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Voltage holding optimization of the MITICA electrostatic accelerator

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HIGHLIGHTS

- A set of electrostatic analyses of the region surrounding the MITICA electrostatic accelerator has been carried out.
- The distribution of the breakdown probability of the system has been calculated.
- The analyses have allowed identifying the weak point of the system to address the future design optimizations.

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ABSTRACT

Two Heating Neutral Beam Injectors (H-NBI) are planned to be installed in ITER with a total delivered heating power of 33 MW [1]. The main parameters are: 870 kV acceleration voltage with 46 A beam current for hydrogen beam, and 1 MV voltage with 40 A current for deuterium beam.

The voltage holding in the 1 MV ITER Neutral Beam Accelerator is recognized to be one of the most critical issues for long pulse (3600 s) beam operation, due to the complex electrostatic structure formed by electrodes polarized at different potentials immersed in vacuum or low-pressure gas. As a matter of fact, the system shall work in a $p \times d$ range at the left of the Paschen curve where the classical Townsend breakdown criterion is no longer valid. The voltage holding is governed by the mechanism of the long gap insulation in high vacuum, not yet well consolidated from the physical point of view.

This paper is aimed to describe the optimization of the voltage holding capability for MITICA electrostatic accelerator. The results of this analysis will constitute the input for the probabilistic model [3] which is adopted to predict the breakdown probability by means of 2D analyses of the multi electrode – multi voltage system.

1. Introduction

The electrostatic design of the accelerator of the 1 MV_{DC} – 40 A Negative Ion Beam Injector MITICA [1] has till now evolved on the basis of extensive experimental and modelling [2] R&D work carried out in the last years in the EU and Japanese Laboratories, in the framework of the ITER Organization. Despite the progresses so far achieved, the great complexity of the electrostatic structure of the accelerator requires further optimization of the electrodes geometry. This qualitative leap in the accelerator design requires moving definitely from 2D to 3D modelling of the electrostatic structure. The first step toward this improvement is to identify an accurate 3D solution of the electric field distribution for the entire accelerator. The paper focuses mainly on this step, producing an accurate 3D solution based on Finite Element Models, and then compares with the 2D solution so far obtained by the existing models. Finally the capabilities of the Voltage Holding Predictive Model – VHPM [3] have been exploited to estimate the performances of the system and to set the basis for further electrostatic optimizations.

2. The MITICA electrostatic accelerator design

The beam accelerator is composed of five acceleration grids (MAMuG, Multi-Aperture-Multi-Grid structure [1]), each polarized at different potentials, from −1 MV to ground with steps of 200 kV. Fig. 1 shows a view of the injector with the details of the accelerator. The negative ion beam is extracted from a radio frequency ion source; the beam is accelerated from the −1 MV to the ground potential passing through the apertures of each accelerating grid. The high voltage electrical insulation is guaranteed by the vacuum surrounding the accelerator. Five groups of alumina solid insulators are located between the accelerating stages to hold the voltage (200 kVdc) and to transmit the structural loads, being the beam

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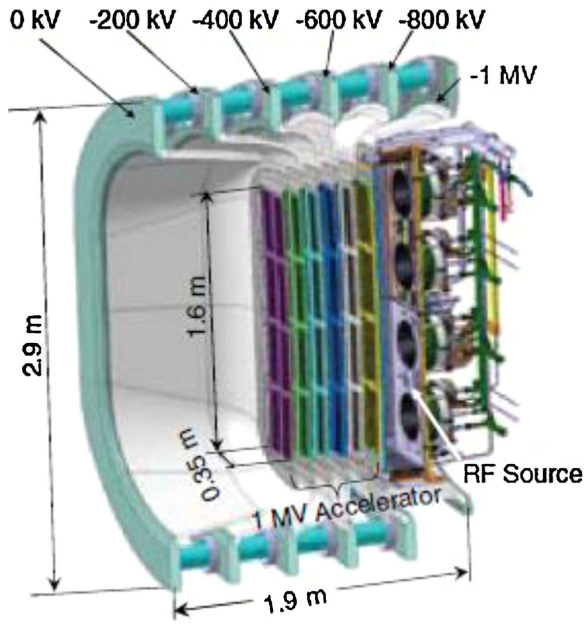

Fig. 1. Section view of the half MITICA beam source electrostatic accelerator, the cut cross section plane is the vertical symmetry plane.

source (BS) and the multi stage electrostatic accelerator (EA) a cantilever structure sustained by the grounded stage.

The electrical power, the cooling lines, the gas line and the diagnostic cables are delivered to the beam source by a suitable high voltage five-stages bushing, the latter has been designed to separate the high voltage transmission line, insulated by SF_6 at 6 bar, from the vacuum vessel where the accelerator is situated. From the electrostatic point of view, the complexity of the whole system is related not only to the geometrical issues, but also to the different insulated media adopted in the design (pressurized N_2 and SF_6, Al_2O_3 and ultra pure water). The present work is focused on the vacuum voltage holding issues which concern mainly the BS and the EA design. The background gas is hydrogen or deuterium, the pressure is in the range 10^{-4}–3×10^{-1} Pa, the lower pressure refers to the high voltage conditioning procedure (CP), while the upper limit corresponds to the operating pressure relative to the maximum extraction of beam current [2]. As concern the voltage holding issues in vacuum, the topic can be divided in two sub-issues depending on the physical mechanism initiating the discharge, a relevant difference exits between the voltage holding in high vacuum ($p < 10^{-2}$ Pa) and the voltage holding in the medium vacuum ($p \approx 10^{-1}$–1 Pa). While the latter case is related to the gas discharge and it is described by left branch of the Paschen curve (in presence of magnetic field), the former is based on a physical phenomenon not completely understood. The consequence is that in literature does not exist a generally accepted design criterion useful to address the design of a multi electrode multi voltage system insulated by large high vacuum gaps. This is the reason why some efforts have been dedicated to propose a design criterion [3] able to predict the voltage holding in such operating conditions. The present work reports a brief introduction on the criterion adopted and its application to optimize the design of the MITICA electrostatic accelerator in high vacuum.

3. The computation of the electric field map, 2D and 3D FEM

The starting point for the analyses is the evaluation of the DC electric field distribution inside the beam source vessel solving the Laplace's equation for the electric potential. The analyses have been carried out considering both 2D and 3D models. The 2D analyses have been carried out considering two cross sections which have been obtained cutting the 3D cad model along both the vertical and the horizontal symmetry plane respectively. Fig. 2 shows the results obtained by the 2D FEM, the latter has been developed considering the symmetry of the system in order to save CPU time. The equipotential surfaces −200 kV, −400 kV, ... −1000 kV surround the electrostatic accelerator passing through the accelerator grids and grid supports. The maximum electric field is achieved inside the accelerator, between each accelerating grids, whereas the supporting structures have been shaped in order to position properly the grids. Although the HV bushing is an axial symmetric 5 stage structure, deserving a dedicated 2D axial symmetric model, anyhow a 2D planar FEM has been adopted to evaluate the electric field map in the vertical symmetry plane passing through the BS and the HV bushing the results are reported in Fig. 3.

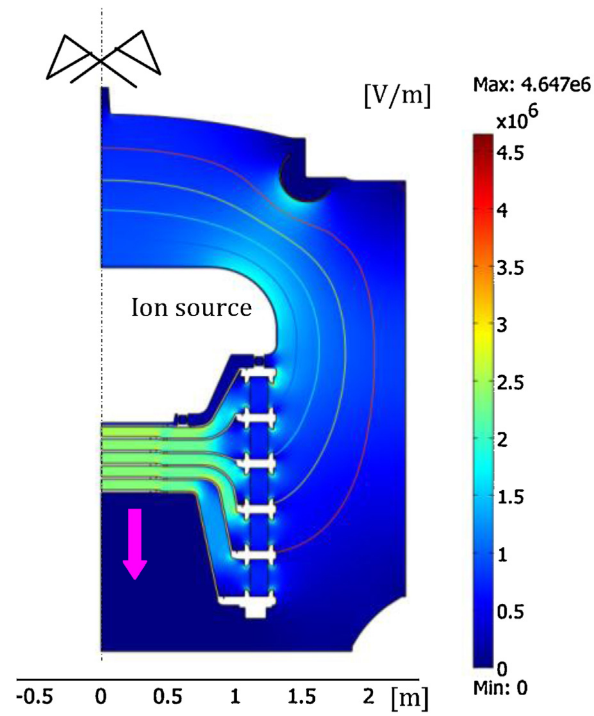

Fig. 2. Electric field map horizontal plane cross section 2D FEM.

The simulation shown in Fig. 3 allows to identify the routing of the cooling pipes connected at each polarized stages.

The cooling pipes have been located along the equipotential surfaces (see dotted paths in Fig. 3) in such a way as to avoid electric field concentration. A preliminary electrostatic 3D model of the bottom part of the electrostatic accelerator has been developed in order to benchmark the 2D FEM results by using a model closer to the real electric field distribution.

Fig. 4 shows the electric field strength ($E = \sigma/\varepsilon_0$) computed by the 3D model on the electrodes surfaces. Although the 3D model highlights some electric field concentrations which is impossible to appreciate by a sole 2D map (e.g. the point P in Fig. 4), it can be noted a satisfactory agreement between 2D and 3D simulations.

This is the reason why the 2D model have been widely adopted to optimized the accelerator geometry, leaving the 3D time consuming analyses the last step of an iterative process which is not merely oriented to minimized the sole electric field.

4. The micro-particles probabilistic model

Although the knowledge of the electric field distribution is widely used to study the high voltage issues, the sole electric field

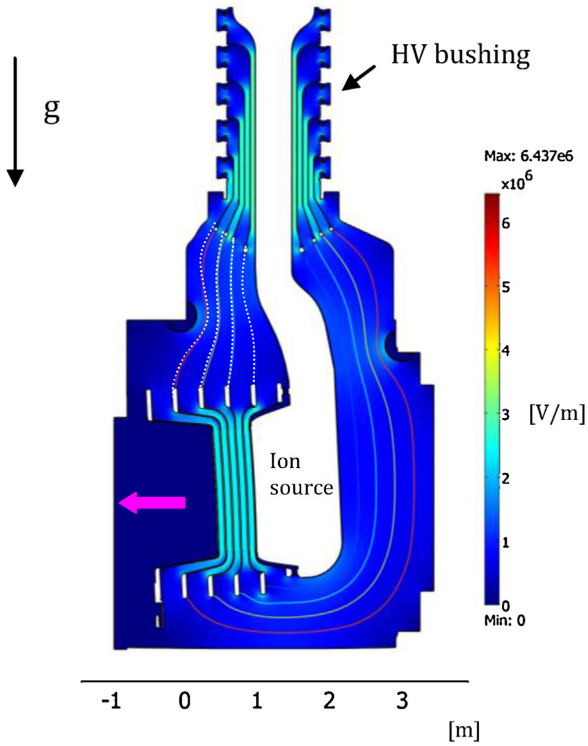

Fig. 3. Electric field map vertical plane 2D FEM.

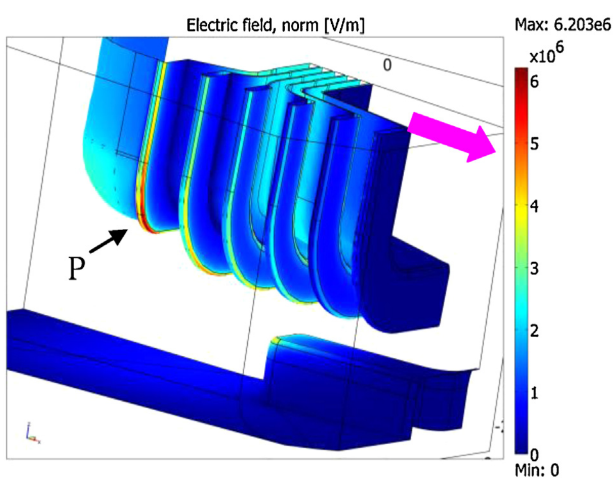

Fig. 4. Electric field norm map on the accelerator metal surfaces.

map is not sufficient to identify the weak point in a system insulated by large vacuum gaps.

As a matter of facts, the breakdown electric field E_{BD} is a monotonic decreasing function of the gap length, typically in the plane parallel configuration, when the vacuum gap length d is large enough ($d > 10$ mm) it is possible to verify the following relation $E_{BD} \propto 1/\sqrt{d} \propto 1/U_{BD}$ [4]. A new design criterion has been proposed and developed [3] to estimate the breakdown probability of a multi-electrode multi voltage system insulated by large high-vacuum gaps.

The criterion is based on the Cranberg–Slivkov [5,6] micro-particle hypothesis, and implements the Slivkov's triple product $W = E_A^{2/3} \cdot E_C \cdot U$ into a probabilistic model. This model considers each possible micro-particle trajectory as the basis for the evaluation of a local value the triple-product W_i and the associated reliability R_i against the breakdown, being $R_i = 1 - P_i$ and Pi the breakdown probability.

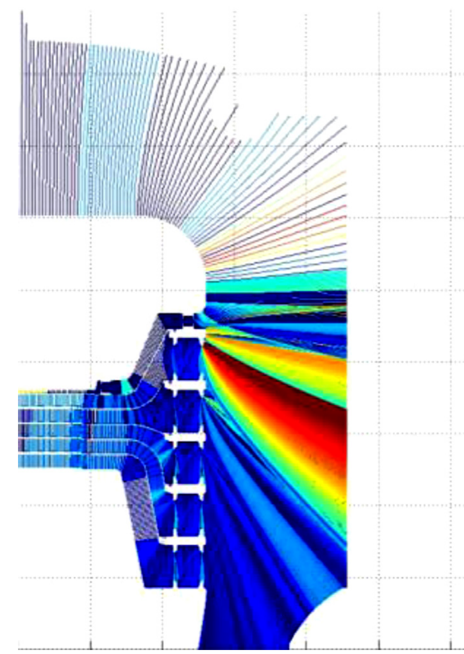

Fig. 5. Micro particles trajectories, accelerator horizontal cross section.

The whole system reliability R will be expressed by (2):

$$R = \prod_{i=1}^{N} R_i \tag{1}$$

This formulation implies that the breakdown of the entire system will occur when at least one of the micro-particle trajectories will satisfy the Slivkov triple-product condition.

5. Analyses and results

The results of the probabilistic model are based on the 2D FE Models described in Section 4. Fig. 5 shows the microparticle trajectories in the horizontal accelerator cross sections, the figure should be analyzed considering the correspondent electric field map shown in Fig. 2. A similar analysis has been carried out for the vertical plane. The breakdown probability equation (3):

$$P = 1 - \exp\left(-\int_{A\_cathode}\left(\frac{E_c \cdot E_A^{2/3} \cdot U}{W_0}\right)^m \cdot dA\right) \tag{2}$$

and the values $m = 8$, $W_0 = 1.15 \times 10^{16}$ $[\mathrm{V}^{8/3}\,\mathrm{m}^{-5/3}]$ have been adopted according with the ones reported in [3].

Each micro trajectory has been colored as a function of the W parameters: the warmer the color, the larger the W. The analysis method based on the trajectories and the associated W computation highlights the "weak points" of the system better than the simple electrostatic analysis. The analyses reveal that the weak points are located on the frames of the source and −800 kV accelerating stage, actually the electric field concentration should be limited as much as possible around such points. The breakdown probability has been estimated considering the 2D planar models (1 m deep); Fig. 6 shows the breakdown voltage distributions for the two analyses (vertical and horizontal plane).

In both cases the average breakdown voltages are located in the range 700–800 kV, they seem quite far from the design voltage (1000 kV) but it is necessary to highlight that the probabilistic model refers to the ideal case without background gas pressure, this condition is closer to the one adopted for the high voltage

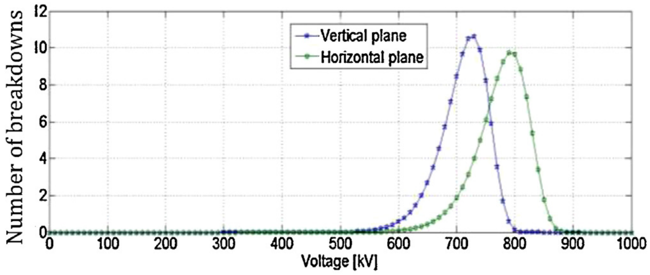

Fig. 6. Breakdown voltage distributions in vertical and horizontal planes.

conditioning procedure (typically $p < 10^{-6}$ mbar) so the numerical results have to be intended a prediction of the maximum voltage achievable at the end of the procedure. In any case, the numerical results obtained by this Voltage Holding Predictive Model are dependent on the choice of the W and m parameters, in this case they have been derived from a similar accelerator, so the Voltage Holding Predictive Model should be thought such a tool useful to optimized an electrostatic configuration rather than a way to determine exactly the distribution of the breakdown voltage.

6. Possible methods to improve the voltage holding

The MITICA electrostatic accelerator adopts mainly stainless steel electrodes, SS is a suitable material for the voltage holding in vacuum, it is relatively easy to shape and weld. The accelerating grids are made by CuCrZr to drain properly the relevant heat fluxes due to the impacts of the stripping electrons, such material has a worse voltage holding than SS but the maximum voltage achievable between the CuCrZr surfaces is limited up to 200 kV. As already shown in Fig. 5 the weak point of the system concerns the direct line of sight between the 1 MV and ground potential, such large vacuum gap does not require the mirror surfaces finishing preparation, typically adopted for the short gap configurations (gap length <5 mm), nevertheless particular care should be dedicated to surface cleaning avoiding the adoption of organic compounds (especially paste) to treat the surfaces [4].

The voltage holding of the large vacuum gaps are characterized by Eq. (3)

$$U \approx K \cdot d^{\alpha} \tag{3}$$

where U is the voltage and d is the gap length, the exponent α is typically in the range 0.5–0.63.

In MITICA the gap lengths have been extended as much as possible by enlarging the vacuum vessel whose dimensions are limited by structural and lay-out reasons.

The easiest way to optimize the system is to reduce the maximum W parameter, e.g. reducing the electric fields around the critical points on the electrodes. This operation has been carried out in the whole accelerator, many details have been rounded by adopting the largest curvature radius, nevertheless the presence of insulators and the shaped grid supports has inserted a stiff constrain to this approach.

If additional voltage holding capability is required the following possible alternatives could be adopted.

It is easy to verify by Eq. (3) that a multi stage system insulated by n vacuum gaps whose length is d_s (and $d = n \times d_s$, $U = n \times U_s$), has a total voltage holding improved by a factor $n^{1-\alpha}$, of course this is not strictly extendable to high n because the area effect is not considered in Eq. (3). Nevertheless a possible design choice could be the implementation of two additional screens to intercept the critical charged particles between the −1 MV stage and the grounded vessel.

The screens should be located along the −600 kV equipotential surface shown both in Figs. 2 and 3, they could be connected respectively with the −600 kV grid frame in the lower part and with the −600 kV cooling pipes above the beam source.

In addition to the geometric modifications, the accelerator voltage can be increased after conditioning by exploiting the “pressure effect”, which is obtained raising properly the background gas pressure up to10^{-4}–10^{-3} mbar. Although the pressure effect is a technique commonly adopted in the technical practice, it has not been understood from the physical point of view so it is not available any model to predict this effect, the experience [7] has shown an increase of performances up to 100–200 kV in a 500–700 kV system; nevertheless it appears a valid and easy method to improve the maximum voltage in the MITICA electrostatic accelerator.

7. Conclusions

A set of electrostatic analyses have been carried out in order to identify the electric field distribution in the region surrounding the MITICA electrostatic accelerator and to estimate the vacuum voltage holding of the system by the breakdown probability. The analyses allow to identify and remove the weak points of the system and to provide guidelines for further improvements.

Acknowledgment

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References

[1] Design Description Document (DDD 5.3) Neutral Beam Heating & Current Drive (NB & CD) System – ITER N 53 DDD 29 01-07-03 R 0.1.
[2] P. Sonato, P. Agostinetti, G. Anaclerio, V. Antoni, O. Barana, M. Bigi, et al., Fusion Engineering and Design 84 (2009).
[3] N. Pilan, P. Veltri, A. De Lorenzi, Voltage holding prediction in multi electrode–multi voltage systems insulated in vacuum, IEEE Transactions on Dielectrics and Electrical Insulation 18 (2) (2011).
[4] F. Rohrbach, Isolation sous vide, CERN Report No. 71-5 (1971).
[5] L. Cranberg, The initiation of the electrical breakdown in vacuum, Journal of Applied Physics 23 (1952).
[6] I.N. Slivkov, Mechanism for electrical discharge in vacuum, Soviet Physics – Technical Physics 2 (1957).
[7] M. Kashiwagi, M. Taniguchi, M. Dairaku, H.P.L. de Esch, L.R. Grisham, L. Svensson, et al., R&D progress of the high power negative ion accelerator for the ITER NB system at JAEA, Nuclear Fusion 49 (2009).