NANOPOSITIONING AND ACTUATION IN EXTREME ENVIRONMENT USING PIEZOELECTRIC MULTILAYER ACTUATORS AND MOTORS

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Abstract

Piezoelectric devices find numerous applications in Science projects, when precise and fast positioning is needed, particularly in harsh environment. This paper reviews some of the latest environmental tests performed on piezoelectric devices, illustrating how they enable higher performance or even new technical solutions.

In the field of particle accelerators and instrumentation, two applications can be mentioned: the precise goniometer to be installed in the Large Hadron Collider (LHC) and active Lorentz force detuning compensation systems. Multilayer actuators have been demonstrated over a wide range of temperatures, from cryogenic (1.8 K) to 220°C, in vacuum and under radiation.

Other examples can be mentioned within the ITER project: the In-Vessel Viewing System (IVVS) and the Electron Cyclotron Emission (ECE) diagnostic. For these applications, a piezo motor is needed. The Piezo Actuator Drive (PAD) was demonstrated at high temperature, vacuum and submitted to high magnetic fields.

INTRODUCTION

Science projects and in particular particle accelerators often have a need for actuation in harsh environment. Requirements cover a wide spectrum, from nanopositioning to long range actuation. In some cases, the capabilities of conventional electromagnetic actuators such as voice coils and stepper motors are exceeded, either in terms of performance (response time for example) or simply because of incompatibilities with the environment.

In such cases, piezoelectric devices can become the preferred choice, offering a combination of fast and precise motion with a low susceptibility to typically occurring environment (vacuum, low temperature, magnetic field). Two families of devices can be considered: actuators and motors. Actuators such as multilayer stacks (Fig. 1) provide solid-state displacements typically in the range 20-200 µm at room temperature and are analogous in terms of function to voice coil actuators. Motors (Fig. 2) make use of a mechanical transmission to accumulate small movements generated by an actuator in order to provide unlimited motion, analogously to electromagnetic motors.

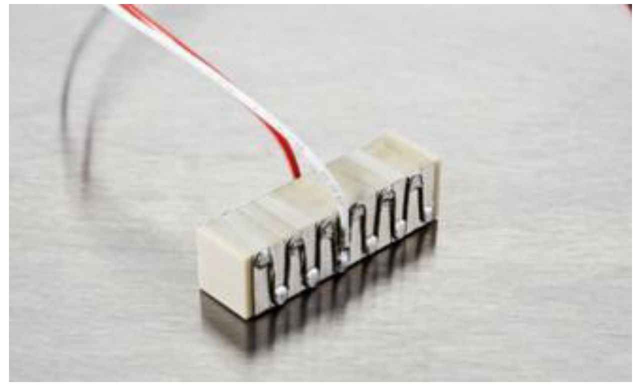

Figure 1: Piezoelectric actuator.

Figure 2: Piezoelectric motor.

Multilayer piezoelectric actuator have been developed since the 1980s [1] and address some of the limitations of electromagnetic actuators, opening-up for new applications. Nevertheless, it is a relatively recent technology and the adaptation and qualification of these products to specific environmental conditions has been a major field of research recently.

APPLICATIONS AND REQUIREMENTS

Actuators

In the field of particle accelerators and instrumentation, two applications can be mentioned as examples: active Lorentz force detuning compensation systems and the precise goniometer to be installed in the Large Hadron Collider (LHC) [2].

Most of the recent accelerators such as the free-electron laser (FEL) that provides tuneable radiation from the vacuum-ultraviolet (VUV) to soft X-rays, built at Deutsche Elektronen-Synchrotron (DESY) laboratory in Hamburg are based on superconducting cavities operated in pulse mode with pulses in the millisecond range. During operation, Lorentz forces change the shape of the cavity, leading to some cavity detuning [3]. There is a

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need for a tuning system combining long-range, slow adjustment, typically using a stepper motor, with short range, fast adjustment, typically using a piezoelectric stack such as the Saclay Piezo Tuning System (PTS), see Fig. 3. Table 1 gives some of the main parameters for two compensation systems.

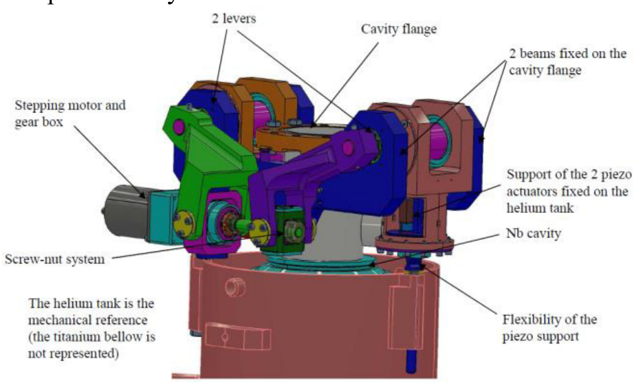

Figure 3: Saclay PTS [4].

Environmental conditions are similar within the LHC. In such systems, a major concern is the long bake-out cycles at 200-220°C which generate extreme stress levels on the electrical connections.

Table 1: Main Requirements for Two Compensation System [3]

	CEA Saclay PTS	KEK Slide Jack Tuner
Coarse range [kHz]	±250	±550
Fast range [Hz]	500	1200
Environment	4 K, vacuum	80 K, vacuum

Motors

Piezoelectric motors are considered typically for applications in high magnetic field where conventional actuation systems are not applicable. There are several examples within the ITER project, of which two are mentioned here: the In-Vessel Viewing System (IVVS) [5] and the Electron Cyclotron Emission (ECE) diagnostic [6].

The role of the IVVS is to perform visual inspection and measure the erosion of plasma-facing surfaces. To that purpose, probes can be deployed in the vacuum vessel using remote actuation (Fig. 4). In order to prevent parasitic movements of the scanning probe during inspection, it is necessary to lock the system motions with latching systems. Due to the high surrounding magnetic field, piezoelectric motors are foreseen for this task.

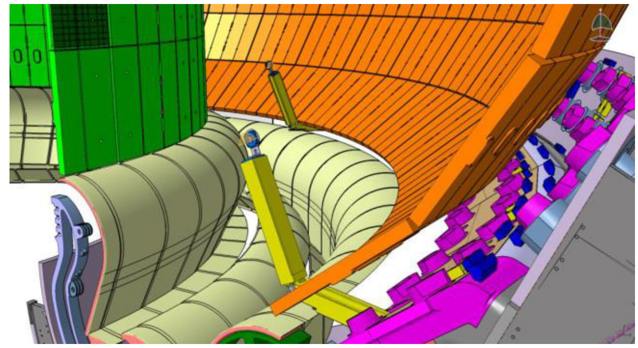

Figure 4: Deployed ITER IVVS [5].

The function of the ECE diagnostic is to perform measurements of the electron temperature profile evolution. Two plasma views are currently being planned, a radial and a moderately oblique view. In-situ 1000 K calibration sources can be switched into the views using actuated mirrors/shutters [6]. Due to thermal and mechanical loads, it may not be practical to use remote actuation, therefore a piezo motor solution is considered.

Both applications require a relatively long range motion, pointing towards a piezo motor solution. Speed, torque and resolution requirements can however be very different, calling for specific designs. Some of the main environmental requirements are summarized in Table 2.

Table 2: Main Requirements for Two Motor Applications

	IVVS locking [5]	ECE diagnostic
Radiation	Gamma 5 MGy 2.10^{17} n/cm2	
Pressure	10^{-5} Pa	10^{-5} Pa
Temperature	120°C	100°C
Magnetic field	8 T	4 T

TESTS AND RESULTS

Actuators

Some of the first tests that have been performed on piezoelectric actuators concerned temperature. Reference [7] reported measurements down to 1.8 K, showing a strong decrease of the available displacement (about 5% of the room temperature value at 4 K) as well as a decrease in capacitance. Nevertheless, with appropriate design precautions these actuators were validated for use in active tuning systems. At the other end of the scale, actuators have been validated and characterised up to 200°C [8].

Similarly, the compatibility of piezoelectric actuators with UHV conditions has been validated. The bake-out process for extended duration at 220°C was identified as a critical issue, since most solder materials lose their mechanical properties at high temperature, leading to a loss of the electrical connection. However this problem could be solved through the use of high temperature materials.

Reference [9] reported radiation tests on piezoelectric actuators in conditions representative of particle accelerator applications. The samples were subjected to irradiation tests at T=4.2 K with a fast neutrons beam (Energy spectrum: 1-15 MeV). A total dose of $1.8.10^{14}$-$3.1.10^{14}$ n/cm^2 was achieved in 20 hours: neither damage nor anomalous behavior or performance degradation of these actuators were observed.

Motors

Piezoelectric motors benefited from the experience acquired from the testing on actuators. Nevertheless, the motor structure itself has to be qualified in the environment. This can be challenging for motor structures relying on resonance in a narrow frequency band and on friction, where commercially available products are often rated for a narrow operating temperature range, typically -10 to +55°C [10]. Also, the radiation environment restricts the use of many materials, so it can be difficult to find suitable materials with the appropriate mechanical properties.

Recently, a PAD motor was validated for operation at 100°C and in vacuum [11]. Successful internal tests at 150°C indicate that the technology could be used at even higher temperatures.

Also the compatibility with extended bake-out cycles was confirmed. The motor was submitted to three bake-out cycles at 200°C during 72 h. During these tests, reduced Residual Gas Analysis (RGA) peaks and reduced RGA total pressure during temperature ramp-up, 72 h soaks and during 100°C temperature operation of the PAD were observed. Pressures as low as 5.10^{-5} Pa could be achieved.

In terms of compatibility with high magnetic field, similar motors are readily used in magnetic resonance imaging (MRI) applications [12], though at lower field strength (1.5 T). For the ITER project, a PAD motor has been validated for use under magnetic field gradients up to 10 T/s [13].

All the reported tests on PAD were performed with a 10m cable between motor and driver. Within the ITER project, it is common to place all electronics far from the tokamak in order to avoid any influence from the high magnetic fields. At a distance of 20 m the magnetic field is still 75-125 mT [5]. For comparison, hearing aids sustain damage from 20 mT so their safety distance to the tokamak is 60 m. Long cables can be an issue for resonant piezoelectric motors, that typically operate at 40 kHz. However in the case of a PAD operating at a few 10 Hz, the length of the wires is less of a concern.

CONCLUSIONS

For nanopositioning, fast adjustment and non-magnetic applications, piezoelectric actuators and motors provide new technical solutions, leading to more compact and more capable systems in Science projects. Four application examples are presented: two in the field of particle accelerators and two within the ITER project.

Owing to the interest in the technology, more and more environmental tests have been performed and results published, illustrating how the technology has gained maturity and robustness in extreme environment.

Wide temperature ranges from 1.8 K to 200°C, vacuum, high radiation levels and high magnetic fields are some of the environmental conditions in which piezoelectric devices have been validated.

Through these latest test results, piezoelectric actuators and motors demonstrate that they can enable higher performance or even new technical solutions and functionality, despite applications being more and more demanding in terms of environment.

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