Positron Emission Tomography of Not-Full-Ring Sensors Arrangement: Simulation and Verification for Internal Imaging of Hydraulic Cylinder

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This work was supported in part by the Natural Science Foundation of China under Grant 61873124, Grant 51875289, and Grant 62071229; in part by the Aeronautical Science Foundation of China under Grant 20182952029 and Grant 2016ZD52036; in part by the Fundamental Research Funds for the Central Universities under Grant NS2019017; in part by the Nondestructive Detection and Monitoring Technology for High Speed Transportation Facilities, Key Laboratory of Ministry of Industry, China Postdoctoral Science Foundation; and in part by the Graduate Student Innovation Projects under Grant kfjj20190315.

ABSTRACT The research goal of this article is to imaging the oil distribution in landing gear hydraulic cylinder by Positron Emission Tomography (PET). Considering the flexibility and commercial cost for automation testing, two kinds of Not-Full-Ring sensors arrangement, Uniform-arrangement and Bilateral-arrangement, are proposed. The Full-Ring PET is used as the contrast template of imaging. Firstly, GATE 7.1 is used as the Monte Carlo simulation platform to simulate the sensors arrangement of the two Not-Full-Ring schemes. The results of scattering fraction, sensitivity and photon energy distribution were used to evaluate the feasibility of the two schemes. Then, a set of verification device with rotating platform and variable sensing diameter is constructed. The two kinds of Not-Full-Ring sensors arrangements were verified through the verification device. By imaging the hydraulic oil in the hydraulic cylinder, the results were evaluated and compared by using Signal Noise Ratio (SNR). According to the simulation and verification results, Not-Full-Ring scheme is feasible for imaging the liquid distribution in the hydraulic cavity. Uniform-arrangement has a more better imaging performance than Bilateral-arrangement. Such sensors arrangement scheme is not only suitable for this research, but also suitable for other PET imaging applications which need to consider the flexibility and commercial cost.

INDEX TERMS Positron emission tomography, gamma photon sensor, PET sensing and imaging, PET sensors arrangement.

I. INTRODUCTION

Aircraft landing gear is one of the key components of aircraft, which needs to meet the requirements of aircraft in high load takeoff and landing conditions. Landing gear structure is a set of hydraulic system, and its core actuator are hydraulic cylinders and hydraulic dampers. The essence of landing gear performance test is to test the hydraulic system health, including drop test, shimmy test and sudden extension test. The health monitoring of landing gear is one of the research hotspots of aircraft safety. At present, the main research focuses on comprehensive performance test and dynamic simulation. Orlando, C studied the wear problem of aircraft nose landing gear, optimized the shimmy suppression ability of hydraulic cylinder, and carried out simulation and verification [1]. Rahmani, M et al. studied the shimmy damper of landing gear and designed a new structure of shimmy damper for nose landing gear [2]. Cristiani, D, et al. simulated the load variation of aircraft landing process. The landing gear was used as the connection between dynamic domain and structural domain, and the displacement and force of landing gear position were analyzed [3]. Merino Martinez, R et al.
Measured and simulated the noise emission and stability of full-scale nose landing gear in wind tunnel [4]. Pytka, J et al. measured the force and torque acting on the landing gear by strain force sensor [5].

At present, there are few researches about the testing of landing gear hydraulic circuit. In this article, a kind of sensors arrangement scheme, based on Positron Emission Tomography (PET), is studied and proposed, which is suitable for the general industrial nondestructive imaging. This imaging scheme is not only for the oil circuit of the landing gear hydraulic cylinder, but the other types of tubes and cavities. By sensing the oil distribution with medical level radiation, the hydraulic performance can be imaging, and then the wear condition can be analyzed according to the results of reconstructed image.

At present, mature commercial PET device is mainly used in the biomedical field for human and small animals. The traditional PET structure is composed of sufficient sensors spliced into a ring. Due to the high unit-price of the sensor and fixed sensing diameter of the ring, it can not meet the demand of the industrial field which pays attention to the commercial cost performance and the automation flexibility. In this context, this article will simulate and verify the feasibility of Not-Full-Ring structure, that is, PET with fewer sensors and variable sensing diameter. Figure 1(a), shows the traditional Full-Ring structure and our application prospects in Not-Full-Ring structure.

In recent years, more and more research teams are developing special PET devices in various fields to meet their research needs. Our designs refer to these cases. Yang et al. studied the characteristics of fluid in industrial parts through PET with flat plate sensors. However, in order to improve the tracking speed, the experiment realized positioning by counting gamma photon pairs instead of imaging [6]. David J et al. proposed the idea of using PET to observe the distribution of lubricating oil in aero-engine [7]. Streun M et al. used PET to study the metabolism and physiological function of plants. The detectors of their system are arranged in a horizontal plane to allow the plants to be measured in the natural upright position. Two groups of four detector modules stand face-to-face and rotate around the field-of-view. This special system geometry requires dedicated image reconstruction and normalization procedures [8]. Wang et al. developed a plant specific high-resolution PET imaging detection device, the system adopts a ring structure, which can detect the vertical growing plants in the circumferential and vertical directions, and the number of sensors is reduced, and the detection cost is greatly reduced [9]. Tasima et al. proposed an open double ring PET, which can bring patients more comfortable space. On this basis, the double ring model is optimized to an elliptical single ring model, and the elliptical one can maintain the original system sensitivity and reduce the cost [10]. Raylman et al. developed a small high-resolution PET named “tandempet”. By arranging crystal sensors with different resolutions on both sides, the optimal position of detector resolution can be adjusted [11]. Corrector et al. evaluated the performance of a single PET sensor in the geometric distance. They developed a new PET with 8 detectors based on SiPM and monolithic LYSO crystals. This design can accurately determine the centroid of the scintillation light distribution [12]. Y. Chen, K. Saha et al. designed a full ring breast PET scanner consisting of 96 rings. They used GATE to simulate the system and used SNR to evaluate imaging quality [13]. Kobayashi, T et al. developed a multi-modal compatible flexible PET scanner. The scanner consists of adjustable two detector units and their support apparatus, and then scans a patient lying on a bed equipped by other medical imaging/non-imaging device. Therefore, depending on the size and shape of the patient and the patient bed and other demands, the detector geometry can be changed flexibly [14]. Chih-Chieh Liu et al. proposed a crystal arrays with curved surfaces to reduce the dead space between detector modules and hence improve the sensitivity of PET. They used detectors based on SiPM arrays coupled to both ends of scintillator arrays with finely segmented and long detector elements [15]. Before this study, we have done some preliminary research work, including imaging of positron tracer distribution in metal cavity and scattering correct algorithm [16], [17].

In this article, as shown in Figure 1(b), we will simulate and verify the performance of the two Not-Full-Ring sensors arrangement styles. The Not-Full-Ring structure includes 3 pairs of sensors. The sensors can rotate around the center of
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FIGURE 2. Modeling parameters of sensors-Ring arrangement. In the Full-Ring arrangement, the arrangement scheme and space size of sensors, the sensitive crystals arrangement structure of a single sensor.

II. MODELING AND SIMULATION OF NOT-FULL-RING SENSORS ARRANGEMENT STYLES

This article used GATE 7.1 for modeling and simulation. In this section, two styles of sensors arrangement will be constructed. The simulation data are output as coincidence events in ROOT format. We will evaluate the system performance of the two arrangement types by the coincidence events parameters, including scattering fraction, sensitivity and energy distribution.

A. MODELING OF SENSORS ARRANGEMENT

The actual Not-Full-Ring PET sensing system will be arranged by 3 pairs of sensors. The sensor model is TRANS-PET BDMII manufactured by RAYCAN Technology Co., Ltd. (Suzhou). The sensor parameters are shown in Table 1. and Figure 2. The simulation will be modeled according to the actual device parameters.

As shown in Figure 2., 24 × 12 sensitive crystals divided into four groups, each group contains one 6 × 12 crystals sub-array. \( R_W \) is the linear width occupied by the sensor on the circumference of the ring, which is 25mm. \( A_L \) represents the axial depth of the sensing area. According to the design requirements, the sensing area should be adjustable in the range of diameter (marked as \( D \)) 200~300mm. The relationship between the Full-Ring pairs number of sensors and the sensing area diameter is shown in Eq.(1).

\[
P_F = \frac{\pi D}{2R_W}
\]

As shown in Eq.(1), \( P_F \) represents the Full-Ring pairs number of sensors, \( D \) represents the sensing diameter. In this article, Not-Full-Ring style that used 3 pairs of sensors are modeled according to \( D = 200\text{mm}, 250\text{mm} \) and \( 300\text{mm} \). The Full-Ring model is used as reference. The models of Uniform-arrangement and Bilateral-arrangement constructed in GATE 7.1 are shown in Figure 3.

B. MODELING OF RADIOACTIVE SOURCE

Physical effects are added after the sensors’ arrangement models complete, that including positron annihilation, photoelectric effect, Compton scattering and Rayleigh scattering. The sensing system is designed for the imaging in industrial field, which mainly detects the low density liquid distribution in the metal cavity. The ratios of \( \gamma \) photons’ scattering and attenuation are larger than that of biological material. In order to make the model consistent with the actual verification, aluminium material parameters are added to the GATE 7.1 material database.

As shown in Figure 4(A), the radiation source model is designed in the aluminium tube. Due to the large number of models to be simulated, it is necessary to reduce the

| TABLE 1. Sensor parameters. |
|-----------------------------|
| PARAMETER | VALUE |
| Axial Length | 100mm |
| Radial width | 25mm |
| Sensitive material | LYSO |
| Single crystal size | 4.2×2.1×20mm³ |
| Scintillator array | 24×12 |
| Photoelectric converter | 24×12 silicon photomultiplier(SiPM) array |
| Energy resolution | 15% |
| Energy reference value | 511keV |
| Time resolution | 310ps |
| Coincidence time window | 2ns |
| Energy window | 250~650keV |
| Dead time | 300ns |

FIGURE 3. The models constructed in GATE 7.1. The 9 simulation models, sensing diameter from 200mm to 300mm, the arrangement styles include Uniform-arrangement, Bilateral-arrangement and Full-Ring.
As shown in Figure 6, the sensors-ring’s rotation is regarded as a static measurement, in which the source model data is collected. \( T_A \) represents data acquisition time and is set to 0.5s, which means each Time-Slice is a interval of period 0.5s. The simulation of rotation process is realized by rotating the geometric model of the sensors-ring between two Time-Slices. \( T_R \) represents the time cost by each rotation action. We mark the step angle of each rotation movement as \( \theta \). We set a constant angular velocity \( \omega = 10\text{°}/\text{s} \) and \( T_R = \theta/\omega \).

The relevant parameters of rotation are calculated as follows. According to Table 1, and Figure 2, single crystal size is 4.2mm × 2.1mm, the linear width occupied by crystal on the circumference of the ring is 2.1mm, we marked it as \( C_W \), and \( R_W = 12 \cdot C_W \). The center angle of \( C_W \) on the ring is marked as \( \sigma \). The step angle \( \theta \) should be an integral multiple of \( \sigma \). We mark the value of integral multiple as \( S_{TP} \), and \( \theta = \sigma \times S_{TP} \). In the Not-Full-Ring style, we mark the number of sensor pairs as \( P_N \). The number of rotation times required by the system to finish a full ring is marked as \( N \). The geometric model of rotation parameters is shown in Figure 6.

As shown in Figure 6, according to Eq.(1) and Arc Length Formula, Eq.(2) can be deduced as follow:

\[
\sigma = \frac{\pi}{12 \cdot P_F} \tag{2}
\]

For Uniform-arrangement, the number of rotation times to cover a full ring is \( N_U \). According to Figure 6, and Eq.(1,2), the calculation formula of \( N_U \) is shown in Eq.(3)

\[
N_U = \frac{\pi - \sigma \cdot P_N \cdot 12}{P_N \cdot \theta} + 1 \tag{3}
\]

For Bilateral-arrangement, the number of rotation times to cover a full ring is \( N_B \). According to Figure 6, and Eq.(1,2),
the calculation formula of $N_B$ is shown in Eq.(4)

$$N_B = \frac{\pi \cdot \sigma \cdot P_N \cdot 12}{\theta} + 1 \quad (4)$$

When the number of rotation times to cover a full ring has been confirmed and according to Figure 5, the calculation formula of the time to complete a complete acquisition is shown as Eq.(5). $T_F$ represents the time of a complete acquisition. $N$ represents $N_U$ in Uniform-arrangement and $N_B$ in Bilateral-arrangement.

$$T_F = N \cdot (T_A + T_R) - T_R \quad (5)$$

According to Figure 6, and Eq.(3,4,5), the rotation parameters for GATE 7.1 simulation are grouped in Table 2. $T_{FU}$ represents the total sampling time in Uniform-arrangement, and $T_{FB}$ represents the total sampling time in Bilateral-arrangement.

As shown in Table 2, we set up a list of 24 models to be simulate. The model name “UA(200)-1” means Uniform-arrangement, $D = 200$mm, $S_{TP} = 1$. By the same naming rules, “BA(300)-4” means Bilateral-arrangement, $D = 300$mm, $S_{TP} = 4$. “FR(200)” means Full-Ring style with aluminium tube in it, $D = 200$mm. “Bio(250)” means Full-Ring style without aluminium tube, $D = 250$mm.

### III. COMPARISON OF SIMULATION RESULTS OF THE TWO STYLES IN SYSTEM PERFORMANCE

After all the 24 models in Table 2 have been simulated, we evaluated coincidence events data of each model. In this section, The evaluate results will be analyzed in detail from energy distribution, scattering fraction and sensitivity. Through these three aspects, the system performances of the two arrangement styles are evaluated comprehensively. And the two styles will be verified by real sensors system in the next chapter.

#### A. PHOTON ENERGY DISTRIBUTION

When positron annihilation $511$KeV $\gamma$ photons penetrate through the aluminum tube wall from the radioactive source, Compton scattering is likely to occur, resulting in energy loss and ray angle deflection. Since Compton scattering probability is proportional to atomic number, and industrial parts are generally metal materials, the photon energy distribution is able to reflect the scattering distribution of industrial field. As shown in Figure 7(A), Photon energy distribution statistics presented the energy distribution of all photons detected by the sensors. According to it, we can evaluate whether the sensor can adapt to industrial sensing and imaging. The sensor filters the scattering events by setting the energy window. If the energy window is too small, a large number of real coincidence events will be excluded. If the energy window is too large, a large number of scattering events will be included. Therefore, The photon energy distribution can provide a very effective reference for the threshold setting of energy window.

#### TABLE 2. The list of all the 24 models simulation configuration.

| No. | Model Name   | $D$(mm) | $\sigma(\%)$ | $S_{TP}$ | $N_U$ | $T_{FU}(s)$ | $N_B$ | $T_{FB}(s)$ |
|-----|--------------|---------|--------------|----------|-------|-------------|-------|-------------|
| 1   | UA(200)-1,   | 200     | 1.25         | 37       | 23    | 109         | 68    |
| 2   | BA(200)-1    | 200     | 1.25         | 37       | 23    | 109         | 68    |
| 3   | UA(200)-4,   | 4       | 5            | 10       | 9.5   | 28          | 27.5  |
| 4   | BA(200)-4    | 4       | 5            | 10       | 9.5   | 28          | 27.5  |
| 5   | UA(250)-4,   | 8       | 10           | 5        | 7     | 14          | 20    |
| 6   | BA(250)-4    | 8       | 10           | 5        | 7     | 14          | 20    |
| 7   | UA(250)-1,   | 1       | 1            | 49       | 20.3  | 145         | 86.9  |
| 8   | BA(250)-1    | 1       | 1            | 49       | 20.3  | 145         | 86.9  |
| 9   | UA(250)-4,   | 4       | 4            | 13       | 11.3  | 37          | 32.9  |
| 10  | BA(250)-4    | 4       | 4            | 13       | 11.3  | 37          | 32.9  |
| 11  | UA(250)-8,   | 8       | 8            | 7        | 8.3   | 19          | 23.9  |
| 12  | BA(250)-8    | 8       | 8            | 7        | 8.3   | 19          | 23.9  |
| 13  | UA(300)-1,   | 300     | 0.83         | 1        | 0.83  | 61          | 35.5  | 181         | 105.5 |
| 14  | BA(300)-1    | 300     | 0.83         | 1        | 0.83  | 61          | 35.5  | 181         | 105.5 |
| 15  | UA(300)-4,   | 4       | 4            | 3.32     | 16    | 46          | 38    |
| 16  | BA(300)-4    | 4       | 4            | 3.32     | 16    | 46          | 38    |
| 17  | UA(300)-8,   | 8       | 8            | 6.64     | 8     | 9           | 23    |
| 18  | BA(300)-8    | 8       | 8            | 6.64     | 8     | 9           | 23    |
| 19  | Bio(250),    | 208     | 0.5          | 1        | 0.5   | 61          | 35.5  | 181         | 105.5 |
| 20  | FR(200)      | 100     | 0.5          | 1        | 0.5   | 61          | 35.5  | 181         | 105.5 |
| 21  | Bio(250)     | 250     | 0.5          | 1        | 0.5   | 61          | 35.5  | 181         | 105.5 |
| 22  | FR(200)      | 100     | 0.5          | 1        | 0.5   | 61          | 35.5  | 181         | 105.5 |
| 23  | Bio(300)     | 300     | 0.5          | 1        | 0.5   | 61          | 35.5  | 181         | 105.5 |
| 24  | FR(300)      | 100     | 0.5          | 1        | 0.5   | 61          | 35.5  | 181         | 105.5 |
FIGURE 7. The photon energy distribution. A. The meaning of photon energy distribution. B. Photon energy distribution data of all models, among them, (a) The energy distribution detected by the 9 Uniform-arrangement models. (b) The energy distribution detected by the 9 Bilateral-arrangement models. (c) The energy distribution detected by the 3 Bio models. (d) The energy distribution detected by the 3 Full-Ring models. C. Causes of photon energy distribution, Bilateral-arrangement has two larger high scattering sector than Uniform-arrangement.

As shown in Figure 7(B), for all models, the energy window covers the valley and peak values on both sides of 511KeV. The sensing diameter $D$ does not affect the distribution of photon energy, but only the total number of the photon counts. The step angle has a great influence on the number of photon counts. The smaller the step angle (represented in integral multiple $S_{TP}$1, 4, 8) is, the larger the total counts is.

In the Uniform-arrangement models, the number of photons in the energy window range is more than that of scattering photons. In the Bilateral-arrangement models, the number of photons in the energy window range is significantly less than that in the Uniform-arrangement ones. It can be easily inferred that there are a lot of scattering events and false coincidence events in the large angle scattering region (250KeV $\sim$ 330KeV).

The photon energy distribution confirms the applicability of the real sensor and reflects that the Uniform-arrangement is better than the Bilateral-arrangement in filtering scattering events. At the same time, Bilateral-arrangement had a large number of false coincidence events, and its effective utilization of photon pairs is obviously lower than that in Uniform-arrangement.

As shown in Figure 7(C), in a single Time Slice, the sensors of Bilateral-arrangement models are concentrated, forming two large high scattering sectors. Therefore, the sensors will collect a large number of scattering photons from the two high scattering sectors. The larger the scattering angle, the lower the photon energy. That is the reason for Bilateral-arrangement having significantly large scattering in low energy (250$\sim$300 KeV). In contrast, the sensors of Uniform-arrangement models are evenly distributed on the circumference, and the angle of scattering sectors are small and dispersed, so it is not easy to receive higher scattering photons.

Although the simulation in this article used a line source model, it is easy to infer that Bilateral-arrangement models would collect a large number of high scattering photons in other ray sources as well.

B. SCATTERING FRACTION

Compared with biological field, in the industrial field, $\gamma$ photons need to penetrate high-density materials, so Compton Scattering is more likely to occur. Therefore, it is necessary to pay attention to the influence of such scattering on evaluate system performance. The scattering we define in GATE 7.1 simulation is that the photons from the line source penetrate the metal and deflect. Scattering fraction is usually used to measure the sensitivity of the sensor to scattering events, that is, the proportion of scattering coincidence events to total coincidence events. Large scattering fraction means a high rate of false-events in coincidence events sensed by the system, which will lead to imaging distortion. In GATE 7.1, we distinguished the scattering event from the false coincidence event according to the energy of the photon pair. Scattering events in our simulation refer to one photon in the 511KeV range and the other below the 511KeV range. Figure 8, shows the scattering fraction obtained from simulation data for all the 24 models.
As shown in Figure 8, for the Full-Ring situation, the existence of aluminum tube leads to a significant increase of scattering events collected by the system. The scattering fraction of Not-Full-Ring style is lower than which of the Full-Ring style. $S_{TP}$ has little effect on scattering fraction. When sensing diameter $D$ increases, the scattering fraction decreases.

It can be concluded from Figure 8, the scattering fraction of the 9 Uniform-arrangement models are lower than that of the Bilateral-arrangement ones, which are the lowest among all the 24 models.

C. SENSITIVITY

The sensitivity represents the ratio of the coincidence events number sensed by the system to the actual annihilation events per unit time. It reflects the efficiency of system sensing coincidence events. The sensitivity is mainly determined by the number and arrangement of sensors. The sensitivity values of all the 24 models are shown in Figure 9.

As shown in Figure 9, The sensitivity of all the Not-Full-Ring style is significantly lower than the Full-Ring style. Which means that both Uniform-arrangement and Bilateral-arrangement systems are far less sensitive than Full-Ring systems. Not-Full-Ring style systems need to spend more data acquisition time for more coincidence events to rebuild high quality imaging.

However, the sensitivity weakness of all the Not-Full-Ring style is expected. Compared with the Full-Ring system, on the premise of the sensing requirements, making appropriate compromise in sensitivity to reduce the system cost to 16% (18pairs) ~ 25% (12pairs) is worth commercial.

IV. VERIFICATION OF NOT-FULL-RING SENSORS ARRANGEMENT STYLES

Through all the sensors-ring models simulation, we find that although the sensitivity of Not-Full-Ring is much lower than that of Full-Ring, there is no obvious disadvantage in scattering distribution and photon energy distribution. For the two Not-Full-Ring styles, Uniform-arrangement is superior to Bilateral-arrangement in scattering distribution, sensitivity and photon energy distribution.

In this section, we will verify the above simulation results by sensors-ring hardware construction, internal sensing process of the hydraulic cylinder and Signal-Noise Ratio(SNR) of reconstructed imaging.

A. HARDWARE CONSTRUCTION

The sensing space size of the hardware system is consistent with the simulation models mentioned above. As shown in Figure 10(a), the main motion parts of the system include 1 Servo turntable and 6 Servo sliders. The Servo turntable is a high-precision worm wheel turntable, which is controlled by an absolute servo motor. Its rotation repeat positioning accuracy is $0.02^\circ$ and meets the accuracy requirements of the single crystal center angle $\sigma$ ($0.83^\circ$ ~ $1.25^\circ$). In order to realize the two sensors arrangements mentioned above, a porous annular plate is installed on the rotating body of the Servo turntable. The 6 Servo sliders can be fixed on the porous annular plate according to the arrangement of sensors in the simulation models. The linear repeat positioning accuracy of the Servo slider is 0.01mm, which meets the accuracy requirement of sensing diameter $D$ (0.1mm). The effective moving distance of each Servo slider is 80mm, which meets the range of sensing diameter $D$, 200mm~300mm(limit only
In order to verify the feasibility of our application assumption and the simulation models mentioned above, the experimental process is shown in Figure 11. First, in order to adapt to the range of sensing diameter \( D \), we customized a reduced scale hydraulic cylinder of the aircraft landing gear. This hydraulic cylinder is made of aluminum. Its outer cylinder has a wall thickness of 5mm, an inner diameter of 65mm and a length of 200mm. The piston diameter is 64.5mm, the length is 75mm, and the effective stroke is 100 mm. It is fixed on the actuating rod by an M24 nut. The piston and the inner wall of the outer cylinder are sealed by two O-rings. Our sensing imaging area is set at the piston position, and the target is the nut on the lower part of the piston. Because of its obvious cross-section shape characteristics, it is easy to compare and analyze the reconstructed images.

In order to be close to the real application scene, we use water-soluble hydraulic oil as the solvent of radiation source. Water-soluble hydraulic oil is widely used in aviation hydraulic system because of its high temperature resistance. For this experiment, due to the water solubility of the hydraulic oil, the commonly used medical positron nuclides\(^\text{18}\text{F}\)-fluorodeoxyglucose\) can be easily and evenly dissolved in the hydraulic oil. With the help of the experts in RAYCAN Technology Co., Ltd. (Suzhou), we successfully prepared the required aviation hydraulic oil containing \(^{18}\text{F}\) and injected it into the hydraulic cylinder.

Due to the limitation of practical conditions, we do not have Full-Ring reference system of sensing diameter \( D \) at 250mm and 300mm. Therefore, we use the commercial PET device, model TRANS-PET-180, as the standard reference imaging template for all arrangement styles. TRANS-PET-180 has 12 pairs of TRANS-PET BDM II sensors with a sensing diameter of 200 mm, and its actual diameter for placing object is 180 mm. Its coincidence events data records format and imaging reconstruction algorithm are completely consistent with our Not-Full-Ring system. We will adjust the imaging reconstructed at sensing diameter 250 mm and 300 mm to that at 200 mm for quantitative comparison of imaging quality.

As shown in Figure 11, “FR(200)” means Full-Ring, \( D = 200\text{mm} \), the standard template. “UA(200)” means Uniform-arrangement, \( D = 200\text{mm} \). “BA(300)” means Bilateral-arrangement, \( D = 300\text{mm} \). According to the 9 arrangements to be verified in Figure 11., we subdivide the experimental process into 19 in Table 3.

As shown in Table 3., considering the half-life of \(^{18}\text{F}\) (110 minutes) and the actual application scenes, it is appropriate to set the processing Time at 600s (10min) for each experiment. In the field of industrial non-destructive imaging, the 10min sensing period is normal in commercial. During this period, the radioactivity of positron nuclide is relatively stable. For Not-Full-Ring system, stable radioactivity can ensure the imaging quality. According to the process Time, and refer to \( T_F \) and \( S_{TP} \) in Table 2.. In the same Time length(600s), the times of complete acquisition (Times of \( T_F \), Table 3.) is different under the various step angle integral multiple \( S_{TP} \). For example, About 600s, process “UA200 STP-1” can complete 25 trips of a full ring in 604s. As comparison, process “UA200 STP-4” has a larger \( S_{TP} \), so it can complete 62 trips of a full ring in 604s. In each
TABLE 3. The list of subdivide experimental processes.

| No. | Process ID | Sy | Times of Ty | Time(s) | Radioactivity (mcCi) | Liquid injection volume (ml) |
|-----|------------|----|-------------|---------|----------------------|-----------------------------|
| 1   | FR200      | 1  | 25          | 406     | 1.02                 | 298                         |
| 2   | UA200      | 4  | 62          | 406     | 1.05                 | 300                         |
| 3   | UA250      | 8  | 82          | 403     | 1.09                 | 301                         |
| 4   | UA250      | 6  | 49          | 409     | 1.07                 | 301                         |
| 5   | UA300      | 8  | 70          | 402     | 1.07                 | 301                         |
| 6   | UA300      | 4  | 44          | 401     | 1.04                 | 300                         |
| 7   | UA300      | 10 | 61          | 401     | 1.09                 | 300                         |
| 8   | BA200      | 6  | 14          | 506     | 1.06                 | 300                         |
| 9   | BA200      | 8  | 27          | 590     | 1.09                 | 300                         |
| 10  | BA200      | 4  | 17          | 589     | 1.04                 | 300                         |
| 11  | BA300      | 8  | 24          | 608     | 1.07                 | 299                         |
| 12  | BA300      | 1  | 5           | 283     | 1.02                 | 300                         |
| 13  | BA300      | 8  | 14          | 574     | 1.02                 | 300                         |
| 14  | BA300      | 2  | 8           | 588     | 1.05                 | 300                         |

C. SIGNAL-NOISE RATIO OF RECONSTRUCTED IMAGING

After completing the above tests, we get the response lines data list of the 19 processes. In order to evaluate the imaging quality objectively and fairly, all experimental data are reconstructed by the same algorithm procedure. In this article, although the reconstruction algorithm process is not the innovation and research point, we think it is necessary to do a brief description. We use the traditional classical PET image reconstruction algorithm to test the universality of all the sensors-ring systems. Firstly, we recombine the three-dimensional response lines data list into two-dimensional sine diagram by Fourier Rebining (FORE). On this basis, the Ordered Subset Expectation Maximization (OSEM) algorithm is used for imaging reconstruction. We use 3D-OSEM algorithm for imaging reconstruction, and the number of subsets is 13. The core iterative formula is shown in Eq. (6).

$$\lambda_{i}^{k+1} = \sum_{j} a_{ij} \sum_{j} \left[ Y_{j} \frac{a_{ij}}{\sum_{j} a_{ij} \lambda_{j}^{k}} \right]$$

As shown in Eq. (6), $\lambda_{i}$ represents the grayscale value of the number $i$ pixel in the image (in this article, it represents the event counts). $a_{ij}$ represents the system matrix of the PET Full-Ring model. In this article, the angle information of the response lines data list in all Not-Full-Ring systems is converted into absolute angle, so the system matrix is calculated as the Full-Ring model ($D = 200mm, 250mm$ and $300mm$ are different only in the space size of the system matrix). $Y_{j}$ represents the number $j$ response line, which is the number $j$ element in the two-dimensional sine diagram. The image reconstruction process is completed in MATLAB, and the corresponding section slice imaging is generated according to the spatial coordinates of the required detection position.

According to the above experimental plan, the cross section of the nut on the lower part of the piston is imaged. As shown in Figure 12., the slice imaging results of the 19 processes are presented. For the Sensing diameter $D = 250mm$ and $300mm$, the slice imaging has been simply enlarged and cut to $200mm$ in MATLAB.

In order to obtain objective and fair evaluation results, we use the classical Signal-Noise Ratio(SNR) method to evaluate the image quality of the 18 Not-Full-Ring processes, by using the FR(200) imaging as template. The SNR results are showed in Figure 13. The template image of FR(200) was used as signal, the image generated by each model subtracted the template image as noise. The calculation formula of SNR is shown in Eq.(7). $P_{M}$ refers to the images generated by each model, $P_{T}$ refers to the template image gained by FR(200).

$$SNR = 10 \times \log_{10} \left( \frac{P_{M}}{P_{M} - P_{T}} \right)$$

Firstly, the imaging quality of Uniform-arrangement and Bilateral-arrangement is compared. As shown in Figure 13., the SNR values of all the Uniform-arrangement are higher than that of Bilateral-arrangement. In detail, using FR(200) image as template, all the Uniform-arrangements’ SNR values are above 1. Especially when $S_{TP} = 1$, they are all higher than 5. However, the SNR values of Bilateral-arrangement was barely maintained around 1, some even less than 0.5. The
result of these SNR values are consistent with the conclusion of the previous simulation. As shown in Figure 7, Photon energy distribution of the previous section, the quantity of photons in Uniform-arrangement is larger than that in Bilateral-arrangement near 511kev±15%. This shows that Uniform-arrangement can collect coincidence events more sufficiently than Bilateral-arrangement.

Next, we analyze all the Uniform-arrangement and Bilateral-arrangement separately. In Uniform-arrangement, we can find that with the increase of sensing diameter $D$, the image quality decrease, but the $D$’s influence on image quality is not as great as $S_{TP}$. As shown in Figure 13, the integral multiple value of step angle has the key impact on imaging quality. The smaller the $S_{TP}$ is, the higher the SNR values will be. We can also see from the Figure 7. Photon energy distribution that when $S_{TP} = 1$, no matter $D = 200mm$, 250mm or 300mm, the curve distributions are relatively close, but when $S_{TP} = 4$, the three curve distributions have a step decline. In Bilateral-arrangement, Since the SNR values of these styles in Figure 13 are very low, it is meaningless to discuss the influence of sensing diameter $D$ and $S_{TP}$ for this arrangement. So far, we have a good reason to believe that Uniform-arrangement has better sensing performance.

Finally, we compare the Uniform-arrangement style with the Full-Ring style. Because it is used to detect the liquid inside the metal cavity, it can be seen from Figure 12, that the liquid profile is not very clear even in the case of Full-Ring. The blocking of the metal cylinder wall does reduce the quantity of coincidence events received. But considering that we use the classical algorithm, there is no specific algorithm to deal with the scattering. In the experimental operation, we can also increase the amount of coincidence events by increasing the radioactivity in the liquid. There is much space for improvement in imaging quality. In Uniform-arrangement, when $D = 1$ and $S_{TP} = 1$, the SNR value is 11.79, It has been able to clearly reflect the characteristics as the template image done.

In summary, Not-Full-Ring sensors arrangement scheme for PET imaging is feasible. Sufficient source radioactivity, proper sensor arrangement, proper step angle and optimized imaging algorithm can make the imaging quality better.

V. CONCLUSION

Through this study, we believe that Not-Full-Ring system is feasible and effective to reduce the number of sensors and increase the flexibility of automation. This scheme is not only suitable for the research described in this article, but also suitable for other research projects that need to use PET imaging.

The unit-price of PET sensor is expensive. The essence of Not-Full-Ring sensors arrangement is to subdivide the demand of the research. In the case of meeting the core research objectives, some compromise or enhancement should be made in the aspects of sensitivity, R & D cost and versatility.

It is hoped that this article can provide an effective research method for the research team with similar technical needs.

ACKNOWLEDGMENT

The authors are very grateful for the technical support from RAYCAN Technology Co., Ltd. (Suzhou).

They would like to thank the team led by Professor XIE Guoqing (Huazhong University of Science and Technology) for their great support to their project.

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