Some design considerations of rotating mK refrigerators

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Abstract

Rotating mK cryostats are used to study He superfluids. A few rotating refrigerators have been constructed which are capable of cooling down to $\sim 100\,\mu$K and to rotate up to ~ 1 rev/s. Rotation can be supported with compressed air or magnetic fluid bearings. The ^{3}He-^{4}He dilution refrigerator, for precooling a series connected nuclear cooling stage, may run continuously using rotating seals in the pumping lines or in single-cycle mode with cryo-adsorption pumping. To investigate single-vortex phenomena, smooth rotation is required which means low rotational friction and good mechanical stability with precession-free motion. We comment on general design principles, discuss the rotation noise spectrum of our installation, and the use cryo-adsorption pumping for autonomous refrigeration during rotation.

Key words: rotation; refrigeration; noise spectrum; NMR measurement; superfluid turbulence; quantized vortex lines

From the forties to the early sixties, rotation was an important tool in investigating the nature of superfluid flow [1,2]. Later research of quantized vorticity in ^{4}He-II has made use of rotation for special tasks [3], but presently it appears to have limited value. In ^{3}He superfluids, in contrast, rotation has proven a most important tool for several reasons: (i) Many different structures of vorticity exist which can both be generated and studied in rotation. (ii) Vortex-line pinning on solid surfaces and related remanent vorticity do not play as important a role as in ^{4}He-II and thus vortex formation processes can be investigated in detail. (iii) Especially in ^{3}He-B critical velocities are high and allow the study of rotating vortex-free states and their critical phenomena. Measurements of this kind have been in the focus of superfluid ^{3}He research during the last two decades. It is inconceivable to imagine that superconductors could be investigated only at zero external field; rotation is as important in the study of the ^{3}He superfluids: There exists no other means to manipulate the multi-component order-parameter field with its multitude of topologically stable defects as conveniently as with rotation.

This year of the LT23 Conference is the 30th anniversary of the discovery of the ^{3}He superfluids and the 20th anniversary since the first measurements on their quantized vortex lines in uniform rotation. The study of vortex structures in the ^{3}He superfluids has uncovered a large number of new phenomena, especially in the anisotropic ^{3}He-A phase. Clearly much remains unanswered. Examples are vortex structures in restricted geometries or the nature of superfluid turbulence in ^{3}He-A. What are the dissipation mechanisms in superfluid turbulence in the zero temperature limit [4]? Broad questions of this magnitude have not been studied systematically, perhaps because of a lack of efficient measuring techniques: For instance, how to create and maintain the turbulent state or how to record the tangled configuration of quantized vorticity in space and time? Rotation clearly provides possibilities for calibrating measuring signals in the presence of a known number and configuration of vortex lines, but it is less clear whether rotation can be efficiently used to generate turbulence.

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Table 1
Characteristics of different rotating mK cryostats.

Cryostat	Ref.	start year	operation	pumping	bearings	electronics
Cornell	[5]	1979	continuous	pumps on rot. platform	pressurized oil	on rot. platform
Helsinki I	[6]	1981	single cycle	one single cryopump	compact air bearings	on rot. platform
Helsinki II	[7]	1988	continuous	alternating cryopumps	compact air bearings	synchronized 2nd carousel
Berkeley	[8]	1990	continuous	rot. pump seals	individual air pads	via slip rings
Manchester I	[9]	1990	continuous	rot. pump seals	individual air pads	on rot platform
Manchester II	[10]	1992	continuous	rot. pump seals	individual air pads	on rot platform

Rotating refrigerator design: To a large extent rotating mK refrigerators have been adapted from the design of standard laboratory refrigerators with a ^{3}He-^{4}He dilution machine as precooler for a nuclear demagnetization stage. There are differences in how the additional requirements arising from rotation are met, namely (i) the rotation bearings, (ii) maintenance of the dilution refrigerator during rotation, and (iii) connection between cryostat and electronic measuring equipment. Table 1 summarizes some of these aspects.

The simplest approach to convert a conventional cryostat for rotation is that of the first two rotating installations in Table 1: The Cornell cryostat is constructed like a standard nuclear demagnetization refrigerator, but the whole system with pumps and electronics is placed on a large platform which is rotated on hydraulic bearings with high pressure oil [5]. The Helsinki cryostat (known as Rota I) is the one which has been longest in continuous use for rotating measurements, since it started operating in 1981. Its design plan is simple and has worked in practice reliably. The only connections from the rotating equipment to the laboratory are (i) four slip rings for the mains voltages and ground, (ii) two axially located optical lines with rotating joints for the digital parallel data bus, (iii) a simple rotating o-ring seal for the He return line from the He dewar, and (iv) the rotation drive via a smooth flexible belt. When the apparatus is floating on its air bearings in a single-cycle mode of operation, the only ohmic contact to the surrounding electric ground in the laboratory is via the slip-ring contact.

In the Rota I cryostat the rotating equipment is suspended from a central axis which is supported by one axial air bearing. Here compressed air is blown through eight nozzles between two flat ⌀400 mm horizontal plates. Laterally the axis is stabilized with one cylindrical ⌀125 mm radial bearing on either side of the axial bearing, 700 mm apart from each other. This system of three air bearings is constructed as one unit and requires little adjustment or maintenance [6]. The simple and mechanically sturdy structure of this rotating suspension system and the absence of critical rotating vacuum seals has meant that friction is small. This is a clear advantage in achieving smooth rotation and in reducing vibrations, heat leaks, and interference with measurements.

Rotation has played an important role in the measurements which have been conducted with rotating cryostats. Nevertheless, no studies are available about the quality of their rotation or of the requirements on the rotation. In this report we describe the rotation noise of the Rota I installation. To achieve low noise, cryo-adsorption pumping can be used to avoid the friction from rotating vacuum seals. An adsorption pump for the still pumping line, to run the dilution refrigerator in single-cycle mode during rotation, is simple to construct and reliable in use. To operate the pump has turned out to be simpler than what its original constructors [6] envisioned.

Rotation noise: Our measurements on quantized vortex lines make use of at least three different types of rotation: (i) rotation at constant angular velocity Ω over extended periods of time (with $\Omega < 4$ rad/s), (ii) a slow linear ramp with $|\dot{\Omega}| \sim 10^{-4}$ rad/s^2, and (iii) sinusoidal modulation $\Omega(t) = \Omega_0 + \Delta\Omega \sin\omega t$, where the modulation frequency ω corresponds to a period $\gtrsim 10$ s and the amplitude $\Delta\Omega \lesssim 1$ rad/s. Modulation of the cryostat rotation at such high frequencies and amplitudes requires a drive with large torque while rotation at constant Ω demands good stability at small torque.

Fig. 1 shows the noise spectrum at two fixed rotation velocities. The input signal for these Fourier spectra is the output from the tachometer of the cryostat as a function of time, $\Omega(t)$. In the uppermost panel the tachometer output is compared to the simultaneously recorded NMR absorption amplitude $A(t)$ of ^{3}He-B. The NMR absorption is measured with a spectrometer which rotates with the cryostat. In the lowermost panel the NMR absorption spectrum of ^{3}He-B is shown at different rotation velocities in the vortex-free *Landau* state. Here the absorption is shifted increasingly from the region of the normal-phase Larmor resonance (approximately at vertical arrow) to a new maximum on the left which arises from the orienting effect of the normal - superfluid counterflow on the order-parameter anisotropy axis. Thus by measuring at fixed magnetic field at the location of the vertical arrow, the absorption decreases with increasing Ω and vice versa. By

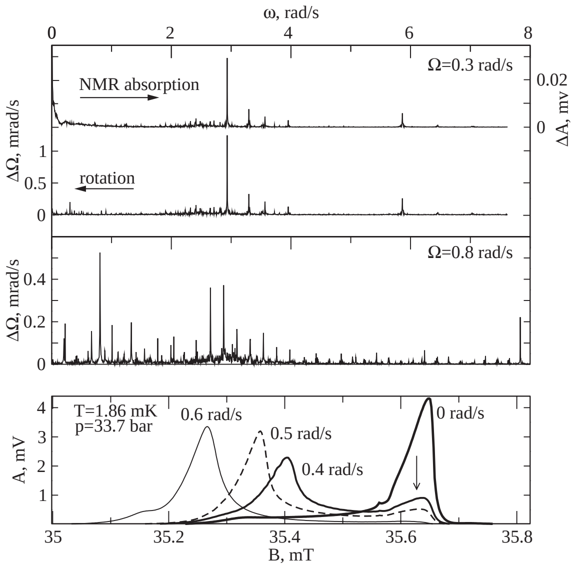

Fig. 1. Rotation noise of Rota I cryostat at constant rotation. *(Top)* Fourier spectrum of $\Omega(t)$, with the deviation $\Delta\Omega$ plotted as a function of the fluctuation frequency ω, at two rotation velocities of 0.3 and 0.8 rad/s (note that the vertical scales differ in resolution). The data for the spectra have been accumulated for 1500 s, with 4 readings per second. The third trace is the corresponding Fourier spectrum at 0.3 rad/s of the B-phase NMR absorption amplitude $A(t)$, given as ΔA versus ω. *(Bottom)* NMR absorption spectra of ^{3}He-B, measured at a constant frequency of 1.15 MHz as a function of the magnetic field sweep. The vertical arrow marks the magnetic field at which the noise spectrum of the absorption amplitude $A(t)$ is measured in the upper panel.

comparing the Fourier spectra of the tachometer and NMR absorption outputs at 0.3 rad/s, measured in the experiment described in Ref. [11], we see that they accurately track each other, *ie.* they both reproduce the same characteristics of the rotation noise. This means that the tachometer reading represents a reliable measurement of the rotation properties.

The rotation spectra in Fig. 1 show that below 0.4 rad/s the noise is characterized by a series of sharp resonances, with Q values of order 100. The largest component, $\Delta\Omega \approx 1.2 \cdot 10^{-3}$ rad/s at 3.0 rad/s, has even a sizeable second harmonic. The origin of this resonance has not yet been identified. At higher Ω the resonances are not quite as dominant and the broad-band noise increases in importance. This change over in the character of the noise is illustrated in Fig. 2 where Ω is slowly increased at constant rate $\dot{\Omega}$: Below 0.4 rad/s the noise consists of large-amplitude resonances, while in the range $0.4 \ldots 1$ rad/s the noise is more broad band and has the smallest amplitude. At still higher Ω both the broad-band component increases and new resonances appear with growing amplitudes, when the mechanical stability of the entire apparatus, primarily due to rotational unbalancing, becomes the bottleneck.

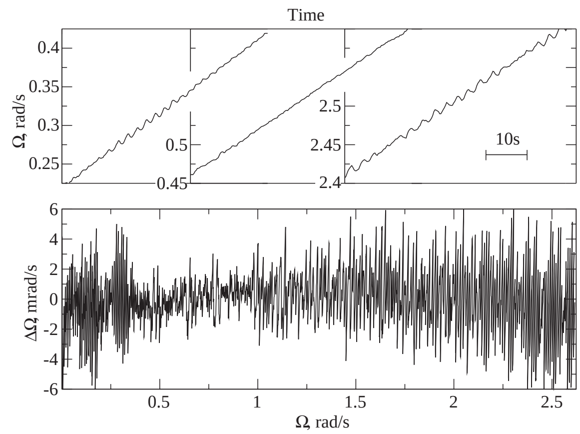

Fig. 2. Noise in slowly increasing rotation at fixed rate $\dot{\Omega} = 4 \cdot 10^{-3}$ rad/s^2. *(Top)* Three separated sections of a linear ramp of increasing Ω illustrate the changing nature of noise in different rotation regimes. *(Bottom)* Deviations of the measured value from its time average, $\Omega(t) - \bar{\Omega}(t)$, plotted as a function of the time average $\bar{\Omega}(t)$.

Mechanical resonances are typical of rotating equipment at low rotation where the angular momentum of the heavy equipment does not yet smooth out instabilities. Large spot noise amplitudes have many adverse consequences in measurement:

(i) They may contribute directly to the noise amplitude of the measuring signal via changes in Ω and their influence on the order-parameter texture, as is the case in the NMR absorption spectrum of Fig. 1.

(ii) In measurements of the total number of vortex lines or their critical velocity, the typical increment in counterflow velocity per one new B-phase vortex line is $\Delta\Omega = \kappa/(2\pi R^2) \approx 0.4 \cdot 10^{-3}$ rad/s (for a sample with a 5 mm radius R). The critical velocity was measured with single-vortex resolution in Ref. [12] for B-phase vortex lines and in Ref. [13] for A-phase vortices. Critical velocities are measured in slowly increasing Ω (case of Fig. 2), while calibration measurements of the total vortex number are most often performed at constant Ω (case of Fig. 1). The latter case becomes important in measurements of the annihilation energy barrier of vortex lines [14]. In both situations large-amplitude noise produces a blurring of the result. Recently it was also established that in ^{3}He-B depinning of vortex lines from geometrical inhomogeneities, such as the edge of an orifice, is directly affected by rotation noise at low temperatures [15].

(iii) The vibrations in large-amplitude resonances may couple into the measurement and modulate directly the measuring signals via differential mechanical motion of the sample with respect to the measuring probes. This interference signal is very clearly seen in NMR measurements as a modulation in the amount

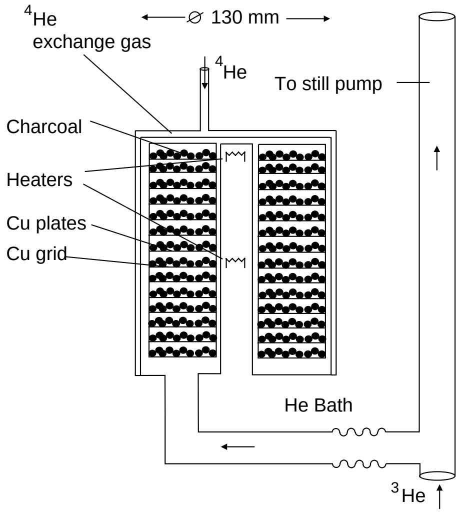

Fig. 3. Cryo-adsorption pump with no moving parts.

of NMR absorption in phase with rotation, when the cryostat is not sufficiently well balanced.

Cryo-adsorption pumping: While rotating the Rota I cryostat, the ^{3}He-^{4}He dilution refrigerator is operated in single-cycle mode by pumping the still with a charcoal adsorption pump. It is located in the liquid He dewar above the refrigerator. The ^{4}He evaporation cooler, which is only used for condensing the incoming stream of concentrated ^{3}He gas, is allowed to warm up to 4 K. This makes it possible to maintain autonomous operation of the cryostat for 12 h without any connection to the pumps or the gas handling system in the laboratory. Preparation of the cryostat for autonomous operation in the morning before the rotating measurements and its reconnection to normal continuous operation in the evening after the measurements requires in both cases half an hour of work. The bonus is simplicity of construction, reliable maintenance free operation, and the minimum of rotation friction.

Different schemes have been developed to operate a cryopump in a liquid He dewar. The simplest approach without any moving parts is probably that shown in Fig. 3. Here the working principle of the original cryopump from Ref. [6] is explained in the simplified form in which the pump is used today, after twenty years of continuous operation. All parts are original and have needed no repair. The pump is a separate unit, contained inside two vacuum tight jackets. A low pressure of ^{4}He exchange gas is admitted in the space between the two jackets. The inner jacket contains 20 copper plates with 6 mm separation on which 200 g of charcoal grains have been packed. The horizontal copper plates are pressed around a central steel tube whose interior connects through the open bottom end directly to the liquid He bath. An electrical heater is inserted in this open steel tube, with good thermal contact to the tube wall. Thus no vacuum sealed electrical feedthroughs are needed for the heater wires and the replacement of the heater is an easy task, should it become necessary.

During pumping the exchange gas provides the thermal connection to the liquid He bath outside the outer jacket, where cold He gas evaporating from the liquid He bath is continuously flowing up along the outer cylinder wall. During desorption the heater in the central steel tube is heated at a rate of ~ 0.4 W. The desorbing gases leave the pump through the still pumping tube. With an effective ^{3}He charge of 1.5 moles in the mixing chamber and no heating applied to the still, a circulation of 35 μmole/s can be maintained for 12 hours. Originally the inlet to the pump could be closed off during desorption with a cold valve. Its actuation mechanism eventually broke and since then the pump inlet has been always open. This means that the desorption heating must be applied continuously, except during pumping. A straightforward calculation gives that this corresponds to an extra boil off of 0.5 l/h from the liquid He bath. However, most of the time the pump is above the liquid He level, the increased cooling from cold gas flow compensates for other losses, and thus the increase in liquid He consumption has been marginal. We conclude that the functioning of a charcoal adsorption pump is not critical with respect to design or operating parameters.

At present a new dilution refrigerator insert is being prepared for installation into the Rota I refrigerator, to achieve lower precooling temperatures. The adsorption pump of the new precooler in Fig. 4 is based on a more sophisticated design [16]. It includes a valve, which is actuated by means of He-gas-pressurized expansion bellows, to close off the inlet to the adsorption pump when the cryostat is not rotated. A separate outlet tube from the pump is added to collect the desorbed gas independently of still pumping. In this way desorption does not interfere with the efficiency of precooling and some time can be gained. The adsorbent is contained in a thin-walled steel cylinder which is placed coaxially around the still pumping tube inside the vacuum jacket of the cryostat. There is thus no separate vacuum container around the pump, no exchange gas is used, and the cooling of the pump takes place via a spiral copper tube through which a cold stream of He gas is blown. The inlet of the copper cooling tube is located at a low level in the liquid He bath. The gas stream through the tube is driven with a heater at the inlet. The outlet of the tube is at room temperature with an on/off valve for the flow of cooling gas. 200 g of charcoal grains are packed between the cylindrical outer jacket of the pump and a double helicoid of copper network, which is silver-soldered in vacuum to the cooling tube spiral. The open space next to the inside wall of the adsorbent volume is provided for efficient gas circulation.

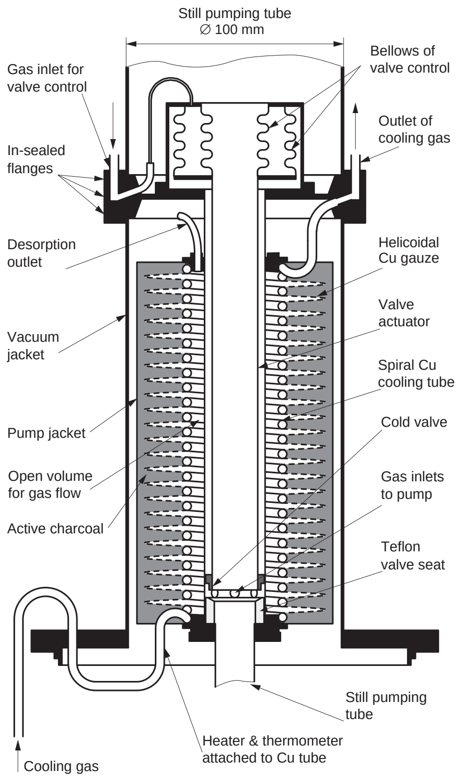

Fig. 4. Second cryo-adsorption pump with controlled gas-flow cooling and cryovalve to separate adsorbent from still.

The new pump design, although more complicated, enjoys a number of advantages: It has compact structure with an efficient ratio of adsorbent to total volume. Effective cooling of the adsorbent is provided with cold He gas flow and a large cold surface in the form of the copper net cage, which contains the adsorbent. The maximum distance of the charcoal grains from the copper net is 3 mm. The gas flow can be regulated by adjusting the heating and the flow resistance of the spiral cooling tube by means of a valve at the outlet at room temperature. In this way liquid He consumption can be minimized, at least in principle [17].

Conclusion: With present techniques it appears feasible to achieve smooth rotation with a noise level within ± 1 mrad/s from the mean up to a rotation velocity of 5 rad/s and down to sub-mK temperatures. This is sufficient for the measurements which now are being planned. However, unlike in ^{4}He-II, the richness of entirely new phenomena in the ^{3}He superfluids has been predicted to continue up to very high rotation velocities [18]. A future challenge remains to achieve one to three orders of magnitude higher rotation velocities than those which are feasible with present technology. This calls for magnetically supported and driven rotation of only the sample with its container.

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References

[1] E.L. Andronikashvili, Yu.G. Mamaladze, in *Prog. Low Temp. Phys.* Vol. V, p. 79 (North-Holland Publ. Co., Amsterdam, 1967)

[2] D.V. Osborne, Proc. Phys. Soc. A **63** (1950) 909

[3] H.E. Hall, Adv. Phys. **9** (1960) 89

[4] W.F. Vinen, J.J. Niemela, J. Low Temp. Phys. in print (2002)

[5] B.C. Crooker *et al.*, Physica B **108B** (1981) 795

[6] P.J. Hakonen *et al.*, Cryogenics **23** (1983) 243

[7] R.H. Salmelin *et al.*, J. Low Temp. Phys. **76** (1989) 83

[8] J.D. Close *et al.*, Physica B **165-166** (1990) 57

[9] M.R. Ardron *et al.*, Physica B **165-166** (1990) 55

[10] H.E. Hall *et al.*, Physica B **194-196** (1994) 41

[11] R. Blaauwgeers *et al.*, arXiv:cond-mat/0111343 and these proceedings.

[12] Ü. Parts *et al.*, Europhys. Lett. **31** (1995) 449; J. Low Temp. Phys. **1**07 (1997) 93

[13] R. Blaauwgeers *et al.*, Nature **404** (2000) 471

[14] V.M. Ruutu *et al.*, Phys. Rev. B **56** (1997) 14089; Physica B **255** (1998) 27

[15] L. Skrbek *et al.*, these proceedings.

[16] S. Boldarev *et al.*, Cryogenics **34** (1994) 251

[17] Test results on the second adsorption pump will be added to the final manuscript.

[18] T. Kita, Phys. Rev. Lett. **86** (2001) 834