HEAT LOAD BUDGET ON A TPS UNDULATOR IN VACUUM

Jui-Che Huang, Yung-Teng,Yu ,Fu-Yuan Lin, Jun-Tune Chen, Ching-Shiang Hwang
National Synchrtorn Radiation Research Center,HsinChu, Taiwan

Abstract

The performance of an insertion device is limited by the magnet gap because a small gap affects the dynamic aperture and results in a short life time of the beam. An in-vacuum undulator is designed to have no vacuum chamber between the magnet arrays so to allow the entire magnet gap to be fully used for the dynamic aperture. An in-vacuum undulator can optimally minimize the gap to achieve continuous energy spectra. One problem of an undulator with a small gap is resistive wall heating by the image current. The heat load depends strongly on the injected mode in the storage ring; injection of multiple bunches might deteriorate the thermal performance for the magnet array. In this paper, we present a calculation of the heat load budget for a magnet array of an in-vacuum undulator of Taiwan Photon Source (TPS).

INTRODUCTION

For Taiwan Photon Source, a 3-GeV synchrotron light source in Taiwan, a decision has been taken to equip with several in-vacuum undulators(IU) to provide high energy X-rays in phase I. An electron beam in a storage ring induces an image current on the inner conducting wall, mainly within a skin depth, of the beam chamber. If an in-vacuum undulator is installed inside a storage ring, unlike a conventional undulator outside the vacuum region that has a smooth vacuum duct, electrons that pass nearby the magnet array cause resistive wall heating due to an image current.

In an accident at ESRF, a stainless-steel magnet sheet became fused because of resistive wall heating; Hara et al. [1] suggested that, to avoid this wall-heating problem, the stainless steel magnet must be replaced with a 10-μm Cu sheet. The resistive wall heating can thus be greatly decreased through the small electrical resistivity.

Another concern is that, if a high-temperature environment is created by resistive wall heating, the residual magnetic-flux density (B_r) decreases. The TPS in-vacuum undulator uses a NEOMAX NMX-38EH magnet block; the temperature coefficient of B_r in this magnet is -0.10 % / K. If the temperature of the magnet block increases 10 K, we lose 1 % of the magnetic-flux density resulting in a 1 % energy shift in the fundamental harmonics. In this case, we must ensure that the cooling capacity suffices to cool the magnet and keep the temperature near the field correction condition, which is for 25 ^{o}C.

MAGNET MODLE

The magnet circuit is designed and fabricated by NEOMAX engineering. A sketch of the magnet and the aluminium I–beam assembly is shown in Figure 1. The magnet holders are made of oxygen-free copper and fixed on an aluminium I-beam. To have a suitable impedance on the magnet array, a copper sheet covers the magnet array surface; this sheet of copper (thickness 60 μm) is coated with nickel (25 μ m) to provide an adequate attractive force and is firmly attached on the magnet array. A water-cooling pipe is firmly attached around the bottom of the aluminium I-beam to remove the heat. We consider two heat sources -- resistive wall heating and heat from the bending-magnet synchrotron radiation.

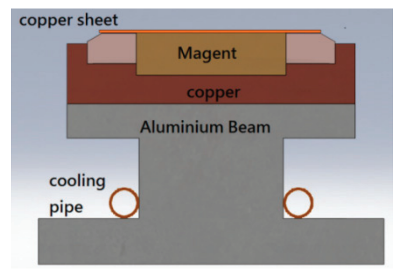

Figure 1: Magnet holder for TPS IU.

RESISTIVE WALL HEATING

For a single Gaussian bunch, the single-pass power dissipation in a metal foil is estimated in the spectrum form of

$$P_\omega = \frac{1}{\pi} I_\omega{}^2 r_\omega \quad (1)$$

$$= \frac{2I_{peak}{}^2\sigma_t{}^2 L\rho}{\pi G}\sqrt{\frac{\omega\mu_0}{2\rho}}\exp(-\sigma_t{}^2\omega^2)\ (\omega > \omega_d) \quad (2)$$

$$= \frac{2I_{peak}{}^2\sigma_t{}^2 L}{\pi G}\frac{\rho}{d}\exp(-\sigma_t{}^2\omega^2)\ (\omega < \omega_d) \quad (3)$$

in which $\omega_d = \frac{2\rho}{d^2\mu_0}$ with bunch length σ_t undulator gap G and length L, peak current I_{peak}, electrical resistivity ρ and thickness t of the magnet sheet.

The total power is integrated over all frequency

$$P = M\frac{\omega_0}{2\pi}\int_0^\infty P_\omega\, d\omega \quad (4)$$

and the final power is calculated from equation 4. We hence obtain the total power analytically from

$$P = M\left(\frac{I_{av}}{M}\right)^2\left(\frac{L}{\pi G}\right)\left(\frac{\Gamma(\frac{3}{4})}{\omega_0\sigma_t{}^{3/2}}\right)\sqrt{\frac{\mu_0\rho}{2}} \quad (5)$$

Where Gama function$\Gamma\left(\frac{3}{4}\right) = 1.2254$,

$$P \propto M_{bunch} I^2{}_{bunch}\frac{\sqrt{\rho}}{\sigma_t{}^{3/2}}\frac{L}{G} \quad (7)$$

The power dissipation is proportional to the bunch number and the bunch current. In the TPS storage ring, the maximum bunch is designed to number 864; we thus calculated the power dissipation from the worst scenario.

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Compared with the SPring8 and ESRF cases, the TPS undulator IU22 operating with maximum bunches and minimum gap 5 mm creates heat load 17.69 W/m; this value is 65 % of calculated heat load from the ESRF accident condition reported (1). Detailed thermal and cooling analyses are required .

Table 1: Resistance Wall Heating in Various Facilities

Style	**TPS 864 bunches**	**Spring-8 16-bunch**	**ESRF 1/3-filling**
I_{av} /mA	500	100	140
bunch number M	864	16	300
bunch length /ps	9.5	30	15
resistance/10^{-8} Ω m	2 (copper)	2 (copper)	80(SUS)
undulator length /m	2.2	4.5	1.5
undulator gap /mm	5	8	8
power /W	39	72	26
power per length /W m^{-1}	17.7	16	28

SYNCHROTRON RADIATION ON A MAGNET ARRAY

Synchrotron radiation from a bending magnet is another source that might heat a magnet array. Figure 2 illustrates the synchrotron radiation from a bending magnet that is incident on an IU magnet array; we must also take into account that a photon absorber blocks the synchrotron radiation from the bending magnet from the side. We estimate the power (using SPECTRA 9.0[3]); the partial power was estimated to be 5.9 W per magnet array, because most power is concentrated along the photon position on the axis;if there is no mis-steering of the electron beam, the magnet arrays receive only little power. Relative to the resistive wall heating, the synchrotron radiation is much smaller and cannot be the main power source.

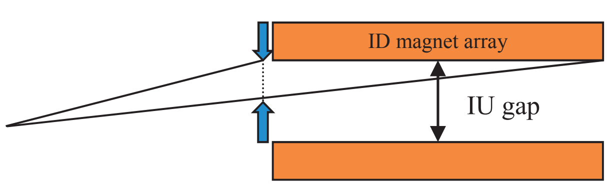

Figure 2: Synchrotron radiation on the magnet array.

COOLING THE MAGNET SHEET

Cooling the magnet sheet is an important issue to avoid sheet fusion. We must thus consider two directions of heat transfer onto the magnet sheet. One is the transverse direction in which the heat transfers from the centre of the sheet to the side of the magnet unit; we consider a half model and heat load as a sinusoidal pattern so that only a quarter of the heat is calculated. According to an equation for conduction, the temperature difference in the magnet sheet is expressed as

$$\Delta T=(Q/4)*(W/2)\ /\ (k\ t) \qquad (8)$$

in which W is the width and t is the thickness of the magnet sheet. k denotes thermal conduction coefficient; ΔT is the temperature difference in a transverse direction.
If the cross section of the magnet sheet is large, we thus have better thermal conduction (small temperature increase). If all heat transfer is on the copper magnet sheet, the temperature increase is 6.62 ℃.
Another direction of heat transfer is through the magnet sheet to the permanent magnet. A one-dimensional conduction for heat transfer is used for the analysis. The thermal resistance of the hybrid magnet and permedur can be considered in a parallel connection and the magnet sheet and the magnet holder are connected in series. The dimensions of model components are presented in Table 2 and the total resistance in equations 9-11.

Table 2: Parameters of Magnet Block Components

Material	**Thermal conduction /W m^{-1} K^{-1}**	**Height /mm**	**Area /mm^2**
NdFeB	10	15	192.4
Permedur	70	11	151.2
Copper sheet	400	0.060	572
Nickel coating	90	0.025	572
Copper holder	400	10	572
Aluminium I -beam	240	56	572

The thermal resistance, R, depends on height, H, thermal conductivity, k, and heated surface, A.

$$R=H/kA \qquad (9)$$

For a magnet of hybrid type, the thermal resistance is calculated with

$$\frac{1}{Rm}=\frac{1}{Rper}+\frac{1}{Rmag}+\frac{1}{Rper} \qquad (10)$$

The total thermal resistance is

$$Rcond = Rfoil + Rm + Rcu \qquad (11)$$

The temperature change is calculated as

$$\Delta T = (Q/2)\ *R_{cond} \qquad (12)$$

The power dissipation on a magnet block is 17.9 W m^{-1} and we consider a safety factor 3; as a result, the temperature rise of one period of magnet is calculated to be 0.28 ℃.

TEMPERATURE DISTRIBUTION

Based on results of the calculation, the temperature rise is small. A possible reason is that the actual thermal contact is imperfect and the actual temperature rise is greater. A three-dimensional model of a real magnet is calculated in Anysis V13. The model is based on an IU22 magnet block design by NEOMAX. To decrease the duration of computation, we used ten magnet blocks for calculation. Because the contact between magnets might be imperfect, we consider a safety factor 3; as a result, the heat source input is 54 W m^{-1}. The water temperature is 25 ℃ as supplied from a TPS utility; we assumed a water pressure drop 202 kN m^{-2} along the 6-m copper cooling pipe.

The TPS IU22 magnet array has a vertical gap smaller than the magnet width; the distribution of the induced current density [4] is expressed as

$$j(x) = 1/\cosh(x/h) \qquad (13)$$

The effective perimeter for the beam chamber, on the magnet sheet, becomes replaced by twice the undulator gap, 2 G. The resistive wall heating source is thus within the 2 G surface area.

Based on the Hazen-Williams formula, and the Sieder-Tate equation, the rate of water flow is calculated with equation 14 and the convection of the cooling pipe with equation 15.

$$q = 0.442\, C\, d^{2.63}\, (\Delta P/L)^{0.54} \qquad (14)$$

$$N_u=(c*0.027*Re^{0.8}*Pr^{1/3})/(\mu/\mu_s)^{1.4} \qquad (15)$$

Here q is the rate of water flow (m^3/h); C is the Hazen-Williams coefficient, 130 for copper pipe, d is the inner diameter of the pipe and L its length; ΔP is the pressure drop over the pipe length; Re is the Reynolds number, Pr is the Prandtl number and μ/μ_s is a viscosity correction factor .

The results show in figures 3 and 5, that for IU22 with gap 5 mm, the magnet and aluminium beam have a maximum temperature difference 2.53 ℃.To investigate the imperfection of contact between the sheet and magnet, we made a small deformation of the magnet sheet. The pimple is 5 mm wide and 1 mm high. We estimate the power from synchrotron radiation from the bending magnet exposed on the spot surface to be 1.43 W. The temperature distribution is shown in Figure 4; we see that the position of the imperfection position has a temperature increase locally by 8 ^{o}C.

SUMMARY

In this paper, we estimate the heat load budget from synchrotron radiation and resistive wall heating. The heat from the image current and synchrotron radiation must not cause the magnet sheet to become fused. Experiments are needed to prove the results of simulation and these are under preparation. Mis-steering of the electron beam and striking the magnet array might be the main reason for the magnet sheet to become fused and for magnet demagnetization.

One concern for heat source on TPS IU is that the temperature variation in the x-direction might have an influence on the magnetic good field region because of the residual magnetic-flux density decrease.

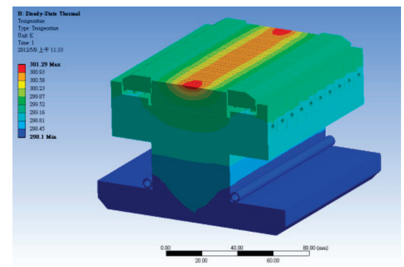

Figure 3: Temperature distribution on magnet blocks.

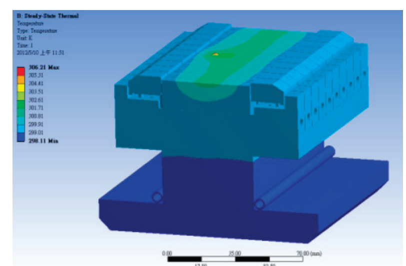

Figure 4: An imperfection case.

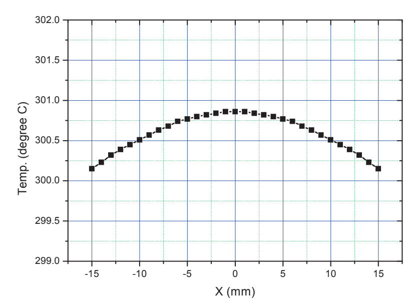

Figure 5: Temperature along magnet blocks.

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