Sviluppo degli iniettori di neutri per esperimenti di fusione: componenti meccanici ad alto flusso termico

Neutral Beam Injectors development for nuclear fusion experiments: thermo-mechanical components under high thermal fluxes

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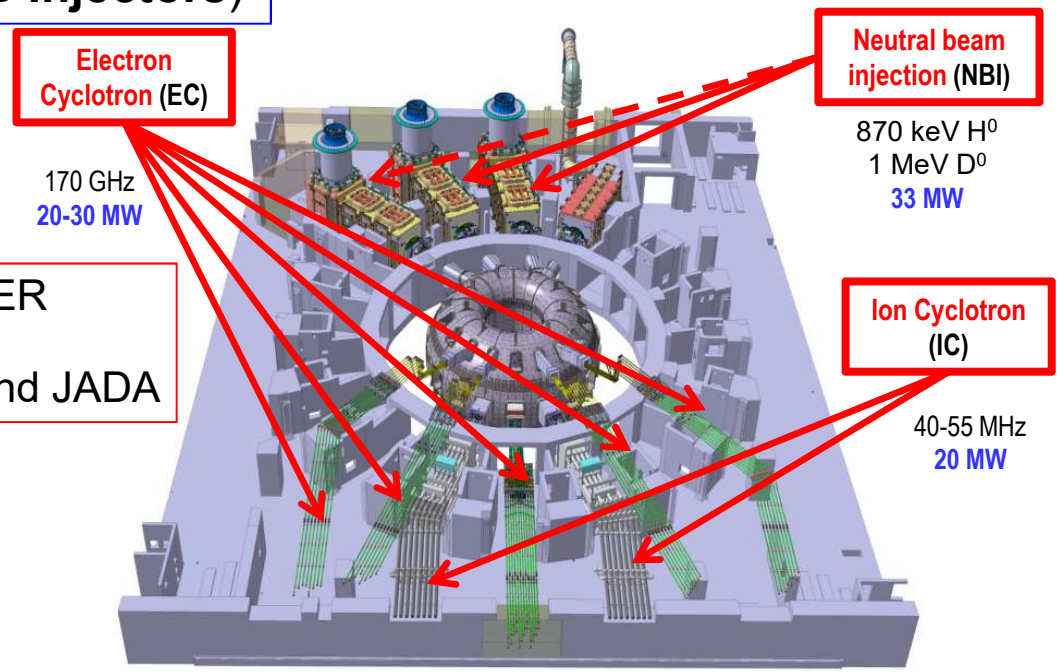
OUTLINE

- ITER Heating Neutral Beam Injectors and reasons for a Neutral Beam Test Facility (NBTF)
- SPIDER – The ITER RF ion source experiment
- MITICA - The ITER HNB full size prototype
- On-going and next procurements

ITER
Heating & Current Drive systems

Target fusion power in ITER: 500 MW
Injected power: 50 MW (**33 MW by NB Injectors**)



2 HNBs (+additional 1) are foreseen in ITER

Procurements are shared between F4E and JADA

Main target parameters of HNBs

	H_2	D_2
Current	46 A	40 A
Beam Energy	0.87 MeV	1.0 Mev
Pulse length	1 hour	1 hour
Injected power	16.5 MW	16.5 MW

HNBs parameters have never been simultaneously achieved and for long pulses in existing NB Injectors or test facilities.

Physics and technological issues called for a Neutral Beam Test Facility aiming to develop, test and optimize the ITER HNB injectors.

Aims of ITER Neutral Beam Test Facility

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- NBTF is an 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 HNB: high voltage holding, beam optics

ITER Neutral Beam Test Facility

JADA, F4E, INDA → PAs

IO ↔ F4E: MoU

F4E ↔ RFX: Agreement

(Duration 2012 – 2019)

- Total area:	17,500 m²
- Covered area:	7050 m²
- Internal Surface:	9170 m²
- Maximum height:	24.0 m

NBTF hosts the two experiments:

the negative ion source **SPIDER** and the 1:1 prototype of the ITER injector **MITICA**

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

Overall schedule of the NB systems for ITER

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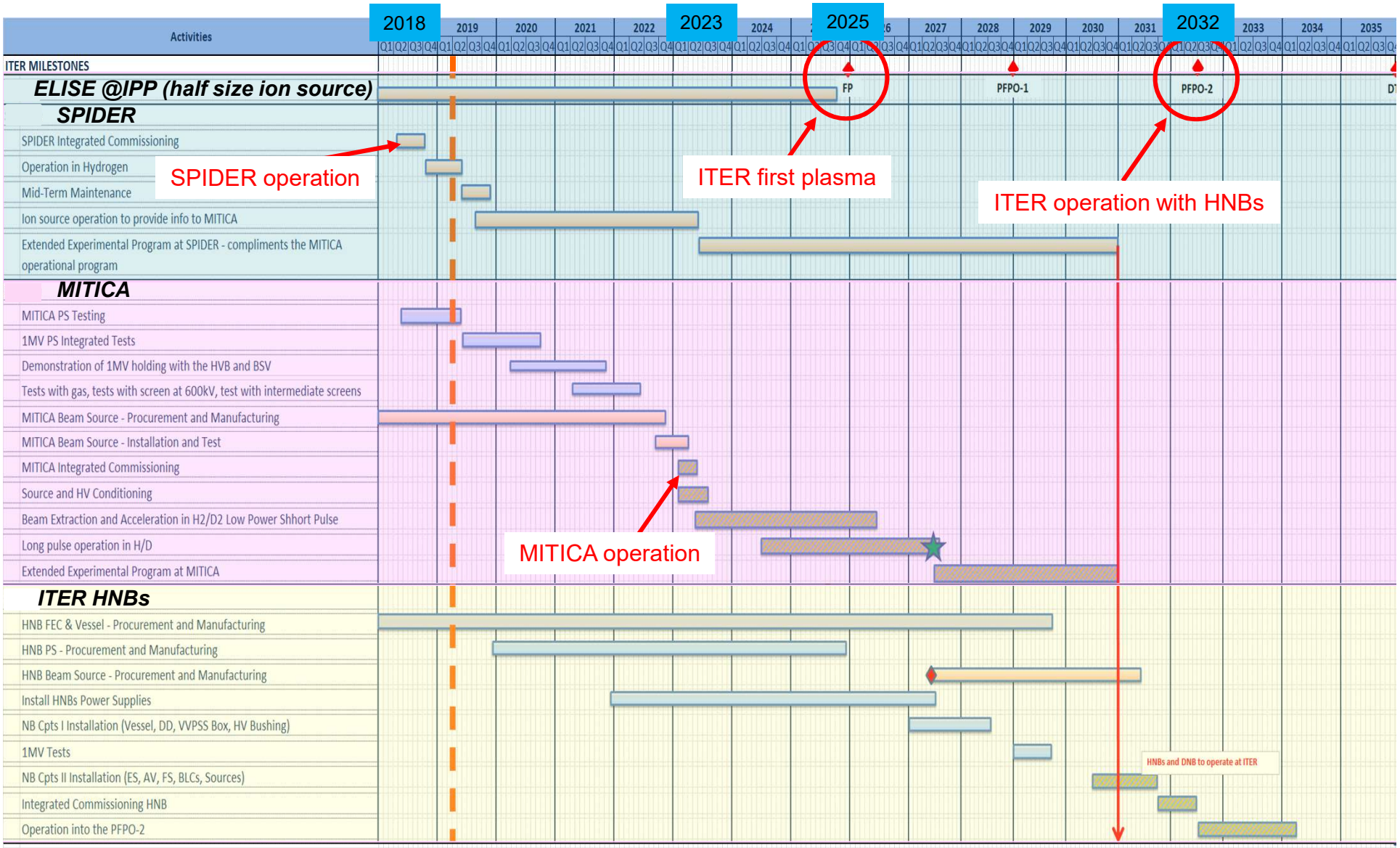

SPIDER Thermo-mechanical components

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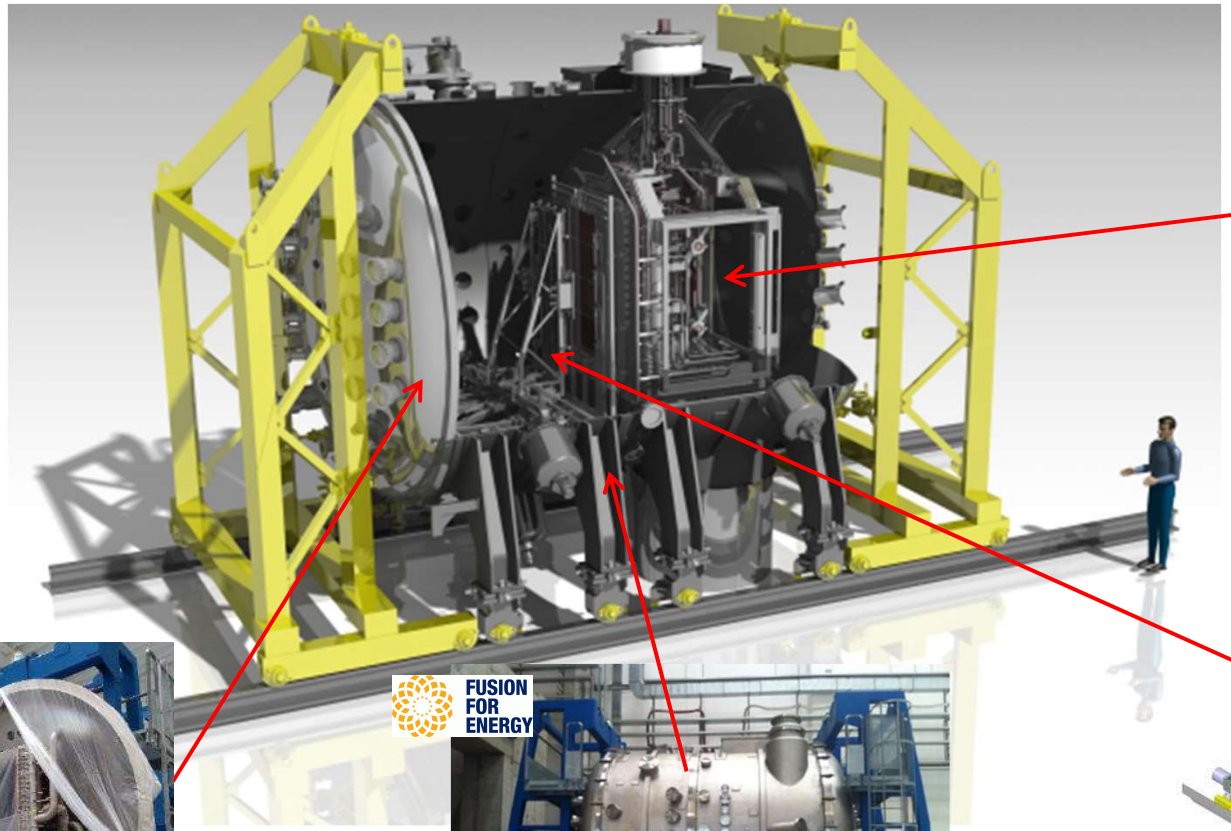
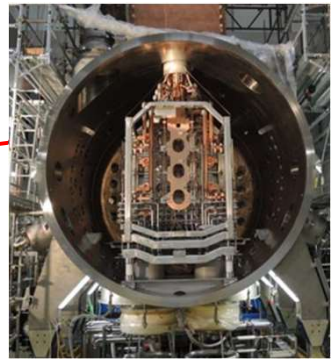
Beam Source inside vacuum environment



FUSION FOR ENERGY



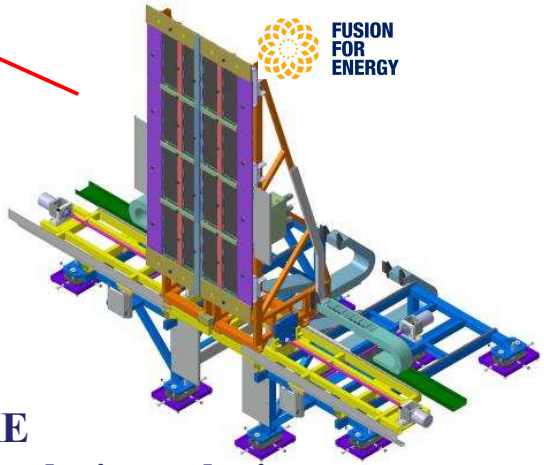
RF Beam Source

Beam Dump for long pulses (up to 1 hour)

FUSION FOR ENERGY

Vacuum Vessel

FUSION FOR ENERGY



STRIKE
High resolution calorimeter for short pulses (up to 5 s)

SPIDER experiment

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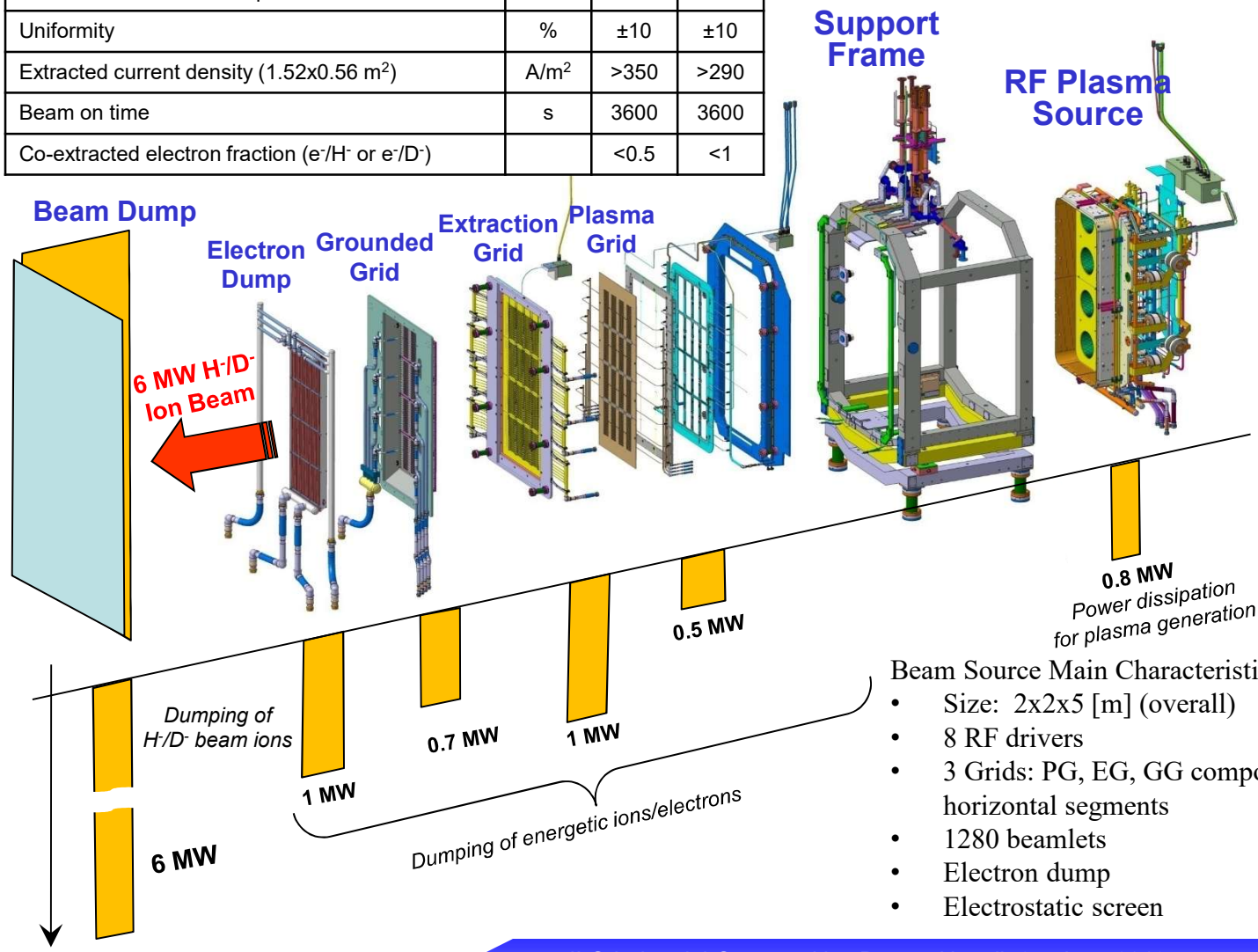
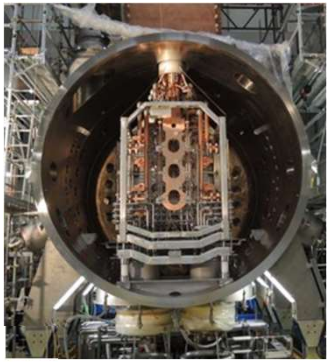
Parameter	Unit	H	D
Beam energy	keV	100	100
Maximum Beam Source pressure	Pa	<0.3	<0.3
Uniformity	%	±10	±10
Extracted current density (1.52x0.56 m^2)	A/m^2	>350	>290
Beam on time	s	3600	3600
Co-extracted electron fraction (e^-/H^- or e^-/D^-)		<0.5	<1

Total power to be removed from SPIDER experiment 10 MW



SPIDER BS at the factory before transport to NBTF site



SPIDER BS as installed inside the Vacuum Vessel

Beam Source Main Characteristics:

- Size: 2x2x5 [m] (overall)
- 8 RF drivers
- 3 Grids: PG, EG, GG composed of 4 horizontal segments
- 1280 beamlets
- Electron dump
- Electrostatic screen

SPIDER Beam Source grids

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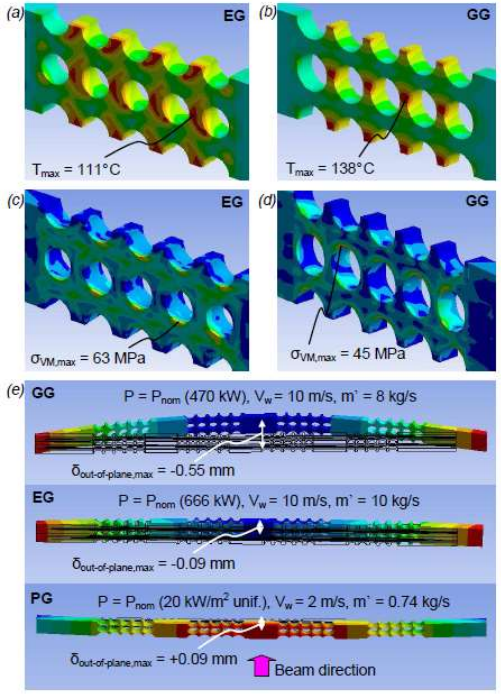
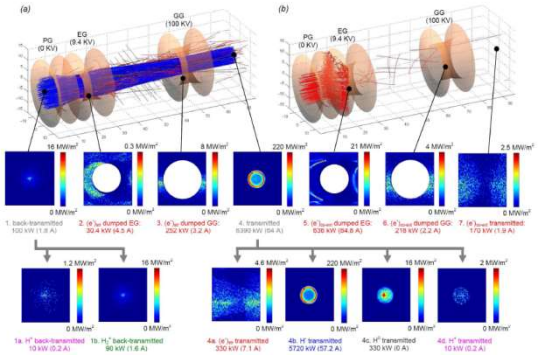
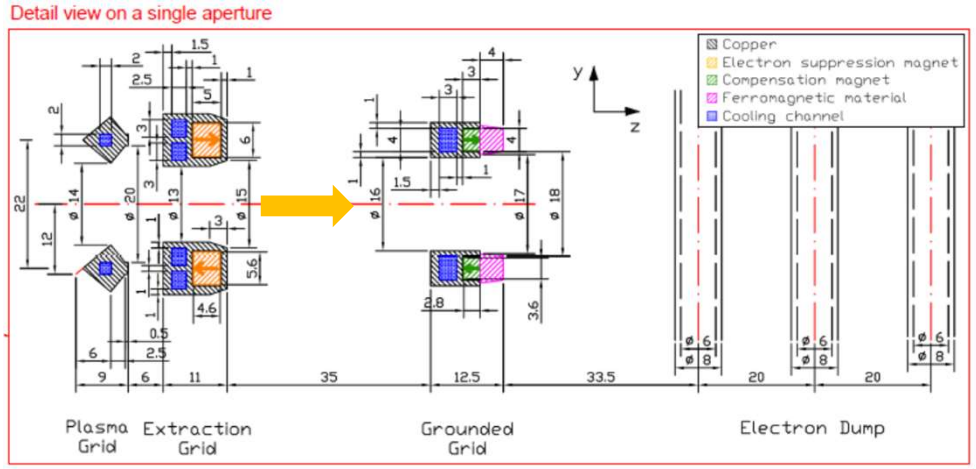
From the beam physics
to power loads
to design
and finally to
manufacturing technology.

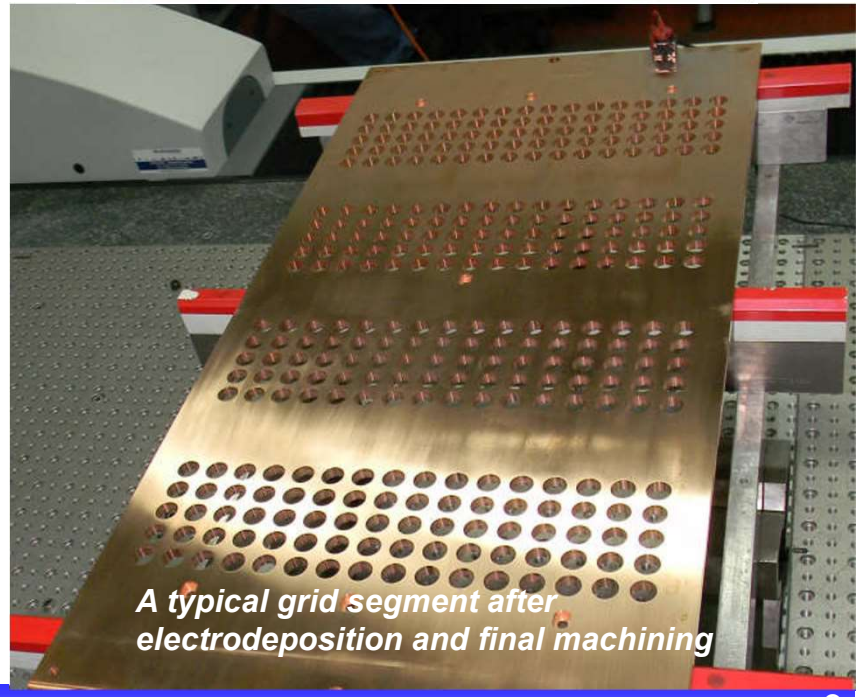






Vertical section view

Machined horizontal cooling channels



A typical grid segment after electrodeposition and final machining

SPIDER Beam Dump

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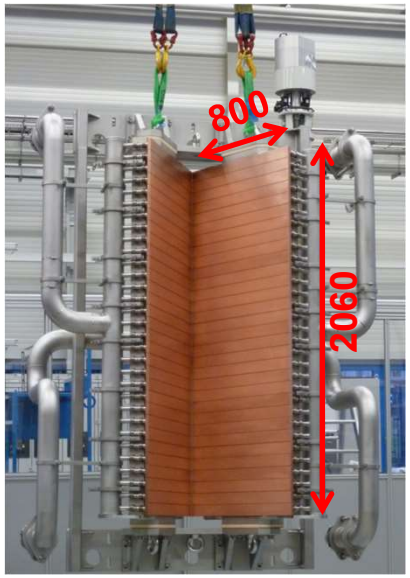
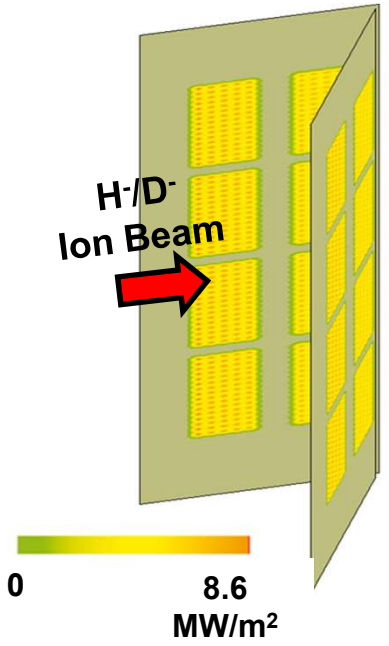
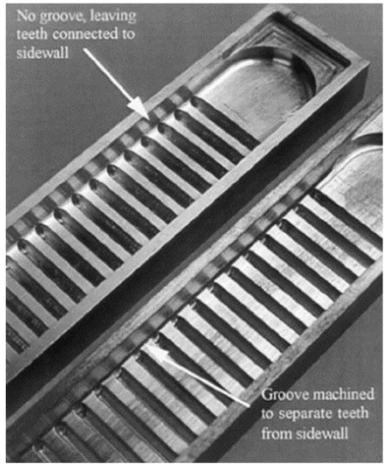


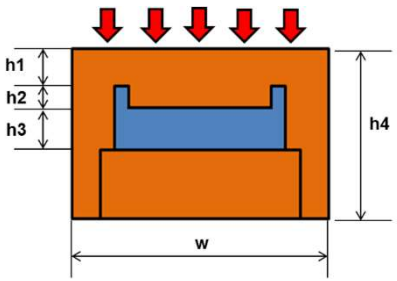
Maximum ion beam power:

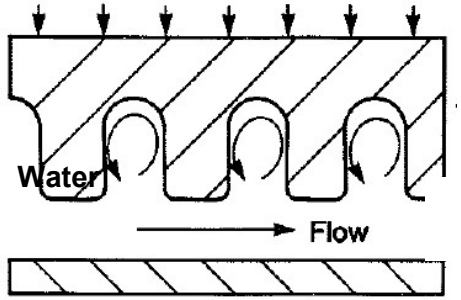
6 MW for 1 hour pulses



31+31 Hypervapotrons as high heat flux elements made up of CuCrZr alloy







Water flow rate: 64 kg/s

Inlet pressure: 1 MPa

Inlet water temperature: 20 - 55 °C

Max. Incident Heat Flux 8.6 MW/m²

Min. Critical Heat Flux 13 MW/m²

SPIDER procurements

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SPIDER is presently in operation and all the main procurements were completed.

Main procurements for SPIDER

Component	Procuring Domestic Agency	Supplier
Vacuum Vessel and Beam Source	F4E	Thales (F), CECOM (I), Galvano-T (D), Zanon (I)
STRIKE	F4E	Several suppliers for different parts
Beam Dump	INDA	PVA TePLA (D)
Diagnostics	F4E	Several suppliers for different diagnostics
Vacuum and Gas Distribution	F4E	ATT (I)
Cooling Plant	F4E	Delta-Ti (I)
Power Supply	*F4E and INDA procurements (see dedicated presentation by Vanni Toigo – Consorzio RFX)*	

Some further procurements to complete beam diagnostics are going on.

Next procurements are directly linked to the outcomes from experiments and possible needs for changes/optimization.

MITICA experiment

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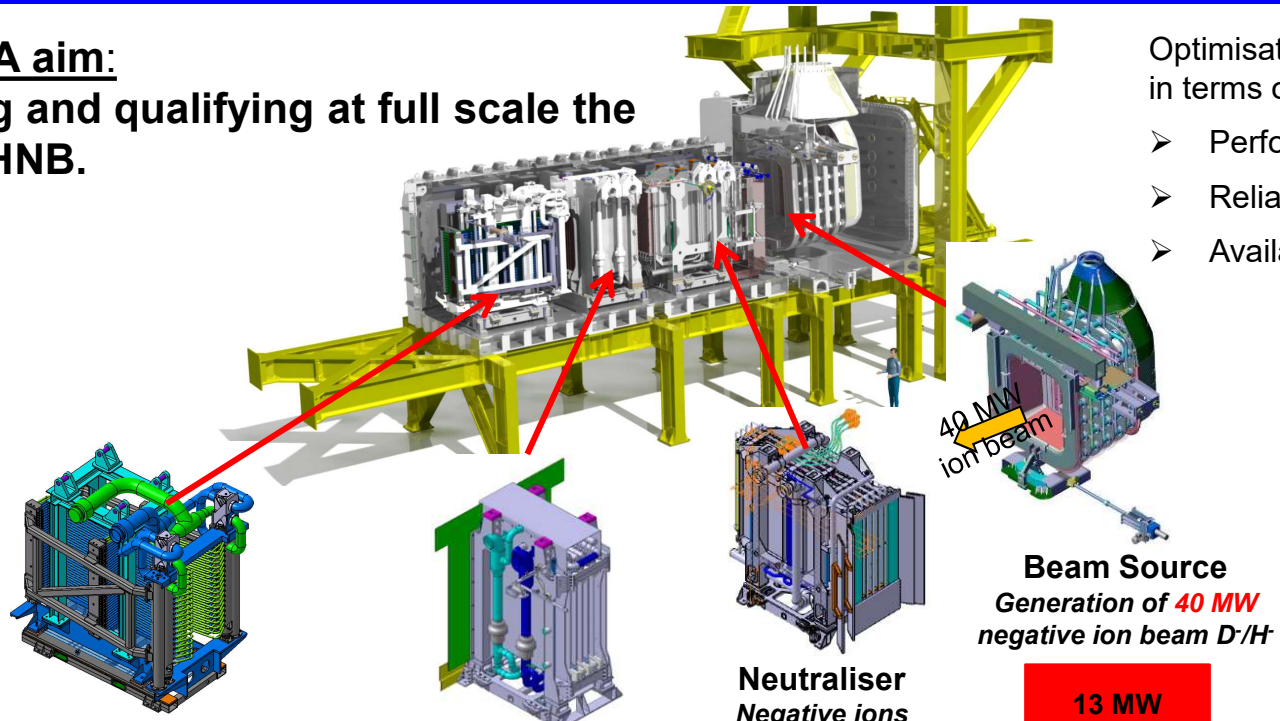
MITICA aim:
testing and qualifying at full scale the ITER HNB.



Calorimeter
Dumping of neutral particles D^0/H^0

19 MW

14 MW/m²

100 kg/s
p_{in}=2 MPa

ERID
Deflection and dumping of ions

17 MW

6 MW/m²

100 kg/s
p_{in}=2 MPa

Neutraliser
Negative ions neutralization

6 MW

5 MW/m²

80 kg/s
p_{in}=2 MPa

Beam Source
Generation of 40 MW negative ion beam D^-/H^-

13 MW

20 MW/m²

130 kg/s
p_{in}=2 MPa

Optimisation of neutral beam injector in terms of:

- Performances
- Reliability
- Availability

High beam losses

↓

High heat fluxes

High power densities

↓

Very high water flow rate and pressure

Required cycles:
beam-on/off $5.0 \cdot 10^4$
breakdowns $4.5 \cdot 10^5$

↓

Fatigue life assessment

MITICA Beam Source

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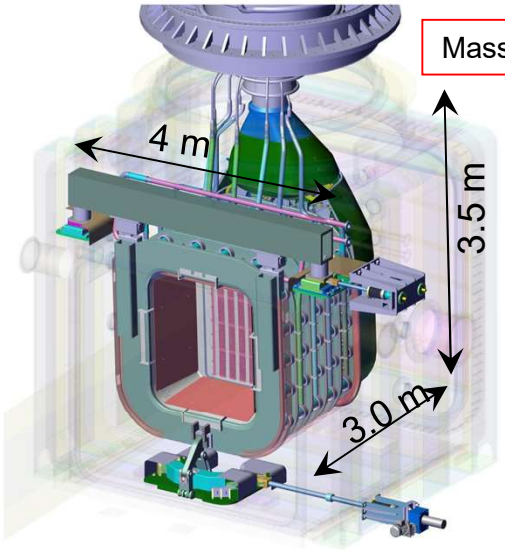
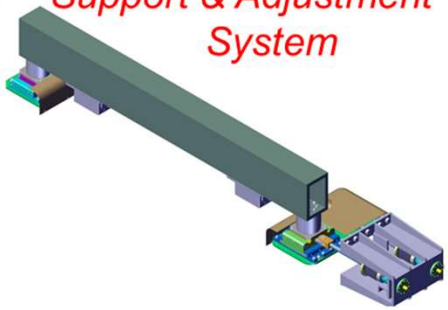
	Unit	H	D
Beam energy	keV	870	1000
Acceleration current	A	49	40
Maximum Beam Source pressure	Pa	0.3	0.3
Beamlet divergence	mrad	≤7	≤7
Beam on time	s	3600	3600
Co-extracted electron fraction (e^-/H^- or e^-/D^-)		<0.5	<1

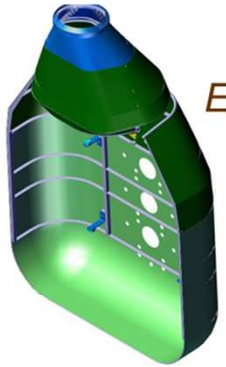


Mass :15 t BS + 5 t support/tilting

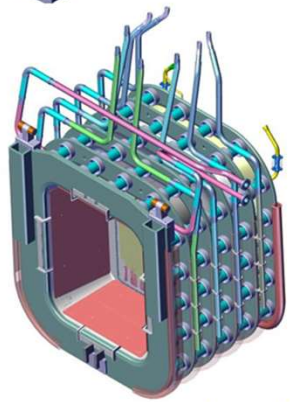
Support & Adjustment System

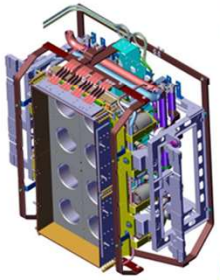


Top connections

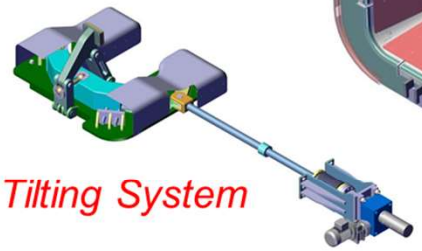


(Rear) Electrostatic shield



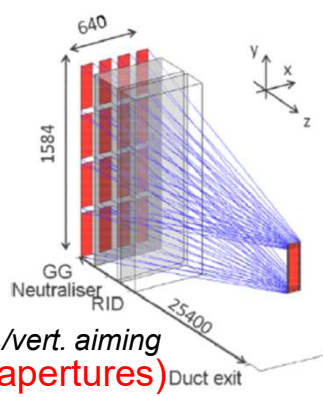


RF ion source

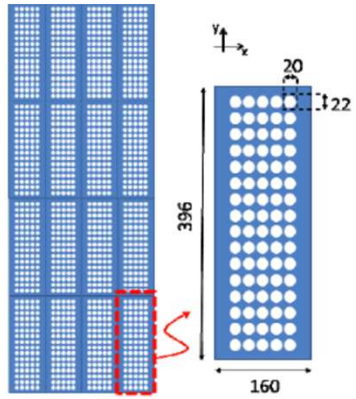


Tilting System

Accelerator / Extractor



Beam hor./vert. aiming

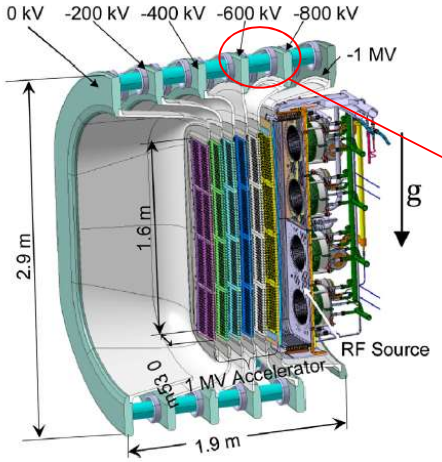


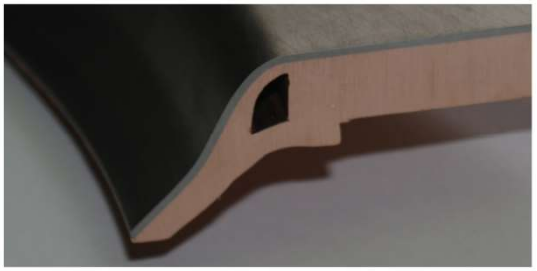
- 16x5 beamlets in each group x 16 groups = 1280 beamlets

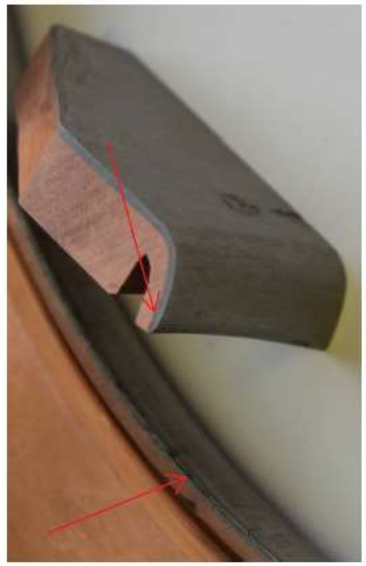
Main challenging requirements for grids manufacturing:

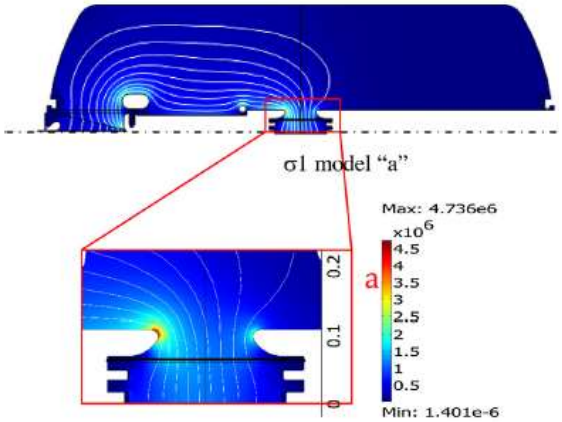
- Double curvature grids for beam aiming
- Extremely precise relative alignment (few tenths of mm among grids apertures)

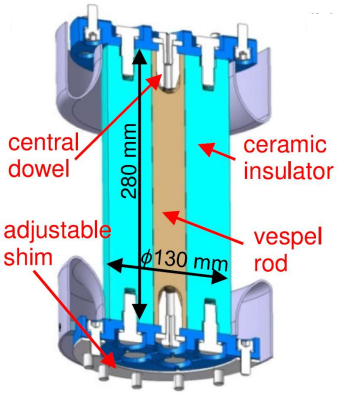
MITICA Beam Source











Ceramic insulators for MITICA accelerator: R&D for electrostatic and mechanical optimization

1 mm thick Mo coating as armour against positive back streaming ions

R&D for explosion bonding process

MITICA Neutraliser and electron dump (NED)

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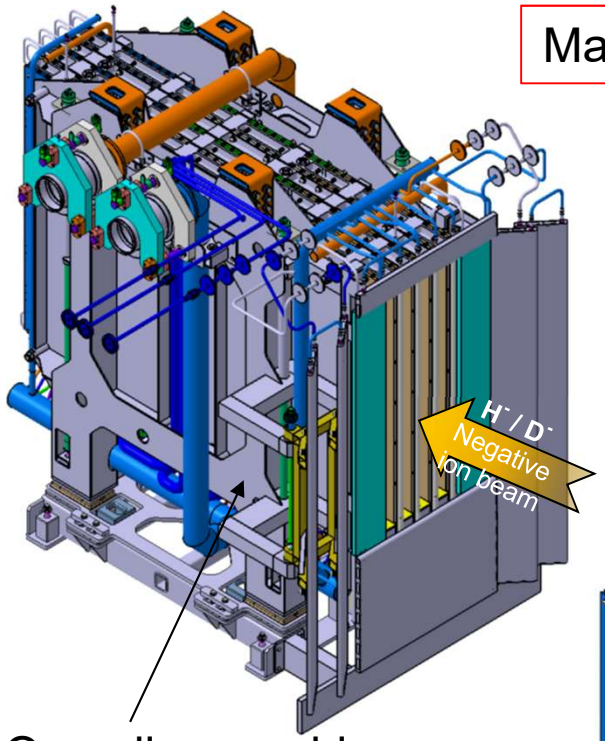
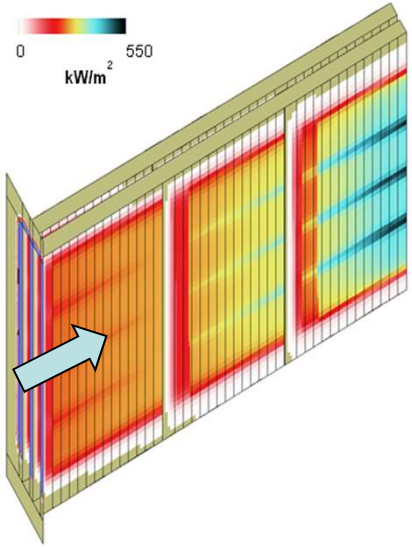
Max. power load 6 MW

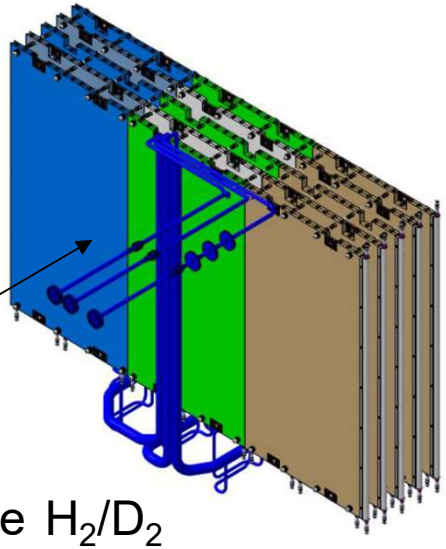


Overall assembly

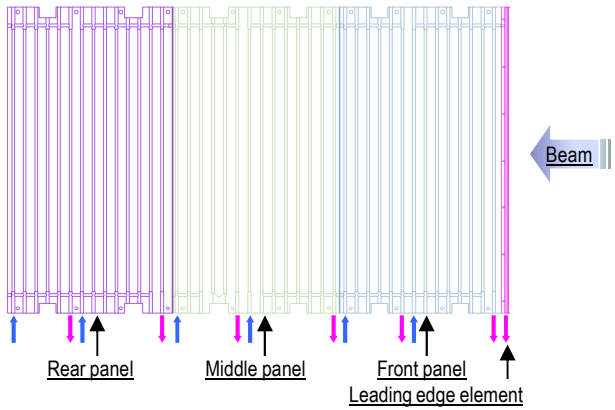
Heat loads due to:
- intercepted beam ions (halo and misalignment)
- post-accelerated electrons

Water flow rate 80 kg/s





Five OF Cu walls forming four channels where H_2/D_2 is injected for ion beam neutralization



Ø18 cooling channels are deep drilled on 34 mm thick OF Cu plates.

MITICA Neutraliser and electron dump (NED)

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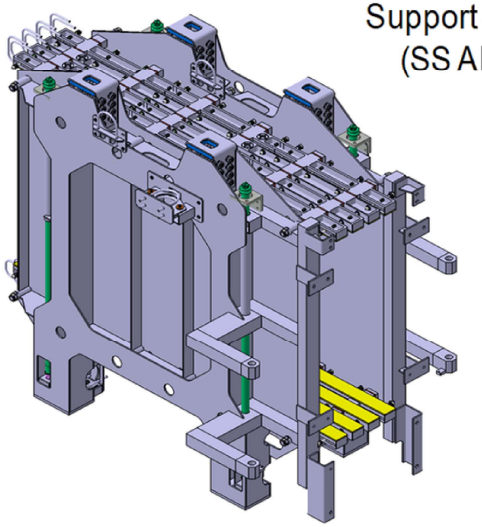
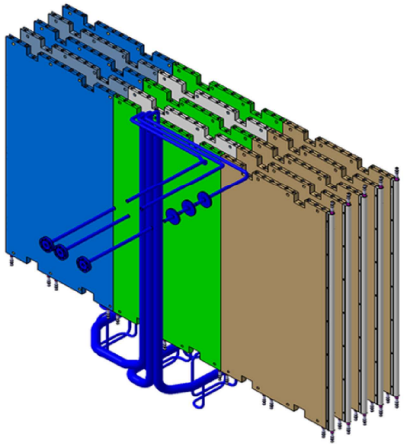
Support Structure
(SS AISI 304L)

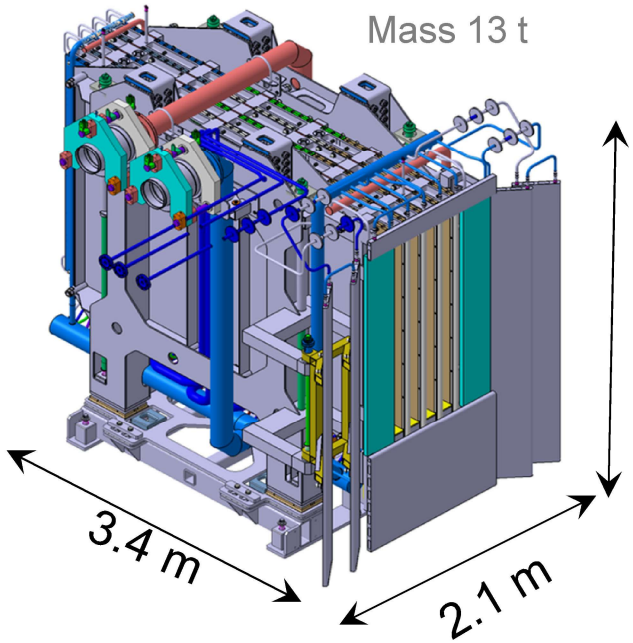


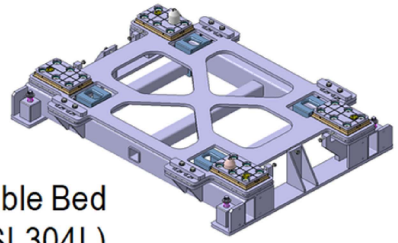
Panels with gas lines (OF copper
and SS TP 316L with junctions
TP 316L-Inconel 625®-OF copper)



Neutraliser assembly

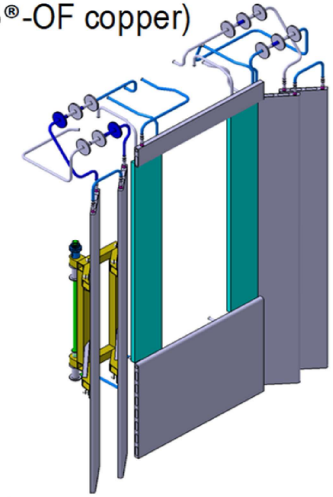
Mass 13 t

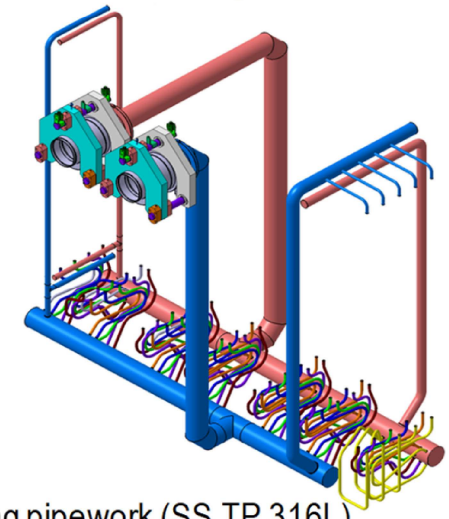




Adjustable Bed
(SS AISI 304L)

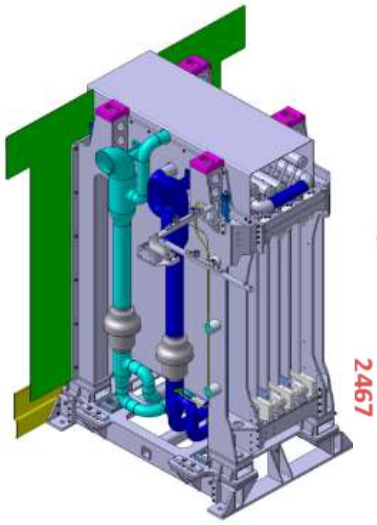
Electron Dump
(OF copper with junctions
TP 316L-Inconel 625®-OF copper)

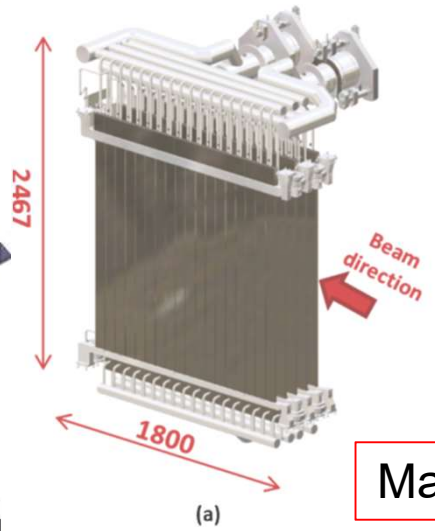




Cooling pipework (SS TP 316L)

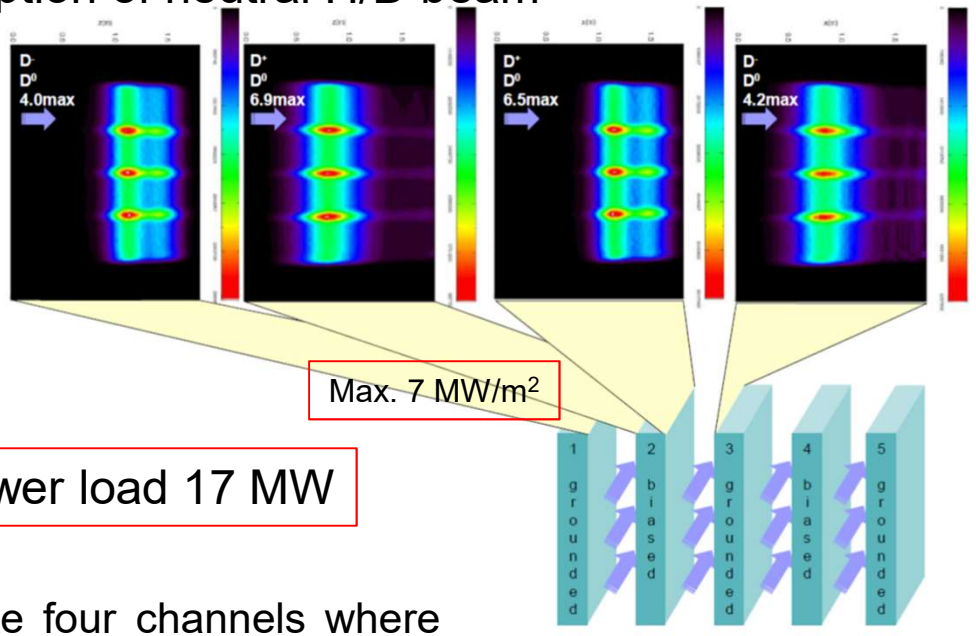
MITICA Electrostatic Residual Ion Dump (ERID)





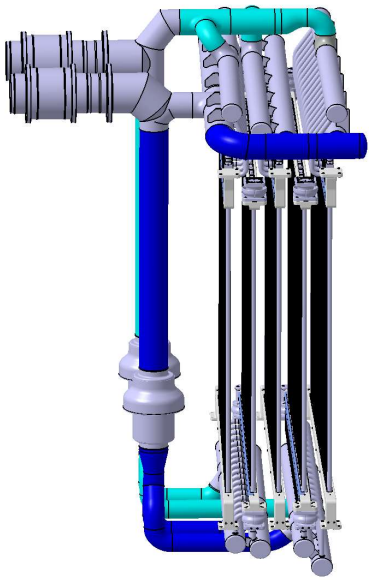
Heat loads onto ERID due to:

- Residual H^-/D^- and reionized H^+/D^+ fractions of the beam
- Direct interception of neutral H/D beam



Power densities for -15/-25 kV biasing
2 mrad hor. misalignment

Max. power load 17 MW



Five CuCrZr walls separate four channels where H^-/D^- and H^+/D^+ ions are deflected by electrostatic fields.
Two intermediate panels are biased at -15/-25 kV.

Water flow rate 100 kg/s

MITICA Electrostatic residual ion dump (ERID)

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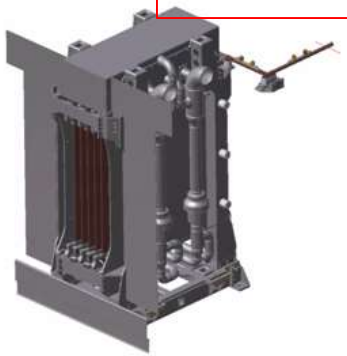
SUPPORT STRUCTURE

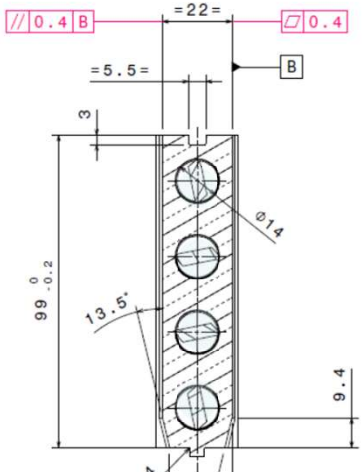
welding 304L

GAS BAFFLE

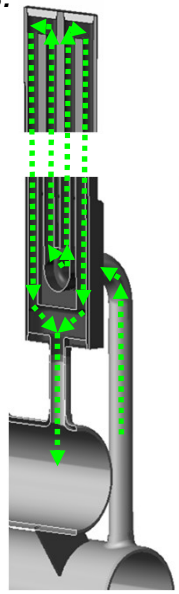
Mass 7.5 t



HHF PANELS

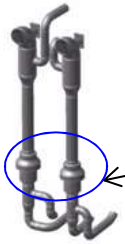


Enhanced heat exchange in sub-cooled boiling conditions at the channels walls of swirl tubes.



ELECTRICAL & INSTRUMENTATION

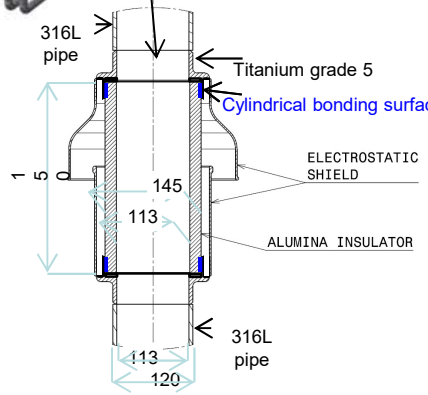
PIPEWORK



Horizontal cross section of CuCrZr panels elements with cooling channels and SS tape inside

Insulation breaks

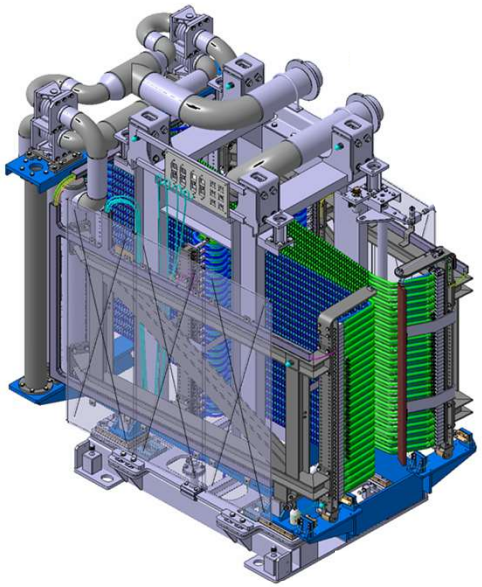
ADJUSTABLE BED

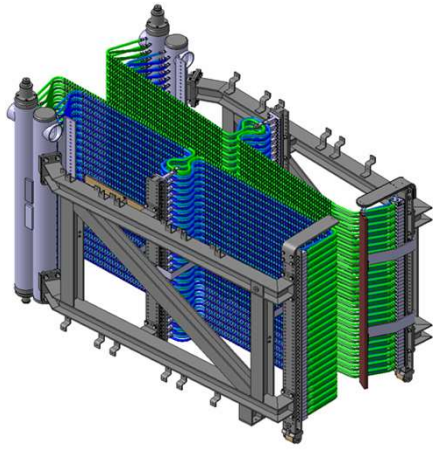


Technologies to be applied:

- welding CuCrZr
- welding 316L-CuCrZr
- deep drilling CuCrZr
- ceramic breaks manufacturing

MITICA Calorimeter





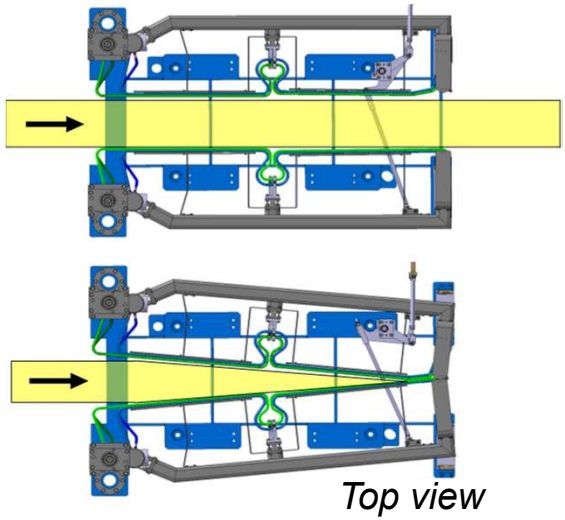
Beam dumping panels

Dimensions:
3.0m (L) x 2.1m (W) x 3.2m (H)
Mass: 6 t

Water flow rate 100 kg/s

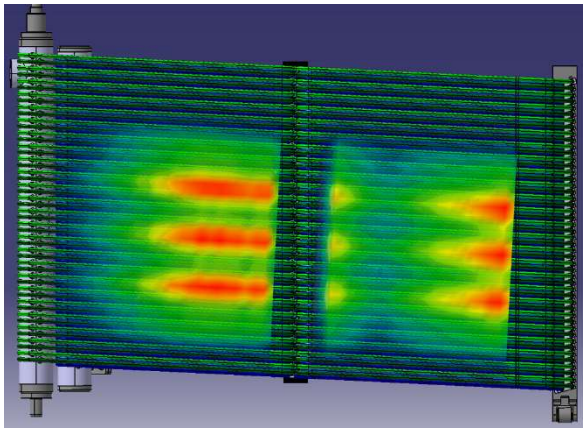
Max. power load 19 MW

Divergence	3 mrad	7mrad
Halo	0%	15%
Misalignment	2 mrad	2mrad
Peak power density	**14 MW/m²**	**7 MW/m²**



Top view

Open and closed configurations for ITER HNB operations



Power densities on the panels

MITICA Calorimeter

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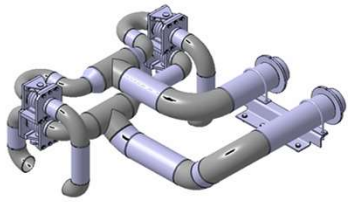
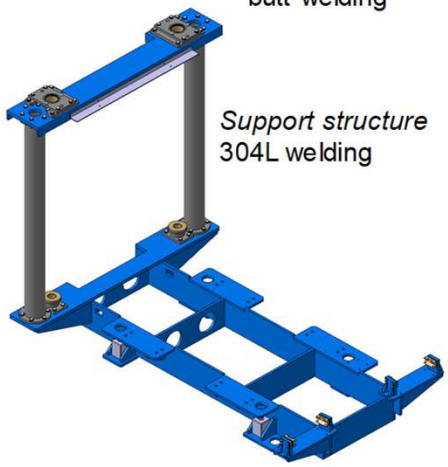


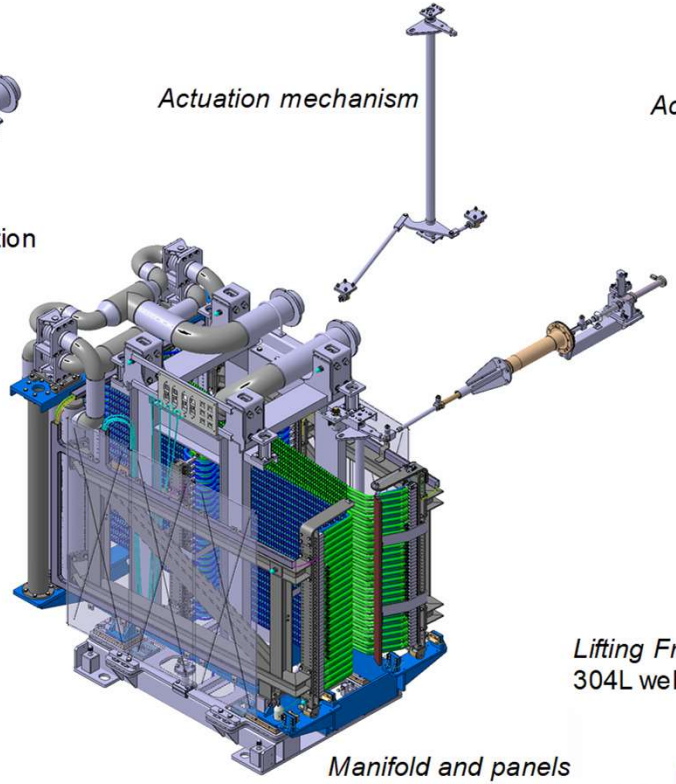
Pipework
316L full penetration
butt welding

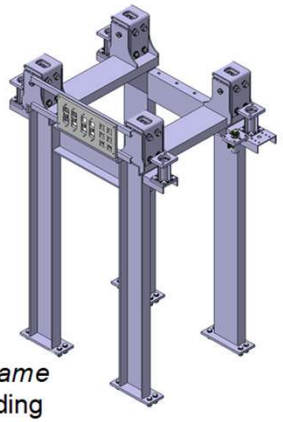
Actuation mechanism

Actuator

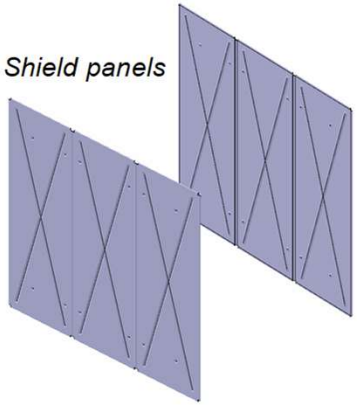


Support structure
304L welding



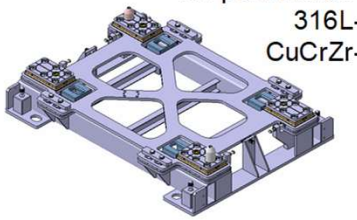


Lifting Frame
304L welding

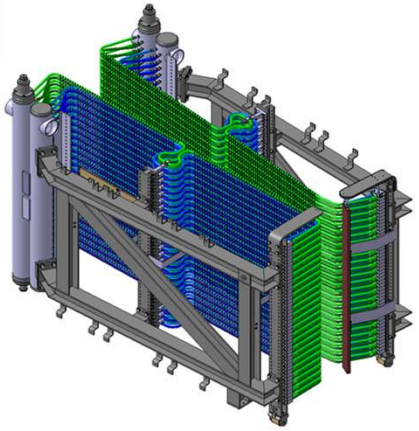


Shield panels

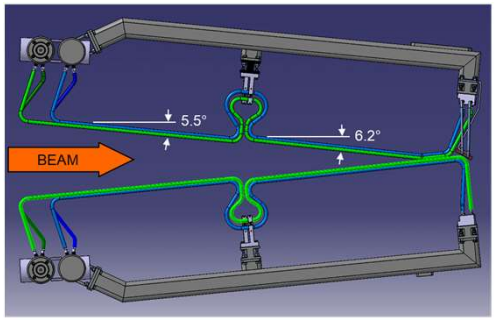
Manifold and panels
CuCrZr tube bending
stub extrusion at 316L manifolds
full penetration butt welding
316L-Inconel 625
CuCrZr-Inconel 625

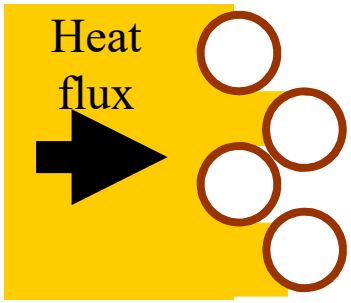


Adjustable Bed

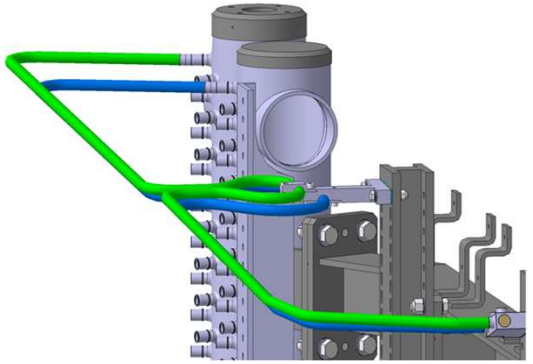


MITICA Calorimeter



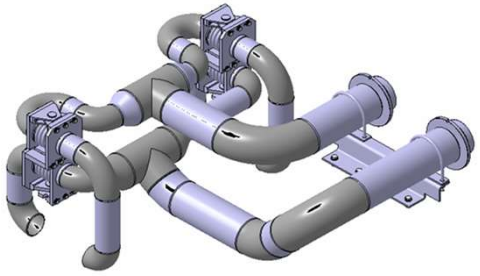


Ø 20 mm CuCrZr swirl tube elements with SS tape inside

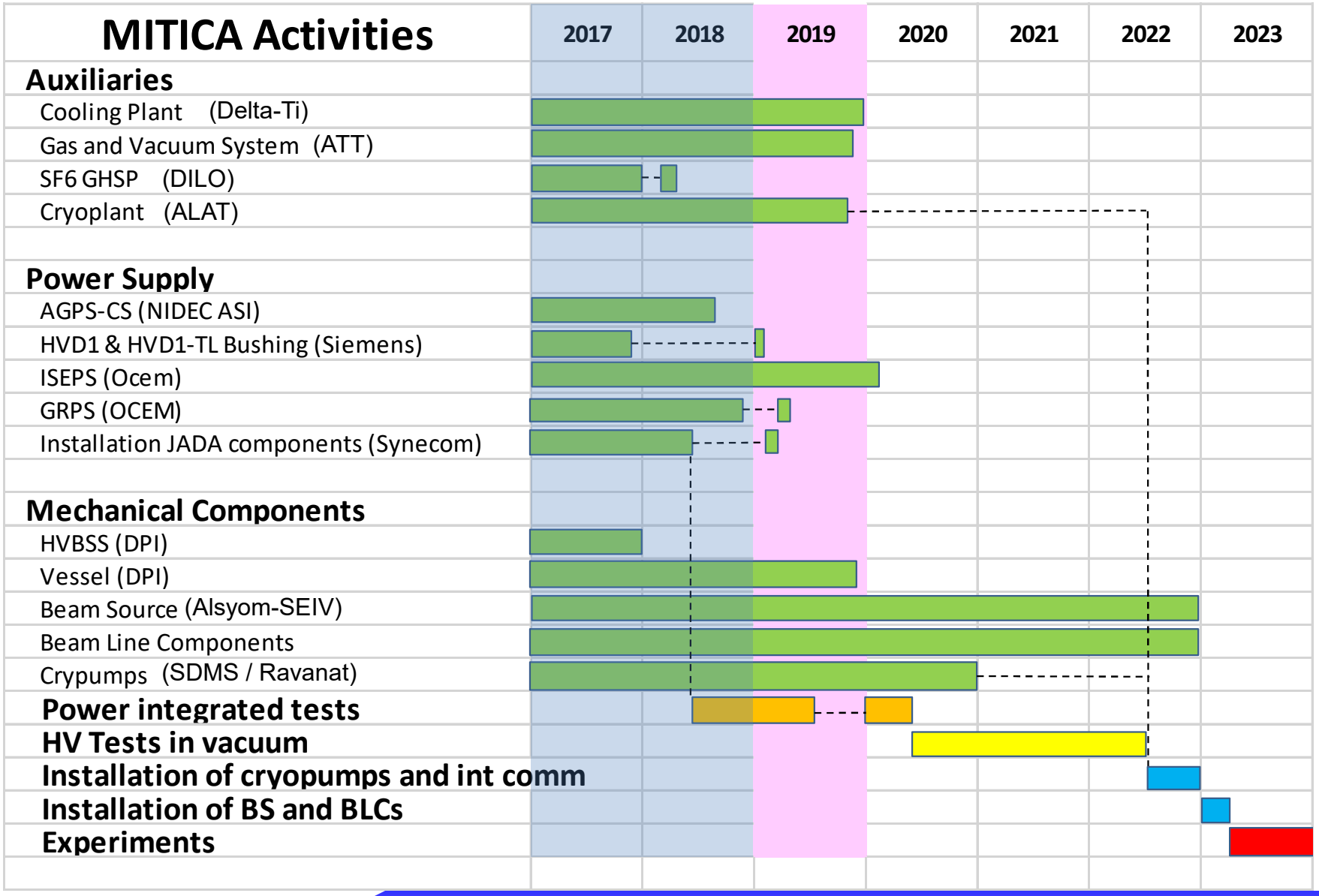


- Insertion of SS helicoidal tapes in CuCrZr tubes
- Precise bending of long CuCrZr tubes

- Manufacturing of AISI 316L hydraulic manifolds with extrusions
- Welding of SS/CuCrZr heterogeneous joints with Inconel® 625 adaptors
- Manufacturing of complex 316L pipeworks with large bellows and pivoting restraints



Present MITICA schedule



Main MITICA procurements

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On-going procurements

Component	Supplier	Status	Foreseen end of contract
Vacuum Vessel	DPI (I)	Manufacturing phase	2019
Vacuum and Gas Distribution	ATT (I)	Under Site Acceptance Tests	2019
Cooling Plant	DELTA-TI (I)	Under Site Acceptance Tests	2019
Cryogenic Plant	ALAT (F)	Under commissioning	Q1 2020
Cryogenic Pumps	SDMS – RAVANAT (F)	Manufacturing phase	end 2020
Beam Source	ALSYOM-SEIV (F)	Start of manufacturing	end 2022
Installation and integration works on-site	SYNECOM (I)	Works on-going	2020
Power Supply and Transmission Line	*Several on-going F4E and JADA contracts (see dedicated presentation by Vanni Toigo)*		

Next procurements

Component	Status
Beam Line Components	Stage 2 restricted CfT on 3rd June 2019 – Contract signature by end 2019 DPI-ATT (I), AVS Tecnalia (E), SIMIC (I)
BLCs Signal Feedthrough Box	CfT in autumn 2019
Cryopump Assembly Tool	CfT 2019-2020
Diagnostics	Many CfTs scheduled in 2019 and next years, organized with specific procurement orders

Contributors to Neutral Beam Test Facility

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iter
china eu india japan korea russia usa

FUSION FOR ENERGY

ITER JAPAN

ITER-India

QST

NIFS

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ENEA

INFN

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

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