Visualization of second sound waves based on laser interferometry

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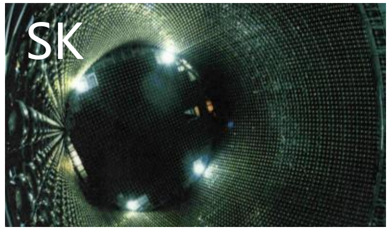
Contents

1 Motivation

- Large-scale scientific facilities **lead and drive the development of disciplines** and **promote major scientific breakthroughs**.
- The superconducting RF resonant cavity is the **core component** of the particle accelerator.
- The superconducting RF resonant cavity **needs to be cooled down to the superconducting critical temperature of the cavity material** to obtain a high acceleration gradient.



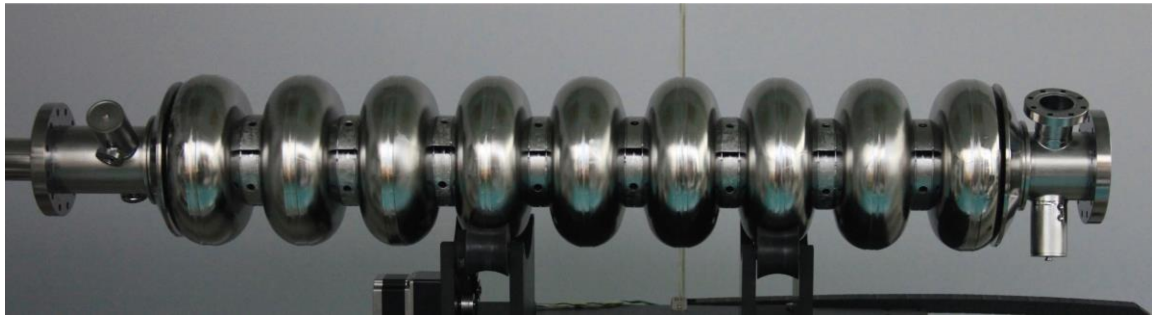
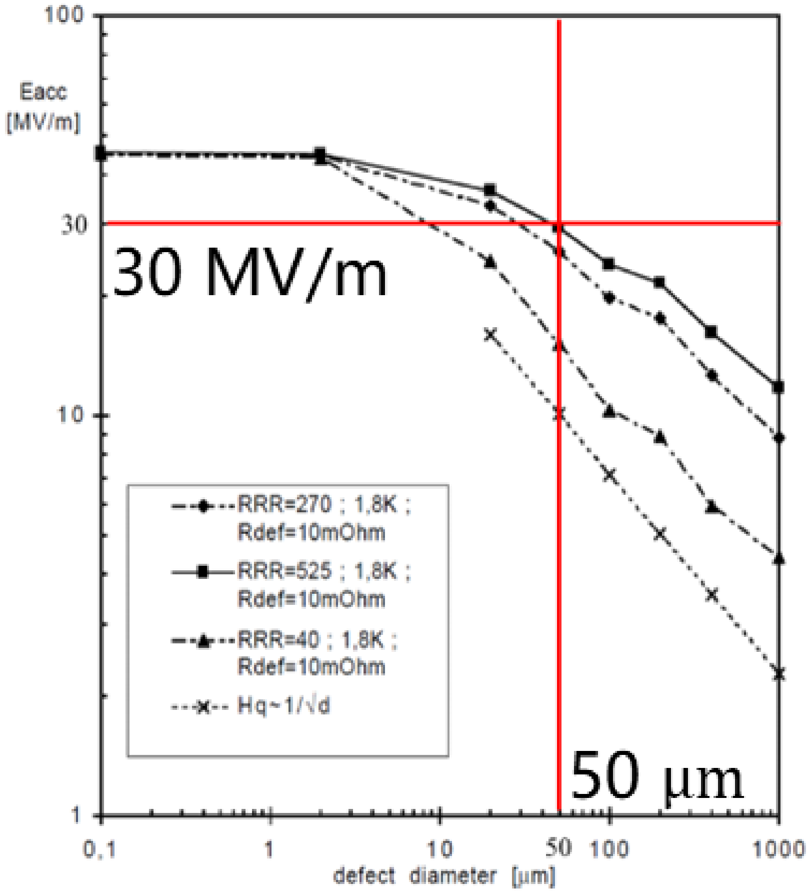


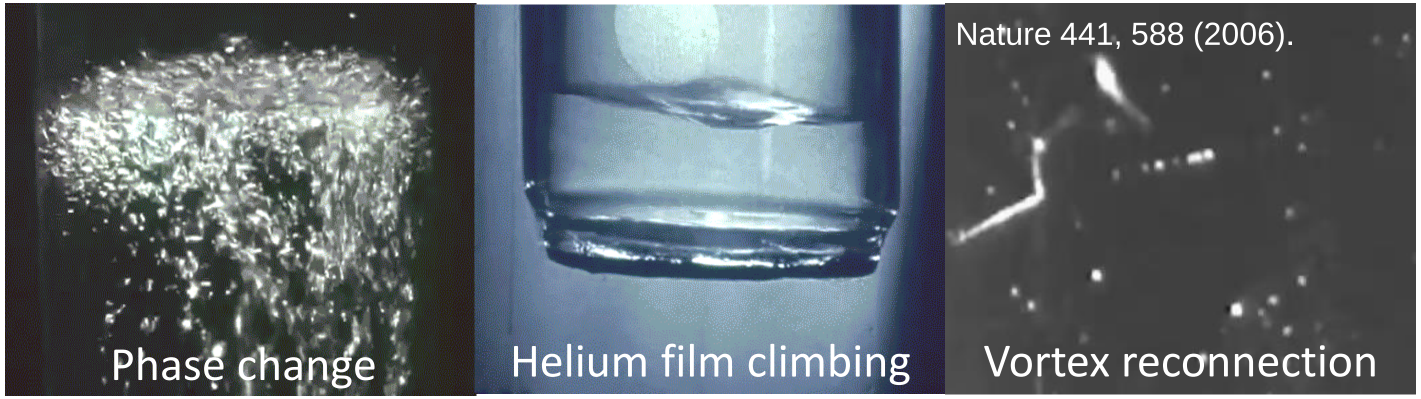
Photo of TESLA type 9-cell superconducting RF resonant cavity*

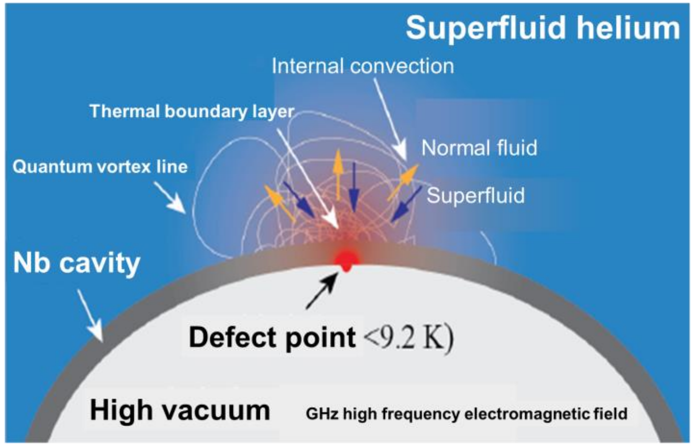
Liu Kexin, Hao Jiankui, Quan Shengwen, et al. SRF accelerating technology applied in light sources[J]. High Power Laser and Particle Beams, 2022, 34: 104014

- Most superconducting cavities are **cooled by saturated superfluid helium**.
- Micron-scale defects or contaminants limit maximum acceleration gradients.
- The heat transfer of superfluid helium varies in different states.

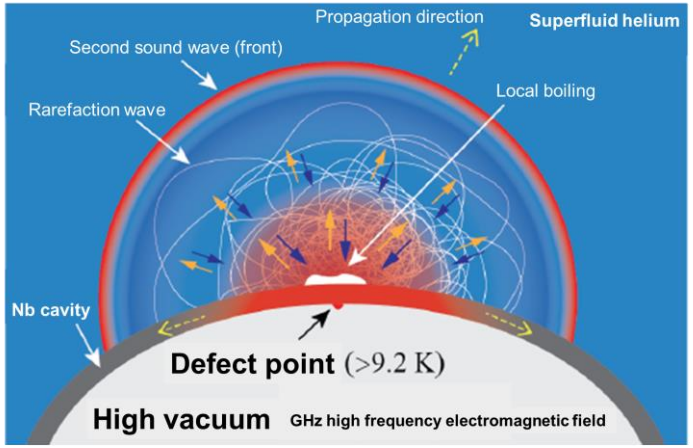


The influence of defect diameter on the maximum acceleration gradient*





Steady state

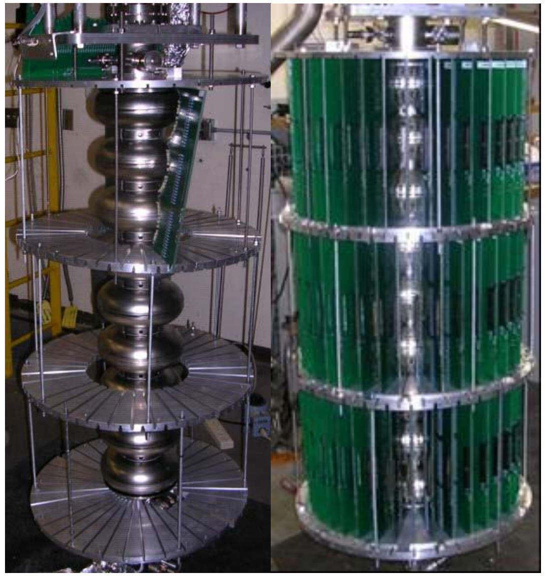


Transient

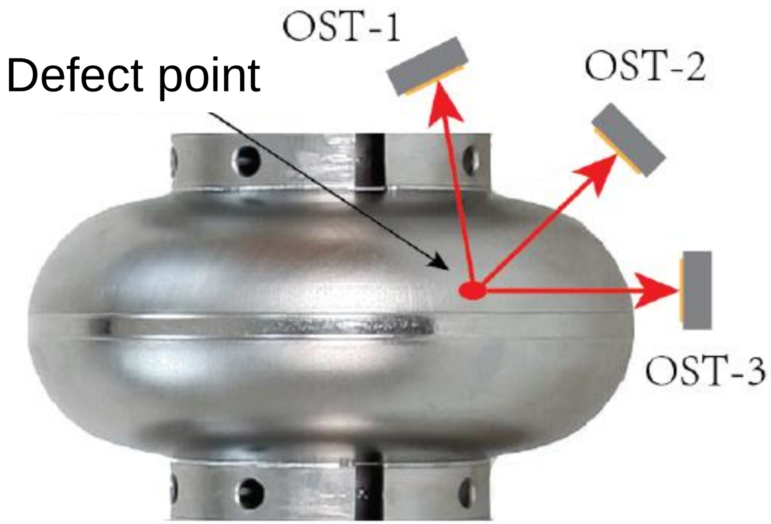
Padamsee H, Knobloch J, Hays T. RF Superconductivity for Accelerators[M]. New York: Wiley, 2008.

1 Motivation

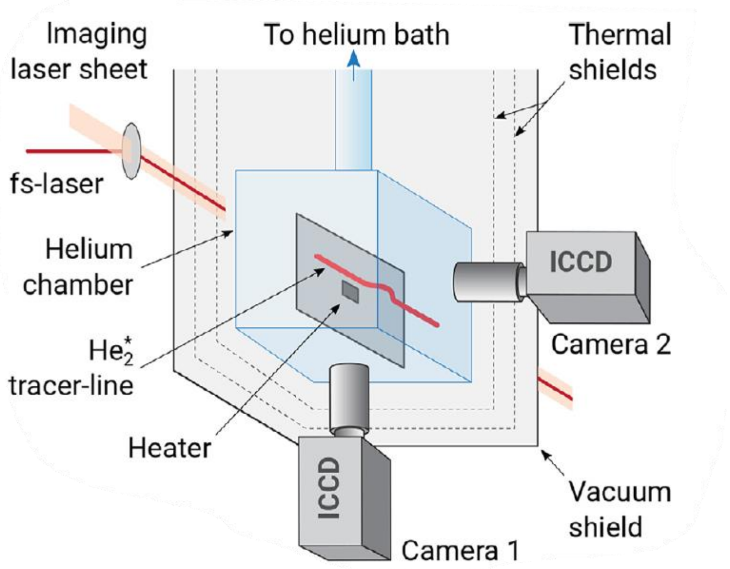
- Defect detection methods: array temperature measurement, second sound wave and flow visualization.
- Areas with high **temperature**s are suspected defect point.
- Reverse derivation of the **propagation time** to obtain the location of the defect point.
- Reverse derivation of **normal fluid velocity field** to obtain defect point.



Array temperature measurement*



Second sound wave



Flow visualization*

Tajima T, Bhatty A, Canabal A, et al. Full Temperature Mapping System for Standard 1.3 GHz 9-cell Elliptical SRF Cavities[C]. PAC. 2010.
Bao S R, Kanai T, Zhang Y, et al. Stereoscopic detection of hot spots in superfluid 4He (He II) for accelerator-cavity diagnosis[J]. International Journal of Heat and Mass Transfer, 2020, 161: 120259.

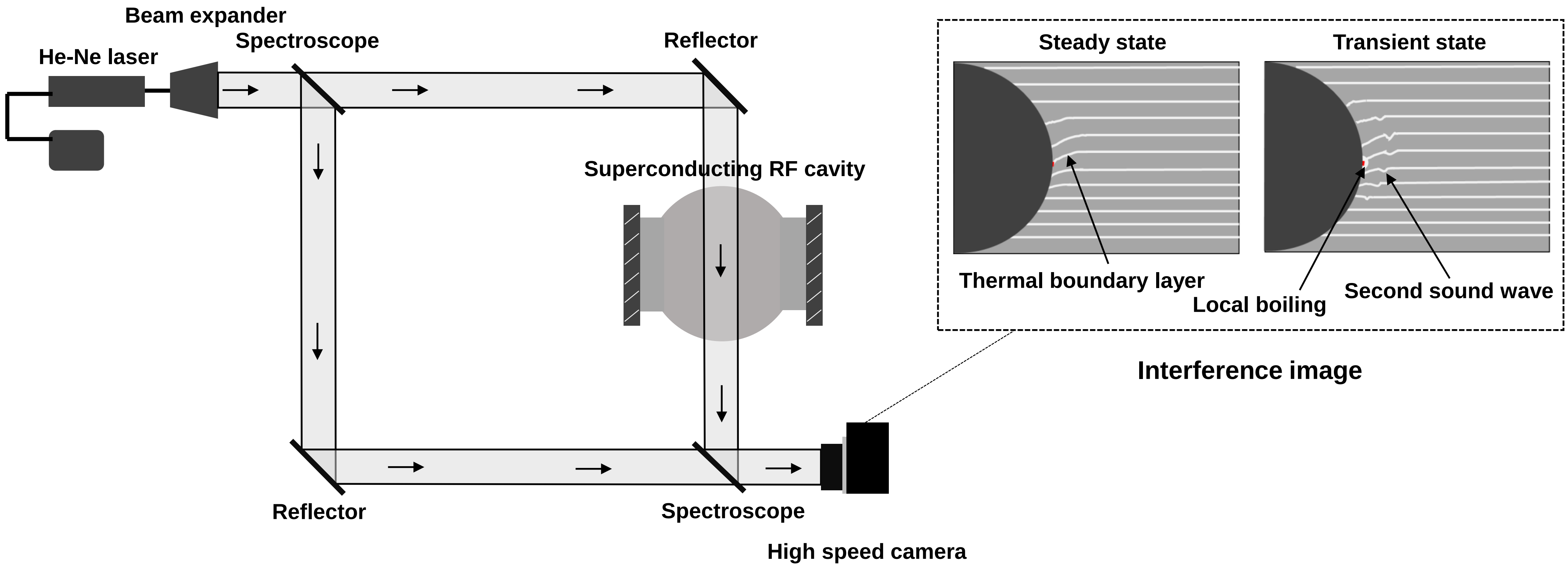
1 Motivation

Comparison of detection methods

Method	Sensor type	Sensor quantity	Accuracy	Feature
Array temperature measurement	Thermometer	Fixed type>1000	Medium	**Contact type**, complex operation, high investment
		Rotary>10	**Low**	**Contact type**, complex operation, low investment
Second sound wave	Superleak sensor; Superconducting phase change sensor; High sensitivity thermometer	≥3	**Low** (5-10 mm)	Non contact, easy operation, low investment
Flow visualization	He_2^* molecular	N/A	High (<1 mm)	Non contact, complex operation, **extremely high investment**

2 Test system design

- This method uses Mach-Zehnder interference optical path.
- The object light sweeps through the cavity surface and interferes with the reference light.
- The interference fringes near the defect point will deform.
- In the experiment, the copper hemisphere simulates the cavity and the heater simulates the defect point.



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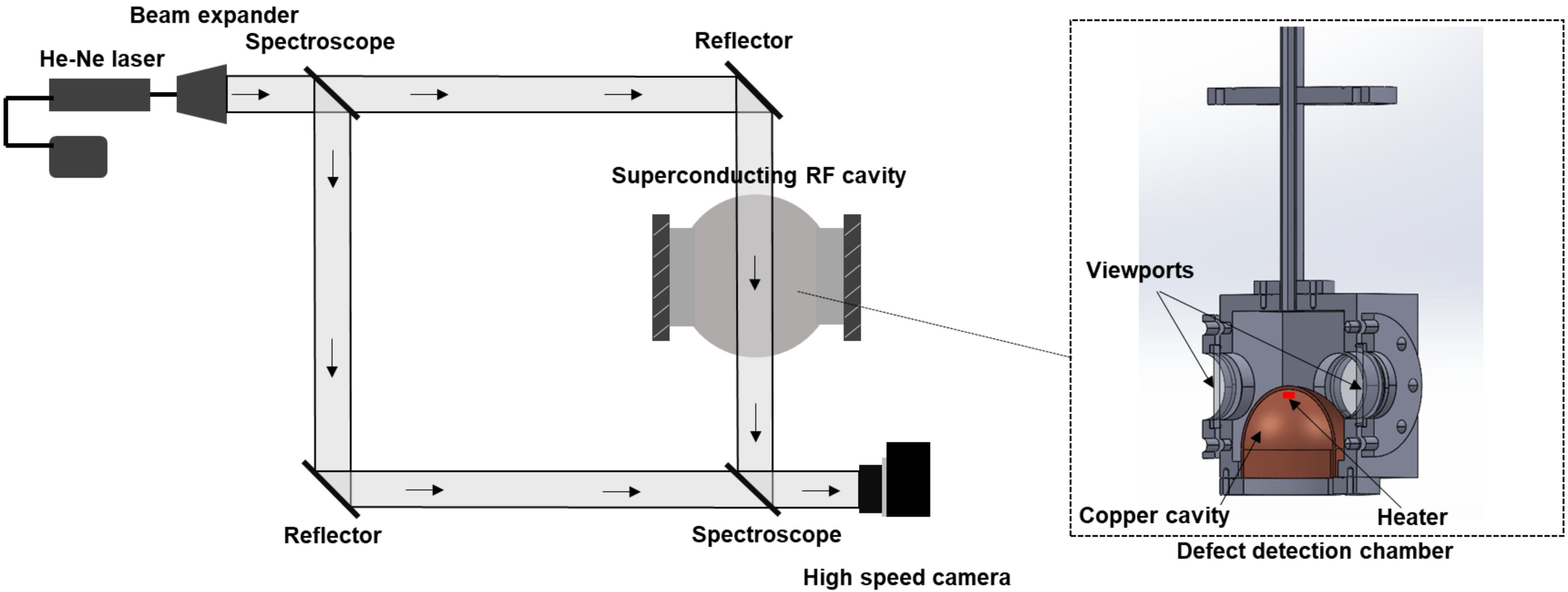
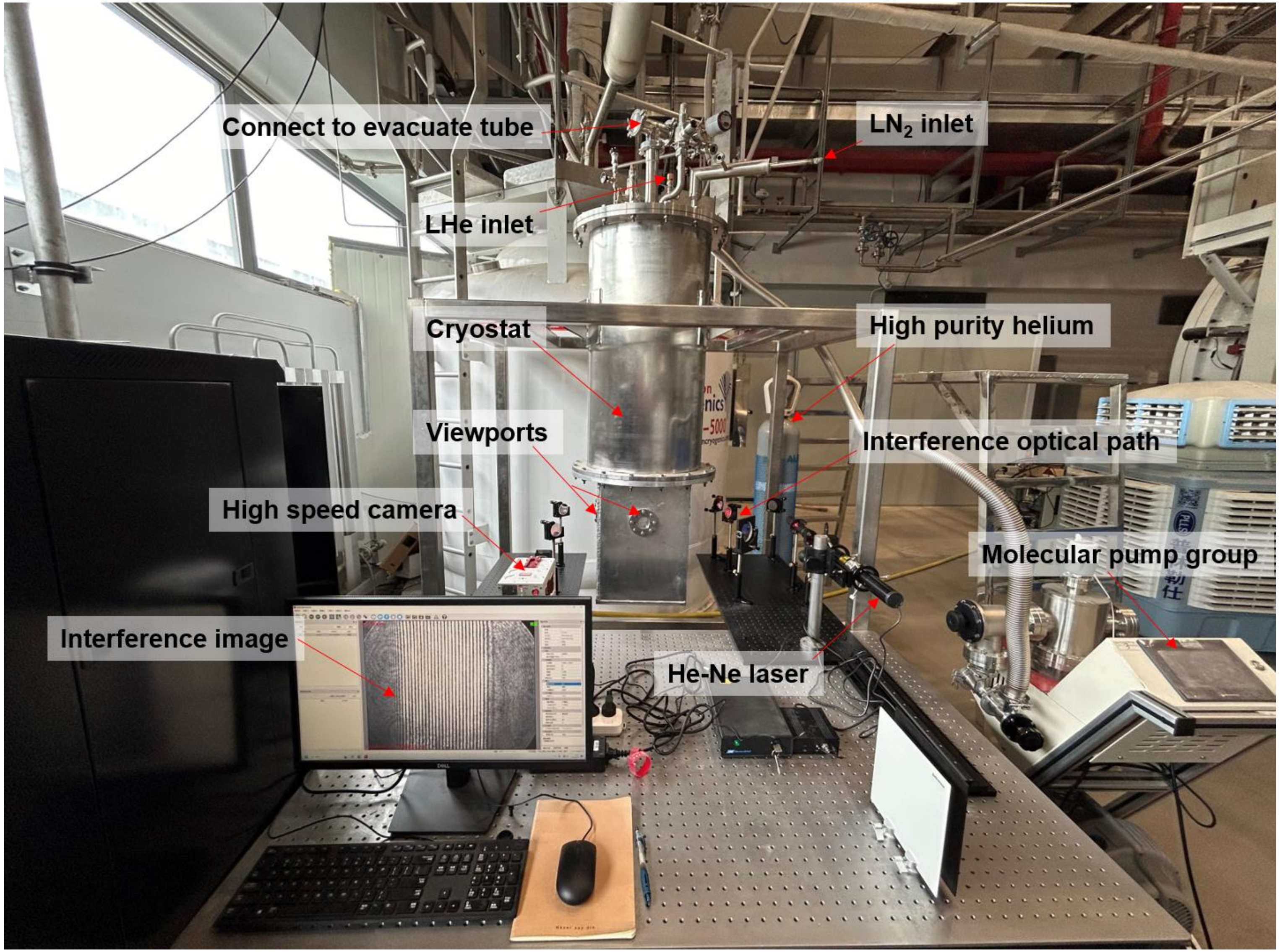
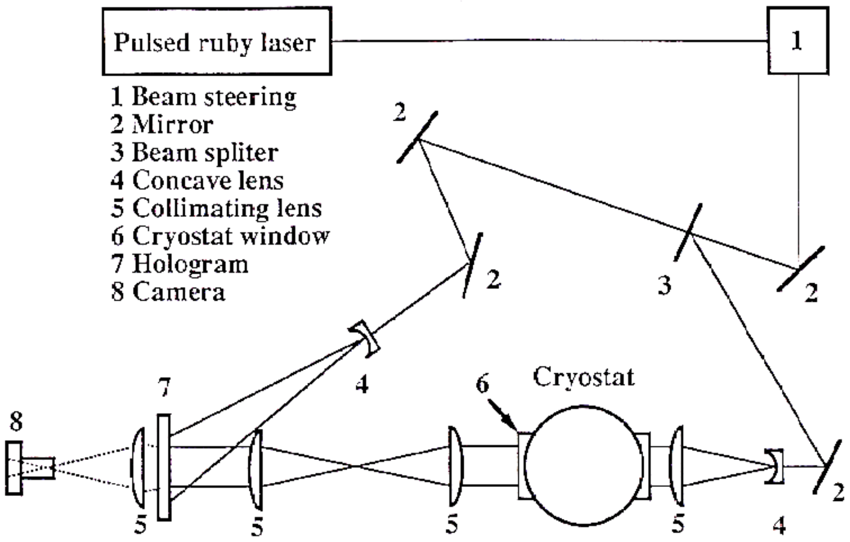


Test system design

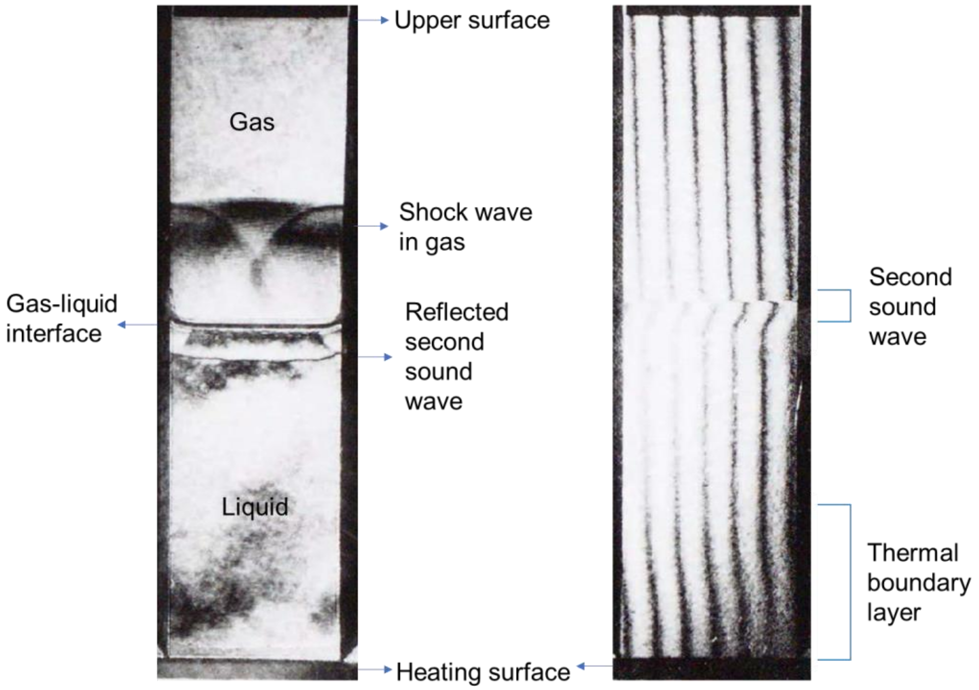
- Precooling with liquid nitrogen and liquid helium.
- By reducing the pressure on the helium bath, we can obtain superfluid helium.
- Maintain low temperature with high vacuum multilayer insulation.
- At present, the test system is still under construction.



- **The interference images we use to process comes from Lida's experiment.**
- The **laser holographic interferometer** is used in the experiment.
- They use interference fringes with **finite and infinite widths** to capture images.
- A lot of information was obtained from the image.
- The experiment did not obtain quantitative data on the flow and heat transfer of superfluid helium.



Arrangement of optical elements for the laser holographic interferometer.

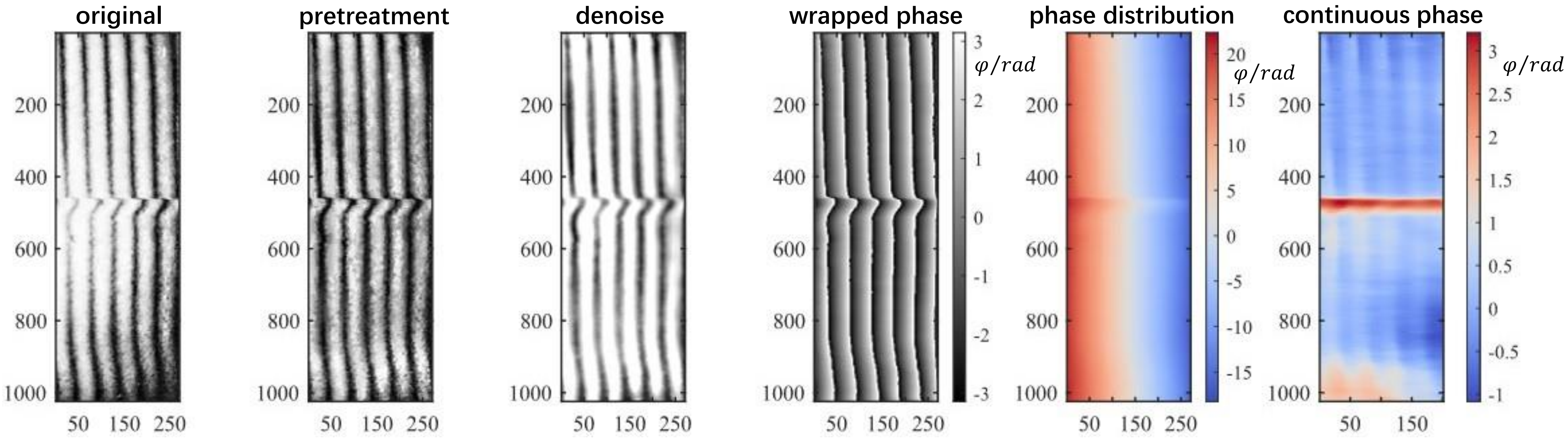


Infinite interference fringes

Finite interference fringes

Teruhito IIDA. (1995) Visualization study of thermo-fluiddynamic phenomena in He II by using laser holographic interferometer.

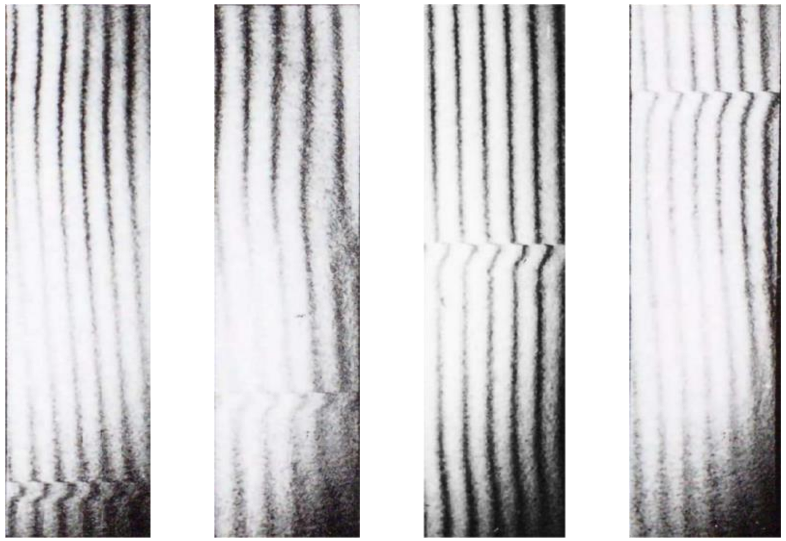
- Based on the treatment method of interference fringes on the depression of the surface of the object by Munther Gdeisat et al*.
- T=1.74 K, heat flux Q=30 W/cm^2, thermal pulse width t_H=80 μs, shooting time t_D=200, 500, 1000, 1500 μs.
- Taking the processing of the interference fringe at t_D=1000 μs as an example.



Interference fringe processing for t_D=1000 μs

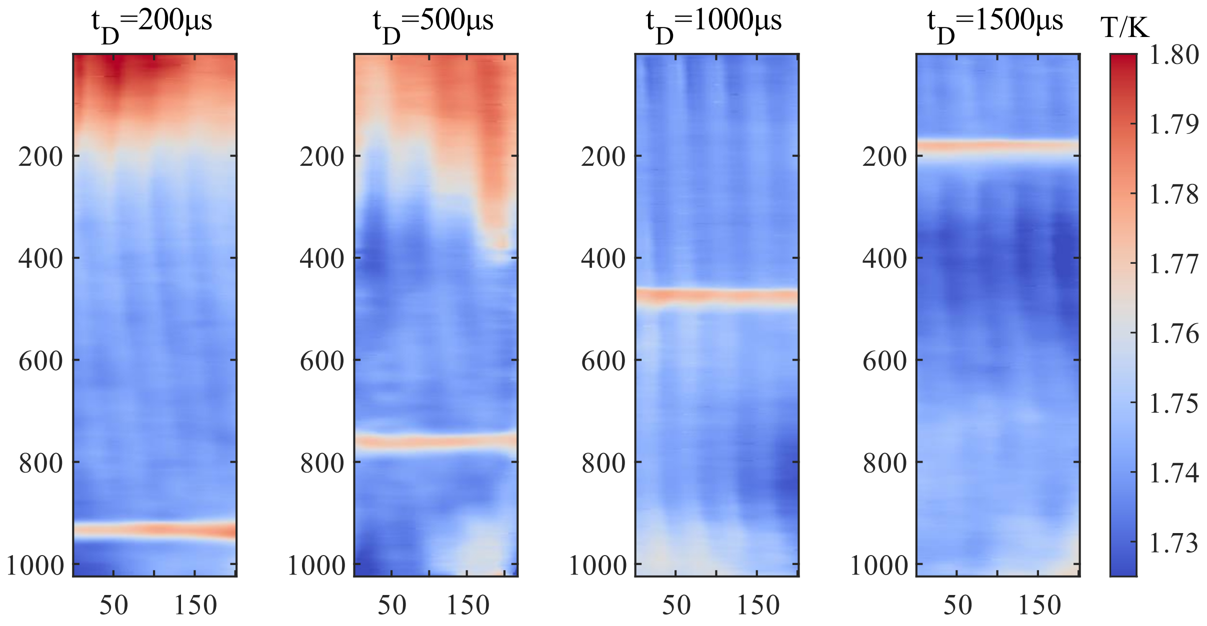
M. Gdeisat, D. Burton, and M. Lalor, "Spatial carrier fringe pattern demodulation by use of a two-dimensional continuous wavelet transform," Appl. Opt. 45, 8722-8732 (2006).

- Temperature distributions obtained by processing interference fringes at t_D=200, 500, 1000, 1500 μs.



(a)t_D=200μs (b) t_D=500μs (c) t_D=1000μs (d) t_D=1500μs

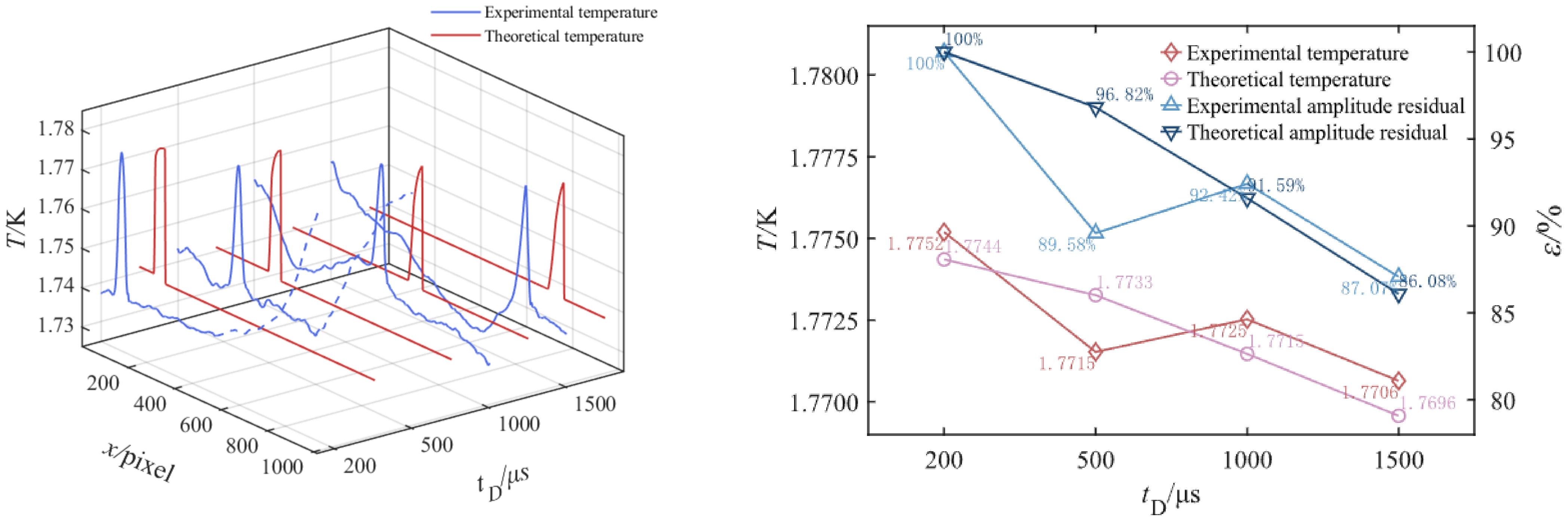
Original interference fringes



Temperature distribution

3 Interference fringe processing

- We also used a 1D superfluid helium hydrodynamic calculation program to verify the processing results.
- The experimental temperature is the average along the path.
- The maximum amplitude is basically consistent.
- The low image quality of 500 microseconds results in significant differences.



Comparison between numerical calculation results and processing results

Summary

- It is proposed to detect superconducting RF cavity defects by **taking interferometric images**, which is expected to have **high accuracy and low cost**.
- We have built a test system including measurement, cryostat, optics, and control.
- **Temperature distribution was obtained** by processing the interference fringes captured by Lida.
- Processing results are in good agreement with simulation results.

Prospect

- The next step is to **complete the preparation work** for the test system and **verify the feasibility of the method through actual experiments**

Thanks!

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