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MASTER

SLAC-CN--294

DE85 010964

CN-294

April 29, 1985

**ENERGY DEPOSITION AND ITS EFFECTS ON THE
E⁺ CAPTURE SECTION AT SECTOR 20***

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Submitted to

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April 29, 1985

ABSTRACT

The temperature profile and resulting stresses and strains of the capture section (positron source accelerator section) at Sector 20 were investigated. The Electron-Gamma Shower program, Version 4 (EGS4) was used to determine energy deposition. For a 31.68 kW, 33 GeV electron beam, the rate of energy deposition in the first accelerator disk downstream from the 90/10 tantalum-tungsten positron target was determined to be 0.56 kW. The calculated resulting temperature difference from the inner disk diameter to the outer disk diameter is 49.4°F. The inner diameter could then reach a temperature of 169.5°F. The maximum stress produced in this first disk would be a compressive stress of 4374 psi, also at the inner diameter.

* Work supported by the Department of Energy, contract DE - AC03 - 76SF00515.

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Studies have shown that the minimum stress causing any noticeable plastic deformation for fully annealed copper could be as low as 800 psi. Since normal operating stresses will exceed 800 psi, work hardening of the capture section will be required to prevent unpredictable plastic deformation.

Assuming that the elastic limit of copper is not exceeded, the calculated strain corresponds to an inner disk diameter expansion of 0.30 mils from the manufactured dimension. This deformation will cause detuning effects which may be unacceptable.

1. INTRODUCTION

Positrons are to be created in Sector 20 of the Stanford Linear Accelerator by steering a beam of electrons through a 90/10 tantalum-tungsten target. The resulting electromagnetic shower contains positrons which must be focused and reaccelerated as soon as possible for most efficient positron production. Therefore, immediately following the target is a 12 cm long flux concentrator which focuses the shower towards a downstream 1.5 meter long capture section.

This special 1.5 m positron accelerator section is forced to absorb a great deal of the unfocused energy, and therefore, its temperature will be higher than a typical 10 foot accelerator section. A temperature gradient will result both along the length of the capture section and radially outward. The non-uniform temperature distribution causes internal stresses and corresponding strains. The strains can lead to very undesirable detuning effects. Concern about these detuning effects is what prompted this investigation. The objective of the following analysis is to predict energy deposition rates and the resulting capture section temperatures, stresses, strains and deformations. In making these predictions, flux concentrator effects will be ignored.

2. THEORETICAL BACKGROUND

Heat Transfer/Temperature Equations

All calculations are based on energy deposition values obtained from the Electron-Gamma Shower program, Version 4 (EGS4). From these energy deposition values, a heat transfer analysis is performed. The resulting temperature profile gives the information necessary to calculate the internal stresses and the corresponding strains that lead to detuning deformations. For the heat transfer and temperature calculations, the following design parameters have been assumed.

Cooling Tubes (copper)

24 Cooling tubes, 0.25 in. I.D., 3/8 in. O.D.

Water enters 12 cooling tubes, flows the length of the capture section, then returns through 12 parallel tubes. The part of the cooling tube that is brazed to the accelerator acts as a fin base (5/16" wide); the rest of the tube can be modeled as a fin.

Cooling water

$V = 15 \text{ fps/tube}$

$T = 100^\circ\text{F}$

$\mu = 1.7 \text{ lb}/(\text{ft} \cdot \text{h})$

$C_p = 1 \text{ Btu}/(\text{lb} \cdot ^\circ\text{F})$

$P_r = 4.6$

(From these values, the flow rate is calculated to be 27.4 gpm.)

Accelerator Section (copper)

$k = 220 \text{ Btu}/(\text{h} \cdot \text{ft} \cdot ^\circ\text{F})$

1.5 meters long with 42 cavities (41 disks)

RF Energy Deposition

Values of RF heating per accelerator cavity were calculated by Harry Hoag. Mr. Hoag also estimated that one-third of the energy per cavity uniformly is deposited on the surface of each of the two side disks, and one-third is uniformly

deposited at the inner diameter of the joining spacer. By dividing up the RF energy according to this $1/3 - 1/3 - 1/3$ approximation, we arrive at the values in Table 1.

The acronyms used are defined as follows:

PSPRF = the Power dissipated in a SPacer due to RF.

PDKRF = the Power dissipated in a DisK due to RF.

PPLRF = the Power dissipated in the cut-off PLate due to RF.

EGS4 User Code/Energy Deposition

The selected planes, cylinders, and bin assignments used in the EGS4 calculations are shown in Fig. 1. Note that there are only five annular bins per disk. This number was chosen to get a rough idea of how the beam energy is deposited throughout the accelerator, so reasonable temperature and stress calculations could be performed. Obviously, if greater precision were necessary, more bins would be required.

Once these bins have been defined in the user code, the EGS4 program calculates where the particles are deposited among the bins, and thus, the percentage of total input energy deposited per bin. From the bin energy depositions, temperatures at various locations within the accelerator are approximated.

Stress-Strain-Deformation

From the EGS4 results, we find a non-linear, radial temperature profile at each cross-section, which induces internal stresses. Once the radial and tangential stresses, and the temperature (with respect to the outer radial temperature), are known for a given point the radial and tangential strains at that same point are evaluated. From these strains, the corresponding deformations are determined.

3. RESULTS AND DISCUSSION

Table 2 gives a listing of the energy deposition rates (power) and the temperature differences for each cross-section of the capture section for a 31.68 kW, 33 GeV electron beam. The following is a list of the acronyms used.

P1	= cut-off plate (P2 = end plate).
S1	= first spacer (S2 = second spacer, etc.).
D1	= first disk (D2 = second disk, etc.).
PED	= power due to energy deposition.
PRF	= power due to RF heating.
DTED	= temperature difference from the inside to outside diameter due to PED.
DTRF	= temperature difference due to PRF.
DTFM	= temperature difference from the outside diameter to the mean cooling water temperature due to film drop (using PED and PRF).
DT ID→H2O	= total temperature difference from the inside diameter to the mean cooling water temperature of the same cross-section.
PSIDE	= the amount of energy that either passed through the side wall of the capture section, or that bypassed the capture section altogether.
PEND	= the amount of energy passing completely through the capture section, and exiting through the end plate.
PTARGET	= the amount of beam energy deposited in the positron target.
PACCEL	= the total energy deposited in the capture section (= beam energy deposition + RF power dissipation).
PTOTAL	= the total amount of power seen by both the positron target and capture section.
DTH2O	= the predicted cooling water temperature rise along the capture section. This temperature rise is calculated using PACCEL.

The corresponding shower picture is given in Fig. 2.

The total power dissipated in the first disk is 0.56 kW, which results in a temperature drop from inside diameter to outside diameter of 49.4°F. If there were no axial conduction, i.e. if all the heat conducted radially outward through an area of length equal to the width of the disk, a film drop of 25.1°F would result. This assumption yields the maximum possible film drop, since further calculations show that the actual length of the convection area could reach two to three times the width of the disk when axial conduction is allowed. Therefore, the actual film drop could decrease from 25.1°F by a factor of two or three, to roughly 10°F.

Another interesting result is that 19.9% of the incident beam energy is deposited in the positron target, 38.8% of the initial beam energy is deposited in the 1.5 meter capture section (i.e. 48.5% of the energy passing through the target), 24.6% passes completely through the capture section, and 16.7% of the original beam is deposited outside the capture section. "Outside" includes particles that either entered the capture section, and then passed through the side wall, or particles that came out of the positron target at such a sharp angle that they bypassed the capture section altogether. Note that a very small portion of the energy that passes through the side wall of the capture section could be directly deposited into either the cooling tubes or water, but was neglected in this analysis.

Fig. 3 shows the radial temperature gradient resulting from beam energy deposition and RF power. This curve was then approximated by the two straight lines, $T_1(r)$ and $T_2(r)$, to simplify the stress calculations. The equations for the two lines are

$$T_1(r) = -5.50r + 53.72$$

and

$$T_2(r) = -13.48r + 68.49$$

where

$$T_i(r) \text{ is in } ^\circ\text{F}$$

$$r \text{ is in cm.}$$

Table 3 gives the results of the stress-strain-deformation calculations for the first accelerator disk. In the table, σ represents the stress, and ϵ represents the strain at radius r_i . The subscripts, r and t, denote "radial" and "tangential", respectively. Also in the table, U_r represents the radial expansion of the disk radius, and Δt denotes the increase in disk width.

Fig. 4a shows a cross-section of the first disk with the estimated deformations due to the temperature gradient alone. Fig. 4b shows the deformations of the disk, including the uniform temperature rise of the whole structure from its manufactured temperature.

It should be mentioned that the stress calculations of Table 3 did not use the data of Table 2. The energy deposition values used in the stress calculations were taken from a shower which resulted in 0.51 kW being deposited in the first accelerator disk, and not 0.56 kW. This should cause a discrepancy of about 10%. Another reason for inaccuracy is that the modulus of elasticity used in the strain calculations was 16×10^6 psi; however, fully annealed copper could have a modulus of elasticity as low as 13×10^6 psi.

According to Dieter Walz, the minimum stress causing any noticeable plastic deformation for fully annealed copper could be as low as 800 psi. However, since operating stresses will exceed 800 psi, work hardening of the capture section will be necessary to prevent unpredictable plastic deformation. Various work hardening procedures have been proposed. A form of hose clamp could be placed directly around each critical section of the accelerator and tightened. This procedure would cold-work the copper, and thus, increase its yield strength.

Another work hardening method involves quenching the hot, freshly brazed (and annealed) copper in liquid nitrogen to create a thermal shock. The concern with this method is that, due to its poor conductivity, the liquid nitrogen

immediately surrounding the copper would boil and blanket the surface with an insulating vapor film. This film may not permit heat to transfer from the copper quickly enough (even with vigorous agitation) to induce a thermal shock. Even if a thermal shock were achieved, there is still concern about whether an unacceptable amount of warping would result. If it is determined that the liquid nitrogen quench would cause too drastic of a thermal shock, a pressurized, dry nitrogen gas quench might suffice.

Finally, it is possible that the cycling of the shower could cause a thermal shock to harden the copper. However, it might be better to simulate the shower by cycling RF power through the accelerator at more uniform, steadily increasing power levels.

4. CONCLUSIONS

- (a) The maximum variation in the temperature of the inside disk diameter for different EGS4 shower simulations is 9.4%. If greater precision is required, more bins would have to be used in the EGS4 user code. However, even if the precision is improved, the results may still not be accurate since the flux concentrator was not included in the calculations. The flux concentrator could either decrease or increase the temperature of the accelerator. The mass of the concentrator would act as a collimator which would tend to reduce the temperature of the accelerator. The function of the concentrator, however, is to focus more particles towards the accelerator, and thus, could increase the accelerator temperature. The overall influence that the flux concentrator would have on the temperature calculations depends on the relative magnitude of the previous two effects.
- (b) The small increase in water temperature (5°F) simplifies the water cooling design. Since the water temperature increases such a small amount, the placement of the cooling tube supply and return headers is not very critical.

For convenience, the cooling water headers should be placed at the downstream end of the 1.5 meter positron accelerator. This would allow more room at the upstream end of the positron target and flux concentrator.

- (c) Work hardening may be required to strengthen the positron accelerator after brazing. Possibly the best method of work-hardening the annealed copper uses RF power to set up thermal shocks in the accelerator section. The process involves quickly heating the accelerator with relatively low power RF, allowing it to cool, and repeating the RF heating procedure with gradually increasing power levels to just beyond the estimated operating power of approximately 20 kW. This method would harden the copper by slowly increasing the induced thermal shocks, and thus, slowly increasing the yield strength. By slowly and uniformly hardening the copper, the possibility of warping is less than would be the case for a liquid nitrogen quench.
- (d) Even if the yield strength of the accelerator were not surpassed, elastic dimensional changes of the cavities due to temperature variations could cause unacceptable detuning effects. One way of reducing the temperature effects in the accelerator is to increase the width of the cut-off plate, and water-cool it. This would decrease the amount of stray energy that is deposited in the accelerator, but would also increase the critical distance that recoverable positrons must travel before they are reaccelerated.

ACKNOWLEDGEMENTS

The author wishes to thank Andrew McFarlane for his help with EGS4, and Bruce Feerick for his help in analyzing the data.

TABLE 1
RF POWER DISSIPATION

<u>Index</u>	<u>Power/Cavity (W)</u>	<u>PSPRF(W)</u>	<u>PDKRF(W)</u>
1	210	70=PPLRF	139
2	208	69	137
3	205	68	135
4	202	67	134
5	200	67	133
6	198	66	131
7	195	65	129
8	193	64	127
9	190	63	126
10	188	63	125
11	186	62	123
12	183	61	121
13	181	60	119
14	178	59	118
15	176	59	117
16	174	58	115
17	172	57	113
18	169	56	112
19	167	56	111
20	165	55	109
21	163	54	108
22	161	54	107
23	159	53	105
24	157	52	104
25	155	52	103
26	153	51	101
27	151	50	100
28	150	50	99
29	148	49	98
30	146	49	97
31	144	48	95
32	142	47	94
33	141	47	93
34	139	46	92
35	137	46	91
36	135	45	89
37	133	44	88
38	132	44	87
39	130	43	86
40	128	43	85
41	127	42	84
42	125	42=PPLRF	

TABLE 2

ENERGY DEPOSITION RATES AND TEMPERATURE DROPS
FOR DIFFERENT ACCELERATOR CROSS-SECTIONS

CROSS-SECTION	PEB(KN)	PRF(KN)	TOTAL POWER (KN)	DTED(F)	DTRF(F)	DTFM(F)	DT ID-W20(F)
P1	2.08	0.07	2.15	63.5	----	29.2	92.6
S1	0.22	0.07	0.29	0.5	0.4	2.6	3.5
D1	0.42	0.14	0.56	38.8	18.6	25.1	74.5
S2	0.23	0.07	0.30	0.6	0.4	2.7	3.7
D2	0.31	0.14	0.44	29.1	18.4	28.6	59.5
S3	0.15	0.07	0.21	0.4	0.4	1.9	2.7
D3	0.30	0.13	0.43	27.8	18.3	19.5	57.6
S4	0.15	0.07	0.22	0.4	0.4	2.0	2.6
D4	0.27	0.13	0.41	26.5	18.2	18.4	55.1
S5	0.15	0.07	0.21	0.4	0.4	1.9	2.6
D5	0.26	0.13	0.40	27.1	18.1	17.8	55.1
S6	0.14	0.07	0.20	0.3	0.3	1.8	2.5
D6	0.28	0.13	0.41	27.4	18.0	18.3	55.6
S7	0.10	0.06	0.17	0.3	0.3	1.5	2.1
D7	0.24	0.13	0.37	26.2	9.8	16.7	52.7
S8	0.09	0.06	0.16	0.2	0.3	1.4	2.0
D8	0.27	0.13	0.40	28.6	9.7	18.8	56.3
S9	0.10	0.06	0.16	0.2	0.3	1.4	2.0
D9	0.28	0.13	0.41	27.1	9.6	18.2	54.9
S10	0.09	0.06	0.15	0.2	0.3	1.4	1.9
D10	0.24	0.13	0.37	24.9	9.5	16.5	50.9
S11	0.09	0.06	0.15	0.2	0.3	1.4	1.9
D11	0.24	0.12	0.36	24.4	9.4	16.3	50.1
S12	0.06	0.06	0.12	0.1	0.3	1.1	1.5
D12	0.22	0.12	0.34	22.4	9.2	15.4	47.0
S13	0.08	0.06	0.14	0.2	0.3	1.3	1.8
D13	0.22	0.12	0.34	22.1	9.1	15.2	46.4
S14	0.06	0.06	0.12	0.1	0.3	1.1	1.5
D14	0.21	0.12	0.33	21.4	9.0	14.8	45.2
S15	0.08	0.06	0.14	0.2	0.3	1.3	1.8
D15	0.15	0.12	0.27	17.4	8.9	12.2	38.5
S16	0.06	0.06	0.11	0.1	0.3	1.0	1.5
D16	0.18	0.12	0.29	17.9	8.8	13.1	39.7
S17	0.05	0.06	0.11	0.1	0.3	1.0	1.4
D17	0.17	0.11	0.29	17.2	8.6	12.9	38.7

CROSS-SECTION	PED(KW)	PRF(KW)	TOTAL POWER (KW)	DTED(F)	DTRF(F)	DTFH(F)	DT 1D-2H20(F)
S18	0.07	0.06	0.12	0.2	0.3	1.1	1.6
D18	0.17	0.11	0.28	15.0	8.5	12.7	37.2
S19	0.06	0.06	0.11	0.1	0.3	1.0	1.5
D19	0.15	0.11	0.26	15.2	8.5	11.5	35.2
S20	0.04	0.05	0.09	0.1	0.3	0.8	1.2
D20	0.17	0.11	0.28	17.9	8.3	12.6	38.8
S21	0.04	0.05	0.09	0.1	0.3	0.8	1.2
D21	0.15	0.11	0.26	15.0	8.2	11.6	35.6
S22	0.05	0.05	0.10	0.1	0.3	0.9	1.3
D22	0.16	0.11	0.27	14.6	8.2	11.9	34.7
S23	0.04	0.05	0.09	0.1	0.3	0.8	1.2
D23	0.15	0.11	0.25	15.8	8.0	11.4	35.2
S24	0.06	0.05	0.11	0.1	0.3	1.0	1.4
D24	0.11	0.10	0.21	11.2	7.9	9.5	28.6
S25	0.05	0.05	0.10	0.1	0.3	0.9	1.3
D25	0.14	0.10	0.25	14.5	7.8	11.1	33.4
S26	0.03	0.05	0.08	0.1	0.3	0.8	1.1
D26	0.11	0.10	0.21	10.9	7.7	9.5	28.1
S27	0.03	0.05	0.08	0.1	0.3	0.8	1.1
D27	0.11	0.10	0.21	10.7	7.6	9.3	27.5
S28	0.05	0.05	0.10	0.1	0.3	0.9	1.3
D28	0.11	0.10	0.21	11.0	7.5	9.3	27.8
S29	0.05	0.05	0.09	0.1	0.3	0.9	1.2
D29	0.12	0.10	0.21	13.2	7.5	9.6	30.3
S30	0.04	0.05	0.09	0.1	0.3	0.8	1.1
D30	0.09	0.10	0.19	9.5	7.4	8.3	25.3
S31	0.03	0.05	0.08	0.1	0.3	0.7	1.0
D31	0.12	0.10	0.22	11.3	7.2	9.9	28.4
S32	0.04	0.05	0.09	0.1	0.2	0.8	1.1
D32	0.10	0.09	0.19	9.6	7.2	8.6	25.3
S33	0.02	0.05	0.07	0.1	0.2	0.6	0.9
D33	0.09	0.09	0.19	9.4	7.1	8.4	24.8
S34	0.03	0.05	0.08	0.1	0.2	0.7	1.0
D34	0.09	0.09	0.18	9.4	7.0	8.2	24.6
S35	0.02	0.05	0.07	0.1	0.2	0.6	0.9
D35	0.07	0.09	0.16	7.4	6.9	7.3	21.6
S36	0.03	0.05	0.08	0.1	0.2	0.7	1.0
D36	0.07	0.09	0.16	7.9	6.8	7.2	21.9

CROSS-SECTION	PEB(KW)	PRF(KW)	TOTAL POWER (KW)	DTED(F)	DTRF(F)	DTFN(F)	DT 10-H2O(F)
S37	0.02	0.04	0.06	0.1	0.2	0.6	0.9
D37	0.11	0.09	0.20	12.3	6.7	9.0	28.0
S38	0.03	0.04	0.08	0.1	0.2	0.7	1.0
D38	0.07	0.09	0.16	7.6	6.6	7.2	21.4
S39	0.02	0.04	0.07	0.1	0.2	0.6	0.9
D39	0.07	0.09	0.15	6.4	6.6	6.8	19.8
S40	0.02	0.04	0.06	0.0	0.2	0.6	0.8
D40	0.09	0.08	0.17	10.5	6.5	7.8	24.8
S41	0.02	0.04	0.06	0.1	0.2	0.6	0.9
D41	0.07	0.08	0.16	8.5	6.4	7.0	21.9
S42	0.02	0.04	0.07	0.1	0.2	0.6	0.9
P2	0.33	0.04	0.37	13.8	---	5.0	10.0

PSIDE = 5.3 kW

PEMD = 7.8 kW

PTARGET = 6.3 kW

PACCEL = 19.1 kW

PTOTAL = PBEAM+PRF = 31.68 + 6.9 = 38.6 kW

DTH20 = 4.8 DEG

radius (cm)	Due to Temperature Gradient							Due to Uniform Temperature Rise $\Delta T = 48^\circ\text{F}$			Totals	
	σ_r (psi)	σ_t (psi)	ϵ_r	ϵ_t	ϵ_z	u_r (mils)	Δt (mils)	ϵ	u_r (mils)	Δt (mils)	u_r (mils)	Δt (mils)
$r_1 = 1.15$	0	-4374	5.6×10^{-4}	1.9×10^{-4}	5.6×10^{-4}	0.086	0.13	4.7×10^{-4}	0.21	0.11	0.30	0.24
$r_2 = 1.85$	-1239	-2527	4.1×10^{-4}	3.0×10^{-4}	5.1×10^{-4}	0.22	0.12	4.7×10^{-5}	0.34	0.11	0.56	0.23
$r_6 = 5.08$	0	3087	-6.7×10^{-5}	1.9×10^{-4}	-6.7×10^{-5}	0.38	-0.015	4.7×10^{-4}	0.94	0.11	1.32	0.10

Table 3

Results of Stress-Strain-Deformation Calculations
for the First Accelerator Disk (D1)

Capture Section

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Figure 2
Typical Energy Shower

Figure 3
Radial Temperature Gradient

Figure 4a Disk Deformations Due to Temperature Gradient

Figure 4b Disk Deformation Due to Temperature Gradient and Uniform Temperature Rise