Conceptual design of the MGI system for JT-60SA

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Disruption mitigation is of high priority for future tokamaks like ITER and DEMO. Massive gas injection (MGI) has proven to be an effective method in medium size machines and will likely be part of future disruption mitigation systems. For further research, the large superconducting tokamak JT-60SA will be equipped with a MGI system as an experimental equipment. This system will consist of two in-vessel MGI valves, which are mounted in opposite segments of the machine, vacuum feed throughs, a gas preparation system and an industrial PLC for control. The MGI valves are a scaled version of the spring-driven valve used in ADSEX Upgrade with an internal gas reservoir of 815 cm³, a maximum mitigation gas pressure of 6.5 MPa, a closing pressure of about 2 MPa, a nozzle diameter of 28 mm and an opening time below 2 ms. CFD simulations with common gas mixtures indicate a peak flow rate of 3.8 kg/s after 1.6 ms. The valve has a size of 140 mm x 110 mm x 292 mm. The gas preparation system allows easy and reproducible mixing of two gases by using an electronic pressure controller.

Keywords: massive gas injection, disruption mitigation

I. INTRODUCTION

For the safe operation of tokamak fusion devices, it is necessary to mitigate disruptions. Electromagnetic forces, high localized heat loads and highly energetic runaway electrons can cause serious damage to the machine if left unmitigated. This is problematic for large tokamak devices like ITER and DEMO, due to their strong magnetic fields, high plasma current and high thermal energy in the plasma. Hence, investigating and understanding disruptions and their mitigation is important for future machines.

Massive Gas injection (MGI) is a well-established method for disruption mitigation. This has been proven at several tokamaks like ASDEX Upgrade[1] (AUG), Alcator C-Mod[2], DIII-D[3-5], JET[6], MAST[7], TEXTOR[8] and Tore Supra[9]. It was decided by the JT-60SA research coordination meeting in 2016 to equip the new large superconducting tokamak JT-60SA with a MGI system to contribute to the ongoing research.

Experiments on AUG have shown that it is favorable to inject the mitigation gas close to the plasma edge, because this results in a high assimilation of the impurities into the plasma[10]. Therefore, fast valves inside the tokamak vacuum vessel are necessary. The AUG spring-driven valve[11] was chosen as best candidate for the implementation into JT-60SA, as this valve type has shown good performance and reliability. Extensive modifications to the AUG design were made to meet to requirements of JT-60SA and to allow high experimental flexibility. Experiments at JET have shown that a MGI system is an important asset for protecting metal plasma-facing components from melting during disruptions[12]. Therefore, the JT-60SA MGI system must be able to operate automatically in sequence with the tokamak control system.

This paper presents the design of the MGI valve, the vacuum feed through and the gas preparation system, the conceptual design of the control system and the setup at JT-60SA, as well as first results of component tests.

II. GENERAL SETUP

The MGI system consists of two MGI valves, two vacuum feed throughs, the gas preparation system and the control system. The MGI valves are mounted inside the vacuum vessel behind the stabilizing plate in upper oblique position in sectors P09 and P18 (Fig. 1). These positions were chosen because they are on opposite sides toroidally, hence reducing radiation asymmetries. The stabilizing plate blocks thermal radiation from the plasma, preventing heat up of the valves during plasma operation. Tubes from the MGI valves, which penetrate the stabilizing plate, guide the gas to the plasma. These tubes end about 25mm behind the contour of the tiles at a distance of about 100 mm from the plasma edge.

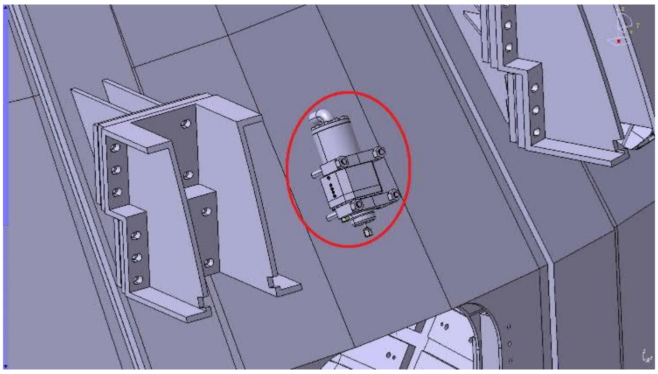

Figure 1: MGI valve (red circle) on the backside of the stabilizing plate inside the JT-60SA vacuum vessel (vacuum vessel not shown)

Two ¼” stainless steel pipes supply each valve with mitigation gas and compressed air. Connections are established via VCR connectors and metal gaskets. Electric voltage is supplied by two cable bundles each, consisting of mineral insulated and PEEK insulated cables. Vacuum feed throughs for the in-vessel cable bundles and pipes are located on the boundary boxes in sectors P10 and P18. ½” stainless steel pipes for mitigation gas and ¼” stainless steel pipes for compressed air connect the vacuum feed throughs with the gas preparation system in the pumping room, located in the basement beneath the torus hall. Cables from the vacuum feed throughs to the valve trigger modules supply the electric voltage. These modules, together with the main PLC, are located in a cubicle in the basement. Communication between the main PLC and the peripheral PLC at the gas preparation system is done with PROFIBUS, whereas communication between the control computer in the control room and the main PLC is realized with optical fibres. ¼" stainless steel pipes connect the gas cylinders outside the torus hall with the gas preparation system. In the case of deuterium, a mechanical pressure booster amplifies the 6.9 MPa in the gas cylinders to the required 8 MPa.

III. VALVE DESIGN

Data from JET[13] experiments indicate that an amount of 10^{22} impurity particles is required for a successful disruption mitigation in a machine the size of JT-60SA. The mitigation gas must also contain 90% H_2 or D_2 to prevent the generation of runaway electrons. Hence, a total of 10^{23} particles or 400 Pam³ is required. The upper boundary for the injected gas amount is given by the cryo pump, which can absorb 10 kPam³ of H_2 or D_2 per discharge. The mitigation gas reservoir in the MGI valve was designed according to the Japanese High Pressure Gas Law (HPGL)[14], which requires the volume to be below 1000 cm³ to avoid an extensive licensing process. The reservoir was designed with 815 cm³ as piping adds to the pressurized volume. The maximum gas pressure in the reservoir is given by the bellows strength. Under the HPGL, the bellows must withstand more than 4 times the system design pressure. The strongest bellows available at the correct size has a pressure rating of 32 MPa, which leads to a system design pressure of 8 MPa. Accounting for the pressure drop during filling of the MGI valve, the maximum pressure in the MGI gas reservoir is 6.5 MPa. This results in a maximum gas amount of 5300Pam³, which is within the safety limits of the cryopump[15]. The valve must be compatible with the in-vessel conditions in JT-60SA, meaning ultra-high vacuum, baking of vacuum vessel at 200 °C, magnetic fields of up to 2.28 T and ionizing radiation. Therefore, the valve materials are chosen to have an outgassing rate below 10^{-8} Pam³/s, deterioration temperatures above 200 °C, relative magnetic permeability below 1.05 and low contents of cobalt. The list of materials can be found in table 1 and the valve composition is illustrated in Fig. 2.

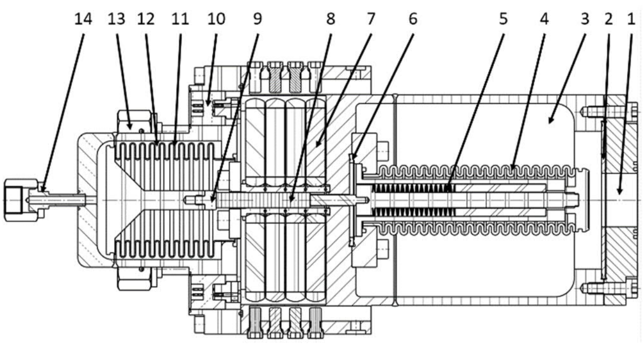

Figure 2: Schematic of the valve with nozzle (1), valve seal(2), mitigation gas reservoir(3), front bellows(4), disc springs(5), copper seal(6), piezoelectric stack actuators(7), ceramic valve stem(8), damper(9), electric feed throughs(10), rear bellows(11), closing volume(12), mitigation gas supply(13) and air supply(14)

The spring-driven valve is a normally open valve. Compressed air at 2 MPa is let into the closing volume (12) and pushes the valve plate into the valve seal (2), closing the mitigation gas reservoir (3) and tensing the front bellows (4) and the stack of disc springs (5). A micro switch is closed indicating the status of the valve. The piezoelectric stack actuators (7) are charged with 120 V, expand and clamp the ceramic valve stem (8). The compressed air is vented from the closing volume and the mitigation gas reservoir is filled with gas. When the valve is triggered, the piezoelectric stack actuators are discharged and the front bellows together with the disc springs pull the valve plate from the valve seal and the gas is released through the nozzle (1), which has a circular orifice of 28 mm diameter. The damper (9) softens the impact of the ceramic valve stem.

Component	**Material**
Valve body + structural comp.	X2CrNiN18-10
Valve seal	Kalrez (FFKM)
Bellows	X6CrNiMoTi17-12-2
Disc springs	X10 CrNi 18-8
Copper seal	CW 008A
Valve stem	Al_2O_3
Piezoelectric stack actuators	PZT
Damper	Vespel (PI)
Screws	X5CrNiMo17-12-2

Table 1: List of materials of the MGI valve

The opening time and the gas flow out of the mitigation gas reservoir are key factors for efficient disruption mitigation. Assimilation of the gas into the plasma is best when the thermal energy of the plasma is still high. Hence, injection of a concentrated gas pulse into the pre-thermal quench phase has shown the best results. Short opening time and high gas flow are therefore favorable. The opening time of the valve depends on the stiffness of the disc spring and the bellows, as well as the masses of the valve plate, the bolt, the pin, the ceramic, the bellows and the disc springs. The equation of motion gives the movement of the valve plate (Eq. 1).

$$z(t) = \frac{F_P}{R_s + R_B} + \left(h - \frac{F_P}{R_s + R_B}\right) \cdot \cos\left(\sqrt{\frac{R_s + R_B}{m_{tot}}} \cdot t\right) \quad (1)$$

The stack of disc spring consists of 35 discs of the type 004 100C stacked in alternating orientation. This results in a linearized spring rate of R_s = 11.7 N/mm. The bolt compresses the disc spring during assembly by 2 mm, leading to a tension force F_p = 23.4 N. The bellows with its spring rate of R_B = 194.7 N/mm remains tension free. The effective moving mass is m_{tot} = 0.217 kg. The necessary lift (h) of the valve plate is estimated by the nozzle inlet (d_i) and outlet (d_a) diameters. The lift shall create a cylindrical area equal or larger than the cross-sectional area of the nozzle outlet (Eq. 2).

$$h \geq \frac{{d_a}^2}{4 \cdot d_i} \quad (2)$$

With an outlet diameter of da = 28 mm and an inlet diameter of di = 30.3 mm, the lift must be at least 6.5 mm. The design value was chosen to be h = 7 mm. The calculated movement of the valve plate is shown in Fig. 3. The valve is open after 1.6 ms.

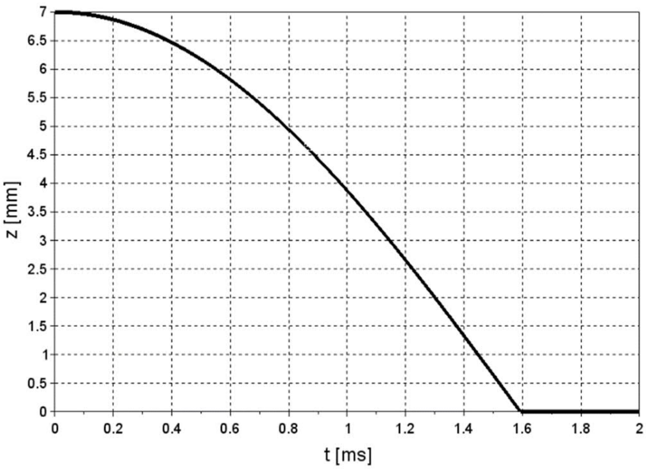

Figure 3: Calculated movement of the valve plate

The flow from the mitigation gas reservoir was simulated with ANSYS Fluent. A 2D axisymmetric model was used to mimic the nozzle, the gas reservoir, the valve plate and the bellows. The solver was a density based implicit solver with a residual condition of 0.01 and a time step of $5*10^{-7}$ s. A duration of 10 ms was simulated, during which the valve plate was moved according to the result of the equation of motion (1). Four different gas mixtures containing 10 % noble gas and 90 % H_2 were investigated, each with an initial gas pressure of 6.5 MPa. The results for the mass flow are shown in Fig. 4. The peak mass flow is reached when the flow area reaches its maximum value at 1.6 ms. The mass flow and thus the evacuation time of the gas from the reservoir strongly depends on the gas constant of the gas mixture, which in turn depends on the molecular mass. Hence, the lightest simulated gas mixture Ne+H_2 reaches 80 % evacuation after 7.7 ms while the heaviest mixture Xe+H_2 requires 10 ms for the same evacuated fraction.

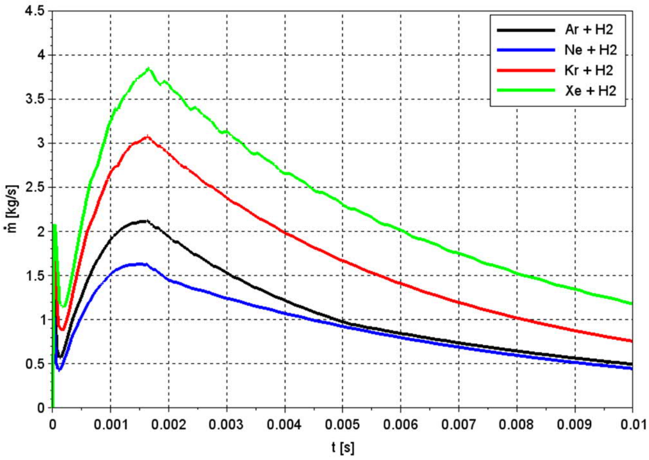

Figure 4: Mass flows of four different gas mixtures through the valve nozzle

The disruption forces on the valve were calculated in a separate model (Fig. 5) using Ansys Maxwell. This model includes a 40° slice of the vacuum vessel, stabilizing plate and poloidal field coils, as well as two toroidal field coils and the MGI valve. The plasma is modelled by 20 circular concentric conductors with equal width to reproduce the current distribution in the plasma. The material of the Vacuum vessel, stabilizing plate and valve was set to stainless steel. A material with a conductivity of 10^{11} Siemens/m was created for the superconducting magnets and the plasma. Symmetry boundary conditions on the edges of the vacuum vessel and the stabilizing plate mimic their toroidal continuity.

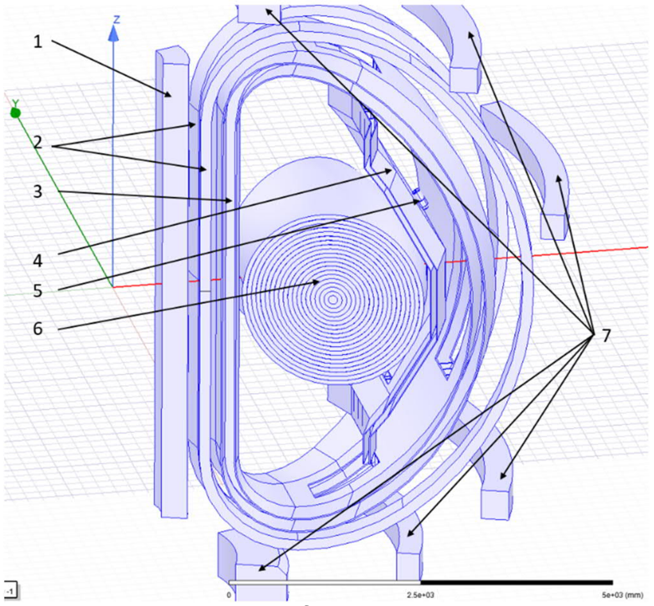

Figure 5: Maxwell model for electromagnetic simulation (air not shown): Central solenoid(1), toroidal field coils(2), vacuum vessel(3), stabilizing plate(4), MGI valve(5), plasma(6), poloidal field coils(7)

Currents of 20 kA were set in the poloidal field coils and the central solenoid, 25.7 kA in the toroidal field coils and the initial plasma current was set to 5.5 MA. The current in each plasma conductor was calculated from this using a plasma minor radius of 1.2 m. A dB/dt of 200 T/s was set for the current quench from which the exponential current falloff in the plasma conductors was derived. The transient simulation was set for 3 ms with a time step of 0.05 ms. The induced currents in the valve lead to a maximal force of 53 N. Vertical displacement events are currently under investigation.

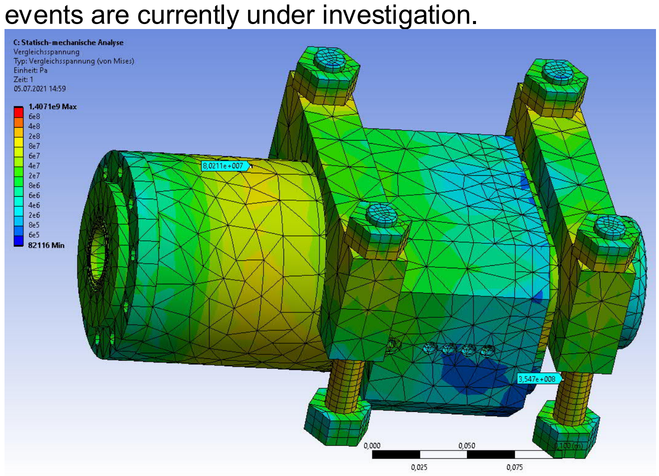

Figure 6: Result of mechanical FEM analysis

The mechanical stability of the MGI valves inside the JT-60SA vacuum vessel was checked with a finite element (FEM) simulation. The disruption force was applied to the FEM model in addition to the maximal gas pressures in both volumes and seismic accelerations of 5g in perpendicular directions. The result (Fig. 6) shows a maximum stress of 35 MPa in the M20 bolts, which hold the valve on the stabilizing plate. This stress is well below the allowable stress for A4-80 bolts ($R_{p0,2}$ = 600 MPa).

IV. VACUUM FEED THROUGHS

The vacuum feed throughs route the mitigation gas, the compressed air and the supply voltage for the MGI valves from the atmospheric side into the vacuum vessel of JT-60SA. Hence, each feed though is equipped with two gas lines and an electric feed through (Fig. 7).

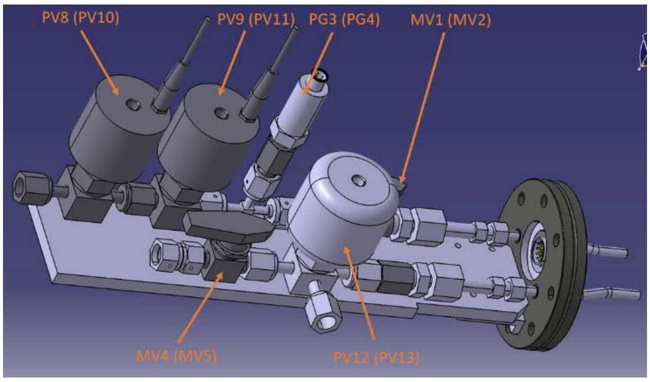

Figure 7: CAD model of the vacuum feed through. Annotations according to Fig. 8

The mitigation gas line has two redundant pneumatic valves as precaution, since there is a direct connection to the torus vacuum. A piezoelectric pressure gauge transmits the mitigation gas pressure and a manual valve allows closing off the mitigation gas lines for maintenance. The compressed air line is equipped with a three-port valve, which is used to blow off the compressed air into the torus hall. Both gas lines are electrically insulated from the vacuum vessel potential by dielectric fittings with a break through voltage of 1 kV. The voltage is transferred through a MIL-C-26482 feed through with 19 pins which can transfer up to 1 kV and 3 A per pin. The entire feed through is built on a standard ICF 114 flange.

V. GAS PREPARATION SYSTEM

The gas preparation system (Fig. 8) is used for mixing the mitigation gases, supplying the compressed air and pumping the MGI system. Up to four gases can be connected to the inlet valves on the gas panel (PV1-PV4). Each gas is let into the line in front of the electric pressure controller (EPC), which then regulates the mixing pressure for this gas in the mixing volume. This allows easy and reproducible gas mixing. Before a different gas is let into the line before the EPC, the residual gas in the line is vented into the stack by opening the blow off valve PV5 before the line is pumped to a pressure below 1 kPa by opening the line pumping valve PV7. The mixing volume on the gas panel has a volume of 4000 cm³. The ½” pipes connecting the gas panel with the vacuum feed throughs adds another 6125 cm³ to the mixing volume. The MGI system is pumped by opening the main pumping valve PV6. The vacuum pressure is monitored by a Pirani vacuum gauge. Since the gas panel is connected to a roughing pump of the JT-60SA pumping system, a vacuum pressure below 10 Pa is expected to be reached in the MGI system. The compressed air is taken from the tokamak’s 0.7 MPa compressed air supply. The pressure is regulated down to a value of about 0.5 MPa (PR1) before being amplified by a factor of four using a mechanical pressure booster (PB2) to the required value of 1.8 MPa. Air and mitigation gas pressures are monitored by piezoelectric pressure gauges.

VI. CONTROL SYSTEM

The control system consists of two valve trigger modules, two trigger signal selection modules, two delay modules, the main PLC, the peripheral PLC at the gas preparation panel and the control computer. The valve trigger module supplies the 120 V for charging the piezoelectric stack actuators in the MGI valve, monitors the charging currents and discharges the actuators on a 24 V trigger signal. This trigger signal is supplied by the trigger selection module, which allows up to three different trigger inputs from which one is relayed to the trigger module, under the condition of an active interlock signal. For MGI experiments, usually the pulse start signal is taken as trigger. The delay module postpones this trigger by a certain time, allowing gas injection at a

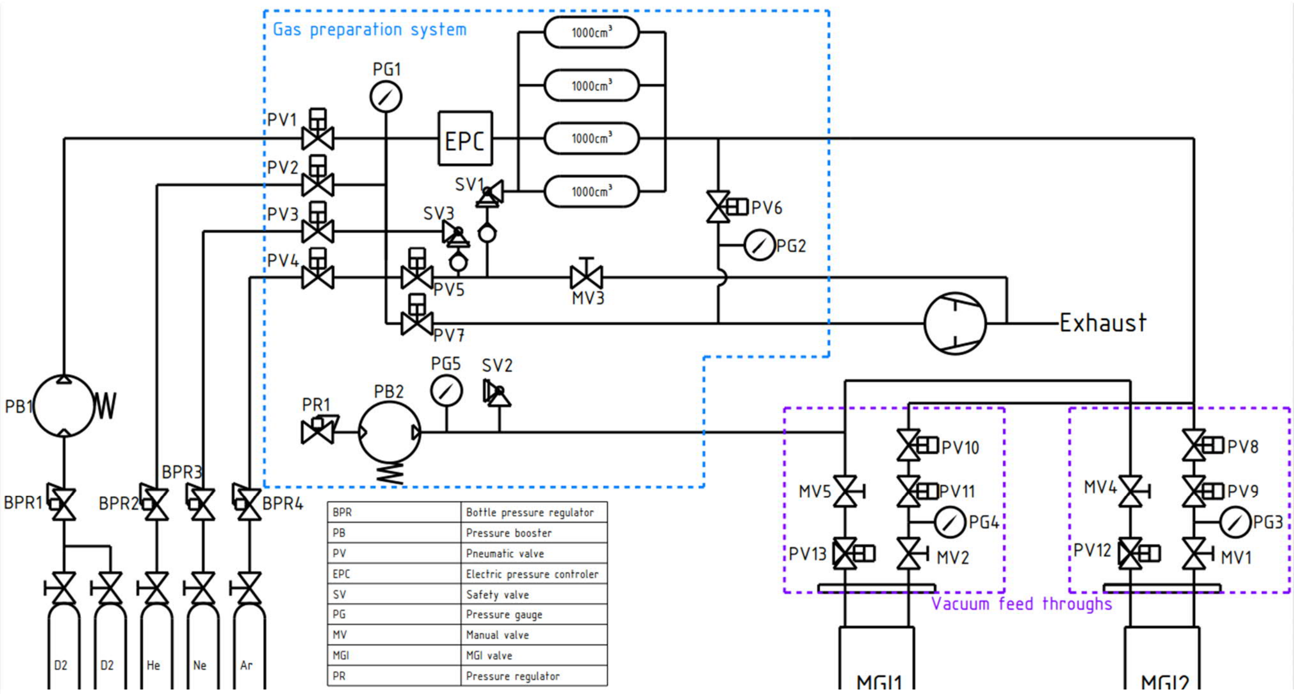

Figure 8: Gas flow schematic of the JT-60SA MGI system

precise time into the discharge. These electronic modules are mounted into the same cubicle as the main PLC, which is a Siemens S7-1500. This PLC monitors the signals form the modules, as well as position indicators and pressures from the vacuum feed throughs. Furthermore, it allows manual triggering of the MGI valves. The peripheral PLC on the back of the gas preparation panel is a Siemens ET200iSP. It is responsible for operating the pneumatic valves on the gas panel and the vacuum feed throughs, monitoring position indicators and pressures on the gas panel, as well as shutting off the compressed air supply to the pressure booster. The control computer in the control room serves as terminal for interacting with the system. It runs the interface from which the operating mode of the MGI system (manual, automatic experimental, automatic machine protection) is set, pneumatic valves are operated or mixing pressures are set. In the manual mode, mixing parameters can be set and the user can operate each valve. In the automatic experimental mode, the user enters the composition and pressure of the mitigation gas in the MGI valves and the system runs a chain of commands to fill the MGI valves with the desired mitigation gas automatically. The automatic machine protection mode mixes a predefined gas mixture and autonomously fills the MGI valve in preparation of the first plasma discharge of the day or after an MGI trigger. The MGI valves are emptied at a predefined time after the last plasma discharge.

VII. COMPONENT TESTS

The bellows in the MGI valves are considered critical components under the HPGL and require additional qualifications for the welds and pressure stability. The bellows in the mitigation gas reservoir are Witzenmann 24x36.5x6x0.25-19, which consist of six layers with a thickness of 0.25 mm and the bellows in the closing volume is a Witzenmann 42x60x2x0.3-10 with two layers, each with 0.3 mm thickness. All bellows are made from stainless steel X6CrNiMoTi17-12-2. The layers are welded in axial direction. These welds were investigated for defects using dye penetration tests at a certified testing facility.

Figure 9: Sample bellows prepared for the dye penetration test

Figure 9 shows the sample bellows with the testing dye on the welds. An original bellows for the mitigation gas volume on the far left, the pressure test sample of this bellows second from the left, an original bellows for the closing volume second from the right and the pressure test sample on the far right. The axial welds on all bellows, as well as the additional welds on the pressure test samples were checked. No defects were found. Both ends of the pressure test samples are closed with plates to keep the testing medium from entering the internal space. Tubes inside the bellows prevent axial compression during the pressure tests. The test samples are placed inside the cylindrical test chamber, which has an inner diameter of 63 mm, a height of 135 mm and a wall thickness of 36 mm. The test chamber is closed with six M16 screws and the chamber is filled with water until the air is completely removed from the chamber. The testing pressure is the applied using a manual pump. The setup is shown in figure 10.

Figure 10: Test setup for the bellows pressure test with manual pump and test chamber

The test pressures are derived from the system design pressure for mitigation gas and compressed air, as well as the tensile strengths of the material at room temperature and at 100 °C (Eq. 3)

$$p_{test} = 4 \cdot p_{design} \cdot \frac{\sigma_0}{\sigma_a} \quad (3)$$

With tensile strengths of σ_a = 130 MPa at room temperature and σ_0 = 129 MPa at 100 °C, the test pressures come up to 32.2 MPa and 8.06 MPa. These test pressures were applied to the corresponding samples for 11 minutes. No deformation could be found after removing the test samples form the chamber.

VIII. SUMMARY

The conceptual design of the JT-60SA MGI system is complete. The system consists of two in-vessel MGI valves behind the stabilizing plate, two vacuum feed throughs, a gas preparation system and the control system. The MGI valves can inject a maximum of 5868 Pam³ each. CFD and FEM simulations prove the necessary performance during disruptions. Design of the valves and component tests demonstrate the conformity to the Japanese HPGL. Vacuum feed throughs, the gas preparation system and the control system allow manual and automated operation to increase simplicity of use and reproducibility of experiments.

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