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Design and test of a module of a breathable Electrostatic Shield for the MITICA 1 MV negative ion Beam Source

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Abstract: The electrical insulation of the MITICA Beam Source at 1 MV is a challenging issue, which has not been fully addressed so far on the basis of experimental results and of theoretical models available in literature. Being MITICA the full-size prototype of the Heating Neutral Beam Injector for the ITER fusion experiment, its electrical insulation is constituted just by vacuum gaps and alumina insulators, since other insulating materials such as SF6 gas or fibreglass-reinforced plastic (FRP) would be quickly degraded by the expected neutron flux produced by fusion reaction. Extrapolations based on HV tests on reduced-scale models have recently indicated the risk of electrical breakdowns in the vacuum gap between electrodes nominally operating at −1 MV and the vacuum vessel (at ground potential). The risk of electrical breakdown can be mitigated by introducing an intermediate Electrostatic Shield (ES), which essentially is an equipotential (metallic) enclosure surrounding the HV electrode, so as to divide the vacuum gap in two independent insulating gaps of 400 kV and 600 kV respectively. However, for optimal negative ion production, the ion source shall operate in H_2 or D_2 at a pressure of ∼ 0.3 Pa and unavoidably produces a flow of gas leaking out in the surrounding vacuum. Thus, the presence of an intermediate shield can substantially increase the background gas pressure in the vacuum gaps, and, due to the large gap length (0.6 m), exacerbate the risk of breakdown when the pressure approaches the conditions of Paschen-type discharges. In addition to this, RF-induced breakdowns were found on the rear side of the ion source during the operation of the prototype source SPIDER, which were somewhat correlated to a relatively high hydrogen pressure in that area. For these reasons, a structure capable of constituting a full equipotential barrier all around the BS and, at the same time, having sufficient gas conductivity (breathability) to allow efficient pumping of background gas, has been designed. In the first part of the paper, the requirements and design optimization of a breathable module of the intermediate ES are described. Then, an experimental campaign for the validation of the electrode implementation the test configurations and the experimental procedure is discussed.

Keywords: Ion sources (positive ions, negative ions, electron cyclotron resonance (ECR), electron beam (EBIS)); Plasma generation (laser-produced, RF, x ray-produced)

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Contents

1 Introduction

MITICA is the prototype of the ITER Heating Neutral Beam Injector (NBI) system, presently under construction in Padova [1], in the framework of a collaboration between the ITER International Organization (Cadarache France), the Japan Domestic Agency of ITER (JADA) and Consorzio RFX. The ITER Heating Neutral Beam Injectors (NBIs) [2] are designed to generate a bundle of 1280 H− or D− negative ion beamlets, which are accelerated in a multi-stage electrostatic accelerator up to an energy of 1 MeV. After passing through a gas neutralizer, the particles will constitute a single well-focused neutral beam of about 16.6 MW power, precisely directed towards the plasma in the ITER Tokamak.

The electrical insulation of the large negative ion Beam Source at 1 MV DC is one of the challenging issues of MITICA. A collaborative effort between QST and Consorzio RFX is presently under way for assessing and optimizing vacuum insulation with stainless steel electrodes [3].

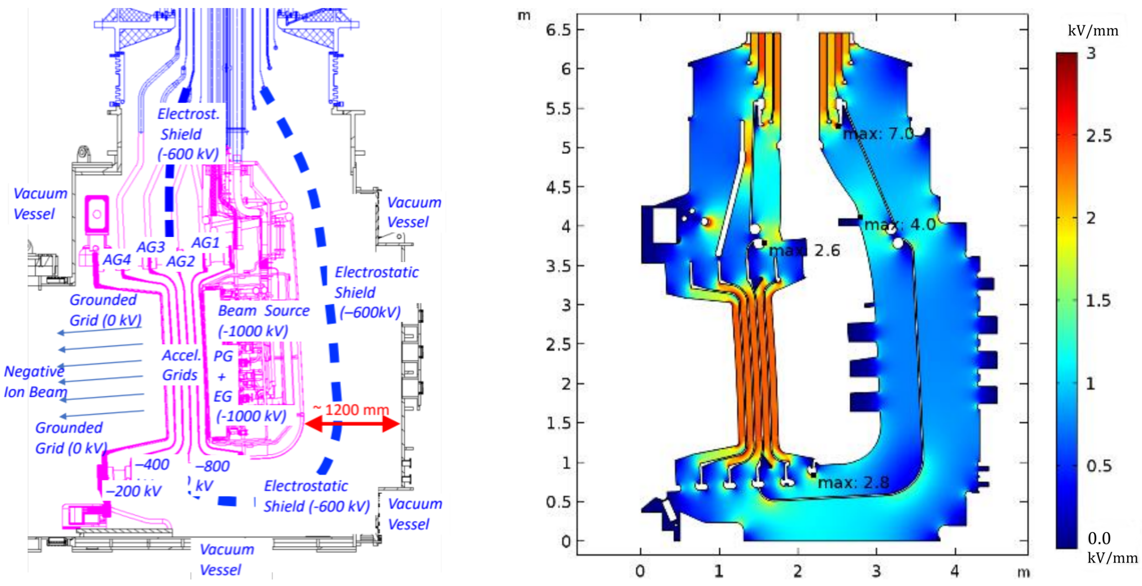
According to extrapolation models based on recent reduced-scale experiments, the DC voltage holding capability of the single-gap vacuum insulation between the Beam Source (electrode at −1 MV) and the Vessel (at ground potential) appears to be critical [4]. However, the same models also show that intermediate electrodes separating the single-gap insulation into 2 (or more) independent gaps, subjected to a fraction of the total voltage, can substantially improve the DC voltage holding capability of the Beam Source insulation [5].

A HV test campaign is already planned using full-scale mock-up electrodes, reproducing in detail the geometry of the Beam Source and Accelerator, with the purpose of optimizing and validating the vacuum insulation under realistic operating conditions. During this campaign, the possibility of introducing an intermediate a metallic structure, called Electrostatic Shields (ES) surrounding the Beam Source (BS) is foreseen, so as to improve voltage holding by dividing the 1 MV vacuum gap in two independent insulating gaps of 400 kV and 600 kV respectively [6]. The shape of the proposed ES, indicated by the dashed line in figure 1(a), closely follows the equipotential surface nominally at −600 kV; figure 1(b) shows the corresponding map of electric field strength, when the BS is kept at −1 MV, the ES is kept at −600 kV and the vessel is grounded. As explained in section 2.1, the shape of the ES is slightly modified with respect to the “pre-existing” equipotential surface, because it has been optimized to produce also a beneficial reduction of the electric field on the surface of the internal electrode (the BS).

However, the introduction of an intermediate ES entails an additional problem. The plasma chamber, where negative ions are produced, is located inside the BS and must be kept at a pressure of ∼ 0.3 Pa by injecting a H_2 or D_2 gas flow, for efficient production of negative ions. On the other hand, the background gas pressure in the vacuum surrounding the BS shall not exceed ∼ 0.04 Pa, to avoid excessive stripping losses in the beamline [7] and also Paschen-type RF-induced discharges, as verified during the recent operation of the prototype source SPIDER [8, 9].

Since the plasma chamber in the BS cannot be vacuum-tight due to the apertures in the grids (where the negative ion beamlets are extracted) and also to other auxiliary fissures, a “leakage” flow of neutral gas is unavoidable and an effective vacuum pumping is necessary in the vessel.

Obviously, an Electrostatic Shield can obstruct such flow, producing a region of relatively high pressure surrounding the rear side of the BS. In order to maintain the background gas pressure below the ∼ 0.04 Pa all around the beam source, the intermediate ES must provide sufficient gas conductance (“breathability”) so as to facilitate the gas flow even at the sides and on the rear side of the beam source.



(a) (b)

Figure 1. (a): vertical section of the MITICA experiment, showing: Vacuum Vessel, negative ion Beam Source with Plasma Grid (PG) and Extraction Grid (EG) (at −1000 kV) and the 5-stage Accelerator Grids (AG1-AG4 and Grounded Grid); the foreseen position of the intermediate Electrostatic Shield (at −600 kV) is indicated by a blue dashed line which surrounds the Beam Source; the typical gap length between the BS and the Vessel is ∼ 1200 mm; (b): vertical section of the MITICA experiment, showing the map of the electric field strength in the presence of an intermediate electrostatic shield at −600 kV. The local electric field concentration can also be slightly reduced by proper shaping of the intermediate Electrostatic Shield.

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In order to improve the voltage holding capability and, at the same time, guarantee sufficient gas conductance, an ES having a modular structure with double-walls and staggered apertures has been conceived. The paper presents the criteria adopted for the design of a prototype ES module, with double-walls and optimized geometry of the apertures (diameter and pitch of the apertures, distance between walls and shape of the aperture edge) for maximum gas conductance.

The results of voltage holding tests performed using the "breathable" ES module as intermediate electrode will also be presented and compared to those obtained in comparable reference configurations, with a flat intermediate electrode (no apertures).

2 Concept of breathable shield

2.1 Beneficial effect of Intermediate Electrostatic Shield on voltage holding in vacuum

In general, when the distance L between electrodes (gap length) is larger than a few cm, the breakdown voltage V between two electrodes in vacuum typically increases as $V \propto L^{1/2}$ (see figure 2 and [10]). The sustainable electric field $E = V/L$ is thus larger for shorter gaps and the total sustainable voltage V between two electrodes can be considerably increased if the gap length is subdivided in 2 gaps (or stages) using an intermediate "electrostatic shield".

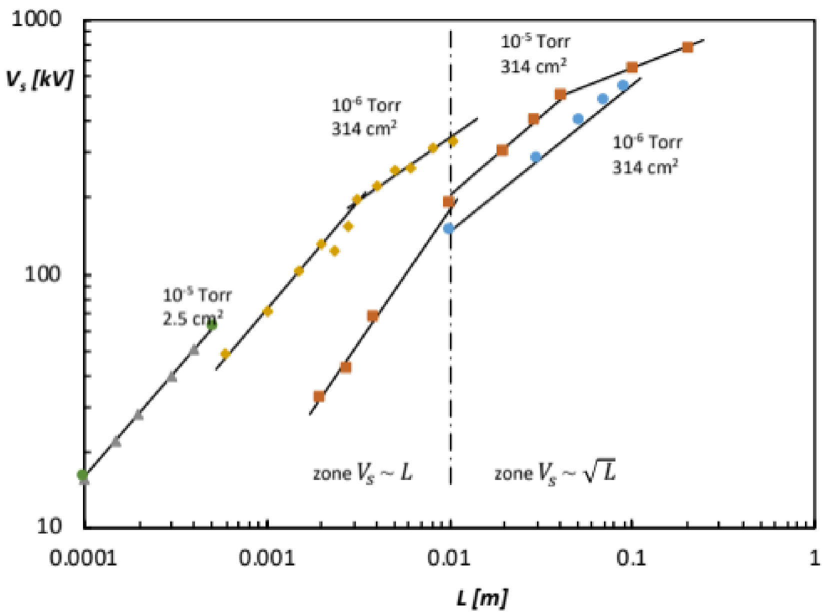

Figure 2. Breakdown voltage V between two stainless steel electrodes in vacuum, as a function of electrode distance L. Reproduced from [10]. CC BY 3.0.

Essentially, for a given vacuum gap between two electrodes, the beneficial effect of introducing an intermediate electrostatic shield is related to the avoidance of the self-sustaining cascade effect caused by secondary charged particles emitted by one electrode, struck by particles previously emitted by the other electrode and accelerated along the gap up to the total applied voltage. On this basis, we deduce that an intermediate conductive shield can increase the voltage holding capability between two electrodes, only as long as the shield constitutes a full electrically-conductive barrier, i.e. all trajectories of accelerated particles between the electrodes are intercepted (no "shine-through" effect through the shield).

On the same basis, the most effective choice for positioning the intermediate shield is to divide the original vacuum gap (L) in two gaps ($L/2$), each having half of the total voltage.

In the case of MITICA, due to the 5-stage structure, the gap between the BS (at −1000 kV) and the vessel (at ground potential) will be subdivided by introducing an intermediate electrostatic shield at −600 kV, so as to constitute an "internal" gap of 400 kV and an "external" gap of 600 kV (see figure 1 and [12]). The intermediate electrostatic shield will be shaped following approximately the "pre-existing" equipotential surface at −600 kV. This choice has 2 advantages: (1) the shield is smaller and less heavy, (2) small modifications can be introduced on the "pre-existing" −600 kV equipotential surface, to allow for a reduction of the electric field on the surface of the internal electrode (the BS), which indeed is where the local electric field is maximum.

2.2 Obstructive effect of Intermediate Electrostatic Shield and requirement on gas conductance

In the RF-driven plasma source of MITICA, the plasma chamber is required to operate with an internal neutral gas pressure of about 0.3 Pa, so as to guarantee an acceptable efficiency in the generation of negative ions. However, the plasma source chamber cannot be vacuum-tight with respect to the surrounding volume, mainly due to the 1280 apertures of the plasma grids (where the negative ion beamlets are extracted) and also due to other auxiliary fissures.

For this reason, the vacuum volume surrounding the plasma chamber and the BS must be pumped, to avoid RF-induced discharges taking place if the residual gas pressure exceeds 0.04 Pa around the rear side of the BS. In steady-state conditions, a continuous gas injection of about 5.1 Pa m^3/s (H_2) or 3.6 Pa m^3/s (D_2) at room temperature will be required for this reason. According to detailed gas flow simulations [13], most of the injected H_2 or D_2 gas will leak out of the plasma source through the Plasma Grid (PG) and Extraction Grid (EG) apertures and more than a half of this flux will exit (laterally and vertically) through the first acceleration gaps (between EG and AG1 and between AG1 and AG2, see figure 1).

On the other hand, in order to fully separate the BS (at −1000 kV) from the (grounded) vacuum vessel, the intermediate electrostatic shield at −600 kV shall necessarily enclose the BS as well as the first two accelerator grids (AG1 and AG2, at −800 and −600 kV respectively).

As a consequence, the intermediate ES shall allow the neutral gas to pass through without causing a dangerous pressure increase around the BS. Considering the neutral gas flow above mentioned, the MITICA intermediate ES shall guarantee an overall gas conductance of the order of some 100 m^3/s for an efficient gas pumping.

2.3 Design of "breathable" Electrostatic Shield and expected effects

Obviously, a number of physical apertures having sufficient area are necessary to achieve a given gas conductance across a metallic shield. However, an intermediate shield consisting of a single metallic layer with apertures would be ineffective for improving the voltage holding capability of a vacuum gap, since charged particles could be directly accelerated between the main electrodes through the apertures, without being intercepted by the shield ("shine-through" effect).

To overcome this situation, a "breathable" ES constituted by flat double-walled panels with staggered apertures has been proposed, so as to obtain a shield with apertures having sufficient gas conductance, and, at the same time, capable of intercepting all accelerated particles and preventing the propagation of breakdown channels from one gap to the other.

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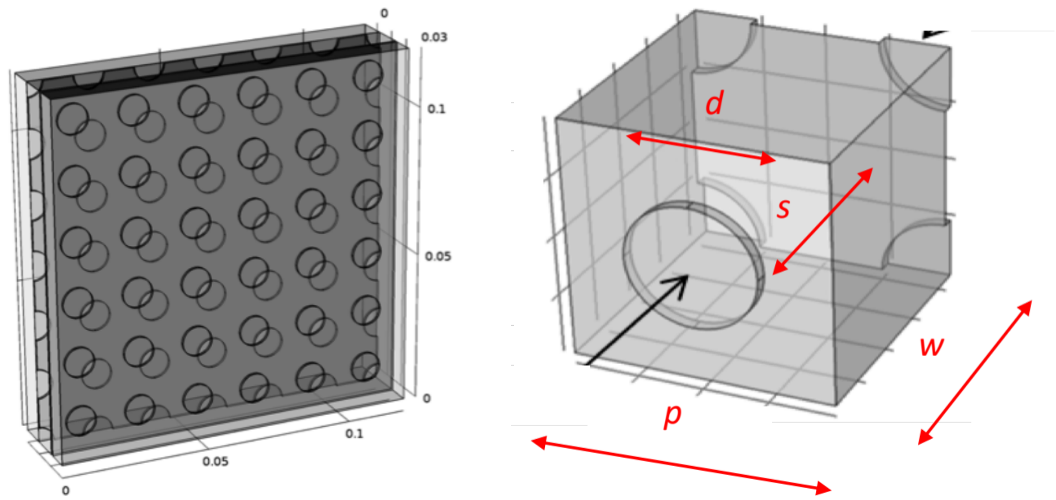
A modular structure of the shield, constituted by a sandwich of two metallic sheets with staggered apertures has been developed and optimized. To this purpose, the structure of the intermediate shield has been described by the following main four geometrical parameters (see figure 3 and figure 6):

- p = pitch between apertures
- d = diameter of apertures
- s = distance between walls (internal, considering the depth of bevel)
- w = thickness of the double wall (external)
- b = depth of the aperture bevel
- t = thickness of the metal sheet constituting a single wall

The shape of the aperture edge is described by the depth of the aperture bevel b, which is assumed to be equal to the rounding radius of the aperture bevel. Therefore the (external) thickness of the double wall w results to be related to the (internal) distance between walls s, to the bevel depth b and to the thickness of the metal sheet constituting a single wall t by the relationship $w = s + 2b + 2t$ (see also figure 6).



(a) (b)

Figure 3. (a) Sketch showing the concept of "breathable" Intermediate Electrostatic Shield with double-wall and staggered apertures, and (b) geometrical parameters of a "breathable" shield Module, with double walls and staggered apertures, as considered in the optimization of gas conductance.

The impact of the main geometrical parameters on the performances of the breathable shield can be described by evaluating the gas conductance per unit surface $\tilde{C}$ at room temperature (specific gas conductance). The behaviour of the gas conductance can be summarized as follows:

- gas conductance strongly decreases when the walls are very close to each other (normalised thickness s/d is small). As shown in figure 4 (left), this occurs if the s/d of the double wall is smaller than 0.5. The limiting case is of course zero conductance at zero distance ($s/d = 0$).

- gas conductance decreases quadratically with the pitch-to-diameter ratio p/d (i.e. with the "opacity" of the walls expressed by the area of the apertures divided by the area of the wall). In particular, in figure 4 (right) we can note that the distance between walls does not influence the normalized

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gas conductance, as long as the distance between apertures s is larger than half the aperture diameter. The limit case of a single wall with circular apertures is also shown by a dashed line. As a note, a specific gas conductance $\tilde{C} = 40$ m/s corresponds to a transmission probability $F \approx 9.1\%$.

The local electric field intensification at the edges of bevelled apertures decreases by increasing the radius and the depth of the aperture bevel. Figure 5 (left) presents the case of the aperture bevel depth $b = 2$ mm, assumed to be equal to the rounding radius of the aperture bevel: the field intensification at the electrode surface results to be less than 20%.

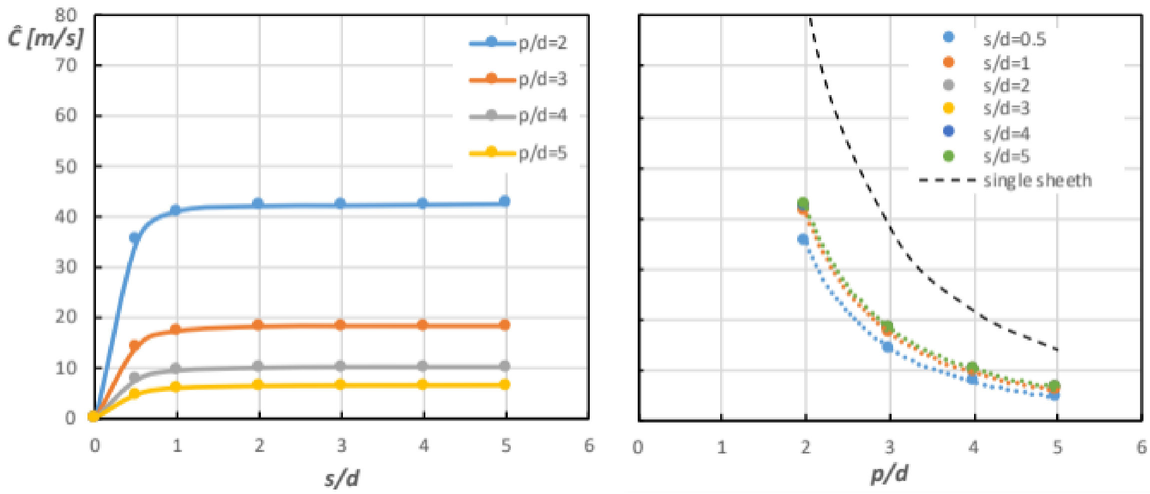

Figure 4. Value of specific gas conductance $\tilde{C}$ as a function of adimensional geometrical parameters s/d (left) and as a function of p/d (right).

The shape of the equipotential lines and surfaces at the bevelled aperture is concave, as shown in figure 5 (left). For this reason, charged particles emitted by one electrode can be deflected while entering an aperture on the first wall of the ES and, in principle, can exit through an aperture on the second wall, without being intercepted (shine-through effect).

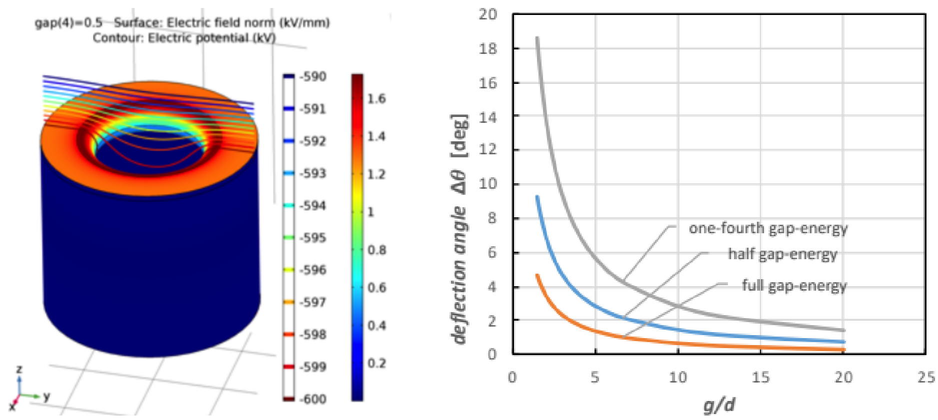

Figure 5. (Left) Equipotential lines and electric field at the edge of shield apertures, the local increase of electric field strength is about 20%; (right) estimated deflection angle of energetic particles $\Delta\theta$ due to electrostatic lens effect in the vicinity of the double wall aperture, as a function of the ratio of gap length g to the aperture diameter d and of the particle energy (g is the gap length between the aperture and the surface where particles are emitted from).

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In order to evaluate this possibility, we consider a charged particle approaching an aperture of the intermediate ES and we estimate the deflection of its trajectory using the classical thin-lens approximation by Davisson and Calbick [11]. We assume that a circular aperture in the breathable wall is equivalent to a thin lens having a focal length $f = 4V_s/(E_2 - E_1)$. In this case, V_s is the voltage between the ES and the electrode, the electric field E_2 inside the double wall is zero, whereas the electric field on the outer side is $E_1 \approx V_s/g$, with g being the gap length between the breathable wall and the source or vessel surfaces. Considering the diameter d of the shield apertures, a charged particle crossing the first wall of the ES is thus deflected by an angle $\Delta\theta = \tan(0.5d/f)$, which is typically small and can be approximated as $\Delta\theta \approx 0.5d/f$; this implies $\Delta\theta \approx -1/8 \cdot d/g$. Therefore, within reasonable ranges of gap size and aperture diameter ($g/d > 5$), particles generated at the beam source surface or at the vessel surface, when approaching an aperture of the ES, (with a non-negligible fraction of the energy of the considered gap) will be subjected to a maximum deflection angle $\Delta\theta \leq 5\,\text{deg}$, as shown in figure 5 (right).

In figure 6, the geometry of the bevelled apertures is shown for the evaluation of the range of incidence angle θ of particles which could not be intercepted by the shield and thus can produce a shine-through effect. The minimum deflection angle for the shine-through is $\theta_{\text{max}} = \text{atan}\left(\frac{\sqrt{2}p/2-d}{s}\right)$ and the maximun is $\theta_{\text{max}} = \text{atan}\left(\frac{\sqrt{2}p/2+d}{s}\right)$.

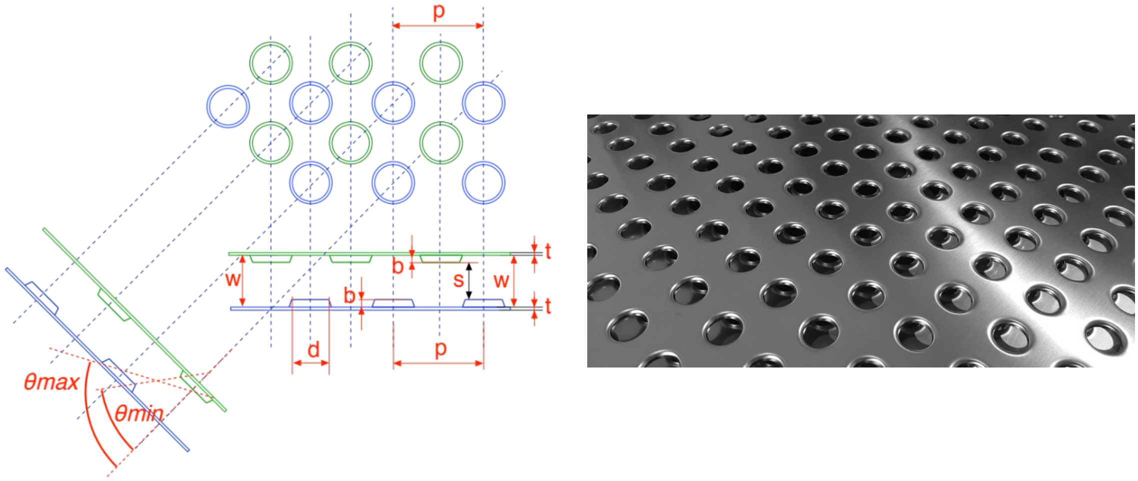

Figure 6. (Left) Evaluation of incidence angle θ of non-intercepted particle trajectories, the first wall is depicted in light green and second wall is blue, b is the depth of the bevel at the aperture edge and t is the thickness of the metal sheet constituting a single wall; (right) picture of a double-walled shield with staggered apertures: all aperture edges are bevelled, and the apertures of the second wall are partially visible through the apertures of the first wall.

2.4 Design Optimization results

The geometry of the shield module has been optimized according to the following logical sequence:

- choose a range of thickness of the metal sheet (AISI304, $t = 0.4$–1 mm, based on manufacturability and weight requirements)
- choose a range of bevel depth ($b = 1$–3 mm, based cold metal forming requirements)

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- choose a range of (external) thickness of the double wall (w = 10–30 mm, small enough with respect to the original vacuum gap and large enough to guarantee mechanical stiffness to the structure of the intermediate shield).

The shield geometry has then been optimized for maximum gas conductance using three main design variables: d = diameter of apertures, p = pitch between apertures, s = distance between apertures = $w - 2b - 2t$. Thus, all the effects described in the previous section as well as mechanical constraints related to manufacturing, assembly and weight have been taken into account, resulting in the following geometrical parameters:

- p = pitch between apertures = 30 mm
- d = diameter of apertures = 15 mm
- s = distance between walls (internal, considering depth of bevel) = 13 mm
- w = distance between walls (external) = 20 mm

The corresponding estimated performances are the following:

- specific gas conductance: $\tilde{C}_{H2} \approx 42$ (m/s) and $\tilde{C}_{D2} = 30$ (m/s) for Hydrogen and for Deuterium respectively;
- electric field intensification at the edges: less than 20% (estimated effect on overall voltage holding is negligible);
- range of incidence angle of particles causing shine-through effect: particles having a total incidence angle between $\theta_{max} \approx 27$ deg. and $\theta_{max} \approx 70$ deg. cannot be intercepted by the shield.

Considering that the particle trajectories can be deflected by an additional 5 deg due to the concave electric field configuration in the apertures, we conclude that only particles having an original incidence angle larger than ∼ 22 deg cannot be intercepted by the intermediate shield.

Since the total surface where the breathable flat double-walled panels can be positioned on the Intermediate Electrostatic Shield of MITICA is about 10 m^2, the equivalent conductance of the breathable shield is about 300 m^3/s for D_2 and 400 m^3/s for H_2.

2.5 Estimated pressure increase in the rear part of the BS

In MITICA, considering an injected gas flow of about 5.1 Pa m^3/s (H_2) or 3.6 Pa m^3/s (D_2), and the lumped equivalent conductance of about 300 or 400 m^3/s, the expected pressure increase in the Intermediate Electrostatic Shield results to be about 0.012 Pa, which seems well compatible with the pressure limit of 0.04 Pa, necessary to avoid RF-induced discharges between the beam source and the vacuum vessel.

The proposed screen was also included in 3D gas flow simulations of the MITICA vessel, as a screen of transparency equivalent to that of the *breathable* screen described previously. Gas flow from the accelerator gaps amounting to 5.08 Pa m^3/s (H_2), and gas flow from the rear side of the source of 0.4 Pa m^3/s (H_2), were included in the model. It is found that the presence of the breathable ES produces a negligible increase of the pressure around the BS, thanks to the distributed gas conductance it offers (see figure 7.

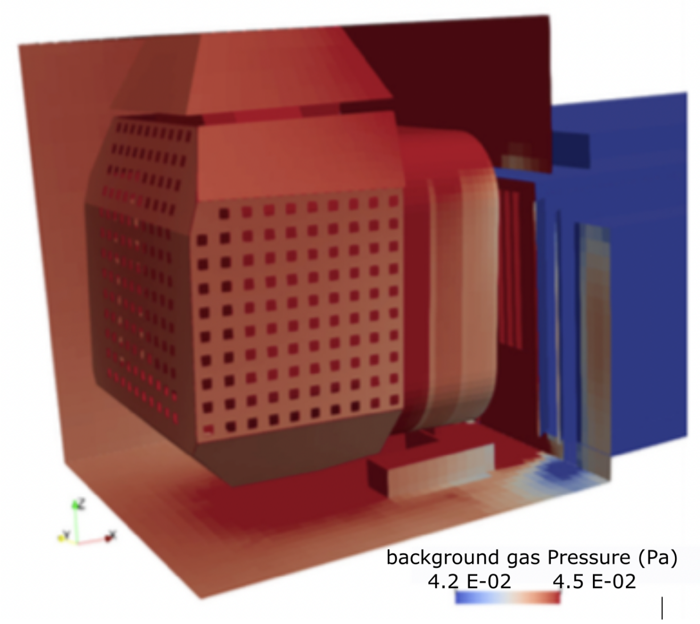

Figure 7. Background gas pressure distribution estimated using a 3D gas-flow model of the MITICA vessel and BS with "breathable" electrostatic shield. Thanks to the optimized shield design, the variation of the gas pressure inside the shield is negligible.

3 Experimental tests

3.1 tests on small prototype shield module

A campaign of HV tests on prototype "breathable" shield modules is presently in progress in HVPTF (High Voltage Padova Test Facilty) for evaluating the effectiveness of the breathable shields. The tests are designed with the objective of comparing double-wall shields vs. single-wall shields vs. flat shields both in single and in double polarity and are carried out using a dual power supply, in such a way that positive potential is applied to one electrode, a negative potential is applied to the other one, and the vacuum vessel is kept at ground potential.

The first series of tests on a set of small-size prototype shields having a diameter of about 18 cm, (see figure 8) has already been completed. The shield is kept at the same potential as one of the electrodes (cathode), with a 250 mm vacuum gap between the cathode and the anode. These tests have been considered the most critical, as their main purpose was to assess whether or not presence of the apertures, which cause a localized electric field intensification of about 20% on the electrode surface (figure 5), can reduce the voltage holding capability. The results, shown in figure 9, clearly indicate that the breakdown voltage probability distribution between electrodes does not change very much with respect to the case of a flat electrode having the same size and no aperture Actually, the breakdown voltage in the presence of apertures appears to be slightly higher, possibly due to the slightly reduced area and to improved vacuum conditioning of the electrode with apertures.

Therefore, these tests confirmed that what was considered the most critical issue of the breathable intermediate ES, which was the local increase of electric field at the edge of the shield apertures was actually solved by suitable bevelling of the edge apertures.

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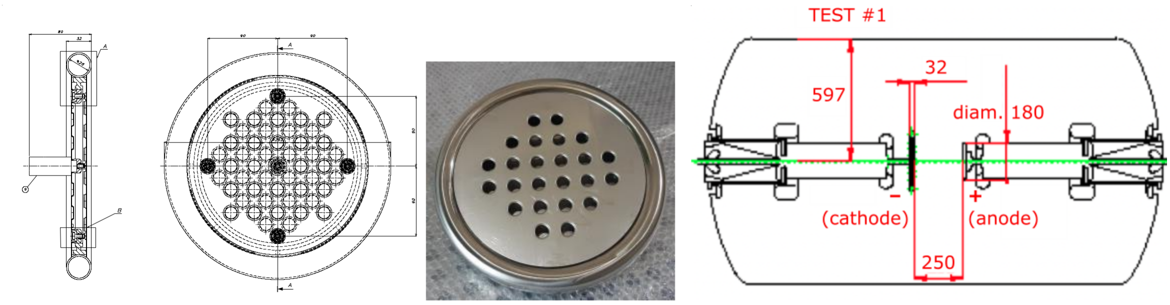

Figure 8. Geometry of tests on small-size electrodes (test #1, #3 and #5): double-walled electrode with staggered apertures (cathode) can be compared to double-walled flat electrode (with no apertures) and to single-wall flat electrode.

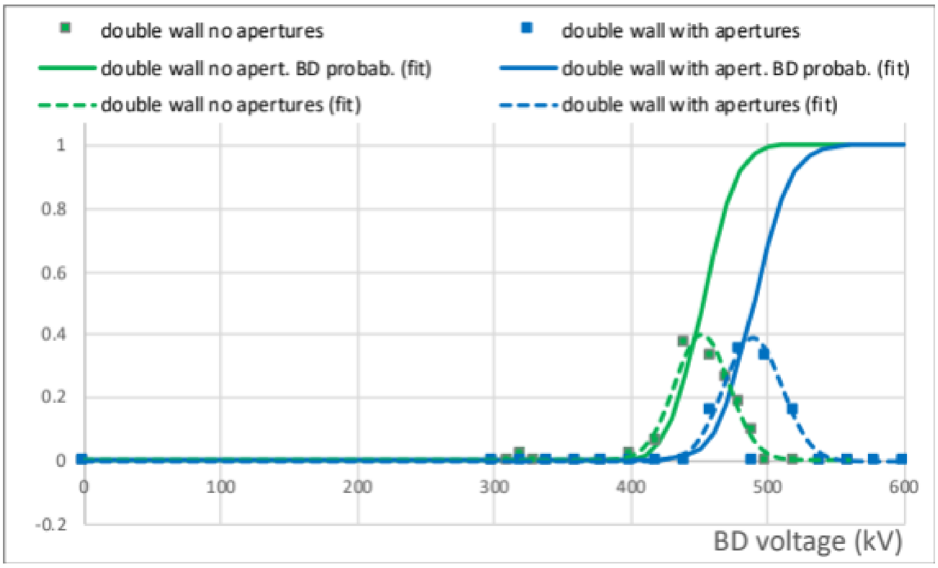

Figure 9. Results of tests on small electrodes: comparison of breakdown probability distributions of double-wall electrode with staggered apertures (blue) vs. double-wall flat electrode having no apertures (green). The corresponding gaussian curves fitting the experimental points are also shown.

3.2 tests on large prototype shield module

A second campaign of HV tests has been planned for experimentally evaluating the actual increase of the total voltage holding capability in a large gap, using a large prototype "breathable" shield module (see figure 10 and figure 11). Similarly to the previous campaign, also these tests will use a dual power supply but, in this case, the intermediate shield is kept at ground potential. The objective of the tests is to compare the case of intermediate shield with double-wall vs. single-wall shields vs. flat shield.

Unfortunately, due to the failure of one of the HV feedthrough of the HVPTF vacuum vessel and the necessary repair work, it will be possible to carry out these tests only during the next months. However, in spite of this situation, thanks to the fully positive results of the test on the small prototype shield module described in the previous paragraph, we can consider that the behaviour of the double-walled shield is really equivalent to that of an ideal flat metallic shield which fully separates the original gap in two independent gaps. Therefore, there are already valid reasons for applying the already consolidated

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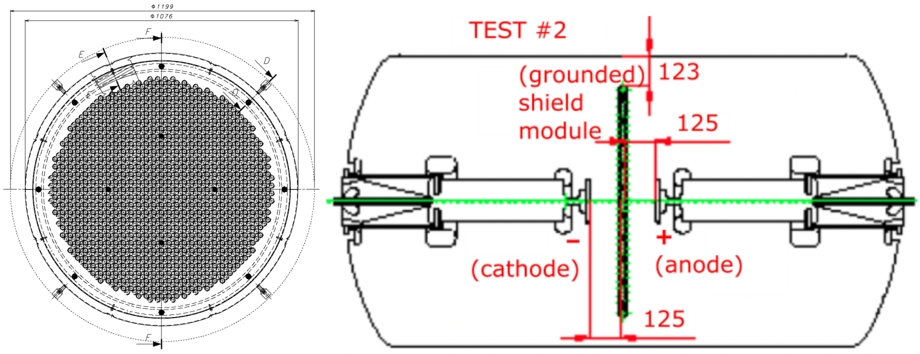

Figure 10. Geometry of tests on large prototype shield modules (test #2, #4 and #6): a (grounded) shield module is inserted between anode and cathode; double-walled shield module with staggered apertures can be compared to double-walled flat shield module (no apertures) and to single-wall flat electrode.

Figure 11. Picture of test #2 electrode: large double-walled shield module with staggered apertures; the apertures on the rear wall are partially visible through the apertures in the front wall.

criteria obtained for flat electrodes [14, 15] and [16], separately on each of the two gaps. This obviously implies that the introduction of the (breathable) intermediate shield is capable to guarantee the substantial improvement of the total voltage holding of the MITICA Beam Source vacuum insulation.

4 Conclusions

The concept of a "breathable" intermediate electrostatic shield module has been developed to achieve a substantial improvement of voltage holding on a long gap between two electrodes in vacuum, without introducing an unacceptable pressure increase in the vacuum around the BS.

The design of the intermediate shield has been optimized on the basis of detailed numerical simulations concerning 3 aspects: (1) the electrostatic field configuration in relation to the unavoidable increase of the electric field on the surface of the apertures on the intermediate shield, (2) the gas

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flow phenomena in relation to the obstruction to the gas flow leaking out of the Beam Source, and (3) the possible "shine through" effect of charged particles across the double-walled shield, which could anyway allow the onset of a breakdown channel between the main electrodes.

These analyses have been complemented by a comprehensive plan of HV experimental tests, so as to provide a complete validation of the design. The tests have demonstrated the most critical issue of the breathable intermediate ES, which was the local increase of electric field at the edge of the shield apertures was in fact solved and the behaviour of the double-walled shield is really equivalent to that of an ideal flat metallic shield which fully separates the original gap in two independent gaps. As explained, the second series of tests has not been completed yet for accidental reasons and will be anyway completed as soon as possible. Therefore, based on the already verified results obtained for flat electrodes and gaps of the same length, the breathable intermediate shield can be considered capable of a clear improvement of the total voltage holding of the MITICA Beam Source vacuum insulation.

Acknowledgments

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