FIP/1-3Ra

TECHNOLOGIES FOR REALIZATION OF LARGE SIZE RF SOURCES FOR –VE NEUTRAL BEAM SYSTEMS FOR ITER -*Challenges, experience and path ahead*

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FIP/1-3Rb

PROGRESS IN ITER NEUTRAL BEAM FACILITY

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FIP/1-3Rc

DEMONSTRATION OF 1 MV VACUUM INSULATION FOR THE VACUUM INSULATED BEAM SOURCE IN THE ITER NB SYSTEM

Kojima et al
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FEC 2018

Presented by: Jaydeep Joshi on behalf of FIP/1-3Ra, FIP/1-3Rb and FIP/1-3Rc

27th IAEA-FEC, Gandhinagar, October 2018

Outline

1. Negative ion systems in ITER
2. ITER Neutral Beam Test Facility (NBTF)
3. Indian test facility (INTF)

4. Technologies for realization of large size RF source for –ve Neutral Beam system for ITER- Challenges, experience and path ahead
   a. Development of 'angled' grid segment, Welding technologies, Post insulators
   b. Overview of components produced till now
   c. Deviation and non-conformities
   d. Learnings

High precision Mechanical system

5. Progress in ITER Neutral Beam Facility
   a. SPIDER- components, installation and first operation
   b. MITICA- mechanical components, power supplies and tests
   c. NBTF Status

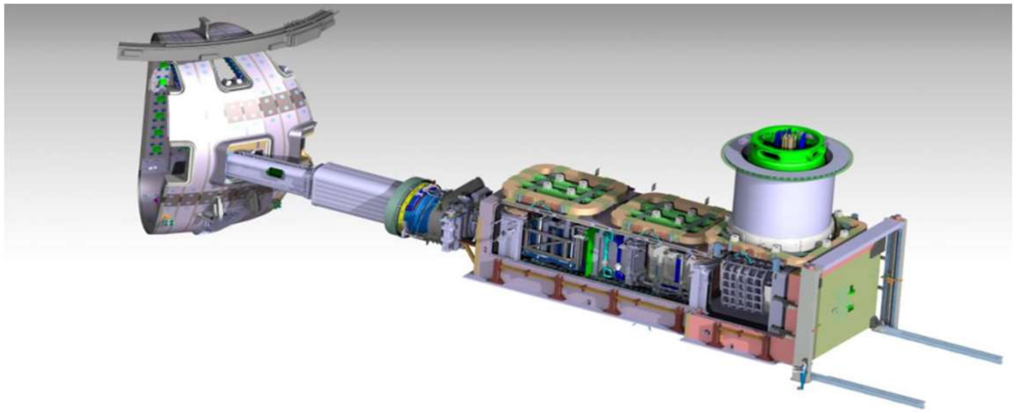
Installation, commissioning and operation of complex system

6. Demonstration of 1 MW Vacuum insulation for the vacuum insulated Beam source in the ITER NB System
   a. Schematics
   b. Electric Field Analysis for BS and HVB
   c. Design of shields for the BS and HVB in the vessel
   d. Demonstration of Improvement by Shields

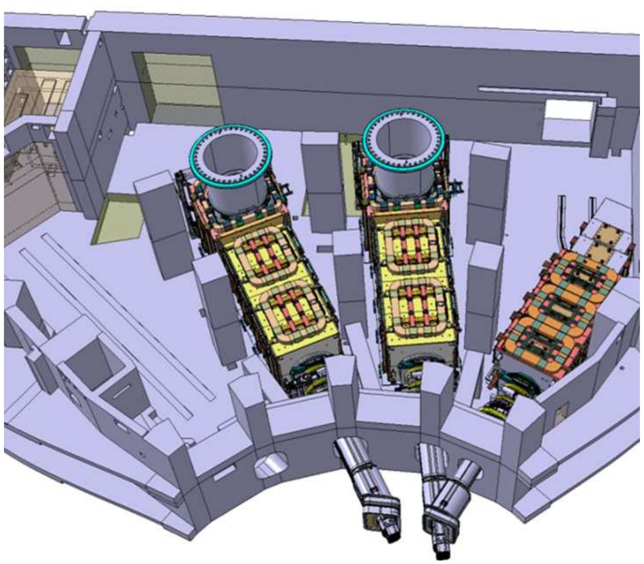
Ultra High voltage systems

7. Summary

Negative ion systems in ITER



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



2 HNBs (+1): deuterium		1 DNB: hydrogen	
• I	= 40 A	• I	= 60 A
• V	= 1 MV	• V	= 0.1 MV
• t_{pulse}	= 3600 s	• t_{pulse}	= 3s every 20s
• P_{beam}	= 16.5 MW	• Modulation	= 5Hz

EUDA & JADA procurement

INDA procurement

Progress in the ITER Neutral Beam Test Facility

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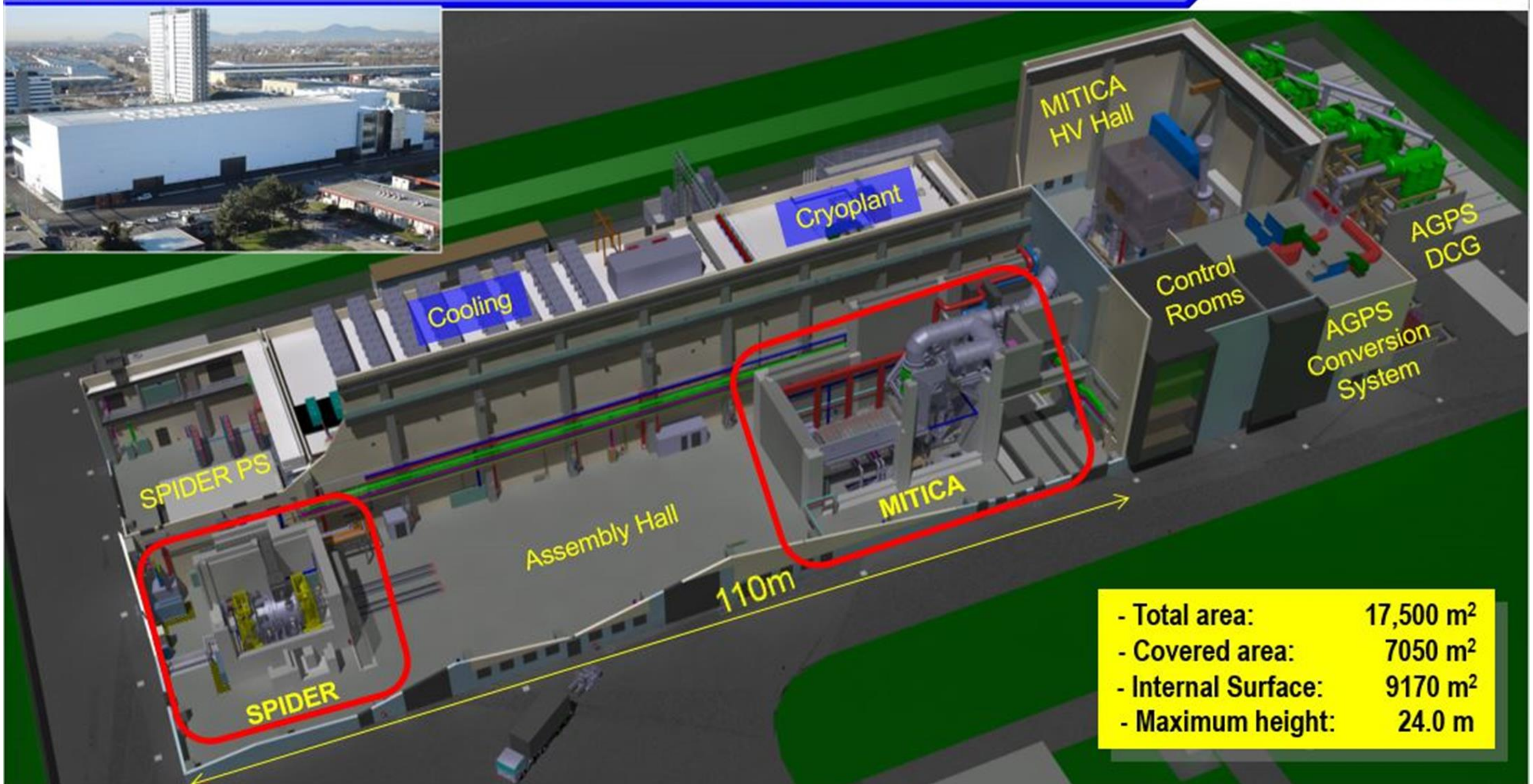
CONSORZIO RFX
Ricerca Formazione Innovazione

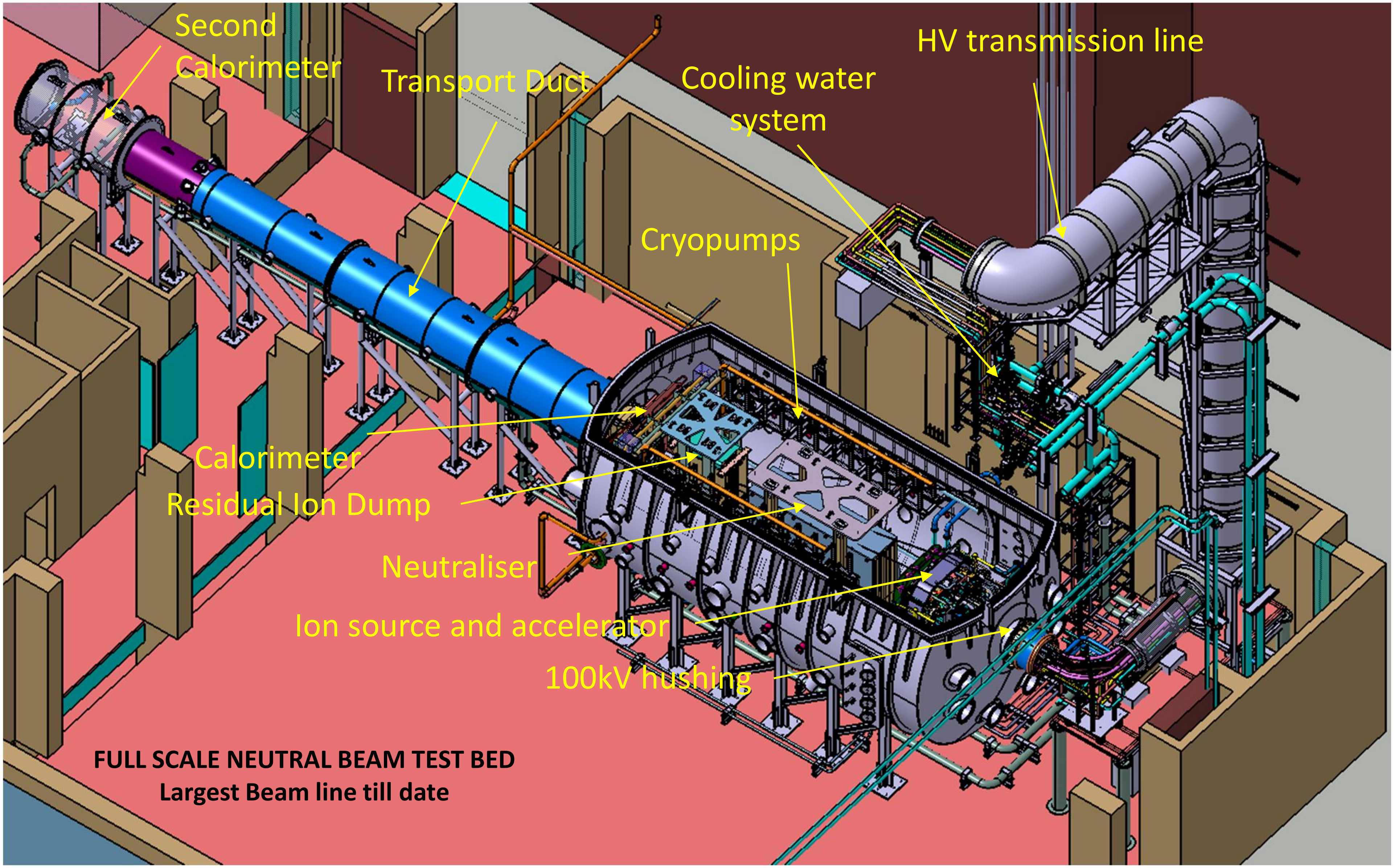


NBTF hosts the two experiments: the negative ion source **SPIDER** and the 1:1 prototype of the ITER injector **MITICA**

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

Indian Test Facility (INTF)



Refer contribution number FIP P1-40 for **R&D STATUS OF INDIAN TEST FACILITY FOR ITER DNB CHARACTERIZATION**

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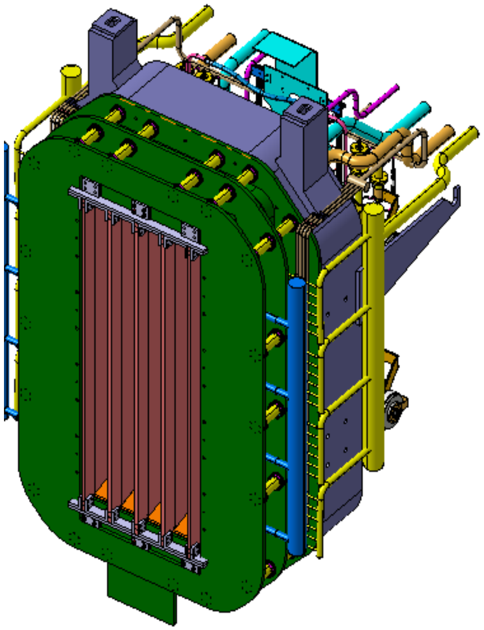
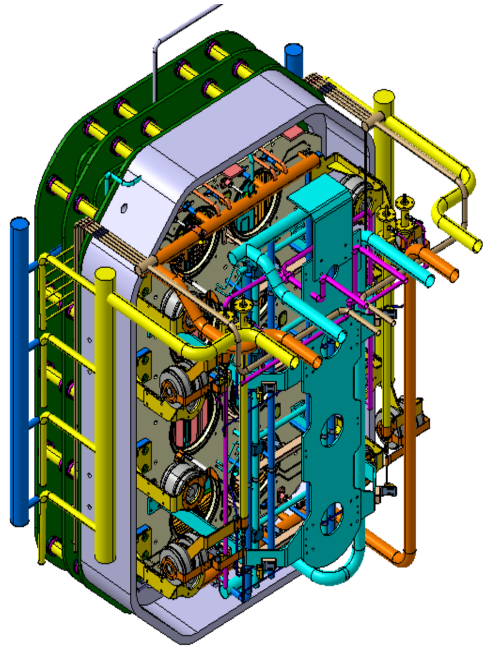
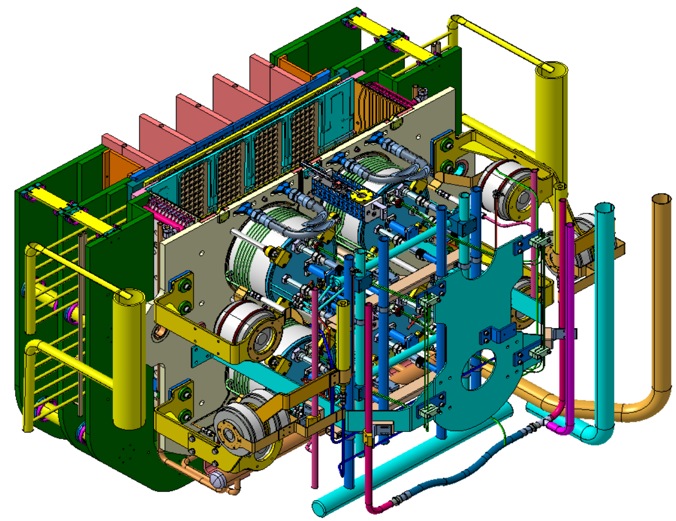
RF Ion Source for –ve Neutral Beam system



Accelerator
(1.4m x 2.2m x 0.4m)



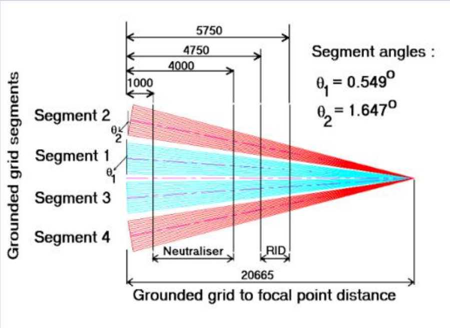
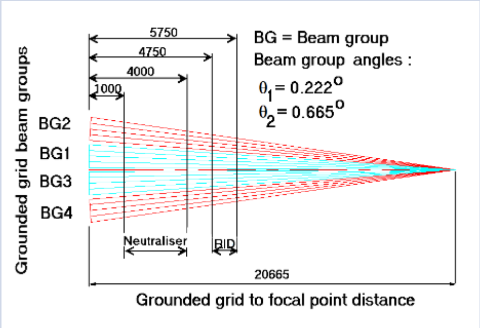
RF Based Ion Source with 8 RF drivers
(1.5m x 1.9m x 1.1m)



Cross section of
Beam Source

- Designed to produce a 100keV, 60A, 60MW Hydrogen beam
- To measure the Helium ash content in the Deuterium–Tritium (D-T) phase of the ITER machine using the Charge Exchange Recombination Spectroscopy (CXRS)

Requirements and related challenges

Requirement	Challenge
Realization of accelerator with focusing requirement of beam at a distance of 20.665m  	Overall assembly tolerance of +/- 0.2mm Aperture positioning of 50 microns Flatness of 40 microns Aangles within the tol. Of +/-0.002
ITER Vacuum Handbook for water to vacuum boundary application	Design of full penetration weld joint with 100% volumetrically inspectable configuration
Functional and configurational requirements	Customized design of alumina insulators to provide the mechanical connection between grid mounting flanges and electrical isolation upto 90kV
Radioactive environment	Material selection and procurement with the restricted chemical composition of Cobalt (Co), Niobium (Nb) and Tantalum (Ta) for adaptability to ITER's radiative environment
QA	Extensive quality interventions Handling of Deviation and Non-conformities

First of its kind manufacturing

Technology development for 'angled' accelerator grid segment

Identification of important geometries → Define the tolerances → Incorporate the manufacturer's feedback on the feasibility → Re-define the achievable tolerances → **Prove the achievability of targeted tolerances by Prototype route** → Implement the recommendations for improvement → **Production of grid**

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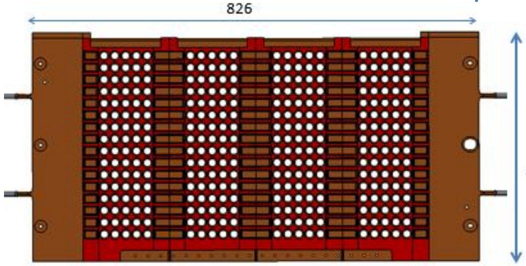
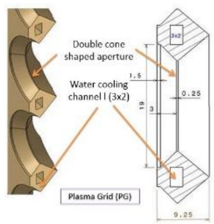


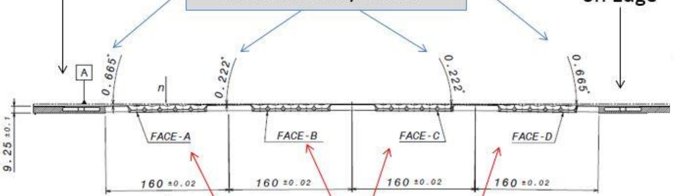
Typical size of a Segment (in mm)



Flat Plane on Edge

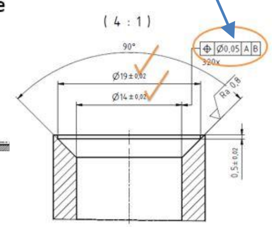
Two stage angle on either side of center line with tolerance of +/-0.002 °

Flat Plane on Edge

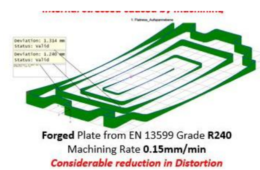


Flatness and Parallelism: 0.04mm

0.050mm



Material selection



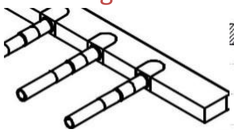
Fixture development

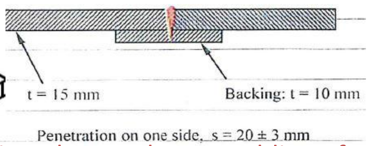
Measuring Technique development

Manufacturing process development

Copper electrodeposition over angled surface

Precision milling of channels and apertures





Full penetration electron beam welding of water connectors*

** This design along with the configuration and its realization has been protected and patent is filed for the same.*

Technology development for 'angled' accelerator grid segment

Production of grid

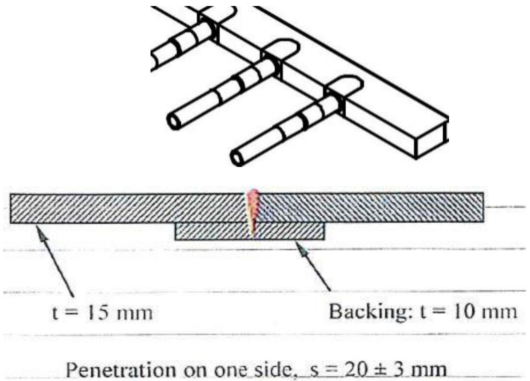
- *Typical values of the achieved dimensions*

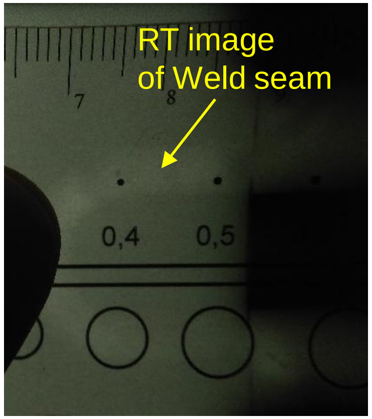
	Beam group angles (Deg)				Beam group plane flatness (microns)				Aperture position (microns)			
	BG 1	BG 2	BG 3	BG 4	BG 1	BG 2	BG 3	BG 4	BG 1	BG 2	BG 3	BG 4
Nominal Value	0.665	0.222	0.222	0.665	0				0			
Targeted Tolerance	+/-0.002	+/-0.002	+/- 0.002	+/- 0.002	40				50			
Deviation-Segment 3	-0.003	0.010	-0.003	-0.011	197	136	86	116	21	23	25	38
Prototype Grid	-0.072	0.031	-0.014	-0.091	166	106	81	75	42	35	67	96

- Production with incorporating the recommendations-> led to the best possible methodology of manufacturing
- Three segments of Plasma Grid segments have been produced till now.
- Effect of minor deviation on functionality is assessed to move ahead for production

Welding Technology development

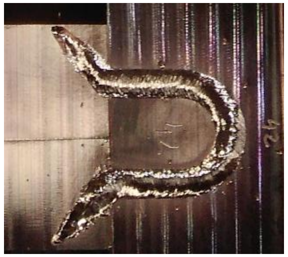
Compatibility * with respect to IVH





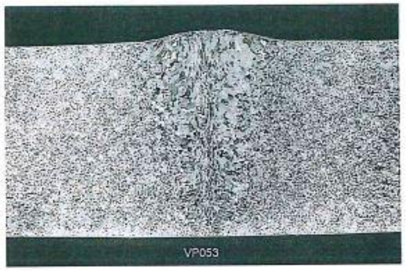
Full penetration CuOF to CuOF EBW joint with 100% volumetric examinable configuration

Weldability*



(a) front side

(b) root side
As welded seam

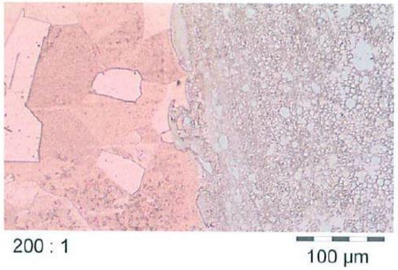


Macro-picture of the weld seam

Repairability

- An important aspect of production of grid
- Requires customized solution for repair, depending on the type of defect and location of defect
- Re-fuse the weld seam, within the parameter range→ Separate qualification has been performed to ensure the strength as equivalent to the original weld seam

Dissimilar material welding



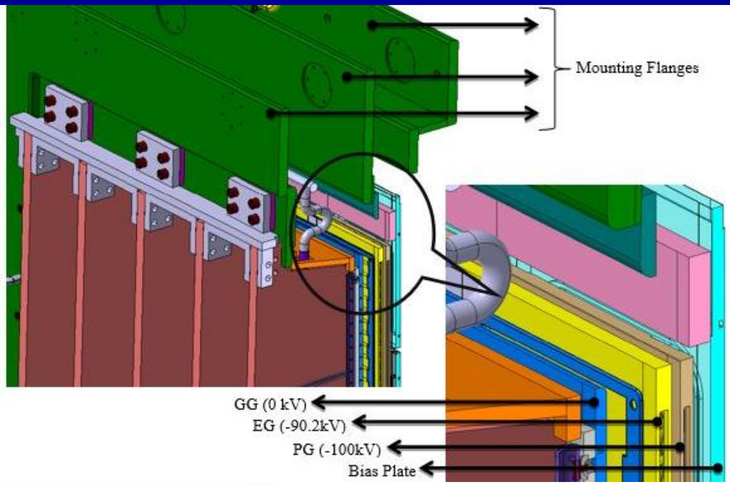
Full penetration EBW of CuOF to Inconel joint with strength in the range of 234 to 261 MPa

* *This design along with the configuration and its realization has been protected and patent is filed for the same.*

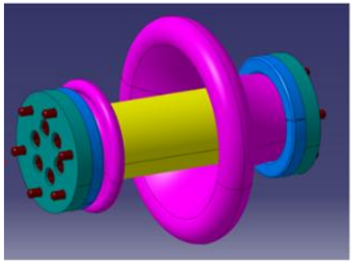
Post Insulator Manufacturing

Multi Aperture Grid System
Composed of Three grids:

- Plasma Grid (PG)…**-100kV**
- Extractor Grid (EG)…**-90kV**
- Grounded Grid (GG)…**Grounded**



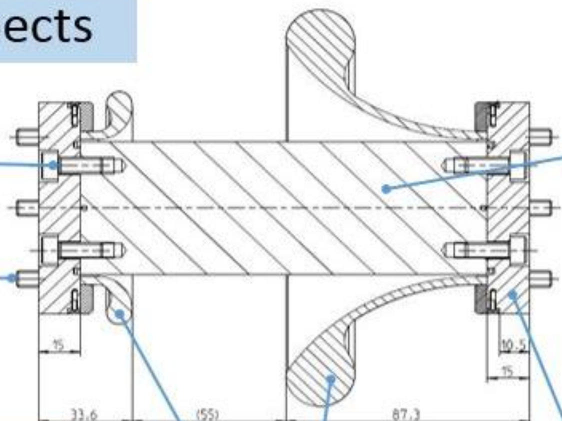
Each grid is **Mechanically connected** and **Electrically isolated** by set of Post Insulators



Configurational Aspects

Bolts to connect Ceramic and SS flange

Bolts to connect SS flange and Grid holder flanges



Alumina; Al_2O_3

- Grade C795 as per IEC 60672-3
- Dia 50mm

- Mechanical Connection by vacuum bolts
- Helical element as compliant element in ceramic threads

Stainless Steel (SS) Flanges

- Link Between the Grid Holder Flanges and Alumina

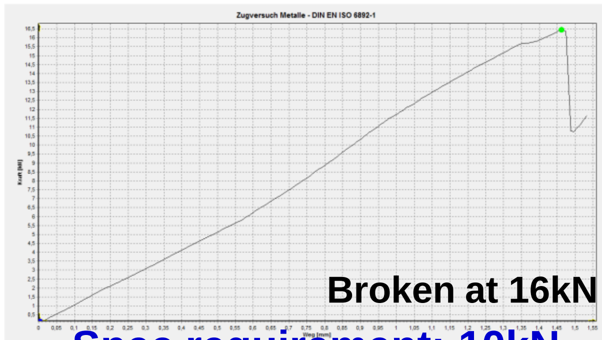
Electrostatic shield

- Size
- Shape
- Distance between anode and cathode

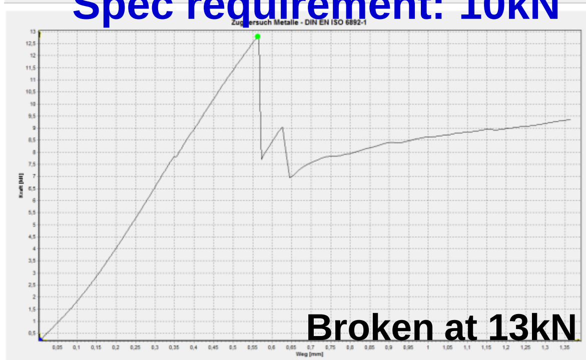
Stringent requirements on assembly dimensions to reach the final alignment of accelerator

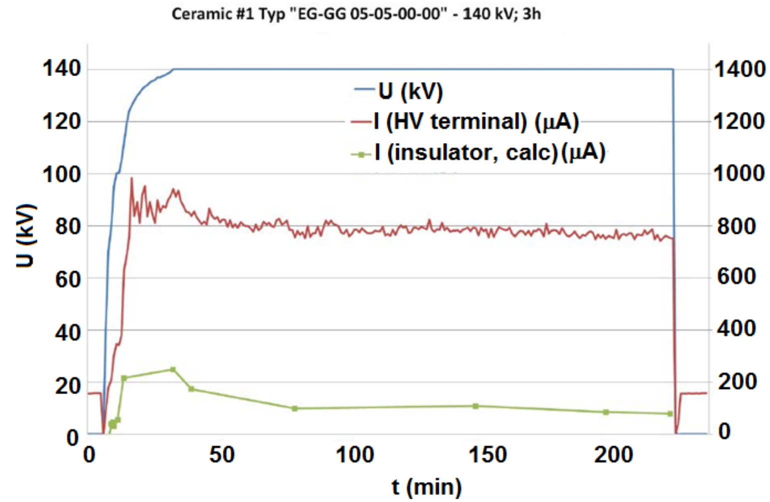
Post Insulator Manufacturing

Prototyping: To establish (1) manufacturing route (2) to qualify them for mechanical and electrical specification (3) to assess the feasibility of stringent tolerances on the assembly



Spec requirement: 10kN





Mechanical test

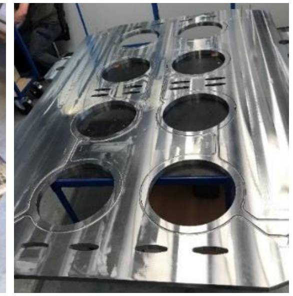
Electrical test

Total 40 Nos. of Post insulators have been manufactured with end flange flatness of 60 microns in assembled condition

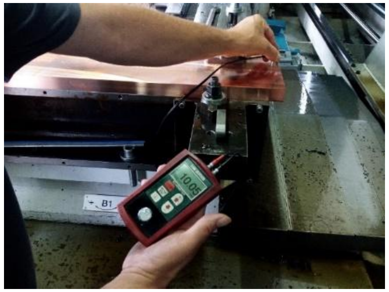
Major components produced till now

Plasma Grid Segments-3 Nos.

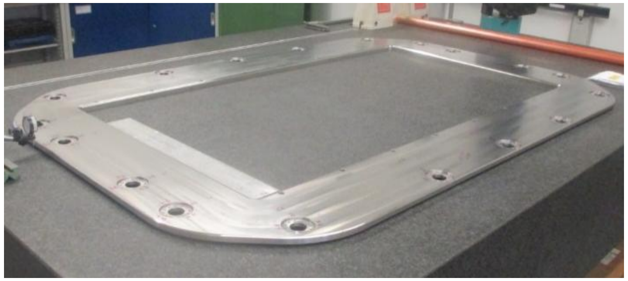
Soft Iron Plate segment



Rear Driver Plate



Electron Dump Panels- 10 Nos.



EG Mounting Flange

GG Flange

Post Insulators- 40 Nos.

Plasma Box components and Faraday shield

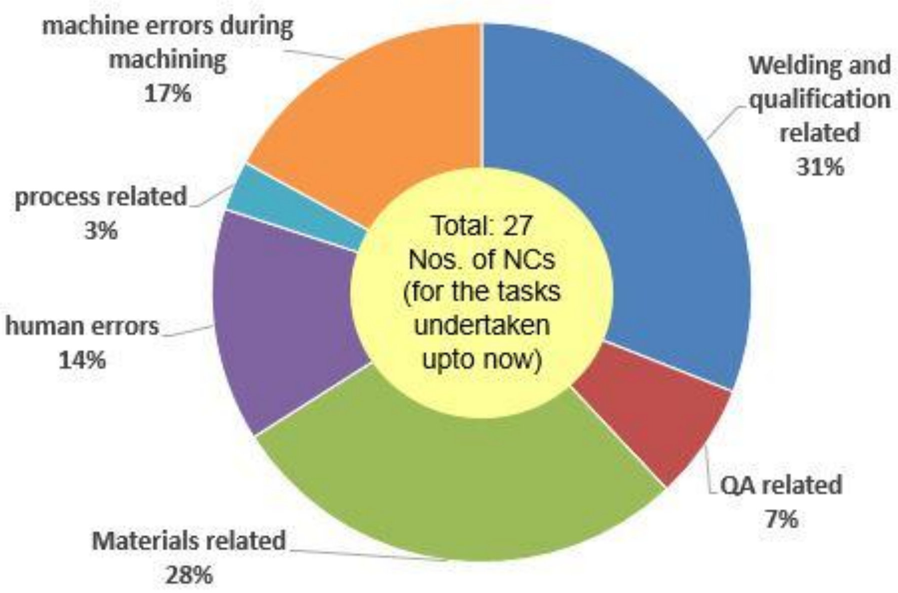
Technologies involved:

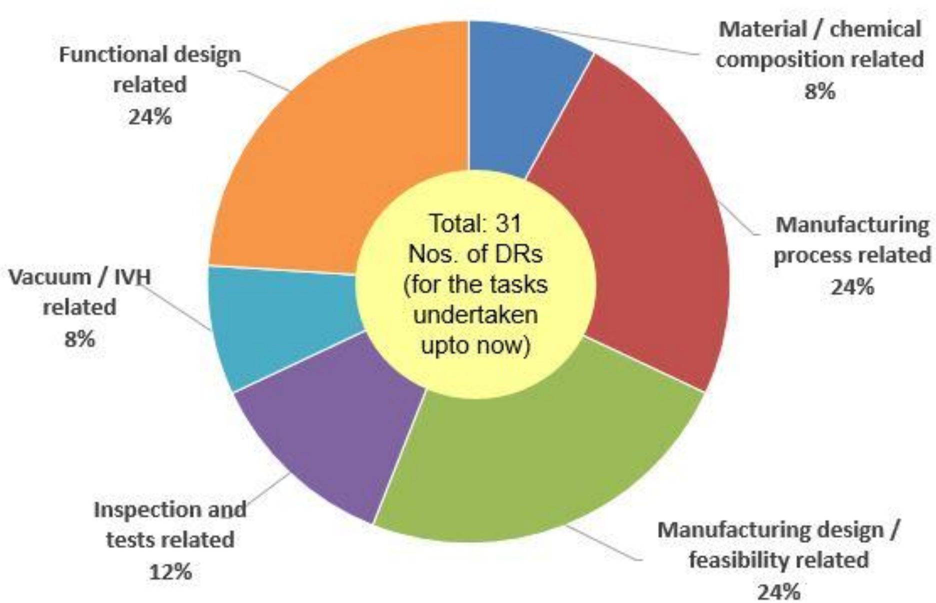
- High precision milling of copper
- Vacuum Brazing
- Electron beam welding of copper and dissimilar material
- Copper Electro deposition
- Ceramic to metal joining
- Heavy fabrication of stainless steel
- Deep hole drilling

Non-conformities and deviation

Extensive Quality interventions:

Tool to ensure and establish the close adherence of manufacturing activities with respect to laid procedures





Each NC and DR to be supported by technical assessments (like FEA, experimentations, prototyping, imposing additional inspection / test etc.) and check that they do not impact the overall functionality of the system

Summary

- 'angled' grid segment manufacturing remains a challenge, even after establishing the complete manufacturing procedure through 1:1 prototype. Each segment has to be handled with careful monitoring at all the stages of production
- Welding for vacuum boundary connection according to ITER requirements, is one of the most critical activity in terms of process selection, configuration and its qualification for timely execution of the project
- Inspite of sufficiently detailed and thoroughly detailed specification, there are possibilities of deviations to suit the manufacturing needs, which have to be accommodated without impact on the function of components
- Prototyping is essential for the components where no past experience is available to establish the feasibility and to unfold the uncertain areas of manufacturing
- It is essential to be a 'Technical Partner' to 'Contractor' for every challenge they come across to fulfil the specification requirement, for the success of such a challenging project.
- Significant learnings generated from this manufacturing is expected to provide the guideline on manufacturing design for upcoming ITER ion sources with similar challenges for seamless manufacturing with reduced time and efforts.

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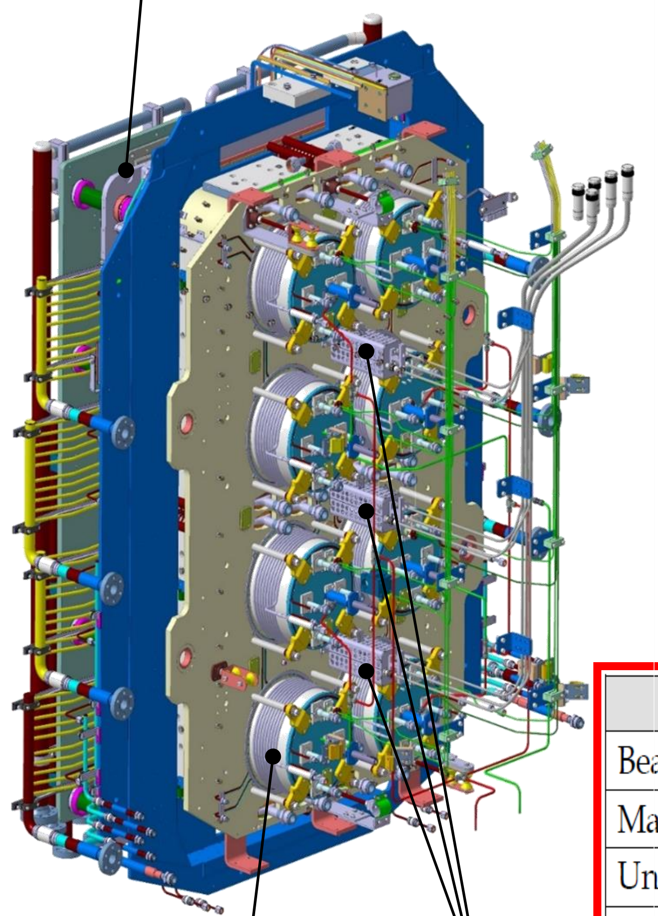


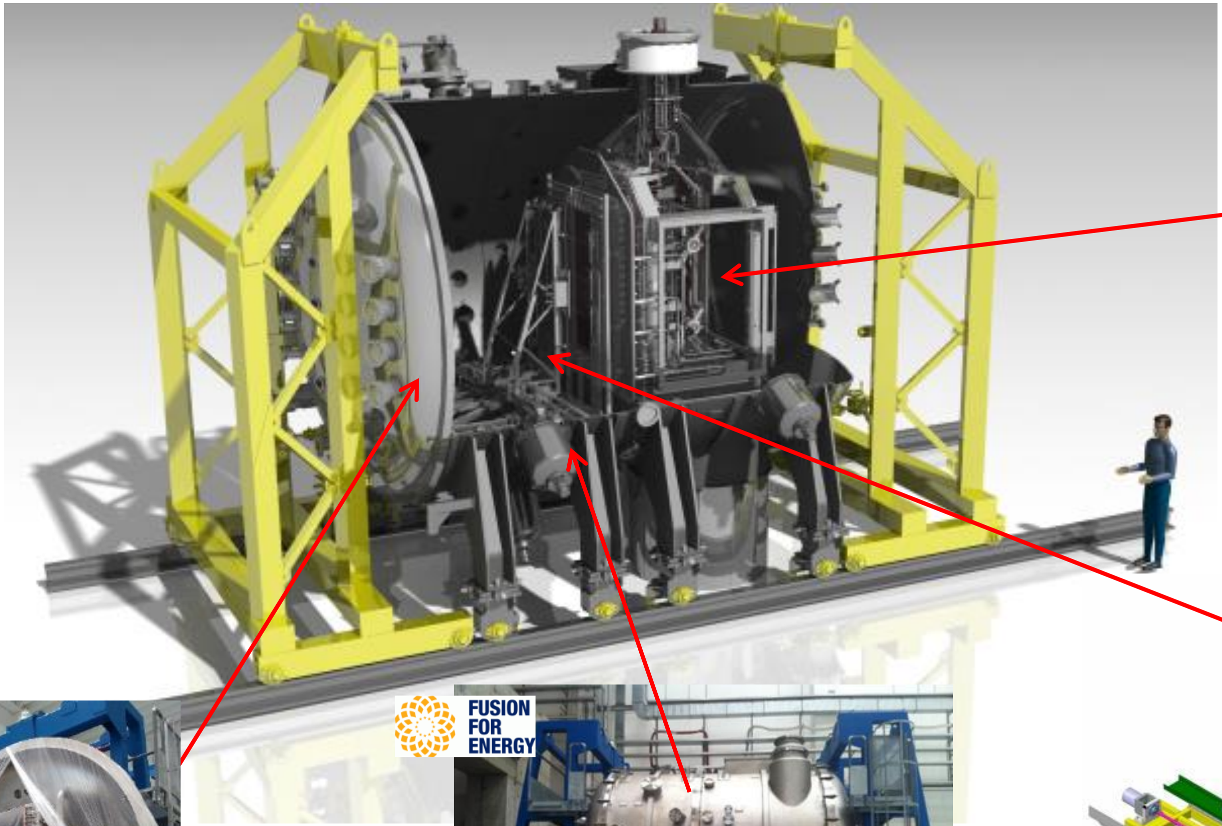
- Optimisation of production of negative ions in terms of:

  - Density
  - Uniformity
  - Stability
  - Co-extracted electrons

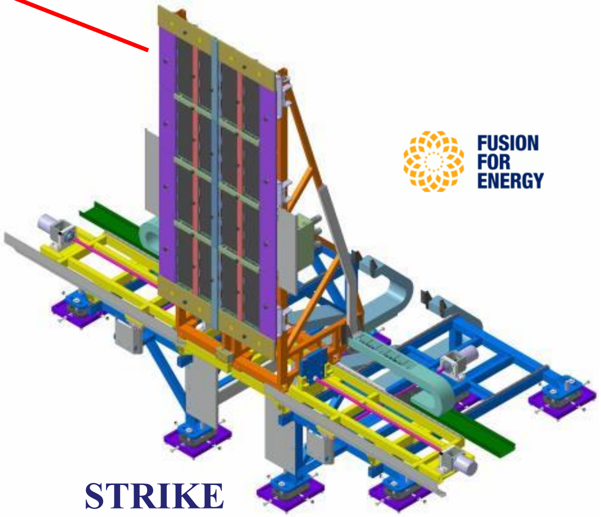
	Unit	H	D
Beam energy	keV	100	100
Maximum Beam Source pressure	Pa	<0.3	<0.3
Uniformity	%	±10	±10
Extracted current density	A/m^2	>355	>285
Beam on time	s	3600	3600
Co-extracted electron fraction (e^-/H^-) and (e^-/D^-)		<0.5	<1

SPIDER Components

Vacuum-insulated beam source



Beam Source

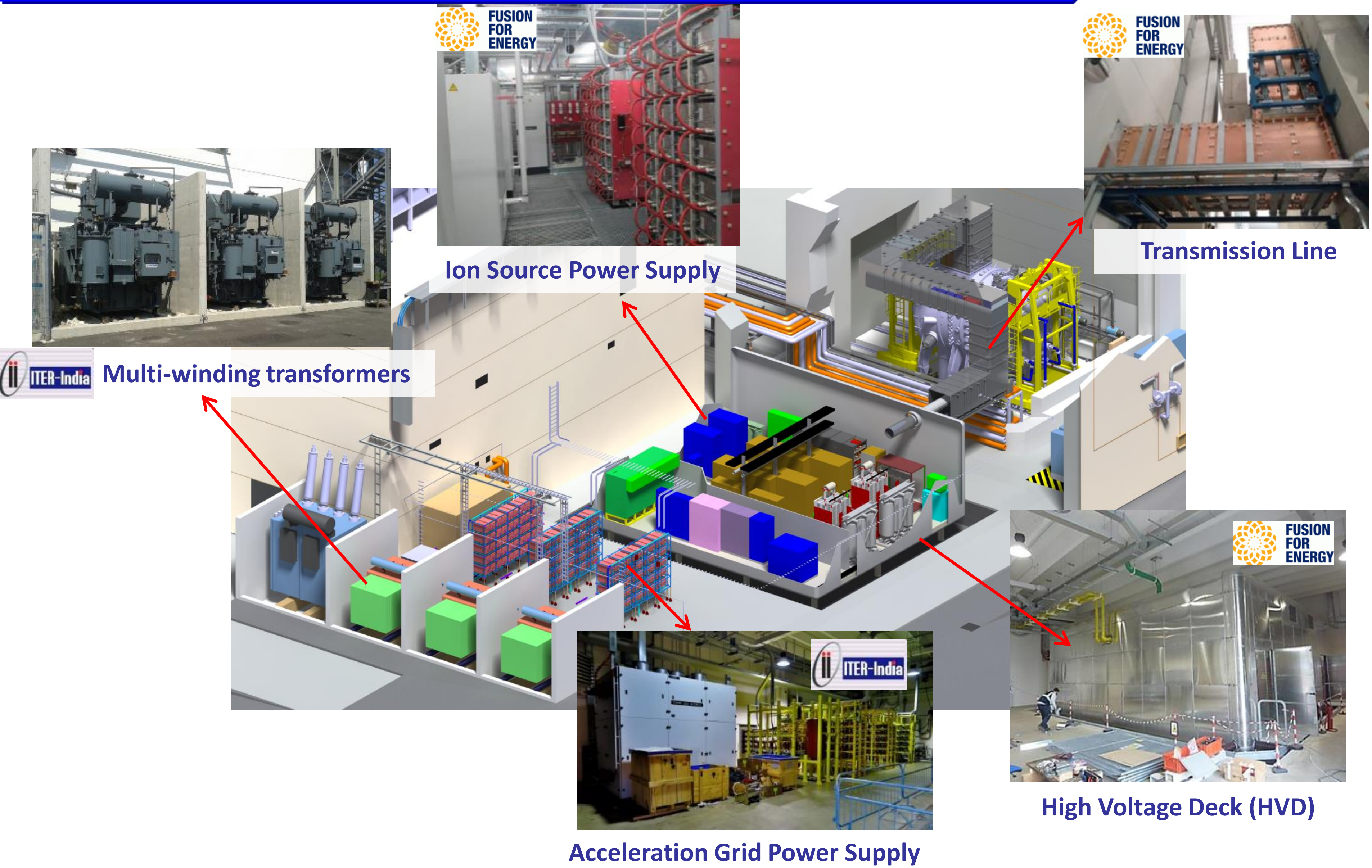


STRIKE
High resolution calorimeter

Beam Dump

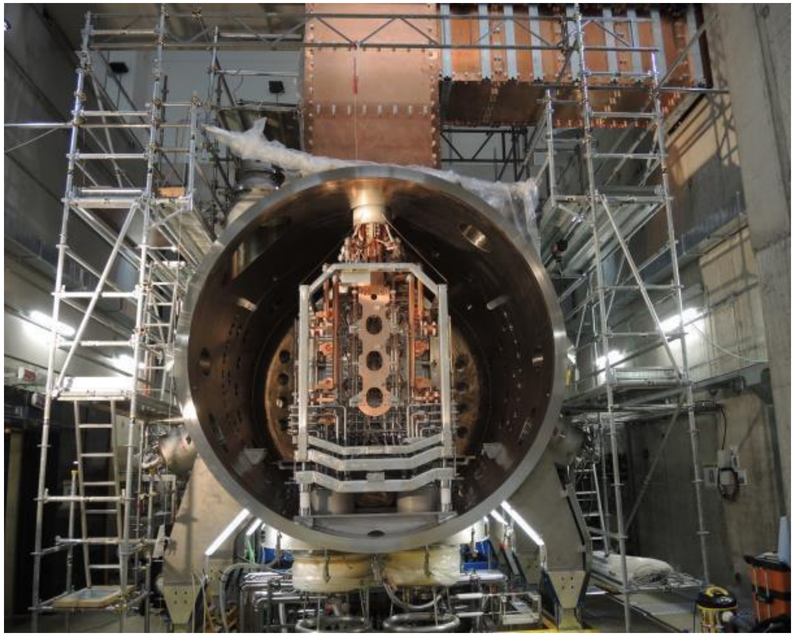
Vacuum Vessel

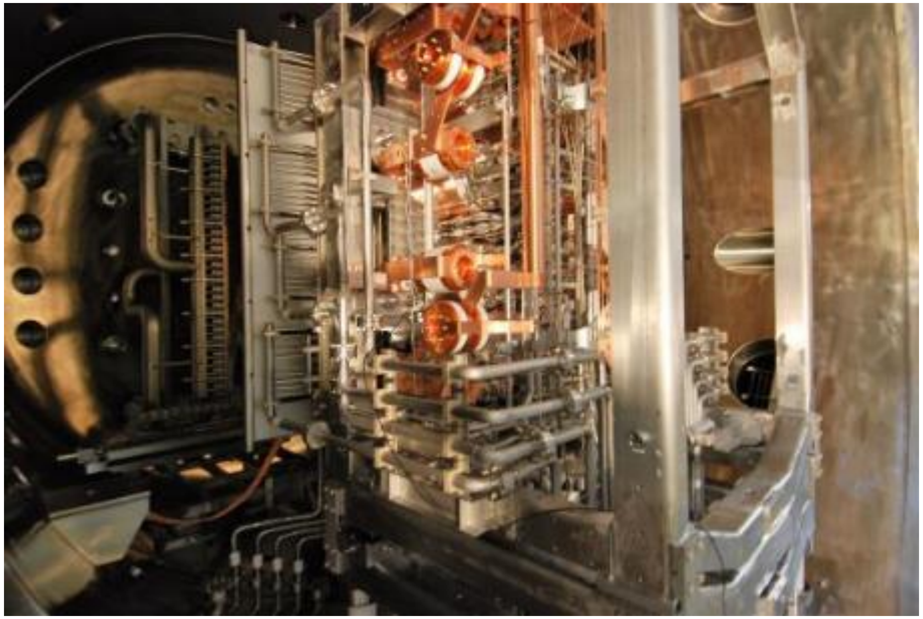
SPIDER power supplies



SPIDER beam source installation

- In March 2018
  - all connections and vacuum vessel lid closed
  - leak test of hydraulic circuits from external flanges started



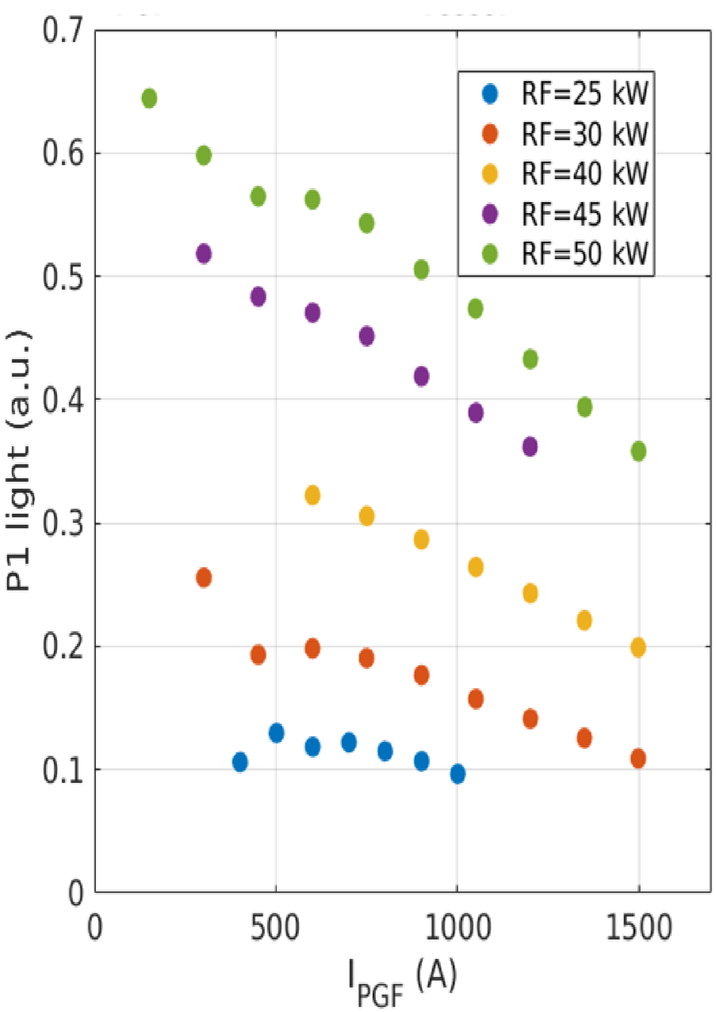


First SPIDER operations

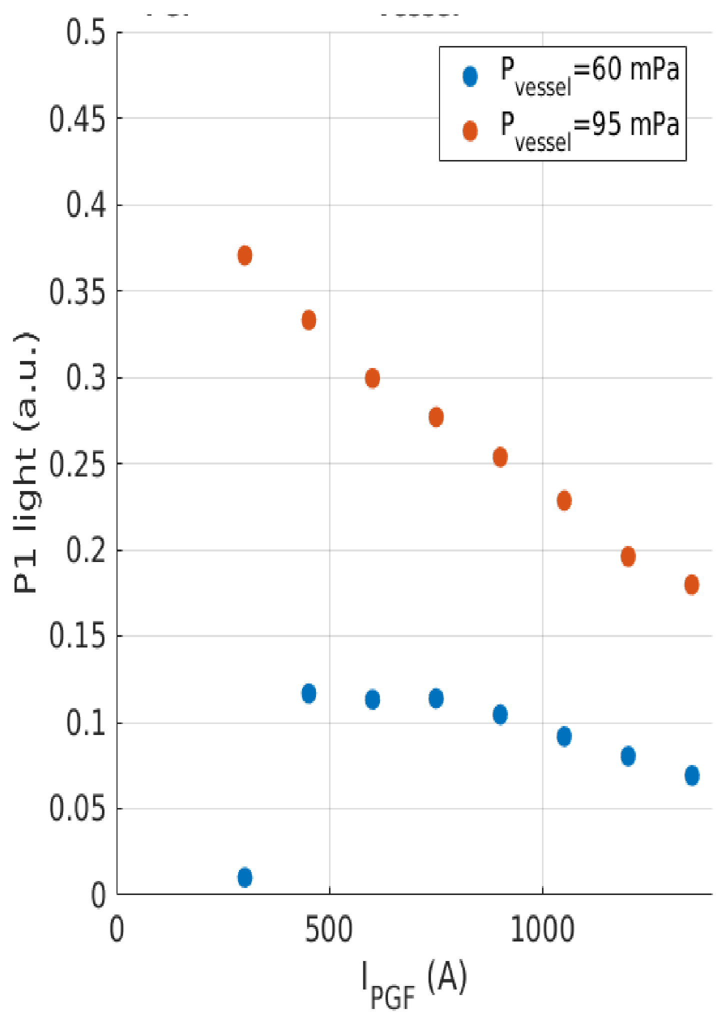
- SPIDER operation started on 4 June 2018
- After some tuning, first plasma ignition on 6 June 2018 with 1/4 source

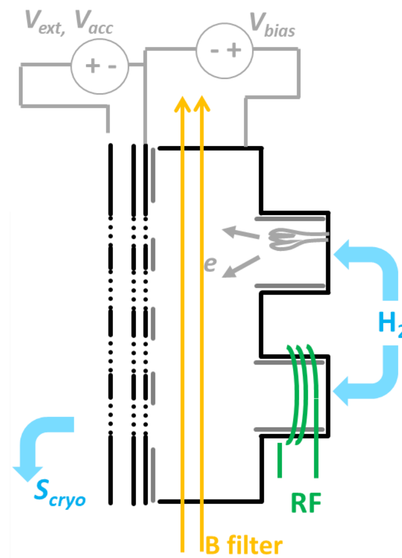
Characterisation of source plasma

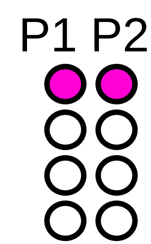
I_{PGF} scan with different RF powers (p_{source}=0.24Pa; I_{ISBI}=0A)



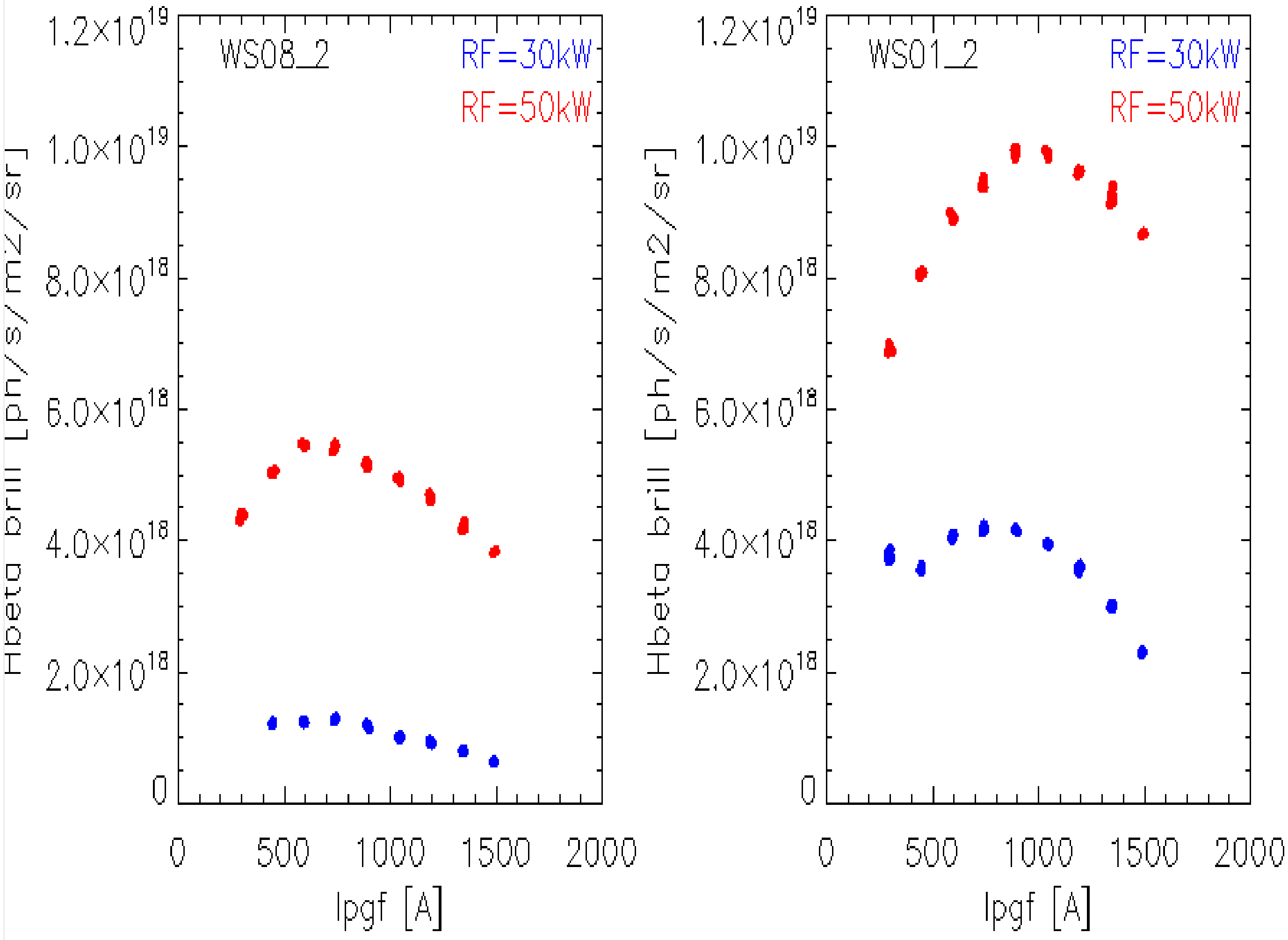
I_{PGF} scan with different p_{source} (RF power=25kW; I_{ISBI}=0A)



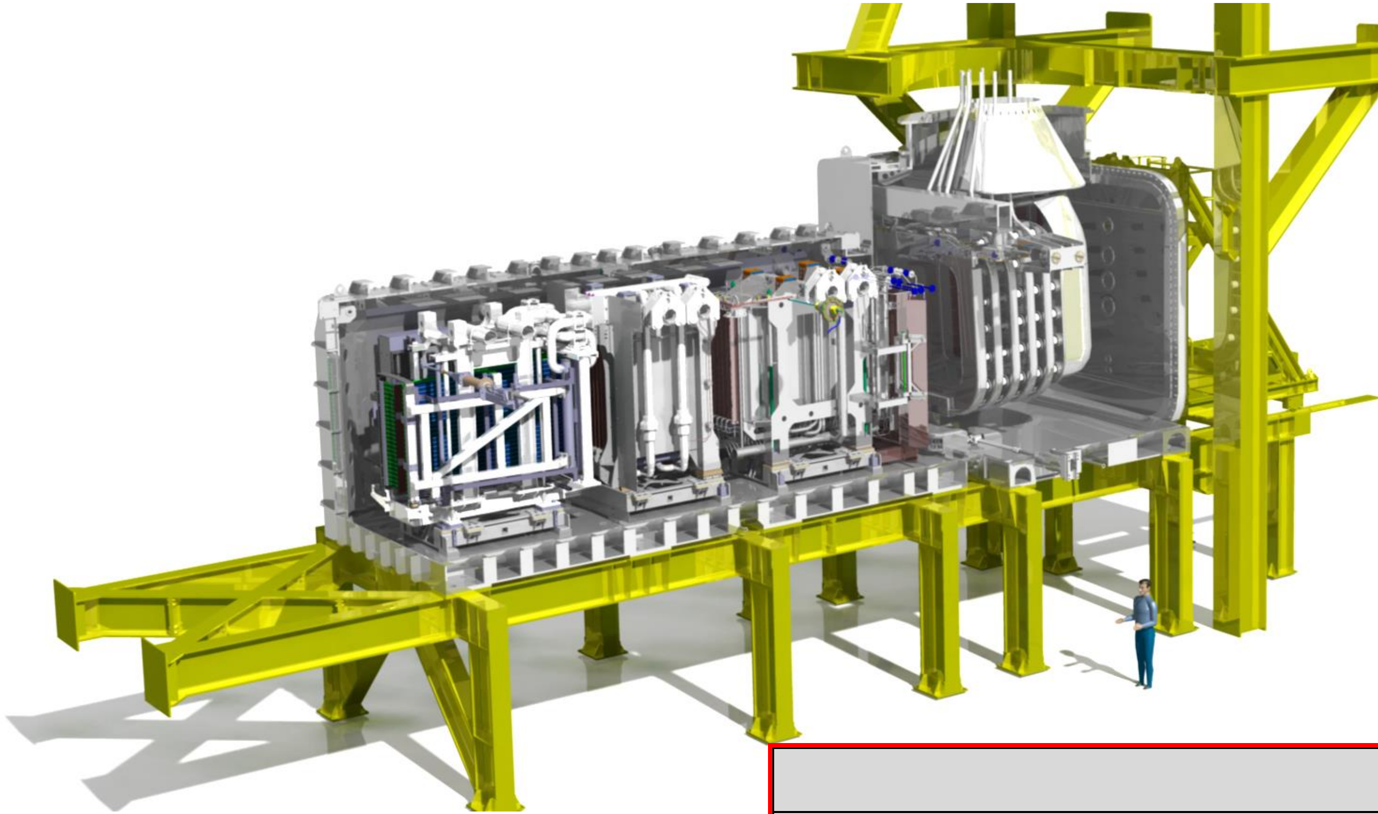




- H_β radiation through drivers: RF power scan



MITICA full scale prototype of ITER HNB

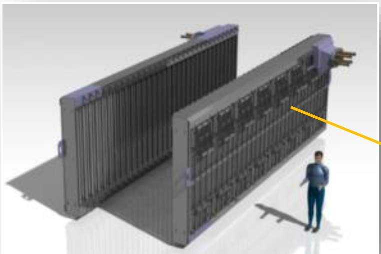


Optimisation of neutral beam in terms of:

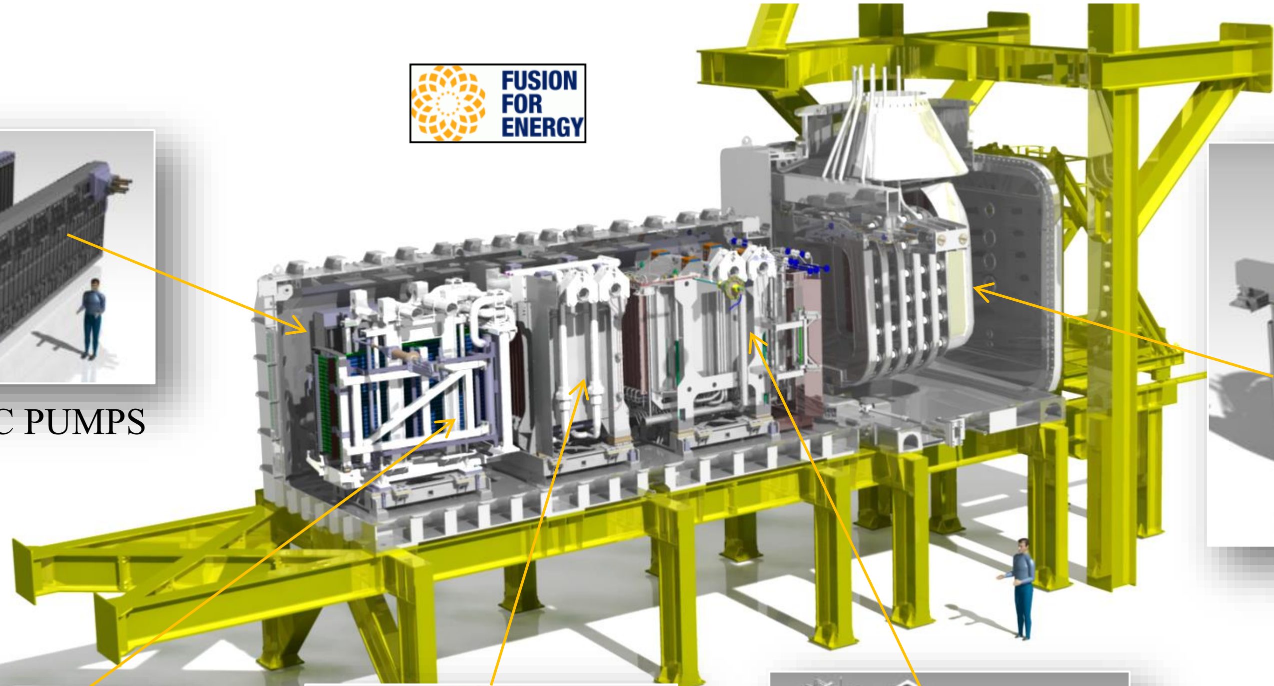
- Performances
- Reliability
- Availability

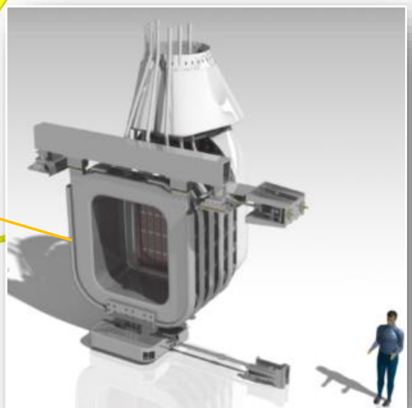
	Unit	H	D
Beam energy	keV	870	1000
Acceleration current	A	46	40
Max Beam Source pressure	Pa	0.3	0.3
Beamlet divergence	mrad	≤7	≤7
Beam on time	s	3600	3600
Co-extracted electron fraction (e^-/H^-) and (e^-/D^-)		<0.5	<1

MITICA components



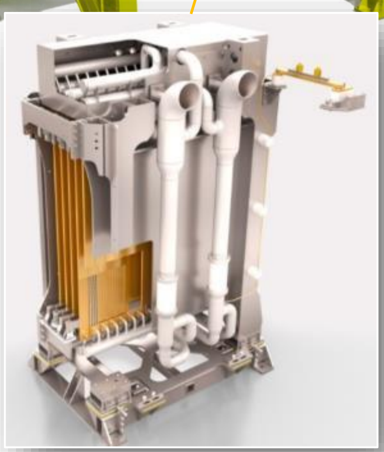
CRYOGENIC PUMPS



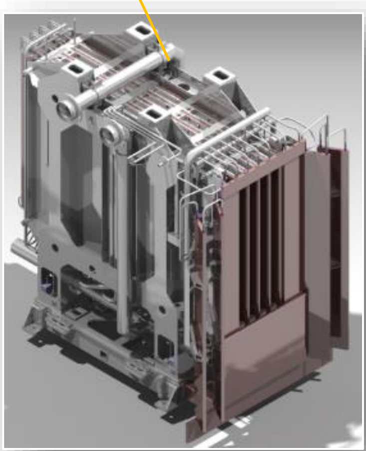


BEAM SOURCE

CALORIMETER



RESIDUAL ION DUMP

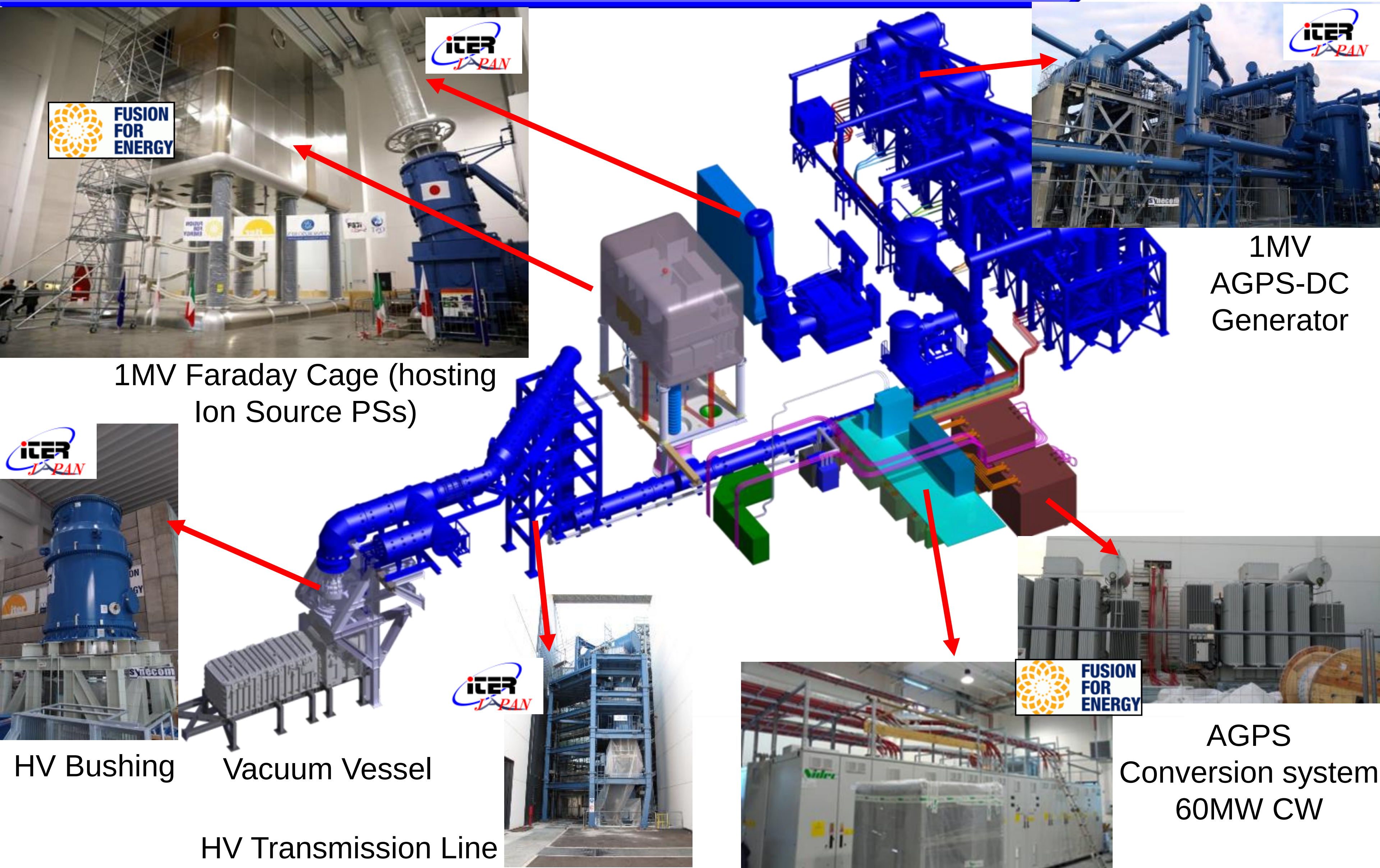


NEUTRALIZER

Procurement contracts of mechanical components are all in progress

Beam Source procurement is in the critical line. Procurement contract signed in 2018; delivery expected in 2022

MITICA power supply system



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

1st STEP 1200kV-1 HOUR

2nd STEP 1060kV-5 HOURS

First HV insulating tests successfully passed

NBTF status

- SPIDER
  - Experimentation started in 2018
  - Plants and diagnostics entering into operation one by one
  - Characterisation of source and beam in progress
  - Increase of parameters planned from 2019

- MITICA
  - High voltage power supplies almost completed and under test on-site
  - Other auxiliary plant systems under installation and/or commissioning phase
  - All procurement contracts for mechanical components in progress
  - Expected delivery on site of Beam Source in 2022

Collaborations of NBTF

CONSORZIO RFX
Ricerca Formazione Innovazione

ENEA

INFN

Max-Planck-Institut für Plasmaphysik
EURATOM Association

KIT
Karlsruhe Institute of Technology

CCFE
CULHAM CENTRE FOR FUSION ENERGY

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

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

ICMATE

CNRNANOTEC
INSTITUTE OF NANOTECHNOLOGY

INFN Laboratori Nazionali di Legnaro

iter
china eu india japan korea russia usa

FUSION FOR ENERGY

ITER JADA

ITER JAPAN

ITER-India

QST

प्लाज़्मा अनुसंधान संस्थान
Institute for Plasma Research

NIFS

FIP/1-3Ra

TECHNOLOGIES FOR REALIZATION OF LARGE SIZE RF SOURCES FOR –VE NEUTRAL BEAM SYSTEMS FOR ITER -CHALLENGES, EXPERIENCE AND PATH AHEAD

Jaydeep Joshi et al
jaydeep.joshi@iter-india.org

FIP/1-3Rb

PROGRESS IN ITER NEUTRAL BEAM FACILITY

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FIP/1-3Rc

DEMONSTRATION OF 1 MV VACUUM INSULATION FOR THE VACUUM INSULATED BEAM SOURCE IN THE ITER NB SYSTEM

Kojima et al
kojima.atsushi@qst.go.jp

FEC 2018

Presented by: Jaydeep Joshi on behalf of FIP/1-3Ra, FIP/1-3Rb and FIP/1-3Rc

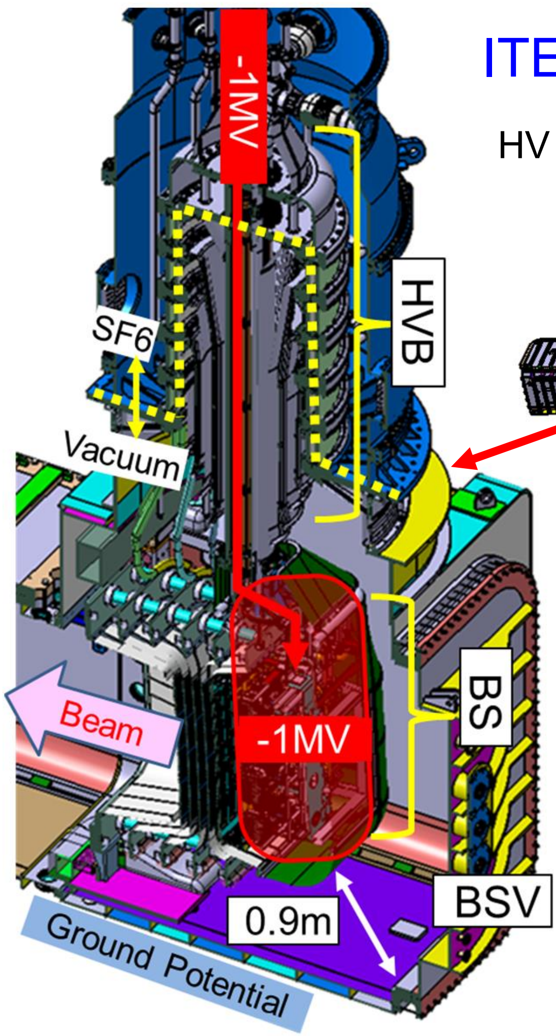
27th IAEA-FEC, Gandhinagar, October 2018

Demonstration of 1 MV vacuum insulation for the vacuum insulated beam source in the ITER NB system

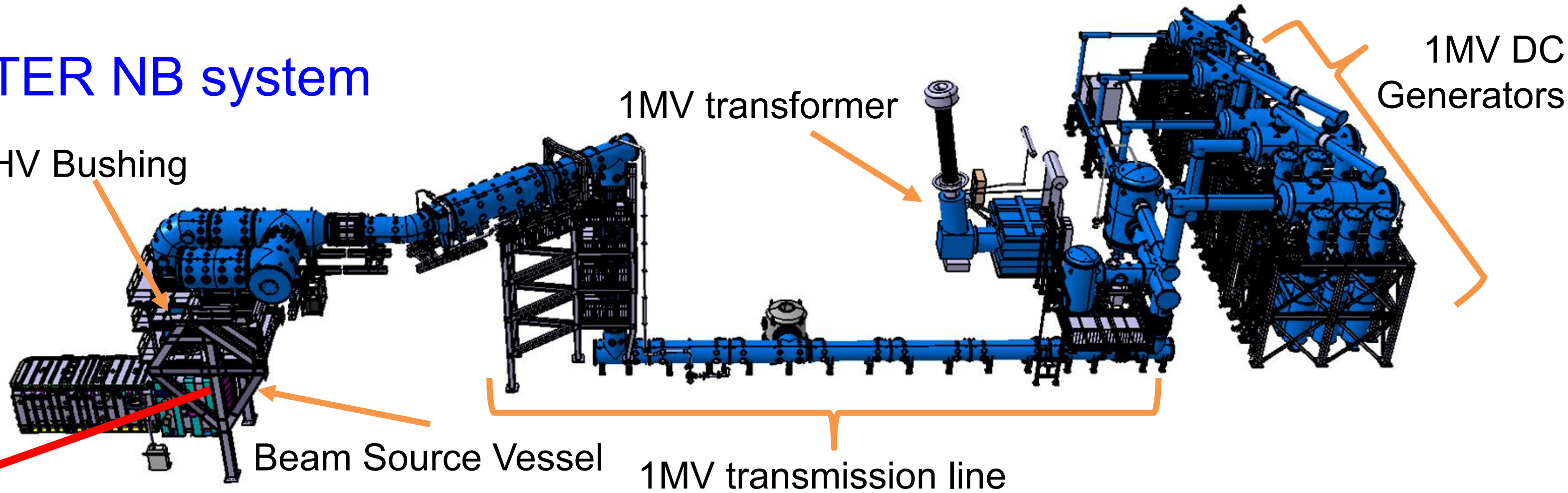
FIP/1-3Rc

- JADA delivers 3 sets of 1 MV power supply and an *1 MV accelerator of beam source* for ITER NB.
- So far, insulation technology for DC 1 MV in gas, oil, water and air has been developed.

Vacuum insulation of ultra-high voltage of 1MV is the most critical issue.



ITER NB system



< Issue of 1 MV insulation for Beam Source >

- Beam Source(BS) installed in vacuum (1 MV) directly faces to the vessel (0 V), therefore *1 MV vacuum insulation with 0.9 m gap is required*, which was originally designed by extrapolation from small-scale experiments.
- Recent experiment indicated *voltage holding with such long gap was much lower than expected*.

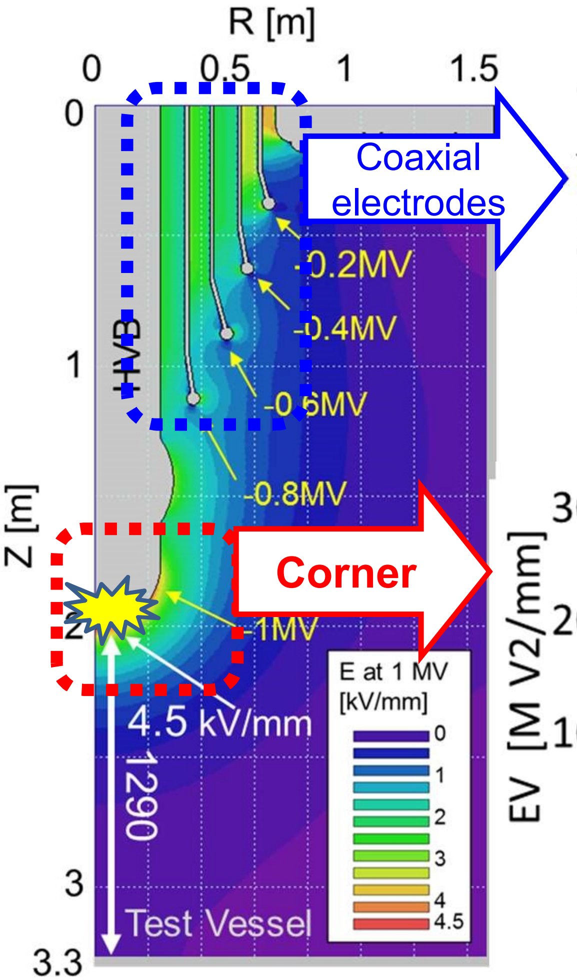
Design basis of voltage holding capability on corner region has been developed for the first time.

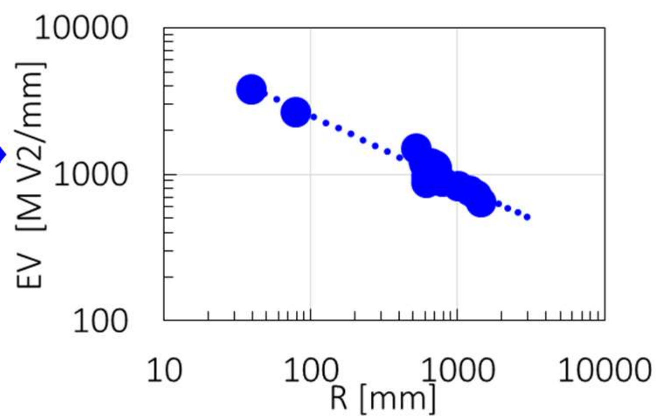
FIP/1-3Rc

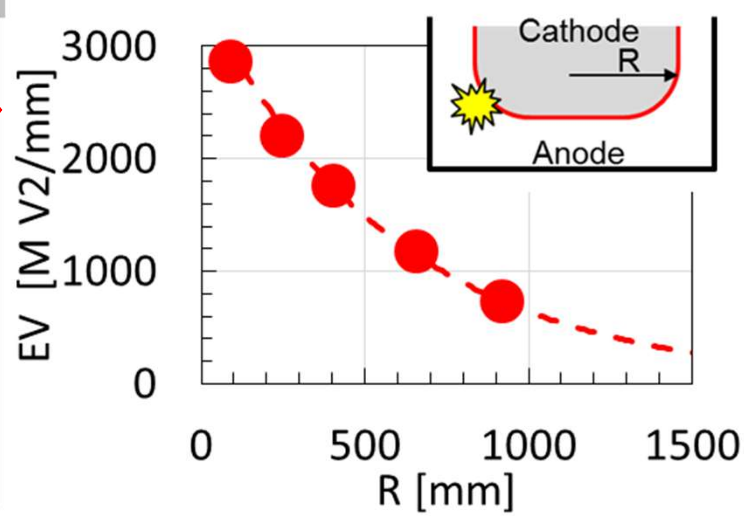
<u><Recent experiment for 1 MV vacuum insulation></u>

- Voltage holding capability of HVB was based on the *empirical scaling for plane and coaxial electrodes*.
- ***Available voltage was limited to 0.7 MV due to breakdowns at 1.3 m single gap*** where >1 MV was expected.

→ Effect of locally concentrated electric field (E_L) on corner was not fully understood







<u><Scaling for design of corner region></u>

- EV value (Breakdown indicator) has been investigated by using several cylindrical configurations.
- Allowable $E_L V$ is found to be limited according to surface area (~R)

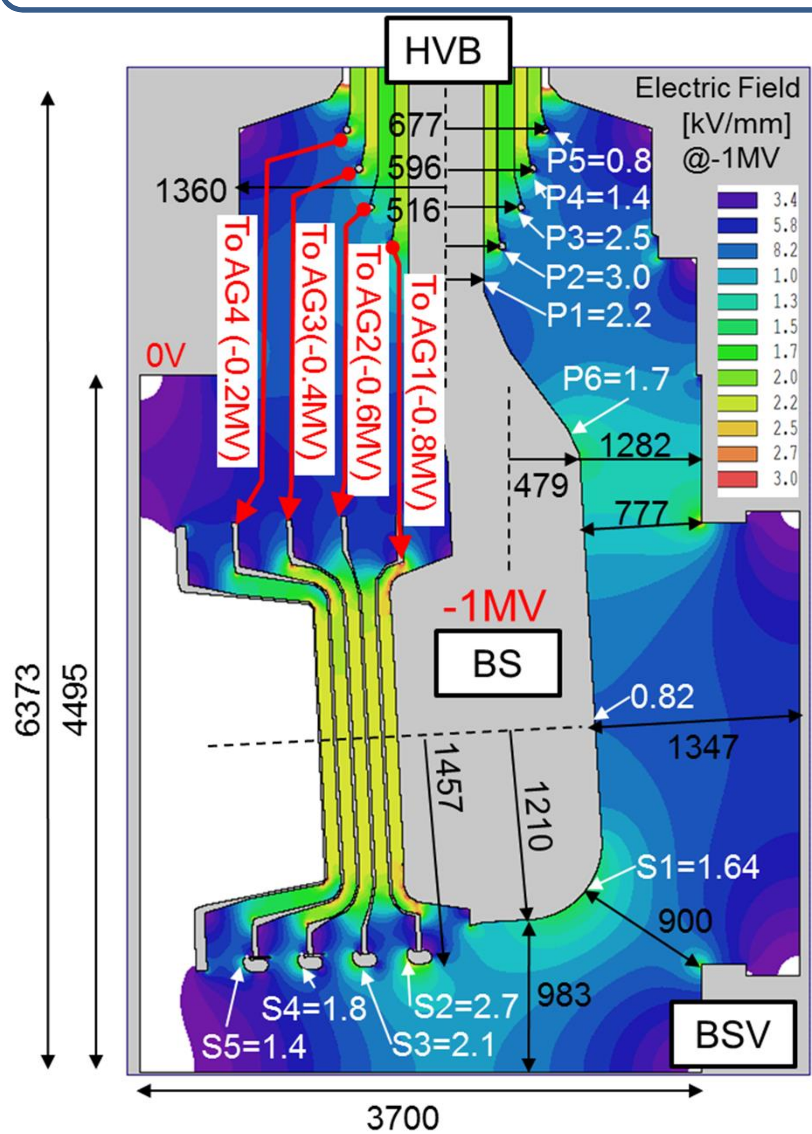
→ ***Empirical scaling to design the electric field on corner.***

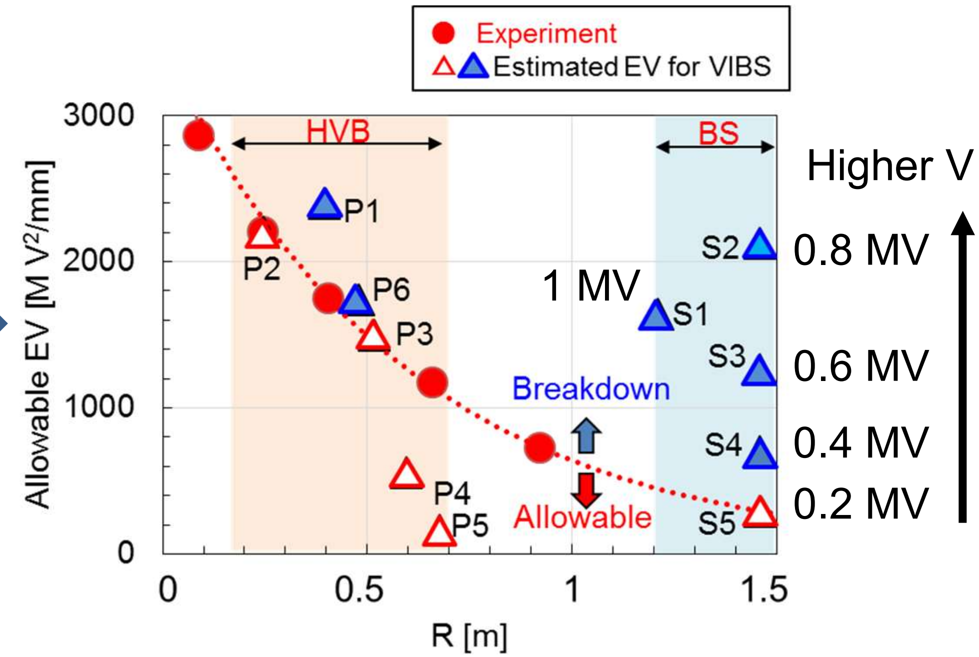
These empirical scaling for plane, coaxial and corner are easily applicable to the design of the ITER BS and HVB.

Voltage holding capability of vacuum insulated beam source has been analyzed by the empirical scaling.

<Electric Field Analysis for BS and HVB >

- Based on the empirical scaling, EV is analyzed for the BS and HVB in the vessel.





- Although the electric field E is not so high (< 3kV/mm) , *high voltages caused higher EV than allowable level*.
- Estimated total voltage holding capability ~ 0.6 MV

→ E is almost saturated even in large R.

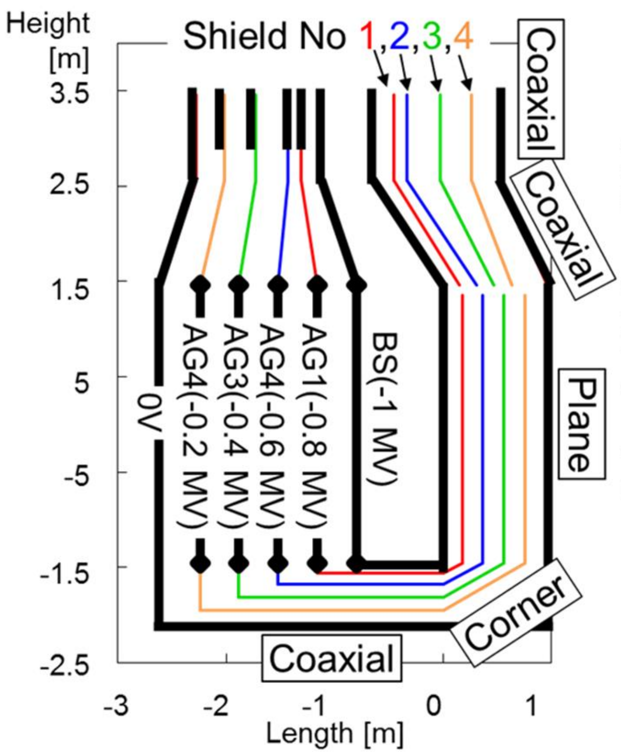
Possible measure is inserting shields having intermediate potentials to reduce applied V.

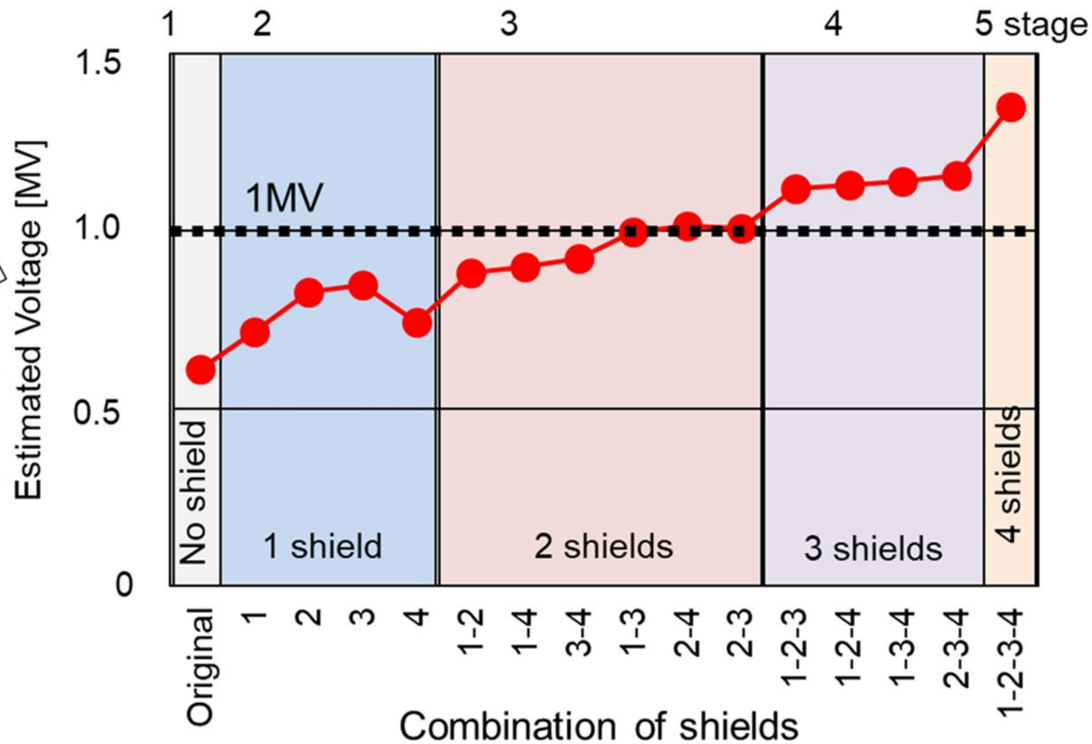
Intermediate shields for the beam source has been developed as measure for the 1 MV vacuum insulation.

FIP/1-3Rc

<Design of shields for the BS and HVB in the vessel>

- An intermediate shield can be simplified as plane, coaxial and corner regions.
- Gap and electric field on corner is optimized to maximize the total voltage holding capability
- Number of the shields has been analyzed.





- Required gap length between shields and electric filed at the corner has been designed.

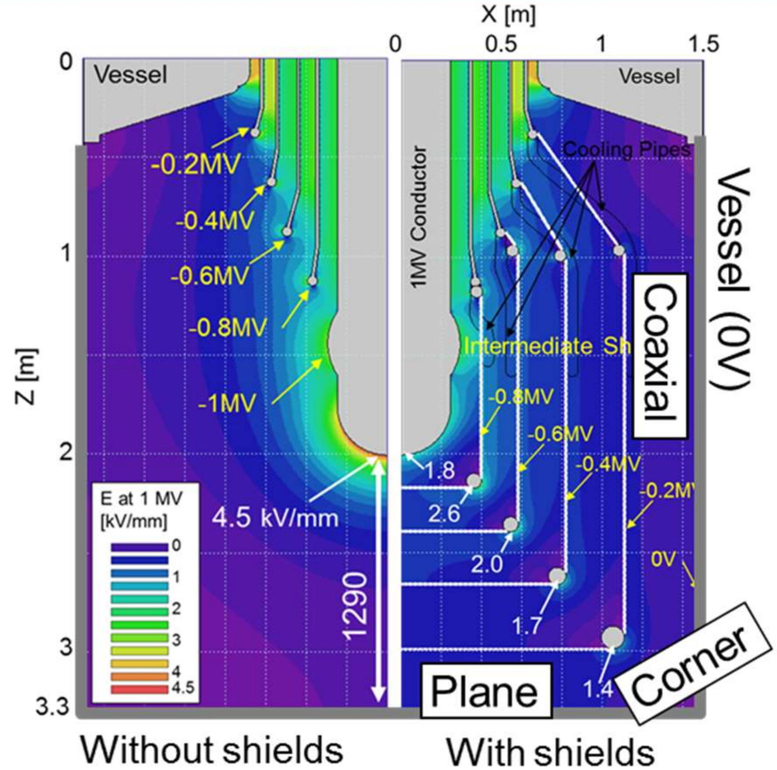
- ***Estimated voltage has been improved from 0.6 MV to >1 MV.***

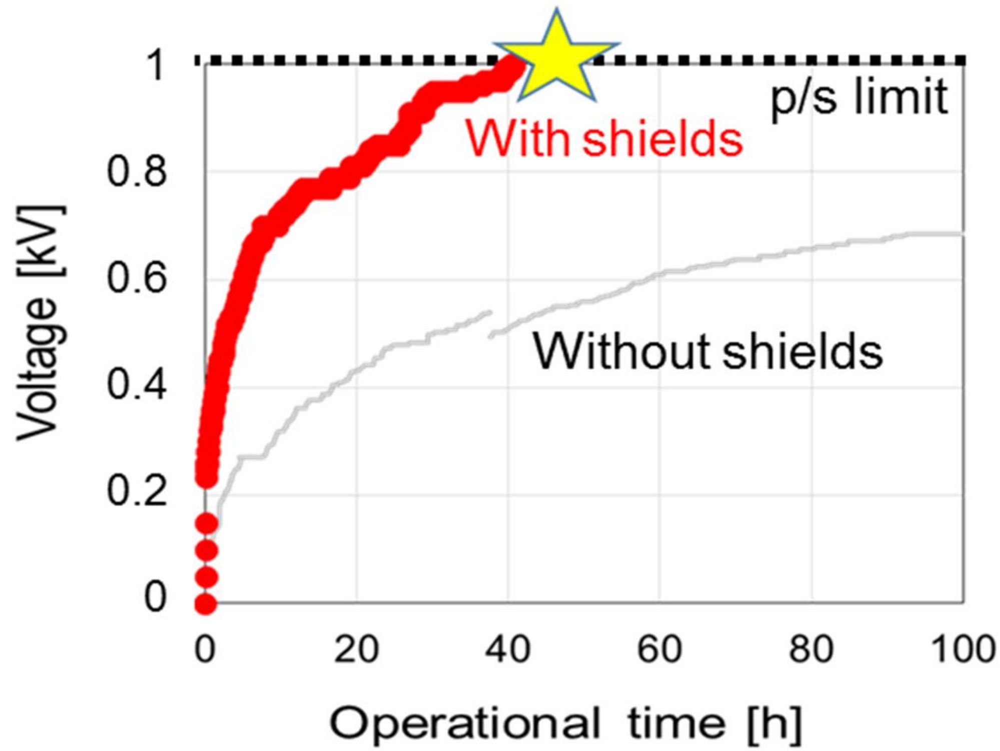
1 MV vacuum insulation has been achieved by applying the developed intermediate shields for the HVB.

FIP/1-3Rc

<Demonstration of Improvement by Shields>

- Intermediate shield for the HVB has been developed by taking into account the all scaling.
- Voltage holding tests in vacuum were carried out by using the HVB with the shields.



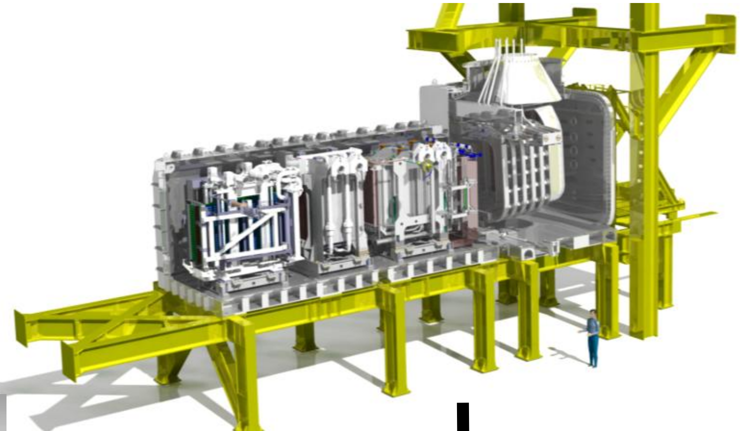


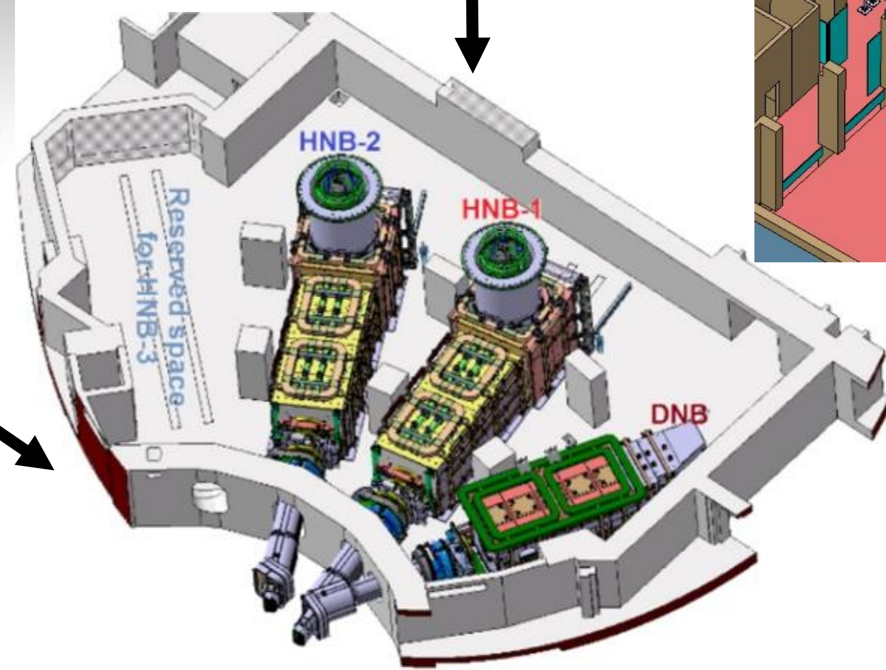
- ***Voltage holding capability has been much improved from 0.7 to 1 MV.***

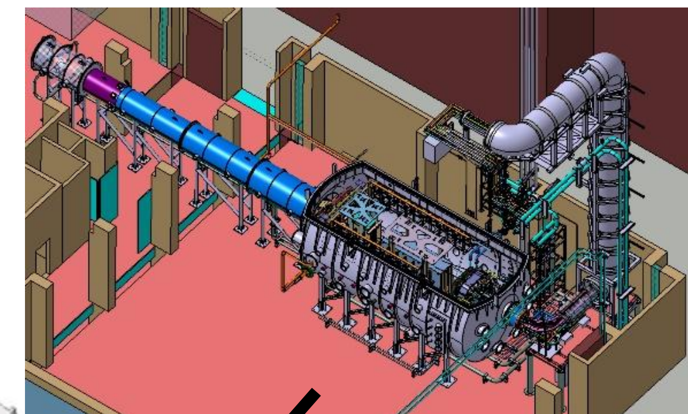
- *The design basis of the 1 MV vacuum insulation with intermediate shields has been demonstrated.*
- *This design technique is directly applicable to the BS for ITER too.*

SUMMARY

Successful demonstration of collaborative efforts in the area of technology developments, installation, operation and physics experiments→ towards the realization of ITER NB system







THANK YOU