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UHV Compatible Chopper System*

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ABSTRACT

A time-of-flight system utilizing a novel mechanical chopper has been developed to measure the energy spectrum of neutral deuterium atoms emitted from a tokamak plasma. The chopper system consists of a motor, a magnetically levitated shaft, and a chopper disc. The 20 gm disc is rigidly attached to a 159 gm shaft assembly and the set is supported against gravity in vacuum by permanent magnets and a stabilizing servo system. All components are UHV compatible to avoid contamination to the tokamak and to the detector. The 25.4 cm OD, .005 cm thick, 301 stainless steel chopper disc has 24 .025 cm wide slots photoetched at an 11.4 cm radius. An effective aperture time of [illegible] sec is achieved during typical steady state operation at [illegible] rpm with a vacuum pressure of 2×10^{-8} torr.

I. Introduction

The velocity spectrum of neutral deuterium atoms D^{O} emitted from a tokamak plasma typically peaks in the range .5 - 3 · 10^{7} cm/sec. Development of a time-of-flight (TOF) diagnostic for measurement of this velocity distribution has hinged upon solution of a vacuum technology problem, that of high speed rotary motion in a UHV environment.

In this experiment the D^{O} neutrals produced by charge exchange reactions in the tokamak are mechanically chopped by a slotted rotating disk, as in the original work of Kofsky and Levinstein.[1] The gated neutrals free stream 2 m where they impinge on a Cu-Be block, thereby ejecting secondary electrons which are subsequently collected and amplified by a bare electron multiplier[2] (Fig. 1). The time evolution of this detector signal can then be inverted to give the D^{O} velocity distribution.[3]

In the above scheme, the physical constraint that adequate energy resolution ($\Delta E/E$ .25) be obtained even for the most energetic particles of interest (1000 eV D^{O}) leads to a need for high rotor speed (20,000 RPM). This numerical relation follows from the usual TOF theory[4] for the case of a 2 m flight path, 25.4 cm diameter disc, and .025 cm wide slots. UHV conditions (p 10^{-8} torr) must be maintained even at these high speeds since contamination of the detector assembly by the outgassing chopper system can greatly reduce its gain and alter its calibration. The problem of the chopper injecting impurities back into the tokamak is less severe, due to the designed low 2 ℓ/sec conductance between the two vacuum systems.

This report describes a solution to the problem of high speed rotation in vacuum utilizing magnetic support of the single moving part, the shaft with rigidly attached disc. The operating principles of the motor and magnetic bearing are discussed, and their application as a chopper drive assembly is evaluated.

II. Magnetic Bearing

When two rigid bodies are maintained in a controlled non-contact relationship purely by means of magnetic fields, a magnetic bearing exists.[3] Typically one body is attached to mechanical ground and all forces on the second body are transmitted to the first body via the magnetic field.

Figure 2 is a schematic of the magnetic bearing used to support the 150 gm shaft assembly and 20 gm chopper disc against gravity. The 2.54 cm OD samarium cobalt disc magnets are arranged in attraction in an alternating north/south-north south pattern concentric with the horizontal rotation axis (z axis). In this scheme four of the six degrees of freedom of the rigid rotor assembly are passively stabilized by the arrangement of the two stator and four rotor magnets. The fifth degree of freedom, motion along the rotation axis, is strongly unstable due to the rapid decrease in the magnetic field intensity with distance. Axial stabilization is achieved with the aid of a servo system which compensates for unbalanced forces in the z direction by driving a current in the appropriate force coil to attract the iron armature at the shaft center. Shaft motion along z is sensed as a magnetic flux change in the 30,000 turn rate coil and the voltage thus induced acts as the servo system input. Position along z is sensed by magnetic field sensitive magnetoresistors located radially outside the rearmost rotor magnet.

Finally, the sixth degree of freedom, the shaft rotation itself, is essentially neutrally stable, being damped only weakly by eddy currents driven in the aluminum housing.

III. Motor

The two phase DC brushless motor is shown schematically in Figure 2. Rotation occurs when the 1.27 cm OD motor magnet, polarized across its diameter and rigidly mounted to the shaft, attempts to align itself with an externally imposed rotating magnetic field. Commutators are avoided by using solid-state Hall-effect probes to sense the angular position of the rotating motor magnet. The motor windings are water cooled to take up the 100 W transient heat load occuring during disc spin-up. This large heat load can disrupt the operation of the temperature sensitive magnetoresistors used in the magnetic bearing servo, and can destroy the Hall sensors if the temperature exceeds 125°C. The heat load is no problem in steady state vacuum operation, however; motor power dissipation, governed only by eddy current losses, is typically less than 2 W for 22,500 rpm rotor speed.

IV. Vacuum Considerations

Figure 3 is a photograph of the motor and magnetic bearing chopper drive assembly. The unit was fabricated entirely from UHV compatible materials. Polyimide coated copper wire is used in the rate coil, force coil, and motor winding. Machinable ceramic, Boron Nitride, and polyimide are used for insulators. The balance of the materials are metals. Bakeout temperature is limited to 100°C in order to avoid damage to the Hall sensors and the Varian Torr-Seal® adhesive.

A base pressure of 5×10^{-9} torr (uncalibrated ion gauge) has been achieved after a two day bakeout at 100°C in a liquid nitrogen trapped diffusion pump system. The unit subsequently ran steady state for 5 days at 30,000 RPM, indicating no deleterious bakeout effects. Typical base pressure during operation at [illegible] RPM with chopper disc in a 500 ℓ/sec turbopump system is [illegible] 10^{-8} torr.

V. Chopper Assembly

Figure 4 is a photograph of the complete chopper assembly used in our TOF plasma diagnostic. The entire chopper system is cantilevered from a single flange so that it can be inserted end on into a cylindrical ferritic stainless steel vacuum vessel. The 1 cm thick vacuum vessel thus shields the magnetic bearing from up to 200 gauss fields produced by the tokamak.

A major problem involved in using the motor of Fig. 3 as a chopper drive stems from the low value of radial stiffness, about 75 lb/in, which when coupled to the 130 gm rotor mass, leads to a system resonance at 35 hz (2100 RPM). In the vicinity of this resonant speed, the shaft begins wobbling and will contact the support structure unless quickly spun up or down. Contact usually leads to loss of levitation: the disc "crashes". The problem is compounded by the relatively large moment of inertia of the 25 cm OD chopper disc which, with the present motor, prevents the rotor from being spun through resonance is less than 3 seconds.

A solution to this problem is to balance the rotor so well that during acceleration the radial runout amplitude near resonance does not build up enough for contact to occur. The main imbalance is due to inhomogeneity of the magnets. Since the balancing must be done in air, and since the viscous drag torque of the large diameter chopper disc at 35 Hz exceeds the maximum motor output torque, the rotor assembly without the disc is actually balanced. This is accomplished by adding a weight equal to the disc weight at the front hub and then using additional weights at the appropriate angular positions on balancing hubs at the front and rear of the shaft. Once through resonance the rotor stabilizes as it spins about its principal moment-of-inertia axis.

Another resonance, due to the flexural motion of the shaft, limits the upper speed of the system to 23,000 RPM when the disc is attached. A new shaft, currently under manufacture, has this flexural resonance above 30,000 RPM.

VI. Summary

Under typical operating conditions of 22500 RPM and a 25.4 cm OD disc with 24 .025 cm wide slots at 11.4 cm radius, the chopper system achieves an effective aperture time (transmission half width) of .55 μsec at $2 \cdot 10^{-8}$ torr. Smaller aperture times can be achieved at higher speeds; however, in order that the stress on the chopper disc due to centrifugal force remain less than the average yield strength of 301 stainless steel, the rotor speed should not exceed 30,000 RPM.

A low speed dynamic resonance problem in the magnetic bearing has been solved by careful balancing of the rotor.

VII. Acknowledgments

The assistance of Paul Simpson of Cambridge Thermionic Corp. in modifying the standard magnetic bearing for vacuum use is gratefully acknowledged. One author (DV) wishes to thank [illegible] K. Owens for several helpful discussions.

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[a]Patented by Cambridge Thermionic Corp., Cambridge, Mass.

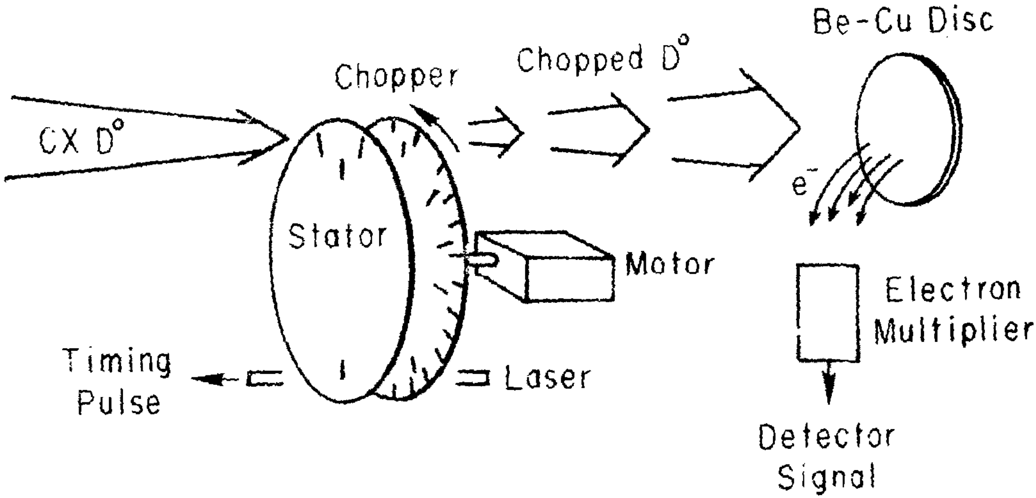
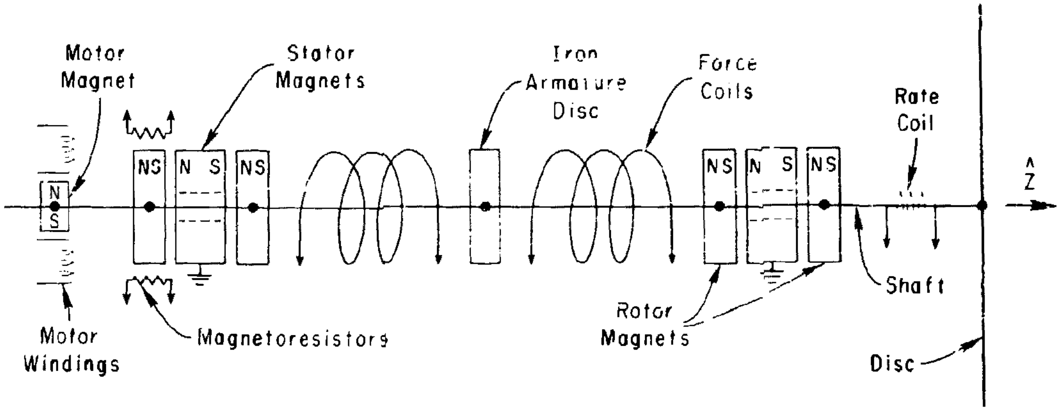


Fig. 1. TOF system. [illegible]
detected by secondary [illegible]



[illegible]6126

Fig. [illegible]. Motor-Magnetic Bearing Operation. Permanent magnets and a stabilizing servo system support the weight of the shaft assembly and upper disc without contact. [illegible] can be driven to 3[illegible] RPM with the 2 phase motor.

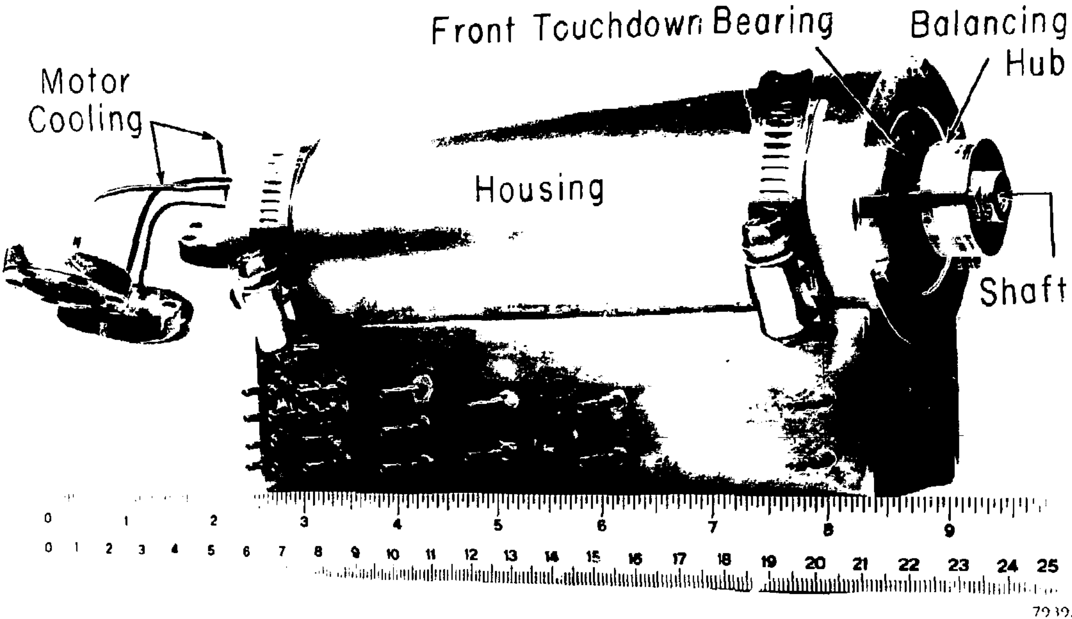


Fig. 3. Chopper Drive. The cylindrical aluminum housing contains the motor and magnetic bearing. Low friction front and rear touchdown bearings made from graphite impregnated polyimide contact the rotating shaft in case of magnetic bearing failure.

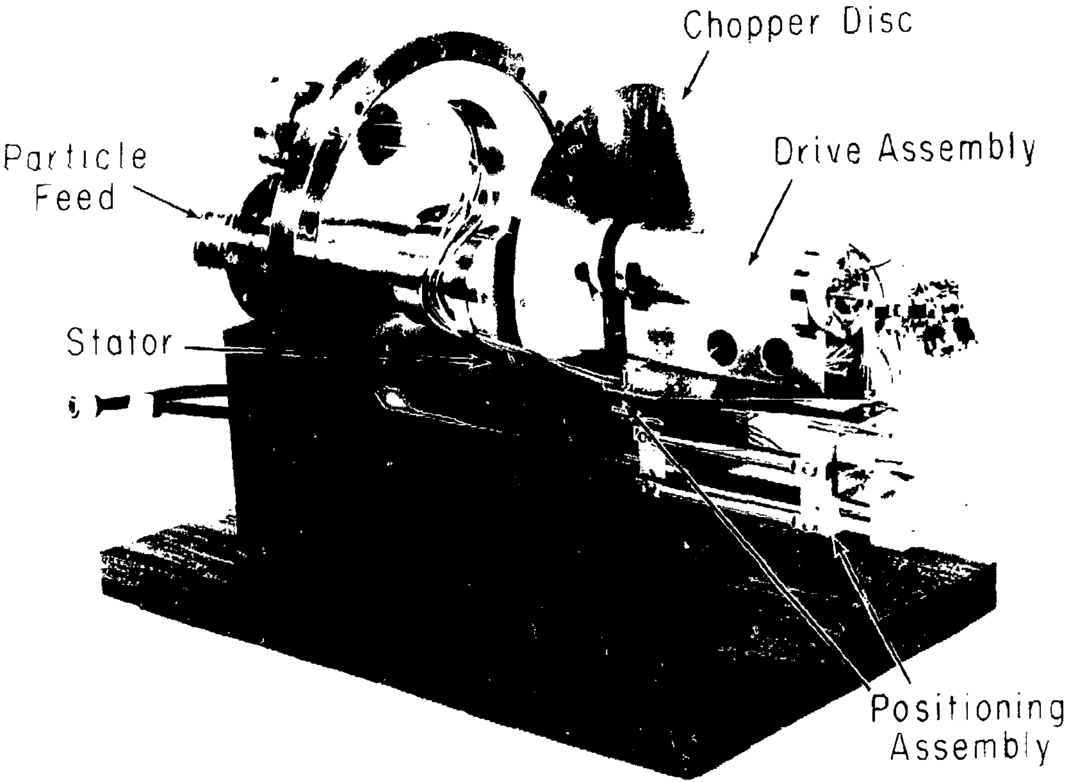


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Fig. 4. Chopper Assembly. Cantilevering the chopper system from a single flange allows it to be inserted into the end of a 406 stainless steel vacuum vessel which also acts as a magnetic shield.