

STUDY ON BEAM-INDUCED HEATING IN INJECTION SECTION OF HEFEI LIGHT SOURCE*

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Abstract

Ceramic chambers distributed with metal striplines on the inner surface are installed in the injection section at Hefei Light Source (HLS). Heating on the ceramics chambers has been observed during machine operation. An air compressor is used to cool these chambers due to concerns of overheating during top-up operation mode. To understand the sources of the heating, a series of experiments are performed with various beam currents and bunch filling patterns. The study shows that the heating is mainly caused by the narrow-band impedances of the ceramic chambers and their adjacent vacuum components.

INTRODUCTION

HLS is the first dedicated synchrotron radiation light source in China, providing radiation from infrared to soft X-ray. It consists of an 800 MeV storage ring with a circumference of 66.13 m and a linac injector which can perform full-energy beam injection. HLS realized the stable top-up operation for user experiments in July 2018. The beam in the storage ring is maintained in the range of 355 – 360 mA and 35 out of the total 45 buckets are filled with electron bunches.

HLS employs a local bump orbit to inject electron beam into the storage ring. The injection system consists of four kicker magnets and one septum magnet, as shown in Fig. 1. Two kickers, K_2 and K_3 , are located in a long straight section. K_1 is in the front of the upstream bending magnet, while K_4 is at the end of the downstream bending magnet [1].

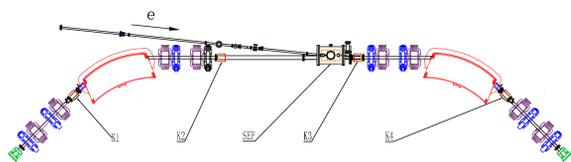


Figure 1: Layout of the HLS injection system where $K_1 - K_4$ are kickers and SEP is the septum magnet.

Ceramic vacuum chambers are adopted inside the kicker magnets to avoid vortex induced by the rapid change of their magnetic fields. The inner surface of the ceramic chamber is coated with a titanium (Ti) layer. Six metal striplines are distributed on the upper and lower sides which aims at minimizing the machine coupling impedance. The ceramic vacuum chamber is shown in Fig. 2.



Figure 2: Ceramic vacuum chamber profile.

Heating of the ceramic chambers has been observed during top-up operation and an air compressor has to be used to cool them down. In order to study this thermal phenomenon, four temperature sensors are installed around the ceramic chamber inside the kicker K_4 . The distribution of the sensors which are labeled from T_1 to T_4 is shown in Fig. 3.

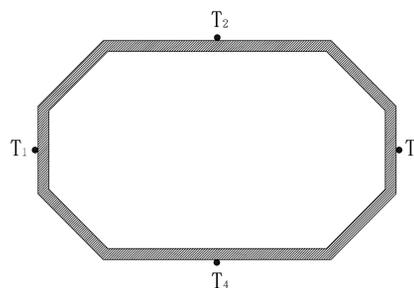


Figure 3: Temperature sensors around the ceramic chamber inside the kicker K_4 , in which T_1 is on the outside of the storage ring.

Since the kicker K_4 is located downstream close to a bending magnet, it is affected by two main heating sources: synchrotron radiation and impedance of the ceramic chamber and its adjacent components. In this paper, we try to figure out the contribution of these two heating sources. Furthermore, the longitudinal impedances of the vacuum structure with the ceramic chamber is studied.

THEORY

When a bunch passes through a given structure, it will suffer an energy change proportional to the square of the charge [2], written as

$$\Delta\varepsilon = -k_{\parallel} q^2, \quad (1)$$

where k_{\parallel} is the longitudinal loss factor which is an integral of the longitudinal impedance $Z_{\parallel}(\omega)$ multiplied by the bunch power spectrum $h(\omega)$ in frequency domain,

$$k_{\parallel} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \text{Re} [Z_{\parallel}(\omega)] h(\omega) d\omega. \quad (2)$$

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For a Gaussian bunch distribution, with rms bunch length $c\sigma_\tau$, the line charge density is

$$\lambda(t) = \frac{1}{\sqrt{2\pi}\sigma_\tau} \exp\left(-\frac{t^2}{2\sigma_\tau^2}\right), \quad (3)$$

and the power spectrum is given by

$$h(\omega) = \hat{\lambda}(\omega)\hat{\lambda}^*(\omega) = \exp\left(-\omega^2\sigma_\tau^2\right). \quad (4)$$

If there are M identical bunches filling at regular intervals in a circular accelerator with a revolution angular frequency ω_0 , every bunch suffers the same energy loss described by Eq. 1. Thus the heat power produced by the structure is given by [3]

$$\begin{aligned} P &= M |\Delta\varepsilon| \frac{\omega_0}{2\pi} \\ &= \frac{I_{av}^2}{M\omega_0} \int_{-\infty}^{\infty} \text{Re}[Z_{||}(\omega)] \exp\left(-\omega^2\sigma_\tau^2\right) d\omega, \end{aligned} \quad (5)$$

where $I_{av} = Mq\omega_0/2\pi$ is the average current.

For a broad-band impedance, Eq. 5 suffices for the calculation of the heat power. However, in a circular machine, the bunch spectra only consists of a series of discrete lines, spaced by $M\omega_0$. For a narrow-band impedance, only spectra near the resonance frequency of the structure can be excited. Therefore, the integral in Eq. 5 has to be replaced by the sum

$$P = I_{av}^2 \sum_{p=-\infty}^{\infty} \text{Re}[Z_{||}(pM\omega_0)] \exp\left(-p^2M^2\omega_0^2\sigma_\tau^2\right). \quad (6)$$

The heat power depends not only on the beam current but also on the filling pattern.

If the vacuum chamber is heated by the synchrotron radiation, on the other hand, the temperature of the sensor is proportional to the average current I_{av} without taking the coherent radiation into consideration. As a result, the steady-state temperature is a quadratic function of the average current,

$$T = aI_{av}^2 + bI_{av} + c, \quad (7)$$

where a , b and c come from impedance of ceramic chamber, synchrotron radiation and the environment temperature, respectively.

EXPERIMENTS

Firstly, temperature data are collected during regular operations with the beam current varying from 100 mA to 350 mA. The air cooling system is turned on during this measurement. 35 of total 45 buckets (#6 and from #12 to #45) are evenly injected with electrons.

The data and its fitting result are shown in Fig. 4. The fitting result of the chamber temperature as a function of the beam current is

$$\begin{aligned} T_1 &= 62.62I^2 + 77.68I + 29.13, \\ T_2 &= 92.36I^2 + 46.02I + 30.17, \\ T_3 &= 2.619I^2 + 81.48I + 27.02, \\ T_4 &= 347.71I^2 - 40.12I + 33.65. \end{aligned} \quad (8)$$

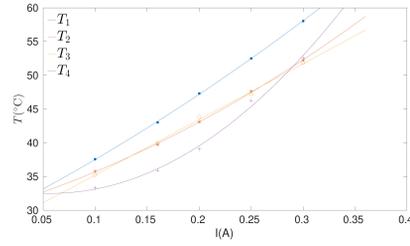


Figure 4: Steady-state temperature of four sensors vs beam current with cooling system on.

We can see that the linear coefficient of T_4 is negative, which is different from the other three cases. This is because the cooling system has most effect on the area where sensor T_4 is located. The experiment result is strongly affected by the cooling system.

To better understand the heating phenomenon, we again measure the temperature change as a function of the beam current with the same bunch pattern, while the cooling system is turned off. The measurement result is shown in Fig. 5 and the fitting result is shown in Eq. 9.

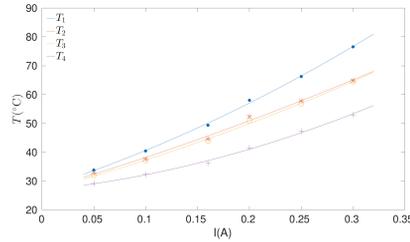


Figure 5: Steady-state temperature of four sensors vs beam current with cooling system off.

$$\begin{aligned} T_1 &= 162.6I^2 + 115.1I + 27.50, \\ T_2 &= 73.75I^2 + 105.0I + 26.97, \\ T_3 &= 100.8I^2 + 95.81I + 26.73, \\ T_4 &= 172.4I^2 + 36.76I + 26.79. \end{aligned} \quad (9)$$

Table 1: Temperature Growth from the Fitting Result

Order	$\Delta T_1(^{\circ}\text{C})$	$\Delta T_2(^{\circ}\text{C})$	$\Delta T_3(^{\circ}\text{C})$	$\Delta T_4(^{\circ}\text{C})$
1st	41.4	37.8	34.8	13.2
2rd	21.1	9.56	13.1	22.3

The temperature growth from the fitting result at $I_{av} = 360$ mA is listed in Tab. 1. We can find that the first order of ΔT_4 is much smaller than $\Delta T_{1,2,3}$ because the sensor T_4 is at the inner side of the storage ring which is far from the direct synchrotron radiation light. Moreover, the second order of ΔT_1 and ΔT_4 are nearly the same and they are both bigger than ΔT_2 and ΔT_3 . The reason is that the sensor T_1 is at the symmetrical position with the sensor T_4 and the height of the chamber is smaller than the width (see Fig. 3).

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Besides that, the metal striplines around $T_{2,3}$ help to reduce the temperature. This is consistent with the theory.

To further prove that the impedance played an role in temperature increment, we carried out the third experiment maintaining the beam current for different filling patterns. During this experiment, the beam current is maintained between 89 mA and 90 mA while the number of the filled bunches are 15, 9 and 5 respectively. The bunches are spaced evenly. The equilibrium temperature of the vacuum chamber with different filling pattern is shown in Fig. 6. The final temperature for 5 buckets does not reach its steady-state because of the limited measurement time. The contribution from the radiation is constant due to the same beam current. Therefore the impedance is the only reason that causes the temperature difference. From Fig. 6, we can draw a conclusion that the impedance is critical to the temperature rise, especially when the bunch number is small.

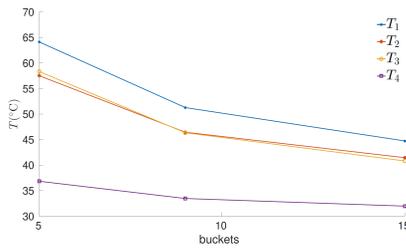


Figure 6: Temperature of sensors in even filling patterns while the beam current is kept at 90 mA.

Finally, we carry out an experiment to figure out the type of the impedance. Electrons are injected evenly to adjacent buckets while keeping I_{av}^2/M the same. The beam current I_{av} and the bunch number M are listed in Tab. 2.

Table 2: The Beam Current and the Bunch Numbers Used in the 4th Experiment

I_{av} (mA)	120	80	100	60	40
M	36	16	25	9	4

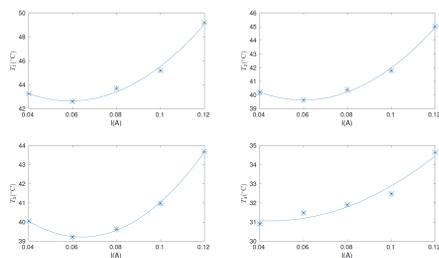


Figure 7: Temperature of sensors in continuous filling patterns while I_{av}^2/M is kept the same.

equilibrium temperature of the vacuum chamber is shown in Fig. 7. If the impedance is wide band compare to the bunch length, its heating effect should be unaffected. Thus, final temperature would be linear with the average current

which is obviously against the results shown in Fig. 7. In other words, the ceramic vacuum chamber has a narrow band impedance. In Fig. 7, $T_{1,2,3}$ reaches minimum around $I_{av} = 60$ mA which can be explained by the charge density distribution spectrum in frequency domain.

We simplify the beam current as Dirac function

$$I(t) = \frac{I_{av}T}{M} \sum_{p=-m}^m \delta\left(t - \frac{pT}{M}\right), \quad m = \frac{M-1}{2} \quad (10)$$

where T is the revolution period. $I(t)$ is a periodic function with a repetition period T . We can always choose an appropriate origin to make $I(t)$ to be an even function. Its Fourier expansion is written as

$$I(t) = \sum_{n=-\infty}^{\infty} I[n] \cos(n\omega_0 t) \quad (11)$$

$$I[n] = \frac{1}{T} \int_{-T/2}^{T/2} I(t) \cos(n\omega_0 t) dt \quad (12)$$

$$= \frac{I_{av}}{M} \sum_{p=-m}^m \cos\left(\frac{2\pi np}{M}\right)$$

Figure 8 shows the beam density in frequency domain with 4 and 6 adjacent buckets. If a particular spectrum n_0 excites

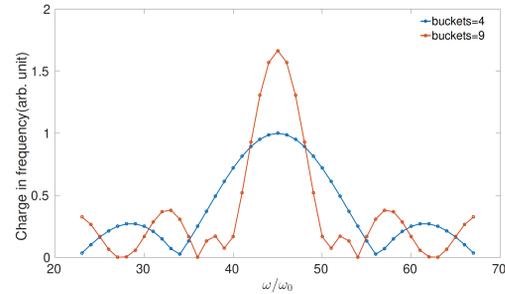


Figure 8: Charge spectrum in frequency domain.

the resonance of the impedance, power generated by the impedance is proportional to $I[n_0]^2$. For example, if the resonance frequency of the ceramic chamber lies in

$$(25 \sim 30 + 45n) \omega_0 \quad n = 0, 1, 2 \dots \quad (13)$$

then the beam induced heating with 9 buckets could be smaller than that with 4 buckets, which can help explaining the result shown in Fig. 7.

CONCLUSION

The heating effect of the vacuum chamber in the injection section of HLS storage ring is studied. The results shows that main contribution to the heating is the narrow-band impedance of the vacuum chamber with ceramic components. The study also shows that, for the kicker which is located downstream near a bending magnet, synchrotron radiation is also one important heating source. By quantitative comparison between them, an optimization of ceramic chamber structure is needed for future upgrade.

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