Cryogenic setup for MJ class laser targets

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P.N. Lebedev Physical Institute of the Russian Academy of Science:

Largest Russian Institute in physics:

1600 staff;

800 researchers,

7 Nobel prize winners,

Highest Russian citation indexes

Cryogenic department:
60 people,
Almost all directions of cryogenic
Cryomagnetic technique

Cryogenic department of Lebedev Physical Institute

Main activities:

Special cryogenic devices

Superconducting cryomagnets

Recent results:

Innovative high magnetic field superconducting MRI systems

60 people stuff

Cryogenic setup for MJ class laser targets

10 T on table pulsed magnet

10 T Cryogen free gyrotron magnet

Cryogen-free cryostat for optical, X-ray and Mossbauer studies

Contents:

50 years of ICF and 40 years of targetry in LPI

- In 1962 N.G. Basov and O.N. Krokhin reported the idea on spherical compression of matter under powerful laser illumination in RAS. 1964 the relevant paper appeared Басов, Н. Г., & Крохин, О. Н. (1964). Условие разогрева плазмы излучением оптического генератора. *Журнал экспериментальной и теоретической физики*, *46*(1), 171.
- Thermonuclear target works started in 1976 in the multi-directional P.N.Lebedev Physical institute in Moscow. Since then it has been supplying targets and equipment to the laboratories in Russia and abroad. The targets are created and used for interaction with laser and particle beams.
- The goal of ICF is to swiftly heat and compress small capsules of hydrogen fuel with a powerful driver. Ideally - spherically symmetric: Hydrogen fuses into helium and emits alpha particles, which trigger a sustained fusion reaction. But Rayleigh–Taylor instabilities subvert spherical symmetry. Target imperfections or variations in laser intensity get magnified as the fuel implodes and the hot, dense plasma needed to drive the reaction escapes. (A.Grant, 2016)
- NIF era opened a door to the highest standards of laser experiments, hopefully demonstrated the scientific breakeven and, at the same time, put serious questions for the additional studies of targets and their behavior when formed, characterized and transformed into plasma.

1. Temperature is 10-20 K

2. ~ 36 hours of the low temperature hold

(Presentation.Commissioning of the NIF Cryogenic Target System 20th Target Fabrication Meeting AM2-1 May 22, 2012)

3. Mechanical vibration

< 1 µm for characterization of inertial confinement fusion (ICF)

“Ignition requirement that the inner-surface ice roughness be less than 1-µm rms in all modes”

Cryogenic DT and D2 Targets for Inertial Confinement Fusion, *LLE Review, Volume 108*

4. Temperature stability: ~ 1 mK (NIF)

(Presentation.Commissioning of the NIF Cryogenic Target System 20th Target Fabrication Meeting AM2-1 May 22, 2012)

1. Cryogenic liquids:

No mechanical vibrations and temperature oscillations

Limited operation time:

Increased vessel volume or high losses in the long transfer line (~ 0.7 W/m)

http://www.cryofab.com/products/cryogenic-transfer-lines/liquid-helium-transfer-line-CFHT

Logistical problems

2. Mechanical cryogenic refrigerator

Continuous operation

Problems to solve: mechanical vibration and temperature oscillation

Cryogenic setup for MJ class laser targets

Pulse tube cooler Cryomech PT410

Other supplier: SHI

Fig.1

The 2nd stage capacity:

1.0 W @ 4.2 K

The 1st stage capacity:

35 W @ 45 K

Weight:19.5 kg

Orientation: Vertical only, the motor is upside

Gifford-McMahon SHI RDK 408

Other: Cryomech, Leybold, CTI, ARS, Suzuki, Ulvac et. al.

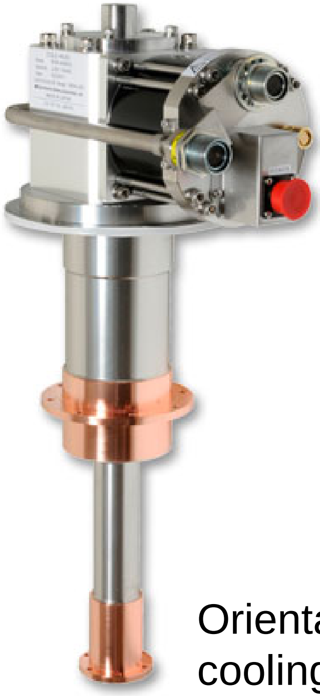

Fig.2

The 2nd stage capacity:

1.0 W @ 4.2 K

The 1st stage capacity:

40 W @ 43 K

Weight:18.0 kg

Orientation: Any, small reduction of cooling capacity in non vertical position

	Sumitomo 4 K GM	Sumitomo 4 K PT
Maximum acceleration of the cold-head (m/s^2)	10	0.1
Displacement of the cold-stage at vibration peak (μm_{pp})	24 (1 Hz)	14 (1 Hz)
Total displacement of the cold-stage (μm_{pp})	26	15

Tomaru T, Suzukia T, Haruyamaa T, Shintomia T, Yamamotoa A, Koyamab T, and Lib R 2004 Vibration analysis of cryocoolers, *Cryogenics* 44 309–317

Cryogenic setup for MJ class laser targets

Common way: flexible connectors (or heat transfer through gas),
bellows seems to be
unsuitable for cryogenic target camera

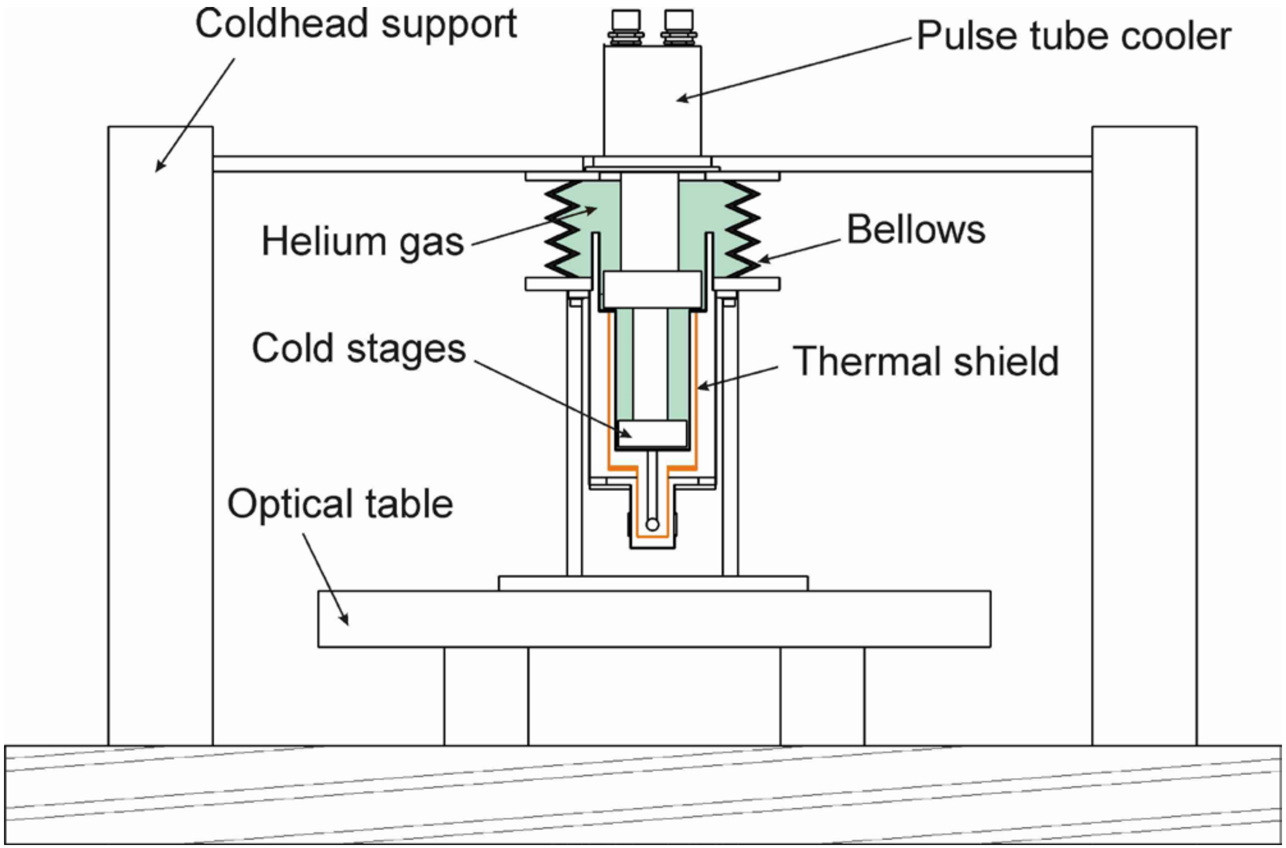

Fig.3. The optical cryostat developed by our group (**< 1** μm vibrations)

Cryogenic setup for MJ class laser targets

The cryocooler should be off during vibration sensitive measurements. Heat reservoir:

1. Rare earth material: HoCu2, Er_3Ni $C_p > 0.3$ J/cm^3*K at 4-10 K

K. Gschneidner, A. Pecharsky, V. Pecharsky, Low Temperature Cryocooler Regenerator Materials, 12th Intern. Cryocooler Conf. June 18-20, 2002 Boston, MA

2. Solid nitrogen: C_p= 0.17 J/cm^3*K at 10 K

3. Solid neon: C_p= 0.4 J/cm^3*K at 10 K

4. Gaseous helium – C_p= 0.47 J/cm^3*K at 10 K and 10 bar

Helium gas in NIF: B. J. Haid, Helium pot system for maintaining sample temperature after cryocooler deactivation, *Advances in Cryogenic Engineering Transactions of CEC, V51*, 2006

5. Liquid helium (this research) –heat of vaporization 2.5 J/cm^3

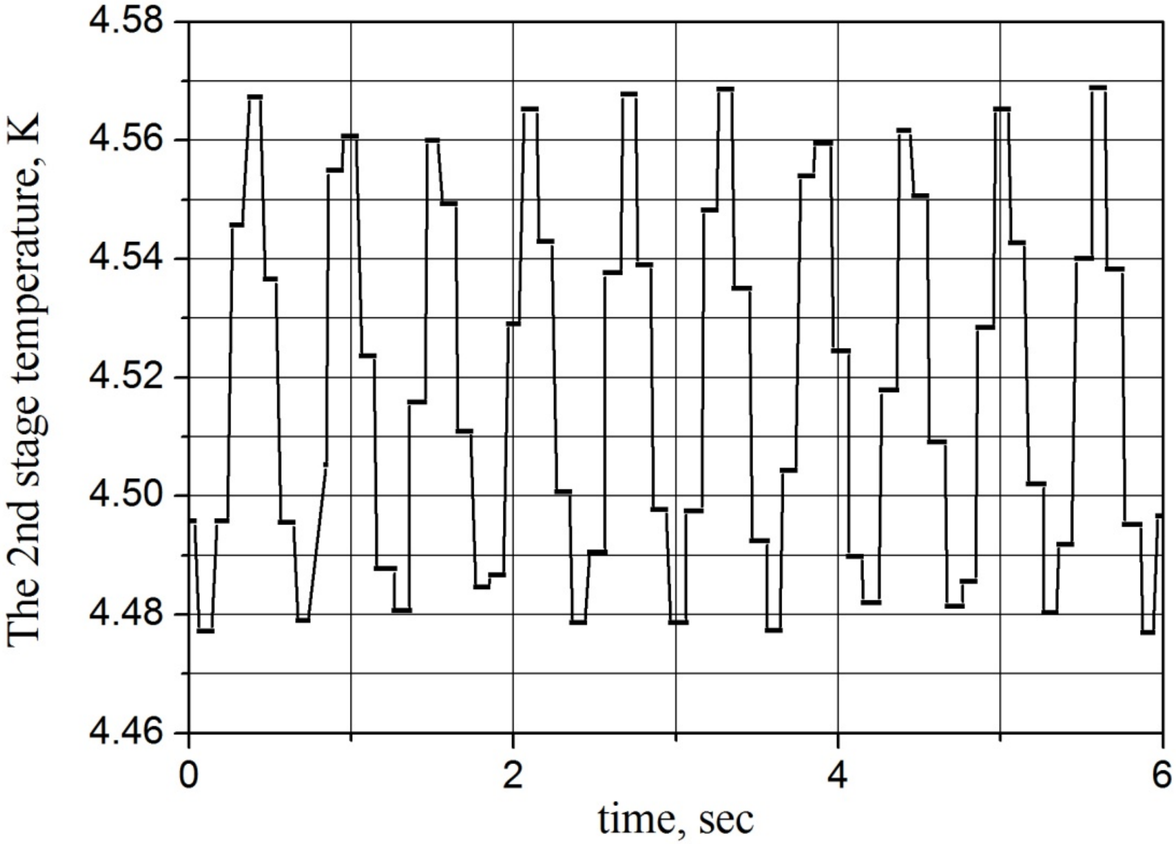

Fig.4 Temperature oscillations of the 2nd stage of SRP 082 B2

Temperature oscillations at 4.5 K are ± 45 mK. ~ 1 mK on the target is required

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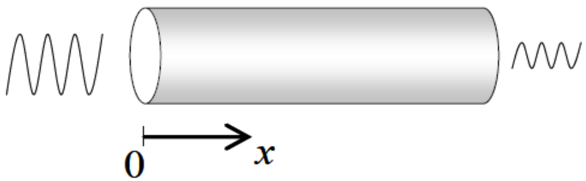
DAMPING OF INTRINSIC TEMPERATURE OSCILLATIONS:

The temperature distribution of the solid by unidirectional heat conduction:



$$A_x = A_0 \exp\left(-x\sqrt{\frac{\pi}{\alpha\tau_0}}\right)\cos\left(x\sqrt{\frac{\pi}{\alpha\tau_0}} - \frac{2\pi t}{\tau_0}\right)$$

x is the distance from the left surface, A0 – amplitude, τ0 – period of oscillations

α - the thermal diffusivity $$\alpha = \frac{k}{\rho c_p}$$

k - thermal conductivity (W/(m·K)), ρ - density (kg/m³), Cp - specific heat capacity (J/(kg·K))

Long lenght, low thermal conductivity and high heat capacity to decrease oscillations:

1. Stainless Steel plate on the 2nd stage

S. Masuyama, N. Fujita, A simple method of temperature smoothing for a 4 K Gifford-McMahon refrigerator, Proc. 22th Int. Cryogenic Engeneering Conf, Seoul, 2008, pp. 69-75

2. Rare earth plate (High heat capacity):

K. Allweins, L.M. Qiu, G. Thummes, Damping of intrinsic temperature oscillations in a 4 K pulse tube cooler by means of rare earth plates, *Advances in Cryogenic Engineering Transactions of CEC, V53*, 2008

3. He pot K. Okidono, et.al., Temperature oscillation suppression of GM, Cryocooler, Journal of Physics: Conference Series 400 (2012) 052026

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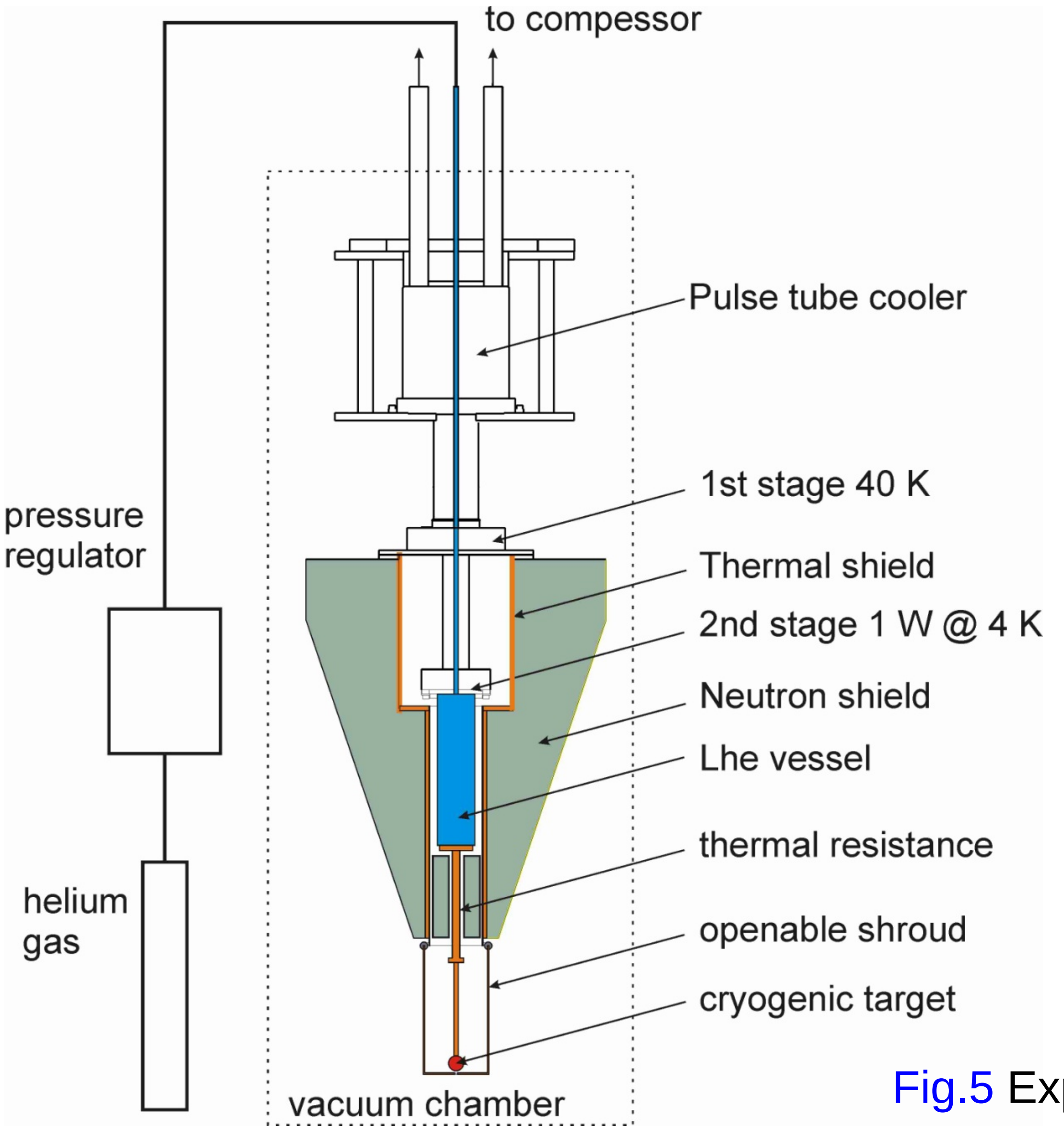

Experimental Setup:

- Heater and PID controller to maintain the target’s temperature

-Total weight of cryostat <70 kg

-operation mode is 3 minutes off and 15 min on

- 0.25 W of cooling on the target assembly

- Cooling / heating rate
1 mK – 3 K per minute

- Temperature stability ~1 mK

Fig.5 Experimental setup

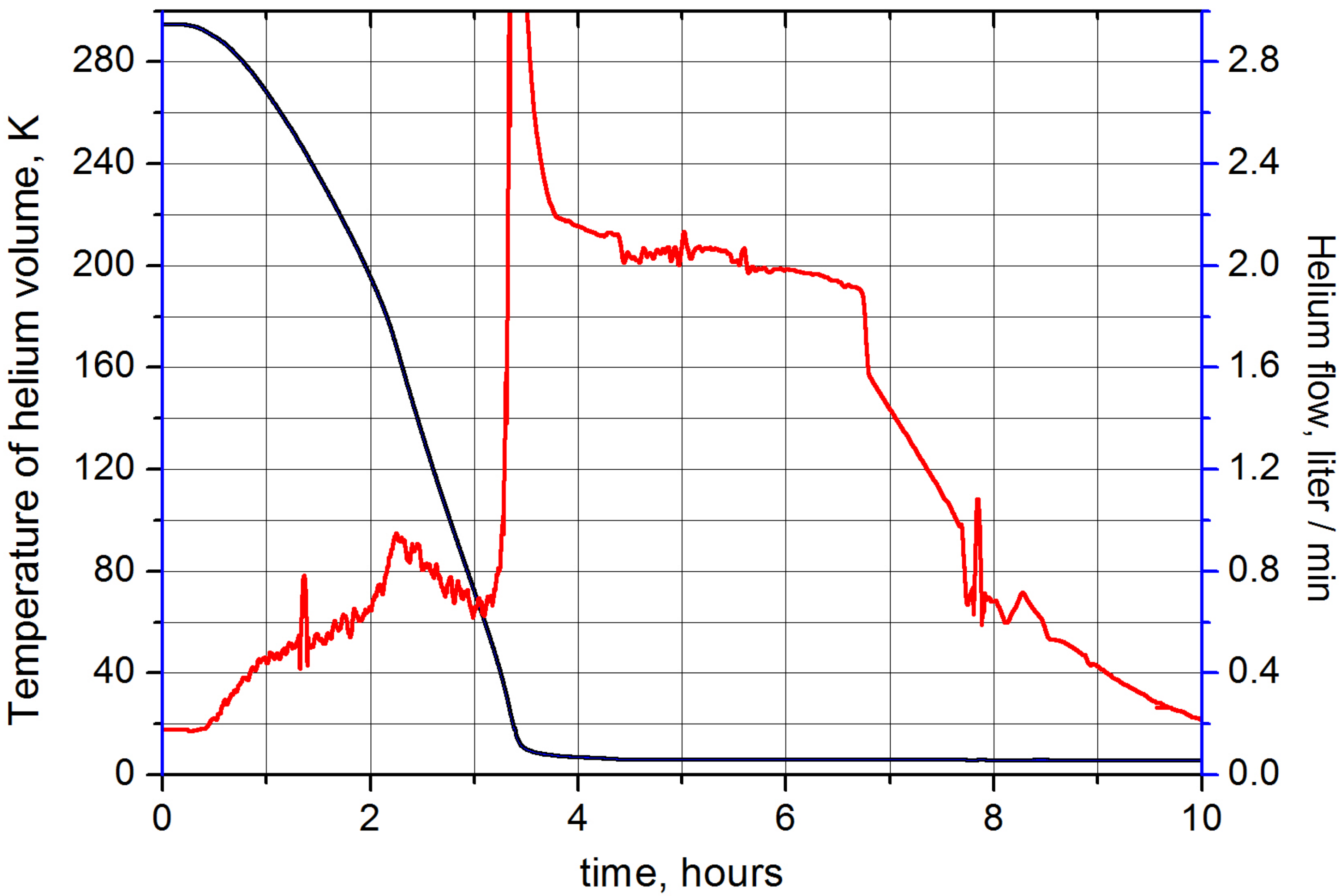

Fig.6. Cooldown process and helium liquefaction

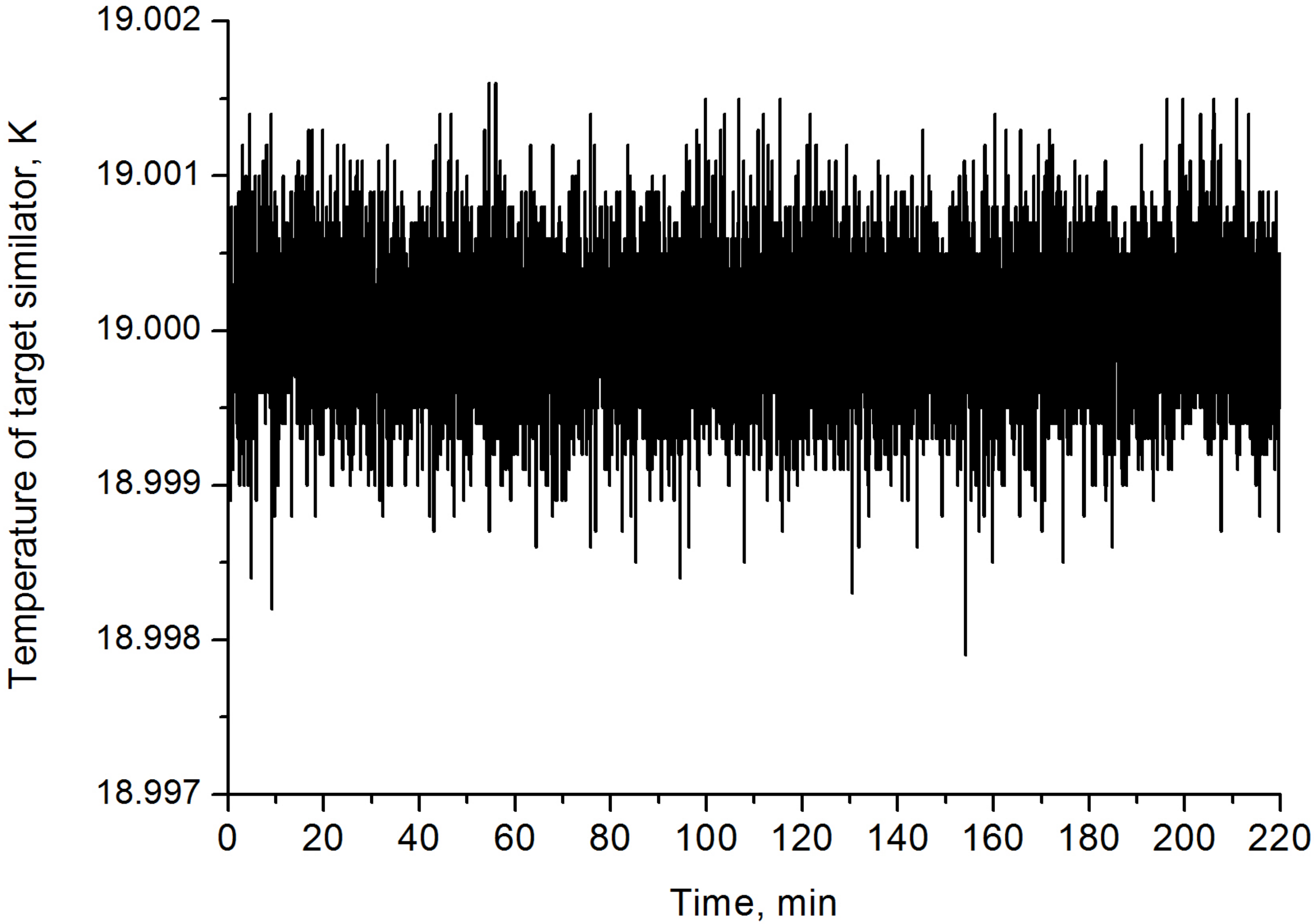

Fig.8 Temporal temperature stability

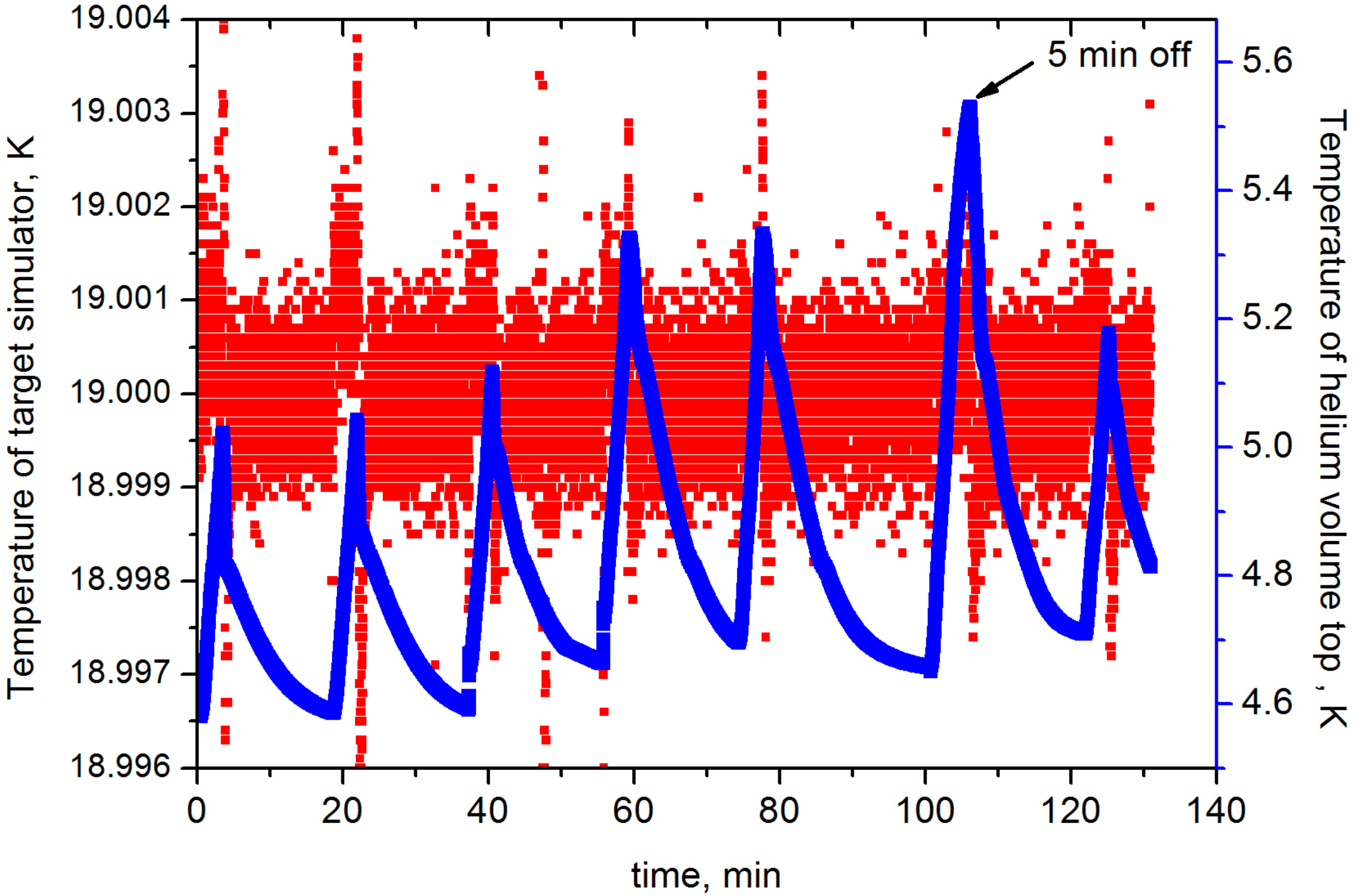

Fig.9 Temperature stability during on/off cycles

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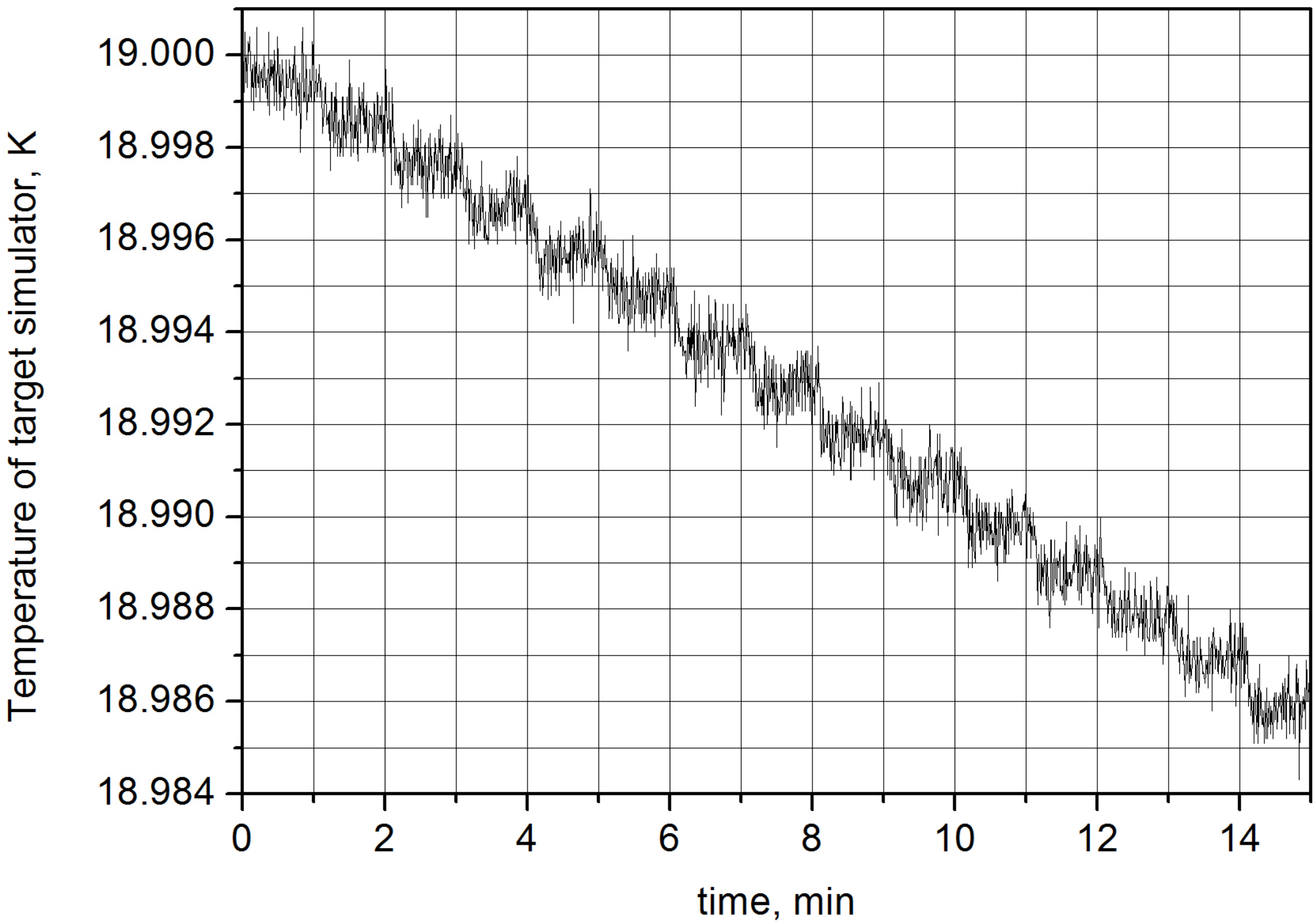

Fig.10 The cooling rate of 1 mK / min

Summary.

1. The concept proof prototype cryostat for MJ class laser target is developed and tested

2. The mechanical cryocooler is the cooling source for Lhe liquefaction. Lhe vessel serve for temperature stabilization during the cooler is off.

3. The basic requirements for cryogenic targets are achieved

4. The further optimization is possible

5. The construction used is capable of modifications such as direct-indirect and other complex target designs implementation in beam experiment