LONGITUDINAL IMPEDANCE OF NONLINEAR KICKER FOR HEFEI ADVANCED LIGHT FACILITY*

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Abstract

The Hefei Advanced Light Facility (HALF) is a vacuum ultraviolet (VUV) and X-ray diffraction-limited storage ring light source. It has a relatively large dynamic aperture, and an injection scheme with a nonlinear kicker (NLK) was considered for the HALF. This kind of magnet was designed with a small gap shield in the central area to gain a flat magnetic field. A complete prototype has also been produced and the measurement of magnetic field was done. In this paper, an improved structure of the nonlinear kicker is presented based on the previous one. Simulation of the longitudinal impedance has also been done and will be given later.

INDUCTION

The Hefei Advanced Light Facility (HALF) will use off-axis injection with a nonlinear kicker in its design. In the current design, a modified hybrid 6BA lattice has been identified as the lattice of HALF with the beam energy of 2.2 GeV, which will be built in a few years. The natural emittance of HALF is very small, so the diffraction-limited emittance can be reached in the main VUV and soft X-ray radiation bands. This results in very high brightness and high transverse coherence of the synchrotron light. The main design parameters of HALF are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection beam energy</td>
<td>$E$</td>
<td>2.2 GeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>$\mathcal{C}$</td>
<td>479.86 m</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>$\varepsilon_0$</td>
<td>86.3 pm · rad</td>
</tr>
<tr>
<td>Number of periods</td>
<td>$N_p$</td>
<td>20</td>
</tr>
<tr>
<td>Betatron tunes</td>
<td>$\nu_x, \nu_y$</td>
<td>48.15/17.15</td>
</tr>
<tr>
<td>Radiation damping time</td>
<td>$\tau_x, \tau_y, \tau_z$</td>
<td>27.2/37.7/23.4 ms</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$\sigma_\varepsilon$</td>
<td>0.00062</td>
</tr>
<tr>
<td>RF cavity frequency</td>
<td>$F$</td>
<td>499.8 MHz</td>
</tr>
<tr>
<td>Straight Sections</td>
<td>$N_s$</td>
<td>40 with 20-long and 20-short</td>
</tr>
</tbody>
</table>

A prototype of the nonlinear kicker (NLK) for HALF has been proposed and developed in the past few years [1,2]. The NLK uses arc-shaped shielding structures to reduce the magnetic field and obtain a relatively flat magnetic field which closed to zero in the central region. The stored beam will not be under influence as it passes through the central region, therefore, it will not deviate from the established orbit. In the previous design, we used a runway-shaped ceramic vacuum chamber structure, which we have changed to a circular ceramic vacuum chamber now that can reduce beam coupling impedance better and make it more convenient to coat inside of the chamber. The structure of the new one is presented in Fig.1, and the 3D model is shown in Fig.2.

Figure 1: The improved structure of NLK.

Figure 2: The 3D model of NLK.

IMPEDANCE RESEARCH

The interaction of high-energy charged particles with a real resistance wall excites wakefield behind the charged particles. The wakefield not only acts on the charged particles themselves, but also disturbs the particles behind them, changing their energy. In the frequency domain, the effect of the wakefield on the particle beam can be represented by the impedance of the vacuum chamber. The impedance can be written as a combination of real and imaginary parts:

$$Z(\omega) = Z_{Re}(\omega) + iZ_{Im}(\omega)$$  \hspace{1cm} (1)

The real parts of the impedance are resistive, which results in beam energy loss. While the imaginary parts are

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capacitive or inductive, which will cause the drift of the frequency of the beam oscillation and the stretching of the beam length.

For non-standard vacuum tubes, we are currently concerned with the longitudinal beam coupling impedance, which leads to energy loss, and energy loss leads to the heating of vacuum components in turn. Therefore, the beam coupling impedance needs to be minimized. In 2021, we manufactured the first NLK prototype, but after calculation and measurement, we found that its longitudinal impedance was at a relatively high level. Therefore, we have made a series of improvements to it, mainly to the transition sections.

Consider that the length of the injected beam of HALF is 2mm, we have calculated the longitudinal impedance of the ceramic chamber at this length of the beam with CST [6]. The real and the imaginary parts of the longitudinal impedance are shown in Fig.3, where the black line indicates the NLK impedance before the improvement and the red line indicates the NLK impedance after the improvement.

It can be seen that the longitudinal impedance of the improved NLK is smaller in both the real or imaginary parts. Based on the data from the real parts of the longitudinal impedance, we can calculate the beam loss factor by using the following equation [3-5], where $\sigma$ is the beam length:

$$k = \frac{1}{\pi} \int_0^\infty Z_{Re}(\omega) e^{-\frac{(\omega^2 \sigma^2 c^2)}{c^2}} d\omega$$

(2)

The calculated loss factors of the NLK before and after the improvement are 1 V/pC and 0.5 V/pC, which are identical to the results obtained directly in CST [6]. During this improvement, we have mainly modified the tapering transition structure at both ends of the NLK to make it smoother so that the beam coupling impedance can be reduced to an acceptable level. In fact, the results of the simulations confirmed it and the effect of the improvement measures on the impedance reduction is positive.

To better understand the impedance contribution of each part, we divided the ceramic vacuum chamber into two separate parts for impedance calculations which are shown in Fig.4.
Table 2: Beam Energy Loss of NLK Under Different Beam Conditions in Two Separate Parts

<table>
<thead>
<tr>
<th>Beam length /mm</th>
<th>Beam current /mA</th>
<th>Energy loss /W (Chamber)</th>
<th>Energy loss /W (Flanges)</th>
<th>Energy loss /W (Total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>175</td>
<td>1.5</td>
<td>39</td>
<td>40.5</td>
</tr>
<tr>
<td>6</td>
<td>175</td>
<td>0.28</td>
<td>0.07</td>
<td>0.35</td>
</tr>
<tr>
<td>6</td>
<td>350</td>
<td>1.1</td>
<td>0.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

In this case, we got the loss factor and beam energy loss of NLK under different beam conditions, and the results are shown in Table 2. As can be seen, the impedance of the ceramic chamber has little effect on the energy loss, which is concentrated inside the flanges at both ends. The beam conditions in the Table 2 are as follows: Case 1 [2mm-length and 175mA-current]: beam injected; Case 2 [6mm-length and 175mA-current]: acceptance standard; Case 3 [6mm-length and 350mA-current]: stable operation.

THERMAL ANALYSIS

To understand the temperature variation of the ceramic chamber during operation, we can proceed with the thermal analysis of the NLK by using the results of the impedance calculations. In addition to the energy loss calculated above, we also need to know the power of the synchrotron light at this position. According to the HALF injection scheme, the deflection angle of the injected beam at NLK is 4.4mrad, and the power of the synchrotron light irradiated to the ceramic chamber of NLK can be calculated to be about 15W at a beam current of 350mA.

We calculated the temperature distribution in the situation of beam injected (beam condition: 2mm-length and 175mA-current) in two cases: natural convection of air and forced convection using fans. Fig.5 shows the temperature distribution with forced convection of NLK, and Fig.6 shows the temperature distribution with forced convection of the internal copper shields. The region with maximum temperature is the transition sections which located inside the flanges. And the maximum temperature on the two copper shields reduced from about 95 °C to 46 °C after forced convection cooling.

CONCLUSION

The beam energy loss is mainly concentrated in the transition sections and flanges, as well as the temperature distribution. Considering that the temperature of the ceramic chamber and copper shields electrode located in the middle part is not very high, further calculations will be performed using water-cooled flanges. The structure of NLK is still being improved, while the calculation of the transverse impedance is currently under study.

REFERENCES

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