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A Superconducting Linear Motor Drive for a Positive Displacement Bellows Pump for use in the g-2 Cryogenics System

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Abstract-- **Forced two-phase cooling of indirectly cooled magnets requires circulation of liquid helium through the magnet cooling channel. A bellows helium pump is one possible way of providing helium flow to a magnet cooling system. Since the bellows type of helium pump is immersed in liquid helium, a superconducting linear motor drive appears to be an attractive option. This report describes a linear motor drive that employs oriented permanent magnet materials such as samarium-cobalt as the stator magnet system and a superconducting loud speaker voice coil type of drive as the armature of the linear motor. This report examines drive motor requirements for a helium pump.**

I. Positive Displacement Bellows Pump

The use of a positive displacement helium pump in a two-phase helium cooling system is not new[1]. A bellows type positive displacement pump driven by a variable speed drive was used to cool the PEP-4 detector magnet in 1980 and 1983. This pump had a maximum pressure rating of 0.4 MPa and it was used to cool down the PEP-4 solenoid from 90 K to 4.4 K [2]. The PEP-4 pump was driven by an external variable speed drive. There was additional heat leak into the dewar due to this drive. One can eliminate much of the added heat leak by replacing the conventional variable speed drive with a superconducting linear motor that is cooled by the helium bath and is part of the bellows pump assembly. The linear motion of the pump can be controlled electronically.

A bellows pump is a driven bellows that is a closed volume. When the bellows is extended, fluid enters the pump through an inlet check valve. Fluid in the flow circuit is kept from entering the expanding bellows by an outlet check valve. When the bellows is contracted, fluid leaves the pump through the outlet check valve while the inlet check valve is forced closed. A double acting pump has two bellows forming two pump chambers. The double acting pump pumps almost twice as much fluid as a single acting pump for a given bellows stroke, bellows diameter, and pump repetition rate.

The mass flow M generated by a bellows pump is a function of the bellows effective diameter D_B, the design stroke of the bellows S_B, the number of pump strokes per second N_R, the mass density of the fluid ρ, and the pump volumetric efficiency η_V. The mass flow for a bellows type pump can be calculated using the following relationship:

$$M = \zeta \eta_V N_R \rho \frac{\pi D_B^2}{4} S_B \qquad (1)$$

$\zeta = 1$ for a single acting bellows pump, and $\zeta = 2$ for a double acting bellows pump. The volumetric efficiency of the pump is a function of the pump repetition rate N_R and the pressure change across the pump ΔP. At low pressures, η_V can be greater than 0.9

The pumping force as the bellows contracts can be estimated using the following expression.

$$F = \frac{\pi D_B^2}{4} (\Delta P + P_{CV}) \qquad (2)$$

where F is the force needed to pump the fluid against the differential pressure across the pump and P_{CV} is the pressure needed to open the outlet check valve.

An approximate expression for a helium pump work is given by the following expression:

$$W_P = \frac{M}{\eta_a} \frac{\Delta P}{\rho} = \zeta N_R S_B \frac{\pi D_B^2}{4} \frac{\eta_V}{\eta_a} \Delta P \qquad (3)$$

where W_P is pump work; and η_a is the adiabatic efficiency of the pump. (Note: the adiabatic efficiency includes the volumetric efficiency, the check valve opening pressure and various other losses.) The PEP-4 bellows pump had an adiabatic efficiency as high as 0.7.

II. The Superconducting Linear Motor

A loud speaker linear motor is governed by two basic equations [3], [4]. The first equation, the Lorentz equation is given as follows:

$$F = B \times i_0 L \qquad (4)$$

where F is the vector force generated by a wire of vector length L carrying a current i_0 in a vector magnetic

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induction **B**. The second governing equation, which is a statement of Faradays law, is given as follows for a wire moving in a magnetic field:

$$\mathbf{E} = \mathbf{v} \times \mathbf{B} \qquad (5)$$

where **E** is the electric field generated in a wire moving at a vector velocity **v** in a vector magnetic induction **B**.

A. The Radial Permanent Magnet

A loud speaker drive linear motor has a permanent magnet that delivers its flux in the radial direction, perpendicular to the solenoidal windings of the voice coil. The length of this radial magnet is slightly longer than the length of the voice coil plus the length of the stroke S_B. One can maximize the magnetic field by using a strongly oriented permanent magnet material (such as samarium-cobalt) to generate the radial magnetic field. The reasons for wanting to maximize the magnetic induction are: 1) A strong magnetic field means that maximum force can be generated with fewer ampere turns. Fewer ampere turns means a lower solenoidal field and less tendency to demagnetize the permanent magnet material 2) A strong radial field means a lower voice coil self inductance (and voice coil stored energy) for a given voice coil design current. Figure 1 shows a cross-section of a bellows pump with a superconducting voice coil linear motor. The permanent magnet design is one that concentrates the flux in the gap where the voice coil is located. The operation of the permanent magnet at 4.2 K should not be detrimental to its magnetic performance if the right magnetic material is selected. Using the magnet design shown in Figure 1, a gap field of 0.8 T is possible.

A superconducting voice coil can generate enough ampere turns to demagnetize the oriented permanent magnet material in the linear motor stator. The magnet design shown in Figure 1 should allow one to energize the voice coil with a current up to 115 A before the samarium-cobalt is demagnetized.

B. A Design for a Bellows Pump

The bellows pump design shown in Figure 1 is based a thirty-two convolution welded bellows that has a mean diameter of 103 mm. The outside diameter of the bellows is about 110 mm. The pump bellows can be flexed up to 25.4 mm (1 inch) for millions of cycles (at room temperature) without fatigue failure in the bellows. The pump is designed with a stroke of 19.1 mm (0.75 inch) at 4.5 K. The pump repetition rate will be about 10000 strokes per hour when the pump pumps 40 grams per second of liquid helium.

The moving mass of the pump shown in Figure 1 is the permanent magnet and the pump bellows assembly. The superconducting wires into the voice coil do not move because the armature is rigidly connected to the pump heat exchanger assembly. The advantage of a stationary voice coil is that the superconductor is always supported. Since the coil is stationary, the moving mass of the pump is the permanent magnet assembly and the bellows assembly. The pump moving mass is estimated to be about 4.5 kg. This 4.5 kg exerts a gravitational force on the pump of 44.1 N. That force is added to the force supplied by the current during the expulsion part of the pump cycle. The downward force supplied by the current can be as high as 980 N when the pump pressure rise is 0.1 MPa (14.6 psi). Table 1 below presents the basic parameters for the bellows helium pump shown in Figure 1. Figure 2 shows the current load lines for various values of ΔP and B.

The superconductor for the pump shown in Table 1 is assumed to be the RHIC correction magnet superconductor This conductor has a bare diameter of 0.330 mm (0.013 inches) and an insulated diameter of 0.457 mm (0.018 inches). The copper to superconductor ratio is 2.5. There are 385 filaments with a diameter of 9 μm in the copper matrix. The conductor twist pitch is 12.7 mm. The half lapped Kapton insulation is more than adequate to carry the voltages that will be found in the pump motor.

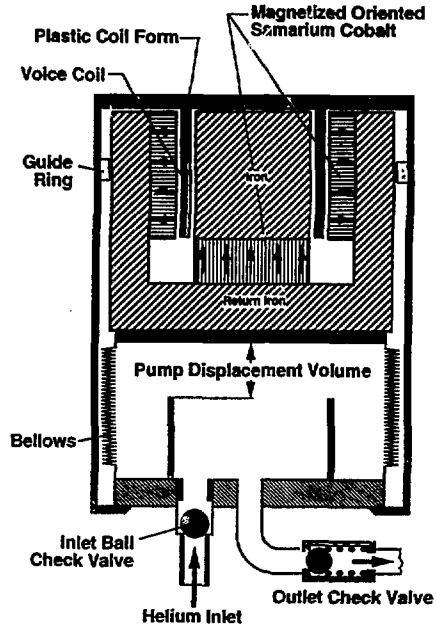

Fig 1 A schematic Diagram of a Bellows Pump Driven by a Permanent Magnet Motor with a Superconducting Voice Coil

Table I Parameters for a Superconducting Positive Displacement Helium Pump

Pump Parameters	
Bellows Effective Diameter D_B (mm)	103.
Bellows Stroke S_B (mm)	19.
Displacement Volume (cm^3)	158.3
Helium Density @ 4.4 K (kg m^{-3})	~120
Design Mass Flow M (g s^{-1})	~40
Nominal Operating Δ P (MPa)	0.0275
Design Volumetric Efficiency	0.90
Design Adiabatic Efficiency	*0.70*
Repetition Rate at Design Flow (Hz)	2.99
Pumping Force @ ΔP = 0.0275 MPa (N)	281.6
Pump Work @ ΔP = 0.0275 MPa and 40 g s^{-1} (W)	16.5
Pump Moving Mass M_M (kg)	~4.5
Design Gap Induction (T)	~0.8
Estimated Demagnetization Current (A)	~115.
Peak ΔP @ B = 0.8 T (MPa)	~0.4
Voice Coil Parameters	
Voice Coil Average Diameter (mm)	50.8
Voice Coil Length (mm)	25.4
Voice Coil Stroke (mm)	19.1
Voice Coil Package Thickness (mm)	2.54
Number of Layers	4
Number of Turns per Layer	*55*
Nominal Stroke Frequency (Hz)	2.99
Voice Coil Self Inductance in Air (mH)	2.42
Voice Coil Stored Energy @ 10 A (J)	0.121
Induction in Voice Coil @ 10 A (T)	~0.07
Current @ ΔP = 0.0275 MPa & B = 0.8 T (A)	6.76
Current @ ΔP = 0.3 MPa & B = 0.8 T (A)	86.2
Peak Voltage Back emf @ B = 0.8 T (V)	6.41

C. Kinematic Motion of the Moving Mass

For a cycle that has a triangular velocity profile, the *maximum values of the pump acceleration* a_M *and pump* velocity v_M are given as follows as a function of the voice coil stroke S_M and the pump frequency f_{cycle}.

$$a_M = 16\, S_M\, f_{cycle}^2 \qquad (6)$$

and

$$v_M = 4\, S_M\, f_{cycle} \qquad (7)$$

For the pump motor described in this report, the S_M = 0.0191 m and f_{cycle} = 2.99 Hz. Then a_M = 2.739 m s^{-2} and v_M = 0.229 m s^{-1}. The predominant acceleration that acts on the moving mass is gravity.

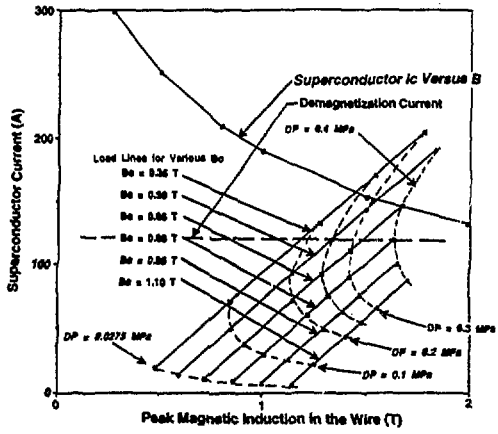

Fig. 2 Voice Coil Current versus Magnetic Induction for Various Radial Magnet Strengths

D. Current, Voltage and Pump Power

An expression for the voice coil current $i_O(t)$ is given as *follows:*

$$i_O(t) = \frac{\frac{\pi D_B^2}{4}(\Delta P + P_{CV}) + M_M\, a(t)}{\pi\, D_C\, N\, B} \qquad (8)$$

where D_B is the pump bellows diameter, ΔP is the change of pressure across the pump; P_{CV} is the pressure needed to open the output check valve; D_c is the diameter of the voice coil; N is the number of voice coil turns; B is the radial magnetic induction seen by the voice coil; M_M is the pump system moving mass; and a(t) is the acceleration of the moving mass. (Note: a(t) include gravity as well as the inertial terms.) A current versus time curve for the nominal pumping cycle is shown in Figure 3

An expression for the voice coil circuit voltage V(t) is *given as follows:*

$$V(t) = \pi D_C\, N\, v(t)\, B + R_1\, i_O(t) + L_1 \frac{di_O(t)}{dt} \qquad (9)$$

where R_1 is the resistance of the non-superconducting leads for the voice coil that go into the control dewar; and L_1 is the self inductance of the voice coil. D_C, N, and B have been previously defined. $i_O(t)$ is the voice coil current defined by Equation 8; v(t) is the velocity of the voice coil, which is a function of the displacement cycle of the pump and $di_O(t)/dt$ is the rate of change of the current in the voice coil.

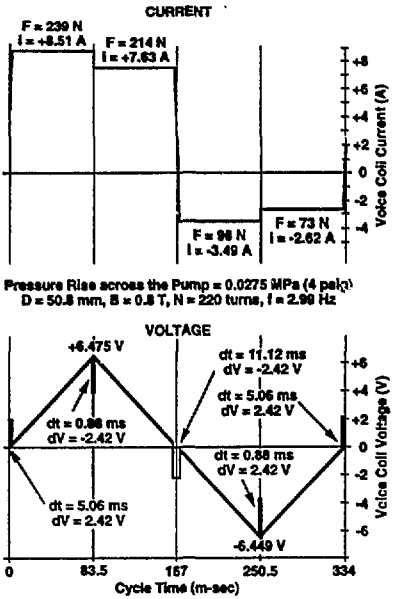

Fig. 3 Voice Coil Voltage and Current Versus Time for a Positive Displacement Pump Linear Motor

The instantaneous input power to the pump is the product of the current and voltage calculated using Equations 8 and 9. Most of the input power is proportional to the mechanical work done on the liquid helium in the pump. The energy dissipated in the leads is a minor part of the total power that is put into the motor by the power supply (less than one percent). The power needed to move the pump mass against gravity is not a factor in the overall power requirements for the pump because current put into the motor during the upstroke is current not put into the motor during the down stroke.

The calculations for the pump work shown in Equation 3 were based on the use of an adiabatic efficiency factor. The sources for pump inefficiency are as follows: 1) change of the bellows shape as they are pressurized (This effect is more pronounced at high differential pressure.), 2) leaks past the inlet check valve, 3) the flashing of the helium as it goes through the inlet valve into the pump (This changes the average helium density in the pump as pressure is applied.), and 4) helium leaks past the outlet check valve. The superconducting motor inefficiencies include the following items; 1) a. c. losses in the voice coil superconductor and 2) joule heating in the leads to the pump motor

The power supply has to produce a current and voltage profile such that the pump will pump the desired mass flow across the pressure drop of the load. The upper limit current for the pump is not the superconductor critical current but it is the voice coil current that will demagnetize the oriented permanent magnet material in the motor. The demagnetization current is estimated to be 115 amperes for the motor shown in Figure 1. A 100 ampere power supply that has peak voltages of ±10 volts should be capable of driving the pump.

III. CONCLUDING COMMENTS

Positive displacement bellows pumps have been successfully used for pumping liquid helium. A superconducting linear motor drive appears to be feasible for this kind of pump. A pump operating at a frequency of a few hertz is not dominated by inertial forces even when the iron and magnetic material mass are part of the moving mass. The differential pressure across the pump is the primary force that must be overcome by the superconducting drive. Key elements for reducing pump work (through reducing inefficiencies in the pump) are reliable (low leakage and low pressure drop) inlet and outlet valves. The peak pressure developed by the pump is limited by the demagnetization current for the motor.

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