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KRISS APPROACH TO PICO-NEWTON STANDARD FORCE REALIZATION

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Abstract − We report the status and progress of Korea Research Institute of Standards and Science (KRISS) in pico-newton standard force realization. To produce and measure discrete magnetic force on a superconducting ring in proportion to the number of flux-quantum, an instrument and facilities are being developed to provide multi-conditions such as low temperature, high field-gradient, high vacuum, vibration isolation, and so on. Design and construction of sub-systems are presented as well as expected and tested specification for each sub-system.

Keywords pico-newton, flux-quantum, instrument

1. INTRODUCTION

Pico-newton range and below is highly interesting academically, such as in fundamental force and bio-molecular dynamics [1,2], and attractive potentially in industry, but an undeveloped area still waiting for a direct force realization provided by National Measurement Institute. As in micro- and nano-force standard [3], new principle and approach is required for pico-newton force realization in contrast to the case of macro-force.

Recently, KRISS suggested a concept of quantum-based force realization using magnetic flux quantization in a superconducting loop [4]. Magnetic force exerted on flux quantums can be increased or decreased by a force step. In a calibrated magnetic field gradient, dB/dz, of 10 T/m, the force step is estimated as 0.18 pN for a niobium ring, for example, of inner and outer radii, 5 μm and 10 μm respectively, and thickness of 50 nm. It may cause ∼ 2 nm static displacement of a cantilever with k = 10^{-4} N/m, on which a niobium ring is mounted.

Superconducting object and extremely small force measurement in combination require demanding extreme multi-conditions: low temperature, high field-gradient, high vacuum, excellent vibration isolation, and so on.

Here, we present the design and/or the expected and tested specification of sub-systems which compose a whole pico-newton force realization facility. Our goal and experimental challenges to it will be also discussed.

2. CONSTRUCTION OF PICO-NEWTON FORCE REALIZATION FACILITY

The schematic of the flux-quantum-based force realization facility is shown in Fig. 1. For excellent vibration isolation, the liquid helium (L-He) Dewar is mounted on air spring II, which is placed on a 20 ton concrete block. The concrete block is also mounted on air spring I or isolation pad, selectively. In the L-He dewar, a He-3 refrigerator can be loaded and unloaded which contains a pico-newton force realization stage at the bottom. Superconducting magnets for generating uniform and gradient magnetic field are immersed in L-He and surrounding the force realization stage in an inner vacuum chamber (IVC) can. The vibration isolation design was inspired by facilities for ultra-stable low temperature scanning probe microscopes.

Fig. 2 is a picture of a constructed facility which can provide low temperature, high vacuum, high field-gradient, and vibration-free environment to a pico-newton force device, i.e., an ultra-soft cantilever with a superconducting ring on it [4]. It shows a triangular table mounted on three air-springs (TMC). In the middle of the table, L-He Dewar is hung which contains superconducting magnets. The He-3 refrigerator is loaded into the He Dewar from the top.

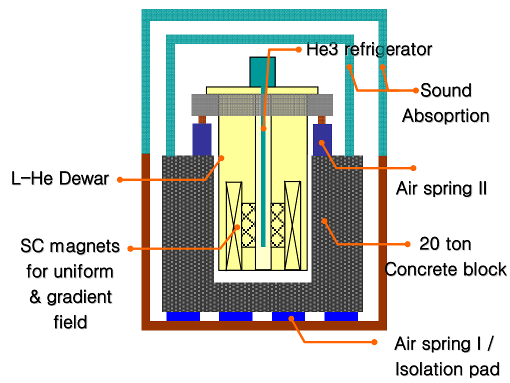

Fig. 1. Schematic of KRISS flux-quantum-based force realization facility. A pico-newton force realization stage is installed at the bottom of He-3 refrigerator.

Fig. 2. Photograph of a constructed facility providing multi-conditions.

The blue floor area is the top of the heavy concrete block which floats on four heavy-capacity air-springs at corners or sits on an isolation pad. An inner box for sound absorption and shielding is not shown but will cover the triangular table area after installation.

The lowest temperature of our He-3 refrigerator (JANIS Research company, Inc.) has been tested without heat load, i.e., pico-newton force realization stage on the bottom of a He-3 pot. By pumping liquid He-3 using an internal (charcoal) pump after condensation in He-3 pot, the lowest temperature was reached and measured to be 278 mK using RuO_2 temperature sensor on the He-3 pot. This low temperature enables us to access flux quantum state with little thermal fluctuation effect in Nb ring case where the superconducting transition temperature, T_c, is 8~9 K and that with minimized thermal fluctuation in Al ring case with T_c of 1.2 K.

After installation of force realization stage, lowest temperatures at He-3 pot and more importantly at the pico-newton force device as well as their duration time may change because of additional heat load and bad thermal conduction of nano-stages. They are to be measured and will be presented elsewhere.

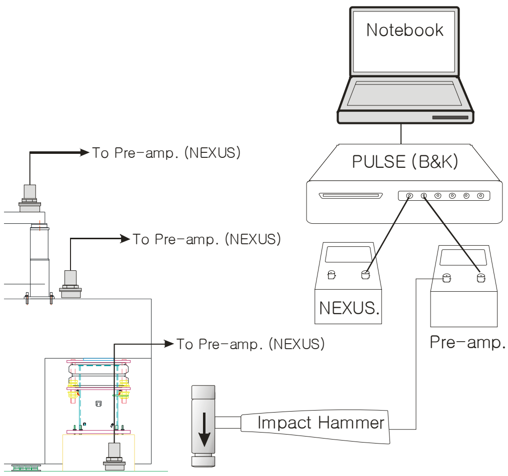

Fig. 3. Schematic diagram of vibration transfer function measurement.

Another important condition for force realization is the field gradient. Our He Dewar contains specially-ordered superconducting magnet system which consists of a gradient magnet inside a uniform magnet. The uniform magnet has been tested to operate up to 9 Tesla, and the gradient magnet at 12 T/m, independently and/or simultaneously. Uniform and linear field zones are 10 mm for the uniform and the gradient magnet, respectively. The latter is crucial for obtaining accurate field-gradient value, which is directly related to the accuracy of generated pN force.

Vibration-free environment for pN force measurement is provided by two-stage vibration isolation: upper and lower isolators. Because both the excitation at a resonance frequency and the static bending of the force device are measured quantities in force realization, the vibration transmission characteristics of isolators are important not only at high frequency of a few kHz, but also at very low frequencies.

Fig. 3 shows the schematics of vibration transfer function measurement that we executed. We used accelerometers (Wilcoxon Research) with sensitivity of 10.4 V/g where g is the gravitational acceleration, and placed them at two sites before and after the lower isolator or the upper isolator. For lower isolator, for example, hitting the floor with an impact hammer generates a vibration pulse and triggers measurement of accelerometers which are connected to a pre-amplifier (NEXUS) and then to a vibration analyzer PULSE (Brüel & Kjær) and a laptop computer. Then, the vibration transmission ratio can be obtained in frequency domain as in Fig. 4.

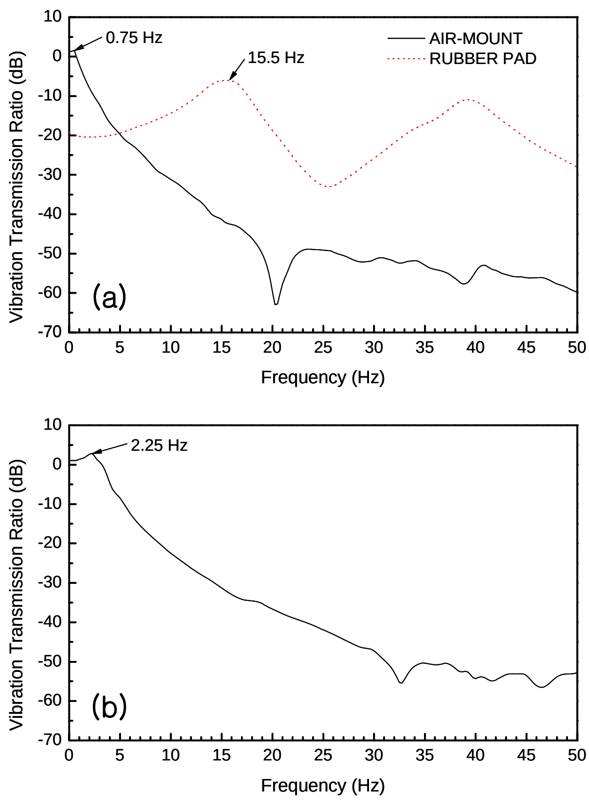

Fig. 4. Vibration transmission ratio of (a) the lower isolator in air-mount and isolation-pad modes and (b) the upper isolator.

In the Fig. 4 (a), the vibration transmission ratios of lower isolators are shown for air-mount and isolation-pad modes, which we can choose for our experimental purpose. The air-mount mode has a resonance frequency at 0.75 Hz and the transmission ratio decreases below -50 dB above 20 Hz. In contrast, in isolation pad mode where pistons of air springs are lowered and the 20-ton block sits on the pad, the transmission ratio has a peak at 15.5 Hz and poor vibration isolation characteristics above 5 Hz in comparison with air-mount mode. But, at less than 5 Hz, vibration attenuation is much better and has a value of -20 dB in isolation-pad mode. Therefore, for experiments in which quasi-static or low frequency vibration is a dominant noise source, the isolation-pad mode can be preferred and chosen.

The vibration transmission ratio of an upper isolator was measured in similar way and displayed in Fig. 4 (b). Only air springs were utilized for upper vibration isolation. The upper isolator has a resonance frequency of 2.25 Hz and transmission ratio less than -45 dB at above 30 Hz. The vibration transferred to the He-3 refrigerator is after attenuation by these lower and upper vibration isolations in combination.

According to estimation in our previous study [4], magnetic field of ~ 0.2 Oe is needed to add one flux quantum or increase one sub-pN force step. The earth magnetism is comparable in magnitude and does not accord in direction with our control magnetic field. Static magnetic background is not serious error source since we measure the difference of force device deflection after adding integer number of flux quantum in principle. But, to cancel the drift and the off-z-axis component of the background field, Helmholtz cancellation coils for three axes were installed as shown in Fig. 5. The centeral area of the cancellation coil hexahedron coincides with the position of pN force stage and device. The dc field cancellation was tested to be achieved within 0.2 mOe. The ac cancellation was measured using a 3-axis fluxgate magnetometer (Bartington MAG-03MSES) and realized within 0.3 mOe.

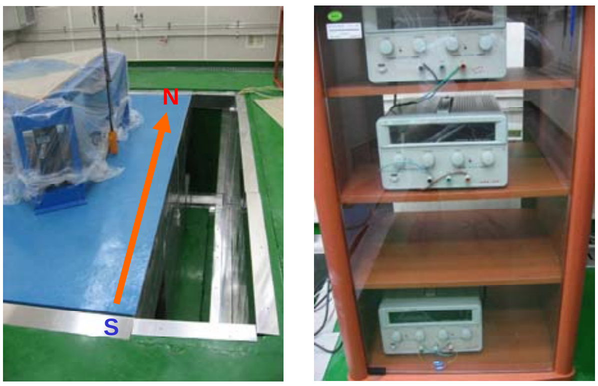

Fig. 5. Earth magnetism and background magnetic noise cancellation coils (covered by stainless steel ducts) and their controllers.

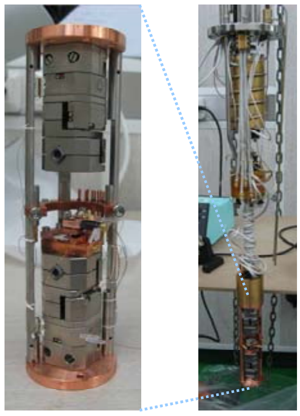

Fig. 6. Pico-newton force realization stage (left) and He-3 refrigerator after installing it (right).

3. PICO-NEWTON FORCE REALIZATION STAGE

Fig. 6 shows an assembled stage for pico-newton force generation and measurement and its view when it is installed on the bottom of He-3 refrigerator. It consists of a force-device holder mounted on a (lower) XYZ nano-positional stage (Attocube Systems Inc.) and an optical fiber holder on the other (upper) XYZ stage. Those stages are bolted to top and bottom copper plates that are supported by Ti columns.

On a lower XYZ nano-stage is a force-device holder part as shown in Fig. 7 (a). For local temperature control of a force-device, a heater and a Cernox thermometer are attached to the holder. Local control of temperature will be useful in increasing or decreasing the temperature of a superconducting ring on the force device above and below T_c, without changing the temperature of the He-3 pot. Sweeping the He-3 pot temperature may cause unwanted misalignment of a force device and an optical fiber due to thermal expansion and contraction of many mechanical and column parts. Z-motion of XYZ nano-stage was tested to walk a step of ~100 nm for a 25 V pulse at room temperature.

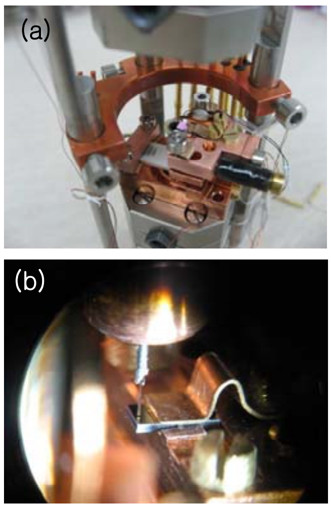

Fig. 7. (a) Force device holder part and (b) the expanded view of a optical fiber approaching a force device chip.

Besides, the force-device holder part has a small-field coil made of NbTi wire for magnetic excitation of a cantilever device and a piezoelectric plate actuator for mechanical excitation. It also has an InAs Hall sensor (Lakeshore Cryotronics, Inc.) for roughly probing the magnetic field and its gradient near the force device.

The upper nano-stage is for aligning an optical fiber onto a 20 μm-sized target on an ultra-thin and narrow force device. Fig. 7 (b) displays an optical fiber approaching a force device chip in expanded view. In the picture the fiber is pointing at the die or the thick silicon area of the force device, not the ultra-soft cantilever area, for optic interferometer test. A bare optical fiber end and a force device make a Fabry-Perot cavity and the interferometer is expected to measure the dc deflection of the force device in sub-angstrom resolution [5]. A 1310 nm diode laser with temperature control is used for avoiding heating effect on an ultra-soft silicon force device.

4. CONCLUSION

The progress of KRISS project for pico-newton standard force realization using superconducting flux quantums was presented. An instrument and facilities were developed and partially tested to provide multi-conditions such as low temperature from 4 K to 280 mK (without heat load), high field-gradient of 12 T/m, high vacuum, and vibration isolation of -95 dB at 30 Hz, for instance, and to measure the deflection of a force device in such condition using a fiber-optic interferometer and nano-positioning stages. Low temperature test of sub-systems and components and proof-of-principle experiments are awaited.

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