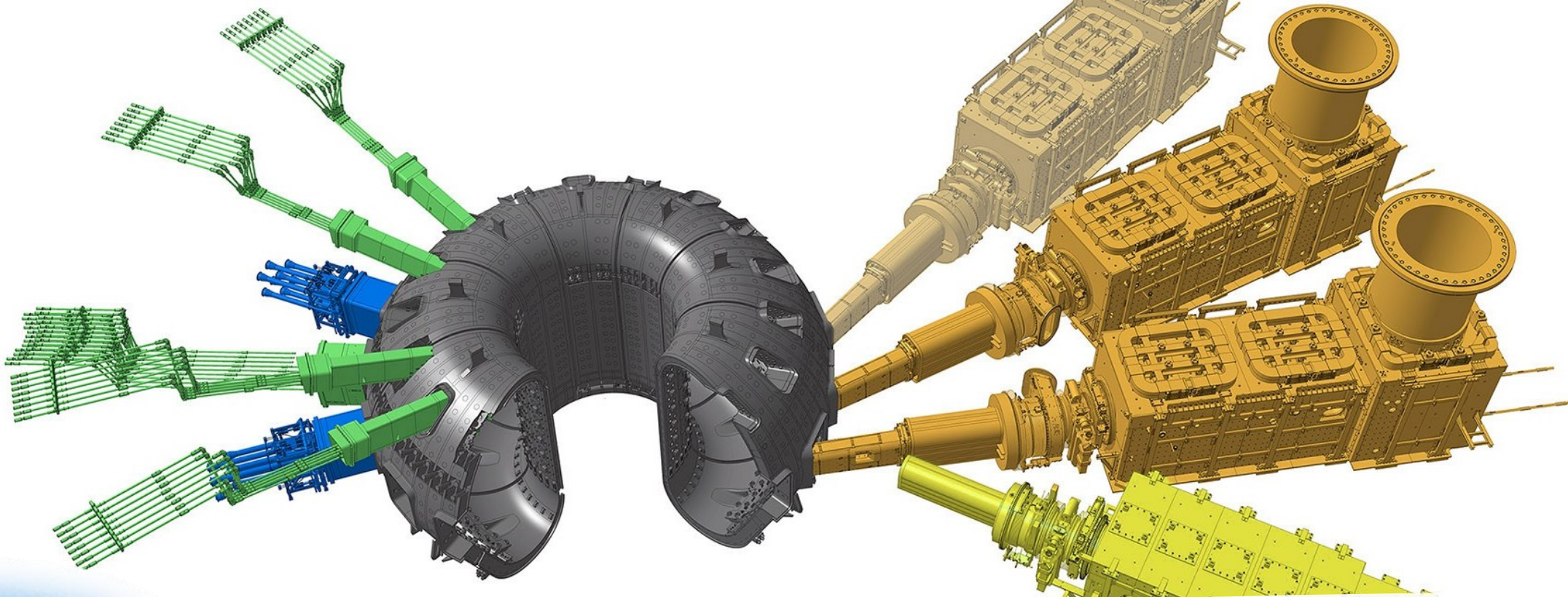




NBI principles: technology overview

22nd July 2026 – ITER International School
Leshan, China

prof. Emanuele Sartori

emanuele.sartori@igi.cnr.it - Università degli Studi di Padova and Consorzio RFX
Scientific exploitation manager/scientific leader of the ITER Neutral Beam Test Facility in Padova

*thanks to all
contributors from the
NBTF team
and international
collaborators*



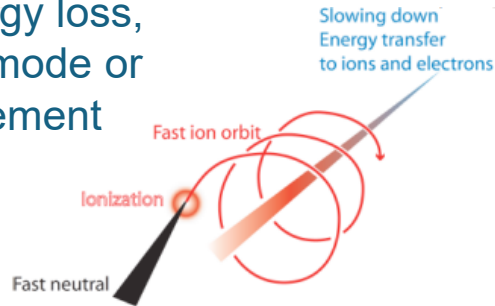
UNIVERSITÀ
DEGLI STUDI
DI PADOVA



What are Neutral Beams used for?

Plasma Heating

Balance energy loss,
access to H-mode or
target confinement
regimes;



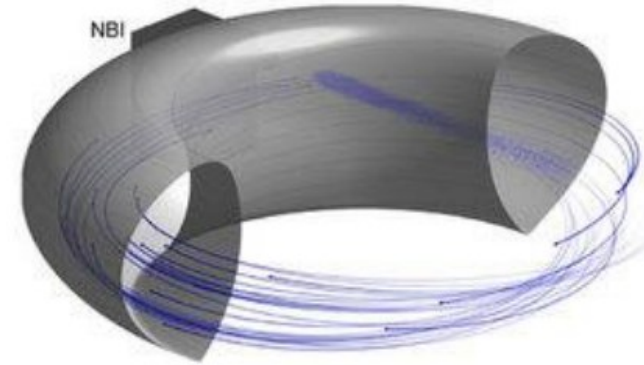
W. Kraus, CAS (CERN Accelerator
School – Ion Sources) 2012

Toroidal Torque

Injected neutral flux imparts
momentum, increasing plasma
fluid rotation

(Plasma Fuelling)

Useful for core fuelling, negligible
for larger devices



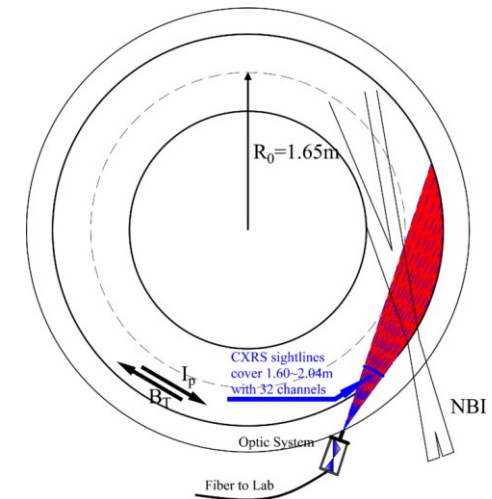
P. Vincenz, RFX

Current Drive

Fast neutrals $\rightarrow$ fast ions $\rightarrow$ non-inductive current

Plasma Diagnostics

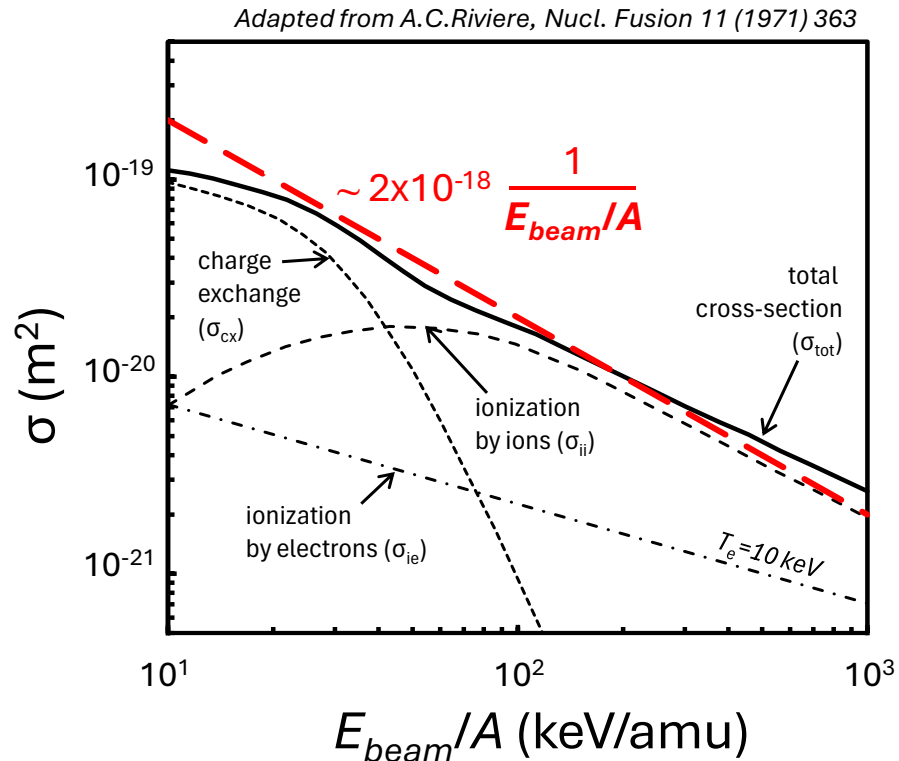
CXRS, MSE – spectral
analysis of light emission
generated by collisions of
fast neutrals with plasma



<https://doi.org/10.1063/1.4897186>

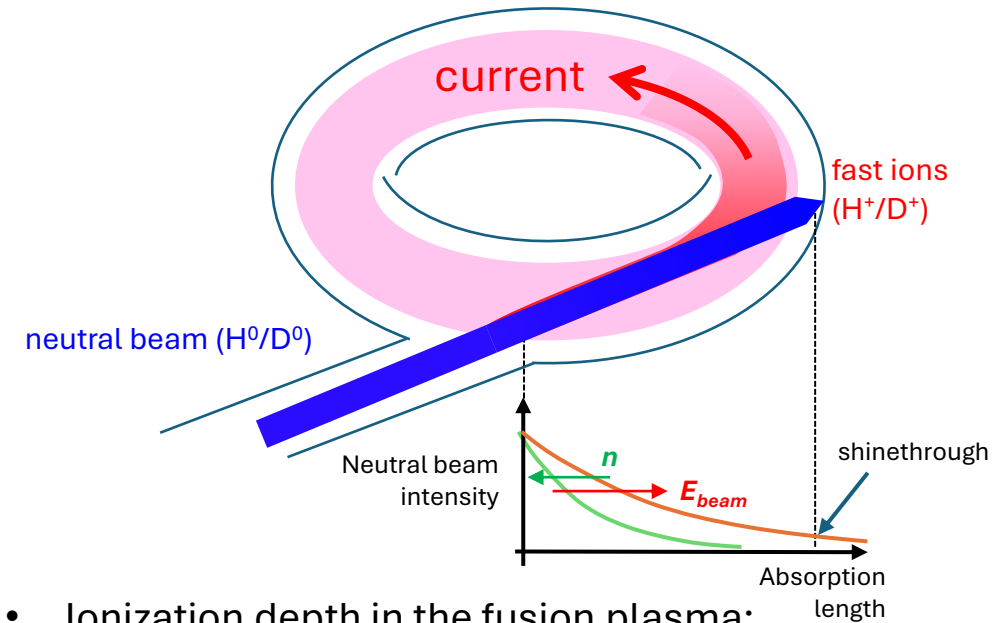
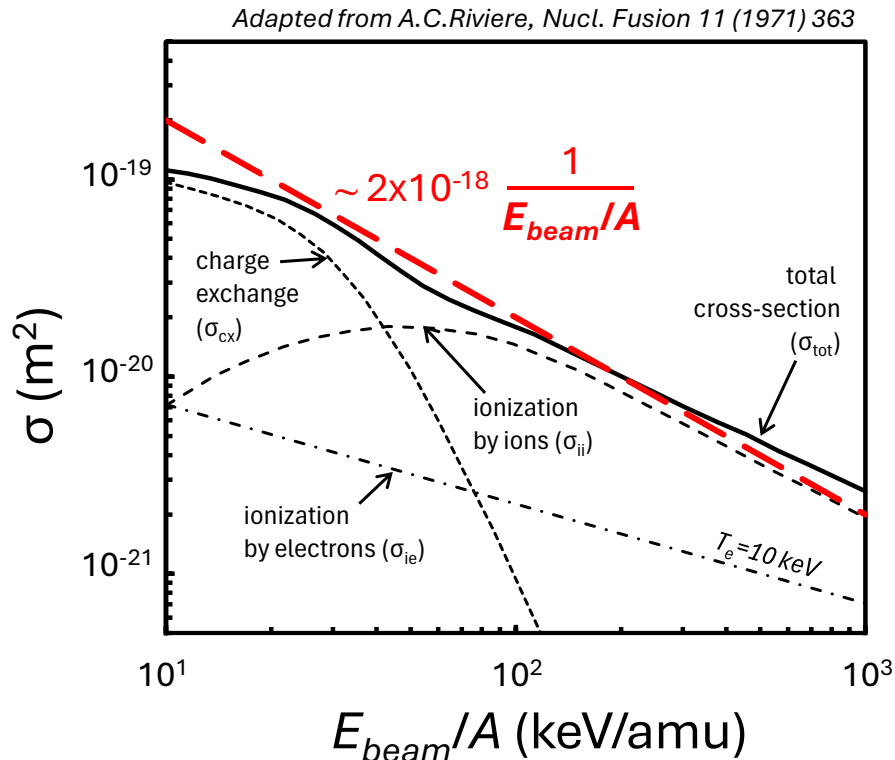
Neutral beam injectors: requirements

- neutral atoms can penetrate through the magnetic field
- **ionization** by collision with plasma ions and electrons:
fast neutrals $\rightarrow$ fast ions
- Fast ion trapped in the magnetic field transfers energy to plasma ions and electrons by Coulomb interaction



Neutral beam injectors: requirements

- neutral atoms can penetrate through the magnetic field
- Ionization by collision with plasma ions and electrons:
fast neutrals $\rightarrow$ fast ions
- Fast ion trapped in the magnetic field transfers energy to plasma ions and electrons by Coulomb interaction



- Ionization depth in the fusion plasma:
characteristic length scales as

$$\lambda \approx \frac{E_{beam}/A}{2 \cdot n}$$

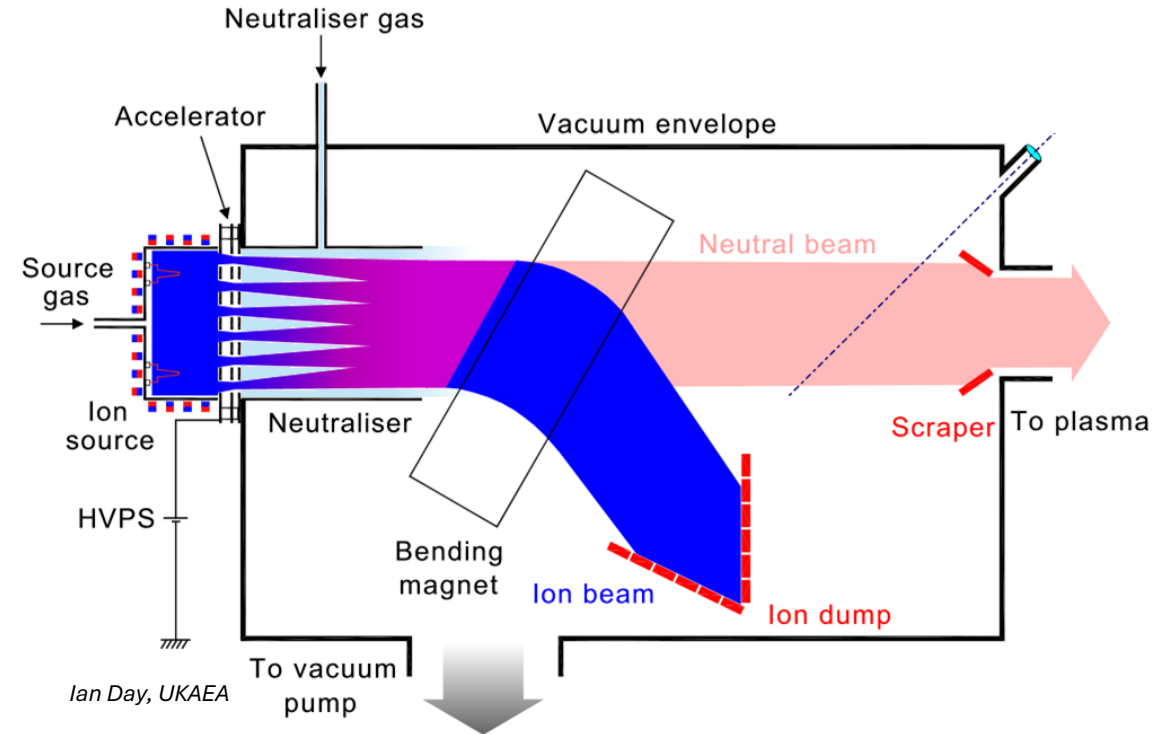
n in 10^{18} m^{-3} ,
 E in keV,
 A in amu

- High densities and large plasma volume require **high energy** for depositing power at the core region of the fusion plasma
- Often, high-confinement regimes are achieved by neutral beam heating
 $\rightarrow$ low plasma target thickness when neutral beam is activated, then, it evolves with time.

Positive and Negative-ion based NBIs

Precursor ion beam:

Most tokamaks until now have used positive ions.



Basic principle:

The ion beam is accelerated electrostatically, through multi-aperture electrodes (beamlets), then neutralised interacting with a thick gas target.

Positive and Negative-ion based NBIs

Precursor ion beam:

Most tokamaks until now have used positive ions.

However, neutralisation in gas cells of high-energy hydrogen ions is only possible from negative ions.

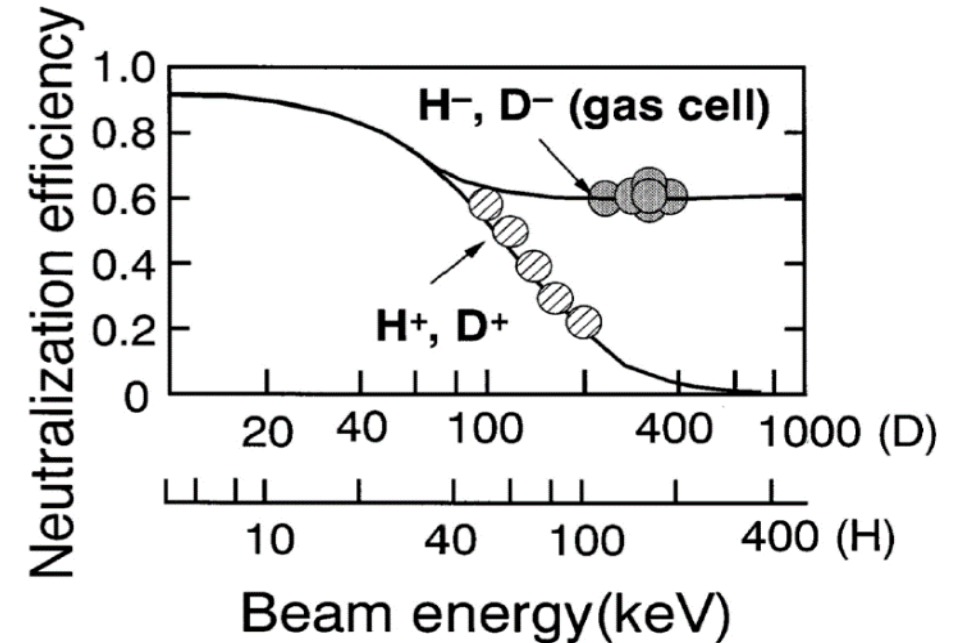
Positive ions

- Easy to produce (2400 A/m^2)
- Multiple ion species (H^+ , H_2^+ , H_3^+)
- Neutralisation efficiency decreases with energy

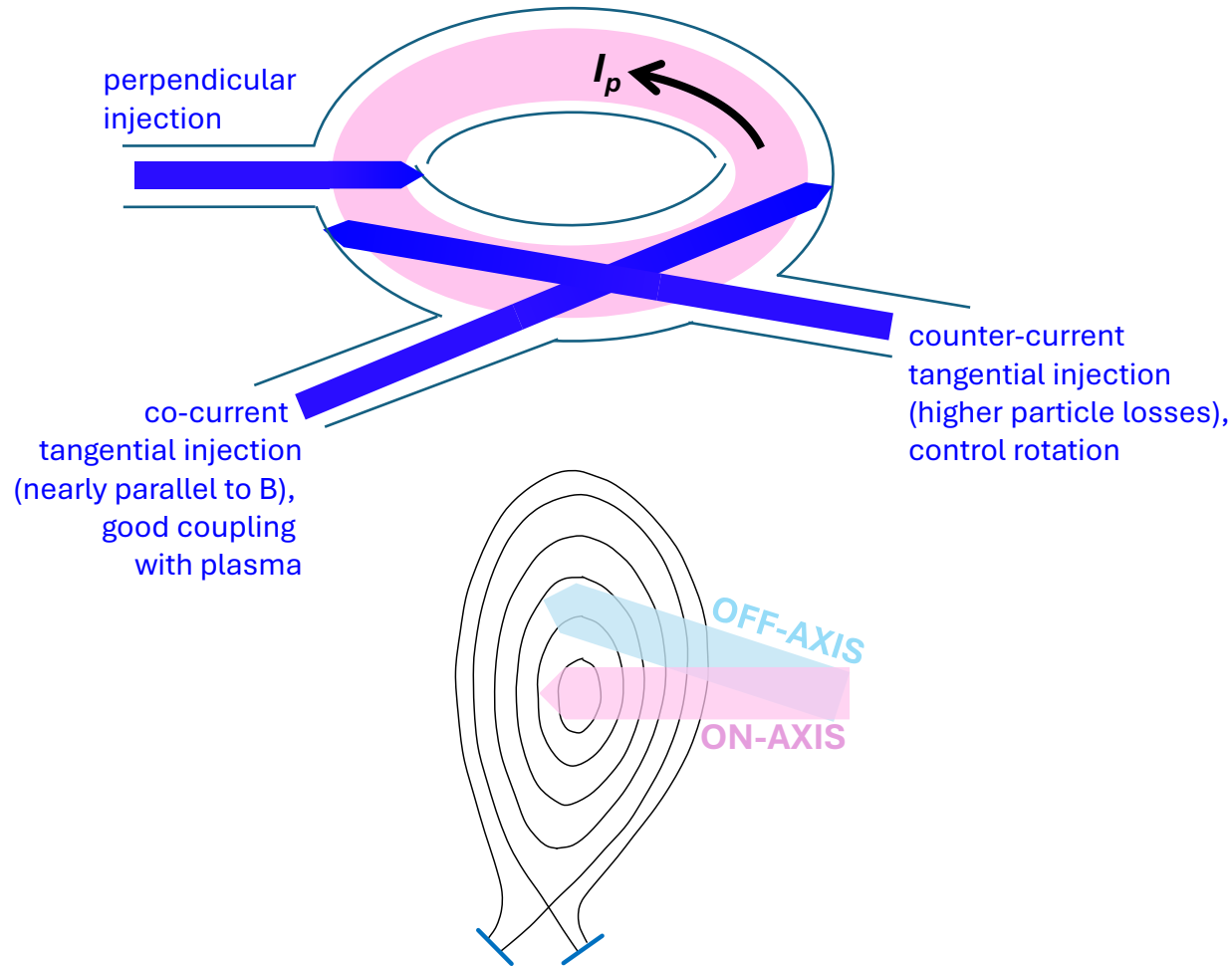
Negative ions

- Hard to produce ($240\text{-}370 \text{ A/m}^2$)
- One species (H^-)
- Co-extracted and stripped electrons constitute additional power load
- Neutralisation efficiency minimum 58%

Experimental Measurement at JT-60U
[M. Kuriyama, *Fus. Eng. Design*, 39-40:115, 1998]



Neutral beam injectors: requirements



NBI physics

- Heating (*temperature*)
- Current drive (*plasma current*)
- Momentum injection (*plasma fluid rotation*)

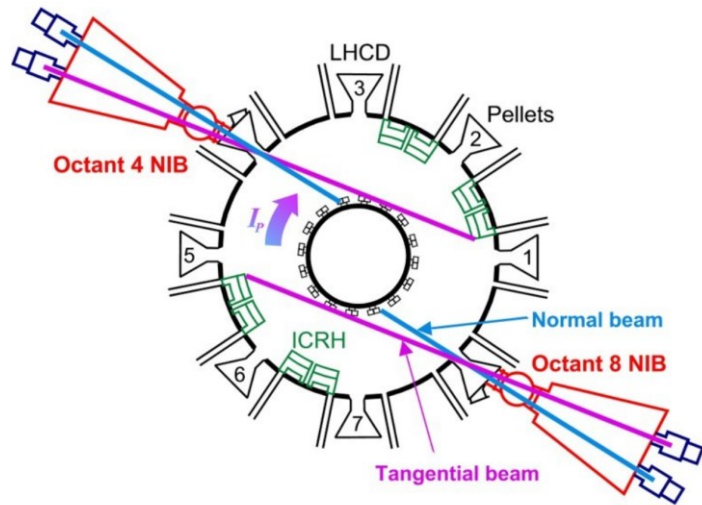
NBI parameters

- **Energy**
- **Direction:**
 - Tangential: longer path into dense plasma, current drive and torque input
 - Perpendicular: easier to integrate, short path into plasma, larger losses
 - On-axis vs off-axis: central heating, longer path into plasma vs larger current drive

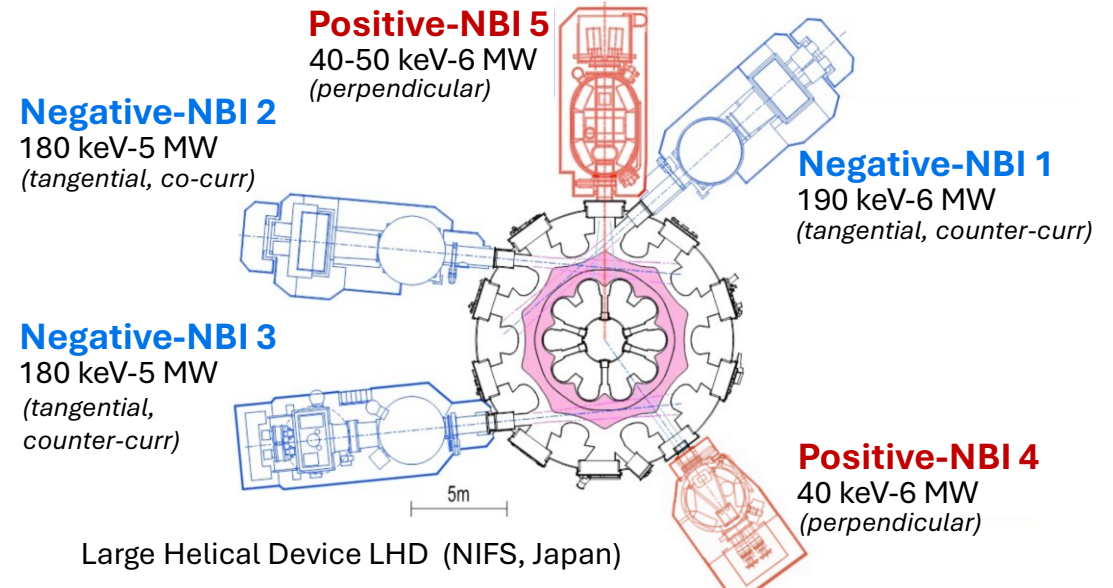
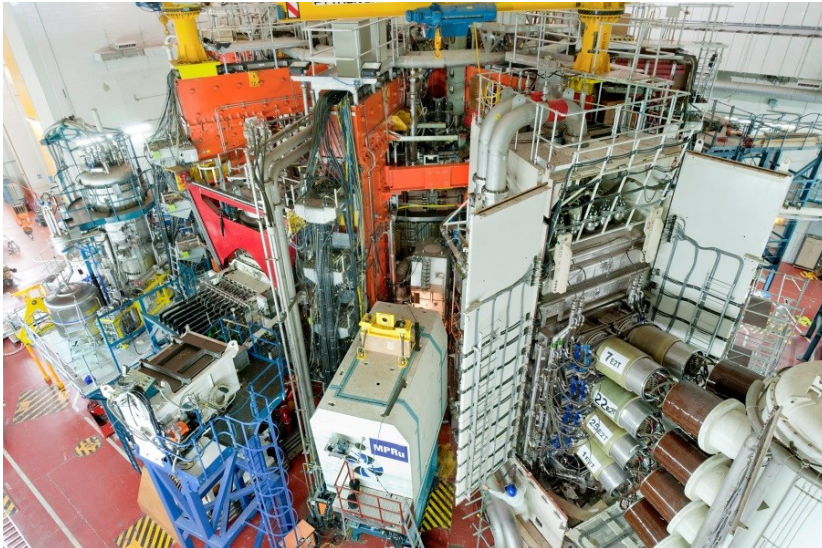
Neutron environment

- Reduced maintenance, and only by Remote Handling
- Low-activation materials

Neutral beam injectors: requirements



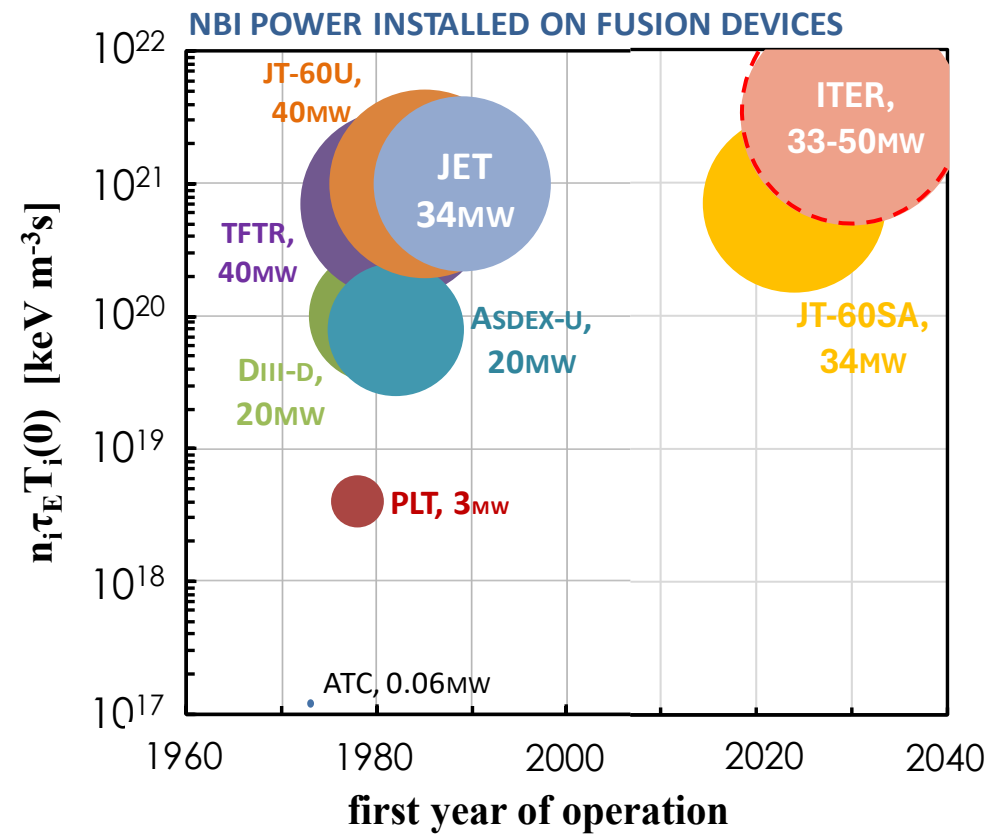
Joint European Torus JET (CCFE, UK)



Large Helical Device LHD (NIFS, Japan)



ITER Heating & Current Drive neutral beam injectors compared to other injectors

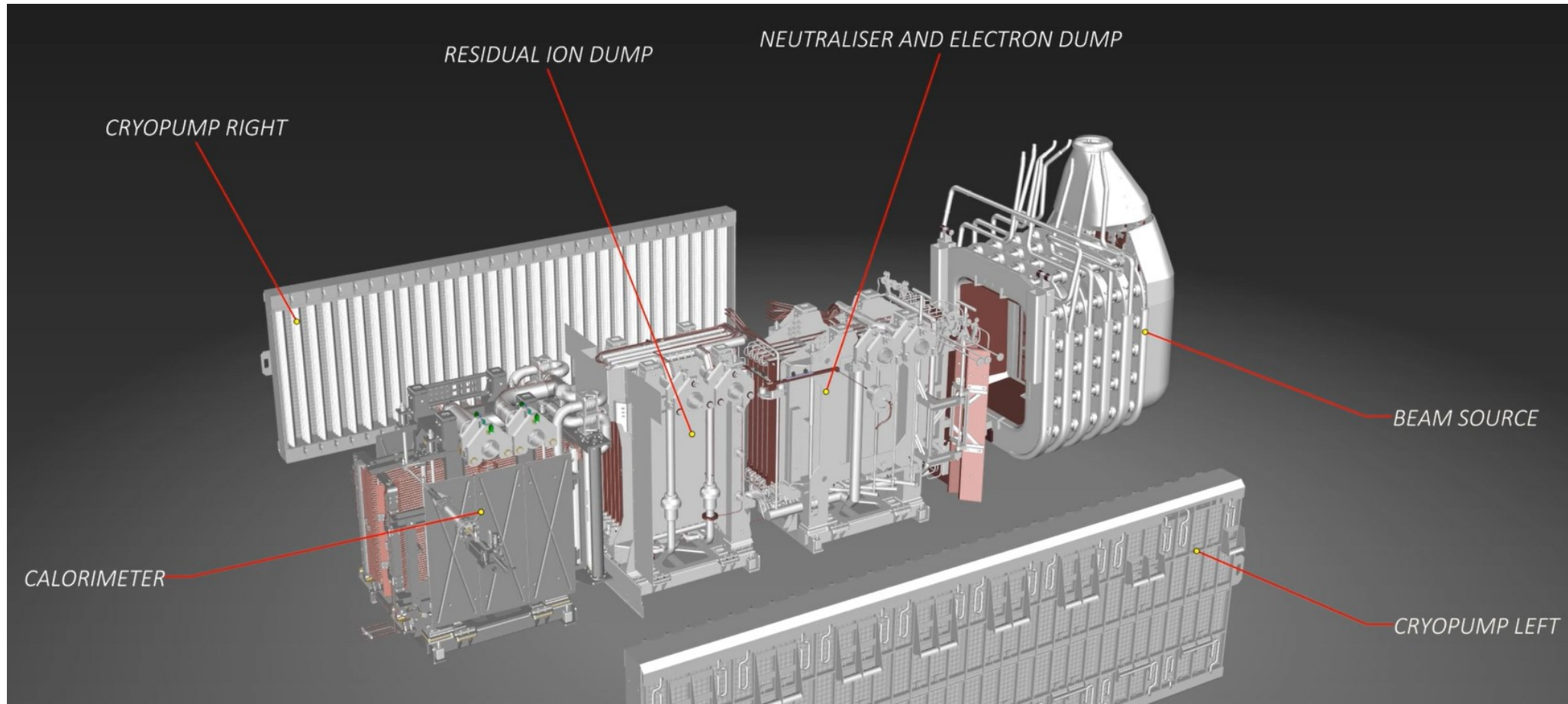


NBI heating is dominant in most past, **present** and **planned** devices

	R ₀ (m)	a (m)	I _p (MA)	B _t (T)	Installed heating power (MW)				
					P-NBI	N-NBI	ECRH	ICRH	LH
TFTR	2.4	0.8	2.2	5	40	-	-	11	-
JET	2.96	1.25	4.8	3.45	34	-	-	10	7
JT-60U	3.4	1.1	5	4.2	40	3	4	7	8
LHD	3.9	0.6		3	12	16	5.4	3	
AUG	1.65	0.65	1.2	3.1	20	@190keV	6	8	-
EAST	1.7	0.4	1.0	3.5	8	-	4	12	10
DIII-D	1.67	0.67	2	2.1	20	-	5	4	-
JT-60SA	2.97	1.17	5	2.25	24	10	7	-	-
HL-3	1.78	0.65	2.5	2.2	20	@400keV	11	6	4
DTT	2.19	0.7	5.5	6	-	10	32	8	-
ITER	6.2	2.0	15	5.3	-	33-50	20-67	10-20	-

@ 1MeV





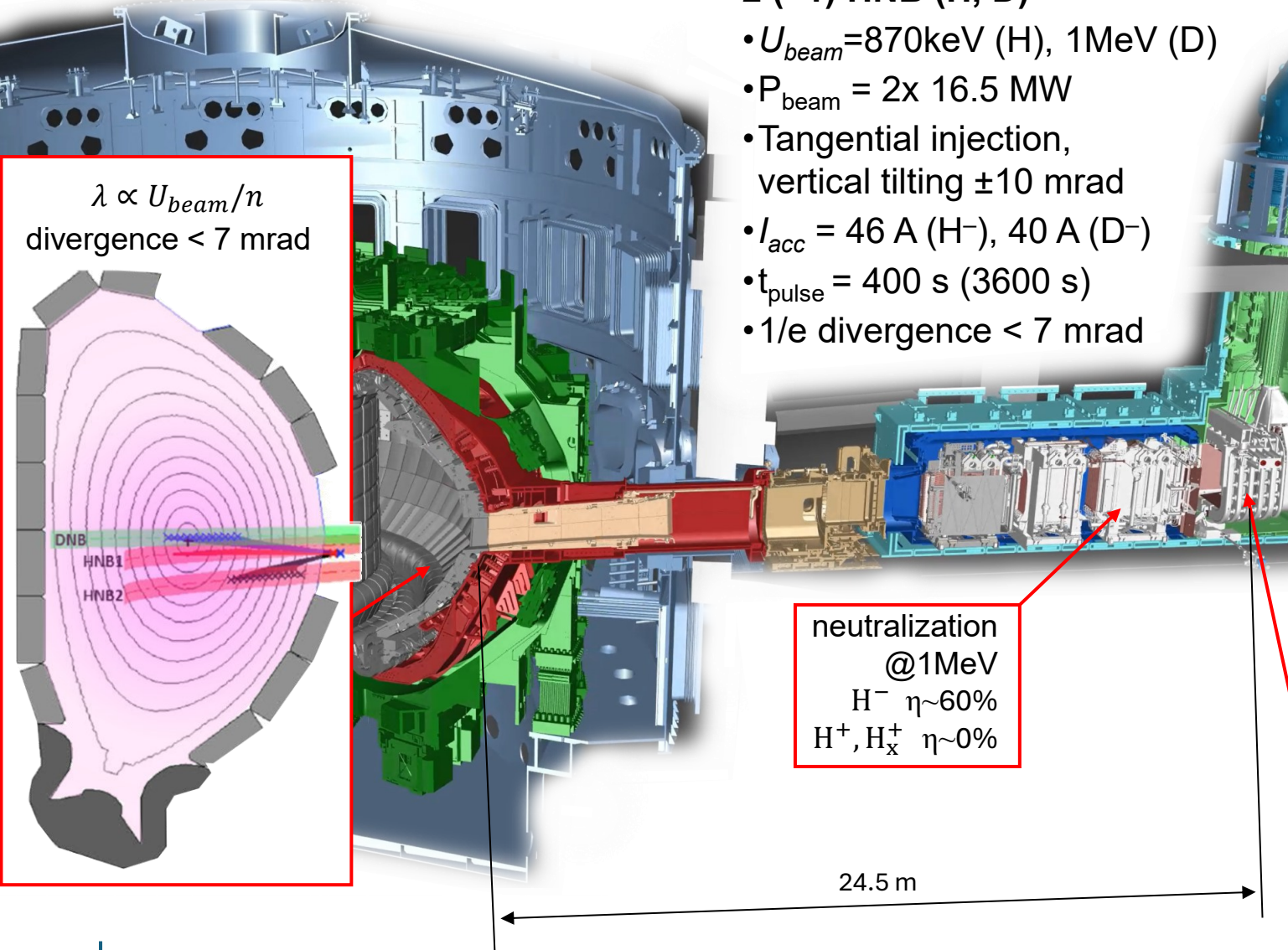
Courtesy Lauro Trevisan

ITER Neutral beam injectors: requirements

2 (+1) HNB (H, D)

- $U_{beam} = 870 \text{ keV (H)}, 1 \text{ MeV (D)}$
- $P_{beam} = 2 \times 16.5 \text{ MW}$
- Tangential injection, vertical tilting $\pm 10 \text{ mrad}$
- $I_{acc} = 46 \text{ A (H}^-), 40 \text{ A (D}^-)$
- $t_{pulse} = 400 \text{ s (3600 s)}$
- $1/e$ divergence $< 7 \text{ mrad}$

$\lambda \propto U_{beam}/n$
divergence $< 7 \text{ mrad}$

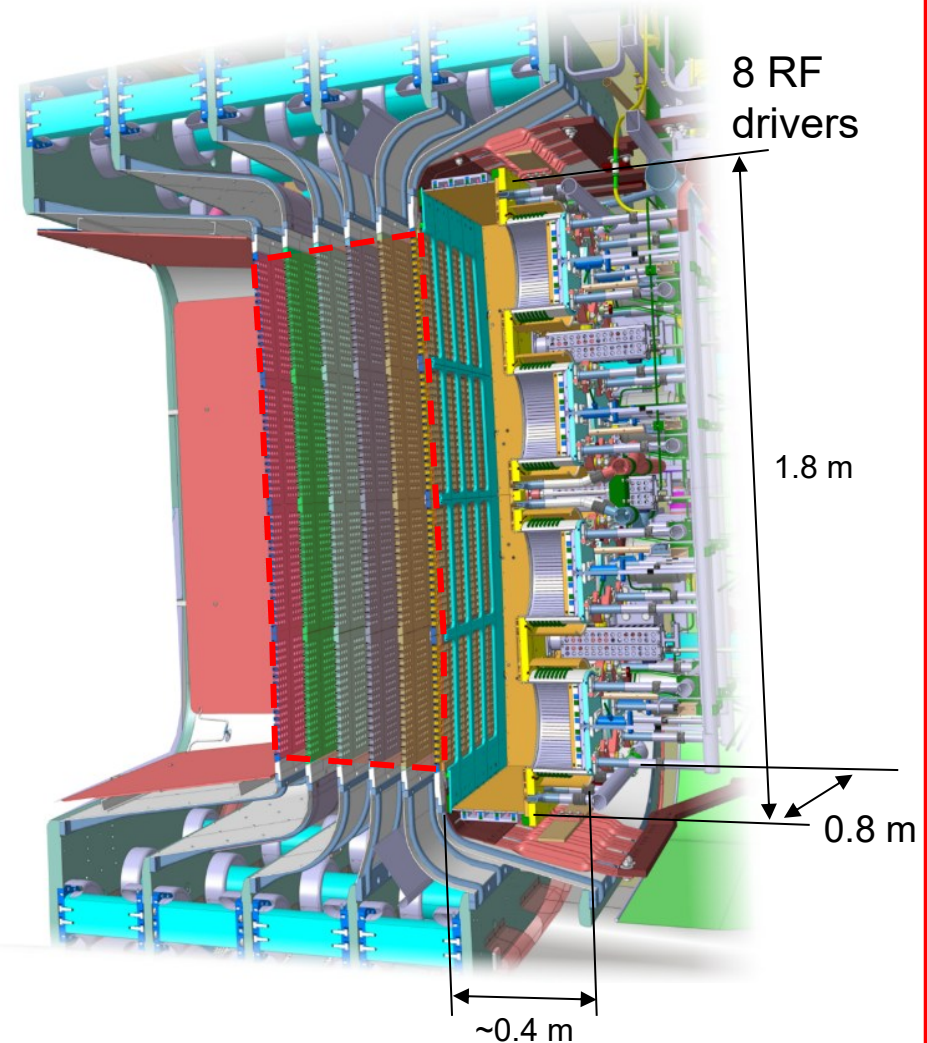


neutralization
@1MeV
 $\text{H}^- \eta \sim 60\%$
 $\text{H}^+, \text{H}_x^+ \eta \sim 0\%$

24.5 m

ITER H-/D⁻ accelerator

- 5 acceleration stages 200kV each;
- 88 mm accel. grid gap, 17 mm thickness;
- 1280 beamlets (homogeneous), single-beamlet aiming



8 RF drivers

1.8 m

0.8 m

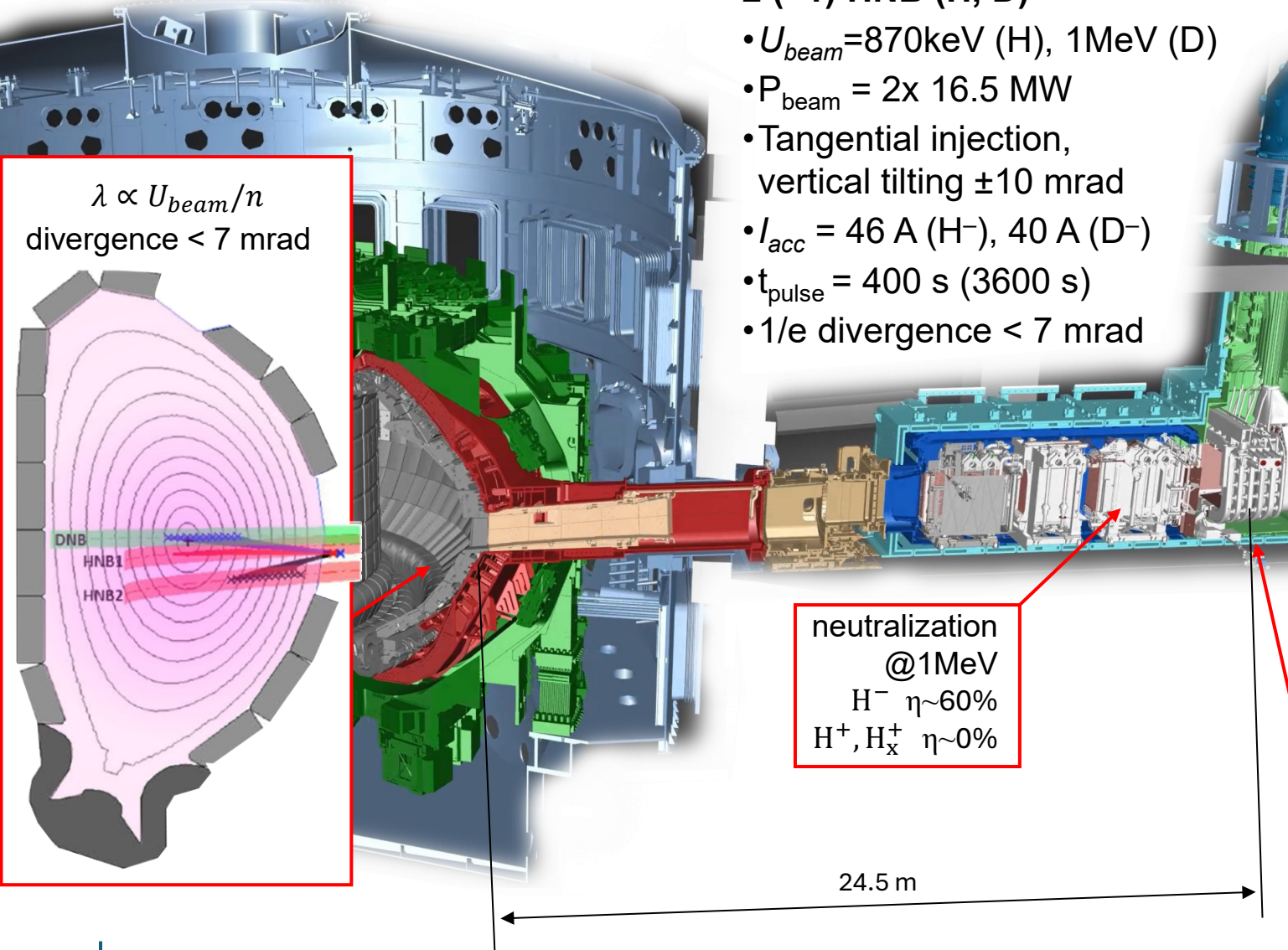
~0.4 m

ITER Neutral beam injectors: requirements

2 (+1) HNB (H, D)

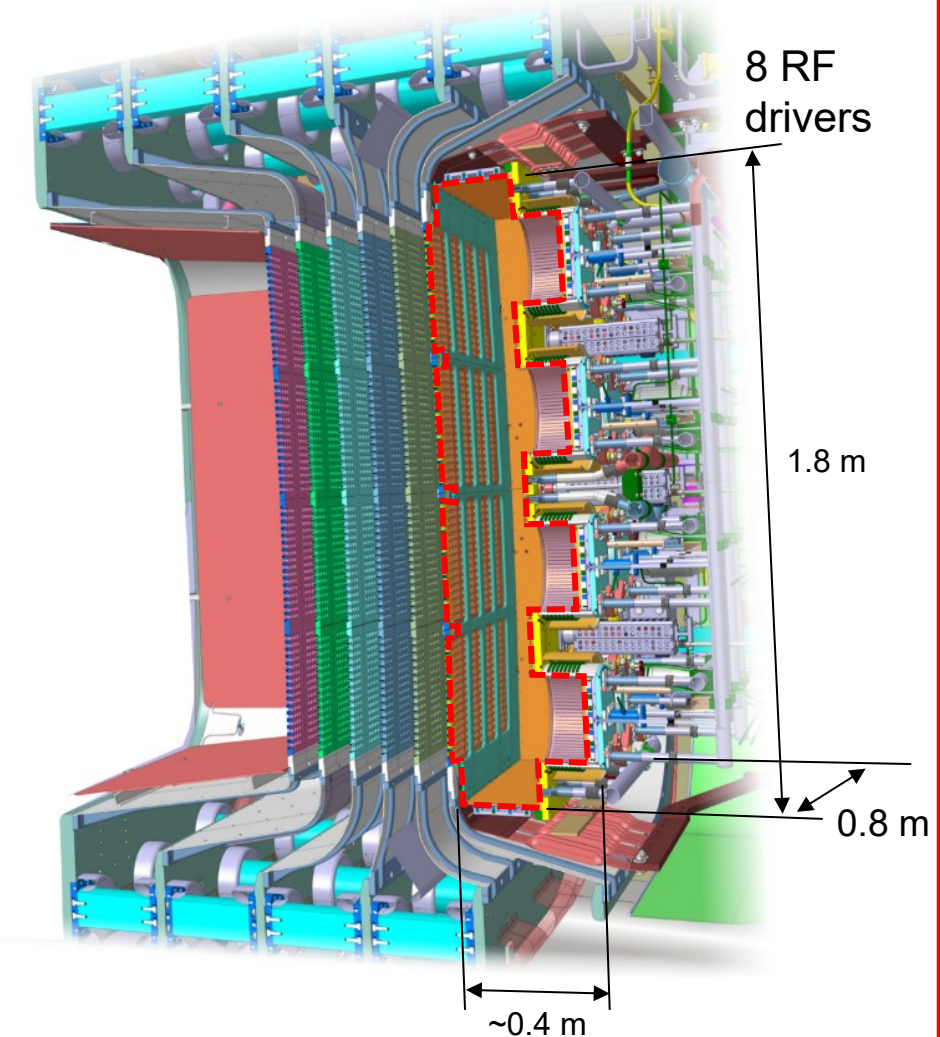
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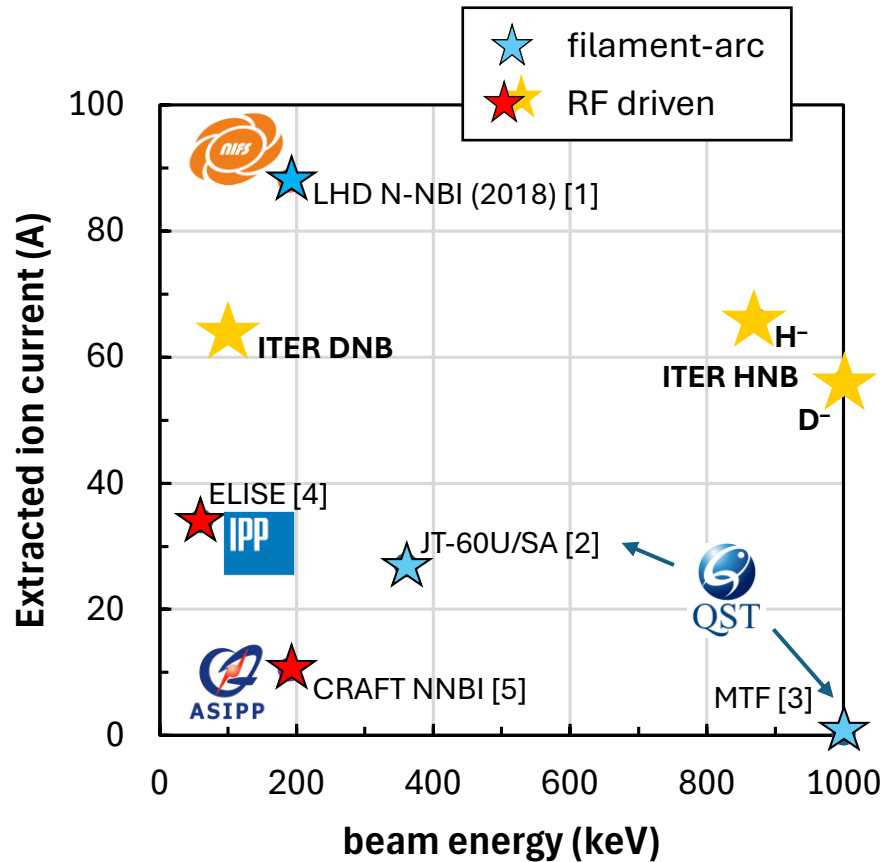


ITER H-/D⁻ source

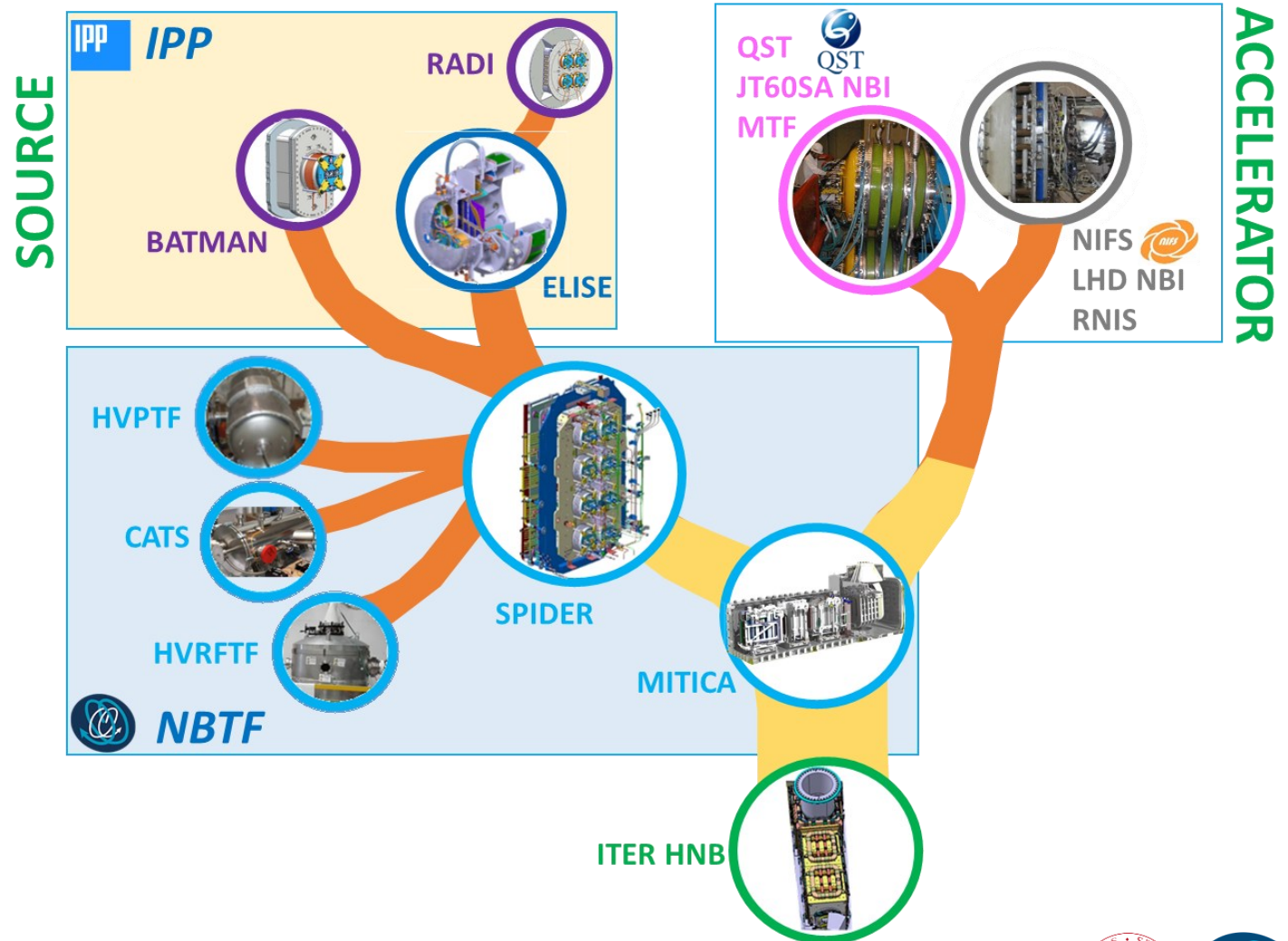
- $J_{ext} = 330 \text{ A/m}^2 \text{ (H}^-)$
- Extraction grid (10kV)
- Cs-assisted plasma-surface production
- 8x RF drivers (total RF power 800 kW)



Negative-ion based injectors for ITER



- [1] K. Ikeda et al 2019 Nucl. Fusion 59 076009
- [2] M. Hanada et al. J. Plasma Fusion Res. SERIES, Vol. 9 (2010)
- [3] M. Kashiwagi et al. Rev. Sci. Instrum. 93, 053301 (2022)
- [4] D. Wunderlich et al 2025 Nucl. Fusion 65 014001
- [5] Jianglong Wei, et al 2026, Nucl. Fusion 66 056006



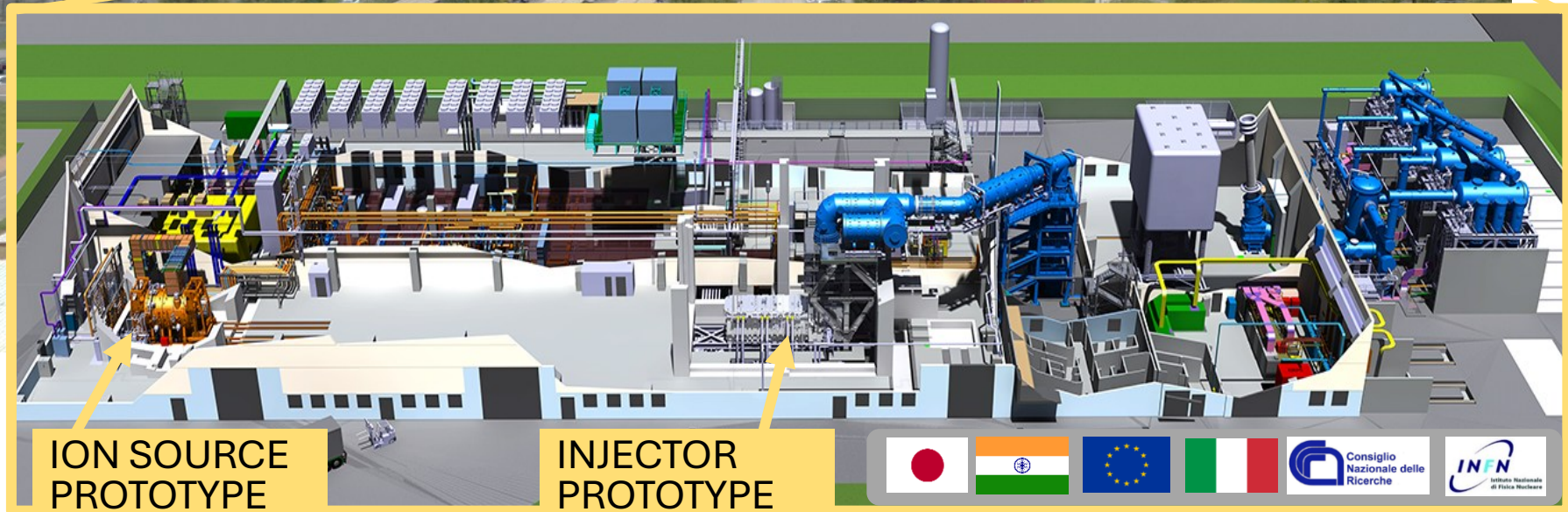
ITER Neutral Beam Test Facility



Padova



Buildings completed 2015
SPIDER started op. 2018
MITICA will start op. in 2027



ION SOURCE
PROTOTYPE
SPIDER

INJECTOR
PROTOTYPE
MITICA



ITER Neutral beam injectors: calculating beam power

Beam acceleration energy and
extracted current

Beam **losses inside** accelerator:
direct interception and stripping

Neutralization yield and
reionization losses

$$P_{HNB} = \overbrace{E_{beam} \cdot j_{ext} A_{ext}}^{\text{Beam acceleration energy and extracted current}} \cdot \overbrace{T_{acc}(1-s)}^{\text{Beam losses inside accelerator: direct interception and stripping}} \cdot \underbrace{T_{Geom}}_{\text{Single beamlet optics and aiming compared to beamline acceptance}} \cdot \overbrace{Y_{neu}(1-R)}^{\text{Neutralization yield and reionization losses}} \geq 16.7 \text{ MW}$$

Single beamlet **optics** and **aiming**
compared to beamline acceptance

j_{ext} = Extracted current density
(330/290 A/m²)

A_{ext} = PG aperture area = 0.197 m²

E_{beam} = beam Voltage
(870 keV/1 MeV)

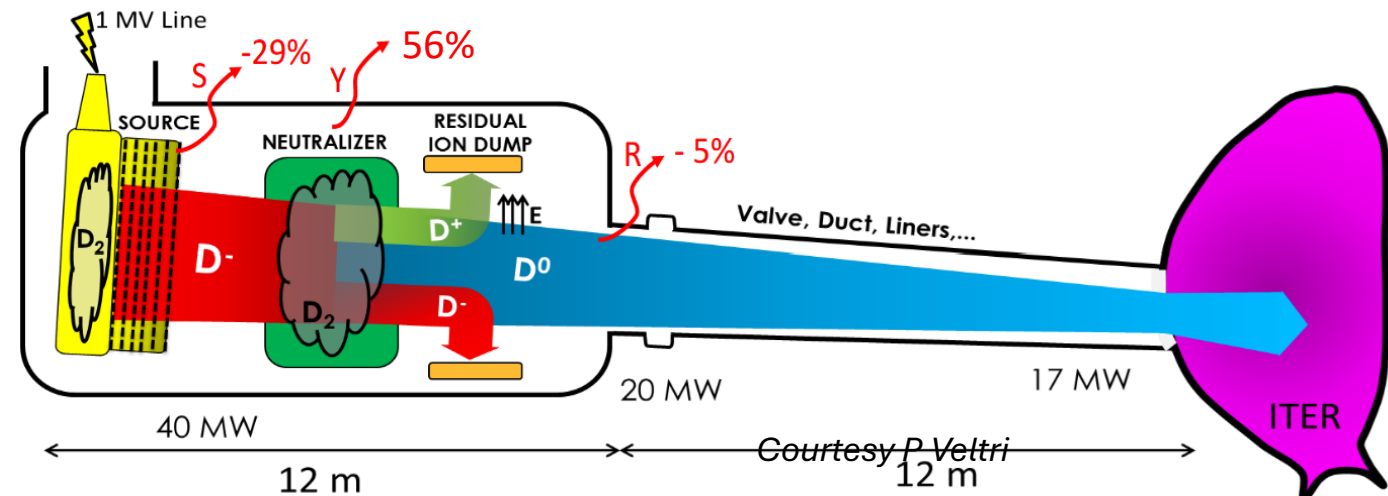
T_{acc} = beam transmission
in the accelerator

S = stripping Losses (25/29%)

Y_{Neu} = Neutraliz. Yield (56%)

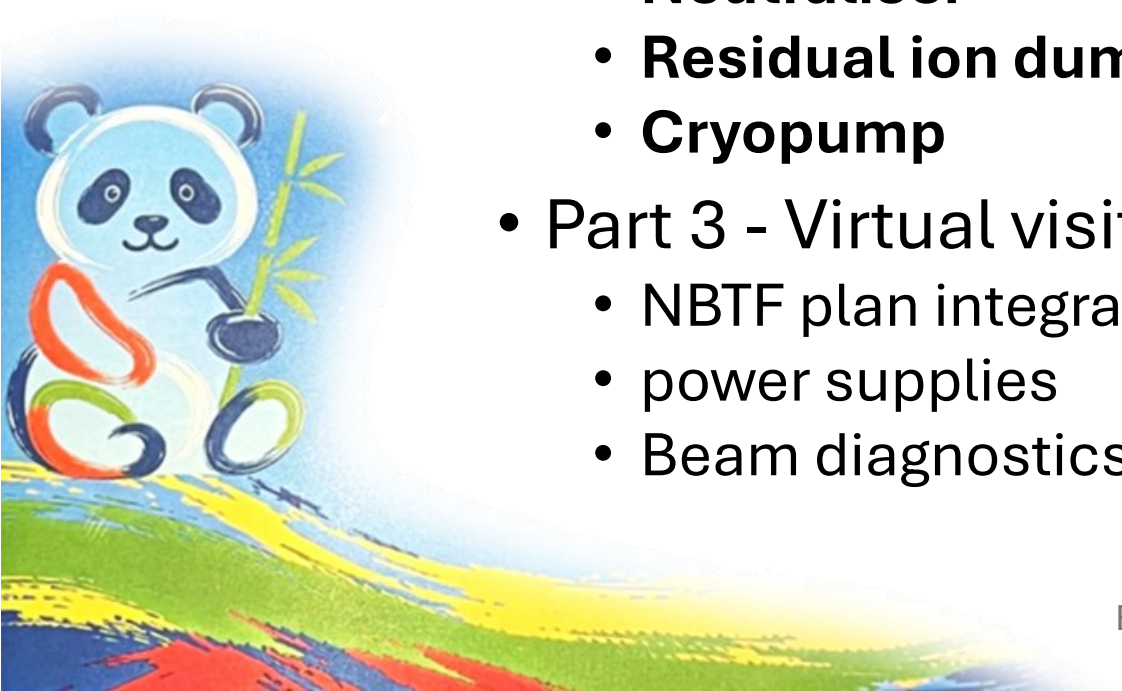
R = Re-ionization Losses (5%)

T_{Geom} (Beamline geometry, divergence,
misalignment, beam tilting)

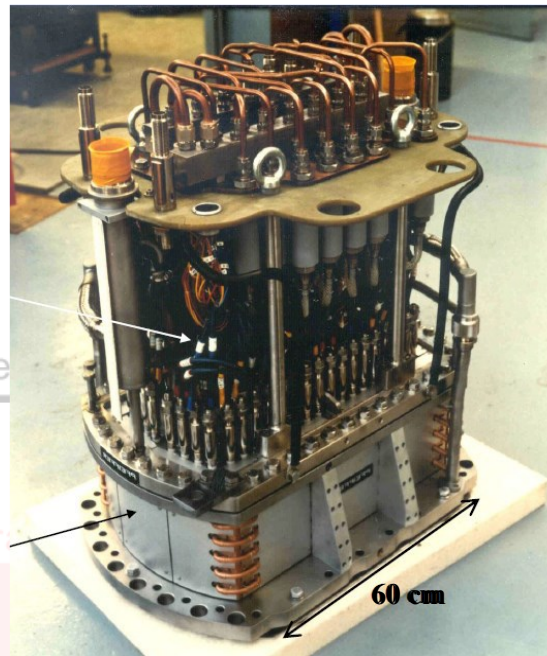
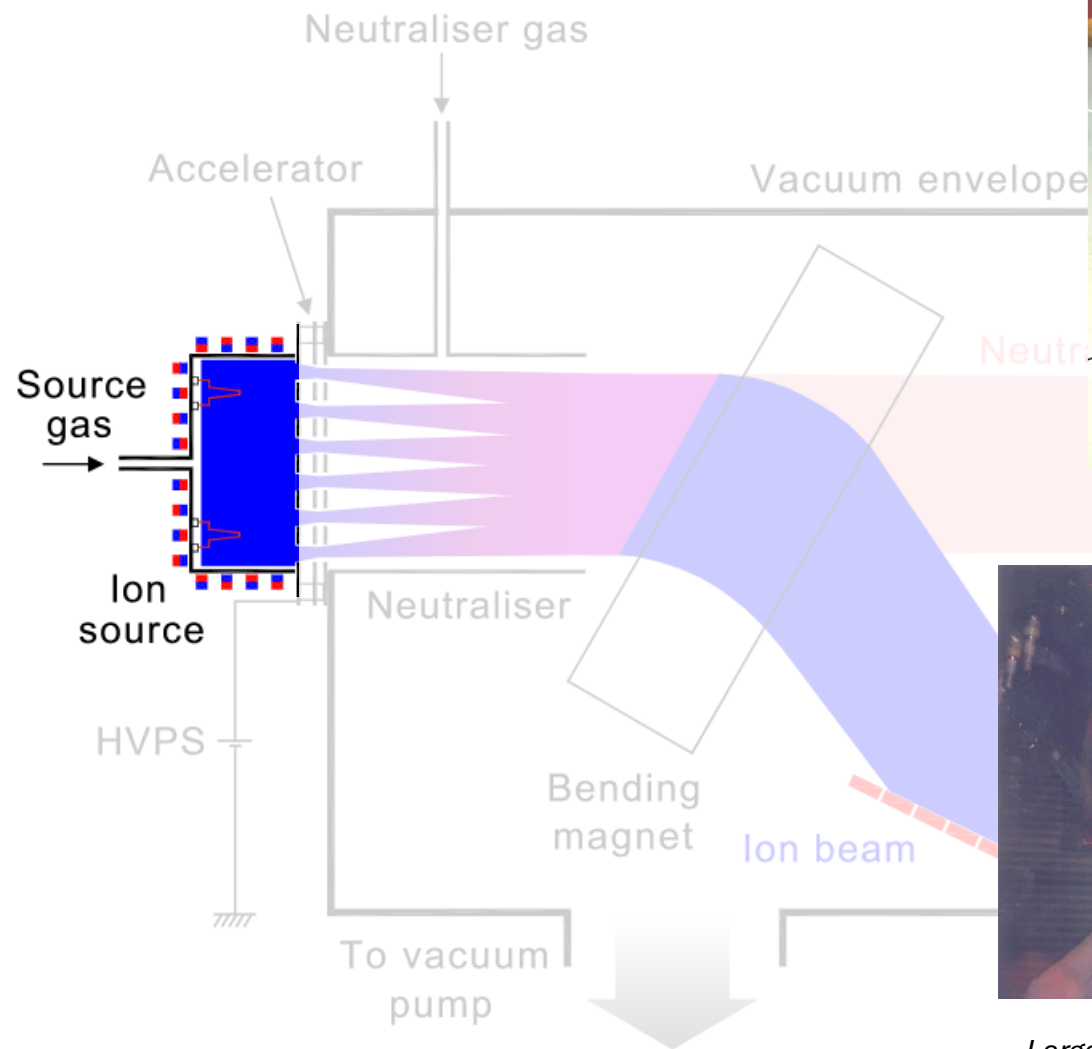


Outline

- Part 1 - Introduction to neutral beam injectors & requirements
 - Beam energy and precursor negative ion beams
 - Present international R&D in view of ITER
- **Part 2 - NBI Systems (general examples and ITER case)**
 - **Ion source**
 - **Accelerator**
 - **Neutraliser**
 - **Residual ion dump and calorimeter**
 - **Cryopump**
- Part 3 - Virtual visit to the ITER Neutral Beam Test Facility
 - NBTF plan integration in ITER plan
 - power supplies
 - Beam diagnostics



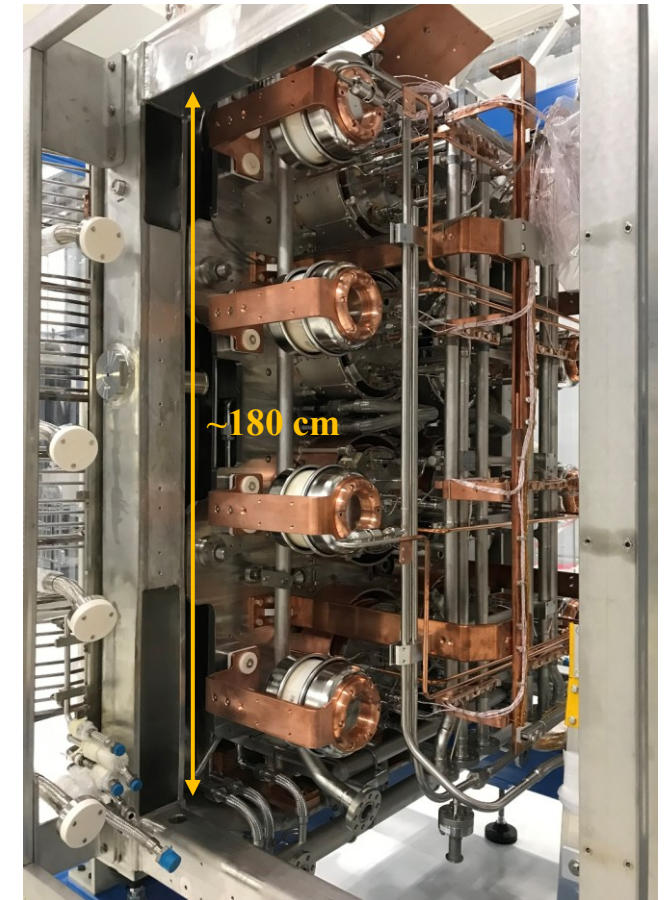
Ion source



JET PINI: a filament driven positive ion source



Large Kamaboko source of JT60-U

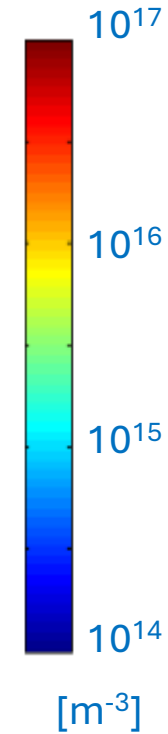
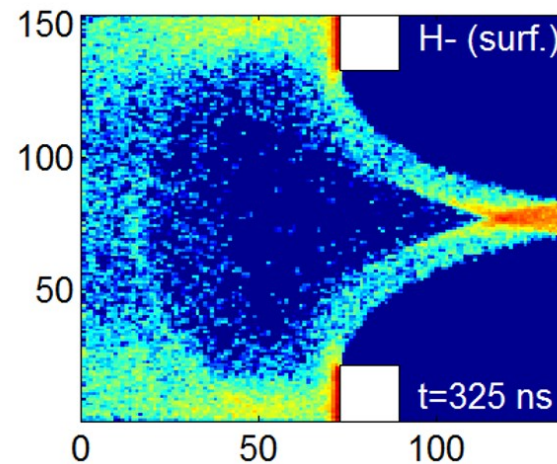
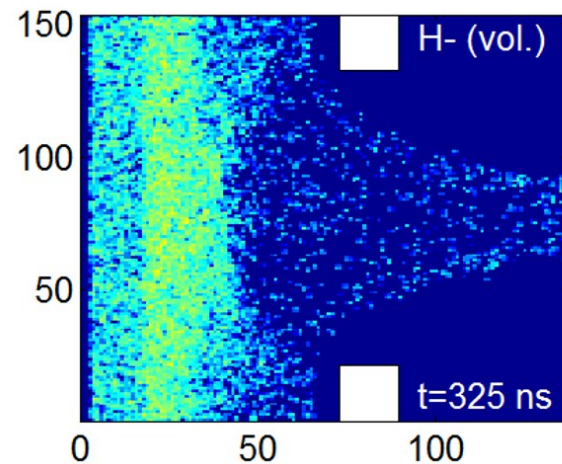
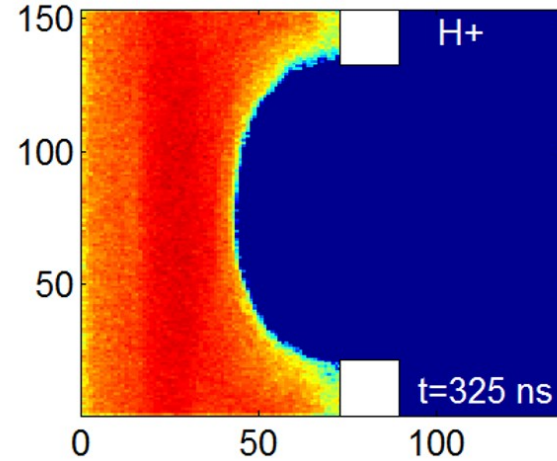
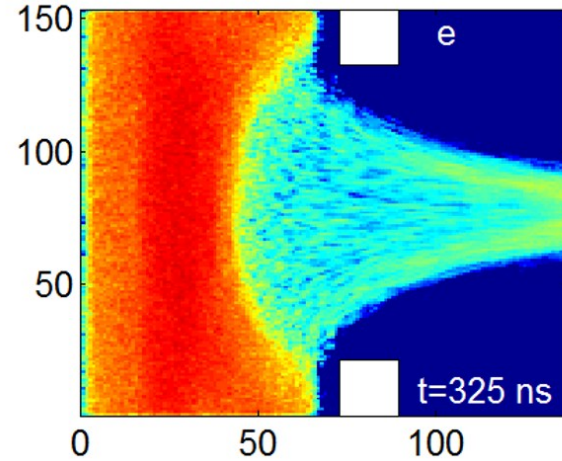


SPIDER source: an RF-driven negative ion source (view from rear side)

Negative ion extraction from the source plasma

PIC simulation, 100 million particles, grid size $3\lambda_D$

$T_e \sim 1$ eV, $T_i \sim 0.1$ eV

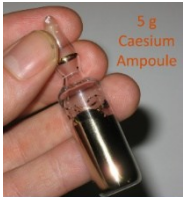


Negative ion sources: caesium and filter field

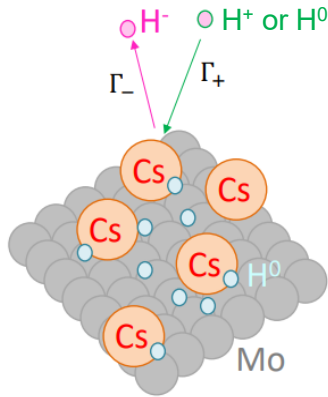
Negative hydrogen ions H^- produced by dissociative attachment of vibrationally excited H_2 molecules... and they are easily destroyed due to the low binding energy of 0.75 eV...

Use of caesium to produce negative ions:

- Coating plasma electrode, lowering work function (binding energy for electrons in a solid)
- H and H^+ can capture electrons to become H^-
- Extractable current density increases by factor ~ 10

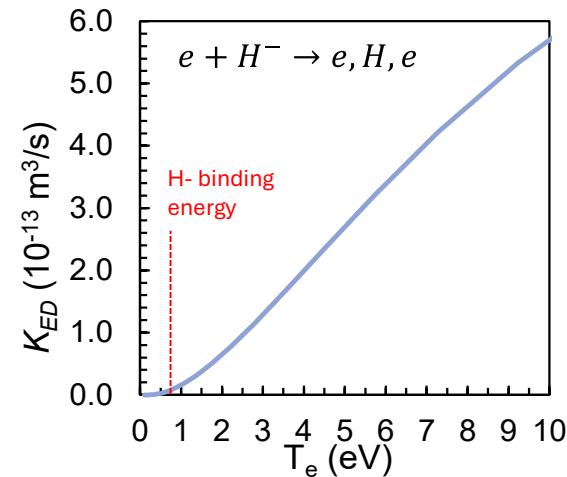
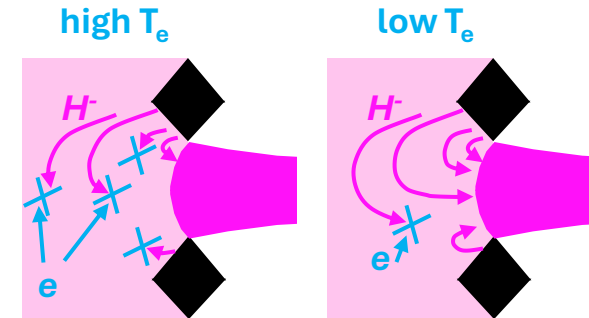


[D. Faircloth, CERN Accelerator School]



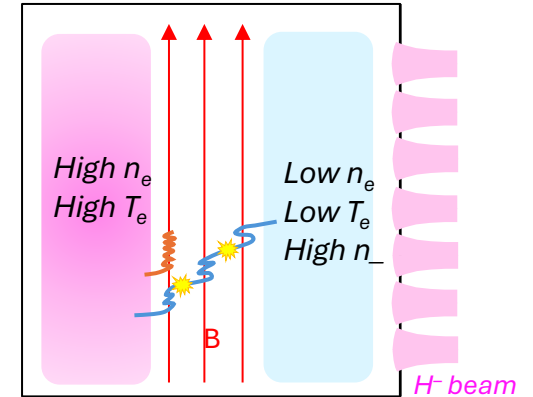
given the quite short λ_- of negative ions before extraction, **uniform H^- production yield** at the extraction region is needed

$$n_- = \frac{(dn_-/dt)_{\text{production}}}{v_{\text{removal}}}$$



At $T_e=2$ eV, electron detachment is 3 times more effective than at $T_e=1$ eV

B field used in negative ion sources to separate in two regions the plasma:

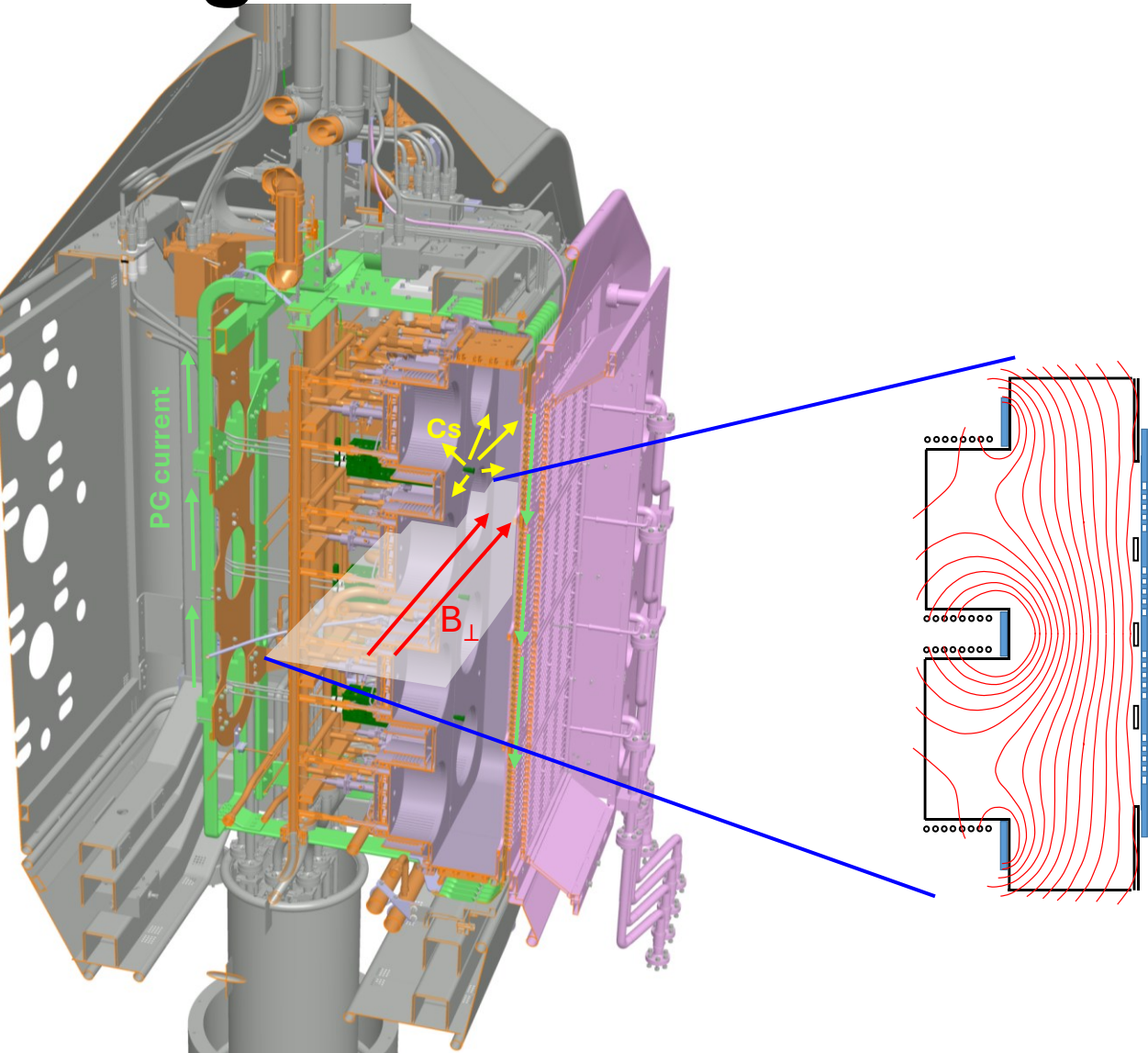


$$D_{\perp} = \frac{D_{\parallel}}{1 + \left(\frac{\omega_c}{v_m}\right)^2}$$

- magnetic **filter field** to reduce diffusion of hot electrons (tandem concept)
- difficult design to get **of uniform effectiveness**, given large dimensions
- Magnetic filter implies vertical drifts (magnetised electrons):

$$\left\{ \begin{array}{l} v_{\nabla B}^{\text{drift}} = (mv_{\perp}^2/2qB) \mathbf{B} \times \nabla B/B^2 \\ v_{\mathbf{E} \times \mathbf{B}}^{\text{drift}} = \mathbf{E} \times \mathbf{B}/B^2 \\ v_{\nabla p \times \mathbf{B}}^{\text{drift}} = -\nabla p_e \times \mathbf{B}/B^2 \end{array} \right.$$

Negative-ion source for ITER: SPIDER

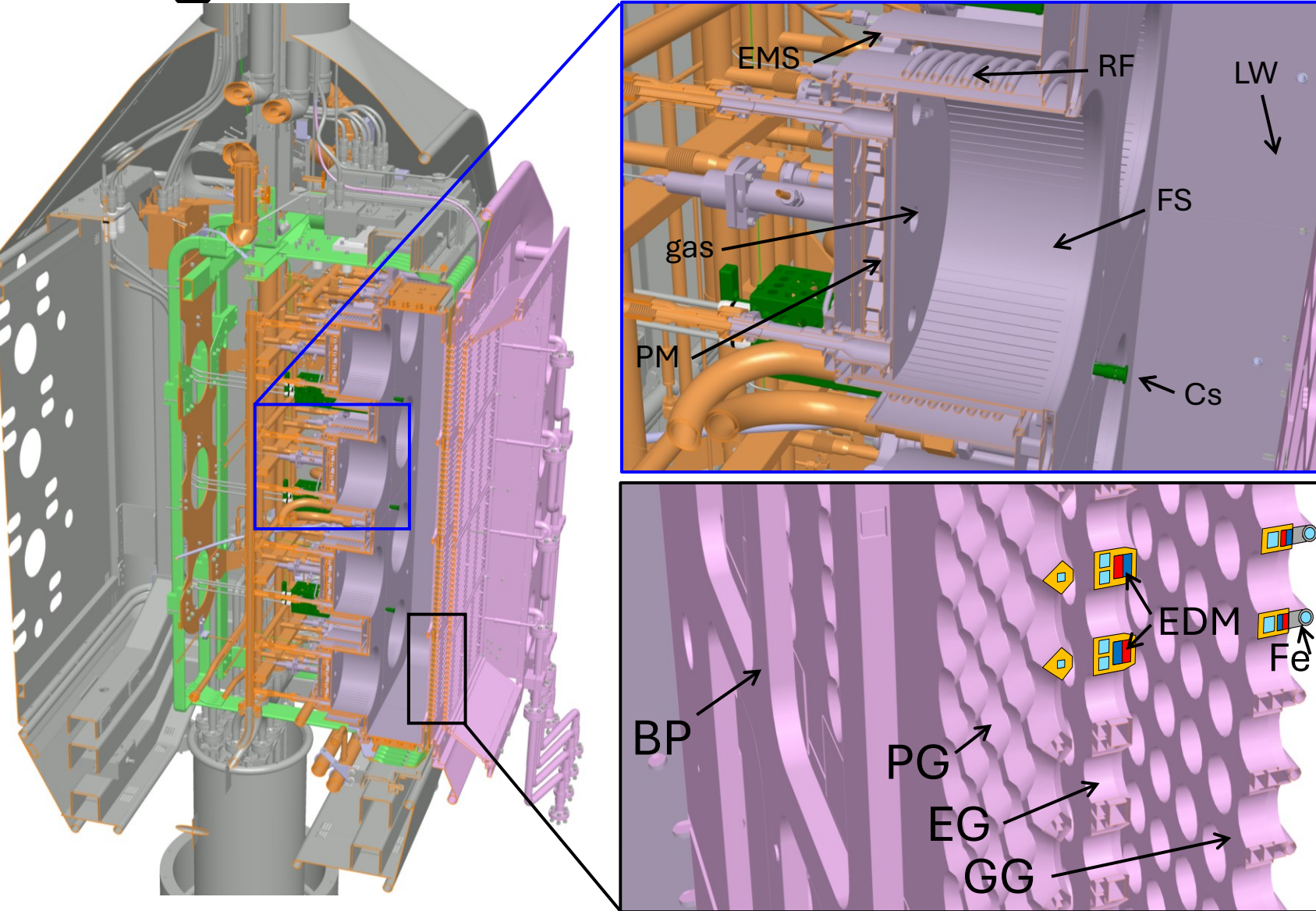


Difficult optimization of $B_{\perp}$, requires **uniform effectiveness:**

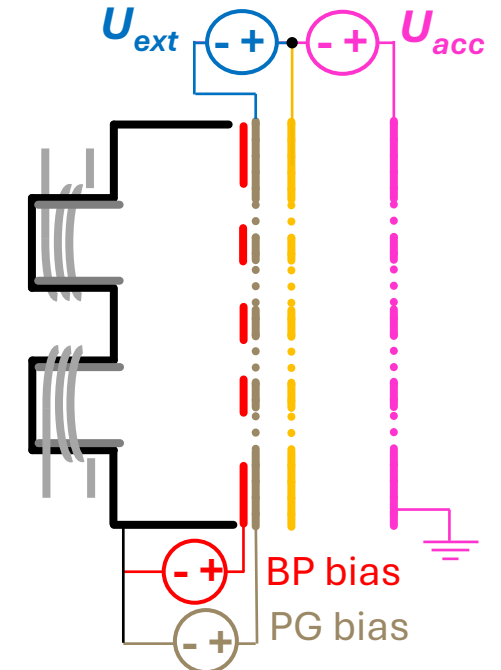
PG current I_{PG} creates horizontal filter field (*before PG, about 1.6mT/kA*)

$B_{\perp}$ causes **perpendicular drifts**

Negative-ion source for ITER: SPIDER



- ICP driven at 1MHz RF frequency: losses on metals
- Source in vacuum, different vacuum levels: «external» antenna
- Slitted Faraday shield: remove capacitive coupling & protect dielectric cylinder from damage and deposition
- EMS Electromagnetic screen: minimize mutual coupling between RF antennas
- Matching circuit on board
- Triode accelerator: Plasma Grid (PG), Extraction Grid (EG), Grounded Grid (GG)
- Electron deflection magnets (EDM) to deflect co-extracted electrons
- Plasma Grid (PG) and Bias Plate (BP) can be biased from the ion source



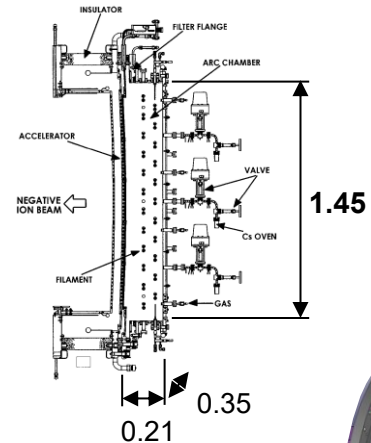
Negative-ion sources for fusion

Test stands for the ITER H⁻ source
(RF sources)

(filament-arc sources)

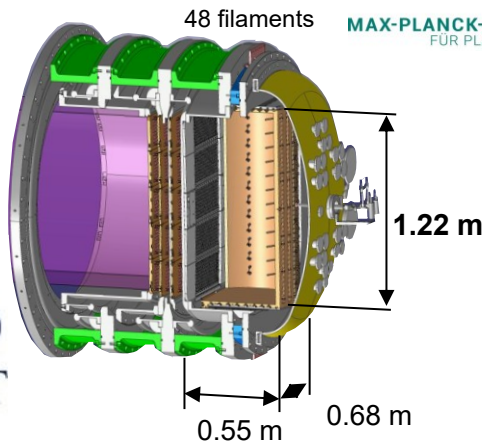
LHD H⁻ source

Volume 0.11 m³
Surface 1.23 m²
1998 (concluded)
 $J_{\text{ext}}=370 \text{ A/m}^2$
div=5.5 mrad



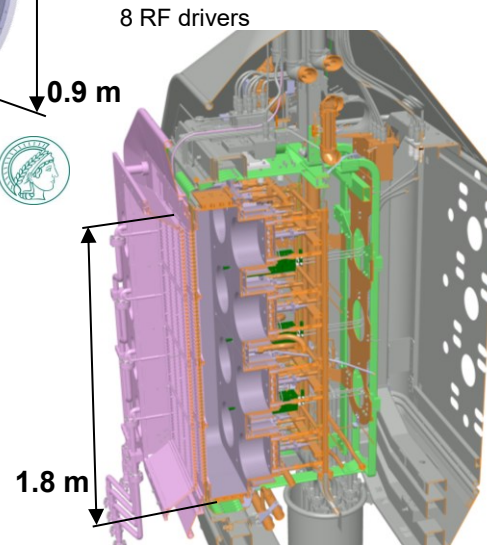
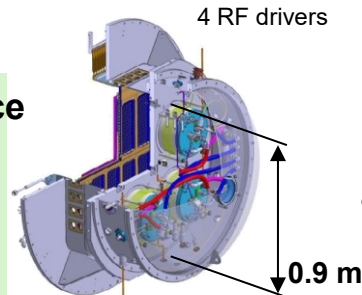
JT60SA H⁻ source

Volume 0.41 m³
Surface 3.2 m²
1996 (mature)
 $J_{\text{ext}}=210 \text{ A/m}^2$
div=8 mrad



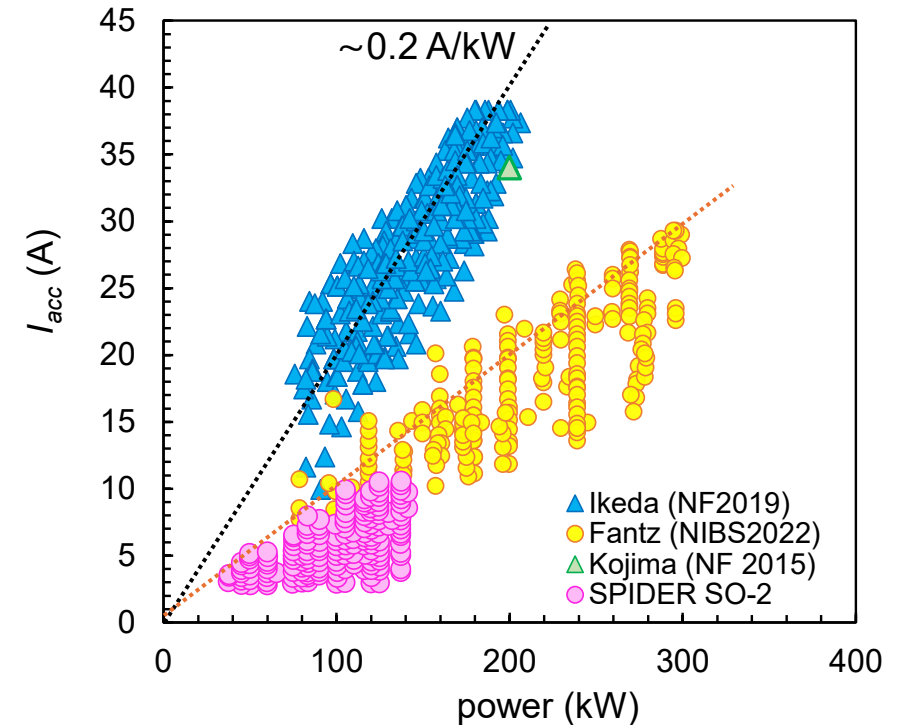
ELISE 1/2 ITER source

Volume 0.24 m³
Surface 2.9 m²
2013 (mature)
 $J_{\text{ext}}=330 \text{ A/m}^2$



SPIDER full-size

Volume 0.44 m³
Surface 5.2 m²
2018 (R&D ongoing)
 $J_{\text{ext}}=220 \text{ A/m}^2$



RF source design:

- Faraday shield (protect dielectric from direct plasma power and metal redeposition, remove capacitive coupling, ...)
- Power coupled to plasma about 50% (i.e. coupling efficiency, loss on metallic structures)

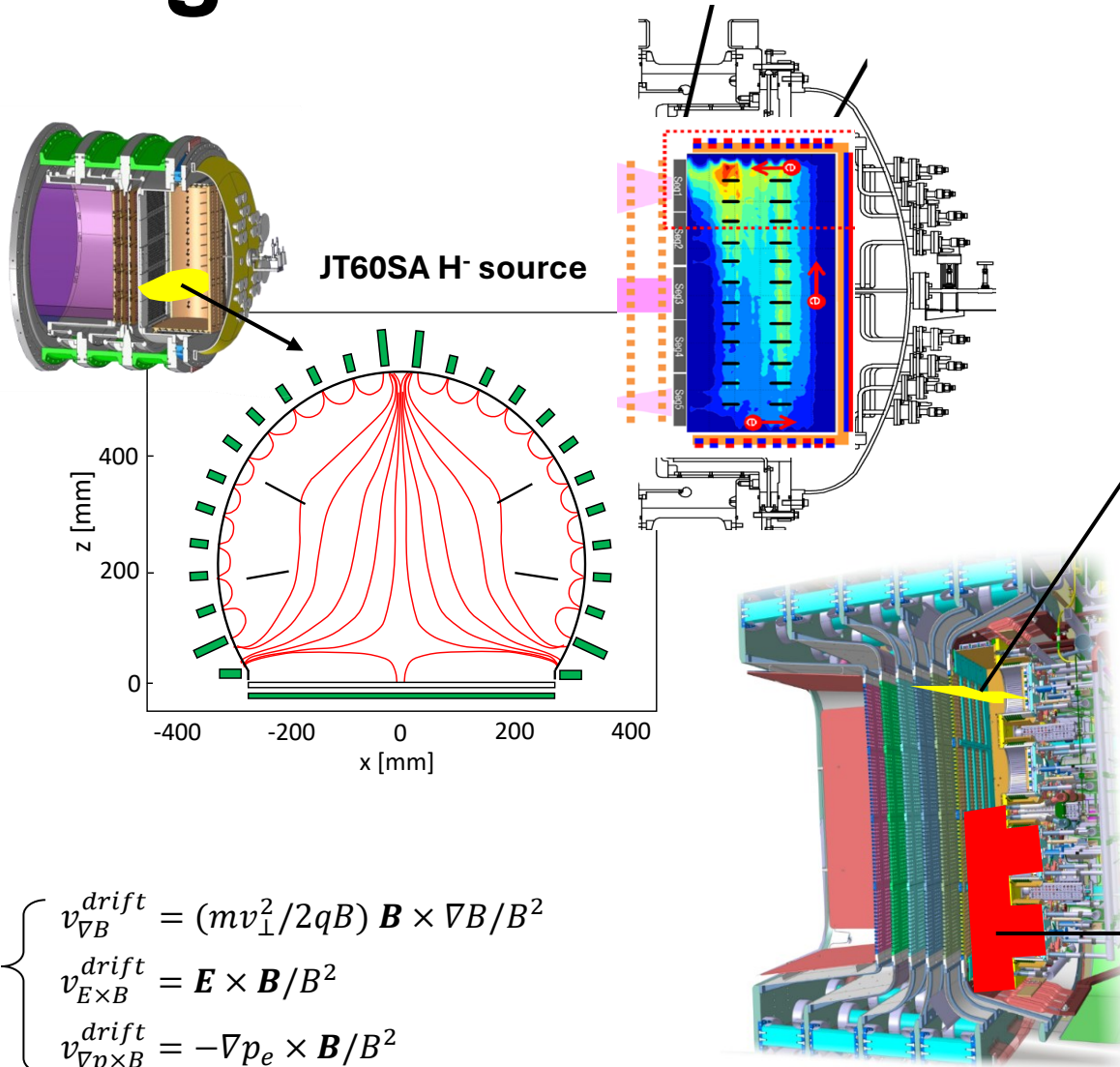
When coupling efficiency is taken into account, **the same conversion negative ion current/coupled power is found (about 0.2 A/kW)**

Y. Takeiri, M. Osakabe, K. Tsumori, Y. Oka,
O. Kaneko, E. Asano, T. Kawamoto, R.
Akiyama and M. Tanaka, J. Plasma Fusion Res. 74, 1434 (1998)
M. Hanada, N. Akino, et al., J. Plasma Fusion Res. Ser. 9 (2010) 208.

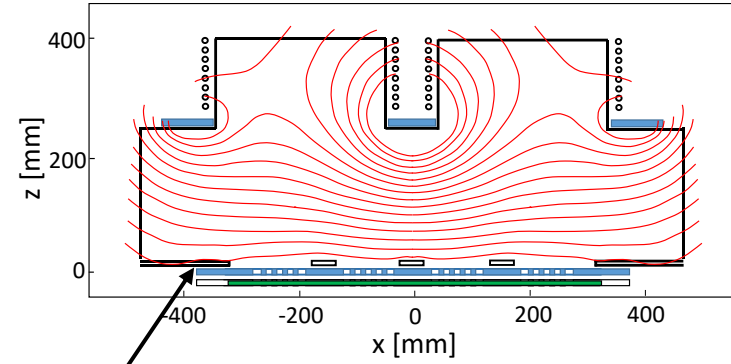
Y. OKUMURA et al., *Rev. Sci. Instrum.*, **67**, 1018 ~1996!
G. Serianni et al. *Rev. Sci. Instrum.* 93, 081101 (2022)
U Fantz *Front. Phys.*, 29 September (2021) Volume 9



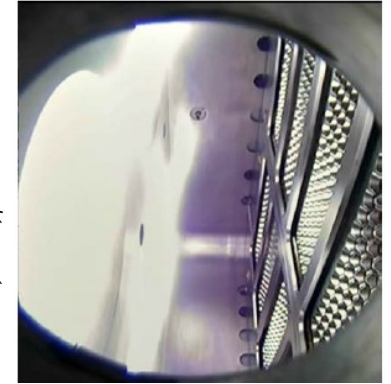
Negative ion sources



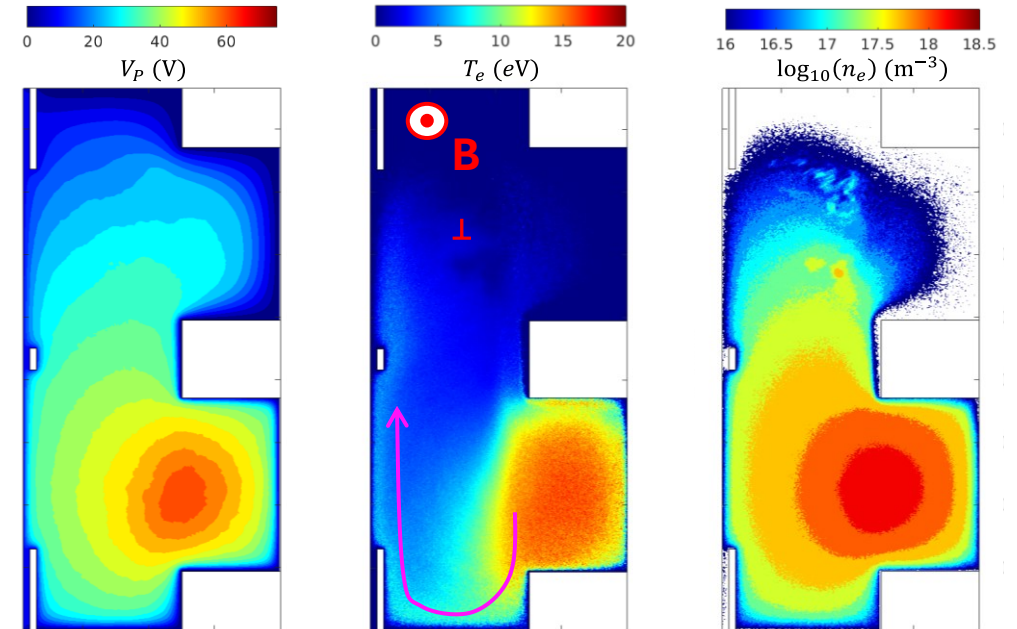
ITER H⁻ source



W. Kraus, ELISE, presented ICIS 2017



V_{BI} 10 V
 V_{BP} 8 V



2D PIC simulation, example with only one RF driver active: hot electrons drifting downward -> Hall current of hot electrons towards the extraction region

RF load

- Inductively Coupled Plasma: 100 kW power per driver, 1MHz frequency
- RF-driven source chosen for ITER to minimize maintenance: Faraday shield and other water-cooled metallic structure reduce the coupling efficiency of the ICP antenna, but they are needed for steady-state, long term op.
- In the RF source, the resonant circuit is on board the source
- Example of load characterization w/ and w/o plasma

P Jain, et al., Plasma Phys. Control. Fusion 65 (2023) 095010

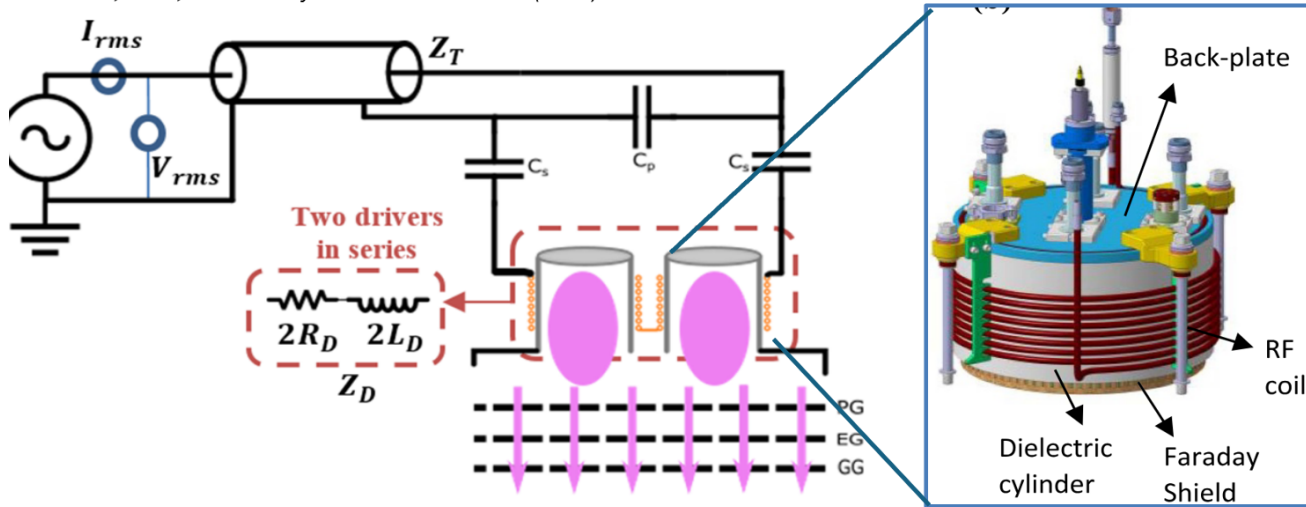
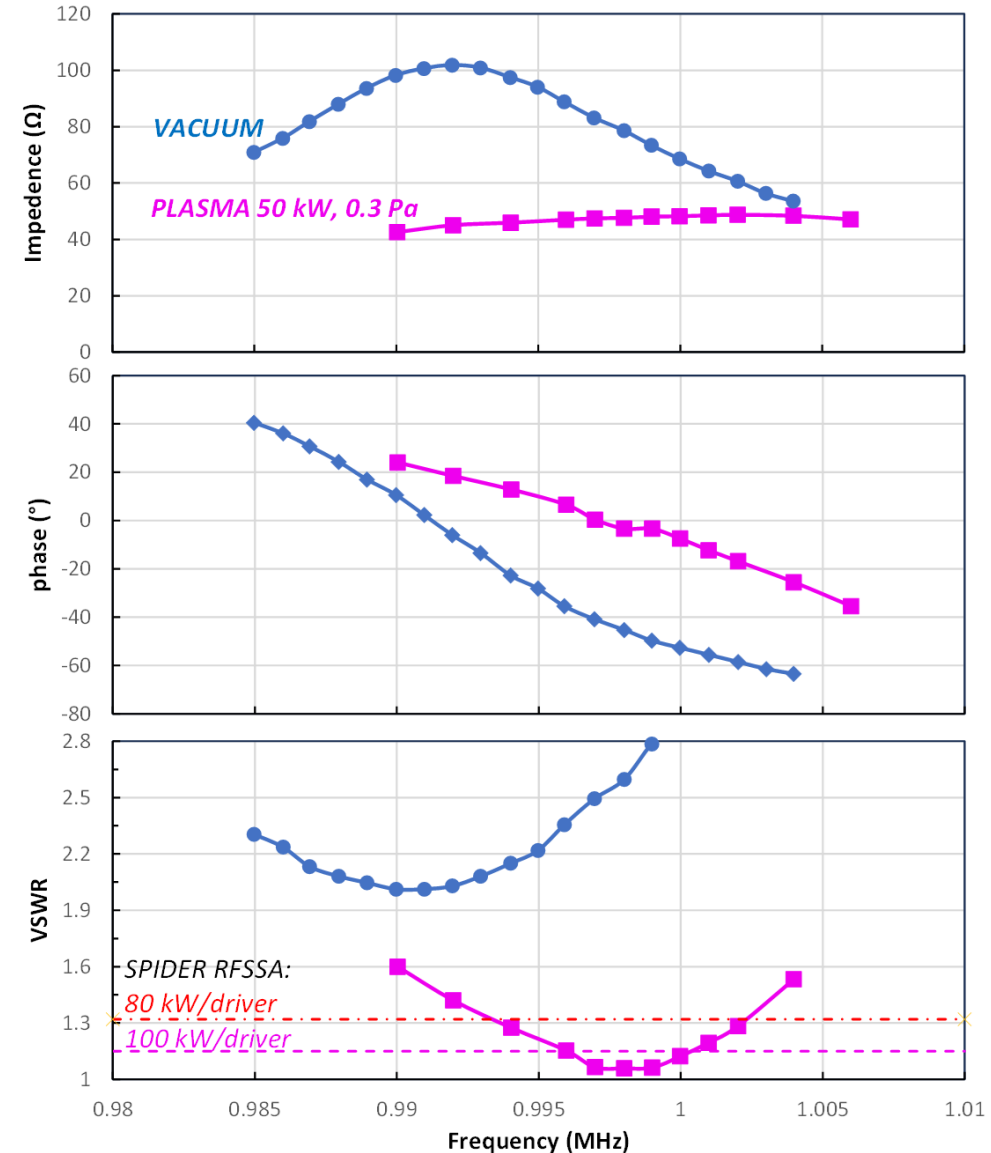
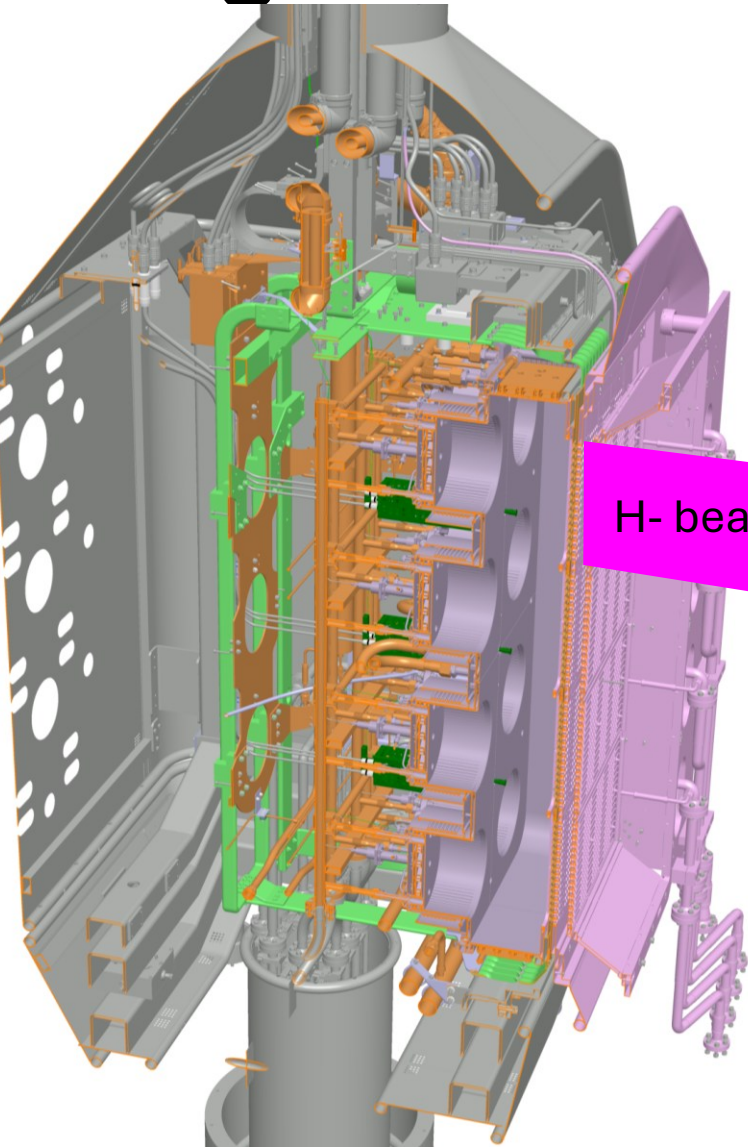


Figure 3. A sketch of an RF circuit of the SPIDER ion source.



Courtesy R Casagrande

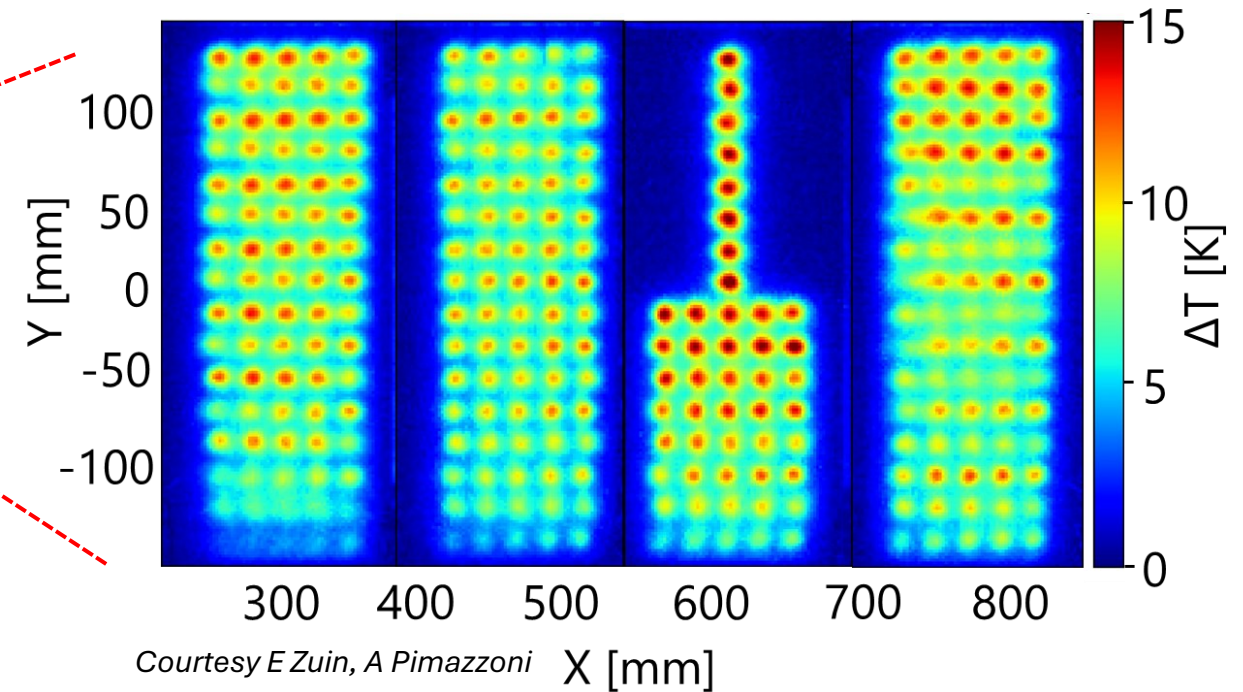
Negative-ion source for ITER: SPIDER



H- beam →



Beam footprint: beam **uniformity** as well as the **single-beamlet properties** (aiming , divergence...) can be obtained on a diagnostic calorimeter STRIKE [1]



example with $\frac{1}{4}$ of the accelerated beam
(4 groups 16x5 beamlets)
→ good result, but it can still be improved

Exercise n. 1

Difficulty: ★★☆☆

Optimize the Caesium injection procedure: reduce the experimental time dedicated to conditioning , yet minimizing the risk of “overcaesiation”

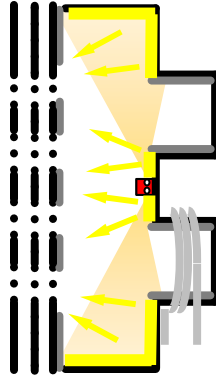


https://www.igi.cnr.it/wp-content/uploads/2026/07/ITER_HNB_CsOvens.html

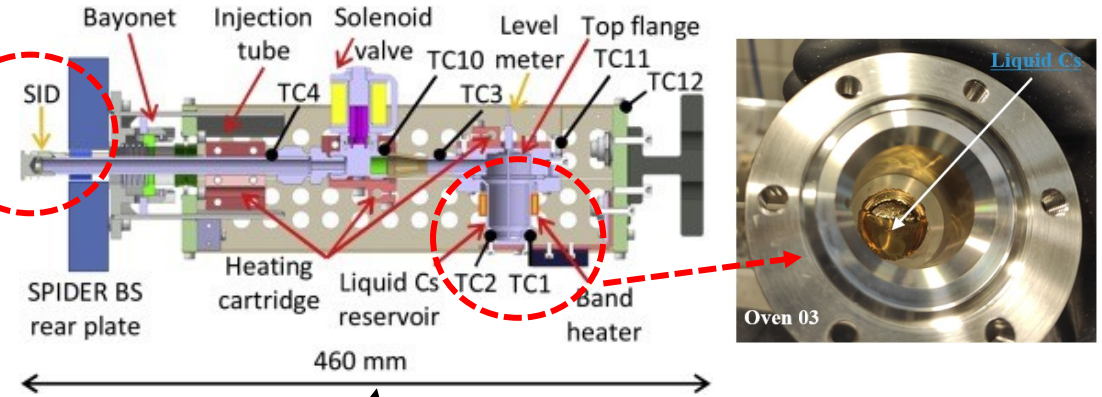
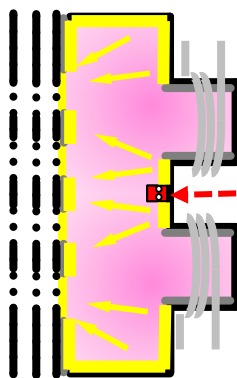


Use of Caesium

Caesium evaporation from three ovens, and ballistic distribution

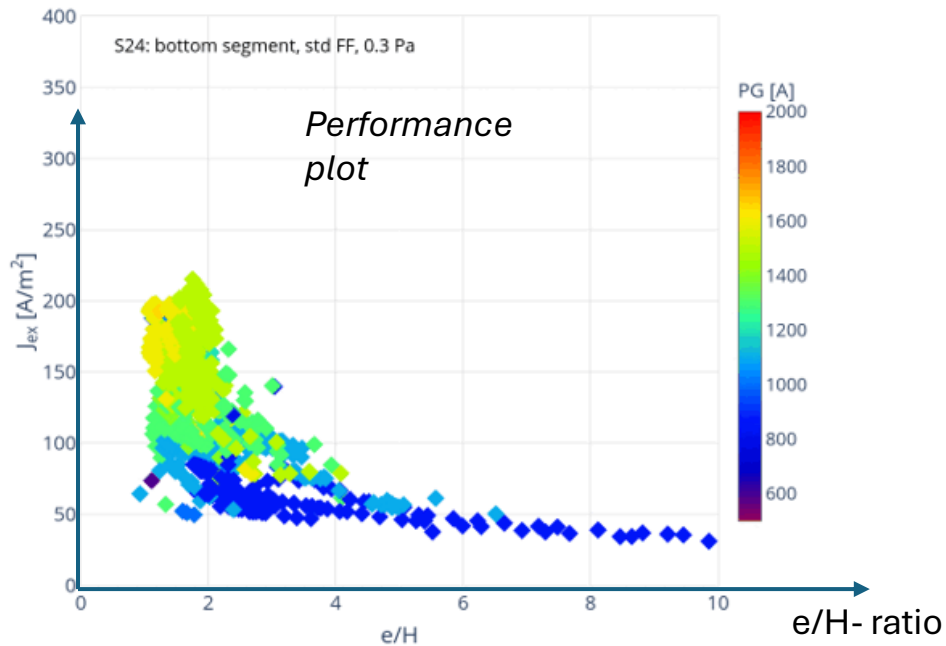


Caesium re-distribution by plasma



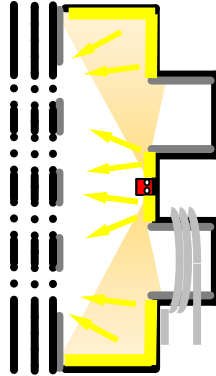
- **Caesium ovens** evaporate Cs vapour inside the plasma source
- **Ratio between coextracted electrons and H⁻** quickly responds to caesium effect

Extracted negative ion current density

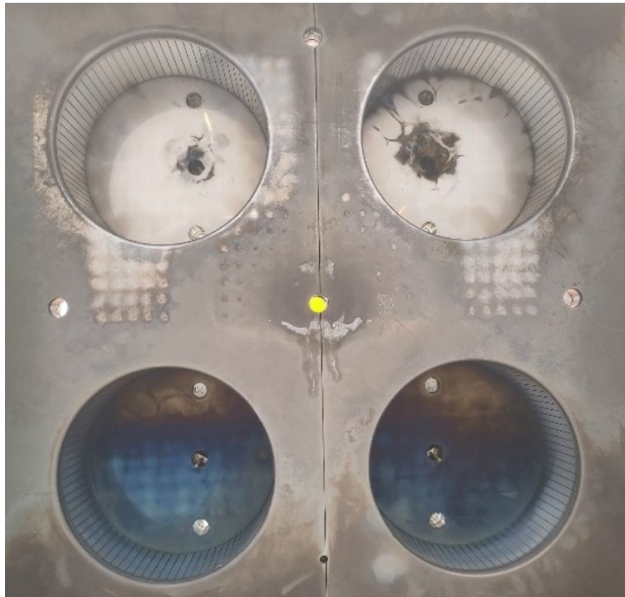
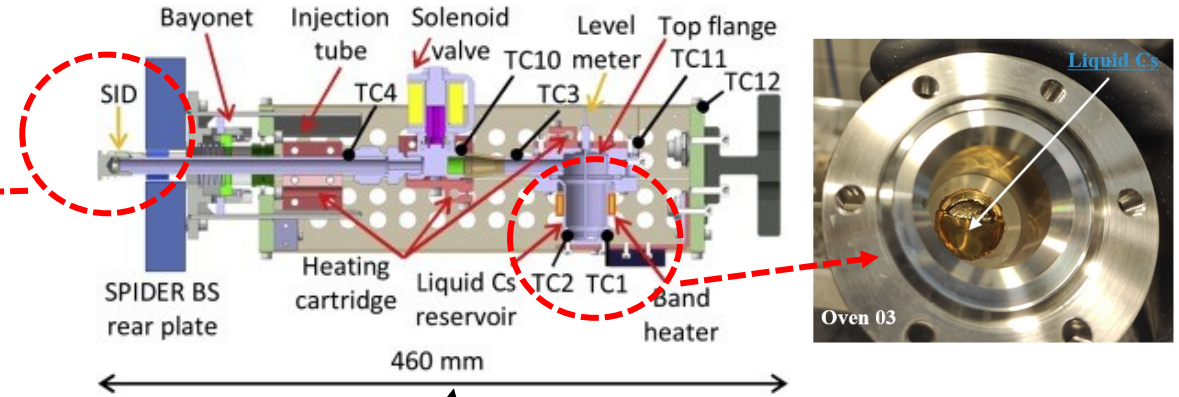
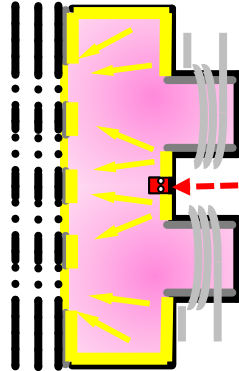


Use of Caesium

Caesium evaporation from three ovens, and ballistic distribution

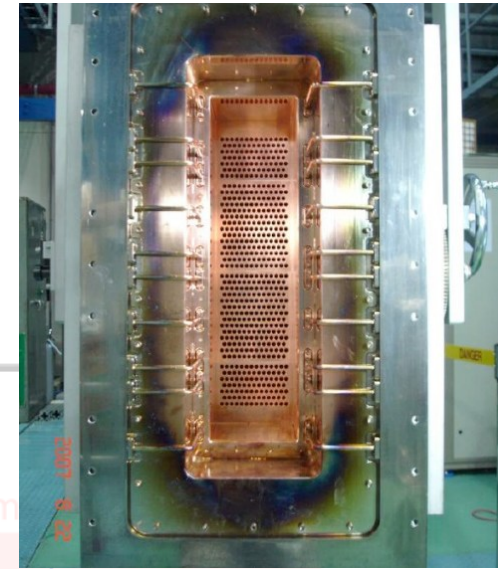
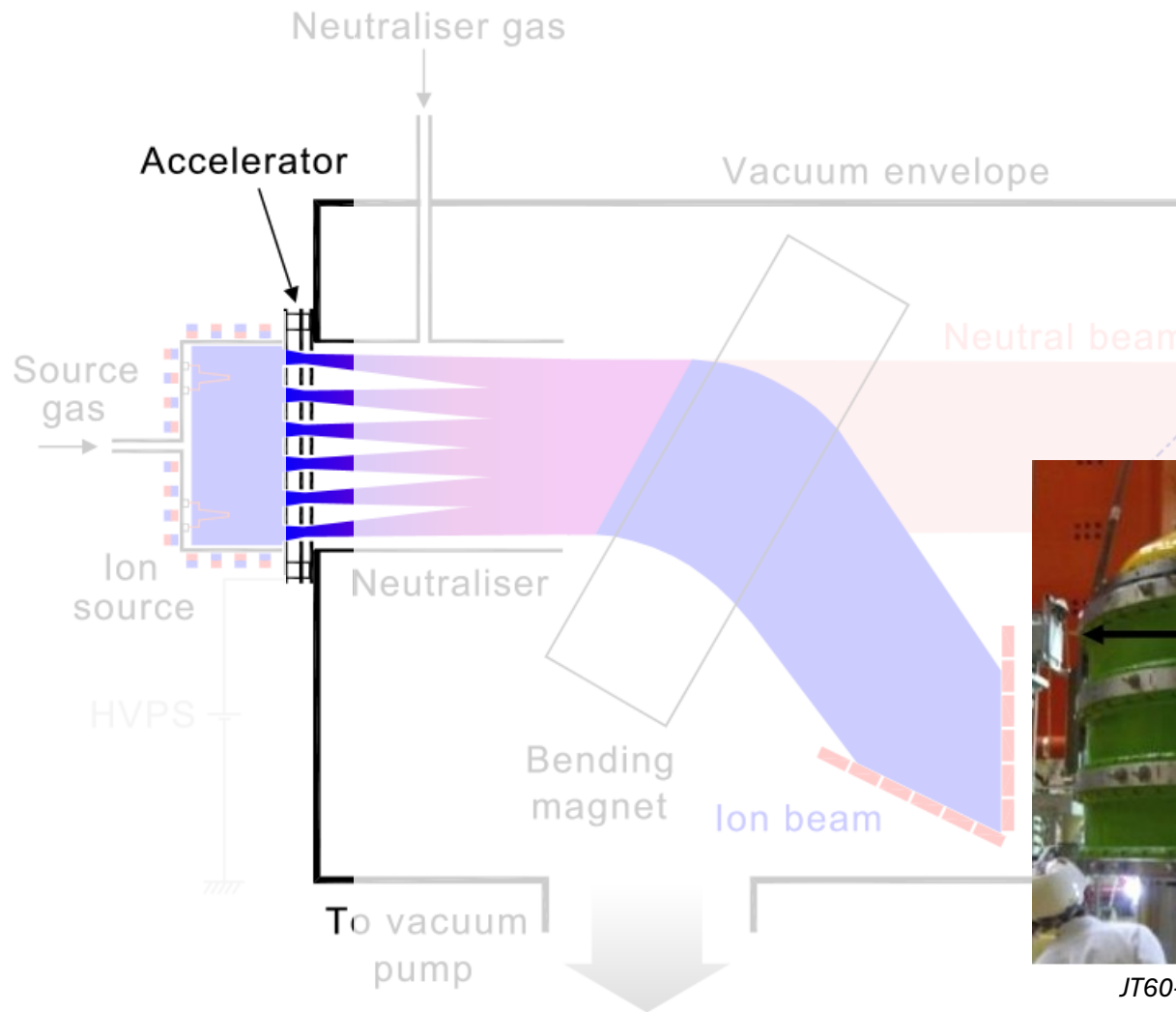


Caesium re-distribution by plasma



- **Caesium ovens** evaporate Cs vapour inside the plasma source
- **Ratio between coextracted electrons and H⁻** quickly responds to caesium effect
- **n_{Cs0} between plasma pulses** (measured by Laser Absorption Spectroscopy) somewhat proportional to instantaneous injection from Cs ovens; effect of daily conditioning; in part, cumulated effects
- **Avoid «overcaesiation»**

Ion beam acceleration



LHD N-NBI accelerator



SPIDER acceleration grid with 1280 apertures

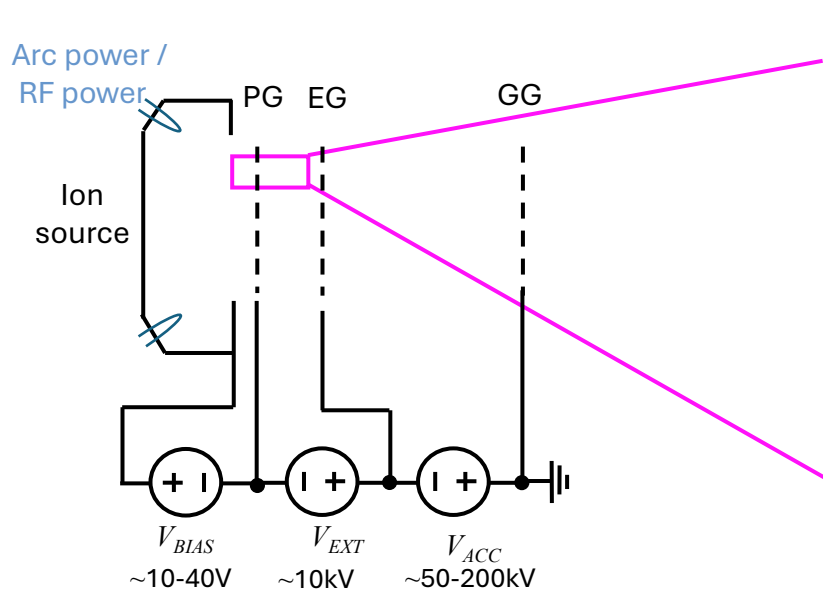


JT60-U 500keV accelerator



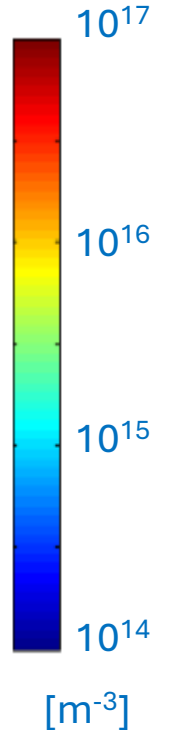
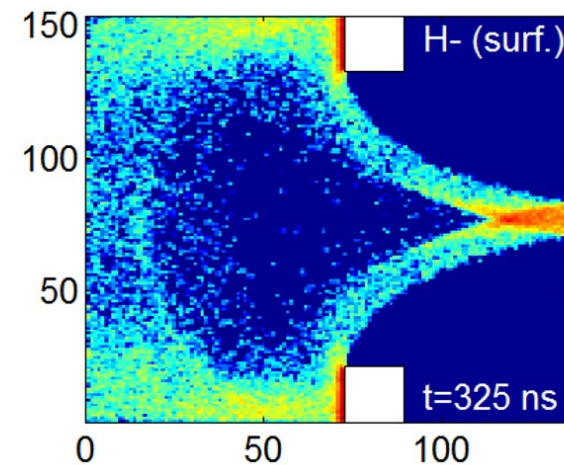
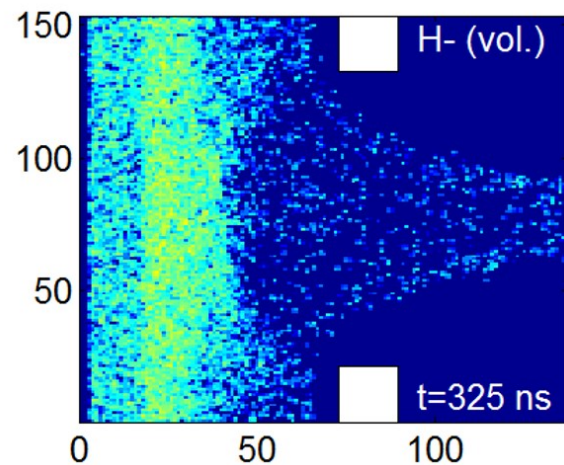
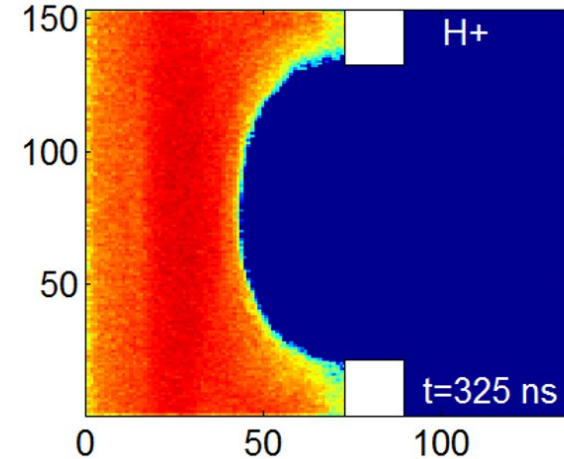
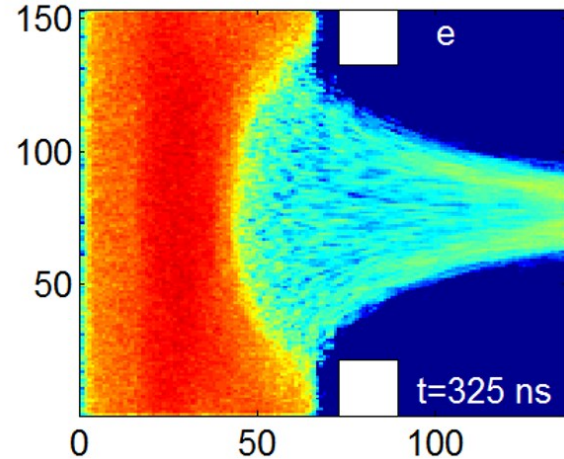
Extractor and accelerator of MITICA during alignment procedures

Ion beam extraction from the source plasma



PIC simulation, 100 million particles, grid size $3\lambda_D$

$T_e \sim 1 \text{ eV}$, $T_i \sim 0.1 \text{ eV}$



Beam composed by multiple beamlets

Ions are extracted from the source plasma through multiple small apertures (10-15 mm diameter) forming “beamlets”

Multiple electrodes are used to **extract ions from the plasma** and accelerate them

Multiple-Aperture-Multiple-Gap (MAMuG)

Exercise n. 2

Difficulty: ★☆☆☆

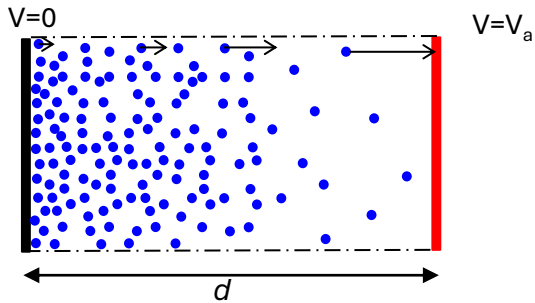
Balance the applied extraction field and the plasma density to avoid incurring in the space-charge limit.



https://www.igi.cnr.it/wp-content/uploads/2026/07/ITER_HNB_CL_RF-1.html

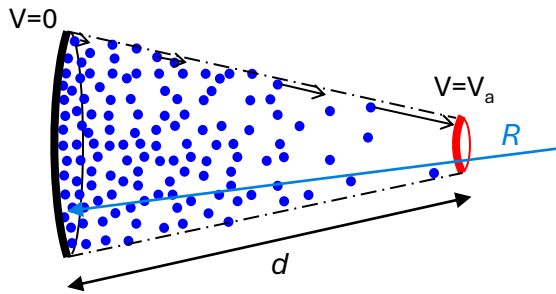


Ion extraction from the source plasma



Child-Langmuir law: current density in a infinite planar diode is limited by the space charge of charges being accelerated.

$$j_s = \frac{4\epsilon_0}{9} \sqrt{\frac{2ez}{m}} \frac{1}{d^2} \cdot V^{3/2}$$



Langmuir-Blodgett law: correction for spherical diodes adding one parameter R

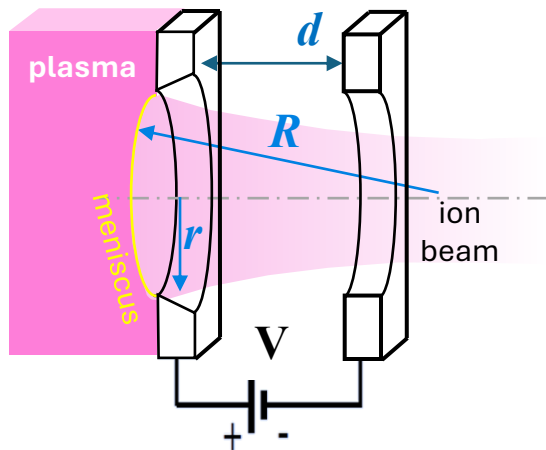
$$j_s \approx \frac{4\epsilon_0}{9} \sqrt{\frac{2ez}{m}} \left(1 - 1.6 \frac{d}{R}\right) \frac{1}{d^2} \cdot V^{3/2} \quad (\text{for } d/R < 0.4)$$

«Meniscus» equipotential surface separating plasma and beam

Meniscus shape depends on beam space charge, described by the perveance

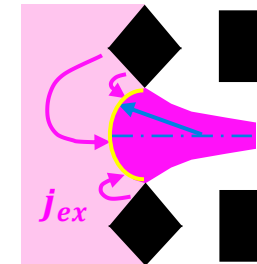
$$\Pi_{ex} = \frac{j_{ex}}{U_{ex}^{3/2}}$$

Convenient units: $1 \mu\text{Perv} = 10^{-6} \text{ Am}^{-2} \text{ V}^{-3/2}$



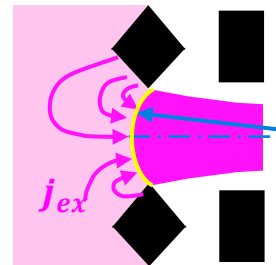
Perveance contribute to beamlet optics (R=focal distance) and to maximum current limit

under-perveance condition

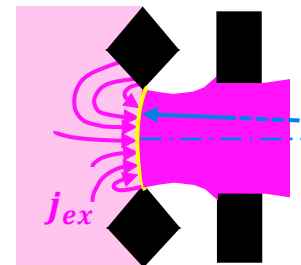


Small Π
→ short R
→ overfocusing

perveance match

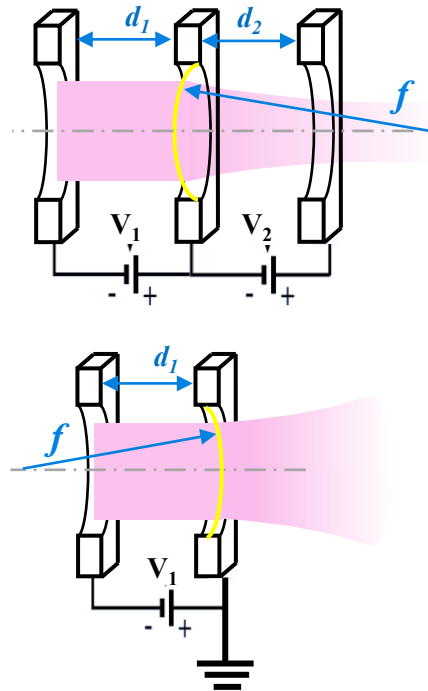
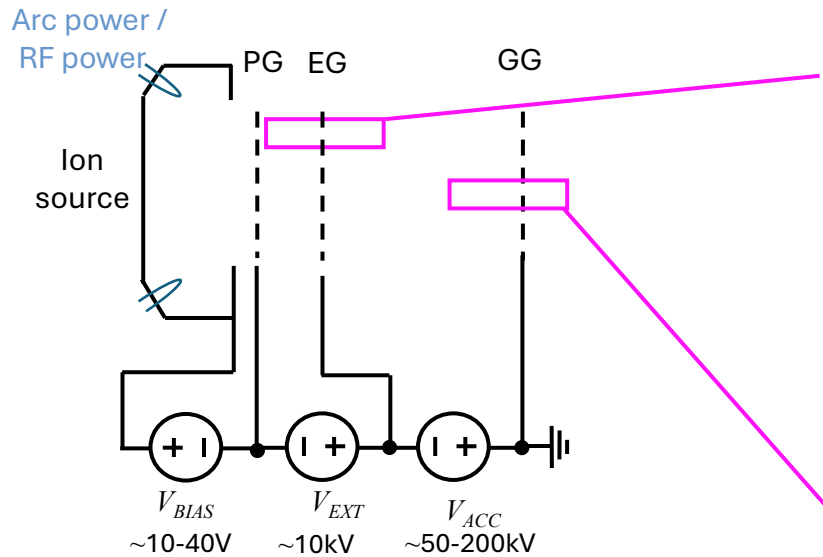


over-perveance condition



High Π
→ large R
→ ions lost on EG

Ion beam optics



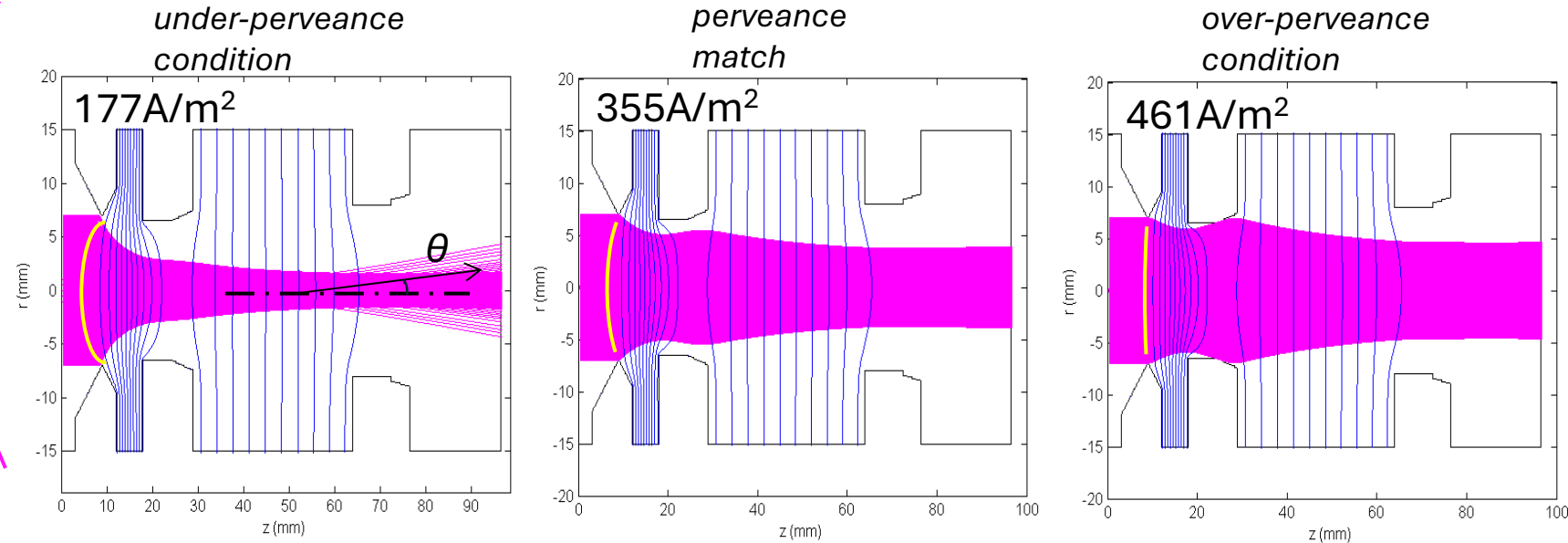
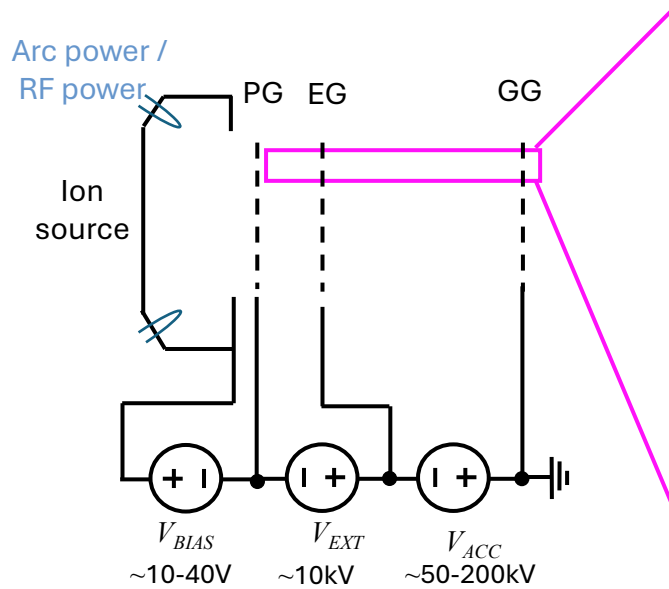
Electrode apertures act as electrostatic lenses: unbalanced electric fields cause focusing or defocusing (thin lens approximation Davidson & Calbick):

$$f = \frac{4V}{E_2 - E_1}$$

V beam energy at electrode,
 E_1 and E_2 electric fields upstream and downstream the electrode
 f focal distance ($f < 0$ diverging beamlet)

The grounded electrode is always defocusing:
 $E_2 = 0 \rightarrow f < 0$

Ion beam optics

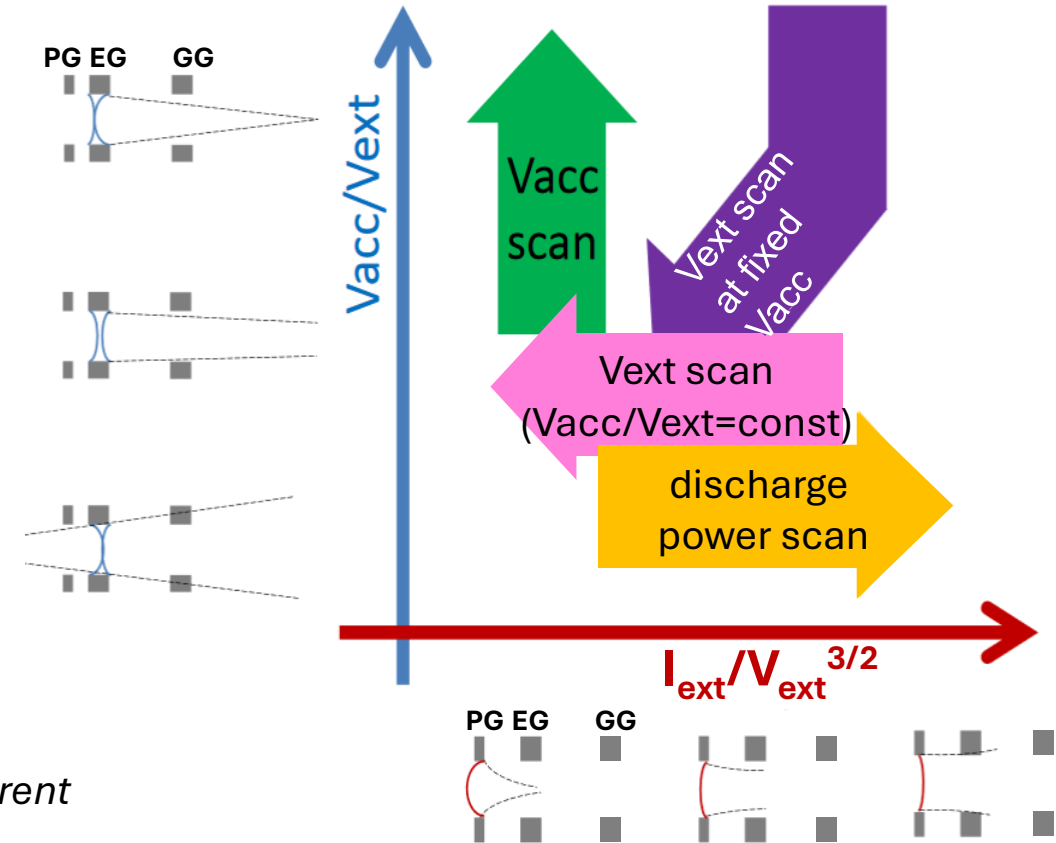
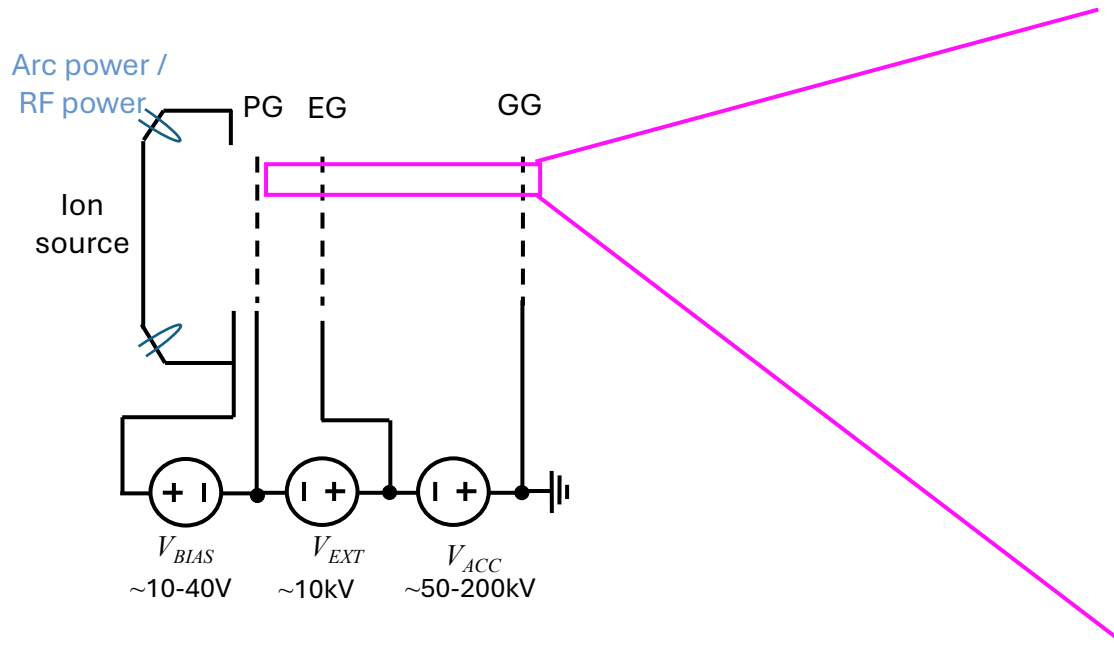


Example of ray tracing simulation of SPIDER triode accelerator, increasing **perveance** by increasing the current density at the meniscus.

The beamlet focusing at the exit of the accelerator can be calculated from the **RMS angle** of ion trajectories with respect to the beamlet axis: “divergence”

OPERA (CTS Studio) was used for the design of the ITER accelerator. IBsimu (<https://ibsimu.sourceforge.net/>) is also being used recently. 3D ray-tracing codes are the standard.

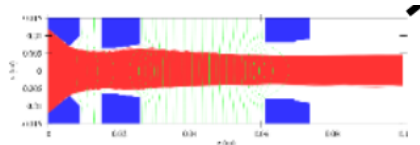
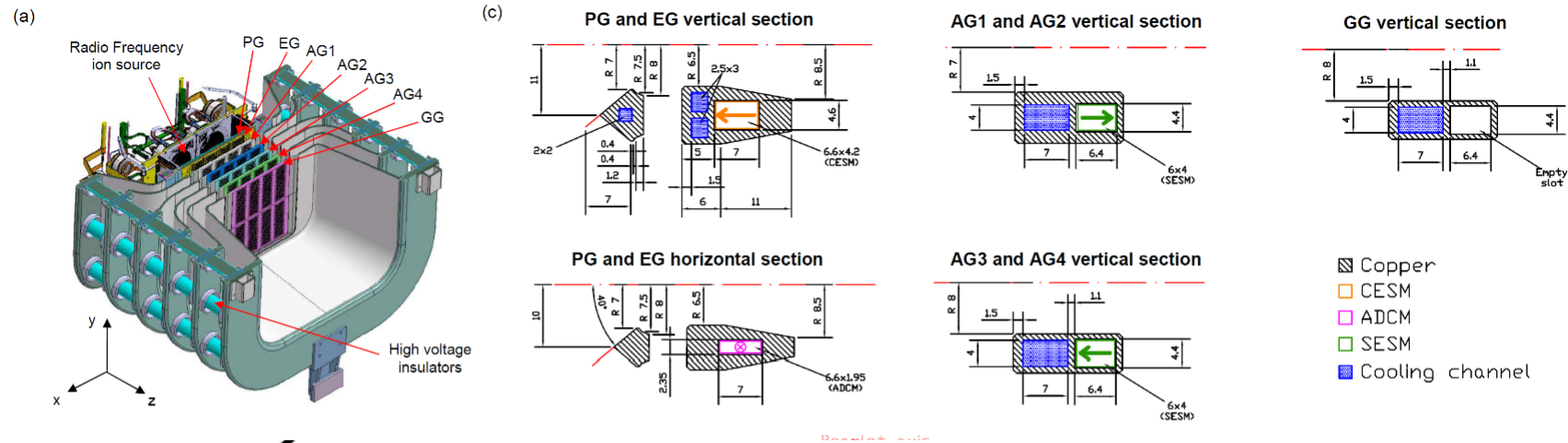
Ion beam optics: experimental characterization



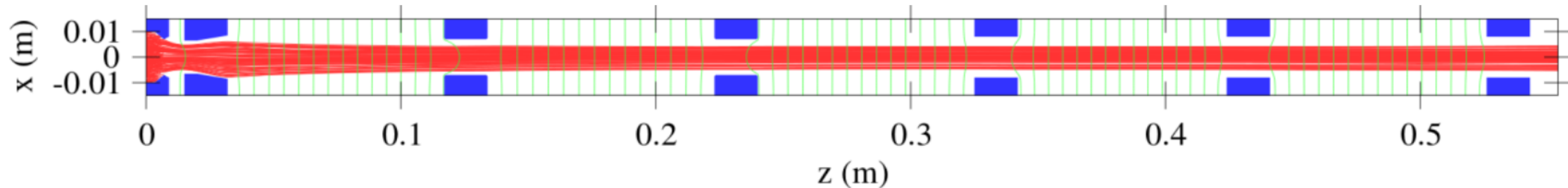
Experimentally, what are the knobs?

- **Power** into plasma discharge (arc power, RF power...) → plasma density → extracted current
→ **perveance**, $I \cdot V^{-1.5}$
- Extraction grid voltage **Vext** → **perveance**, $I \cdot V^{-1.5}$
→ **electrostatic lenses**, $f=4U/(E2-E1)$
- Acceleration grid voltage **Vacc** → **electrostatic lenses**, $f=4U/(E2-E1)$

Ion beam optics: from triodes to ITER MAMuG



Example beam acceleration @SPIDER

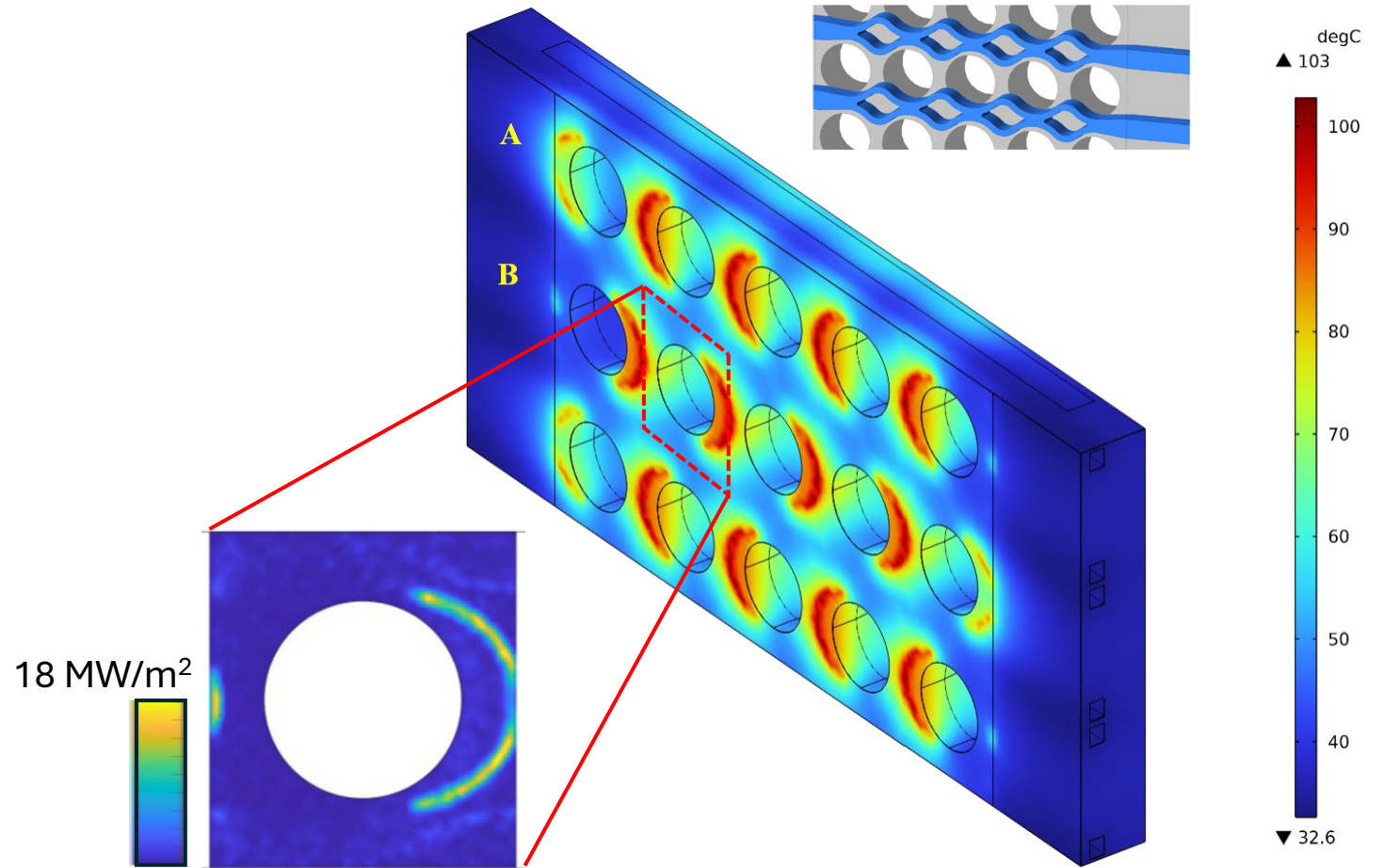
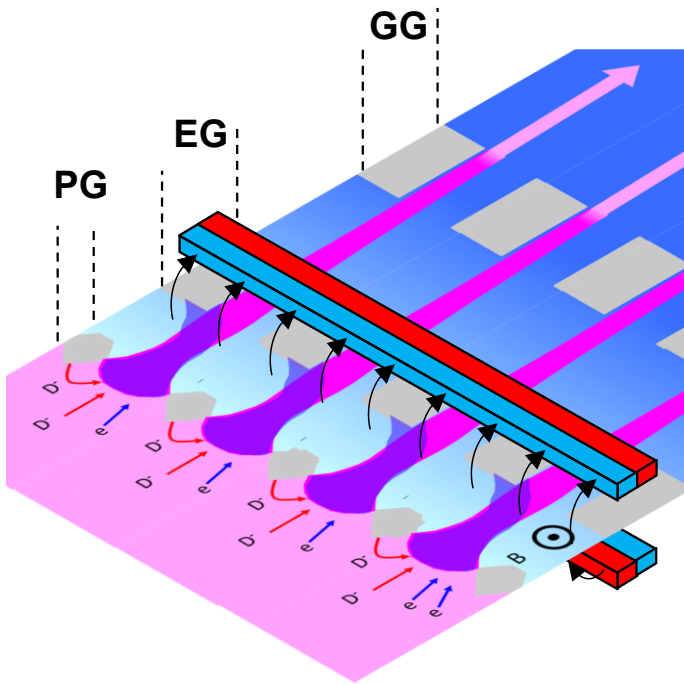


Example beam acceleration @ MITICA

ITER beam optics: removal of co-extracted electrons

- Permanent magnets in extraction grid **deflect co-extracted electrons** to avoid accelerating them to full energy...

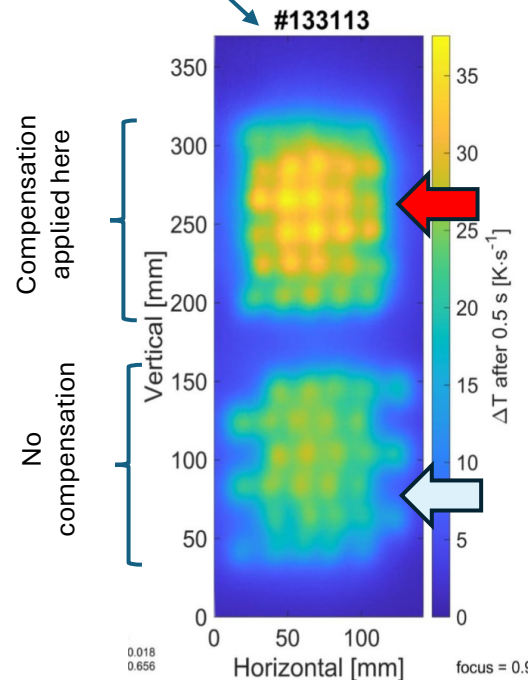
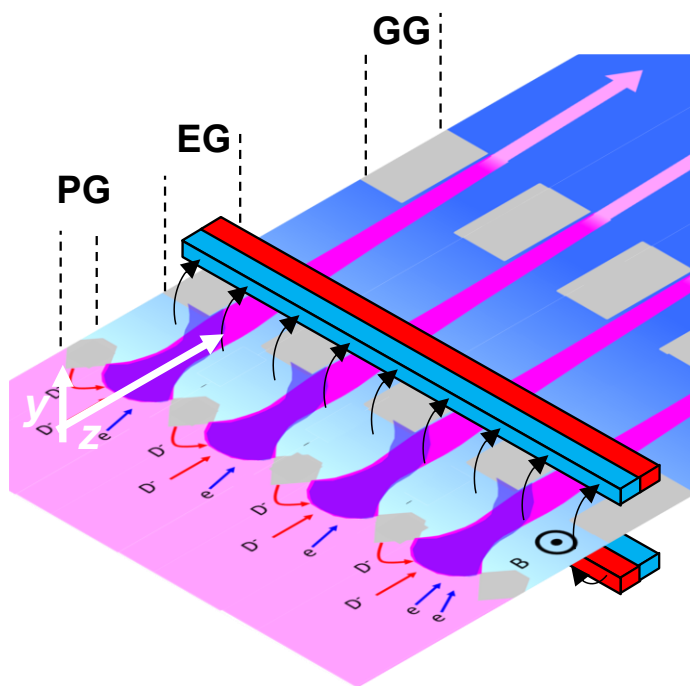
Example for nominal case D- (j_e 355 A m⁻² at 9.4kV)
Localized cooling on electrodeposited Cu



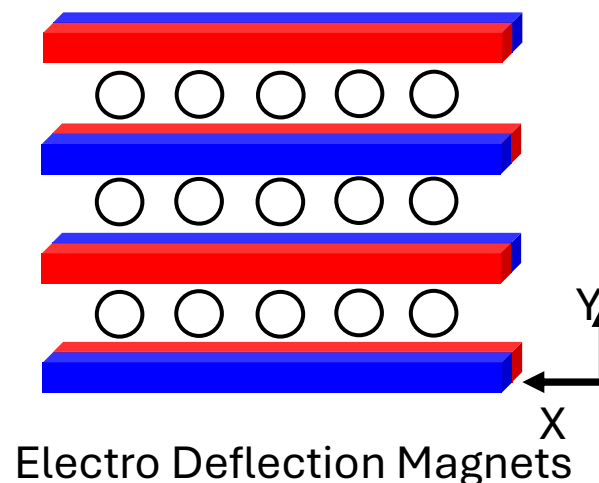
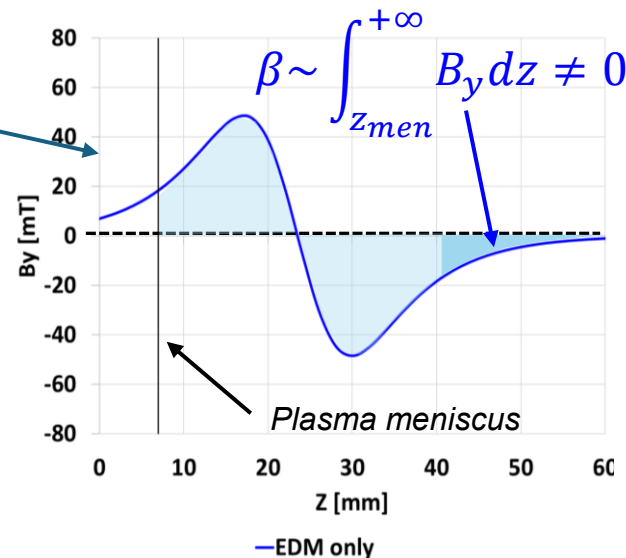
courtesy P Agostinetti, F Veronese

ITER beam optics: removal of co-extracted electrons

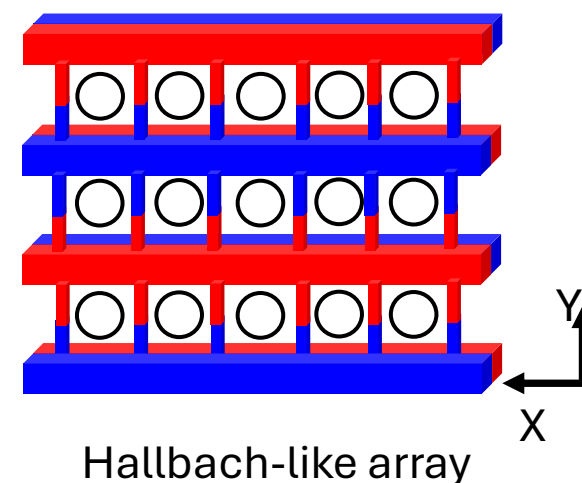
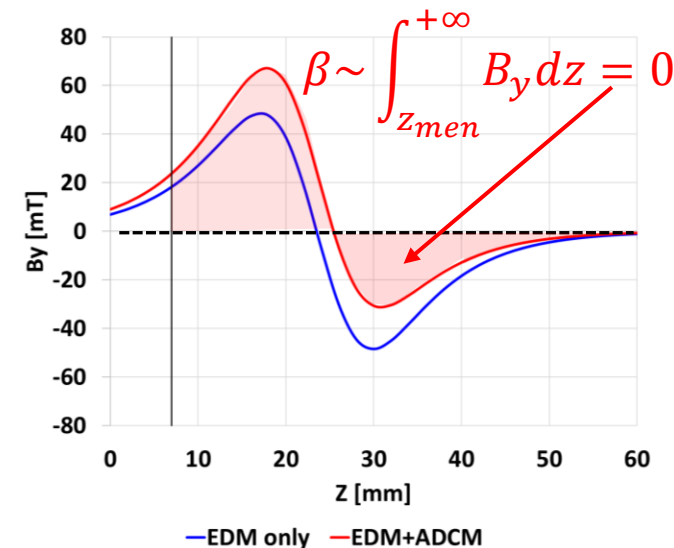
- Permanent magnets in extraction grid **deflect co-extracted electrons** to avoid accelerating them to full energy...
- They also slightly **deflect ions** despite higher mass! uncompensated deflection is unacceptable (5 mrad)
- Compensation methods required for ions:
Electrostatic compensation at EG (steering grid),
or compensating magnets inside EG or GG...



Result in BUG,
courtesy B Segalini



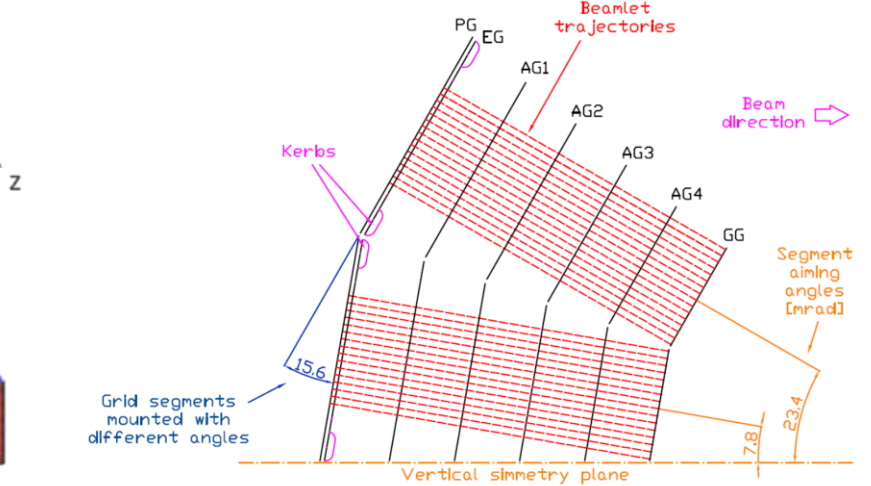
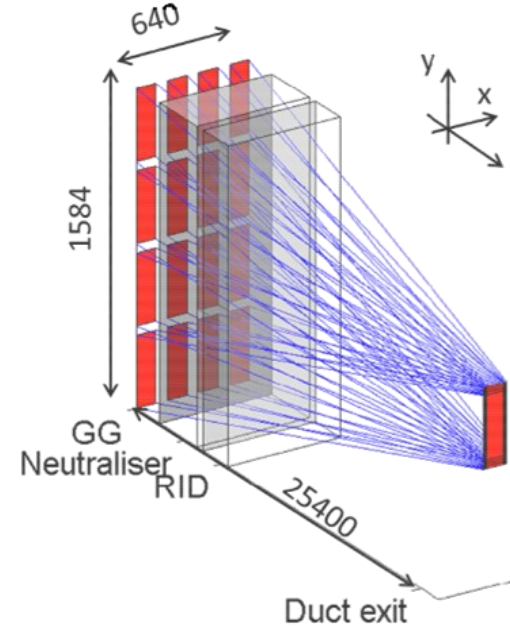
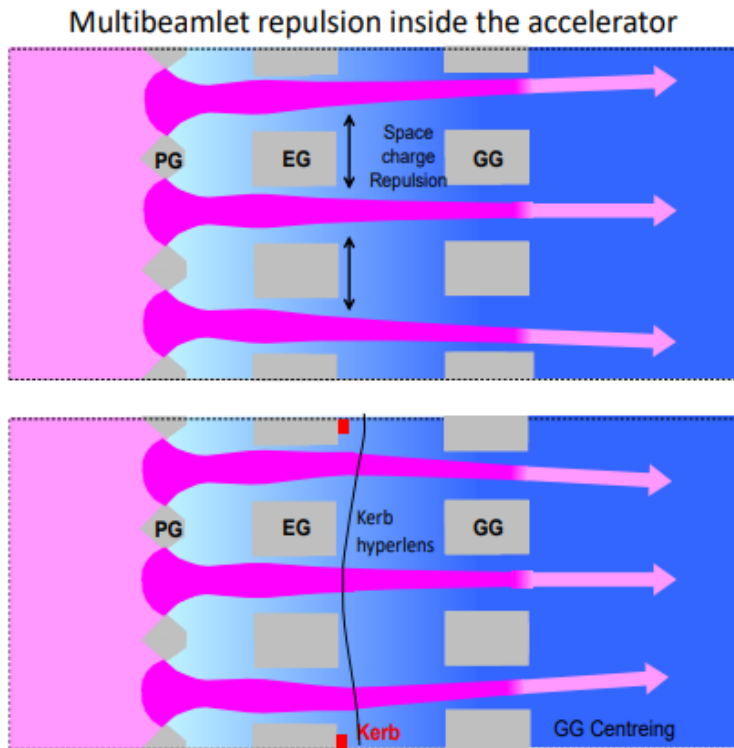
Electro Deflection Magnets



Hallbach-like array

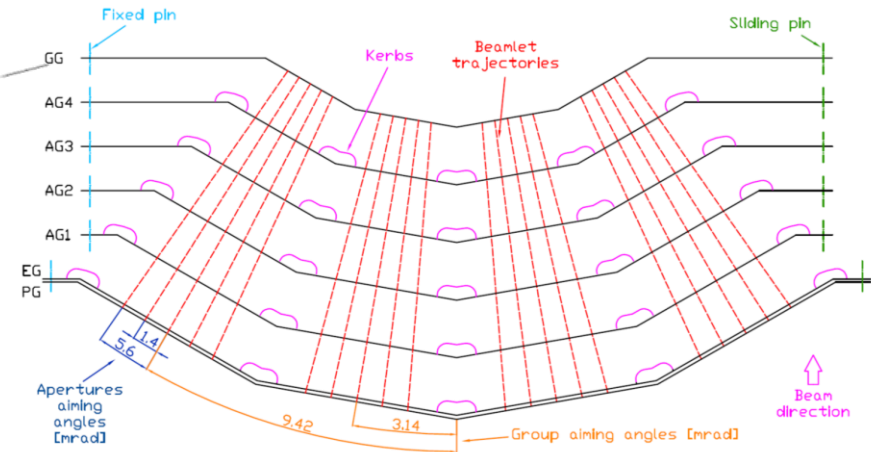
ITER beam optics: multibeamlet complex interactions

- Complex interactions between beamlets:
coulomb repulsion (acting especially in the low energy part of the accelerator)
- Compensation** must be applied to correct the steering angle



Complex Aiming:

- Horizontal beamlet aiming*
- Horizontal beamlet group aiming*
- Vertical beamlet group aiming*



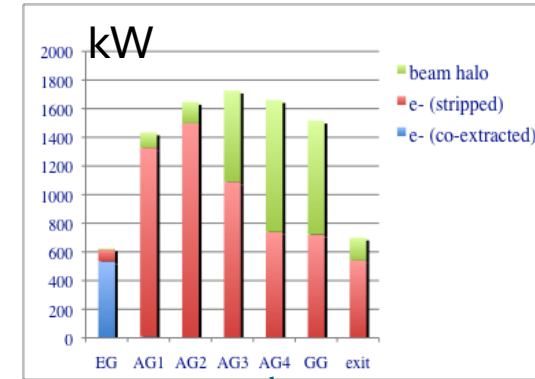
P Agostinetti, et al., *Nucl. Fusion* 56, 016015 (2016)
H.P.L. de Esch et al 2015 *Nucl. Fusion* 55 096001

1.6 m



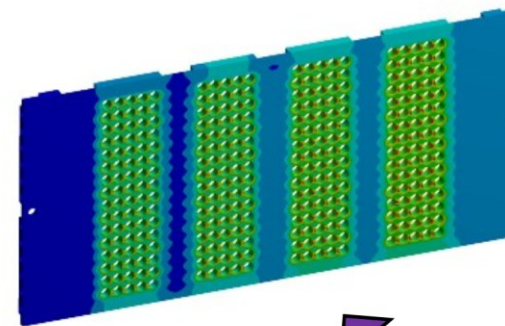
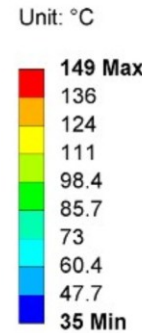
ITER beam optics: multibeamlet complex interactions

- Complex interactions between beamlets:
coulomb repulsion (acting especially in the low energy part of the accelerator)
- **Compensation** must be applied to correct the steering angle
- Design and dimension must consider the **expected deformations at steady-state** temperature (i.e. correct aiming achieved only after grid thermalization!)



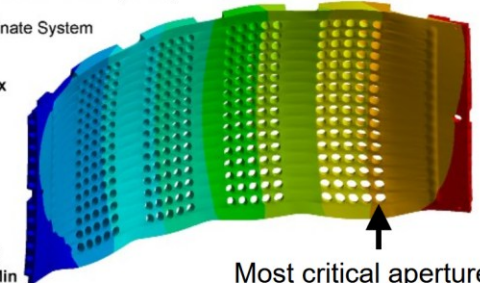
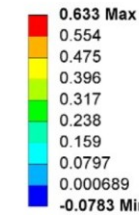
Note: AG4 is taken as an example (the other AGs are similar)

- $\dot{m}=18.8$ kg/s for the whole grid
- Heat load: nominal scenario (1596 kW)



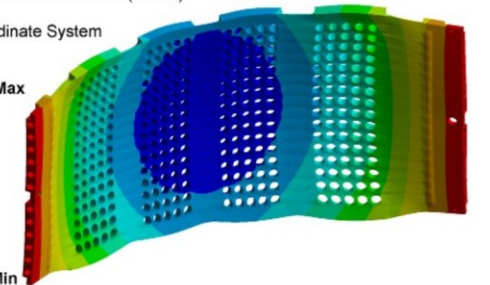
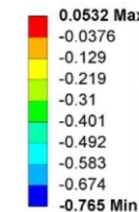
Beam direction

Type: Directional Deformation(X Axis)
Unit: mm
Global Coordinate System
Time: 1



Most critical aperture column regarding alignment

Type: Directional Deformation(Z Axis)
Unit: mm
Global Coordinate System
Time: 1



Courtesy P Agostinetti

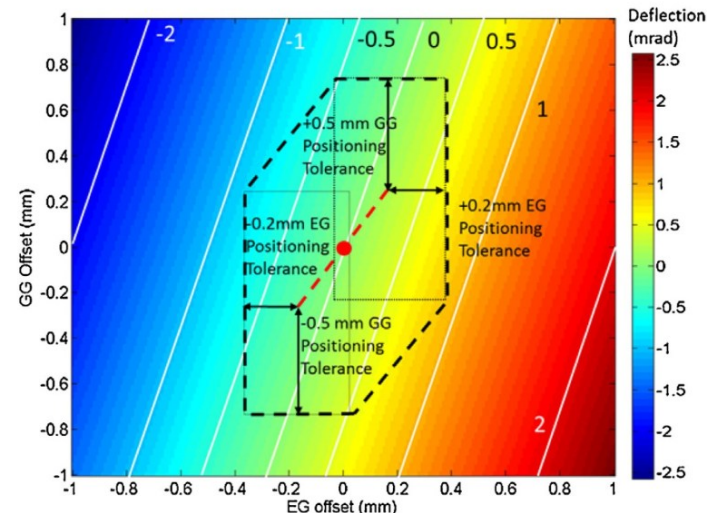
ITER beam optics: multibeamlet complex interactions

- Complex interactions between beamlets:
coulomb repulsion (acting especially in the low energy part of the accelerator)
- Compensation** must be applied to correct the steering angle
- Design and dimension must consider the **expected deformations at steady-state** temperature (i.e. correct aiming achieved only after grid thermalization!)
- Steering constants:** error angle on beamlet trajectory vs positioning error or grid tilting

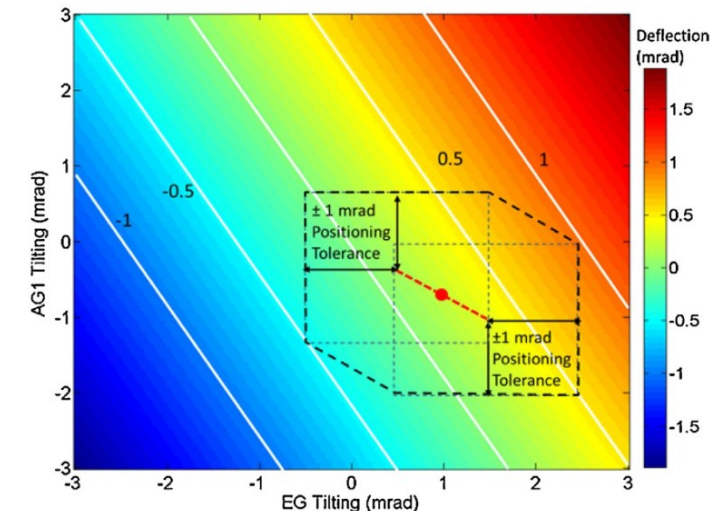
Steering constant of any grid as a consequence of in-plane and out-of-plane positioning errors.

Grid	Steering Constant	
	In plane positioning (mrad/mm)	Out of plane tilting (mrad/mrad)
EG	2	0.4
AG1	-0.15	0.23
AG2	≈ 0	0.1
AG3	≈ 0	≈ 0
AG4	≈ 0	≈ 0
GG	-0.58	≈ 0

Possible deflection range as a result of a wrong in-plane positioning

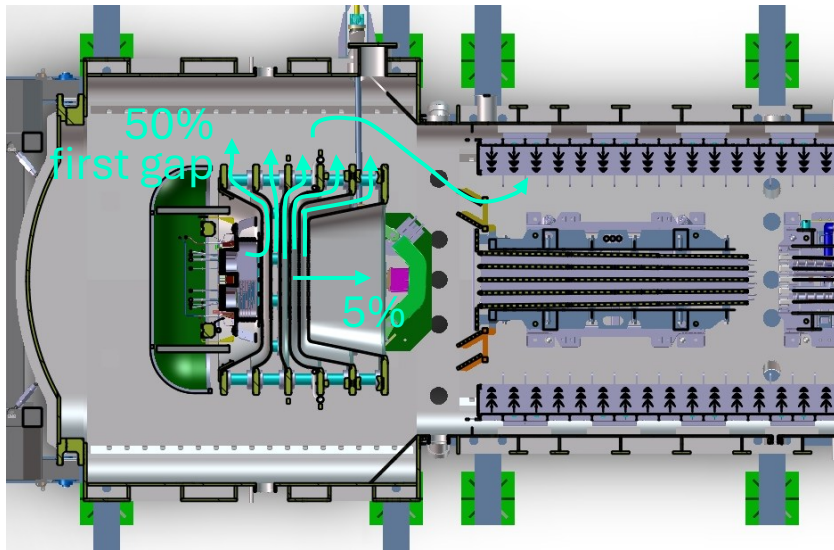


Possible deflection range as a result of a wrong out-of-plane positioning

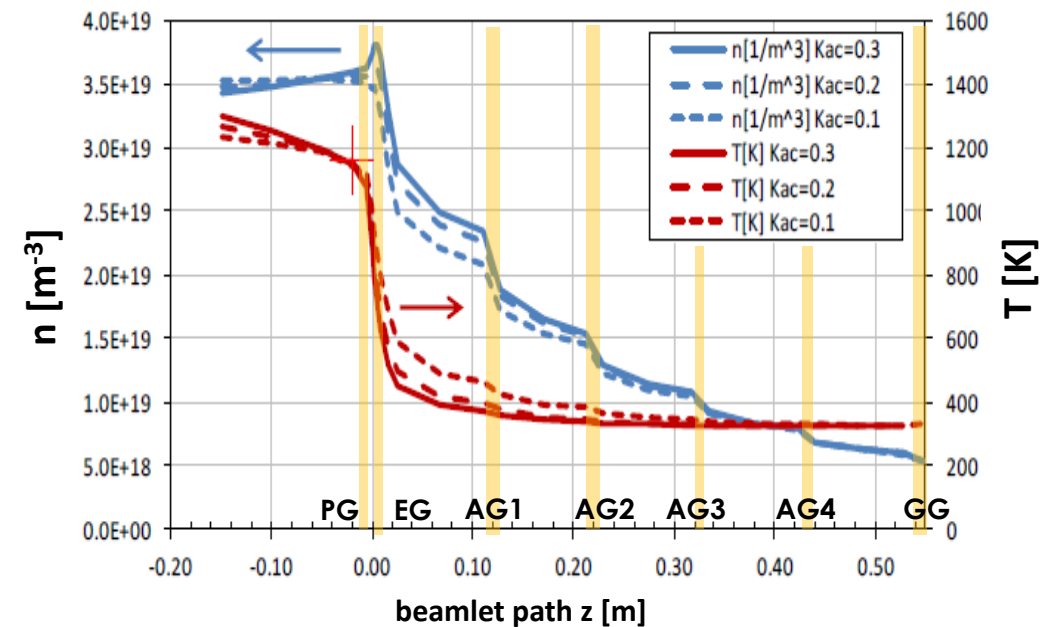


P. Veltri, et al., *Fus. Eng. Des.* 107 (2016) 64–69

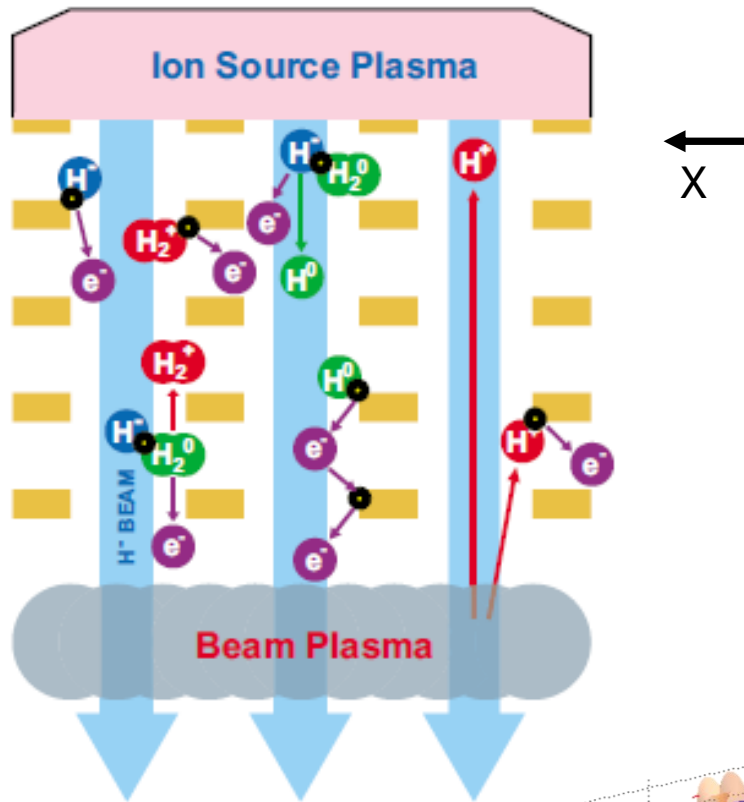
Stripping losses and power loads on electrodes



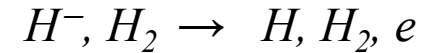
Vacuum
Insulated
Source



Stripping losses and power loads on electrodes



In Negative ion beams, electron detachment from H^- is highly probable → **stripping**.

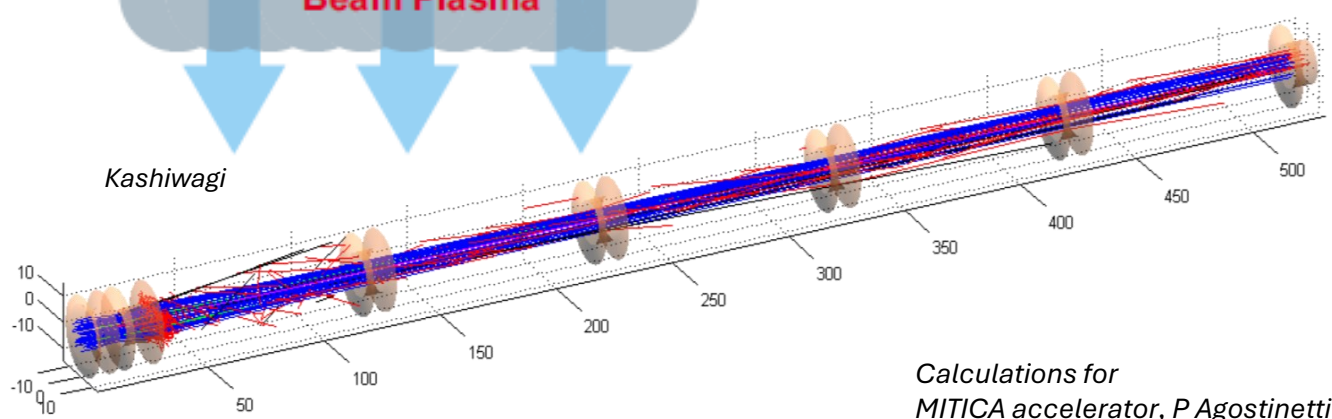


- If it occurs at incomplete acceleration, neutral particles are useless for plasma heating! With σ total stripping cross-section, the stripping loss reads:

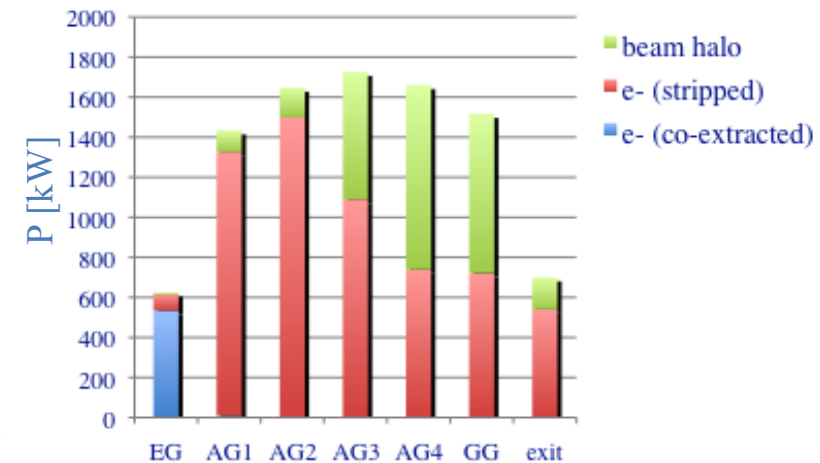
$$L_s = \int_0^{x_{GG}} -\sigma(V(x))n_g(x)dx$$

(up to 30% of negative ion current is lost in MITICA/ITER HNB!!)

- the stripped electron is accelerated by the electric field onto the electrodes: losses of efficiency and large heat loads



Calculations for MITICA accelerator, P Agostinetti



Exercise n. 3

Difficulty: ★☆☆☆

Optimize the RF power to maximise the transmitted negative ion current.



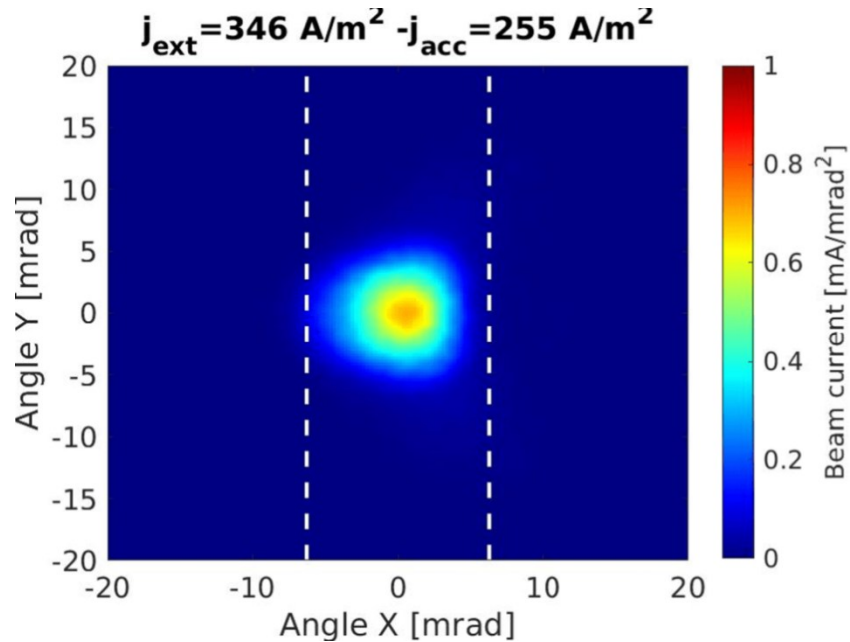
https://www.igi.cnr.it/wp-content/uploads/2026/07/ITER_HNB_acc_sim-1.html



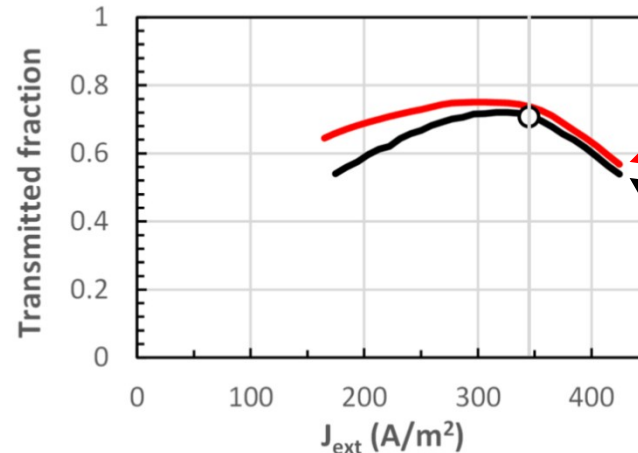
Angular distribution and ion losses

MITICA single beamlet simulation with IBIsimu, H^- , E_{beam} 870kV

Angular distribution v_x, v_y distribution compared to the beamline horizontal acceptance angle:

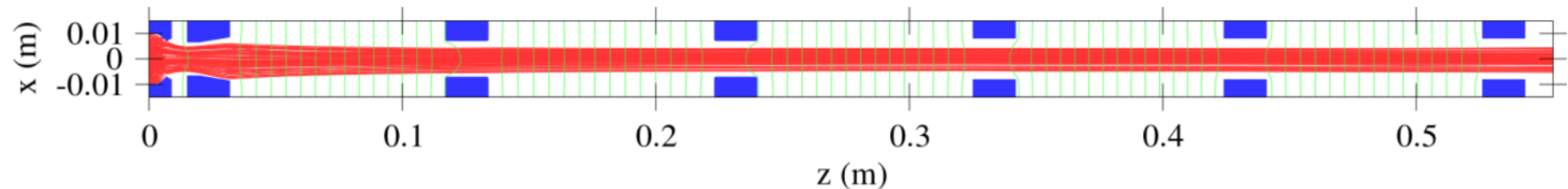


Beamline horizontal acceptance angle

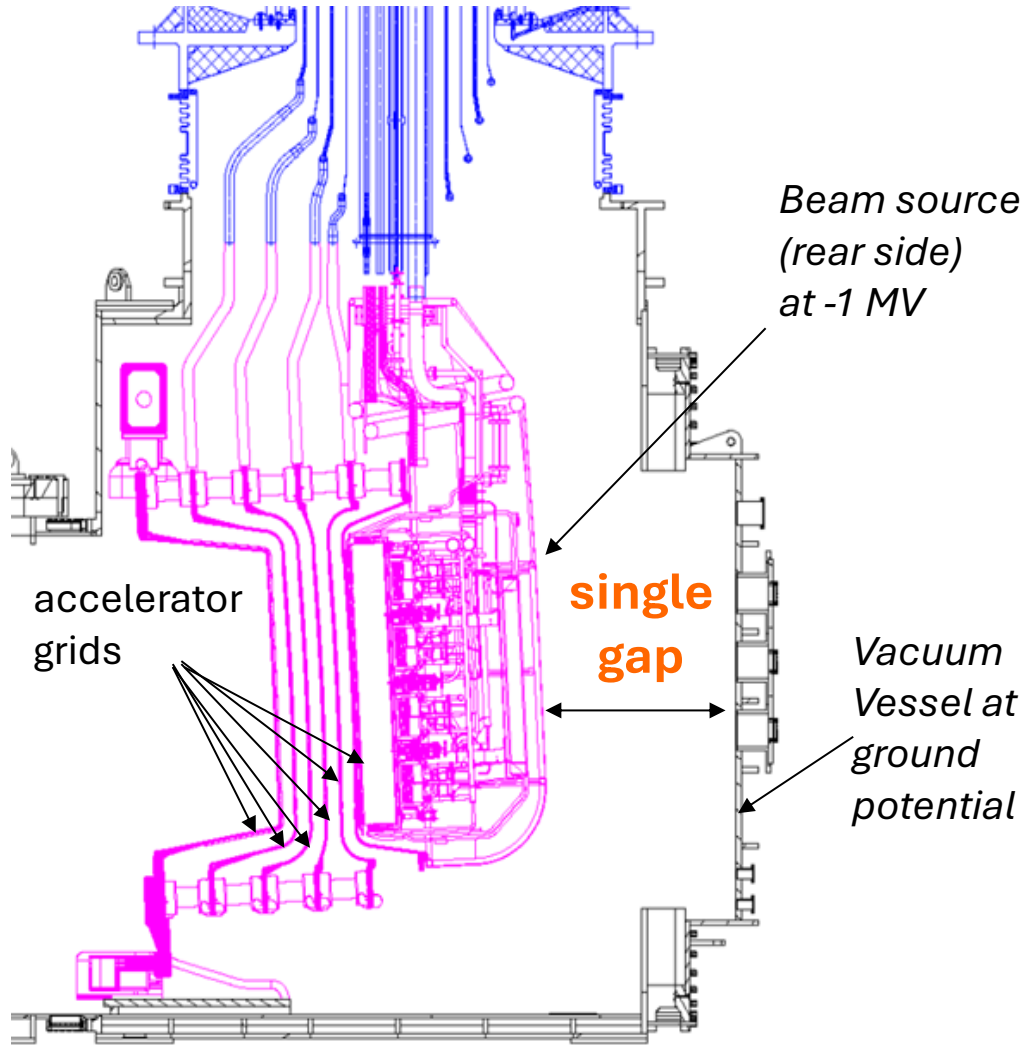


$I_{acc}/I_{ext} = T_{acc}(1 - s)$
 Fraction of the extracted current reaching **full acceleration**

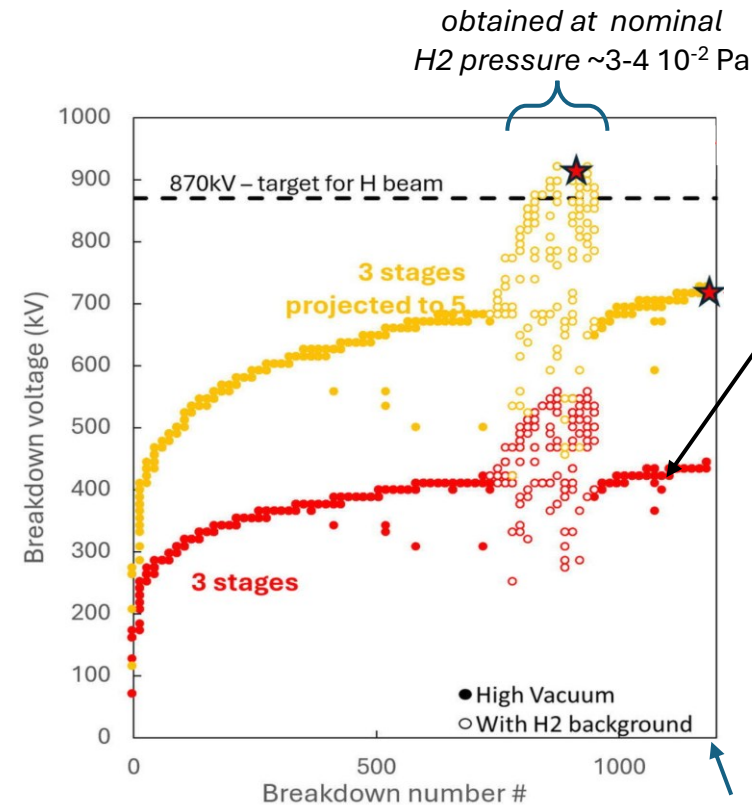
$I_{acc}/I_{ext} = T_{acc}(1 - s)T_{geom}$
 Fraction of the extracted beam current accelerated **within the beamline acceptance angle**



High Voltage conditioning on ITER source mockup



- proceeds by applying an increase voltage to the electrodes, causing the emission of charges, up to a breakdown;
- When the voltage is applied again, a slightly higher voltage can be reached:



What are these points?

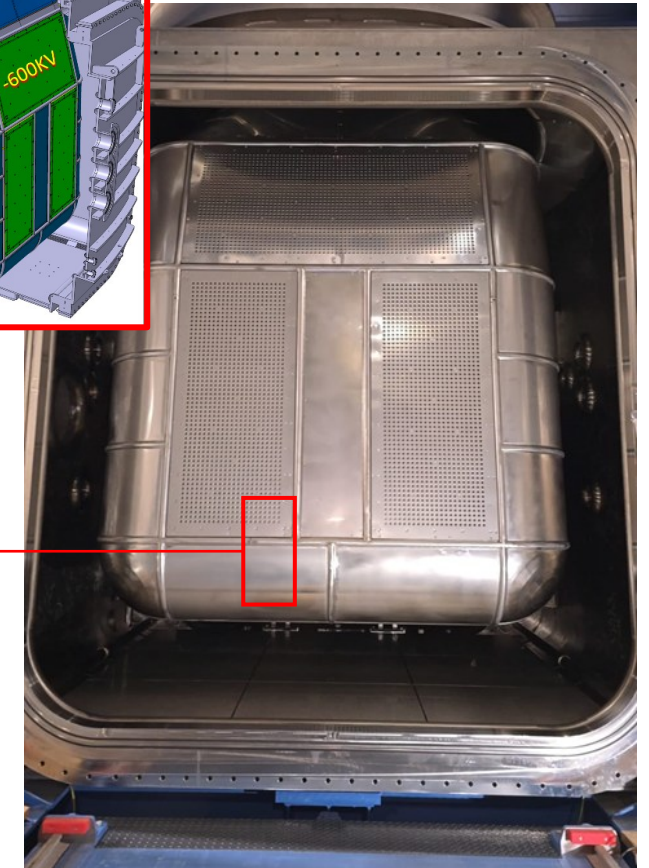
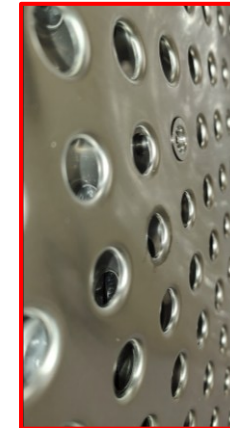
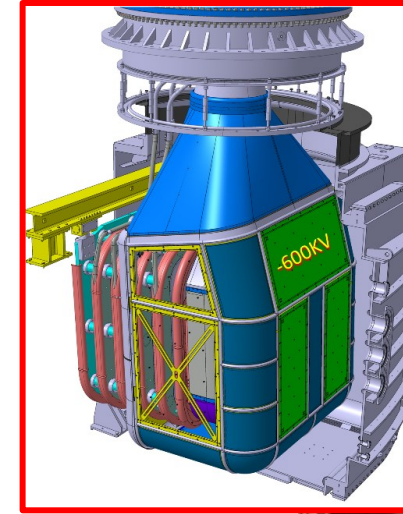
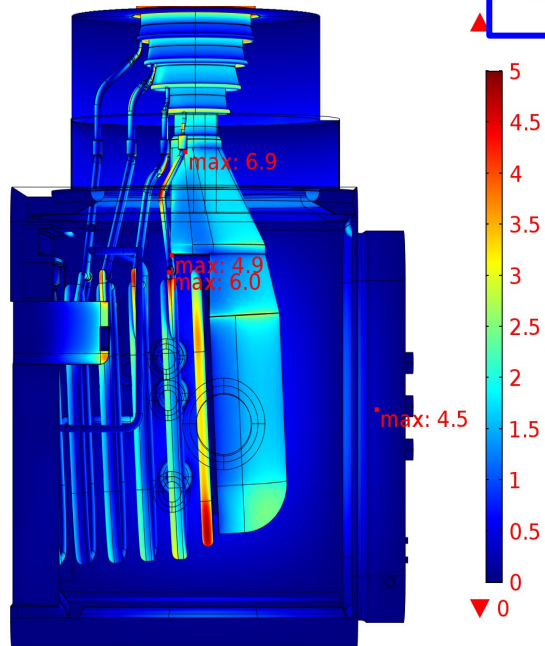
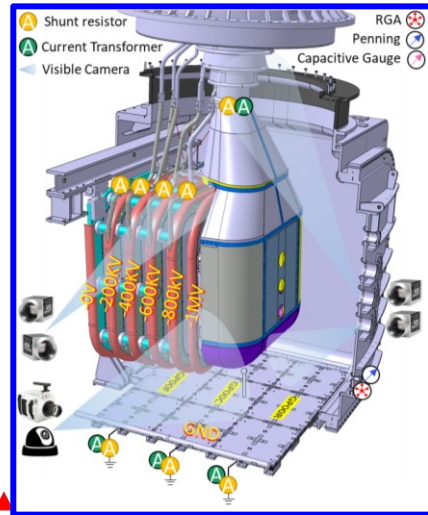


about 100 h of HV applied

High Voltage conditioning on ITER source mockup

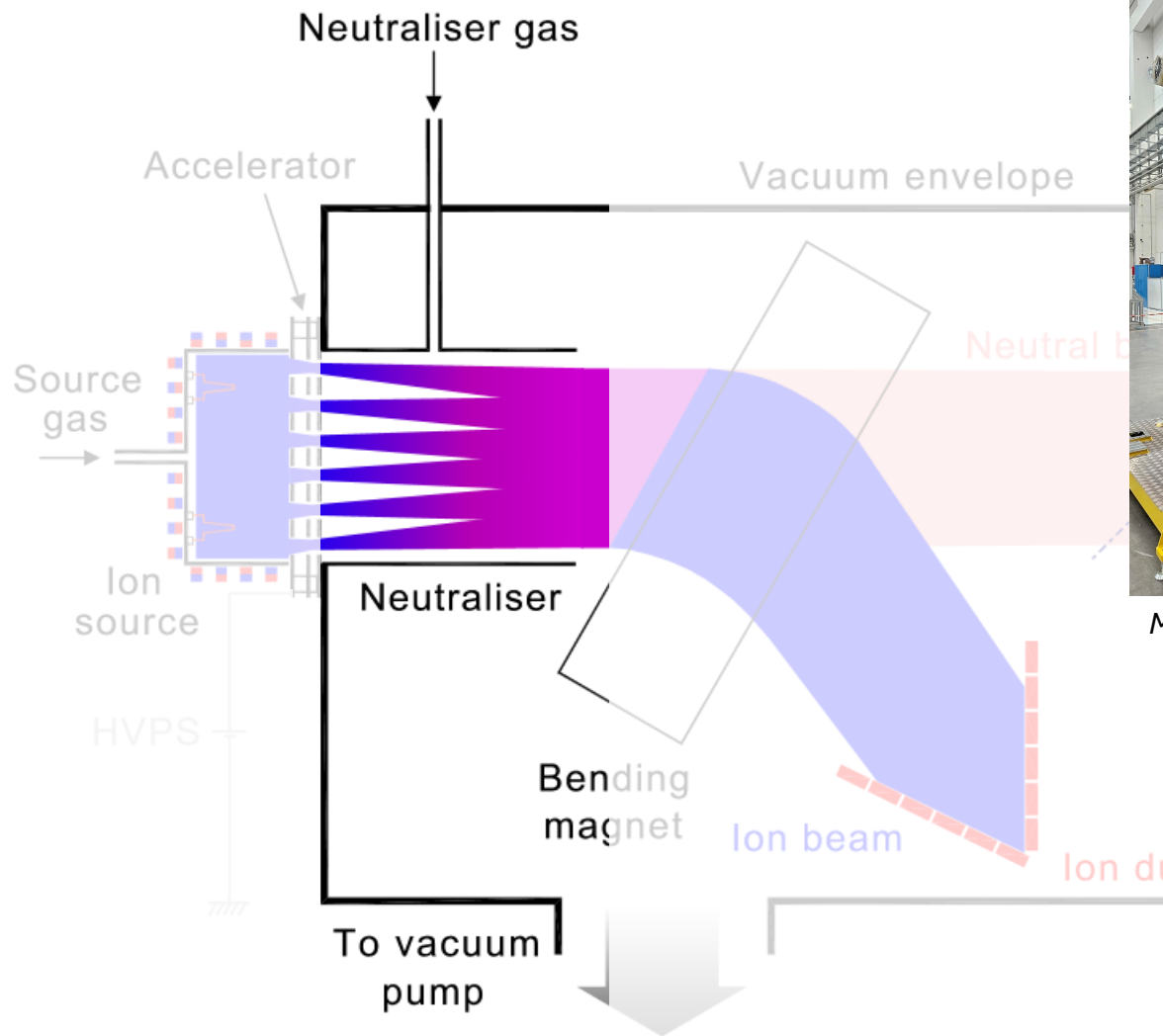
Target:

- 1 MV during D- beam acceleration
- 870 kV during H- beam acceleration



Courtesy G Chitarin, T Patton

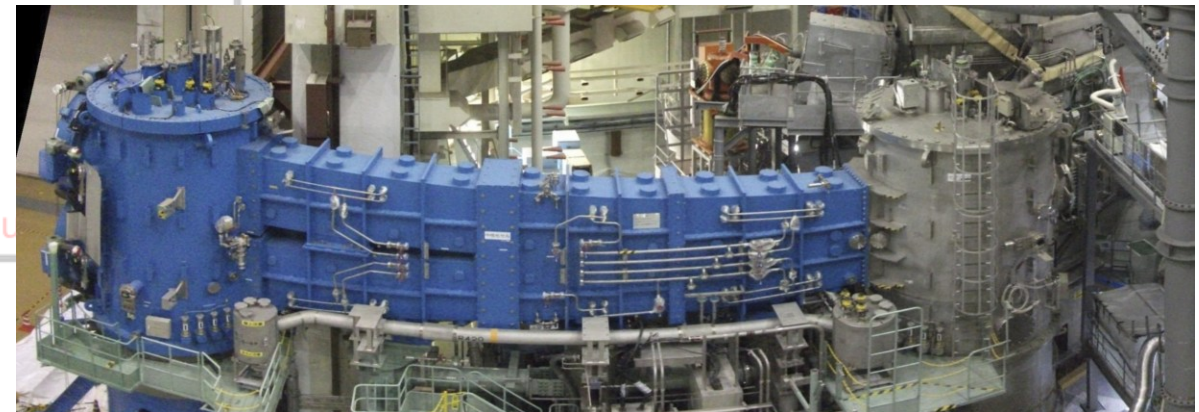
Neutraliser cell



MITICA neutraliser

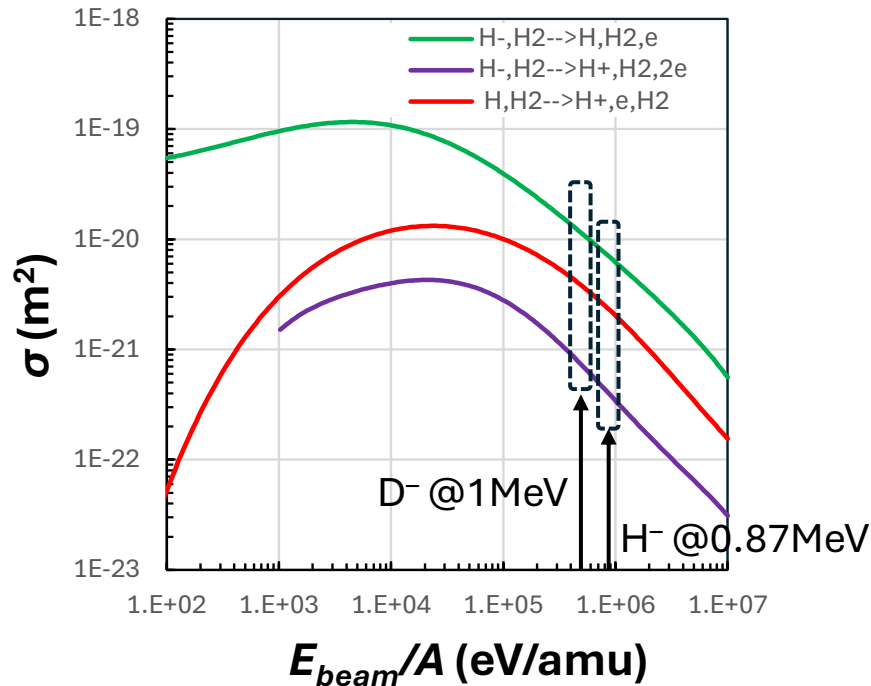


Neutraliser integrated with each ion source at JET



~10m long neutraliser cell in JT60-SA

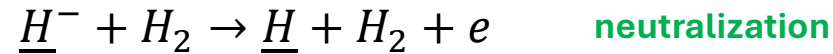
Ion beam interaction with gas: neutralization



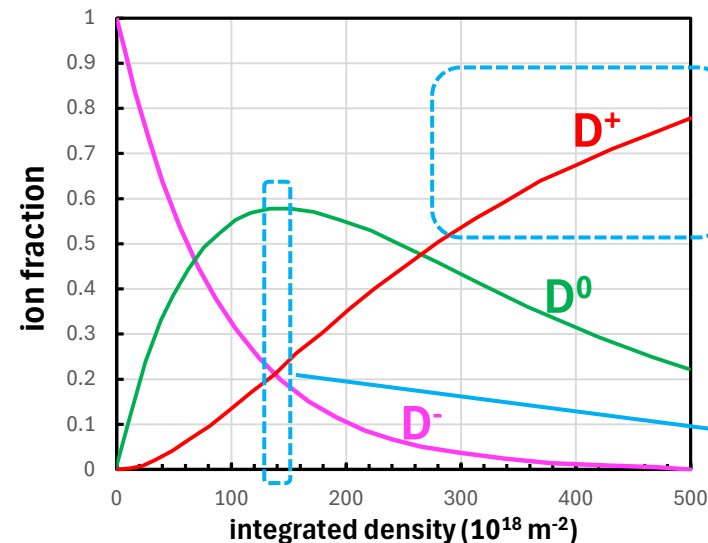
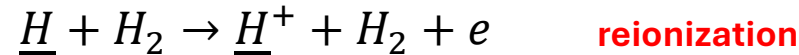
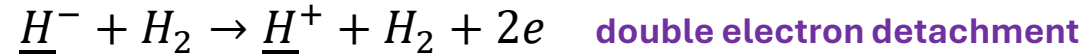
neutralization yield as a function of the integrated gas density (or “target thickness”) has a maximum, then decreases due to reionization losses.

Example: deuterium D^- beam accelerated at 1 MV

- Beam neutralization: normalized fluxes of beam species evolve as a function of x : $\frac{d\Gamma}{\Gamma} = \pm \sigma_{ij} n_g(x) dx$
- Cross-sections σ_{ij} (e.g. Barnett’s ORNL “Red book”, IAEA “Aladdin”) $\pm 20/25\%$
- **Competing charge-changing channels are always present**, for instance:



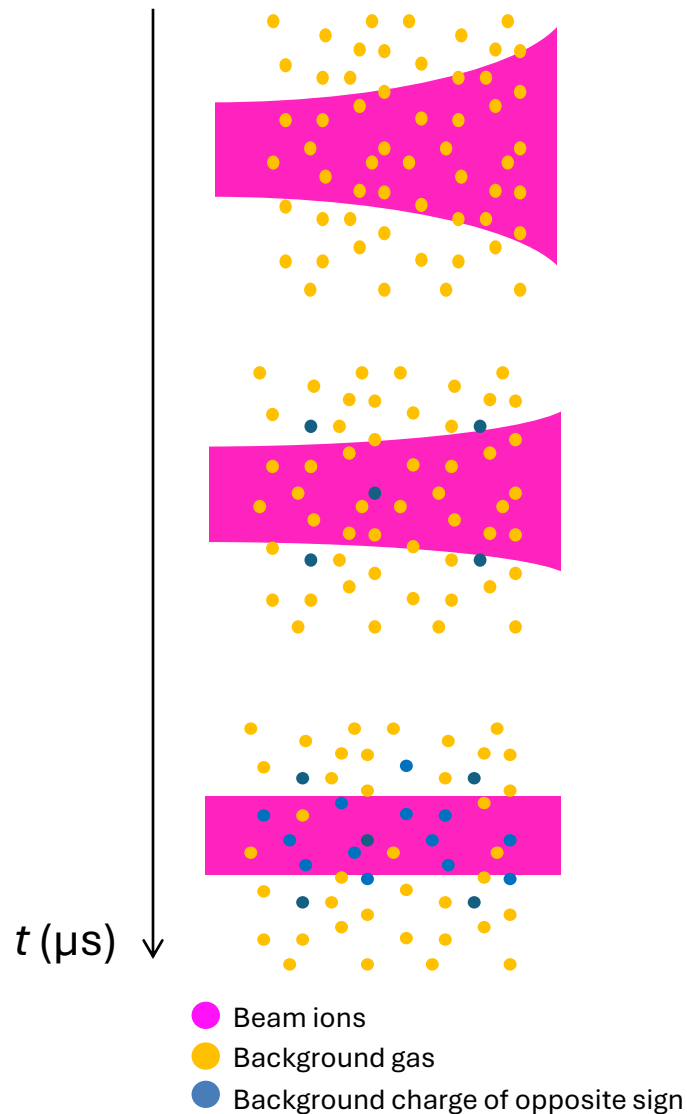
VS



Exceeding the optimal target thickness only causes reionization losses: **optimize gas profile** along the beamline

Need for a component along the beam line dedicated to dump 40% of the beam power, of the negative and positive ion fractions: **RESIDUAL ION DUMP**

Ion beam drift: beam plasma formation



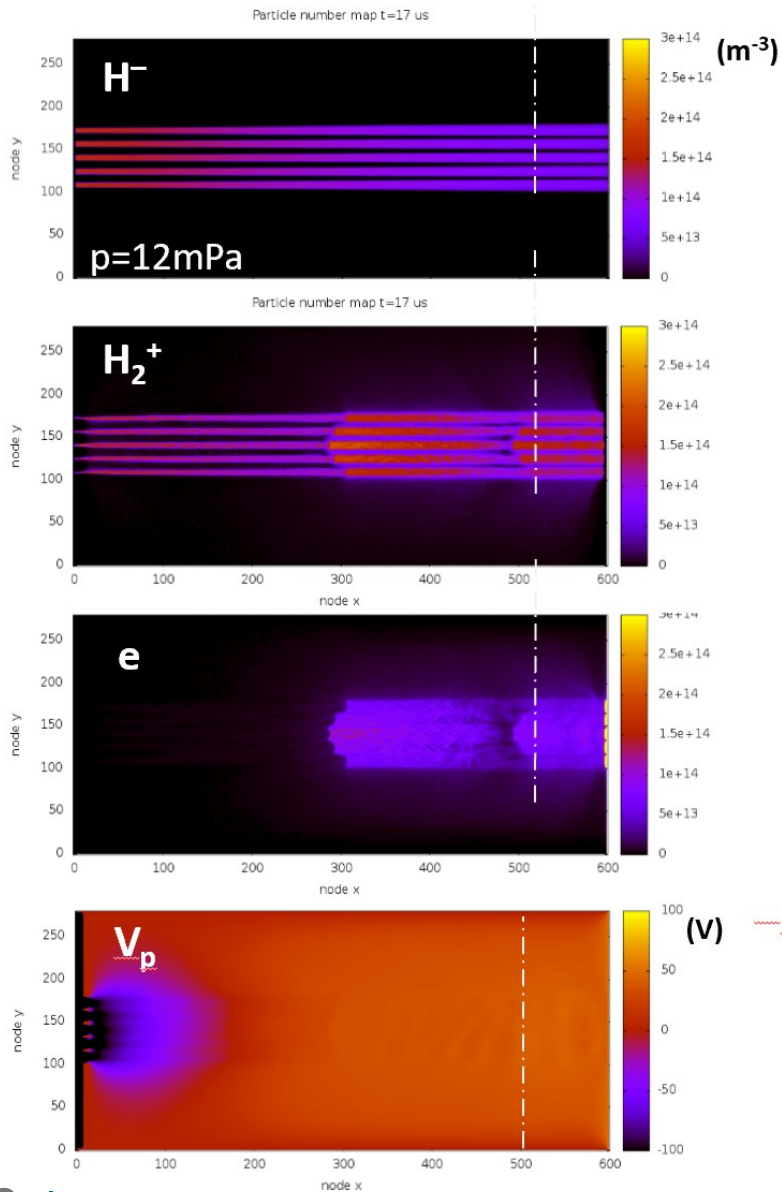
- Ion beam cannot propagate in a vacuum: beam ions are “repelled” by Coulomb interaction
- Space Charge Compensation (SCC): potential well produced by beam charge density traps secondary charges of opposite sign



- electrons compensate H^{+} beams, H_2^{+} ions compensate H^{-} beams; positive ion beams are usually slightly undercompensated, negative ion beams are slightly overcompensated.
- Beams can travel long distances in low density gases! Studied in the 70s for space-war applications
- If complete compensation is assumed, the beamlet optics is fixed after the accelerator (fixed divergence angle ω).

G Serianni, et al., *New Journal of Physics* 19 (4), 045003 (2017)

Ion beam drift: beam plasma formation



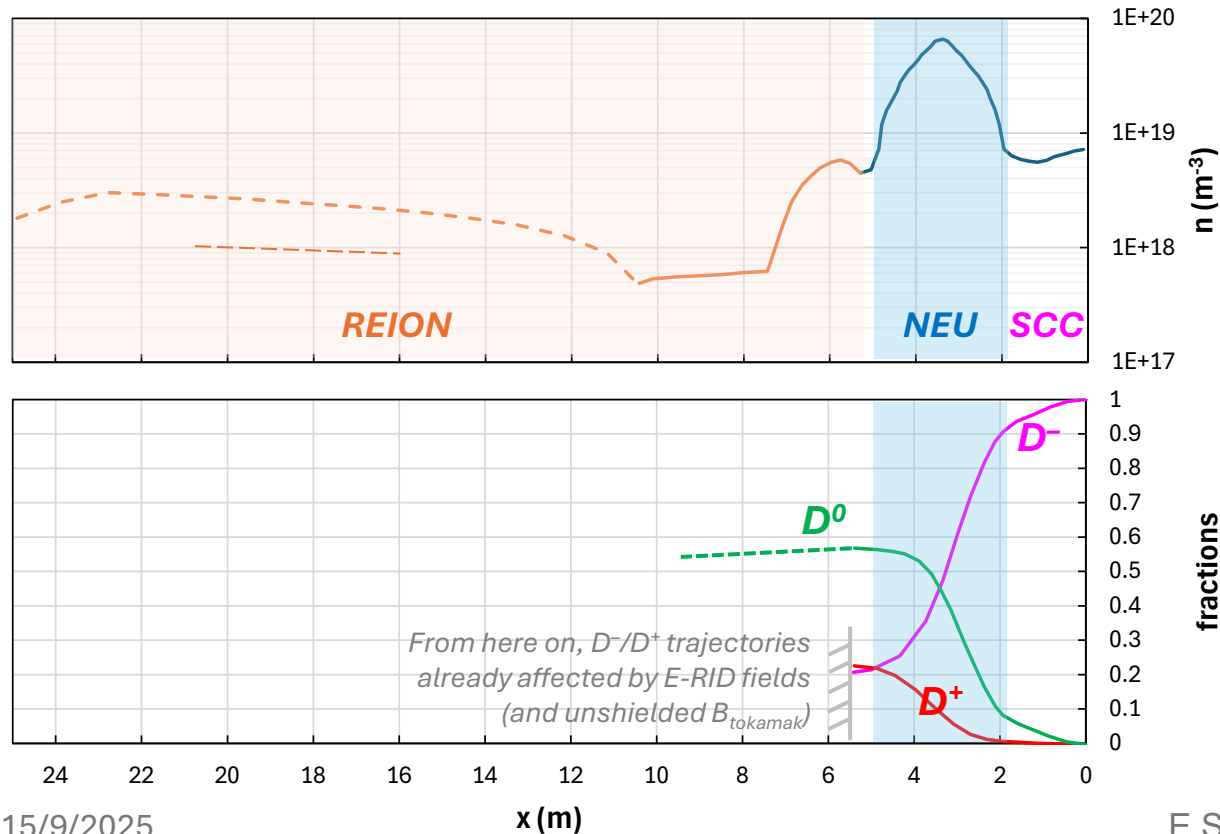
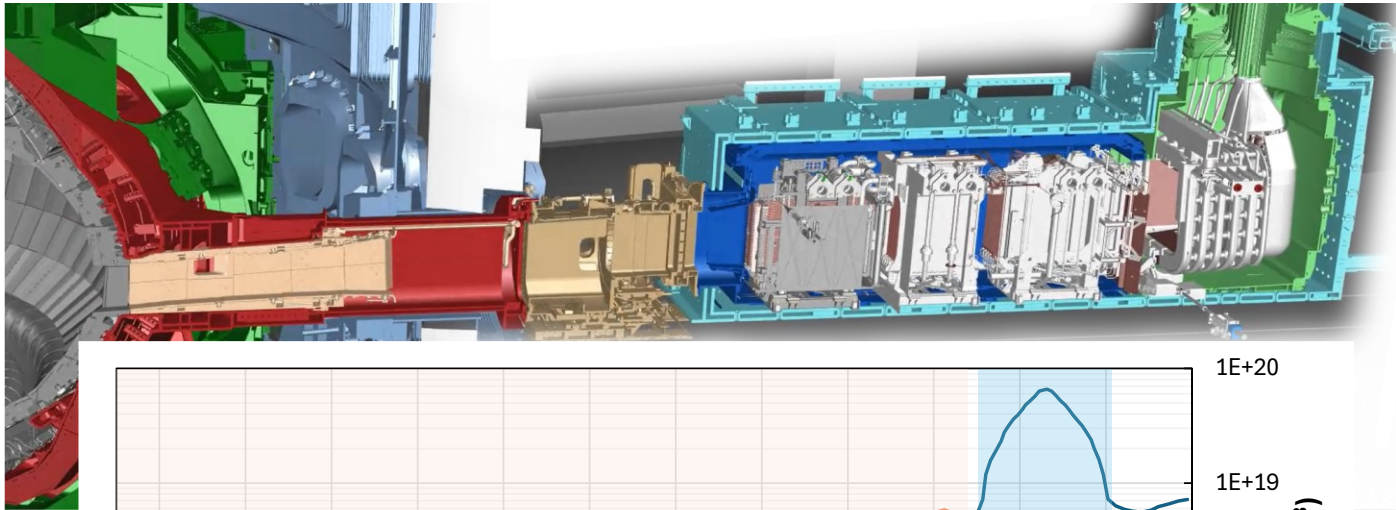
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E Sartori, et al., Rev. Sci. Instrum. 87, 02B917 (2016)

ITER gas profile optimization in HNBs

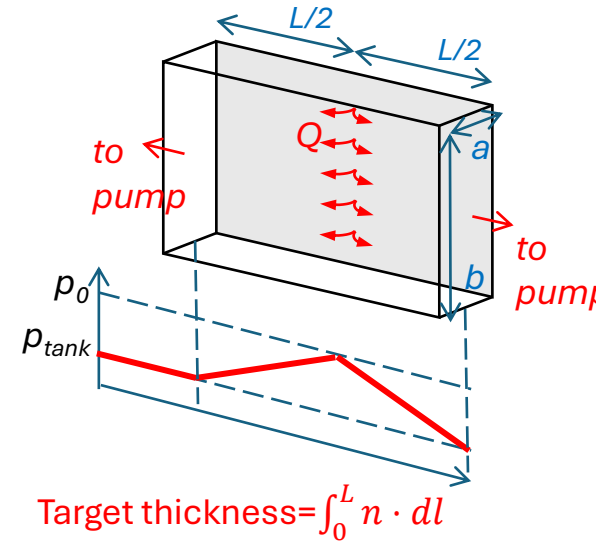


SCC: The precursor negative ion beam can only propagate in a gas (space charge compensation):
 $0.01\text{-}0.02\text{ Pa}$
 → *more than enough density naturally occurring in between beam source and gas neutralizer*

NEU: integrated density «target thickness» is required to reach 60% neutralization
 $\int n \cdot dx = 1.25 \times 10^{20} \text{ m}^{-2}$
 → *provide proper gas density profile: Q between 32 and $43 \text{ Pa m}^3/\text{s}$ in H_2*

REION: Neutral beam is reionized (=lost) in residual gas (e.g. 15m at $1.5 \times 10^{18} \text{ m}^{-3} = 10\%$ loss)
 → *minimize gas density*

ITER HNB neutralizer



Gas flowing out of a rectangular duct with injection in the center.

Total throughput:
 $Q = 2 \cdot C_{1/2} \cdot (p_0 - p_{\text{tank}})$,
 with gas conductance
 $C_{1/2} \propto 1/L_{\text{neu}}$

$$C_{1/2} \approx \frac{9.7}{0.5L_{\text{neu}}} \sqrt{\frac{T}{m}} \cdot \frac{a^2 \cdot b^2}{a+b}$$

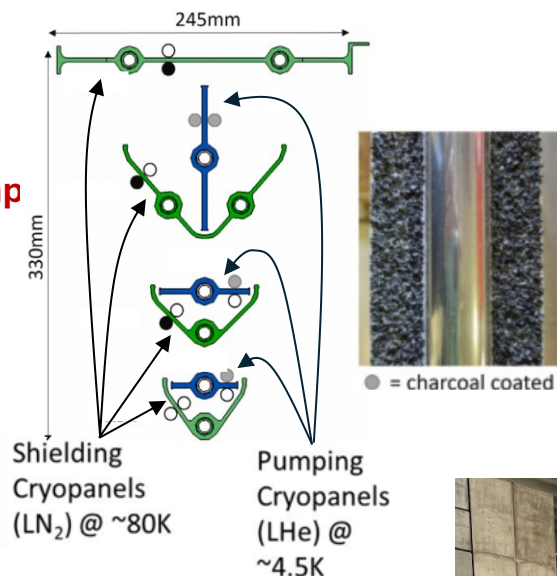
- Gas throughput Q shall be pumped $\rightarrow$ requirements for **vacuum pumping system**
- Due to cryopump limited capacity, the operation time is inversely proportional to Q
- space constraint: relatively small a , **large L** (see JT-60 N-NBI, $L \sim 10\text{m}$) $\rightarrow Q$ is **minimized**
- In ITER: neutron radiation, tritium, **volume of activated material shall be minimized** $\rightarrow$ short $L \sim 3\text{m}$, four parallel beam channels to minimize a

ITER HNB Cryopump design and requirements

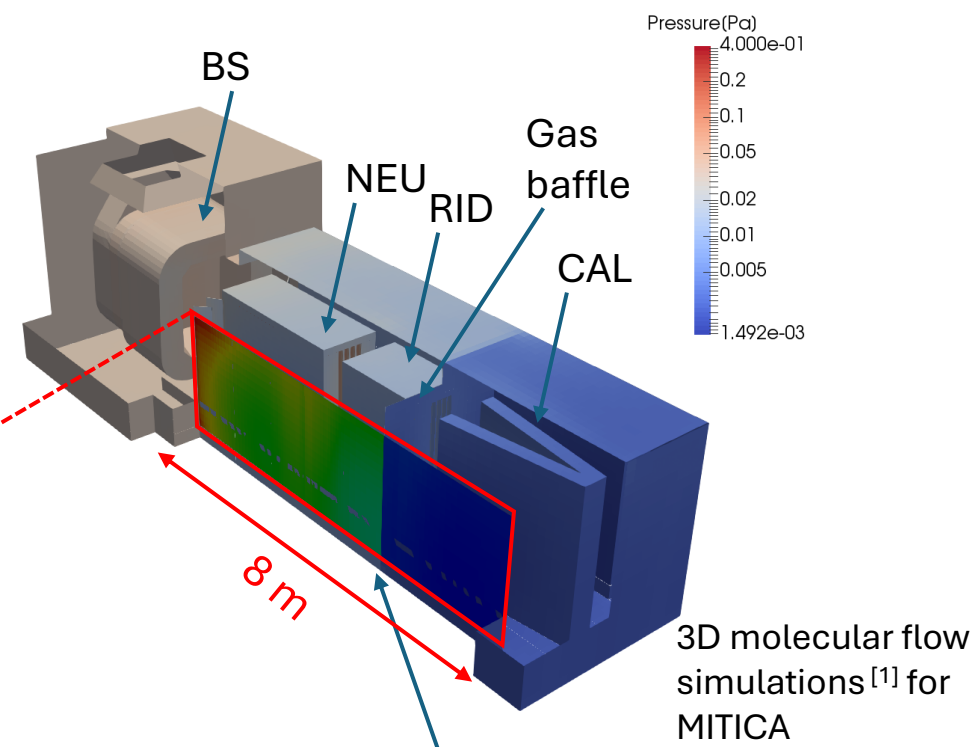
ITER HNB cryopump

- $A = 38 \text{ m}^2$
- $S = 4700 \text{ m}^3/\text{s}$
- $Q = 48 \text{ Pa} \cdot \text{m}^3/\text{s}$
- $p = 3 \times 10^{-2} \text{ Pa}$

J Buckerfield, et al., Fus. Eng. Design 215 (2025) 114991



One of the two cryopanel of MITICA



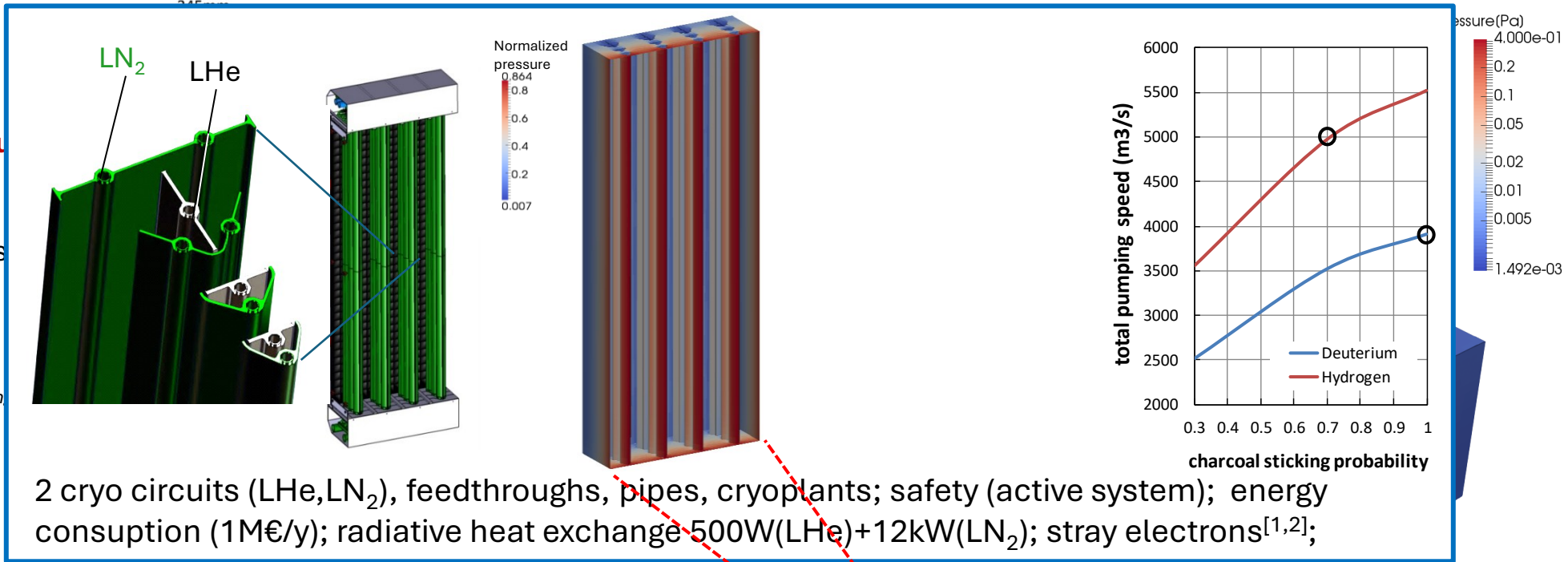
Non uniform gas load (specific throughput $\tilde{Q}$) on cryopanel: gas baffle separates the beamline into a high-throughput region (source and neutralizer) and a low-pressure region (after calorimeter)

ITER HNB Cryopump design and requirements

ITER HNB cryopump

- $A = 38 \text{ m}^2$
- $S = 4700 \text{ m}^3/\text{s}$
- $Q = 48 \text{ Pa} \cdot \text{m}^3/\text{s}$
- $p = 3 \times 10^{-2} \text{ Pa}$

J Buckerfield, et al., Fus. Eng. Design 215 (2025) 114991



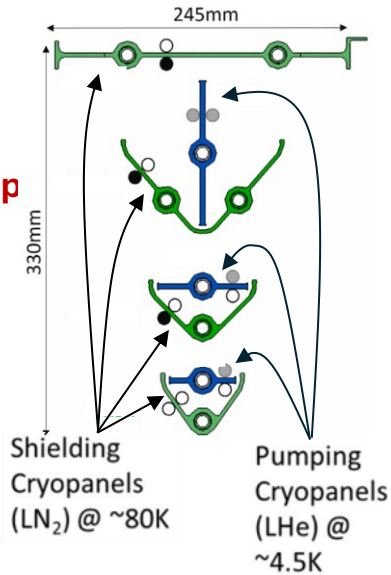
- [1] P Veltri, et al. Rev Sci Instr **87**, 02B313 (2016)
 [2] E Sartori, et al., Fus Eng Des **109**, 377-382 (2016)

ITER HNB Cryopump design and requirements

ITER HNB cryopump

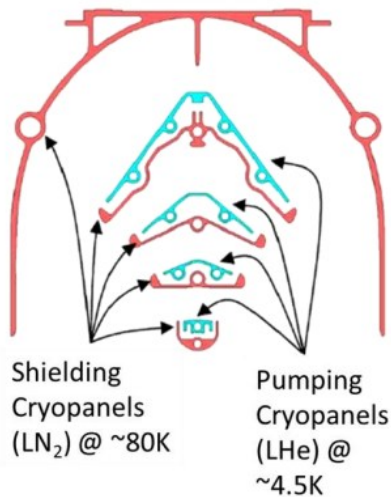
- $A = 38 \text{ m}^2$
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- $p = 3 \times 10^{-2} \text{ Pa}$

J Buckerfield, et al., Fus. Eng. Design 215 (2025) 114991



JET cryopump

- $A = 40 \text{ m}^2$
- $S = 8000 \text{ m}^3/\text{s}$
- $Q = 25 \text{ Pa} \cdot \text{m}^3/\text{s}$
- $p = 5 \times 10^{-3} \text{ Pa}$



ITER NBI (H_2)^[2]

[2] M. Dremel, et al, Nucl Fus
49 075035 (2009)

JET NB Injector cryopump

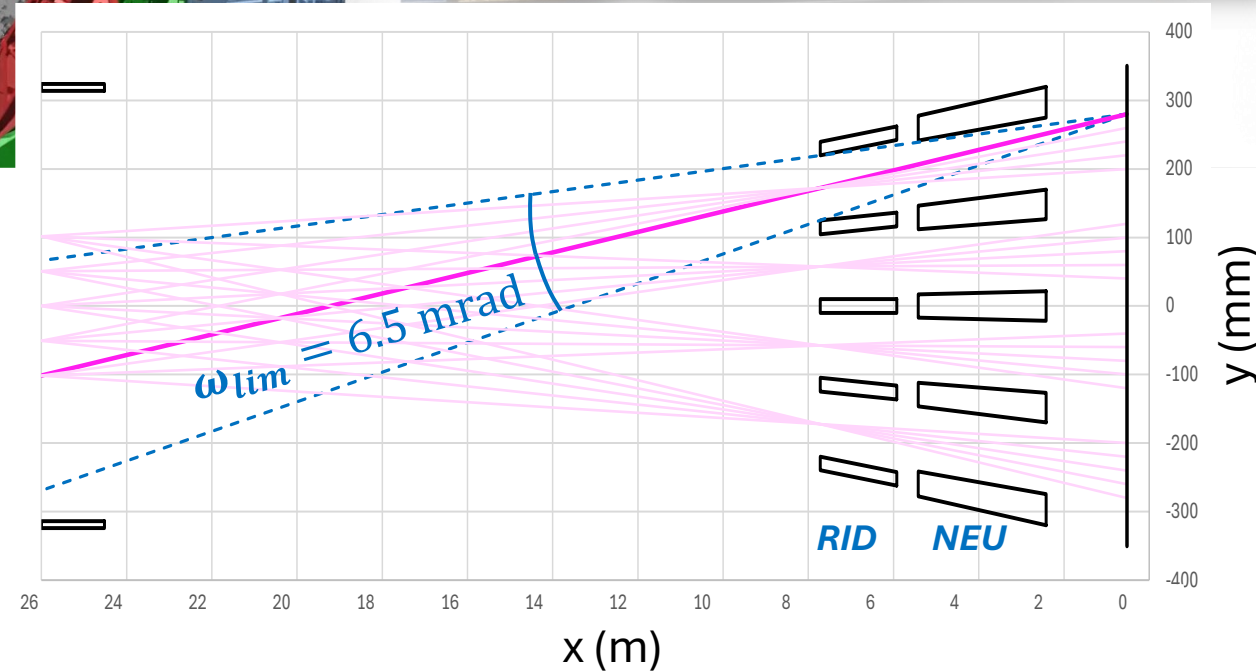
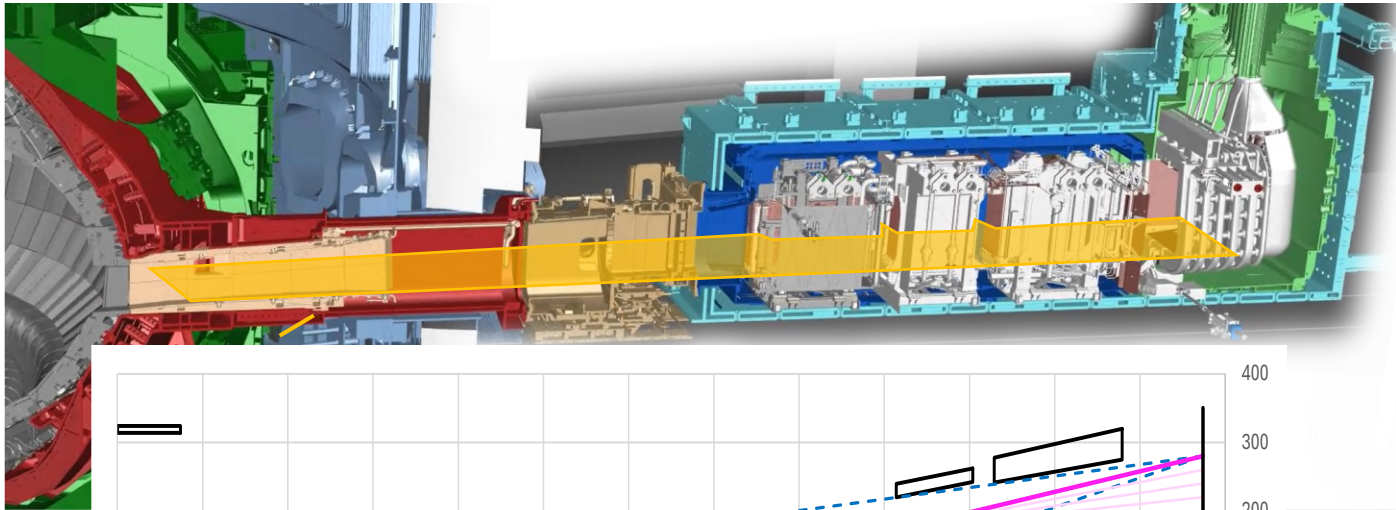


One of the two cryopanel of MITICA

JET NBI (H_2)^[1]

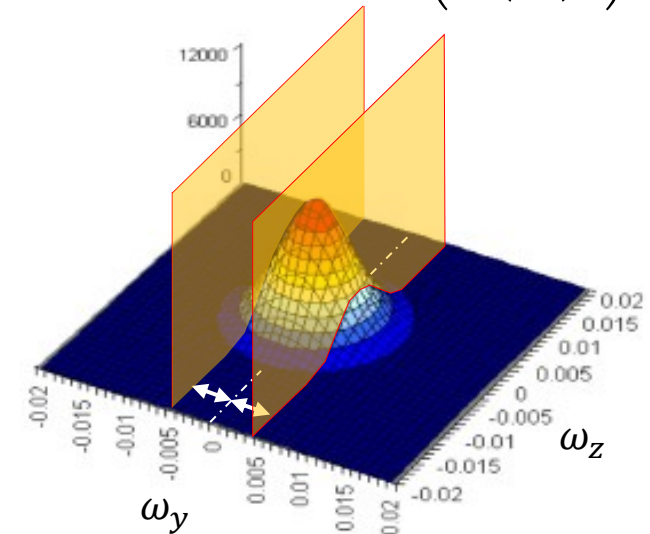
[1] G Duesing, Vacuum **37** 309-315 (1987)

ITER beamline geometrical transmission



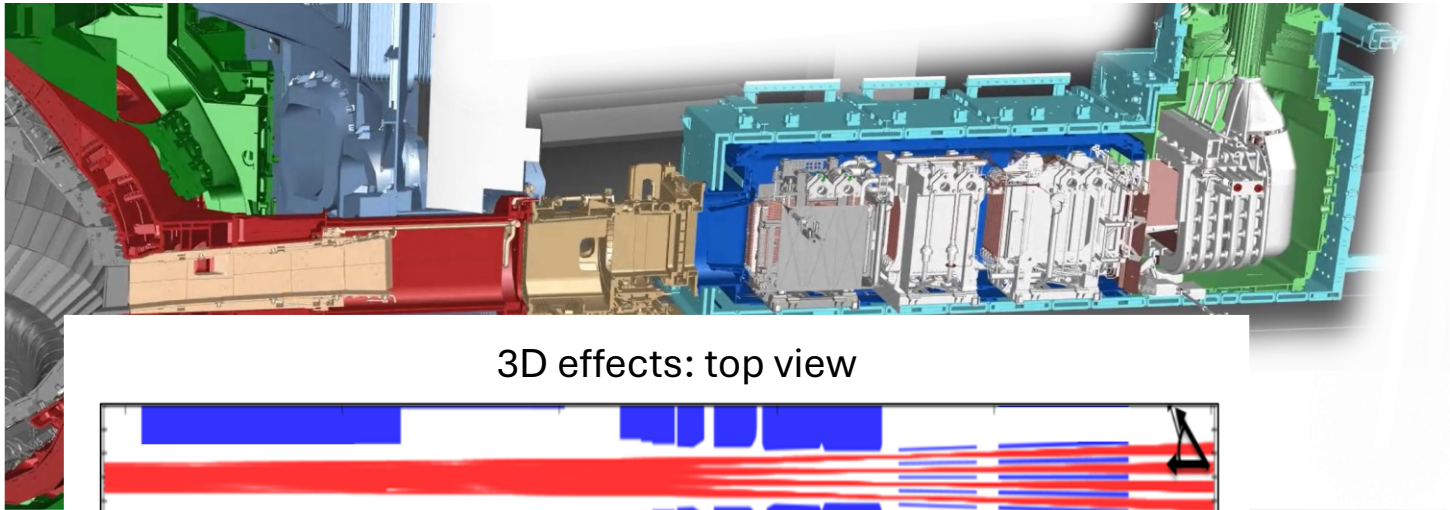
- Beamlet-group focal point at 7.2 m (RID exit), focal point for beamlets within groups at 25.5 m
- RID panels are at the same angular distance from each beamlet axis (caveat)
- Power density as a function of angle ω and x distance from GG: gaussian distribution with 1/e divergence ω_c

$$\frac{q(\omega)}{P_{tot}} = \frac{1}{\pi(x\omega_c)^2} \exp\left(-\left(\frac{\omega}{\omega_c}\right)^2\right)$$

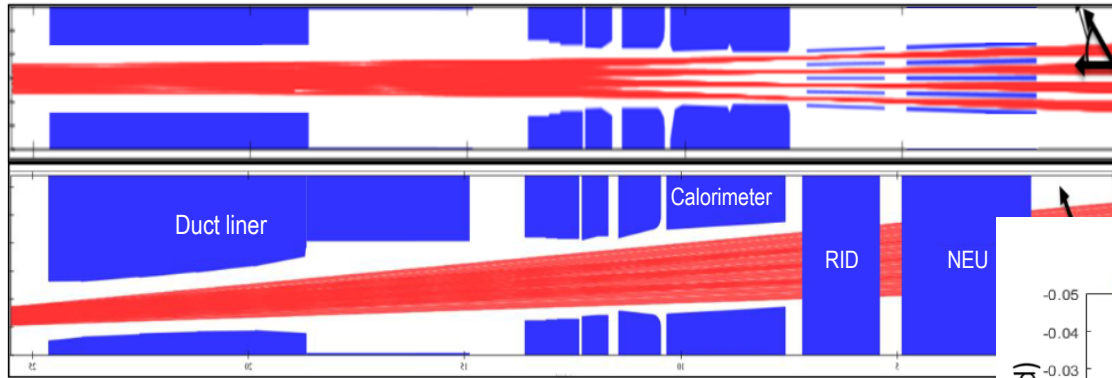


- fraction of beam power F within the limit angle w_{lim} can be calculated as: $F = \text{erf}\left(\frac{w_{lim}}{w}\right)$

ITER beamline geometrical transmission

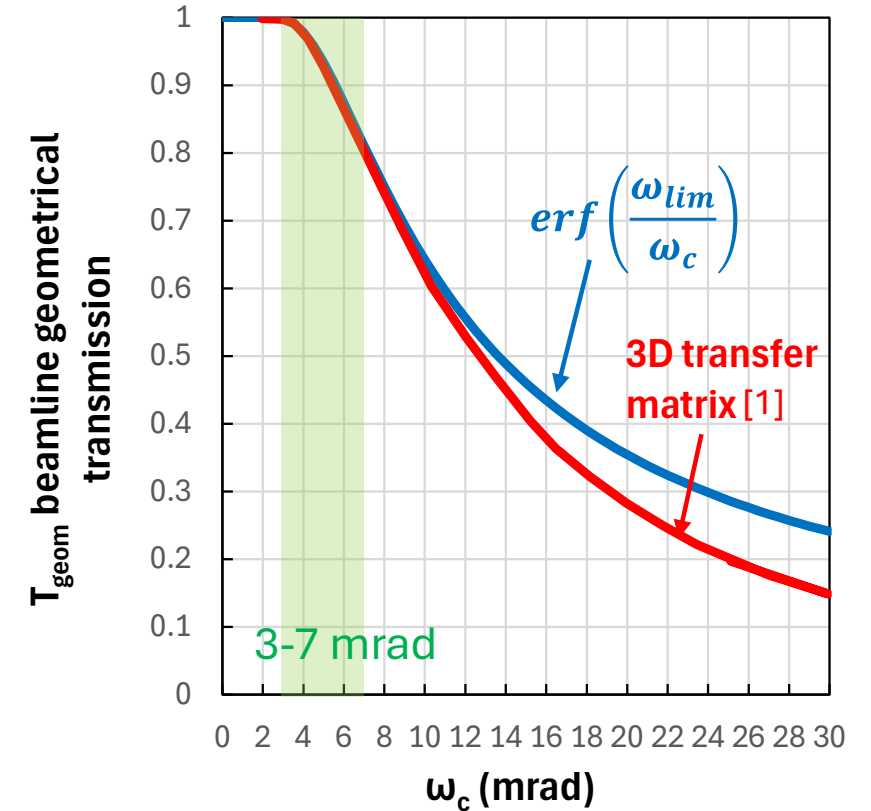
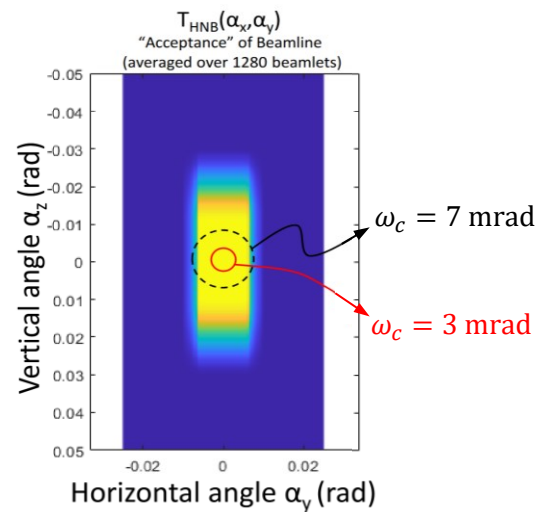


3D effects: top view



3D effects: side view

[1] P Veltri, presented NIBS conference 2022



If divergence < 0.7 mrad,
 $T_{\text{geom}} > 0.8$

Exercise n. 4

Difficulty: ★★☆☆

Simulate the beam power of the ITER HNB.

Tune the extraction and acceleration voltage, the extracted H⁻ current density, the neutralizer gas throughput Q, and see the effect of non-uniformities in the source plasma!

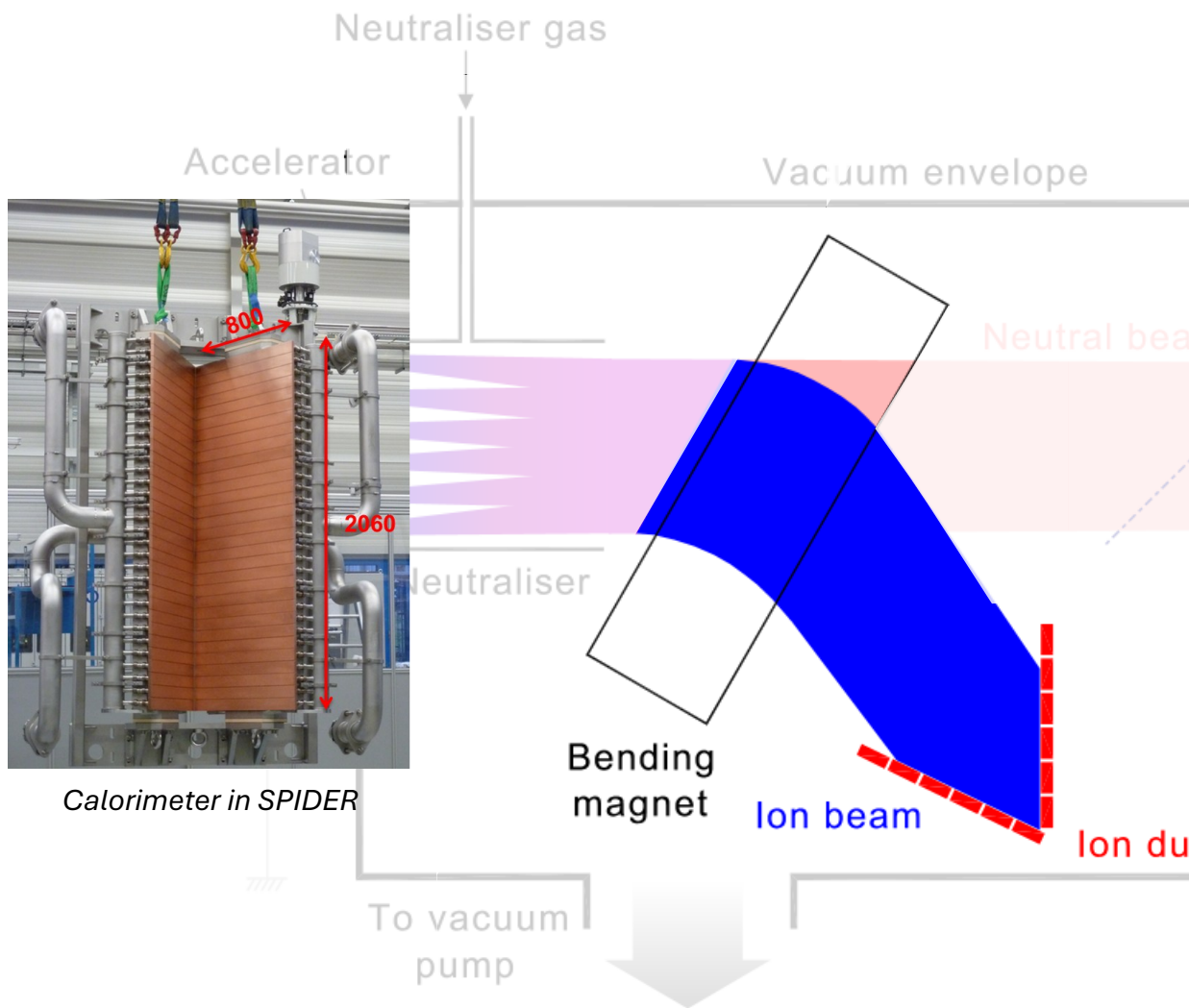


$$P_{HNB} = E_{beam} \cdot j_{ext} A_{ext} \cdot T_{acc}(1 - s) \cdot T_{Geom} \cdot Y_{neu}(1 - R) \geq 16.7 MW$$

https://www.igi.cnr.it/wp-content/uploads/2026/07/ITER_HNB_sim.html



Residual ion dump and calorimeter

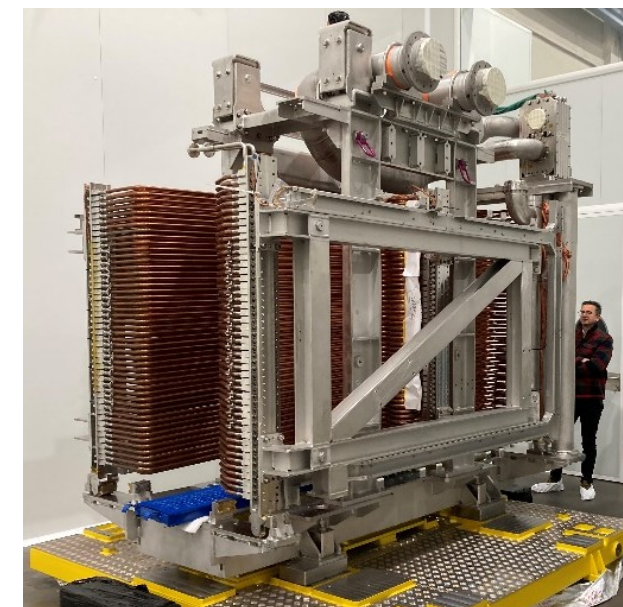


JET NB deflection magnet, residual ion dumps and calorimeter

F. Dhalla et al, Fusion Engineering and Design 96–97 (2015) 458–462



Electrostatic Residual Ion Dump and swirl-tube calorimeter in MITICA

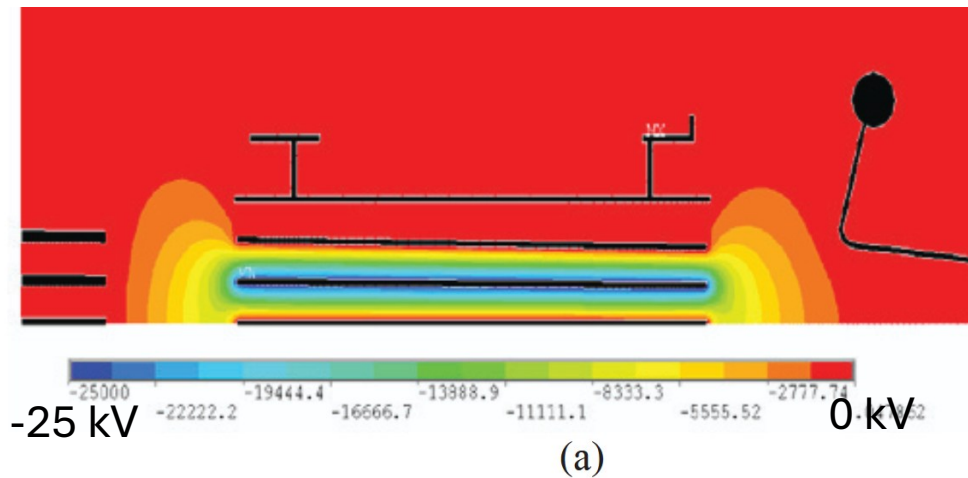


ITER Electrostatic Residual ion dump

Remaining ions (positive and/or negative) need to be removed from the beam before reaching the tokamak field. **Residual ion dump based on electrostatic deflection (ERID)** minimize the required volume with respect to magnetic deflection.

Concept from Kurchatov Institute (Moscow, Russia); with positive ions [1]

Initial experimental verification with negative ions up to 170 keV @ ASIPP (Hefei, China) in 2024 [2].



- [1] A. A. Panasenkov, E. D. Dlugach, AIP Conf. Proc. 2052, 040019 (2018)
- [2] J. Wei et al., Nucl. Fusion 66 (2026) 026020
- [3] A.F. Lifschitz et al. 2014 Nucl. Fusion 54 043020

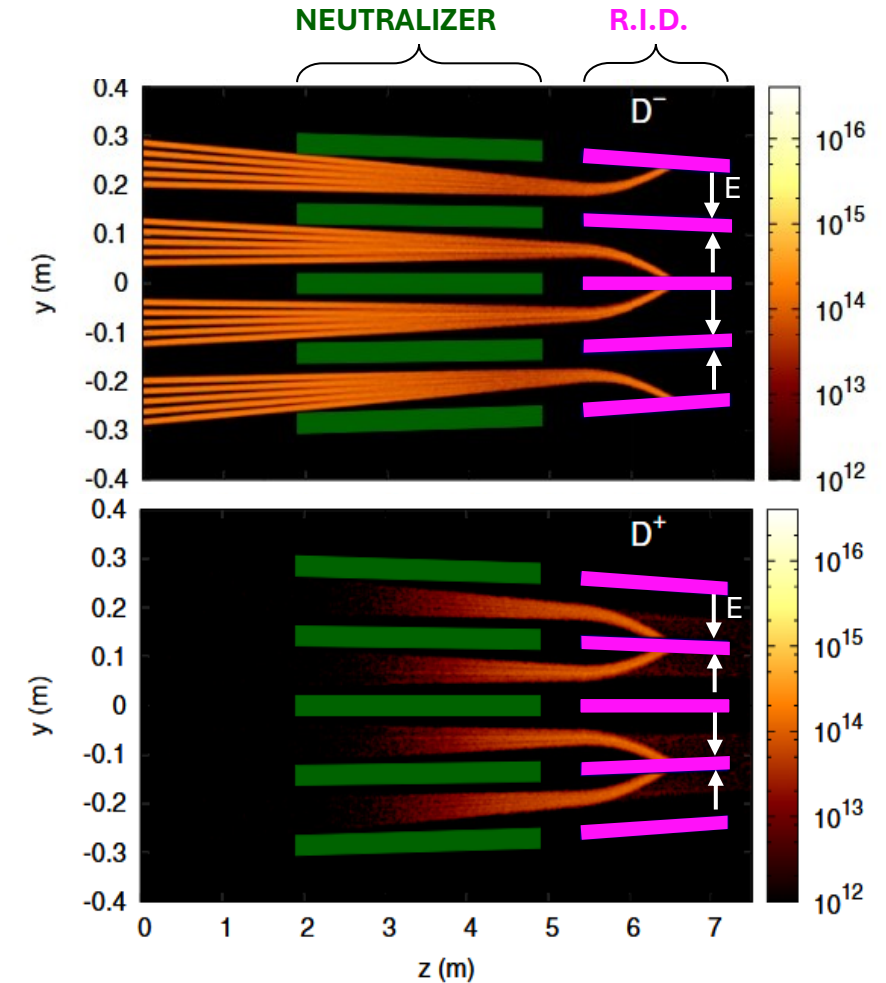


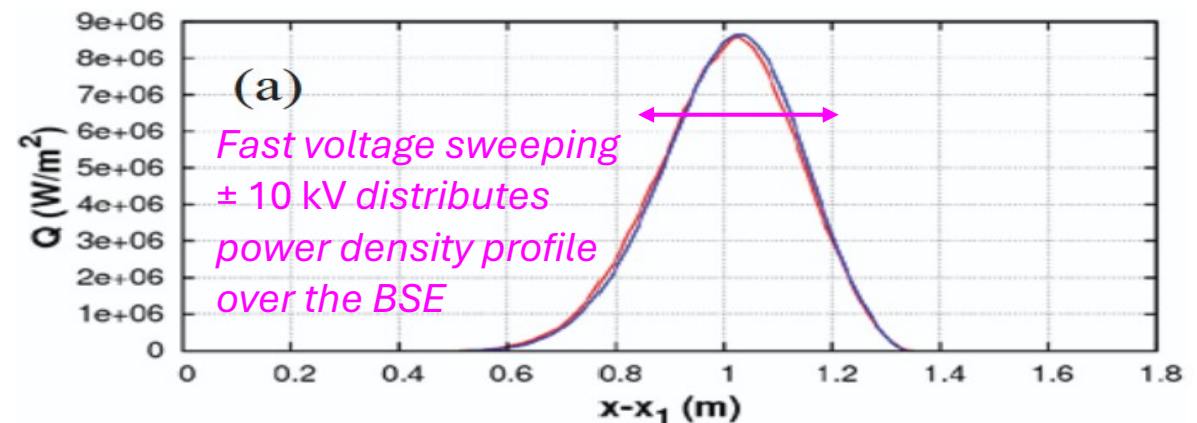
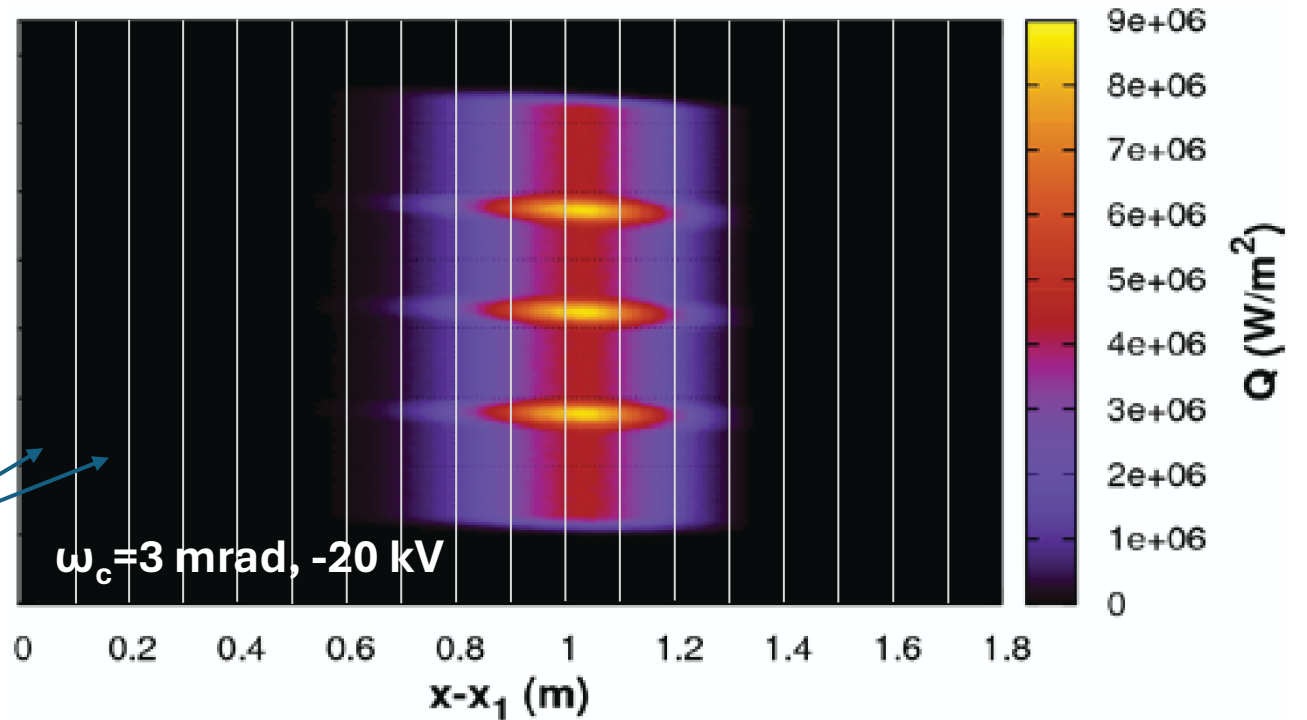
Figure 7. Spatial density distribution of the different component of the beam at $t = 15 \mu s$ at the middle plane ($x = 0$).

ITER Electrostatic Residual ion dump



ITER E-RID

- **Sweeping voltage:**
-20kV $\pm$ 10 kV
- **Design heat fluxes:**
from 3 MW/m² (7 mrad divergence)
to 8.5 MW/m² (3 mrad divergence)
- **18 BSE:** CuCrZr “Beam Stopping Elements” each having 4x cooling channels with swirl tapes



Calorimeter

Use:

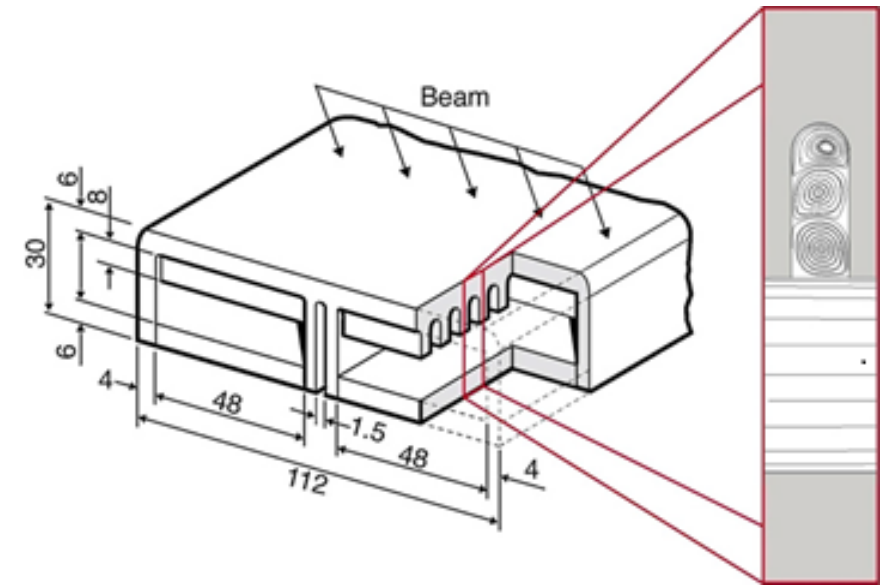
- Needed for beam conditioning outside of tokamak pulses (HV, Cs...)
- Measure beam power, beam footprint, neutralisation fraction

Thermomechanical design:

- High Heat Flux component design ($\sim 15\text{--}20 \text{ MW/m}^2$): use of *swirl tapes* or *hypervapotron* to enhance local heat transfer coefficient.
- Number of beam cycles: fatigue life
Beam on/off cycles
Breakdowns
- Material activation: subject to direct neutron flux from the torus $\rightarrow$ minimize volume, low-activation materials

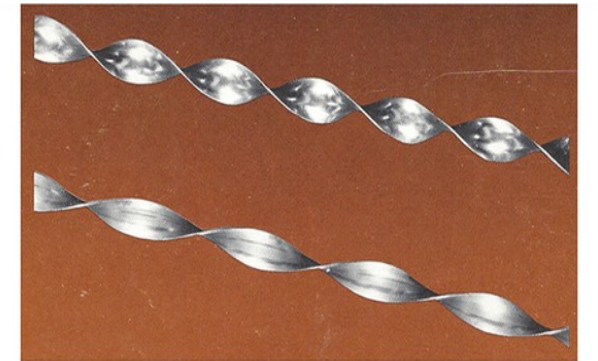
MAST-U calorimeter

- 12 MW/m^2
(hypervapotrons)

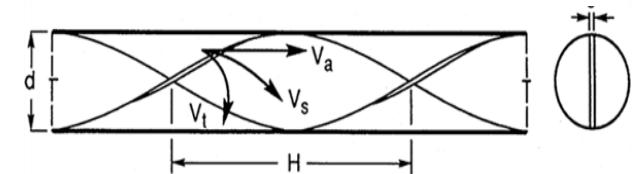


ITER calorimeter

- From 7.3 MW/m^2 (7 mrad divergence) to 14.3 MW/m^2 (3 mrad divergence)
- 13 MW/m^2 (swirl tubes)
- Steady-state: 100 kg/s cooling water

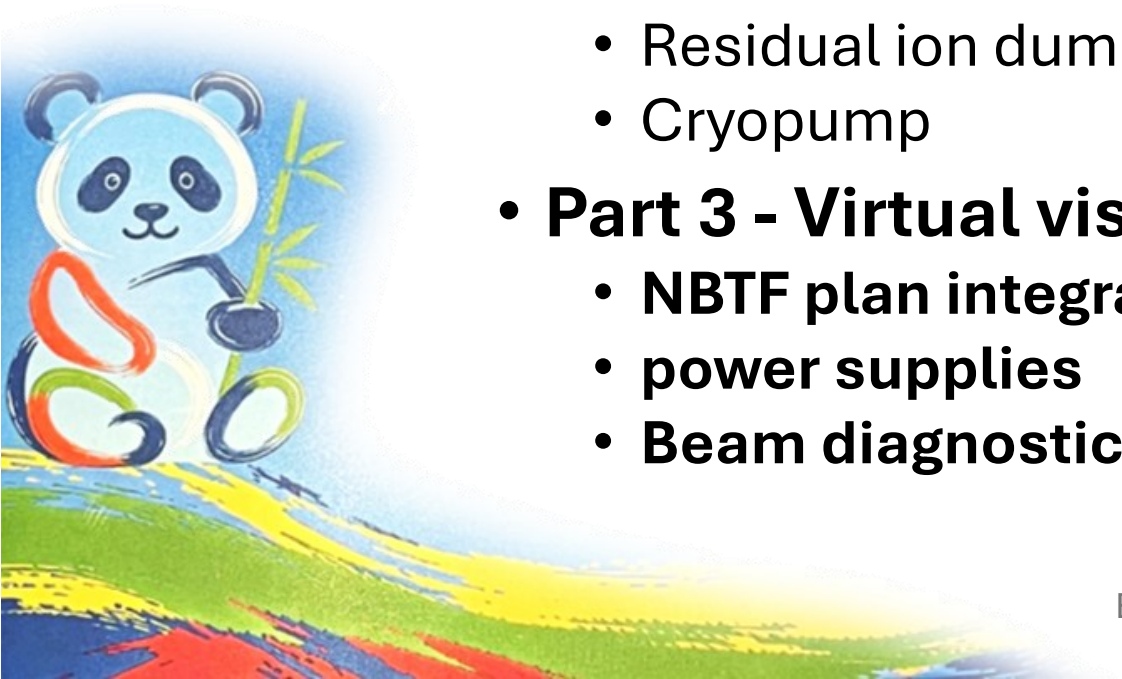


- ✓ *Boiling & turbulence to improve heat transfer coefficient*
- ✓ *Stress from internal pressure of coolant*
- ✓ *Material considerations limit temperature of element e.g. $\text{CuCrZr} < 450^\circ\text{C}$ to avoid precipitation of Cr leading to hardening*

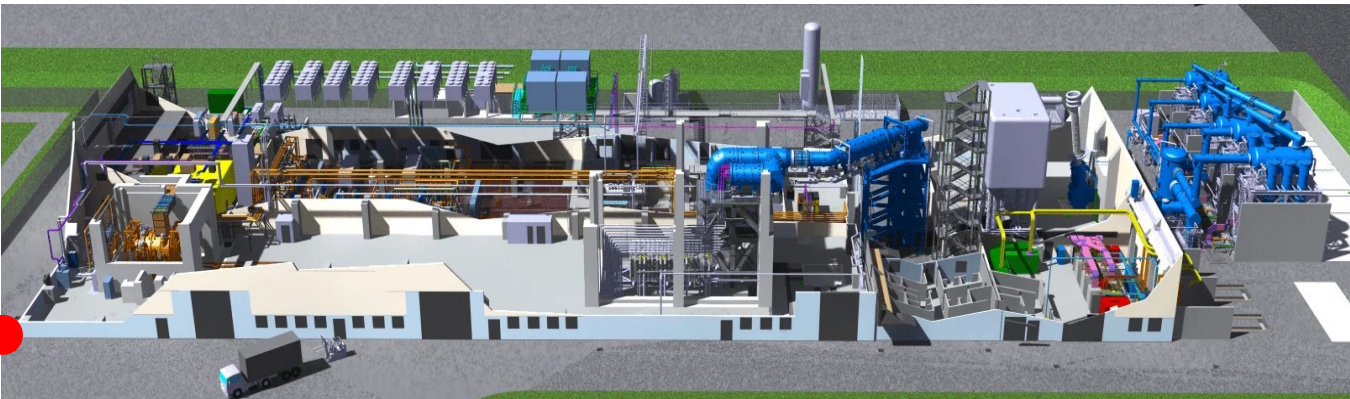


Outline

- Part 1 - Introduction to neutral beam injectors & requirements
 - Beam energy and precursor negative ion beams
 - Present international R&D in view of ITER
- Part 2 - NBI Systems (general examples and ITER case)
 - Ion source
 - Accelerator
 - Neutraliser
 - Residual ion dump and calorimeter
 - Cryopump
- **Part 3 - Virtual visit to the ITER Neutral Beam Test Facility**
 - NBTF plan integration in ITER plan
 - power supplies
 - Beam diagnostics



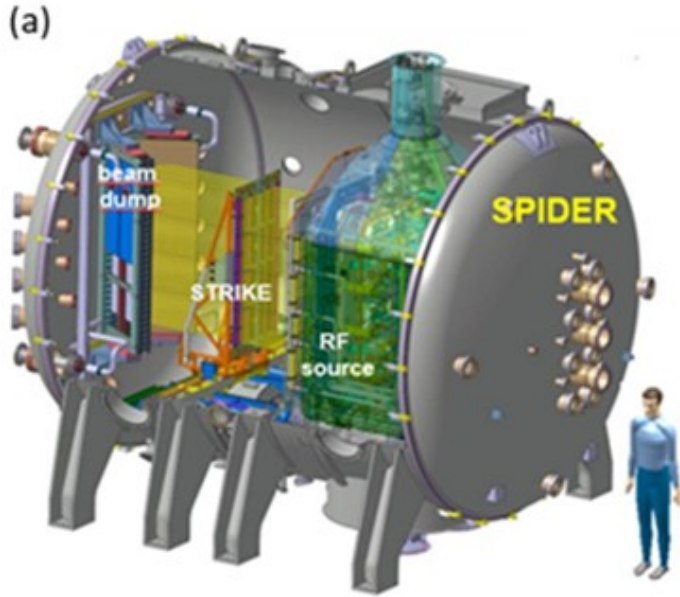
Virtual visit of the ITER Neutral Beam Test Facility



V. Toigo *et al* 2019 *Nucl. Fusion* **59** 086058



Virtual visit of the ITER Neutral Beam Test Facility



SPIDER (H-/D-)

$$J_{\text{ext}} = 355/285 \text{ A/m}^2$$

$$E_{\text{beam}} = 0.1 \text{ MeV}$$

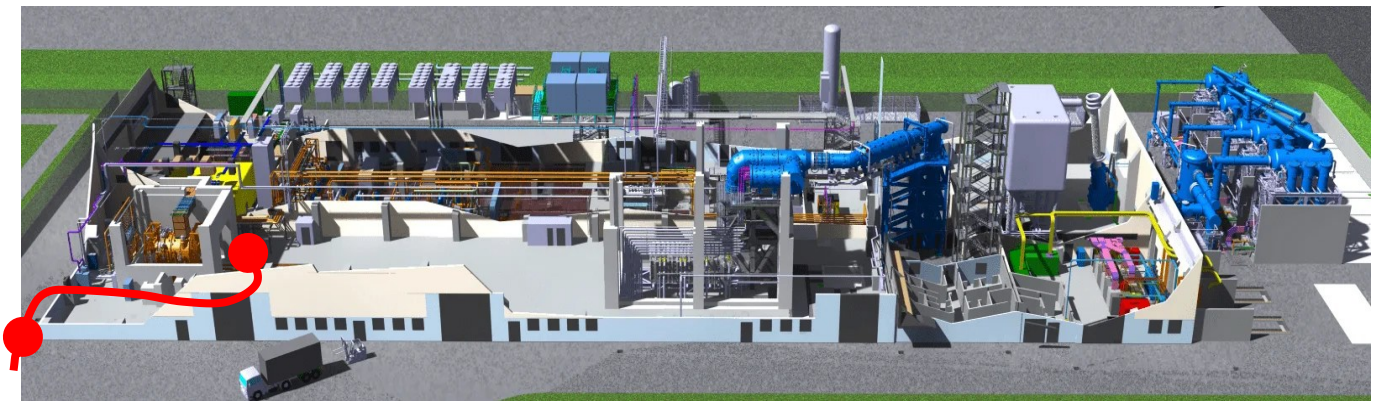
$$P = 0.3 \text{ Pa}$$

$$\text{Ele/Ion} < 0.5/1$$

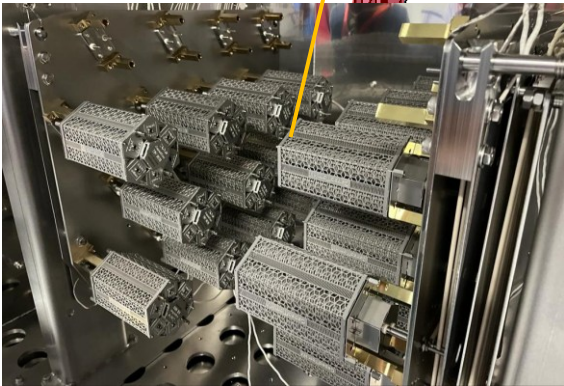
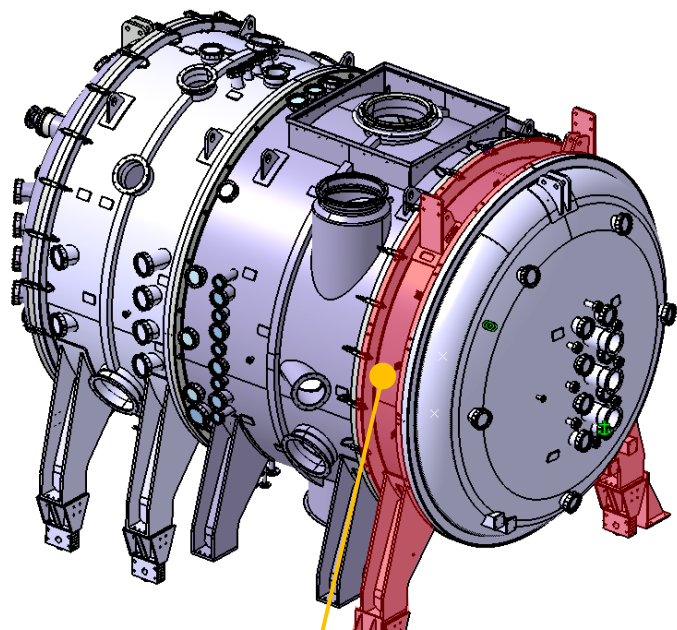
$$\text{Uniformity} \pm 10\%$$

$$\text{Beam on time} = 1000/3600 \text{ s}$$

*In Operation
since 2018
Addresses the
challenges of the
Beam Source*



Virtual visit of the ITER Neutral Beam Test Facility

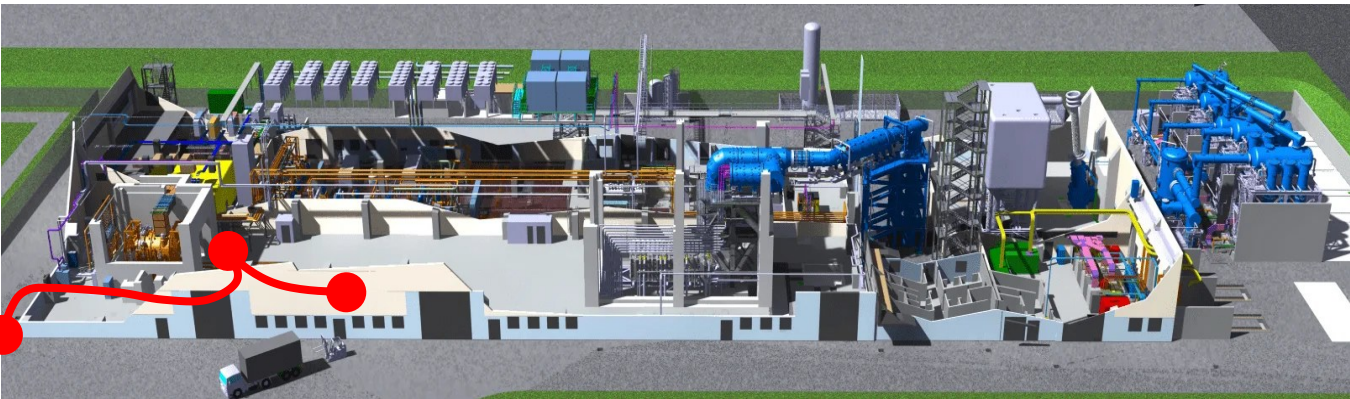
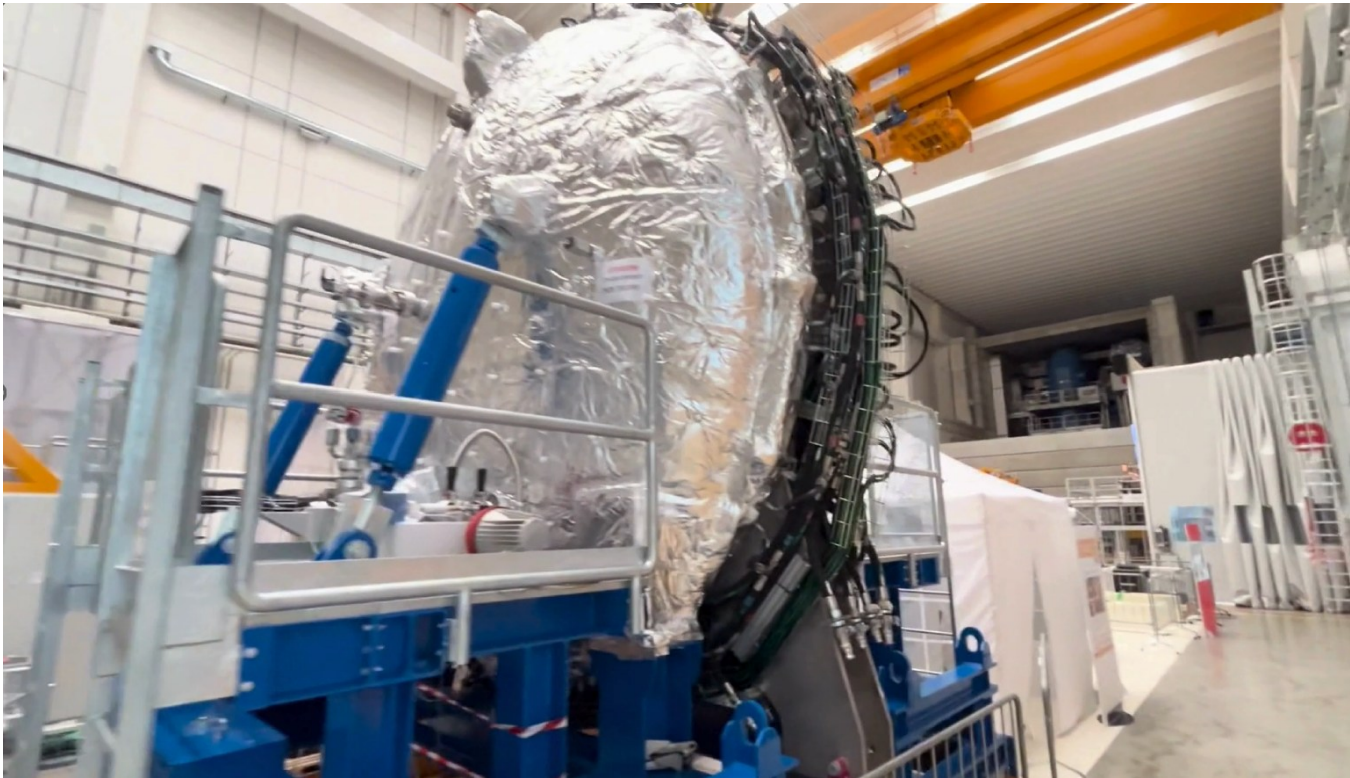


SPIDER pumping module

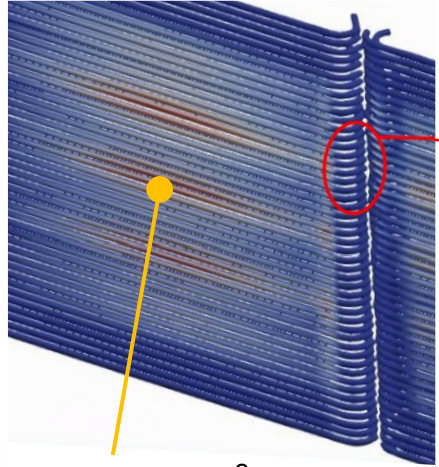
384 NEG cartridges
pumping speed for H₂
~300 m³/s

H₂ Capacity for 384 NEG
cartridges 440000 Pa·m³

E. Sartori, et al., Vacuum 214: 112198 (2023)
E. Sartori et al, J. Vac. Sci. Technol. B 41, 034202 (2023)



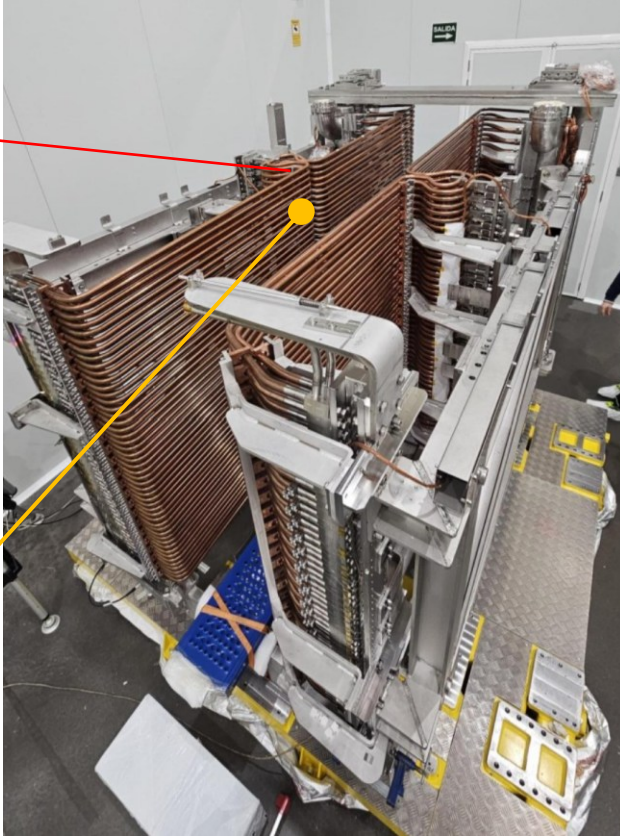
Virtual visit of the ITER Neutral Beam Test Facility



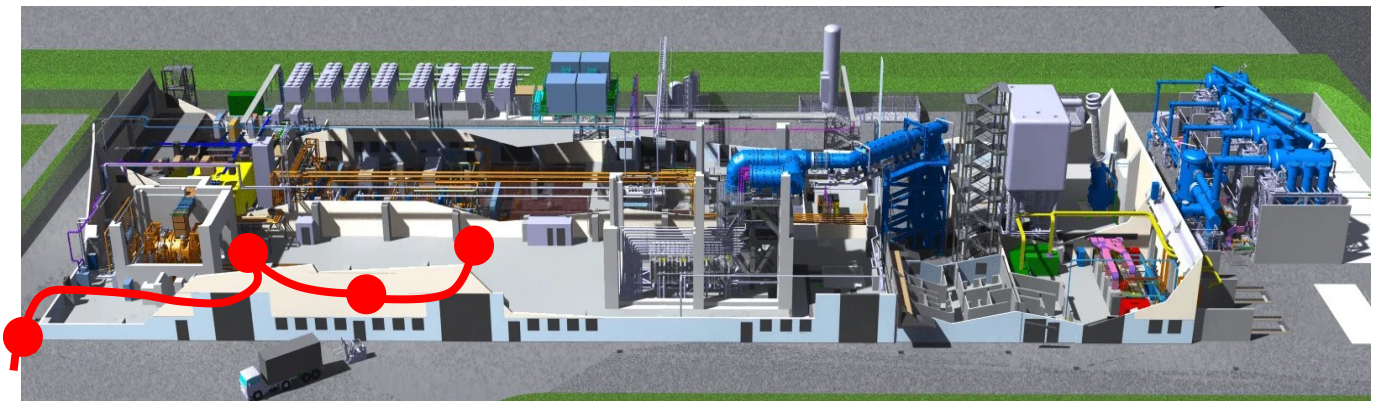
$\sim 8.7 \text{ MW/m}^2$
@5 mrad div.

MITICA Calorimeter
HHF design based on
parallel swirl-tubes

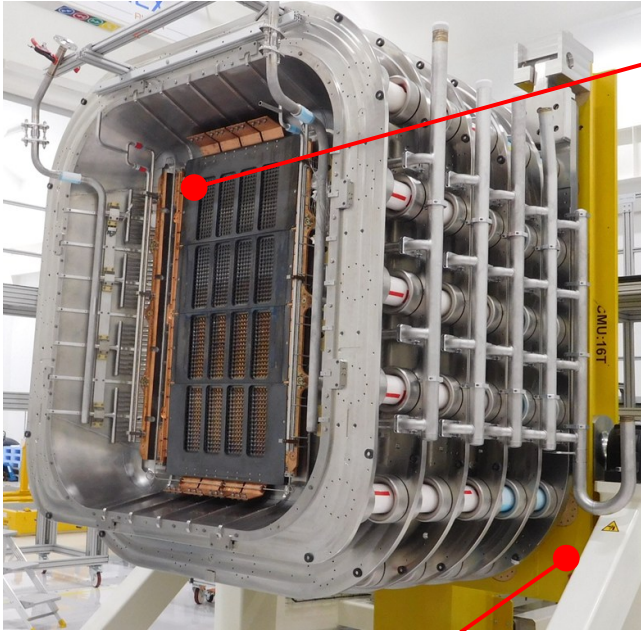
Key correction of tube
alignment to avoid
shine-through; panels
can open/close



M Dalla Palma et al., Fus Eng Des 96-97: 557-562 (2015)
M Dalla Palma et al. Fus Eng Des 171: 112559 (2021)



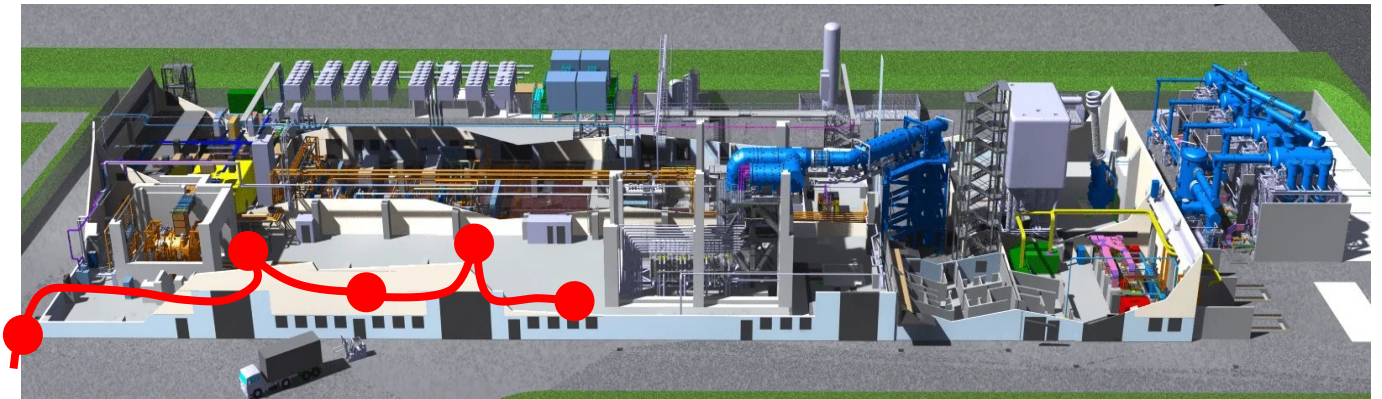
Virtual visit of the ITER Neutral Beam Test Facility



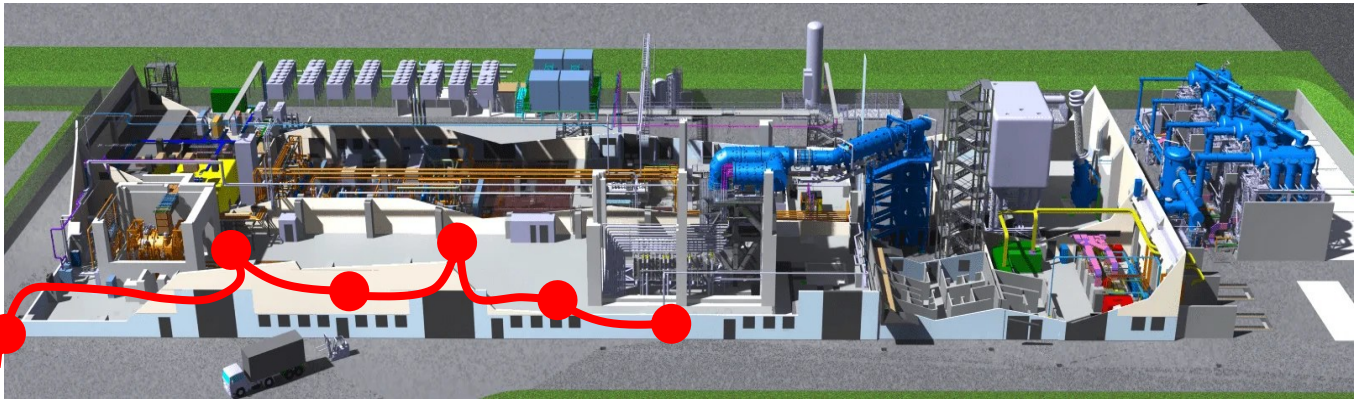
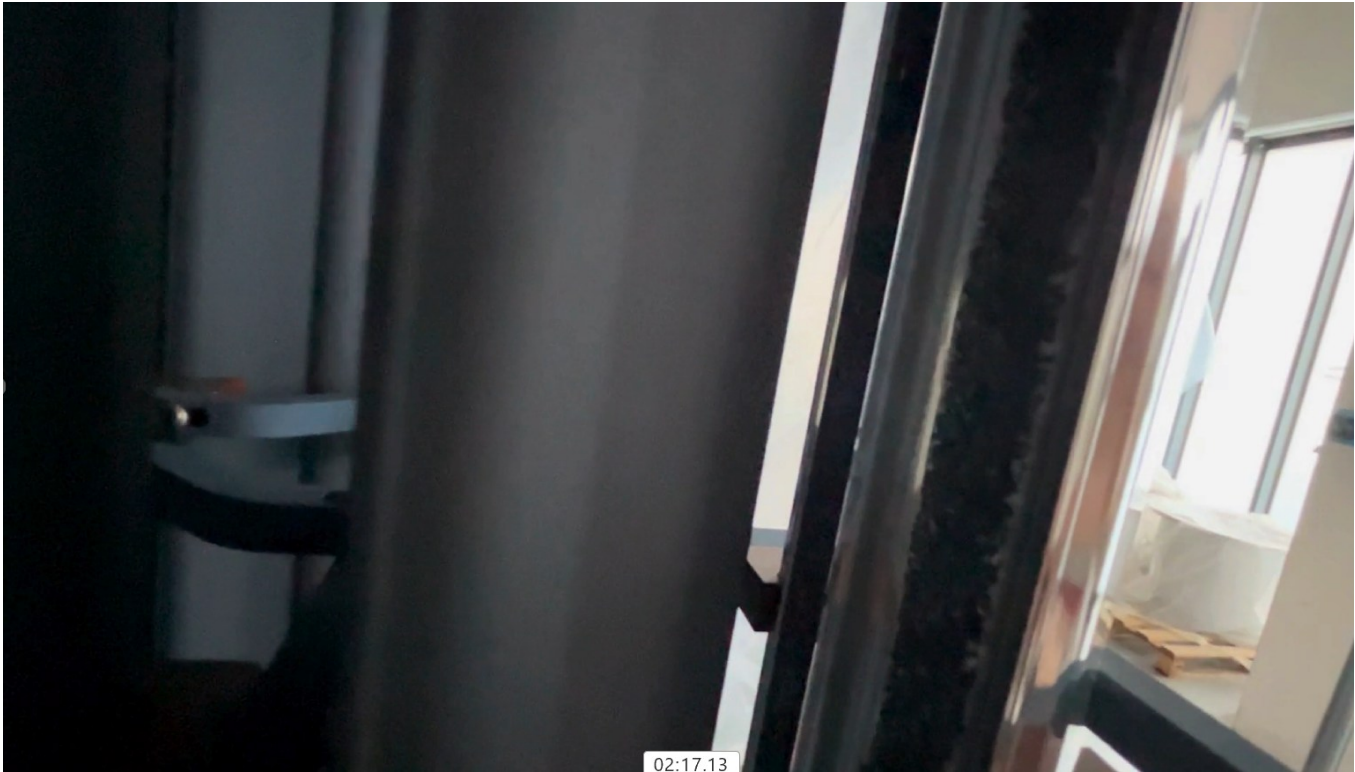
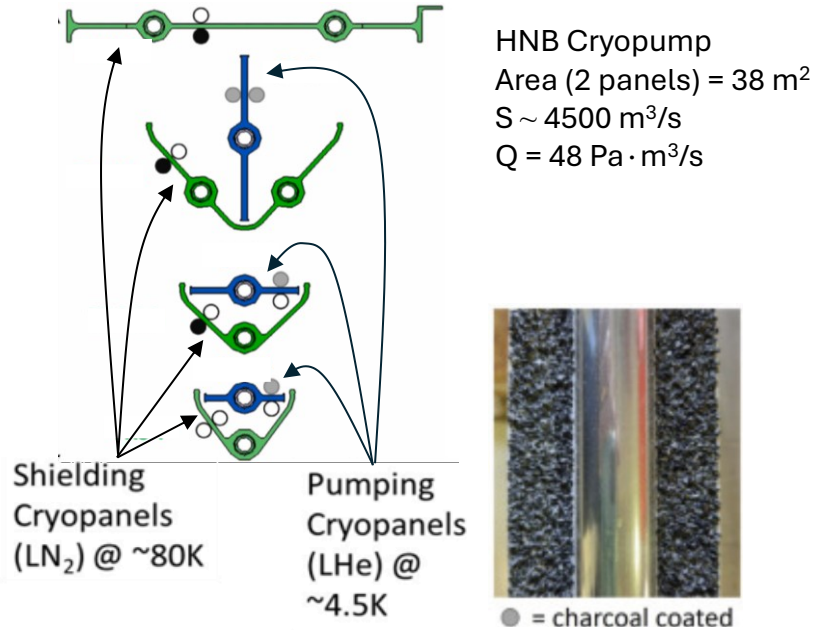
7 grids, 1280
apertures:
alignment
tolerance for
each aperture
 ± 0.2 mm
from beamlet ideal
axis
(correction for
hot alignment)

Temporary tilting support for grid positioning:
metrology of grids in reference position (laser
tracker), apply correction in lay-down position,
rotate back to check result (iterative procedure!)

P Agostinetti, et al., *Nucl. Fusion* 56, 016015 (2016)
D Marcuzzi, et al., *Rev. Sci. Instrum.* 87, 02B309 (2016)



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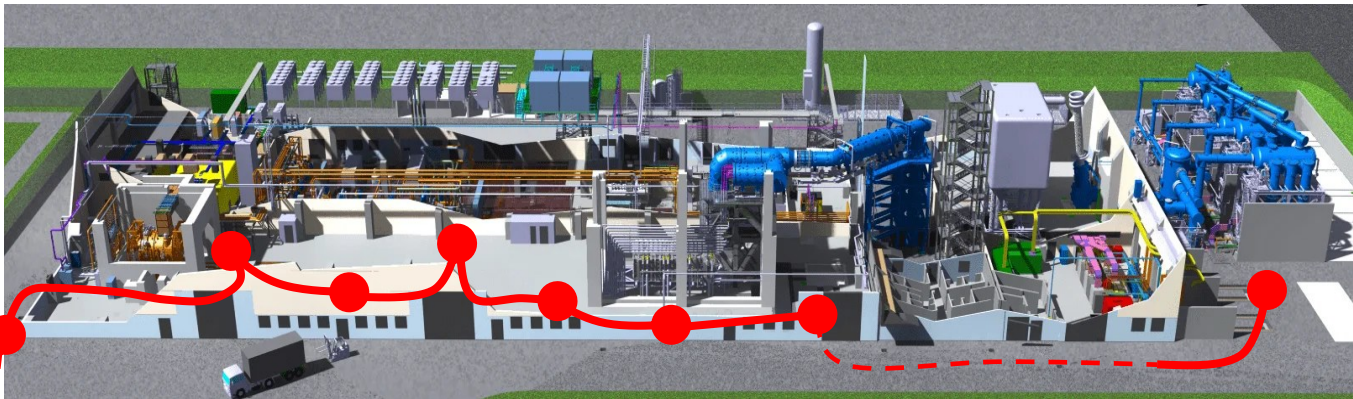
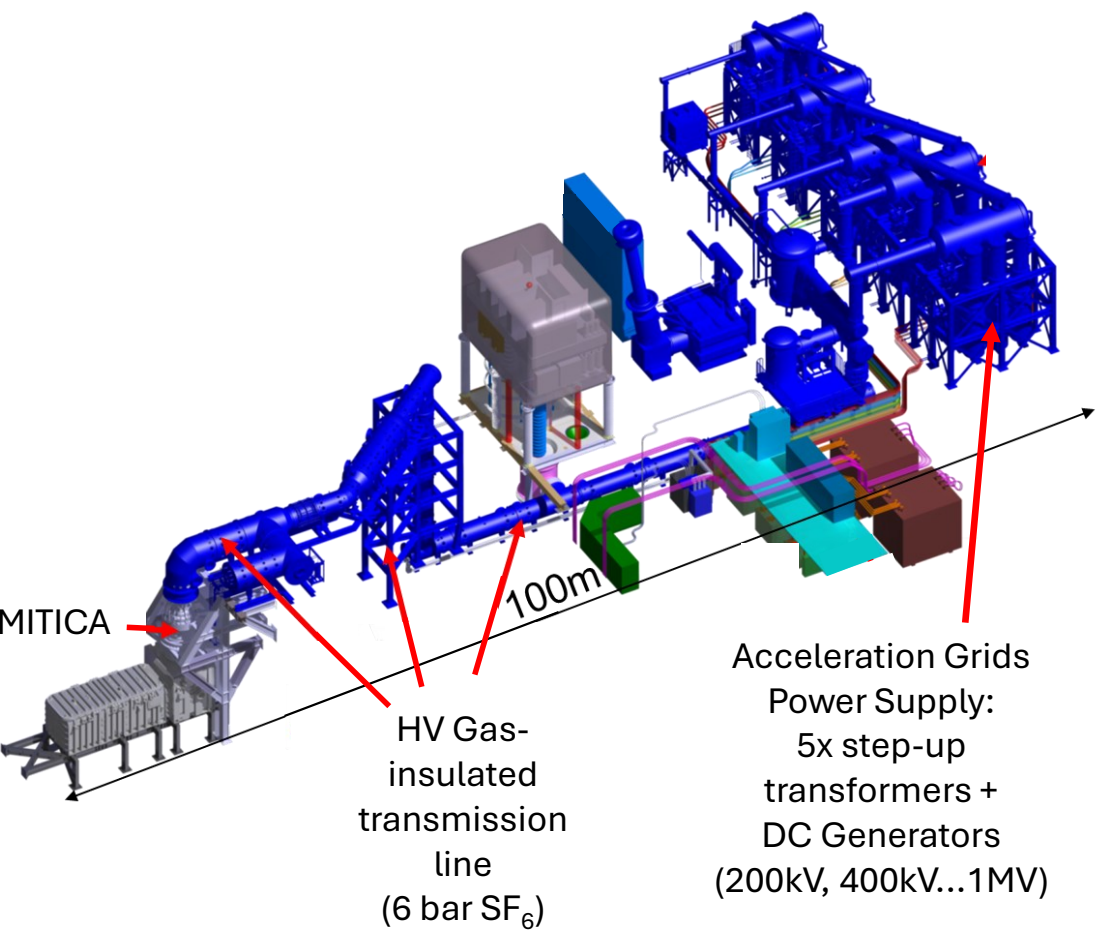


gas adsorption **first test** carried out in **2025**:
simulation-based analysis gives $\bar{S} \sim 3250 \text{ m}^3/\text{s}$

Target for next tests (Oct 2026):
+20% (cryoplant improvements)

J Buckerfield, et al., Fus. Eng. Design 215 (2025) 114991

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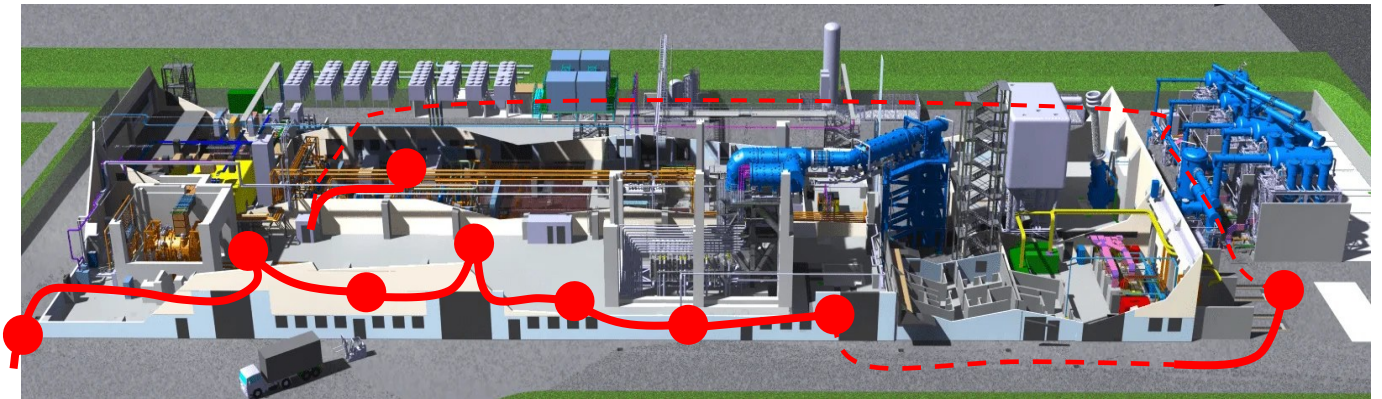
Virtual visit of the ITER Neutral Beam Test Facility

Primary cooling circuits:

- MITICA, SPIDER, Auxiliaries: total of **70 MW**
- Chemical Control System (CCS) produce **ultrapure water** (very low conductivity for cooling of HV components)

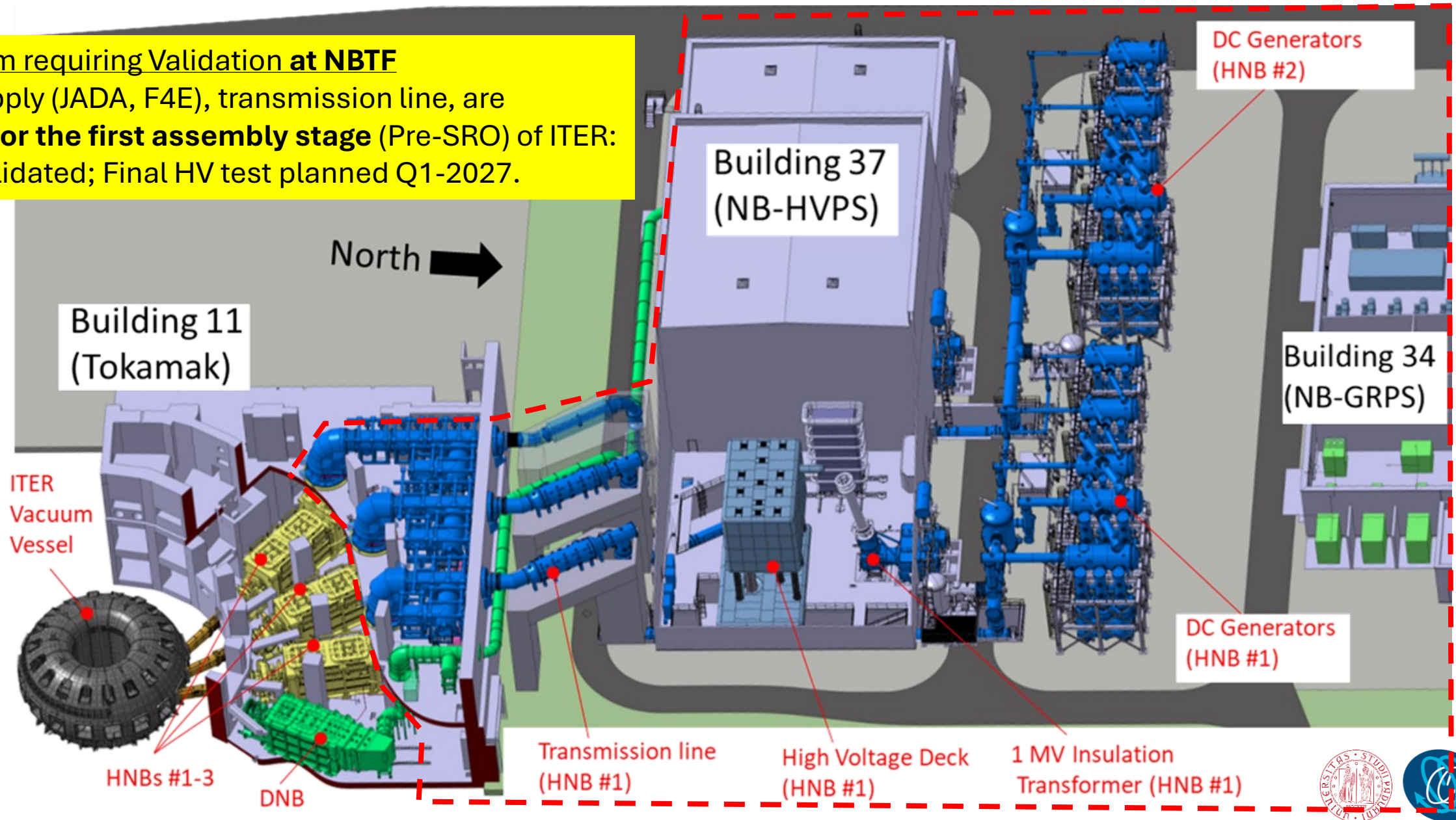
and secondary cooling circuits:

- cooling towers and dry coolers 23 MW
- water basins

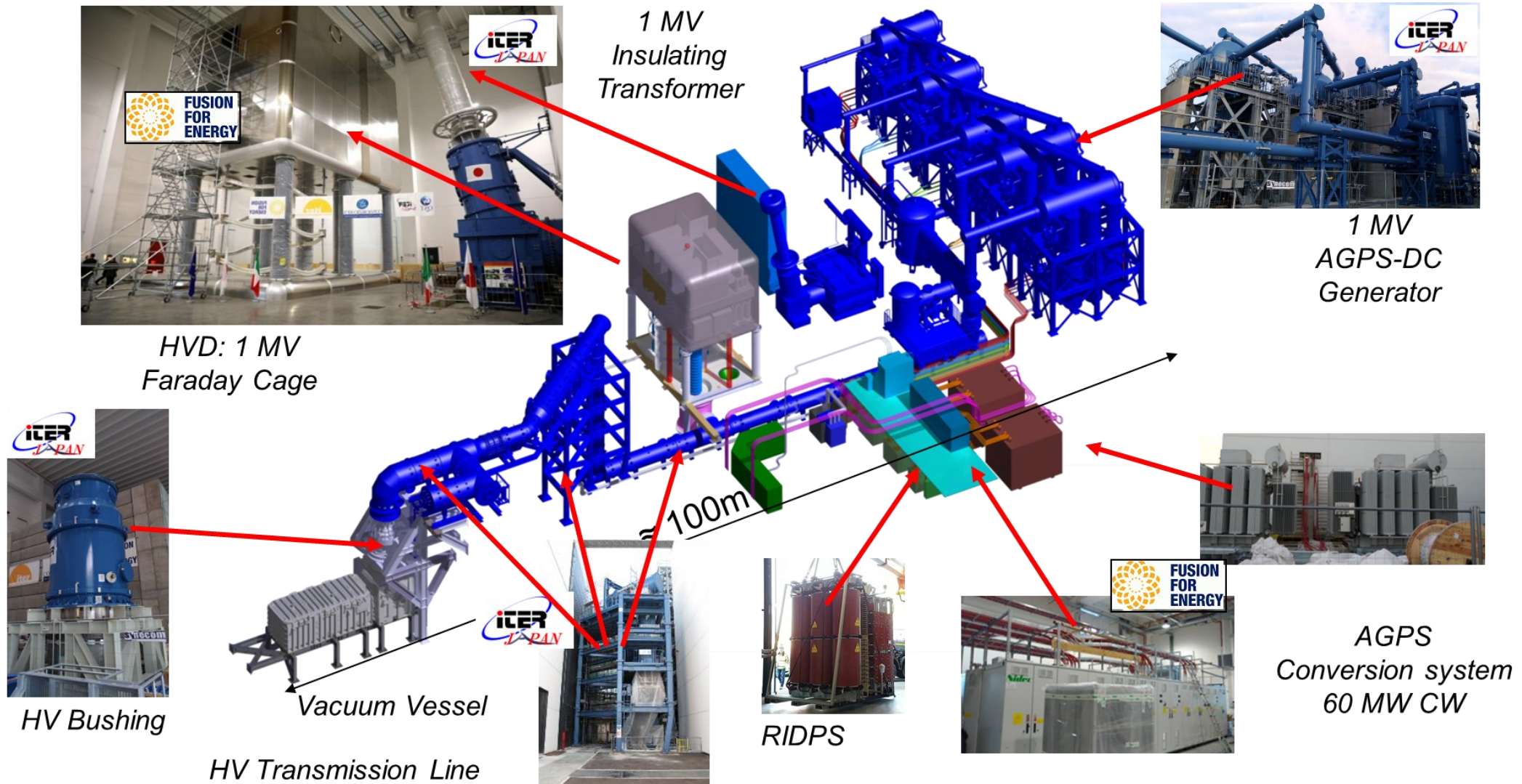


Overview of NB System at ITER

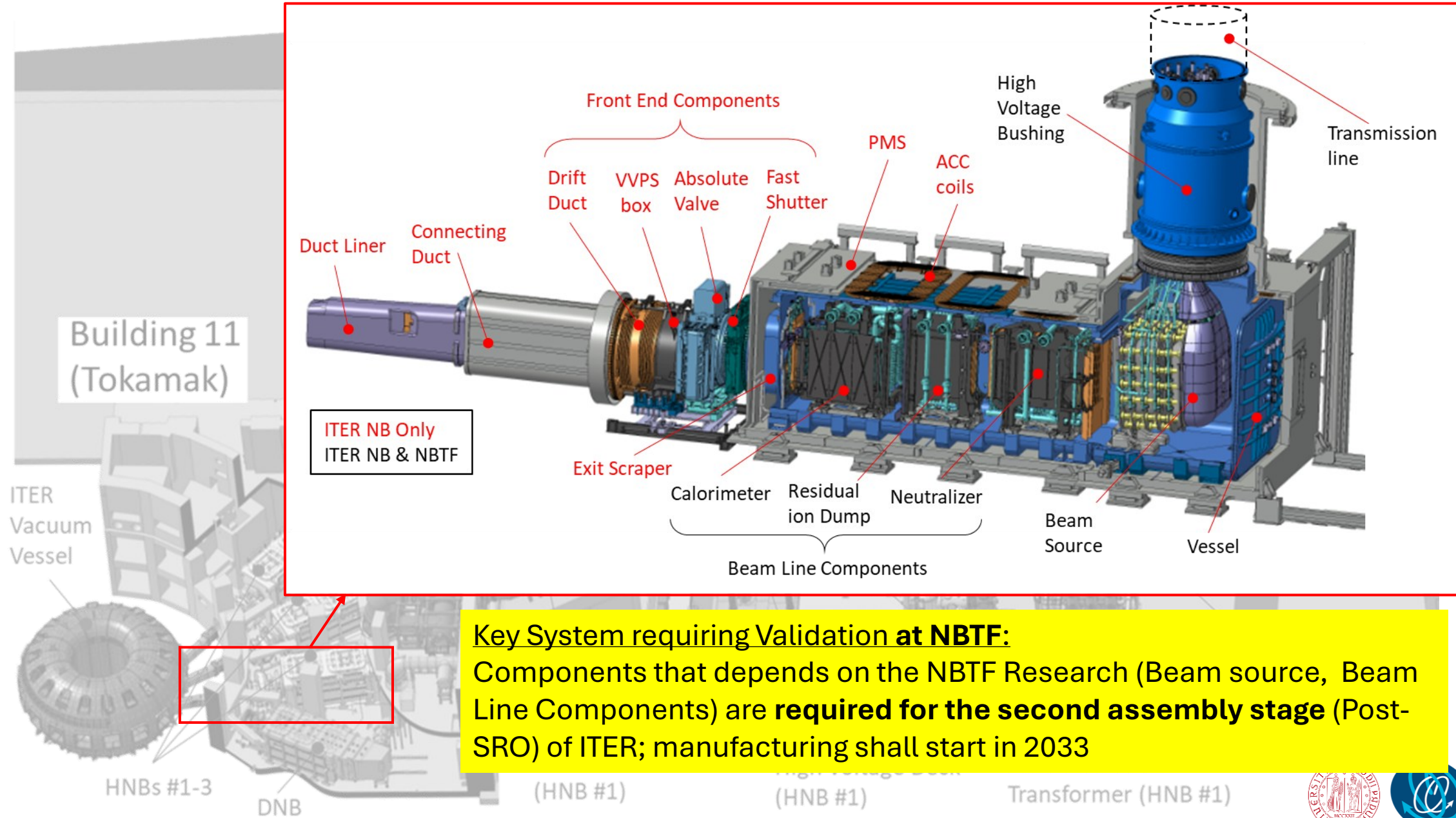
Key System requiring Validation at NBTF
Power Supply (JADA, F4E), transmission line, are **required for the first assembly stage (Pre-SRO)** of ITER: mostly Validated; Final HV test planned Q1-2027.



Power supplies



Overview of NB System at ITER



ITER, NB and NBTF Baseline Plan

