Development of femtosecond laser vacuum cryogenic system

Guopeng Wang[1,2], Xueliang Li[1,2], Jia Quan[1], GuoTong Hong[1]
1 Key Laboratory of Space Energy Conversion Technologies, Technical Institute of Physics and Chemistry CAS, Beijing, 100190, China
2 University of Chinese Academy of Sciences; Beijing, 100190, China;

System architecture

Figure 1 shows the Schematic diagram of the system, which consists of three parts: the cryogenic liquid store Dewar, the main body of the system, and the electronic control system. The cryogenic liquid store Dewar and delivery pipe are used to store and transfer liquid nitrogen or liquid helium. The main body of the system consists of a vacuum chamber, a flexible cooling system and a two-dimension move platform. The structure of the cooling system is showed in figure 2, and the crystal is fixed in the bottom of the cryogenic container which is inside the system and there is a heat exchanger on the top of the container which is used to utilize the cooling capacity of the cold helium gas or nitrogen gas. The container and the crystal are enclosed by a copper cold shield. The flexible liquid pipe inside the cooling system connects to the cryogenic delivery pipe so that the cryogenic liquid can enter into the container and the crystal can be cooled. The flexible gas pipe inside the cooling system is used for the exhaust of the evaporated gas to the atmosphere. Four parallel heater band and a diode thermometer are pasted on the surface of the container. They are used to heat the crystal and measure its temperature. The cooling system is fixed on a two-dimension move platform, as shown in the left of the figure 3. For this system, two flexible pipelines transporting cryogenic liquid nitrogen and helium to the container and exhausting the nitrogen or helium gas to the atmosphere are invented. As shown in figure 2, using this flexible pipelines and a two-dimension move platform which is used for fixing the cryogenic container, the container and the crystal sample can rotate more than ±30° on the horizontal plane and move more than ±10mm in X and Y directions. The control system consists of a temperature controller which is used to control the heat power and monitor the temperature and a platform controller which is used to control the two-dimension move platform.

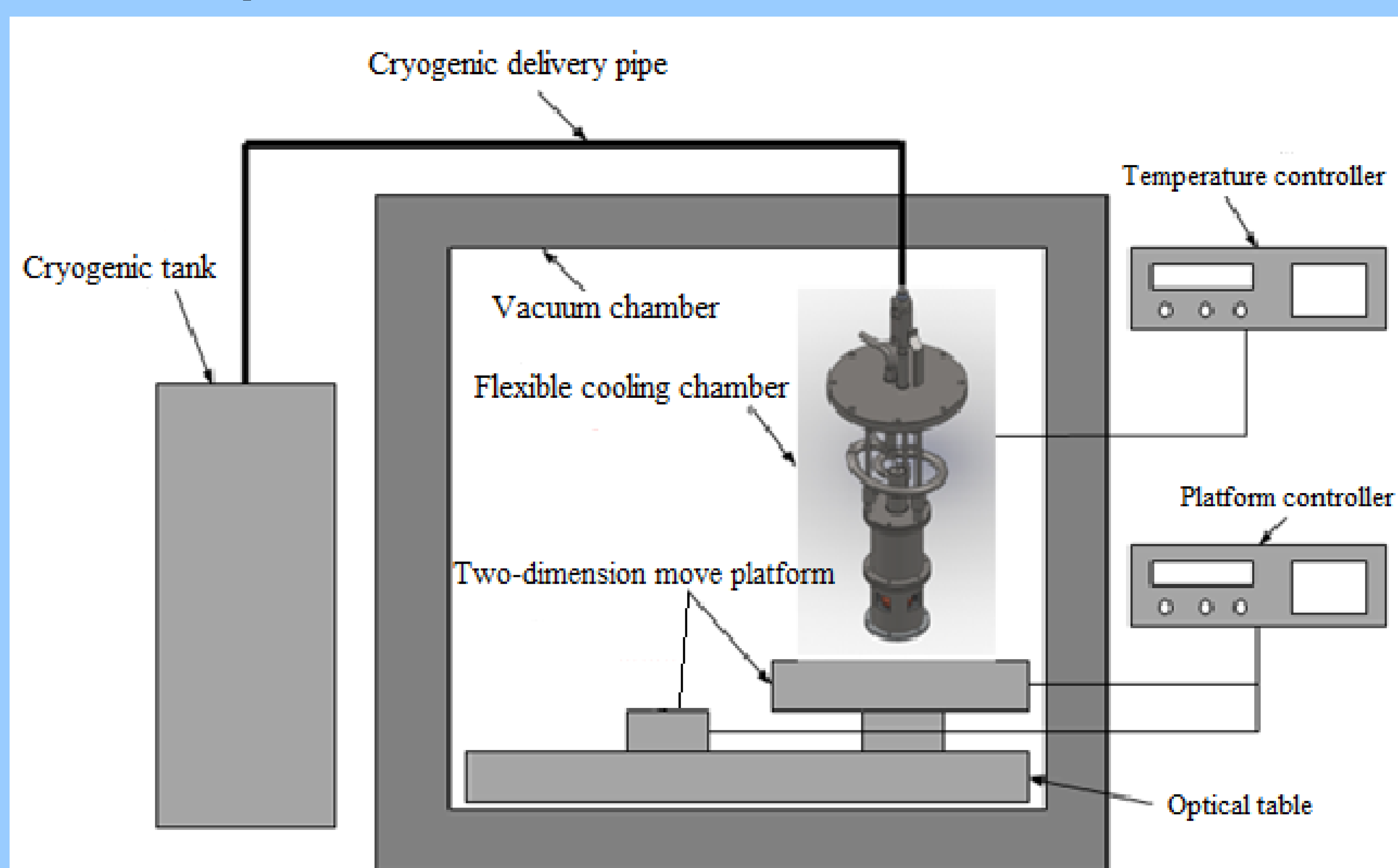


Figure 1. Schematic diagram of the system.

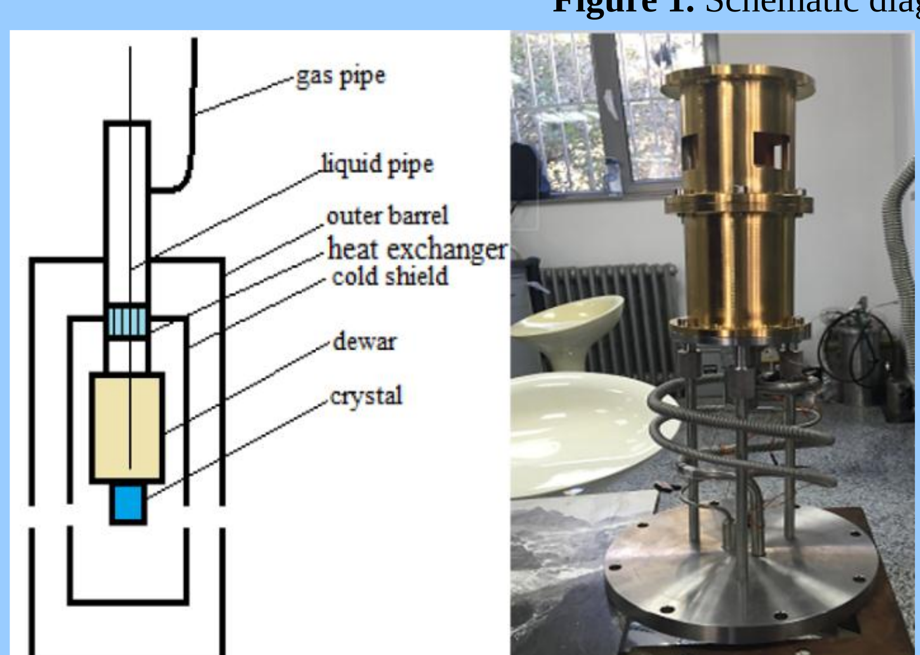


Figure 2. Schematic diagram of the Flexible chamber.

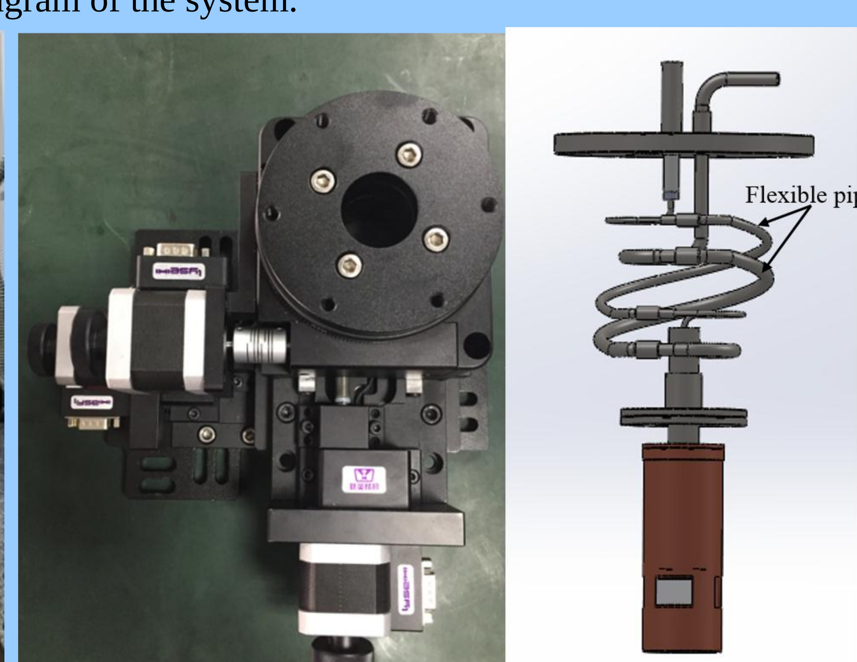


Figure 3. move platform and flexible pipe

Thermal analysis

Heterogeneous temperature will cause deformation and generate thermal stress in the crystal. These will influence the beam quality and damage the crystal. So it's important to keep the temperature uniform of the crystal. Heat leakage is another important parameter for this cryogenic system. The lowest temperature of the crystal in the cooling system must be below 5K, so the cold source in this temperature range is liquid helium, and the latent heat of the liquid helium is small, the bigger heat leakage means more liquid helium that needed in the experiment. If the heat leakage is too big, the lowest temperature of the crystal won't reach 5K. In order to predict the performance of the system before experiment, it's necessary to make a numerical analysis. The numerical model is built in the software Ansys. Table 1 is the boundary conditions and the figure 4 is the mesh model.

Table 1. Boundary conditions of the cooling chamber.

temperature of the vacuum chamber(K)	temperature of the bottom of the Dewar(K)	heat exchanger parameter	
		Gas temperature(K)	convective heat transfer coefficient (W/(m^2.K))
295	4.2	40	1
295	77	110	1

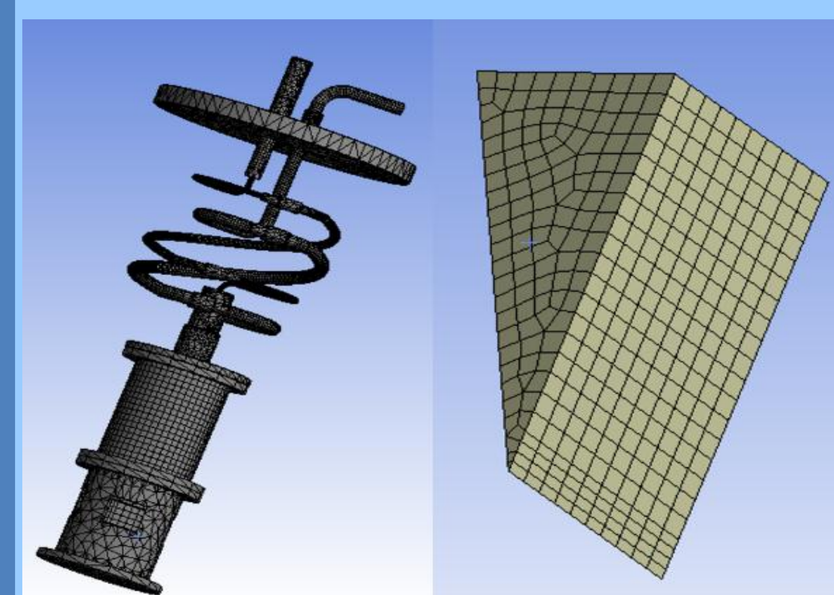


Figure 4. Mesh model of the system and crystal

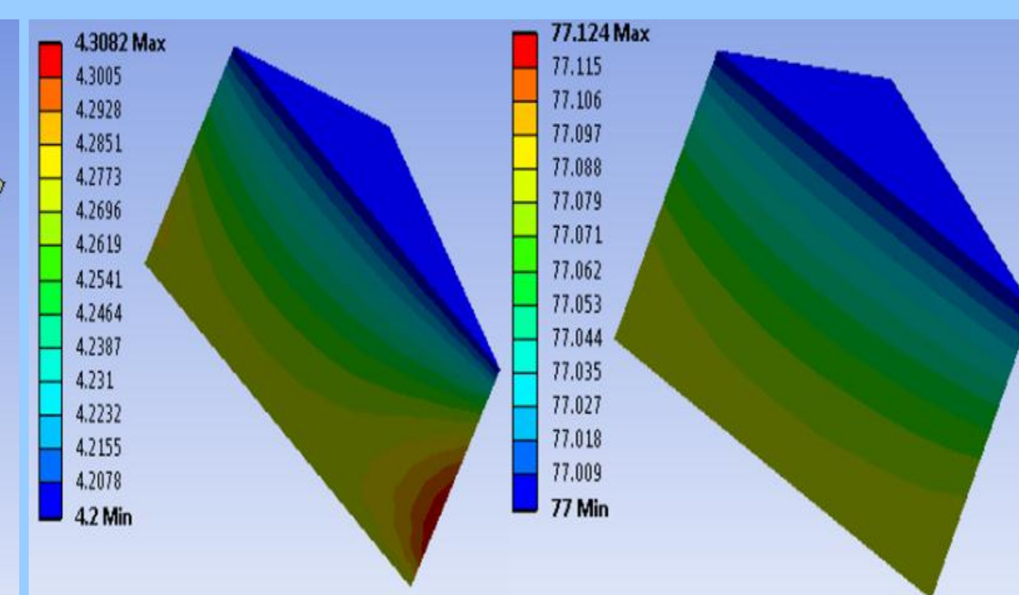
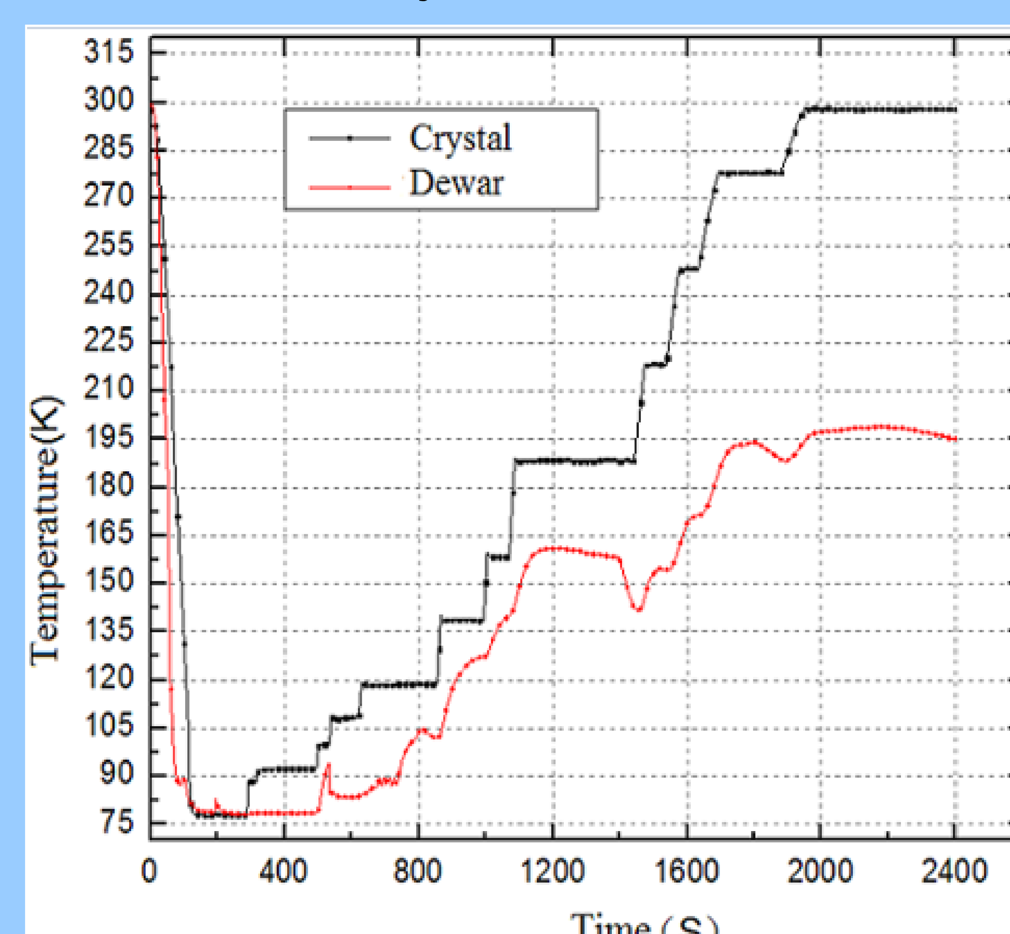


Figure 5. Temperature distribution of the Crystal

Figure 5 shows the simulation of the temperature field of the crystal. When the temperature of the container is 4.2K, the heat leakage to the whole system is 1.24W and that to the container is 0.45W. The biggest temperature difference of the crystal is 0.1K.When the temperature is 77K, the heat leakage to the whole system is 1.02W and that to the container is 0.42W. The biggest temperature difference is 0.12K. The heat exchanger utilizes much of the cooling capacity of the cold gas to cool down the copper shield, so the heat leakage of radiation is very small. And the temperature uniform of the crystal is good. In two different boundary conditions, the maximum temperature difference is about 0.1K. So the influence it caused to the beam quality and thermal stress can be ignored.

Test results and analysis



test point（K）	fluctution（K）
78	+0.8/-0.1
92	+0.6/-0.2
108	+0.7/-0.4
118	+0.8/+0.2
138	+0.9/+0.4
158	+1.0/+0.1
188	+1/-0.1
218	+0.9/-0.2
248	+0.6/-0.5
278	0.4/-0.3
298	+0.5/-0.3

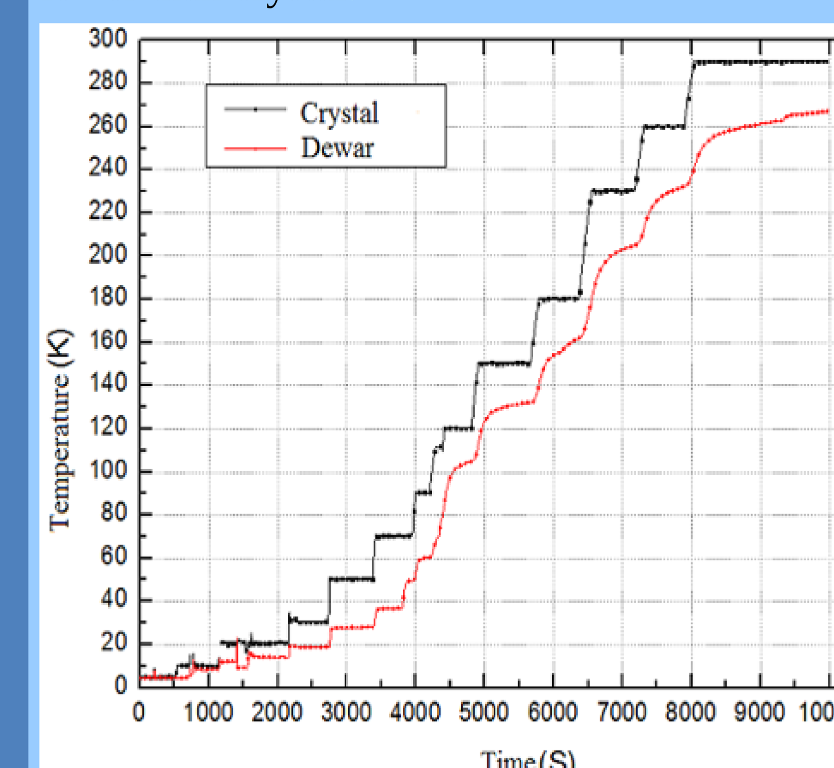
Figure 6. Temperature of Dewar and Crystal (nitrogen).

Figure 6 shows the result using liquid nitrogen as cold source. There are 11 temperature control points in this experiment. The fluctuation of the crystal's temperature is lower than 1.3K. Figure 7 shows the results using liquid helium as cold source. The number of the temperature control points between the temperature ranges 5 to 80K is seven. And the fluctuation is lower than 0.9K.

Figure 6 and figure 7 also show that the temperature of the container is not as stable as the crystal and changes as the time goes on. This is different with the numerical simulation. In the numerical model, the temperature of the container is one of the boundary conditions and it is not changed. Because in this experiment, a new method is used to control the temperature. What mainly stored in the container is cold gas. The boiling point of the liquid helium is 4.2K and the liquid nitrogen is 77K, according the Fourier's law

$$q = kA\frac{\Delta T}{L}$$

The power needed to heat the crystal is in proportional to ΔT. If the parameter k, A and L are not changed and the temperature difference between the crystal and container with cryogenic liquid is too much, the power need is very big. For example, if the distance between the container and the crystal is 20mm, when the temperature of the crystal needs to be controlled at 200K, the power of the resistive heater is more than 200W. So the cold gas is used as cold source in the container. When the heat leakage of the liquid delivery pipe is big enough to cause all the flowing cryogenic liquid inside evaporating, the phase of the nitrogen or helium will wholly changes from liquid to gas and the temperature of the container will keep same as that of the cold gas inside the container. It can be easily changed when the flow rate of the flowing liquid is regulated. With this method, the container temperature can be roughly regulated to that a little lower than that of the crystal needed. On this base, using the PID controlling strategy of the Lake shore temperature controller, the temperature of the crystal can then be accurately controlled to the aim. As the lower temperature difference between the crystal sample and container, the control heat power needed is sharply reduced. What need to be ensured is that the temperature of the container is lower than crystal.



test point（K）	fluctution（K）
5	+0.1/-0.2
10	+0.3/0
20	+0.5/+0.4
30	+0.7/+0.2
50	+0.4/+0.1
70	+0.5/-0.4
90	+0.6/-0.1
120	+0.7/+0.2
150	+0.9/0
180	+1/-0.2
230	+0.9/-0.1
260	+0.6/-0.1
290	+0.8/-0.1

Figure 7. Temperature of Dewar and Crystal (helium).

Conclusion

The femtosecond laser vacuum cryogenic system is successfully developed and the test experiments is conducted. The lowest temperature of the crystal sample can reach 5K and can be changed from 5 to 300K. The controlled temperature stability from 5 to 80K is lower than 0.9K and from 80 to 300K is lower than 1.3K. The flexible liquid and gas pipes of the cooling system can make the crystal sample rotate more than ±30° on the horizontal plane and move more than ±10mm in the X and Y directions. The system performs well and successfully satisfy all the requirement.