

HIGH FREQUENCY UHV MECHANICAL X-RAY BEAM CHOPPER

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Abstract

An in vacuum mechanical chopper has been designed and built to perform X-ray Absorption Spectroscopy (XAS) experiments with operating liquid electrochemical cells at the Near Ambient Pressure Photoemission (NAPP) end station of ALBA Synchrotron (BL24, CIRCE Beamline). While operating the liquid electrochemical cell, in order to separate the weak currents induced by the X-ray absorption process at the working electrode in contact with the liquid electrolyte (total electron yield signal or TEY) from the faradaic current established between the electrodes when applying a bias, the incoming beam must be chopped at a certain frequency (ω) and then, by means of a lock in amplifier, the signal at this frequency ω can be extracted and measured. The in vacuum chopper developed at ALBA can operate at variable frequencies and when inserted in the X-ray beam path, produces pulses with a certain frequency ω , therefore modulating the TEY signal. This new chopper design, improves previous designs which used piezo-actuated choppers constrained to work at fixed oscillating frequencies [1].

The design consists of a slotted disk that spins around an axis by means of an UHV stepper motor. A LED and photodiode based UHV sensor ensures that frequency drifts do not affect the measurements. The motor is hold by an internally water cooled oxygen-free high thermal conductivity copper (OFHC) support, which allows long duration experiments at high speeds without stopping.

INTRODUCTION

In some soft X-ray absorption experiments, when performing electrochemical characterization of electrode-electrolytes systems under operando conditions, the big currents prevent from effectively collecting the tiny total electron yield currents (TEY) that shape the XAS spectra that contain the information that one wishes to extract from the operating electrode.

In order to separate these weak currents induced by the X-ray absorption process from the dominant faradaic currents (typically 10^6 times bigger), the incoming X-ray is chopped at certain frequency ω and then, by means of a lock in amplifier, the Fourier component of the signal corresponding to the ω frequency is extracted and measured. To modulate the TEY current, ALBA has developed an in vacuum mechanical chopper with variable frequency that, if inserted in the X-ray incoming beam, modulates the TEY signal whose amplitude is measured with a lock in amplifier

This technique has been typically performed using piezo actuated choppers with a fixed oscillating frequency, however, in this paper the viability of using a stepper

motor driven chopper and the required surrounding elements is described.

SYSTEM DESCRIPTION

The chopper consists of a slotted spinning disk driven by an UHV stepper motor. The main requirements of the mechanical chopper are the following:

- Sustain a high and stable rotation speed up to 1 kHz continuously for hours.
- Have a controlled and variable frequency.
- Be fully UHV compatible (10^{-9} – 10^{-10} mbar).
- Enable in-out motion in order to remove it from the beam path, if necessary.
- Allow the synchronization with the chopped electron yield current by means of a lock-in amplifier.

The selection of a stepper motor is the key issue of the design since a speed around 2.000 rpm was required. This velocity is beyond the normal working speed for standard stepper motors, which are capable to work at up to 6.000 rpm in air. However, due to the fact that the motor is placed in UHV and therefore, without air cooling at all, the working speed is limited -according to the manufacturer catalogue [2] - to 600 rpm. Because of the negligible cooling capacity in vacuum environments, the motor may overheat, stop and even be damaged in just a few seconds.

The proposed solution to the above mentioned issue is to support the motor with an internally water cooled clamp made of massive oxygen-free high thermal conductivity copper (OFHC). The gap between the motor and the water recirculation path is reduced to its minimum, 2mm. In this way the water arrives as close as possible to the motor's body and hence, the heat exchange between the motor and the water is maximized. A thermocouple connected to the motor's body controls the operating temperature continuously. Fig. 1 shows the basic cooling solution with the motor at the bottom, the holding clamp column with internal concentric water cooling and the brazed CF flange with the corresponding water and electrical connections

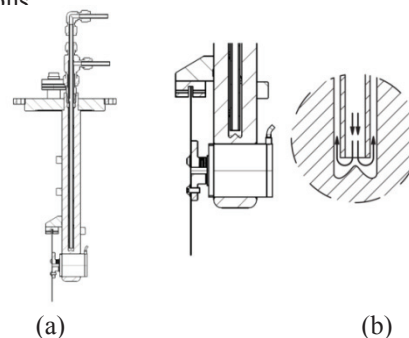


Figure 1: a) Cross section of the motor cooling elements. (b) Detailed view of the water recirculation.

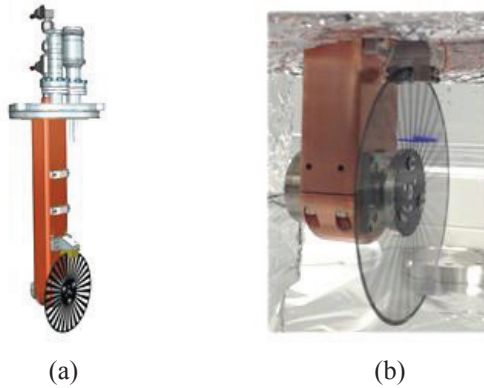


Figure 2: (a) Basic components of the device. (b) Chopper disk, motor and support.

A Thorlabs' slotted disk of 0,25mm thickness and Ø101,6mm was chosen for chopping the beam. The disk was tested in UHV and the RGA showed no evidence of any compatibility issues under UHV. The blade is available with different numbers of slots. The more slots, the higher the frequency but the smaller the beam size that can be chopped. A ray tracing calculation was performed to estimate the beam size at the chopper position and a 30 slots disk was chosen for the first experiments.

A thin aluminium support holds the disk directly coupled to the motor axis to both reduce the mass inertia and to avoid introducing possible frictions in the motion system.

At the top part of the spinning disk, a fully UHV compatible speed sensor, based on a LED transmitter and a photodiode, is installed in order to generate a periodic signal with the frequency of rotation of the disk. The photodiode output feeds into the lock in reference input. This ensures that frequency drifts do not affect the measurements since the X-ray beam is chopped at the same precise frequency that the one of the sensor current. All the components of the device are shown in Fig. 2.



Figure 3: Complete chopper unit.

A UHV linear manipulator allows inserting or removing the chopper unit from the beam path. Both the cooling and electrical connections are located on the top CF63 flange to prevent relative movements of the cables. The system is mounted in a vacuum chamber over a rigid and stable structure, which includes levelling elements in order to adjust chopper disk position, as shown at Fig. 3. The whole chopper unit is installed in a vacuum chamber after the M3 mirror of the CIRCE beamline, just upstream a fluorescence screen unit of the NAPP branch.

SIMULATIONS

Thermal Calculations

In order to study the thermal behaviour of the in-vacuum components with the water cooling system, a steady state thermal calculation was performed in Ansys, assuming the following boundary conditions:

- Electrical power given to the motor and therefore, approximate power to be dissipated [Eq.1]

$$\left. \begin{array}{l} \text{Serial Bipolar Connection} \\ I = 0,6A \\ V = 25V \end{array} \right\} P = V.I = 15W \quad (1)$$

- Cooling water temperature: 23,5°C

The most significant temperature maps for two different subcases are shown in Fig. 4, both of them assuming a non-perfect contact between the components with a thermal conductance value of $k = 2000W/m^2 \cdot ^\circ C$, which corresponds to the worst case.

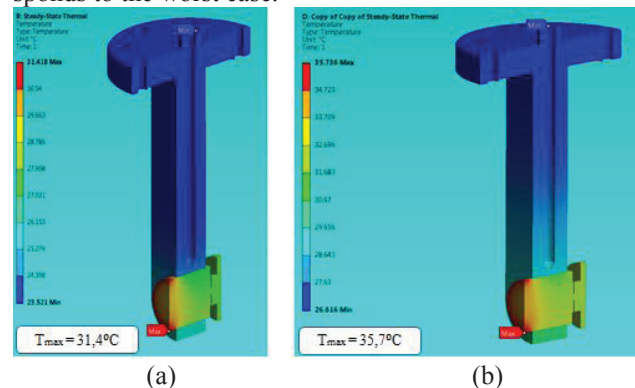


Figure 4: (a) Temperature map with $V_{\text{water}} = 3\text{m/s}$. (b) Temperature map with $V_{\text{water}} = 0,5\text{m/s}$ (minimum flow).

As seen in Fig. 4 above, the maximum temperature of the motor is below 40°C, which is completely acceptable.

Static Analysis and Vibrational Behaviour

In order to check the vibrational stability and static behaviour of the whole system, both the static and vibrational analysis simulations were performed in Ansys. The results show a maximum deformation of $3\mu\text{m}$ at the chopper disk and the 1st vibration mode at 66,6Hz, validating the system' stability.

TEST & RESULTS

First Results

After mounting the whole system and before baking it out, the chopper commissioning was done under vacuum. The motor was moved at 13.500 halfsteps/s (2.000 rpm), corresponding to a chopping frequency of 1kHz for a 30 slots' disk, with a water flow of 2l/min at 23°C. As shown in Fig. 5 a steady state temperature of 30,2°C was achieved, which was in the range of the calculated values.

After performing a bake out for 1 week at 120°C, the temperature of the motor stabilized at about 60°C, as shown in Fig. 5. This difference might be explained because of the contact loose between the clamp and the motor due to thermal deformation drifts during the bakeout, causing a loss of heat exchange capacity.

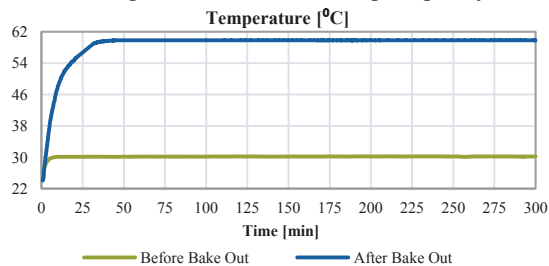


Figure 5: Temperatures in vacuum at 2.000 rpm with a water flow of 2l/min at 23°C before the bake out and after the bake out.

Results After Intervention

In order to improve the contact between the motor and the cooled support, and therefore, to enhance the cooling capacity, a 50µm thick indium foil was installed between the motor and the support. After the intervention, and before doing a bake out, the steady state temperature was stabilized at 48°C, with same flow and speed conditions as the ones tested before the intervention. After doing a bake out at 120°C during 8 days, the temperature stabilized at 51°C, which means that the cooling capacity had improved with the indium foil but also, that the contact had been loosen a bit again during the bake out. The two temperature graphs are shown in the Fig. 6.

The chopper was used continuously for more than 10 hours in different shifts during one week, without temperature readings above the ones shown in Fig. 6.

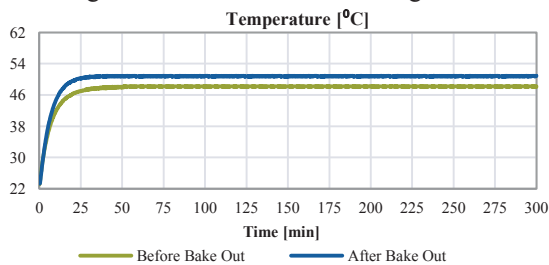


Figure 6: Temperatures in vacuum at 2.000 rpm with a water flow of 2l/min at 23°C after the foil installation before the bake out and after the bake out.

CONCLUSIONS

Even if the steady state temperature of the motor is higher than calculated, the feasibility of using a stepper motor in UHV at rotation speeds above 600 rpm with the cooling system developed in-house has been validated.

The variable frequency operation is an important quality of this device since the operating frequency in a real experiment has to be determined to be different from the eigen frequencies of the mechanical vibrations induced by fluids, vacuum pumps or other stimuli and of the electrical noise.

In general terms, the chopper could be used to filter low frequency electrical noise whose origin are mechanical vibrations, network noise or accelerator feedback (150 Hz). Operating at higher frequencies than noise sources (2 or 3 times), noise could be filtered thanks to a lock in amplifier so as to have cleaner signals with a better signal/noise ratio. This is useful when measuring weak signals or in general where signal's intensity is comparable to the noise level.

Furthermore, the chopper disk is interchangeable, allowing maximum flexibility regarding the frequency working range, up to 3,3kHz for a disk with 100 slots. This is at variance with other choppers used in most laboratories that consist of resonant vibrating metal foils excited by piezoelectric resonators and are limited to work at a certain fixed frequency. Besides, in these cases, due to the inertia of the vibrating foils, the achievable frequencies are below ca. 200 Hz. In our case, the operating frequency was determined experimentally by looking to the quality of the spectra. The results obtained in the first experiment showed spectra of good quality..

This design was registered as utility model at the Spanish patent and trademark office the 1st of August 2016 [3].

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REFERENCES

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- [2] Phytron Vacuum Stepper Motors VSS Catalogue.
- [3] Utility Model registration no. U201630988.