Wrinkle analysis and mounting optimization of the primary stripper foil for CSNS

HE Zhe-Xi(何哲玺)[1,2] QIU Jing(邱静)[1] LI Chun-Hua(李春华)[1] CHEN Jia-Xin(陈佳鑫)[1]
KANG Ling(康玲)[1] QU Hua-Min(屈化民)[1] ZOU Yi-Qin(邹易清)[1,2]

[1] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: The primary stripper foil's lifetime is very important for high intensity proton accelerators. Besides high temperature, the wrinkle of the stripper foil is also harmful for the lifetime and the injection efficiency. However, the recent wrinkle simulation is still not perfect. In this paper, a new method for wrinkle analysis has been proposed for the first time, which is integrated with the buckling theory. Based on this method, the wrinkle vibration and the maximum wrinkle shape of the normally mounted foil have been simulated. Then, two mounting schemes for reducing the wrinkle have been contrasted. Finally, the foil mounting structure for CSNS has been designed.

Key words: primary stripper foil, wrinkle analysis, mounting optimization

PACS: 29.20.dk, 29.27.Ac **DOI:** 10.1088/1674-1137/37/10/107003

1 Introduction

In China Spallation Neutron Source (CSNS), the injection process of rapid cycling synchrotron (RCS) will be done by stripping the H^- beam provided by the linac. A carbon primary stripper foil of 100 μg/cm^2 will be used to fully strip the two electrons and convert the injection ions into protons. The 80 MeV injection beam from the linac has a pulse length of 0.2–0.4 ms with the repetition rate of 25 Hz and the average particle number over a single pulse is 1.56×10^{13}. The energy deposition will heat the foil and quickly destroy it. It is desirable to have the foil's lifetime as long as possible, so the calculations and the optimizations for the stripper foil are very important.

In general, the maximum temperature is the only factor which could be calculated for predicting the foil's lifetime [1–3]. However, many experiments show that the wrinkle is also harmful for the foil's lifetime and the injection efficiency: (1) the wrinkle vibration will produce a positioning error between the foil and the beam. (2) If the inner stress grows over the yield strength, the wrinkle deformation cannot perfectly recover again. While this plastic wrinkle is accumulated to an unacceptable value, the beam loss is increased. (3) The large wrinkle displacement will easily tear the foil [4].

Although the wrinkle is very important, the recent simulation for the foil's wrinkle is still not perfect. In this paper, a new method of analysis of the foil's wrinkle has been proposed for the first time. This method is integrated with the buckling theory which is used to calculate the wrinkle of thin membrane [5]. It defines the wrinkle displacement which is caused by the instability and the beam hitting. First, the energy deposition and the temperature rising for CSNS will be calculated. In order to test the dependability of the new analysis method, the wrinkle analysis for the foil of SNS will be done to compare with the actual situation. Then, the wrinkle vibration and the maximum wrinkle shape of the normally mounted foil for CSNS will be simulated. Finally, the mounting scheme optimization for CSNS will be done in order to reduce the wrinkle.

2 Thermal analysis

2.1 Energy deposition

The energy loss for one particle passing through the foil can be expressed by the following formula:

$$\Delta E(J)=eT|\mathrm{d}E/\mathrm{d}z|, \tag{1}$$

where T is the foil's thickness; $|\mathrm{d}E/\mathrm{d}z|$ is the stopping power between particle and carbon and e is the charge of an electron. The H^- ion injection can be estimated as 1 proton and 2 electrons traversing the foil.

The injection painting process for CSNS is shown in Fig. 1 [6]. In order to simplify the calculation, the analysis assumes that the cycling beam will keep its distribution and only have a horizontal movement during the injection process.

Received 5 December 2012

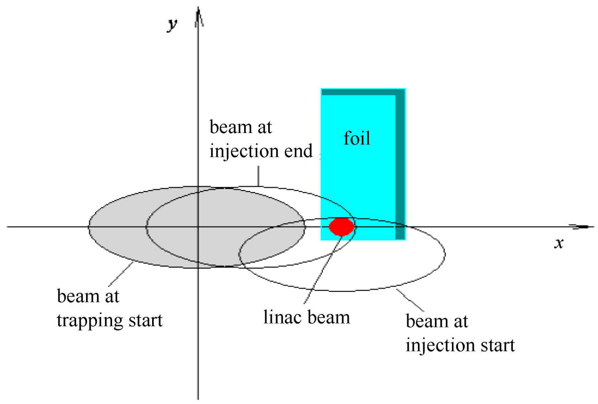

Fig. 1. The injection painting process of CSNS [6].

Fitting the beam distribution with Gaussian function, the power density distribution is expressed as:

$$P(\mathrm{W/mm^2}) = \frac{E_{\mathrm{H-}}N}{2\pi\sigma_x\sigma_y t_{\mathrm{in}}}\exp\left(-\frac{(x-7)^2}{2\sigma_x^2}\right)\exp\left(-\frac{(y-7)^2}{2\sigma_y^2}\right) + \frac{E_{\mathrm{H+}}nN}{2\pi\sigma_x\sigma_y t_{\mathrm{in}}}\exp\left(-\frac{(x-7+x_m(t))^2}{2\sigma_x^2}\right)\exp\left(-\frac{(y-7)^2}{2\sigma_y^2}\right), \quad (2)$$

where $E_{\mathrm{H-}}$ is the energy deposition for one $\mathrm{H^-}$ particle; $E_{\mathrm{H+}}$ is the energy deposition for one cycling proton; t_{in} is the pulse length; N is the particle number per pulse; n is the average cycling protons traversing times, 3–5 and $x_{\mathrm{m}}(t)$ is the movements of the cycling beam center during the injection process.

Because the extremely thin foil is set in the vacuum environment, the only means of heat dissipation is thermal radiation. According to the study of Dr. Liaw et al. [2], the thermal radiation heat flux can be simplified as follows:

$$q_{\mathrm{rad}}(\mathrm{W/mm^2}) = \varepsilon\sigma(T_{\mathrm{f}}^4 - T_0^4), \quad (3)$$

where ε is the emissivity of carbon; σ is the Stefan-Boltzmann constant; T_{f} is the temperature on foil and T_0 is the ambient temperature.

In addition, the wrinkle analysis cannot ignore the pulse pressure caused by the beam hitting. While a bunch of beam passes through a foil, only a little proportion of the energy deposition converts into the pressure which increases the potential energy (wrinkle) of the foil. According to the momentum theorem and the conservation of energy, the average interaction force between the foil and the injection beam can be expressed as:

$$\overline{F}(N) = \Delta p/t_{\mathrm{in}} = ((\Delta E_{\mathrm{k}}\eta + m_0c^2)^2 - m_0^2c^4)^{1/2}/(ct_{\mathrm{in}}) \approx (2\Delta E_{\mathrm{k}}\eta m_0)^{1/2}/t_{\mathrm{in}}, \quad (4)$$

where Δp is the equivalent momentum conversion; ΔE_{k} is the total kinetic energy loss; η is the conversion rate; m_0 is the rest mass of the particle and c is the light velocity.

Therefore, the pressure distribution of the beam hitting can be expressed as:

$$P(\mathrm{N/mm^2}) = \frac{\Delta p_{\mathrm{H-}}}{2\pi\sigma_x\sigma_y t_{\mathrm{in}}}\exp\left(-\frac{(x-7)^2}{2\sigma_x^2}\right)\exp\left(-\frac{(y-7)^2}{2\sigma_y^2}\right) + \frac{\Delta p_{\mathrm{H+}}}{2\pi\sigma_x\sigma_y t_{\mathrm{in}}}\exp\left(-\frac{(x-7+x_{\mathrm{m}}(t))^2}{2\sigma_x^2}\right) \times\exp\left(-\frac{(y-7)^2}{2\sigma_y^2}\right), \quad (5)$$

where $\Delta p_{\mathrm{H-}}$ is the equivalent momentum conversion for the injection particles and $\Delta p_{\mathrm{H+}}$ is the equivalent momentum conversion for the cycling protons.

2.2 Temperature analysis

According to the characteristics of the energy deposition, the transient temperature analysis is performed to check the working condition of the primary stripper foil for CSNS. The previous analysis proves that the pulse length of 0.2 ms will produce the maximum temperature. The analysis result shows that the maximum temperature for CSNS is 1334 K. The temperature vibration is shown in Fig. 2 and the temperature distribution of each injection pulse after the dynamic balance is shown in Fig. 3.

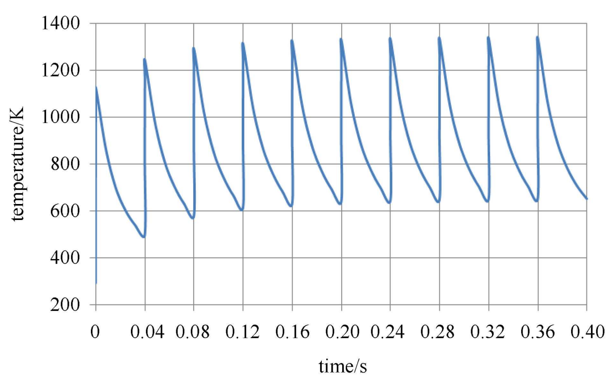

Fig. 2. The temperature vibration on foil.

As this temperature is much lower than SNS (2243 K) [2] and J-PARC (1800 K) [3], the primary stripper foil of CSNS will have longer lifetime and higher stability.

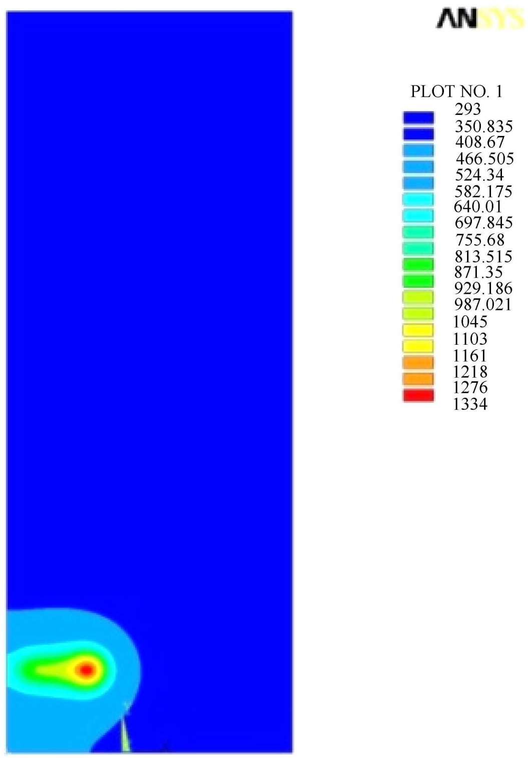

Fig. 3. The temperature distribution of each injection pulse.

3 Wrinkle analysis

3.1 Buckling theory

Buckling theory is used for estimating the instability of mechanical structure. Its balance equation can be written as follows:

$$([K]+\lambda_i[S])\{\psi_i\}=0, \tag{6}$$

where $[K]$ is the stiffness matrix of the structure; λ_i is the characteristic value corresponding to the order of i; $[S]$ is the stress matrix in the structure and $\{\psi_i\}$ is the modal corresponding to the order of i.

In general, the stripper foil is very thin so even a tiny disturbance or an inner defect will cause the wrinkle. This case is quite similar to the wrinkle of thin membrane, and many calculations and experiments have been done to prove that the buckling theory is appropriate to this kind of wrinkle analysis [5].

Different from the other cases, the inner stress of the stripper foil is produced by the temperature distribution and the pressure of the beam hitting. It means that the wrinkle is caused by the instability and the beam pressure. The analysis flow chart is shown in Fig. 4.

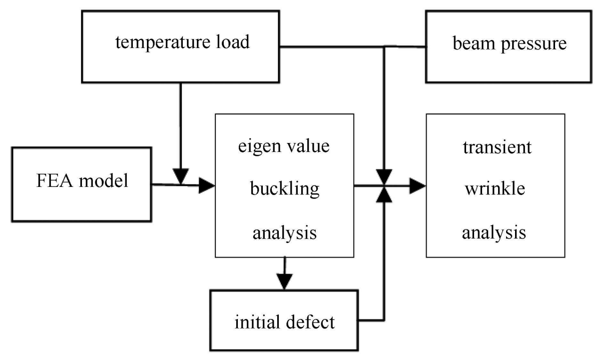

Fig. 4. The foil wrinkle analysis flow chart.

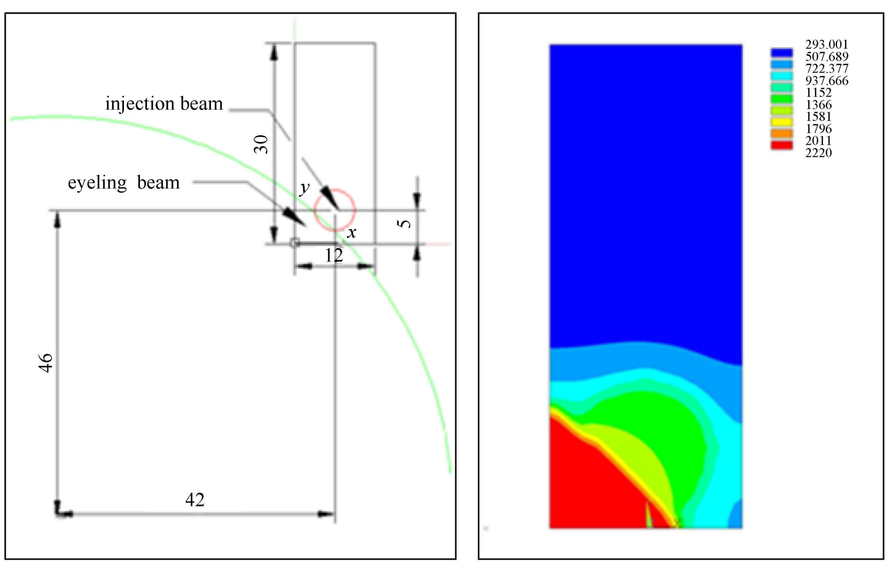

Fig. 5. The loads of wrinkle analysis for SNS. (L: The beam conditions of SNS; R: The foil's temperature distribution for SNS).

In order to test the dependability of this method, the foil wrinkle analysis for SNS has been done. The beam conditions and the temperature analysis result are shown in Fig. 5. The wrinkle simulation result is shown in Fig.6 and compared with the actual situation. The result shows that the displacement shape of the simulation corresponds to the reality qualitatively. The beam hitting corner is curved along the beam direction and the other unfixed corner is curved conversely.

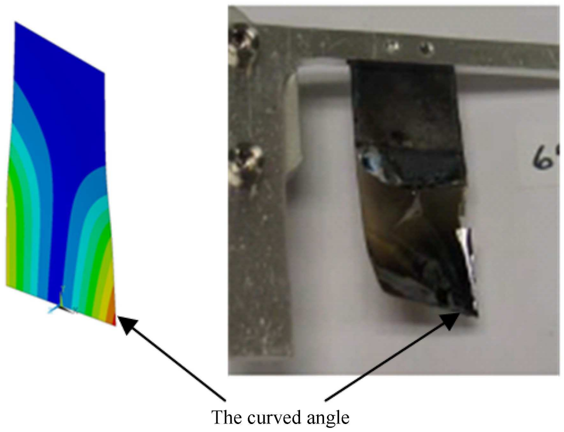

Fig. 6. The comparison of wrinkle shape between the simulation and the reality of SNS.

3.2 Analysis for the normally mounted foil

For CSNS，the two edges which always keep ambient temperature will be fixed in order to provide stronger support. In order to check the wrinkle situation, the analysis of 200 injection periods for the normally mounted foil has been done.

The wrinkle vibration is shown in Fig. 7. Because of the elasticity of the foil, the wrinkle displacement will shift like a spring. The displacement will grow over the force equilibrium position and finally get to its maximum value and then the displacement will recover to its minimum value by the resilience force. Because of the non-linear effect of buckling phenomenon, this kind of displacement shaft doesn't periodically vary with the frequency of 25 Hz and the amplitude is not a constant. Therefore, the wrinkle vibration has several non-periodic peaks.

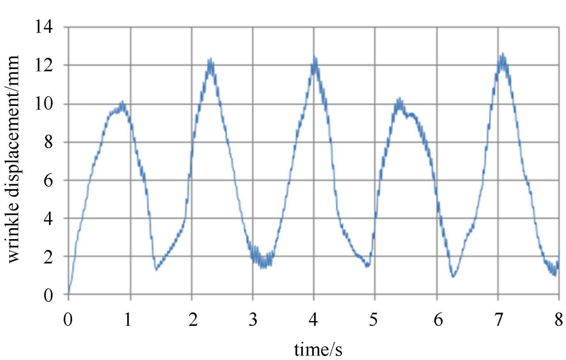

Fig. 7. The wrinkle vibration of the foil.

The maximum wrinkle shape of the foil is shown in Fig. 8. The maximum displacement is 12.67 mm, appearing at the unfixed corner. The result also shows that the pressure of the beam hitting is the main factor which causes the wrinkle vibration and the positioning error.

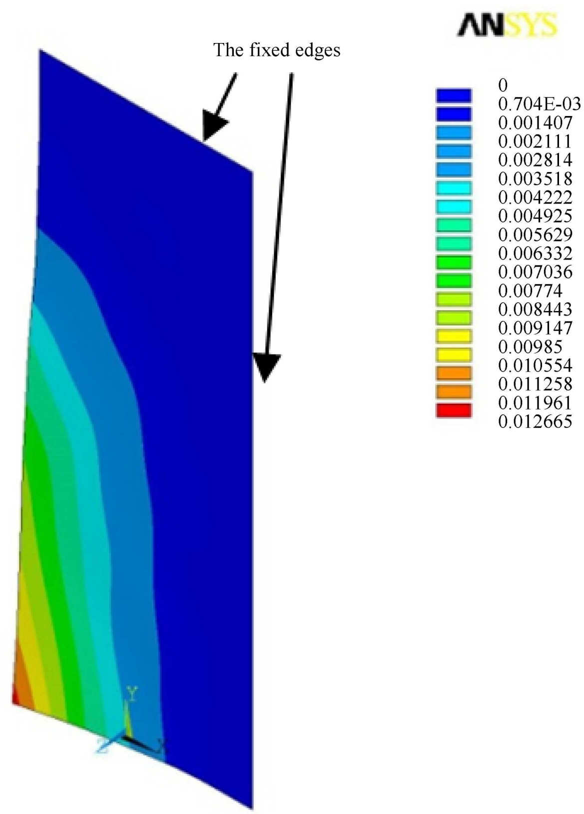

Fig. 8. The maximum wrinkle shape of the foil.

CSNS will use a new type of HBC carbon foil, which is strong enough to afford the displacement of centimeter level, as Fig. 9 shows [7].

In the theorem of material, the high temperature will decrease the yield strength. Once the inner stress grows over the yield strength, the wrinkle deformation won't perfectly recover again. After a period of operation, this unrecoverable wrinkle will be accumulated to an unacceptable value that increases the injection beam loss.

However, because of the lack of data of the foil's yield strength and the limitation of the finite element analysis, it is very hard to simulate the severe plastic deformation of the foil. But according to the theorem of material mechanics, the smaller the maximum vibration displacement is, the slower the unrecoverable wrinkle will be accumulated. As a result, the mounting scheme optimization is still necessary which is used for reducing the maximum wrinkle vibration displacement.

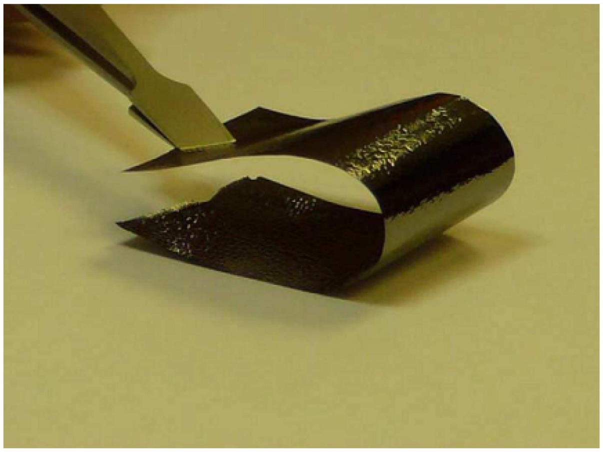

Fig. 9. The new type of HBC foils [7].

4 Mounting scheme optimization

For the case of the wrinkle due to high temperature and pressure, the injection efficiency and the lifetime will become worse. Thus, the scientists make many efforts to optimize the mounting scheme in order to reduce the wrinkle [8, 9]. The engineers of SNS cut an angle of the foil and effectively reduce the wrinkle. A C-type frame is utilized in J-PARC for installing many carbon fibers in order to give additional support [4]. For CSNS, both of these methods will be taken into account.

As to minimizing the influences with the kinetic energy loss and the scattering, the acceptable design for cutting angle and installing carbon fibers is shown in Fig. 10.

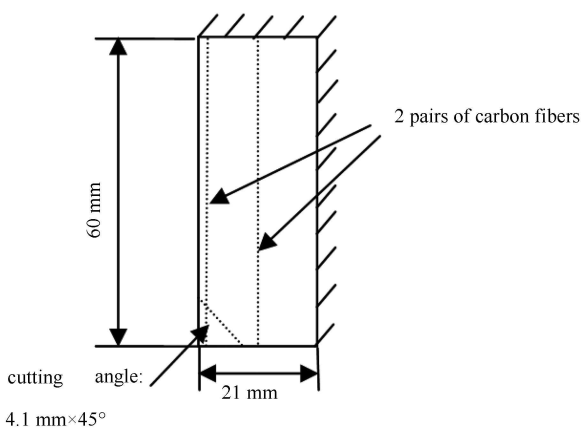

Fig. 10. The mounting optimization design for CSNS.

According to the new method of wrinkle analysis, the mounting scheme optimization can be done not only by experiment but also by simulation. The influences over the energy deposition caused by cutting angle and carbon fibers should not be ignored. The comparison with the effects of two mounting schemes is shown in Fig. 11.

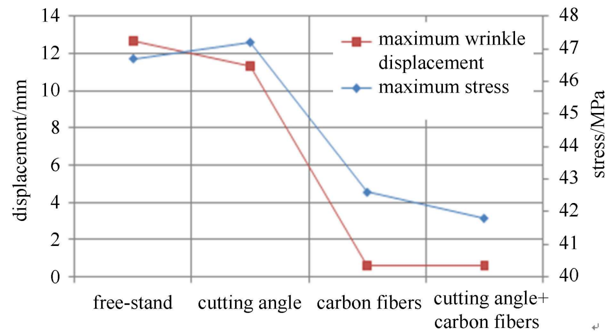

Fig. 11. The comparison between the effects of two mounting schemes.

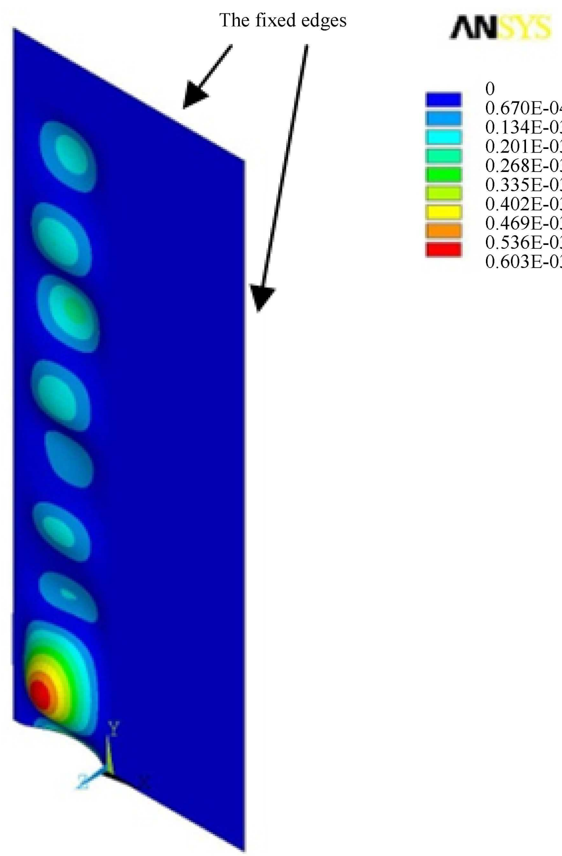

Fig. 12. The maximum wrinkle shape of installing carbon fibers scheme.

For CSNS, it seems that the design of installing 2 pairs of carbon fibers is more effective. The maximum wrinkle shape for installing carbon fibers is shown in Fig. 12. The maximum displacement will be decreased to 0.6 mm and the thermal stress will also be decreased to 42.6 MPa. The wrinkle distribution will be limited in the two pairs of fibers and the maximum displacement appears at the injection beam center. According to the theorem of material mechanics, a bulge on the thin foil will bring a series of visible wrinkle traces fluctuating along the fixed fibers direction. But these wrinkle traces are too small, so it won't make the injection efficiency and the lifetime worse.

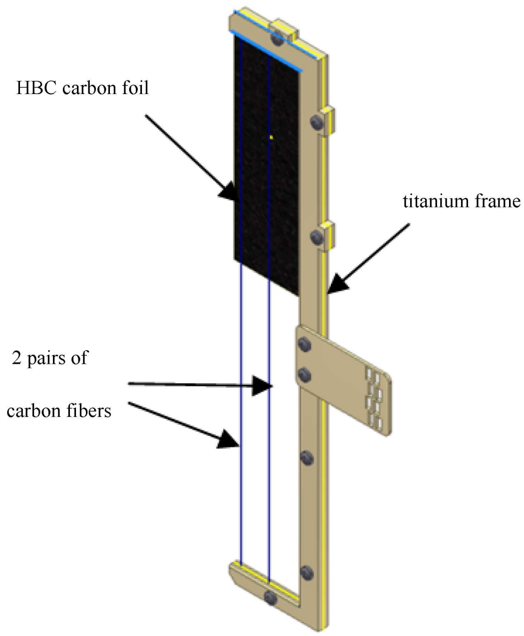

Fig. 13. The preliminary design of mounting scheme for CSNS.

As a result, the scheme of installing carbon fibers will be utilized for CSNS. In order to install the carbon fibers, a C-type titanium frame is designed. The T700 carbon fiber is chosen for its strong mechanical strength (>5 GPa). The diameter of a single fiber is 7 μm. The design of the foil mounting structure for CSNS is shown in Fig. 13.

5 Conclusion

The lifetime of the primary stripper foil is crucial to CSNS. In this paper, two important factors which are related to the foil's lifetime have been analyzed respectively.

According to the beam characteristics, the energy deposition has been calculated. The thermal analysis shows that the maximum temperature of the stripper foil is 1334 K. This means that the primary stripper foil of CSNS will have longer lifetime and higher stability.

A new method for wrinkle analysis has been proposed for the first time based on the buckling theory. To measure its dependability, the foil wrinkle analysis for SNS has been done and compared with the actual situation.

Because of the lack of data and the limitation of finite element analysis, the unrecoverable plastic wrinkle after a long operation period cannot be perfectly simulated. However, based on this new method, the simulation of the normally mounted foil for 200 injection periods has been done. The result shows the maximum displacement is 12.67 mm, and won't periodically vary with the frequency of 25 Hz. In order to reduce the wrinkle displacement, the effects of two mounting schemes have been contrasted, which shows that the installing carbon fibers scheme is more effective. It will reduce the maximum displacement to 0.6 mm. Finally, the design of foil mounting structure for CSNS has been brought out.

Recently, the foil exchanger and the foil frame have been manufactured. In the future operations and experiments, this wrinkle analysis method and mounting scheme would have a further improvement.

The authors would like to thank the CSNS colleagues for their help and advice.

References

1 CHOU W, Kostin M, TANG Z. Nucl. Instrum. Methods Phys. Res. A, 2008, **590**: 1–12

2 Liaw C J, Lee Y Y, Alessi J et al. PAC1999, 1999. 3000–3002

3 Sugai I, Takeda Y, Oyaizu M et al. Nucl. Instrum. Methods Phys. Res. A, 2010, **613**: 457–461

4 Sugai I, Takeda Y, Oyaizu M et al. Fermilab Accelerator Division Document Database, Beam Document 3496-v1, 2009

5 WONG Y W, Pellegrino S. In: 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structure Dynamics, and Materials Conference, 2002, AIAA 2002–1369

6 QIU J. Physical Design and Study of Chinese Spallation Neutron Source Injection System. Beijing: IHEP, 2007

7 Zeisler S K, Jaggi V. Nucl. Instrum. Methods Phys. Res. A, 2010, **613**: 434–435

8 Jolivet C S, Miller S A, Jr. Strner J O et al. Nucl. Instrum. Methods Phys. Res. A, 2008, **590**: 47–50

9 Jolivet C S, Jr. Strner J O. Nucl. Instrum. Methods Phys. Res. A, 2008, **590**: 51–56