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Piezo-driven valve for disruption mitigation studies in tokamaks

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HIGHLIGHTS

- Design criteria for the valve.
- Valve operation principle.
- Design of the piezoelectric driver.
- Design of functional valve components (bellow, nozzle, valve seal).
- Experimental results concerning opening time, stroke and gas expansion.

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ABSTRACT

Disruptions are a major issue for the safe operation of tokamaks. Hence the mitigation of disruptive effects is of high priority in view of ITER and DEMO. Previous experiments at ASDEX Upgrade have shown that the injections of massive amounts of gaseous impurities using in-vessel valves mitigate disruptions very efficiently, due to short time of flight of the gas towards the plasma edge and the applicability of pure noble gases. A new valve concept for in-vessel massive gas injection has been developed at ASDEX Upgrade to replace the old valves which suffered from reliability problems. This new valve is a normally closed valve since the valve plate is pressed into the main sealing by a stainless steel bellow (acting as a spring), sealing off the gas reservoir, which can hold 42 cm^3 of gas at a pressure of up to 5 MPa. The valves actuator consists of 4 piezoelectric stacks which are mounted in two parallel pairs into a monolithic titanium frame. This frame is rigidly connected to the valve plate and it amplifies the stroke of the stacks to allow a total stroke of the valve plate of 2.2 mm, which is reached after 5 ms. The diameter of the straight valve nozzle is 14 mm allowing a peak flow rate of 44 $kPam^3/s$ after 1 ms. The valve has a size of 173 mm × 88 mm × 70 mm.

1. Introduction

Disruptions are a serious issue for the safe operation of tokamak fusion devices. Exceeding stability limits or technical errors can cause MHD modes which lead to a sudden loss of the plasma thermal energy. This leads to a disruption in which the divertor is exposed to a significantly higher heat flux than in normal operation. This can cause damages if the plasma thermal energy is high. Additionally, elongated plasmas can move towards the upper or lower divertor during disruptions if their vertical position is perturbed beyond the controllable region. This movement induces eddy currents in conducting structures and drives halo currents [1]. Both currents lead to tremendous forces on the vessel. Further, strong toroidal electric fields can give rise to runaway electrons (RE) with relativistic energies, depending on the plasma density and current. These can cause massive damage to plasma facing components if they lose confinement.

Massive gas injection (MGI) has proven to be an effective method to mitigate the heat loads, forces and REs. This has been observed at several different machines like ASDEX Upgrade [2] (AUG), Alcator C-Mod [3], DIII-D [4–6], JET [7], MAST [8], TEXTOR [9] and Tore Supra [10]. MGI is performed using fast valves. It was proven favorable to use valves close to the plasma because the assimilation fraction is high [11]. In the last years, spring-driven valves were used for this purpose in AUG, but they suffered from reliability issues. An examination of these old valves revealed prob-

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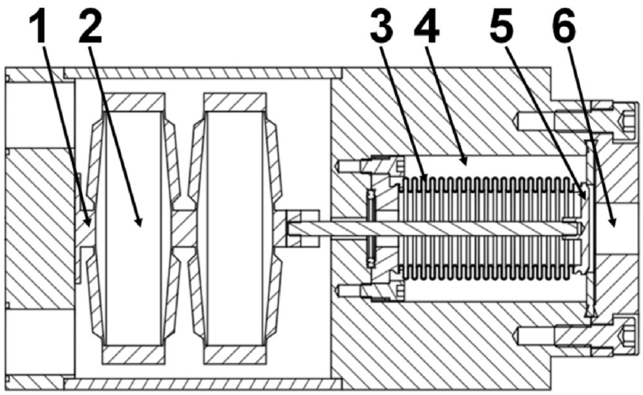

Fig. 1. Scheme of the valve with the titanium frame (1), the piezoelectric stack actuators (2), the bellow (3), the gas reservoir (4), the valve plate (5) and the nozzle (6).

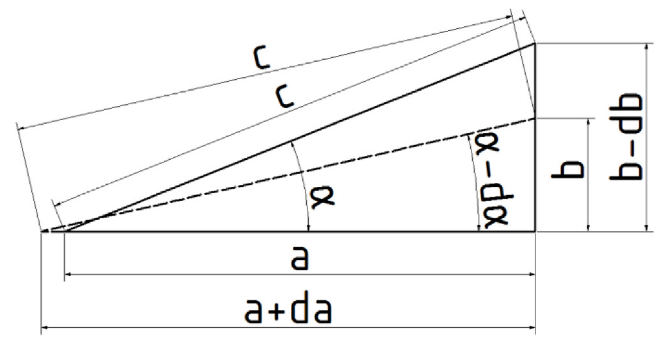

Fig. 2. Scheme of one leg of the titanium frame. The solid line indicates the original state and the dashed line the state when the actuators have expanded. a: half-length of a stack, da: half stroke of one stack, b: height of the rhomb, db: amplified displacement, α: original angle between the leg and the stack, dα: angle variation, c: length of the leg.

lems with the valve seal, the clamping mechanism and the sensitive adjustment of the piezoelectric stacks.

In addition to an improved spring-driven valve [12] a new piezo-driven valve was developed at AUG as a normally closed counterpart to the spring-driven valves. This paper presents the basic valve design, the design of the active components, especially the piezoelectric actuator and first test results.

2. Valve design

The valve has to fulfill both physical and technical requirements to be suited for operation. The physical requirements are given by the phenomenology of disruptions as explained before. The pre-TQ is of the order of milliseconds; hence the opening time of the valve must be at least of the same order. The total amount of required impurity atoms has been found to be about 10^{21} particles in AUG. The gas reservoir must be designed accordingly. As for the technical requirements, the valve must be suitable for in-vessel conditions. This is first of all compatibility with ultra-high vacuum, meaning the valve, the seals and gas lines must have a leak rate blow 10^{-8} Pam^3/s and the used materials must not emit gas themselves. Secondly the valve must be insensitive to magnetic fields and must not create any. The valve must withstand the baking temperature of 150 °C and ionizing radiation without taking damage. The piezo-driven valve fulfills these requirements due to its actuation concept and used materials, which are ceramic, titanium, fluoroelastomer (FKM), copper and stainless steel. The composition of the valve with its main components is illustrated in Fig. 1.

The piezo-driven valve is a normally-closed valve, meaning, that in the idle state the conical valve plate (5) is pressed into the FKM seal by the bellow (3) closing off the gas reservoir (4). The reservoir can hold 42 cm^3 of gas at a maximum pressure of 5 MPa. This corresponds to a maximum particle inventory of 5×10^{22} atoms assuming the gas is at room temperature. When the reservoir is filled and the valve is triggered, the piezoelectric stack actuators (2) are supplied with a voltage of 200 V. The stacks expand 0.1 mm and the titanium frame (1) amplifies the stroke by a factor of 14. The valve plate is directly connected to the frame, allowing a fast movement of 1.4 mm. The inertia of the stacks and the frame add to the nominal stroke which reaches its maximum at 2.1 mm. The gas flows from the reservoir through the straight nozzle (6), which has a circular orifice of 14 mm diameter.

2.1. Piezoelectric actuator

The piezoelectric actuator consists of 4 piezoelectric stack actuators and a monolithic titanium frame. The stacks are of the type Noliac NAC2023-H64 [13], meaning they have a length of 64 mm, corresponding to a stroke of 0.1 mm, and a quadratic cross-section with 225 mm^2, corresponding to a blocking force of 9450 N each, when supplied with 200 V DC. They are mounted into the frame, which consists of two connected rhomb shaped sections, each holding two parallel stacks. The frame is manufactured from a solid block of Ti6Al4 V. The material was chosen because of its unique properties with respect to elasticity and tensile strength and the monolithic design guarantees UHV compatibility, as well as heat and wear resistance. The frame serves two purposes: it pre-stresses the piezoelectric stacks with 150 N each and it amplifies the stroke of the stacks significantly. The pre-stress is necessary to keep the stacks under compression stress for all conditions. Without this counteracting force, the stacks could delaminate due to their own inertial force when they are charged and expand. The amplification is achieved by geometric deformation of the frame. It can be derived from trigonometric relations. Fig. 2 illustrates how the amplification is achieved using one leg of the titanium frame. The solid rectangular triangle indicates the leg in the original state while the dashed triangle shows the deformed state.

Relations for the angle variation $d\alpha$ and the displacement db depending on the half length of the stack a and the half stroke da, which are determined by the piezoelectric stack, and on the original angle α are derived from the trigonometric relations of the triangles shown in Fig. 2.

$$\tan\, d\alpha\,(a, da, \alpha) = \frac{\sqrt{a^2 tan^2\alpha - 2ada - da^2} - (a + da)\tan\alpha}{\sqrt{a^2 tan^2\alpha - 2ada - da^2}\tan\alpha - a - da} \quad (1)$$

$$db\,(a, da, \alpha) = a\,\tan\alpha - \frac{(\tan\alpha - \tan d\alpha\,(a, da, \alpha))(a + da)}{1 - \tan\alpha\,\tan d\alpha\,(a, da, \alpha)} \quad (2)$$

Since the frame consists of two serial rhombs, it has four serial legs that contribute to the stroke amplification. Hence, the overall stroke of the piezoelectric actuator is 4xdb.

The blocking force F_B is the force that the actuator produces if it is not allowed to perform any movement. Hence, in this state, only the legs are stretched by the force of the piezoelectric stacks. The blocking force therefore depends on the original angle α, and the geometry (mean cross-sectional area A, length c) and material (elasticity E) of the leg, as well as the blocking force of a single stack F_0 and the half stroke da of the stacks (Eq. (3)).

$$F_B = \frac{1}{2}\sin(2\alpha)\frac{F_0}{da}\left(da - \frac{F_0}{\frac{F_0}{da} + \frac{E*A}{c}}\right) \quad (3)$$

The blocking force is independent from the number of serial rhombs in the frame. The linear relation between force and elonga-

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