Design of the first vacuum and low-pressure gas Insulation Tests for the MITICA 1 MV electrostatic Accelerator

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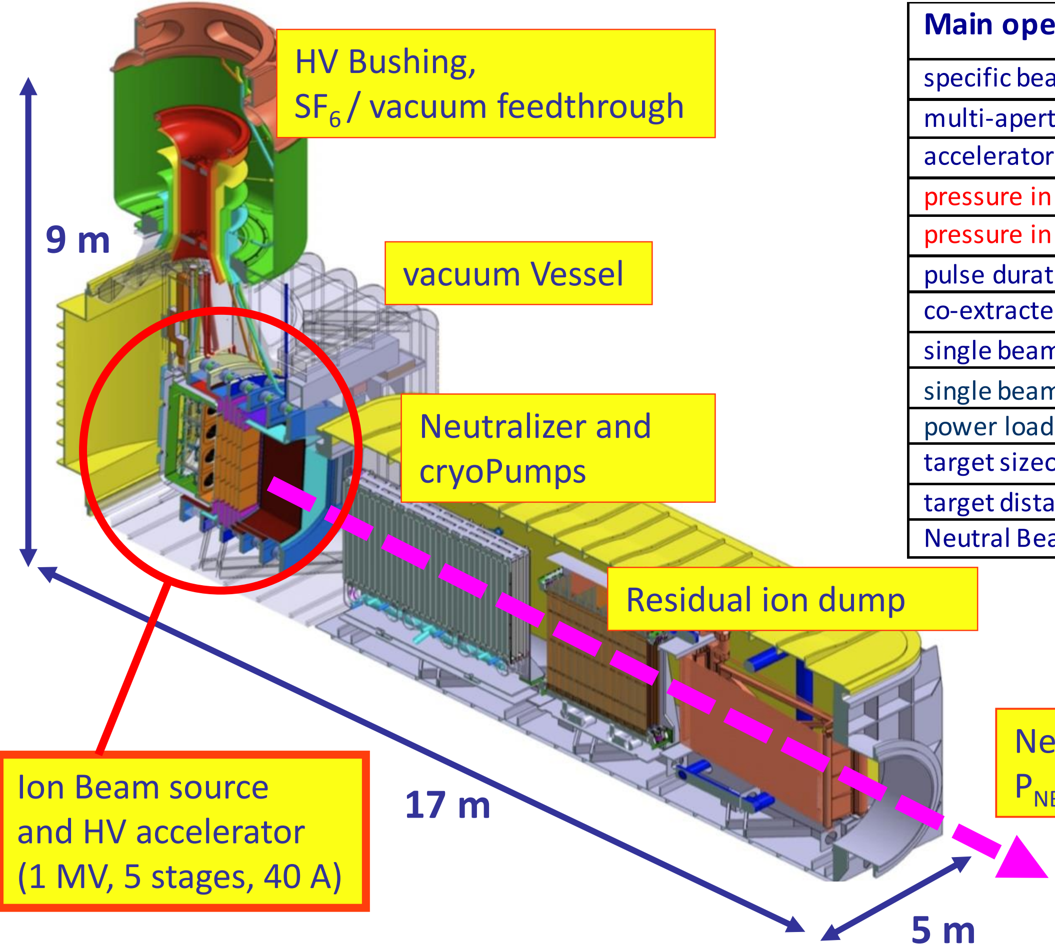
Outline

- The MITICA experiment and the rationale of HV insulation Tests in vacuum and low-pressure gas in the MITICA Vessel
- HV Test set-up and plan: objectives and phases
- Requirements for experimental tests :
  - design of the electrodes
  - electrostatic and voltage holding analyses
  - vacuum system and low-pressure gas injection
  - HV Power Supplies
  - measurement, data acquisition and control equipment, surge protection
- Conclusions

MITICA, the prototype Neutral Beam Injector for ITER

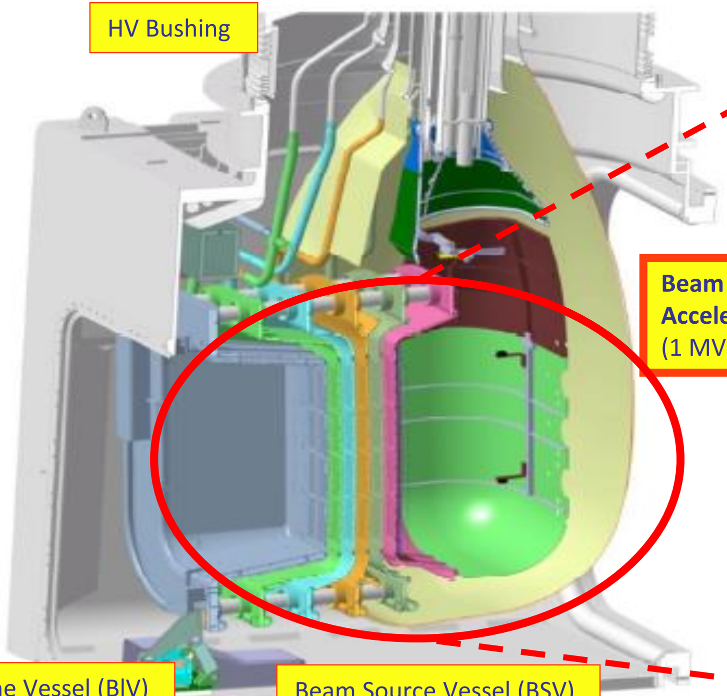
Main operational Parameters		H^0	D^0
specific beam energy	keV	870	1000
multi-aperture, multi-stage configuration		1280 beamlets, 5 stages,	
accelerator current	A	46	40
pressure in plasma source (H2)	Pa	0.3	
pressure in vacuum vessel	Pa	**10^{-5} - $5\ 10^{-2}$**	
pulse duration	s	3600	
co-extracted electron fraction (e-/H- or e-/D-)		<0.5	<1
single beamlet divergence	mrad	<7	
single beamlet deflection	mrad	<3	
power load on accelerato	MW	~ 1.5	
target sizeo (ITER)	m^2	0.23 x 0.4	
target distance (ITER)	m	25.5	
Neutral Beam power	MW	16	



MITICA vacuum vessel

Beam Source Vessel (left) and Beam Line Vessel (right), during construction, both parts are made of AISI 316L stainless steel

MITICA Beam Source and HV insulation

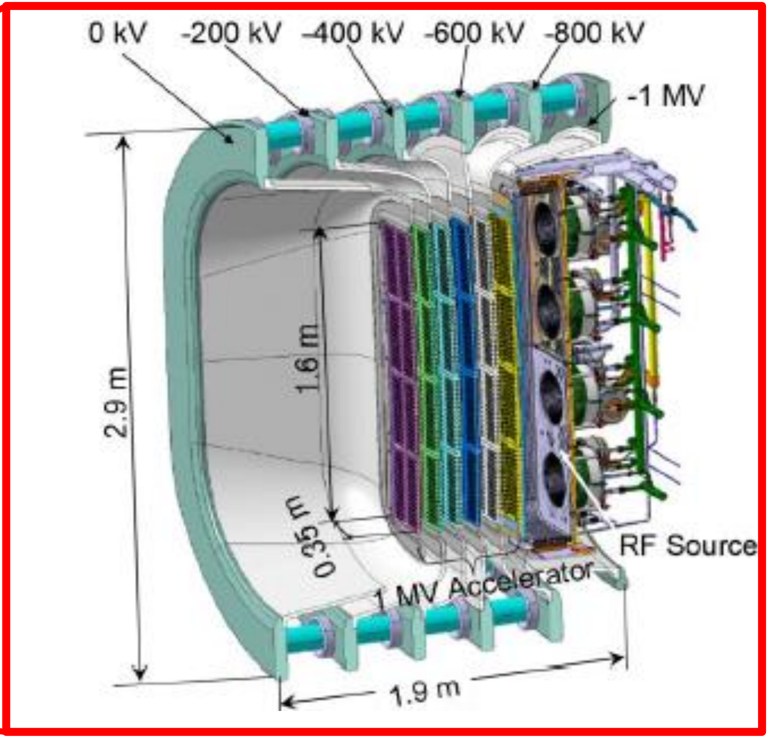


HV Bushing

Beam Source and Accelerator
(1 MV, 46 A, 5 stages)

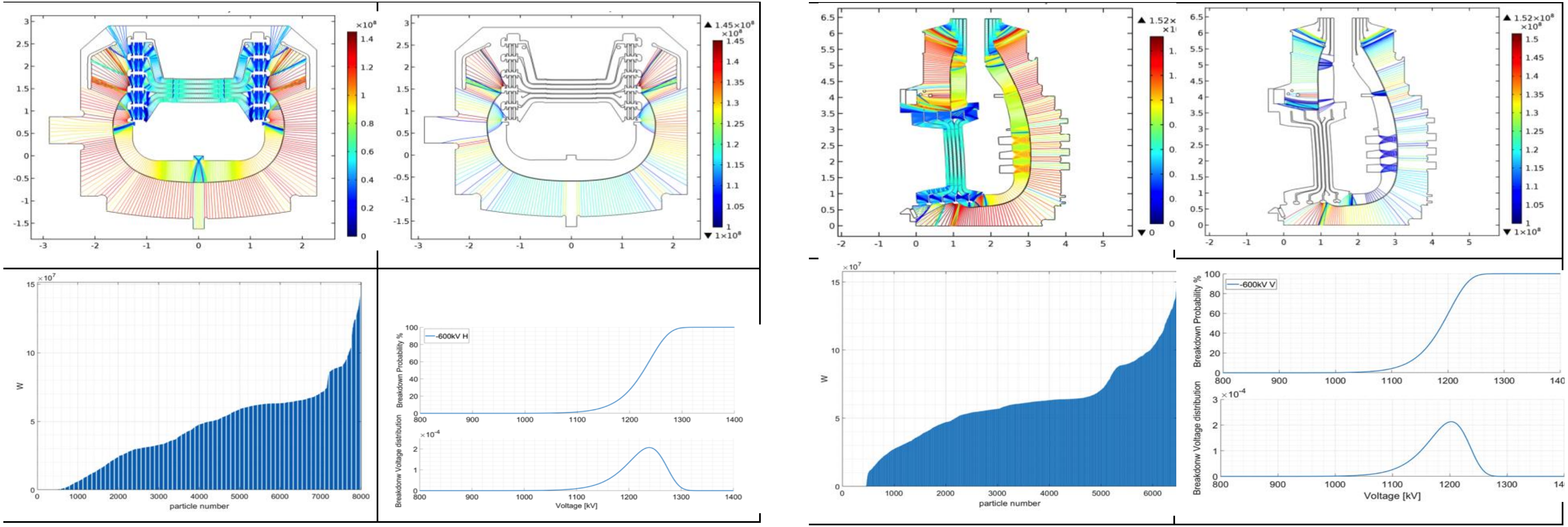
Beam Line Vessel (BlV)

Beam Source Vessel (BSV)



- the Beam Source and Accelerator is a very complex device, electrodes will be made of stainless steel or copper, (for the grids), solid insulator will be made of alumina, delivery is foreseen in ~3y.
- 1 MV voltage holding with respect to the vacuum vessel shall be guaranteed both in high vacuum (~10^{-5} Pa) and in low-pressure gas, up to 5 10^{-2} Pa.

example of Voltage Holding Prediction Model (VHPM)



Horizontal and Vertical cross-section of the MITICA beam source with intermediate electrostatic shield at -600kV: breakdown parameter values and their distribution on different paths, overall breakdown probability as a function of the applied voltage (T. Patton, 2019)

rationale of the HV insulation tests

- numerical prediction models based on most recent experimental results (*) indicate that **voltage holding capability of a single gap (~1 m) between a large electrode at -1 MV and ground may be critical.**

⇒ **HV insulation tests on a full-size mockup**, BEFORE the installation of Beam Source in the MITICA vessel are planned (risk-mitigation measure)

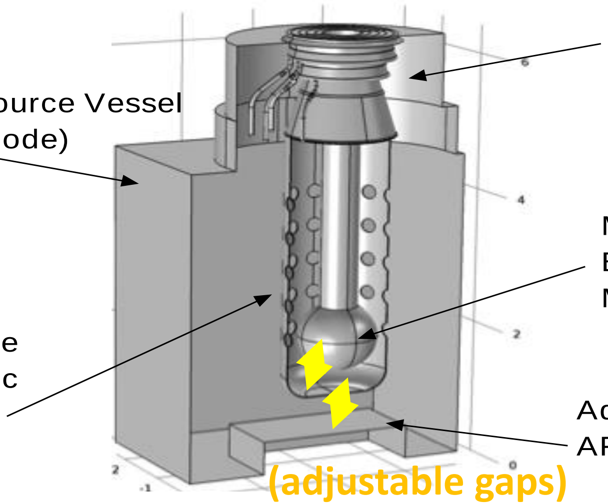
- very "essential configuration" (vessel + one large electrode), with possibilities of geometrical modifications for verification / optimization.
- insulation to be tested both **in vacuum and in low-pressure gas**, using a 1 MV, 10 mA Test Power Supply

⇒ An **Intermediate Electrostatic Shield (2-gap configuration)** can be tested and optimized, if necessary

- two-gap configurations are expected to provide better safety margin.
- general plans and design solutions are ready for review/discussion

(*) N. Pilan, A. Kojima, R. Nishikiori et.al, "Numerical–Experimental Benchmarking of a Probabilistic Code for Prediction of Voltage Holding in High Vacuum", IEEE Transactions on Plasma Science 46 (2018)

setup for the HV tests in the MITICA vessel



High Voltage Bushing
HVB
(with intermediate rings)

Beam Source Vessel
BSV (anode)

Mock-up of
Beam Source
MBS (cathode)

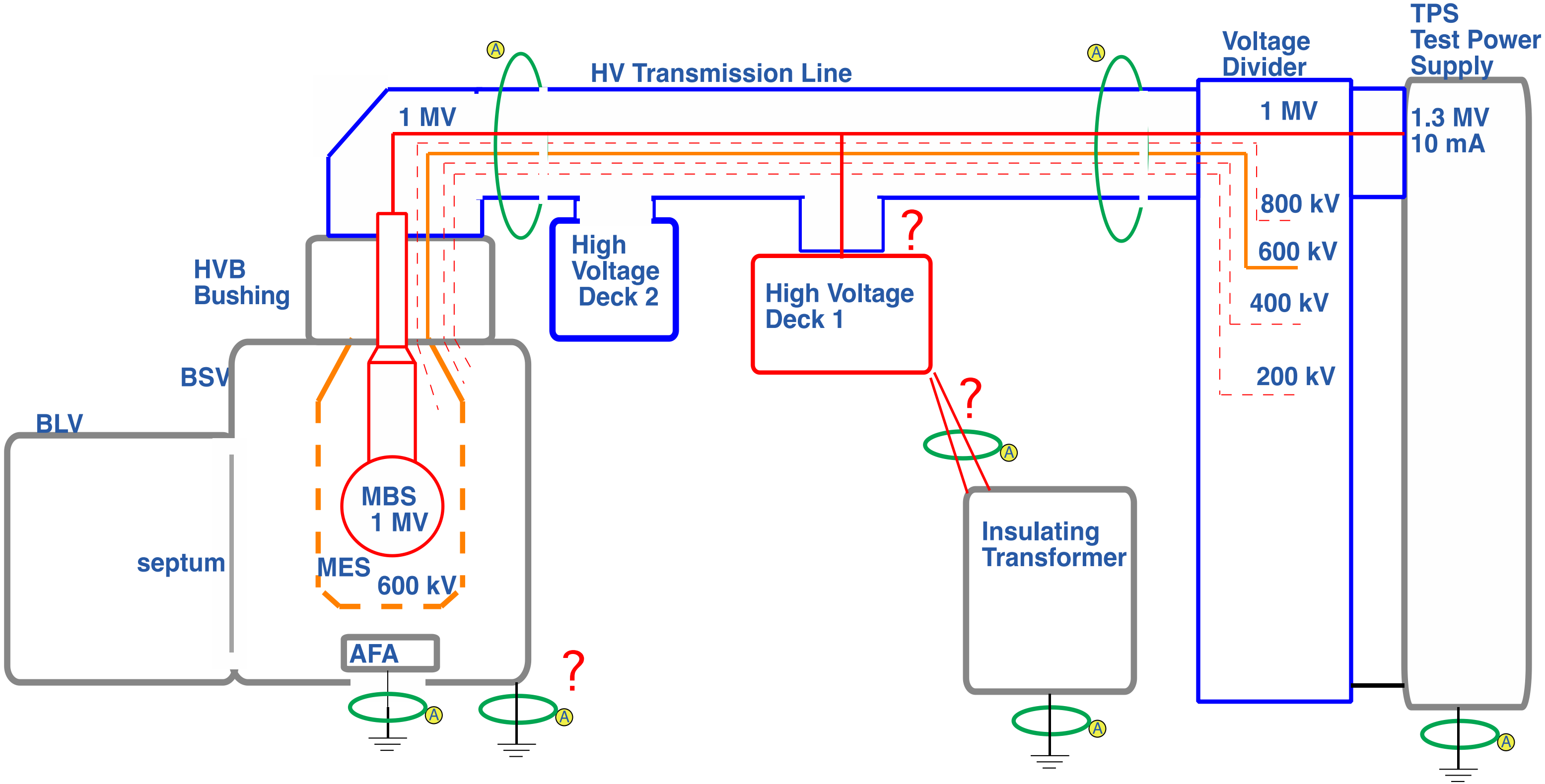
Mock-up of
intermediate
Electrostatic
Shield MES

Additional Flat Anode
AFA

(adjustable gaps)

- Mock-up of the Beam Source (**MBS**) (sphere + cylinder)
- Mock-up of the intermediate Electrostatic Shield (**MES**) (cylinder with holes)
- Additional Flat Anode (**AFA**) (adjustable plane)
- Beam Source Vessel (**BSV**), High Voltage Bushing (**HVB**)
- (not shown) Beam Line Vessel (**BLV**)
- (not shown) High Voltage Transmission line (**TL**)

electric circuit scheme for MITICA HV insulation tests



objectives and phases of the experimental campaign

Phase (a):

measure the voltage holding capability of single-gap insulation between a large electrode representing the Beam Source (Cathode) and the Vacuum Vessel (Anode at ground potential) with:

- adjustable single-gap configuration: 20 mm < minimum gap length < 1.1 m;
- applied electric potential of Cathode: up to -1 MV;
- adjustable pressure conditions: from **high vacuum** ($<10^{-6}$ Pa) to **low-pressure Hydrogen gas** ($\approx 5 \cdot 10^{-2}$ Pa), in steady-state conditions.

Phase (b):

update the Voltage Holding Prediction Model (VHPM) parameters.

- If predicted voltage holding with one gap is sufficient for reliable operation at -1 MV, **proceed with Beam Source construction without Electrostatic Shield**;
- If predicted voltage holding is considered not sufficient for reliable operation at -1 MV, **prepare Mock-up of intermediate Electrostatic Shield and proceed with phase (c)**;
- If predicted voltage holding is marginal, additional experiments with modified electrode geometry and/or specific treatment of electrode surface can be considered for evaluating safety margin (?).

objectives and phases of the experimental campaign

Phase (c):

measure the voltage holding capability with **Intermediate Electrostatic Shield** (2-gap configuration) in the following conditions:

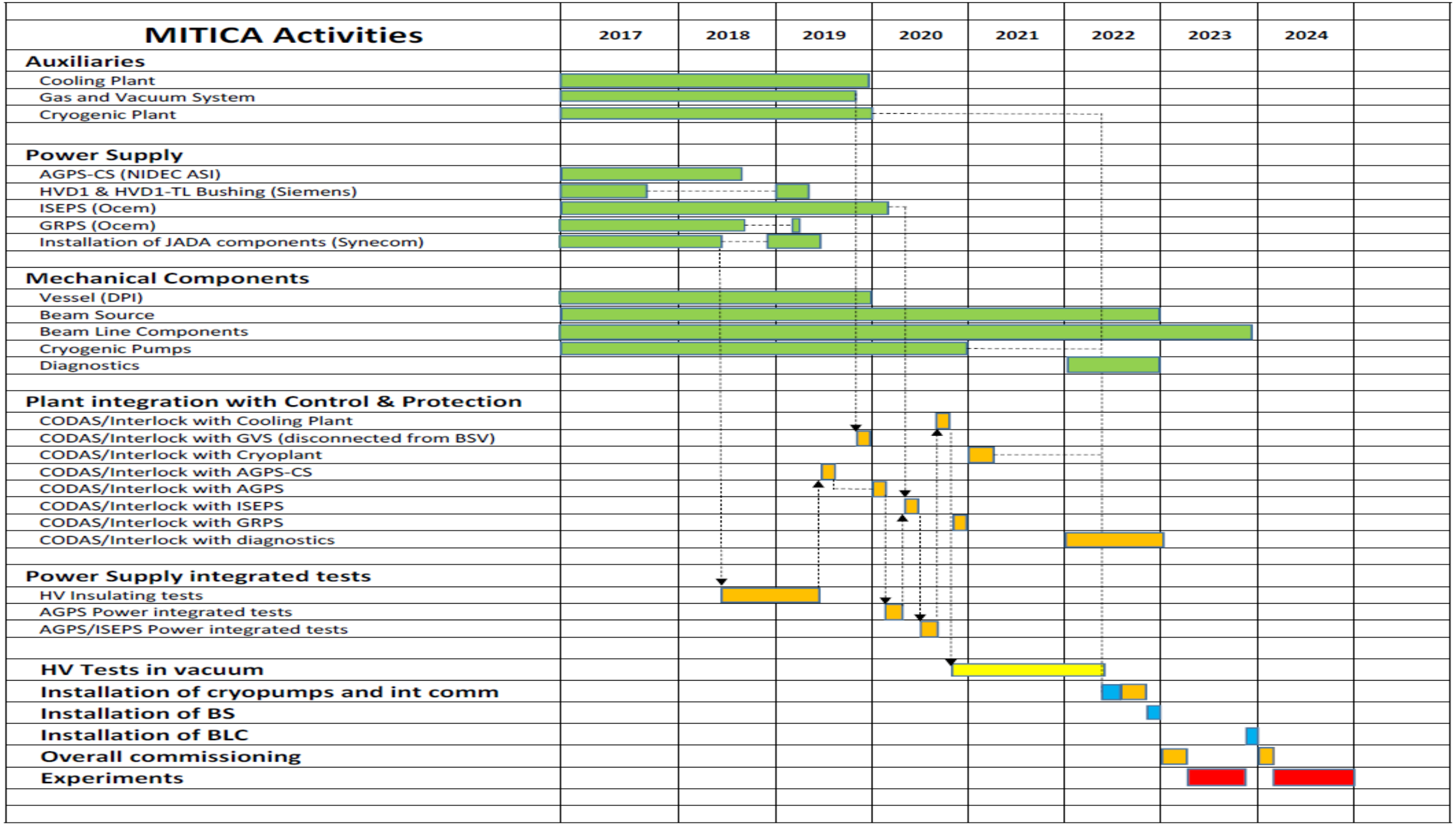
- total gap length ≈ 0.9 m, different position of the Electrostatic Shield;
- Intermediate Electrostatic Shield connected to 2nd or 3rd HVB stage (-400 kV or -600 kV);
- adjustable pressure conditions: from **high vacuum** ($<10^{-6}$ Pa) to **low-pressure Hydrogen gas**, ($\approx 5 \cdot 10^{-2}$ Pa), possibly with pressure gradient (?).

Phase (d):

update the VHPM parameters and **design an optimized Intermediate Electrostatic Shield for the MITICA** Beam Source, so as to achieve a voltage holding capability of 1 MV.

Additional experimental tests similar to phase (c) with improved Intermediate Electrostatic Shield could be performed in the MITICA vessel during this phase.

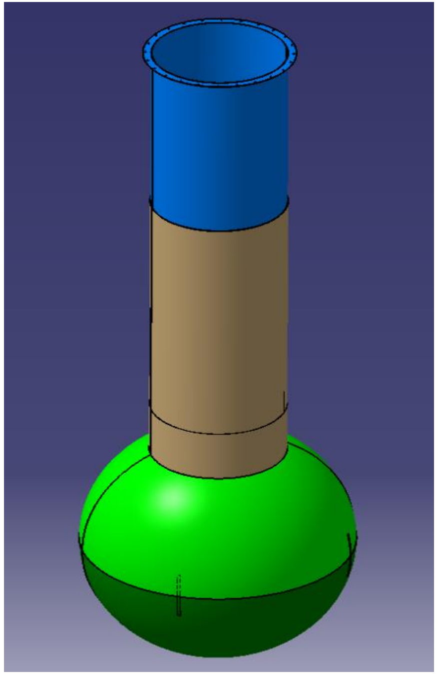
MITICA construction and experimental schedule



MITICA Activities	2017	2018	2019	2020	2021	2022	2023	2024
Auxiliaries								
Cooling Plant	🟩	🟩	🟩					
Gas and Vacuum System	🟩	🟩	🟩					
Cryogenic Plant	🟩	🟩	🟩					
Power Supply								
AGPS-CS (NIDEC ASI)	🟩	🟩						
HVD1 & HVD1-TL Bushing (Siemens)	🟩		🟩					
ISEPS (Ocem)	🟩	🟩	🟩	🟩				
GRPS (Ocem)	🟩	🟩	🟩					
Installation of JADA components (Synecom)	🟩	🟩	🟩					
Mechanical Components								
Vessel (DPI)	🟩	🟩	🟩					
Beam Source	🟩	🟩	🟩	🟩	🟩	🟩		
Beam Line Components	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
Cryogenic Pumps	🟩	🟩	🟩	🟩				
Diagnostics						🟩		
Plant integration with Control & Protection								
CODAS/Interlock with Cooling Plant				🟧				
CODAS/Interlock with GVS (disconnected from BSV)			🟧					
CODAS/Interlock with Cryoplant					🟧			
CODAS/Interlock with AGPS-CS			🟧					
CODAS/Interlock with AGPS				🟧				
CODAS/Interlock with ISEPS				🟧				
CODAS/Interlock with GRPS				🟧				
CODAS/Interlock with diagnostics						🟧		
Power Supply integrated tests								
HV Insulating tests		🟧	🟧					
AGPS Power integrated tests				🟧				
AGPS/ISEPS Power integrated tests				🟧				
HV Tests in vacuum				🟨	🟨	🟨		
Installation of cryopumps and int comm						🟦🟧		
Installation of BS						🟦		
Installation of BLC							🟦	
Overall commissioning							🟧	🟧
Experiments							🟥	🟥

HV insulation test requirements – **cathode**

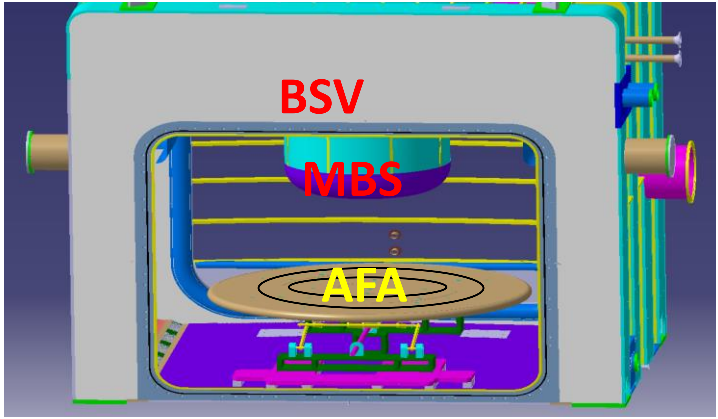
- the **Mock-up of the Beam Source (MBS)** allows starting the tests before the installation of the (real) Beam Source and avoids risks of damages.
- the MBS will be a lightweight structure mechanically attached to the HVB inner conductor. It will consist of a **telescopic cylinder and a sphere** whose diameter (~1m) corresponds to the outer curvature of the real Beam Source.
- the MBS geometry (albeit not 100% representative of the real Beam Source) also allows to adjust (manually) the position of the cathode, facilitating the identification of critical paths for breakdown initiation.
- the outer metallic surface of the MBS (cathode) shall be subjected to the same treatments/cleaning as the real Beam Source.

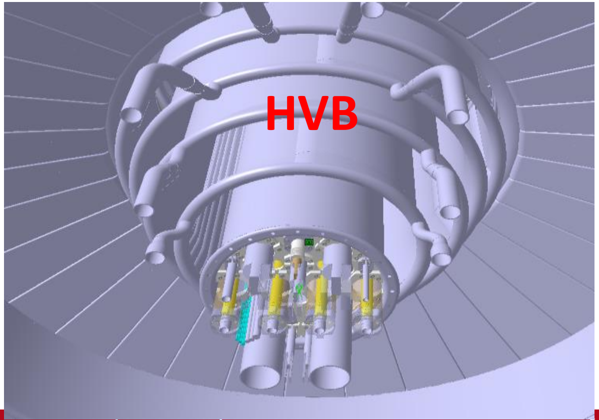


Mock-up of the Beam Source (MBS)

HV insulation test requirements – **anode**

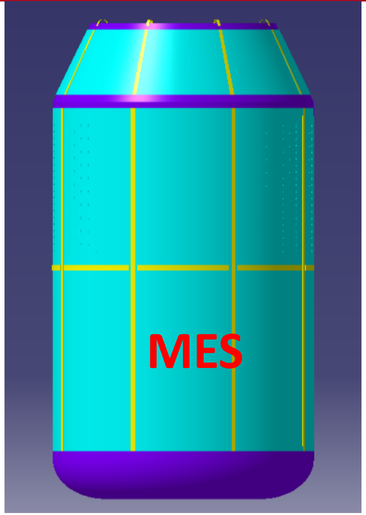
- the anode (at ground potential) will be constituted by the inner Vessel surface.
- an additional anode called **"Additional Flat Anode" (AFA),** consisting of a **flat** stainless steel **surface with rounded edges** will be installed below the MBS. The AFA position can be adjusted manually, or by remote control (?).
- the AFA will constitute the area of the anode where the breakdowns are more likely and will consist of 3 insulated concentric sections, each equipped with a current sensor.
- the surface finishing shall be similar to the inner surface of the vessel, roughness Ra ≤ 3.2 micrometers. If damaged due to breakdowns, the AFA surface can be replaced.
- The tests can start at low voltage (<100 kV) with just few cm gap, then the length of the gap can be increased.

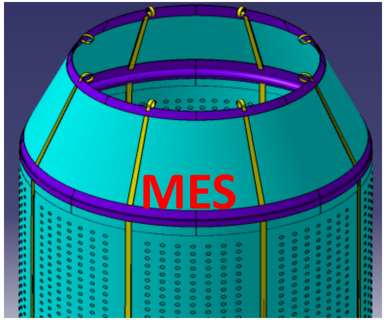




HV test requirements – **intermediate electrostatic shield**

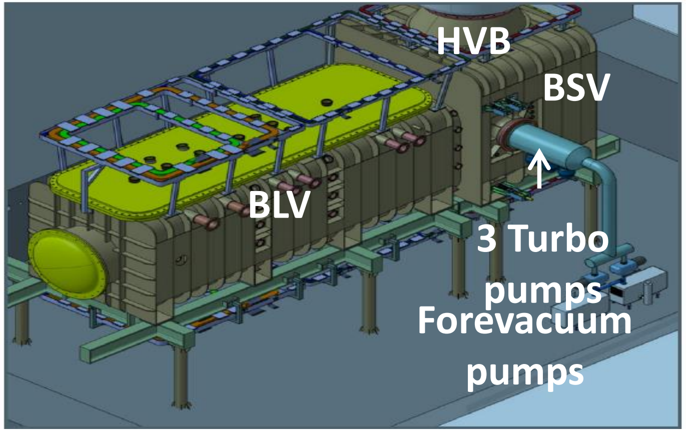
- the Intermediate Electrostatic Shield shall constitute a closed conductive structure, conforming to the shape the equipotential surfaces around the cathode, so as to reduce the electrostatic field and to intercept any accelerated particles (**no straight line of sight**).
- For MITICA, the Intermediate Electrostatic Shield shall also be **“transparent” to gas flow**, to allow efficient gas pumping out of the ion source. It shall consist of **two thin metallic layers, with staggered holes**, mechanically supported by a structure placed in between.
- the Intermediate Electrostatic Shield to be used during phase **(c)** of HV tests is named **"Mock-up of intermediate Electrostatic Shield" (MES)** and shall also be double-walled and shall conform to the shape of equipotential surfaces of the MBS.



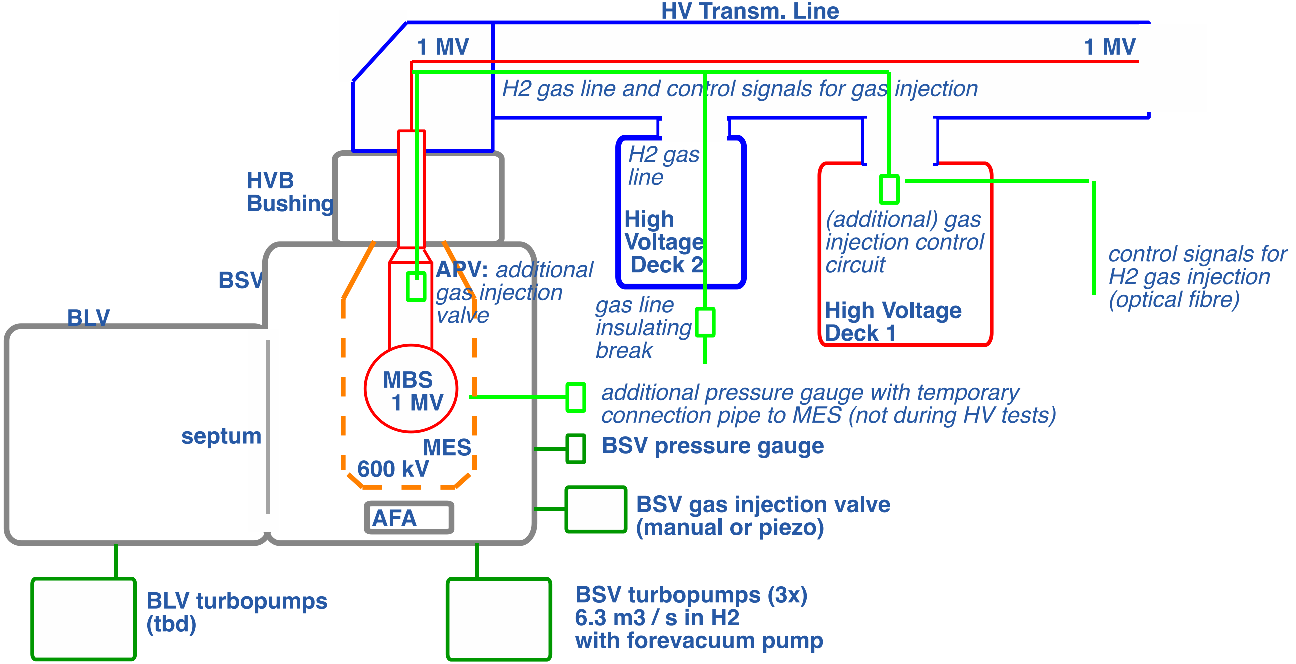


HV test requirements – **vacuum and low-pressure gas**

- turbomolecular pumps with pumping capacity of 6.3 m^3/s are availiable **to pump the BSV** from atmospheric pressure down to 10^{-5} Pa **in a time of the order of 2-3 days.**
- During phase (a), the tests in low pressure gas (≈ 5 10^{-2} Pa) can be carried out by injecting a small flow of Hydrogen gas from a valve located on a port of the vacuum vessel wall.
- a temporary **Septum** between the BSV and the BLV could be used to avoid Townsend-type discharges along very long paths from the MBS towards the BLV (?). The Septum will not be vacuum-tight, but an additional pumping system will be necessary for the BLV.



vacuum pumping and gas injection for MITICA HV tests



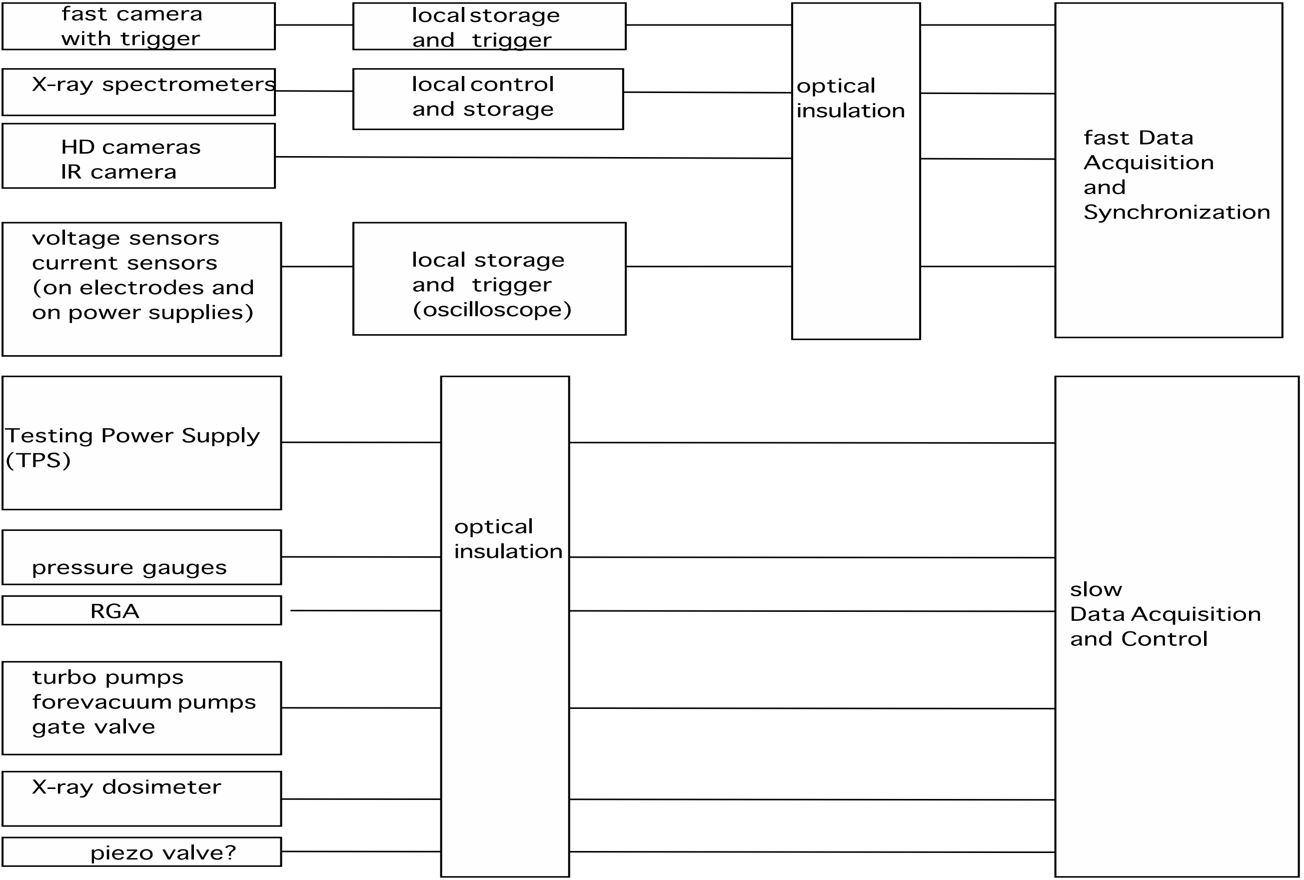
HV insulation test requirements – **gas injection**

- the gas pressure distribution inside and outside the MES shall reproduce the pressure gradient foreseen due to Hydrogen gas flow during the MITICA Beam Source operation.
- for the tests in low pressure gas (up to 0.05 Pa), two options are considered for Hydrogen gas injection
  - Gas Injection from the BSV: **Hydrogen gas is injected using a valve located on a flange on the wall of the BSV**. This solution allows a simple control of the gas flow, the pressure will be uniform in the BSV. However, during phase (c), in the presence of the MES, the pressure distribution will not be representative of the pressure during MITICA operation.
  - Gas Injection from the MBS: **Hydrogen gas is injected through the MBS using a valve located on the -1MV electrode of the HVB** (?) . This will produce a gas flow from the MBS to the pumps through the MES and the BSV. In this case, a realistic gas pressure distribution can be obtained both inside and outside the MES. The gas valve control system shall be insulated for a voltage up to 1 MV.

HV test requirements – **electric circuit and HV Power Supplies**

- a **Testing Power Supply** (TPS) (rated up to –1.3 MV , 10 mA) and the **Resistive Voltage Divider** (RVD) (5 stages of 2000 MΩ) is available from, QST for the insulation tests.
- the High Voltage Deck 2 (HVD2) will remain connected to the TL (?). In order to reduce the stored energy, **the Insulating Transformer and/or the High Voltage Deck 1 (HVD1) will be disconnected from the TL** (?). The MITICA DG Generator (DCG) and DC Filter (DCF) will also be disconnected from the TL.
- on the HVB, in order to avoid transient overvoltages **higher than 200 kV/stage** (which could damage the alumina insulation), surge arrester or spark-gaps shall be installed**.** (?)
- when the Intermediate electrostatic shield (MES) will be installed, it will be connected to the corresponding intermediate ring of the HVB (-600 or -400 kV).

Data Acquisition and Control scheme



fast camera with trigger
X-ray spectrometers
HD cameras IR camera
voltage sensors current sensors (on electrodes and on power supplies)
local storage and trigger
local control and storage
local storage and trigger (oscilloscope)
optical insulation
fast Data Acquisition and Synchronization

Testing Power Supply (TPS)
pressure gauges
RGA
turbo pumps forevacuum pumps gate valve
X-ray dosimeter
piezo valve?
optical insulation
slow Data Acquisition and Control

Conclusions on HV insulation tests in MITICA vessel

- first tests at full voltage (1 MV) , with full-size gaps and electrodes
- simplified geometry and slightly smaller surface area
- single gap (no intermediate shield) or double gap (one intermediate shield)
- tests with gas pressure gradient very complicate
- additional shields (3 or more gaps) not considered at the moment
- many questions are still open

- Comments and suggestions are very welcome !

thank you !