The ITER Neutral Beam Test Facility: status and perspectives

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ITER heating requirements

Neutral Beam Injection (NBI)

- 2(+1) Heating Neutral Beam (HNB)
- 33 MW

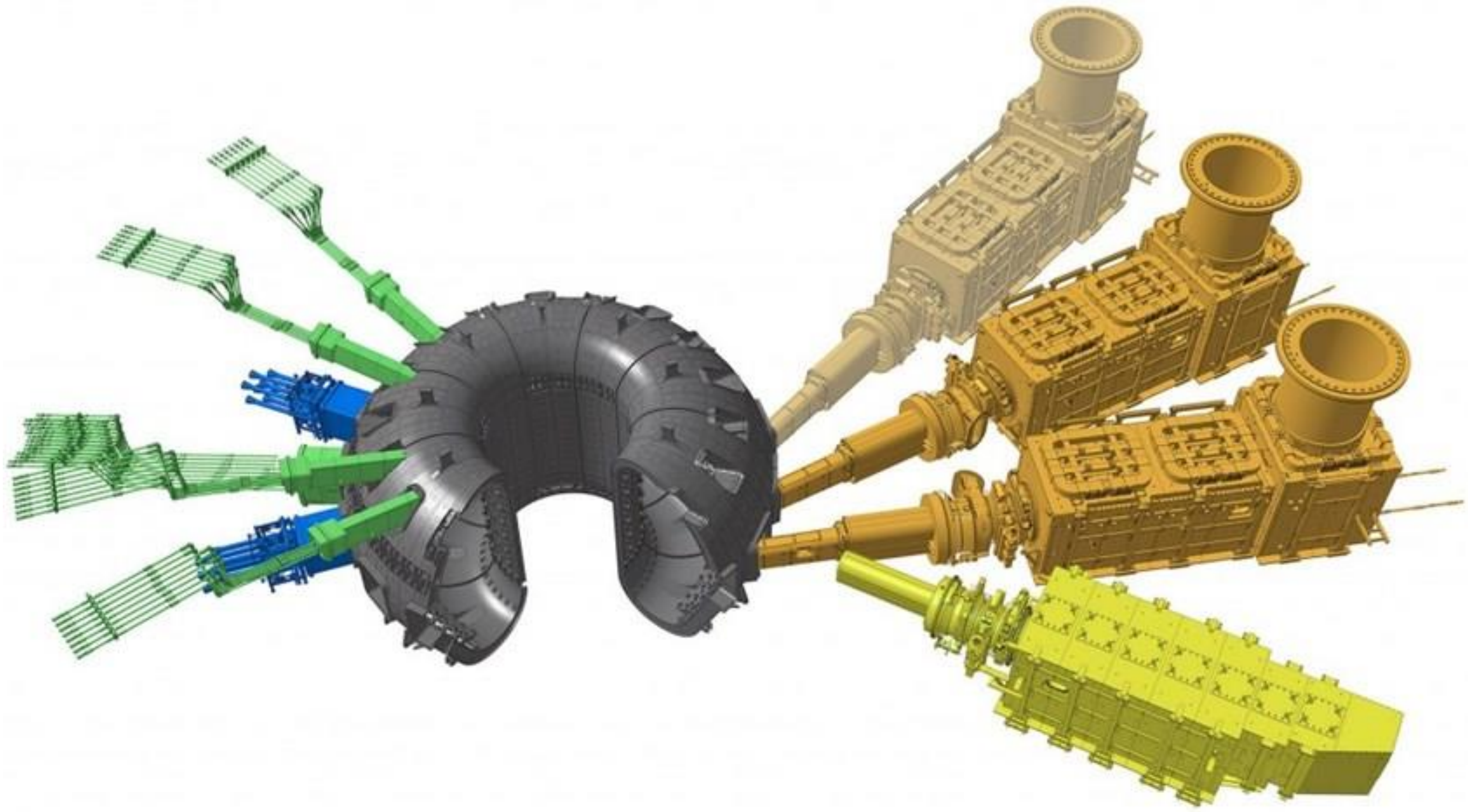
Electron Cyclotron (EC)

- 170 GHz
- 20-30 MW

Ion Cyclotron (IC)

- 40-55 MHz
- 20 MW

1 Diagnostic Neutral Beam (DNB)



https://www.iter.org/mach/heating

ITER NBI

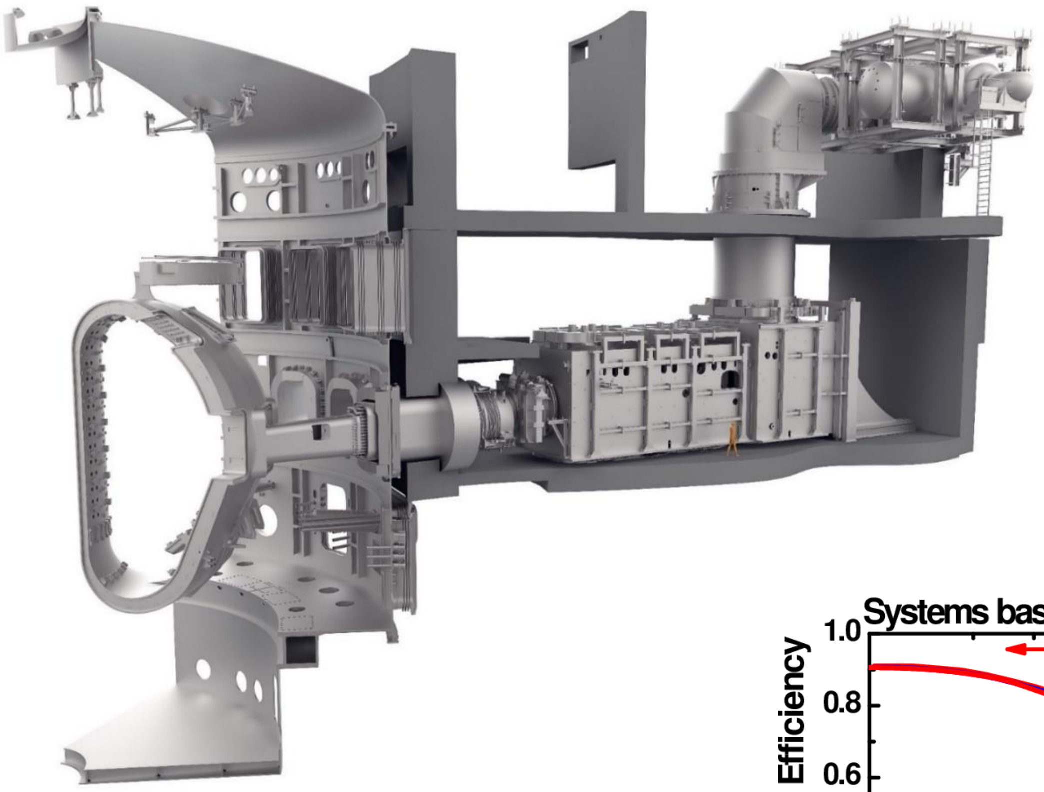
2 (+1) HNB (deuterium)

- V = 1 MeV
- I = 40 A
- div = 7 mrad
- t_{pulse} = 3600 s
- P_{beam} = 16.5 MW

1 DNB (hydrogen)

- V = 100 keV
- I = 60 A
- t_{pulse} = 3 s every 20 s
- F_{mod} = 5 Hz

Negative ion beam source needed!



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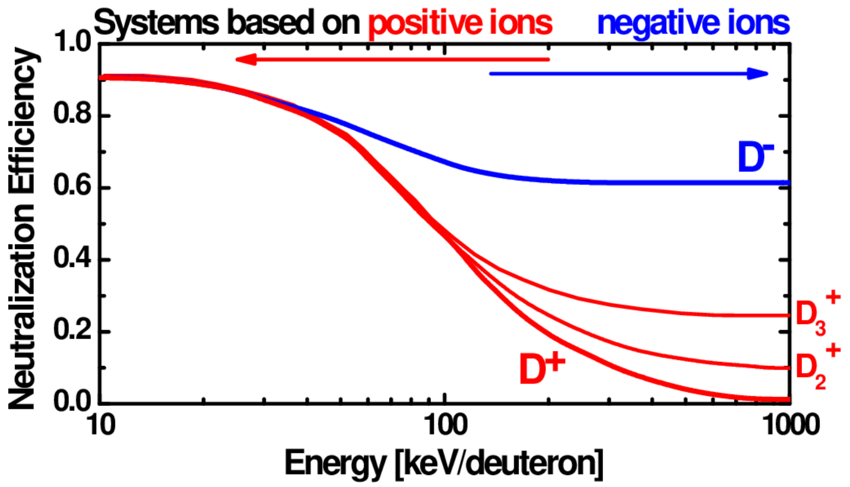
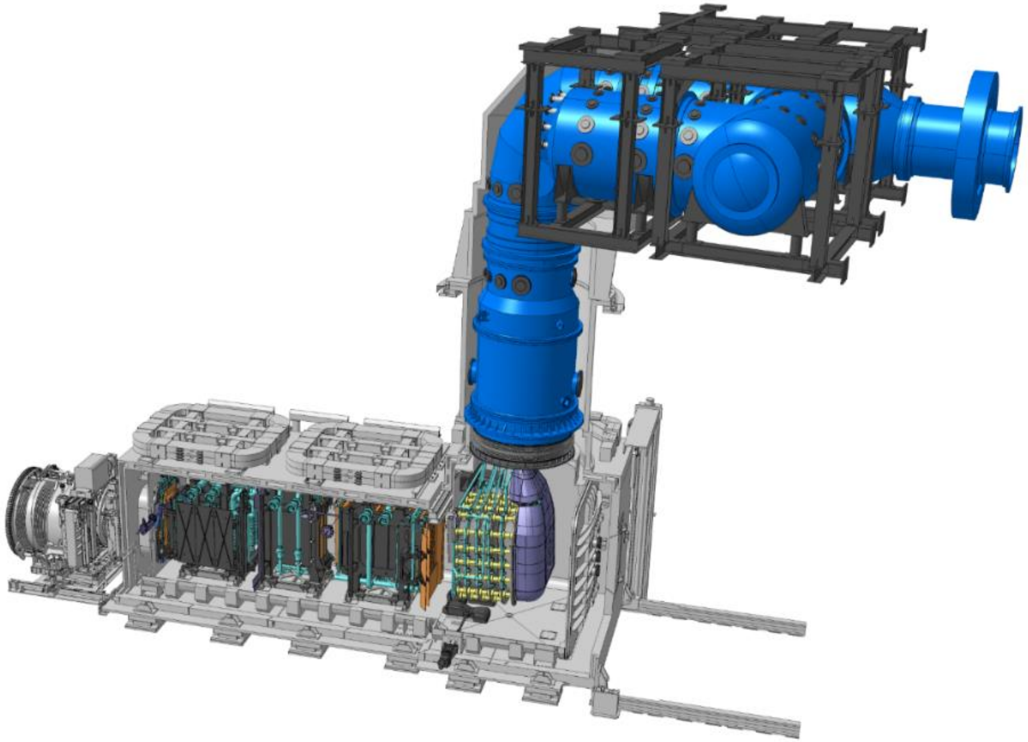


(HNB) Critical components

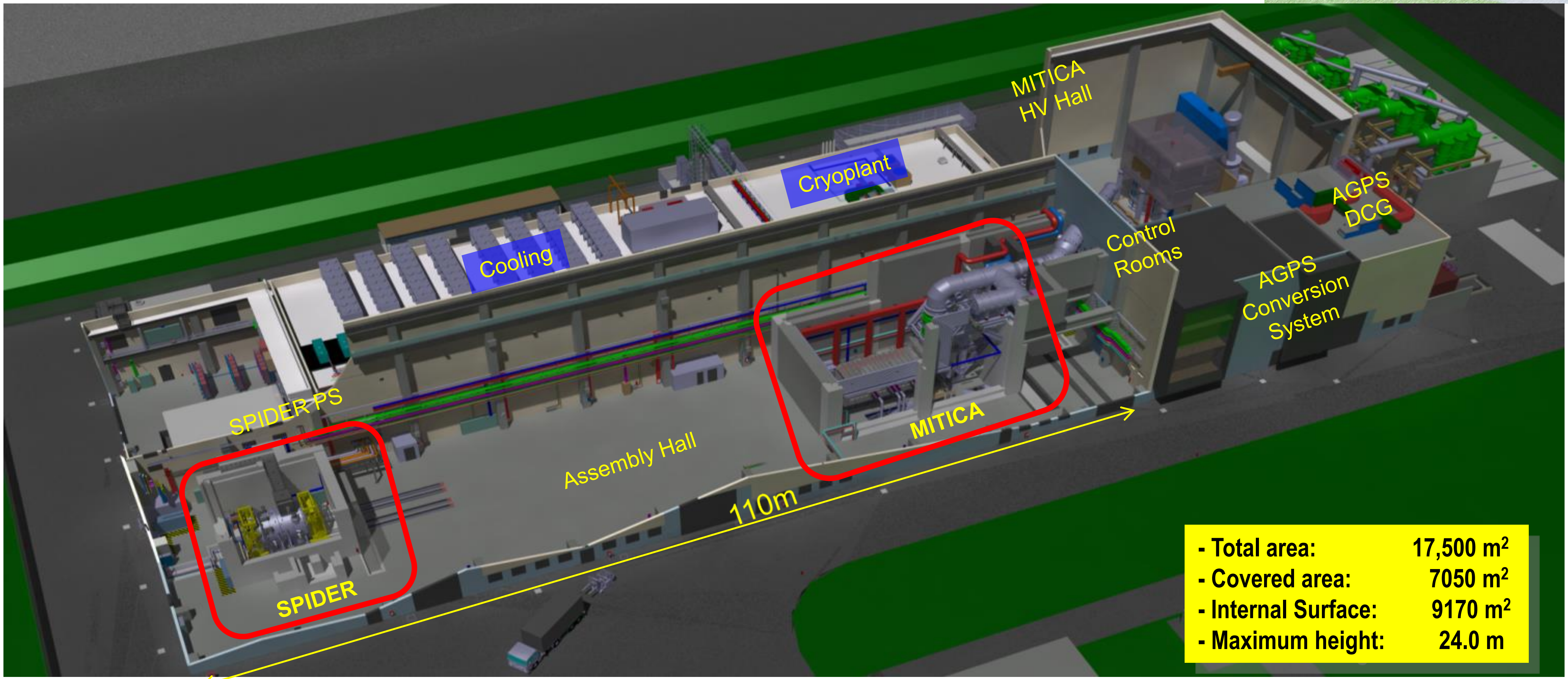
- Critical components which have direct impact on functionality:
  - Negative ion beam source to produce 40A of D-,
  - Caesiated source
  - 1280 beamlets
  - Vacuum insulated source
  - 1MV beam acceleration
  - 1MV voltage holding
  - 1MV Transmission line and feedthrough - HVB
  - Electrostatic RID



- The criticality and step from current technologies used in NBI justified the need for a Neutral Beam Facility (NBTF), aimed mainly at:
  - *achieving nominal parameters of source and beam*
  - *optimizing HNB operation*

- and consisting of:
  - ✓ **SPIDER:** optimisation of ion source: current density, uniformity, stability
  - ✓ **MITICA**: full-size prototype of ITER NBI: high voltage holding, beam optics

The ITER Neutral Beam Test Facility



- Total area:	17,500 m^2
- Covered area:	7050 m^2
- Internal Surface:	9170 m^2
- Maximum height:	24.0 m

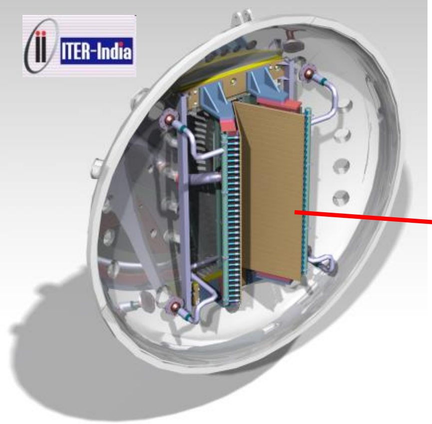
NBTF hosts the two experiments: the negative ion source **SPIDER** and the 1:1 prototype of the ITER injector **MITICA**

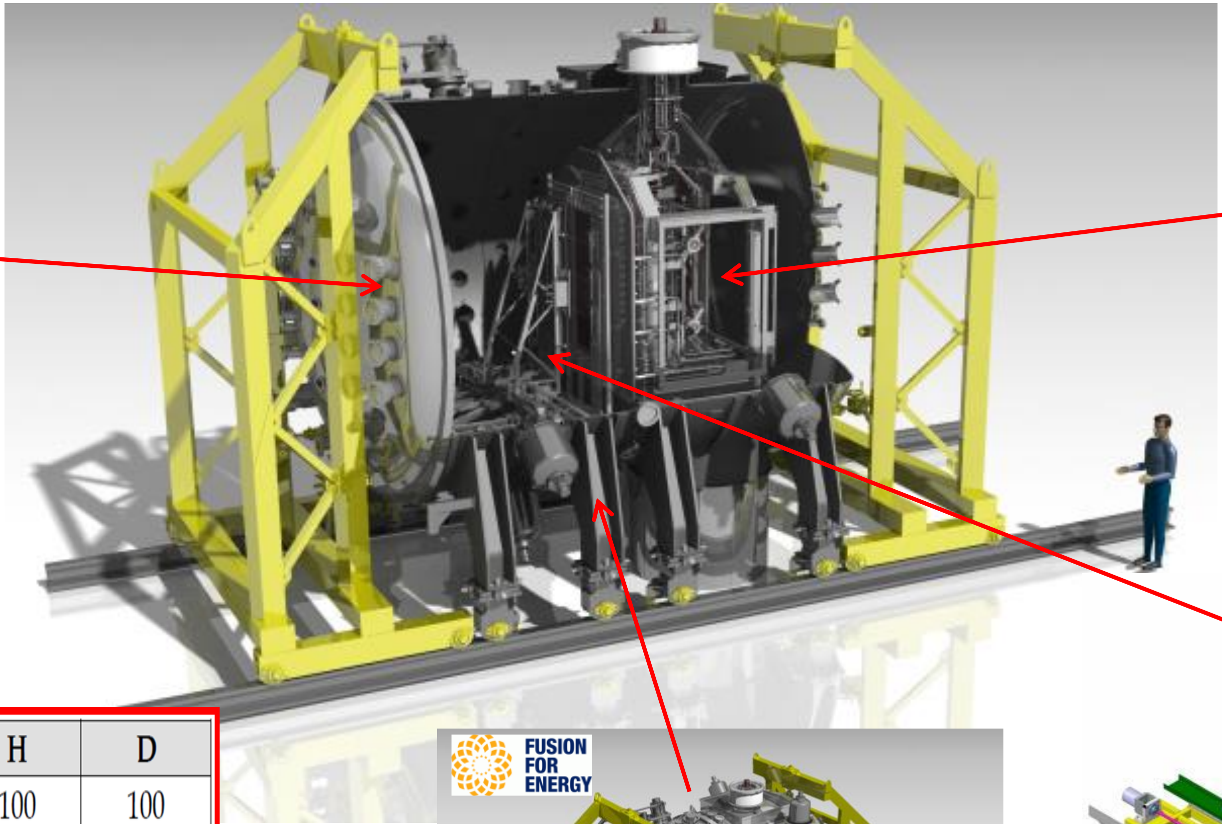
Each experiment is inside a concrete biological shield against radiation and neutrons produced by the injectors

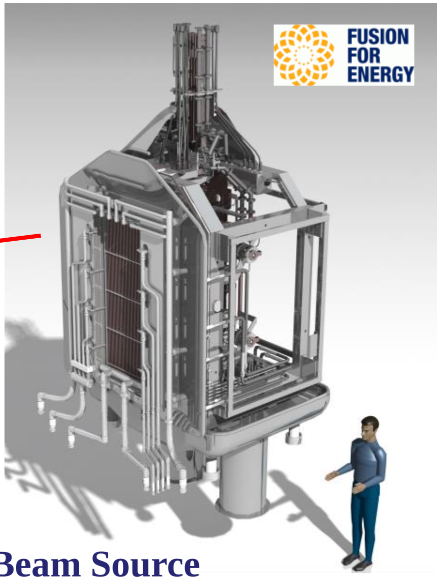
Thanks to these shielding the assembly/maintenance area will be fully accessible also during experiments

SPIDER: the full scale prototype of the ITER HNB/DNB ion sources

Vacuum-insulated beam source

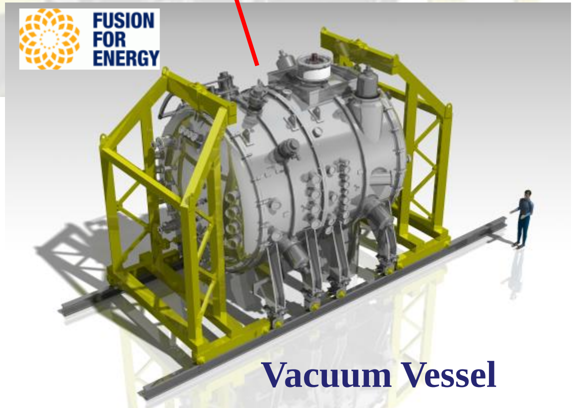




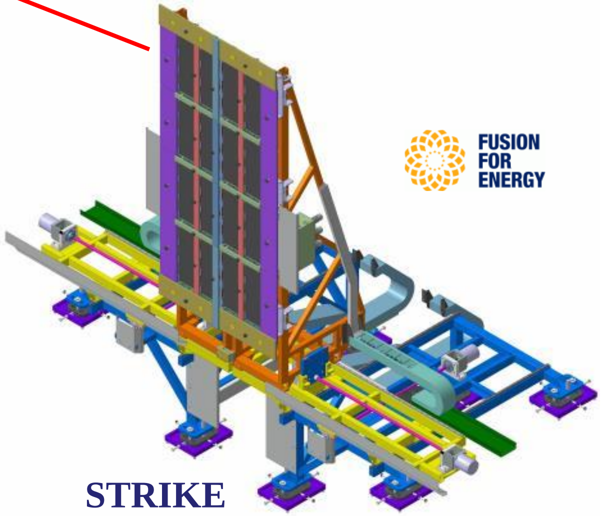


Beam Source

	Unit	H	D
Beam energy	keV	100	100
Maximum Beam Source pressure	Pa	<0.3	<0.3
Uniformity	%	±10	±10
Extracted current density	A/m²	>355	>285
Beam on time	s	1000	3600
Co-extracted electron fraction (e^-/H^-) and (e^-/D^-)		<0.5	<1

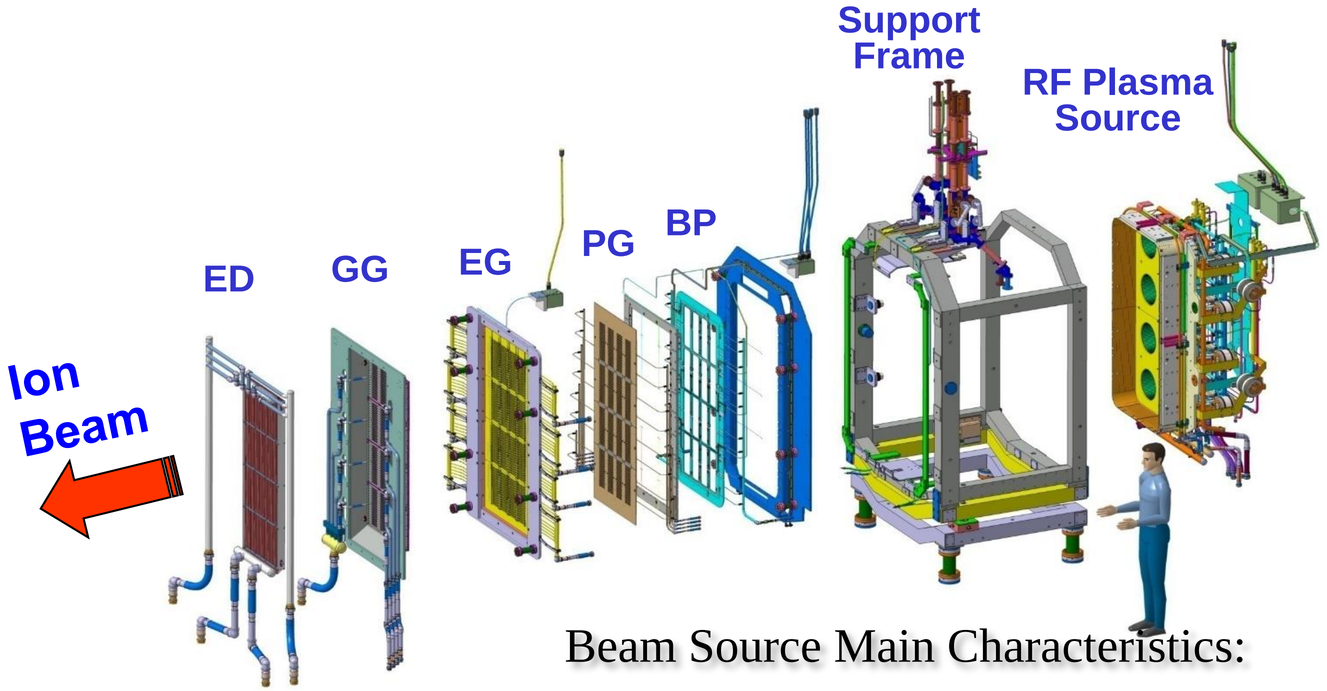


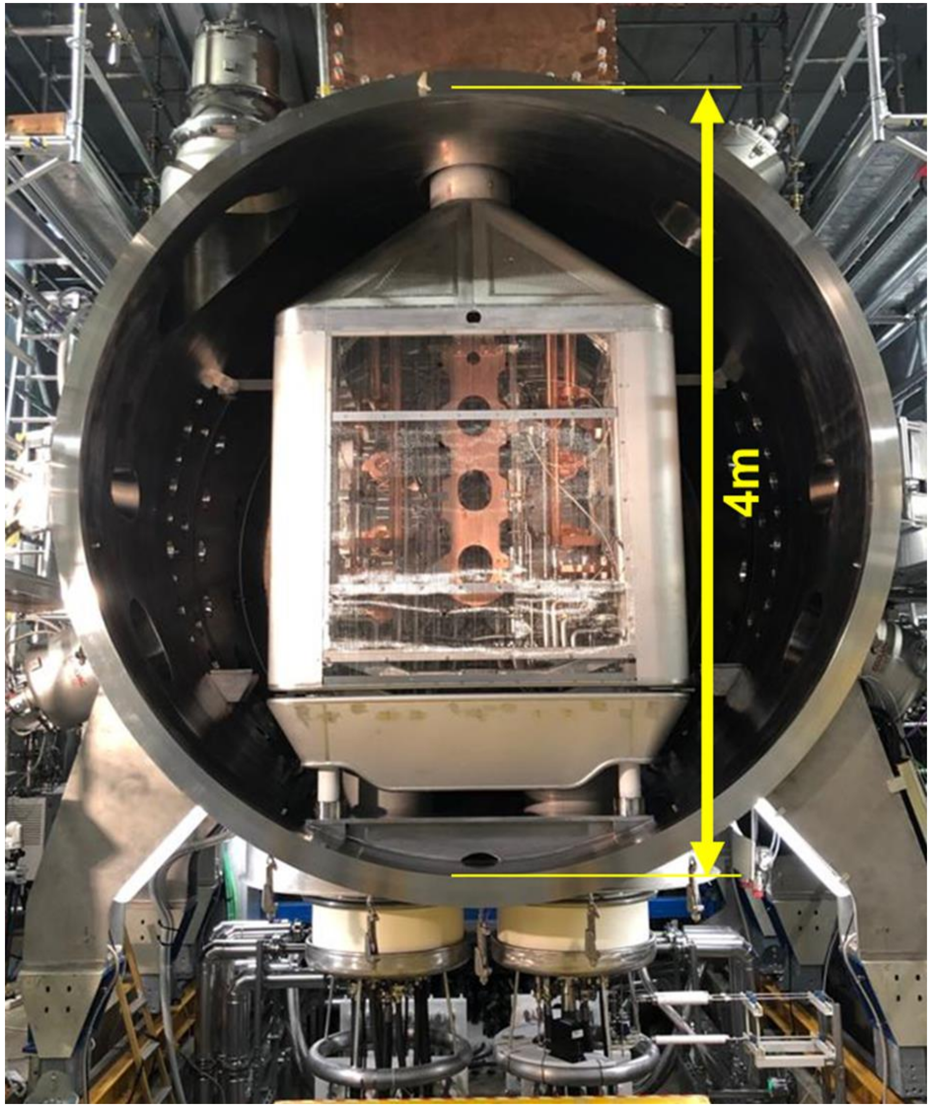
Vacuum Vessel



STRIKE
High resolution calorimeter

The SPIDER Negative Ion Source





- BP = Bias Plate
- PG = Plasma Grid
- EG = Extraction Grid
- GG = Grounded Grid
- ED = Electron Dump

Beam Source Main Characteristics:

- Size: 2x2x5 [m] (overall)
- 8 RF drivers
- 3 Grids: PG, EG, GG
- 1280 beamlets
- Electron dump
- Electrostatic screen

SPIDER Status

first plasma — 2018

influence of vessel pressure on RF discharges clarified

first extracted beam, masking most extraction apertures — 2019

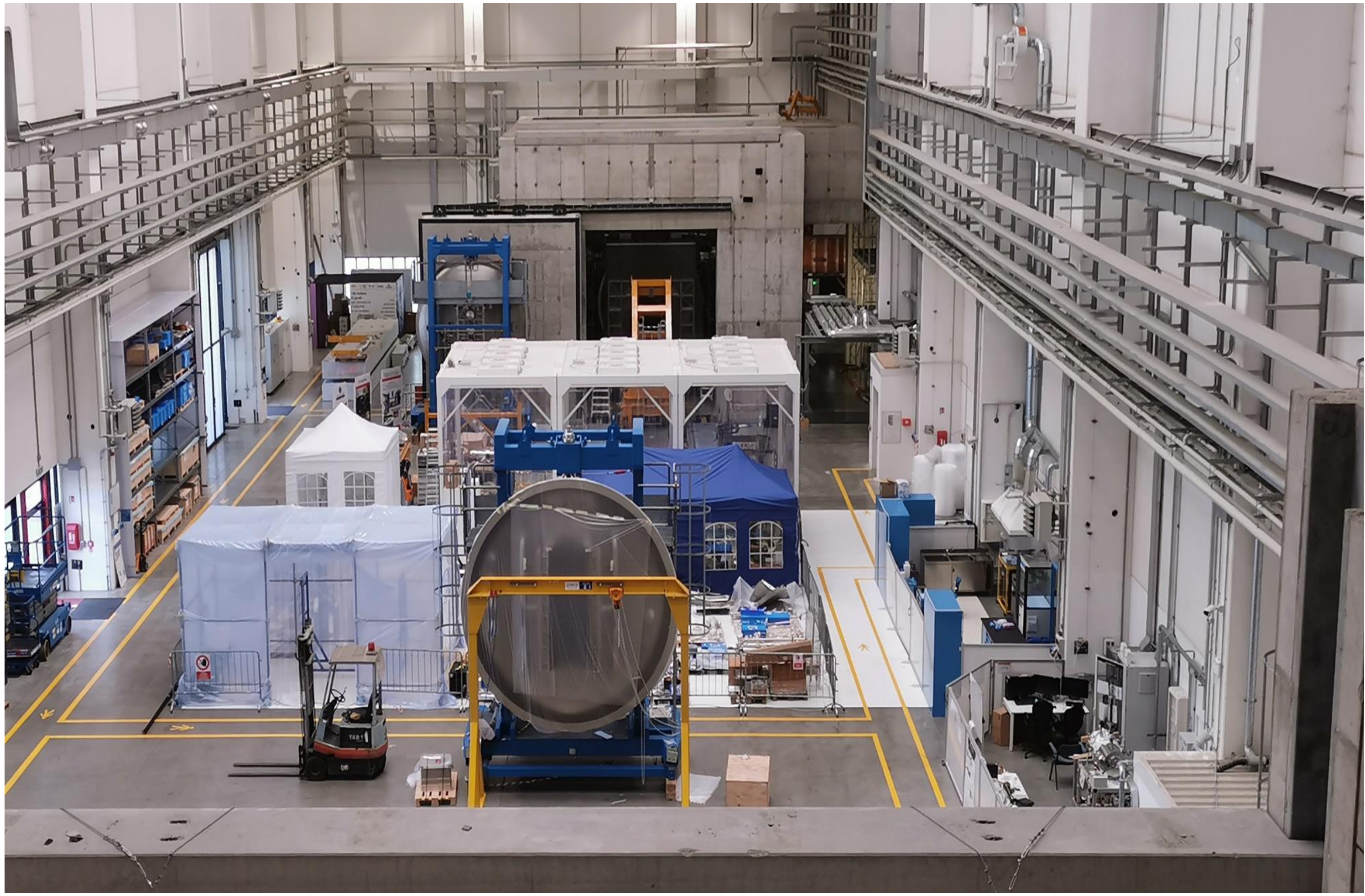
source plasma studied with movable probes

Improving availability and reliability [1h/day plasma on] — 2020

HV >30kV available

First operation with caesium — 2021

shutdown for improvements

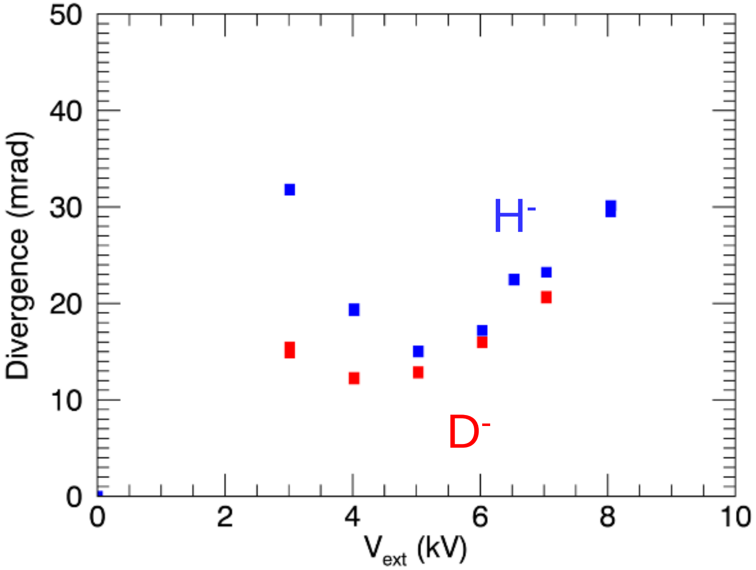


Main results of SPIDER: first caesium operation

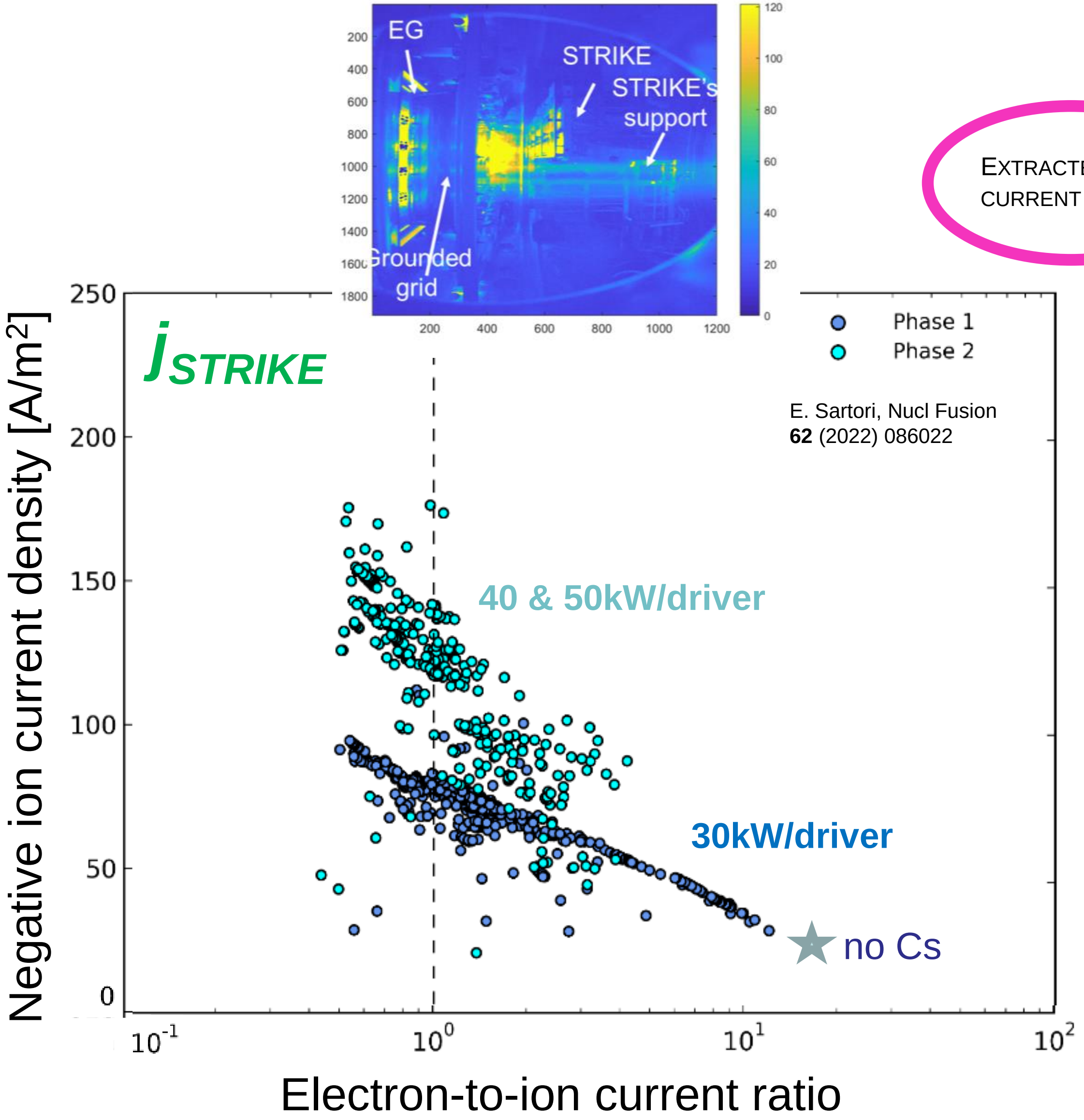
Target **electron to ion ratio** already obtained

Current density still lower than requested, waiting to increase further P_{RF}

Investigation ongoing to improve **divergence** towards 7 mrad target (and negative ion current density): plasma density to be increased

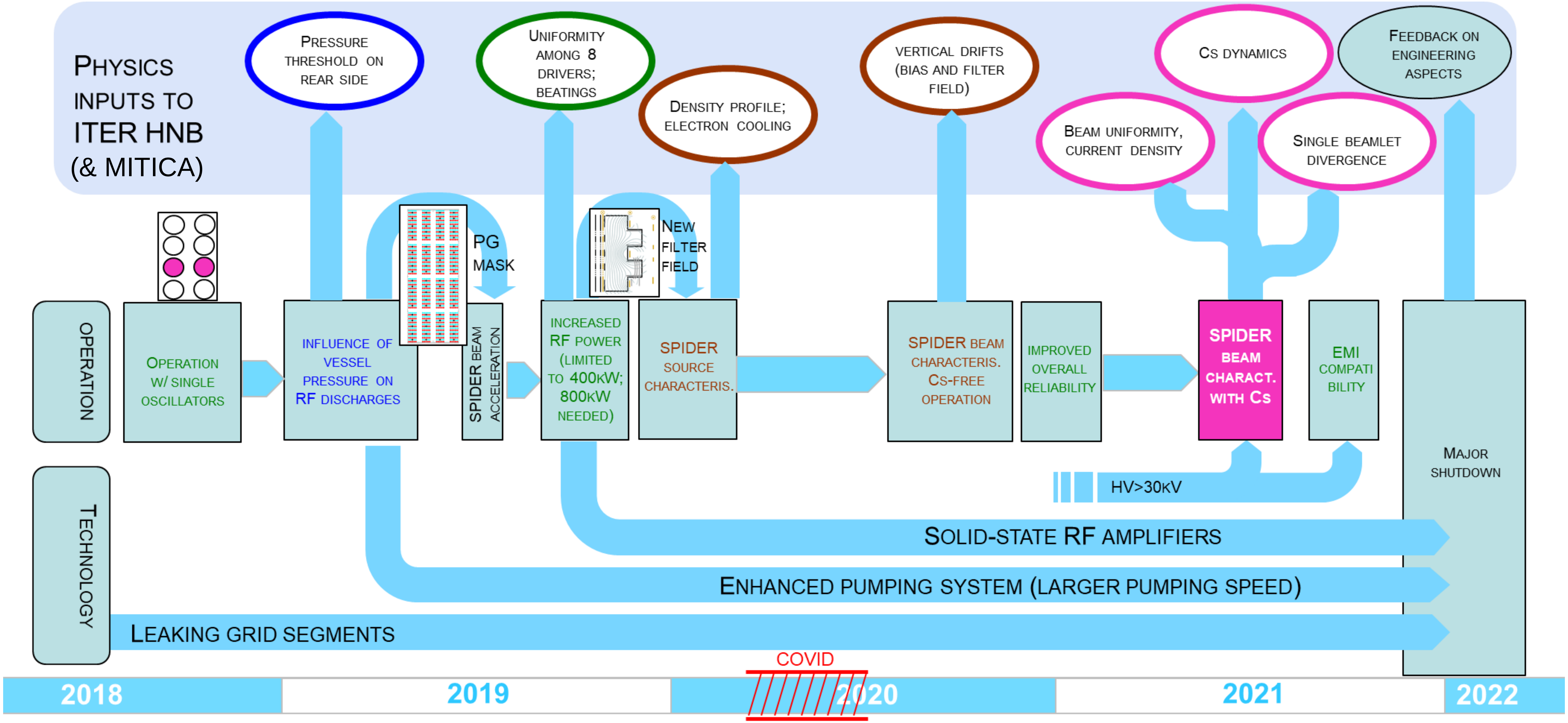


DIVERGENCE



EXTRACTED CURRENT DENSITY

SPIDER: summary of the campaign so far

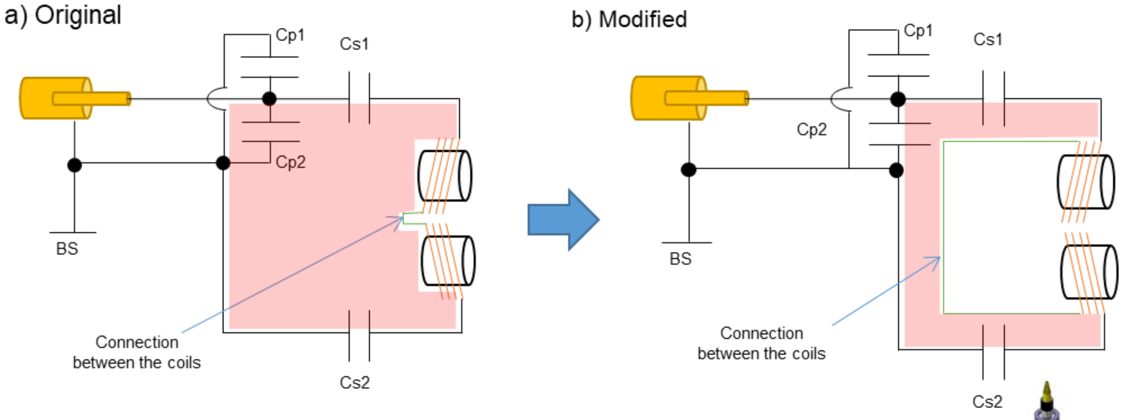


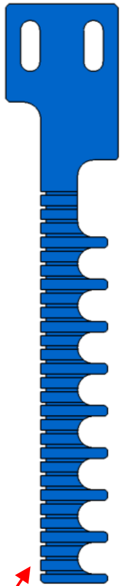
SPIDER shutdown: refurbishment & upgrade

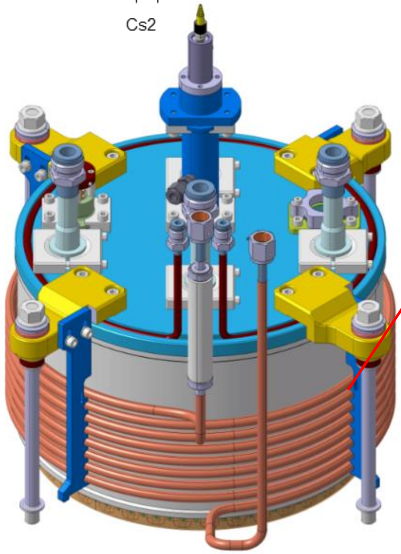
Among a large number of refurbishments and modifications, the core line of shutdown activities tackles the quest to the target SPIDER parameters (uniformity, current density, divergence), hence implying **full beam**, **high RF power** and **high voltage** with no discharges:

- Vacuum pumping system enhancement, in order to keep pressure outside of the source under threshold values with no masking, hence all beamlets
- Replacement of RF generators based on tetrodes with solid-state amplifiers, in order to maximize the power transferred to the plasma and maximize ion current density
- SPIDER - RF Driver & electrical layout enhancement: minimization of discharge ignition chances, via improvement to the RF circuit layout and connections onboard the beam source, to enhance local electric field distribution and minimize cross talk between RF circuit

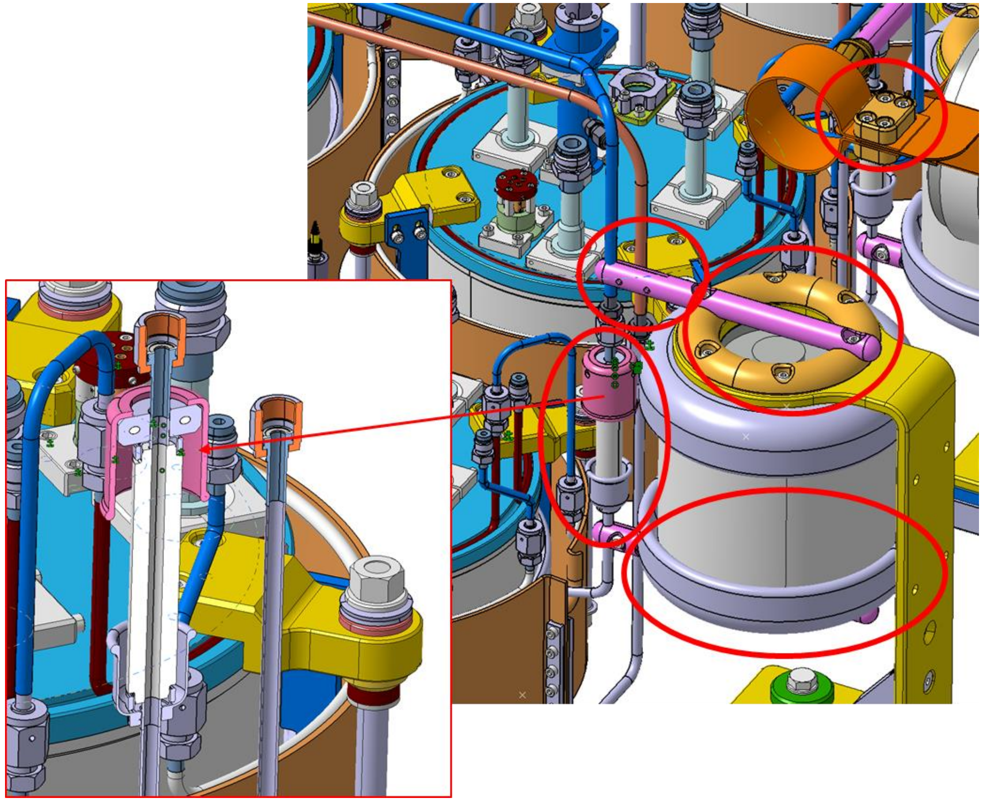
Beam Source modifications







	Original configuration	Improved configuration
Driver case material	Alumina C799	Quartz
RF coil material	Cu-DHP	AISI 304 + electrodeposited Cu
Number of turns	8.5	8



RF driver modifications *(quartz case, stainless steel -copper coated RF coils, 1mm distance between RF coil and driver case, new coil support combs, EMSs electrically insulated from RDP) =>* **reduction of local E-field**

RF power circuit modifications *(electrostatic screens around triple points, new smooth electrical connections, overall RF circuit layout revised to reduce mutual inductance among drivers)*

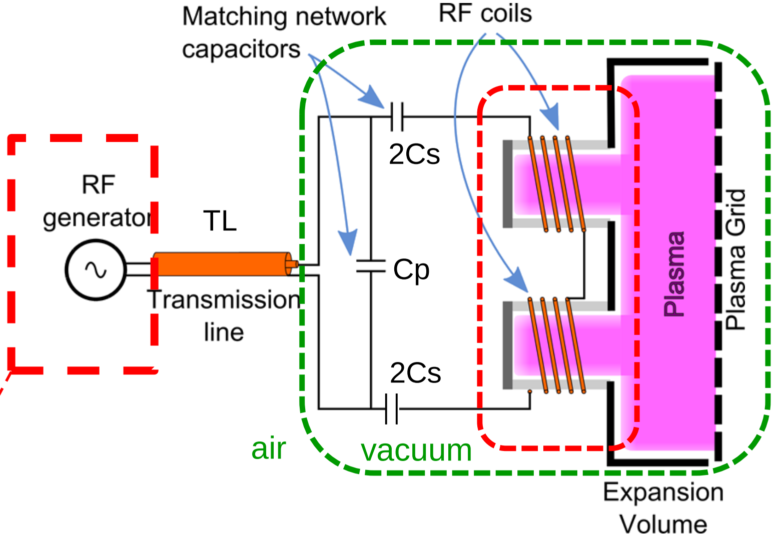
Procurements for new parts ongoing

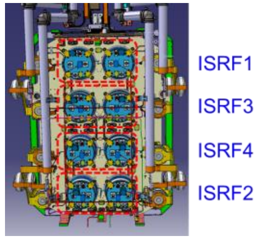
RF power supply generators

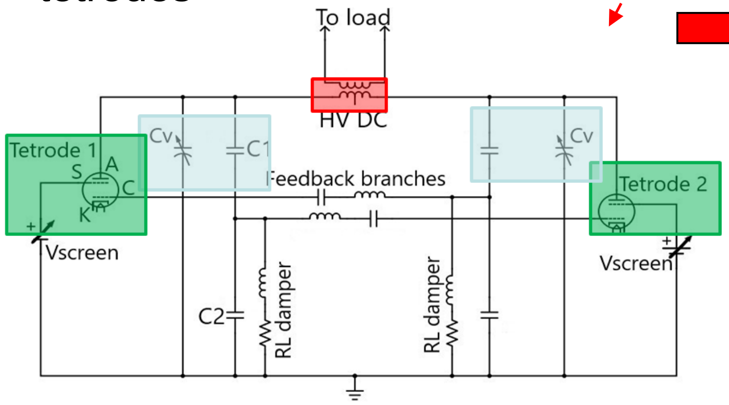
Radio-Frequency electrical circuits are used to ionize the gas and excite plasma particles

The best operating point to maximize power transfer to plasma is achieved when the load is matched

In SPIDER the generator can vary the frequency with regulations on Cv, within a self-oscillating scheme based on tetrodes



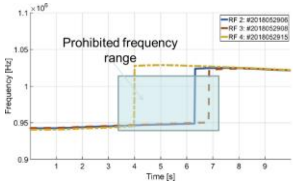


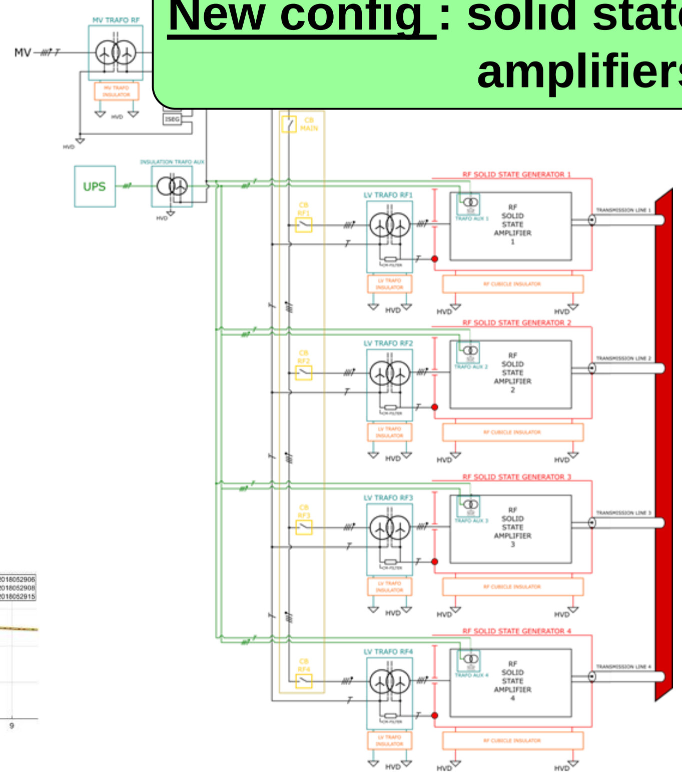


Config so far: tetrode oscillators

The operation of the RF oscillators has been hindered by some important limitations:

- The appearance of the so called **"frequency flips"**
- The presence of **high voltage** (12kV dc) inside the oscillators
- Coupling of the drivers combined with oscillator operation results in **cross-talking between generators**





New config : solid state amplifiers

Roadmap:

All ITER-relevant source will adopt the solid state amplifiers (*already @ IPP*)

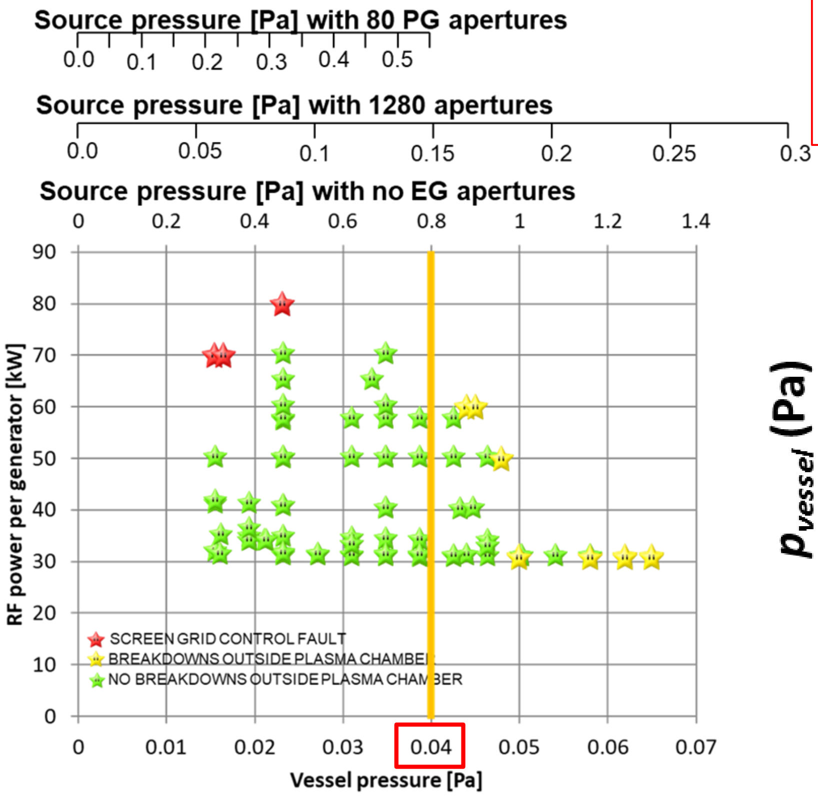
SPIDER procurement ongoing

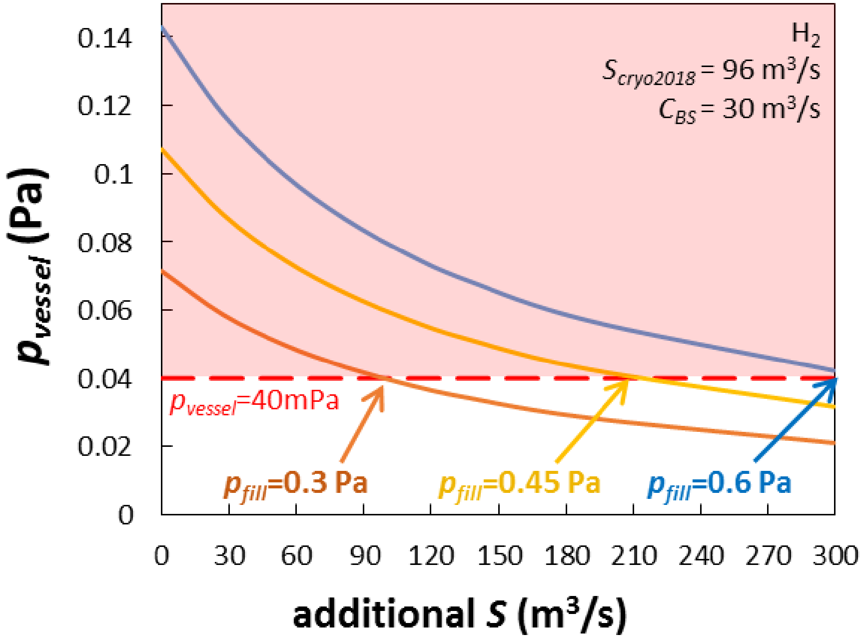
MITICA, HNB & DNB next, already planned

Vacuum Enhancement system

Background

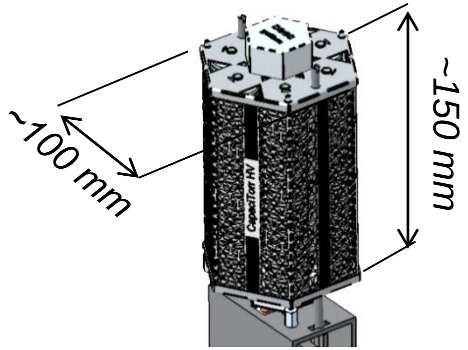
A series of concurrent factors resulted in a vacuum system not powerful enough:
- Design range of pressure/conductance vs actual operation
- Cryopump performances
- **RF discharges in vacuum**





- The base unit of the pump is the NEG cartridge
- **2 x 192 NEG cartridges** have a pumping speed for H_2 of about **300 m³/s**
- **H_2 Capacity** for 2 x 192 NEG cartridges = **440000 Pa*m³**
- Heaters needed for the regeneration with dedicated power supply and control unit

NEG Cartridge

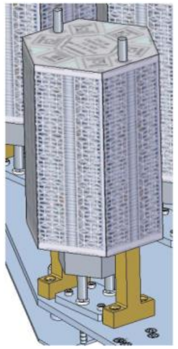


A preliminary assessment compared possible solutions (commercial cryopumps, custom cryopumps and NEG pumps), leading to the final choice

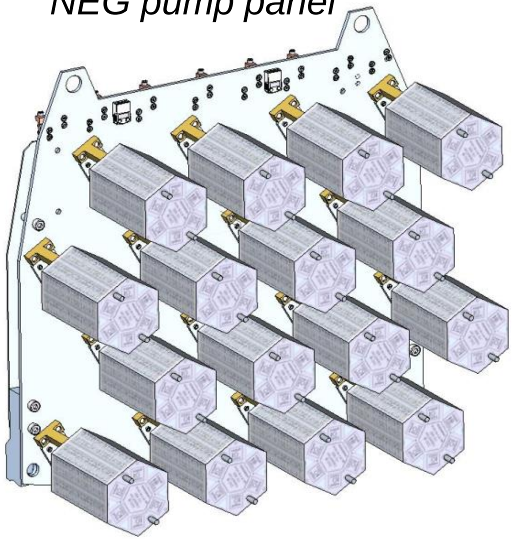
Vacuum Enhancement system

- **Main components of the NEG pumping system**
  - NEG pump panel
  - Wiring panel
  - NEG cartridge
  - Power Supply and Local Control system layout (PSLCU)
- *Procurement is ongoing*

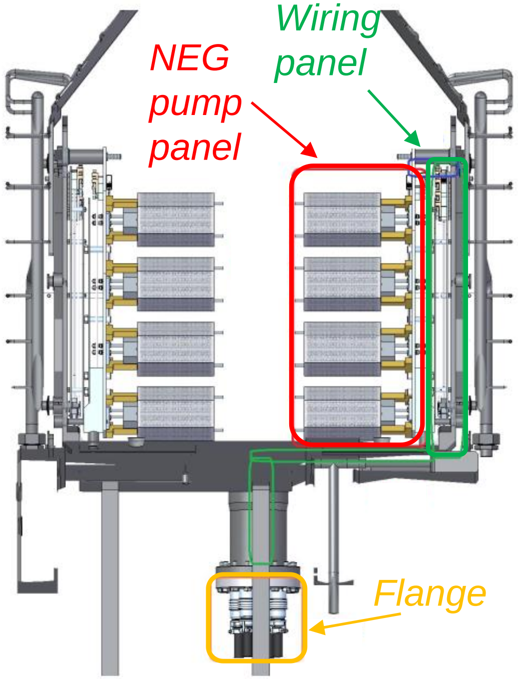
NEG cartridge



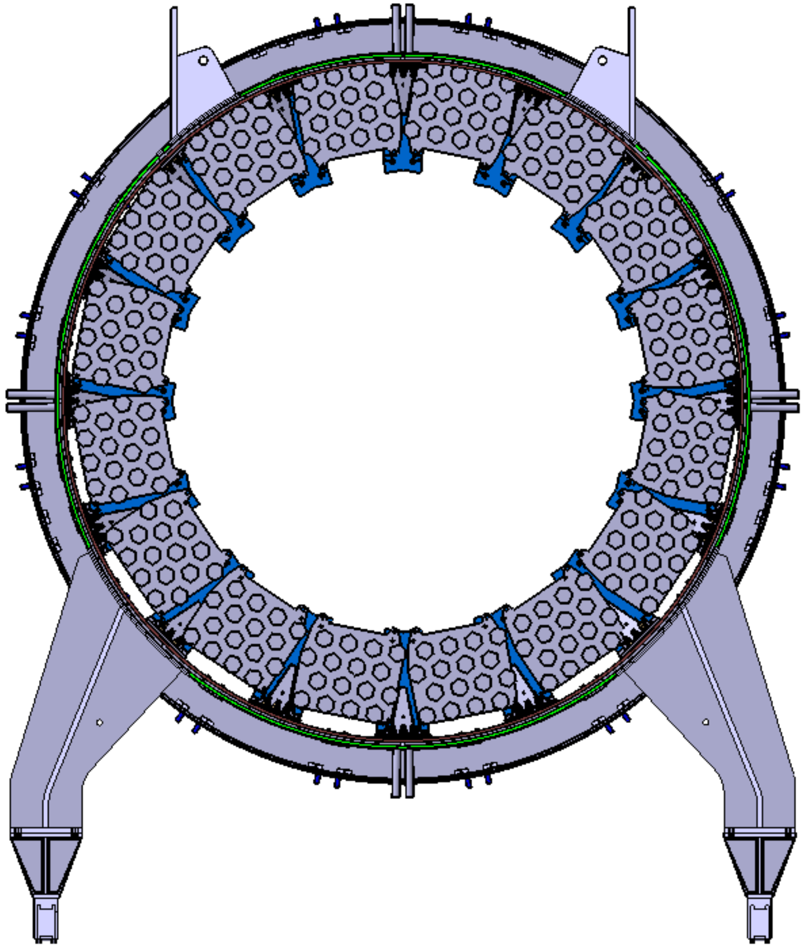
NEG pump panel



VEVV lateral section view



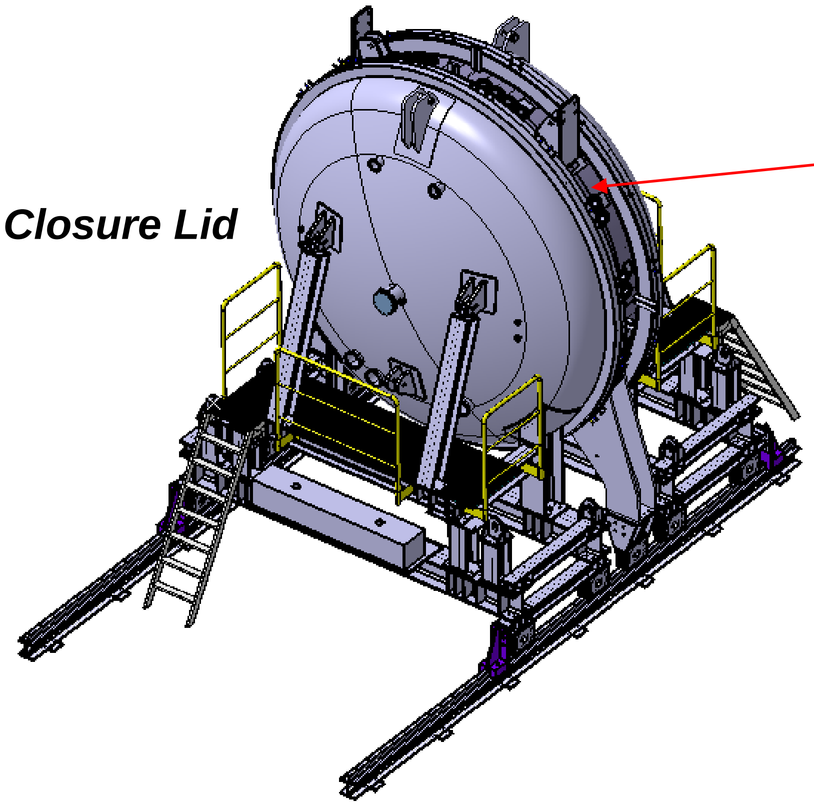
VEVV frontal section view

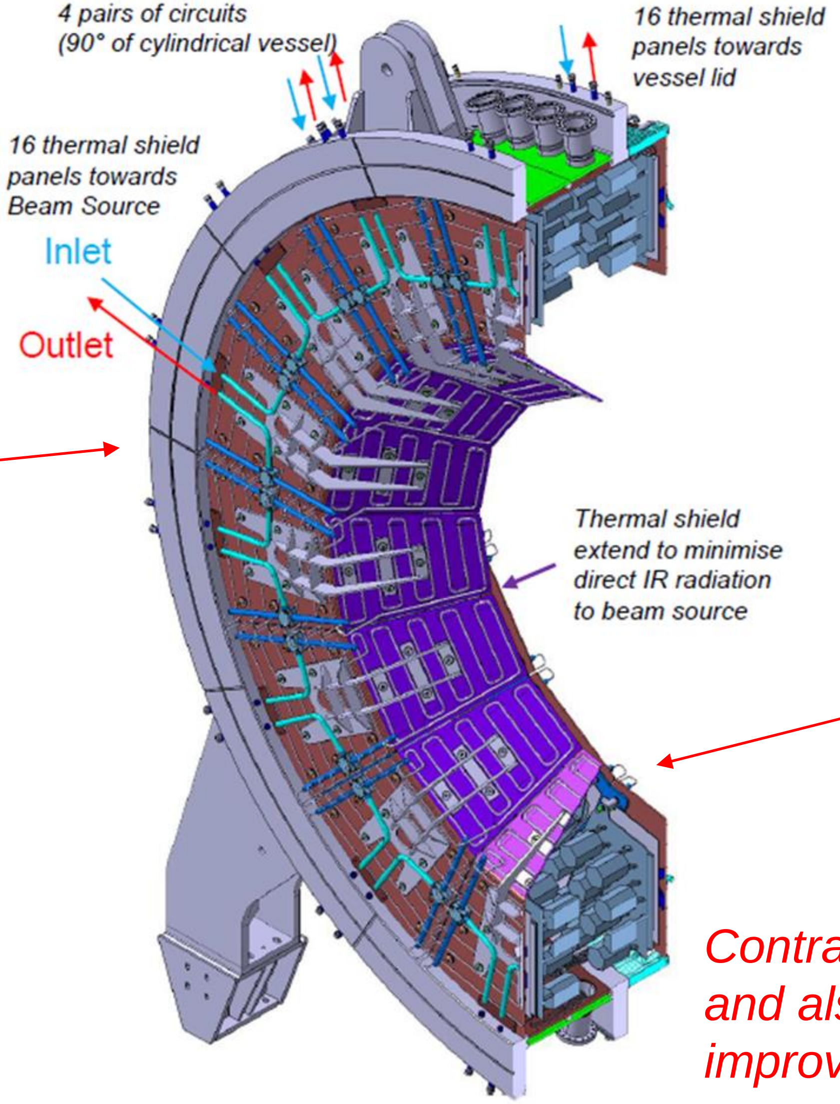


Vacuum Enhancement system

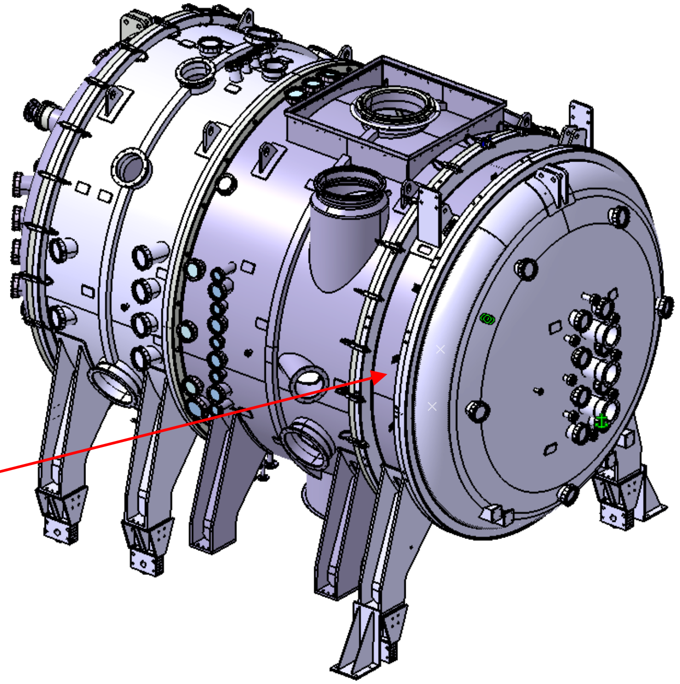
- **Main components of the new Vacuum Vessel Module**
  - Vacuum Enhancement Module (VEM)
  - Closure Lids
  - Thermal-Electrostatic Shields (TES)
  - Support brackets

Closure Lid



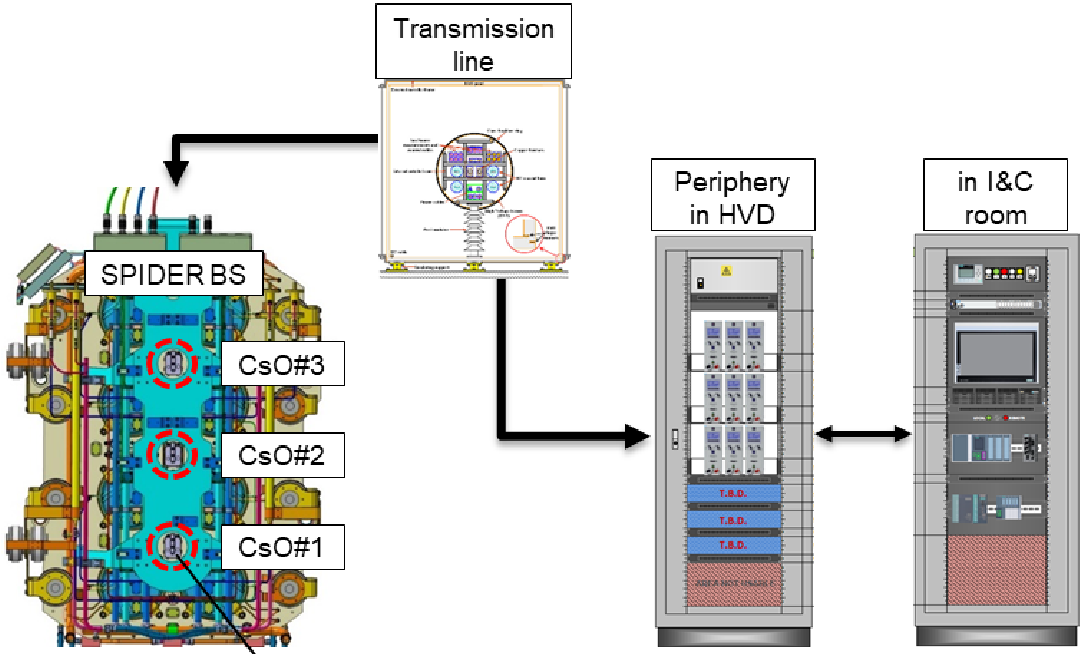


SPIDER VV + Vacuum Enhancement Module (VEM)

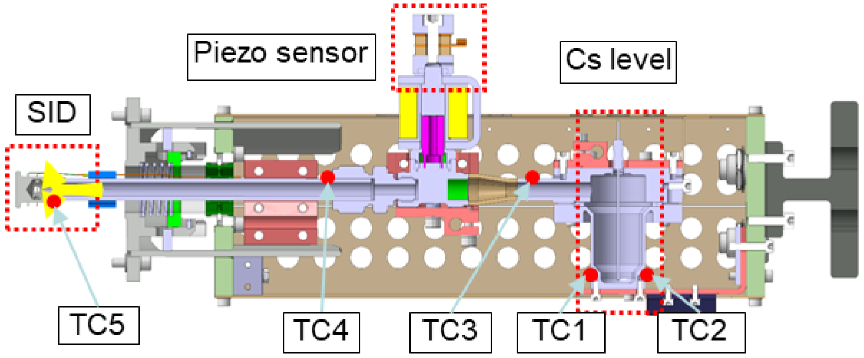


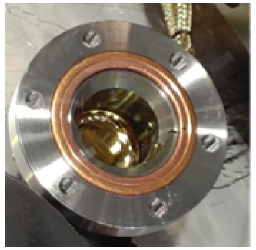
Contract being signed for the VEM+TES, and also for original vacuum system improvements

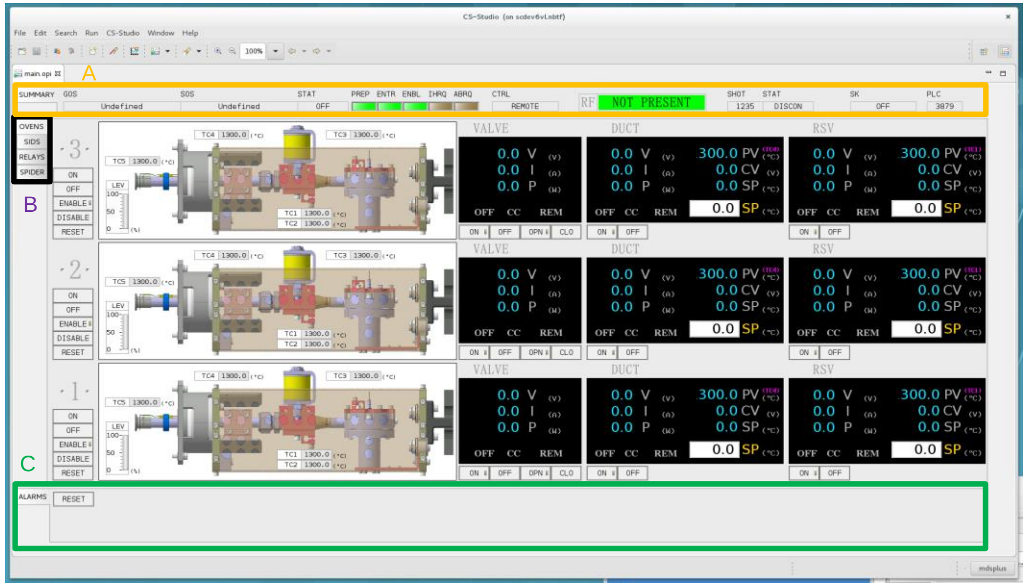
Anything … working so far, at all ??



SPIDER Cs oven system – System overview







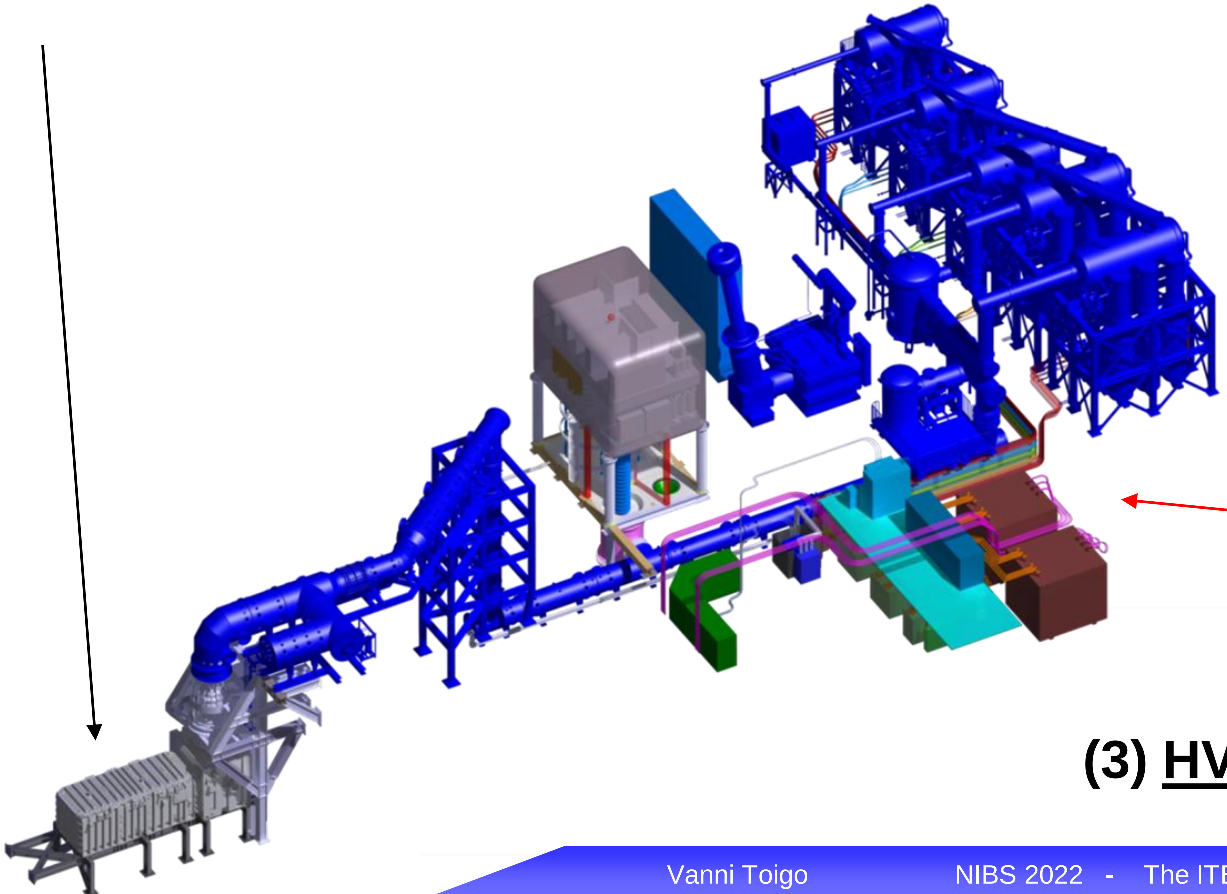
Cs oven features

- 3 fully independent ovens
- 2 heating circuits (duct and reservoir) per oven
- Surface Ionization Detector (SID) for on-line Cs flux measurement
- Solenoid valve for Cs flux control

MITICA Activities

(1) Components and auxiliaries completion

- Procurement ongoing for in-vessel mechanical components (F4E procurement)
  => beam source, beam line components, cryopumps
- Auxiliary plants procurement under completion (F4E procurement)
- One to one "single-plant"/CODAS integrated commissioning started



(2) Power supply integrated tests

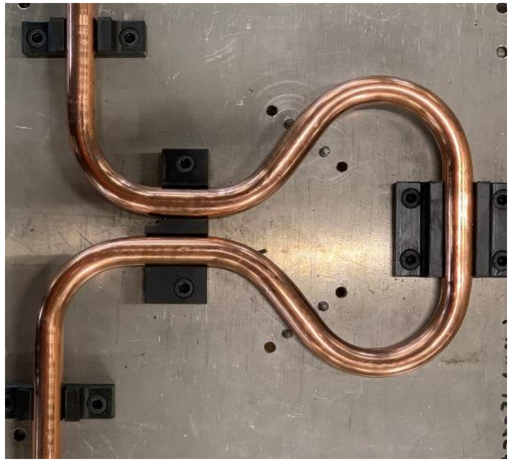
(3) HV tests in vacuum preparation

MITICA outstanding procurements

Mechanical drives

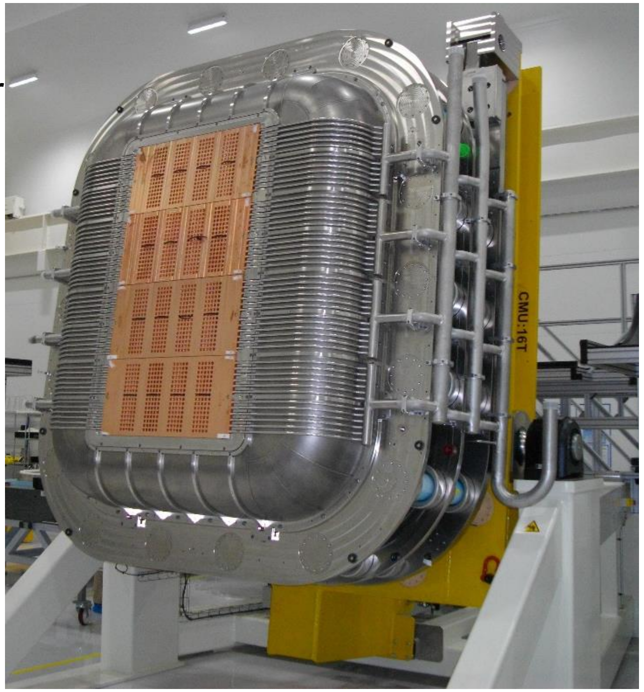
Cryopumps *(SDMS)*

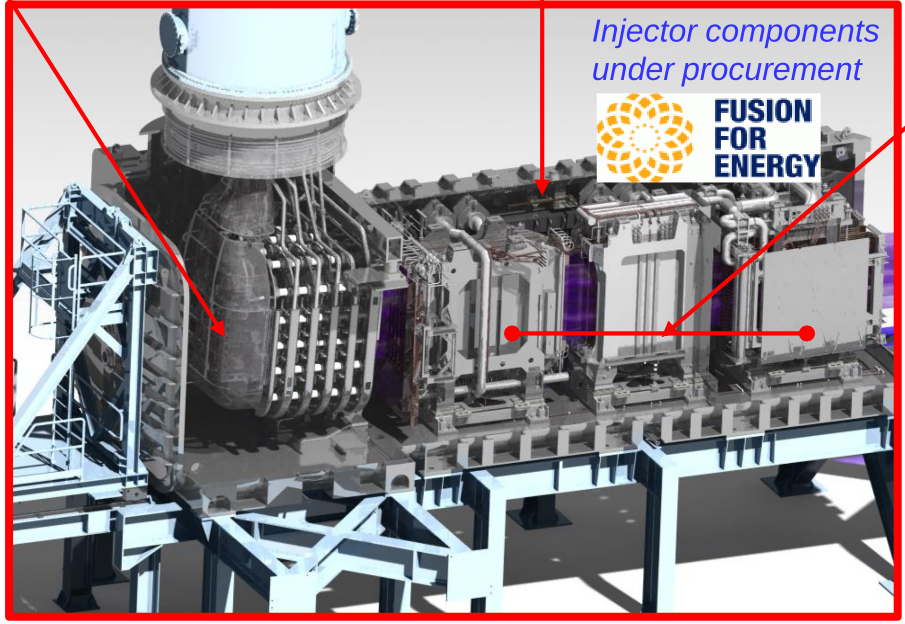
Calorimeter tube detail



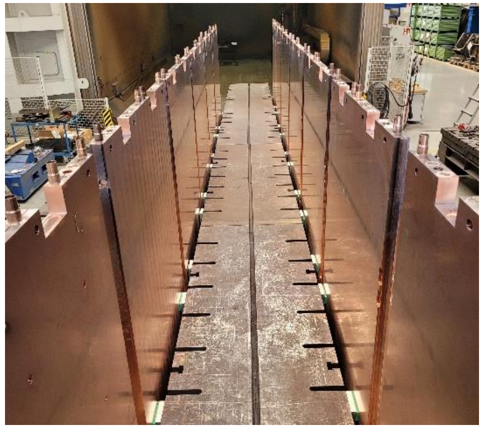
Beam Source *(Alsymex)*

Accelerator assembly





Beam Line Components *(AVS Tecnalia)*



Neutralizer panels

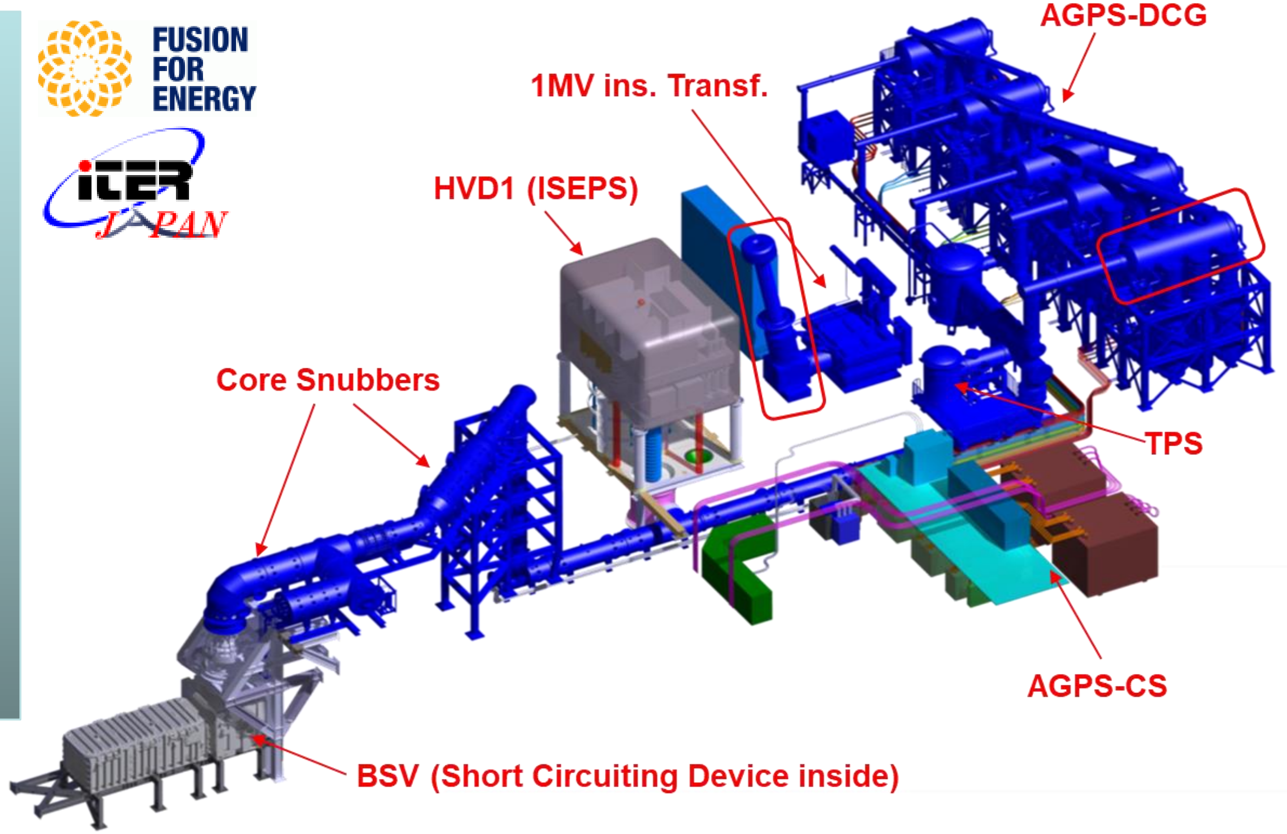
MITICA Power Supply

- MITICA power supply is a very complex system, beyond the limit of modern technologies
- It is the first prototype developed in the world at 1MVdc with such power rating. *One purpose of MITICA is to test and fine-tune these power supplies*
- JADA and F4E supplied its share, including installation onsite and standalone Site Acceptance Tests, **BUT**…

…systems at the end are strongly integrated and this required a deep coordination for the **<u>interfaces</u>** and an **<u>integrated commissioning</u>** process, very complex in technical terms and also responsibility-wise

MITICA Power Supply:

AGPS-CS	F4E
AGPS-DCG	JADA
HVD1+HVBA	F4E
1MV insulation Transf.	JADA
Transmission Line	JADA
HVD2	JADA
HV Bushing	JADA
ISEPS	F4E
GRPS	F4E
CODAS & Interlock	F4E



MITICA Power Supply: integrated commissioning

The integrated commissioning consists of three main steps:

Insulation tests (up to 1.2MV for 1h, and 1.056kV 5 ore): long process carried out between 09/2018 and 11/2019, with a series of steps in order to integrate progressively each part supplied by either DA

Functional and low power tests (integration of control and protections with CODAS and Interlock): successfully carried out in 2020, notwithstanding covid pandemia

Power integrated tests (including different test types to check full operability of the overall system, up to target performances): during no-load tests some breakdowns occurred which caused damages to some parts (diode bridge, 1MV insulating transformer)

Strategy undertaken (IO+JADA/QST+NBTF team) to face and solve the issue:

- Plant inspections following breakdowns: in air and in gas
- Development of fast transient modelling by the NBTF team for failures explanation
- Additional dedicated low power tests with enhanced set of sensors to identify BD location
- Root cause analysis
- Development of recovery solutions and improvement of power supply system with introduction of additional protection systems

MITICA Power Supply: integrated commissioning

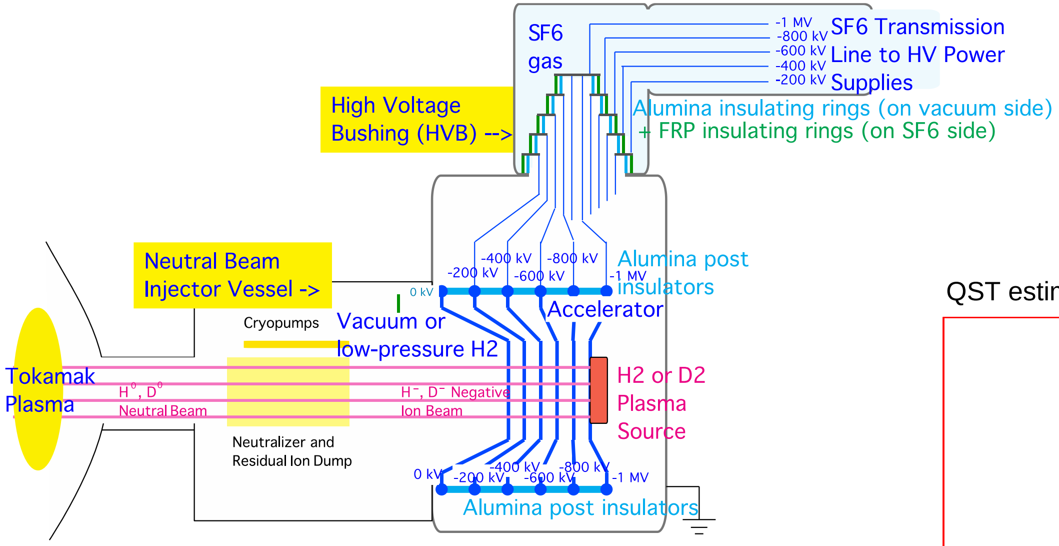
Lot of work has been done, lot of understanding reached. Still way to go to complete the repair of damage parts and complete the power integrated tests

Lessons learned up to now:

- Despite a design based on reference standards, available previous experience and prior development of dedicated mock-ups, MITICA power supplies go well beyond the limits of current expertise
- Thanks to new models developed ad-hoc, phenomena causing damages have been explained and the remedial actions (additional protections) identified, in order to avoid future risks
- Even if cold comfort, the Neutral Beam Test Facility has demonstrated its necessity

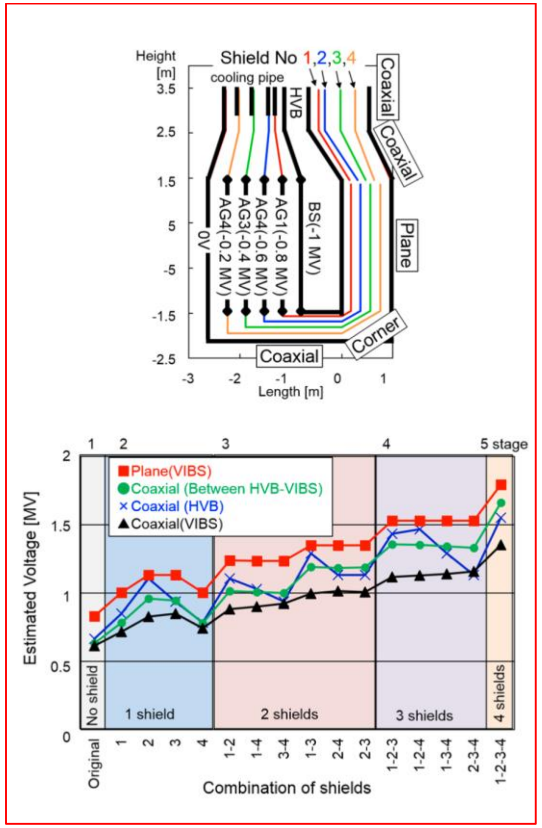
HV tests in vacuum

One of the main issues to face in MITICA is the high voltage holding in vacuum. Directly derived from expertise in JADA/QST, the accelerator features 5 stages x 200 kV, but the rear side of the ion source facing the grounded vessel is at -1 MV

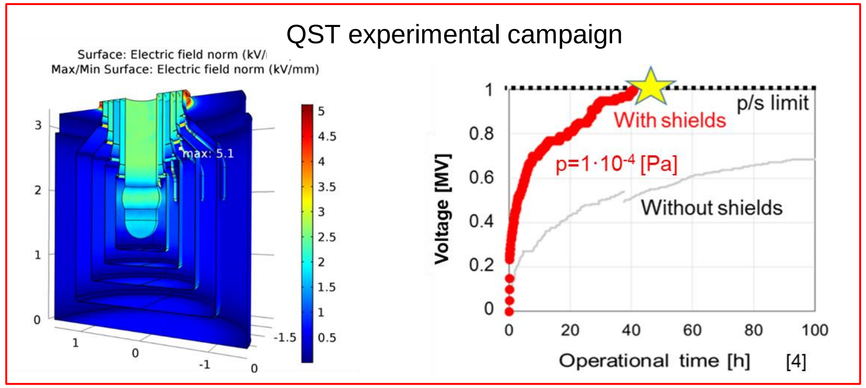


The source had been designed to guarantee minimum distances with respect to voltage difference in relation to available experimental results

QST estimation based on experimental data



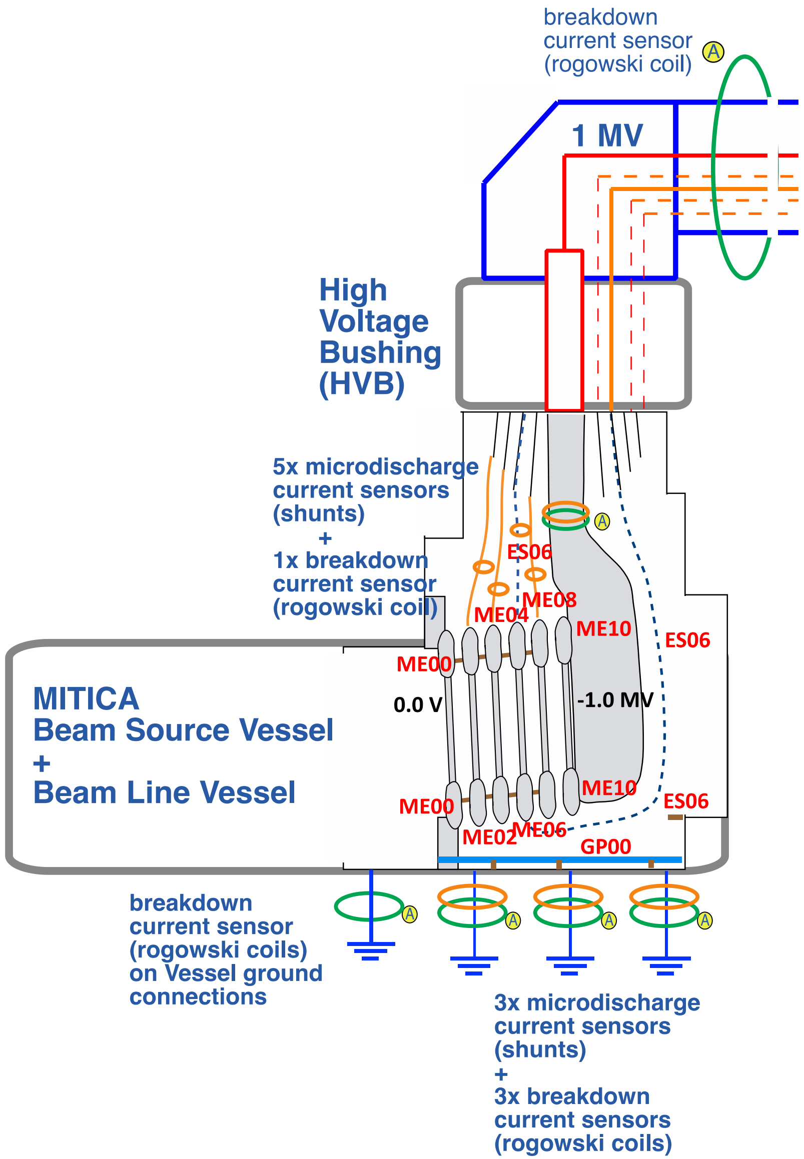
More recently, dedicated experiments at QST indicated that in order to reach 1 MV voltage holding intermediate shields that «break» the gap are definitely effective, likely essential



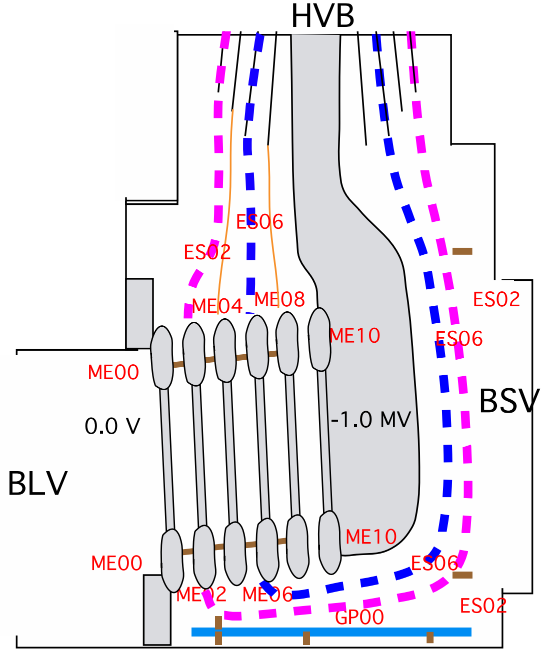
HV tests in vacuum

Mitigation strategy

- Isolation and pre-focus on such critical aspect for HNB/MITICA
- Exploitation of time window (waiting restoration of power supply and installation of in-vessel components) for dedicated experimental campaign on a source mock-up
- Design and test of the intermediate electrostatic screen for voltage holding enhancement
- Conceptual option to add another intermediate shield, if necessary

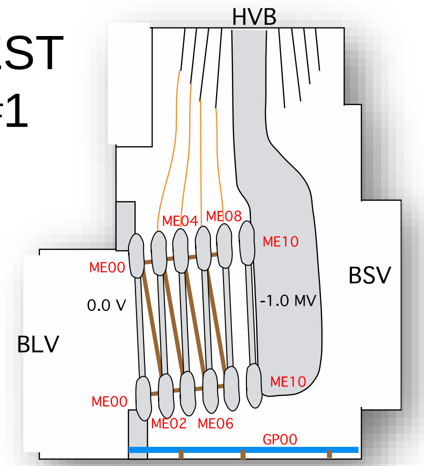


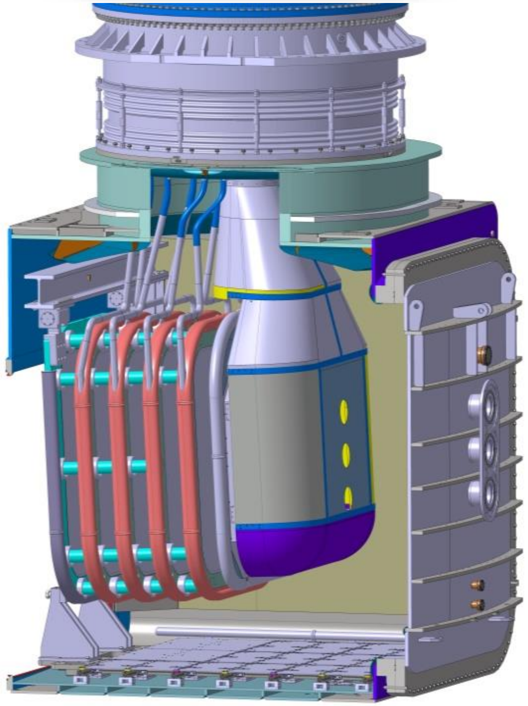
If ES06 Not enough



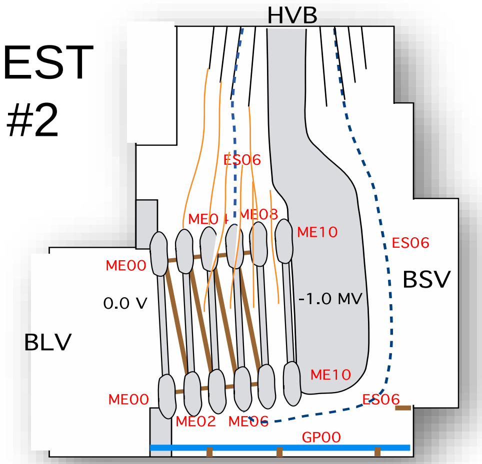
HV tests in vacuum

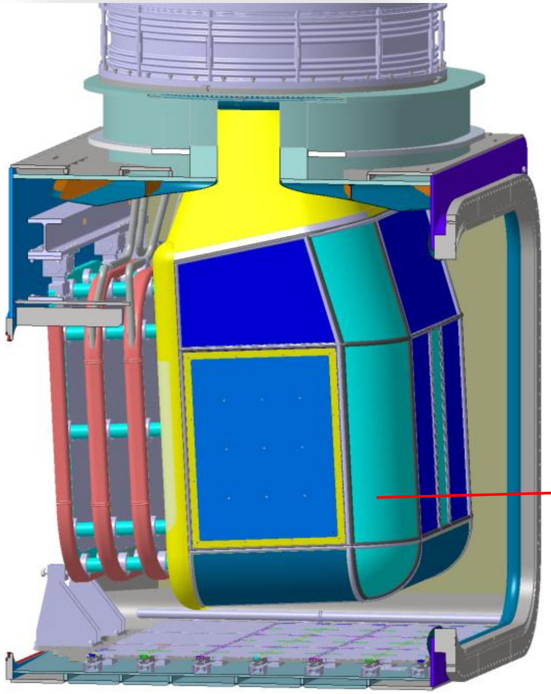
TEST #1



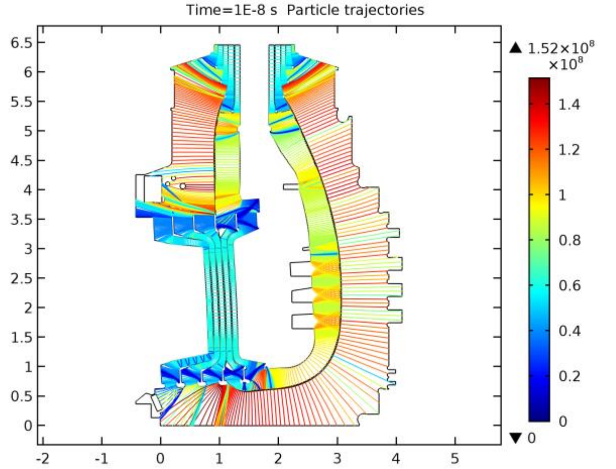


TEST #2

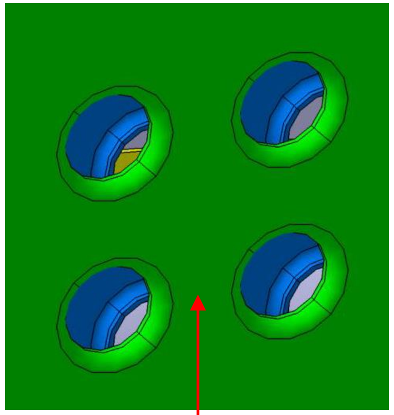


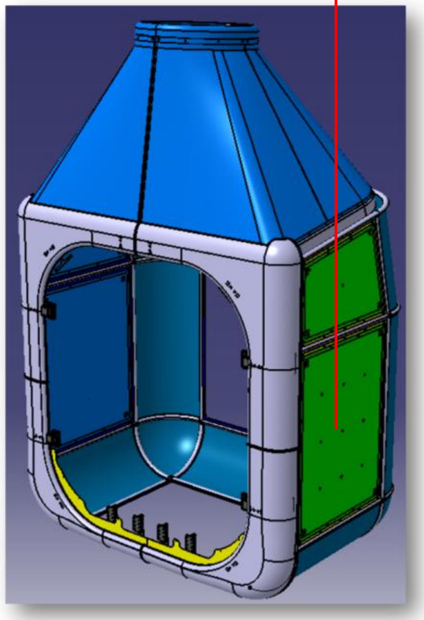


Discharge probability estimation, supporting the design



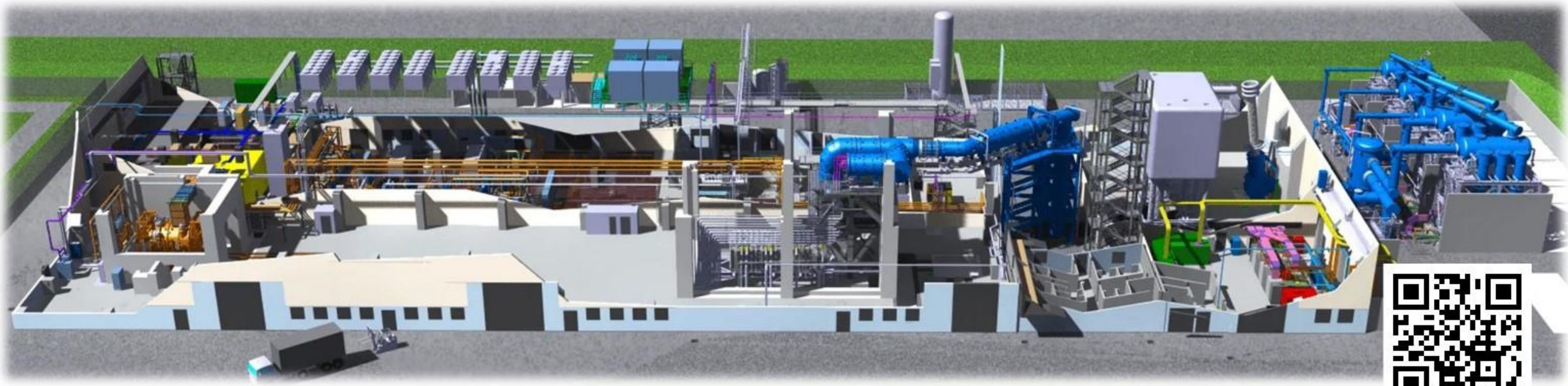
Two «skins» with staggered holes





600 kV shield on-going design

The ITER Neutral Beam Test Facility: status and perspectives



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Thank you for your attention