IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

THERMAL DESIGN OF SYNCHROTRON RADIATION EXIT PORTS AT CESR*

Dennis M. Mills, Donald H. Bilderback, and Boris W. Batterman**

Abstract--CESR, running at the maximum design parameters (8 GeV, 100 ma), produces 177 watts/mrad of synchrotron radiation at the exit ports for CHESS (Cornell High Energy Synchrotron Source). Due to the low angle of incidence, this corresponds to a linear heat loading of 55 watts/cm at the normal vacuum chamber wall. At the exit line crotch, radiation striking at normal incidence results in an average linear load of 885 watts/cm. For a beam height of 0.12 mm this translates to a power density of 740 watts/mm^2. We present a design for a crotch which can effectively dissipate this high power density and will be compatible with the ultra-high vacuum system of CESR. The structure is a composite of a beryllium heat diffuser and an axially cooled copper cylinder. At 8 GeV and 100 ma we anticipate no component temperatures higher than 330°C.

*This work supported by a grant (DMR7826662) from the National Science Foundation and from the Materials Science Center at Cornell University (DMR7681083).

As is well known, electron synchrotrons are copious sources of electromagnetic radiation. The emitted radiation, whose frequency can extend well into the x-ray regime, is very intense and strongly peaked in the forward direction due to the ultra-relativistic nature of the accelerated electron. These intrinsic characteristics, high flux, continuous spectrum and natural vertical collimation, makes synchrotron radiation (SR) a very appealing source of photons in the ultraviolet and x-ray regions.

These same properties present severe problems in the design of exit ports for radiation from the storage ring vacuum chamber. At CESR, (Cornell Electron Storage Ring) running at 8 GeV and 100 ma the radiated power in the high bend region is 177 watts/mrad per beam. Because of the low incidence angle, this translates to a linear heat loading of 55 watts/cm at the normal vacuum wall. However, at normal incidence (at approximately 2 meters from the tangent point of the electron's orbit) the linear heat load is 885 watts/cm. With a radiation beam height of ∿0.12 mm this corresponds to a power density of about 740 watts/mm.^{2} Since this power density is greater than used in electron beam welding, it is clear that exit port design for CHESS (Cornell High Energy Synchrotron Source) is quite critical. Fig. 1 compares heat loading in various situations.

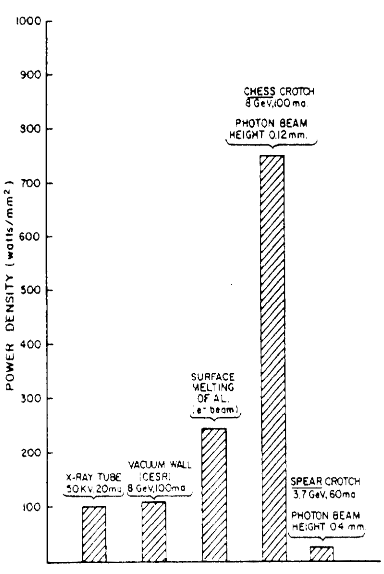


Fig. 1 Comparative, specific power loadings.

**Cornell University, Ithaca, New York, 14853.

The main difference between power deposition with e-beam welding and SR is that, in the former, heat is deposited mainly on the surface while the radiation from CESR (whose spectrum peaks in the angstrom region --see Fig. 2) can penetrate considerably into the material, thus distributing the absorbed power over a large volume. The material separating the storage ring vacuum chamber and the SR exit line (the 'crotch') must be capable of withstanding very high power densities and still be compatible with the ultra-high vacuum system (10^{-9} to 10^{-10} torr) of CESR.

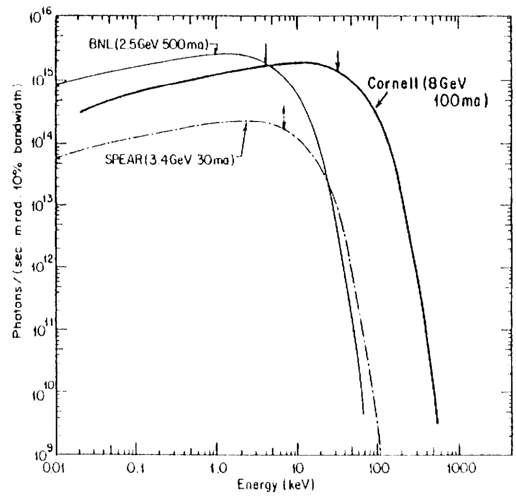


Fig. 2 Synchrotron Radiation Spectrum from CESR, SPEAR and BNL.

The basic design for the crotch is a cylindrical tube with the axis perpendicular to the emerging sheet of SR. Cooling will be achieved by axial water flow through the interior of the cylinder. An inherent requirement in fluid cooling is to maintain the heat flux through the wall-coolant interface below the critical heat flux (CHF). Flux above this value causes the fluid to vaporize instantly upon contact with the wall, producing between the coolant and wall a thin vapor film with poor heat transfer properties, resulting in physical damage or even melting. The CHF for nonuniform axially heated tubes has not been studied extensively. It is a complicated function of the length of the boiling region, the total tube length, tube diameter, mass flow, coolant pressure, etc. After examining the available literature, we decided that the heat flux should be kept below 200 watts/cm^2 at the coolant wall.

A FORTRAN program was developed to simulate the power deposition and heat flow within the crotch walls. The program solves a scaled 2-dimensional heat problem for a distributed heat load $\nabla^2\theta=f(x, y)$ (θ=scaled temperature) with prescribed boundary conditions using a finite difference method based on an energy balance for each of the finite elements. This results in a set of n equations with n unknown temperatures which, in principle, can be solved exactly. A faster, more efficient method to calculate the element temperatures is the Gauss-Seidel technique, an iterative process which is especially suited for computer analysis. The Gauss-Seidel algorithm was chosen because it requires only one temperature array to be stored and converges for any initial guess of temperature distribution.

The heat loading f(x,y) was determined from the calculated SR spectrum folded with the total cross-section for the particular wall material desired, giving heat absorbed as a function of depth within the wall. This can then give the actual heat loading for any combination of operating parameters and absorbing

0018-9499/79/0600-3854$00.75 © 1979 IEEE

materials. The pulsed nature of the radiation has no effect on the final steady state solution of the heat transfer calculation.

Because of the inherent symmetry of the problem, we needed only to consider the half plane including the orbital plane (Fig. 3). A nonuniform grid size was employed in both the x and y directions. This permitted finer thermal sampling where the thermal gradients are large (point of incidence of the radiation with the wall) and a coarser sampling where the gradients are smaller, thus minimizing computer core requirements and CPU time. The only restriction placed on the actual size of the elements was that at least 3 grid points be within the 1/e distance of the total absorbtion depth of the radiation and the grid height in the mirror plane be equal to the radiation beam height at the crotch (~0.1 mm).

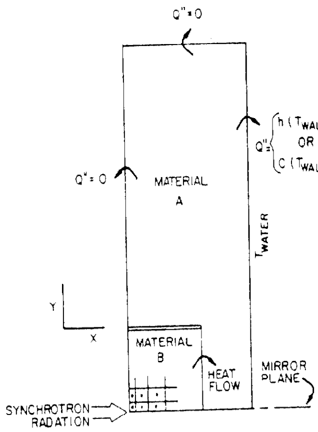


Fig. 3 Conditions for heat flow computation.

The boundary conditions were set to allow heat transfer only at the back (wall-coolant) interface. Since we expect some additional heat transfer through top surface, this restriction is a conservative one. The heat transfer at the water cooled back wall is somewhat complicated. Initially, only a forced convection heat transfer boundary condition was used:

$$Q''=h\ (T_{wall}-T_{water}) \tag{1}$$

The heat transfer coefficient, h, was calculated using the Dittus-Boelter[1] correlation for turbulent flow

$$N_u = .023\ Re^{4/5}\ Pr^{1/3} \tag{2}$$

where N_u=Nusselt No.=hd/k, Re=Reynolds No.=$u_f\ d/\nu_f$, Pr=Prandlt No.=ν_f/α_f with d the diameter of the duct carrying the coolant, u_f, k_f, ν_f and α_f the coolant's average velocity, thermal conductivity, kinematic viscosity and heat diffusion coefficient, respectively. It was found that with an h=1.2 watts/cm^2-°K that some of the wall temperatures were above the coolant boiling temperature (a function of coolant pressure). When boiling heat transfer is allowed, the heat flux through the wall can be increased significantly over that of forced convection. Considering this possibility, we allowed for heat transfer via boiling in the program.

Most correlations for boiling heat transfer consider only the case of fully developed nucleate boiling. Bergles and Rohsenow[2] give a correlation to include a smooth transition from forced convection through incipient boiling to nucleate boiling. We used their correlation in conjunction with the correlation given by Thom et. al.[3] for fully developed nucleate boiling

$$Q''(\text{watts/m}^2)=1970\exp(2P/8.69\text{x}10^6)\,(T_{wall}-T_{sat})^2 \tag{3}$$

where P is the coolant pressure (n/m^2 absolute), T_{sat} (°K) is the boiling point at pressure P.

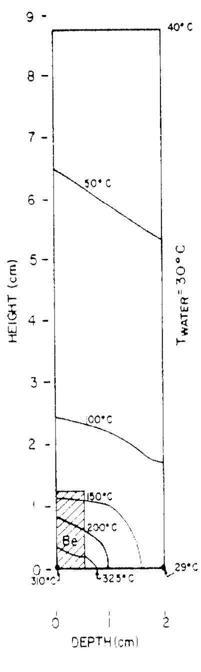
At each iteration of the calculation, the program adjusts the boundary condition to Eqs. (1) or (3), depending on whether $T_{wall}>$ or $<T_{sat}$. In this manner the program was internally self-consistant in determining the wall temperature and the corresponding heat transfer mechanism.

The ideal crotch would be a low Z material of high thermal conductivity. This would allow a more even heat loading and reduce temperatures compared with a high Z wall. Although beryllium (Z=4; k=1.85 watts/cm-°K) satisfies these two requirements quite well, engineering considerations precluded its use in ultra-high vacuum environment.

Aluminum (6061-T6)(Z=13) has a thermal conductivity of 1.55 watts/cm-°K and is a convenient material from an engineering viewpoint, since it is UHV compatible and easily welded and machined. However, it was found that the maximum temperature of the wall could not be kept below the characteristic annealing temperature of 6061 Al (~230°C) without exceeding CHF.

Copper has a high thermal conductivity of 3.8 watts/cm-°K which, to some extent, offsets its relatively high Z. It has good machinability and joining properties and could be made thick enough to keep heat flux to the coolant less than our design value of 200 watts/cm^2. The surface temperature, however, would reach 500°C at 8 GeV 100 ma operation, which would be inconsistent with UHV criteria.

Our final design consists of a composite Be-Cu crotch (see Fig. 4a) based on the following considerations: It was necessary to combine the good heat loading distribution intrinsic to low Z materials with the strength, joinability and high thermal conductivity of copper. By putting a piece of beryllium in the copper wall it is possible to combine the advantages of both materials. The beryllium insert acts as a heat diffuser, spreading out the heat that would be deposited at the surface of a pure copper wall, while the thermal conductivity of the copper allows good vertical heat flow to distribute the heat flux more evenly along the water cooled wall. Note that the Be-Cu joint does not require ultra-high vacuum integrity and there are no water-vacuum joints, the water-vacuum separation being maintained by the copper wall.



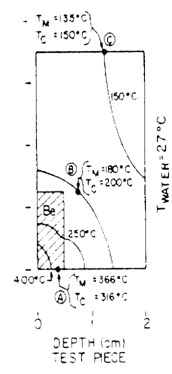


Fig. 4 Computed and Experimental Temperature Distributions. a) Upper half cylinder under SR Load of 7 Kw. b) Experimental short cylinder tested in e-beam welder. Points A,B,C give positions of thermocouples and the experimental (T_M) and calculated (T_C) temperatures. The loading is 6.5 kW and is considered to be deposited at the surface.

With a 20 cm high cylinder and 2.0 cm thick wall (Be insert 2.5 cm high and 0.5 cm thick) the heat flux at the cooling wall could be kept below 140 watts/cm^2. This geometry, along with an h=1.2 watts/cm^2-°K, kept the calculated maximum temperature (at the Cu-Be interface) below 330°C. Further details of the actual design will be discussed below.

In order to test both the computation of temperature distribution and the Be-Cu braze integrity as a function of thermal cycling, a prototype crotch was constructed.

The prototype consisted of two half-rings of beryllium, each about 9.5 cm in diameter, 0.5 cm thick and 2.5 cm high, brazed onto a machined copper cylinder with a silver alloy (BAg18 alloy). (See Fig. 4b.) The total height of the copper test cylinder (7.0 cm) was about one third that of the projected final assembly. The inside bore of the cylinder (5.7 cm) was fitted with spiral tapered plug to raise the Reynolds number of the cooling channel to about 33,000 corresponding to a heat transfer coefficient of 1.3 watts/cm^2-°K. Temperatures were measured in the beryllium and copper with .003" diameter iron-constantan thermocouples interfaced to a six channel Analog Devices digital thermometer.

Heating tests were performed in a Sciaky Electron Beam Welder capable of supplying many kilowatts of power to locally heat a beryllium half-ring in a vacuum of better than 5x10^{-5} torr. Heat was supplied to a 6.5 cm x 1 cm area on one of the beryllium rings by sweeping the beam at a 3 KHz rate to uniformly heat the area. Tests were made with a power level of 6.5 kW (50 KV, 130 ma) for as long as five minutes at a time. This is just under the 7 kW value the cylinder will dissipate with SR at 8 GeV, 100 ma. The test sample starting from 27°C (the water temperature) would reach its final temperature about 30 seconds after switching on the electron beam. Further heating for several minutes produced no more than 2°C changes in the measured temperatures. Fifty heating-cooling cycles at the 6.5 kW power level were performed with the final cycle showing the same maximum temperature as the first one to within 2°C. This implies that the thermal conductivity of the brazed joint did not change during the tests.

An important check was to compare the experimentally measured temperatures with those computed by the heat transfer computer program. The thermocouple .020" away from the center of the brazed joint (Point A, Fig. 4b) in the beryllium measured 336°C, while the computed value was 316°C. The one in the copper behind the joint (pt. B) measured 180°C, while the computed value was 200°C. This satisfactory agreement lends confidence to the predicted temperature profiles to be encountered when the real piece will be heated with synchrotron radiation. The computed surface temperature of 527°C appears consistent with the red-orange color seen from the electron beam heated ring (no surface melting was observed).

With SR, the same area heat loading is distributed deep in the beryllium and copper as opposed to surface absorption in the Be with e-beam. Fig. 4a shows the computed temperature distribution using the SR spectrum at 8 GeV and 100 ma. Note that the highest temperature is 325°C at the Be-Cu interface and the Be surface temperature is 310°C.

Hence, we see that the thermal stresses in the beryllium are more severe with the e$^-$-beam heating than with SR heating. Also, 6.5 kW of heat from the electron beam had to pass through the brazed joint, whereas, the beryllium will only absorb 2 kW of SR with the remaining 5 kW being directly absorbed in the copper backing. This greatly lowers the amount of heat passing through the brazed joint.

In summary, e$^-$-beam testing of the beryllium-copper test cylinder showed no degradation of the brazed joint when the joint was heated to its highest proposed operating temperature of 330°C for 50 thermal cycles. The beryllium successfully withstood higher thermal stresses than will be encountered during heating with synchrotron radiation.

The entire crotch assembly (including vacuum cham-

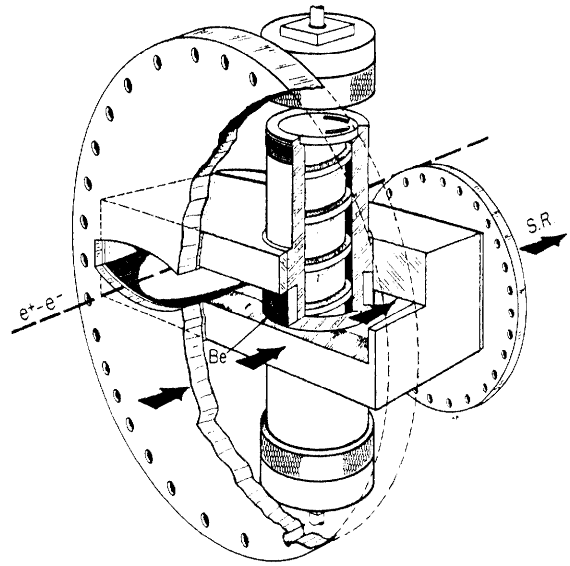


Fig. 5 Schematic of Crotch Assembly.

ber section) is shown, schematically, in Fig. 5. The copper vacuum chamber section is numerically milled so that the e$^-$ - e$^+$ beam passageway matches the cross-section of the normal vacuum chamber, thereby minimizing the higher mode losses at the crotch. The flange assemblies permit the whole crotch section to be removed or replaced without alteration of any of the standard storage ring vacuum chambers. Fig. 5 also shows the spiral swirler used to raise the Reynolds number of the coolant. With the water flow available to us (12 gal/min @ 100 PSIA & 20°C) the swirler allows the heat transfer coefficient to surpass 1.3 watts/cm^2-°K.

All parts of the copper crotch vacuum chamber were carefully designed to shadow the welds and stainless-steel portions of the crotch assembly from any possible interception of SR eminating from either the electron or positron beams.

The beryllium insert was attached as described in the section detailing the prototype testing.

In all, four crotch assemblies are being produced for CHESS, three to be installed at CESR, one being kept as a reserve.

References

1. F. W. Dittus and L. M. K. Boelter, University of California, Pub. in Engineering, Vol. 2 (1930).
2. A. E. Bergles, and W. M. Rohsenow, Trans, ASME, J. Heat Transfer, 86, 365 (1964).
3. J. R. S. Thom, J. Clark, E. Lady, H. Merte, Trans, ASME, J. Heat Transfer 89, 235 (1967).

Acknowledgements

We are particularly indebted to N. B. Mistry of the CESR staff. He and J. Kirchgessner contributed significantly to the mechanical and vacuum design of the crotch which we show here schematically in Fig. 5. J. Brawley provided invaluable help with the e$^-$-beam welder. We gratefully acknowledge the National Science Foundation and the Materials Science Center at Cornell University for supporting this work.