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

UNIVERSITÀ DEGLI STUDI DI PADOVA

CONSORZIO RFX Ricerca Formazione Innovazione

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1- Background:

MITICA is the prototype of the Heating Neutral Beam Injector for ITER [1], [2]. The vacuum insulation of the Negative Ion Beam Source and Accelerator at 1 MV is still considered a challenging issues.

Extrapolation of recent experiments to the present design indicates that voltage holding capability of the single-gap vacuum insulation between the Ion Source (at -1 MV) and the Vessel (at ground potential) might be critical [3].

A collaborative effort between QST and Consorzio RFX is presently under way for the realization and optimization of this insulation.

An Intermediate Electrostatic Shield, separating the 1 MV vacuum gap in two independent gaps of 400 kV and 600 kV, is presently under consideration as a risk-mitigation measure [4].

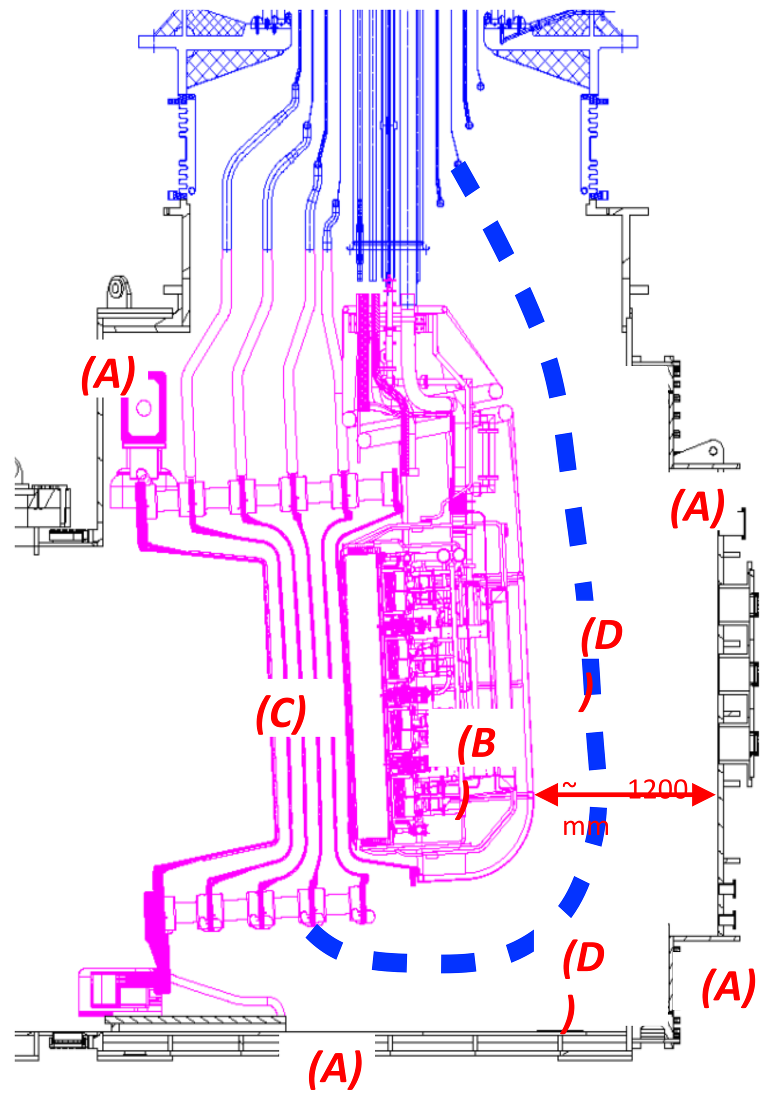
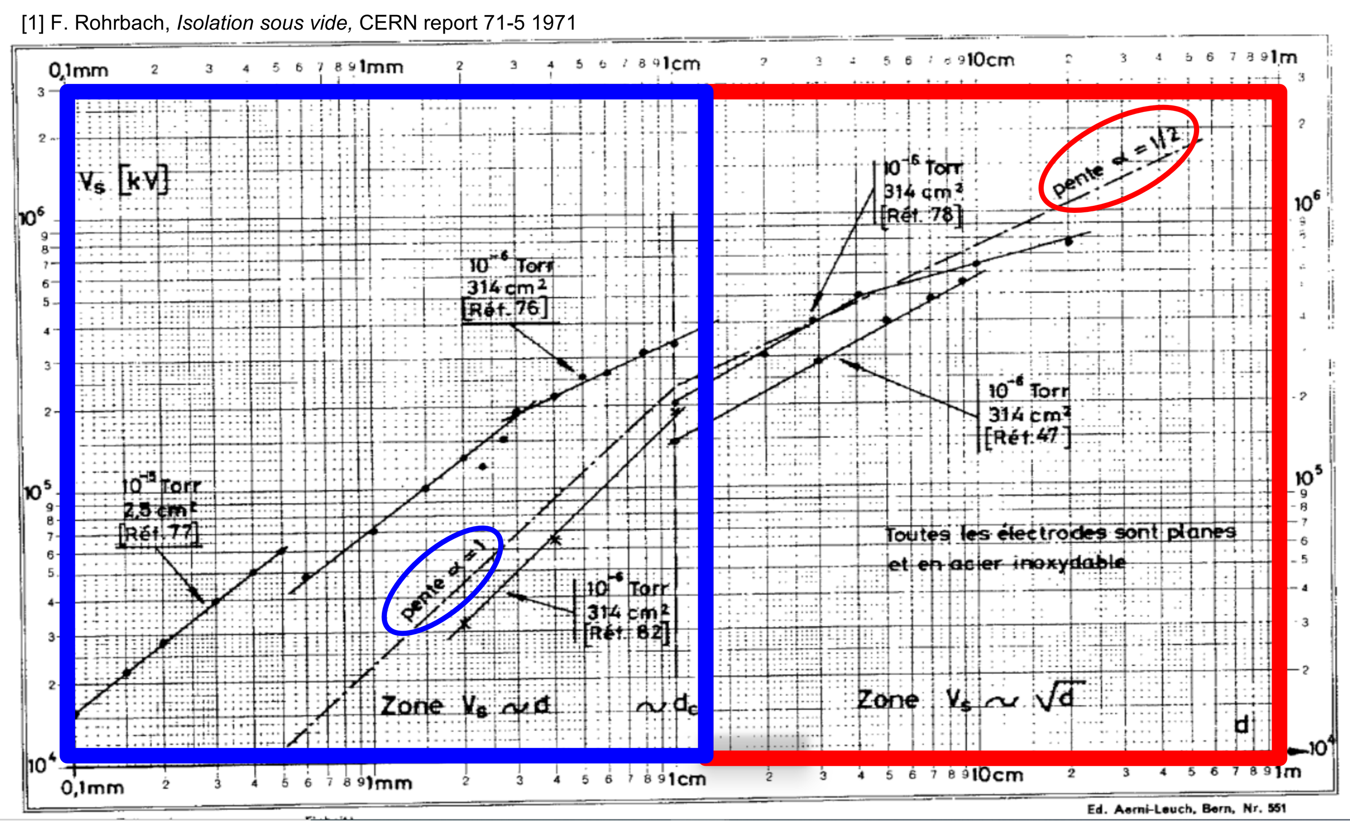


Fig. 1: vertical section of the MITICA experiment, showing: Vacuum Vessel (A), Ion Beam Source (B) and Accelerator (C); the foreseen position of the Intermediate Electrostatic Shield is also indicated by a dashed line (D).

2- Beneficial effect of Intermediate Electrostatic Shield: the breakdown voltage V between two electrodes in vacuum typically increases as $V \propto d^{1/2}$, when the distance d between electrodes (gap length) is increased above a few cm (see fig. 2).

The sustainable electric field $E=V/d$ is larger for shorter gaps and therefore, the total sustainable voltage V between two electrodes can be considerably increased if a gap is subdivided in 2 stages using an "intermediate electrostatic shield".

The intermediate shield in vacuum can improve considerably the overall voltage holding capability, as long as it can intercept the undesired particles accelerated and thus prevent the propagation of breakdown channels from one gap to the other (shine-through effect).



Microprotrusions: electric field driven **Clumps: electric field and voltage driven**

Fig. 2: breakdown voltage V between two electrodes in vacuum as a function of electrode distance

3- Obstructive effect of an Intermediate Electrostatic Shield and requirement on gas conductance:

in order to efficiently generate negative ions, the MITICA ion source shall operate with an internal H_2 or D_2 gas pressure of ~ 0.3 Pa. Obviously, to allow the extraction of the beam through the plasma grid, the ion source cannot be vacuum-tight with respect to the surrounding volume.

On the other hand, the residual pressure in the surrounding vacuum volume shall not exceed about 0.04 Pa, to avoid Paschen-type discharges between the source (nominally at -1 MV) and the vacuum vessel (at ground potential).

In practice, the intermediate electrostatic shield for MITICA shall guarantee an overall gas conductance of the order of some 100 m^3/s for an efficient gas pumping. However, a single metallic layer with apertures (like a Faraday cage) is considered ineffective due to shine-through effect.

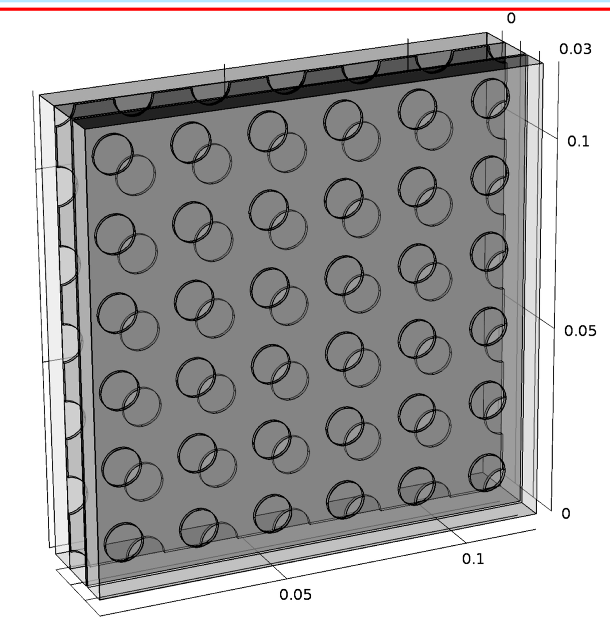


Fig. 3: sketch showing the concept of "breathable" Intermediate Electrostatic Shield with apertures:, with double walls and staggered apertures

4- Concept of "breathable" Electrostatic Shield:

A metallic shield having **modular structure,** with **double-walls** and **staggered apertures** has been proposed. The structure of the shield can be fully described by the following geometrical parameters (fig. 4):

p = pitch between apertures
d = diameter of apertures
w = distance between walls
s = distance between apertures (considering the depth of bevel)

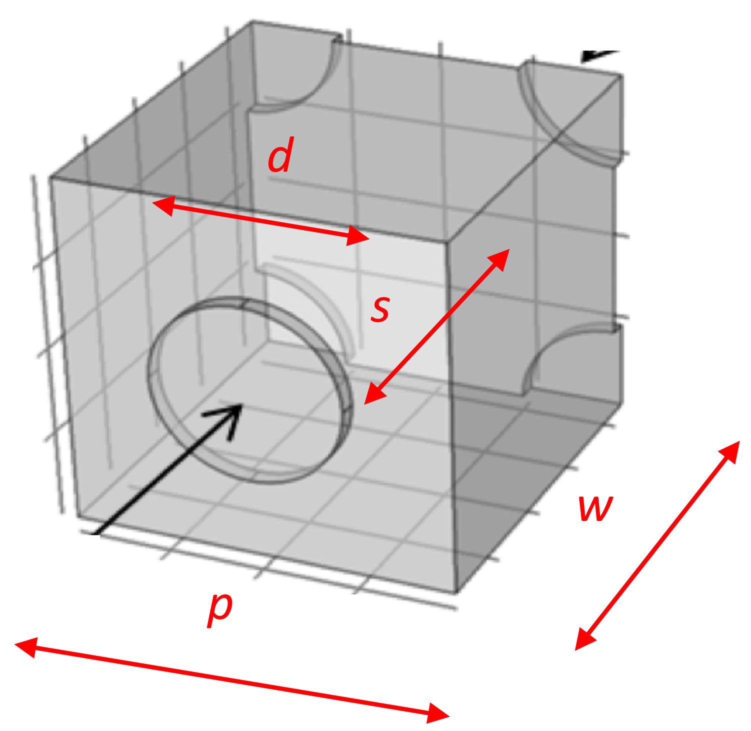


Fig. 4: geometrical parameters of a "breathable" shield Module, with double walls and staggered apertures, as considered in the optimization of gas conductance

Fig. 5: example of bevelled aperture edges, considered for the reduction of the local electric field concentration at the aperture edges

5- evaluation of the effects of the geometrical parameters of the shield module

The Impact of the geometrical parameters can be summarized as follows:

- **gas conductance per unit surface** (specific gas conductance) strongly decreases when "opacity" of the walls increases (p/d >>1) and when the walls are very close to each other (s/d < 1)
- **shine-through probability** (range of incidence angle of particles causing shine-through effect) increases with s/d and decrease with p/d
- Local **electric field intensification at the edges** of the apertures decreases by increasing the bevel depth of the aperture

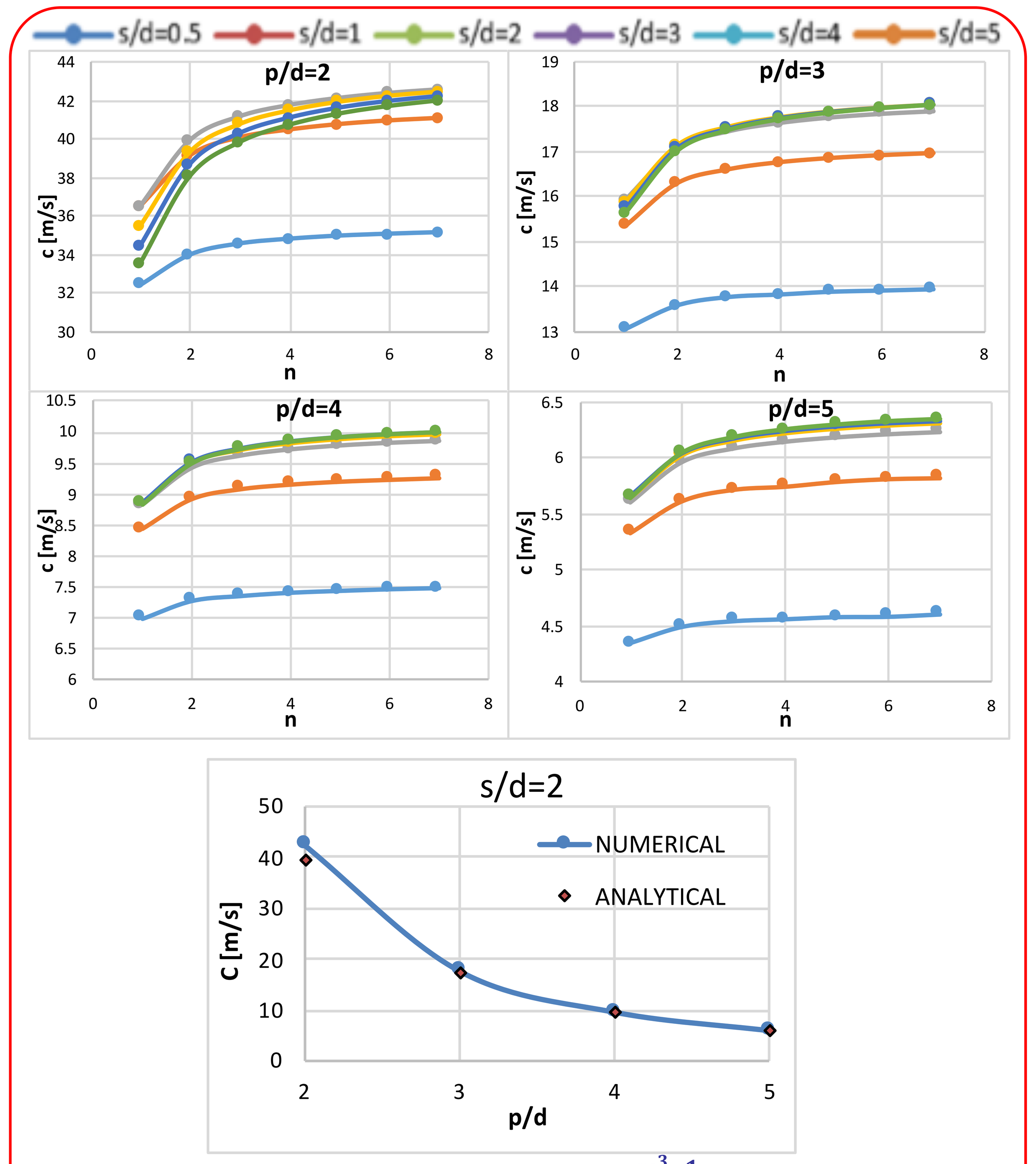


*Fig. 6: value of specific gas conductance ($\frac{m^3}{s}\frac{1}{m^2}=\frac{m}{s}$) as a function of number of modules (n) and of geometrical parameters **p, d, w, s***

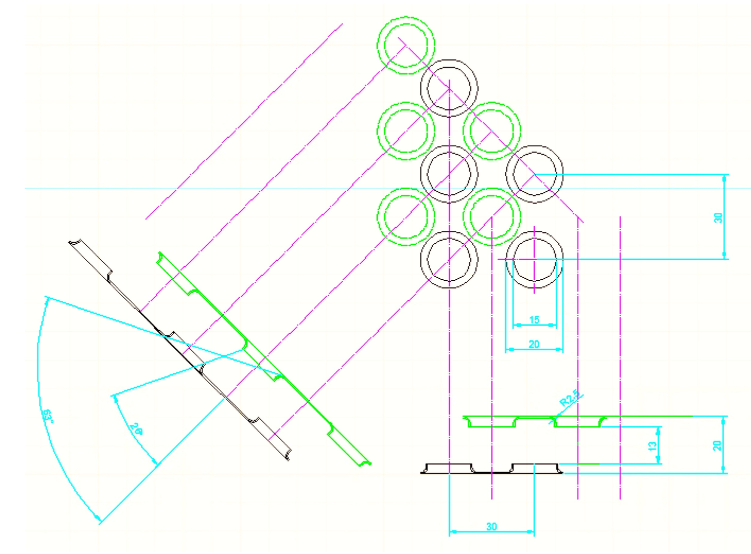


Fig. 7: evaluation of the "shine-through" effect: the estimated range of incidence angle is $20 < \vartheta < 60$ deg

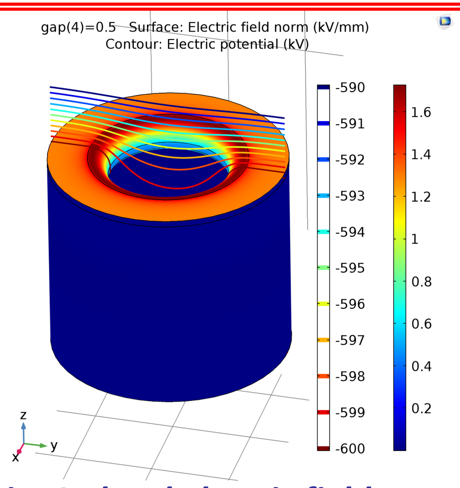


Fig. 8: local electric field concentration at the edge of shield apertures is less than 20%

6- Design Optimization

The geometry of the shield module has been optimized as follows:

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

The corresponding performances are the following:

- range of incidence angle of particles causing **shine-through effect**: ***is $20 < \vartheta < 60$ deg***
- **electric field intensification at the edges**: ***less than 20%*** *(estimated effect on overall voltage holding is negligible)*
- **specific gas conductance: $C_{H2} \approx 42$** (m/s) and **C_{D2}=30** (m/s) for Hydrogen and for Deuterium respectively
- *the total "breathable" surface of the MITICA Intermediate Electrostatic Shield is about 10 m^2, leading to an equivalent conductance of 300-400 m^3/s*

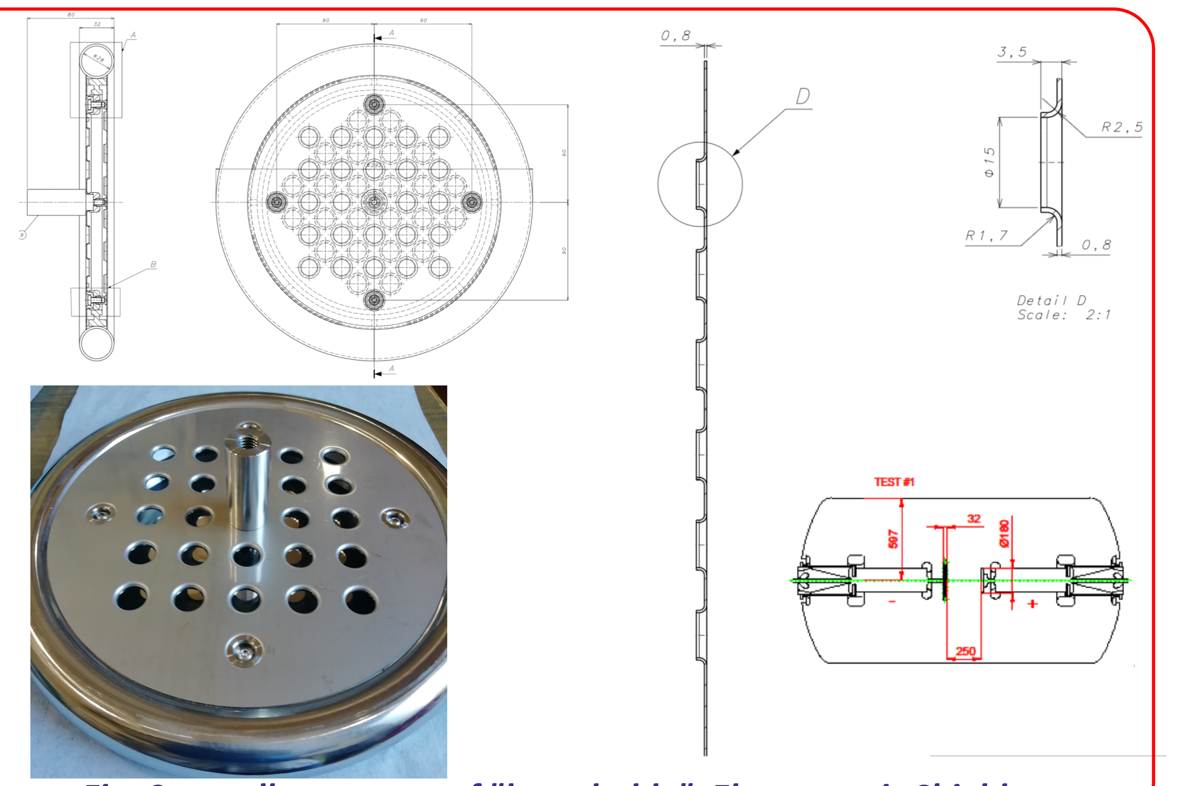


Fig. 9 small prototype of "breathable" Electrostatic Shield

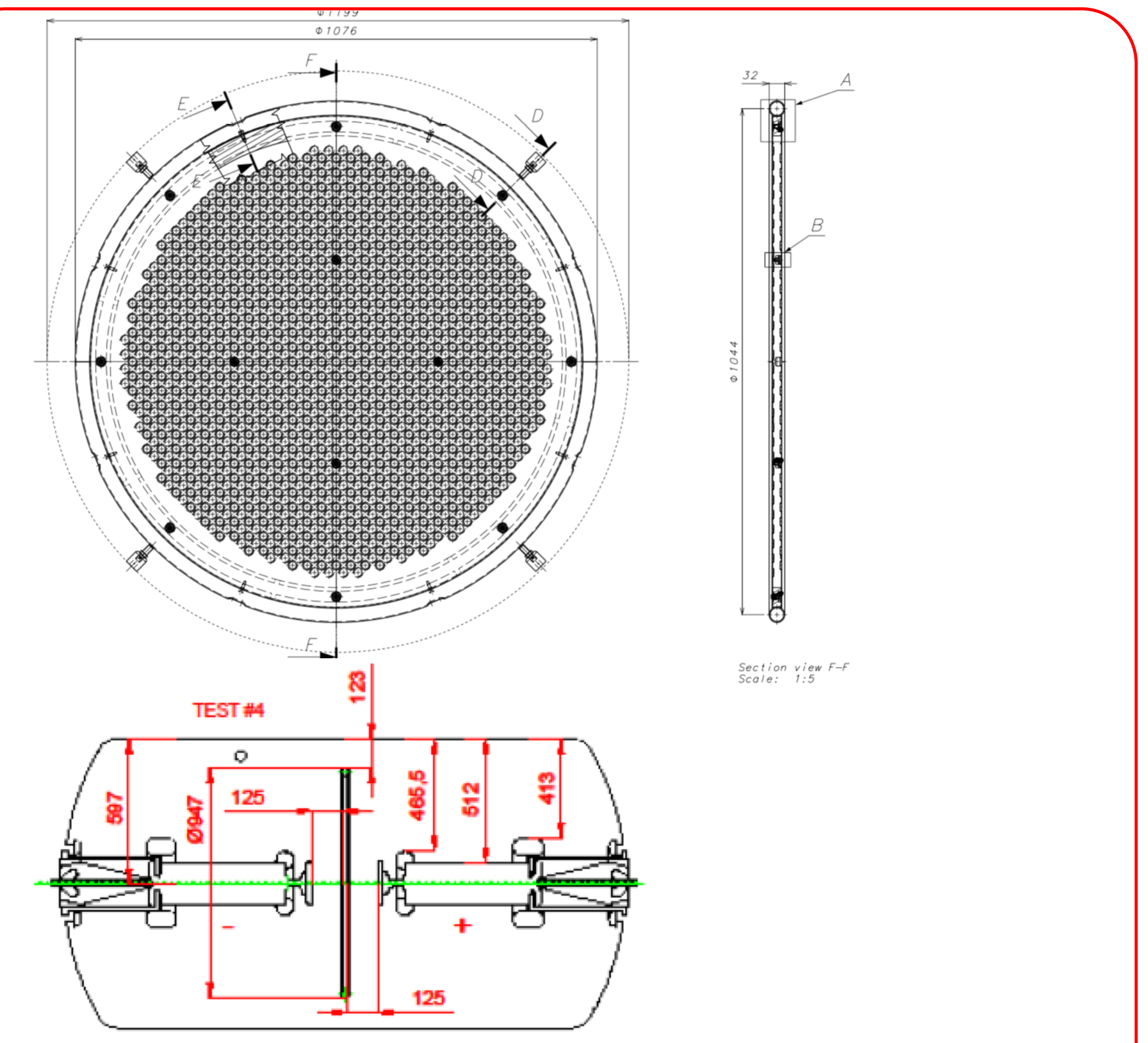


Fig. 10 large prototype of "breathable" Electrostatic Shield

7- tests on prototype shield

voltage holding tests on prototype "breathable" shield modules are in progress in HVPTF to compare **double-wall shields vs. single-wall shields vs. flat shields both in single and in double polarity**

[1] R. S. Hemsworth et al., "Overview of the design of the ITER heating neutral beam injectors," New J. Phys., vol. 19, no. 2, Feb. 2017. 025005, https://doi.org/10.1088/1367-2630/19/2/025005

[2] V. Toigo et al., "The PRIMA test facility: SPIDER and MITICA test- beds for ITER neutral beam injectors," New J. Phys., vol. 19, no. 8, Aug. 2017, https://doi.org/10.1088/1367-2630/aa78e8

[3] A. Kojima et al., "Vacuum Insulation in Negative Ion Accelerator with Long Gap and Large Surface for Fusion Application," 2020 29th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), 2021, pp. 420-425, https://doi.org/10.1109/ISDEIV46977.2021.9587111

[4] G. Chitarin et al "Strategy for Vacuum Insulation Tests of MITICA 1 MV Electrostatic Accelerator," IEEE Transactions on Plasma Science (2022), https://doi.org/10.1109/TPS.2022.3168341

[5] N. Pilan et al., "Numerical–experimental benchmarking of a probabilistic code for prediction of voltage holding in high vacuum," IEEE Trans. Plasma Sci., vol. 46, no. 5, pp. 1580–1586, May 2018, https://doi.org/10.1109/TPS.2017.2775246