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# Sviluppo degli iniettori di neutri per esperimenti di fusione:

## Alimentazioni elettriche e linee di trasmissione in alta tensione e corrente continua

V. Toigo

# ITER H&CD systems

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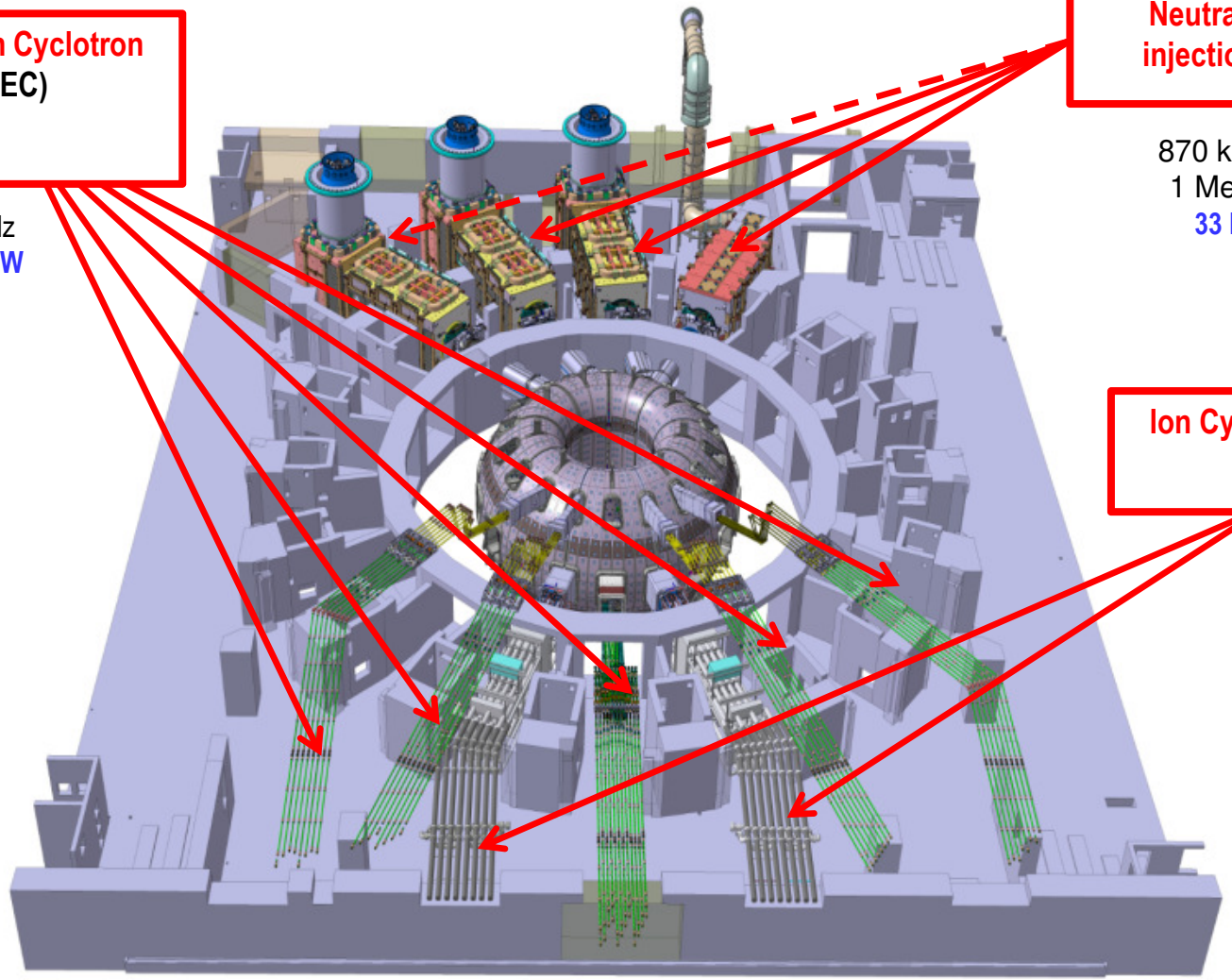
**Electron Cyclotron (EC)**

170 GHz
**20-30 MW**



**Neutral beam injection (NBI)**

870 keV $H^0$
1 MeV $D^0$
**33 MW**

**Ion Cyclotron (IC)**

40-55 MHz
**20 MW**

# Negative ion beams in ITER

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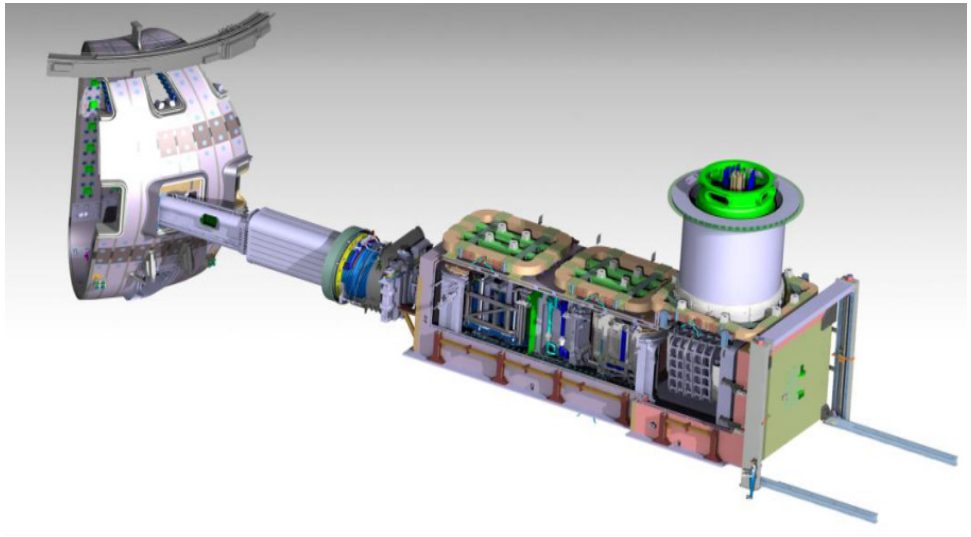
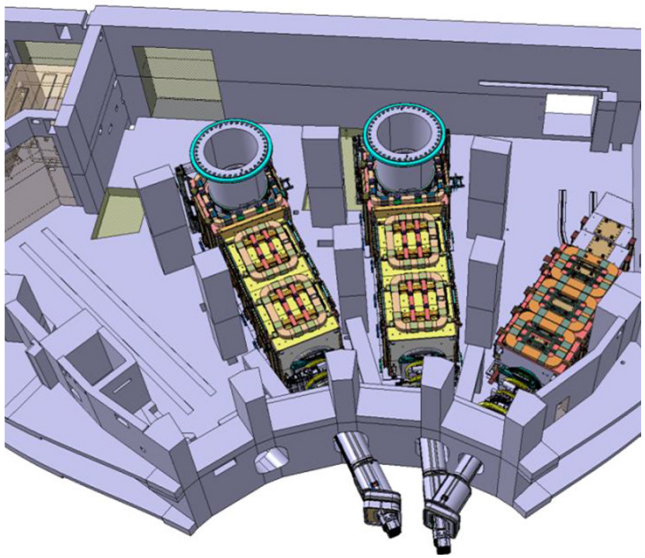


- 2 (+1) HNB: Heating Neutral Beam
- 1 DNB: Diagnostic Neutral Beam
- NBTF: Neutral Beam Test Facility



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2 HNBs (+1): deuterium
- I = 40 A
- V = 1 MV
- $t_{pulse}$ = 3600 s
- $P_{beam}$ = 16.5 MW

EUDA & JADA procurement

ITER-India

1 DNB: hydrogen
- I = 60 A
- V = 0.1 MV
- $t_{pulse}$ = 3s every 20s
- Modulation = 5Hz

INDA procurement

# Aims of ITER Neutral Beam Test Facility

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- Accompanying facility in preparation and support of ITER operation:
  - *To achieve nominal parameters of source and beam*
  - *To optimize HNB operation*
  - *To improve reliability and availability of injectors*
  - *To realise and commission systems: e.g. HV components @1MV, cryopumps, …*
  - *To finalise HNB design*
  - *To solve HNB issues during ITER operation*

- NBTF hosts two experiments:
  - **SPIDER** Optimisation of ion source: current density, uniformity, stability
  - **MITICA** Full-size prototype of ITER NBI: high voltage holding, beam optics

# ITER Neutral Beam Test Facility

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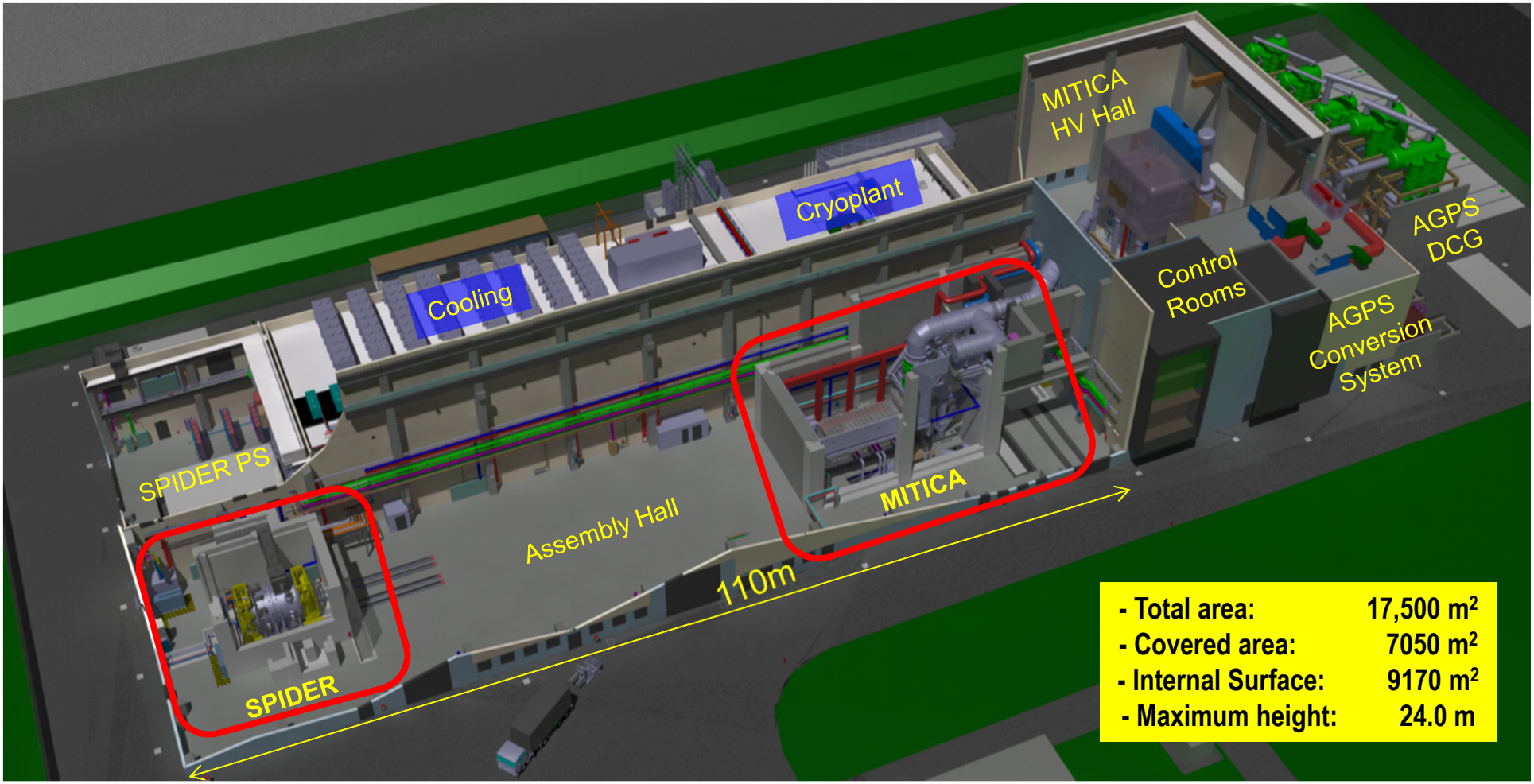


NBTF hosts the two experiments: the negative ion source **SPIDER** and the 1:1 prototype of the ITER injector **MITICA**

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: full scale prototype of HNB/DNB source

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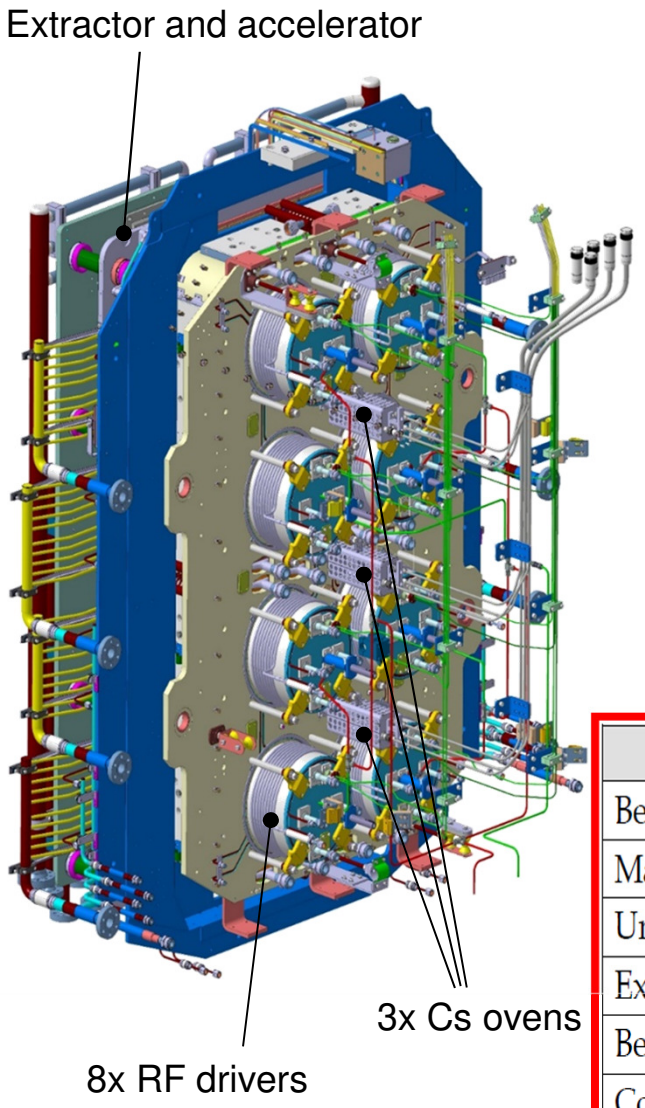


Grid size about 2 x 1m$^2$

Optimisation of production of negative ions in terms of:

- Density
- Uniformity
- Stability
- Co-extracted electrons

| | Unit | H | D |
|---|---|---|---|
| Beam energy | keV | 100 | 100 |
| Maximum Beam Source pressure | Pa | <0.3 | <0.3 |
| Uniformity | % | ±10 | ±10 |
| Extracted current density | A/m$^2$ | >355 | >285 |
| Beam on time | s | 3600 | 3600 |
| Co-extracted electron fraction ($e^-/H^-$) and ($e^-/D^-$) | | <0.5 | <1 |

# The SPIDER Beam Source

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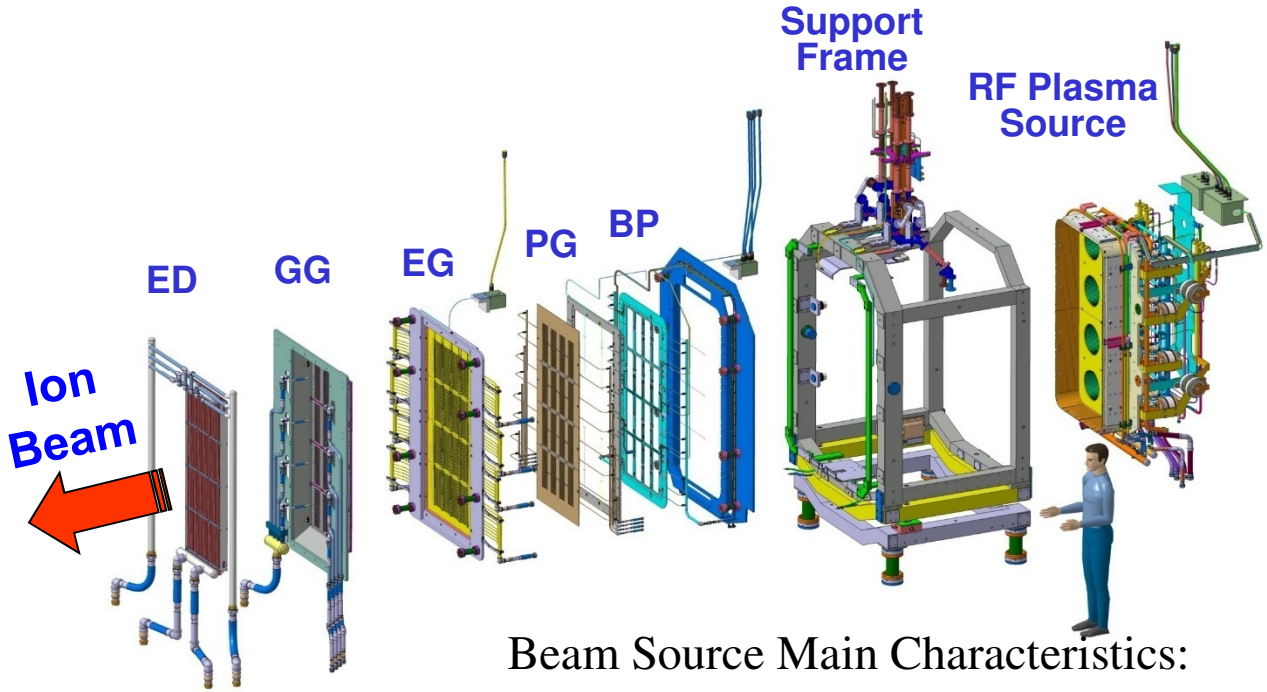
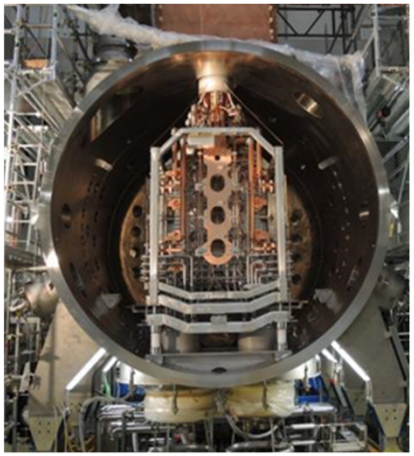



- BP = Bias Plate
- PG = Plasma Grid
- EG = Extraction Grid
- GG = Grounded Grid
- ED = Electron Dump

Beam Source Main Characteristics:

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

*SPIDER BS at the factory before transport to NBTF site*



*SPIDER BS as installed inside the Vacuum Vessel*

# SPIDER Components

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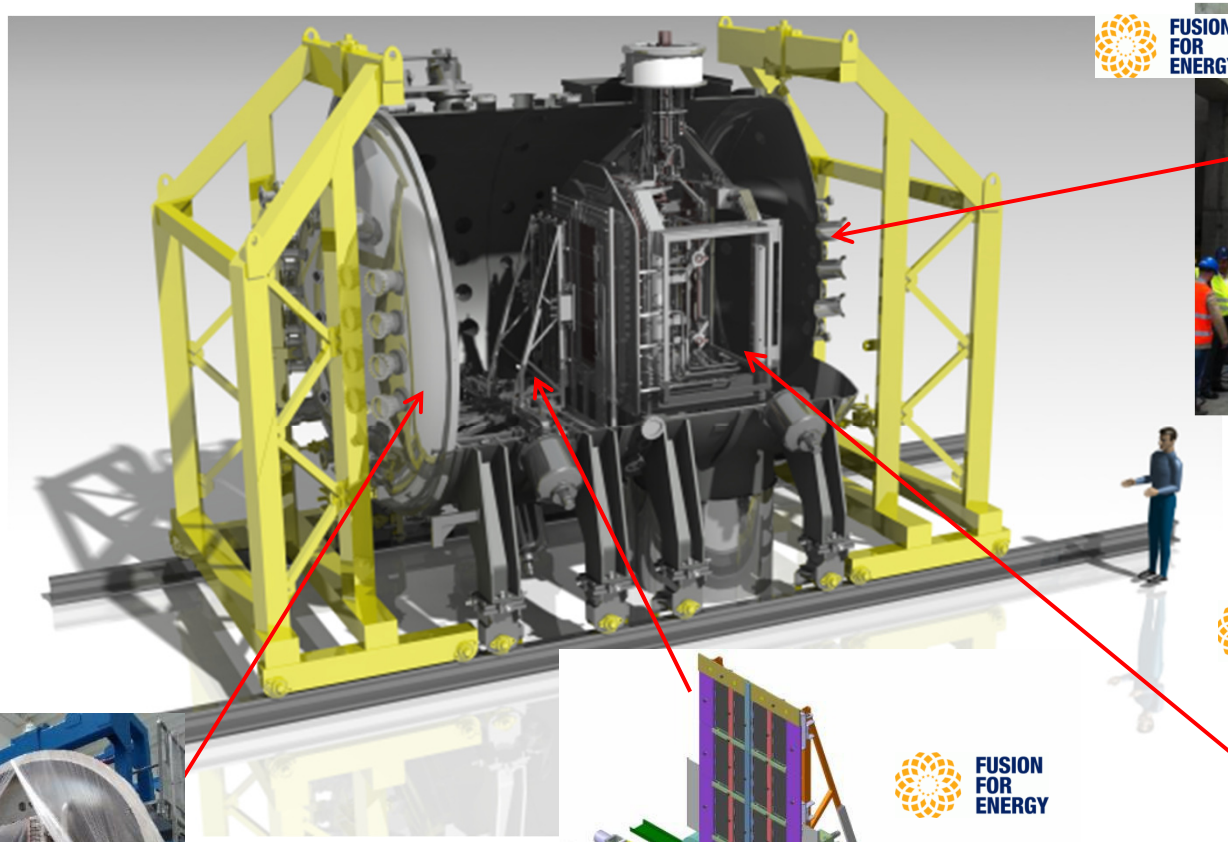
**Vacuum-insulated beam source**



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**Vacuum Vessel**

ITER-India

**Beam Dump**

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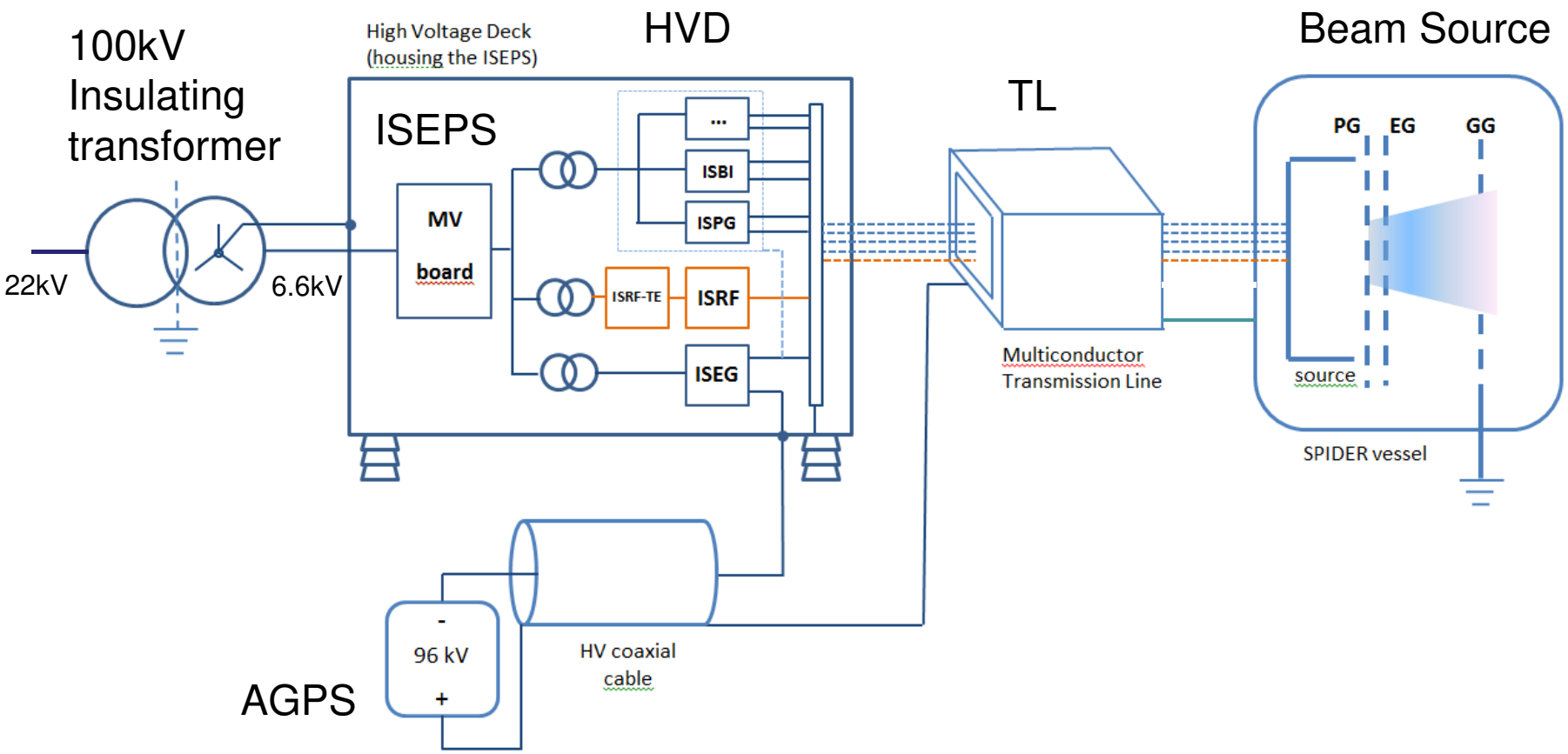
**STRIKE**
**High resolution calorimeter**

FUSION FOR ENERGY

**Beam Source**

# SPIDER Power Supply




Conceptual scheme of the SPIDER PS system

# Acceleration Grids breakdowns

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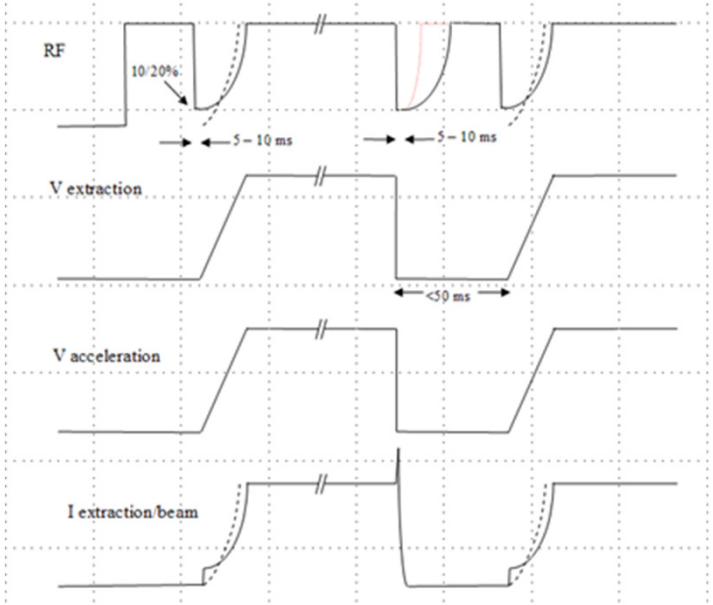
- The acceleration grids operate close to breakdown and, during normal operation of the injector, breakdowns can occur frequently and unpredictably, even every few seconds
- Grid Breakdowns (BD) have to be considered as a normal operational condition
- To avoid damage to the acceleration grids due to breakdowns it is very important to limit the energy discharge in the arc. This is achieved by acting on various aspects:
  - Switching-off the power supply as fast as possible
  - Limiting the electrostatic energy stored in the HV components
  - Introducing passive protection systems to limit the current and the energy dissipated in the arc

# Grid breakdowns: power supplies

- From the point of view of the power supply it is equivalent to a short circuit on the load
- BD detector have to discriminate BD from fault:
  - In case of fault the protection system intervenes by switching off the power supply as soon as possible. Furthermore, the system cannot restart until it has been reset
  - In case of BD the power supply are switched off in tens on microseconds, kept off for about 20ms and then restarted following a pre-programmed sequence




Operating sequence of the power supply system during and after a breakdown

| Parameter | Value |
|---|---|
| Maximum detection time[1] | 50 µs |
| Maximum inverter switch-off time[2] | 100 µs |
| Maximum charge measured upstream TL1[3, 4] with AGPS conversion system off | 200 mC |
| Time for the line current (measured upstream TL1) decay under 100 A with AGPS conversion system off | 300 µs |
| Maximum charge measured upstream TL1[3, 5] with AGPS conversion system in operation | 250 mC |
| Maximum energy dissipated inside the ion source arc[6] | 50 J |
| Time to be ready for restart after a BD | 20 ms |
| Maximum number of BD for a single pulse | 200 total (for t = 3600s)<br>50 consecutive |

AGPS parameters to be satisfied in case of grid breakdown

# Grid breakdowns: passive protections

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- Electrostatic energy depends on the square of the accelerator voltage
  - if possible, to adopt PS topologies that do not require output filters → PSM
  - If necessary, they must be kept to a minimum and equipped with a series resistor to dissipate as much as possible the energy in case of a BD
  - keep the parasitic capacities of high voltage components as low as possible

- To insert dissipative and damping elements in series with the conductors
  - Insertion of high permeability magnets around the conductors to increase the series inductance: core snubbers
  - Insertion of resistors in series with conductors feeding low currents

# SPIDER Power Supply

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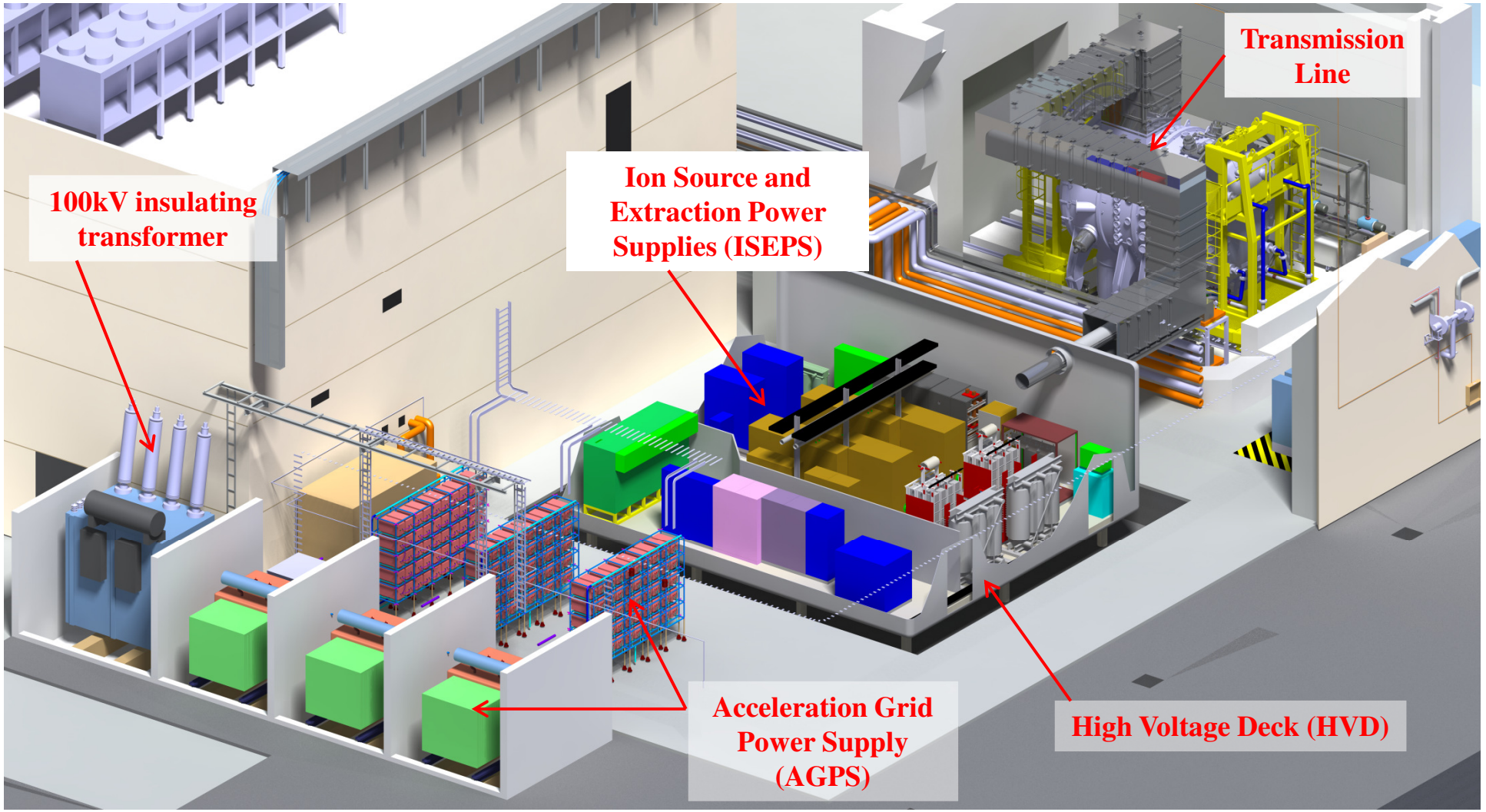
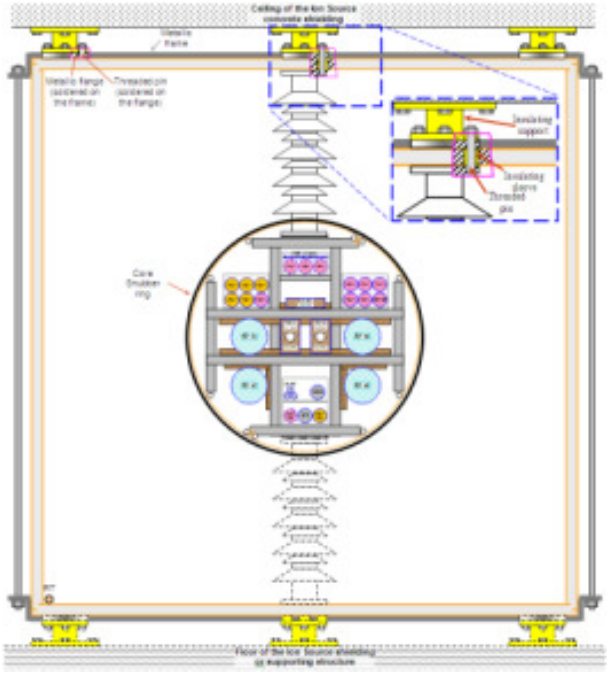



3D CAD view of SPIDER Power Supply, TL and Vessel

# SPIDER HV Deck & Transmission Line

- Simple and cost-effective design based on air insulated unsealed solution
- **Internal conductor:** cylindrical shape (0.5m diameter) containing all the ISEPS connections (RF lines, busbars, power and signal cables, optic fibers, etc.)
- **Outer conductor:** square section (1.2 x 1.2 $m^2$), grounded
- **Installation and SAT concluded in 2016**
- **Insulation:** 130kV between internal and external conductors



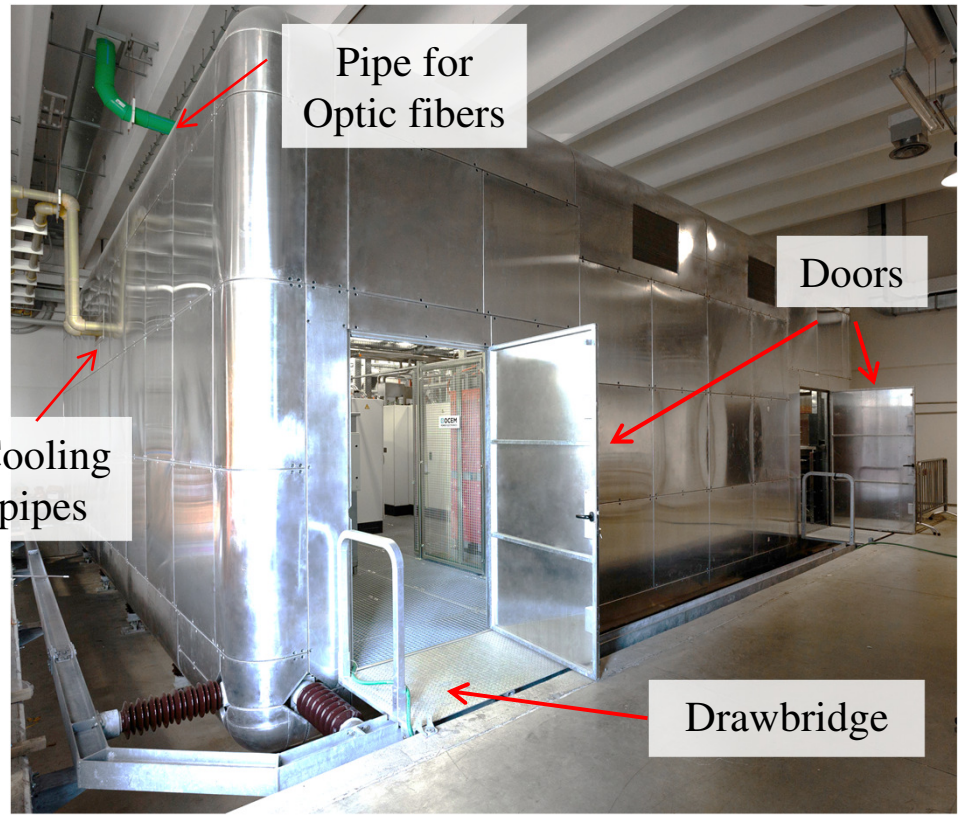
Transmission Line cross-section

SPIDER TL installed outside the Bio-shield

# SPIDER HV Deck

**HV Deck is a Faraday cage, air insulated to ground at -100kV, hosting Ion Source Power Supply**

- External size: 13m x 11m x 5m
- Insulating distance from ground and walls of 1m (post-insulators installed in a pit to have access at ground level)
- Access to internal side via two drawbridges
- Cooling pipes and Optic fibers made by plastic material
- Installation and SAT concluded in 2015



# SPIDER Ion Source Power Supply

**ISEPS is an heterogeneous set of power supplies including:**

- RF Generators: 4 x 200kW, 1MHz (self-oscillator based on tetrodes)
- High Voltage generators: 2 x 12.8kV, 140A dc (pulse step modulator technology)
- High current generator: 30V, 5kA (resonant technology)
- Insulating transformer: 22kV/6.6kV, 100kV$_{dc}$ to ground, 5MVA
- Auxiliaries, including MV, LV Distribution Boards, step-down transformers, etc.

**Installation and commissioning concluded in 2016**

ISEPS factory acceptance tests

ISEPS inside HVD: on the right side, view of the Extraction Grid PS (12.8 kV 140A)

# SPIDER Acceleration Grid PS

**The SPIDER 100kV Power Supply feeds the acceleration grids**

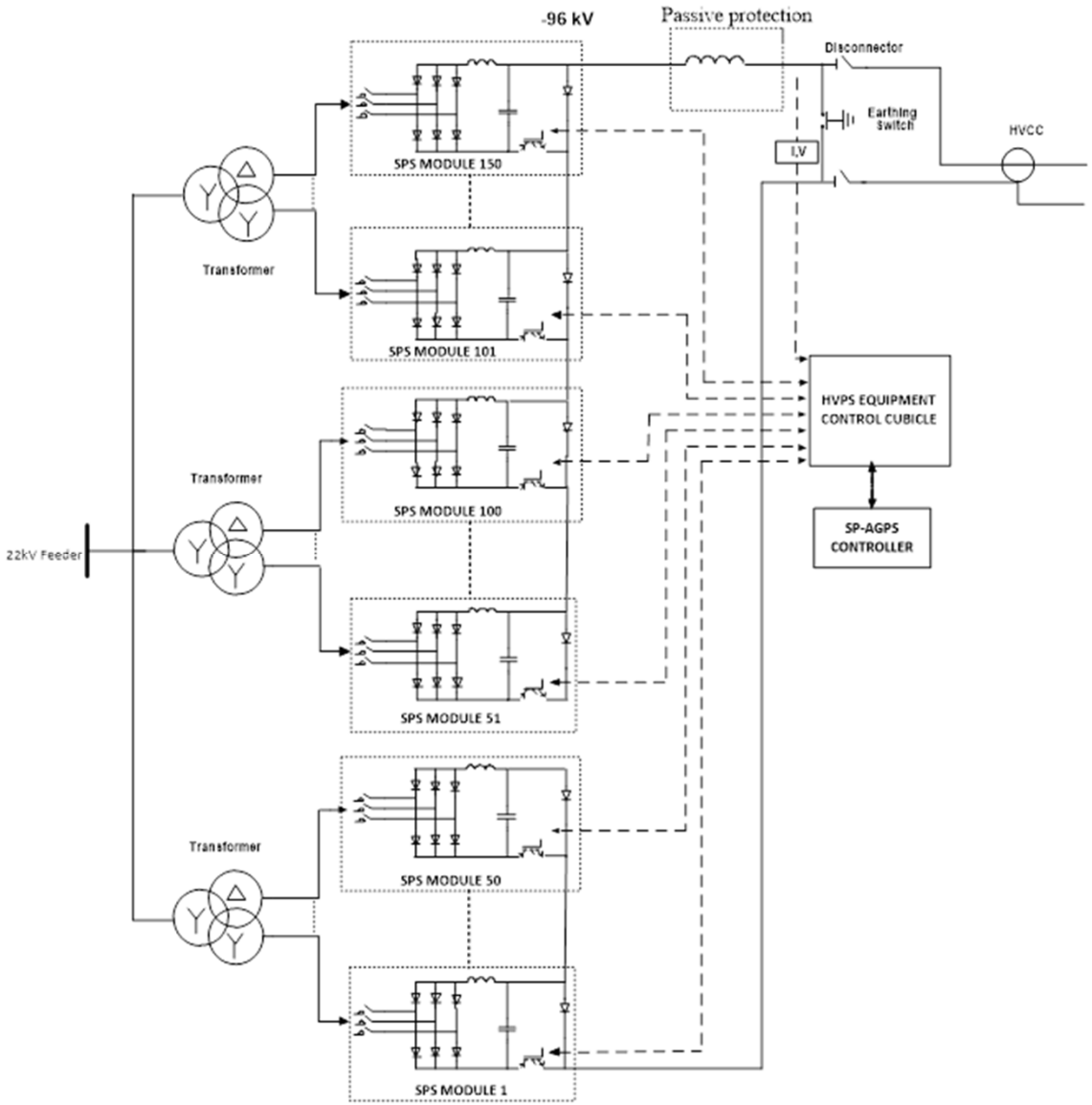
- It is provided by INDIA Domestic Agency
- Main requirements:

| | |
|---|---|
| Nominal voltage | 96kV |
| Nominal current | 71A |
| Topology | one quadrant, pulse step modulator |
| Switch off time | 10 micro seconds |


SPIDER AGPS: Dummy load (left side) and insulating frames supporting Pulse Step Modulator modules (right side)

100kV Multi-winding transformers

# SPIDER Acceleration Grid PS



# MITICA full scale prototype of ITER HNB

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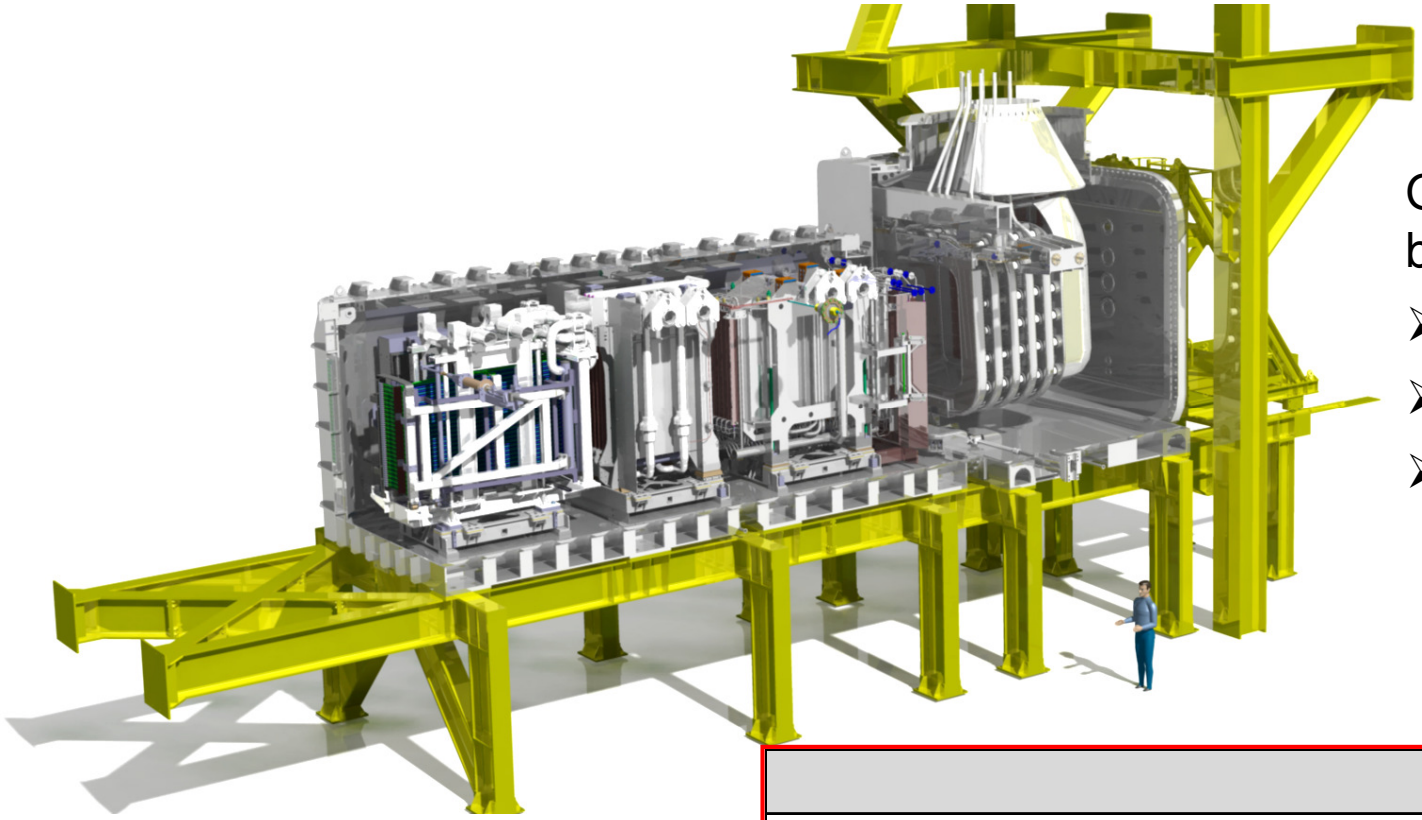

Optimisation of neutral beam in terms of:

- Performances
- Reliability
- Availability

| | Unit | H | D |
|---|---|---|---|
| Beam energy | keV | 870 | 1000 |
| Acceleration current | A | 46 | 40 |
| Max Beam Source pressure | Pa | 0.3 | 0.3 |
| Beamlet divergence | mrad | ≤7 | ≤7 |
| Beam on time | s | 3600 | 3600 |
| Co-extracted electron fraction ($e^-/H^-$) and ($e^-/D^-$) | | <0.5 | <1 |

# The MITICA Power Supplies

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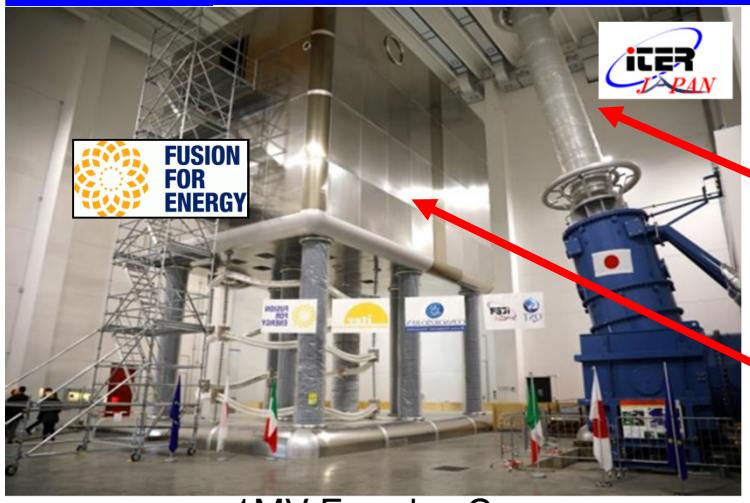


1MV Faraday Cage
(hosting Ion Source PSs)

1MV Insulating Transformer


1MV
AGPS-DC
Generator


HV Bushing

Vacuum Vessel

≈ 100m


HV Transmission Line

RIDPS


AGPS
Conversion
system
60MW CW

# MITICA Power Supply: AGPS

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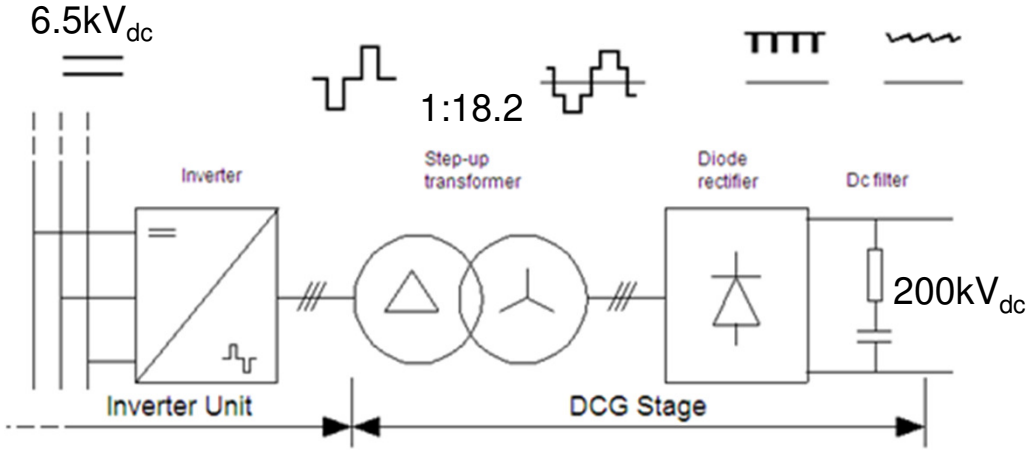
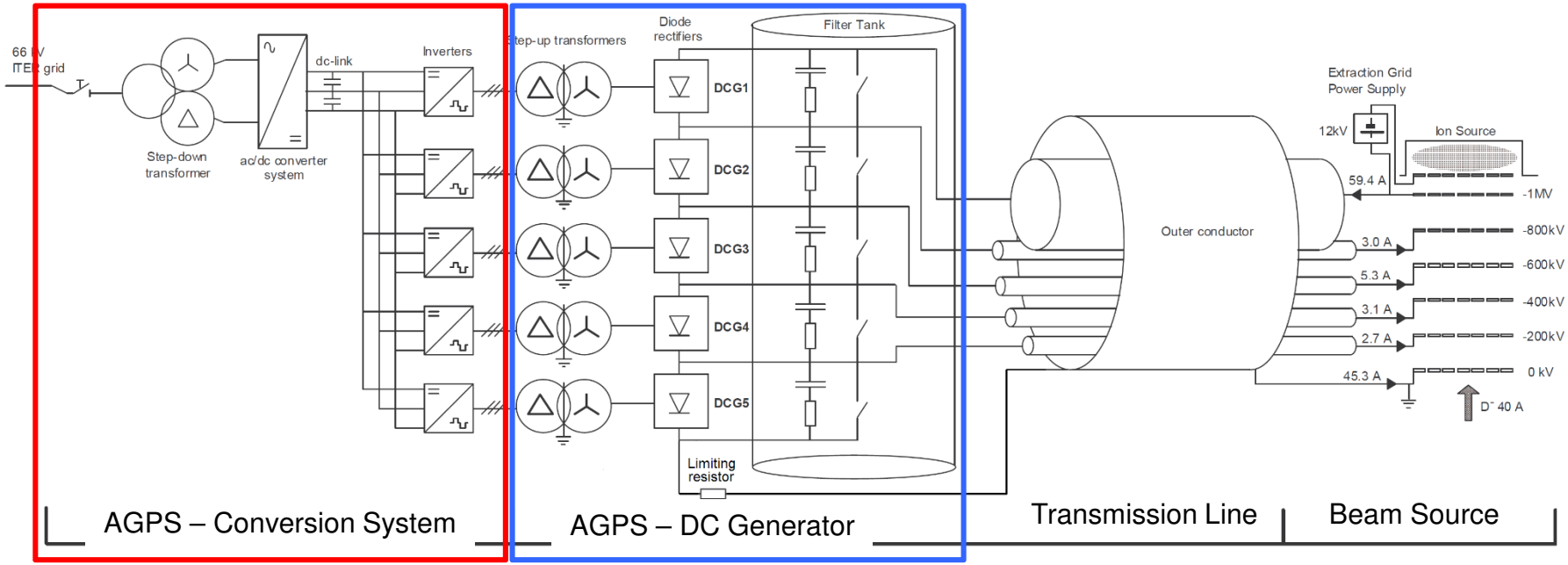
| Parameter | $D^-$, 1MeV, 40A | | $H^-$, 870keV, 46A | |
|---|---|---|---|---|
| | Voltage [kV] | Current [A] | Voltage [kV] | Current [A] |
| Main Supply | -1000 | 59.4 | -870 | 62.8 |
| Grid 1 | -800 | 3.0 | -696 | 2.4 |
| Grid 2 | -600 | 5.3 | -522 | 4.3 |
| Grid 3 | -400 | 3.1 | -348 | 3.1 |
| Grid 4 | -200 | 2.7 | -174 | 2.1 |
| Grounded conductor | 0 | 45.3 | 0 | 50.9 |

AGPS main output ratings




AGPS stage based on Neutral Point Clamp Technology



# AGPS Conversion System

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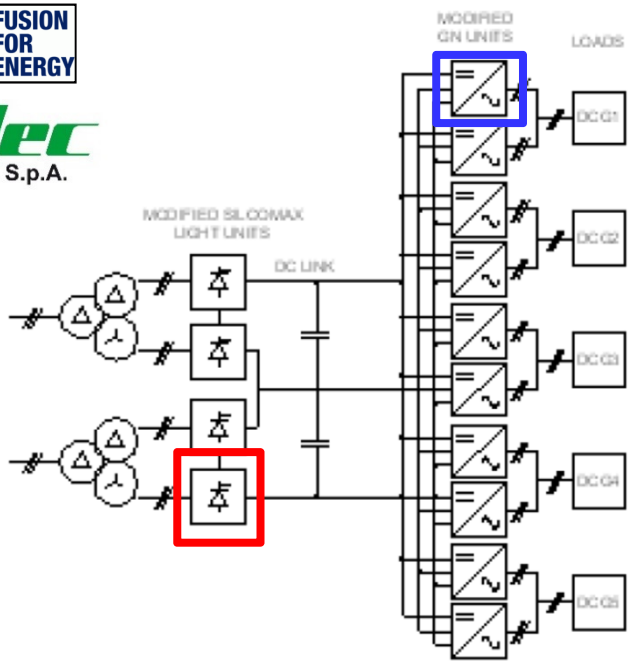
Nidec ASI S.p.A.




**Installation and commissioning concluded in 2018**

Rectifier main ratings

| Parameter | Value |
|---|---|
| Output voltage | 1625V dc |
| Output current | 9kA dc |
| # of thyristors per valve | 4 |
| # of units | 4 in series |

Inverter unit main ratings

| Parameter | Value |
|---|---|
| Output voltage | 5500V rms |
| Output current | 850A |
| Waveform | NPC square wave at 150Hz |
| # of units | 2 in parallel per stage (10 in total) |

# MITICA HVD1 & Bushing

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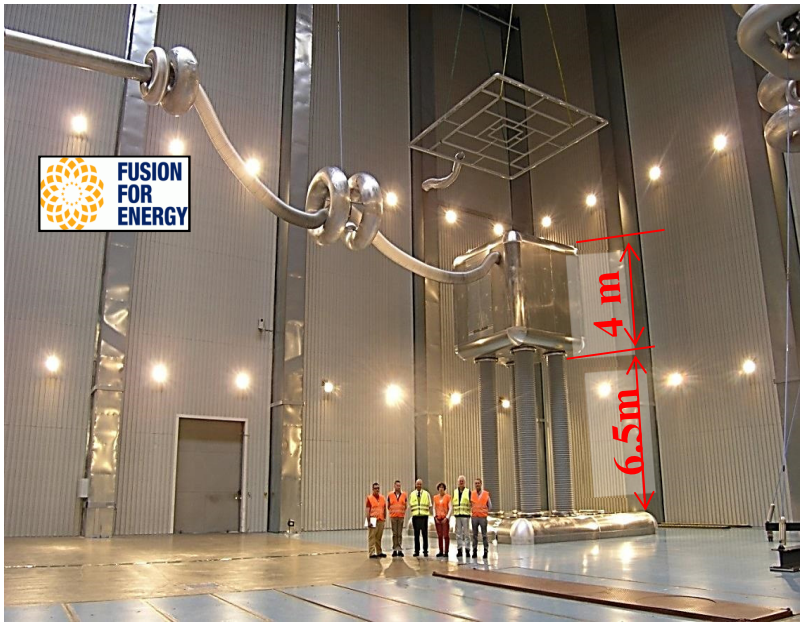
SIEMENS

**HVD1 is the 1MV Faraday cage, air insulated, hosting the Ion Source PS**

- Cage size: 12m x 8m x 10m
- Post insulator length: 6.5 m
- Installation completed in 2017 including partial acceptance tests
- SAT (1.2MV dc for 1 hour) in progress




Factory acceptance tests on HVD1 1:5 mock up

HVD1 during installation

# AGPS-DCG & Transmission Line

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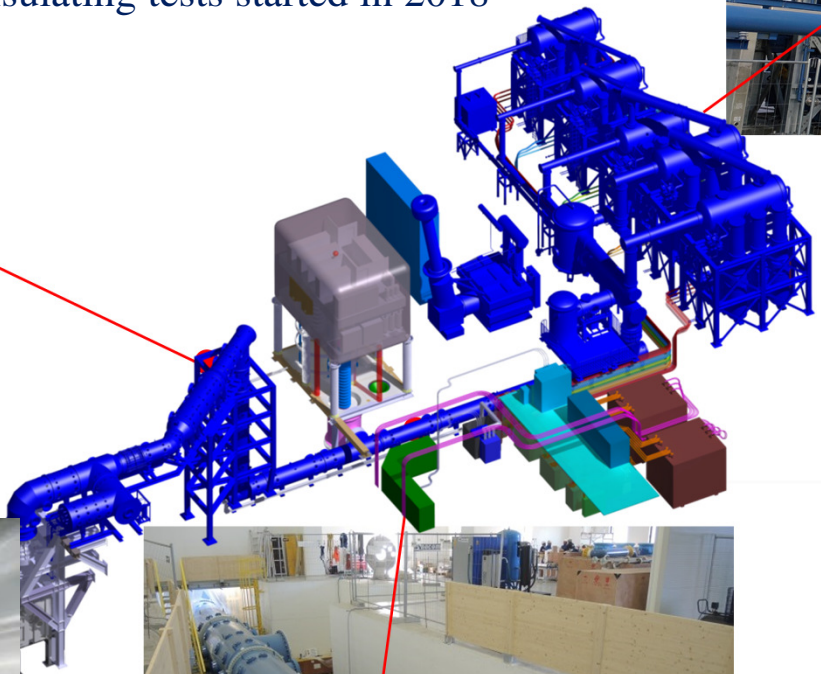
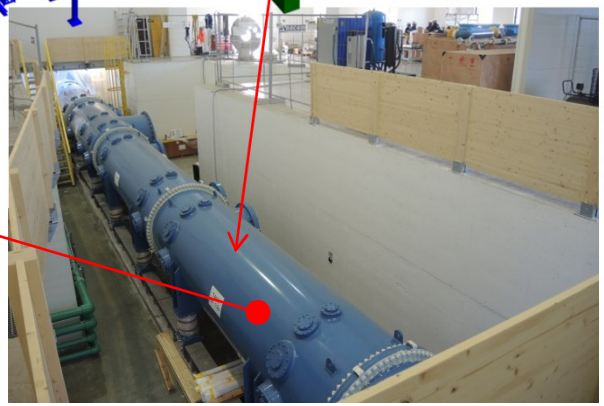
- Installation of JADA components started in Dec. 2015
- Now about 95% installed
- Insulating tests started in 2018

Support for the Transmission Line 2

AGPS-DCG



Inside Transmission Line 1



Transmission Line 1 & 2

ITER JAPAN

HITACHI
Inspire the Next

synecom S.R.L.

# SF6 Gas Handling & Storage Plant

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- The insulation of the HV components (DCG, TL) is guarantee by SF6 gas at **6 bar**
- About **34 tons** of gas stored at **50 bar** (liquid)
- Special handling tools allow to move gas from storage tanks to HV components and vice versa




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DILO

# AGPS-DCG insulating tests: 1.2MV (1h),1.06MV (5h)

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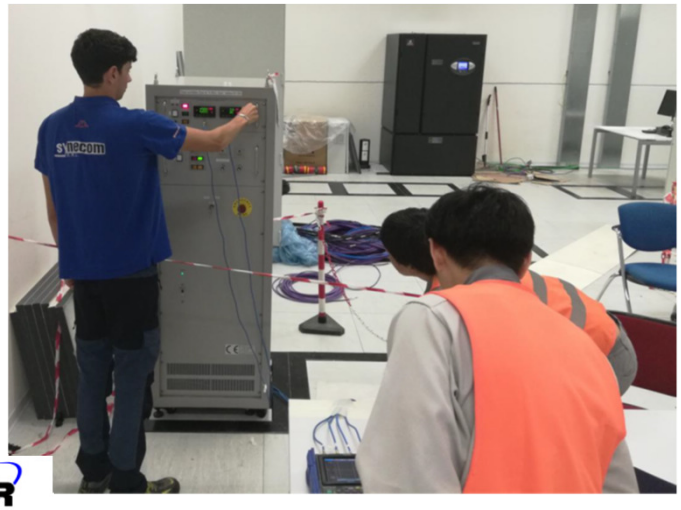
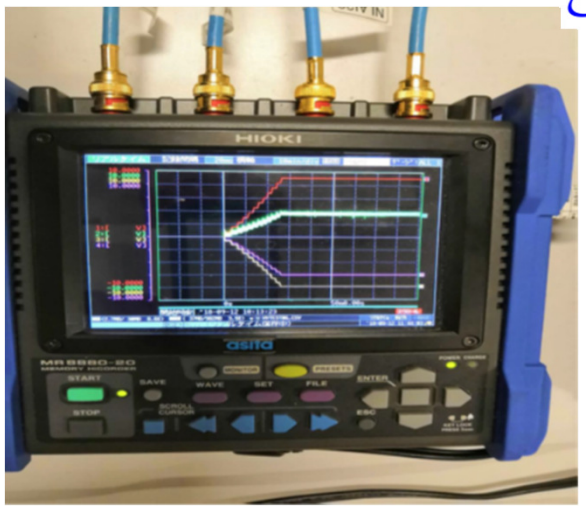


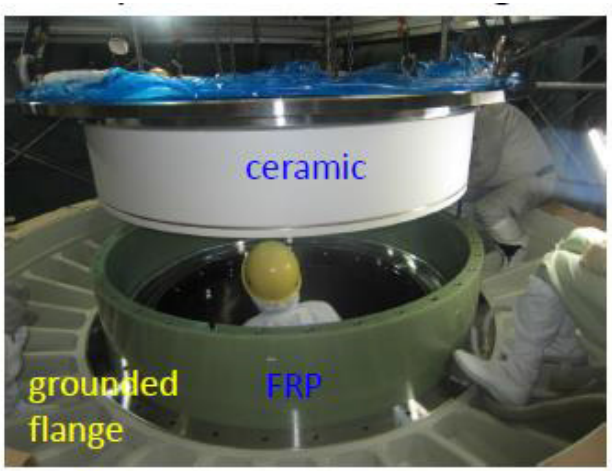



1st STEP 1200kV-1 HOUR

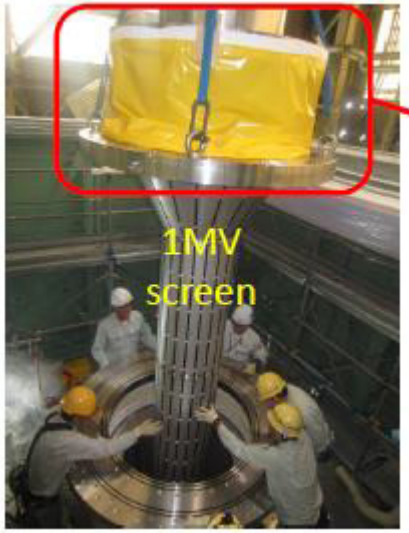

2nd STEP 1060kV-5 HOURS

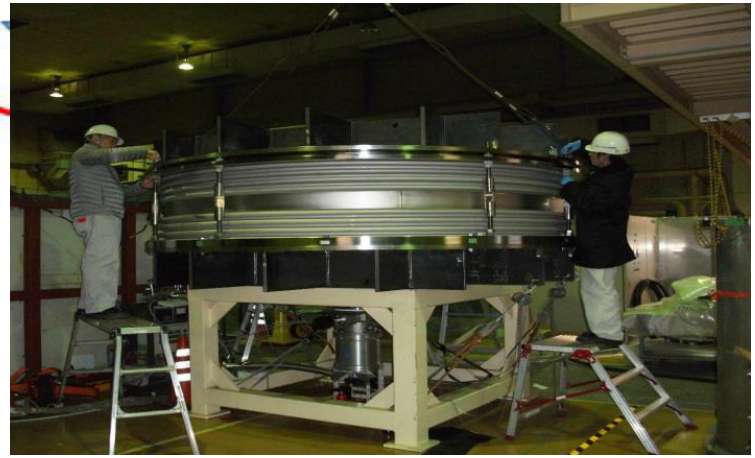
**First HV insulating tests successfully passed**

# HV Bushing and bellows

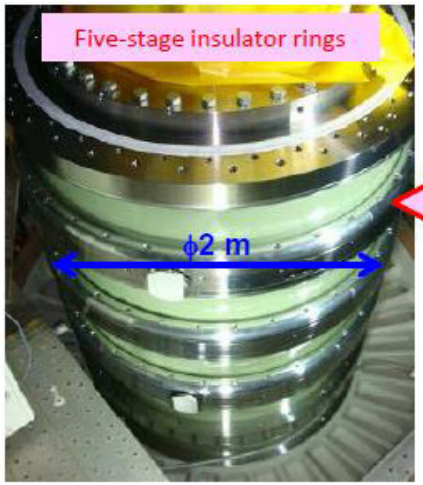



Ceramic and FRP rings

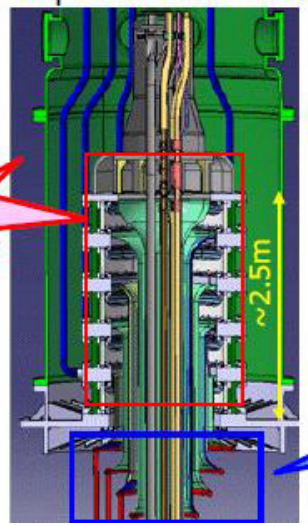


Bellows




Completion of assembly





- HV Bushing interfaces TL, SF6 gas insulated, and Vessel
- It is the most critical HV components: very challenging requirements
- Deep R&D was performed in order to define manufacturing procedure
- Stored in the Site ready to be installed

# Overall schedule of the NB systems for ITER

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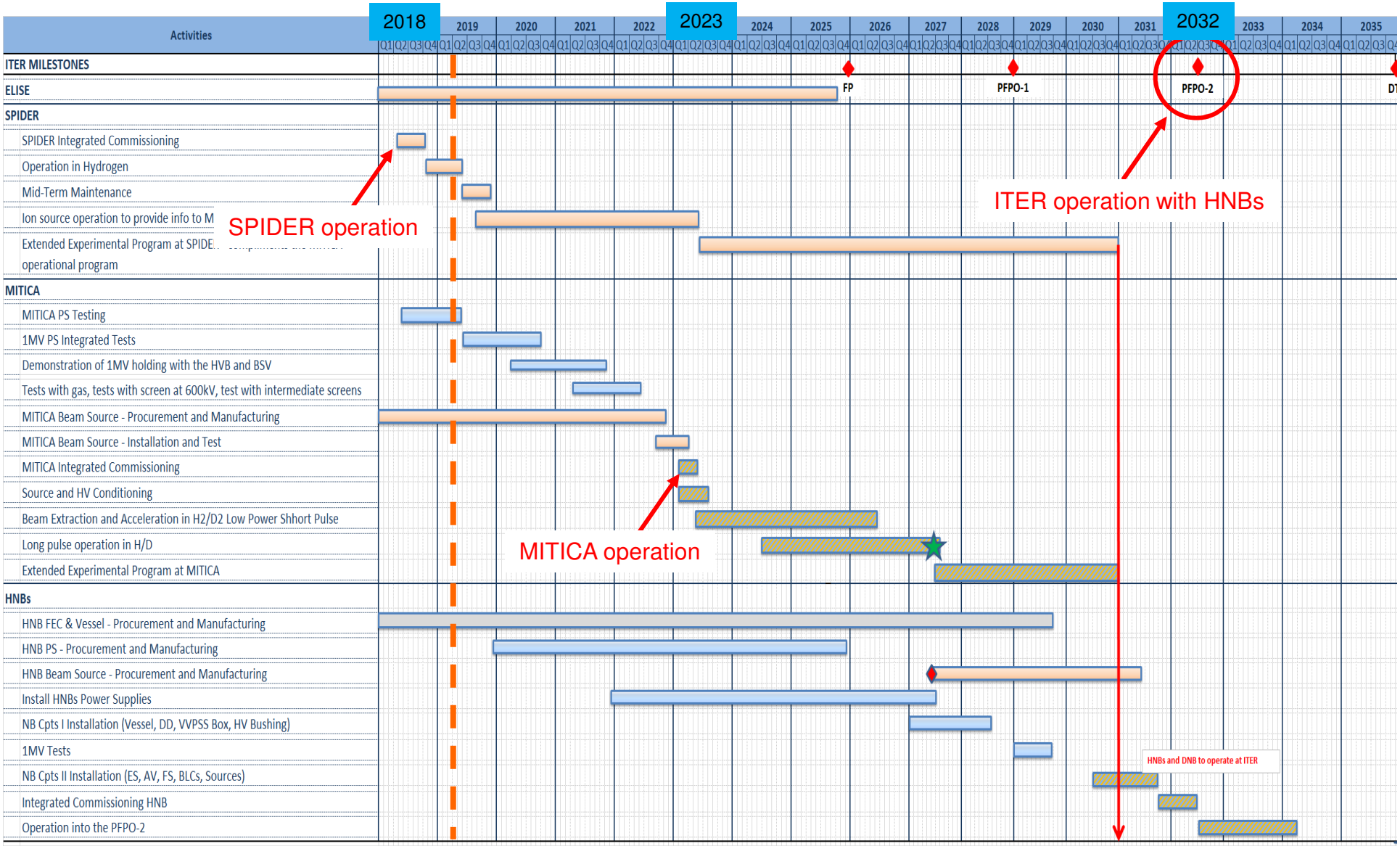

# Contributors to NBTF Project

CONSORZIO RFX
Ricerca Formazione Innovazione

iter
china eu india japan korea russia usa

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ENEA
INFN

FUSION FOR ENERGY

ITER JAPAN

ITER-India

QST

NIFS

IPP Max-Planck-Institut für Plasmaphysik
EURATOM Association

KIT Karlsruhe Institute of Technology

CCFE CULHAM CENTRE FOR FUSION ENERGY

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

IFP Istituto di Fisica del Plasma "Piero Caldirola"
Consiglio Nazionale delle Ricerche

CNR NANOTEC INSTITUTE OF NANOTECHNOLOGY

ICMATE

INFN Laboratori Nazionali di Legnaro

# Thanks for your attention