DESIGN AND ANALYSIS OF CSNS-II PRIMARY STRIPPER FOIL

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Abstract

Stripper foil is a key equipment for converting negative hydrogen ions into protons in the RCS injection zone of CSNS. The structure of the CSNS primary stripper foil adopts a rotating steel strip structure, and the maintenance time is long, requiring operators to carry out maintenance work in close proximity for a long time. The energy of CSNS-II injection beam has significantly increased from 80 MeV to 300 MeV, and the radiation dose in the injection area will also increase, making it impossible to maintain the equipment in close proximity for a long time. Therefore, it is necessary to redesign the primary stripper foil. This article will analyze the stripper efficiency and beam injection thermodynamics of CSNS-II stripper foil, carry out automatic foil store replacement structure design, motion analysis, and prototype testing, and envision remote maintenance solutions to achieve maintenance and repair of the stripper foil with minimal human intervention.

INTRODUCTION

Stripper foil is a key equipment for converting negative hydrogen ions into protons in a Spallation Neutron Source device. The CSNS stripper foil includes the primary stripper foil and the secondary stripper foil. The primary stripper foil adopts 100 μg/cm^2 diamond-like carbon film with a capacity of 22 pieces and a theoretical stripping efficiency of 99.7% [1-3]. The proton beam after being peeled off by the primary stripper foil enters the RCS for acceleration. The secondary stripper has a foil storage capacity of 1 piece with a 200 μg/cm^2 diamond-like carbon foil. A negative hydrogen ion absorption block is designed on the secondary stripper foil to absorb negative hydrogen ions that have not been stripped off through the primary stripper foil. The H_0 particles, after stripping one electron through the secondary stripper foil, are change into protons and extracted to the beam dump [4, 5]. The structure of the primary stripper foil of CSNS adopts a rotating steel strip structure, and the foils are uniformly distributed on the rotating steel strip. Each foil needs to be installed separately. At the same time, according to the radiation protection requirements of CSNS, the stripper foil does not consider radiation shielding and does not reserve installation space for radiation shielding. During the operation of the CSNS accelerator, the service life of the primary stripper foil is less than 1 month per piece, and the residual dose on the surface of the foil rack after operation can reach up to 2000 μSv/h, in addition, the operator needs to carry out maintenance work in close proximity for a long time. The secondary stripper foil structure is similar to the primary stripper foil structure, but there is no rotating steel strip structure. According to physical requirements, the CSNS-II stripper foil still adopts two sets of stripper foil devices, including one primary stripper foil and one secondary stripper foil, which have the same function as the CSNS stripper foil. However, due to the increase in radiation dose, it is impossible to maintain the equipment in close proximity. Therefore, a new overall foil store quick replacement mechanism must be adopted and a new maintenance plan must be redesigned.

ANALYSIS OF THE FOIL DURING BEAM INJECTION

According to the physical design scheme of the CSNS-II RCS injection zone, as shown in Fig. 1, the RCS injection beam energy is increased from 80 MeV to 300 MeV. After the injection energy of CSNS-II is increased to 300 MeV, according to the relationship between foil thickness and stripping efficiency shown in Fig. 2, in order to maintain a stripping efficiency of 99.7%, the thickness of the primary stripper foil needs to be increased to 260 μg/cm^2, and according to the size of the beam spot, the transverse size of the foil is required to be no less than 20 mm * 60 mm [4], and the material is HBC.

According to the analysis of beam injection into the stripper foil, when the injection energy is 300 MeV and the film thickness is 260 μg/cm^2, the number of repeated beam passes is 15, and the half axis size of the elliptical beam spot is 3 * 1.5 mm. Assuming that the beam spot is uniformly distributed within the central range, the rest is Gaussian distribution. The mathematical model of a Gaussian heat source is shown in formula (1).

$$D(x,y)=\frac{E_{\text{total}}}{2\pi\sigma_x\sigma_y}\exp\left(-\frac{x^2}{2\sigma_x^2}\right)\exp\left(-\frac{y^2}{2\sigma_y^2}\right) \tag{1}$$

Among them, E_{total} is the total energy deposited on the foil, and σ_x, σ_y are the radius of the major and minor axes of the elliptical Gaussian heat source. It is known that the injection point is 7 mm away from the edge of the foil. Therefore, the mathematical model of the Gaussian heat source is shown in formula (2).

$$D(x,y)=\frac{E_{\text{total}}}{2\pi\sigma_x\sigma_y}\exp\left(-\frac{(x-0.007)^2}{2\sigma_x^2}\right)\exp\left(-\frac{(y-0.007)^2}{2\sigma_y^2}\right) \tag{2}$$

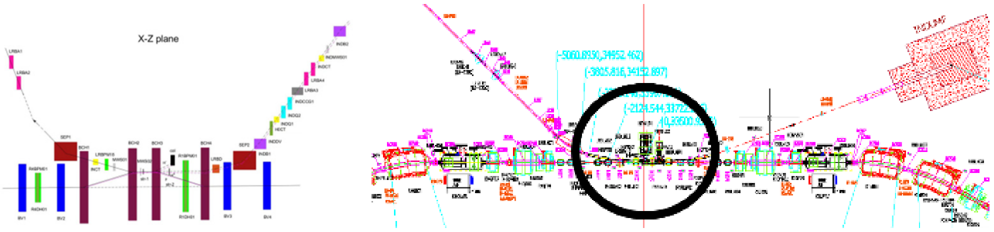


Figure 1: CSNS-II Injection Zone Layout.

Using ANSYS for simulation analysis, uniformly distributed power was loaded at the center, an elliptical Gaussian heat source was loaded at the periphery, and the temperatures of each sub step of the highest temperature node were obtained. The results are shown in Fig. 3. From the figure, it can be seen that after ten cycles, the temperature trend remained stable, with the highest temperature being 1483 K and the lowest temperature being 681 K. The temperature distribution is shown in Fig. 4, and the melting point of the carbon film is about 3800 K, so the temperature is within the range that the film can withstand.

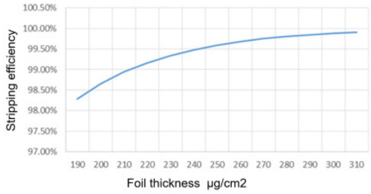


Figure 2: Stripping efficiency.

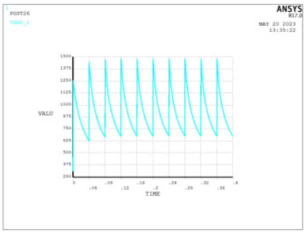
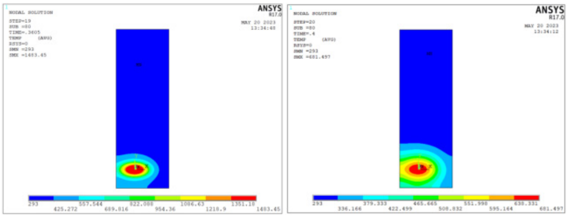


Figure 3: Temperature Curve of stripper foil.



a The highest temperature b The lowest temperature

Figure 4: Distribution of the highest and lowest temperatures of the foil.

STRUCTURE SCHEME OF STRIPPER FOIL

Due to the high dose in the injection area and the high risk of personnel operating in close proximity, the CSNS-II stripper foil is planned to adopt an automatic replacement foil store structure and have remote maintenance capabilities, in order to complete the maintenance and repair of the stripper foil with minimal personnel intervention. At the same time, in order to reduce the overall radiation dose level in the injection area, it is necessary to extend the movement distance of the foil frame to provide installation and maintenance space for radiation protection shielding. The primary stripper foil needs to consider functions such as automatic replacement of the foil store, remote maintenance, and shielding. According to the frequency of use, the guiding mechanism should guide no less than 2000 times; The repeated positioning accuracy of the foil frame is ± 0.2 mm; During the movement of the foil frame, there is no detachment of the docking mechanism; The repeated positioning accuracy of the foil store is ± 0.05 mm.

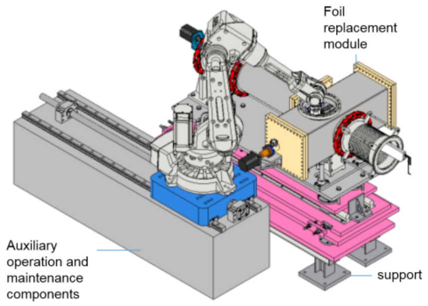


Figure 5: CSNS-II primary stripper foil.

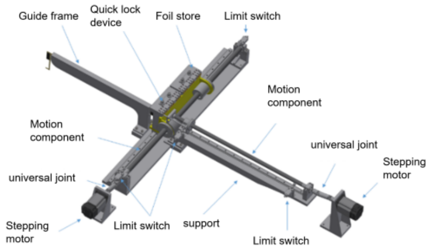


Figure 6: Internal structure of foil replacement module.

The primary stripper foil structure and foil replacement module are shown in Fig. 5, and the equipment mainly consists of foil replacement components, chassis components, and auxiliary operation and maintenance components. The foil replacement component is a key component for storing foils and achieving automatic foil replacement. In order to achieve rapid replacement of the stripper foil, a design scheme of an integral foil store was adopted. During maintenance, the maintenance of the stripper foil system can be completed by simply replacing the entire foil store, greatly reducing maintenance time and reducing residual radiation dose to personnel. Its internal structure is shown in Fig. 6, consisting of components such as foil frame guide, foil store components, guide rods, and support frames. The auxiliary operation and maintenance component adopt a series robot for maintenance work. After the series robot takes out the entire foil store that needs to be replaced, the new foil store is loaded into the cavity of the foil replacement component. After evaluation, the foil replacement time is saved by more than 80% compared to the foil replacement time of the steel strip structure, effectively reducing the time for maintenance personnel to operate close range.

When replacing the foil, a high-precision automatic docking structure is used, which pushes the foil from the foil store to the working position through the docking between the guide rod and the slider; When the foil needs to be replaced, the slider is pulled back into the foil store through the guide rod, and then a new foil is switched to achieve the replacement of the foil. In order to achieve the overall replacement process of the foil store, the slider returned to the foil store needs to be locked to prevent it from sliding out. Therefore, a special mechanism needs to be set between the foil frame and the foil store to achieve self-locking functions. An asymmetric V-shaped plate spring is used to lock and open the slider. The force is shown in Figure 7. When the guide rod pushes the slider outward, it needs to overcome the locking force F of the leaf spring to push it out. When the guide rod pulls the slider back to the stripper foil, it needs to overcome the stopping force F of the leaf spring to retreat. The force situation of the leaf spring structure is shown in Fig. 7.

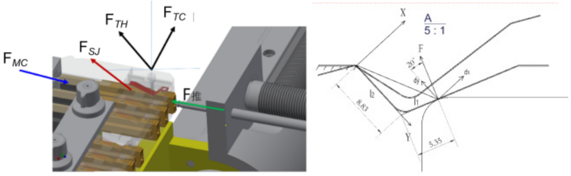


Figure 7: Force situation of self-locking structure.

E is known to be the elastic modulus of the material; I is the moment of inertia, $I = hb^3/12$, where b is the cross-sectional width and h is the cross-sectional thickness. According to the design parameters, $\theta = 20^{\circ}, L1 = 5.35, L2 = 8.8, h = 0.25\text{mm}$. It can be calculated that when the guide rod pulls the slider back to the foil store for self-locking $F_{TH} \approx 15.1N$, and when the guide rod inserts the slider for self-locking $F_{TC} \approx 6.28N$, it opens automatically. The actual measurement of the mechanism was carried out using a tension meter. When the guide rod is inserted into the slider for self-locking, its tension is 7.37 N, and when the guide rod exits the slider, its unlocking tension is 14.25 N, which has a small deviation from the calculated results.

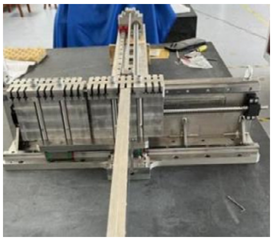


Figure 8: Prototype of stripper foil motion mechanism.

In order to verify the stability and motion accuracy of the structure, a set of experimental prototypes was developed, as shown in Fig. 8. Key parameters were tested, including reciprocating motion testing, repeated positioning accuracy testing, docking testing, and self-locking structure testing. After testing, the guiding mechanism has reciprocated more than 2000 times, and the repeated positioning accuracy is better than ± 0.1 mm. The lateral motion accuracy of the foil magazine is better than ± 0.007 mm.

CONCLUSION

The injection power of the CSNS-II primary stripper foil has been increased to 300 MeV, and the foil's thickness is 260 μg/cm^2. Using a combination of uniformly distributed and elliptical Gaussian analysis, the highest temperature on the foil is 1483 K, which is within the acceptable range of the foil. Due to the increase in injection power, the regional dose will increase. Adopting an overall foil storage structure design combined with the use of series robots for operation and maintenance work will effectively reduce maintenance time. Through the development and testing of the prototype, it has been proven that the structure has good stability and high motion accuracy, meeting the requirements for the foil system.

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