

Neutral Beam Injectors for ITER Progress of Design and Manufacturing activities

C. Poggi, P. Veltri on behalf of ITER NB project team

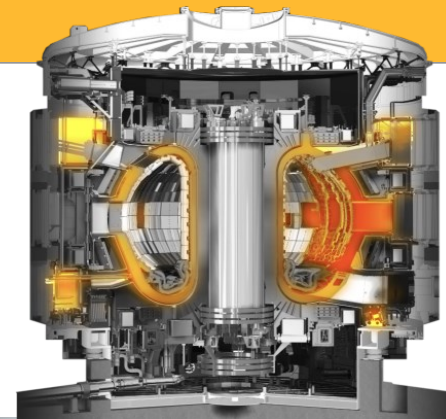
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Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

The ITER project: status and challenges



- Largest tokamak under construction
- Built through contributions from the seven ITER Members

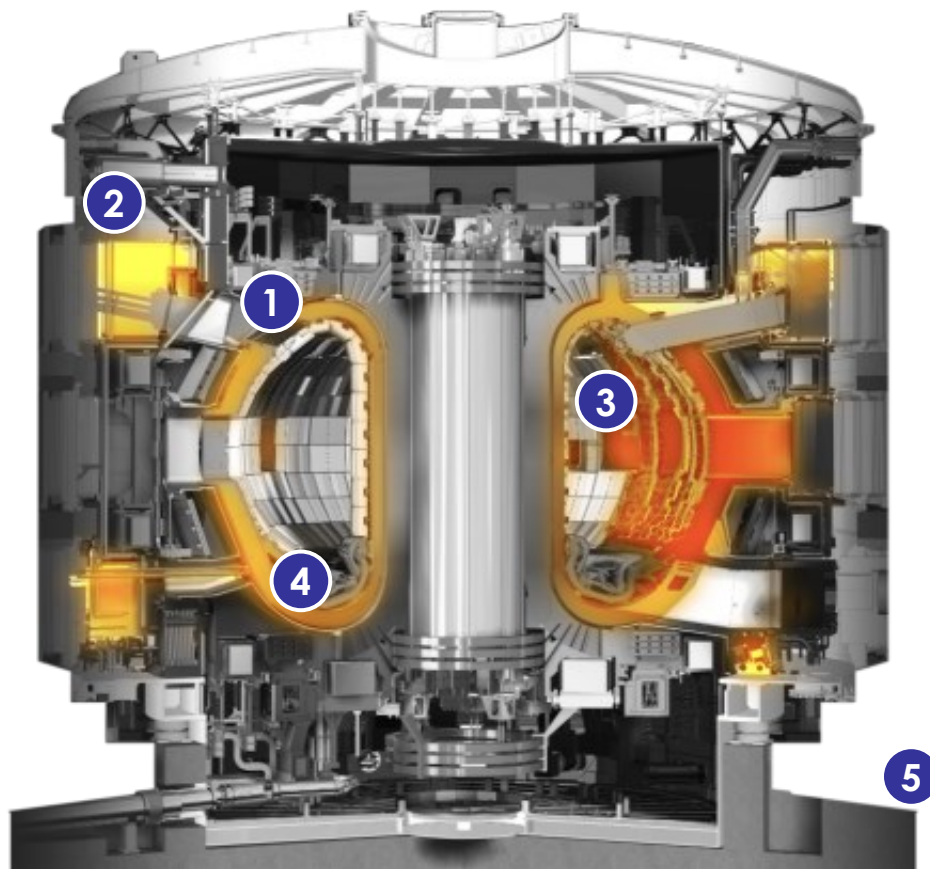


Targets net fusion gain ($Q \geq 10$) and to demonstrate the feasibility of a fusion reactor

Will strongly rely on negative ion based neutral beam injectors to achieve its targets



The ITER project: status and challenges



- 1 Vacuum vessel sectors**
Weld non-conformities and dimensional deviations; repairs done on site
- 2 Thermal shield**
Cooling-pipe corrosion cracking and coolant leaks
- 3 First wall**
Beryllium armour replaced by tungsten
- 4 Blanket & divertor**
Procurement and delivery resequenced
- 5 Assembly sequence**
Machine assembly reordered; prioritization of experiment results
- 6 External factors**
COVID-19 and other geopolitical events

The ITER project: the 2024 re-baseline

- The repair of the VV sectors was performed onsite, and the tokamak assembly is progressing
- Time window for testing the FOAK super-conducting magnets
- New **Start of Research Operation (SRO)** phase
 - Validation of ITER design and operation in DD, with reduced neutron budget, up to full magnetic energy
 - W (in place of Be) water cooled divertor with addition of boronization system
 - 40MW ECH and 10MW ICH

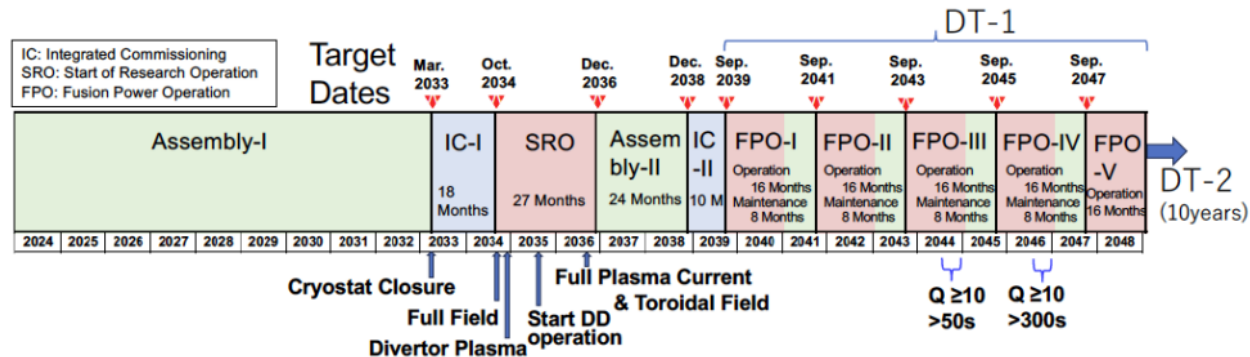


FIG.8. The overall approach of the ITER New Baseline 2024 with the main target dates

From P. Barabaschi et al 2026 Nucl. Fusion **66** 116001, DOI: [10.1088/1741-4326/ae4d5c](https://doi.org/10.1088/1741-4326/ae4d5c)

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- Next phase is full nuclear operation: **DT-1**
 - Fully W water cooled first wall
 - 60-67MW ECH, 20MW ICH, **33MW NBIs**
 - Achievement of ITER target $Q \geq 10$
- Then the next nuclear phase: **DT-2**
 - Optional **50MW NBIs**
 - $Q > 5$ for 1h

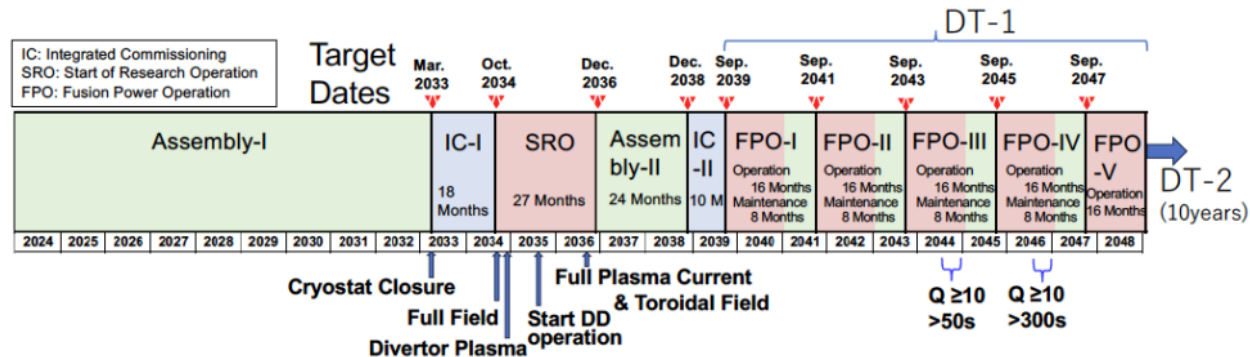


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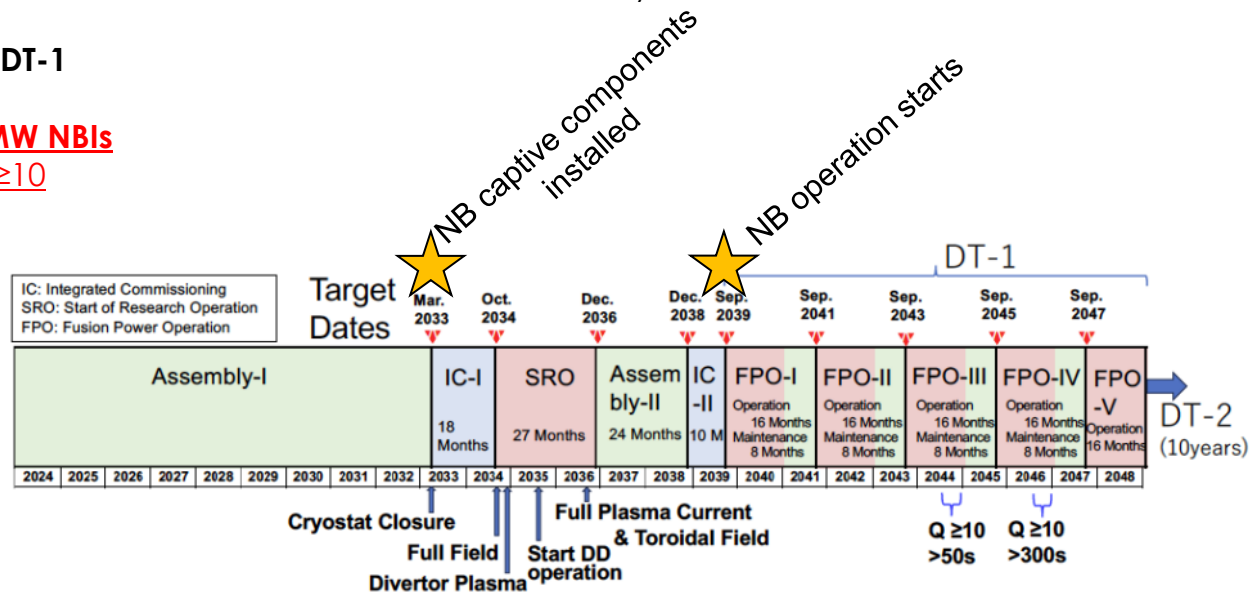
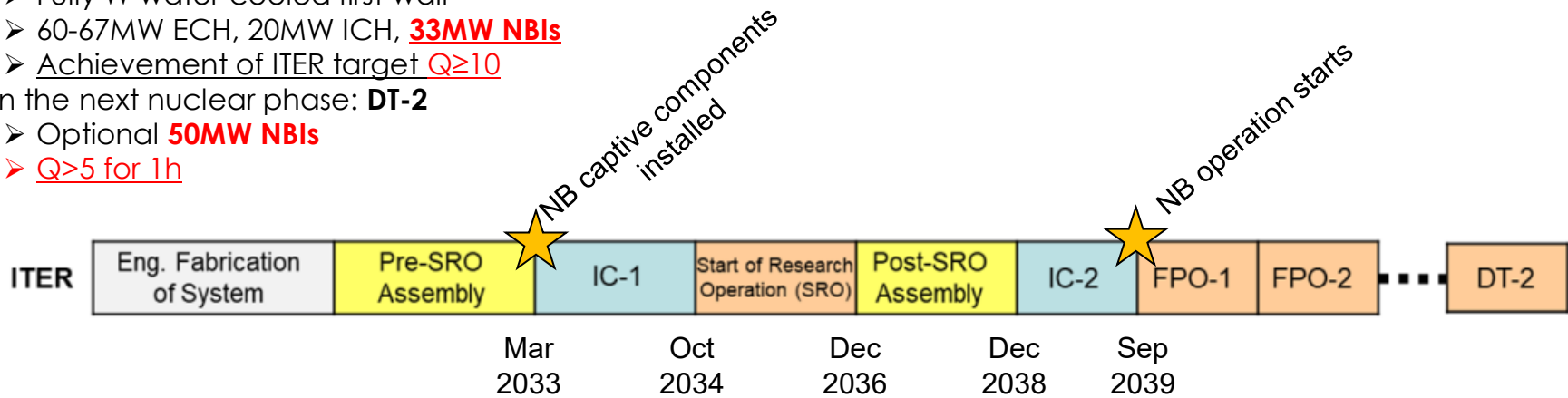


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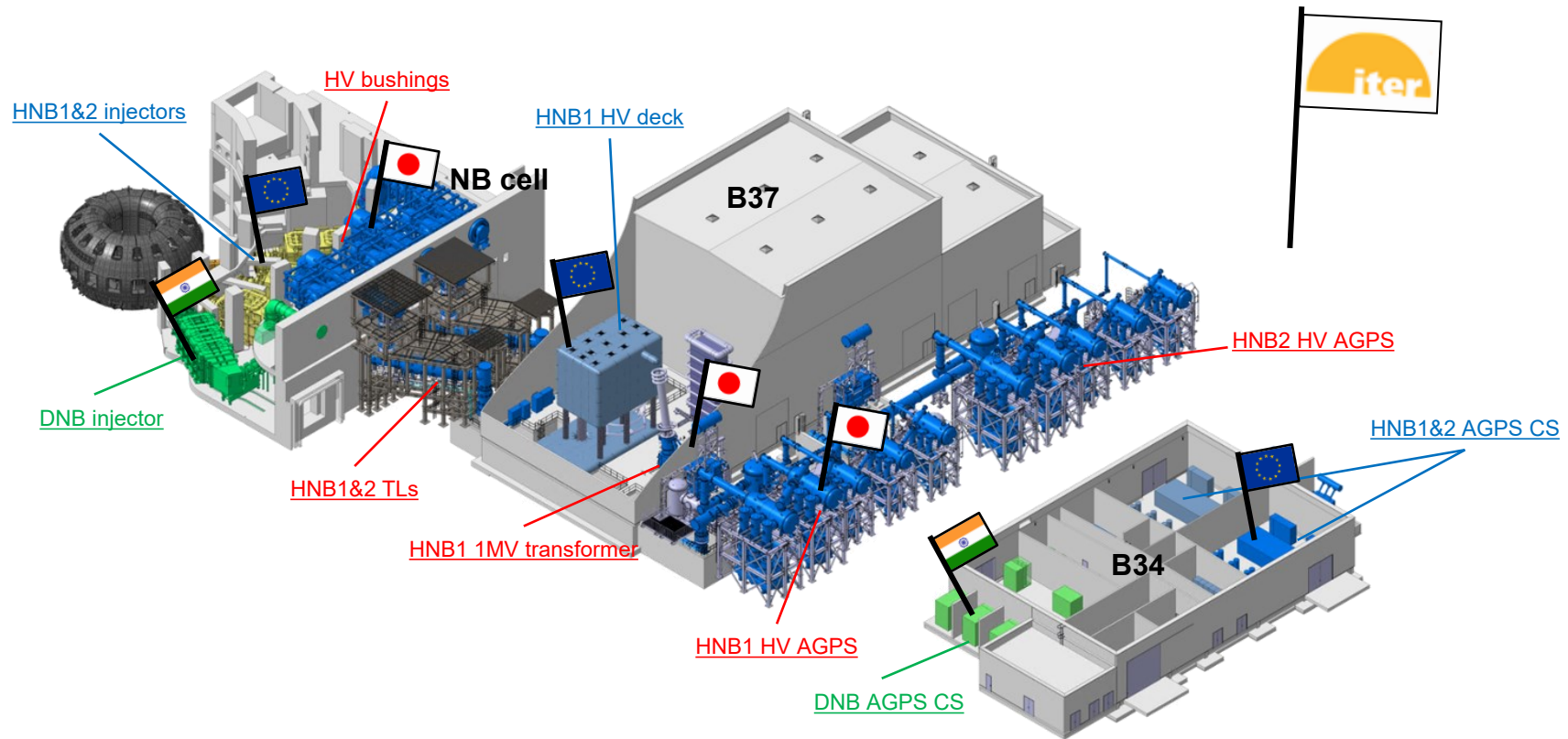
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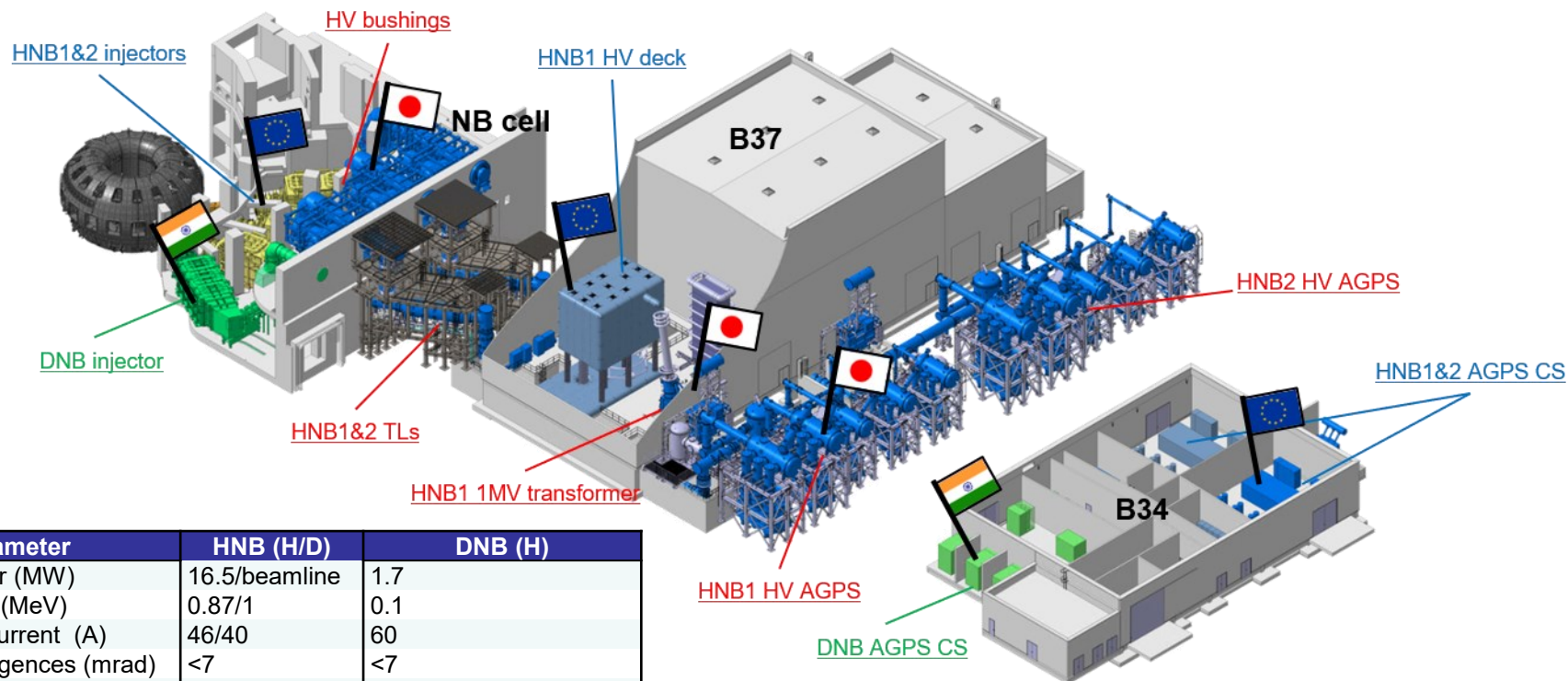
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- ITER NBIs – System overview
- The Neutral Beam 2024 baseline
 - Planned installations
 - Tackling the technological challenges
- NBTF RoX: the calorimeter example
 - Accurate 3D modelling of the beamline
- Conclusion



ITER NBIs – System overview

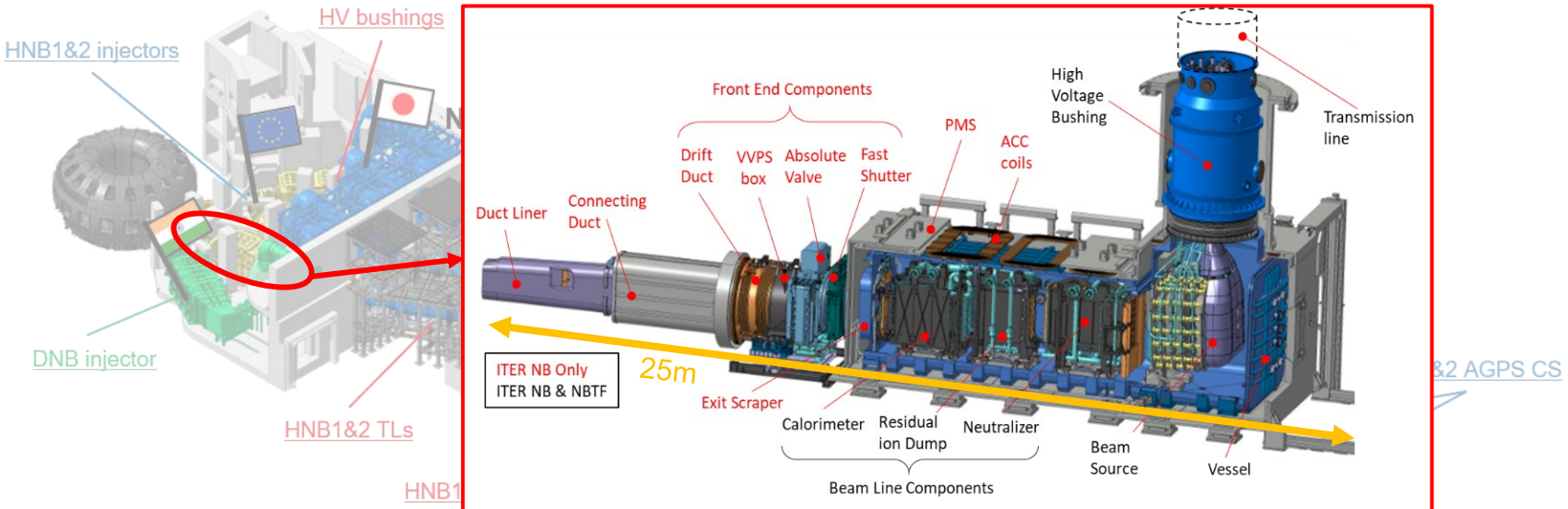
- ❑ HNB prototype being developed and tested at NBTF in Italy
- ❑ DNB being developed and tested at IPR in India



Parameter	HNB (H/D)	DNB (H)
Injected power (MW)	16.5/beamline	1.7
Beam energy (MeV)	0.87/1	0.1
Accelerated current (A)	46/40	60
Beamlet divergences (mrad)	<7	<7
Pulse length/duty cycle (s)	3600/25%	3s ON (5Hz), 20 s OFF 0.1s ON 1.4s OFF

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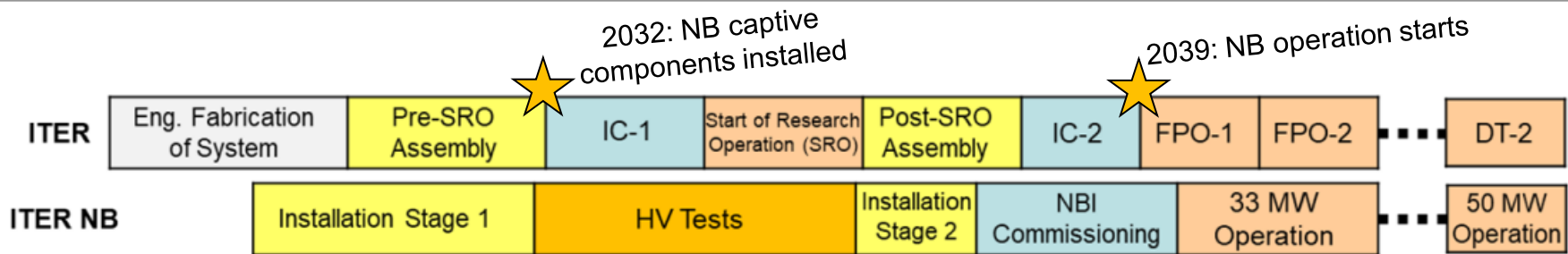


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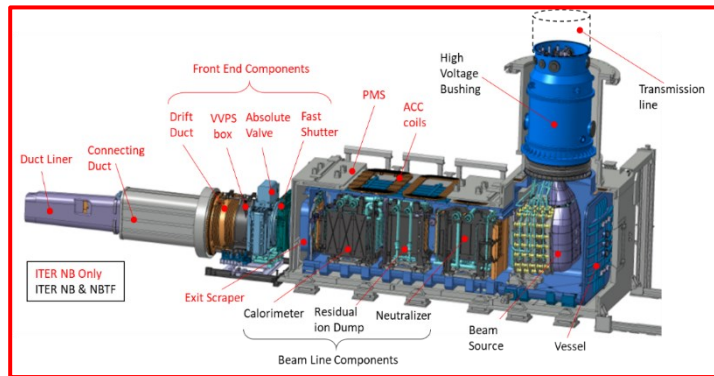
Neutral beam based on **800kW RF negative ion source** concept, with **gas neutralizer** and **electrostatic RID**

>10 large FOAK components involved

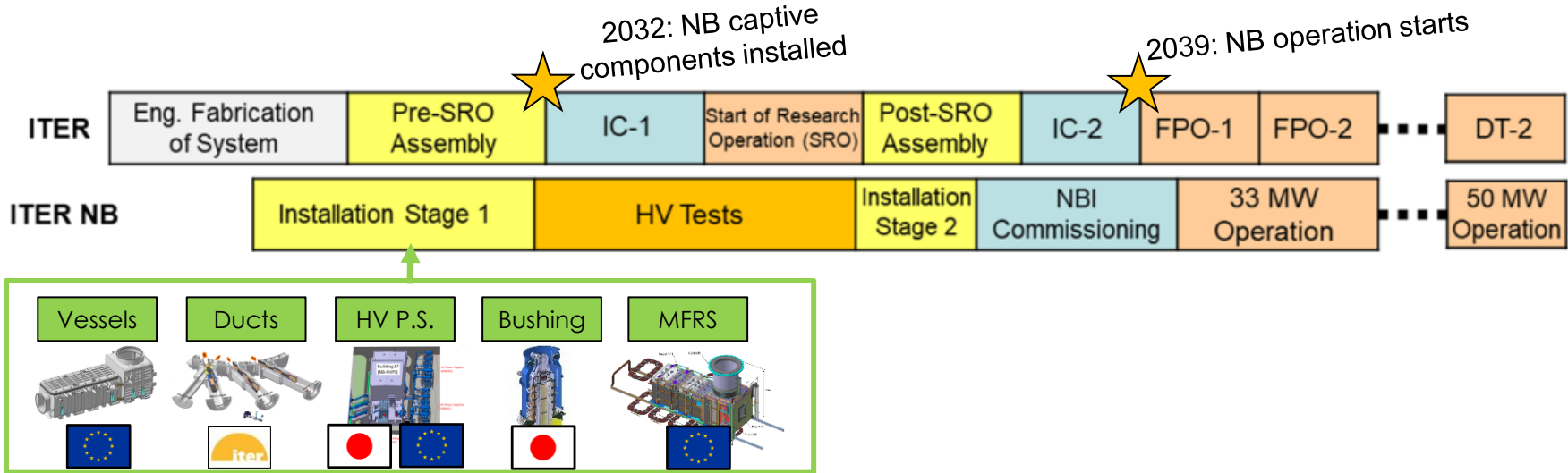
NBIs for ITER: a phased approach towards DT-1 operation



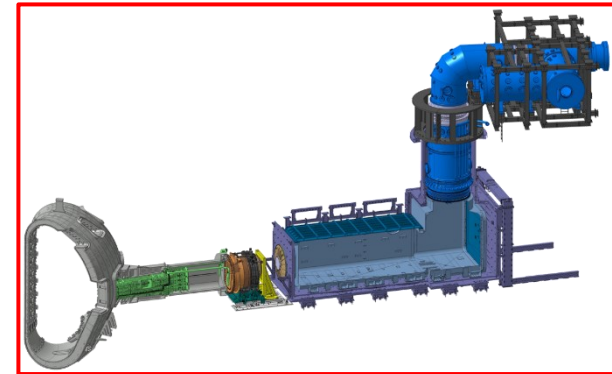
- Beam operation will start in DT-1
- Installation will happen in two stages, before and after SRO
- During the SRO phase the HV power supplies and the magnetic field reduction systems will be commissioned



NBIs for ITER: pre-SRO installations

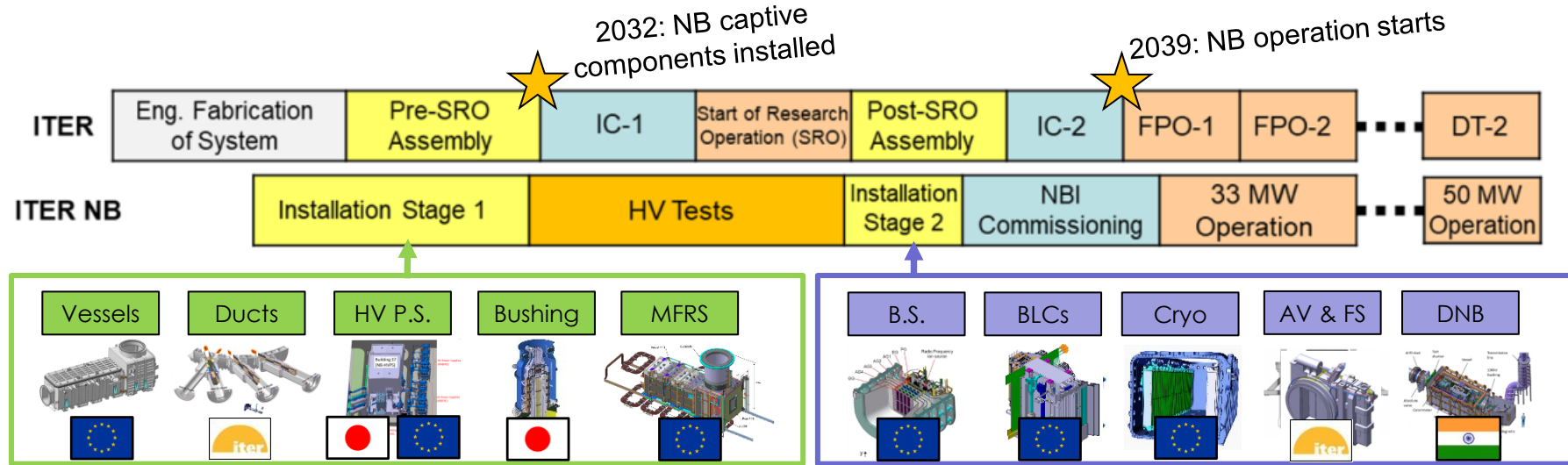


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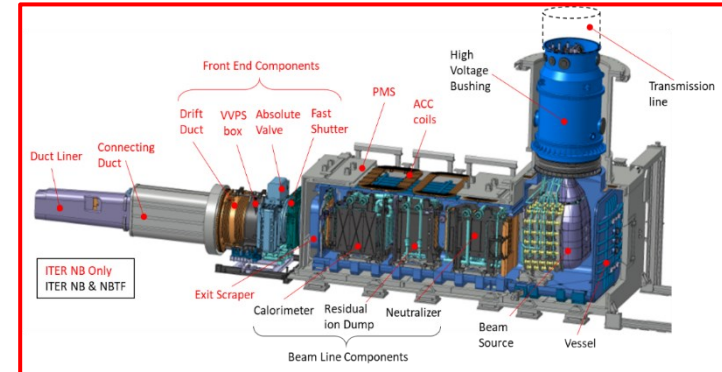


J. Zacks et al., "An update on ITER and the ITER Neutral Beam progress and development", 2025, JINST 20 C08016

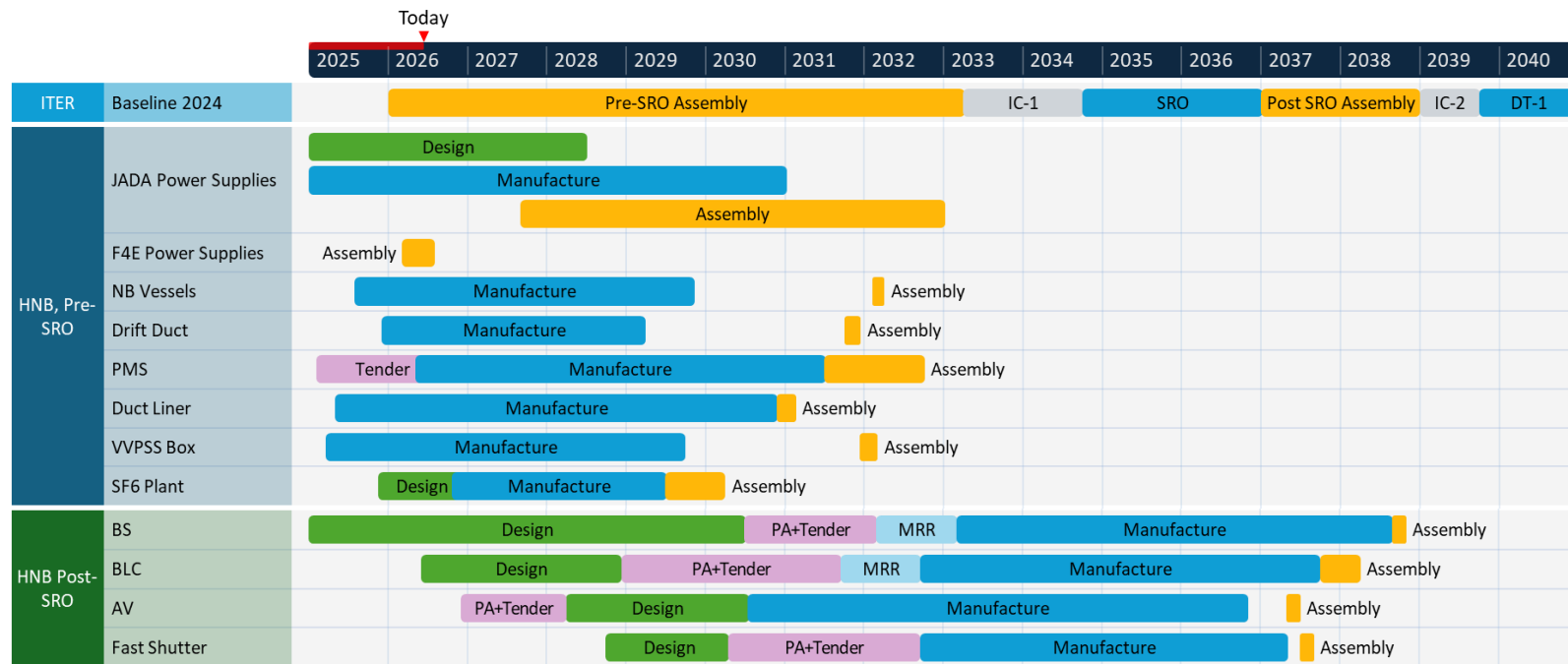
NBIs for ITER: post-SRO installations → towards DT-1



- Beam operation will start in DT-1
- Installation will happen in two stages, before and after SRO
- During the SRO phase the HV power supplies and the magnetic field reduction systems will be commissioned
- In vessel components are required after SRO

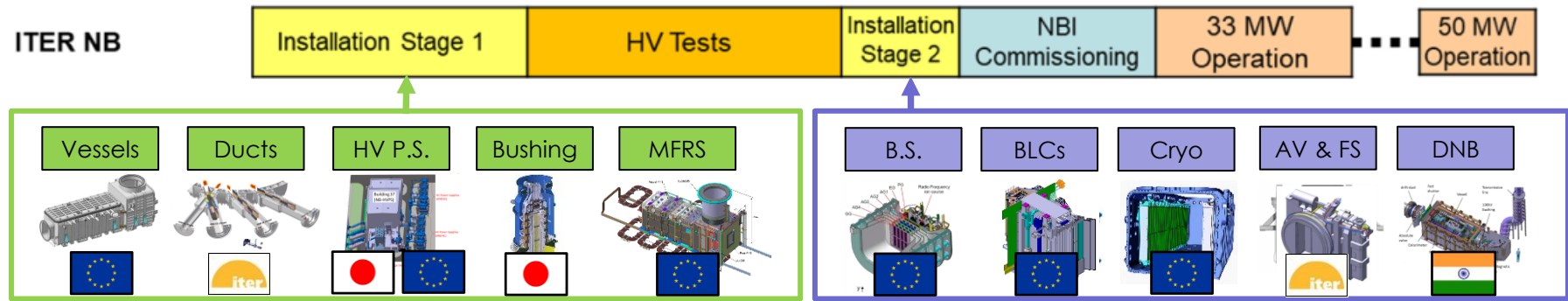


NBIs for ITER: a phased approach towards DT-1 operation



- Pre-SRO components have all started or are about to start the manufacturing phase, being in time for cryostat closure, benefitting from the experience gained in the NBTF construction
- Post-SRO components are in the design phase, incorporating inputs from NBTF

NBIs for ITER: tackling the technological challenges 1 by 1



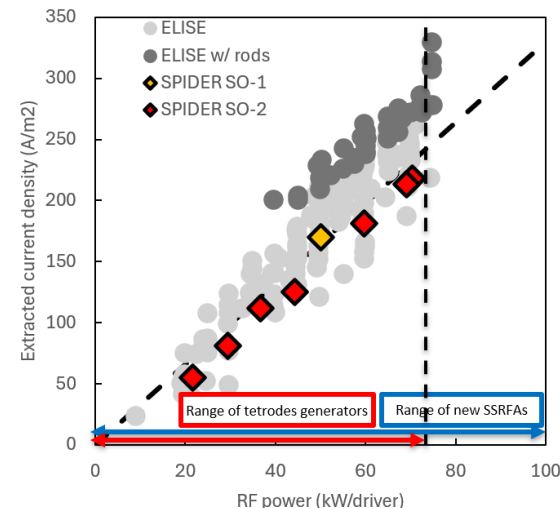
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What are the main technological challenges?

IT

>330A/m² H- extracted current density required

- ✓ ELISE recently achieved 100% target for short pulses, 90% for long pulses
- ✓ SPIDER experiment confirmed the scaling operating 1 segment up to 70kW/driver
- ✓ With the replacement of tetrodes oscillators with solid-state RF amplifiers SPIDER is expected to confirm the scaling



1

Large negative ion current

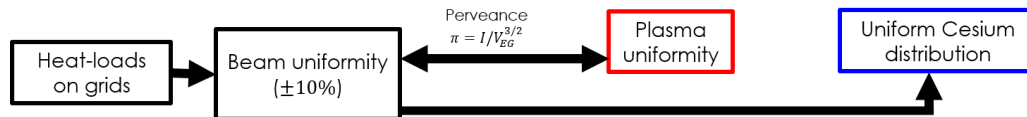
IT

Non-uniformity $< \pm 10\%$

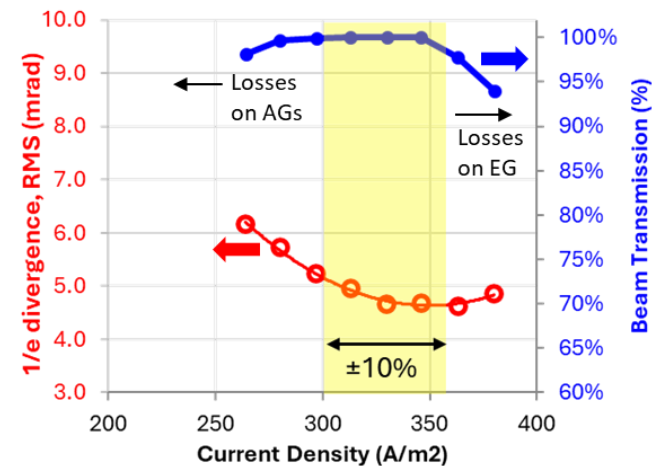
- Requirement driven by heat loads on the accelerator grids
- It depends on negative ion uniformity (plasma+Cs)

How we tackle it?

- ❖ Working on improved Cs handling
- ❖ Working on the reduction of the plasma asymmetry
- ❖ Decoupling source and accelerator validation



- 1 Large negative ion current
- 2 Current uniformity (to work at perveance match)



IT

Low beamlet divergence <7 mrad

- Required to deliver 16.5MW to ITER

$$\text{Beam Power} = I_{\text{ACC}} \cdot V_{\text{ACC}} \cdot Y_N \cdot (1 - T_R) \cdot T_G$$

I_{ACC} = Accelerated current = 40 A

Y_N = Neutraliz. Yield = 56%

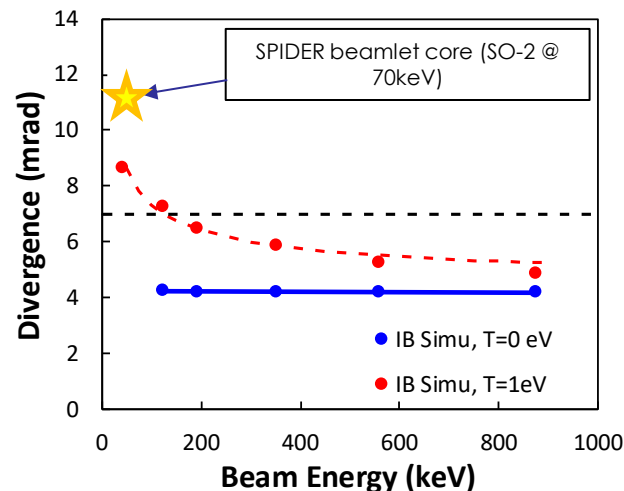
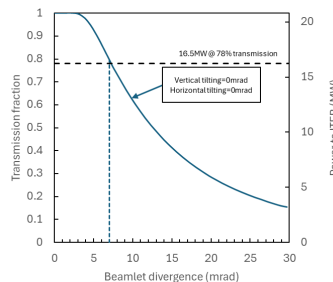
$T_G = T_G$ (divergence, aiming, tilting)

V_{ACC} = Acceleration Voltage = 1 MV

T_R = Re-ionization Losses = 4.8%

$$\text{Beam Power} \geq 16.5 \text{ MW} \Rightarrow T_G \geq 78\%$$

- ✓ Expected to be ok for HNB
- ❖ Investigating the dependence of divergence on source parameters
- ❖ >7mrad scenario for DNB is being developed



1

Large negative ion current

2

Current uniformity
(to work at perveance match)

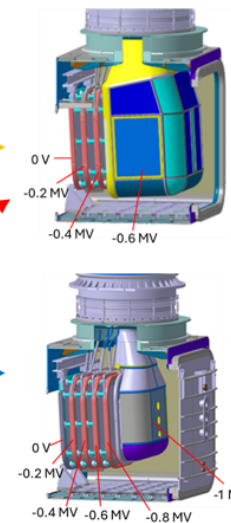
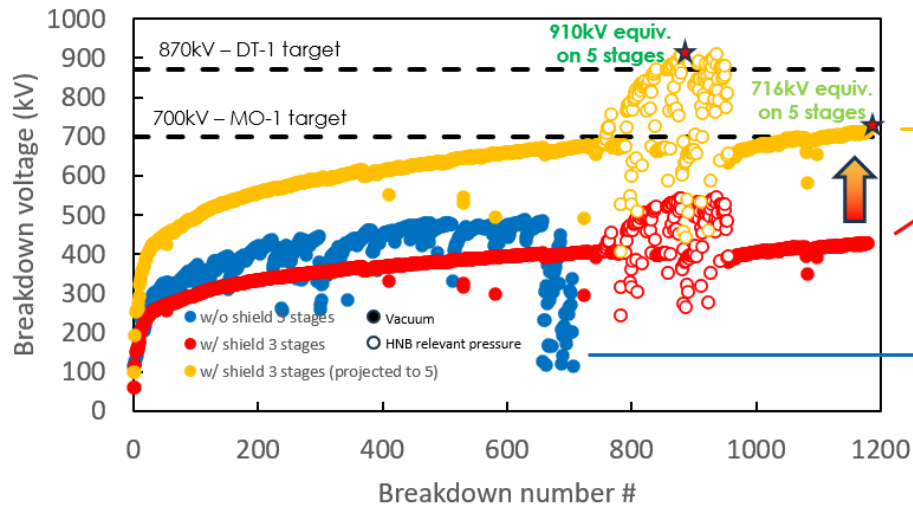
3

Low beamlet divergence
(to ensure proper beam transmission)

IT

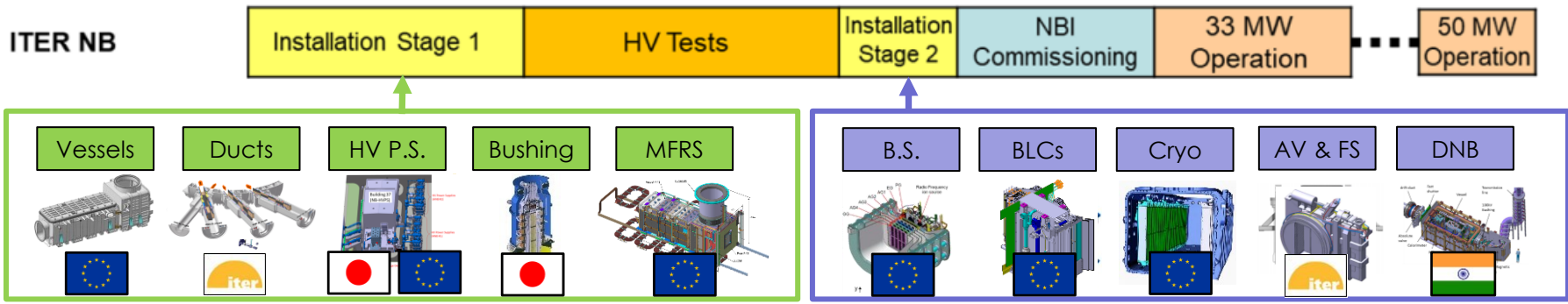
Need to withstand the 1MV voltage in vacuum

- The ITER NB ion sources are in vacuum
- ✓ Recent results at NBTF showed the 1MV target is in reach with current design



- 1 Large negative ion current
- 2 Current uniformity (to work at perveance match)
- 3 Low beamlet divergence (to ensure proper beam transmission)
- 4 High voltage holding in vacuum (the ion sources are in vacuum for nuclear radiation issues)

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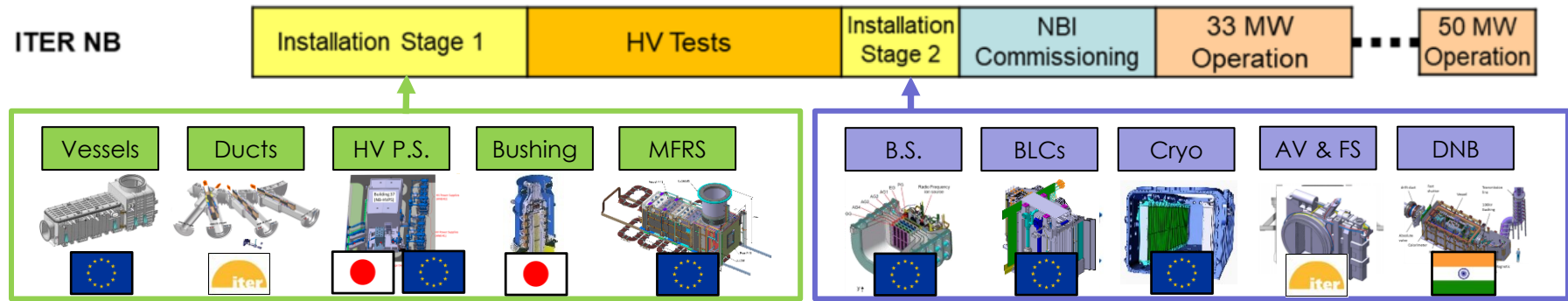
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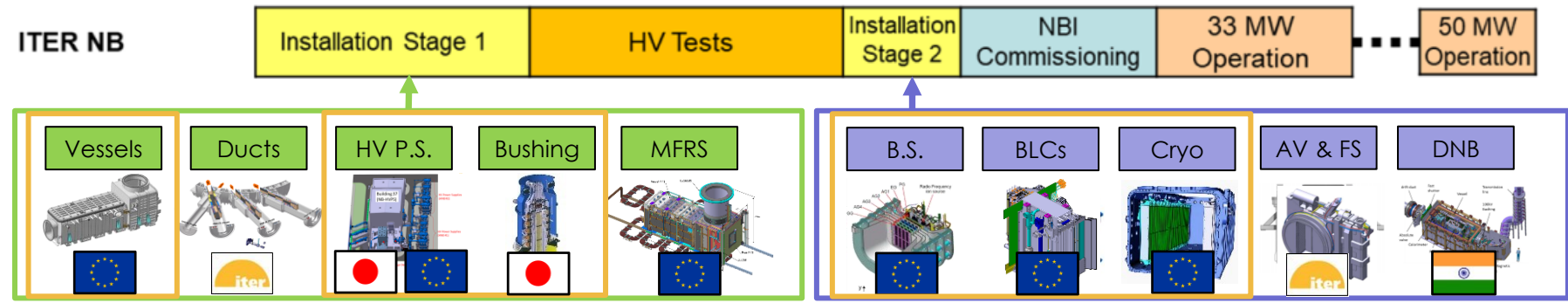
Investigations in partner facilities at IPP, QST, IPR

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See for example D. Wunderlich and C. Wimmer presentations, this conference

NBIs for ITER: tackling the technological challenges altogether



Phased research plan, included in the ITER Research plan, prioritizing H target achievements

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NBTF

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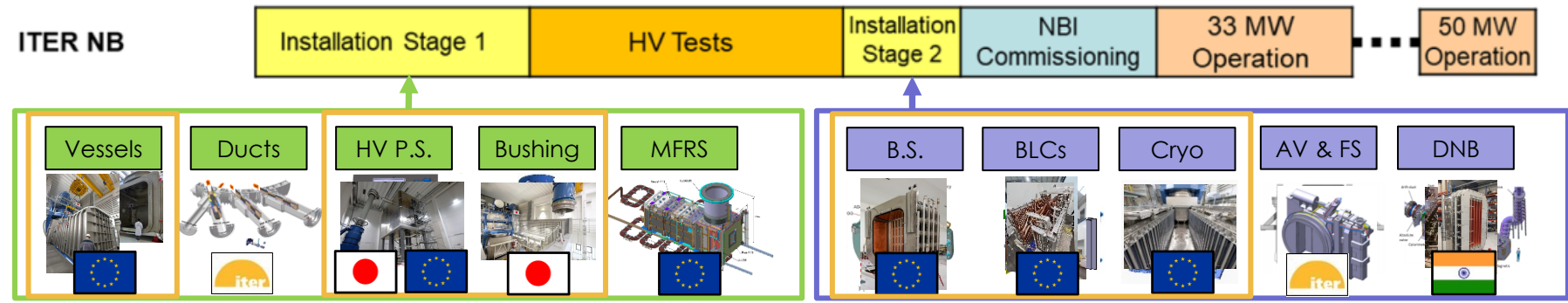
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NBIs for ITER: tackling the technological challenges altogether



BS vessel
(installed in 2021)



High voltage deck
(installed in 2021)



Beam Source (SAT
completed in 2026)



Gas neutralizer (SAT
completed in 2026)



DNB source (FAT
September 2026)



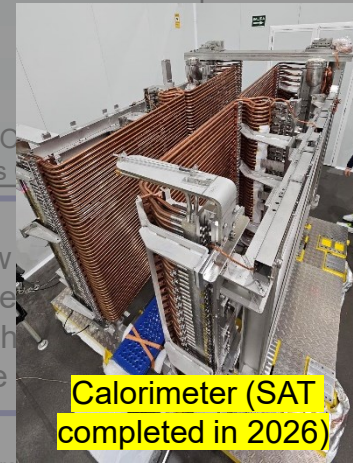
BL vessel
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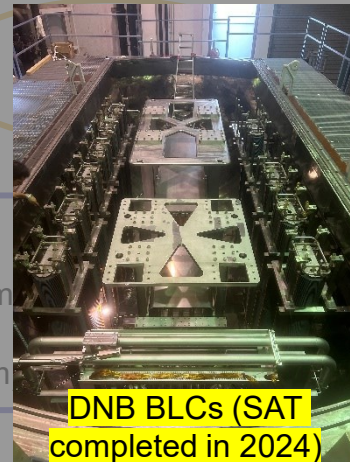
High voltage bushing installation
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Electrostatic Residual
Ion Dump (SAT
completed in 2026)



Calorimeter (SAT
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DNB BLCs (SAT
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NIBS'26 – September 24, 2026

NBIs for ITER: NBTf RoX – The calorimeter example



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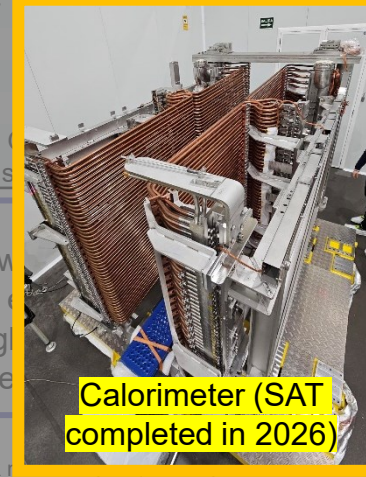
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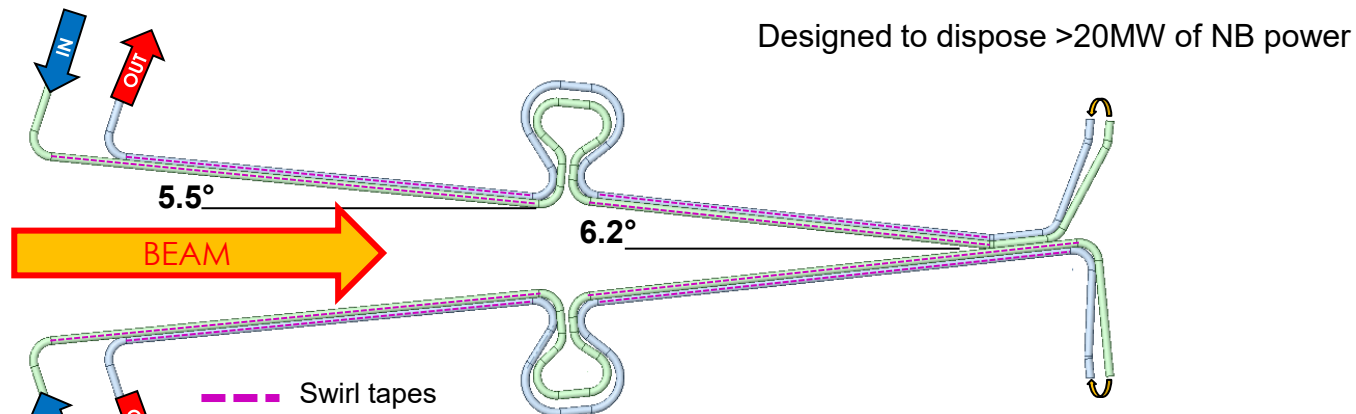
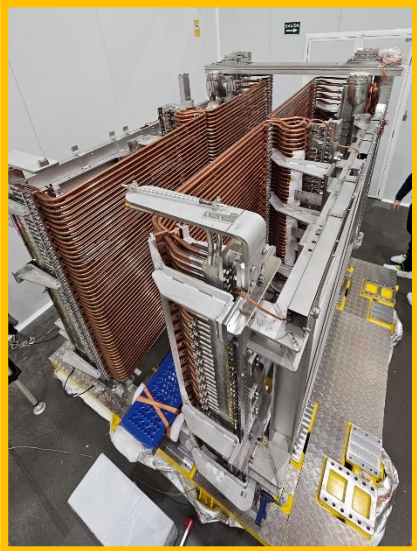
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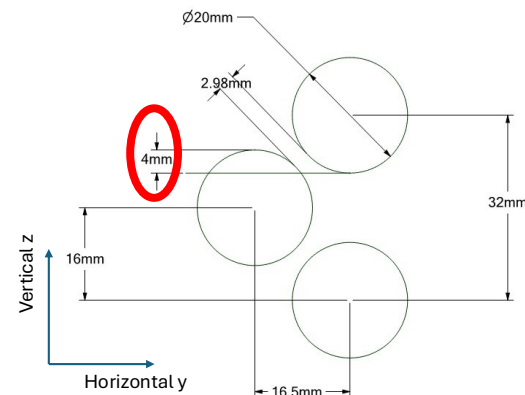
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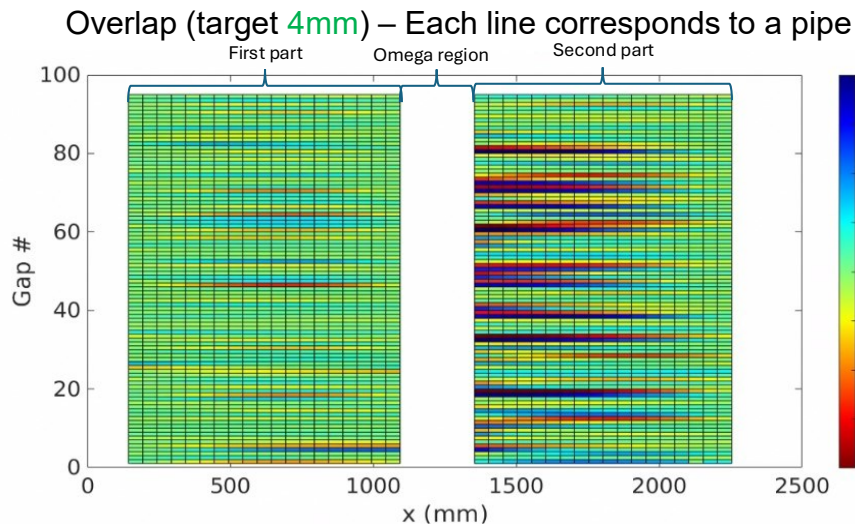
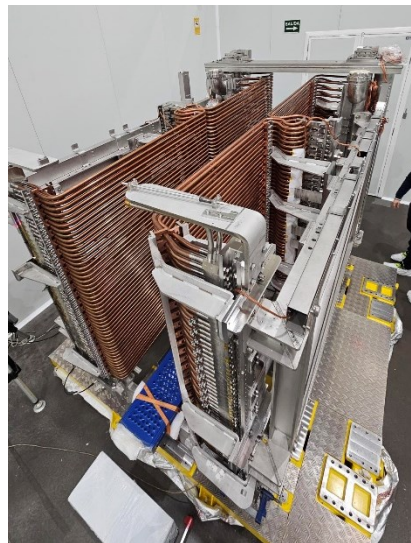
NBIs for ITER: NBTf RoX – The calorimeter example



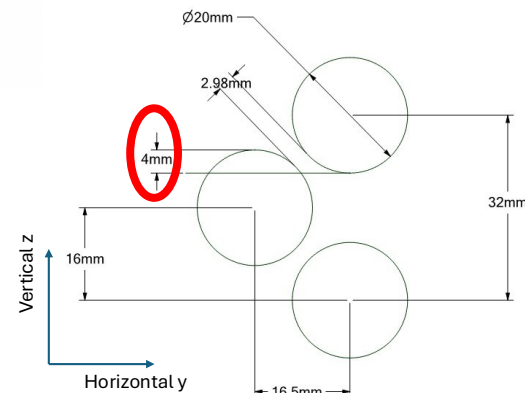
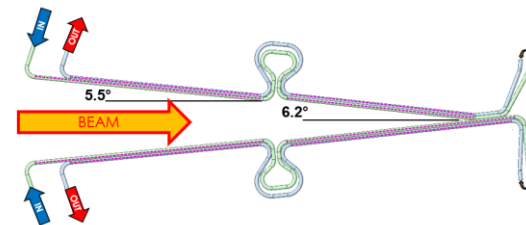
- 48 front and 48 rear (48 circuits) DN20, ID16 CuCrZr pipes
- Length exposed to the beam: ~2.5m
- Each front pipe is connected to a neighbour rear pipe
- 2mm thick, 16mm width and 50mm pitch twisted tapes are inserted along the straight parts of the pipes
- Front and rear pipe arrays are horizontally spaced by 16.5mm and are vertically spaced by 32mm and alternated → 4mm overlap



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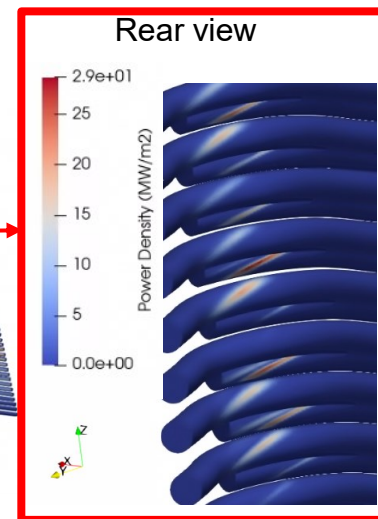
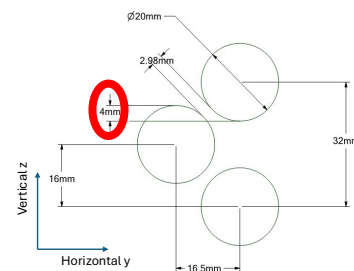
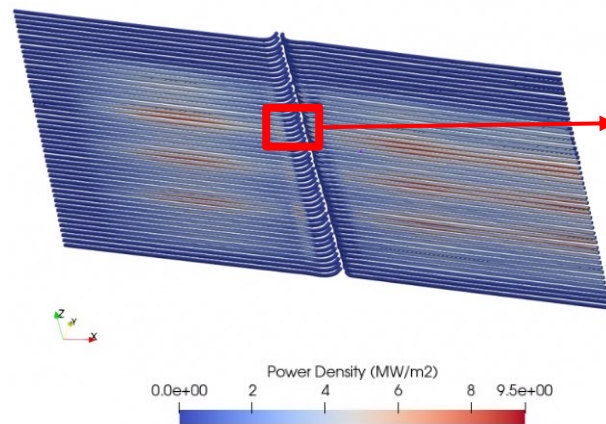
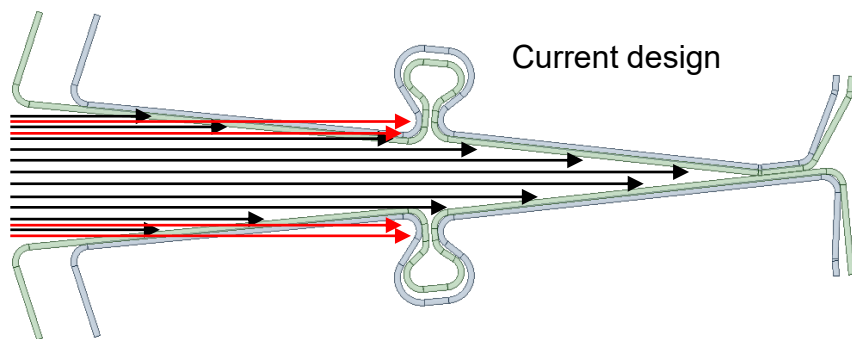


NBIs for ITER: NBTf RoX – The calorimeter example

- Metrology measurements were included in beam tracing simulations
- This allowed to estimate the loads on the delivered calorimeter

29MW/m² in the “omega” region due to the shinethrough neutrals impinging perpendicularly

- We need a more reliable design in view of the ITER HNB

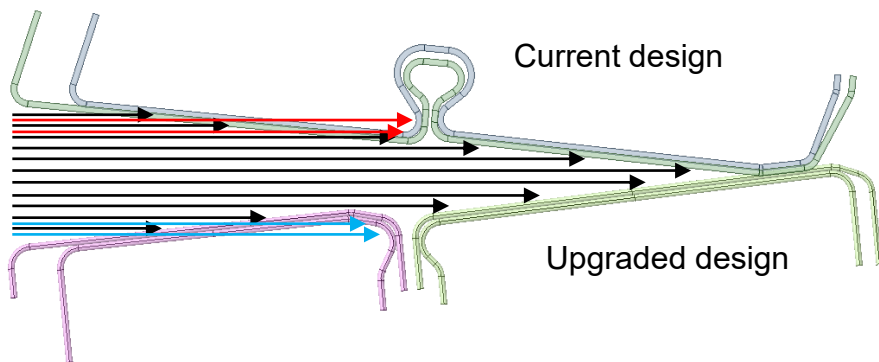
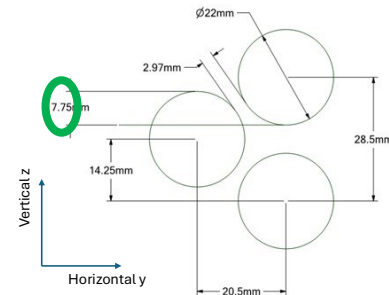


NBIs for ITER: NBTF RoX – The calorimeter example

- Metrology measurements were included in beam tracing simulations
- This allowed to estimate the loads on the delivered calorimeter

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- ✓ Slight increase of the pipe angle (up to 7.05deg)
- ✓ Increased of pipe diameter and overlap (from 4 to 7.75mm)
- ✓ Addition of bends at the end of the swirl-tape regions
- ✓ Replacement of the omega with blocks
- ✓ Improved manufacturing of the manifolds

DESIGN UPGRADE

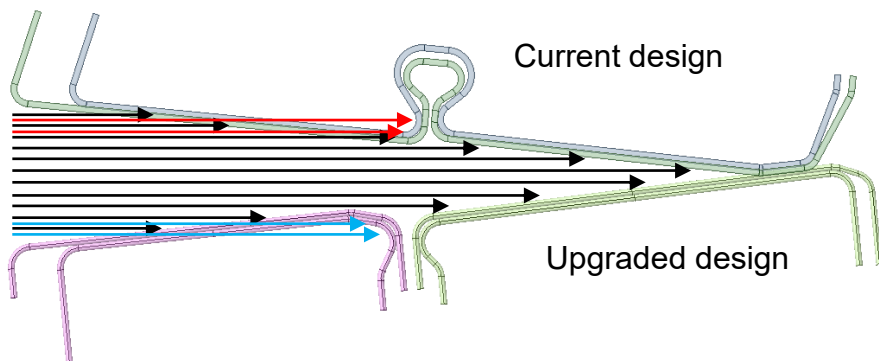
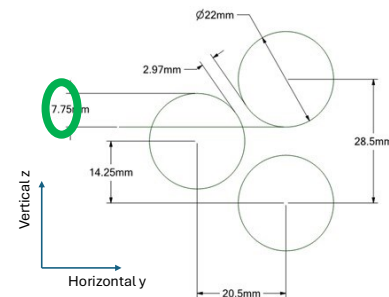
to reduce the possibility of shinethrough and better dispose the few particles passing.

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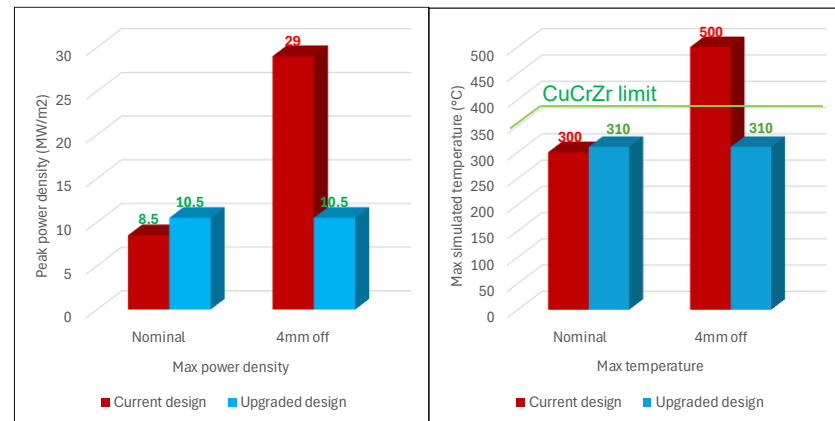
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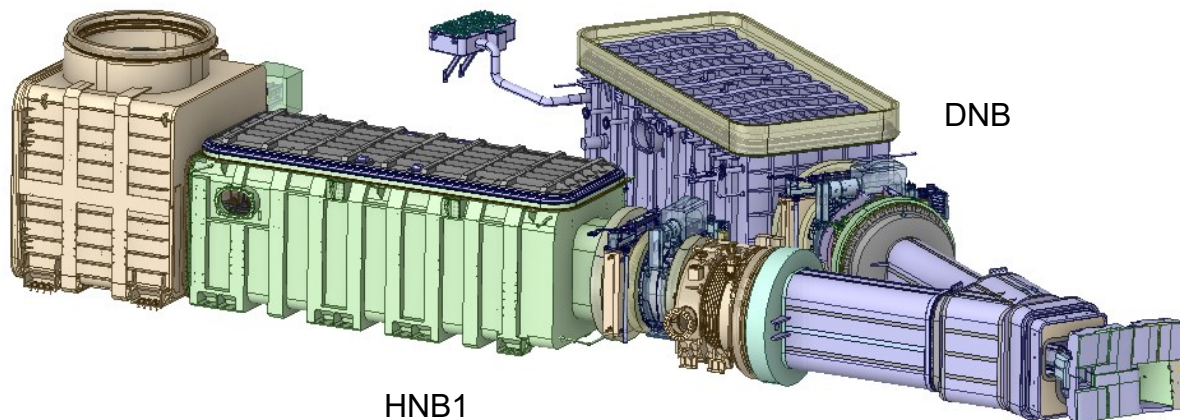


Results for 5mrad divergence beam with -10mrad tilting.
Temperatures are obtained from Ansys thermal-structural coupled simulations

The new design keeps PD at a manageable level, with a maximum temperature below CuCrZr critical limit of 350°C

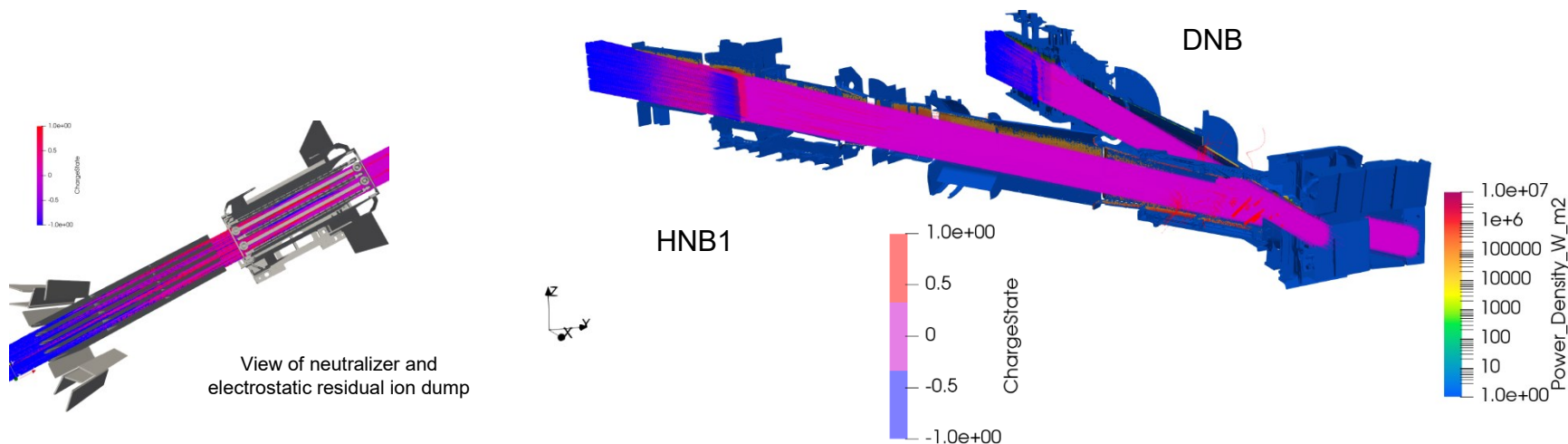
NBIs for ITER: accurate 3D modelling of the beamline

Power-load prediction is essential to design NB beamlines.
Available codes usually assume simplified geometries.
In advanced design phases, including accurate modelling of the beamline can be a great advantage.



BEAM ON TARGET

- Allows import of geometry as STL files
- Uses open-source ray-tracing acceleration libraries
- Works standalone (with GUI) or can be integrated into different simulation frameworks
- Two types of simulations:
 - Fast ray-cast simulations (for quick transmission calculations)
 - Full EM tracing in external E and B fields using Boris algorithm
 - Modelling of beam-species transformations due to beam-gas interaction
 - Used to estimate neutralization and re-ionization



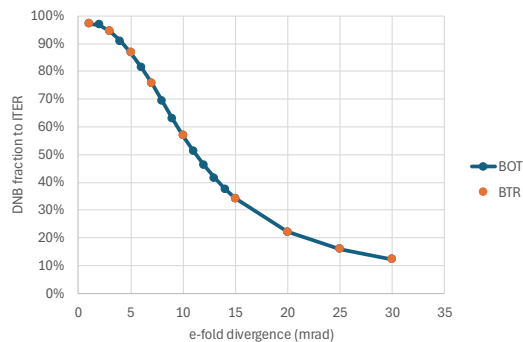
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 - Provides power-load estimation on realistic CAD geometries

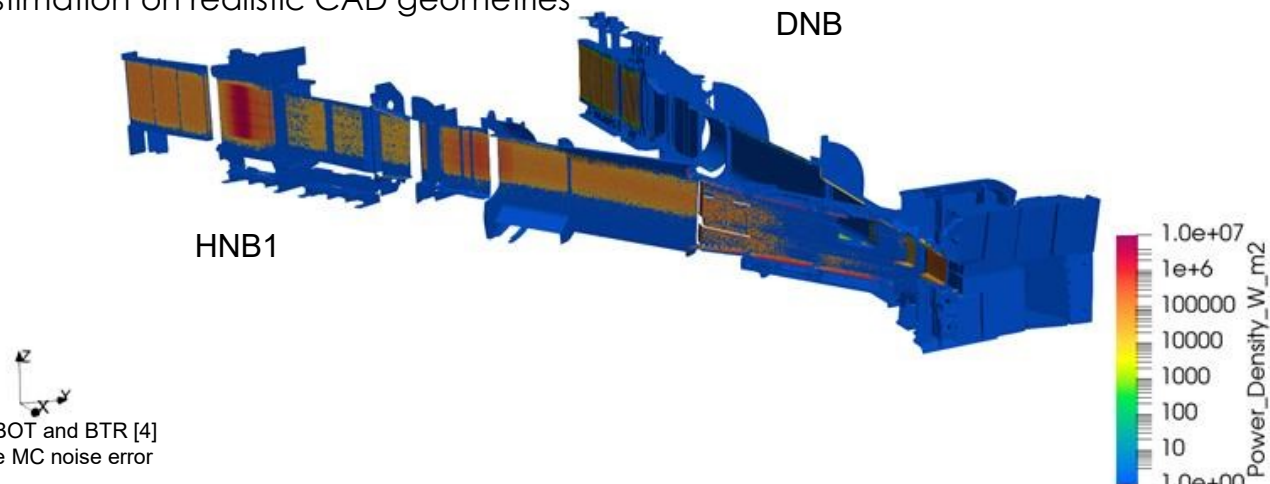


BTR vs BOT



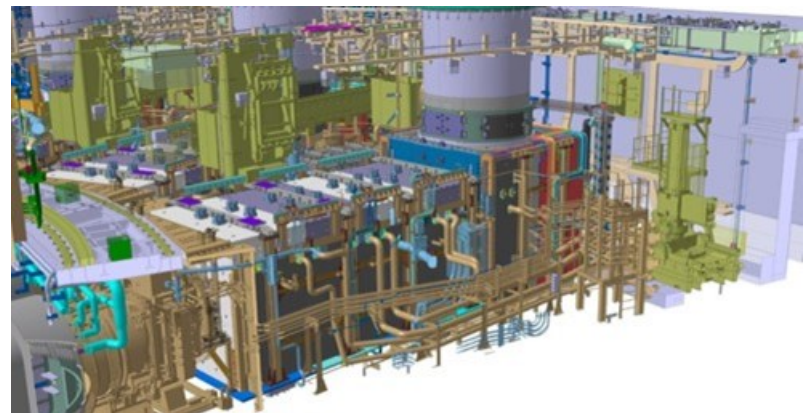
Comparison of the DNB power transmitted to ITER calculated by BOT and BTR [4] codes for different beamlet divergences → in agreement within the MC noise error

[4] E. Dlougach, "BTR code for NBI design and optimization", AIP Conf. Proc. 2373, 080004 (2021)



Conclusions

- The 2024 ITER baseline is progressing according to the plan
- ITER NBIs are moving forward, with two major installation milestones foreseen:
 - Installation of pre-SRO components
 - HNBs and DNB ready to install for DT-1 operation
- The technological challenges are being tackled at the NBTF, with the most crucial NNBI research topics being addressed also with the help of partner laboratories
- NBTF return of experience is already being incorporated into the ITER NBI design, as illustrated by the calorimeter upgrade.
- A new modelling tool using realistic CAD geometry has been developed to support component design, and is now publicly available at [ITER GitHub](#)



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Thank you for your attention!

