Enhancement of neutron irradiation uniformity for the CFBR-II fast burst reactor with a biaxial rotational technique*

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A biaxial rotational technique is proposed to improve the neutron irradiation uniformity for a large sample, and the theoretical method is established to predict and design the main parameters. The technique used a device to rotate the target sample around two perpendicular axes simultaneously. Numerical calculations found that the lowest common multiple of the two angular speeds should be large enough to improve the uniformity, and the minimal experimental time should be no less than 600 s. For a three-dimensional sample with a size of 20 cm × 12 cm × 14 cm, the maximal non-uniform neutron irradiation factor of the sample is mainly determined by the distance between the center of the sample and of the point neutron source. It was computed to be less than 10% when the distance was no less than 34 cm. Experiments were carried out on the CFBR-II reactor and the experimental results were in good accordance with the theoretical analysis. As a result, the theoretical conclusions given above are reasonable and of reference value for the design of future irradiation experiments.

Keywords: Biaxial rotational technique, The Chinese Fast Burst Reactor-II (CFBR-II), Neutron irradiation uniformity

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I. INTRODUCTION

For the electronic materials and devices used in the space or nuclear radiation environment, neutron irradiation effects are widely studied to provide the foundation for radiation hardening design [1–4]. In practice, some of the electronic devices are relatively large, and it is often desirable to irradiate these large samples uniformly at high neutron fluence levels.

A fast burst reactor is often adopted as the neutron source [2, 5, 6]. However, the neutron flux distribution is generally not flat by itself [7, 8], and the non-uniform fluence may become unacceptable for the study of the irradiation effects of a large sample [9, 10]. A more uniform neutron field can be achieved at a longer distance away from the source [7], but it may result in dramatic reduction in neutron flux in most cases [9, 10]. Ideal multiple radiation sources may improve the irradiation uniformity [10], but there is no such device available yet. A possible solution to this dilemma is to conduct irradiation experiments in the core of an advanced fast-neutron reactor, as these reactors generally have large central cavities. The SPR III in the USA has a 16.5 cm diameter central cavity for the radiation testing of electronic parts and systems [2]. In Russia, the BR-1 reactor has a ϕ10 cm × 18 cm central cavity [11], and the BARS-5 reactor has two cores with diameters of 9 cm and 11.5 cm, respectively.

When the room in the core of a reactor is not enough for a large sample, as is the situation for the Chinese Fast Burst Reactor-II (CFBR-II) [12], an auxiliary device is required to improve the irradiation uniformity at a certain distance away from the neutron source. A general rotator can be used to improve the irradiation uniformity, but is still not satisfactory for a large three-dimensional sample.

This study aims to provide a theoretical foundation for the design of experiments with a novel biaxial rotational device, which will provide an enhanced neutron irradiation uniformity for the CFBR-II fast burst reactor. The biaxial rotational device rotates a sample around two perpendicular axes simultaneously. Numerical calculations and experimental verifications were carried out, and these results are of reference value for the design of irradiation experiments.

II. THEORETICAL MODELS

To provide a basis for the prediction and design of irradiation experiments, the effect of the biaxial rotation on the irradiation non-uniformity of a three-dimensional sample was analyzed. The model of irradiation is shown in Fig. 1.

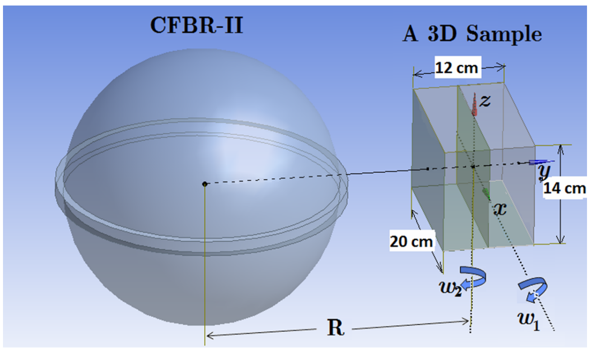

Fig. 1. (Color online) Model of the irradiation experiment.

The irradiated target is assumed to be a three-dimensional sample with a size of 20 cm × 12 cm × 14 cm, and the loca-

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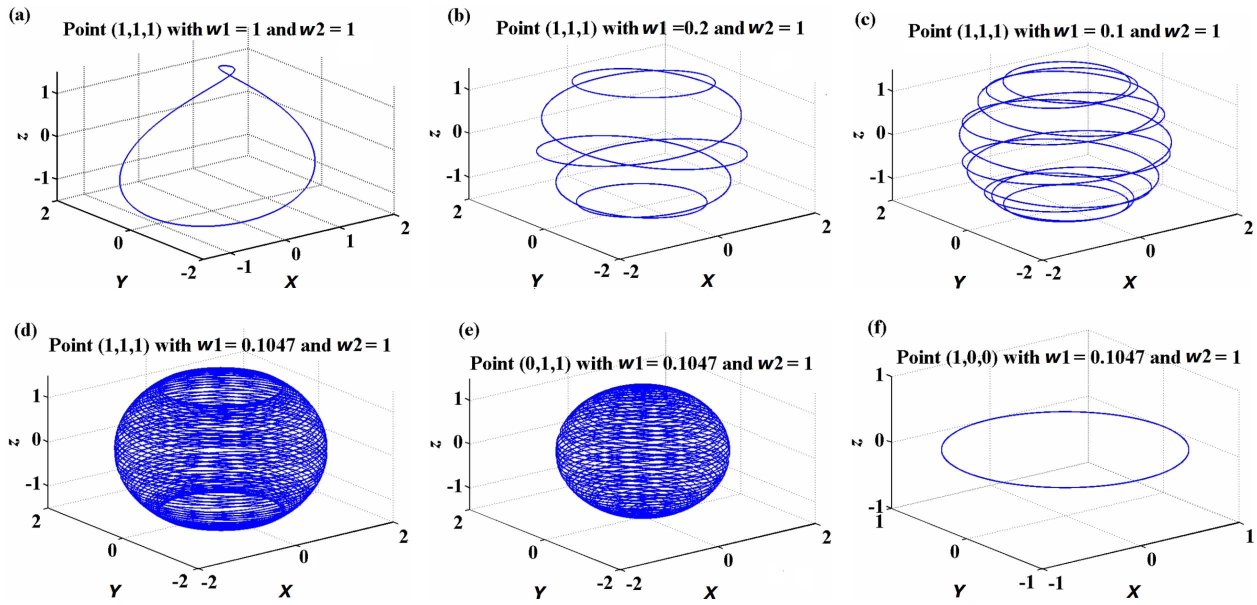

Fig. 2. (Color online) Typical trajectory patterns of a point located on the sample.

tion of the sample center is assumed to be the origin of coordinates. The biaxial rotational device rotates the sample around two axes simultaneously. The horizontal axis initially coincides with the X-axis and the angular speed around it is w_1(rad/s). The vertical axis always coincides with the z axis, and the angular speed is w_2(rad/s).

Before analyzing the irradiation non-uniformity, the trajectory of a point on the sample must be computed. For a point initially located at (x_0, y_0, z_0) on the sample, we computed the time-dependent space coordinates of the point as follows.

$$\begin{cases} x = x_0 \cos(w_2 \times t) - y_0 \cos(w_1 \times t) \sin(w_2 \times t) + z_0 \sin(w_1 \times t) \sin(w_2 \times t) \\ y = x_0 \sin(w_2 \times t) - y_0 \cos(w_1 \times t) \cos(w_2 \times t) - z_0 \sin(w_1 \times t) \cos(w_2 \times t), \\ z = y_0 \sin(w_1 \times t) + z_0 \cos(w_1 \times t) \end{cases} \quad (1)$$

Obviously, it would be difficult to treat a three-dimensional neutron source as the CFBR-II reactor. A point neutron source located at $\vec{R} = (0, -R, 0)$ is considered in this model, and both scattering and absorption of the neutron field due to the sample are also neglected. The neutron fluence rate for a point located at $\vec{r} = (x, y, z)$ is $\phi(\vec{r})$, which is proportional to $\frac{1}{(\vec{r}-\vec{R})^2}$. As a result, the average neutron fluence rate over time T for a point initially located at (x_0, y_0, z_0) is

$$\Phi(x_0, y_0, z_0) = \frac{1}{T}\int_0^T \phi \mathrm{d}t \propto \frac{1}{T}\int_0^T \frac{1}{(\vec{r}-\vec{R})^2}\mathrm{d}t. \quad (2)$$

The average neutron fluence rate at the center of the sample is selected as the reference value, $\Phi(0)$, and the non-uniform neutron irradiation factor of this point is defined as follows,

$$\eta = \frac{|\Phi(r) - \Phi(0)|}{\Phi(0)} \times 100\%. \quad (3)$$

The maximum η for any point on the irradiated sample is regarded as the η of the sample. The goal of theoretical analysis is to get a relatively small η, e.g. less than 10% of the sample considered, and the distance away from the neutron source, R, should be as small as possible to provide a relatively high neutron fluence level.

The theoretical expressions were solved numerically by Matlab software.

III. NUMERICAL CALCULATIONS

A. Trajectory patterns

As the sample center coincides with the origin of coordinates, the trajectory of a point on the sample is always located on a spherical surface. If the trajectory is more uniform, the non-uniform factor η should be smaller. The trajectory depends on both initial locations and the ratio of w_2/w_1 (if $w_1 \neq 0$). Typical trajectory patterns are shown in Fig. 2.

When the angular speed, w_2, around the vertical axis is set to be 1 rad/s, the change in w_1 would result in different kinds of trajectory patterns as shown in Fig. 2(a)– 2(d). For most cases, if the initial coordinates of a point on the sample are located neither on the Z axis nor on the middle horizontal plane, the trajectory pattern is similar to that of the point initially located at (1, 1, 1). The trajectory patterns in Fig. 2 and other unlisted results suggest that the distribution of the trajectory path becomes more uniform as the lowest common multiple of w_1 and w_2 becomes larger. The trajectory line is sparsely distributed if the w_1 is equal to 1 rad/s, 0.2 rad/s, or 0.1 rad/s, but a uniformly distributed barrel structure can be obtained if $w_1 = 0.1047$ rad/s. A more uniform trajectory pattern is supposed to result in a smaller η, and this assumption will be confirmed in the following text.

The trajectory patterns also depend on initial location. On the condition of $w_1 = 0.1047$ rad/s and $w_2 = 1$ rad/s, the point initially located on the yz plane would result in a spherical trajectory pattern with an increase in time, and the point initially located on the x axis would result in a simple two dimensional circle.

B. Minimal experimental time

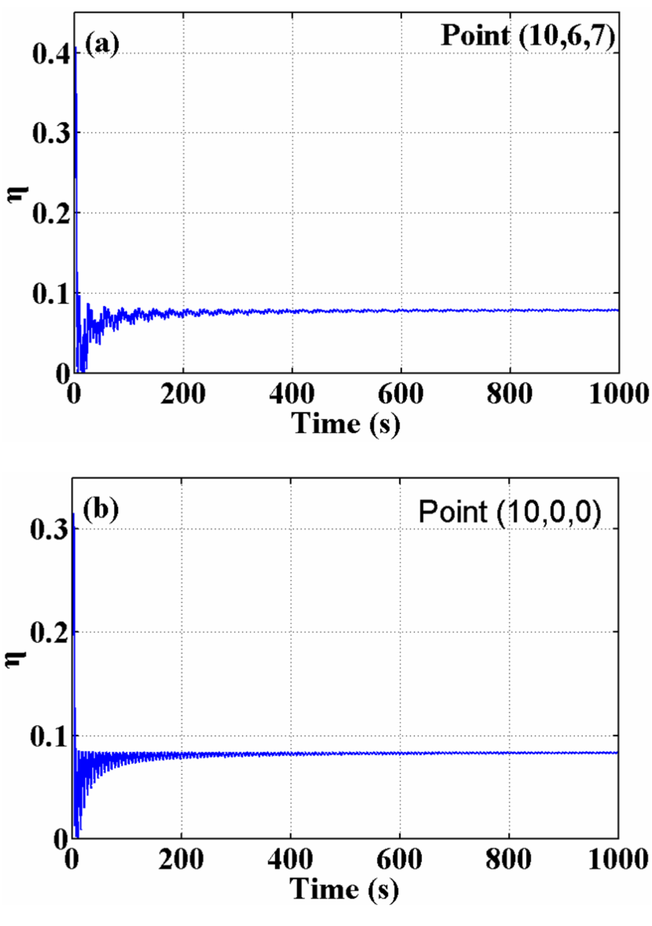

Fig. 3. (Color online) The η as a function of time.

Based on the relationship between the angular speeds and the trajectory patterns, the angular speeds of the biaxial rotational equipment were set to be $w_1 = 0.1047$, $w_2 = 1$. If the distance away from the neutron source is 36 cm, the non-uniform neutron irradiation factor, η, as a function of time for the points initially located at (10,6,7) (Coordinates are in centimeters, so as the following text) and (10,0,0) are shown in Figs. 3(a) and 3(b), respectively. It can be observed that the oscillation of η becomes moderate with an increase in time for both cases, and the maximum difference of η is less than 0.4% after about 600 s. As a result, the minimal experimental time should be no less than 600 s under the condition given above, and this requirement is generally easy to meet.

C. Minimal R

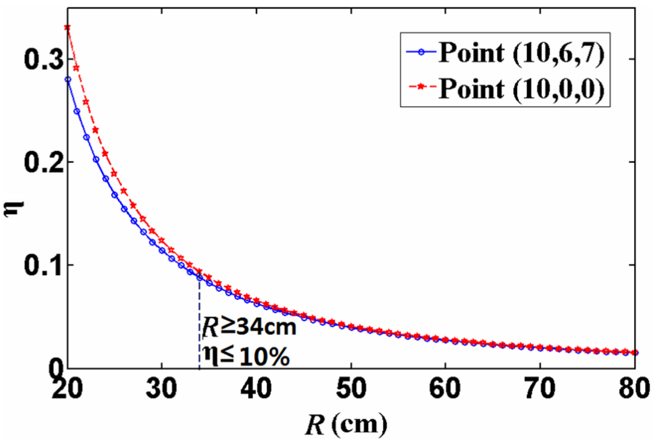

Fig. 4. (Color online) The η as a function of the distance away from the neutron source.

R has the greatest influence on the neutron fluence levels for most of the irradiation experiments, and it should be as small as possible to save experimental time. Under the condition of $w_1 = 0.1047$ and $w_2 = 1$, the theoretic value of η was shown in Fig. 4 as a function of R for the points initially located at $(10, 6, 7)$ and $(10, 0, 0)$. In order to alleviate the deviation caused by time, the η provided is the average result around time 600 s. As expected, the η decreases quickly with the increase of the distance away from the neutron source R for both cases. The η for point $(10, 6, 7)$ is less than that for point $(10, 0, 0)$, and R should be no less than 34 cm if $\eta < 10\%$. Since the CFBR-II is treated as a point neutron source, we conjectured that $R = 36$ cm might satisfy $\eta < 10\%$ under experimental situation.

D. Angular speeds of the biaxial rotational equipment

When $R = 36$ cm and $w_2 = 1$, the η of point $(10, 6, 7)$ and point $(10, 0, 0)$ as a function of w_1 were computed, as shown in Fig. 5. It can be observed that w_1 has little effect on the η of point $(10, 0, 0)$ because the corresponding trajectory path is always a circle, but the η of point $(10, 6, 7)$ is sensitive to the selection of w_1 due to the change of trajectory patterns as shown in Fig. 2. The results suggest that the distribution of the

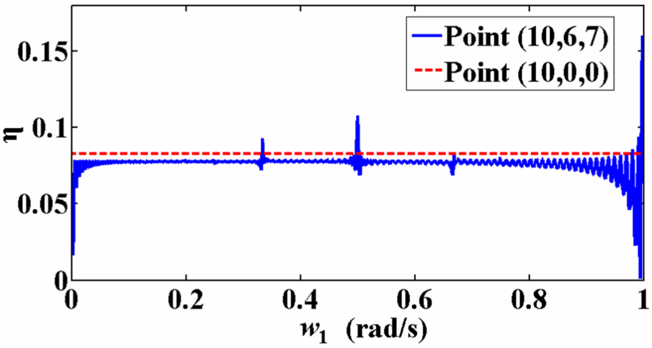

Fig. 5. (Color online) The η as a function of w_1 when $w_2 = 1$.

trajectory path should be as uniform as possible to enhance neutron irradiation uniformity. In the design of the irradiation experiment, the lowest common multiple of w_1 and w_2 should be large enough, e.g., when $w_1 = 0.1047$ and $w_2 = 1$.

E. Spatial distribution of η

The above discussions generally focused on the η of typical points when $w_1 = 0.1047$, $w_2 = 1$, and $R = 36$ cm. Based on analysis of the trajectory pattern of a point initially located at (x_0, y_0, z_0), the spatial distribution of η was shown in Fig. 6(a) to evaluate the η of the sample under the same conditions, where $r_{yz} = \sqrt{y_0^2 + z_0^2}$. It can be observed that r_{yz} has little effect on η, suggesting that the η is almost the same for a sample with a larger y_0 and z_0. The maximum η mainly depends on the value of x_0. More explicitly, the computed η is less than 1% when $|x_0|$ is less than 3.5 cm, and the η is less than 8.5% when $|x_0|$ is not larger than 10 cm.

For the generally adopted single axis rotator (around axis Z), the typical space distributions of η were shown in Fig. 6(b) with $w_1 = 0$ and $w_2 = 1$. It can be observed that η depends on both z_0 and r_{xy} ($r_{yz} = \sqrt{y_0^2 + z_0^2}$), and the maximum η is about 12%. For the static state irradiation experiments, the spatial distribution of η on the horizontal middle plane was shown in Fig. 6(c). η is very sensitive on the space location, and has a maximum value of 44%. As a result, we demonstrated that a sample rotating around two perpendicular axes simultaneously can result in significant enhancement of the irradiation uniformity.

IV. EXPERIMENTAL VERIFICATION

The schematic diagram and a picture of the biaxial rotational equipment are shown in Fig. 7. The real-time operational state of the equipment can be monitored and controlled by a computer, and the angular speeds can be easily changed according to experimental requirement.

The experimental layout is designed to be in accordance with the theoretical model given in Fig. 1, and the distance between the centers of the sample and the CFBR-II reactor is 36 cm. The neutron fluence was measured by the neutron

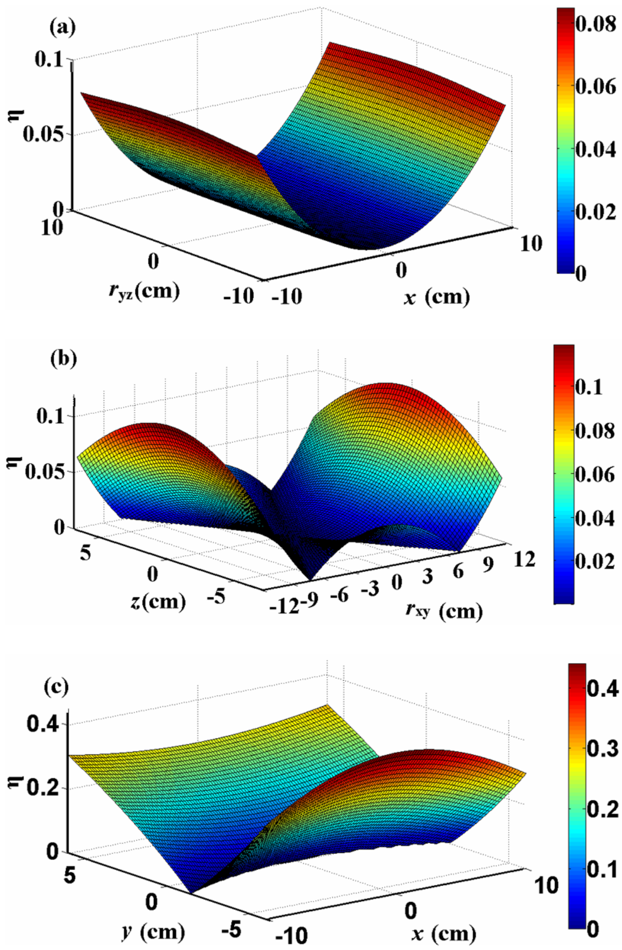

Fig. 6. (Color online) Spatial distributions of η when (a) $w_1 = 0.1047$ and $w_2 = 1$; (b) $w_1 = 0$ and $w_2 = 1$; and (c) $w_1 = w_2 = 0$.

activation method and nickel discs were adopted. 28 nickel disc were stuck on the 7 faces (6 outer faces and 1 vertical inner face) as shown in Fig. 1. With $w_1 = 0.1047$ and $w_2 = 1$, the maximal η measured in the experiment was 9.3%, in accordance with the theoretical value of 8.5%. For the static state irradiation experiments with $w_1 = w_2 = 0$, the maximal η measured in the experiment was 49.0%, which also agrees with the theoretical value of 44%. As a result, the theoretical analysis given above is reasonable and of reference value for the design of future irradiation experiments.

V. CONCLUSION

Because the room in the core of a reactor may be not enough for a large sample, an auxiliary equipment is required to improve the irradiation uniformity at a certain distance away from the neutron source. A biaxial rotational technique is proposed to improve the neutron irradiation uniformity for a large sample, and the theoretical method is established to predict and design the main parameters. The lowest common multiple of the two angular speeds should be large enough to

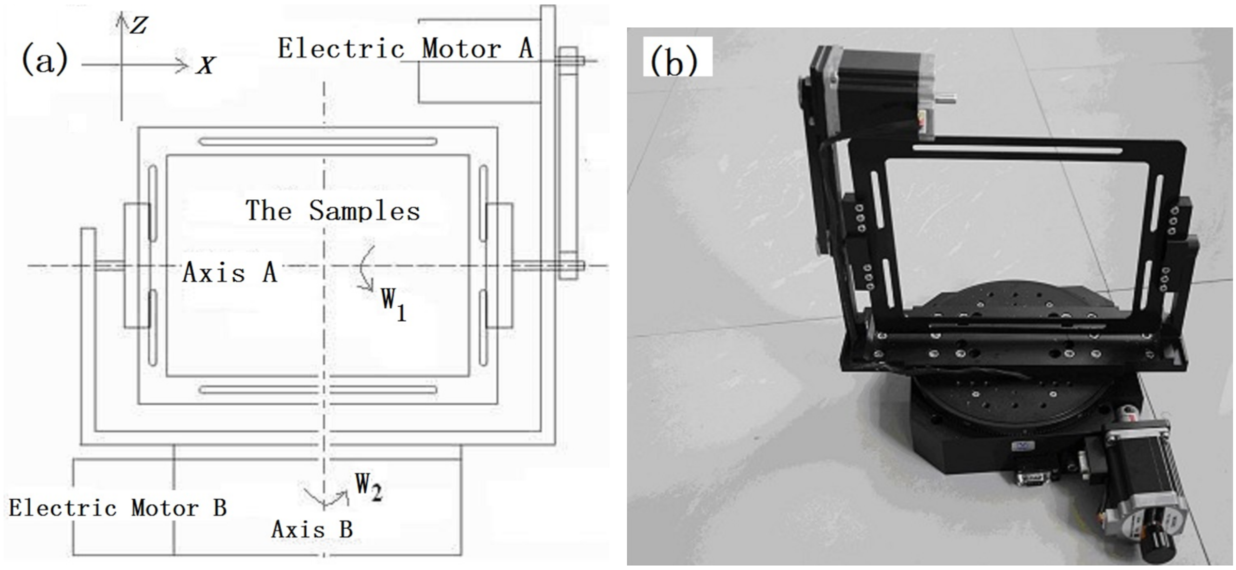

Fig. 7. (Color online) (a) The schematic representation and (b) the picture of the biaxial rotational equipment.

improve the uniformity, and the minimal experimental time should be no less than 600 s. For a three-dimensional sample with a size of 20 cm × 12 cm × 14 cm, the maximal non-uniform neutron irradiation factor of the sample is mainly determined by the the distance between the centers of the sample and the point neutron source. It was computed to be less than 10% when the distance was no less than 34 cm. Experiments were carried out on the CFBR-II reactor and the experimental results were in good accordance with the theoretical analysis. As a result, the theoretical conclusions given above are reasonable and of reference value for the design of future irradiation experiments.

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