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INSTALLATION AND THERMAL DESIGN OF SYNCHROTRON RADIATION BEAM PORTS AT SPEAR

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Introduction

The modification of SPEAR (Stanford Positron Electron Asymmetric Ring) to a highly effective source of synchrotron radiation for SSRL (Stanford Synchrotron Radiation Laboratory) was begun in 1973, with the installation of a beam port for SSRL's Beam Line I. Later, four more ports were added and an additional one is scheduled to be installed in 1979. The design of the first beam port was the accomplishment of J. Jurow, N. R. Dean and F. J. Johnson, with contributions from G. E. Fisher and E. W. Hoyt, all of SLAC. Subsequent port designs were modified versions of the initial one.

The beam port is simply an opening into and extension of the storage ring vacuum chamber, aligned along the path of the emerging synchrotron radiation. Its design in constrained to a large extent by space limitations due to the various magnets, as shown schematically in Figure 1. Because of this space constraint, the largest horizontal angle of the extracted radiation is 18 mrad per port. Cooling of the port, and in particular, the narrow region, identified as the "crotch" in Figure 1, becomes another major design consideration. Two beam ports are shown in this figure: the Beam Line III port is typical of four other ports looking tangentially at the circular electron orbit. The Beam Line IV port is, however, an extension of a straight section of the storage ring and a wiggler magnet located in this section is responsible for the radiation that emerges. The design of this port led to the work described in this report. Figure 2 is a photograph of the SPEAR vacuum chamber (G5) with the two beam ports installed.

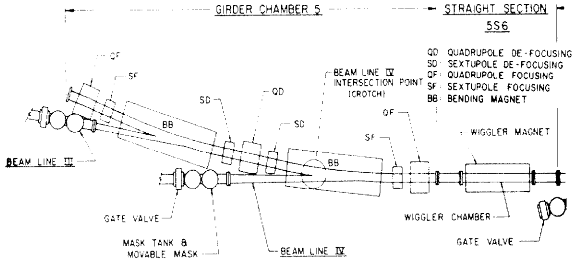

Figure 1. Schematic of a section of SPEAR with two synchrotron radiation beam ports.

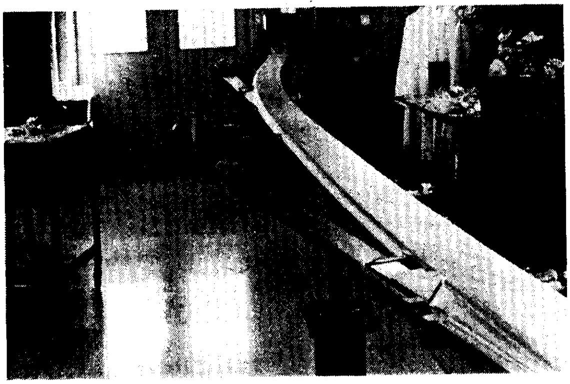

Figure 2. SPEAR vacuum chamber G5 with the Beam Line III and IV ports installed.

Radiated Power and Crotch Temperature

The relatively high flux density of synchrotron radiation absorbed by the crotch requires the calculation of the surface temperatures at the crotch. The result determines then the limitation imposed on the power safely radiated by SPEAR without exceeding the established maximum wall temperature of 185°C.

Approximate calculations on the Beam Line I port established that for a 200 kW total radiated power the crotch surface temperature will not exceed 177°C.[1] The Beam Line IV port is located, however, at 142 cm distance from the origin of the radiation, thus it is exposed to a flux density 4.5 times higher than the first port, at a 300 cm distance. Thus, a more exact calculation of the crotch temperature was needed. In addition, the designers of the port wanted to determine the radius of curvature of the crotch tip that would result in the lowest temperature rise.

The actual design of the water cooled beam port (Beam Line IV) is shown in Figure 3: a rectangular opening is created in the vertical wall of the vacuum chamber for the synchrotron radiation beam. Cooling water (LCW) flows around this opening and also through a narrow, angled slot milled into the crotch, parallel to the radiated surface. The material of the port is the same as that of the vacuum chamber itself: 6061-T6 Aluminum. Figure 4 is a further illustration of the port and the crotch and also indicates the narrow strip where virtually all the radiated power is absorbed.

The linear power density, P_L, of the radiation impinging on the crotch is found from

P_T, the total SPEAR radiated power (see ref. 2)

d, the tangential distance to the circular electron orbit

α, the angle between the incident beam and a normal to the radiated surface.

$$P_L = \frac{P_T \cos\alpha}{2\pi d} \quad \text{w/cm}$$

All of the radiated power is assumed to be contained in a strip of width $w = \psi d$, where ψ is the vertical opening angle of the radiation (see ref. 2,3). The average flux density on the radiated surface is then

$$Q = \frac{P_L}{w} = \frac{P_T \cos\alpha}{2\pi d^2\ \psi} \quad \text{w/cm}^2$$

It is evident from Figure 4 that a large radius at the crotch tip would create larger average local flux densities, whereas a small radius would result in a narrow region with poor heat conduction from the surface.

Analysis

The analysis employed the finite difference heat transfer program HEATING3[4,5] which is capable of solving the Poisson equation (or Laplace equation in the absence of internal generation) in one, two or three dimensions in the rectangular, cylindrical or spherical coordinate system. Several simplifications were applied first to the crotch as shown in Figure 4, to arrive at a suitable heat transfer model. These simplifications are:

1. Only the wedge shaped metal which receives all of the radiated power (illustrated in Figure 5) is considered.
2. The sides of the wedge are insulated, except for the shaded region, indicated by B in Figure 5, where convective cooling is imposed simulating the effects of the two side cooling channels C, Figure 4.
3. The wedge is cut along the line D-D, Figure 5, and is insulated along this line.
4. The heat input is uniformly distributed across the .39 mm wide strip and is assumed to be applied only at the surface.

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All of the above simplifications are on the conservative side and result in the model shown in Figure 6, which also indicates the boundary conditions. Since the problem is symmetrical about the center of the heated strip, the z=0 plane of Figure 6 is located at the center of the strip and only the positive z domain is considered. Finally, the heat transfer model of Figure 6 is divided into regions defined by mutually orthogonal planes and the regions are further divided into nodes, as dictated by the program.

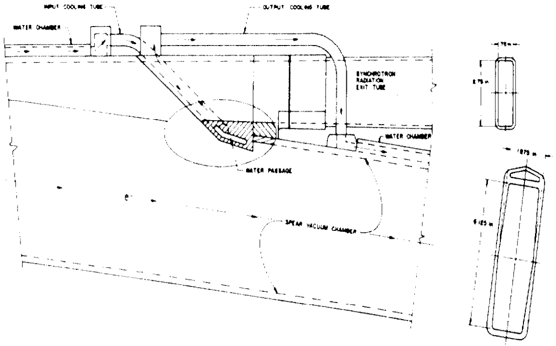

Figure 3. Horizontal section of the Beam Line IV port.

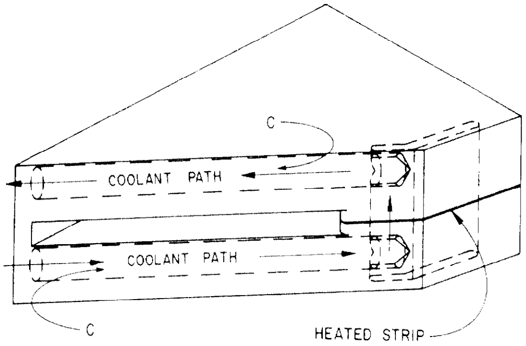

Figure 4. Isometric view of the beam port.

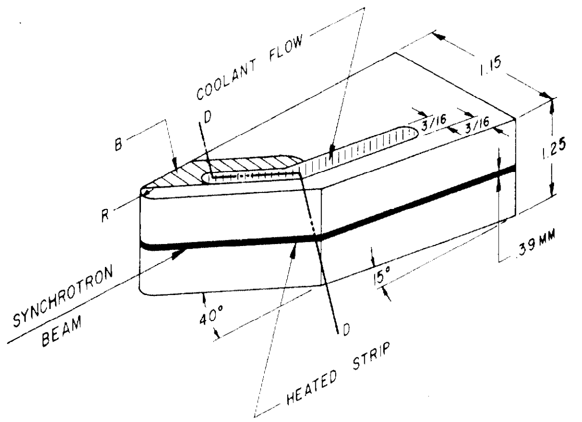

Figure 5. Isometric view of the crotch region, as considered for the purposes of the analysis. Shaded areas are cooled by convection. Model is simplified further by assuming a cut along the line D-D.

The Convective Heat Transfer Problem

Because of the complex hydrodynamics, the convective heat transfer coefficient for flow through the sinuous coolant path of Figure 4 can be only roughly approximated. A preliminary study showed that, even with pessimistically low values of the convective heat transfer coefficient, the temperature drop across the liquid film represented only ∿ 15-20% of the overall temperature drop from the hottest spot in the metal to the coolant bulk temperature. Since the film ΔT was small and since no empirical data was available for the particular geometry shown in Figure 4, a value was calculated for the convective heat transfer coefficient assuming fully developed turbulent flow in a tube and then reduced by ∿25% to arrive at a conservative value for the analysis. The value of the convective heat transfer coefficient thus arrived at, was:

$$h = 15{,}000 \ \mathrm{w/m^2{}^\circ C} .$$

In the actual piece, large scale eddies resulting from the abrupt area changes in the channel are expected to enhance the convective heat transfer considerably making the above calculation quite conservative.

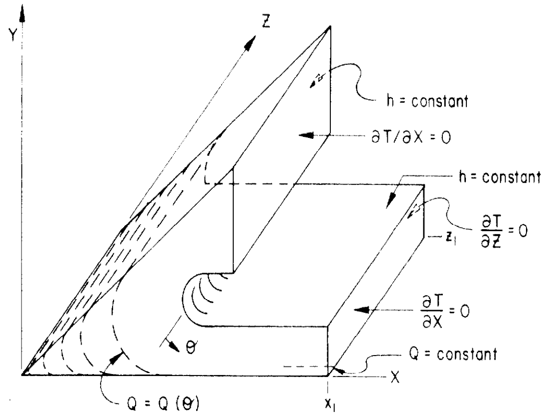

Figure 6. Simplified heat transfer model of crotch region. Dashed lines indicate the variation in tip radius for several cases studied. Also shown are the coordinate system employed and the boundary conditions imposed on the analysis. The boundary condition on the $Z=Z_1$ plane is divided into two regions: (a) above the dashed line shown h=constant and (b) below the dashed line the surface is insulated.

Experiment

In addition to the analytical work previously described, a test was performed on a replica of the crotch which was fitted with thermocouples. This experiment was designed to provide practical measurements of temperatures within the crotch model under varying thermal loading conditions, comparable to those experienced with intense synchrotron radiation. In addition, the test was intended to assess the accuracy of the computed temperatures.

An electron beam welder was chosen as a heat source closely simulating the linear strip heating pattern produced by the synchrotron radiation on the crotch. In the experimental setup, illustrated in Figure 8, the beam of energetic electrons was swept rapidly back and forth along a line on the water-cooled aluminum model corresponding to the strip heated by the radiation in the actual crotch. These electrons deposit all their kinetic energy within about 0.04 mm of the aluminum surface. By measuring the accelerating voltage and varying the beam current, the incident linear power density along the strip could be accurately controlled over a wide range. The width of the heated strip was also varied during the experiment from approximately 0.067 mm to 0.32 mm. This variation was accomplished by defocussing the electron beam.

Two of the thermocouples used were within the domain covered by the computer calculations; the thermocouples were potted into holes drilled into the non-illuminated side of the crotch model, as shown in the insert in Figure 7. The centers of the the thermocouple beads were directly beneath the heated strip at a depth of approximately 1 mm from the surface. The thermocouple readings T_1 and T_2 were continuously recorded, allowing sufficient time for thermal equilibrium to be reached at each current setting.

Figure 8 shows the measured equilibrium temperature rises (above the cooling water temperature) $T_1-T_{H_2O}$ and $T_2-T_{H_2O}$ plotted as a function of P_L, the average linear power density incident upon the crotch model. The temperature rises are seen to be directly proportional to P_L, as is to be expected. In addition, to within the experimental scatter of the data there were no significant differences between the results for the narrow and the wide heated strips, even though the surface power density (watt/cm^2) varied by a factor of 5 or 6 between these two cases. This can be explained by considering that the distance of the thermocouple from the surface, while only one millimeter, was several times the width of the heated strip.

At the higher power levels and using the narrow beam, some surface melting was observed visually during the test and confirmed upon subsequent microscope examination of the surface. The surface power density at which this melting just began to occur was approximately 23 kW/cm^2, which is well above the value produced by the synchrotron light source.

The computer calculations were carried out for an assumed incident linear power density of 36 watts/cm. From Figure 8 at P_L = 36 watts/cm, the measured temperature rises were $T_1-T_{H_2O}$ = 16.5°C and $T_2-T_{H_2O}$ = 10.5°C. The corresponding computed values were approximately 39°C and 26°C respectively. Thus the computed temperatures were approximately 15°C to 22°C higher than the measured temperatures.

The discrepancy between computed and measured temperature results from several factors: 1. addition of the thermocouple caused a distortion of the original temperature field, 2. the thermocouple was slightly offset from the centerline of the heated strip, 3. assumptions made regarding the heat transfer model were conservative, 4. assumptions made regarding the convective heat transfer coefficient were conservative.

Assuming that the measured temperatures were accurate, then the maximum surface temperature can be arrived at by making use of the calculated temperature differential between the surface and the point of measurement. This maximum surface temperature was found to be 80°C, corresponding to a linear power density of 36 w/cm (50 kW total radiated power).

Conclusions

With SPEAR operating at 3.7 GeV, 38.3 ma and radiating a total of 50 kW, the maximum crotch temperature was calculated to be 105°C. The value obtained by extrapolation of experimental data was 80°C. The discrepancy between the two figures is due, in part to the inherent limitation of temperature measurements in the presence of a high thermal gradient, and, in part, to the assumptions made in the analysis. It can be concluded, however, that the temperature at the crotch surface resulting from the synchrotron radiation is comfortably below the 185°C limit and that the total radiated power can be raised to at least 75 kW without exceeding this limit.

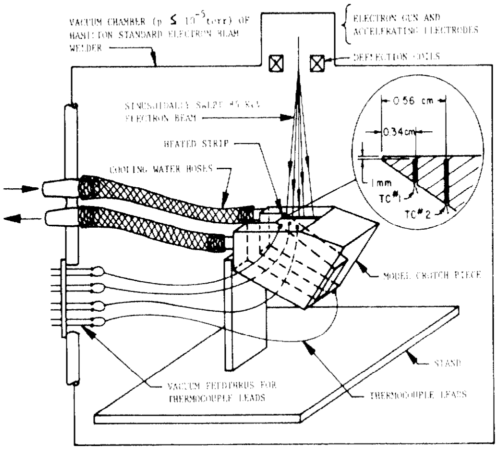

Figure 7. Schematic of the experimental setup for temperature measurements on a crotch model heated by an electron beam.

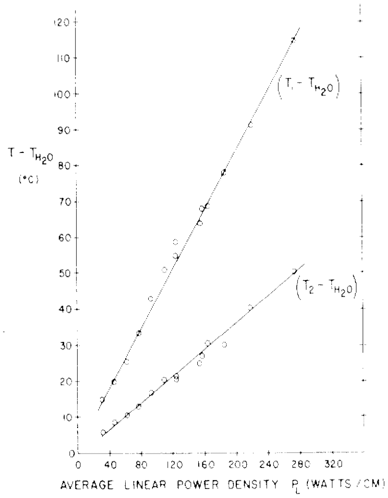

Figure 8. Results of the thermocouple measurements on the crotch model.

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Acknowledgment

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