A new laser-based monitoring method for the cryomodule components in CSNS II

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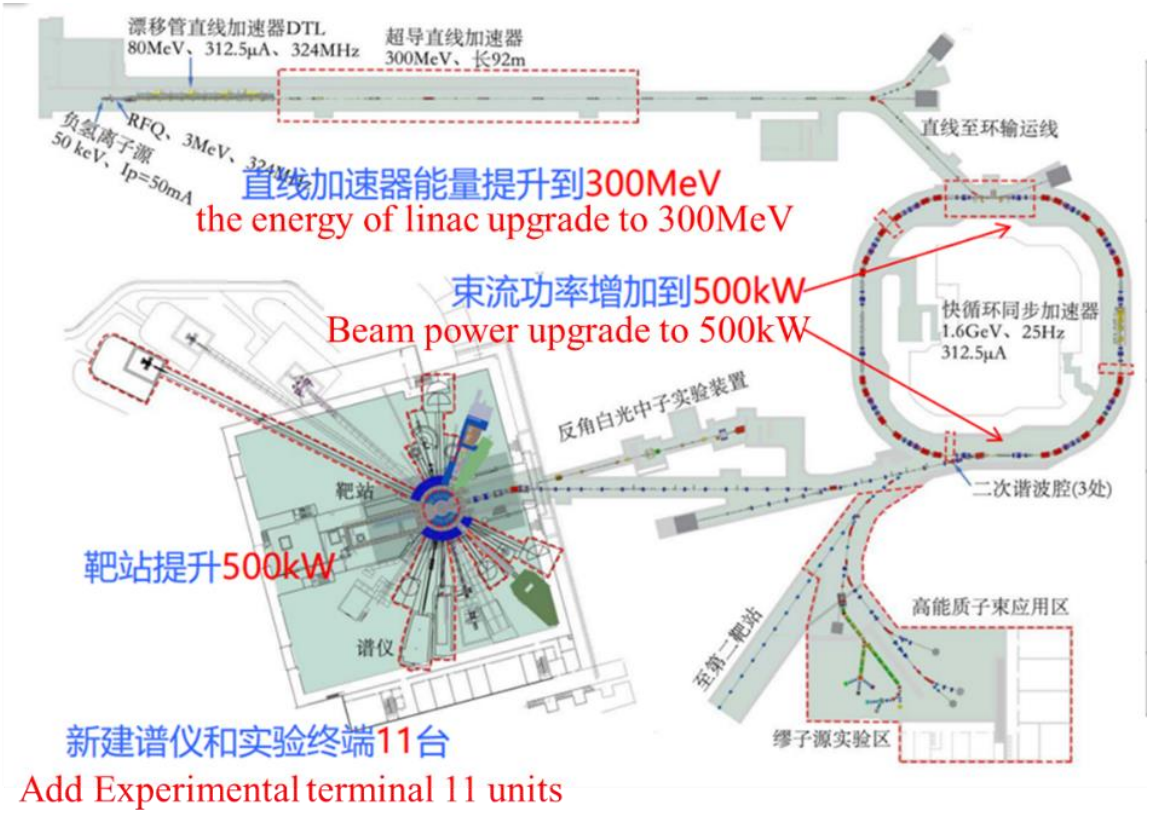
Contents

Introduction

- The China Spallation Neutron Source Phase II (CSNS-II) officially started on March 30, 2024, with a planned construction period of 5 years and 9 months and a total investment of 2.956 billion yuan.

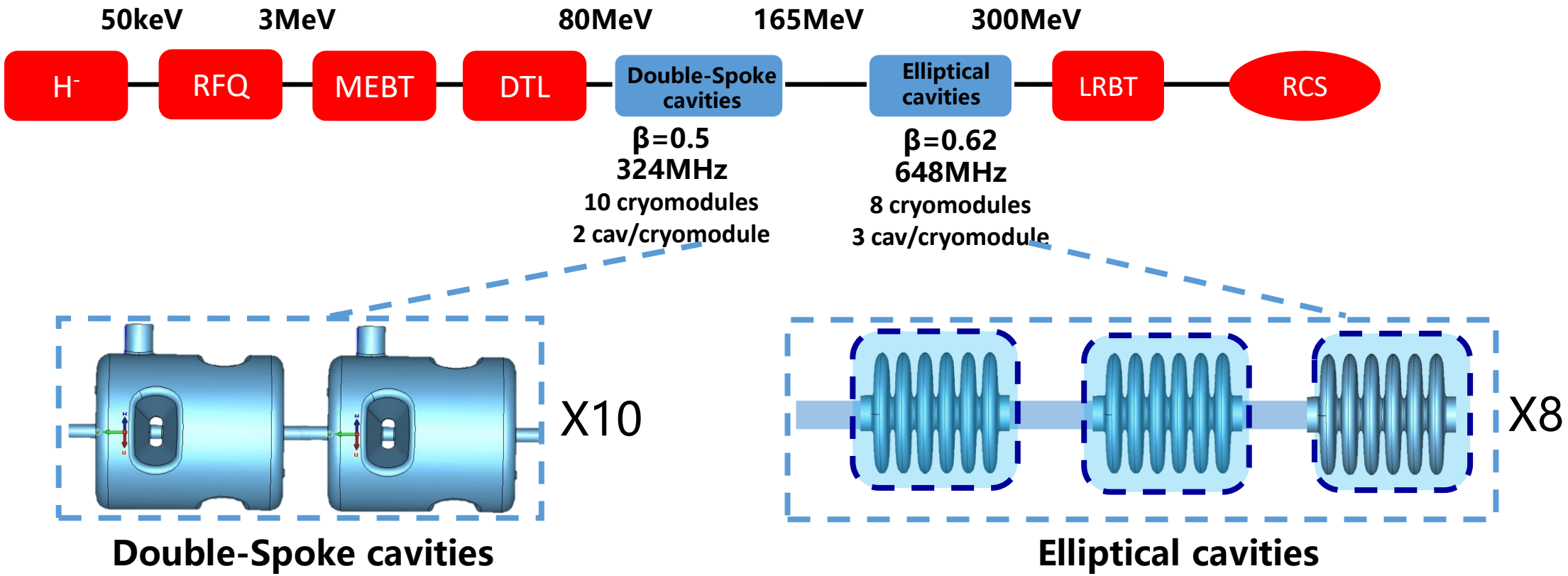
- The construction of the CSNS-II accelerator includes:

1. Development of a new high-frequency ion source to improve the performance of the front-end system ;
2. Adoption of a superconducting linac accelerator to raise the beam energy to 300MeV;
3. By adding longitudinal painting injection and second RF systems, the RCS beam power will be increased to 500kW;
4. Constructing 11 experimental spectrometers.



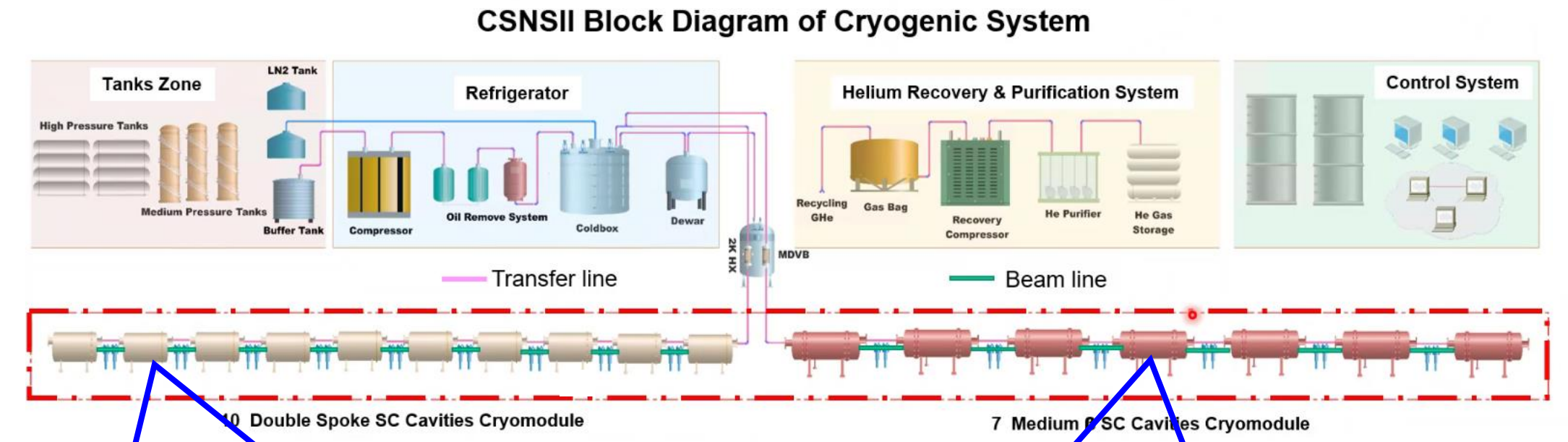
The most critical part of the upgrade is the development of superconducting accelerators! !

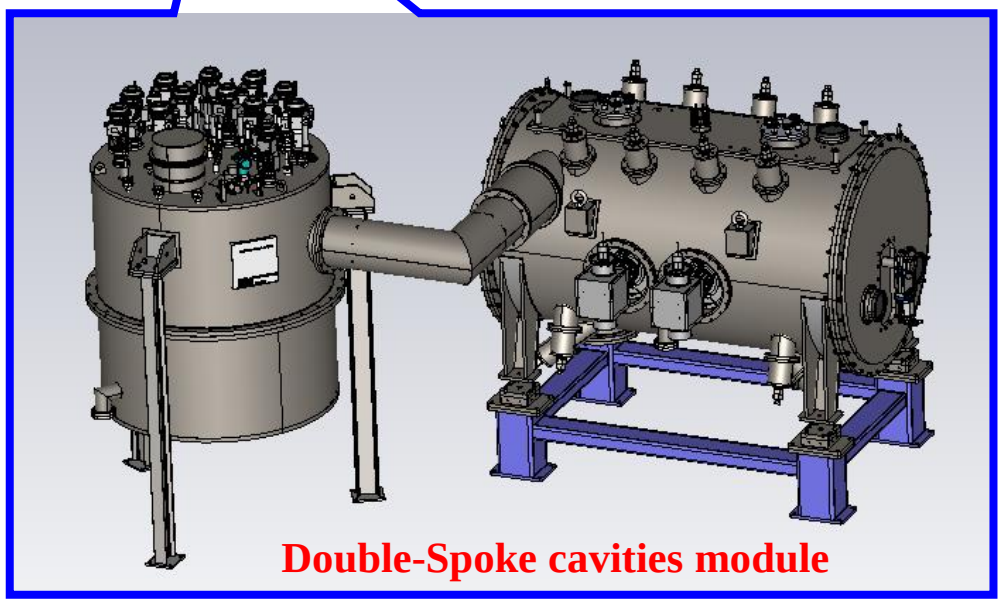
Introduction

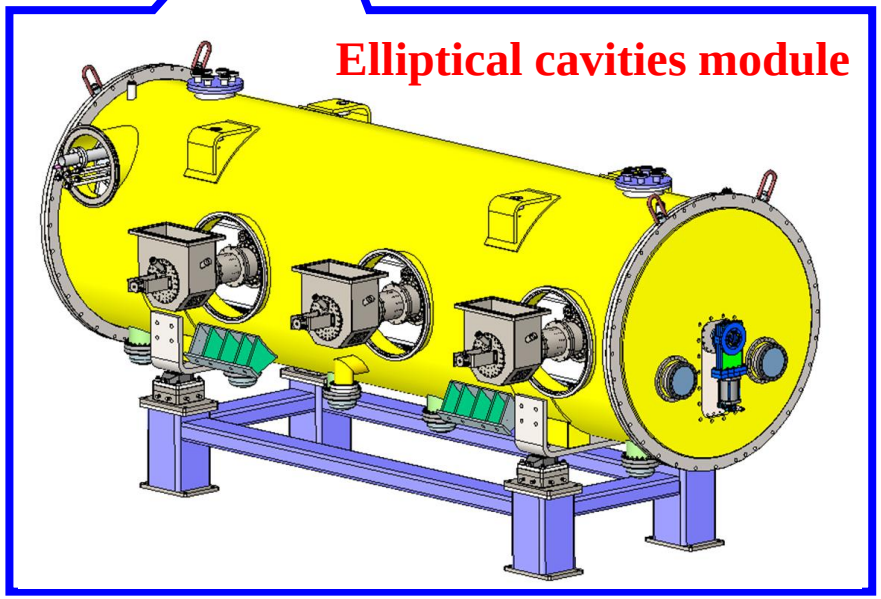


- There are 10 cryomodules with 2 double-spoke superconducting cavities inside and 8 cryomodules with 3 elliptical superconducting cavities inside.
- The peak beam current of the linac accelerator will be increased from 15mA to 50mA;
- The beam energy will be increased from 80MeV to 300MeV.

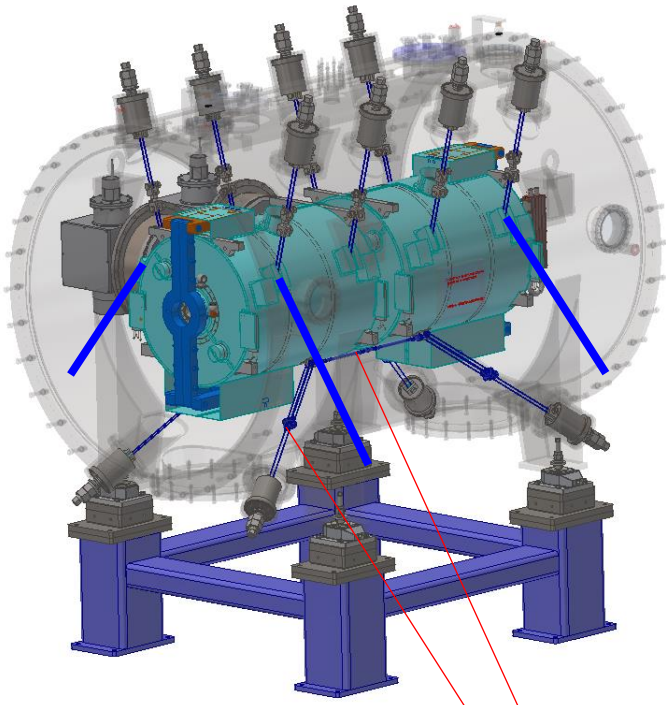
Introduction

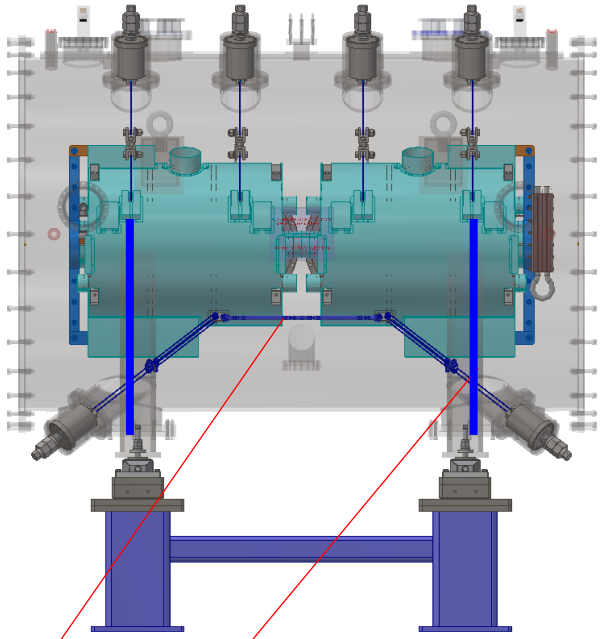


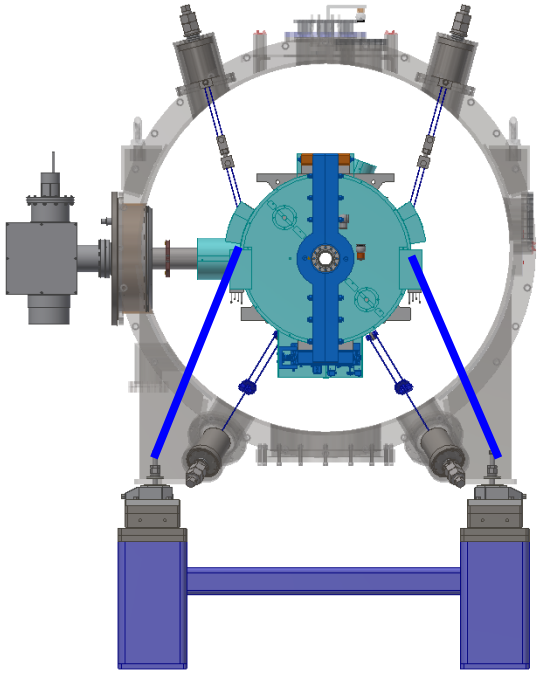


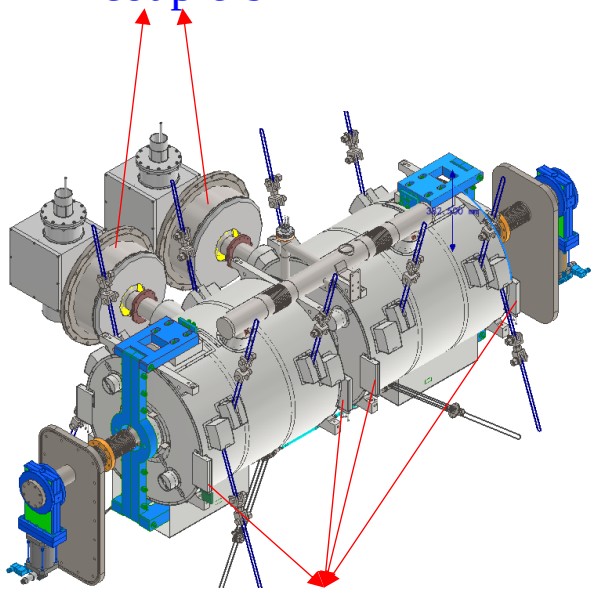


Introduction









indium steel rods

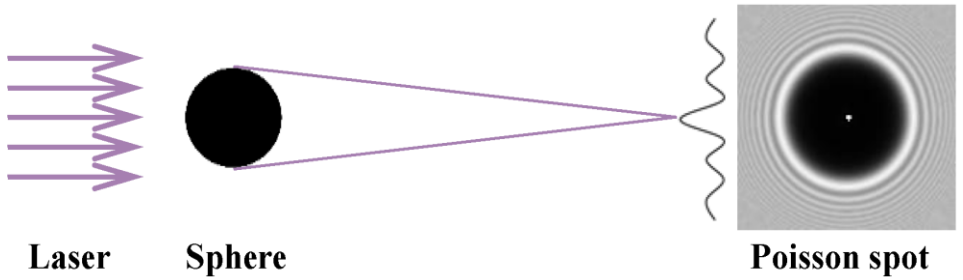
carbon fiber rods

- The cavities are fixed to the vacuum vessel with carbon fiber rods. Each cavity has 4 sets of hanging rods at the top and 4 sets at the bottom, with two cavities connected at the bottom by two Invar rods.
- A coupler is installed on the side of each cavity.

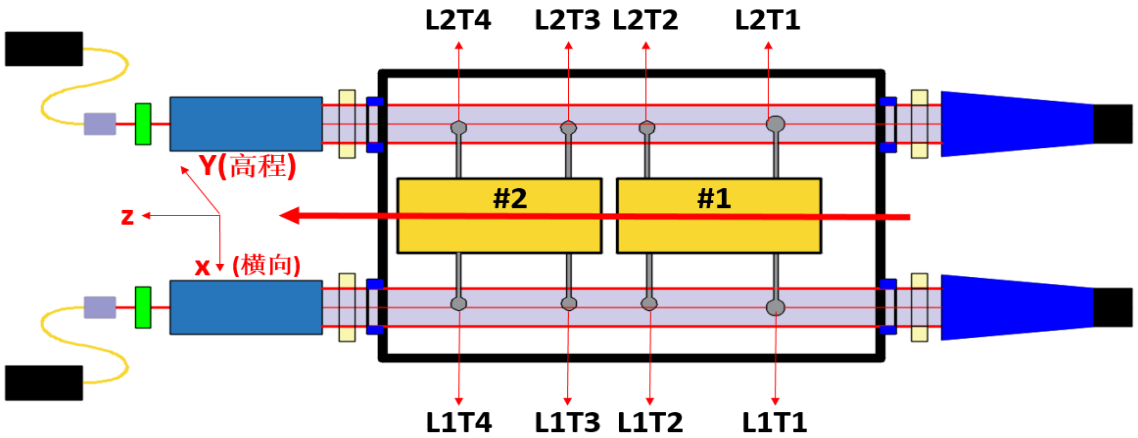
Error Source	RMS error (when cold)
X misalignments(transverse）	0.5mm
Y misalignments (vertical)	0.5mm
Z misalignments (longitudinal）	1mm

2.The Laser-based Poisson Spot Monitor (PSM) system

- To monitor the displacement of cavity under cooling precisely, simply and stably, we newly developed a laser-based monitoring method based on Poisson spot (PSM system).
- The PSM system is based on the Poisson spot, which is a diffraction effect that occurs when an opaque sphere is illuminated with a plane wave from a laser beam. A tiny bright spot appears at the center of the Poisson spot. The center pixel coordinates of the Poisson spot can be obtained through image processing. The displacement of the spherical target can be obtained by monitoring the center of this Poisson spot in real time.
- The PSM system consists with four spherical monitoring targets fixed onto the cavity, laser input system to produce quasi-parallel laser beam broad enough to cover the face of the spherical monitoring targets and imaging system to transform the projected images of each target to digital images.



The formation principle of Poisson spot.

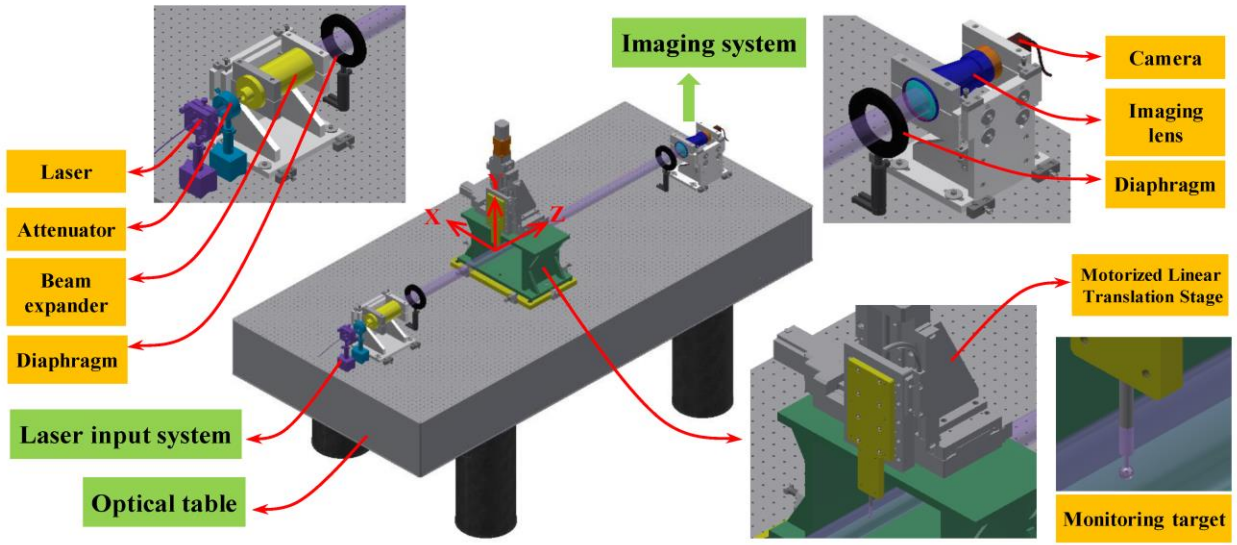


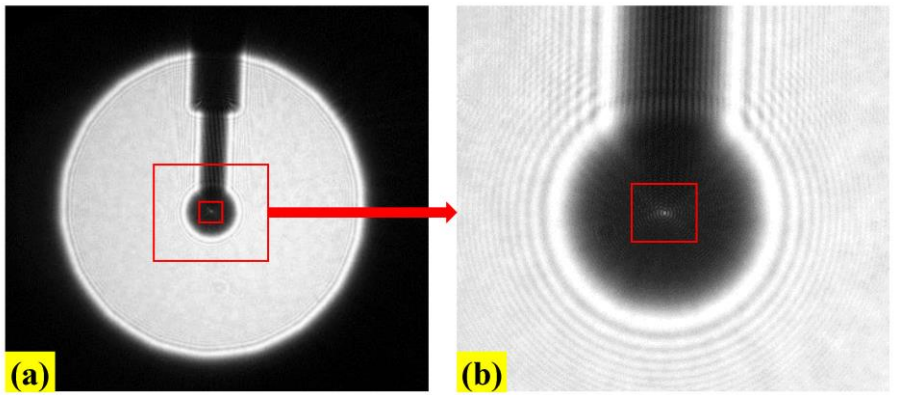
The PSM scheme (Optical path diagram).

2.The Laser-based Poisson Spot Monitor (PSM) system

In order to verify the feasibility of the monitoring scheme, prototype system was first built in the laboratory. The system is mainly composed of three parts:

- The laser input system: A commercially available 10mW semiconductor laser with 405 nm wavelength is chosen as the light source. The laser beam is expanded by the beam expander to approximately 60 mm.
- The monitoring target was fixed on the motorized linear translation stage .
- The imaging system: The CMOS sensor is commercially available with 4096*3000 pixels and 3.45μm pixel size. Telecentirc lenses are designed to have a constant magnification regardless of the objects distance or location in the field of view. So it is very ideal for the monitoring. The telecentric lenses converge the projected image of the sphere monitoring target to the CMOS sensor with a magnification of 0.1102 which means the spatial resolution of the imaging system is about 3.45μm/0.11=31.31μm, which can also be obtained by calibration. The lenses manufacturer is Opto engineering and its model is TC12056.



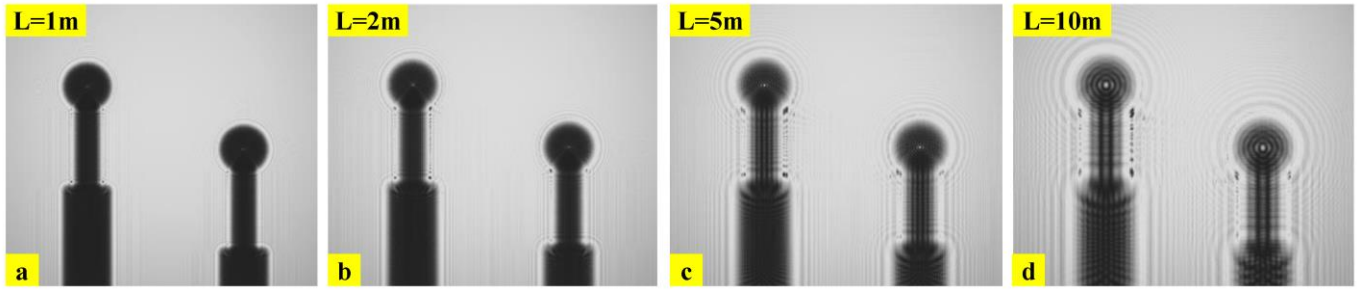


Poisson spot image of spherical target. (a) is original image and (b) is an enlarged view.

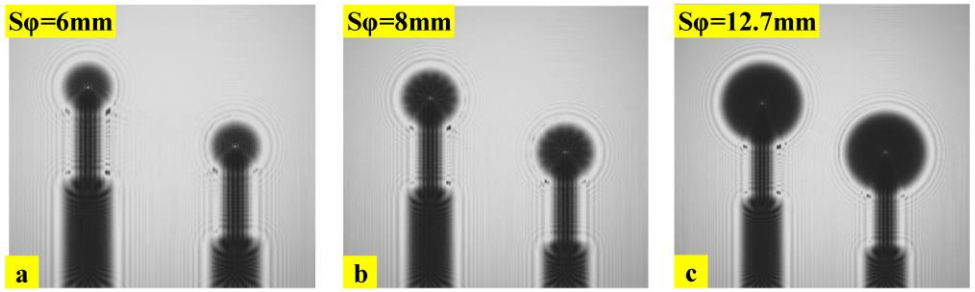
2.The Laser-based Poisson Spot Monitor (PSM) system

- The system's optical path has been simulated with ZEMAX. In order to prevent the interference, the sphere targets will be staggered on the cross section of the optical path. The evaluation standard is mainly that the Poisson spot should be clear enough, which is mainly related to the spherical diameter of the target and the distance from the target to the CMOS camera.

- Through simulation, we found that when the spherical diameter of the target is constant, the closer the target is to the camera, the clearer the Poisson spot. When the distance from the target to the camera is constant, the larger the target sphere diameter, the clearer the Poisson spot. The optimal spherical diameter of the target and the optimal distance from the camera were obtained through simulation.



The Poisson spot images of sphere monitoring targets obtained by simulation with ZEMAX. The spherical diameter of the target is 6mm, and the distance from the target to the CMOS camera is 1 meters, 2 meters, 5 meters and 10 meters respectively.



The Poisson spot images of sphere monitoring targets obtained by simulation with ZEMAX. The distance from the target to the CMOS camera is 5 meters, and the spherical diameter of the target is 6mm, 8mm and 12.7mm respectively.

2.The Laser-based Poisson Spot Monitor (PSM) system

- By combining the extreme value method and the gray centroid method, an algorithm suitable for extraction of Poisson spot centers was proposed. The algorithm has been realized with a Python script. First, the image was converted to grayscale, and then select the ROI (Region of Interest) area centered on the Poisson spot in the image. There is a bright area in the center of the Poisson spot, whose center represents the center of the target.

- The function *cv2.minMaxLoc* in Python is used to find the point with the largest gray value in the ROI area. Then a new ROI area is re-extracted with the point with the largest gray value as the center. Finally the center of the Poisson spot is found by the gray-scale centroid algorithm. The size of the ROI area needs to be appropriately adjusted according to the size of the Poisson spot. The equation of the gray-scale centroid algorithm is as follows.

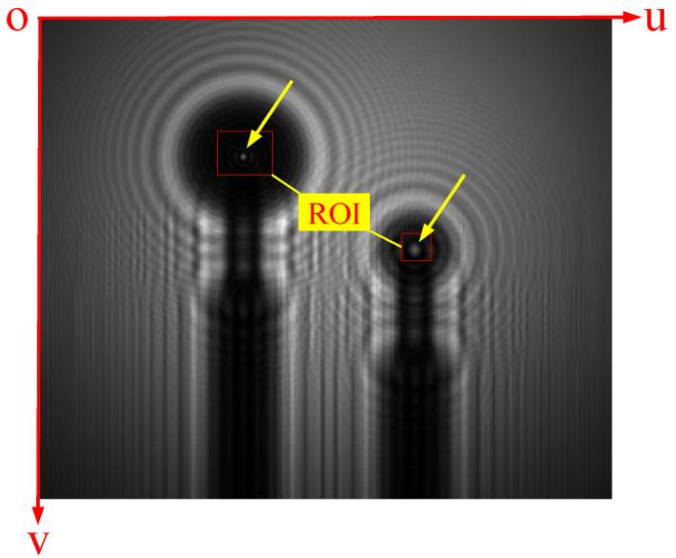


Fig 7. Region of Interest

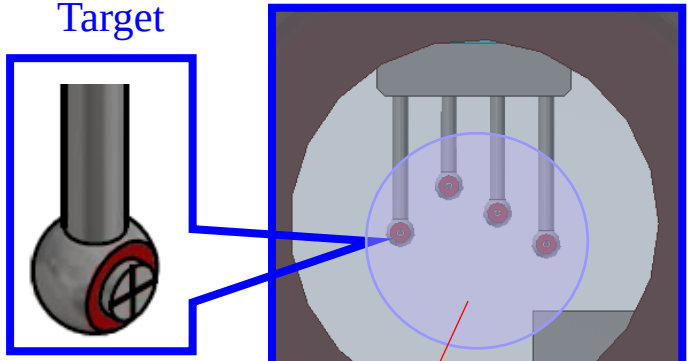
$$x_0 = \frac{\sum_{(i,j)\in S} x_i f_{ij}}{\sum_{(i,j)\in S} f_{ij}} \quad (1)$$

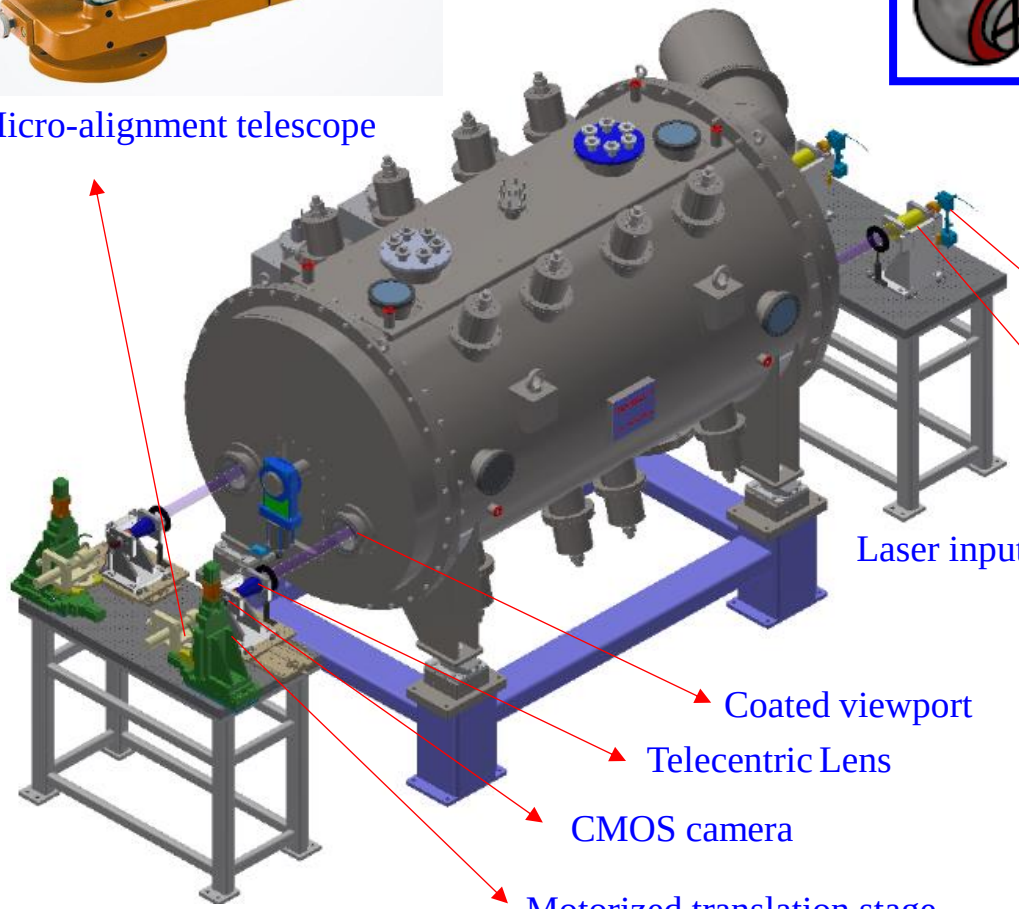
$$y_0 = \frac{\sum_{(i,j)\in S} y_i f_{ij}}{\sum_{(i,j)\in S} f_{ij}} \quad (2)$$

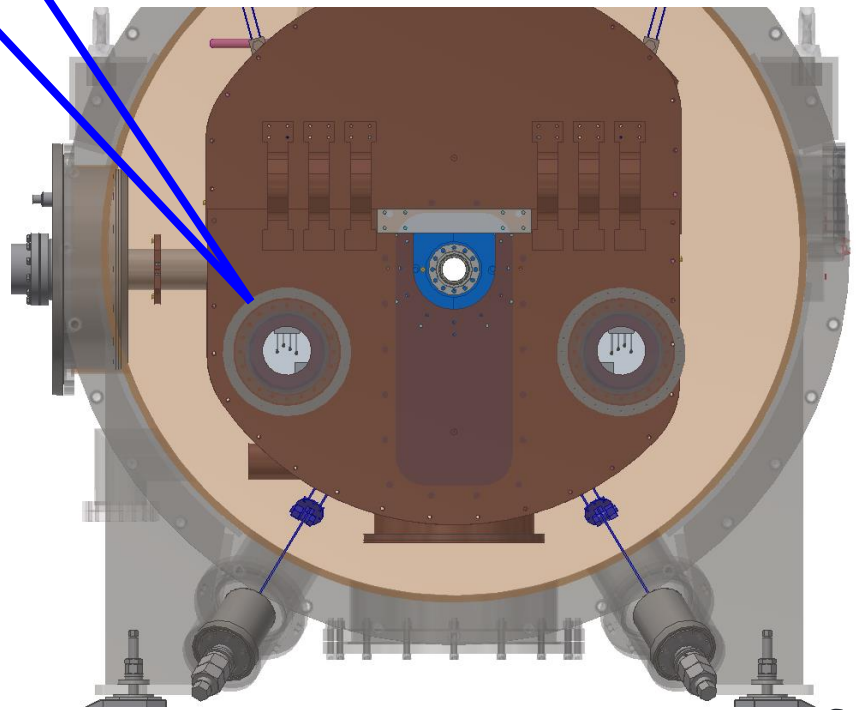
Where S is the region where the gray centroid is extracted. $f(i, j)$ is the gray value at (i, j) and its value range is (0,255). (x_0, y_0) is the extracted centroid coordinates.

2.The Laser-based Poisson Spot Monitor (PSM) system

Micro-alignment telescope

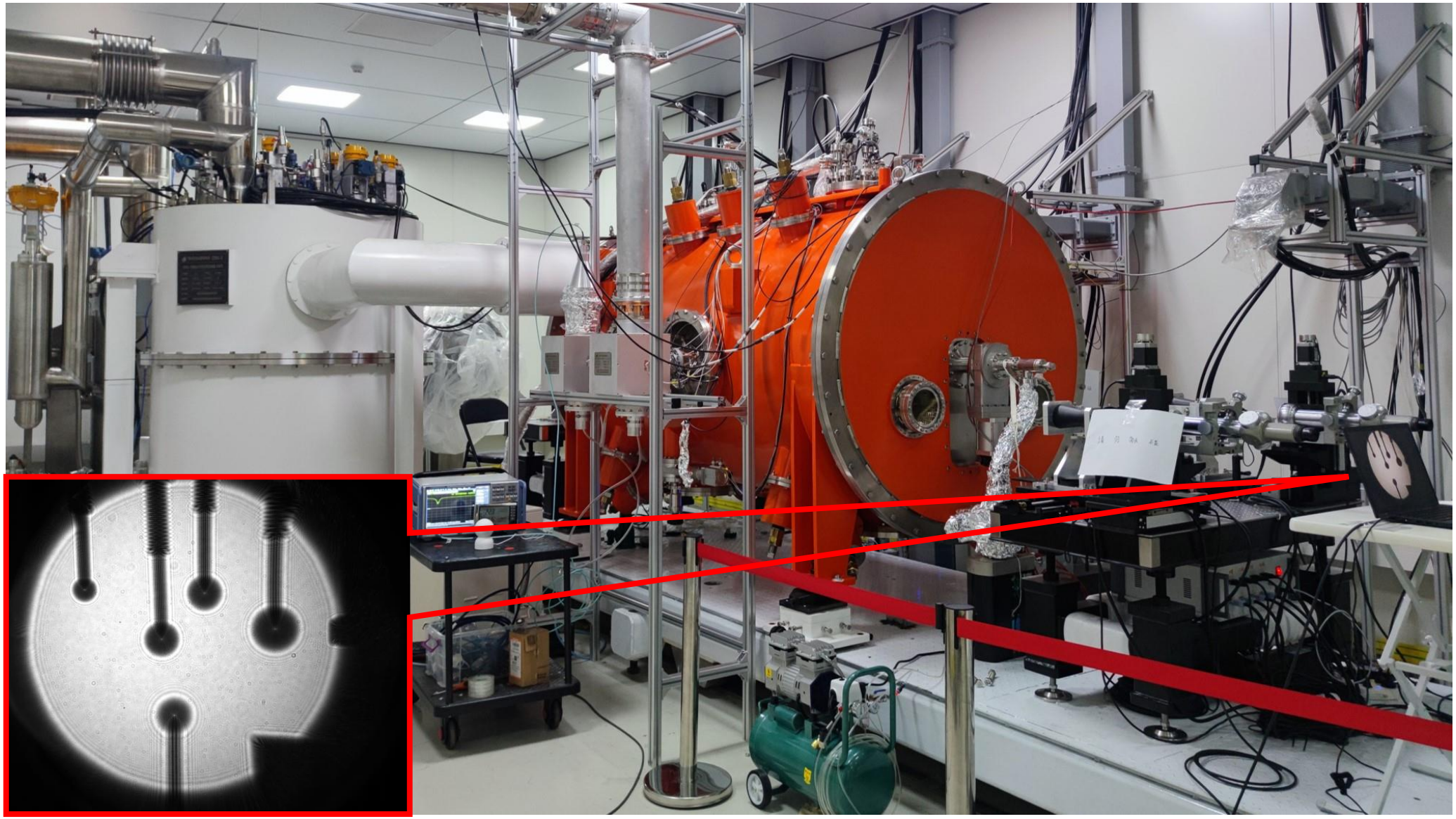






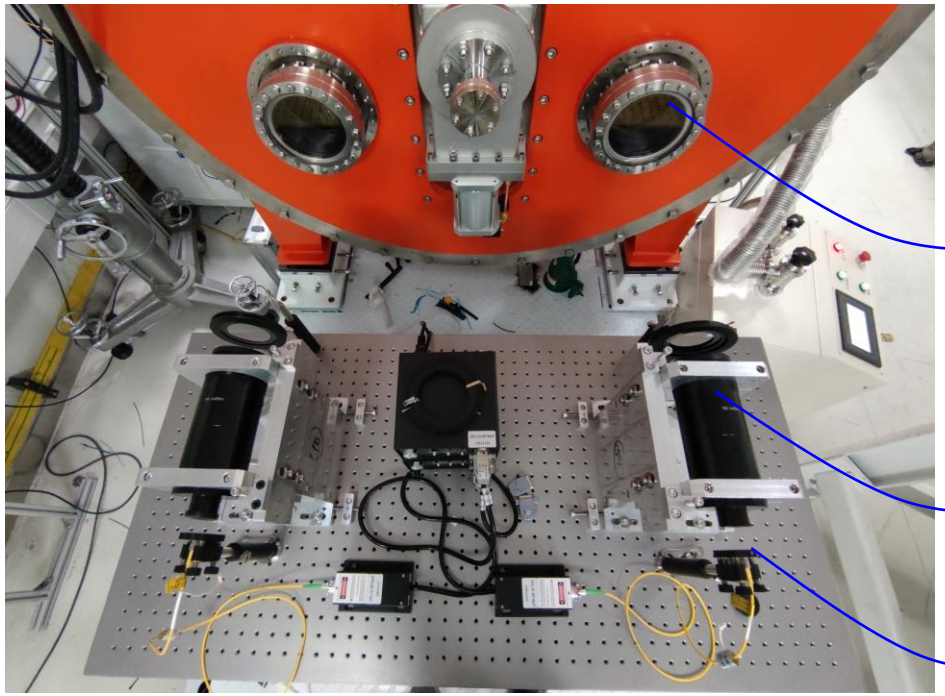
- The micro-alignment telescope is fixed on a motorized translation stage, and the position of the crosshairs on the target is recorded.
- The two monitoring methods are cross-validated and verified to ensure the accuracy of the measurement results.

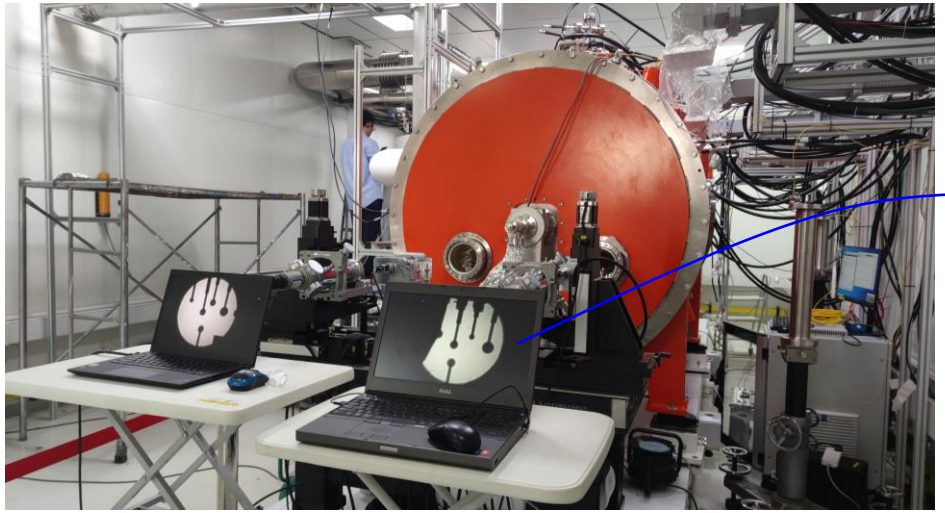
2.The Laser-based Poisson Spot Monitor (PSM) system



The double-spoke cavity cryomodule and PSM system located in the horizontal test stand.

2.The Laser-based Poisson Spot Monitor (PSM) system





Anti-reflective coated viewport with 405 wavelength

Telecentric Lenses

CMOS camera

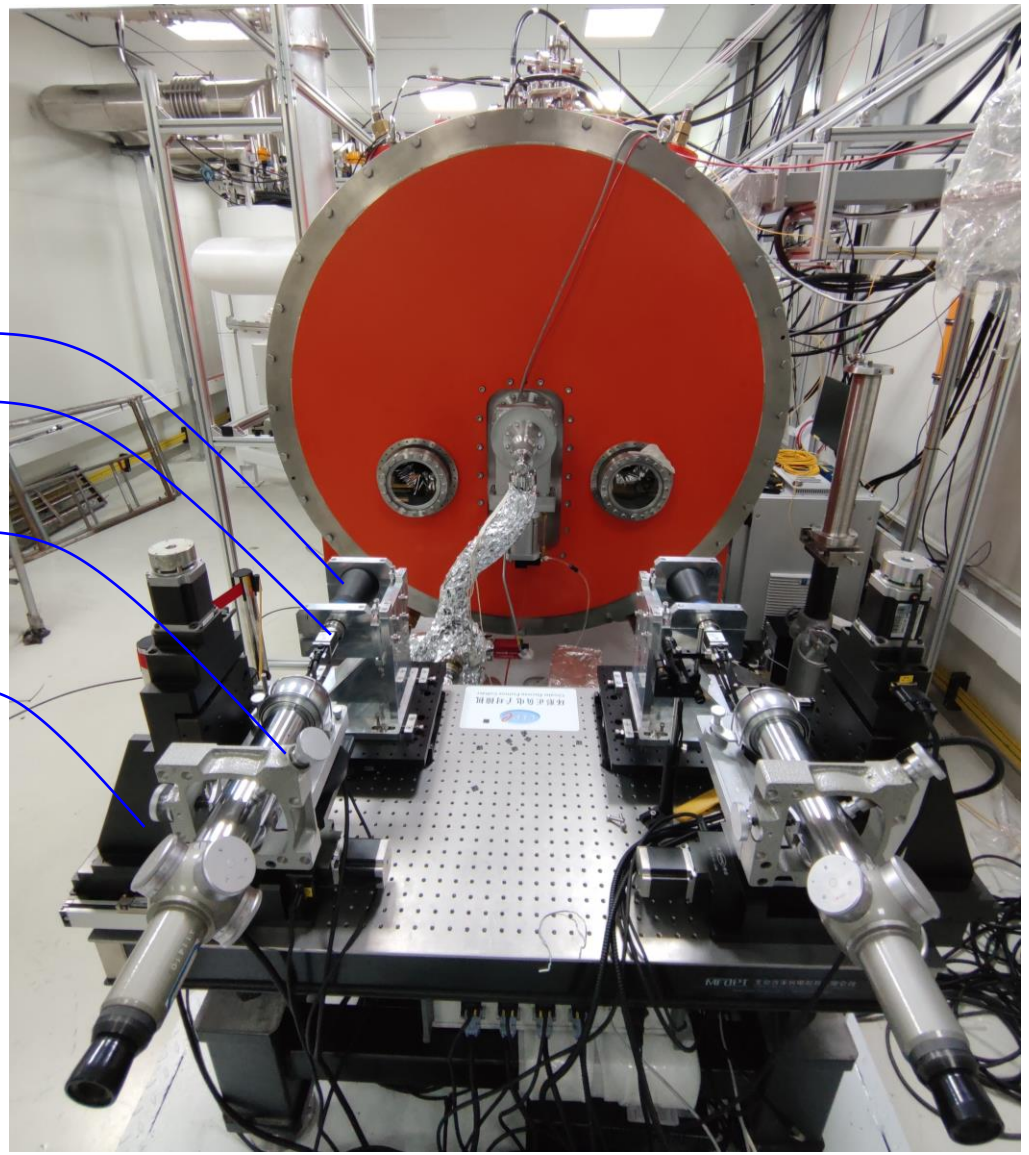
Beam expander

Micro-alignment telescope

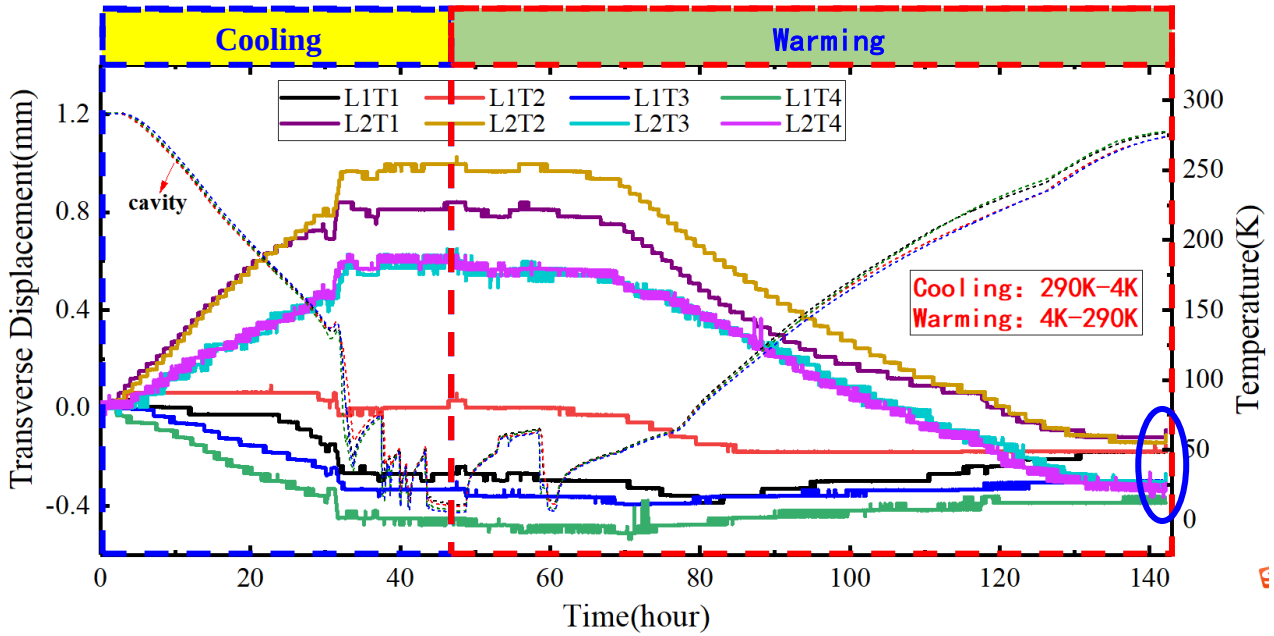
Laser

Motorized translation stage

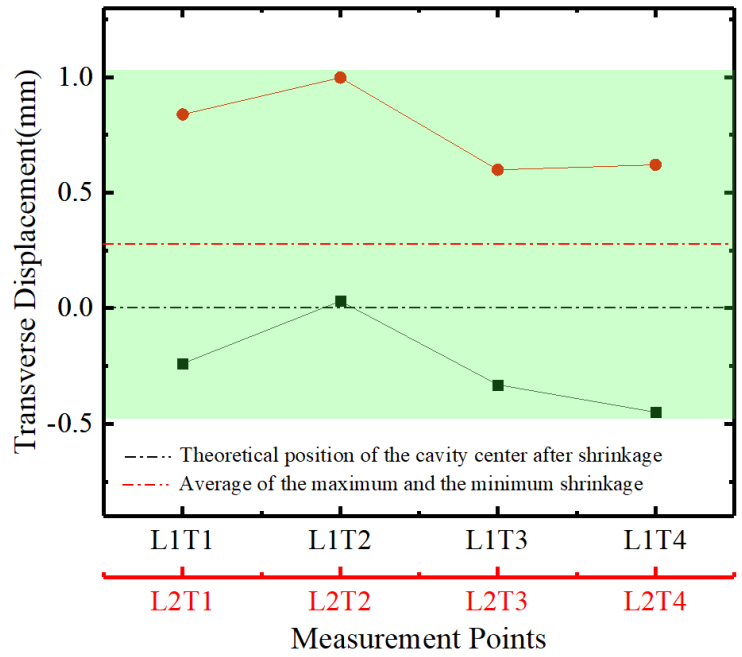
Images



3. Monitoring results of the double-spoke cavity

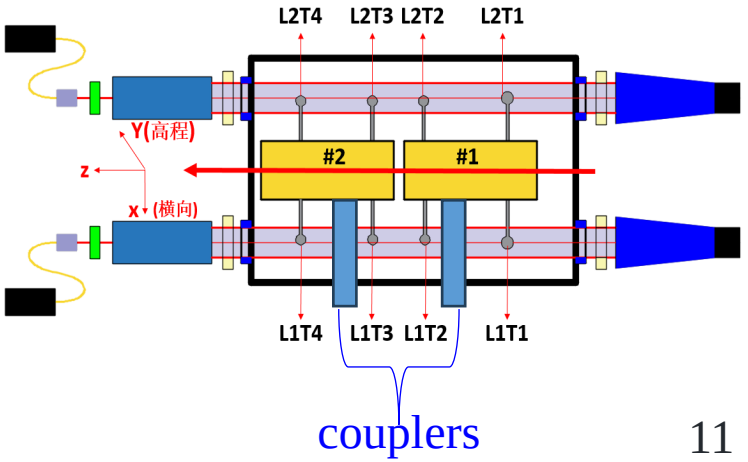


The transverse offsets of the targets during cooling down and warming up compared to the temperature curve of the cavity.

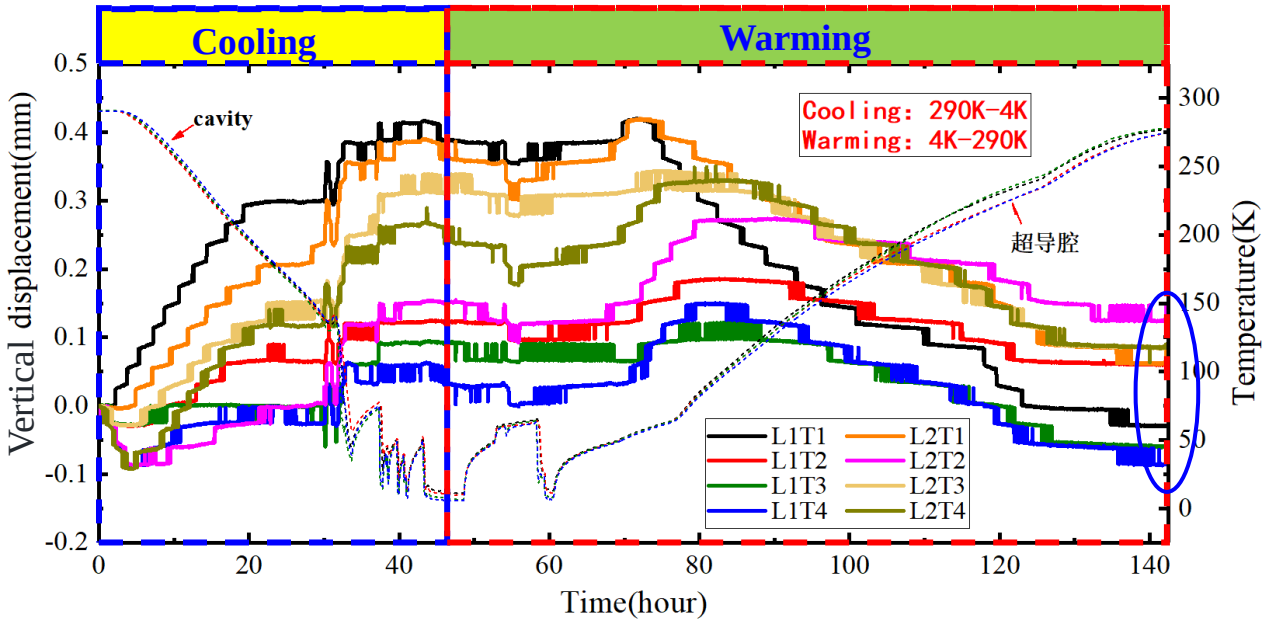


The transverse offsets of the targets before and after cooling.

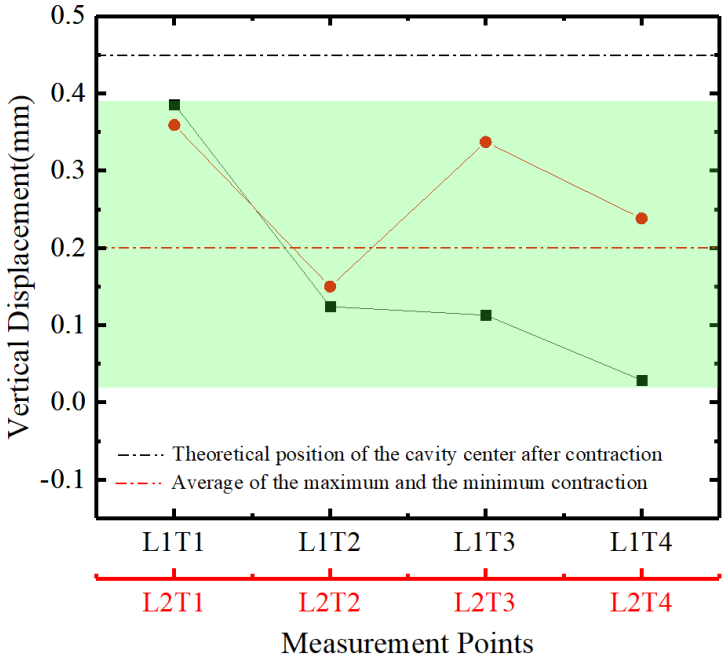
- The displacement of the targets on both sides of the cavity should theoretically be symmetrical relative to the center. That is to say, the transverse position of the cavity center should remain unchanged. However, targets on one side far away from the couplers shows a larger displacement, while targets on the couplers side shows a smaller displacement after cooling down. This indicates that the transverse center of the cavity shifted towards the side of the coupler after cooling, with a displacement of approximately 0.26mm. This asymmetry may be due to the coupler set on the side limiting the cavity from contracting uniformly towards the center during cooling down.
- Furthermore, after warming up, the center of the cavity did not fully return to its initial position, showing a deviation of around 0.1mm.



3. Monitoring results of the double-spoke cavity

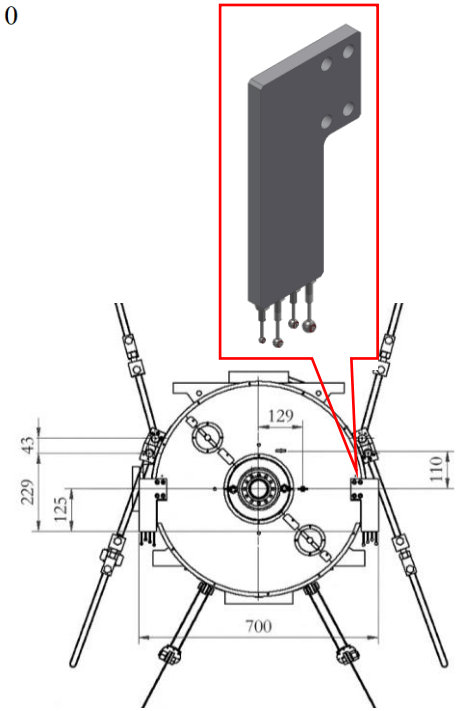


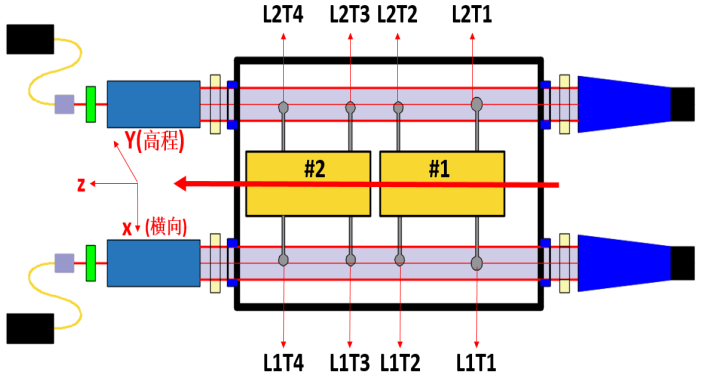
The vertical offsets of the targets during cooling down and warming up compared to the temperature curve of the cavity.



The vertical offsets of the targets before and after cooling.

- In theory, the vertical displacement of monitoring targets after cooling down should be the same. However, the contraction varies, and the average contraction value is approximately 0.2mm, which is smaller than the theoretical calculation. This discrepancy may be related to the distribution of the hanging rods.
- Due to the contraction of the connecting components that fix the monitoring targets, which is approximately 0.3mm, the average displacement in the vertical direction of the cavity center can be calculated to be around 0.1mm.



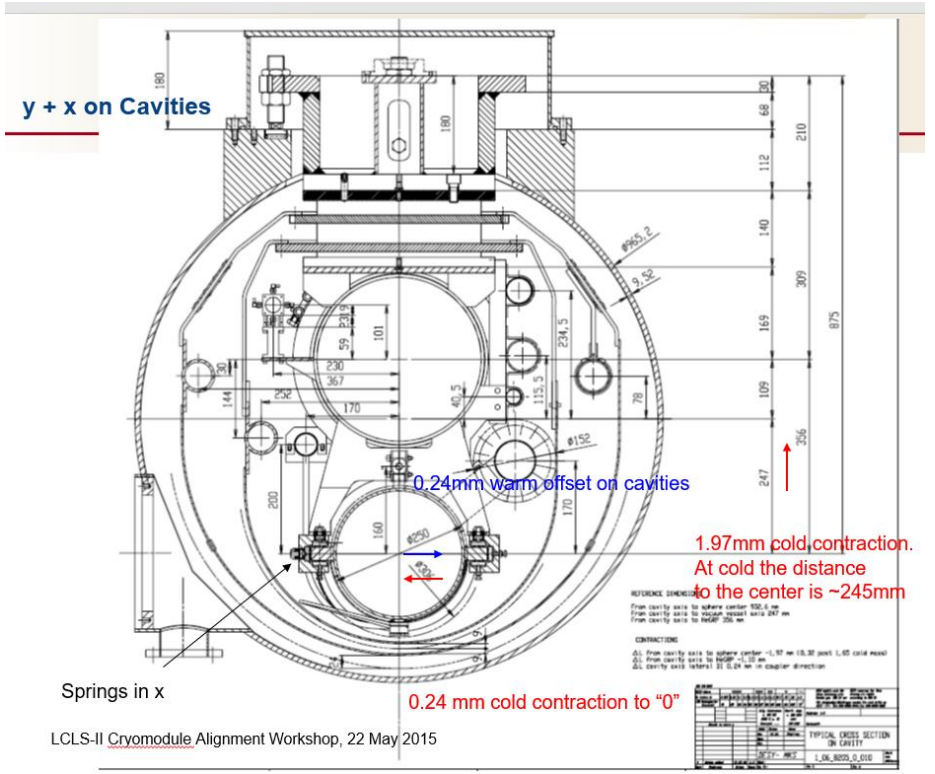


3. Monitoring results of the double-spoke cavity

- Based on the cooling data from these rounds, we calculated the thermal expansions coefficient of the cavity in the temperature range from 290K to 2K to be 1.564mm/m. This value is highly consistent with the thermal expansion coefficient of titanium in the 9-cell superconducting cavity at Desy, which is 1.6mm/m.
- By recalculating the theoretical contraction amounts for each target using the obtained thermal expansion coefficient, we compared them with the measured values. The differences between the theoretical and measured values are typically within 0.05mm, confirming the validity of the thermal expansion coefficient calculation.
- This coefficient allows us to determine the theoretical contraction displacement for each point and the displacement of the cavity center.

THERMAL EXPANSIONS COEFFICIENT

80°K Shield Alluminium	300°K	to	70°K	= 4 mm/m
5°K Shield Alluminium	300°K	to	4°K	= 4,2 mm/m
Cold mass St. Steel	300°K	to	2°K	= 3,1 mm/m
Titanium Cavity from	300°K	to	2°K	= 1,6 mm/m
Invar Bar	300°K	to	2°K	= 0,4 mm/m
Niob	300°K	to	2°K	= 1,5 mm/m



4、Summary

- After several cooling measurements, the transverse displacement of the cavity center is approximately 0.26mm, with a deviation towards the coupler side. The vertical displacement of the cavity center is 0.1mm, showing a trend of higher values at both ends and lower in the middle, which we attribute to the layout of the hanging rods.
- Because the crosshairs on the monitoring target are a bit coarse, the accuracy of the alignment telescope is approximately 0.1mm. The deviation between the measurement results of the PSM system and the alignment telescope is about 0.12mm, further confirming the reliability of the PSM system.
- The repeatability of the cavity center position before cooling down and after warming up is poor, with RMS deviations of 0.19mm, 0.21mm, and 0.08mm for three cycles of cooling down and warming up.
- The absolute positions of the 8 monitoring targets have shifted after multiple cooling cycles, with an RMS change of 0.22mm, unable to completely return to the original positions. Frequent cooling and warming in future operations may introduce uncertainties in maintaining the absolute positions.
- Although the current results may meet the requirements without correction, we aim to obtain more accurate correction values to enhance the final alignment accuracy of the cavity.
- Currently, measurements have only been conducted on one module, and it is essential to apply the same method to measure other modules to obtain more reliable data.

Thank you for your attention !