * \int_{54}^{TE} k\,dT$$

$$TE = 60\ K$$

<u>2nd iteration</u>

$$Q' = S_{AE} / L_{AE} * \int_{60}^{300} k\,dT$$

$$= S_{AE} / L_{AE} * k_{ave60-300} * \Delta T$$

$$= (0.149)\ cm\ \{[(4.44+1.68)/2]\ BTU/ft\ hr\ ^\circ F * (0.0173734908\ W/cm\ K\ /(BTU/ft\ hr\ ^\circ F)\}\ (300-60)\ K$$

$$= 1.89\ W$$

$$Q' = 1.89\ W$$

	=	$S_{DC} / L_{DC} * \int_{48}^{54} k\, dT$
	=	$S_{DC} / L_{DC} * k_{ave48-54} * \Delta T$
	=	(0.3 n) / (25.9) * (1.46 * 4.186) * (6)
	=	0.424 n W
n	=	(1.89 / 0.424)
	=	4.5 sheets → 6 sheets
Q'	=	$S_{ED} / L_{ED} * \int_{54}^{TE} k\, dT$
TE	=	60 K

If we now assume TD - TC = 10 K, and TE = 48K, we have:

<u>1st iteration</u>

Q'	=	$S_{AE} / L_{AE} * \int_{48}^{300} k\, dT$
	=	$S_{AE} / L_{AE} * k_{ave48-300} * \Delta T$
	=	(0.149) cm {[(4.44+1.42)/2] BTU/ft hr °F * (0.0173734908 W/cm K /(BTU/ft hr °F)} (300-48) K
	=	1.90 W
Q'	=	1.90 W
	=	$S_{DC} / L_{DC} * \int_{48}^{58} k\, dT$
	=	$S_{DC} / L_{DC} * k_{ave48-58} * \Delta T$
	=	(0.3 n) / (25.9) * (1.44 * 4.186) * (10)
	=	0.698 n W
n	=	(1.90) / 0.698)
	=	2.7 sheets → 4 sheets
Q'	=	$S_{ED} / L_{ED} * \int_{58}^{TE} k\, dT$
TE	=	64 K

<u>2nd iteration</u>

Q'	=	$S_{AE} / L_{AE} * \int_{64}^{300} k\, dT$
	=	$S_{AE} / L_{AE} * k_{ave64-300} * \Delta T$
	=	(0.149) cm {[(4.44+1.75)/2] BTU/ft hr °F * (0.0173734908 W/cm K /(BTU/ft hr °F)} (300-64) K
	=	1.88 W
Q'	=	1.88 W
	=	$S_{DC} / L_{DC} * \int_{48}^{58} k\, dT$

	=	$S_{DC} / L_{DC} * k_{ave48-58} * \Delta T$
	=	$(0.3\ n) / (25.9) * (1.44 * 4.186) * (10)$
	=	0.698 n W
n	=	(1.89 / 0.698)
	=	2.7 sheets → 4 sheets
Q'	=	$S_{ED} / L_{ED} * \int_{58}^{TE} k\, dT$
TE	=	64 K

Results:

	Q'	TA	TE	n
TD- TC = 6 K	1.89 W	300 K	60 K	6
TD- TC = 10 K	1.89 W	300 K	64 K	4

(In this eventual scenario, the possible radiation heat transfer from the beam to the screen would be, with very brutal schematization

$Q'_{radiation:beam-screen} = A_{beam} * \varepsilon_{beam-screen} * \sigma * (T_{beam}^4 - T_{screen}^4)$

where

A_{beam} = 2 m^2

A_{screen} = $\pi * \varnothing * L$

= $\pi * (440) (2200)$

= 3041062 mm^2 = 3 m^2

ε_{beam} = 0.018 (Marks' STANDARD HANDBOOK for MECHANICAL ENGINEERS, page 19-35)

ε_{screen} = 0.008 (Marks' STANDARD HANDBOOK for MECHANICAL ENGINEERS, page 19-35)

$\varepsilon_{beam-screen}$ = $1/[1/\varepsilon_{beam} * A_{beam}/A_{screen} * (1/\varepsilon_{screen} - 1)]$

= 0.007235

σ = $5.672 * 10^{-8}$ $W/m^2 K$

T_{beam} = 100 K (assume)

T_{screen} = 48 K

Finally we would have

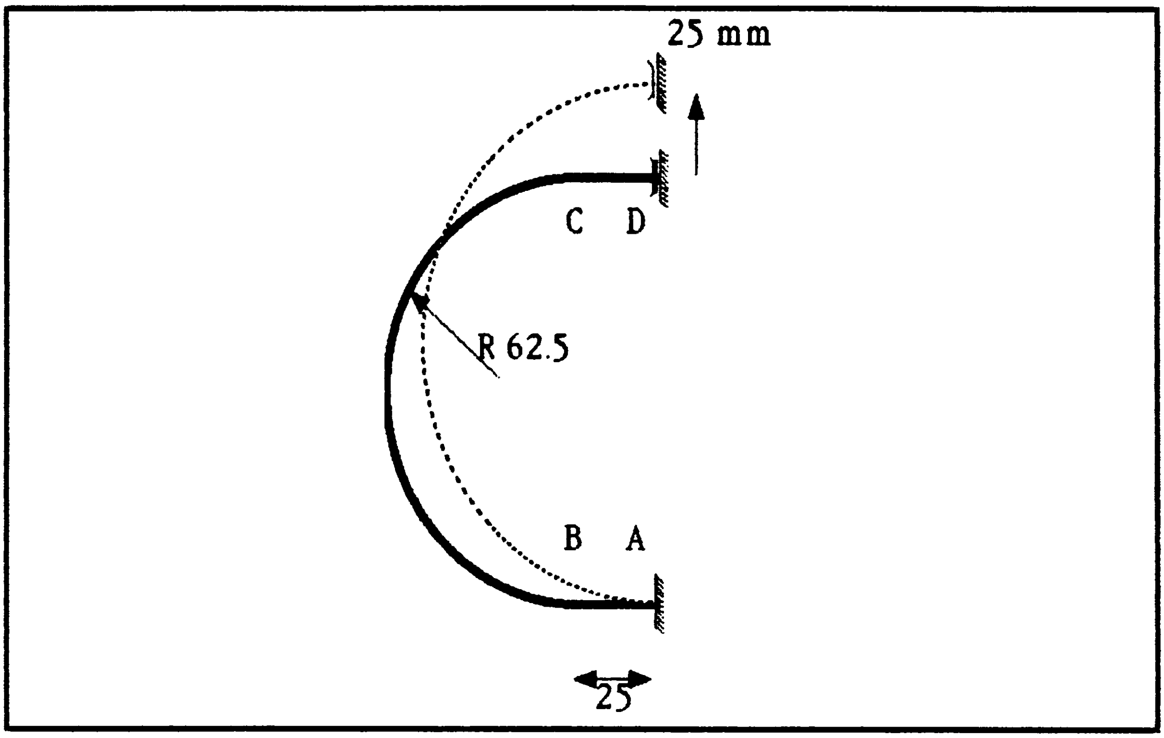
$Q'_{radiation:beam-screen} = (2)(0.007235)(5.672 * 10^{-8})(100^4 - 48^4)$

= 0.078 W

therefore negligible (4%).)

Fatigue

The most stressed case is the one where the radius of curvature is minimum, therefore we take case of point D. To study such a case, we assume the following static representation



By Finite Element Method calculations (ANSYS™-large displacements) we have, for the highest stessed points (A and D), taking into account static and dynamic (inertia), a fatigue behaviour,

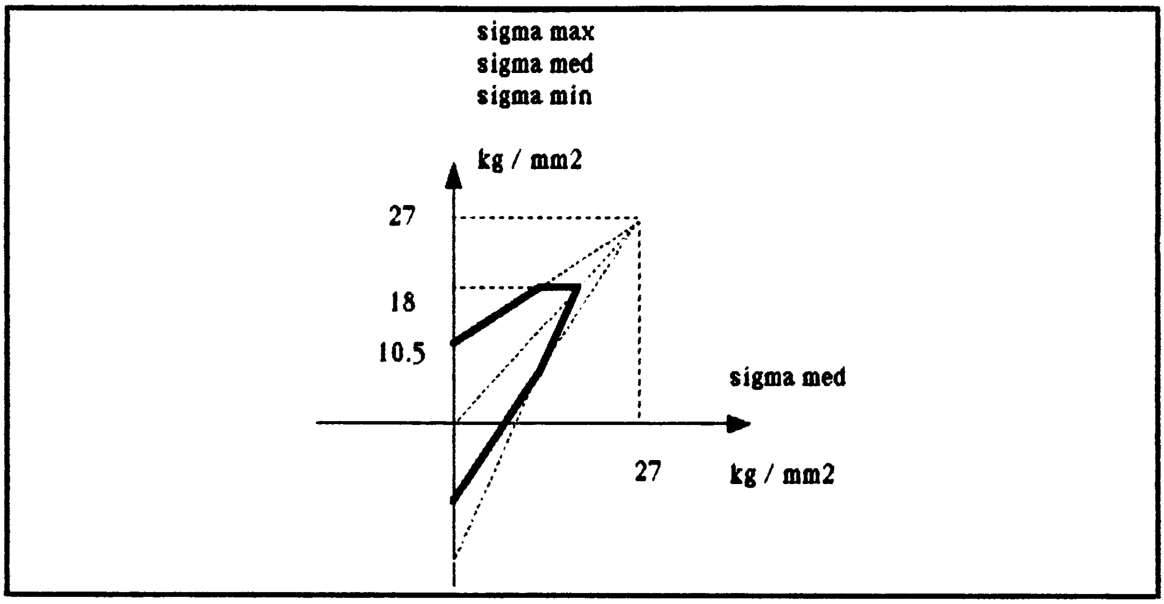
σ_{max} = 9 kg / mm^2

σ_{min} = 0 kg / mm^2

σ_{ave} = 4.5 kg / mm^2

For Cu-OFS, reversed bending test, infinite number of cycles, the fatigue limit is 10.5 kg / mm^2, while for annealed metal the tensile strength is 27 kg / mm^2, and proof stress, 0.2% offset is 18 kg / mm^2.

From these data, we can draw a Schmidt diagram giving a $\sigma_{max\ adm} = 15\ kg / mm^2$



A safety coefficient $\eta = \sigma_{max\ adm} / \sigma_{max} = 15 / 9 = 1.67$ is assured.
This safety accounts for the worst conditions possible. In effect, at low temperatures the fatigue limit is certainly higher. Beyond that, we considered annealed conditions, typical of post-brazing conditions at point A and D. A training cycle for the material can be eventually foreseen.
On the other hand, it should be more accurately defined and verified the dynamic effect of motion of the sheet on stresses: excitation of vibration modes and force amplification. However these events would be somehow smoothed and adjusted by the parallelism of the model: every prebent sheet will act as a spring with its peculiar characteristics. A further discussion on this point is compulsory at a more refined calculation stage, supported by physical data.
The static reaction force and moment (spring reactions) are 0.14 kg, and 6.8 kg mm.

Additional weight brought by the proposed solution consists of

V (Cu-OFS)	=	$(0.15)(200)(\pi * 125/2 + 2*25)$		
	=	$7391\ mm^3$	=	$0.007391\ dm^3$
ρ	=	$8.94\ kg / dm^3$		
W (Cu-OFS)	=	$4 * n * \rho * V$ + different lengths		
	$\cong$	1.5 kg		
V (Cu-OFHC)	=	(2) (150) (80) + (2) (150) (218)		
	=	$89400\ mm^3$	=	$0.0894\ dm^3$
ρ	=	$8.94\ kg / dm^3$		
W (Cu-OFHC)	=	$4 * \rho * V$		
	=	3.2 kg		

To be underlined is that these masses could introduce important changes in the dynamic behaviour of the whole system. At this stage a set-up for experimental tests would be adequate to completely examine fatigue and dynamics.

Conclusion

It has been shown that it should be possible to lower the beam pick-up temperature by a factor 2 (120K→60K), without additional power demand (negligibile additional load).

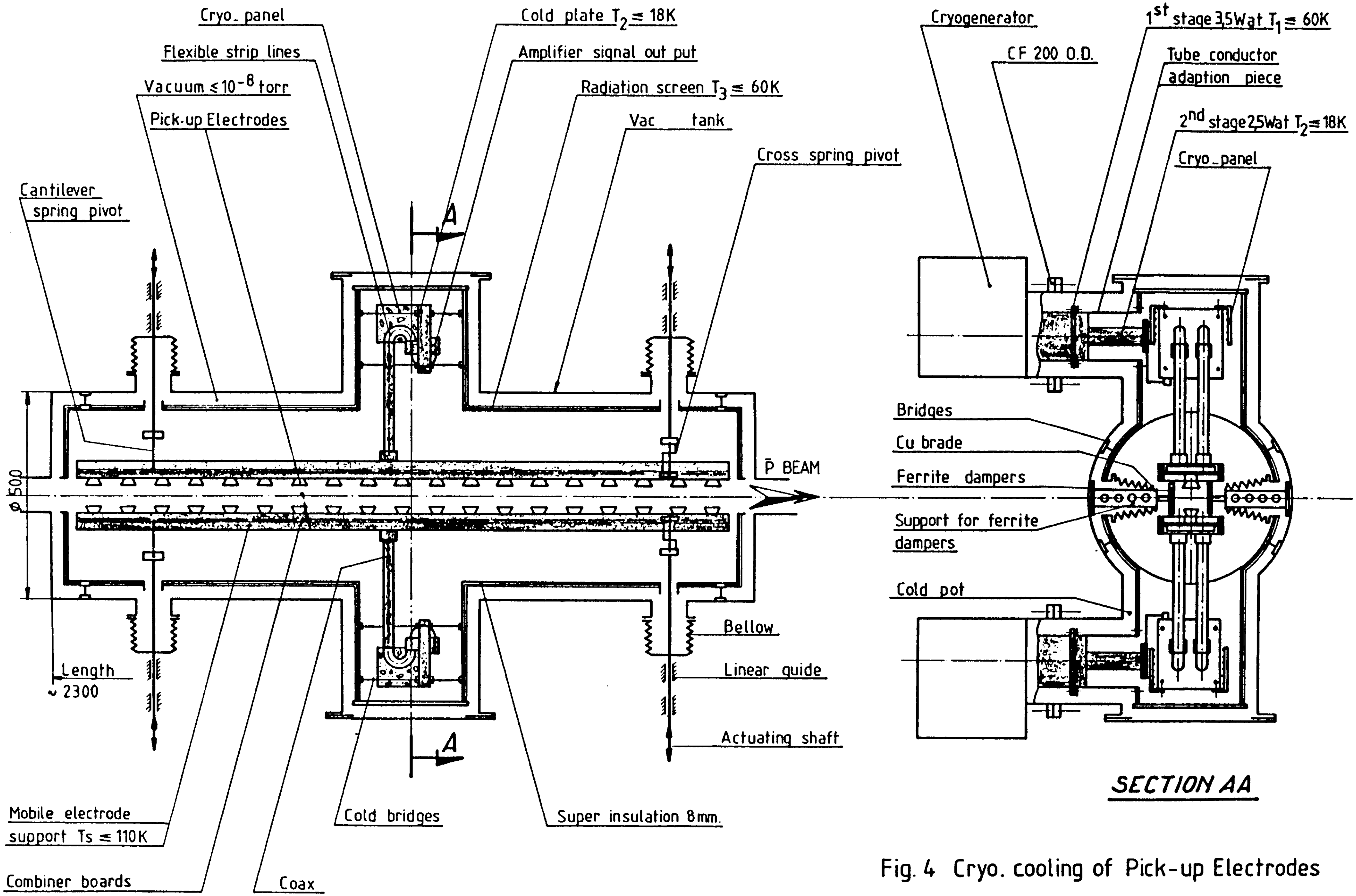


Fig. 4 Cryo. cooling of Pick-up Electrodes

$\int_{T_0}^{T_L} kdT$ WATT CM^{-1}

TEMP DEGREE KELVIN	COPPER: Elect Tough Pitch	COPPER: O.F.H.C.	COPPER ALLOYS: Phos Deox	COPPER ALLOYS: Be/Cu 98 Cu 2 Be	COPPER ALLOYS: German Silver 60 Cu 25 Zn 15 Ni	ALUMINIUM: Comm Pure 99 Al	ALUMINIUM: Mn/Al (Approx N3) 98.5 Al 1.2 Mn plus traces	ALUMINIUM: Mg/Al (Approx N5) 96 Al 3.5Mg plus traces	SS: Average Types 303,304 316,347	CONSTANTAN
6	8.0	6.1	0.176	0.047	0.0196	1.38	0.275	0.103	0.0063	.024
8	19.1	14.5	0.437	0.113	0.0524	3.42	0.670	0.25	0.0159	.066
10	33.2	25.2	0.785	0.189	0.10	6.07	1.17	0.443	0.0293	.128
15	80.2	61.4	2.08	0.499	0.30	15.2	2.90	1.12	0.0816	.375
20	140	110	3.95	0.954	0.613	27.6	5.34	2.10	0.163	.753
25	208	168	6.35	1.55	1.02	42.4	8.50	3.38	0.277	1.24
30	278	228	9.25	2.29	1.53	59.2	12.3	4.90	0.424	1.81
35	345	285	12.6	3.16	2.11	77.3	16.7	6.68	0.607	2.44
40	406	338	16.4	4.15	2.75	96.2	21.7	7.70	0.824	3.12
50	508	426	25.3	6.50	4.15	134	33.0	12.4	1.35	4.57
60	587	496	35.5	9.30	5.68	170	45.5	17.9	1.98	6.12
70	651	554	46.8	12.5	7.28	202	58.9	24.2	2.70	7.75
76	686	586	53.9	14.6	8.26	220	67.2	28.2	3.17	8.75
80	707	606	58.9	16.0	8.93	232	72.8	30.9	3.49	9.43
90	756	654	72.0	19.9	10.60	258	87.1	38.2	4.36	11.1
100	802	700	85.8	24.0	12.3	284	102	45.9	5.28	12.8
120	891	788	115	33.0	15.7	330	132	62.7	7.26	16.2
140	976	874	146	43.2	19.2	376	162	81.1	9.39	19.7
160	1060	956	180	54.4	22.9	420	194	101	11.7	23.2
180	1140	1040	215	66.4	26.6	464	225	122	14.1	26.9
200	1220	1120	253	79.1	30.6	508	257	144	16.6	30.6
250	1420	1320	353	113	41.5	618	337	205	23.4	40.6
300	1620	1520	461	150	53.2	728	417	271	30.6	51.6

The flow of heat through a solid of uniform cross section is given by $Q = \frac{A}{L}\int_{T_1}^{T_2} KdT$

where Q = rate of heat conduction K = thermal conductivity

A = cross sectional area T_1 and T_2 are the temperatures at the ends of length L

The thermal conductivity integrals given in the tables are values of $\int_{T_0}^{T_L} KdT$ where T_0 and T_L are temperatures along a heat flow path joining two reservoirs at $T_0 = 4^oK$ and T_L at a length L from T_0. The heat flow through length L may then be determined from the difference in thermal conductivity integrals, i.e.

$$Q\frac{L}{A} = \int_{T_1}^{T_2} KdT = \int_{T_0}^{T_2} KdT - \int_{T_0}^{T_1} Kdt$$

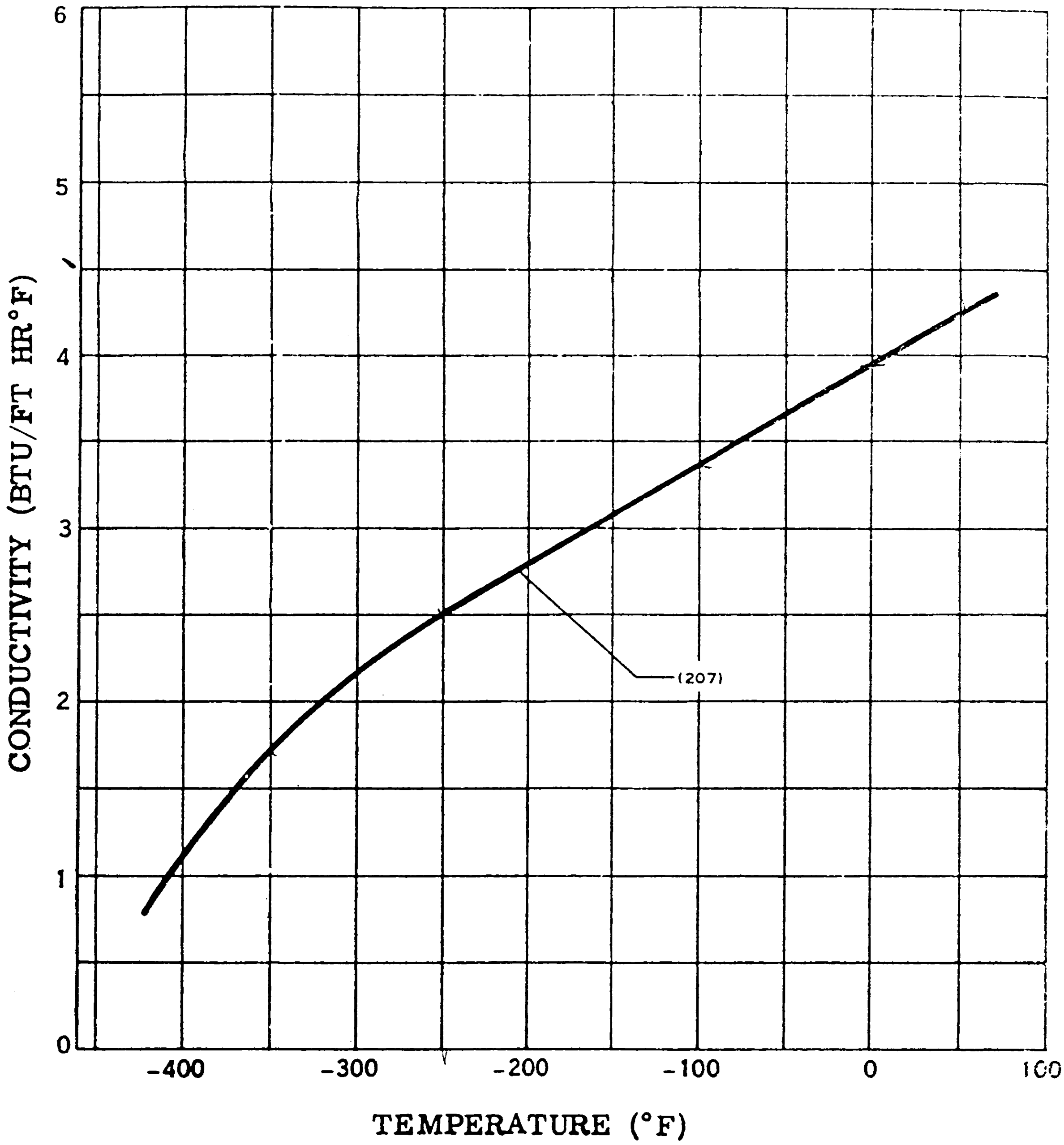
The units used are as follows:-

Q (watts) L (cm) A (cm^2)

K (watts/cm) T^oK.

AC TANKS TEMPERATURE STATUS (KELVIN)   1988-06-20-09:19:55

TANK	POSITION	TEMP	POSITION	TEMP
UVM 2907	SCREEN IN	47.8	AMPLI UP	19.7
	SCREEN OUT	47.0	AMPLI LOW	19.7
UHM 3007	SCREEN IN	44.4	AMPLI RGT	20.3
	SCREEN OUT	43.3	AMPLI LFT	18.4
UHM 3107	SCREEN IN	44.1	AMPLI RGT	19.7
	SCREEN OUT	44.6	AMPLI LFT	17.8
UVM 3207	SCREEN IN	48.6	AMPLI UP	20.3
	SCREEN OUT	48.3	AMPLI LOW	20.3
UHM 4207	SCREEN IN	43.6	AMPLI RGT	22.1
	SCREEN OUT	12.2	AMPLI LFT	22.1
UHM 4307	SCREEN IN	45.4	AMPLI UP	19.7
	SCREEN OUT	44.9	AMPLI LOW	19.7



THERMAL CONDUCTIVITY OF 6Al-4V TITANIUM

(6-68)

Distribution List:

B.	Autin	/ PS
P.	Bourquin	/ PS
B.	Gay	/ PS
E.	Jones	/ PS
P.	Lebrun	/ LEP
F.	Malthouse	/ PS
P.	Mann	/ PS
S.	Milner	/ PS
A.	Pace	/ PS
F.	Pedersen	/ PS
A.	Poncet	/ PS
P. L.	Riboni	/ PS
B.	Szeless	/ PS
L.	Thorndahl	/ LEP
M.	Van Rooy	/ PS