Application of the Voltage Holding Predictive Model- VHPM

A. De Lorenzi, N. Pilan, N. Marconato, P. Bettini

Consorzio RFX

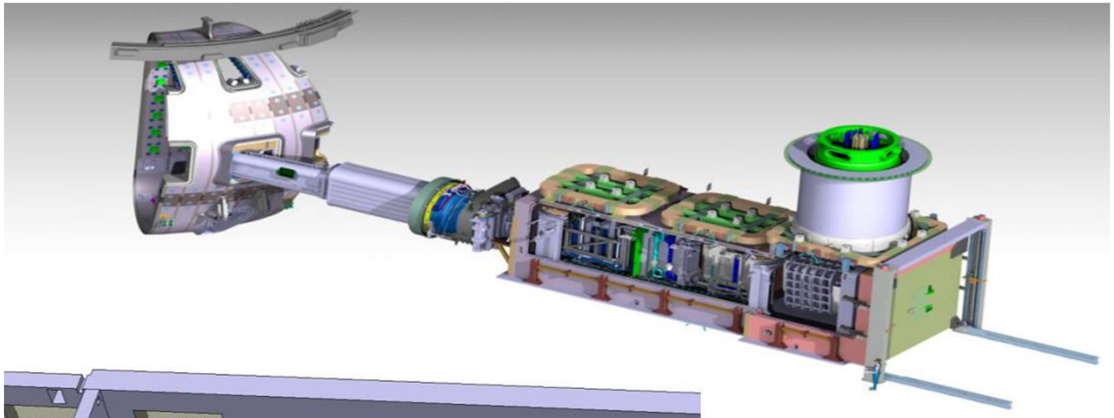
Outline

CONSORZIO RFX
Ricerca Formazione Innovazione

- **The Context**
- **Model Description**
- **Application**
  - ***Validation against simple geometries***
  - ***NBI Accelerators***
  - ***Vacuum Circuit Breakers***
- **Conclusions**

The Context

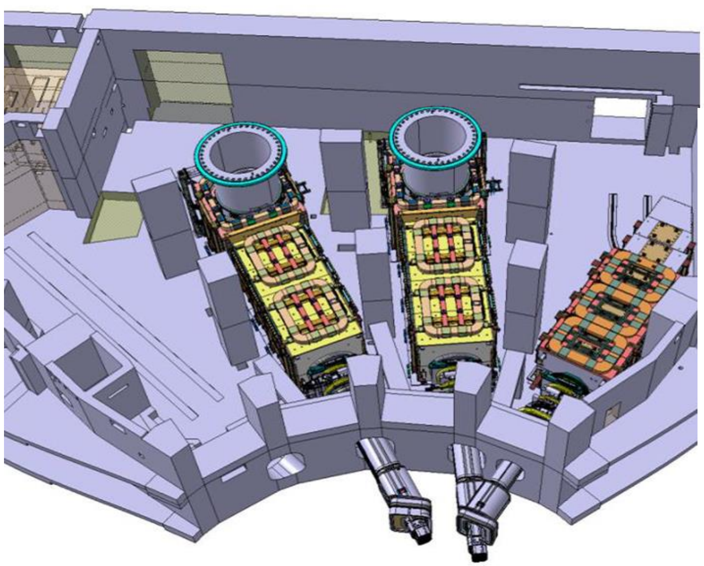
To guarantee transition from L to H modes (i.e., to ignite the plasma to thermonuclear D+T reaction) ITER requires at least 30 MW of D injected in the plasma, through a Heating Neutral Beam System



2 HNBs (+1)

- P_{beam} = 16.5 MW
- I = 40 A
- V = 1 MV
- T_{pulse} = 3600 s

EUDA & JADA procurement



- The parameters exceed by far those of existing HNB.
- ITER program includes the construction of the Neutral Beam Test Facility - NBTF
    - Full scale prototype of Ion Source (SPIDER)
    - Full scale prototype of the HNB (MITICA)
- **Consorzio RFX – Padova (I) has been identified as the research structure to host the NBTF.**

The Context

Status of the construction at RFX ***Buildings***

Oct 2012: start of building erection

Green Field

Sept 2015: delivery of all buildings

The Context

Status of the construction at RFX ***SPIDER***

Most of components ready and commissioned

Operation: Beginning of 2018

The two hydraulic 100 kV bushings

The Context

Status of the construction at RFX *MITICA – The 1MV DCG & Line*

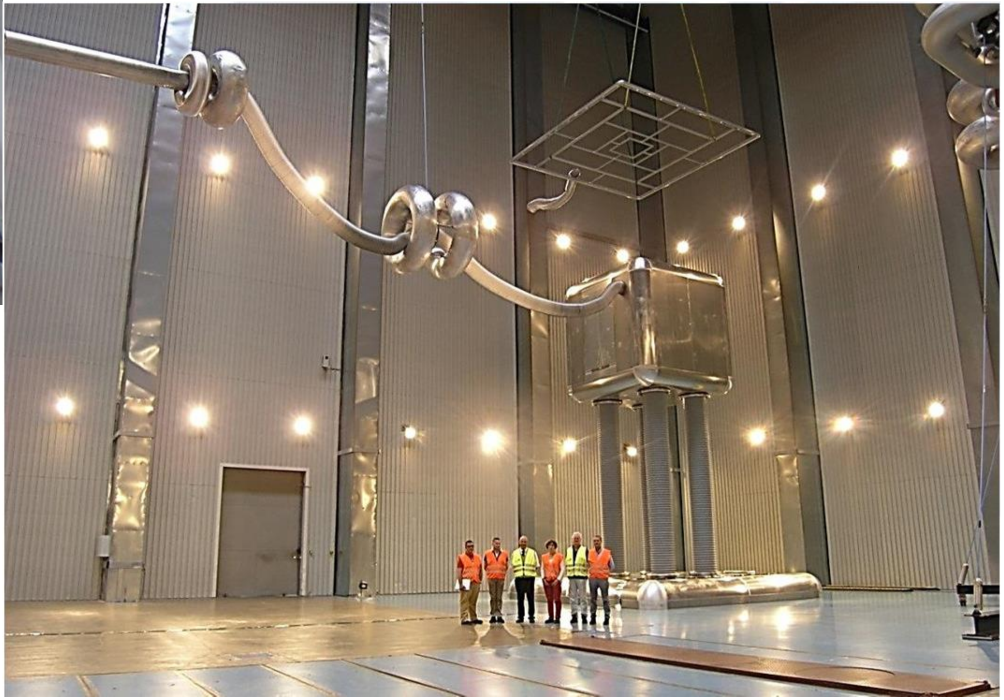
5 x 200 kV – 60 A units in series

Multi conductor 1 MV TL

The Context

Status of the construction at RFX ***MITICA – The High Voltage Hall***

The 1 MV insulating trasformer to feed the Ion Source Power Supplies



The 1 MV Faraday Cage hosting the Ion Source Power Supply

(Reduced Sized @ manufacturer premises)

The Context

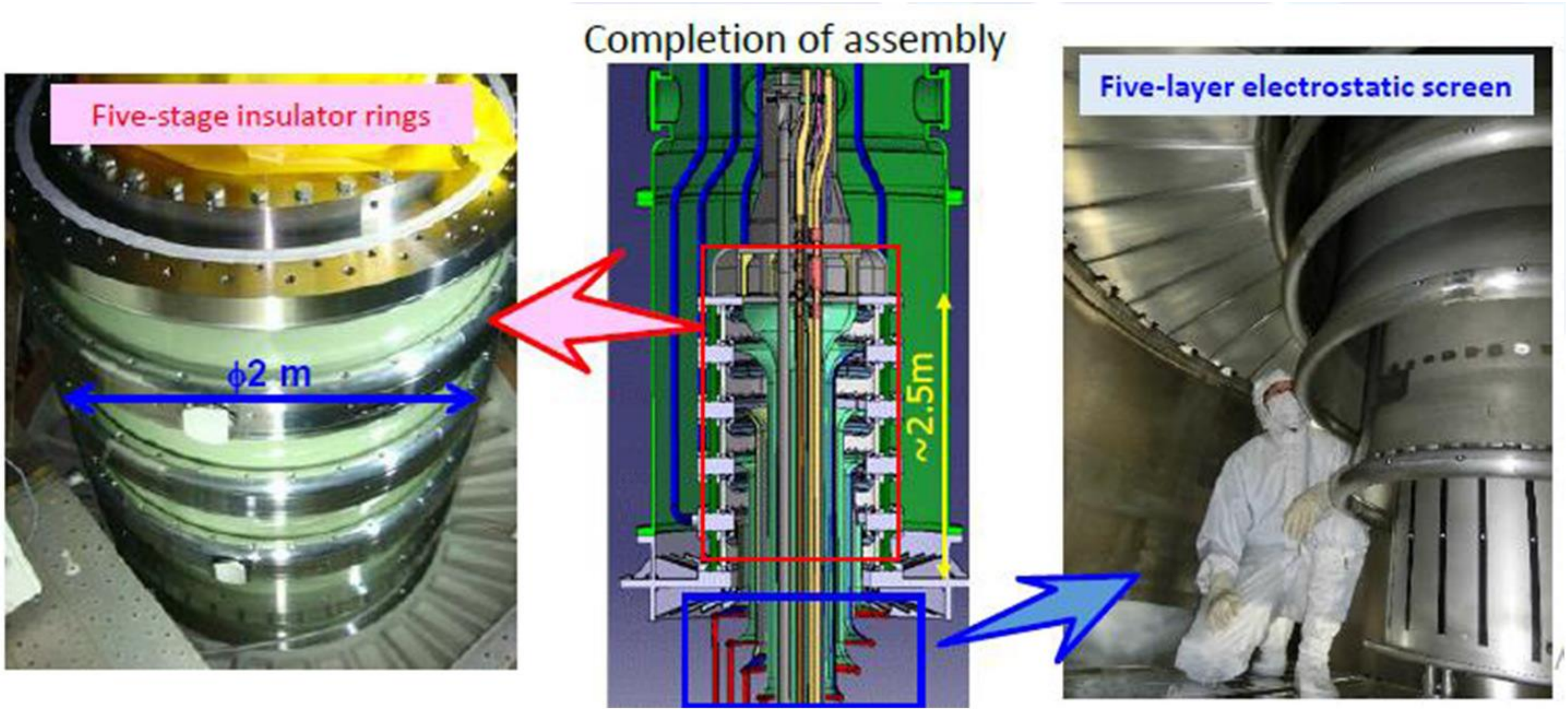
Status of the construction at RFX *MITICA – Passive protection*

The Magnetic Core Snubber to limit current during breakdown

The Context

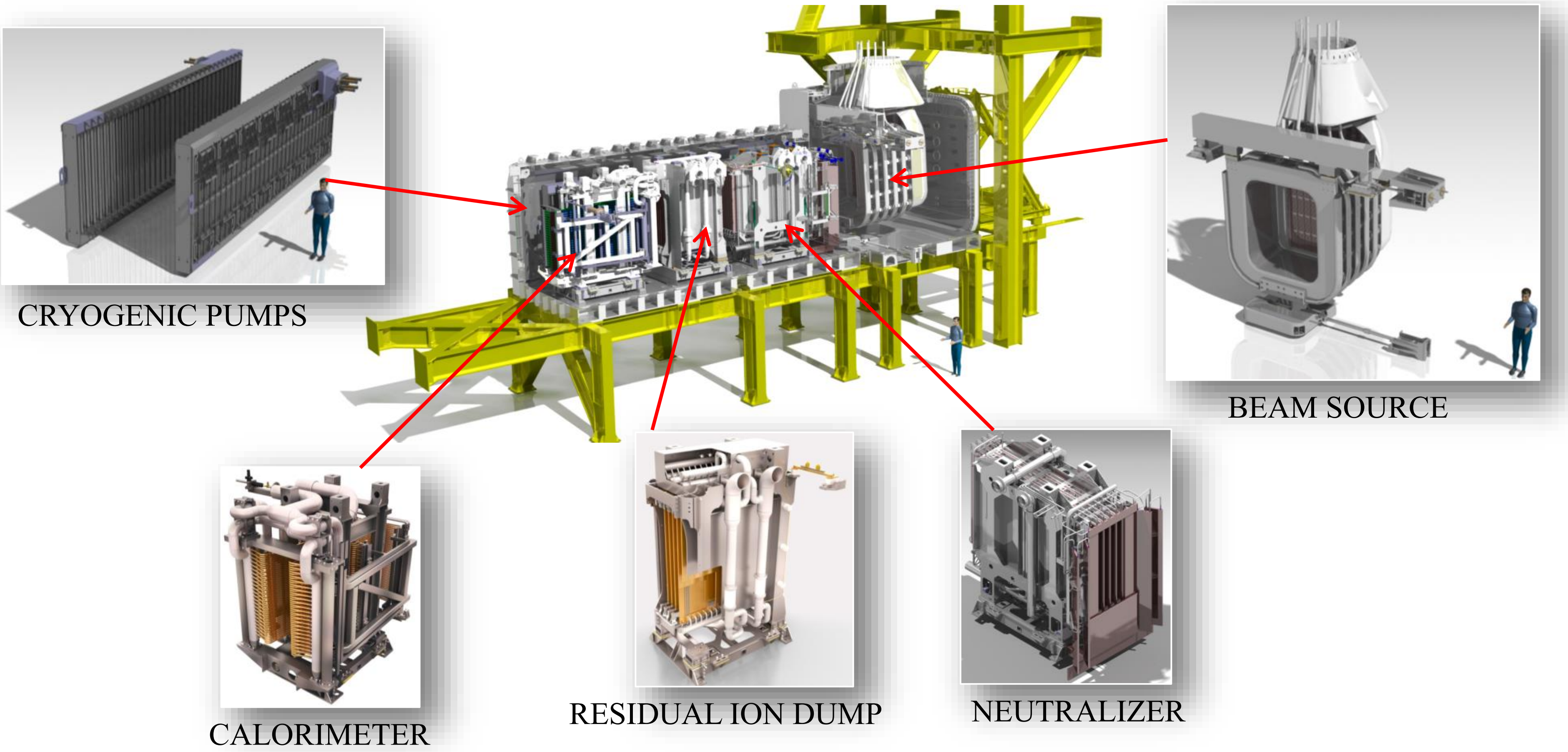
Status of the construction at RFX ***MITICA – The Bushing***

The complex feedthrough from SF_6 insulated TL to the Vacuum insulated accelerator



The Context

The structure of the NBI



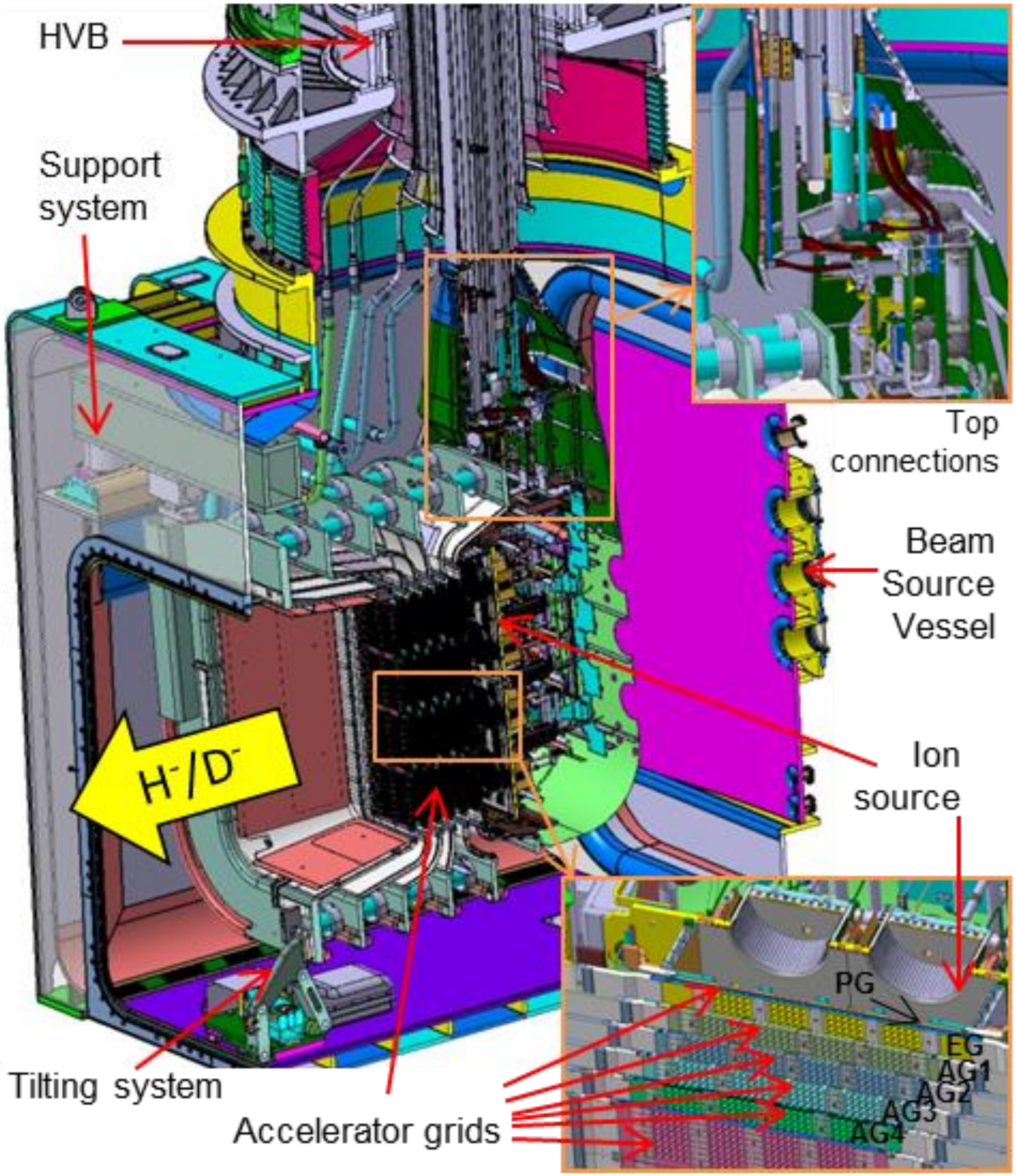
The Context

- The NBI accelerator, hosted inside a vacuum tank, has a very complex structure.:

  - *<u>The Beam Source and the Accelerating Grids</u> form a multi-voltage (-1.0MV; -0.8MV; -0.6MV; -0.4MV; -0.2MV) electrodes system, facing the anode (the tank); 1 MV electrode size is about 10 m^2; the gap is about 1 m.*
  - *<u>The Bushing</u>, connecting the 1 MV Line insulated in SF_6 to the accelerator, transfer through pipes the potential to the Grids as well as cooling water. It is built by 5 stacked alumina rings (2.0 m diameter; 0.3 m heigth)*

- The geometry is further complicated by the pipes, that enhance the local electric field in critical areas.

The Context



Details of the accelerator

The Context

- Both design and operation phases will require a combination of improvements in techiques to keep voltage holding to a safe value. These techniques are:
  - Voltage conditioning process
  - Electrodes treatment.
  - Electrodes shapings

- Electric field minimization not suitable for optimization because:
  - Total voltage effect not considered
  - «measurable» objective function for optimization not defined.
  - Area effect not considered

The VHPM fulfills these requirements

Model Description

CONSORZIO RFX
Ricerca Formazione Innovazione

- Total Voltage Effect

  – The quantity $W = E_K^{\alpha} \cdot U \cdot E_A^{\gamma}$ as «breakdown driver» is introduced; this quantity is associated to a generic «particle» that leaves the cathode K, and clashes at the anode.

  – For $\alpha = 1$; $\gamma = {}^{2}/_{3}$ we have the Slivkov-Cranberg breakdown model.

  – **The VHPM calculates all the trajectories of the «particles» from cathode to anode to associate to each particle its W value.**

Model Description

CONSORZIO RFX
Ricerca Formazione Innovazione

- Objective Function.
  - Given N the surface density of particles that potentially can induce the voltage breakdown, it is shown [1] that the overall (cumulative) breakdown probability is $P = 1 - e^{-\int_{A_K} N \cdot dA_K}$, the integral extended to all the «emitting» cathode surfaces.
  - Assuming $N(W) = N_0 \left(\frac{W - W_s}{W_0}\right)^m$, the breakdown probability follows is the Weibull distribution.
  - **The VHPM output is a Weibull Breakdown Probability Curve.**

[1]Pilan, N.; Veltri, P.; De Lorenzi, A., *Voltage holding prediction in multi electrode-multi voltage systems insulated in vacuum* IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 18 , Issue: 2 DOI 10.1109/TDEI.2011.5739461

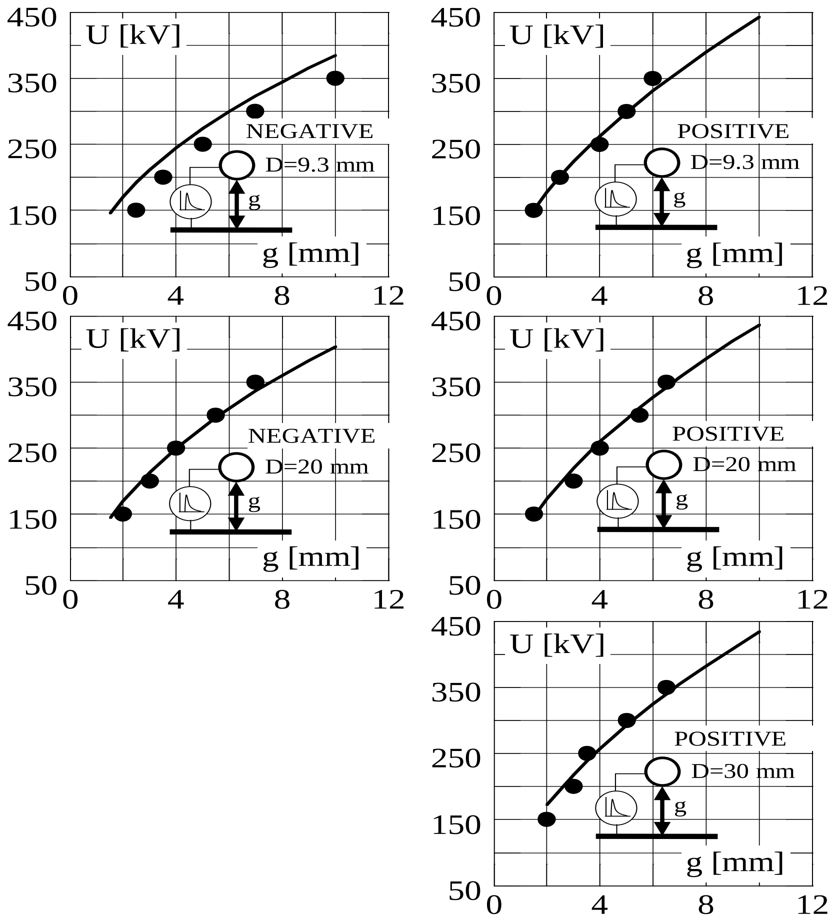
Model Description

- Area effect.
  - The formulation of the breakdown probability is done through a surface integral along the cathodic surfaces.
  - **VHPM takes intrinsically into account the Area Effect.**
- Input parameters
  - W_0; W_s and m do not depend upon geometry, but only on electrode material, surface treatment, vacuum level, conditioning technique. They are derived from experiment through best fit techniques, in two ways:
    - Experiment on simple geometry. The parameters are derived easily from the experiment, but VHPM prediction is reliable only if the system under analysis has the same material, surface, vacuum, conditioning..
    - Experiment on a mockup of the system under analysis. In this case suitable shape function have to be calculated.
  - **In both cases, a «good» breakdown voltage distribution is necessary from the tests .**

Application

CONSORZIO RFX
Ricerca Formazione Innovazione

Validation against simple geometries [1-2]   Sphere Plane geometry – Pulsed Voltage



<u>Parameters derived from fitting 63% voltage breakdown probability - Ordinary Steel</u>

$W_0 = 9.5 \cdot 10^{17}\,[V^8 m^{-5}]^{1/3}$

m = 10

<u>Results</u>

Prediction 63% voltage breakdown probability

Over estimation of the

D=9.3 mm negative polarity case.

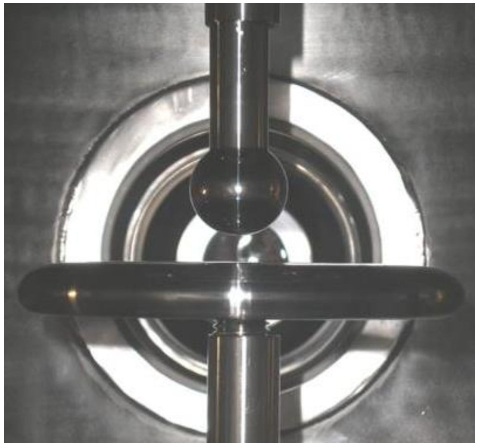
[1]A. De Lorenzi, N. Pilan, E. Spada, Progress in the Validation of the Voltage Holding Prediction Model at the High-Voltage Padova Test Facility IEEE Transaction on Plasma Science, Vol. 41, NO. 8, 2013

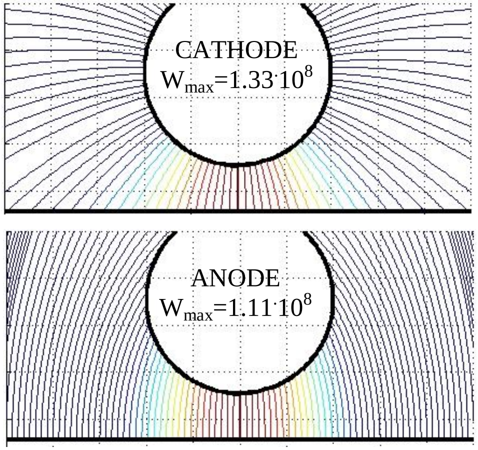
[2]Slivkov I.N. "Mechanism for electrical discharge in vacuum" Soviet Phys. Techn. 2, 1928 (1957)

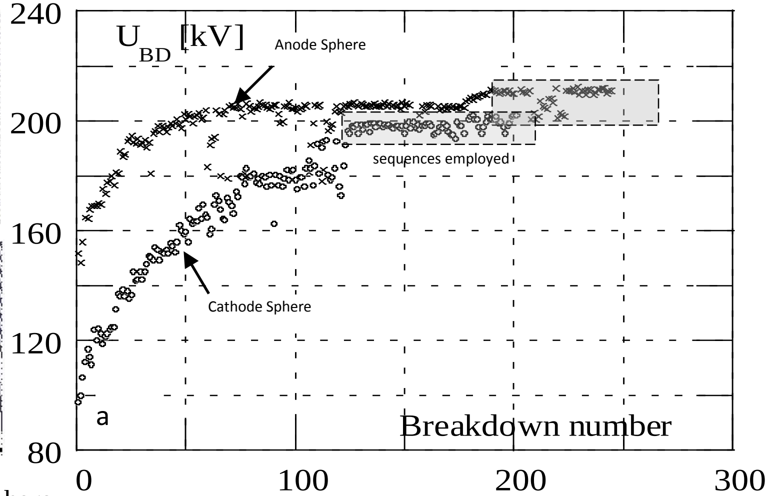
Application

Validation against simple geometries [1] – dc voltage

HVPTF Padova - Sphere Plane geometry

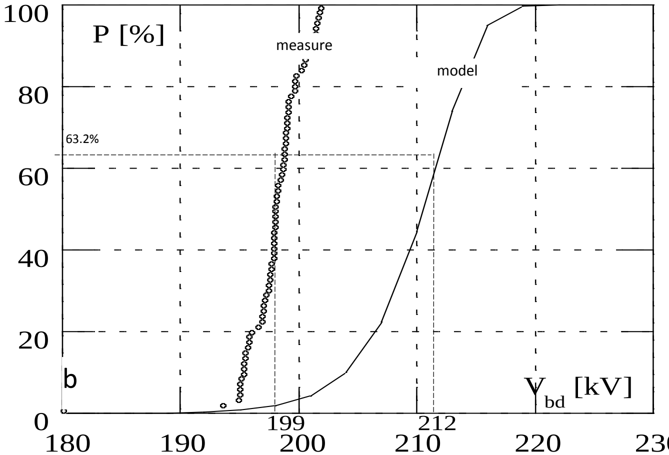


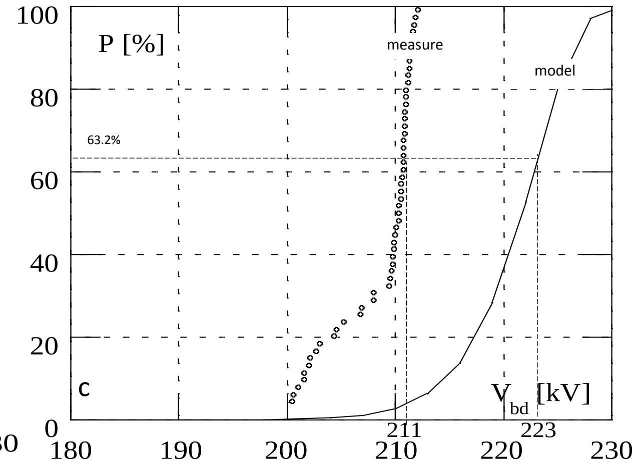




Cathode Sphere

Anode Sphere





[1]A. De Lorenzi, N. Pilan, E. Spada, Progress in the Validation of the Voltage Holding Prediction Model at the High-Voltage Padova Test Facility IEEE Transaction on Plasma Science, Vol. 41, NO. 8, 2013

<u>Parameters derived from disk-disk geometry –Stainless Steel</u>

$W_0 = 2.65 \cdot 10^{17}\,[V^8 m^{-5}]^{1/3}$

m = 18.4

<u>Results of sphere-plane geometry</u>

Prediction in excess of 6%

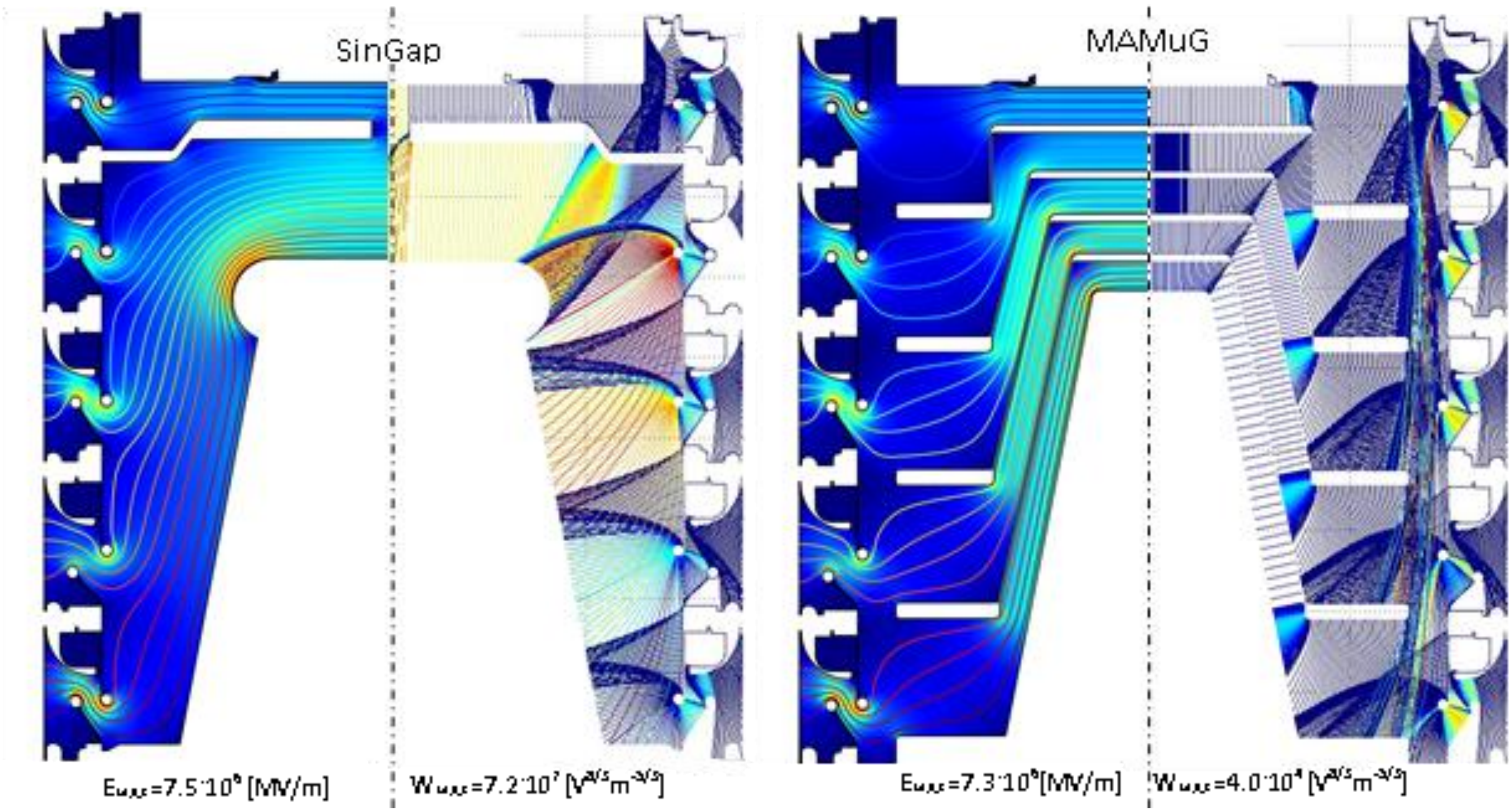
Correct prediction of polarity effect

Application

NBI Accelerators ***The Megavolt Test Facility in Naka (J) – dc voltage***

Two different configuration tested. Single Gap and Multiple Gap

On the right: the trajectories. The warmer the color, the highest the W.



NBI Accelerators — The Megavolt Test Facility in Naka (J) [1] – dc voltage

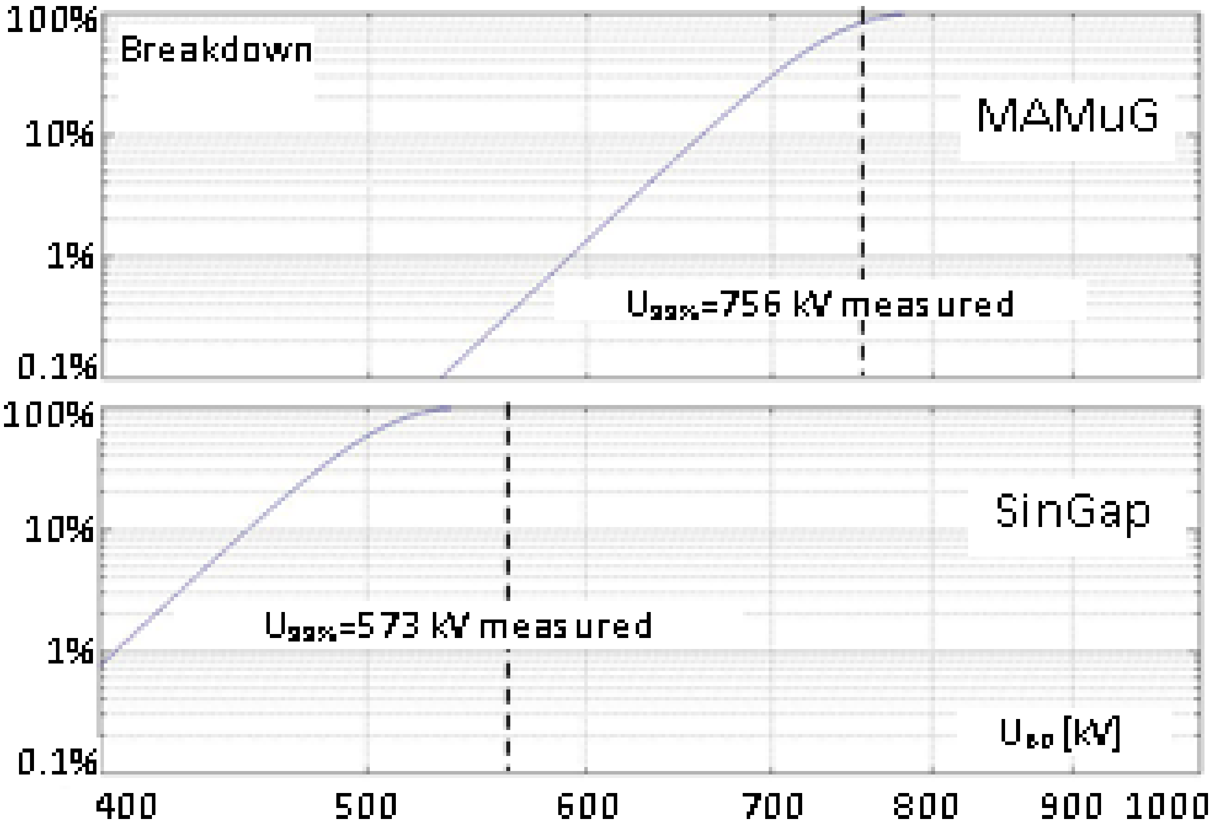


Figure 11 Weibull plot for the SinGap and MAMuG configurations of the MTF.

Parameters derived from MaMuG configuration fitting 99% breakdown probability 756 kV dc

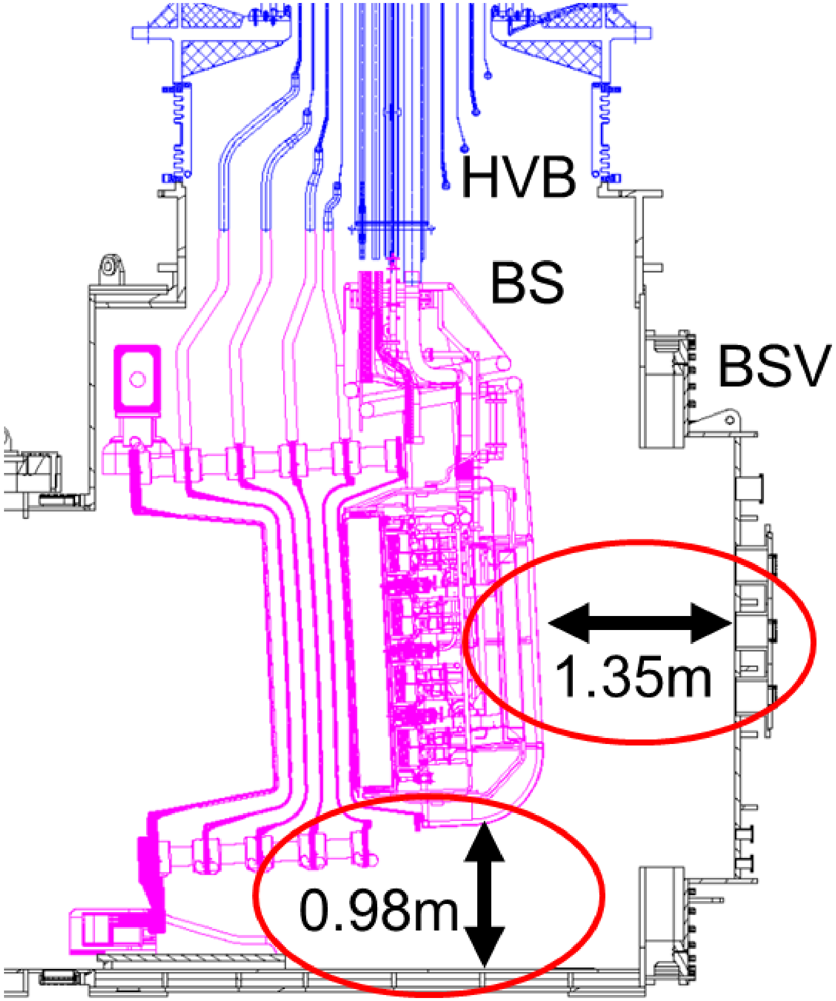
$W_0 = 0.115 \cdot 10^{17}\,[V^8 m^{-5}]^{1/3}$
m = 8

Results
Prediction of SinGap Configuration:
99% breakdown probability 541 kV dc

[1]Pilan, N.; Veltri, P.; De Lorenzi, A., *Voltage holding prediction in multi electrode-multi voltage systems insulated in vacuum* IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 18 , Issue: 2 DOI 10.1109/TDEI.2011.5739461

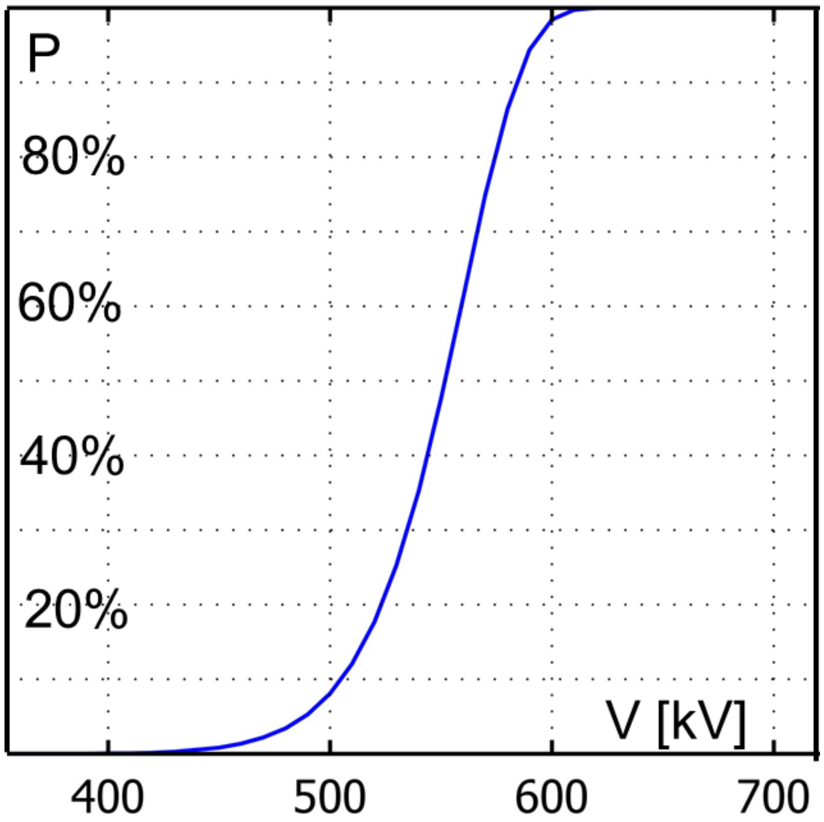
Application

NBI Accelerators *The Neutral Beam Source of ITER – NBTF – dc voltage*



Application

NBI Accelerators** **The Neutral Beam Source of ITER – NBTF – dc voltage



Test done using the same parameters used for the MTF Facility

$W_0 = 0.115 \cdot 10^{17}$ $[V^8 m^{-5}]^{1/3}$; m = 8

2D modelling of a pure 3D geometry

Results

Predicted breakdown voltage much less (!) than the target (1 MV)

- *Assessment of the W_0 value*
- *Revision of W α and γ exponents*
- *To implement 3D capability*

Application

Vacuum Circuit Breakers Research with Siemens Berlin – Pulsed Voltage (LIWV)

In 2015 has started a research funded by Siemens Akiengesellschaft (Berlin/Munich) aimed to investigate the applicability of the VHPM to the design process of the VCB tubes.

The VHPM should reduce the effort in developing new components, limiting the number of prototypes.

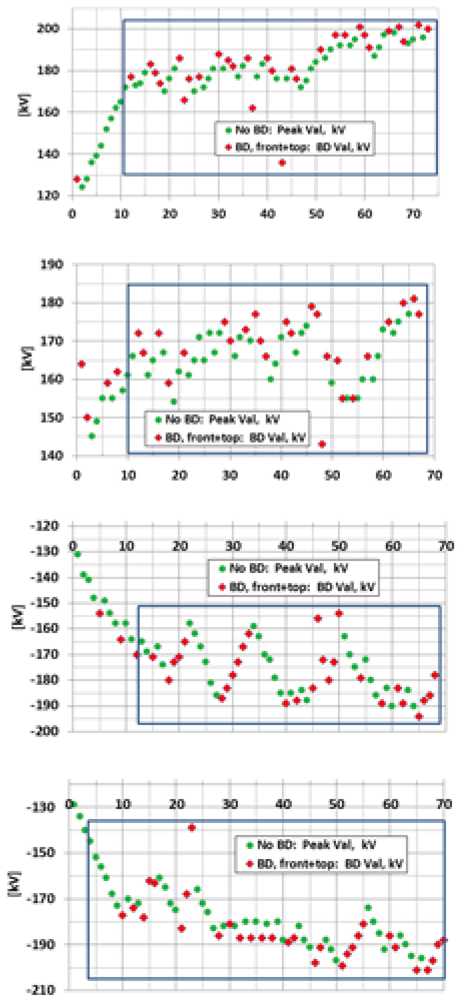
The voltage applied are the IEC standard Lightning Impulse Withstand Voltage 1.2/50 μs

VHPM has been applied to an AMF design and a RMF design at two different voltage ratings.

Application

Vacuum Circuit Breakers

Research with Siemens – Pulsed Voltage (LIVW)



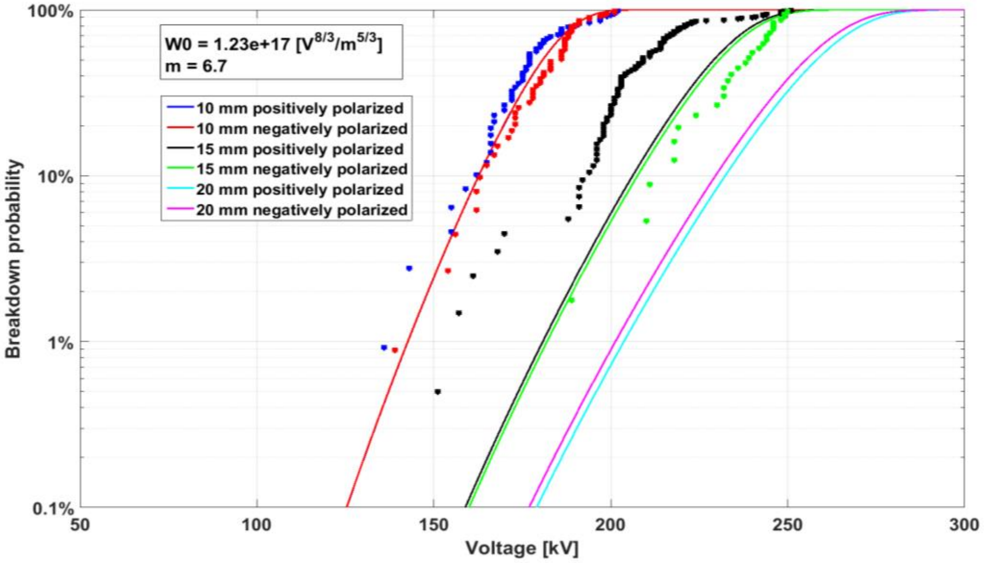
4 tubes tested– AMF

Contact distance 10 mm

Tube	W_0 $[V^3 m^{-5/3}] \cdot 10^{17}$	m
No. A - positive	1.25	6.3
No. B - positive	1.43	9.4
Merged data - positive	*1.09*	*6.2*
No. C - negative	1.29	7.2
No. D - negative	1.69	8.6
Merged data - negative	*1.37*	*7.2*

Application

Vacuum Circuit Breakers **_Research with Siemens – Pulsed Voltage (LIVW)_**



Parameter derived from fitting 10 mm case

$W_0 = 1.23 \cdot 10^{17} \, [V^8 m^{-5}]^{1/3}$; $m = 6.7$

Prediction for d=15 mm

- *Ultimate voltage correctly predicted*
- *Weibull distribution differs from prediction*
- *Large polarity effect unpredicted.*

Mismatch reason is likely due to conditioning process not completed.

To have a "good" sequence of breakdown voltages is fundamental to obtain reliable parameters and effective comparison

Application

Vacuum Circuit Breakers ***Research with Siemens – Pulsed Voltage (LIVW)***

The RMF tube has a remarkable 3D shaping of the contacts.

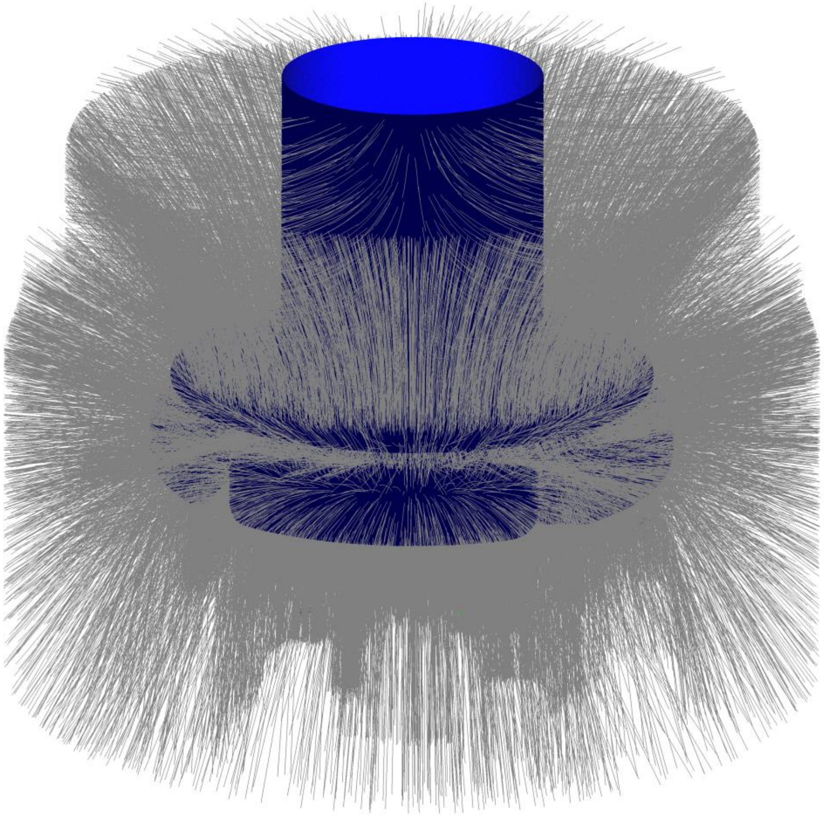
A strong effort has been deployed to upgrade the VHPM to fully 3D features.

The 3D implementation required the use of innovative techinques of mesh optimization, necessary to guarantee correcteness in the trajectory computation, with a reasonable computing time.

A prediction test has been also performed, using W_0 and m derived from AMF tubes, with d=8 mm

Application

Vacuum Circuit Breakers ***Research with Siemens – Pulsed Voltage (LIVW)***



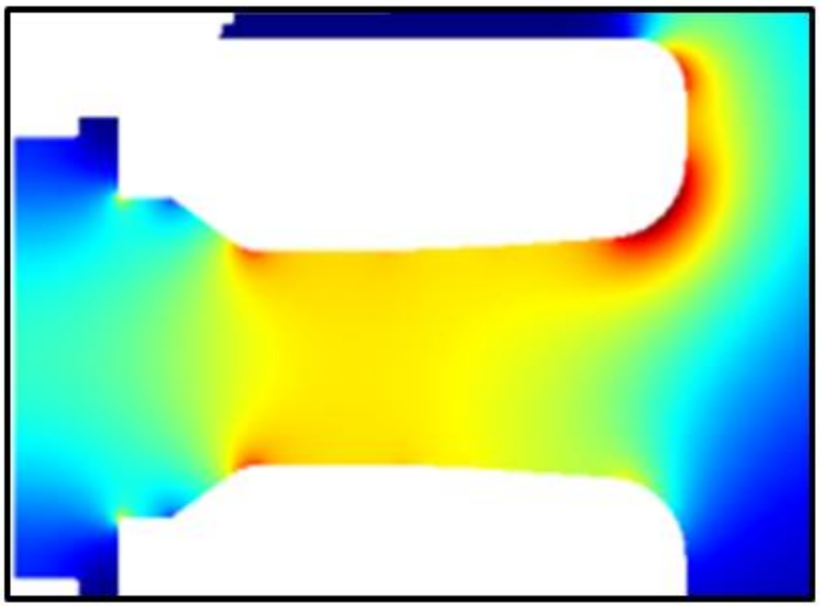
Some million trajectories calculated (only a few shown))

Application

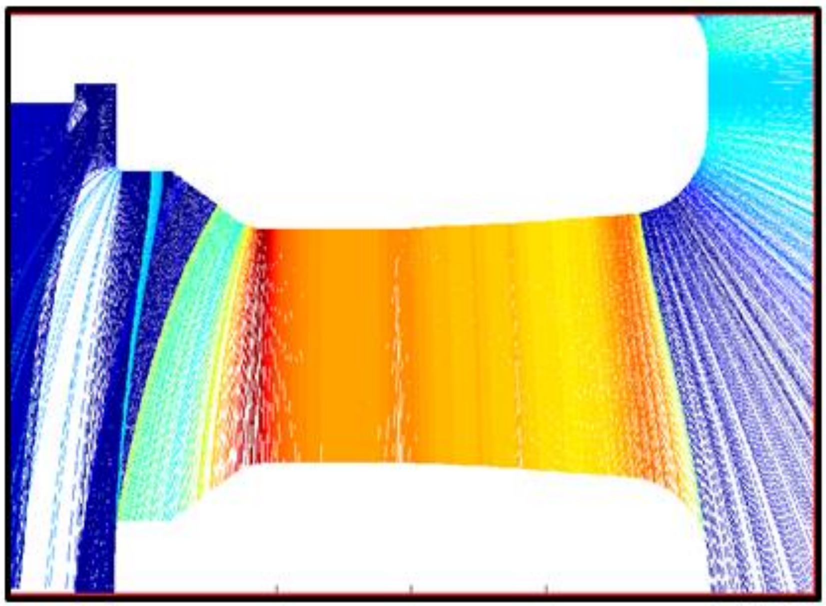
Vacuum Circuit Breakers ***Research with Siemens – Pulsed Voltage (LIVW)***

The most critical points do not correspond necessarily to the highest electric field

Electric Field - Negative Polarity

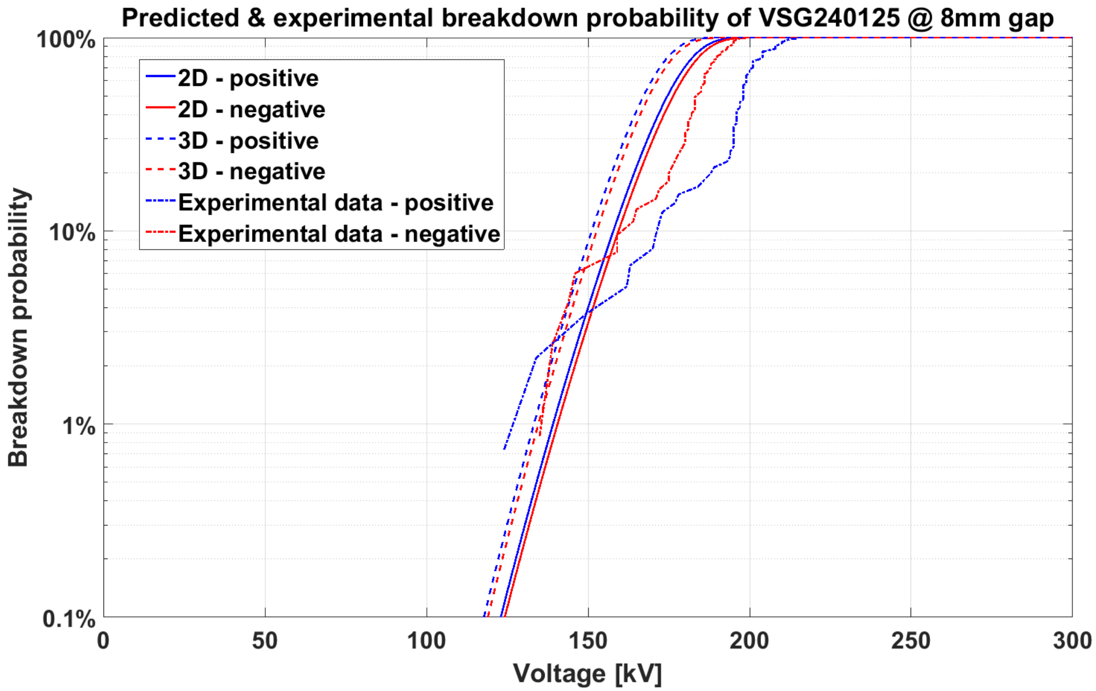


SC triple product- Negative Polarity



Application

Vacuum Circuit Breakers *Research with Siemens – Pulsed Voltage (LIVW)*



<u>Parameters derived from AMF tube</u>

$W_0 = 1.23 \cdot 10^{17}\ [V^8 m^{-5}]^{1/3}$; m = 6.7

<u>Results</u>

- *3D model predicts lower BD voltage than the 2D simplification of the tube*
- *Measured distribution show (surprisingly) a higher voltage than the prediction.*
- *Furthermore, there is a strong polarity effect, that seems not compatible with the gap length (8mm).*
- *A new experimental campaign is planned.*

Conclusions

CONSORZIO RFX
Ricerca Formazione Innovazione

The VHPM has been tested against very different conditions, each characterized by a range of W_0 and m

V_{dc} 200-300 kV Plane-Plane Sphere-Plane Stainless Steel 10-15 mm		V_{dc} 600-1000 kV Accelerators Stainless Steels Copper 200-1000 mm		V_{pulsed} 150-300 kV Sphere -Plane Stainless Steels 10-30 mm		V_{pulsed} 150-250 kV VCB tubes CuCr - Copper Stainless Steels 5-20 mm	
$W_0 \cdot 10^{17}$	M	$W_0 \cdot 10^{17}$	m	$W_0 \cdot 10^{17}$	m	$W_0 \cdot 10^{17}$	m
2.65	**18**	0.115	8	9.5	10	**1.23**	**6.7**
±22%	±45%	-	-	-	-	±18%	±25%

- WHPM seems to be «size dependent». Parameters derived from small setup cannot be used for larger electrostatic configurations.
- Material clearly plays a great role in the W_0 determination
- Error bar in the determination of parameters is still too high. It is due to a non optimal distribution of the voltage breakdown after voltage conditioning.

Conclusions

Future plan

- To obtain «good» voltage breakdown distribution, automatic voltage conditioning procedure will be employed
  - For dc voltage application it is now working
  - For pulsed voltage application to be implemented (work in collaboration with Siemens)
- Implementation of 3D VHPM for the ITER-NBTF accelerator. (to test the effectiveness of intermediate potential screens.
- Investigation on effect of α, γ on the prediction capability.

Thank you for your attention !