L'impianto di prova NBTF
(Neutral Beam Test Facility)

nel progetto PRIMA
(Padova Research on ITER Megavolt Accelerator)

La Fusione Nucleare

Il progetto ITER, un contributo per l'energia di domani

27 novembre 2015

Mauro Dalla Palma

CONSORZIO RFX
Ricerca Formazione Innovazione

Consiglio Nazionale delle Ricerche
Istituto Gas Ionizzati

Presso: Udine, Polo Scientifico Rizzi, aula B

DIPARTIMENTO DI INGEGNERIA ELETTRICA, GESTIONALE E MECCANICA
Università degli Studi di Udine

Evento organizzato da:

A.P.I.
Associazione Politecnica Italiana

Tokamak

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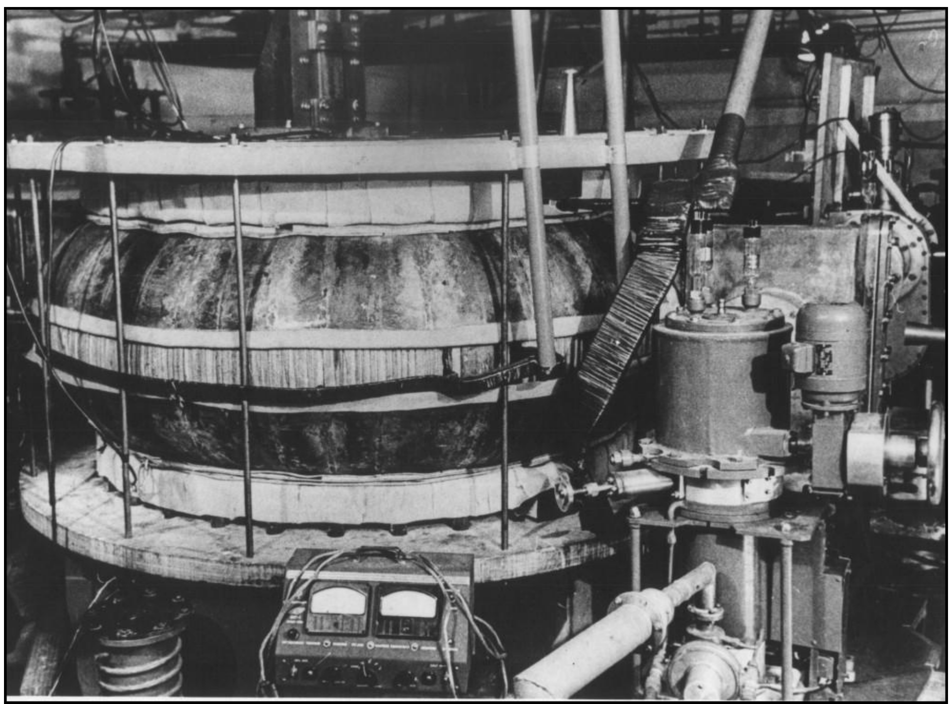
An article about the "Stability and Heating of Plasmas in Toroidal Chambers“ was submitted to the Second Atoms for Peace conference, held in Geneva in October 1958

The paper presented the results Soviet fusion scientists had achieved in an "experimental arrangement“, a small fusion machine which is generally considered as the first tokamak in history [www.iter.org/newsline/55/1194]

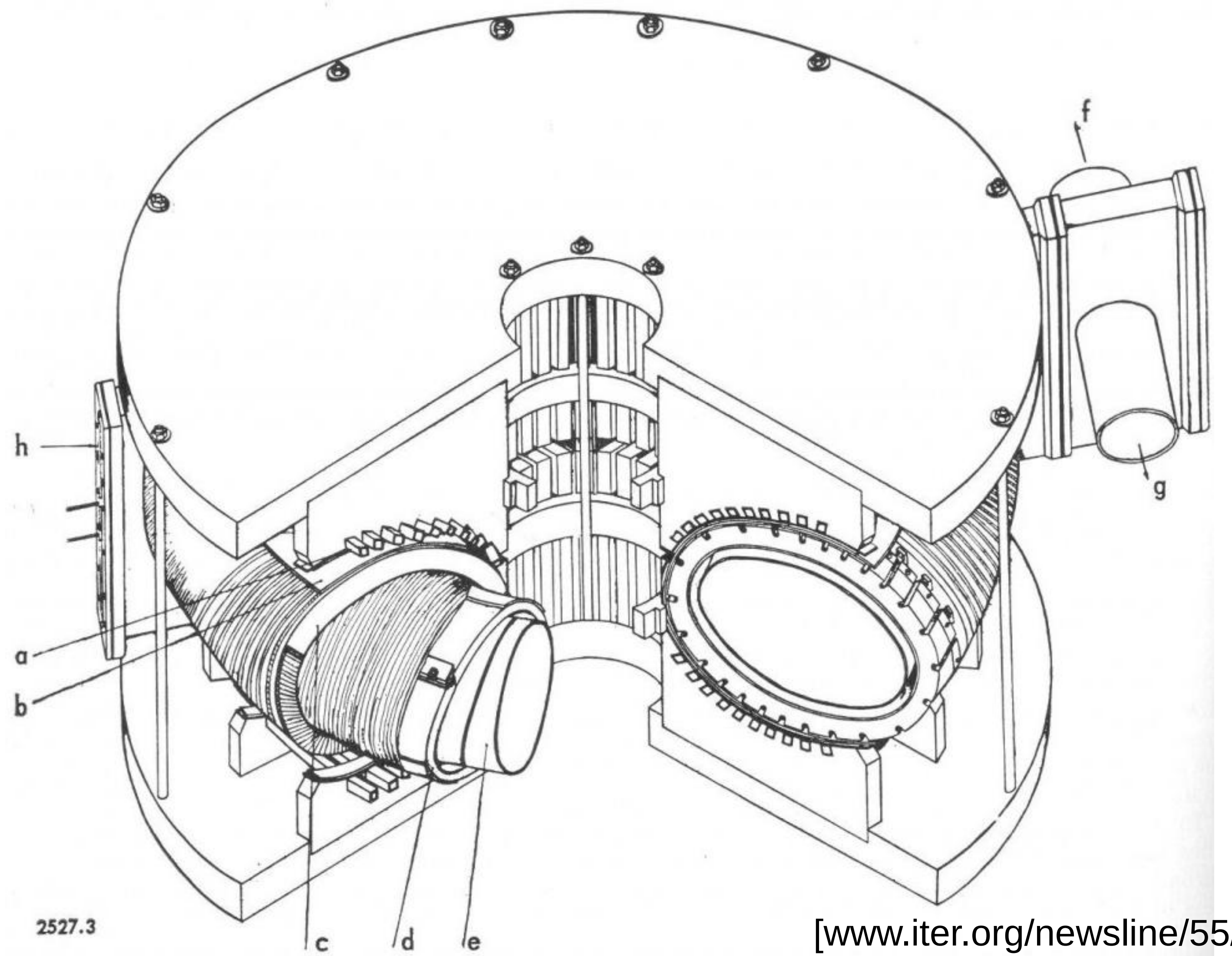
The work “tokamak” is derived from the Russian words

toroidalnaya **ka**mera and **ma**gnitnaya **k**atushka

meaning “toroidal chamber” and “magnetic coil”



Schematic of a tokamak experimental arrangement

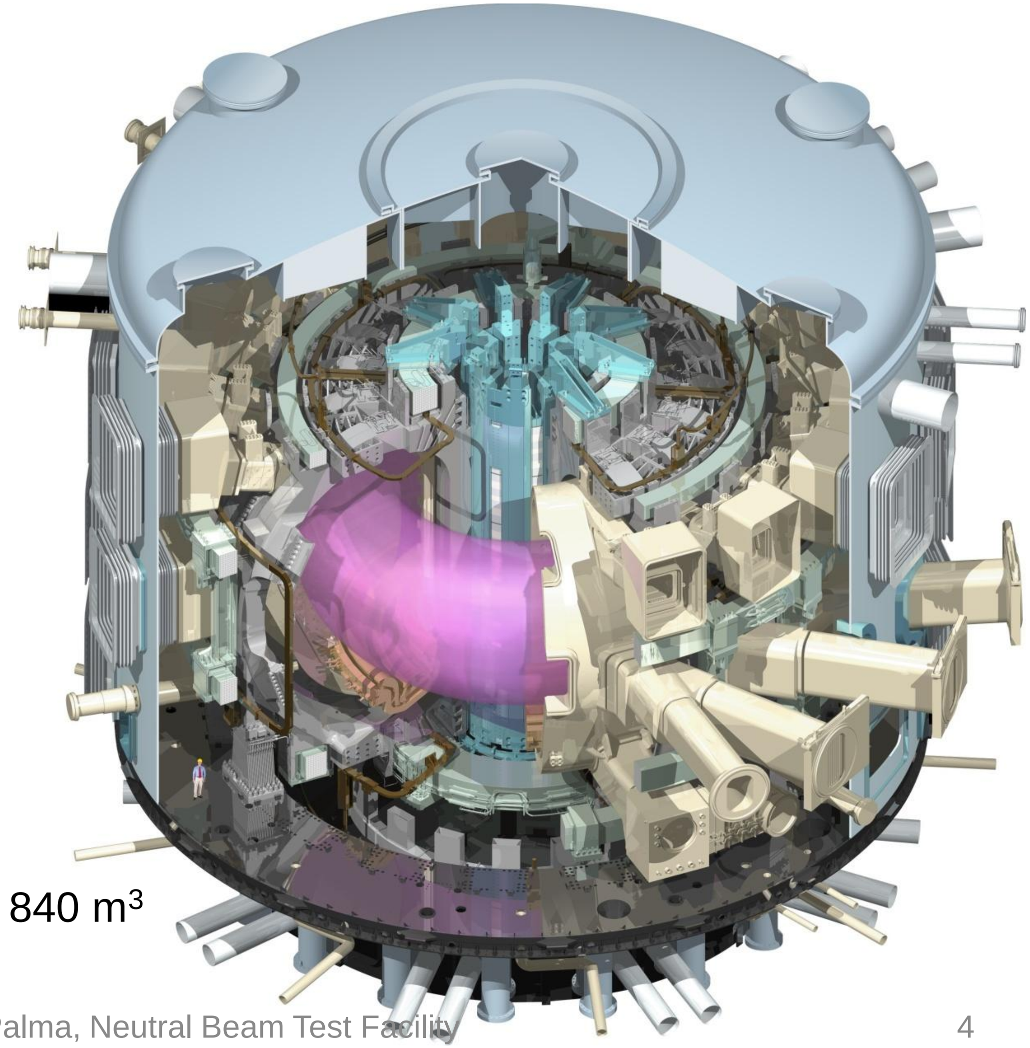


[www.iter.org/newsline/55/1194]

Figure 3. Schematic diagram of experimental arrangement; a, coil for excitation of a vortex electric field; b, copper shield for reduction of scattered fields; c, longitudinal magnetic field coil; d, copper stabilizing coil; e, thin-walled vacuum chamber made of a high-resistivity alloy; f and g, nipples for evacuation of the chamber and forechamber; h, observation window (for photography, ultra-high-frequency probing, spectral measurements, adjustment of measuring belts and magnetic probes)

L'esperimento internazionale ITER

Principale obiettivo dell'esperimento ITER: dimostrare la fattibilità tecnologica e scientifica della produzione di energia da fusione termonucleare



potenza termica da fusione: 500 MW
potenza immessa: 50 MW
volume di plasma nella camera da vuoto: 840 m^3
massa: 23000 tonnellate
data prevista per il primo plasma: 2021

ITER site

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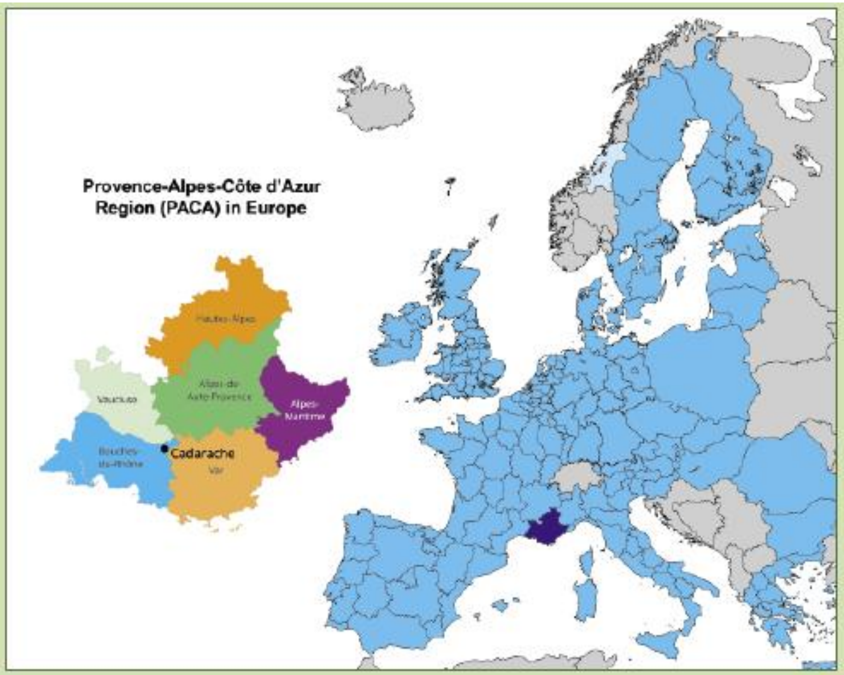
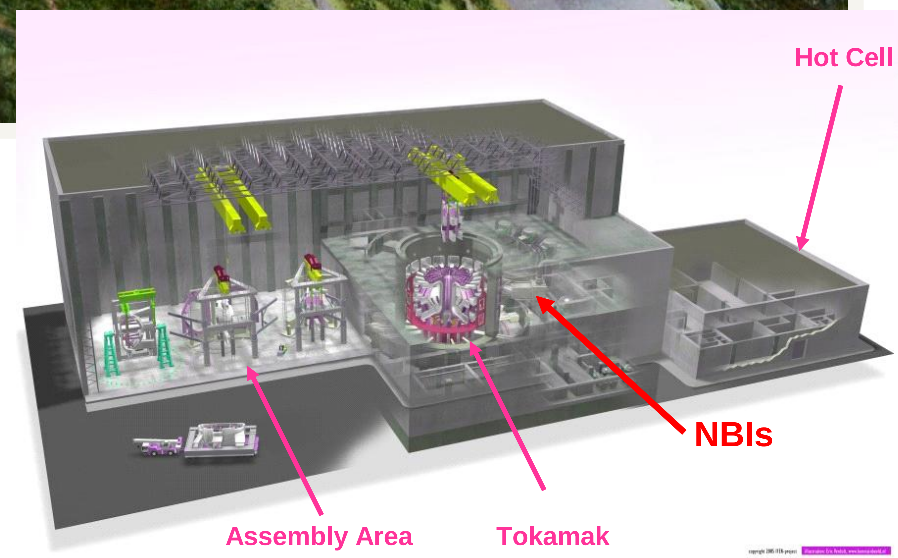




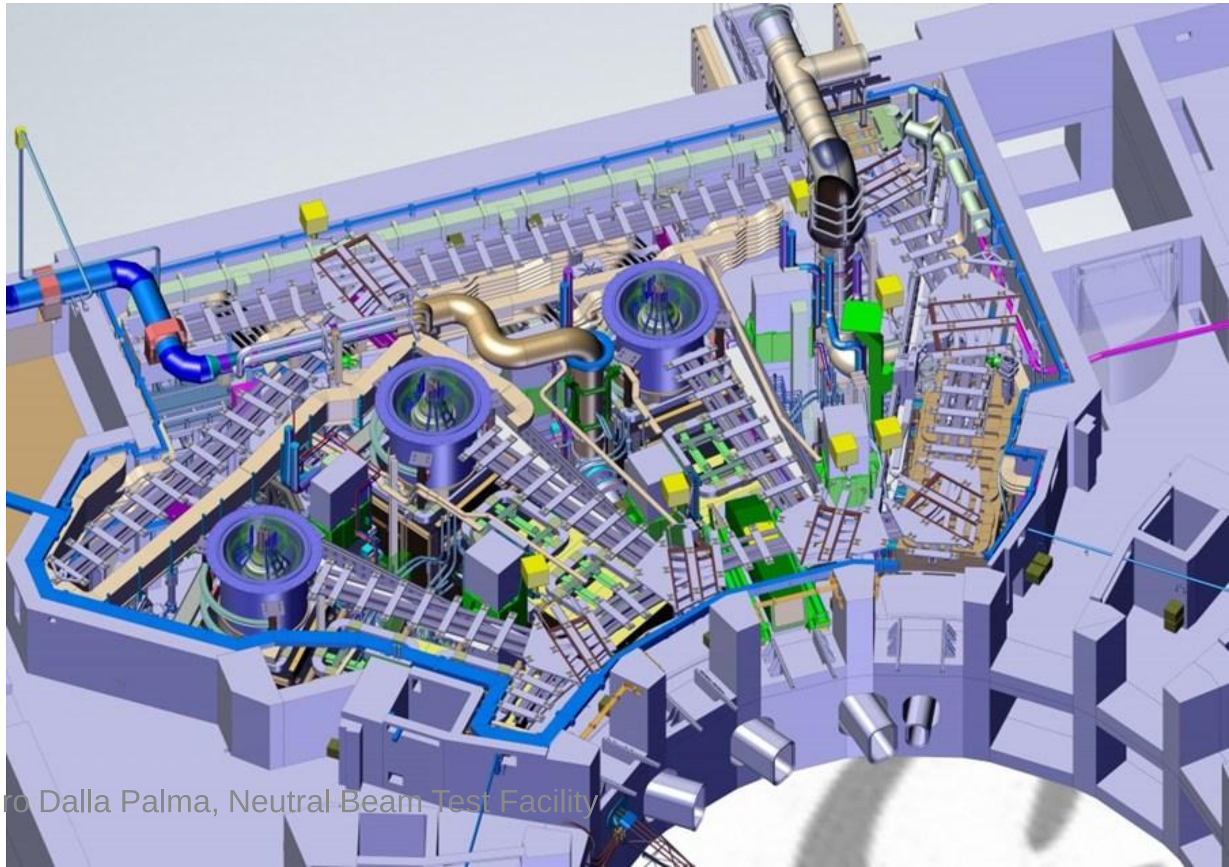
- Will cover an area of about 60 ha
- Large buildings up to 170 m long
- Large number of systems

Riscaldamento addizionale del plasma di ITER

Le particelle del plasma di ITER dovranno essere riscaldate fino a 150 M°C per realizzare la reazione di fusione: ${}_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1$ (3.5 + 14.1 MeV)

Metodi di riscaldamento del plasma interfacciati con il tokamak di ITER:

- iniezione di fasci di particelle neutre
- onde elettromagnetiche ad alta frequenza



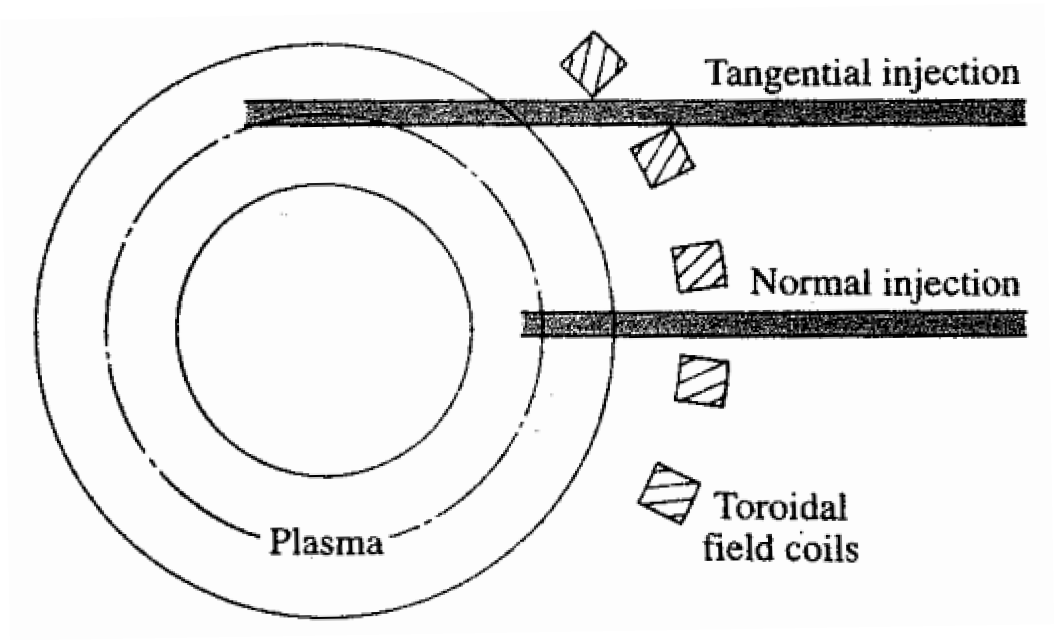
Complesso dei 3 iniettori di riscaldamento del plasma di ITER (3 x 17 MW)

Neutral beam injection - tangential injection

The NB absorption length is increased with tangential injection

However, the ability to do this is restricted by the difficulty of access between the toroidal field coils and the increased pumping requirement in the longer drift ducts

The selected injection angle is therefore a compromise between these constraints



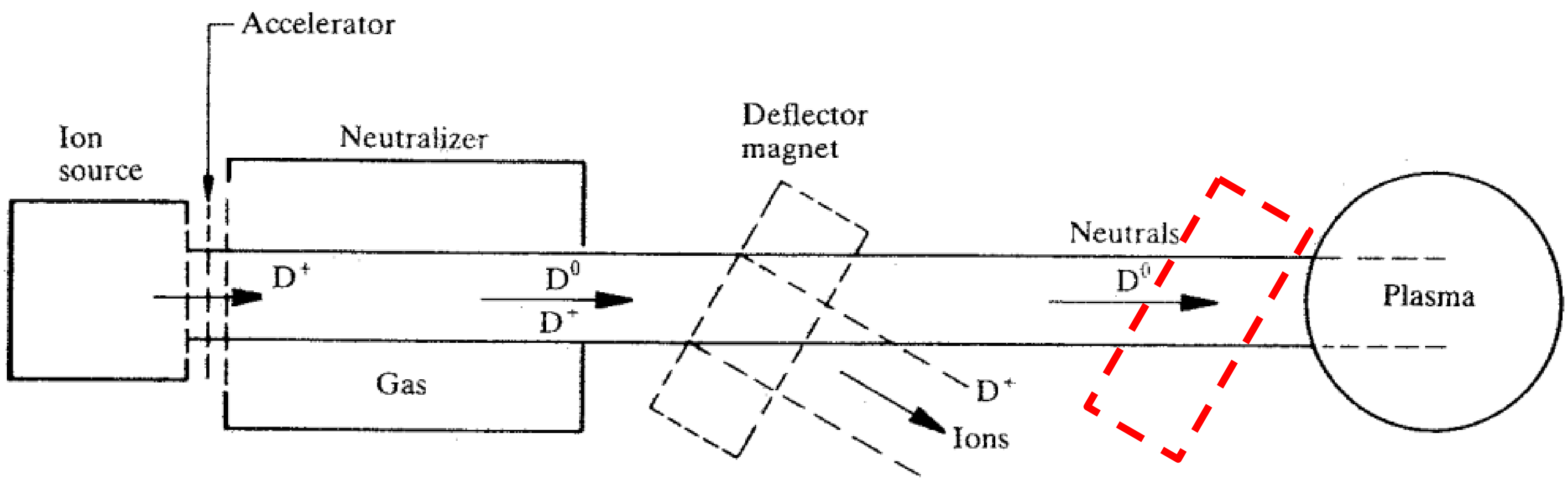
A disadvantage of NB systems is the large scale of the equipment

On the other hand they have the advantages that they can be developed and tested separately from the tokamak itself, and the heating profile can be predicted independently of the magnetic configuration

Neutral beam production - beamline

Ions must first be produced and accelerated to the required energy

They are then neutralized by charge exchange in a gas target, and the unwanted residual ions removed

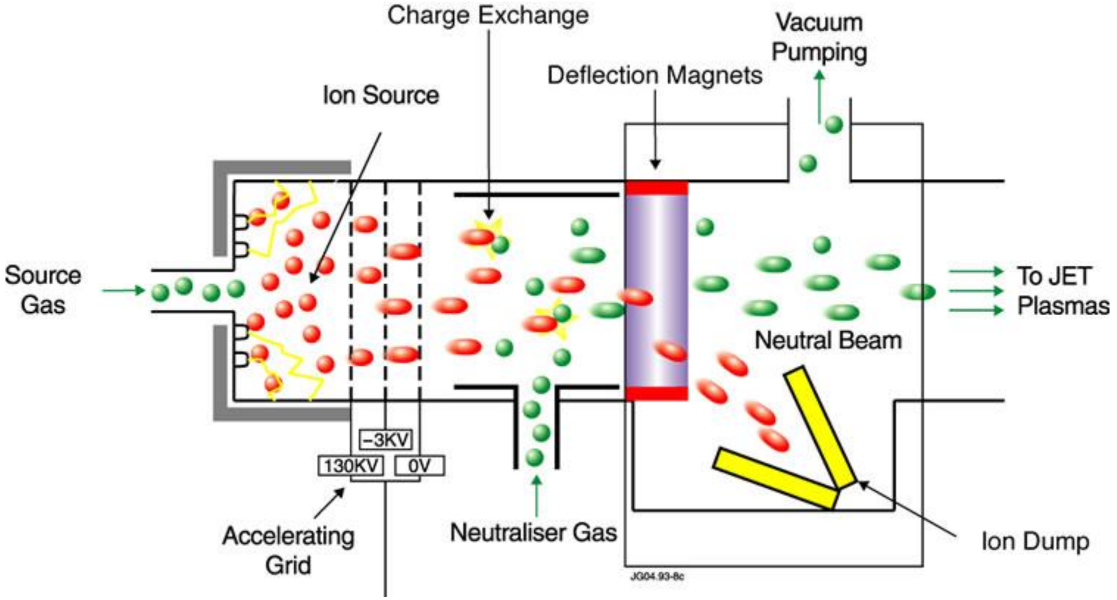


Arc/RF driven source

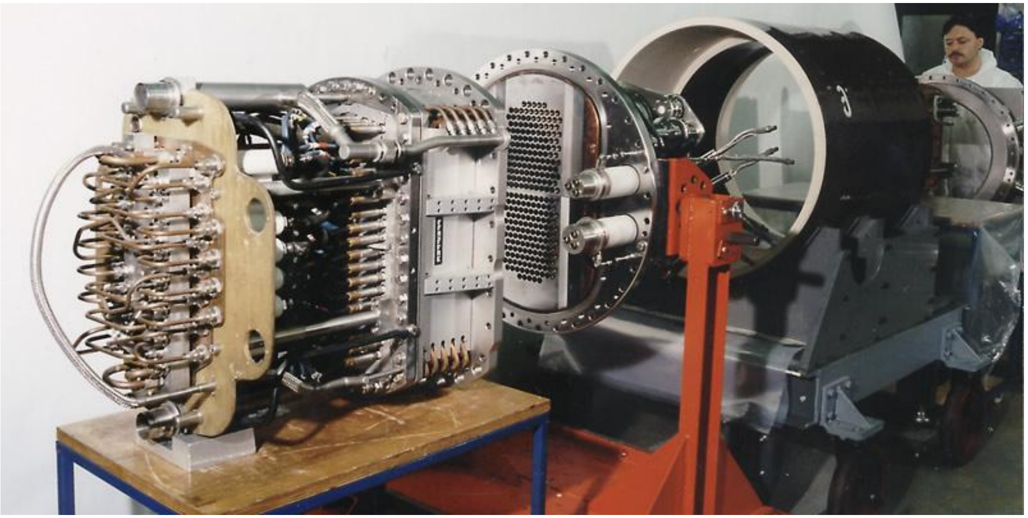
Residual ion dump

Calorimeter

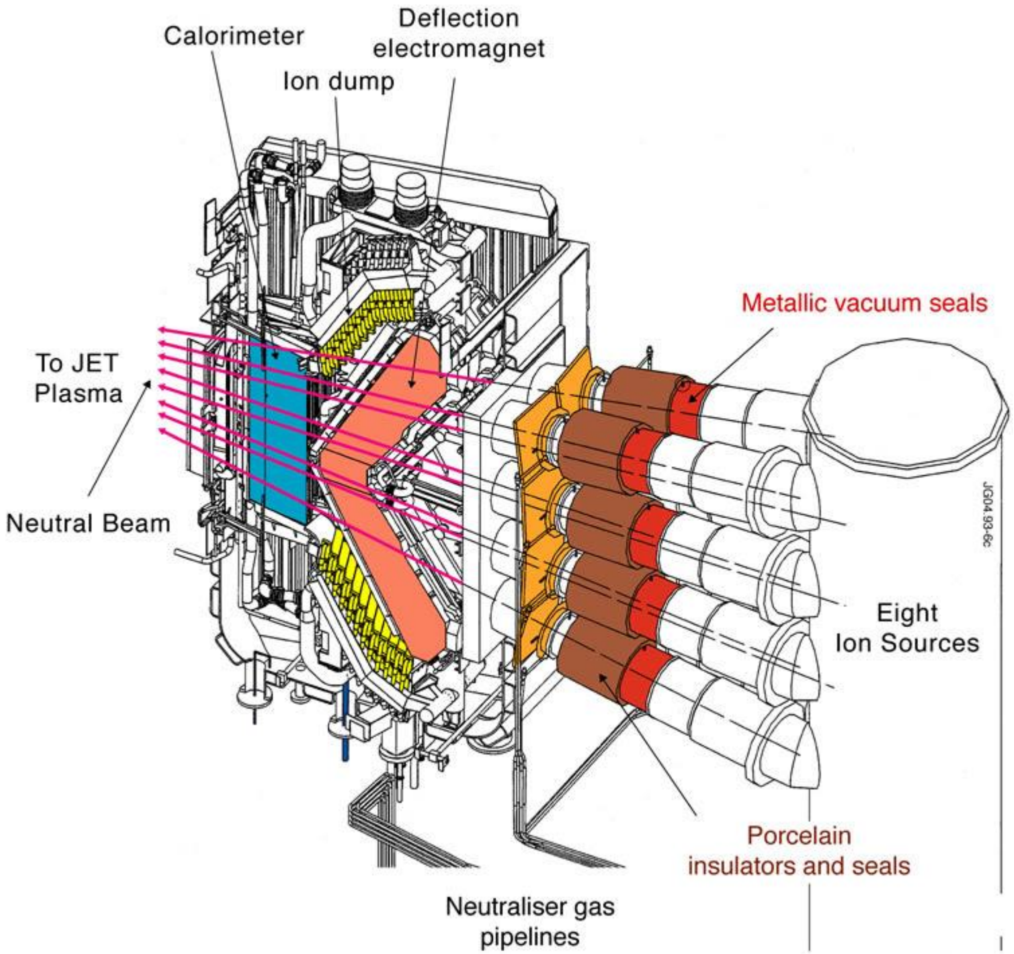
NBI: JET - 1



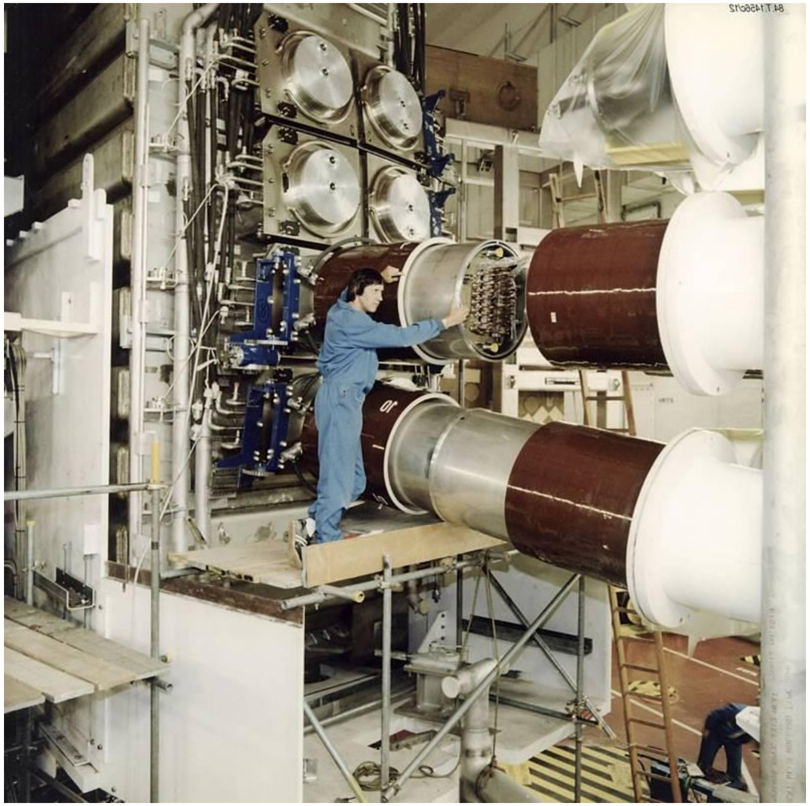
Charge Exchange
Vacuum Pumping
Deflection Magnets
Ion Source
Source Gas
To JET Plasmas
Neutral Beam
-3KV
130KV
0V
Accelerating Grid
Neutraliser Gas
Ion Dump
JG04.93-8c



NBI: JET - 2



Calorimeter
Deflection
electromagnet
Ion dump
Metallic vacuum seals
To JET
Plasma
Neutral Beam
Eight
Ion Sources
Porcelain
insulators and seals
Neutraliser gas
pipelines

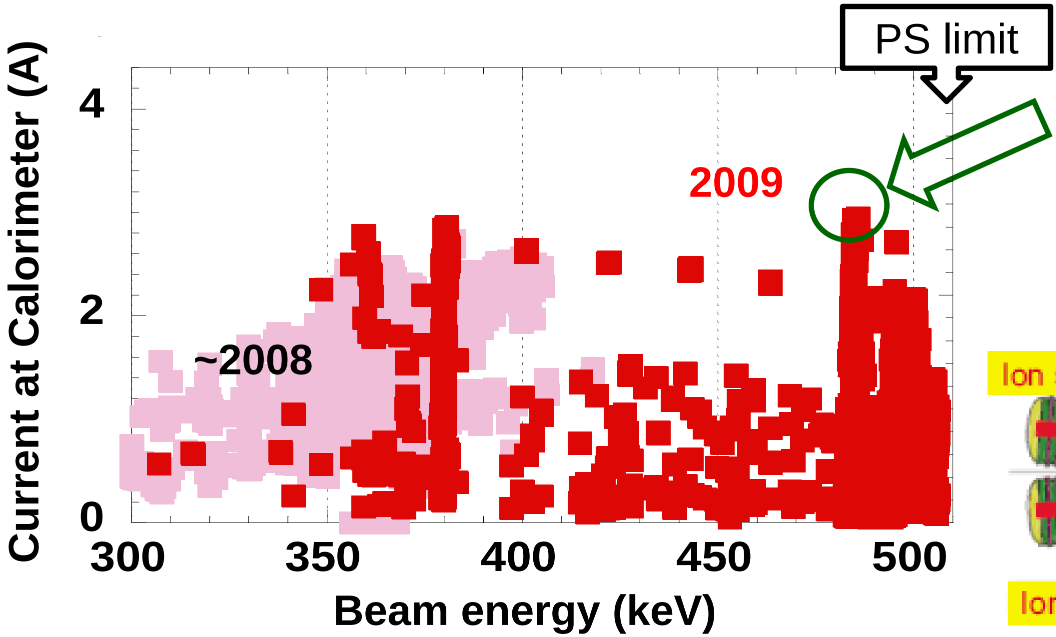


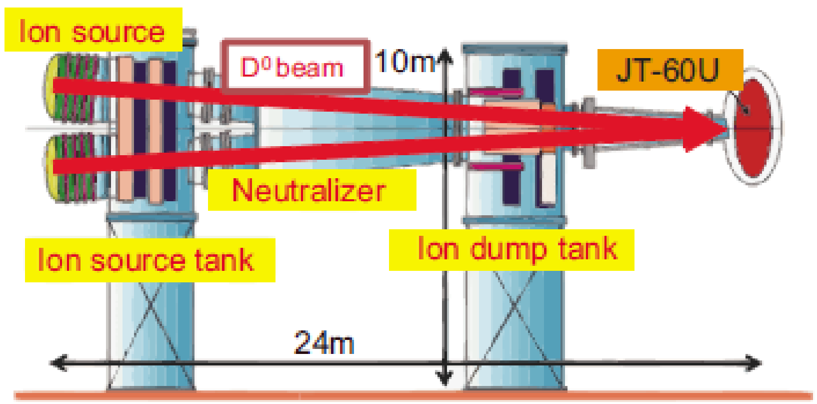
NBI: JT-60U

Nominal parameters of voltage holding with and w/o beam acceleration have been reached at JT-60U NNBI in 2009

Result obtained with increased gap length

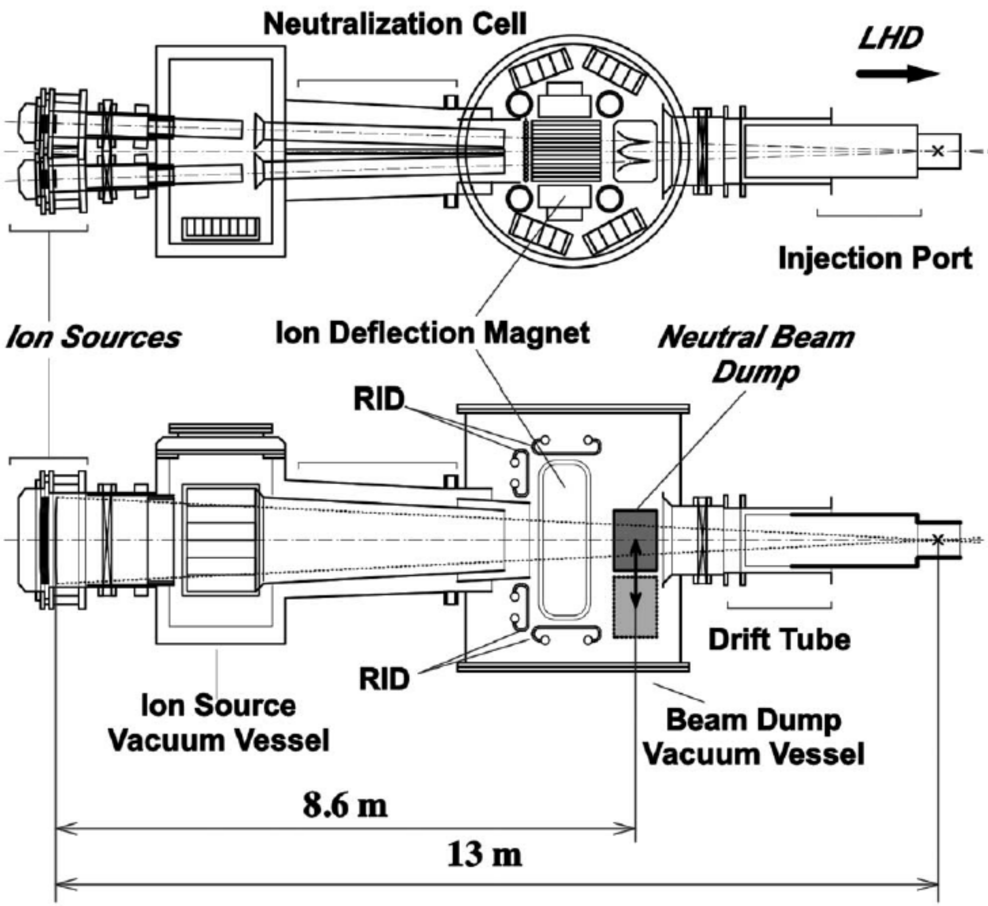
Summary of achievements in 2009	
Beam energy	Negative ion current
507keV	**~1A**
486keV	**2.8A (84A/m²)** **(4.4A = 130A/m²** **for 10MW** **for JT-60SA)**

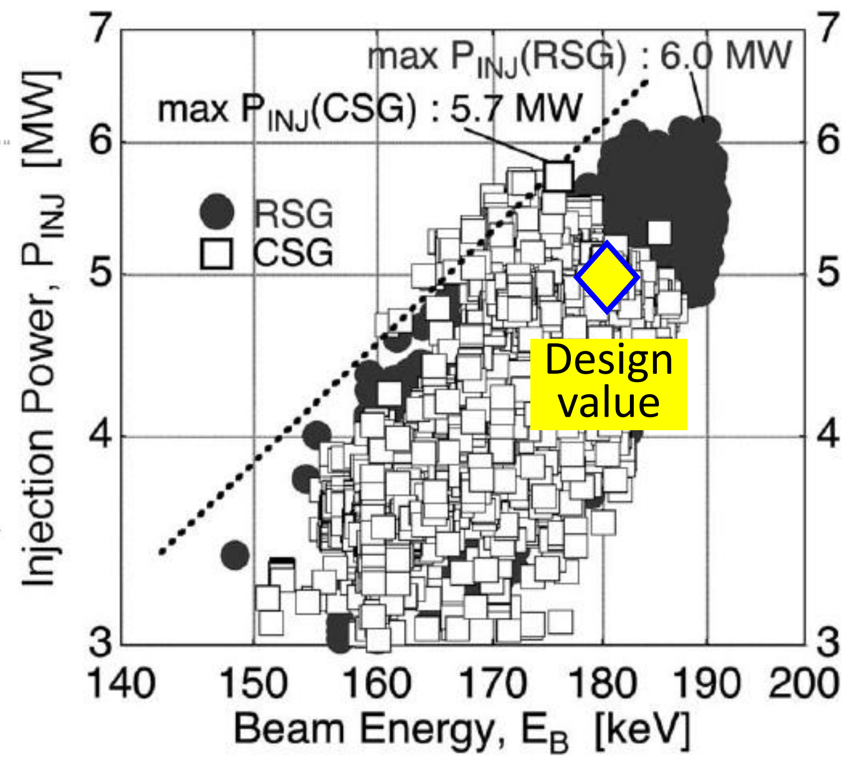




[A. Kojima, Rev. Scient. Instr. **81**, 2010]

NBI: LHD



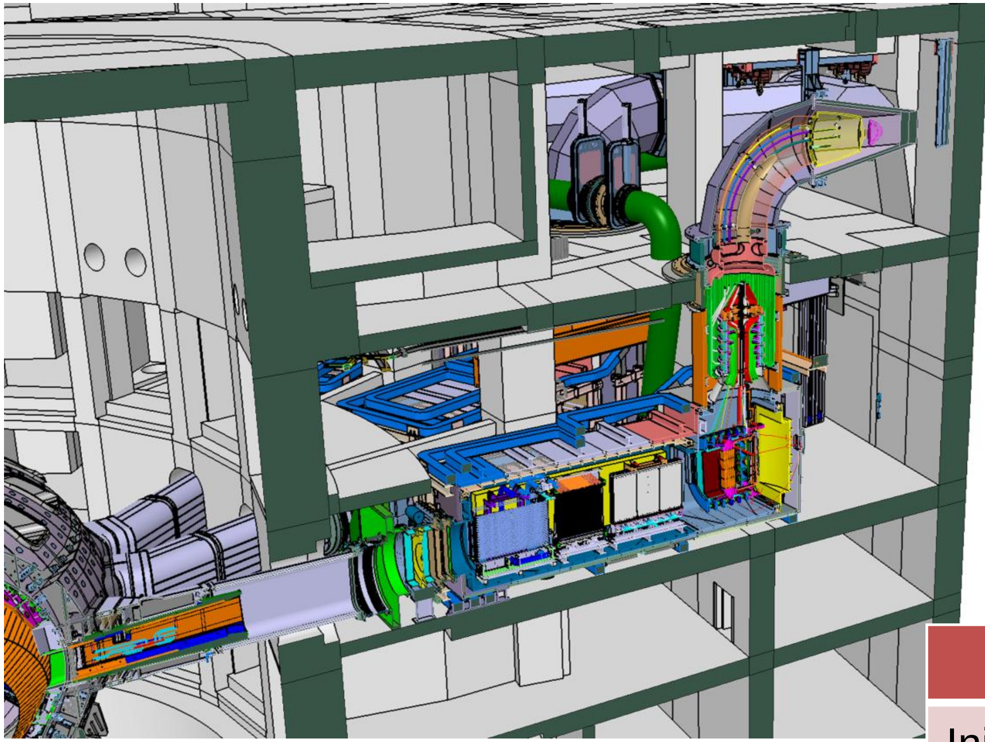


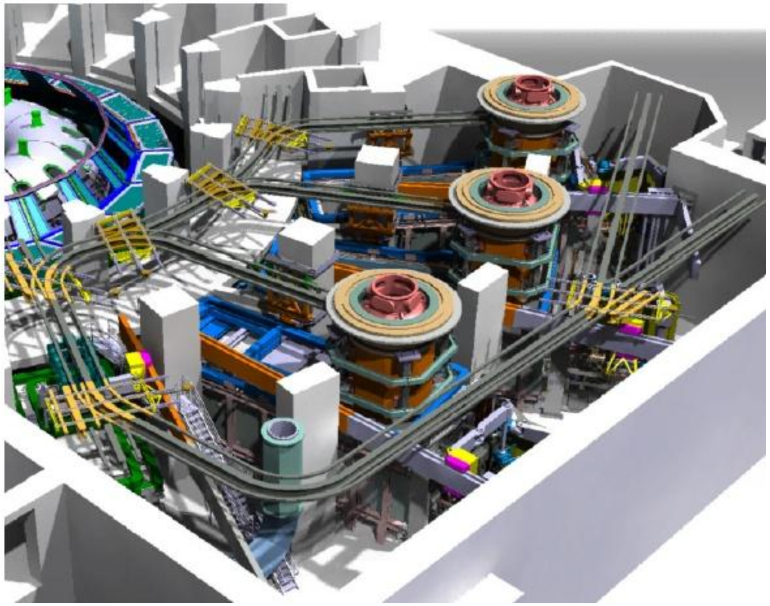
[K. Tsumori, Rev. Scient. Instr. **79**, 2008]

Parameters of heating and current drive neutral beam (HNB) injectors

Device	No. of injectors	Ion polarity	Energy [keV]	Total power [MW]	Pulse duration [s]
JET (Culham, UK)	2x8	positive	130	34	10
ASDEX-U (Garching, D)	2x4	positive	90	20	10
DIII-D (San Diego, USA)	2	positive	84	6	3
LHD (Toki, Japan)	3	**negative**	180	23	**100**
JT60-U (Naka, Japan)	12	positive	85	24	30
	1	**negative**	**500**	2	30
ITER (Cadarache, F)	2 (+1)	**negative**	**1000**	33	**3600**

Parameters of the ITER HNB injectors





ITER HNB	D-	H-
Injected particle power	16.5 MW	16.5 MW
Injected particle energy	1 MeV	850 keV
Input power	~60 MW	~60 MW
Acceleration voltage	1 MV	0.87 MV
Beam current	40 A	46 A

Gli iniettori di ITER e il prototipo MITICA

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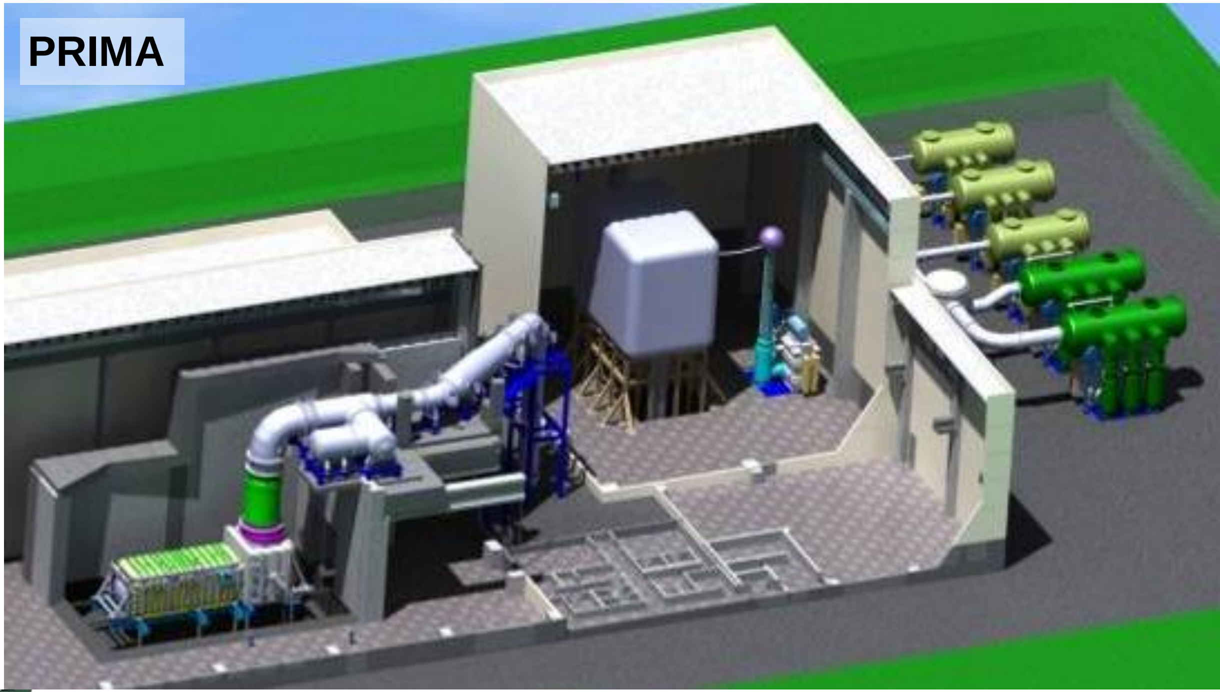
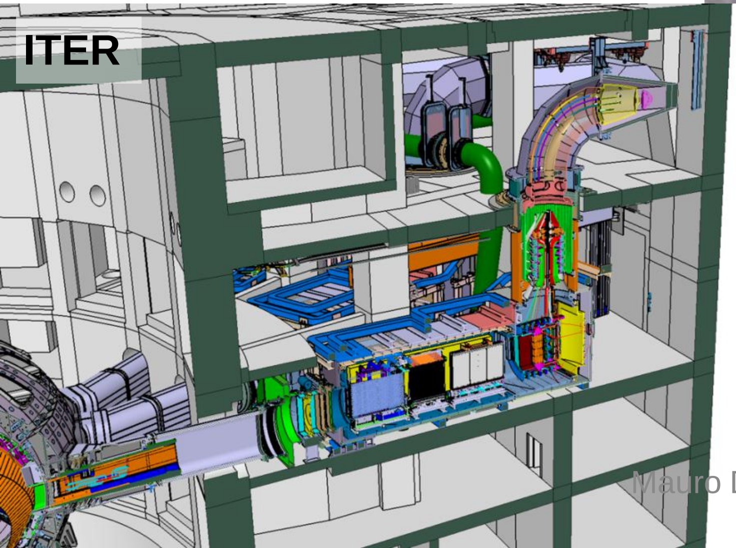


Le prestazioni richieste agli iniettori di ITER non sono mai state sperimentalmente raggiunte

Necessità di allestire un impianto di prova, Neutral Beam Test Facility (NBTF) nel progetto PRIMA (Padova Research on ITER Megavolt Accelerator) a Padova



Contributo principale:
Europa tramite l'Agenzia Fusion for Energy (F4E)
Consorzio RFX che ospita l'impianto di prova

Gli Enti nazionali giapponese ed indiano partecipano all'impresa PRIMA

Collaborano anche laboratori europei: IPP-Garching, KIT-Karlsruhe, CCFE-Culham, CEA-Cadarache

L’impegno italiano: Neutral Beam Test Facility

L’Italia si è impegnata a realizzare gli edifici e le infrastrutture di base:

- Il MIUR ha affidato la realizzazione degli edifici e delle infrastrutture a CNR e INFN
- Gli Enti a loro volta hanno assegnato al Consorzio RFX il compito di progettare e appaltare la realizzazione degli edifici di NBTF presso l’Area della Ricerca del CNR di Padova

ITER Organisation ha affidato al Consorzio RFX la progettazione dei componenti e delle apparecchiature scientifiche

SPIDER e MITICA

PRIMA comprende una sorgente di ioni negativi, SPIDER, e il prototipo degli iniettori di ITER, MITICA

Il complesso degli edifici di PRIMA si estende su una superficie totale di circa 15500 m^2 di cui 7400 m^2 al coperto realizzando un volume di 150000 m^3

Gli esperimenti sono contenuti ciascuno in uno schermo biologico di calcestruzzo con spessore di parete:

- 1,0 m per SPIDER (in alto)
- 1,8 m per MITICA (in basso)

Lavori nell'edificio che ospiterà gli impianti sperimentali, agosto 2014

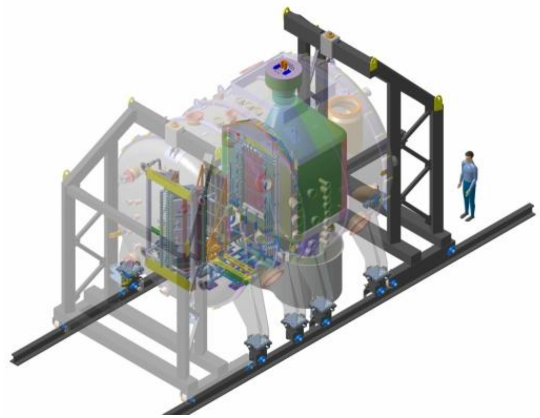
PRIMA, SPIDER, and MITICA: mission

PRIMA
Padova **R**esearch on **I**TER **M**egavolt **A**ccelerator

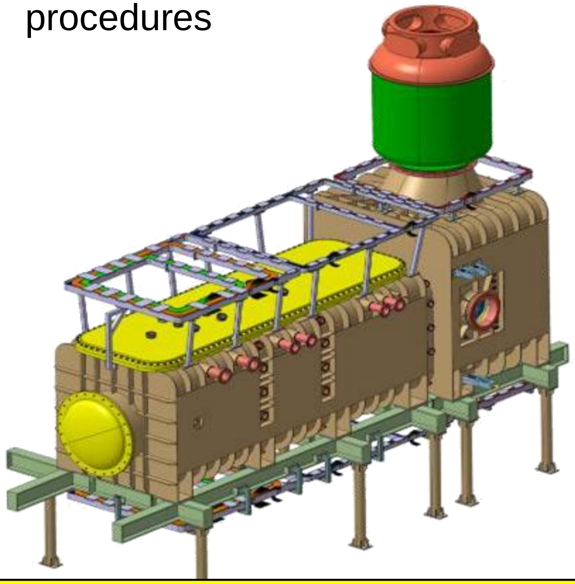
Mission of PRIMA, SPIDER, MITICA:

Realize and operate the ITER HNBs relevant prototypes to:

- Achieve the ITER HNBs ***nominal parameters***
- ***Optimise*** the NBI operation
- Maximize the ***reliability*** of the injectors
- ***Develop technologies*** for the injectors
- Test ***key remote handling*** tools and procedures



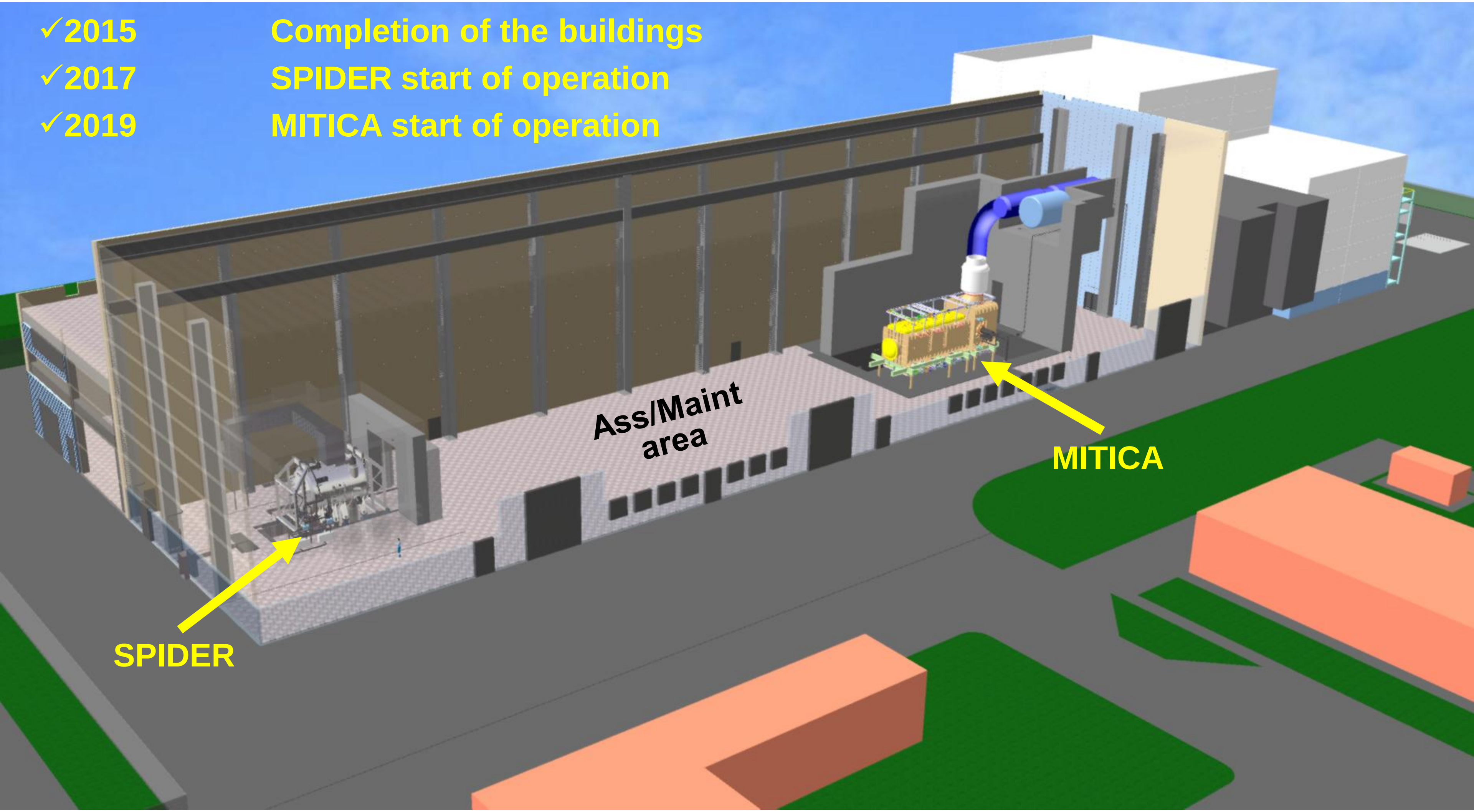
SPIDER
Source for **P**roduction of **I**on of **D**euterium **E**xtracted from **R**f plasma



MITICA
Megavolt **IT**ER **I**njector & **C**oncept **A**dvancement

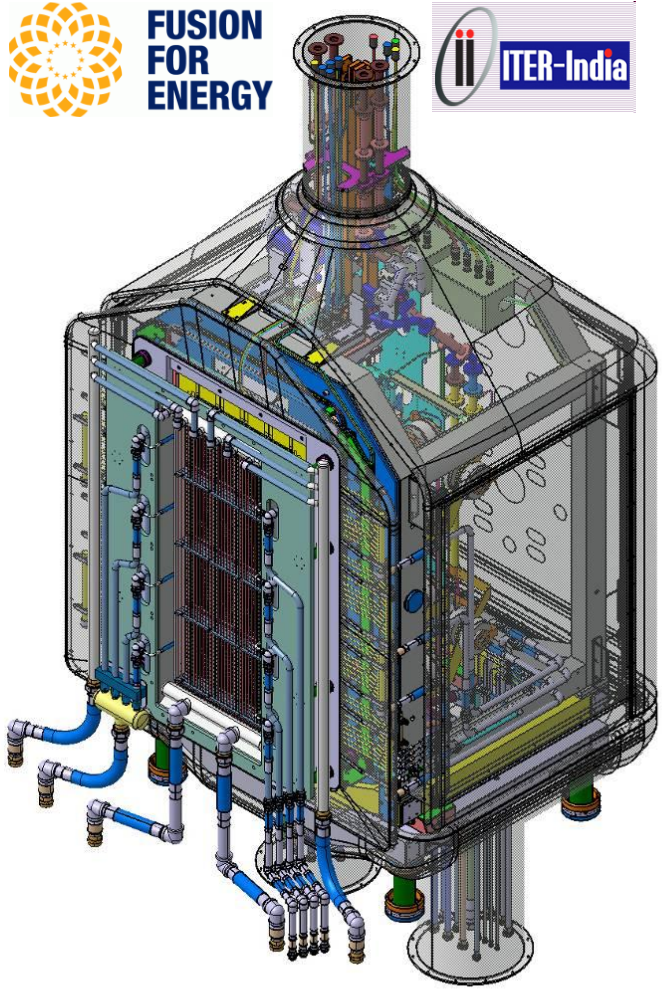
PRIMA: layout of SPIDER and MITICA

- ✓2015 Completion of the buildings
- ✓2017 SPIDER start of operation
- ✓2019 MITICA start of operation



SPIDER: HNB and DNB full size ion source

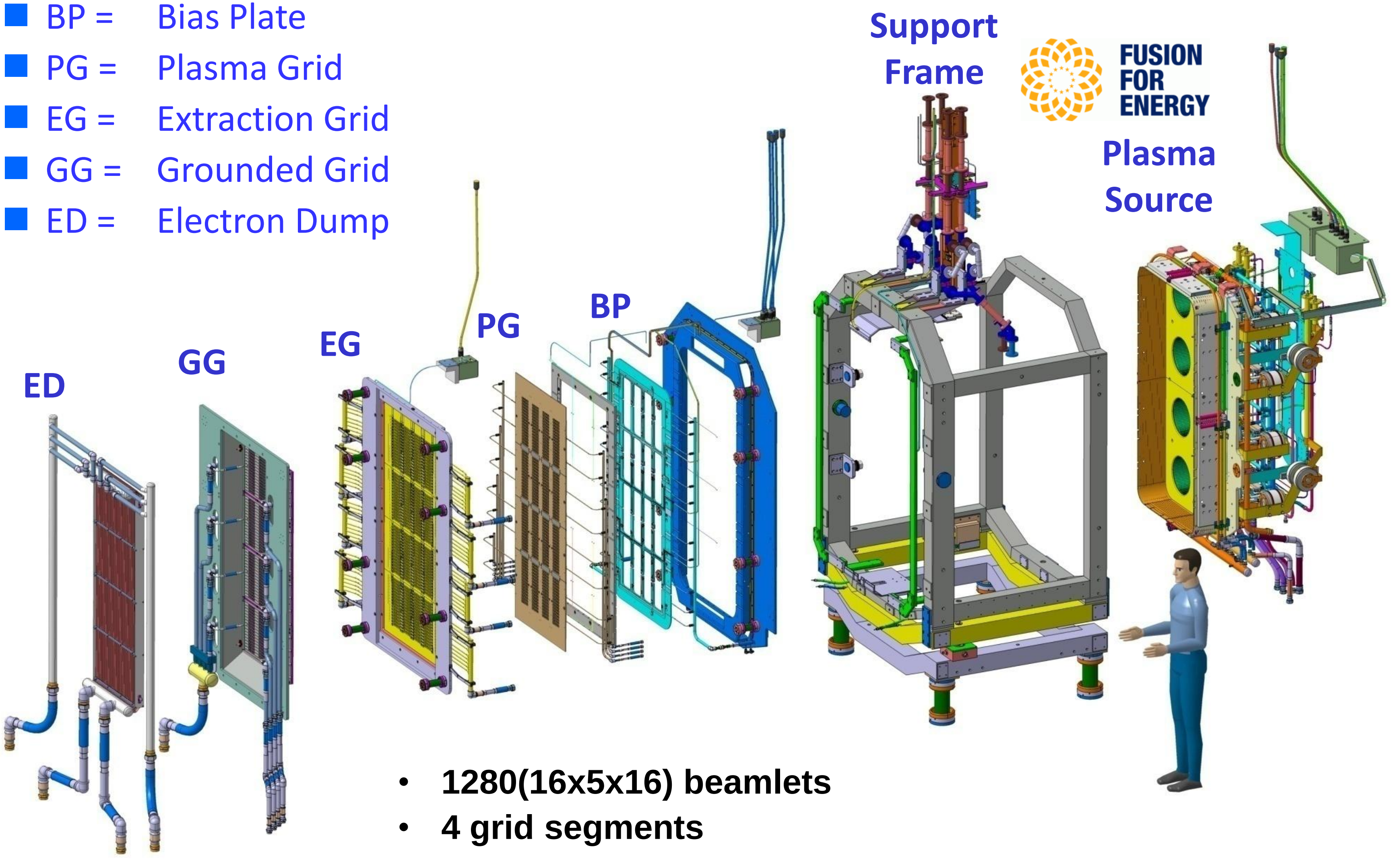
- Mission of SPIDER:
  - Develop the plasma source to guarantee on a large extraction surface of 1.52x0.56 m^2:
    - Necessary current density
    - At the lowest pressure
    - With the required uniformity
    - With the lowest percentage of co-extracted electrons



	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**	**>350**	**>290**
Beam on time	**s**	**3600**	**3600**
Co-extracted electron fraction (e^-/H^- or e^-/D^-)		**<0.5**	**<1**

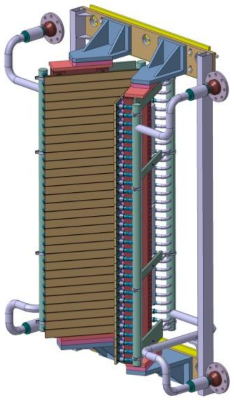
SPIDER: the beam source

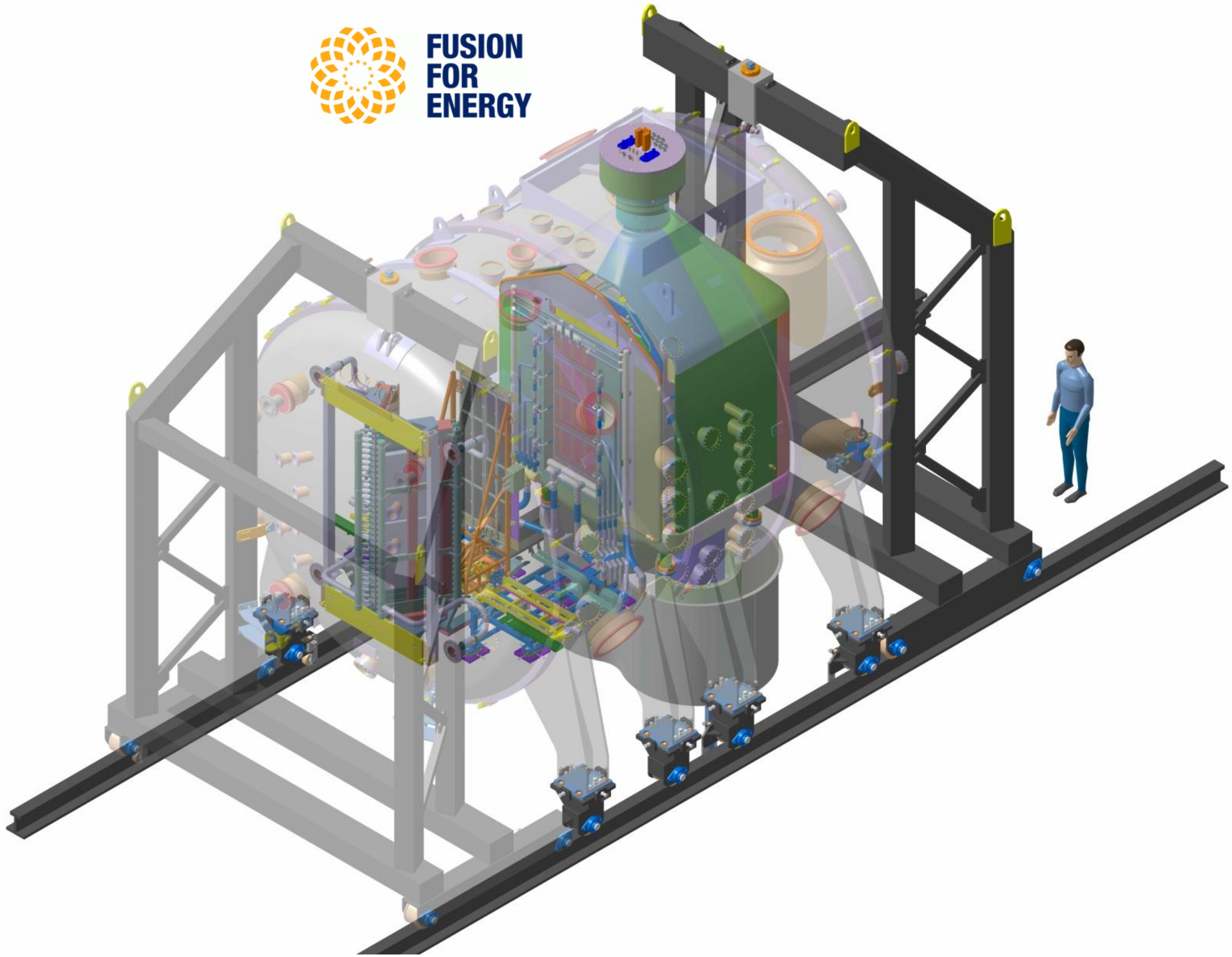
- BP = Bias Plate
- PG = Plasma Grid
- EG = Extraction Grid
- GG = Grounded Grid
- ED = Electron Dump



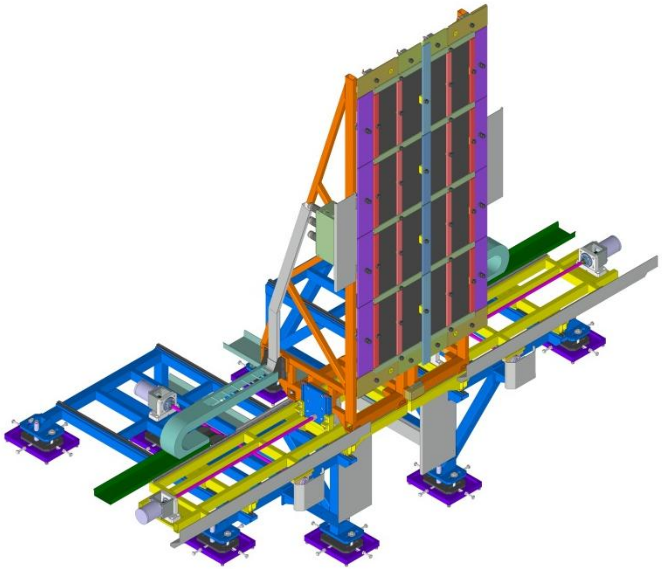
- **1280(16x5x16) beamlets**
- **4 grid segments**

SPIDER: Vessel, Beam Dump

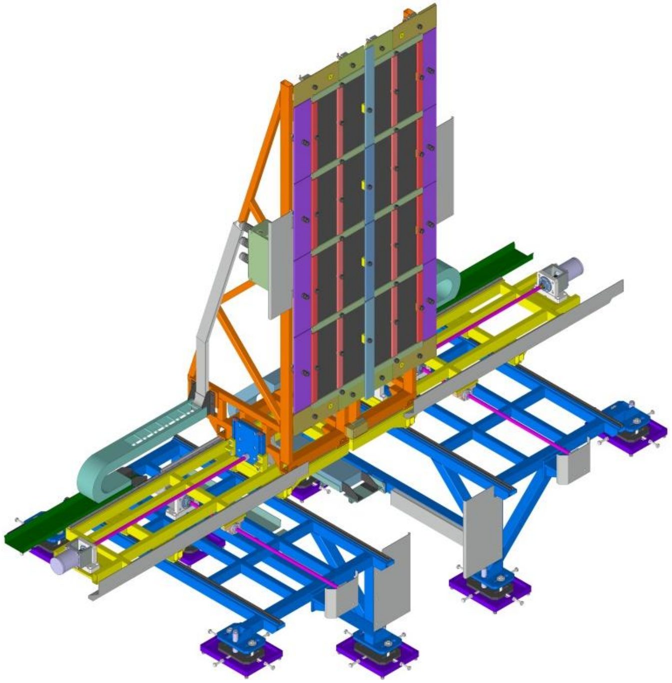




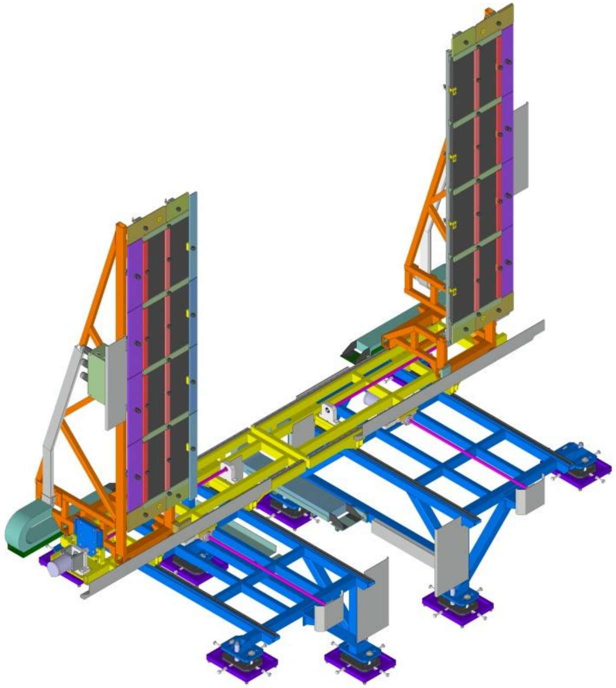
SPIDER diagnostic calorimeter: STRIKE



upstream, closed

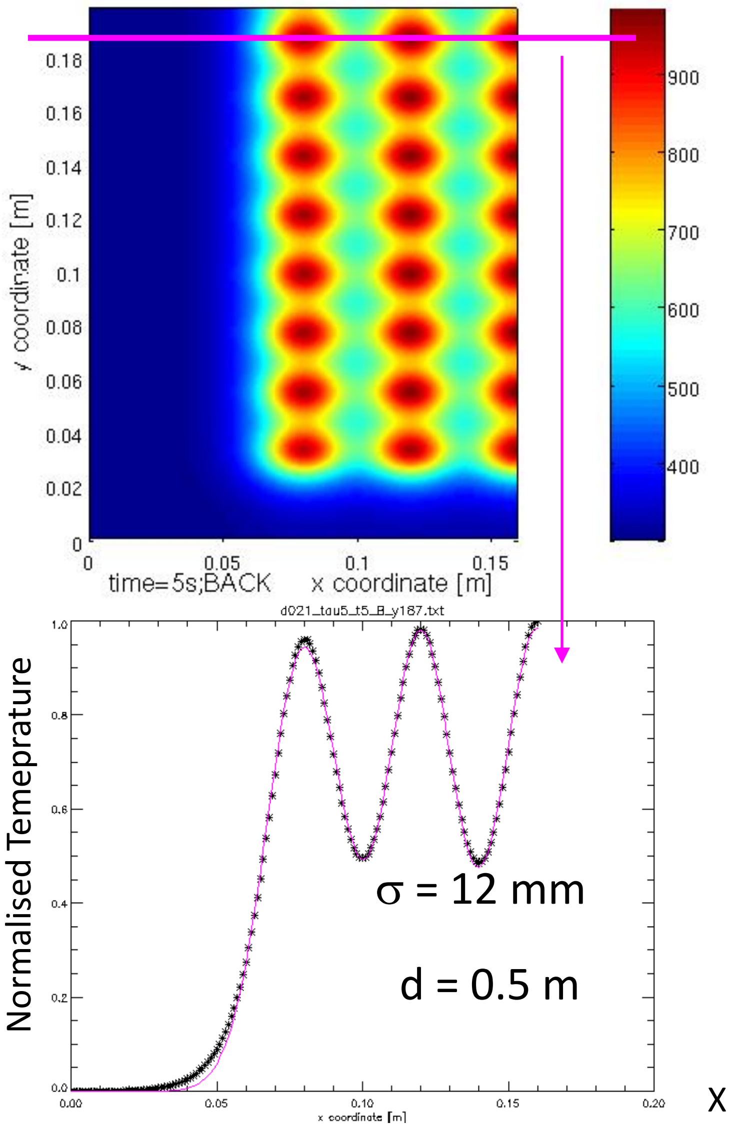


downstream, closed



downstream, open

STRIKE: beamlets footprint



Rear side;

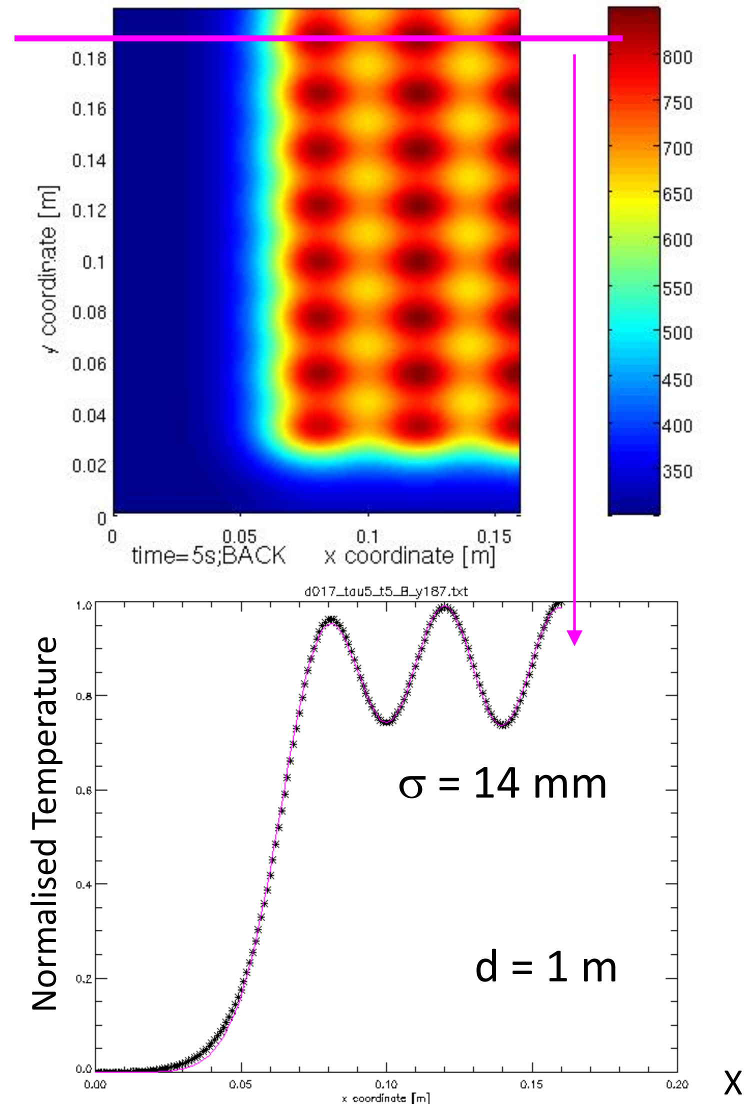
τ= 5s;

t = τ;

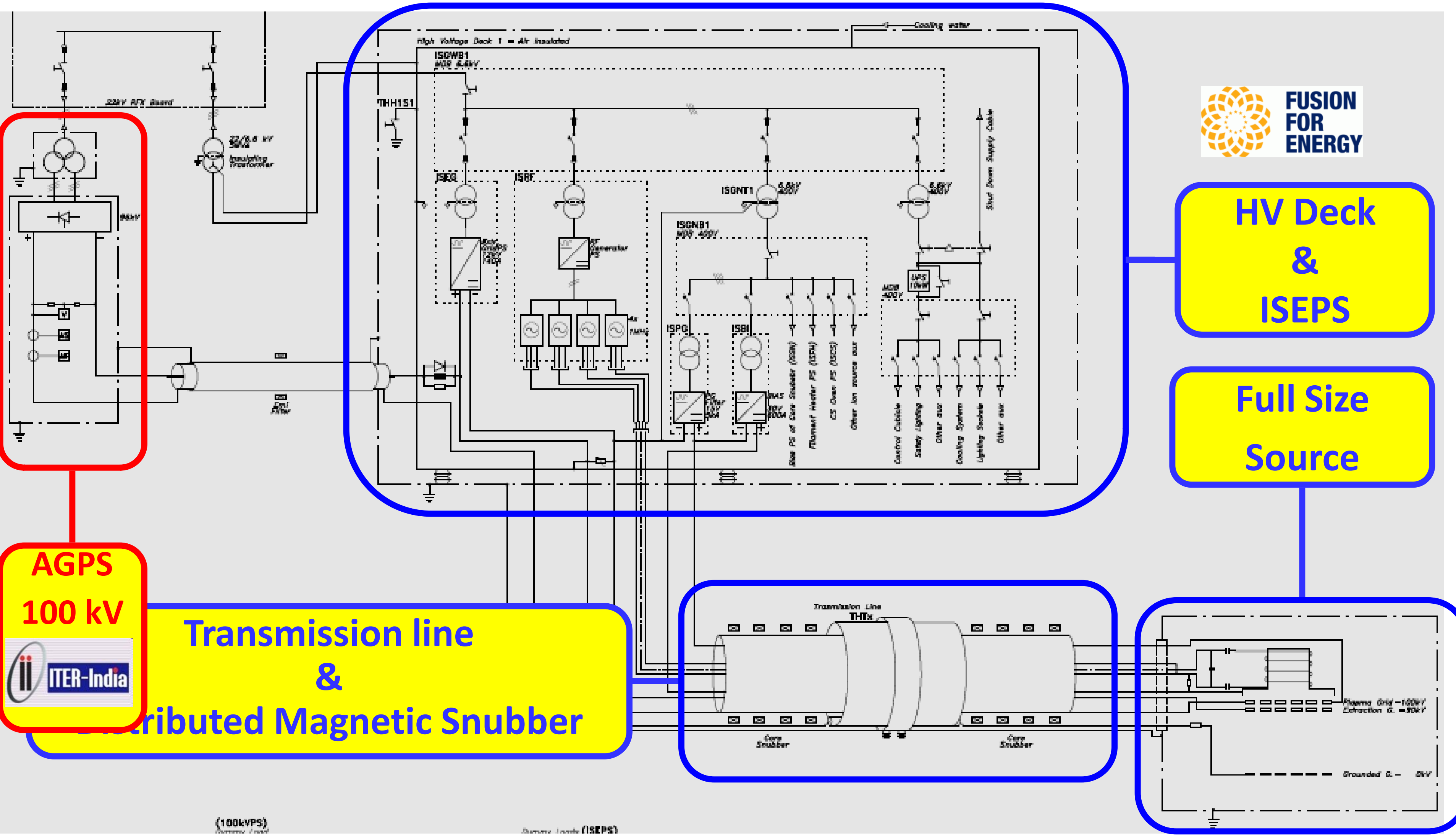
γ= 60°;

δ = 3 mrad;

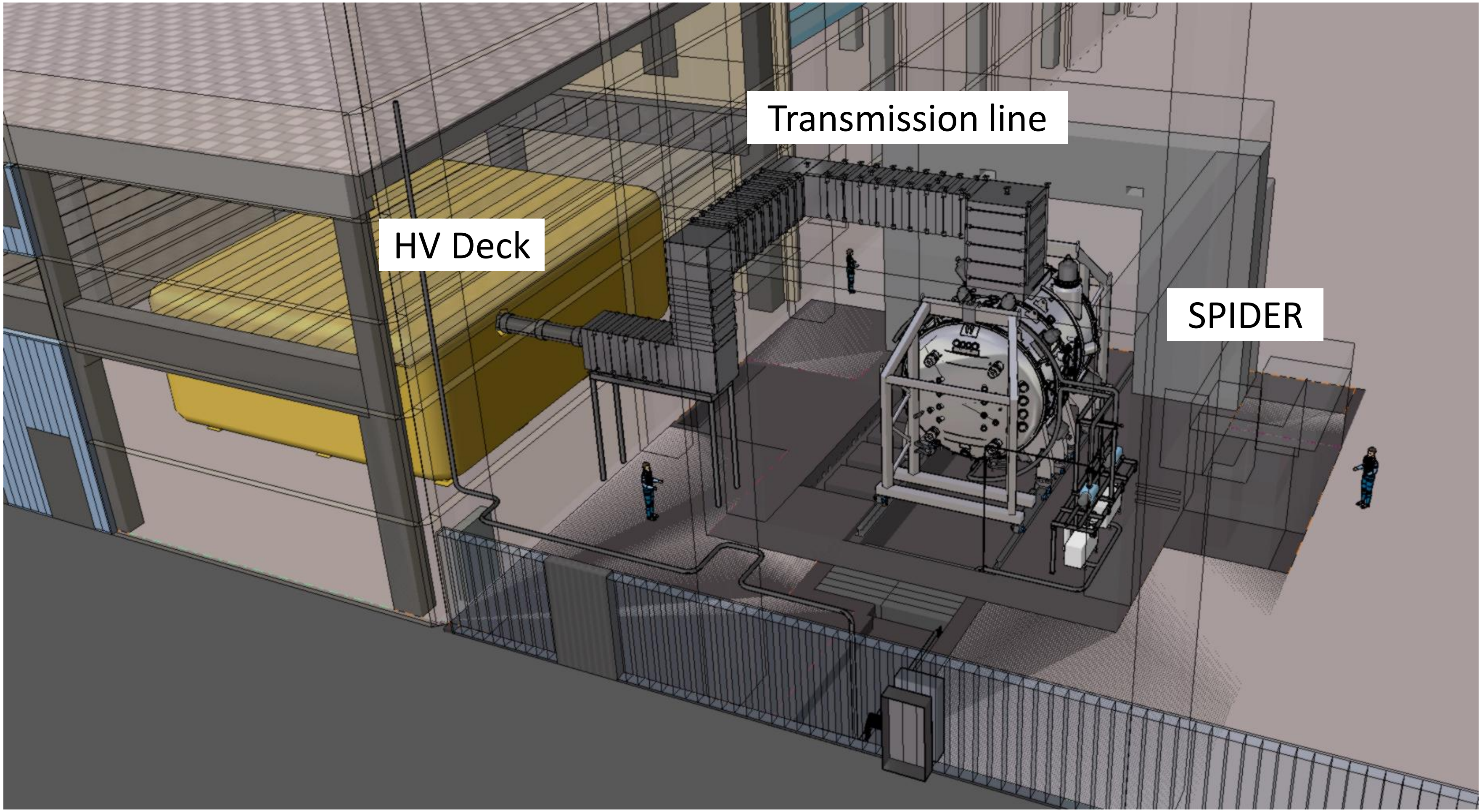
y = 187 mm



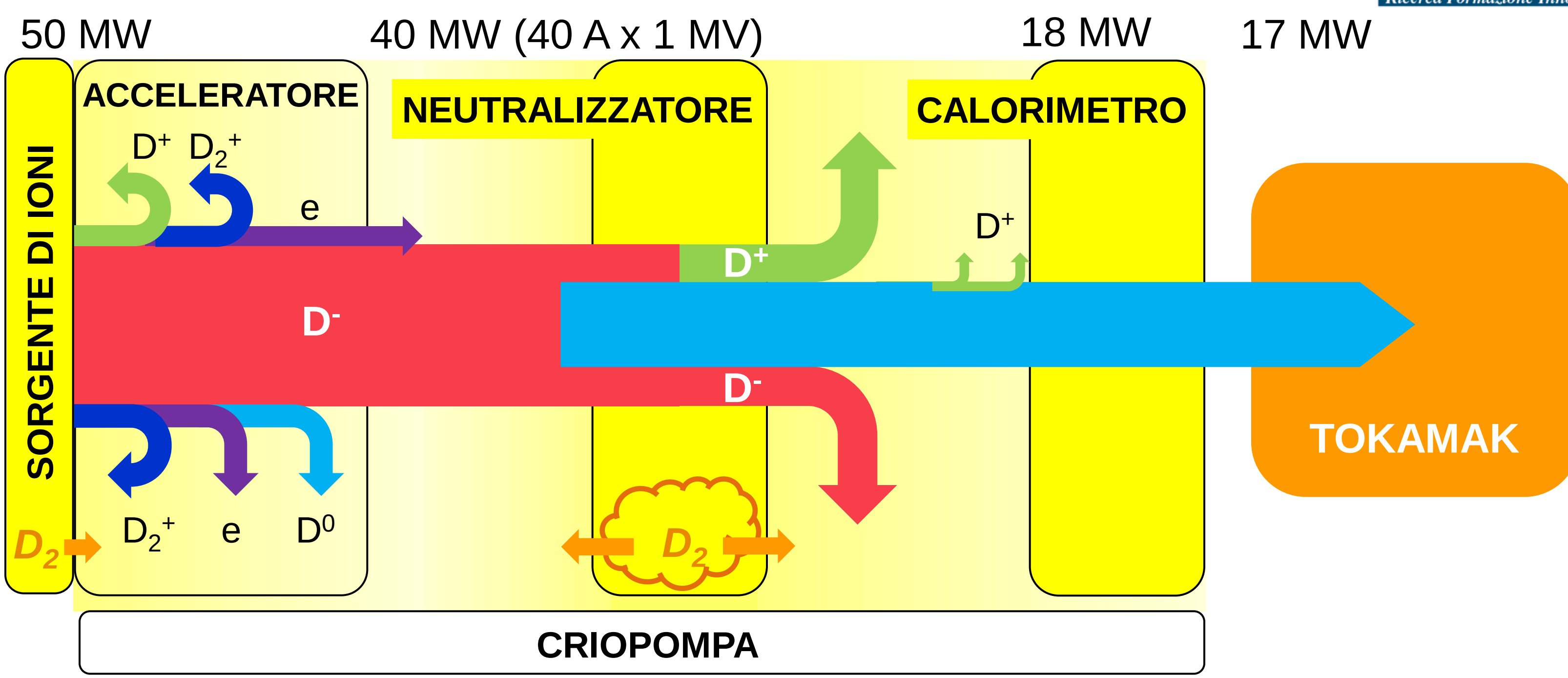
SPIDER: the power supply system

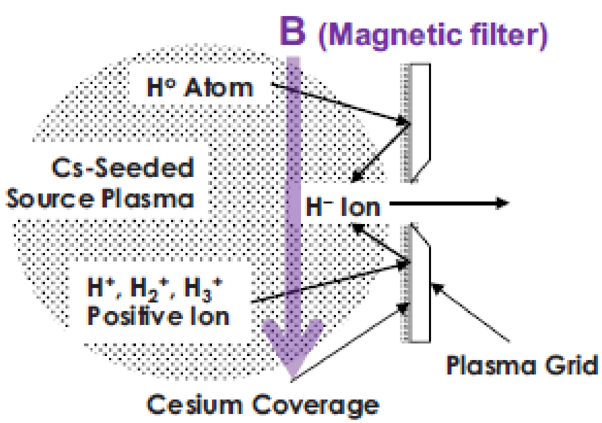


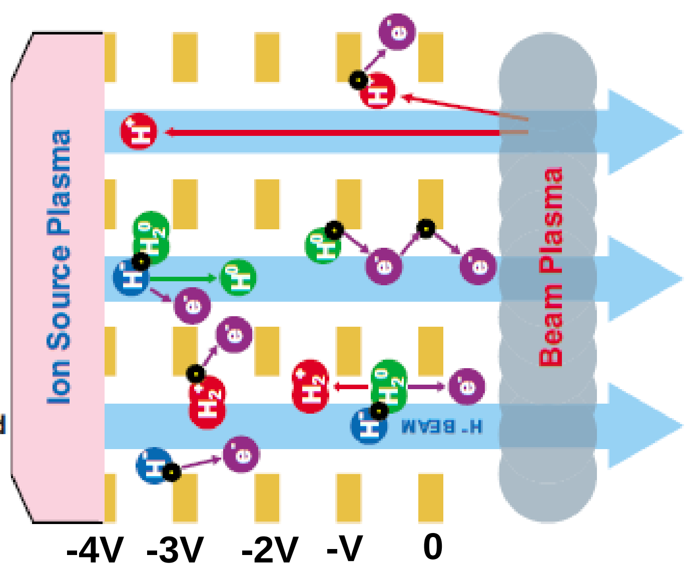
SPIDER: layout

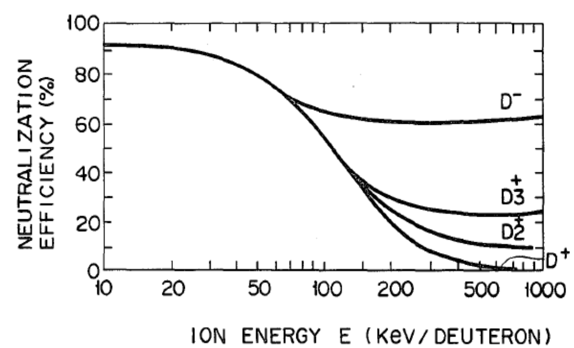


MITICA: la linea di iniezione









Il progetto dei componenti dell'impianto sperimentale MITICA

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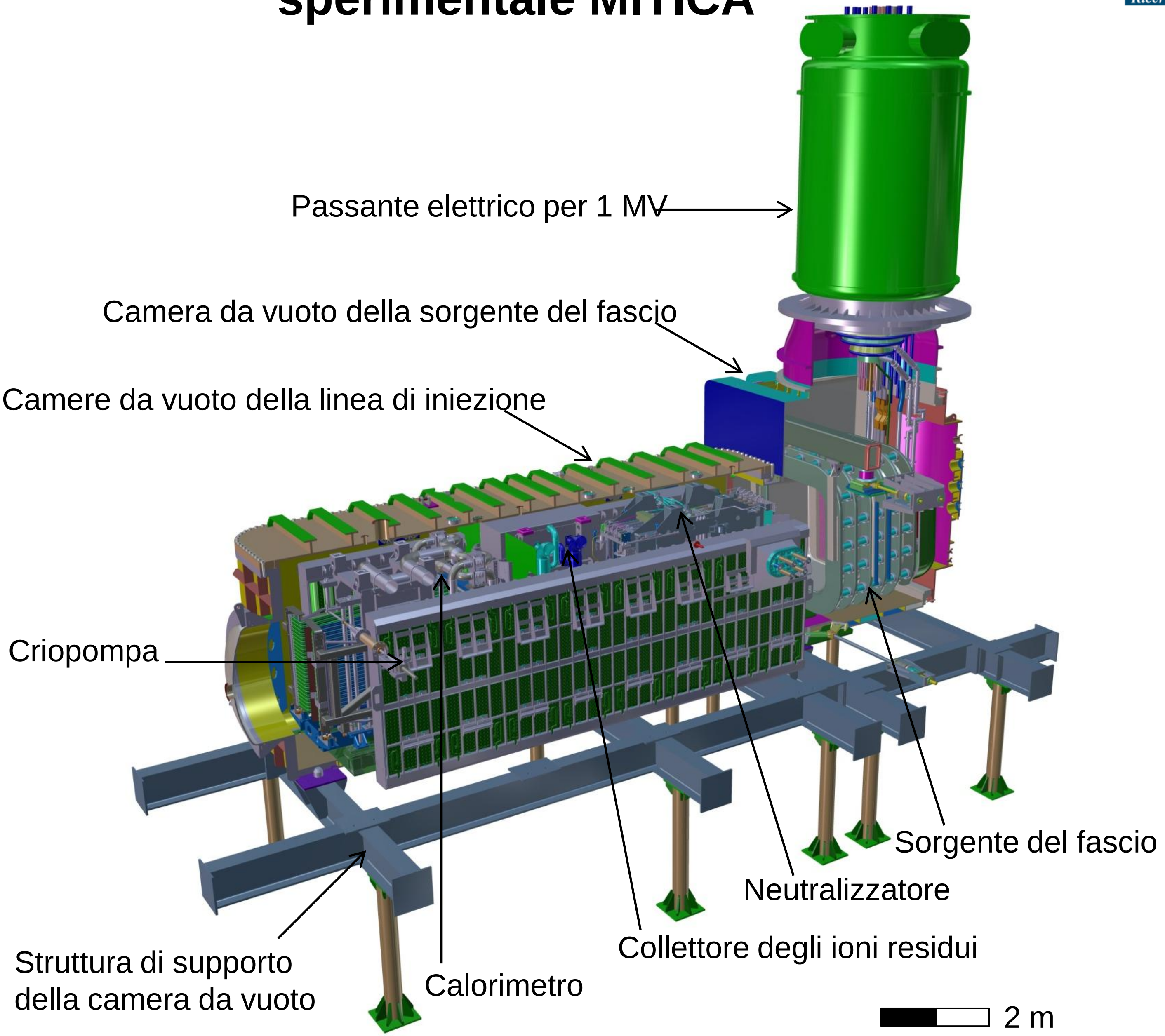
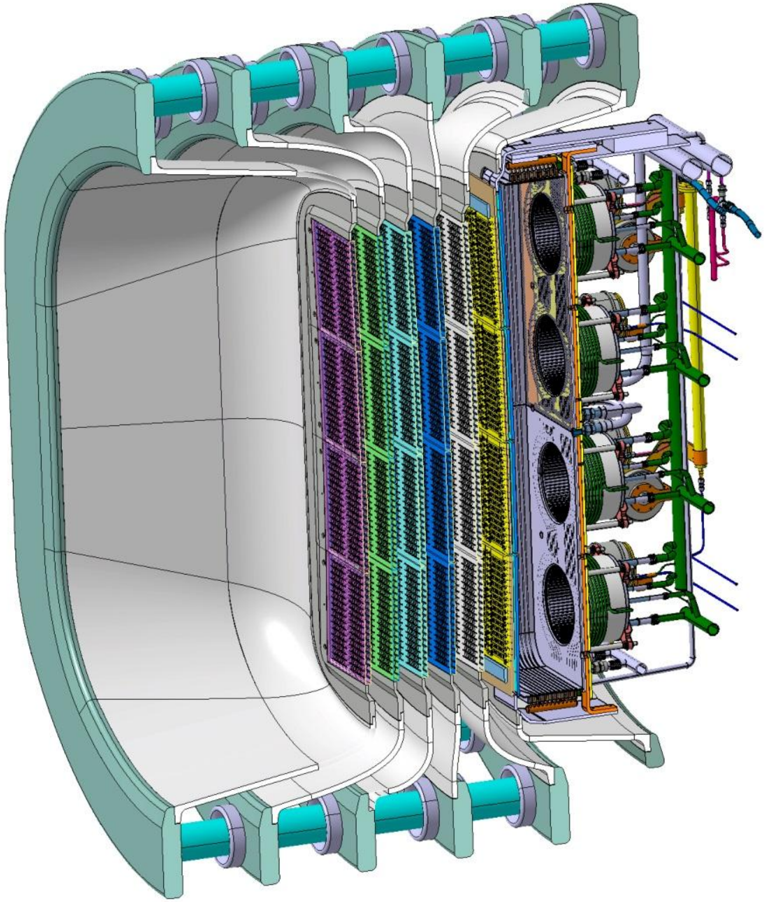
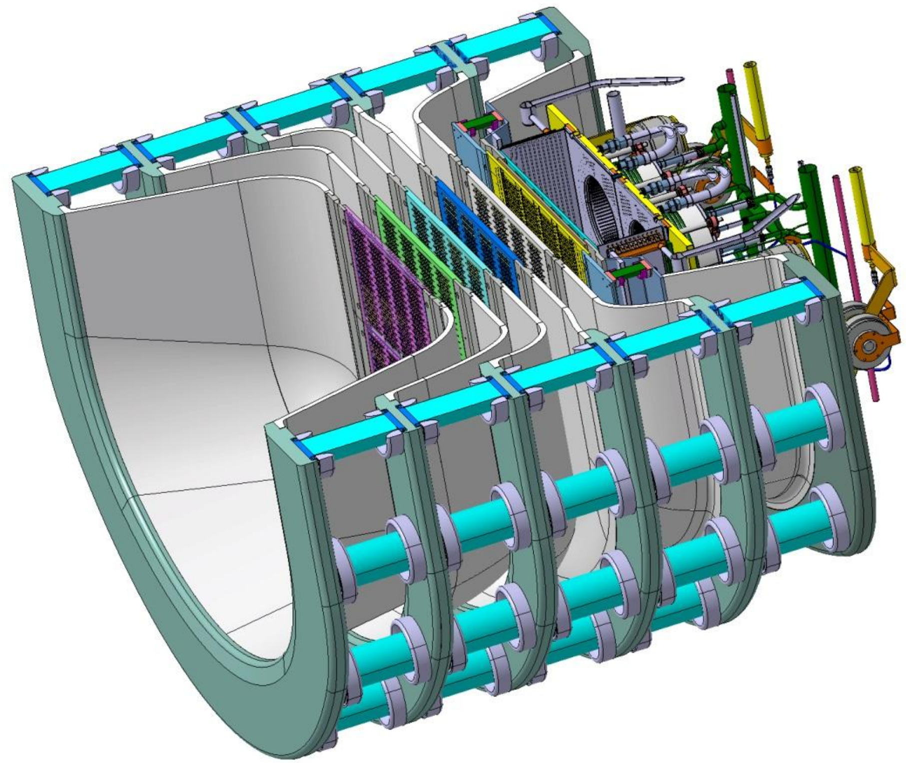


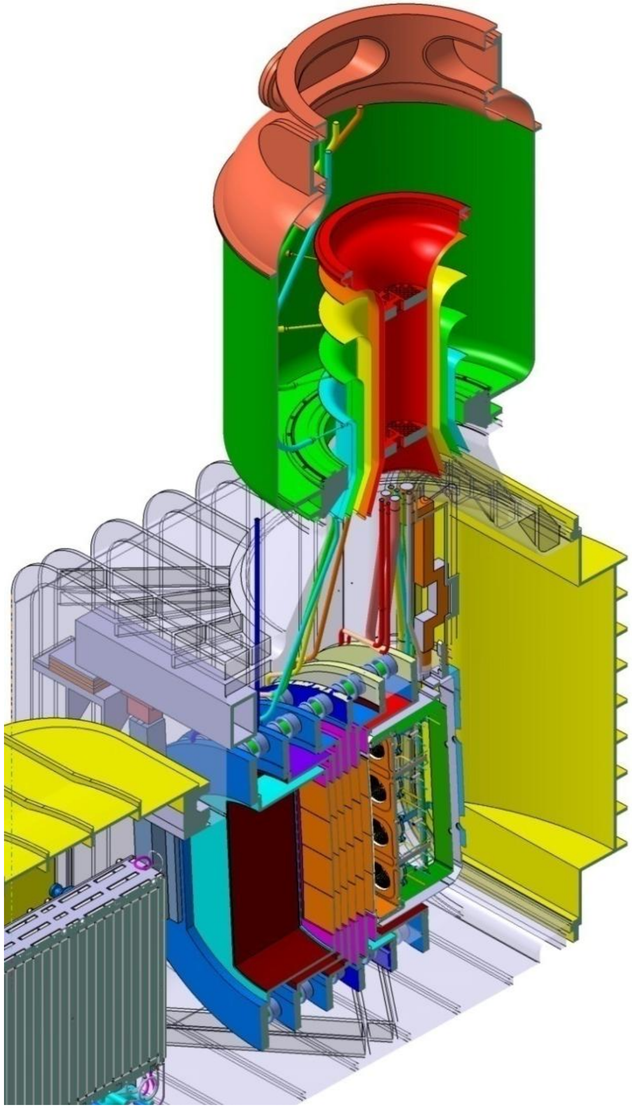
MITICA: the Beam Source

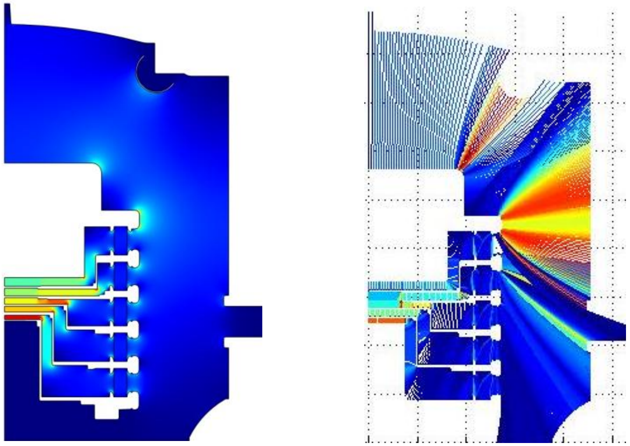
Same plasma source of SPIDER
5 stage acceleration system (200 kV each)



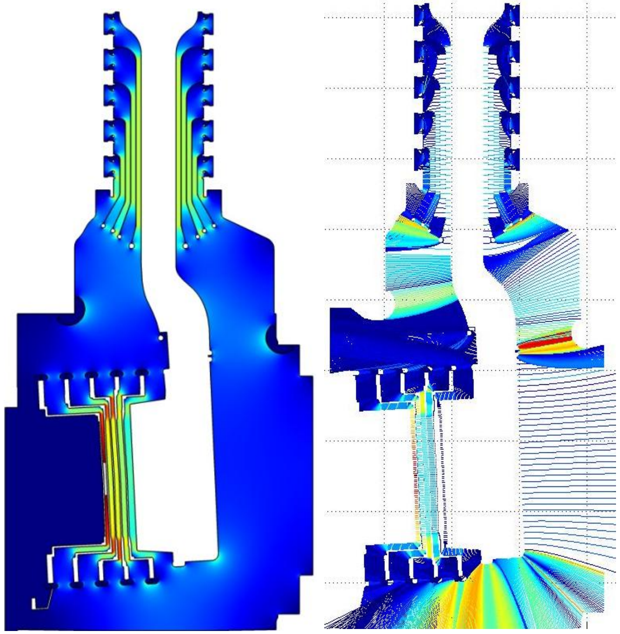


MITICA: electrostatic design of long distances high voltage vacuum insulation





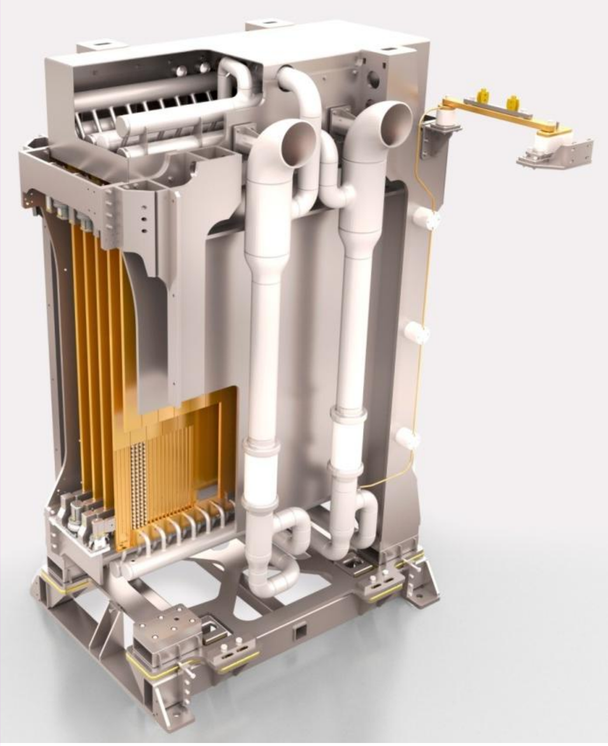
Horizontal section



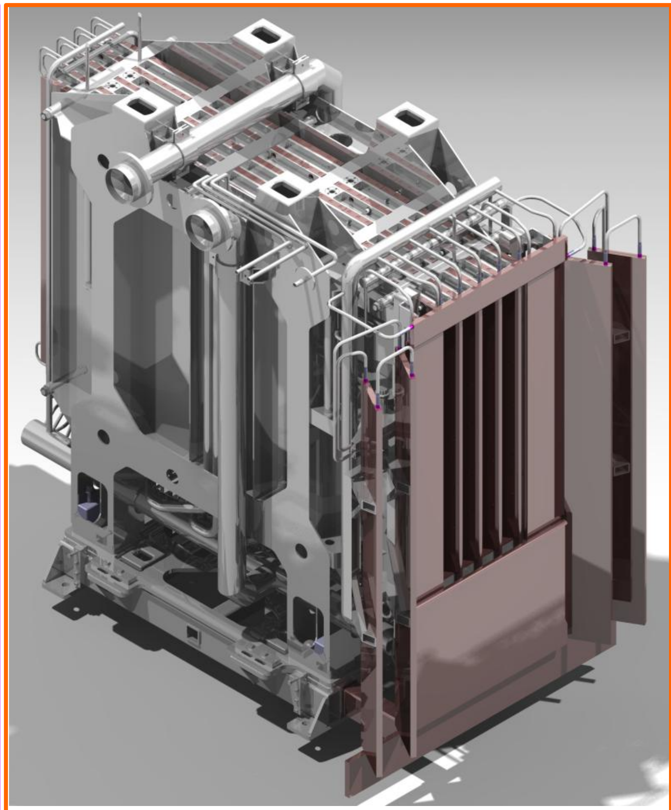
Vertical section

MITICA Beam Line Components: scope of the supply

Calorimeter
6.1 t mass, 100kg/s water
3.0m (L) x 2.1m (W) x 3.2m (H)



Residual Ion Dump (RID)
7.5 t mass, 100kg/s water
2.2m (L) x 2.1m (W) x 3.2m (H)

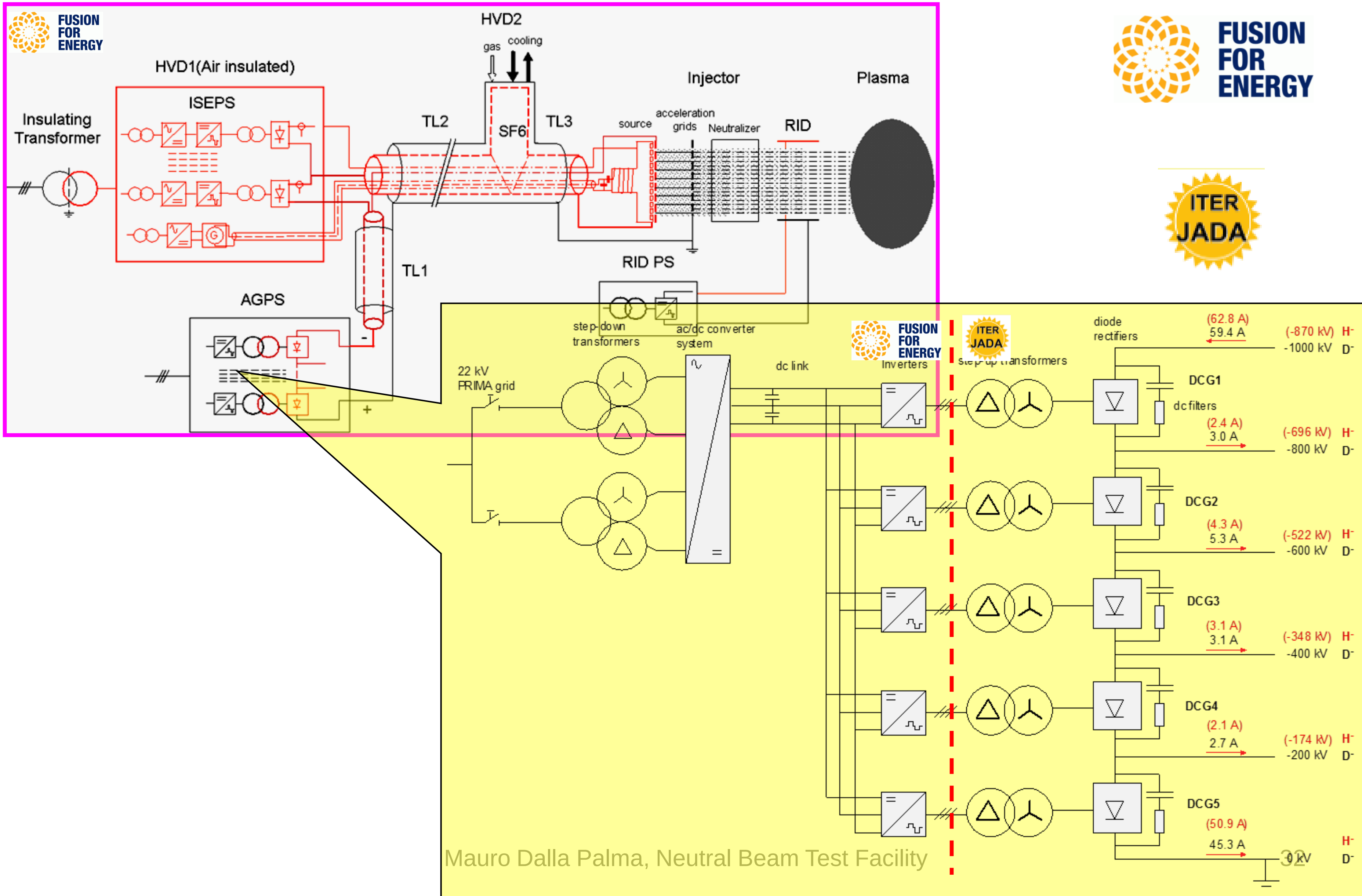


Neutraliser
13 t mass, 55kg/s water
3.4m (L) x 2.1m (W) x 3.2m (H)

Competency requirements to main contractor:

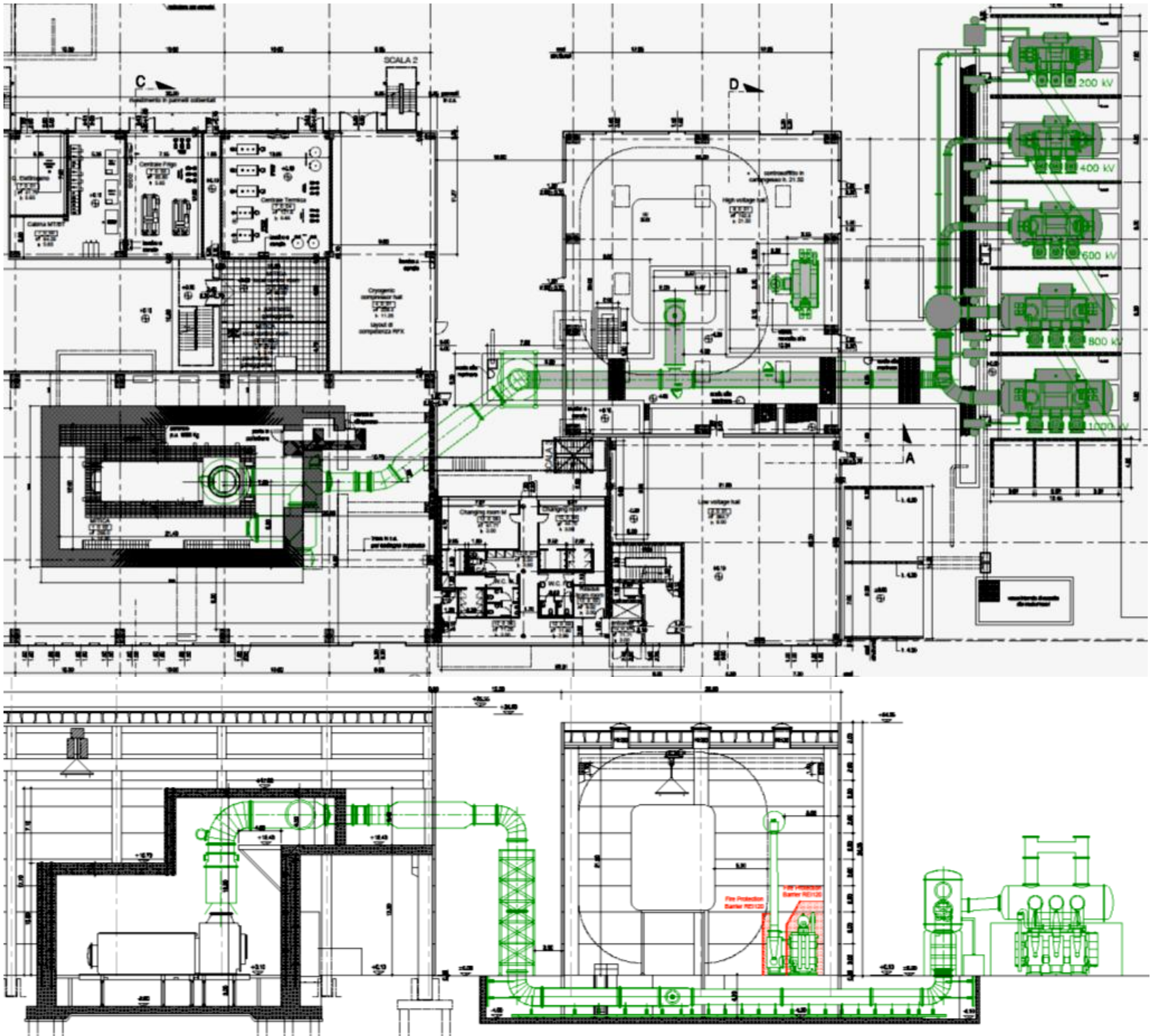
i. Vacuum technology (cooling vacuum barriers)
ii. Assembly and metrology (coordinate tracking and recording during assembly)
iii. Development of production drawings based on engineering design
iv. Project management with subcontractors

MITICA: power supply schemes



MITICA: layout of Power Supplies and Transmission line

CONSORZIO RFX
Ricerca Formazione Innovazione



Cooling System: main cooling requirements

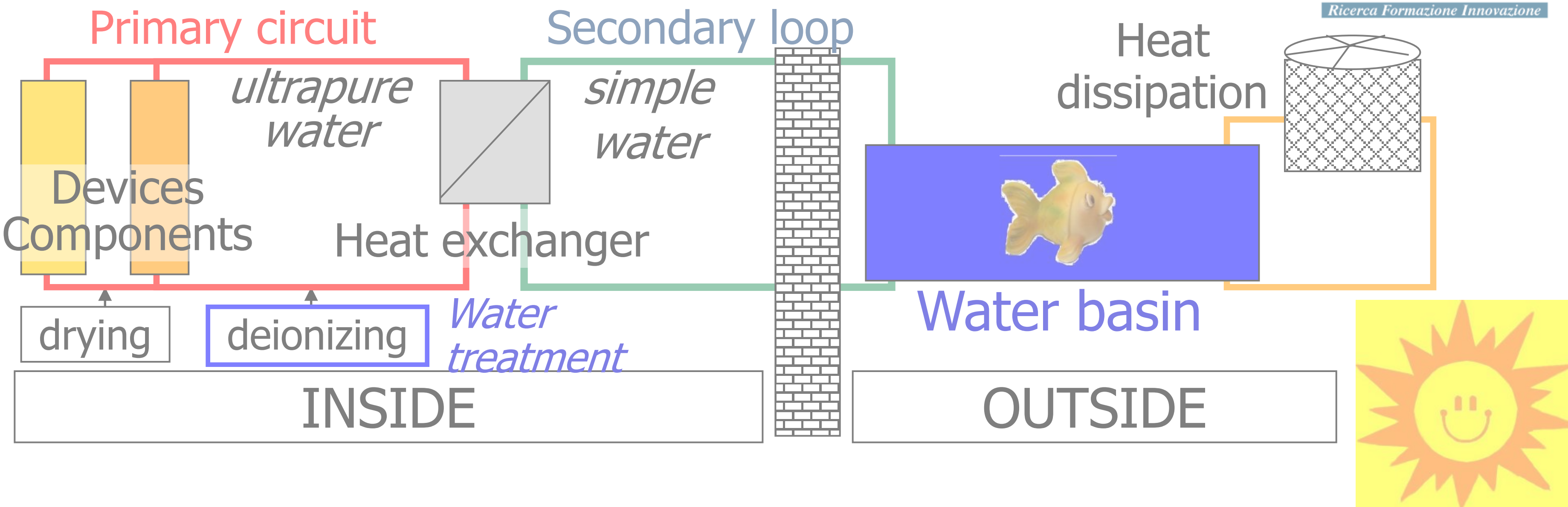
- Primary Cooling Fluids:
  - For HV components:
    - deionized water 5-10 MΩ cm @25°C
  - For others component and system including PS:
    - demineralized water 1-2 MΩ cm @25°C
  - Three level of different water inlet temperature will be supplied

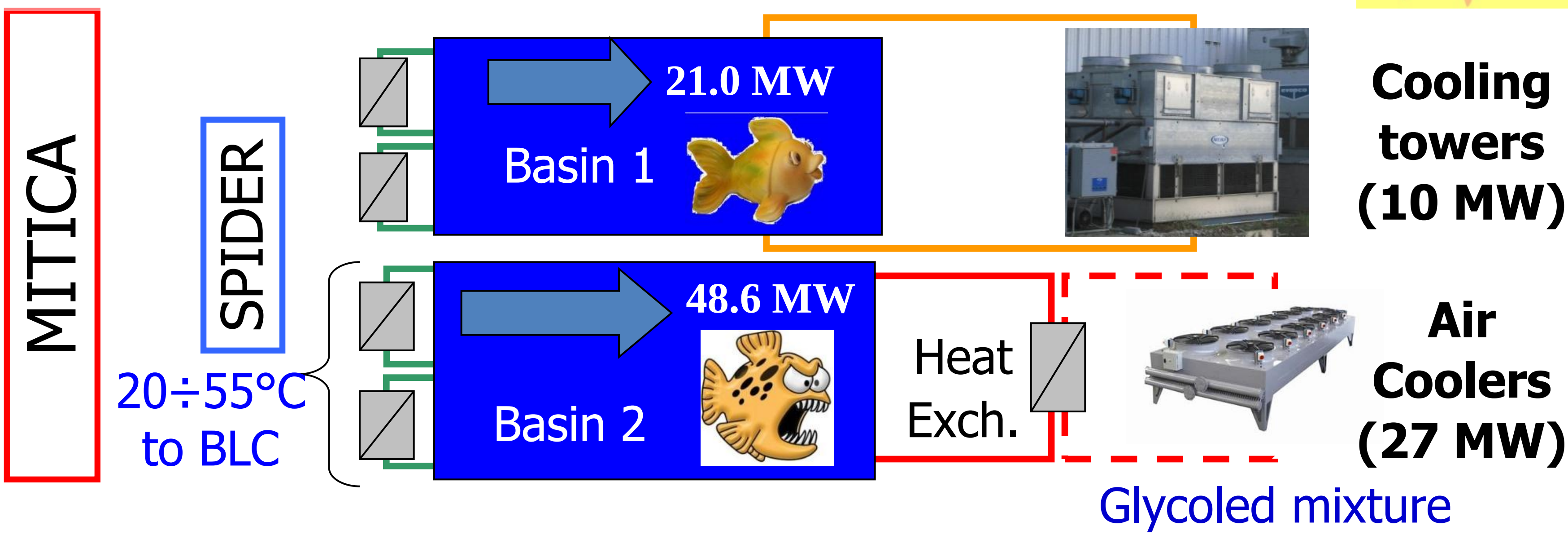
	PRIMARY CIRCUITS		
	Mass flow rate for each component [kg/s]	**Rejected thermal power for each component [kW]**	**Total rejected thermal power [kW]**
SPIDER	0.6÷64.0	10 ÷ 6100	9700
SPIDER PS	12.8 ÷ 36.8	400 ÷ 1000	1400
MITICA	0.6 ÷ 131.3	25 ÷ 19000	54800
MITICA PS & Aux.	4.6 ÷ 48.0	150 ÷ 1500	3800

~11 MW (SPIDER + SPIDER PS)

~58.5 MW (MITICA + MITICA PS & Aux.)

Cooling circuits





International cooperation for the Neutral Beam Test Facility

- Strong international cooperation for:
  - PRIMA SPIDER MITICA
  - ITER Heating NB
  - ITER Diagnostic NB

Grazie per l'attenzione!