FUSION FOR ENERGY

The RoX (Return of Experience) of the MITICA beam source and beam line components manufacturing and assembly – link to the Technology Readiness Level (TRL)

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*presenting author

2 ATG europe accelerating innovation 3 CONSORZIO RFX Ricerca Formazione Innovazione 4 iter china eu india japan korea russia usa 5 Consiglio Nazionale delle Ricerche

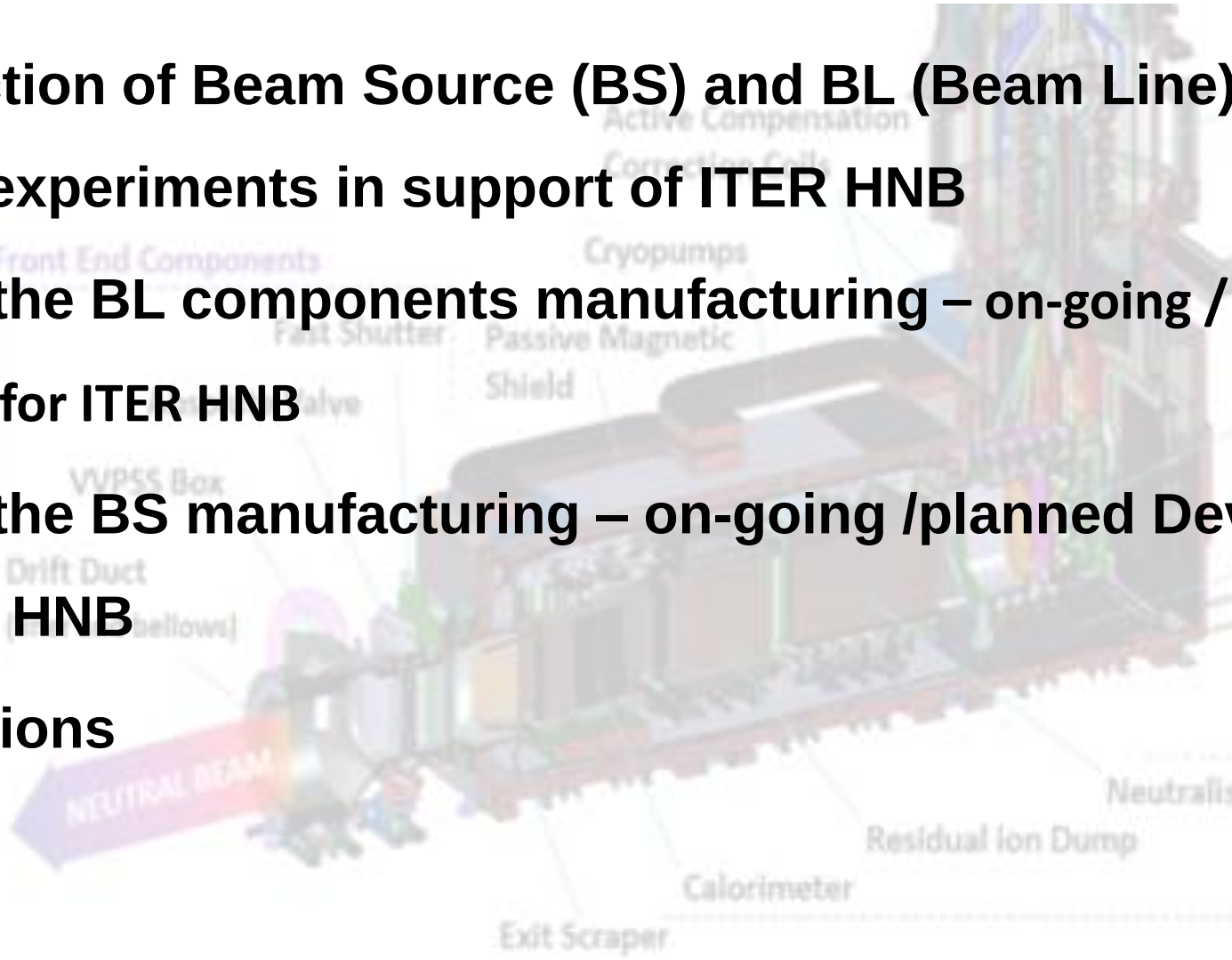
SOFT presentation

Topic C Tuesday 22nd Sept. 26



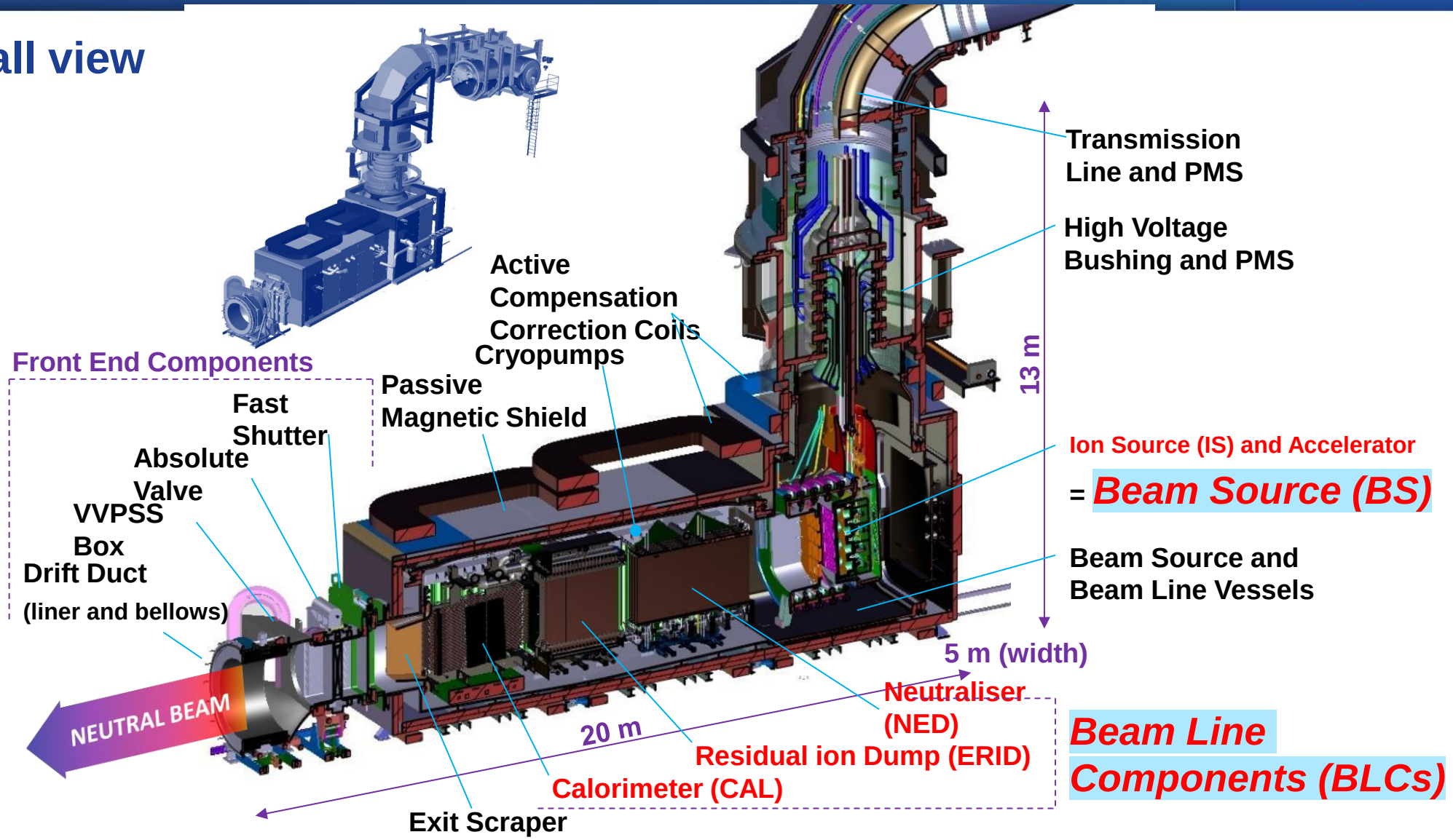
Outline

- Introduction of Beam Source (BS) and BL (Beam Line) components (BLC) – MITICA experiments in support of ITER HNB
- RoX on the BL components manufacturing – on-going /planned Development activities for ITER HNB
- RoX on the BS manufacturing – on-going /planned Development activities for ITER HNB
- Conclusions



The Neutral Beam Injector

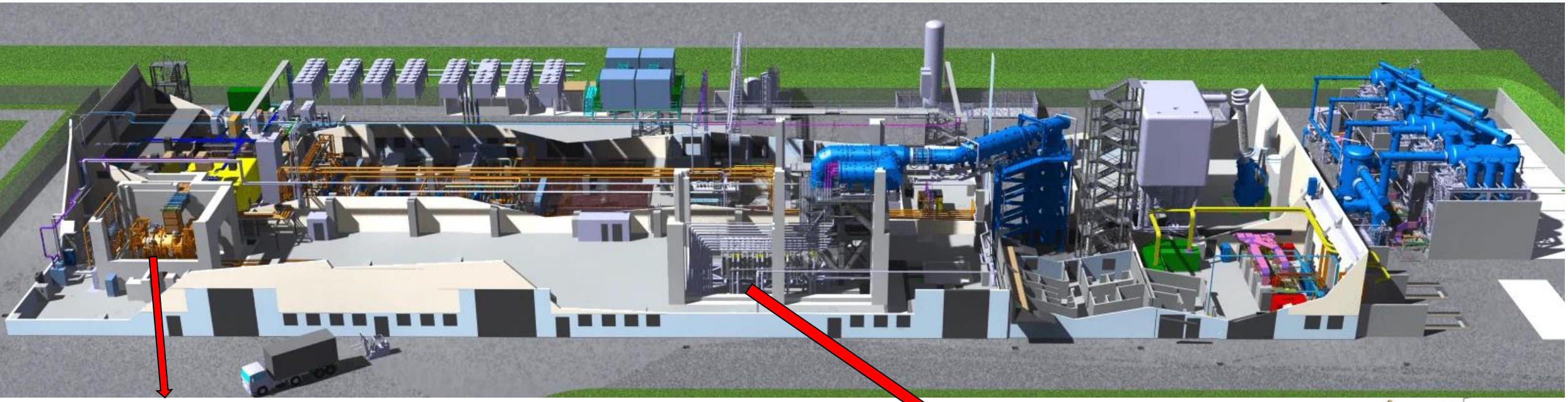
Overall view



The Neutral Beam Test Facility (NBTF)

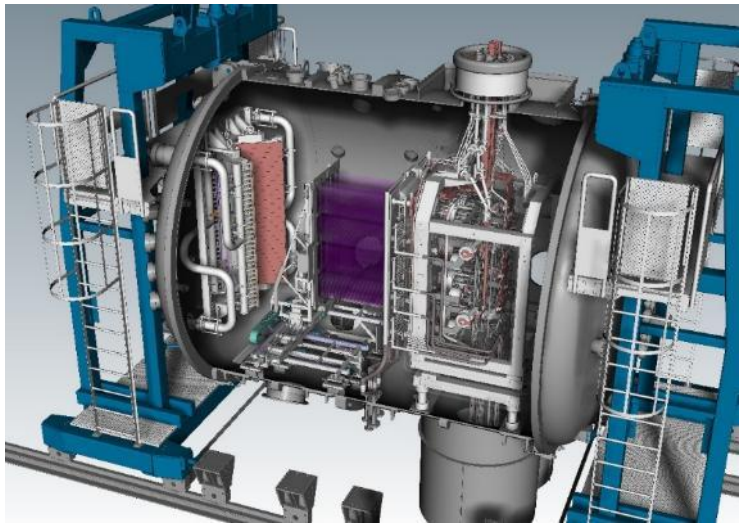
CONSORZIO RFX
Ricerca Formazione Innovazione

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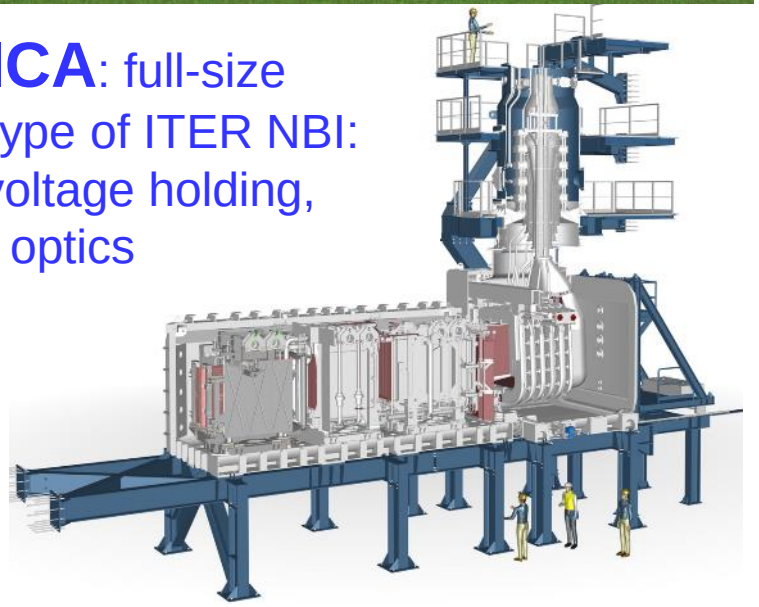
SPIDER: the first full-size ITER beam source
(optimisation of ion source: current density, uniformity, stability)

Source for Production of Ion of Deuterium Extracted from Radio frequency plasma.



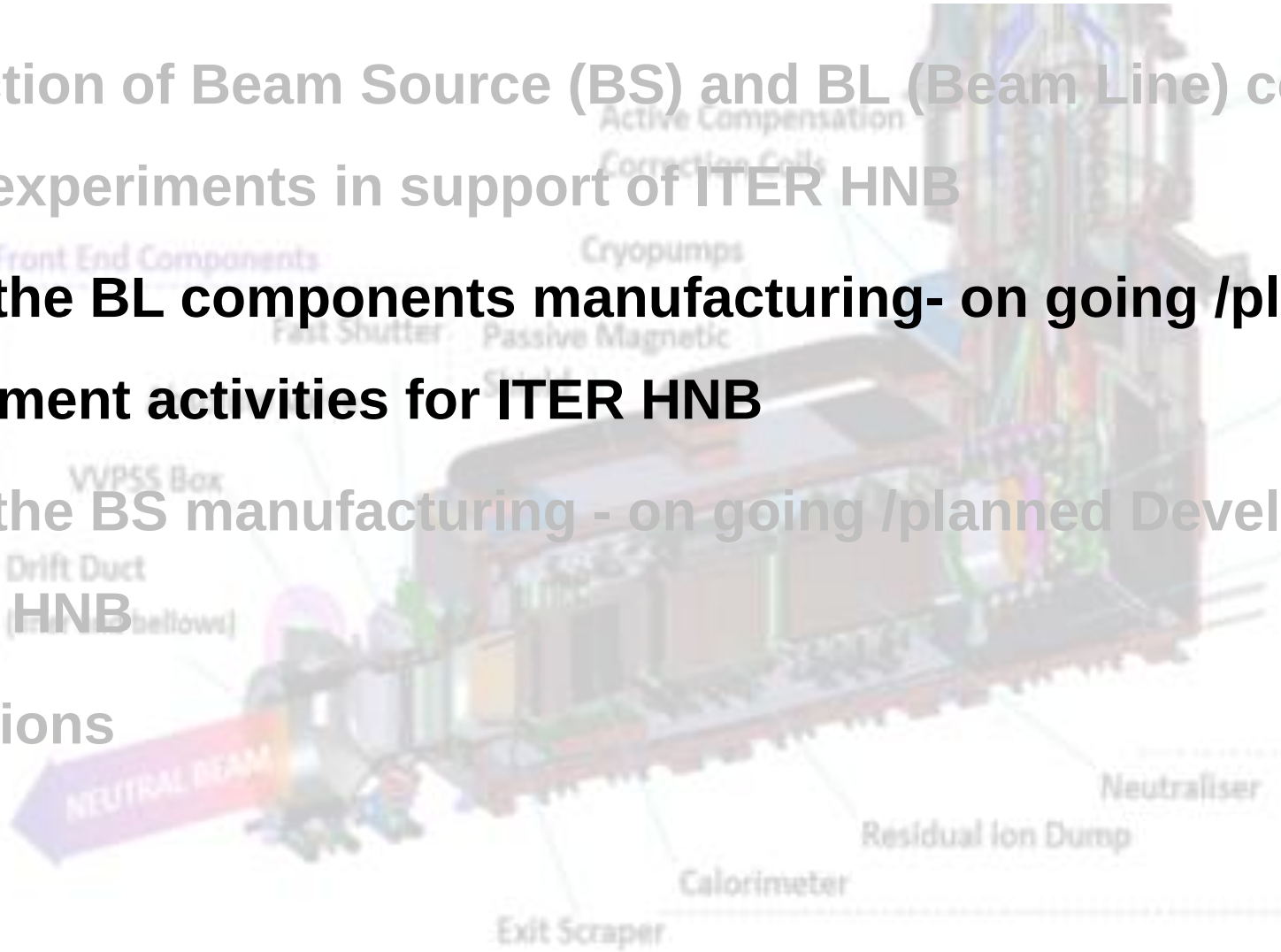
MITICA: full-size prototype of ITER NBI: high voltage holding, beam optics

Megavolt ITer Injector & Concept Advancement



Outline

- Introduction of Beam Source (BS) and BL (Beam Line) components – MITICA experiments in support of ITER HNB
- **RoX on the BL components manufacturing- on going /planned Development activities for ITER HNB**
- RoX on the BS manufacturing - on going /planned Development activities for ITER HNB
- Conclusions



Summary timeline of MITICA BLCs manufacturing, assembly and testing

2018 - 2020

Engineering documentation preparation

Prototypes Design for NED, ERID and CAL completed

MRR for prototypes approved



2021

NED, ERID and CAL Delta-MRRs started

Manufacturing of NED & CAL prototypes completed

NED, ERID and CAL Start of Manufacturing



Leak during Leak test in the CB for the ERID

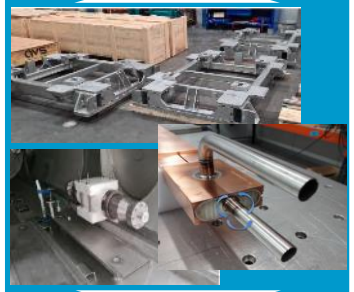
2022

NED Delta-MRRs completed

Manufacturing of the panels and adjustable bed completed for NED

Manufacturing of Support Structure and Adjustable Bed for ERID

All EB welding on STEs for CAL completed



Failure during Pressure Test on the CB for the ERID

Delay on CAL due a metal sector strike in Spain

2023

NED, ERID & CAL Global MRR completed

Start of NED & ERID Assembly

Manufacturing of Support Structure, Adjustable Bed and Manifolds for CAL completed



Failure of CB prototype for ERID during Pressure Test

Descope of CB from the Contract

2024

NED & ERID Assembly completed

FAT / Delivery / SAT

Assembly of CAL RH-LH completed and leak tested.



Indications in dissimilar welds on the STEs assemblies to the manifolds → sagging. No standard for dissimilar material.

2025

Assembly of cooling pipework for CAL completed.



Class 1 Dimensional testing non-compliant. Review of the design parameters and proposal of different solutions.

Study of the need of a new CAL

2026

Solution for STE supports on CAL approved and performed

CAL assembly complete

FAT / Delivery



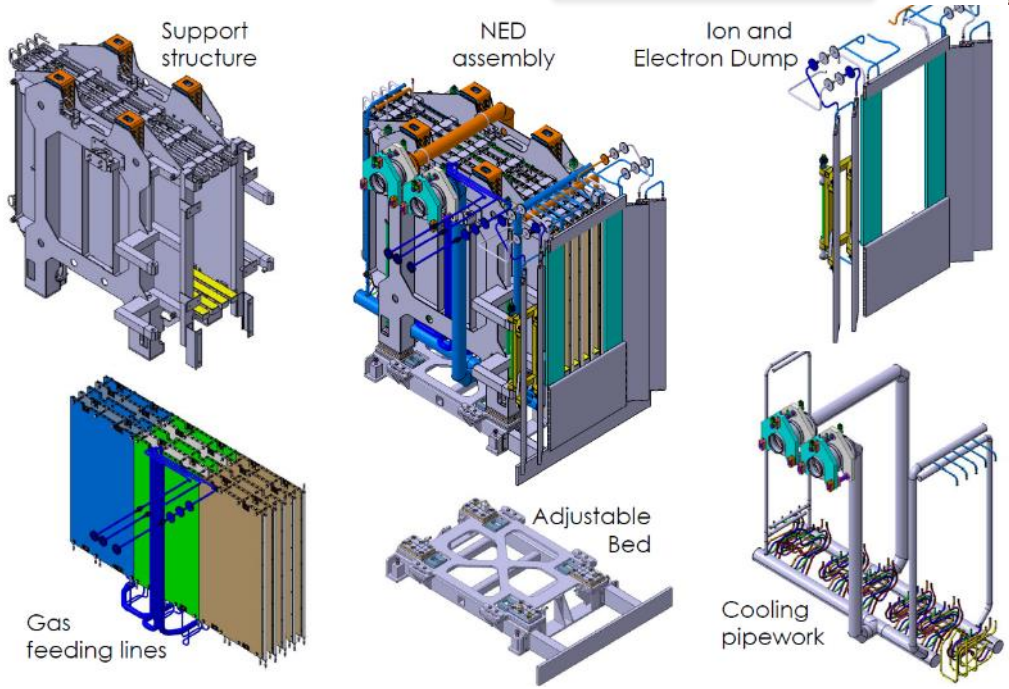
Negotiation for a new CAL settled , considering new design solutions for the STEs.

Final delivery and Site Acceptance Tests – Neutraliser (NED)

Key function

Neutralise (with D_2 gas) the accelerated **D**euterium ions coming from the Beam Source.

Length ≈ 3.2 m
Width ≈ 2 m
Height ≈ 2.9 m
Weight ≈ 12 t

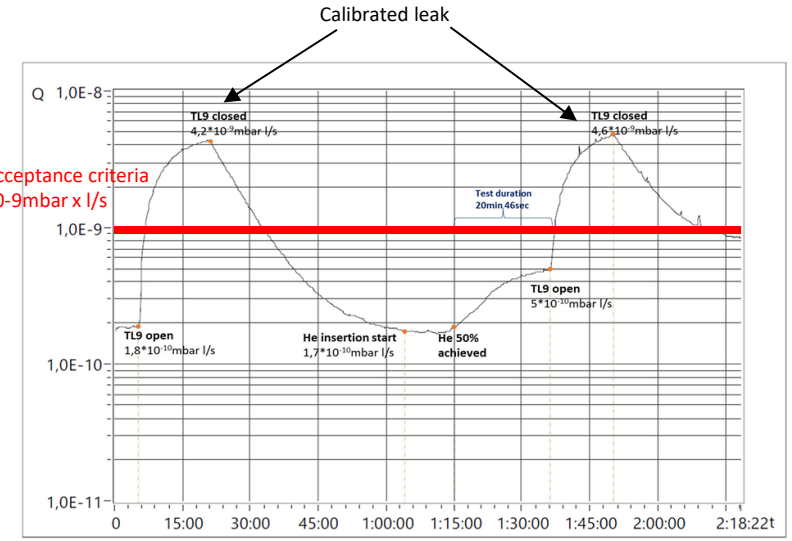




- **Neutraliser** – **delivered at MITICA in Q3-2024**. **Deep drilled** copper panels protected by leading edges swirl tube, with **complex connecting piping** and **fine alignment** of panels assembly. Electron dump opens in the front of the Neutraliser

- SAT for Neutralizer was performed successfully at MITICA site in **September 2024**,



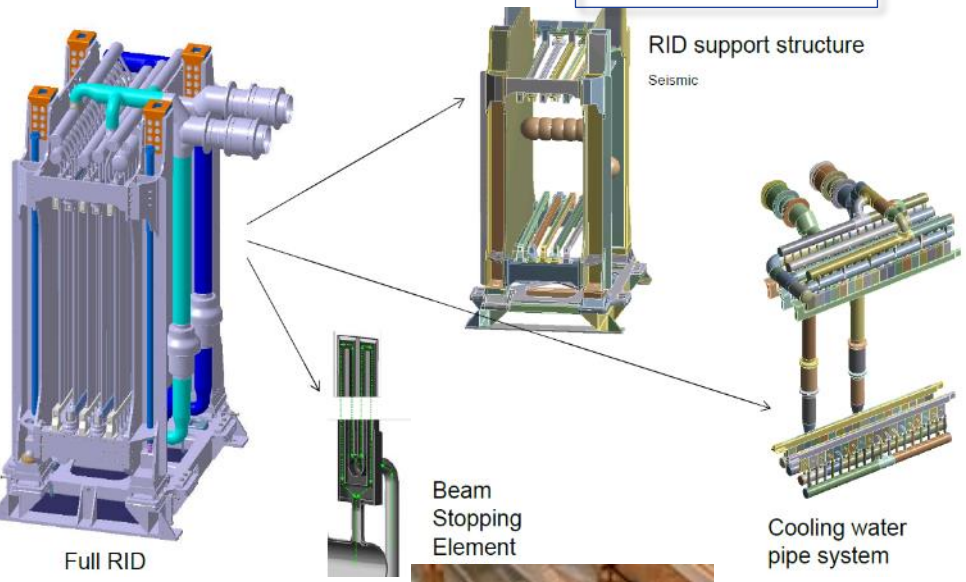


Final delivery and Site Acceptance Tests - ERID

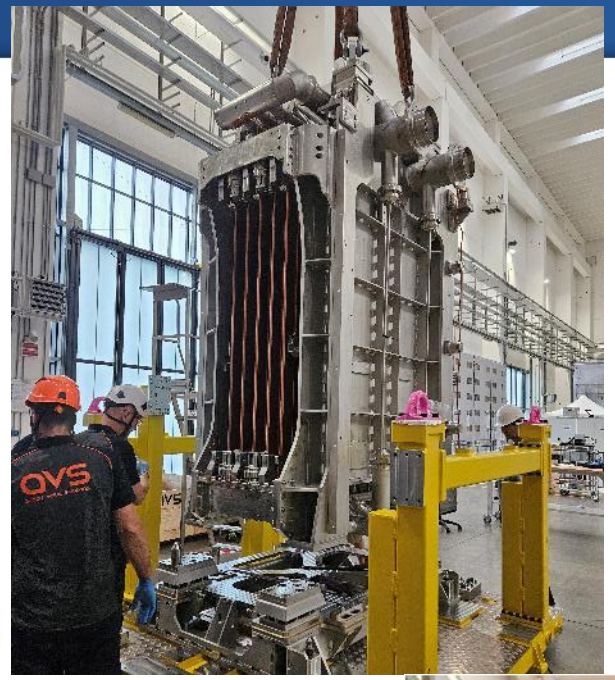
Key function

Capture (with electrical fields) the **residual ions** from the Neutraliser to **leave only a neutral beam**.

Length ≈ 2.2 m
Width ≈ 1.4 m
Height ≈ 2.9 m
Weight ≈ 14 t

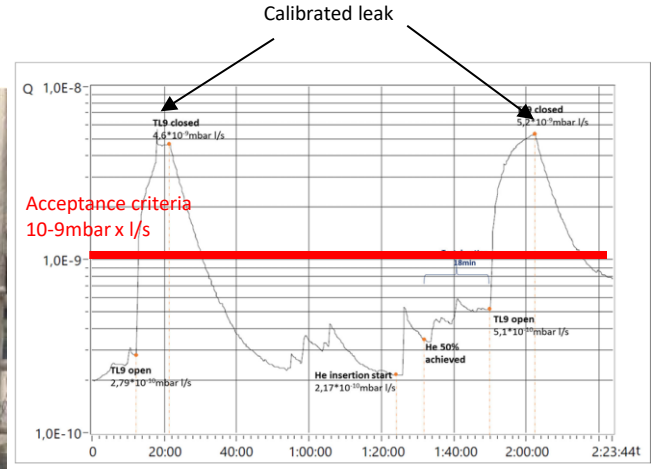






- **ERID** – **delivered at MITICA in Q3-2024**. Over 90 Beam Stop Elements are assembled in 5 CuCrZr panels. Two panels **electrically insulated** by ceramic supports. Some hundreds of sensors installed
- SAT for ERID was performed successfully at MITICA site in **September 2024**.



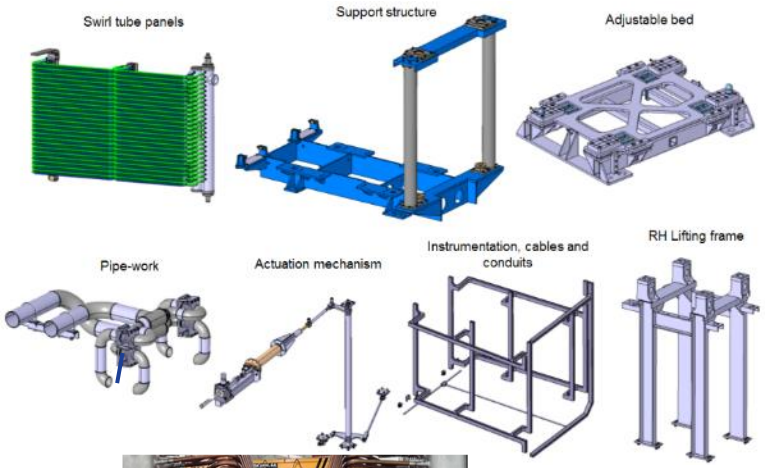


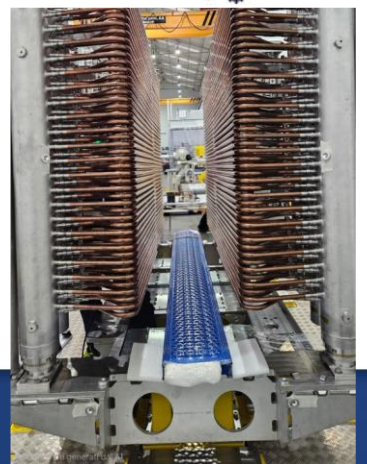
Final assembly and Factory Acceptance Test - Calorimeter

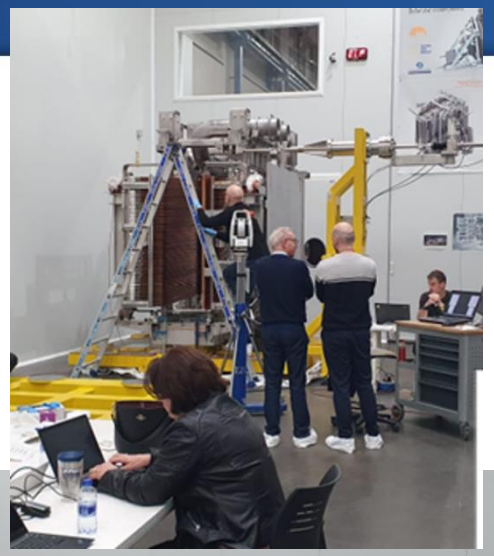
Key function

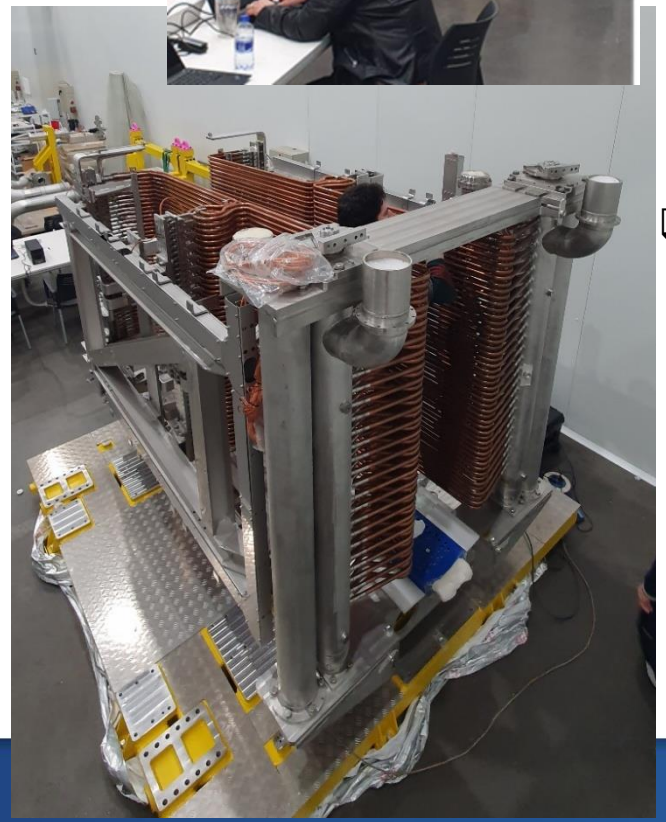
Perform the **commissioning** of the Neutral Beam (in closed position ⇒ no injection into the plasma).

Length ≈ 3.3 m
Width ≈ 2.7 m
Height ≈ 3.2 m
Weight ≈ 5 t



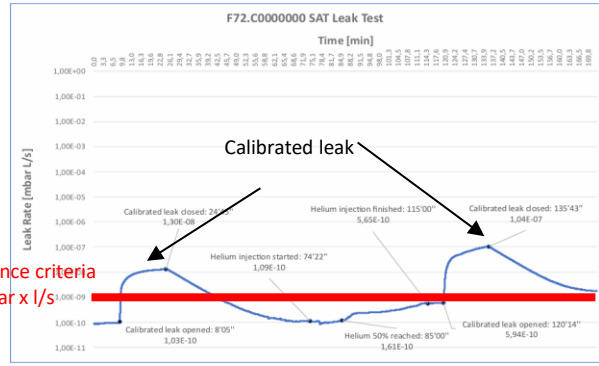






- **Calorimeter** was **delivered at MITICA end June 2026**. it consists of two panels moved by actuation mechanism. Each panel is made of 48 horizontal Swirl Tube Elements. On each panel, the STEs are arranged with vertical and horizontal overlaps which ensure shine through control.
- FAT for Calorimeter were performed successfully in **June 26**, they consisted of checking the “as assembled” overlapping of the STEs, the leak tightness, the repeatability of opening / closure positioning with laser tracker and final pressure test
- SAT performed successfully in **July 26**





avs tecnalia
added value solutions

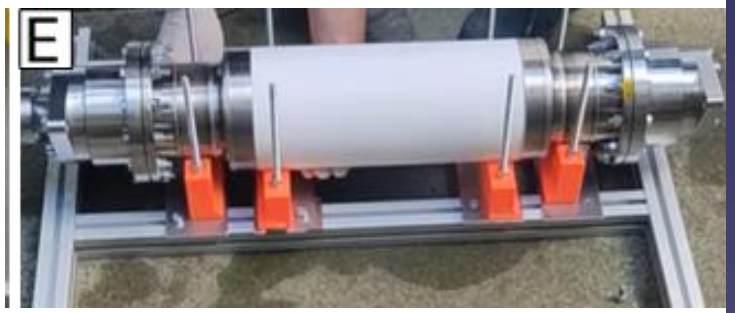
Emerging technical challenges and mitigation actions related to the Ceramic Breaks (CBRK)

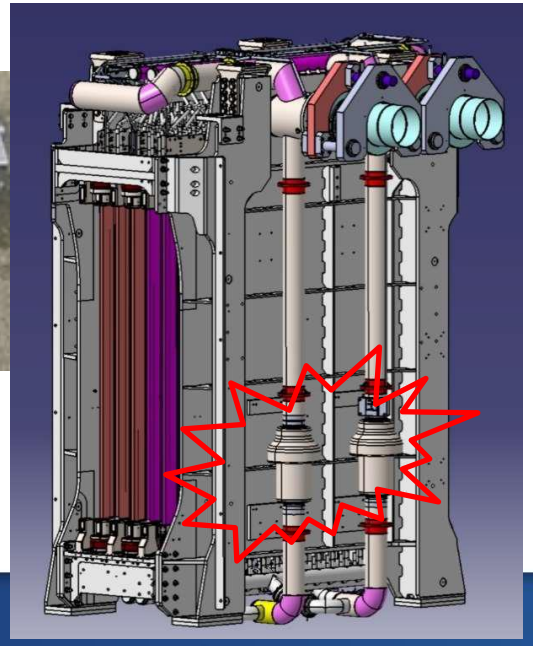
- **ERID Case** :

❑ During combined pressure and tensile stress testing, the CBRK prototype failed,

❑ The brazing process of the prototype used a silver-copper-titanium alloy known for its effective wetting properties with ceramics and metals

❑ A revised design, currently under study, aims to reduce the CBRK's diameter, add bellows in the pipework, better control the brazing process, lower residual stresses and improve performance. Future tests will validate this new approach.



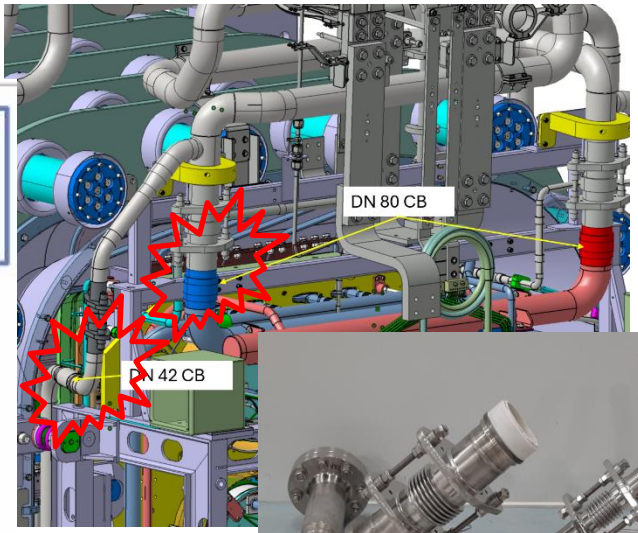


- **BS Case**:

❑ During the final nitrogen gas pressure test on a water circuit, 2 ceramic breaks failed at 23,5 bars. DN42 break seems to be an outcome of DN80 break.

❑ A revised design aiming at removing the bottom groove in the alumina (location at origin of the crack during burst test failure @37bar and final pressure test).The SS sleeve replaced by Kovar (better compatibility for brazing adhesion on alumina: e.g: similar CTE) and coating of Kovar to protect from exposition to ultra pure water.



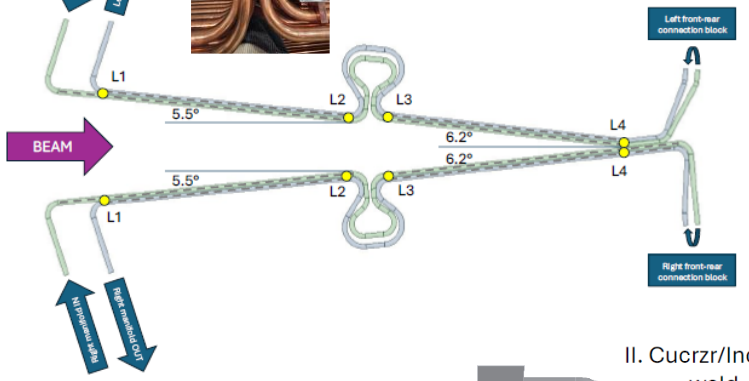


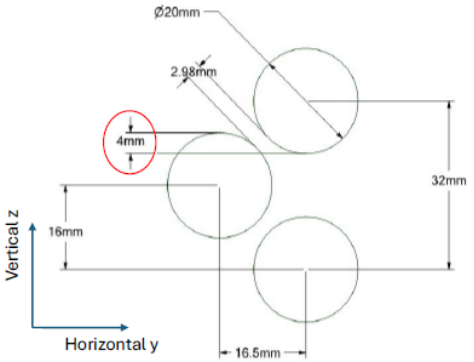
Emerging technical challenges and mitigation actions related to the Calorimeter

- During manufacturing, a pipe alignment non-conformity was identified, as the required positioning tolerance could not be achieved
- A mitigation strategy based on adding combs to improve overlap, was implemented leading to limited improvement of the performance still allowing implementation in the first phase of MITICA campaigns
- In parallel an improved design, removing the omega bend, increasing the pipe diameter to optimize overlap, modifying the BSE and bending angles is engineered and manufactured

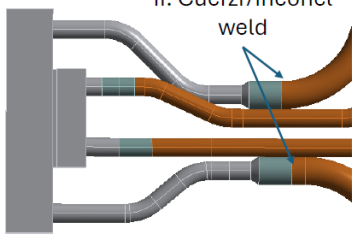
Original design layout

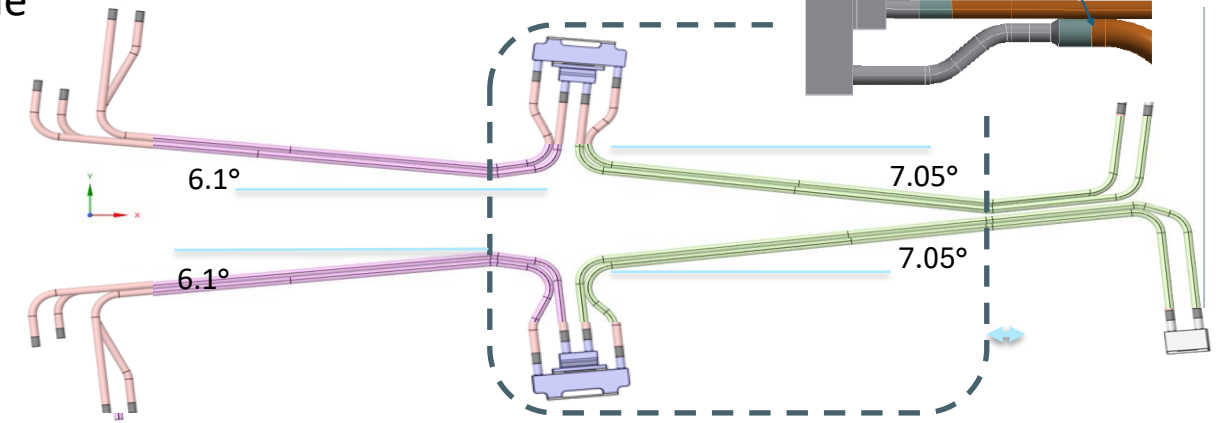






New design layout





Outline

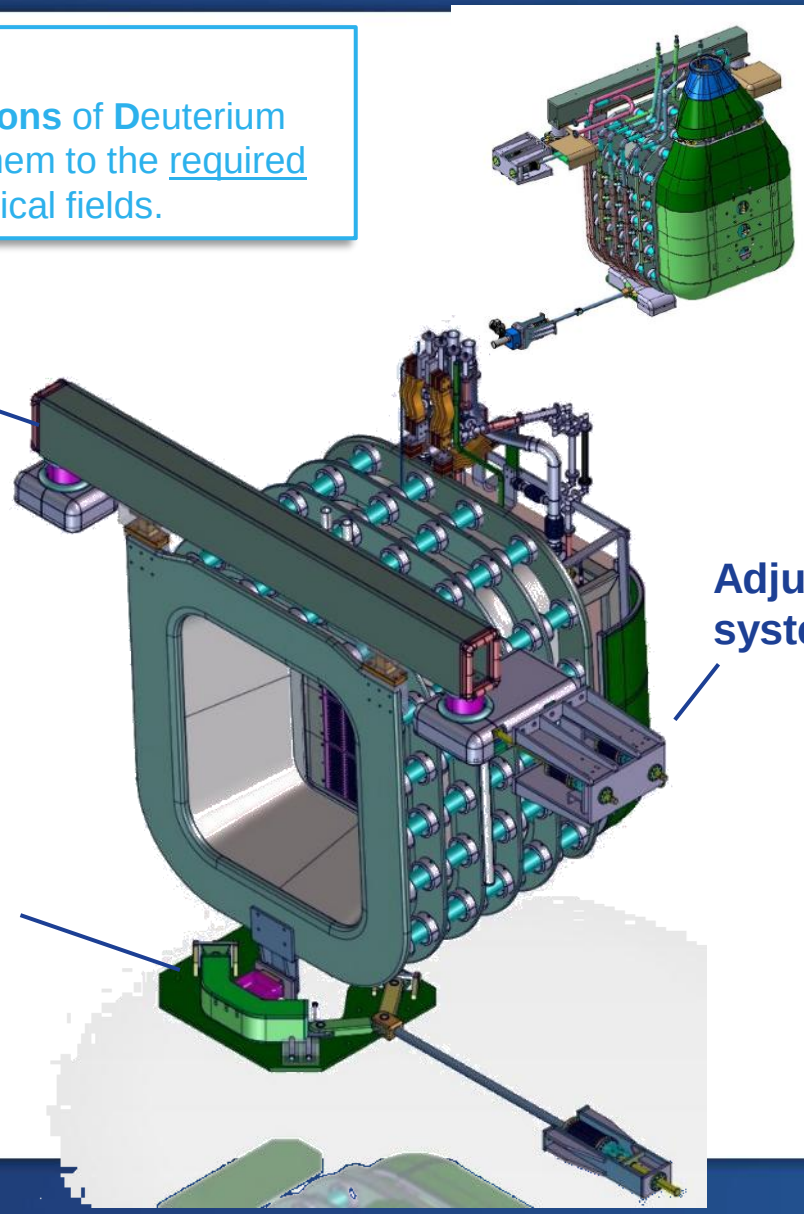
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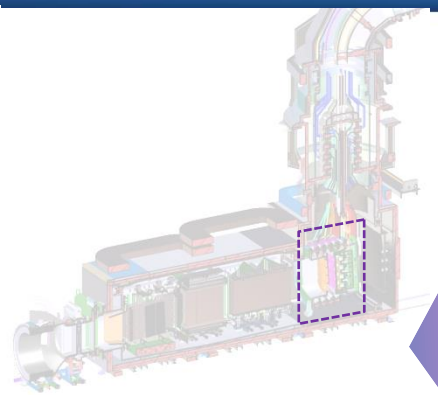


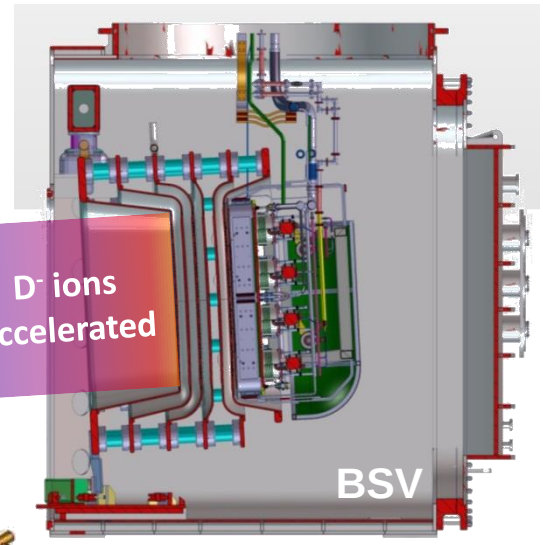
Beam Source (BS= Ion Source + Accelerator)

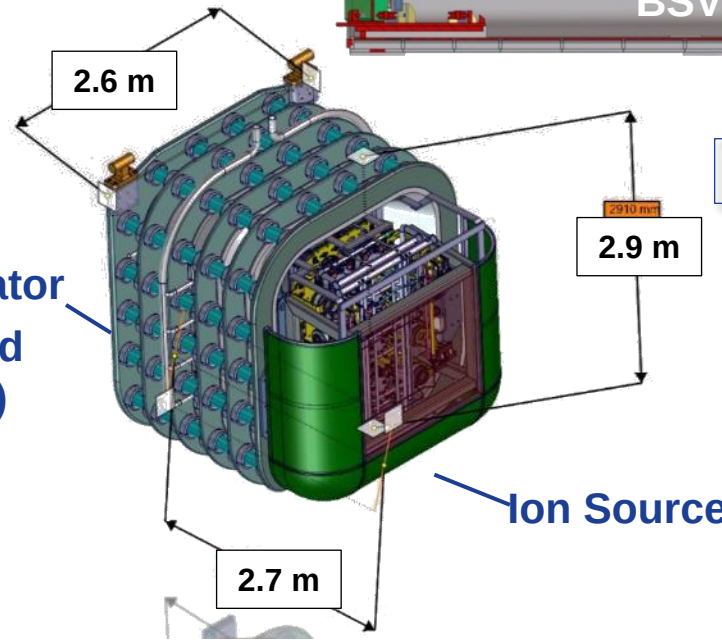
Key function

Create negative **ions** of **D**euterium and **accelerate** them to the required energy with electrical fields.









Total weight ≈ 12 t

Summary of timeline for MITICA BS manufacturing, testing and assembly

ALSYMEX ALCEN

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2018/19

Engineering documentation preparation

Design of tooling

Launching of long lead items

BSAS completed

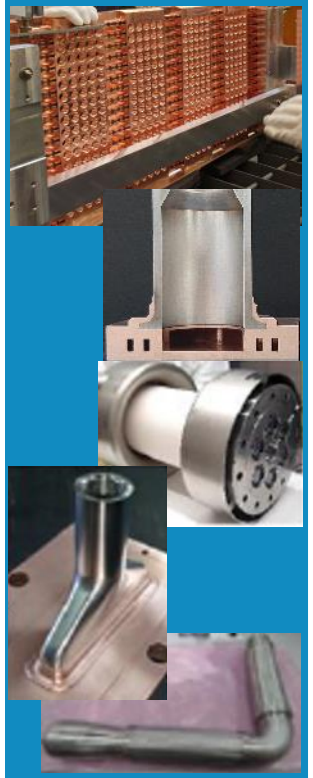
AG4 full stage



2020

Beam Source MRR completed

Most of the proto-types completed



2021

Last prototype completed (PDP)

Start of Accelerator assembly

BSHT assembled



2022

Completion of manufacturing activities

Assembly of Accelerator

Start of Ion Source assembly

Tooling completed and tested



Ion Source Molybdenum thin coating issues

2023

Accelerator assembly completed

Top connection assembly completed



PDP pressure test first failure: Bellows issue

PDP PT second failure: PDP screws issue

2024

Ion Source assembly



PDP PT third failure issue: Cooling pipes supports issue

Molybdenum thin film darkening issue persistence

Long repairs and design changes

2025

Ion Source assembly



Contact between Driver RF coils and quartz insulators

Leak on FSBP heterogeneous joint

New leak on another FSBP HJ

Leak on BP Grid Segment VTTJ Joint

2026

Beam Source assembly complete

FAT / Delivery / SAT



PG Filter Cu bars short-circuit detected

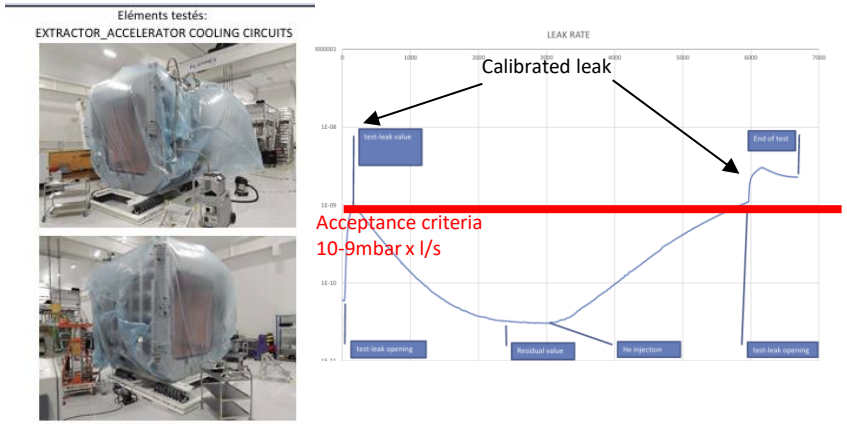
Final PT failure: Two Ceramic Breaks broken

20% of the +100 thermocouples found Non-Conform after assembly

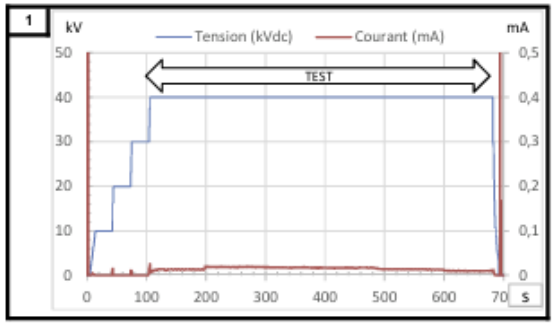
Beam Source Assembly, Factory acceptance Tests and delivery

- The Beam Source assembly was finalized in **Feb-2026** = FATs took place during **March to May 26**
- The date of the Beam Source and its handling system delivered at C-RFX on the **5th to 8th of June-26**
- Supplier activities at C-RFX were ongoing until **10th September 26** including management of co activities with SPIDER and BLC-Calorimeter

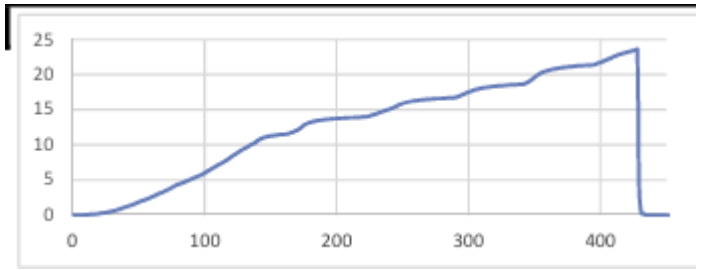




Set-up and Results of the Helium leak test



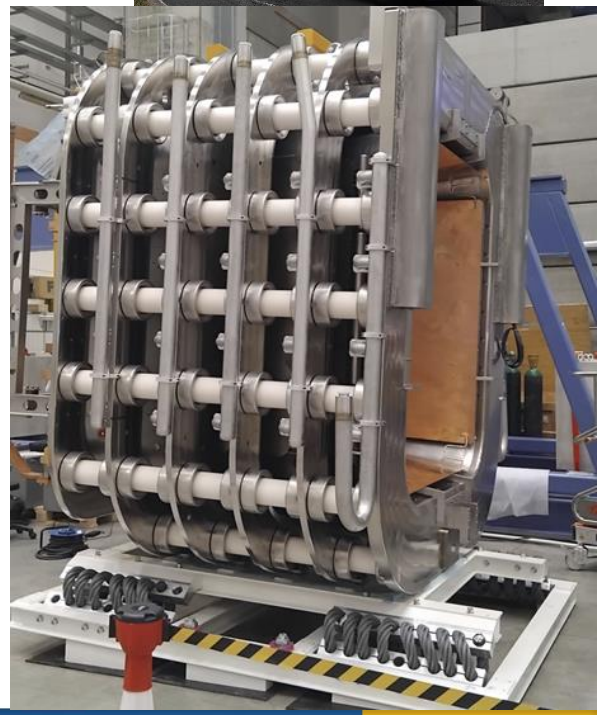
Results of the Electrical test





Set-up and Results of the pressure test



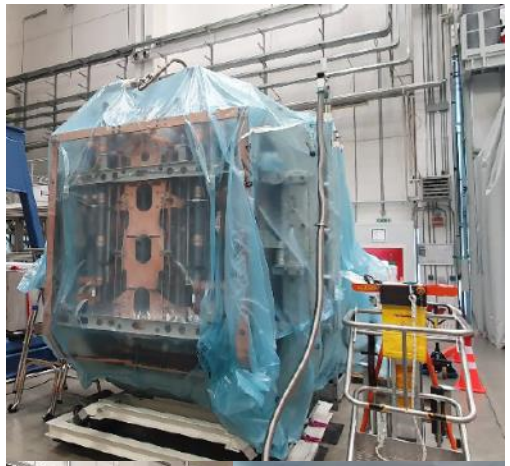


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Site Acceptance Tests for the Beam Source

He leak test

- The test is required to guarantee leak tightness among all the cooling circuits in both the BS and the ACC stages.
- The results were used to check that the transport didn't compromise the tightness of any cooling circuit.

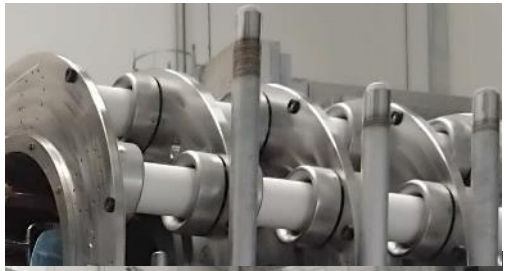




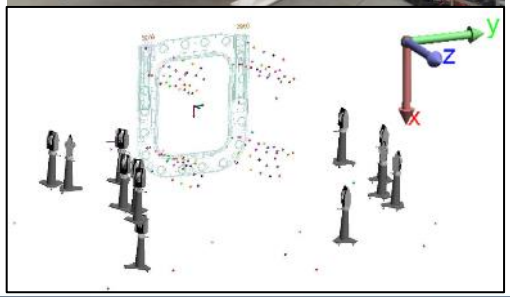


Dimensional tests

- The measurement compared positions of fiducial points on Mounting Flanges, Frame Flanges and shells between FAT measurements and Site Acceptance
- The results were used as reference to implicitly validate the transport influence over the highly sensitive ACC grids positioning.

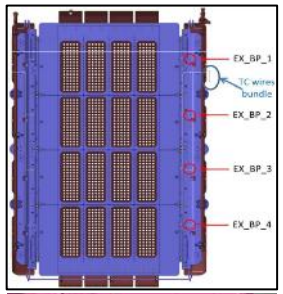




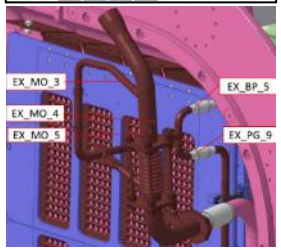


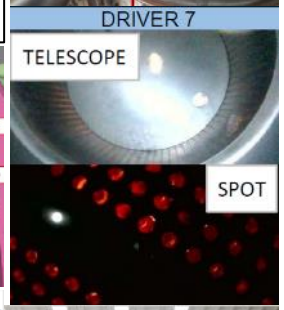
Electrical tests

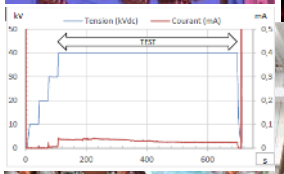
- Thermocouples (+120 TCs)
- Telescopes
- Global insulation (up to 40 kV)

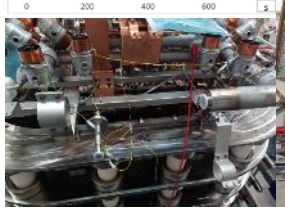








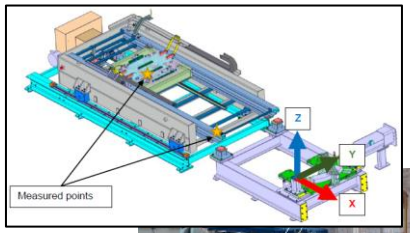


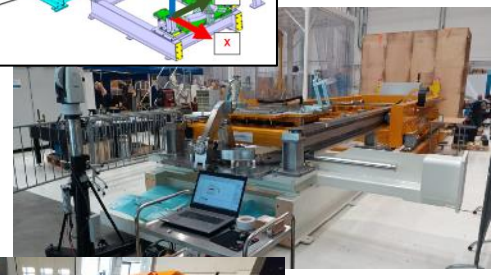




Handling Tool functional tests

- BSHT function and movement tests to verify coupling of the beam source in the vacuum vessel hinges and maintenance operations.
- Test Facilities rail system and rotating platform functional tests to verify insertion/extraction of the BS through the vacuum vessel access gate.

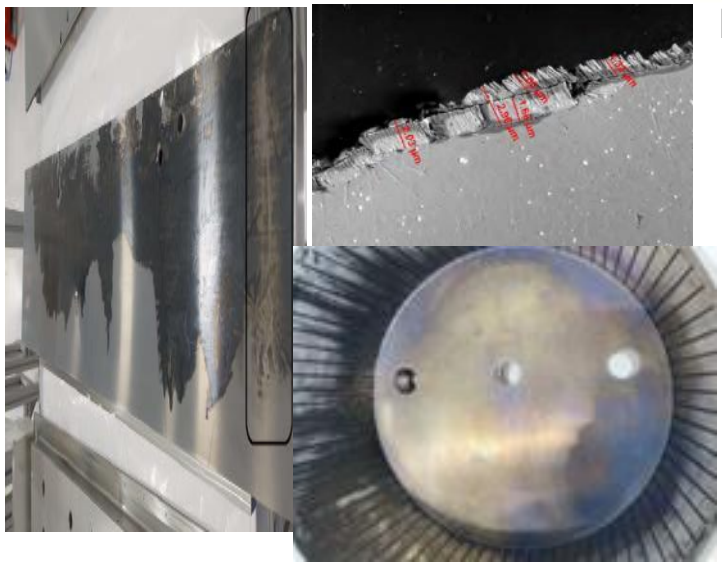








Emerging technical challenges and mitigation action related to Ion Source Mo thin coating



SCLW (Source Case) and FSLW (Faraday Shield Lateral Wall) coating darkening examples. Cross section cut electron microscopy image of FSLW Mo coating structure.

Darkening Analysis – Key Findings

- **Observation**: Coating darkening was also found on **explosive-bonded Mo parts**, indicating it is **not exclusive to PVD coatings**.
- **Background**: Previous studies identified **poor coating quality** on geometrically constrained surfaces but did **not determine the root cause** of darkening.
- **Investigation**: Evidence suggests the darkening is primarily associated with **molybdenum oxidation**.
- **Recommendation**: Improve coating process quality to assess the influence of **coating structure on precocious oxidation/darkening**.

R&D activity with Nano4Energy

- The Source Case inner-wall **coating reduces** self-sputtering originated **Plasma contamination**.
- **SPIDER experience:** PVD-Mo coatings on FSLW showed significant degradation, acute on complex geometries.
- **Proposed approach:** F4E/IO recommended **process refinement** and evaluating **W coatings.**
- **Technology: HiPIMS** (High Power Impulse Magnetron Sputtering) with **cylindrical magnetrons** is proposed to improve coating **adhesion, density and uniformity**, enabling a direct **Mo vs. W comparison**.

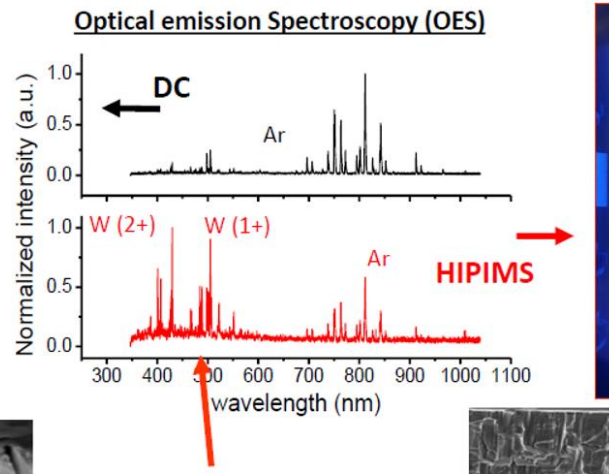
Comparison between PVD standard sputtering and HiPIMS



Conical sputtering cathode used for inner cylindrical geometries coating











Evidences of highly ionized tungsten metal plasma

(*) Metal ions on this particular case

Emerging technical challenges and remedial actions related to the FSBP Heterogeneous Joint leak

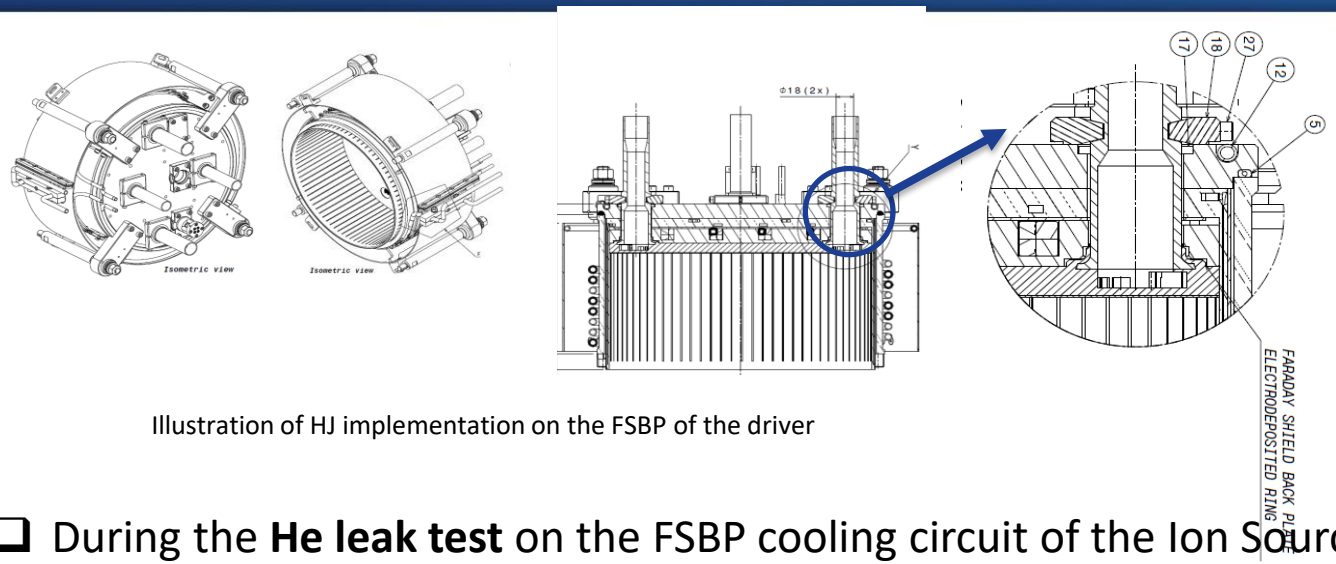
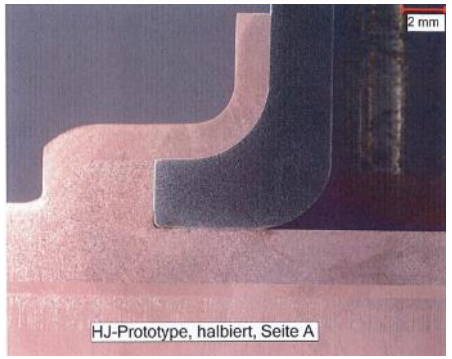


Illustration of HJ implementation on the FSBP of the driver



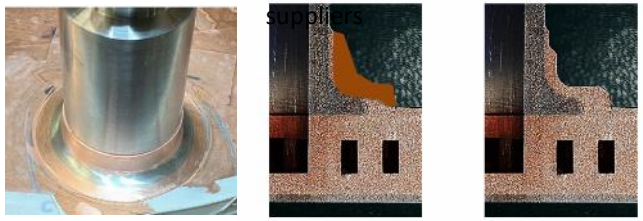
Leak mark on the Base Plate after dismounting



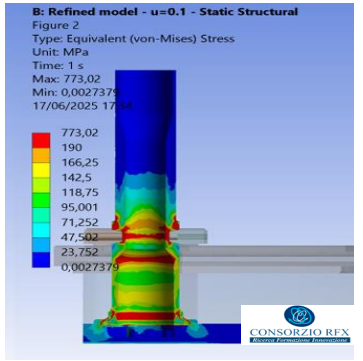


Comparison of macrographic analysis of electro deposited copper around stainless steel stub btw 2 suppliers

- During the **He leak test** on the FSBP cooling circuit of the Ion Source, a leak has been detected on one FSBP,
- The **Root Cause Analysis** identified a combination of issues related to the clamp assembly/associated chain of tolerance and qualitatively speaking to the state of ED copper,
- **Repair option** was to modify clamp design and remove/implement ED copper,
- **Technical RoX** is the need for multiplying intermediate leak tests on assembled parts, challenging the use of water for pressure test, better defined assembly procedures for FOAK component, increase/define full qualification scope according to ITER stringent requirements
- **Supplier chain RoX** related to the “niche” aspect of the Electro Deposition technique – criticality of the supplier, challenging manufacturing techniques, limited market availability & industrial capacity, difficulty to cope with quality documentation /justification requirements



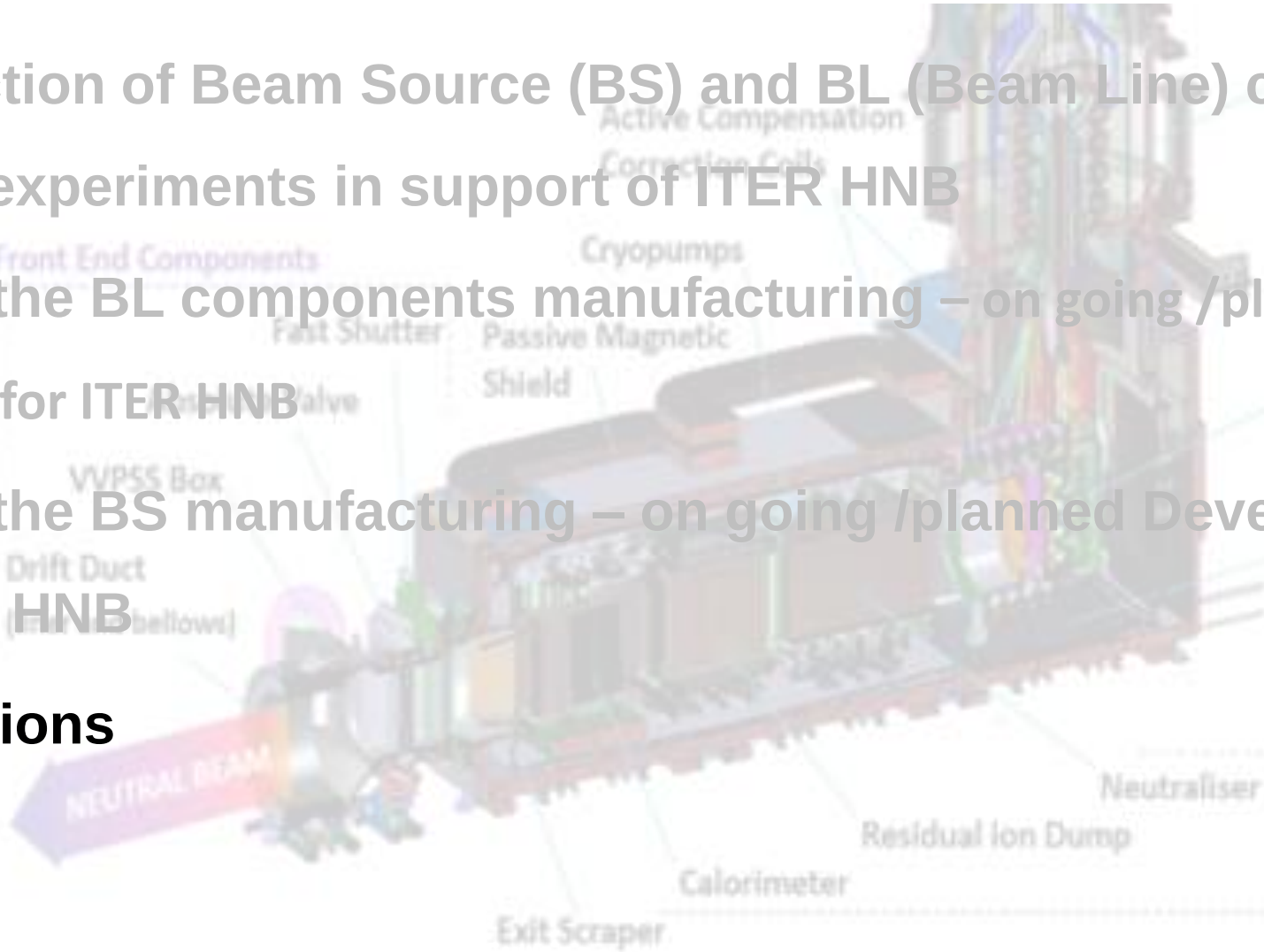
Implementation of repair solution : grinding and new copper ED



Analysis supporting clamp pull-out effort

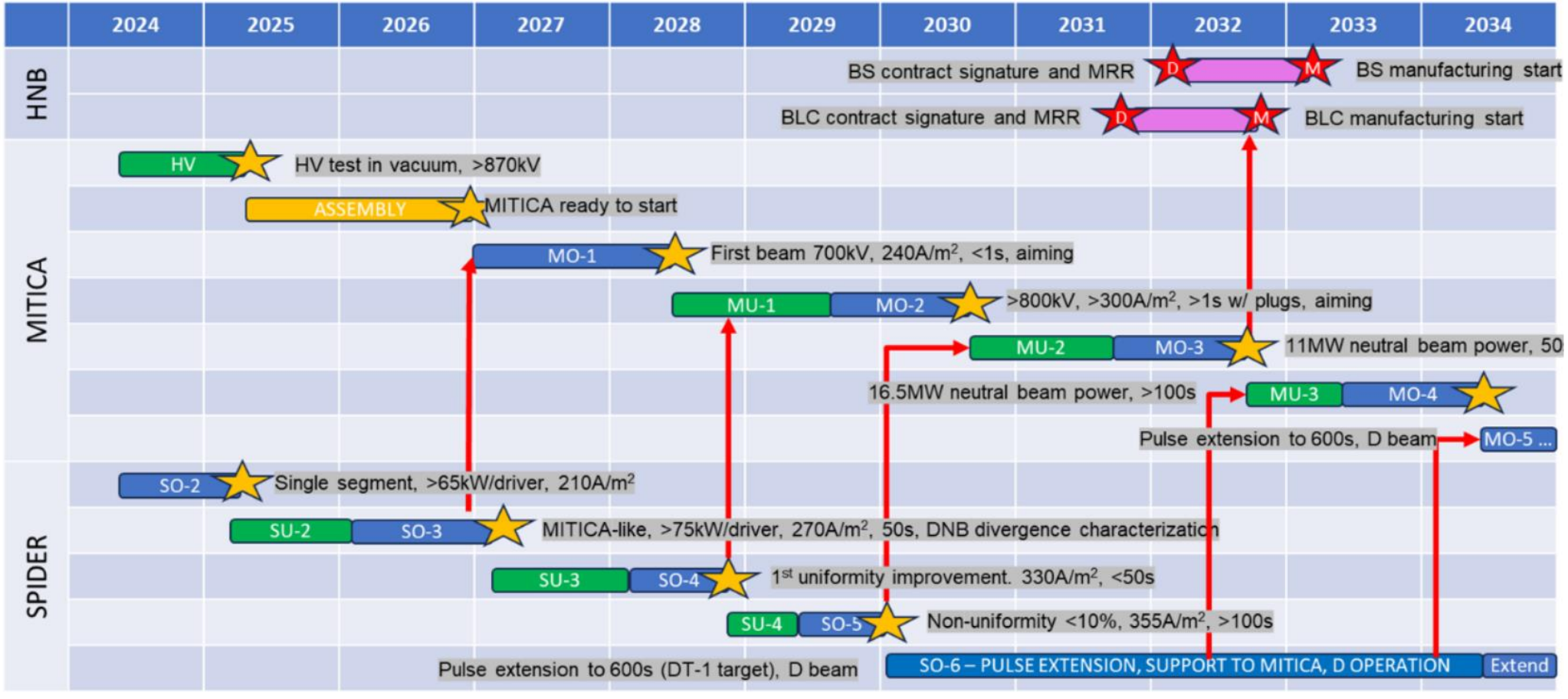
Outline

- Introduction of Beam Source (BS) and BL (Beam Line) components – MITICA experiments in support of ITER HNB
- RoX on the BL components manufacturing – on going /planned Development activities for ITER HNB
- RoX on the BS manufacturing – on going /planned Development activities for ITER HNB
- **Conclusions**



Looking ahead - ITER Research Plan (for NBTF)

- Development of the ITER HNB prototype = design, procurement follow-up, integration commissioning and operation according to required performance and schedule



And finally, the link with the TRL exercise…

- Internally to F4E an **extensive exercise of TRL (Technology Readiness Level)** has been launched and developed to a well-advanced level of maturity especially in the case of the Beam Source
- A set of **critical technologies or critical items** has been established through the TRL exercise and illustrated below

Critical Technology	Grid segments manufacturing - Geometrical & Dimensional Tolerances	Grid segments manufacturing - Cu ElectroDeposition Reliability	Grids assembly	Vacuum Tight Threaded Junction Heterogeneous Joints between stainless steel pipes and copper for cooling circuits	Electro-Deposited Cu Heterogeneous Joints between stainless steel pipes and copper parts for cooling circuits	Ultra-High Voltage hold-off in vacuum	Double barrier bellows' qualification	Caesium Oven	Explosive Bonding of Mo Protective Coating	Thermocouple & Junction Box design & RH compliance	Physical Vapour Deposition for IS Protective Coating	Design and manufacturing of the Ceramic Break	Design and manufacturing of the Accelerator Post Insulators

- Watch the space for a workshop to be organized 2027 - Technology development and supply chain effective and efficient oversight in view of the ITER HNB – *especially needed as some original equipment manufacturers have left the marketplace*

- **Successful FOAK (first of a kind) lays the groundwork for the successful deployments of the ITER HNBs**

FUSION FOR ENERGY

Thank you!

Any questions ?

