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FINAL REPORT ON THE START PROGRAMME

Development of a Compact Device for Tensioning a Boron Carbide Foil Converter

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Abstract

In this work, a compact mechanical device for uniformly tensioning boron carbide-coated aluminum foil used in neutron detector systems was developed and optimized. The motivation stems from the need to ensure the geometric stability of converter foils mounted at grazing incidence angles in modern high-efficiency detectors. An existing prototype was analyzed and found to have limitations in spring force control, leading either to insufficient or excessive tension. To address this, a revised design was proposed, incorporating a crank-slider mechanism with torsion springs. Analytical calculations and finite element simulations were performed to determine the appropriate spring parameters and stress distribution in the foil. The final design ensures a sufficient safety factor and improved compactness.

Introduction

In the context of increasing demands for accuracy and speed in neutron research—particularly at pulsed sources such as IBR-2—high-performance and radiation-resistant detectors are becoming crucial. One of the promising approaches involves the use of boron carbide (B_4C)-based converters [1], enriched with the isotope ^{10}B. These converters offer high neutron detection efficiency, stable operational characteristics even under intense neutron flux, and low sensitivity to gamma background. Their implementation is especially important for the upgrade and modernization of the IBR-2 facility at JINR, which was relaunched in February 2025. New detector systems based on such converters will significantly enhance measurement accuracy and ensure compliance with the global standards of neutron diagnostics—an essential factor under the current shortage of neutron capabilities in Russia.

An essential structural component of detectors with B_4C converters is a thin foil (in our case, aluminum) onto which the active coating is applied. To ensure geometric stability, minimize parasitic vibrations, and maintain a constant angle of neutron incidence into the detector layers, it is necessary to develop a specialized device for uniform and reliable foil tensioning. This is particularly important in detector designs where the converter is mounted at a grazing angle to the neutron beam, such as in Multi-blade and Multi-foil configurations [2]. Uncontrolled sagging or deformation of the foil can lead to distortions in registration geometry, reduced spatial resolution, and diminished detection efficiency. Therefore, the development of a compact tensioning device for foil-based converters is a critical step toward creating stable and highly efficient next-generation neutron detectors.

1. Existing prototype

A larger prototype of the target device has already been developed at the design bureau. It was intended for the preparation of boron-coated foil with strip dimensions of 264 mm in length (within the active area) and 200 mm in width, with a thickness of 50 microns. The device itself is shown in Fig. 1.

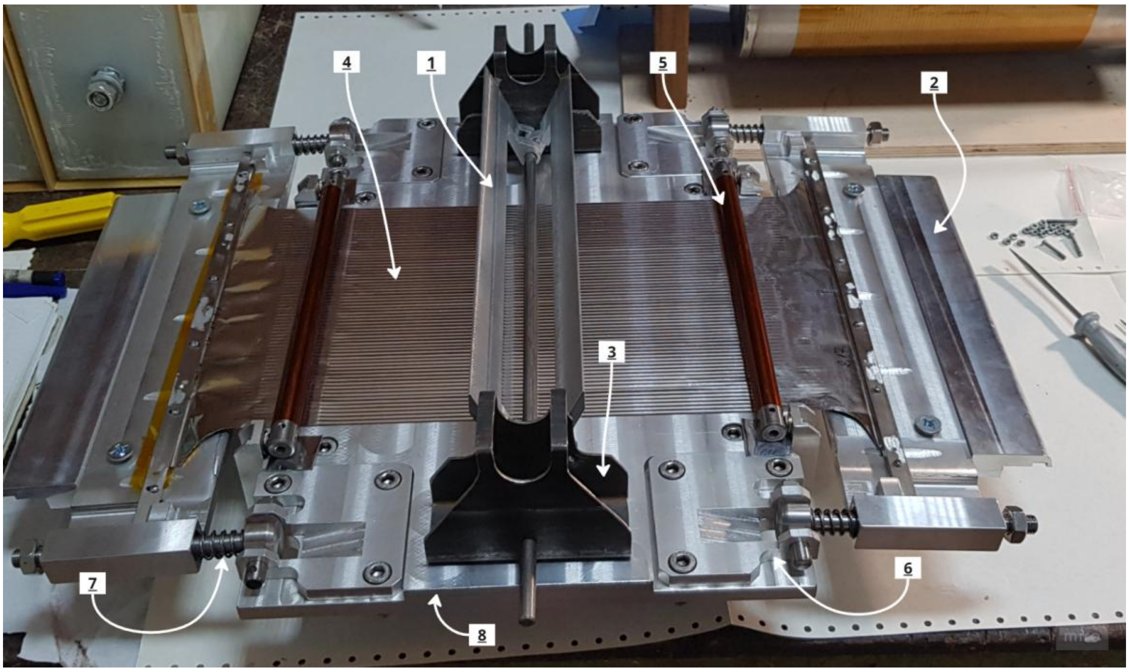

Fig. 1. Foil tensioning device

The main structural elements of the device are:

1. Latches for holding the handles in the tensioned position.
2. Arm and handle to which the stretched foil is attached.

3. Mounting support for securing the axis with latches.
4. The foil itself with strips coated with boron carbide.
5. Axis for stretching the foil by rotating the handles toward the latches.
6. Hinged mounts with an axis for the springs.
7. Two tension springs connected in series.
8. Base plate to which all components are attached.

The main elements of this device, apart from the boron-coated foil, are the tension springs, which maximally stretch the foil in the position shown in Fig. 1.

The main drawbacks of this design were:

1. Insufficient foil tension when using a thin spring with a diameter of 1 mm. In the position shown in Fig. 2, the handle of the device would hang loose and failed to provide the required tension.

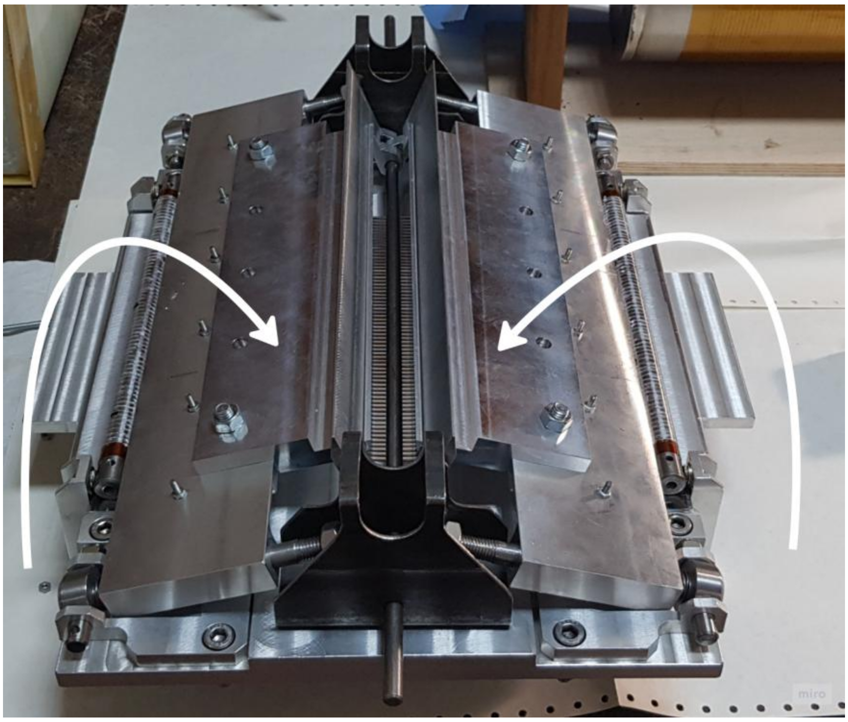

Fig. 2. Spring compression position

2. Excessive stretching when slightly thicker springs (1.6 mm in diameter) were used, which often resulted in the foil tearing. In this case, the handle could not physically reach the latch in the position shown in the figure, making it impossible to apply proper tension.

Given these circumstances, it was decided to use two springs with a diameter of 1 mm on each axis to provide the minimum required tension.

1.1. Required changes

Accordingly, the following technical specifications were formulated for the development of a more compact tensioning device for small-scale monitors:

1. Reduction of foil dimensions to 208.5 mm in length (within the active area) and 120 mm in width, as determined by the size of the monitor under development.
2. Modification of the foil tensioning mechanism to avoid issues related to insufficient or excessive spring force.

All subsequent design changes to individual components were driven by the need to simplify the manufacturing process and facilitate the operation of the resulting device.

2. Resulting device

The result of the optimization work on the model is the transition from the assembly of the device shown in Figure 3 to a more compact device in Figure 4.

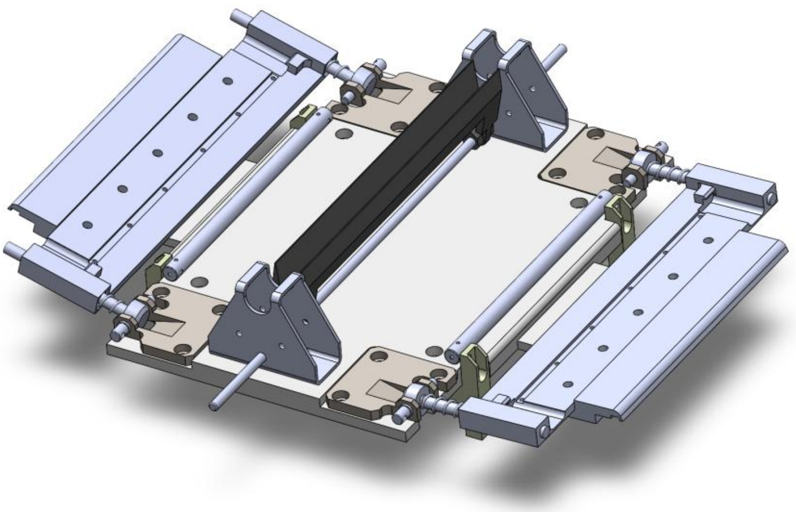

Fig. 3. Initial assembly model of the device.

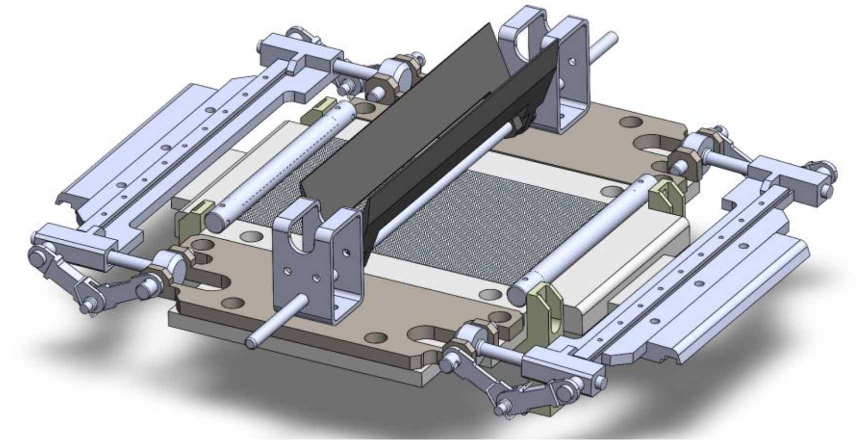

Fig. 4. Final assembly model.

The main significant cosmetic changes included the lightening and simplification of the shoulder and handle model, as well as the integration of the joints on each side into a single part.

The key structural change in the assembly is the crank-slider mechanism with a torsion spring on the axis connecting this mechanism. As shown in Figure 4, each shoulder, as in the previous model, uses a spring on each side.

2.1. Spring Calculation.

To avoid repeating the previous mistake in selecting a suitable spring, a series of calculations was carried out to determine the appropriate torque for the torsion spring along with a sufficient safety factor within the range of 0.7–3.0 [3]. However, due to the necessity of ensuring the absolute integrity of the foil, a more conservative safety factor range of 1.0–3.0 was adopted.

The initial step was to define the input parameters of the spring:

- Material – 12X18H10T;
- Number of coils N – 6.25;
- Inner diameter D (shaft) – 6 mm;
- Coil diameter d – 2.5 mm.

The next step was to determine the spring stress correction factor, which can be calculated using Equation 1:

$$k = \frac{d^4 E}{64 D_m N} \ , \tag{1}$$

where E is the modulus of elasticity for the specified steel grade (1.95–2 × 10^5 N/mm²).

Substituting all the values into the formula, we obtain that with the given parameters the stress correction factor equals:

$$k = \frac{2{,}5^4 \cdot 2 \cdot 10^6}{64 \cdot 8.2 \cdot 6.25} = 2293.8 \frac{N \cdot mm}{rad}$$

Since we need to use the spring rotation in degrees, we convert this value to N·mm/deg using Formula 2:

$$k_1 = \frac{k \cdot \pi}{180} = 40.1 \frac{N \cdot mm}{deg} \tag{2}$$

Next, we calculate the torque M using Formula 3 and the force using Formula 4:

$$M = k_1 \cdot \theta \tag{3}$$

$$F = T \cdot l, \tag{4}$$

where θ – maximum spring torsion angle – 42.65°;

l – spring arm length, 14 mm.

Thus we obtain:

$$M = 1710.43 \ N \cdot mm, \qquad F = 122.17 \ N$$

2.2. Strength verification of the device

Next, we use Formula 5 to calculate the stress on the aluminum foil (2F, since there are two springs on each side):

$$\sigma = \frac{2F}{t \cdot w} \tag{5}$$

where t – foil thickness, 0,05 mm;

w – foil width, 120 mm.

The resulting stress value is:

$$\sigma = \frac{2 \cdot 122.17}{6}\ MPa = 40.72\ MPa$$

The next step involves comparing the obtained calculated data with experimental simulations performed in Solidworks Simulation. Figure 5 shows the von Mises stress distribution in the solid foil.

Fig. 5. Stress distribution in the solid foil at standard mesh resolution.

According to this analysis, under uniform tension applied from both sides with a force of 151.9 N each, the average stress equals approximately 40.7 MPa, which generally agrees with the calculated data.

However, it should be noted that our foil contains strips 1.65 mm wide with 0.15 mm spacing between them. In this configuration, the stress distribution changes, as shown in Figure 6.

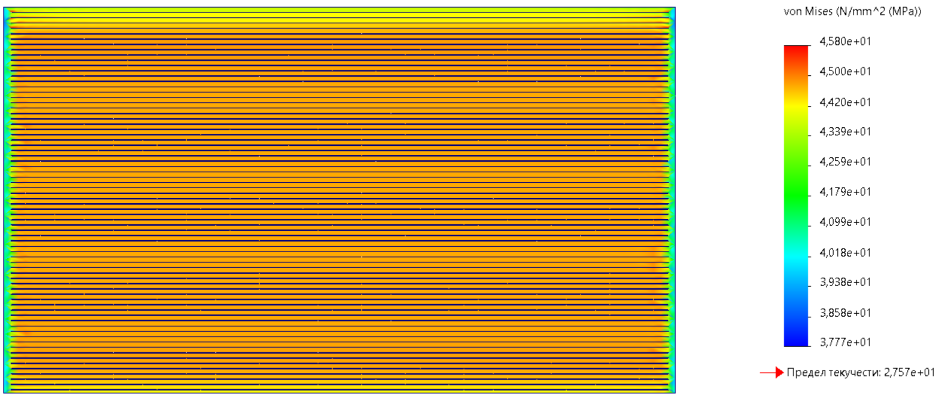

Fig. 6. Stress distribution in the foil with strips at standard mesh resolution.

According to GOST 618-2014 [4], the ultimate tensile strength σ for foil with thickness 0.045-0.200 mm is 120 MPa.

Thus, according to Formula 6, the safety factor equals:

$$n = \frac{\sigma_{ult}}{\sigma} = \frac{120}{45.8} = 2.62 \qquad (6)$$

This falls within our previously specified safety factor range (1.0-3.0).

Results

As a result of the conducted work, calculations were performed for the torsion springs used in the updated version of the foil tensioning device for converter-based detector systems. A finite element analysis was carried out to determine the stress distribution in the foil, and the corresponding safety factor was established. Based on these results, a more compact and reliable design was developed, incorporating a crank-slider mechanism with an optimized spring configuration. In addition, a complete set of technical documentation was prepared for the subsequent manufacturing of the device.

The proposed device is directly related to the development of detectors utilizing boron-based converter materials, which are increasingly relevant due to the global shortage of ^{3}He and the shift toward solid-state neutron detection technologies. These devices are particularly in demand for use in monitoring systems at high-intensity and compact neutron sources currently being developed in Russia, including the "Darya" project and upgraded scattering stations at IRT-T and IBR-2.

Thus, the completed work represents a significant contribution to the development of the hardware and methodological base of the Russian neutron research infrastructure and meets the needs of ensuring efficient operation of next-generation detector systems, especially important in the context of limited access to foreign neutron sources.

References

1. M. Anastasopoulos, R. Bebb, K. Berry, I. Stefanescu, Multi-Grid detector for neutron spectroscopy: results obtained on time-of-flight spectrometer CNCS, J. Instr. 12 (2017) P04030. https://doi.org/10.1088/1748-0221/12/04/P04030
2. F. Messi, G.Mauri, F. Piscitelli, The Multi-Blade: The ^{10}B-based neutron detector for reflectometry at ESS, Nucl. Instrum. Meth. A 936 (2019) 499-500. https://doi.org/10.1016/j.nima.2018.10.058
3. SP 128.13330.2016. Steel Structures. Design Standards [in Russian], Ministry of Construction of Russia, Moscow (2016) p. 49, Table 37. URL: https://files.stroyinf.ru/Data2/1/4293747/4293747699.pdf
4. GOST 618-2014. Aluminum and Aluminum Alloy Foil. Technical Specifications [in Russian], Standartinform, Moscow (2014) p. 4, Table 4.