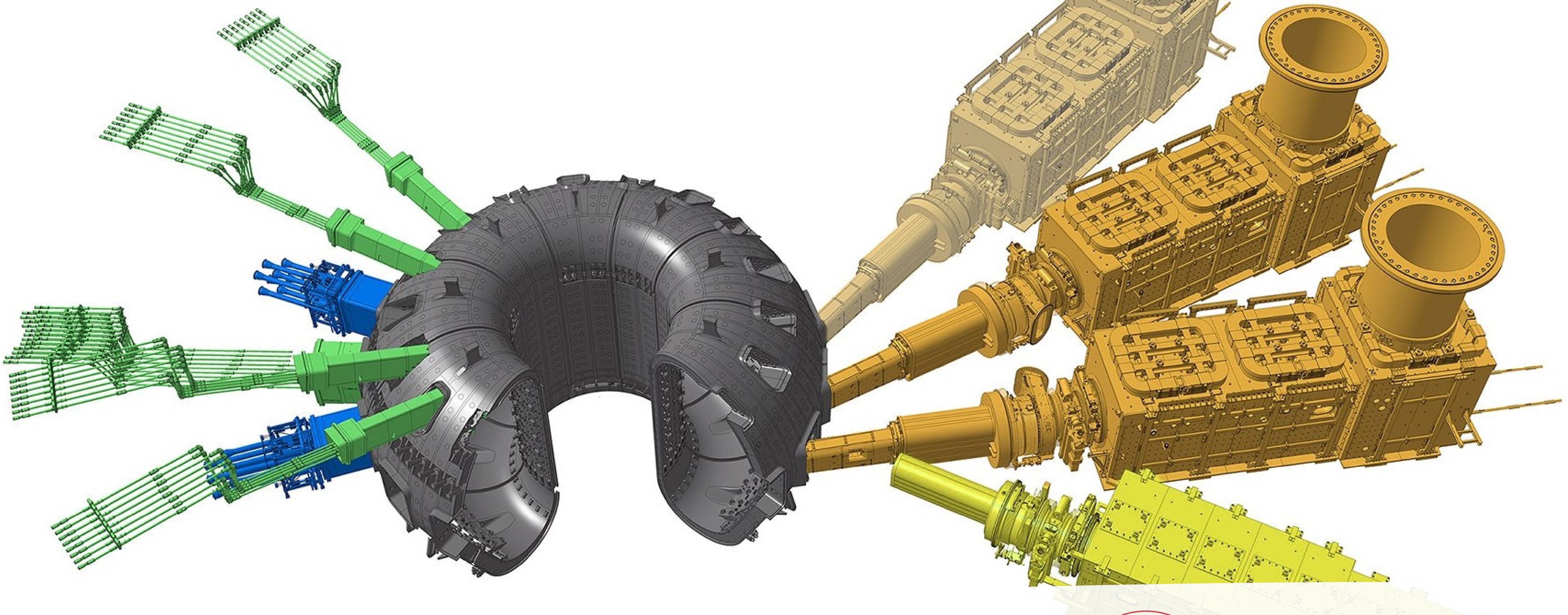


Neutral Beam Injectors

22nd May 2025 – Joint ICTP-IAEA Fusion Energy School
International Centre for Theoretical Physics – Trieste

prof. Emanuele Sartori

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

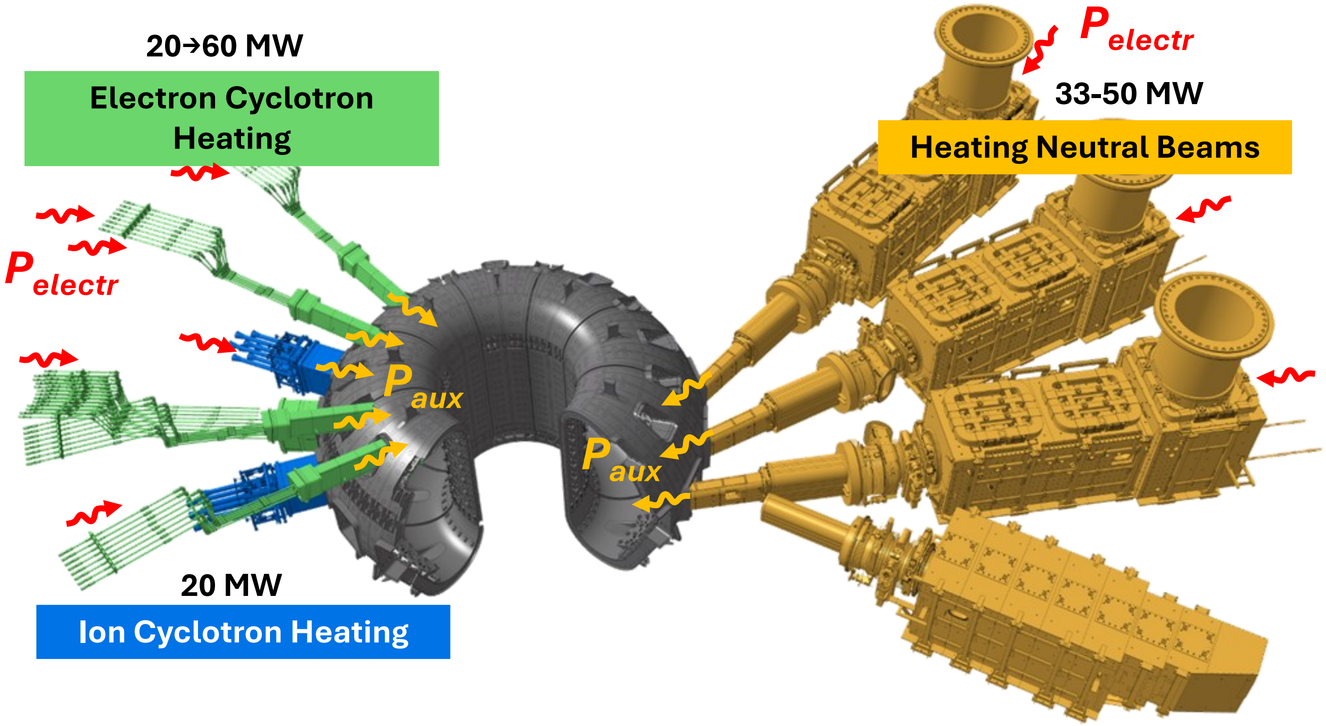
The Abdus Salam International Centre for Theoretical Physics

IAEA International Atomic Energy Agency
Atoms for Peace and Development

Università degli Studi di Padova

Consorzio RFX
Ricerca Formazione Innovazione

Heating & Current Drive



Role of Additional heating systems

- Ohmic heating is not sufficient to reach fusion-relevant temperatures
- Access to H-mode or target confinement regimes
- Sustain non-inductive currents (current drive)
- Energy loss channels must be balanced, e.g.: thermal conduction, radiation, neutron power…

Power balance

$$P_{ohmic} + P_{aux} + P_{alpha} = P_{loss}$$

Ohmic power limited to T_i ~3 keV

Auxiliary heating system bridge the gap

Alpha particle power effective at high T_i ~10-15 keV

tokamaks: $P_{ohmic} + P_{aux} + P_{alpha} = P_{loss}$

stellarators: $P_{aux} + P_{alpha} = P_{loss}$

ignition: $P_{alpha} = P_{loss}$

Efficiency

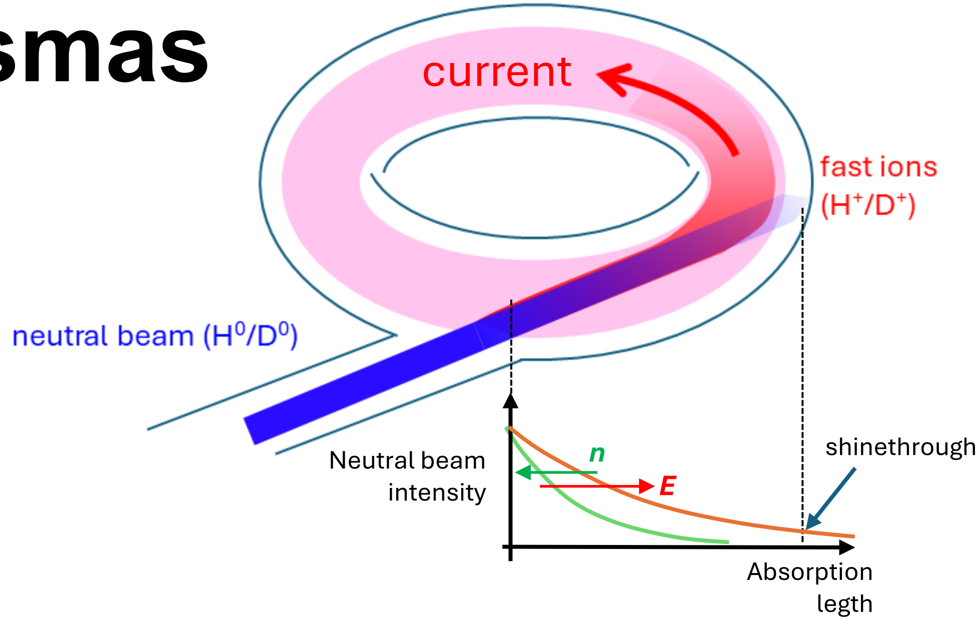
Auxiliary heating systems have their own efficiency:

$$P_{aux} = \eta_{coup}\, \eta_{conv}\, P_{electr}$$

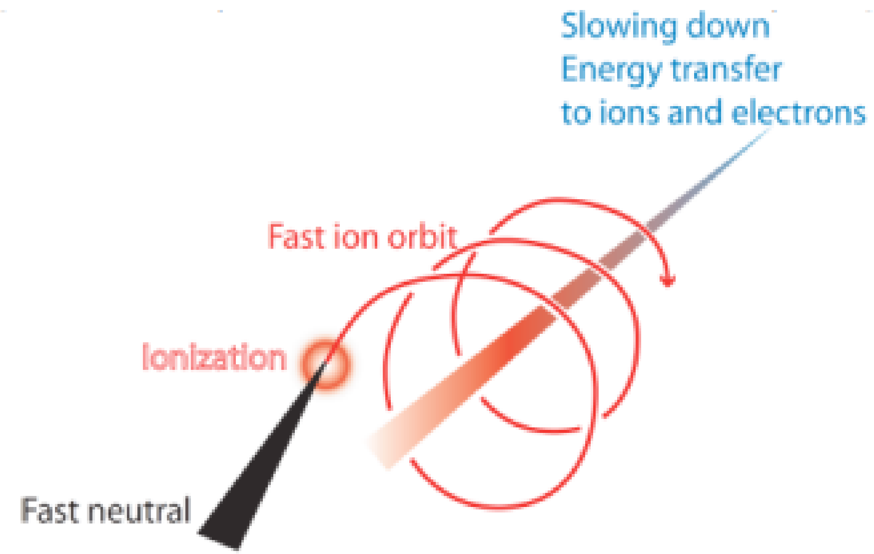
Coupling of injected power to plasma

Conversion from wall-plug to injected power

Neutral beams in fusion plasmas



- neutral atoms can penetrate through the confining magnetic field
- Ionization by collision with plasma ions and electrons
- Fast ion trapped in the magnetic field transfers energy to plasma ions and electrons by coulomb interaction



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

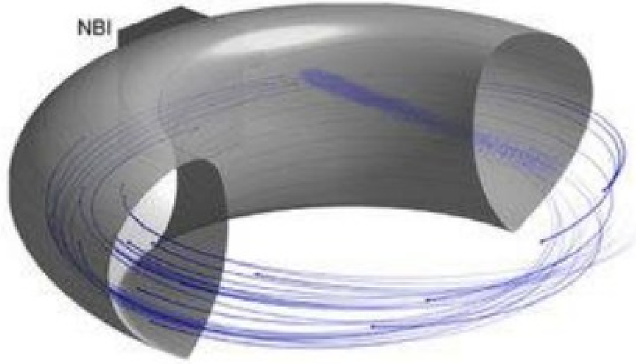
- Ionization depth in the fusion plasma: characteristic length scales as

$$\lambda \approx \frac{E}{18 \cdot n \cdot A}$$

n in 10^{19} m^{-3}, E in keV, A in amu

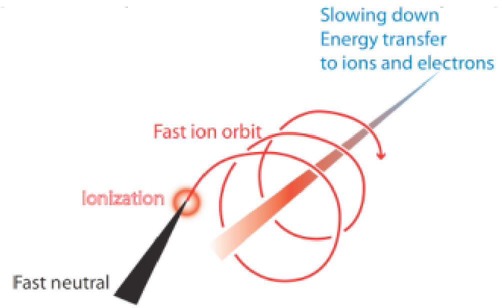
- High densities and large plasma volume require **high energy** for depositing power at the core region of the fusion plasma
- Often, high-confinement regimes are achieved by neutral beam heating -> low plasma target thickness when neutral beam is activated, then, it evolves with time.

What are Neutral Beams used for?



P. Vincenz, RFX

Plasma Heating



Current Drive

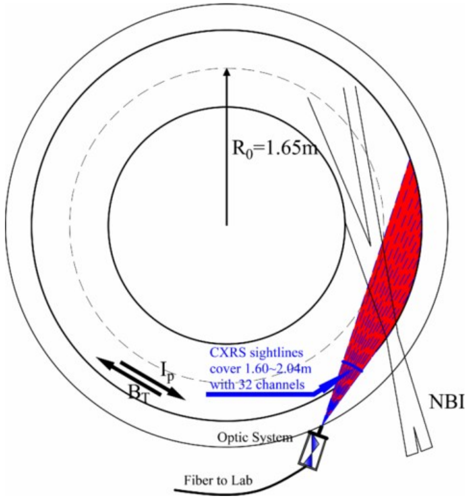
Fast neutrals → fast ions → non-inductive current

Toroidal Torque

Injected neutral flux imparts momentum, increasing plasma rotation

Plasma Diagnostics

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

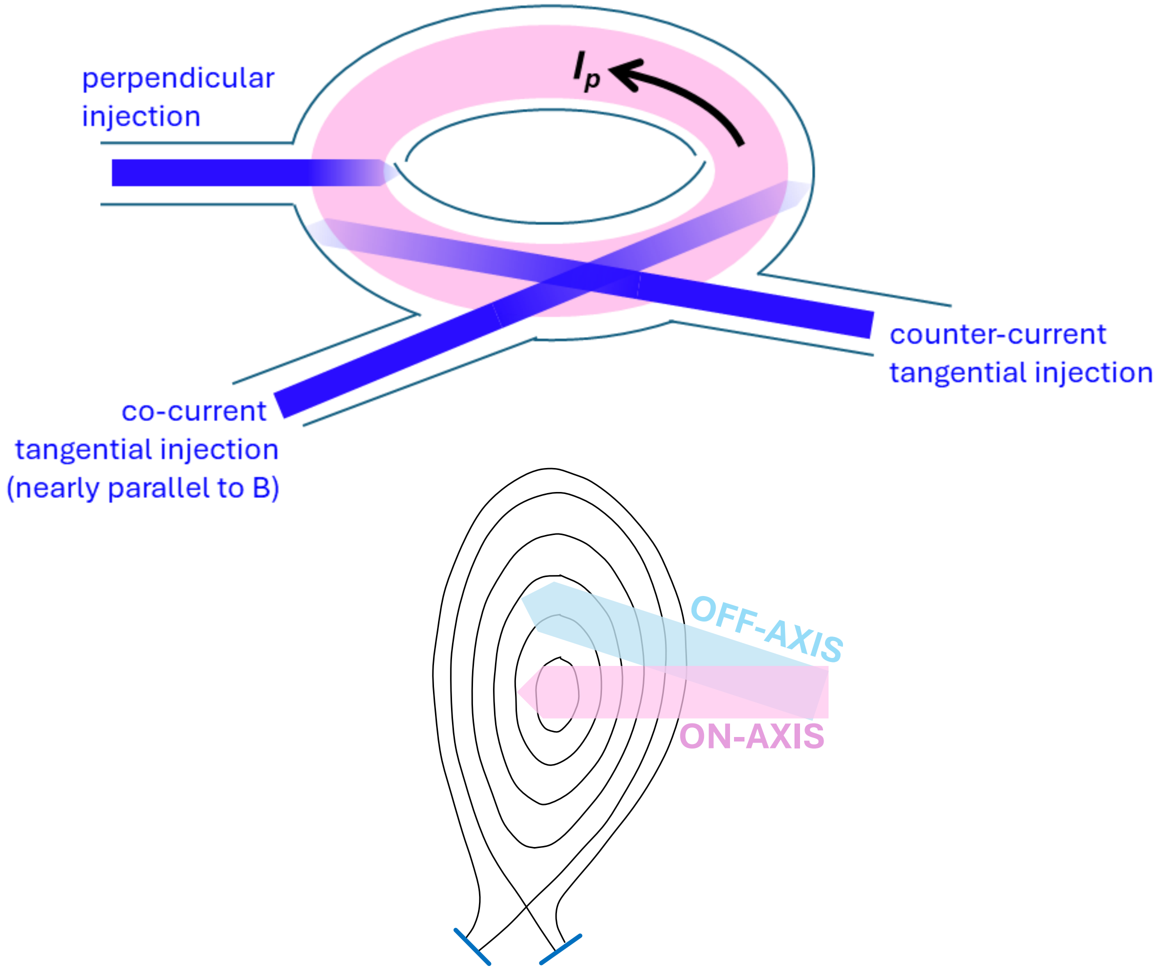


https://doi.org/10.1063/1.4897186

Plasma Fuelling

Useful for core fuelling, negligible for larger devices

Neutral beam injectors integration



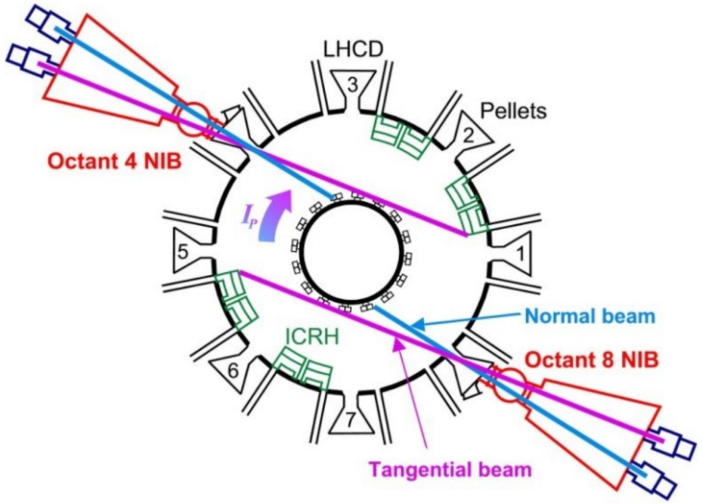
NBI physics

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

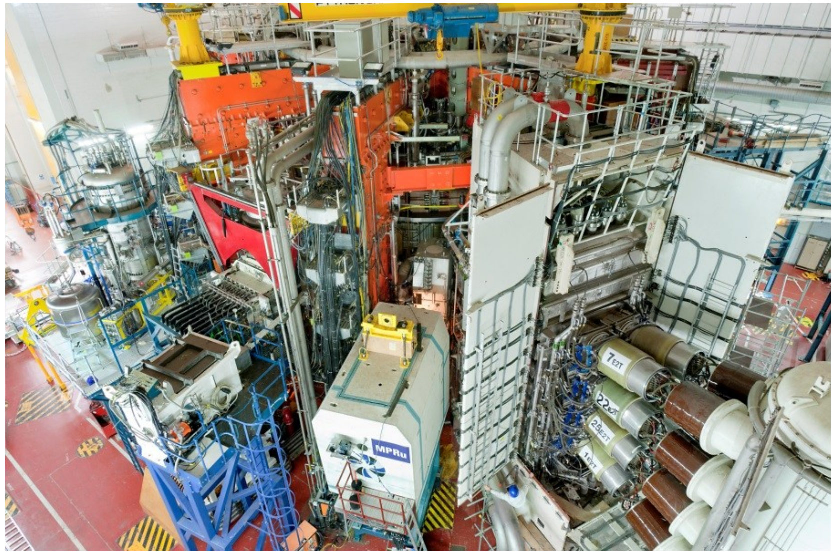
NBI parameters

- Energy:
  - low -> small plasma/low density
  - high -> big plasma/high density, current drive
- 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

Neutral beam injectors integration



Joint European Torus JET (CCFE, UK)



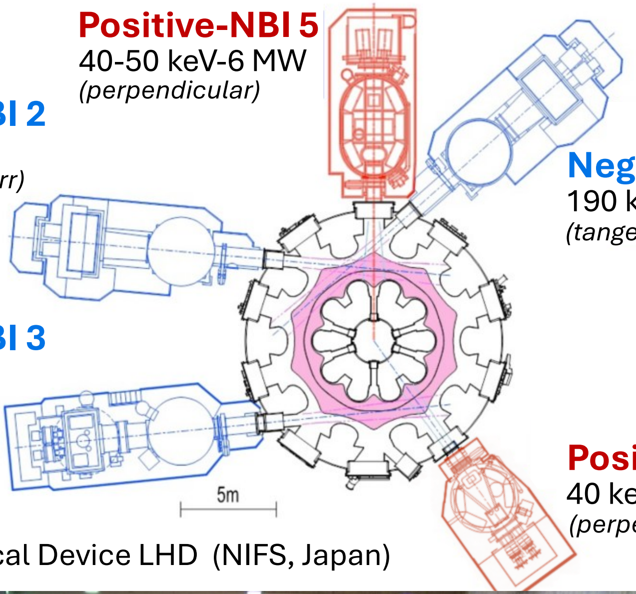
Positive-NBI 5
40-50 keV-6 MW
(perpendicular)

Negative-NBI 2
180 keV-5 MW
(tangential, co-curr)

Negative-NBI 1
190 keV-6 MW
(tangential, counter-curr)

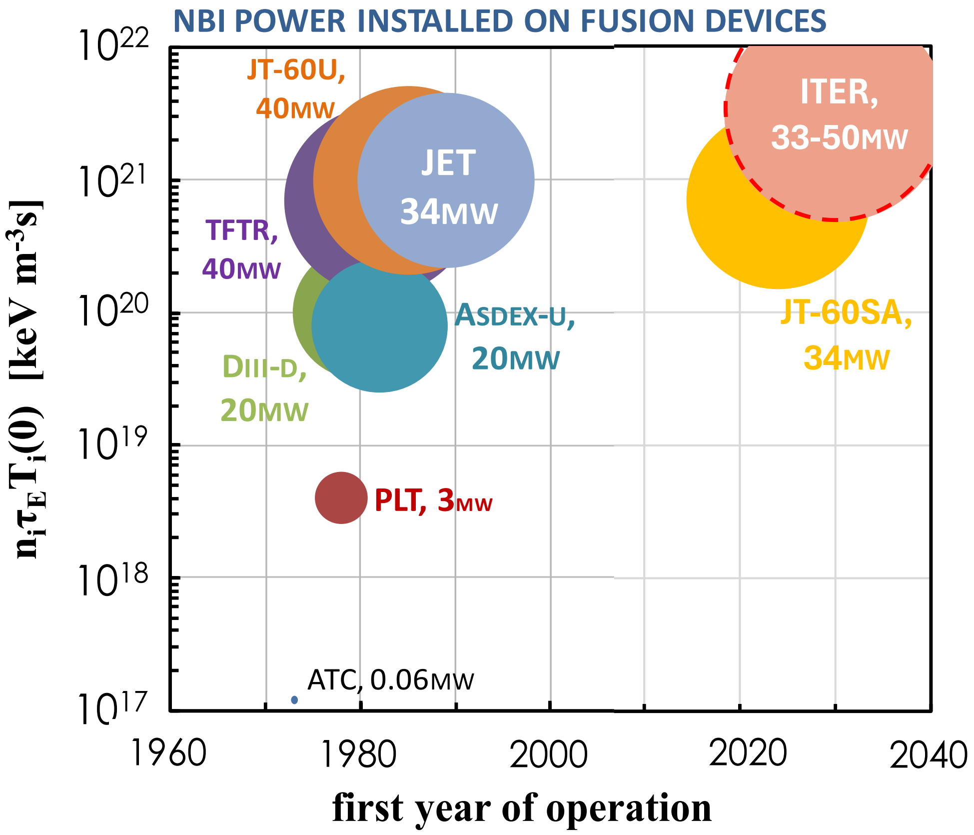
Negative-NBI 3
180 keV-5 MW
(tangential, counter-curr)

Positive-NBI 4
40 keV-6 MW
(perpendicular)



Large Helical Device LHD (NIFS, Japan)

Present and future Neutral beam injectors (NBI)

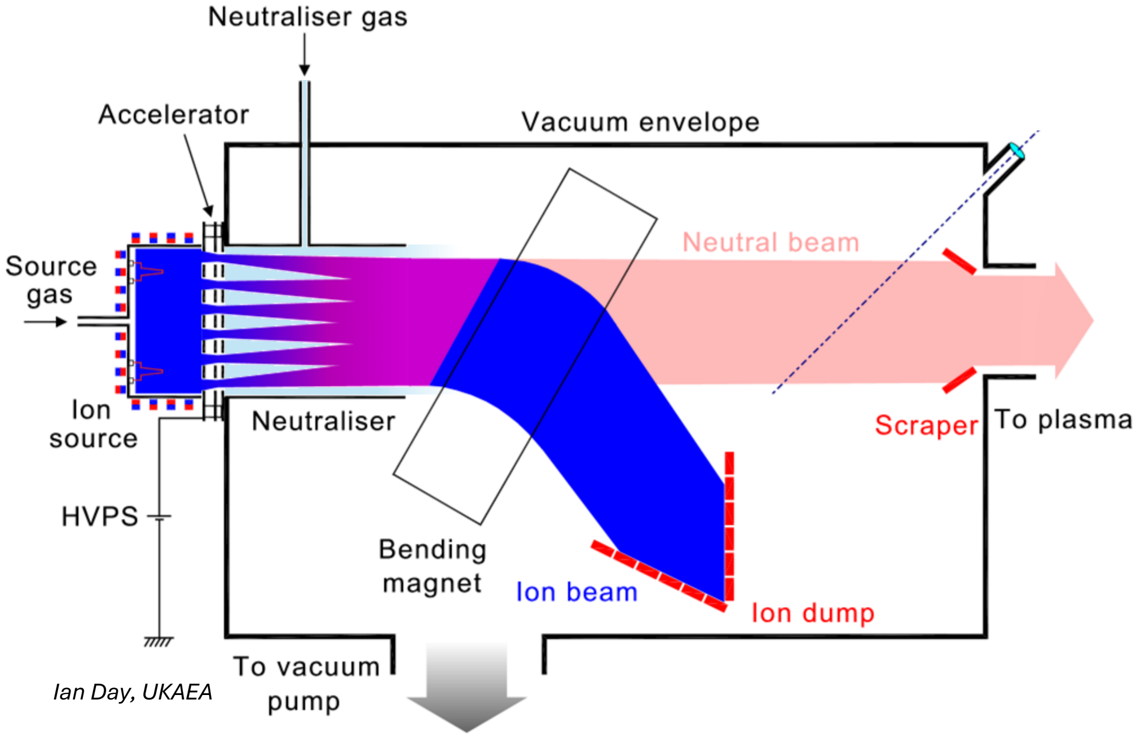


NBI heating is dominant in most past, present and planned tokamaks

	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
AUG	1.65	0.65	1.2	3.1	20	-	6	8	-
EAST	1.7	0.4	1.0	3.5	8	-	4	12	10
DIII-D	1.67	0.67		2.1	20	-	5	4	-
JT-60SA	2.97	1.17	5	2.25	24	**10**	7	-	-
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*	-

Positive and Negative-ion based NBIs

Precursor ion beam:
Most tokamaks until now have used positive ions.



Ian Day, UKAEA

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

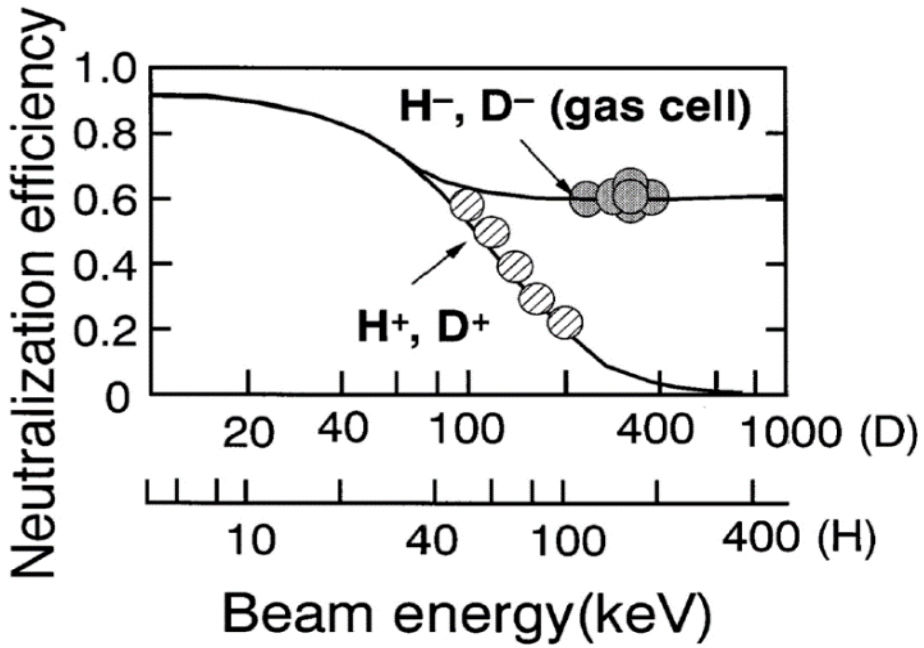
Precursor ion beam:
Most tokamaks until now have used positive ions.

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

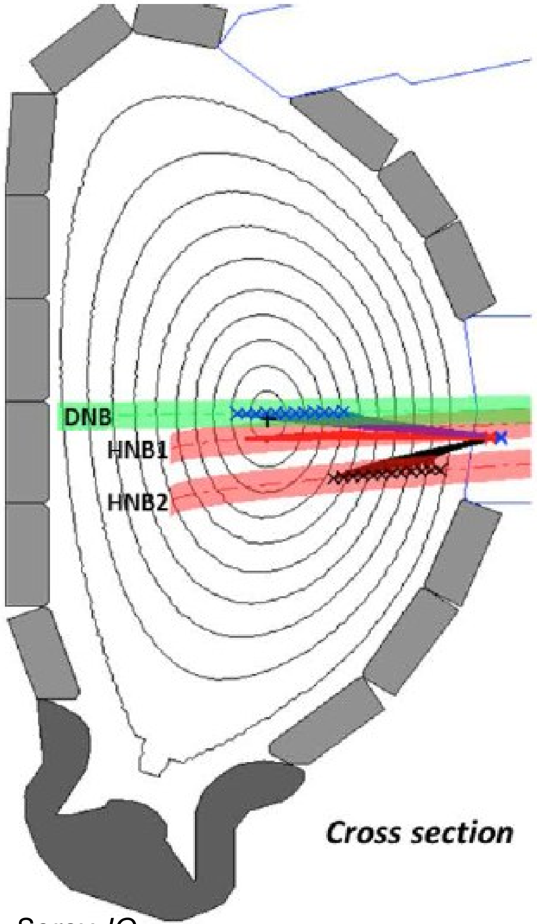
Positive ions
- Easy to produce (2400 A/m^2)
- Multiple ion species (H^+, H_2^+,H_3^+)
- Neutralisation efficiency decreases with energy

Negative ions
- Hard to produce (240-370 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]



Negative-ion based injectors for ITER



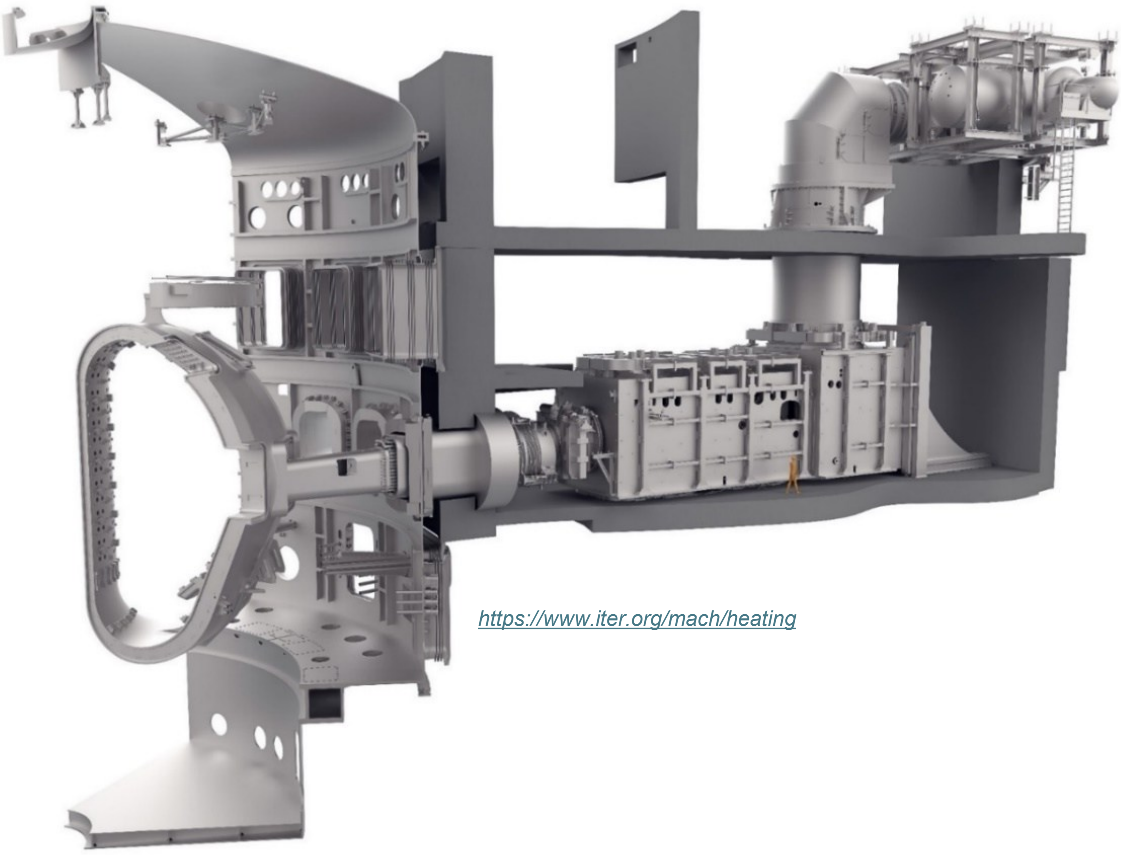
S. Serov, IO

2 (+1) HNB (H, D)

- V = 870 keV (H), 1 MeV (D)
- I = 46 A (H), 40 A (D)
- 1/e divergence < 7 mrad
- t_{pulse} = 3600 s
- P_{beam} = 16.5 MW

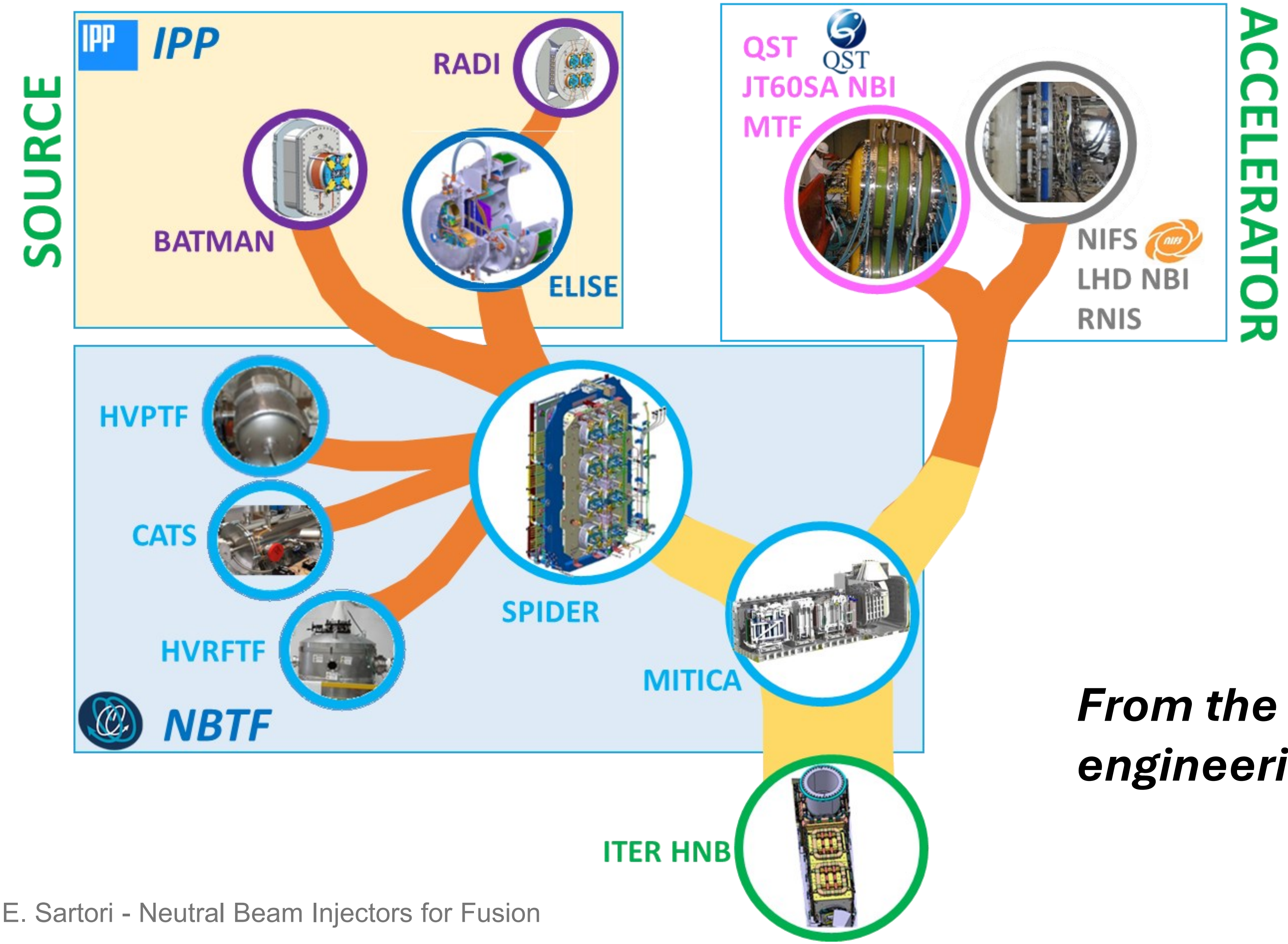
1 DNB (H)

- V = 100 keV
- I = 60 A
- t_{pulse} = 3 s every 20 s
- F_{mod} = 5 Hz



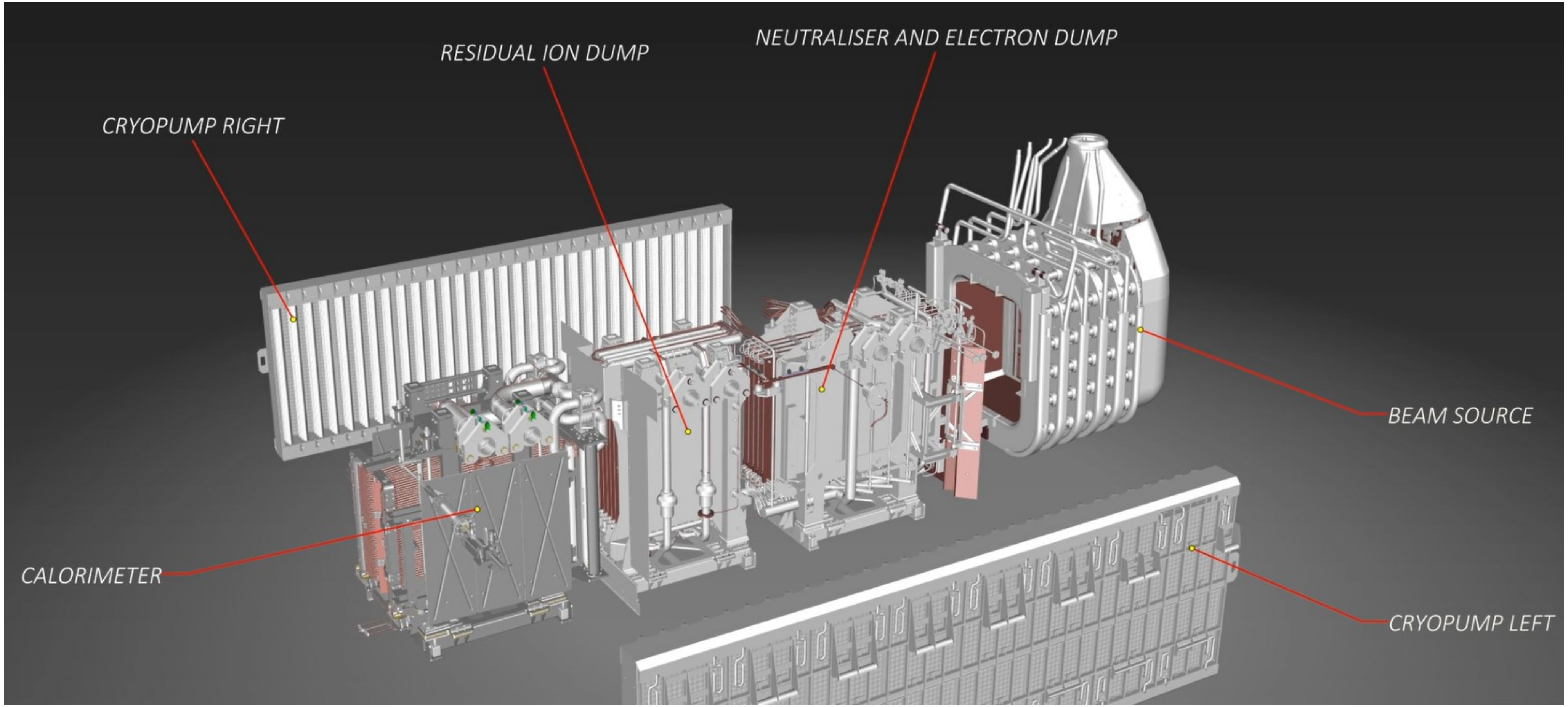
https://www.iter.org/mach/heating

Negative-ion based injectors for ITER



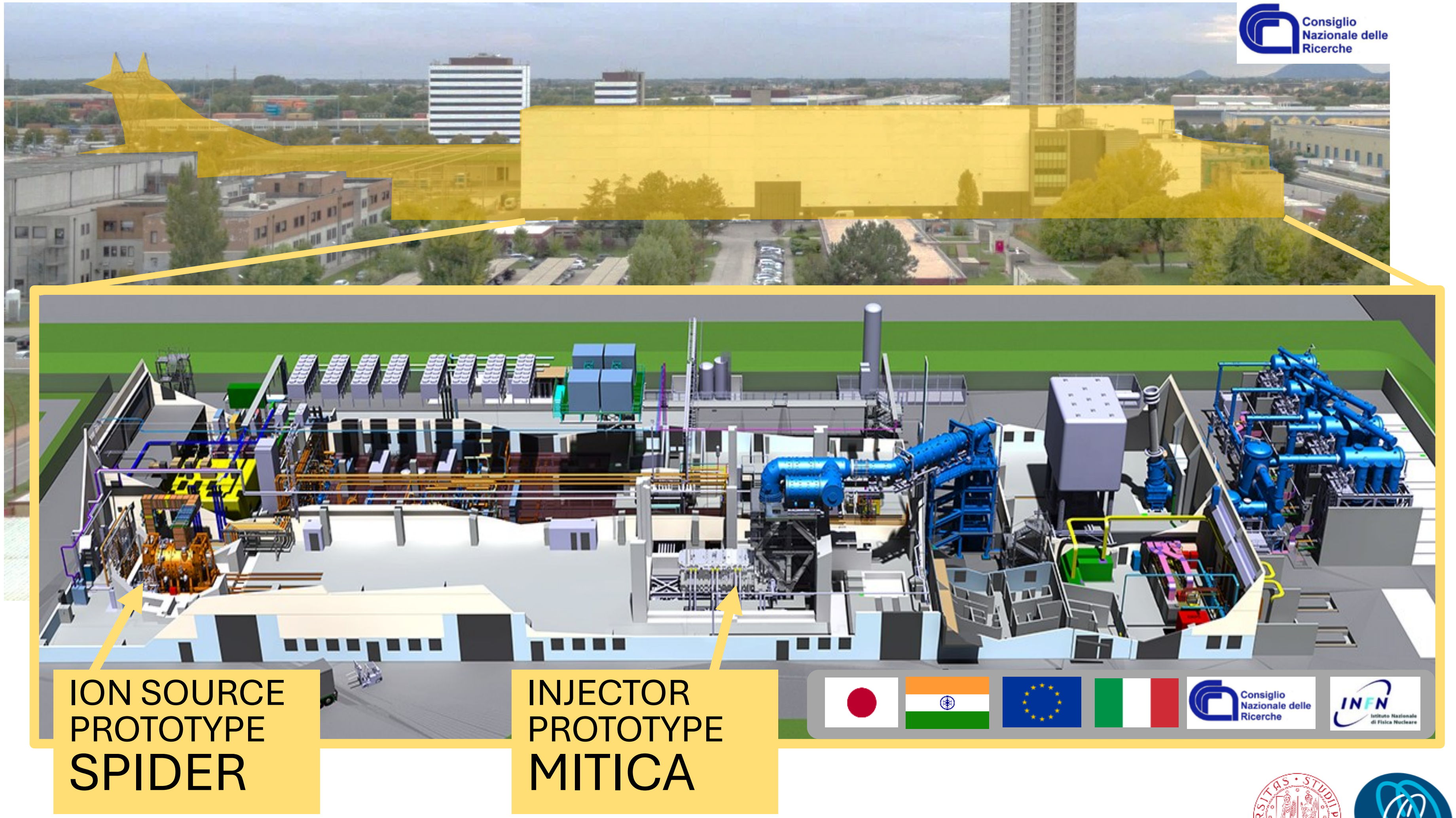
From the concept to the engineering design…

Negative-ion based injectors for ITER



ITER Neutral Beam Test Facility

Padova

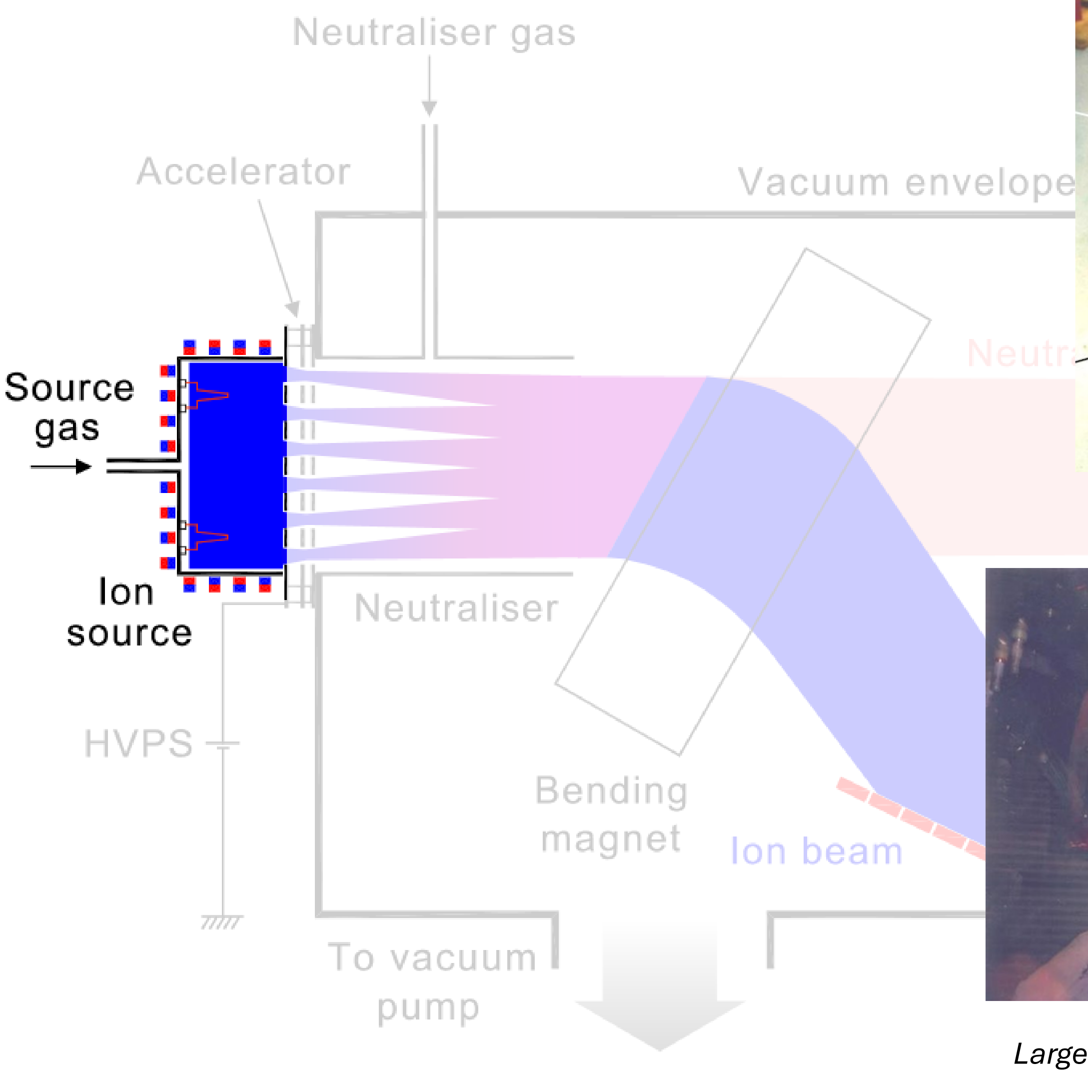


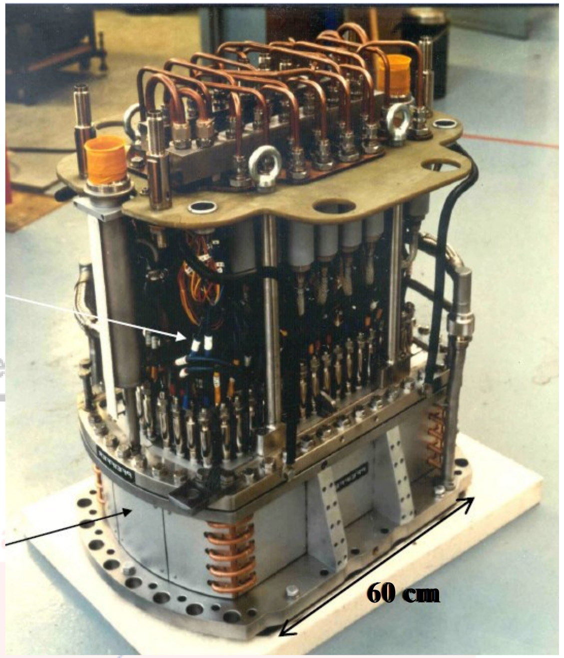
Buildings completed 2015
SPIDER started op. 2018
MITICA will start op. in 2027

Outline

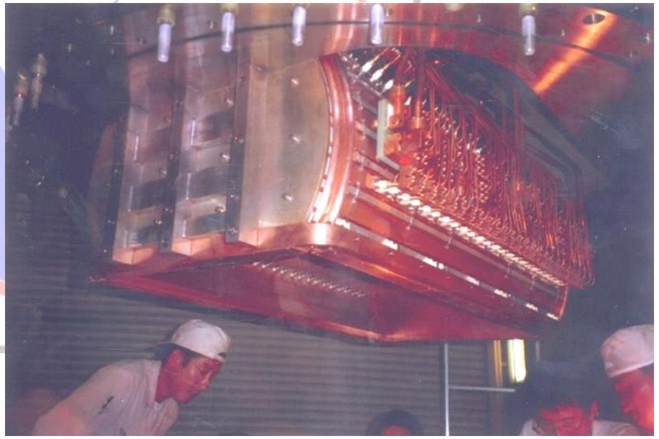
- Introduction to neutral beam injectors
  - What are used for
  - Beam energy and precursor negative ion beams
  - Present international R&D in view of ITER
- **NBI Systems**
  - Ion source
  - Accelerator
  - Neutraliser
  - Residual ion dump and calorimeter
  - Beam diagnostics
  - Vacuum and power supplies
- Summary

Ion source

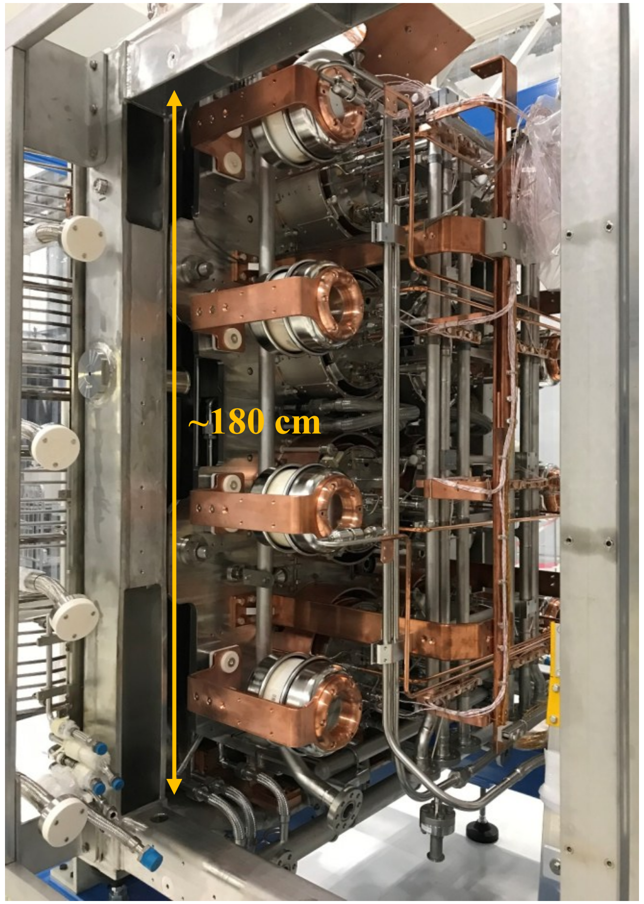




JET PINI: a filament driven positive ion source



Large Kamaboko source of JT60-U



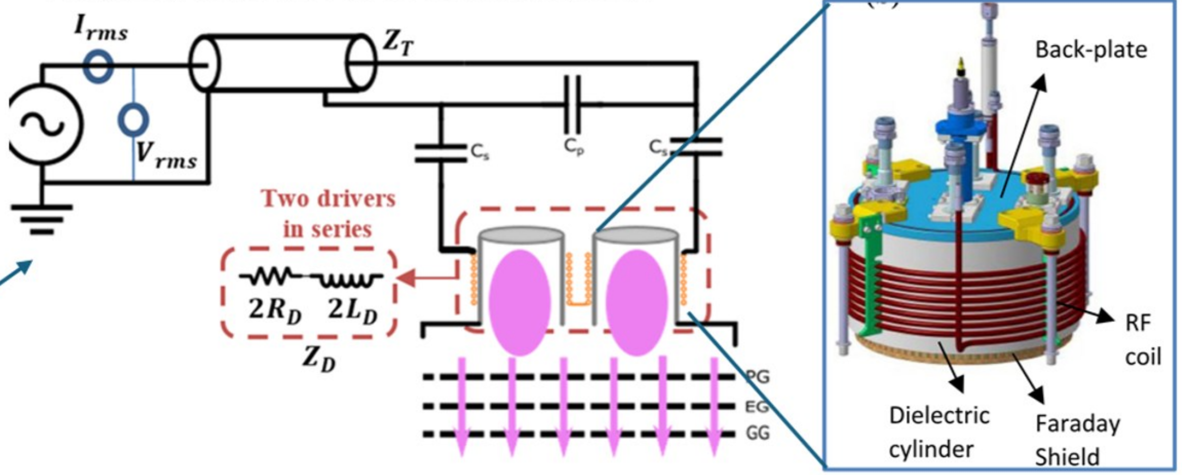
SPIDER source: an RF-driven negative ion source (view from rear side)

Ion source

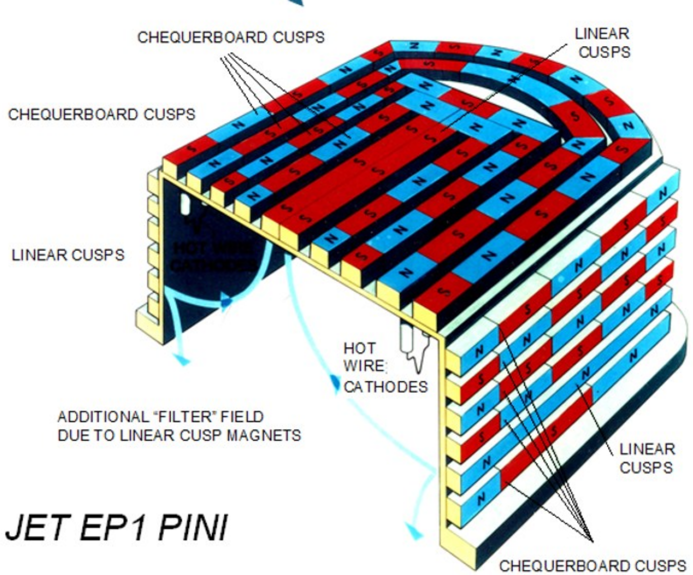
- Plasma near a wall forms a sheath → losses to the walls

- Filament or RF driven discharge
- In the RF source, the resonant circuit is on board the source;
- Magnetic confinement is mandatory in filament sources to confine the primary electrons (magnets in multi-cusp configuration - strong field on the walls, field-free region in the centre of the source).

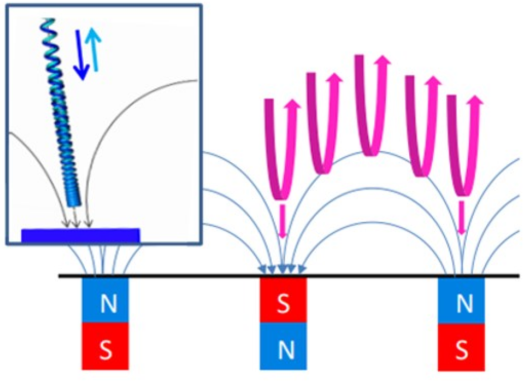
P Jain, et al., Plasma Phys. Control. Fusion 65 (2023) 095010

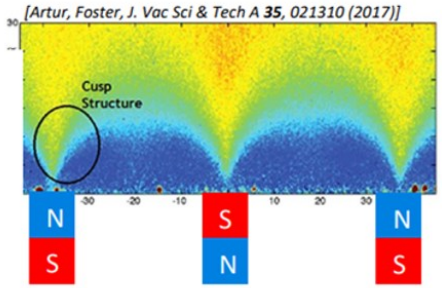


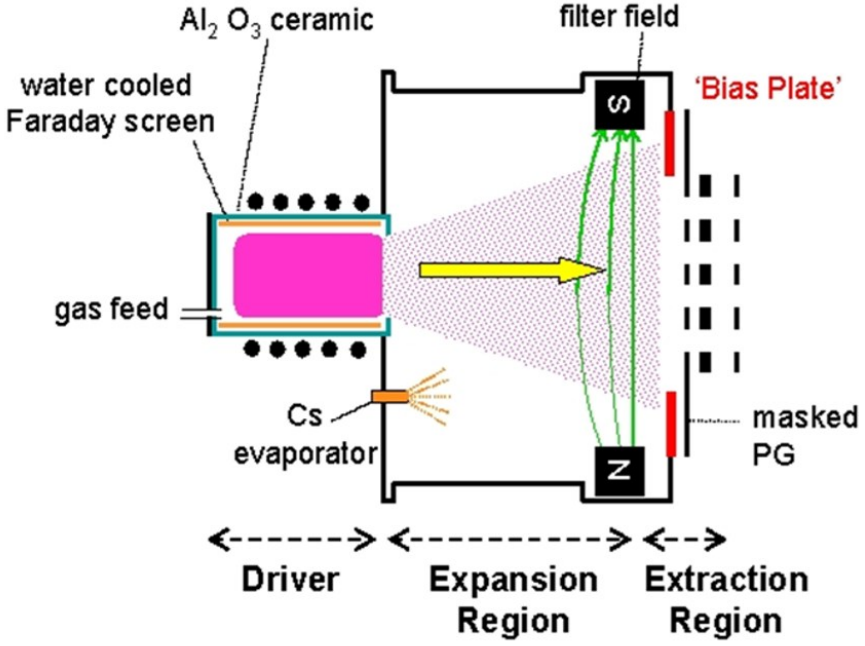
A sketch of an RF circuit of the SPIDER ion source.



JET EP1 PINI





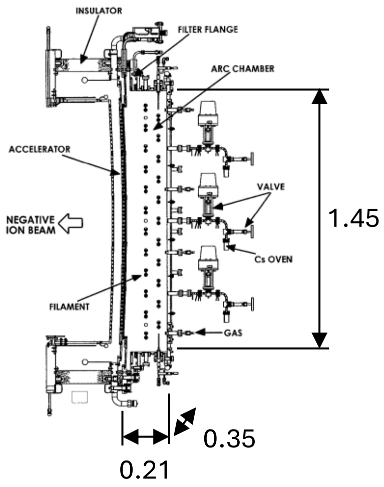


IPP BATMAN

Negative ion sources

LHD H⁻ source

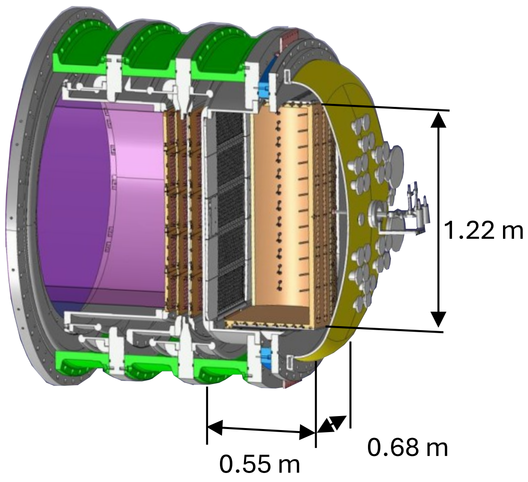
Volume 0.11 m³
Surface 1.23 m²
1998 (concluded)
J_{ext}=370 A/m²
div=5.5 mrad



(filament-arc source)

JT60SA H⁻ source

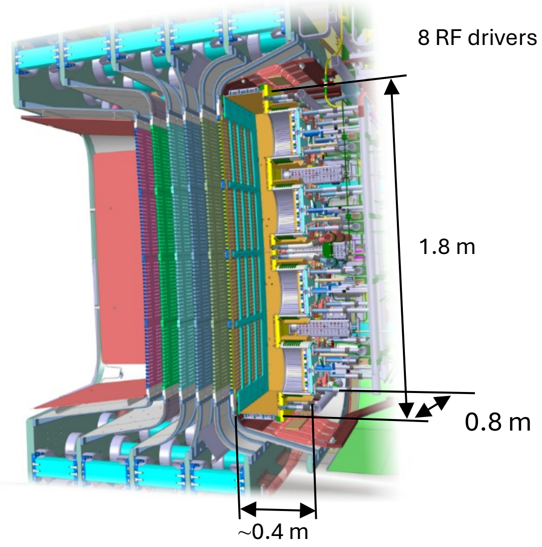
Volume 0.41 m³
Surface 3.2 m²
1996 (mature)
J_{ext}=210 A/m²
div=8 mrad



(filament-arc source)

ITER H⁻⁻ source

Volume 0.44 m³
Surface 5.2 m²
Deployment 2027
J_{ext}=330 A/m²
div=5-7 mrad



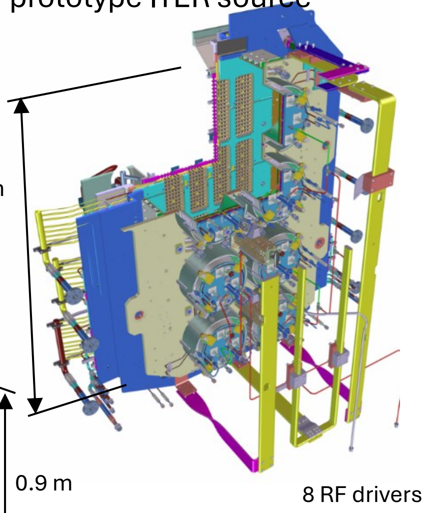
(RF source)

Test stands for the ITER H⁻⁻ source

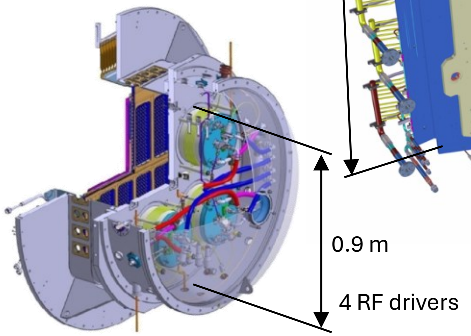
Volume 0.24 m³
Surface 2.9 m²
2013 (mature)
J_{ext}=330 A/m²

Volume 0.44 m³
Surface 5.2 m²
2018 (R&D ongoing)
J_{ext}=220 A/m²

SPIDER
prototype ITER source



ELISE
½ ITER source

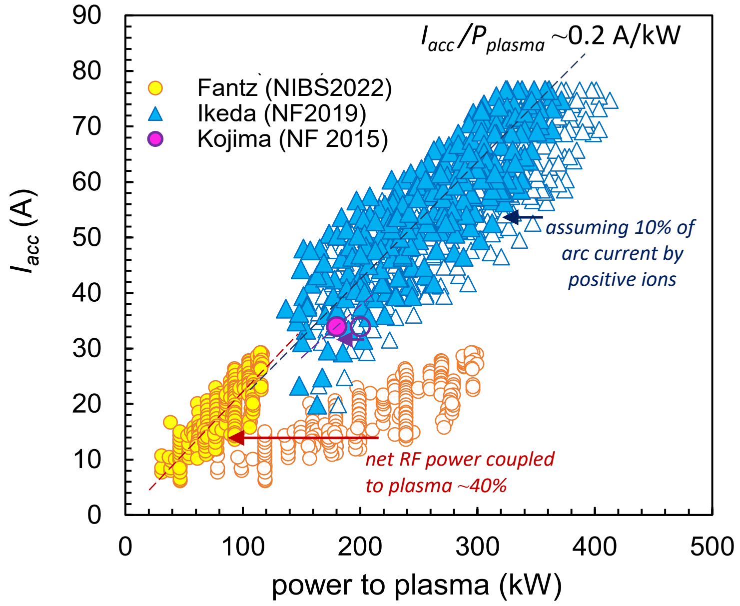


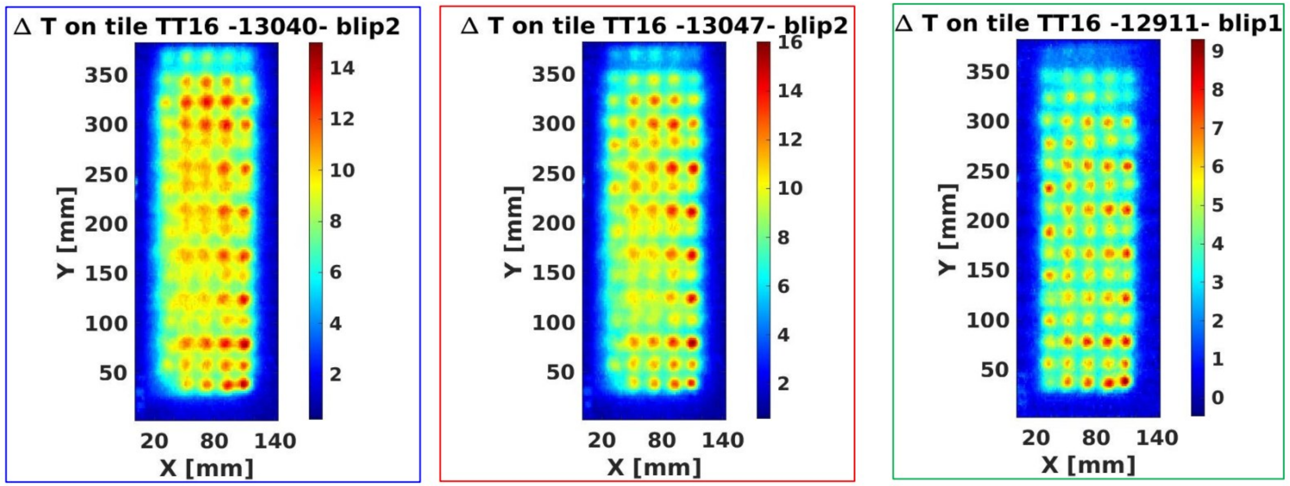
(RF sources)

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)

Negative ion sources

- RF-driven source for ITER to minimize maintenance
- Extracted negative ion current density is comparable
- Considering the effective power coupled to the plasma, the negative ion current scales similarily, despite the different source type
- Uniformity of the extracted beam pattern is rather good



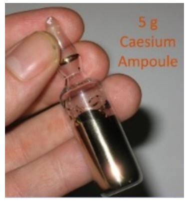


Examples of beam uniformity in SPIDER, various source parameters (pressure and RF power)

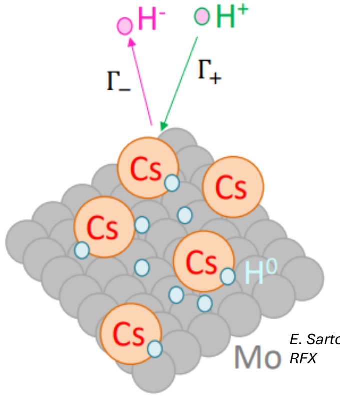
Negative ion sources: caesium and filter field

Use of caesium to produce neative ions:

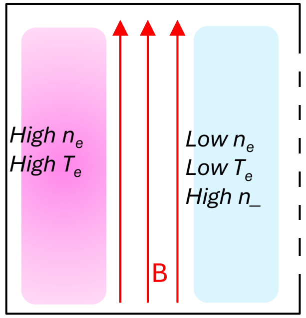
- Coats extraction grid and lowers work function (binding energy for electrons in a solid)
- H and H^+ can capture electrons to become H^-
- Extractable current density increases by factor of 10



[D. Faircloth, CERN Accelerator School]

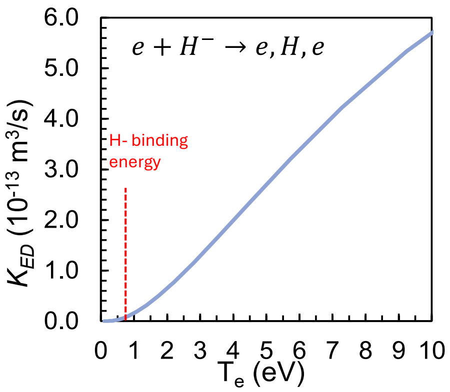


E. Sartori, RFX



W. Kraus, ELISE, presented ICIS 2017

B field used in negative ion sources to separate in two regions the plasma: ***tandem concept*** *implies vertical drifts (magnetised electrons)*



At T_e=2 eV, electron detachment is 3 times faster than at T_e=1 eV

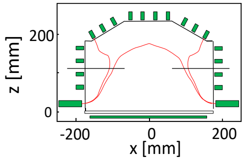
needs **filter field of uniform effectiveness**

Difficult design, given large dimensions.

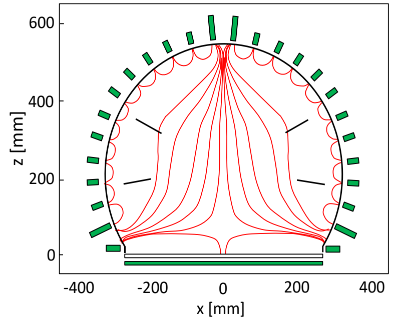
given the quite short λ_- of negative ions before extraction, **uniform H^- production yield** at the extraction region is needed

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

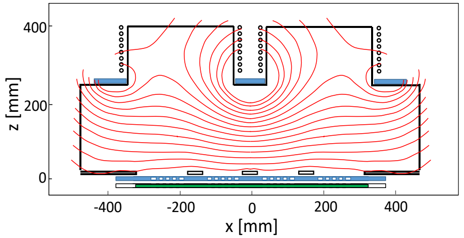
LHD H^- source



JT60SA H^- source

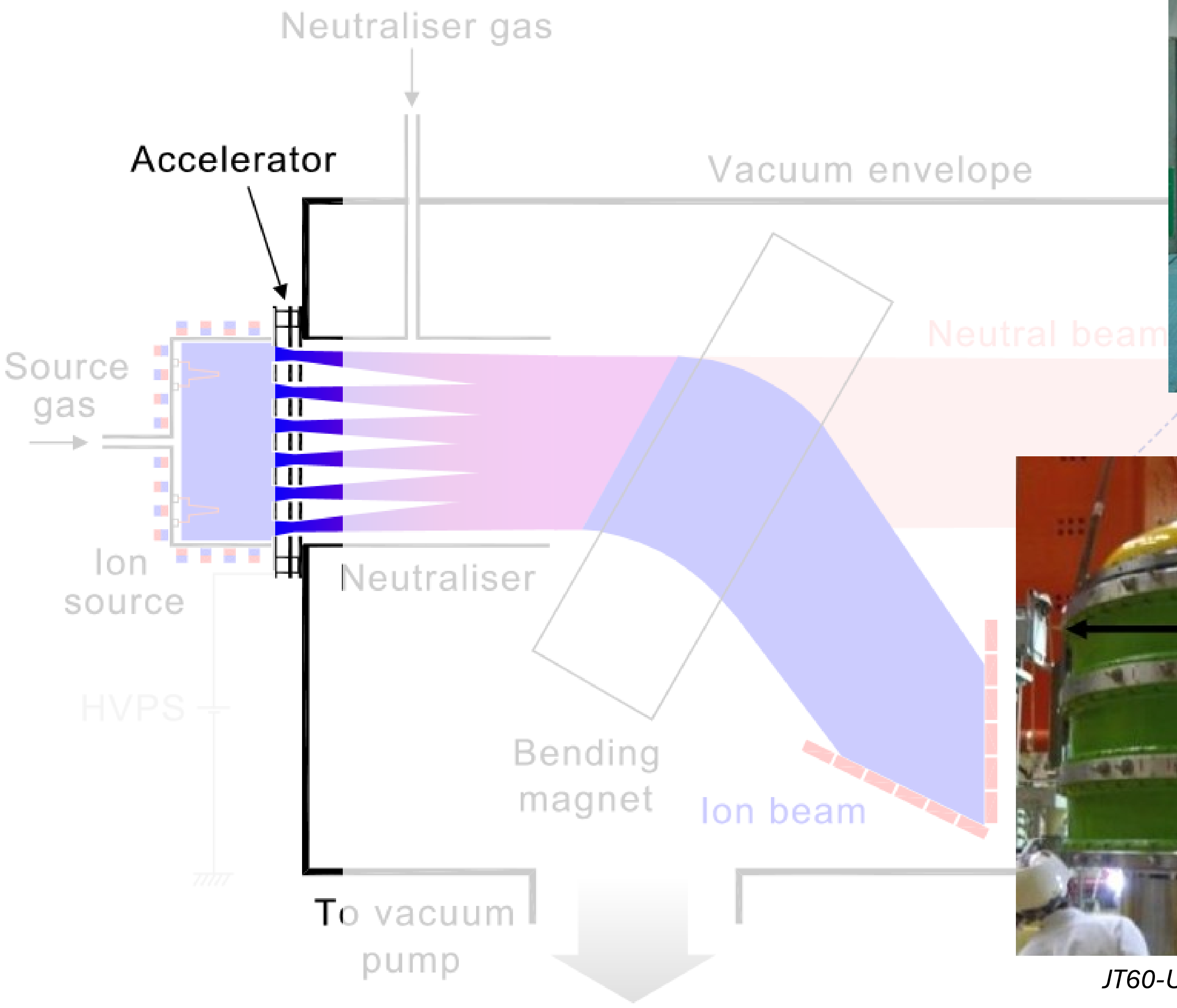


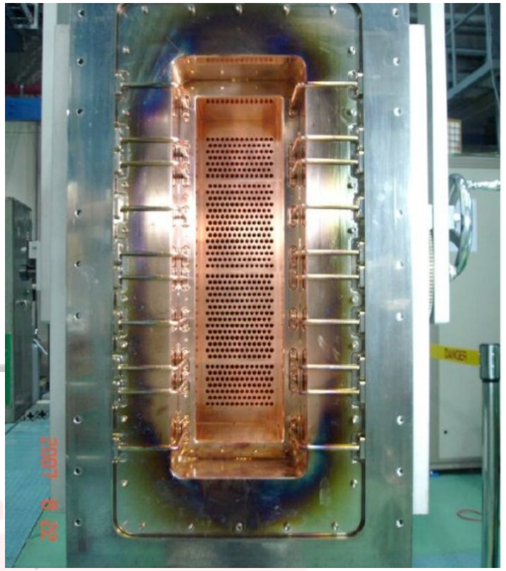
ITER H^{--} source



$$\begin{cases} v_{\nabla B}^{drift} = (mv_\perp^2/2qB)\,\boldsymbol{B} \times \nabla B/B^2 \\ v_{E\times B}^{drift} = \boldsymbol{E} \times \boldsymbol{B}/B^2 \\ v_{\nabla p \times B}^{drift} = -\nabla p_e \times \boldsymbol{B}/B^2 \end{cases}$$

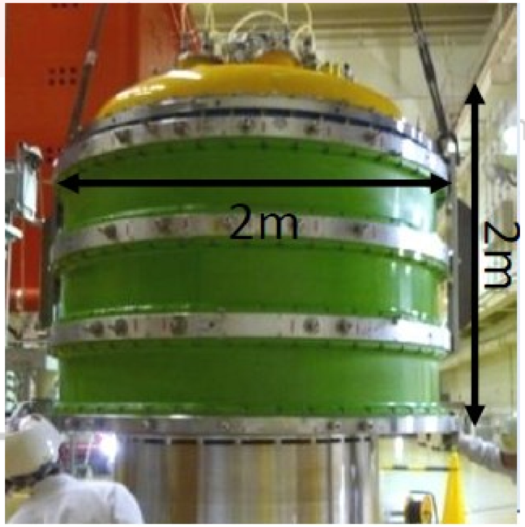
Ion beam acceleration





LHD N-NBI accelerator

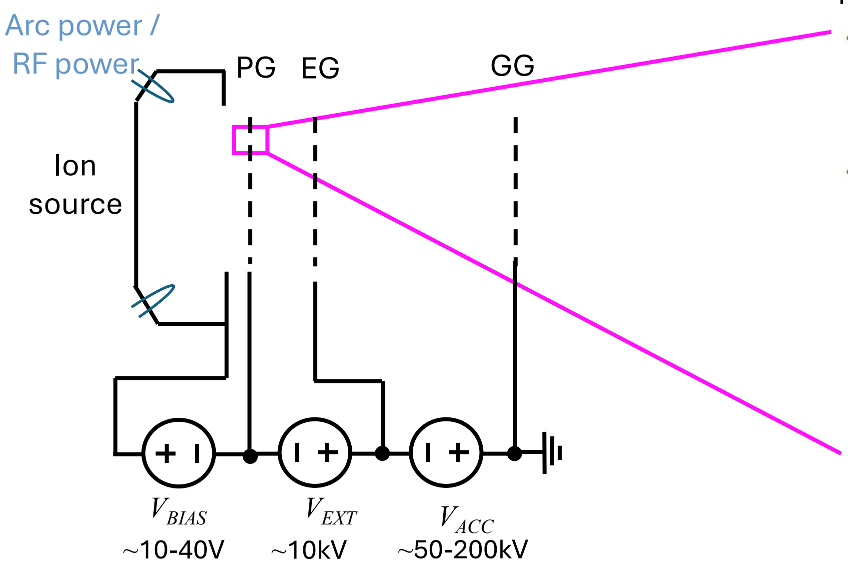
SPIDER acceleration grid with 1280 apertures



JT60-U 500keV accelerator

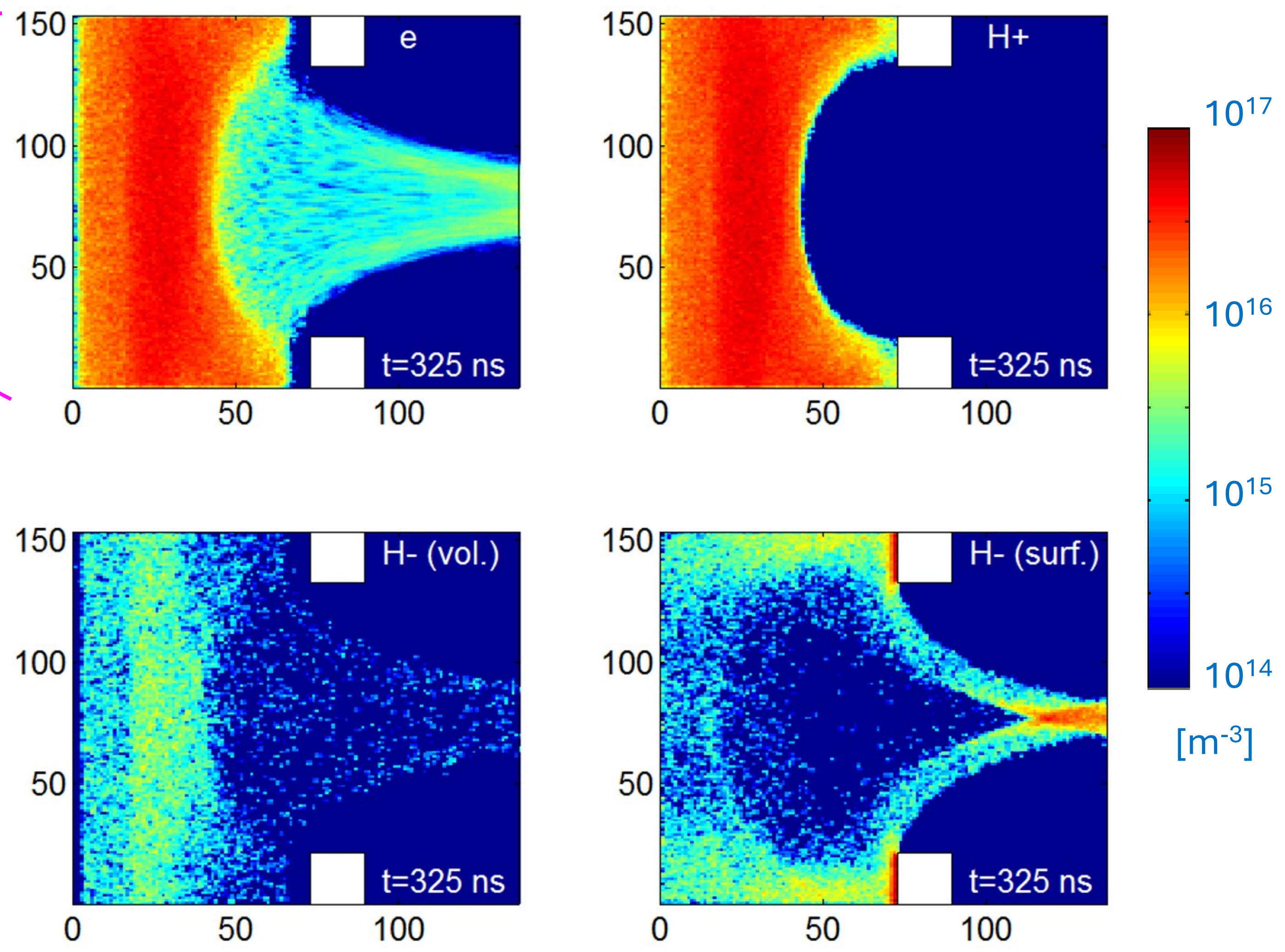
Extractor and accelerator of MITICA duing alignment procedures

Ion beam extraction from the source plasma



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

T_e~1 eV, T_i~0.1 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

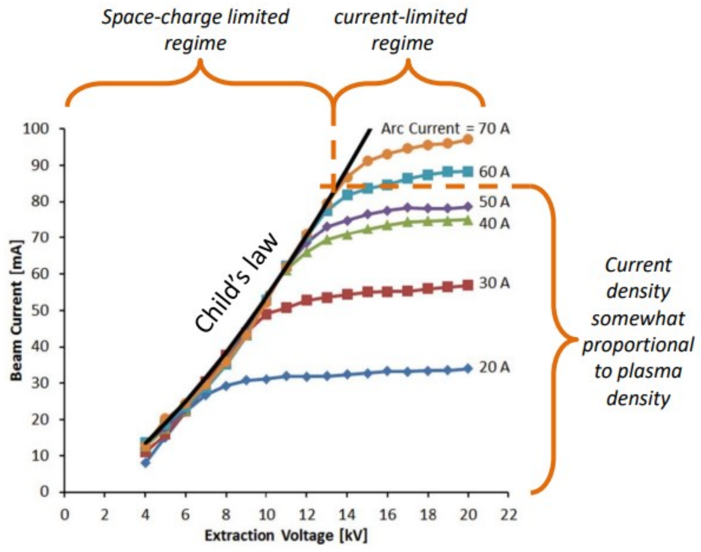
Ion beam extraction from the source plasma

Beam composed by multiple beamlets
Extractable current limited by space-charge
(Child-Langmuir law, planar diodes):

$$j_s = \underbrace{\frac{4\varepsilon_0}{9}\sqrt{\frac{2ez}{m}}}_{\chi} \cdot \frac{1}{d^2} V^{3/2}$$

electrons, $\chi = 2.334 \cdot 10^{-6}$ A/V$^{3/2}$
protons, $\chi = 5.45 \cdot 10^{-8}$ A/V$^{3/2}$

(e electron charge, z ion charge state, ε_0 vacuum permittivity)



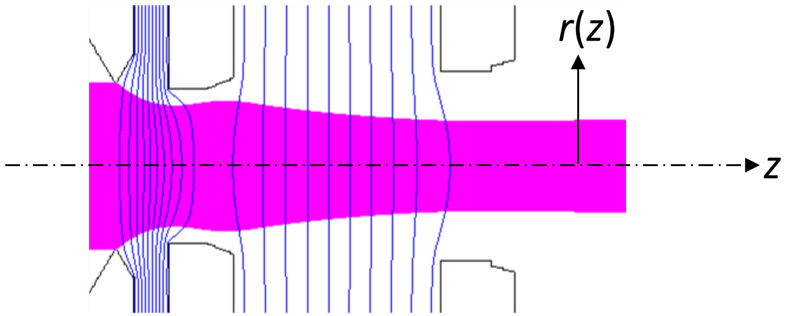
S. R. Lawrie, et al. Rev. Sci. Instrum., vol. 87, p. 02B122, 2016.

In negative ion sources, due to the low negative ion production rate, a limit given by the available current is reached.

By increasing the discharge power, normally, the available negative ion current density increases.

The extractable ion beam current is proportional to $V^{3/2}$; the proportionality constant is called **perveance *P*** of the extraction system:

$$P = \frac{I}{V^{3/2}} \quad [\mathrm{AV}^{-3/2}]$$

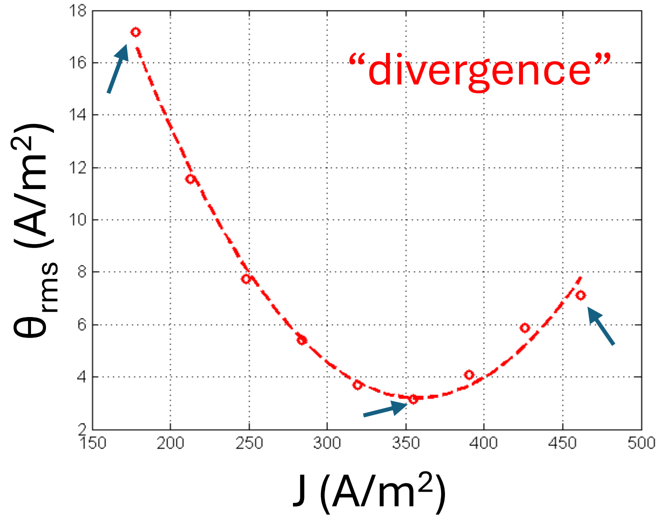


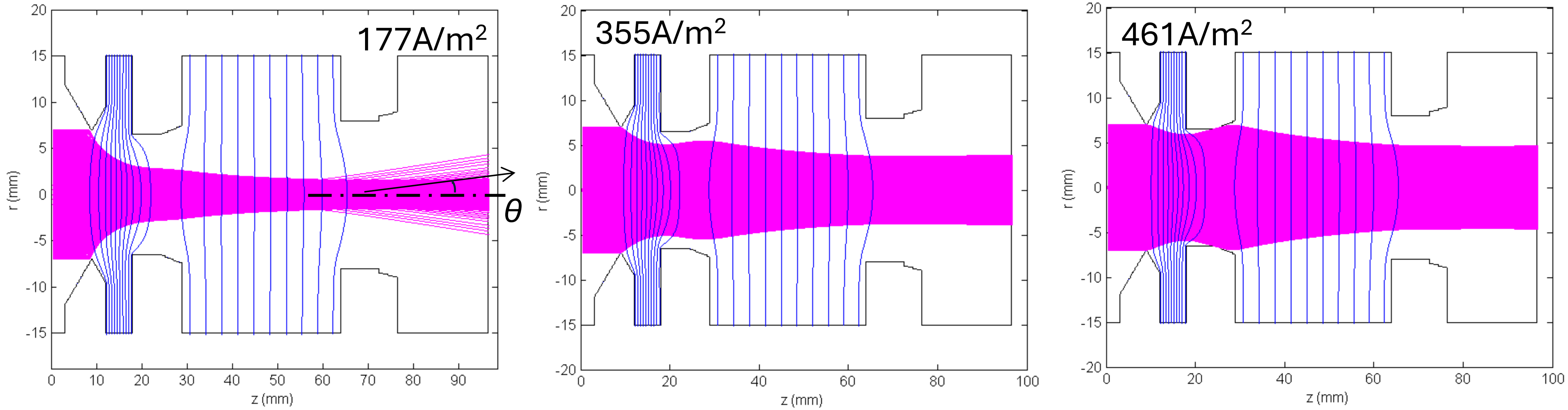
At the same perveance, the beam shape is identical!
i.e. ion space-charge effects have the same significance compared to externally applied electric fields.

Ion beam extraction from the source plasma

Example in SPIDER triode accelerator, increasing perveance (i.e. increasing discharge power in the source plasma) .

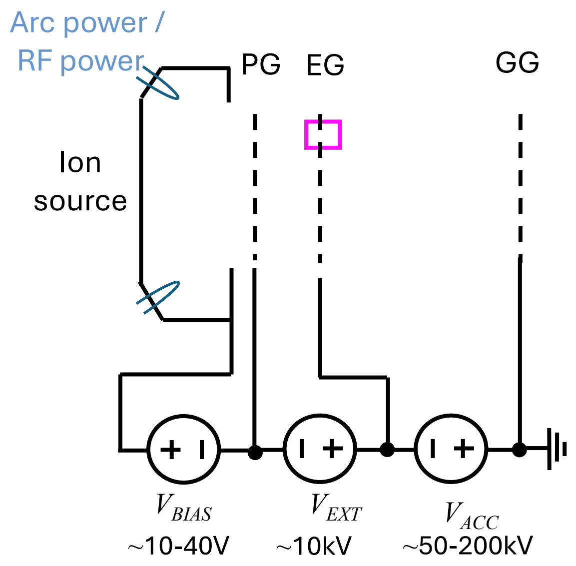
The beamlet focusing at the exit of the accelerator can be calculated from the RMS angle of ion trajectories with respect to the beamlet axis: "divergence"





Beamlet simulation via axisymmetric ray tracing & Poisson solver code – courtesy P Veltri

Ion beam acceleration



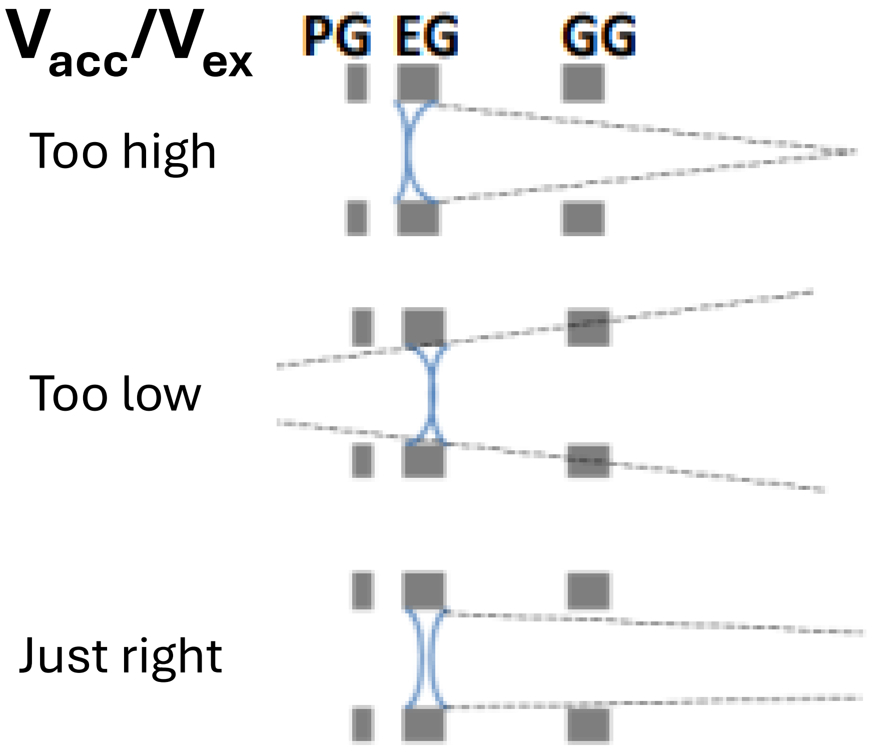
Larger accelerating voltage applied between EG and GG to reach 100s keV.

Each electrode act as an electrostatic lens, in particular EG:

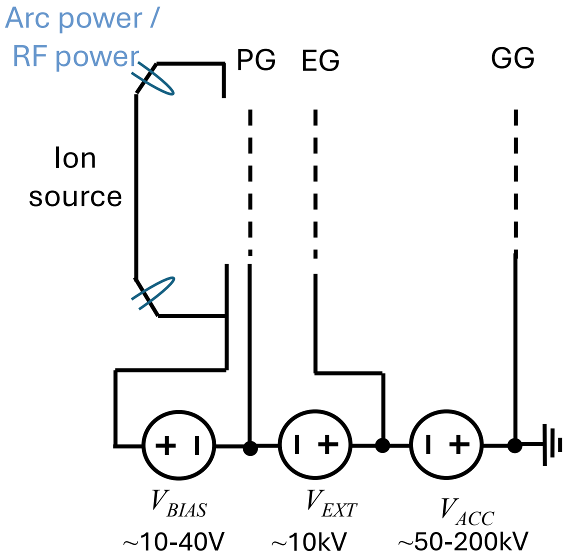
$$f = \frac{4V}{E_2 - E_1}$$

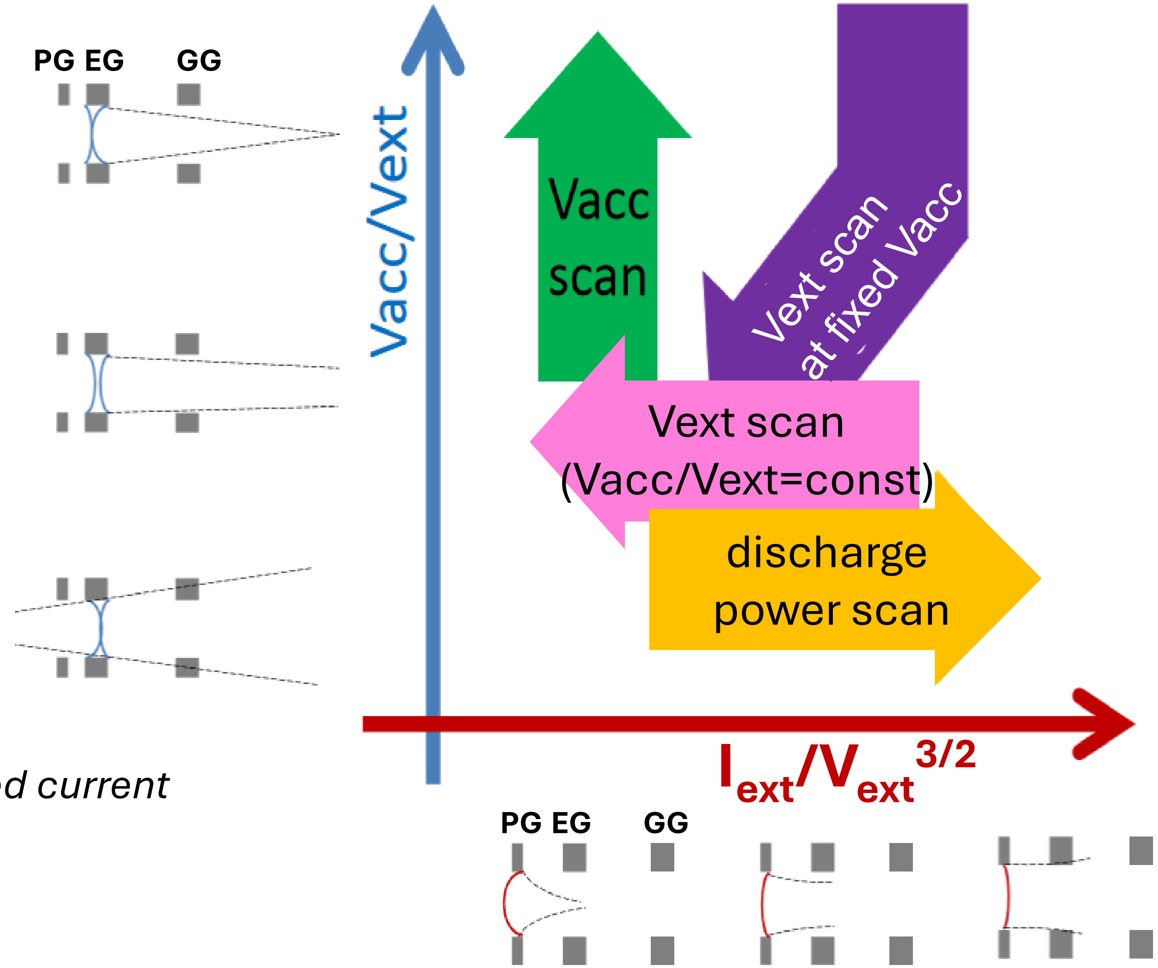
V beam energy at electrode,
E_1 and E_2 electric fields upstream and downstream the electrode
f focal distance (f<0 diverging beamlet)

An optimum ratio of potentials $\mathbf{V_{acc}/V_{ex}}$ shall be applied for minimizing the beam divergence:



Ion beam optics



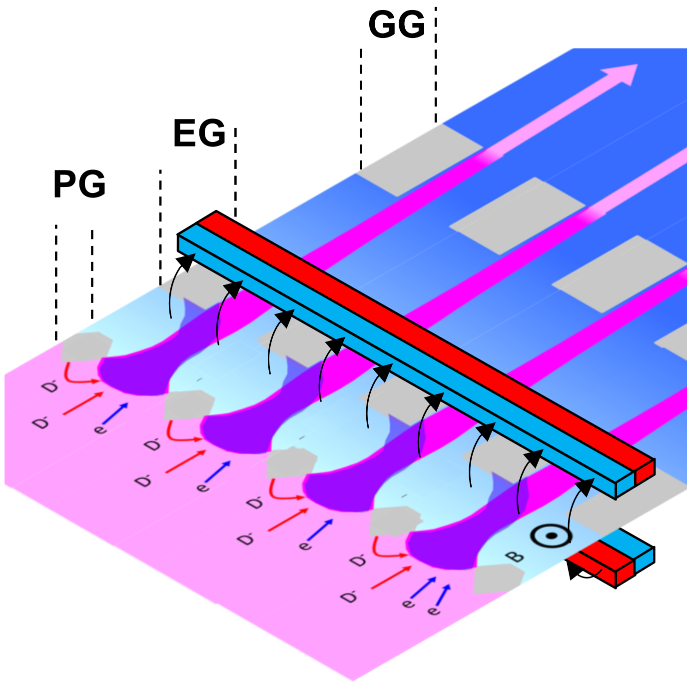


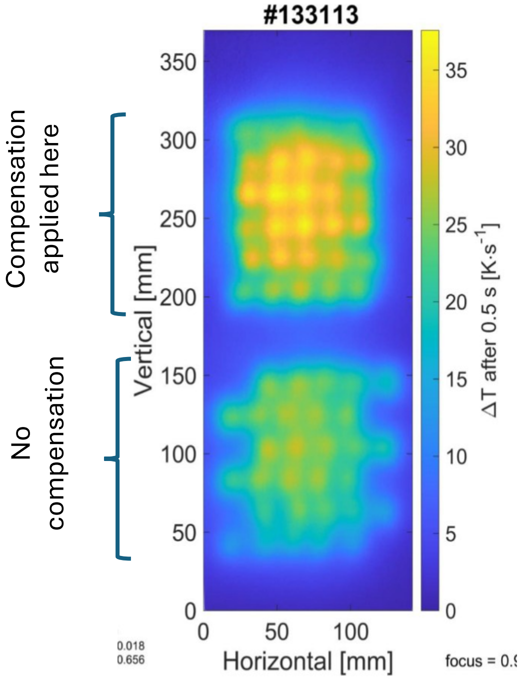
Experimentally, what are the knobs?

- ***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: complex interactions

- Permanent magnets in extraction grid deflect electrons… but also ions!
- Compensation methods required for ions: Electrostatic compensation at EG (steering grid), or compensating magnets inside EG or GG…

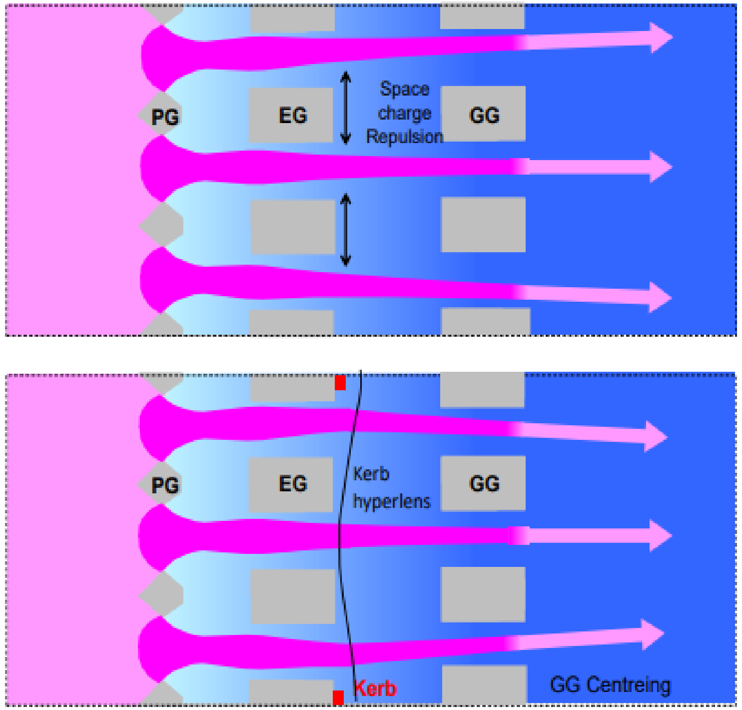




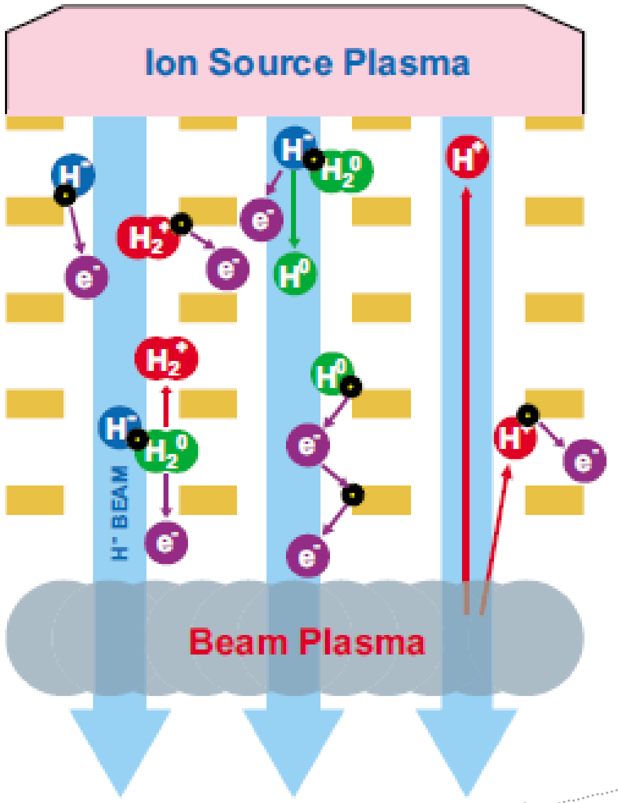
Result in BUG, courtesy B Segalini

- 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

Multibeamlet repulsion inside the accelerator



Losses and power loads on electrodes



Kashiwagi

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

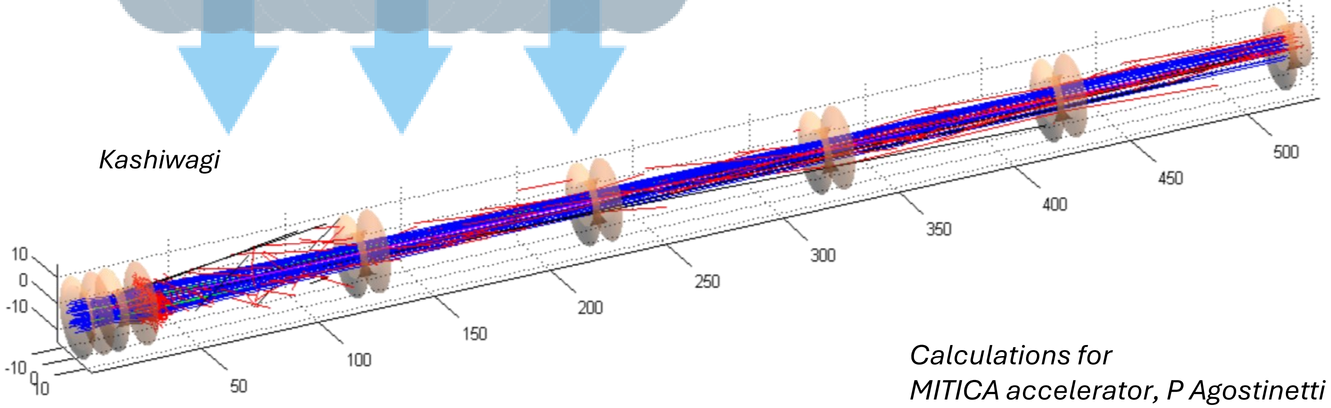
$$H^-, H_2 \rightarrow \ H, H_2, e$$

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

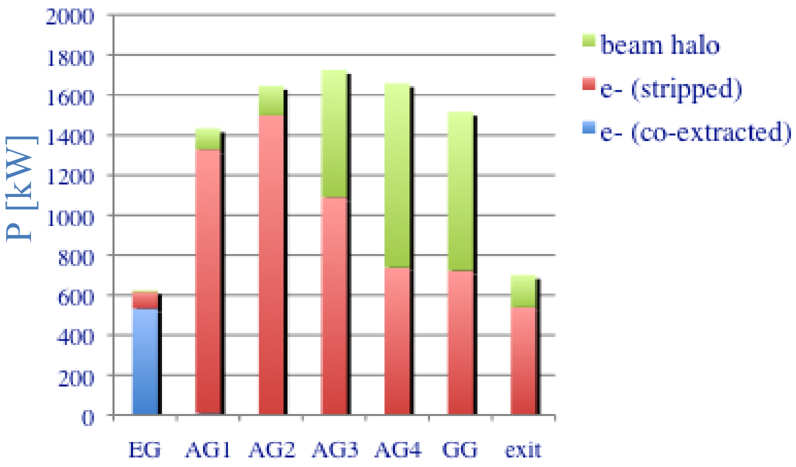
$$L_s = \int_0^{x_{GG}} -\sigma(V(x))n_g(x)dx$$

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

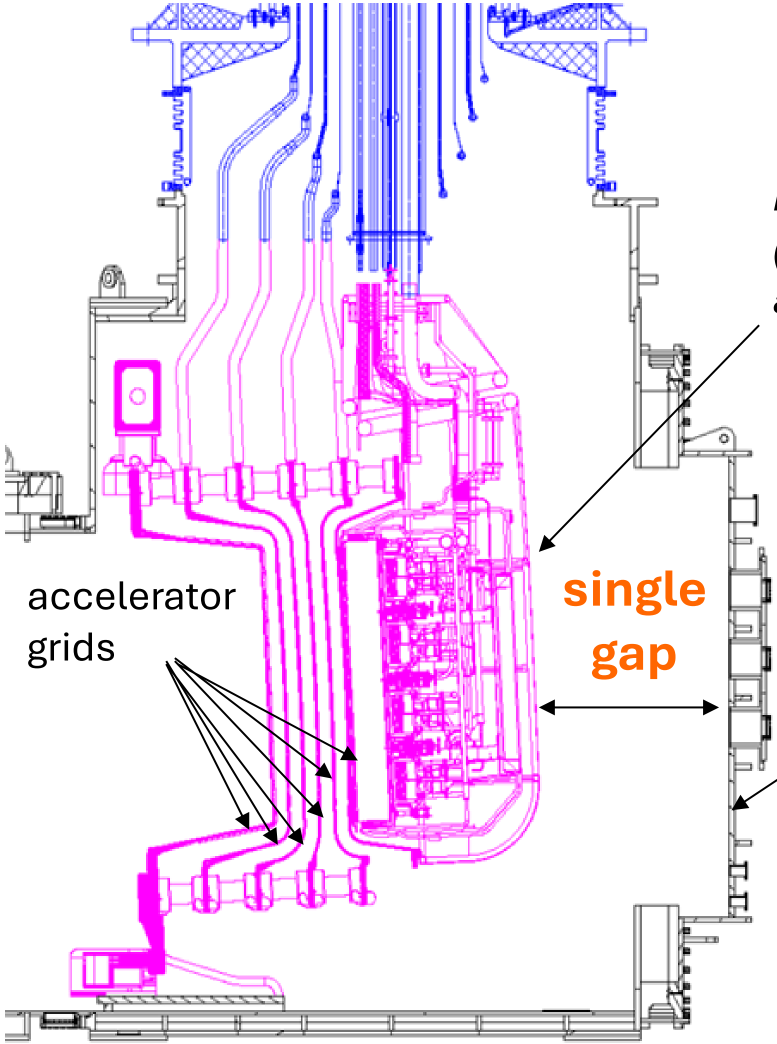
- the stripped electron is accelerated by the electric field onto the electrodes: losses of efficiency and large heat loads



Calculations for MITICA accelerator, P Agostinetti



High Voltage conditioning



Beam source (rear side) at -1 MV

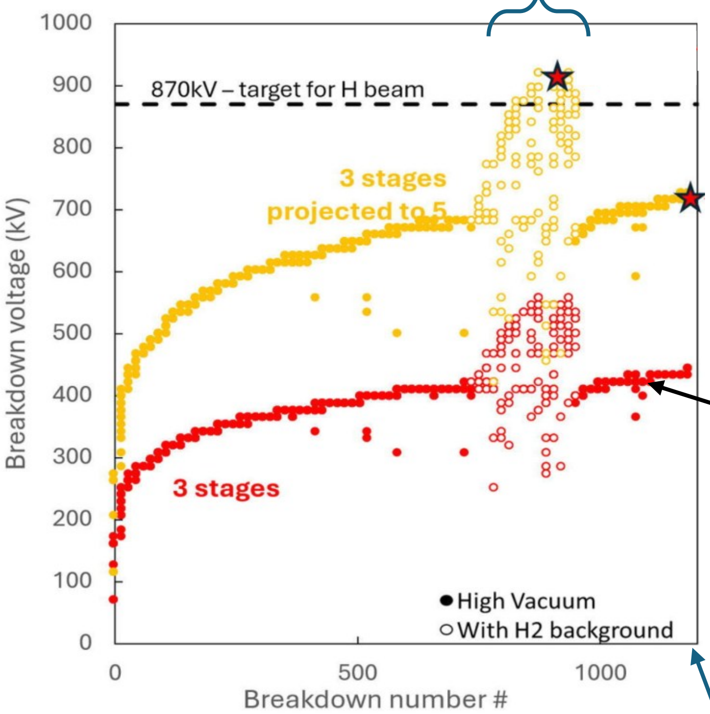
accelerator grids

single gap

Vacuum Vessel at ground potential

- 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:

obtained at nominal H2 pressure ~3-4 10^{-2} Pa

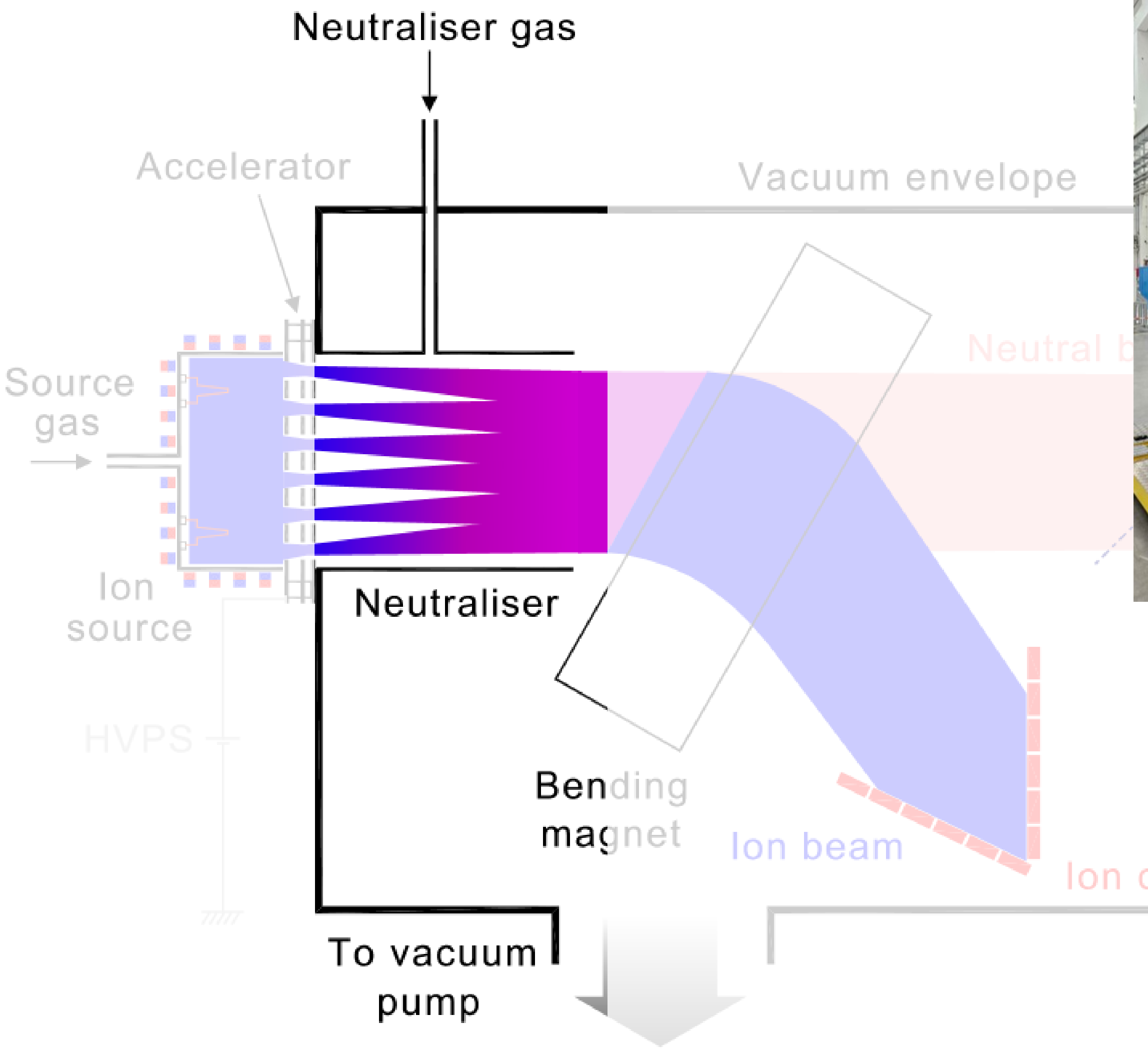


What are these points? Movie...

about 100 h of HV applied

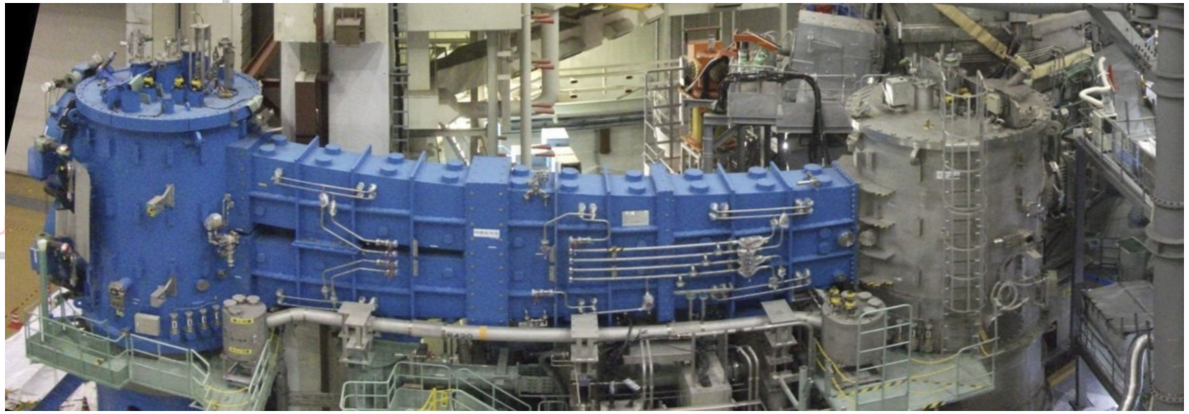
https://www.iter.org/node/20687/successful-round-tests-mitica

Neutraliser cell



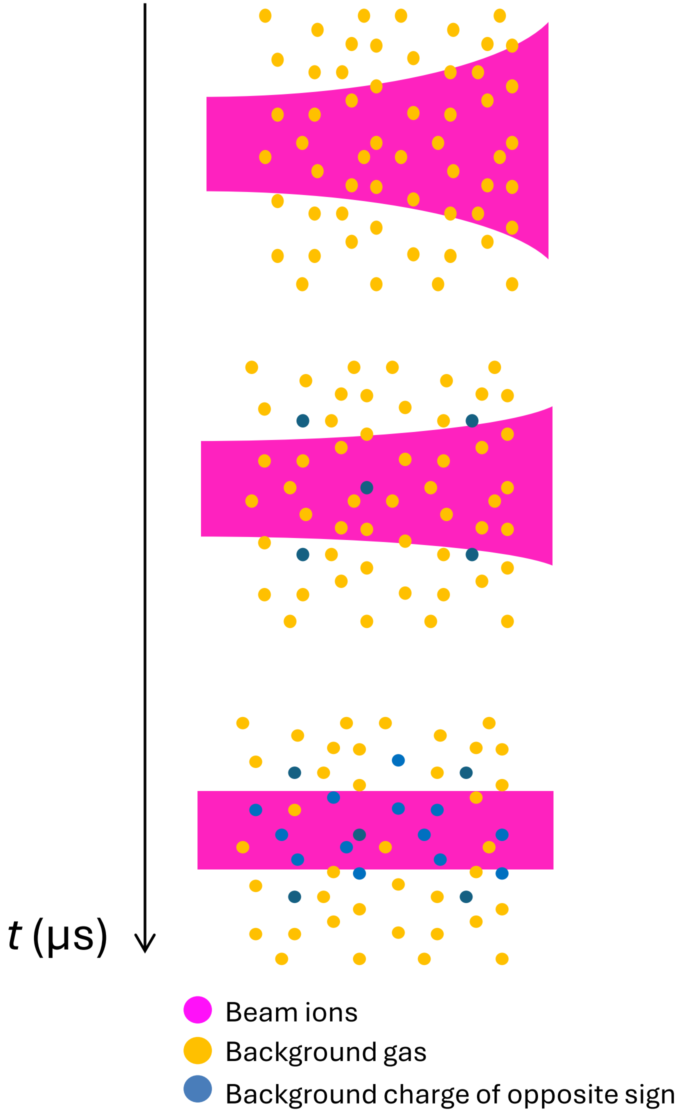
MITICA neutraliser

Neutraliser integrated with each ion source at JET



~10m long neutraliser cell in JT60-SA

Ion beam drift: beam plasma formation

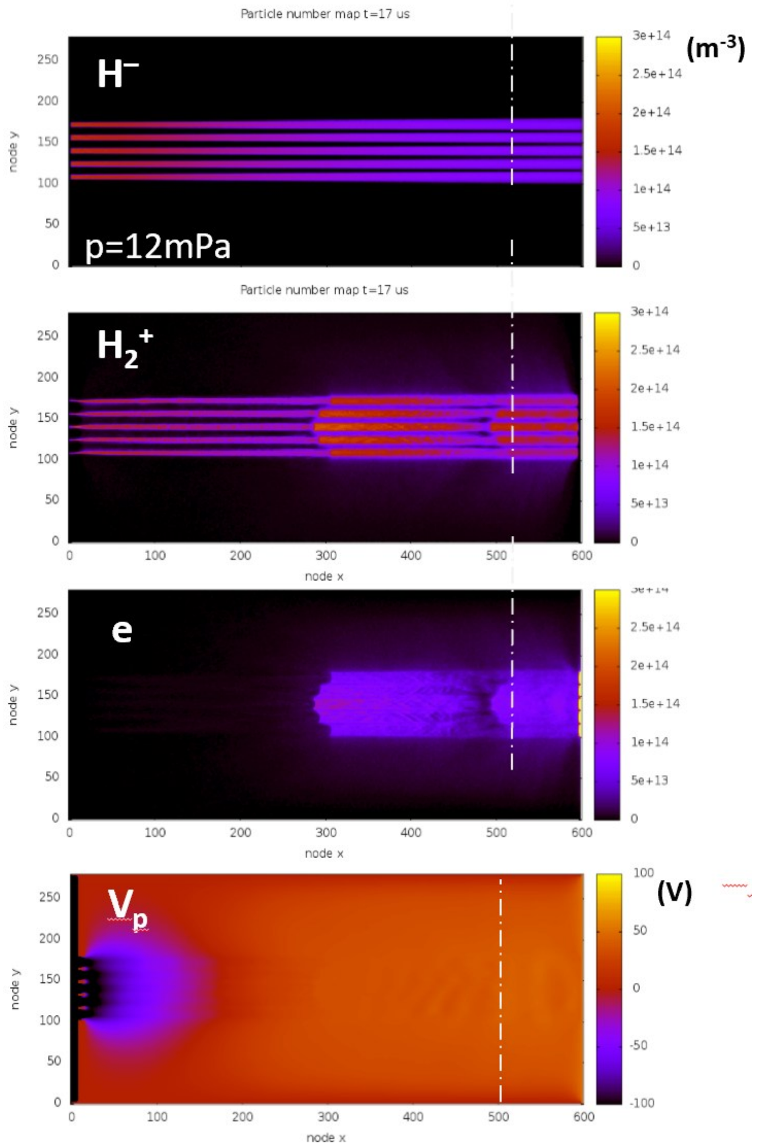


- Ion beam cannot propagate in a vacuum: beam ions are "repelled" by Coulomb interaction
- Space Charge Compensation (SCC): potential well produced by beam charge density traps secondary charges of opposite sign

$\underline{H}^{\pm} + H_2 \rightarrow \underline{H}^{\pm} + e + H_2^{+}$	Ionization of background gas by beam particle
$\underline{e} + H_2 \rightarrow 2e + H_2^{+}$	Ionization of background gas by secondary electrons
$\underline{H}^{-} + H_2 \rightarrow \underline{H}^{0} + \underline{e} + H_2$	Stripping of beam particle (Negative Ion Beam only)

- 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).

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

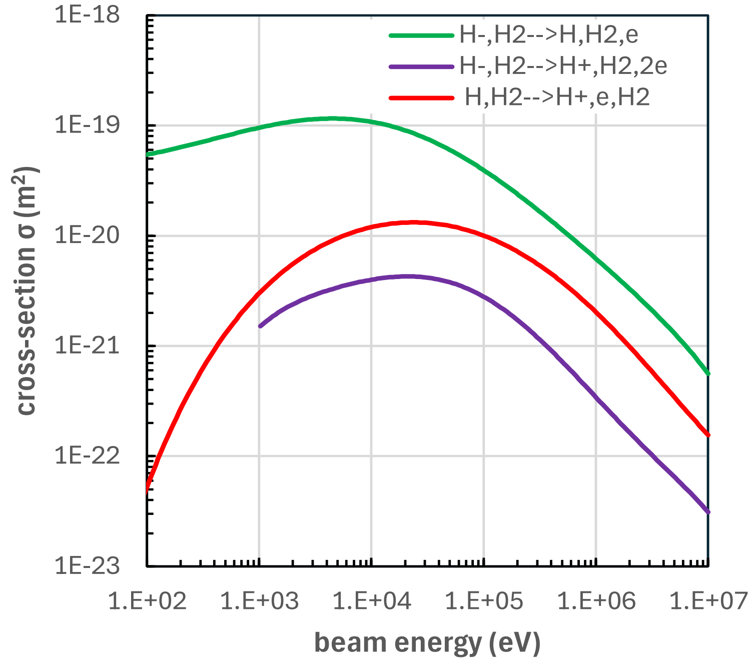
$$\underline{H}^{\pm} + H_2 \rightarrow \underline{H}^{\pm} + e + H_2^+$$ Ionization of background gas by beam particle

$$\underline{e} + H_2 \rightarrow 2e + H_2^+$$ Ionization of background gas by secondary electrons

$$\underline{H}^- + H_2 \rightarrow \underline{H}^0 + \underline{e} + H_2$$ Stripping of beam particle (Negative Ion Beam only)

- 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).

Ion beam neutralization



- 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")
- Competing charge-changing channels are always present, for instance:

$$\underline{H}^- + H_2 \rightarrow \underline{H} + H_2 + e$$ **neutralization**

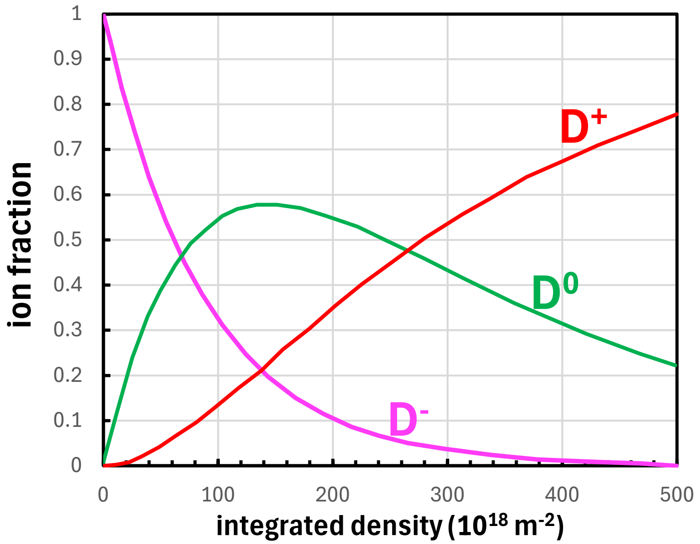
vs

$$\underline{H}^- + H_2 \rightarrow \underline{H}^+ + H_2 + 2e$$ **double electron detachment**

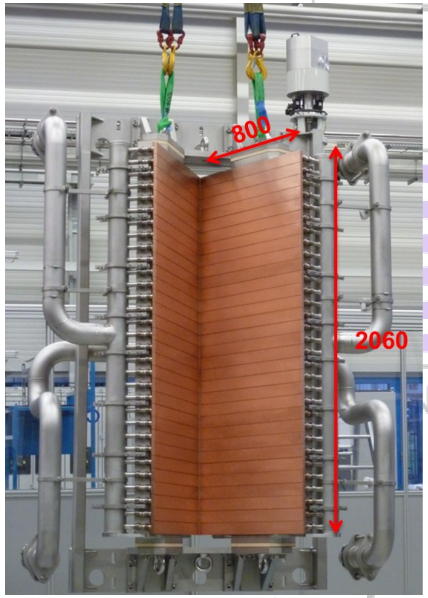
$$\underline{H} + H_2 \rightarrow \underline{H}^+ + H_2 + e$$ **reionization**

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

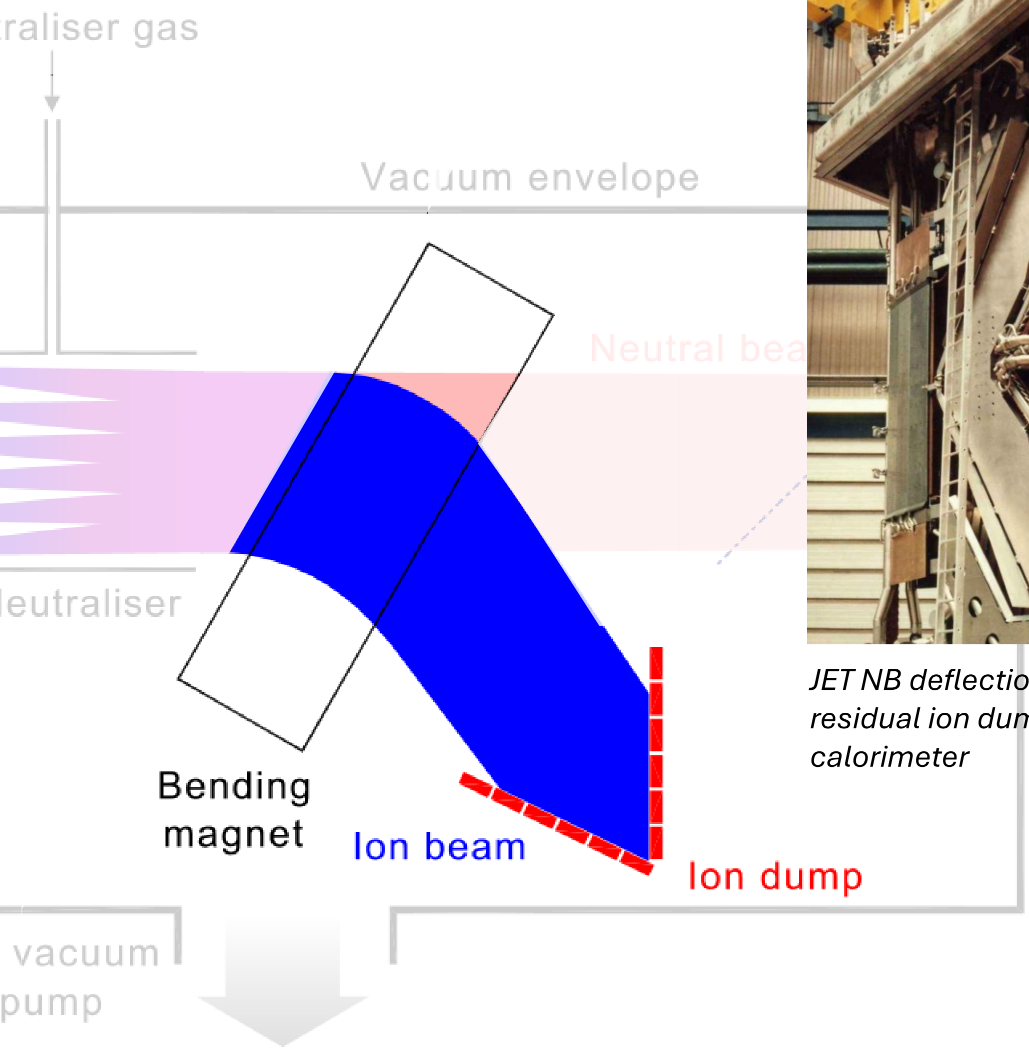
Example: deuterium D⁻ beam accelerated at 1 MV

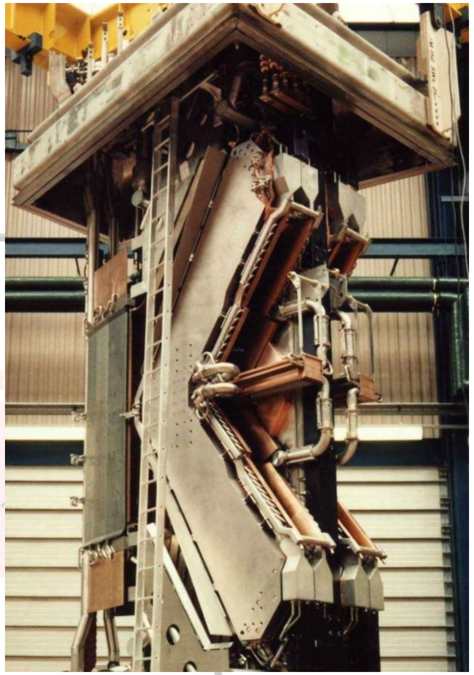


Residual ion dump and calorimeter

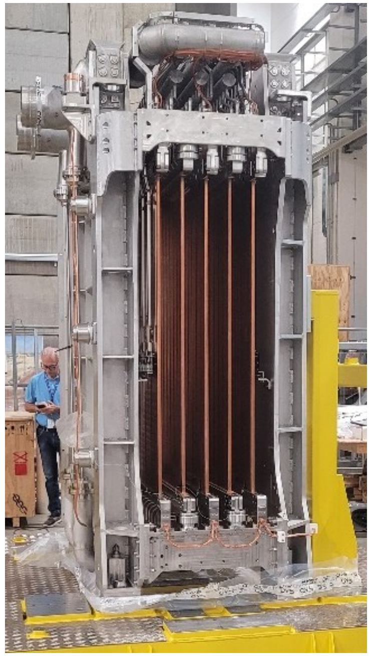


Calorimeter in SPIDER

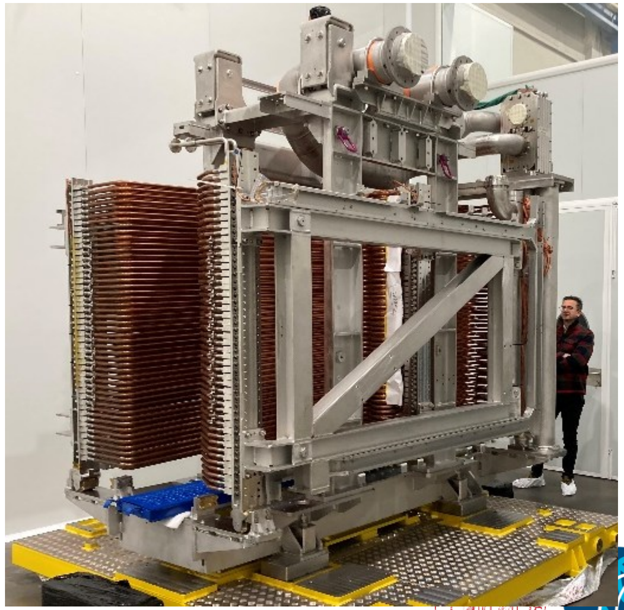




JET NB deflection magnet, residual ion dumps and calorimeter



Electrostatic Residual Ion Dump and swirl-tube calorimeter in MITICA



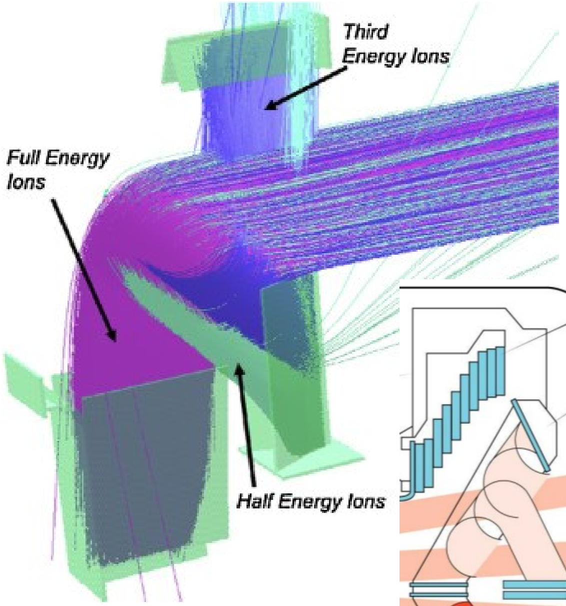
Residual ion dump

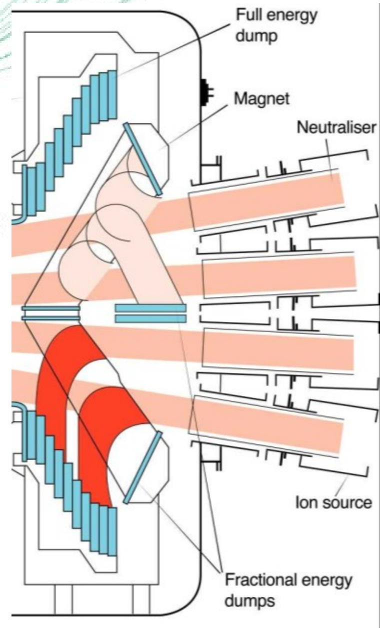
Remaining ions (positive and/or negative) need to be removed from the beam before reaching the tokamak field.

- Deflected either magnetically or electrostatically
- Cooled plates intercept ions at off-normal incidence

MAST-U RID

- 12 MW/m^2
- hypervapotrons





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

ITER E-RID

- 20kV ± 10 kV
- From 3 MW/m^2 (7 mrad divergence) to 8.5 MW/m^2 (3 mrad divergence)
- CuCrZr panels with swirt tapes

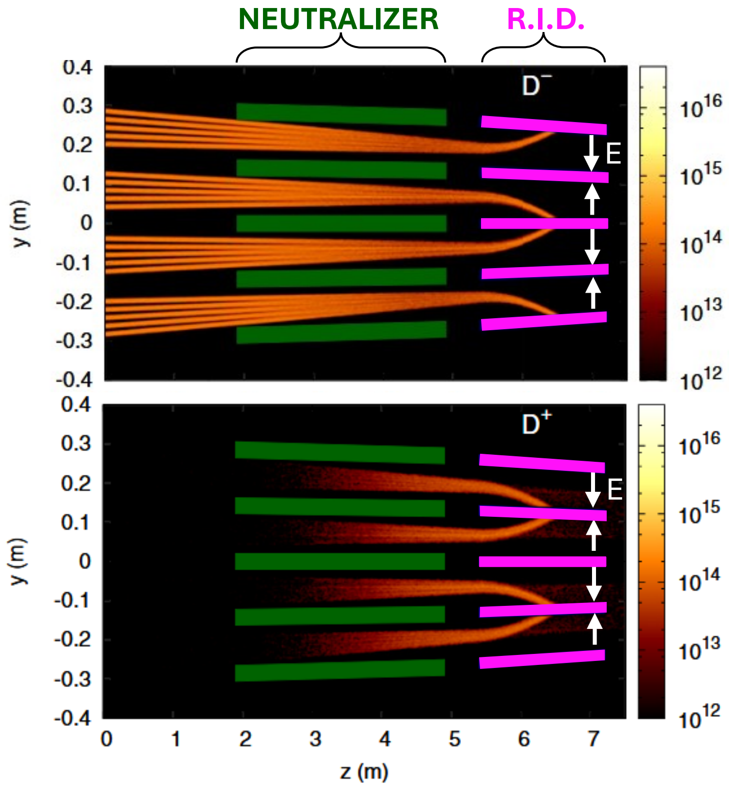


Figure 7. Spatial density distribution of the different component of the beam at $t = 15\ \mu s$ at the middle plane ($x = 0$).

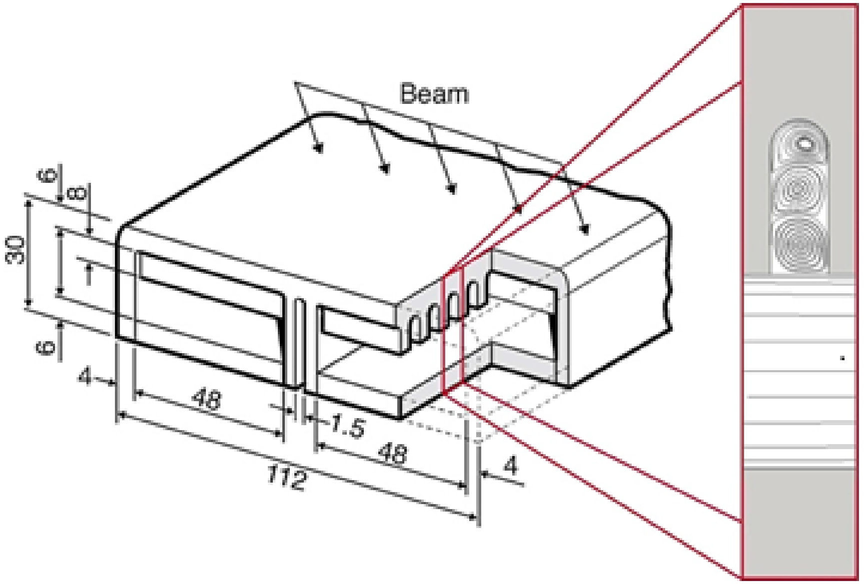
A.F. Lifschitz et al 2014 Nucl. Fusion 54 043020

Calorimeter

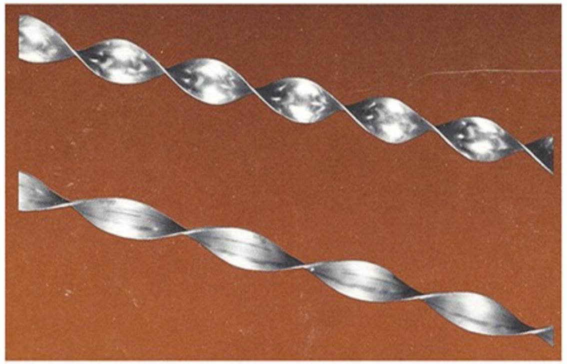
Use:
- Needed for beam conditioning outside of tokamak pulses (HV, Cs…)
- Measure beam power, beam footprint, neutralisation fraction

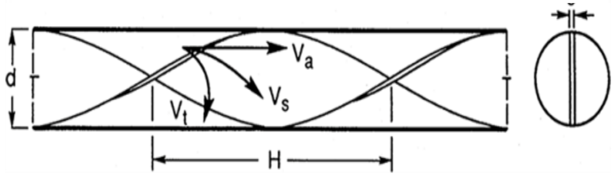
Thermomechanical design:
- High Heat Flux component design (~15–20 MW/m^2): use of *swirl tapes* or *hypervapotron* to enhance local heat transfer coefficient.
- Number of beam cycles: fatigue life
  - *Beam on/off cycles*
  - *Breakdowns*
- Material activation: subject to direct neutron flux from the torus → 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. CuCrZr<450C to avoid precipitation of Cr leading to hardening*

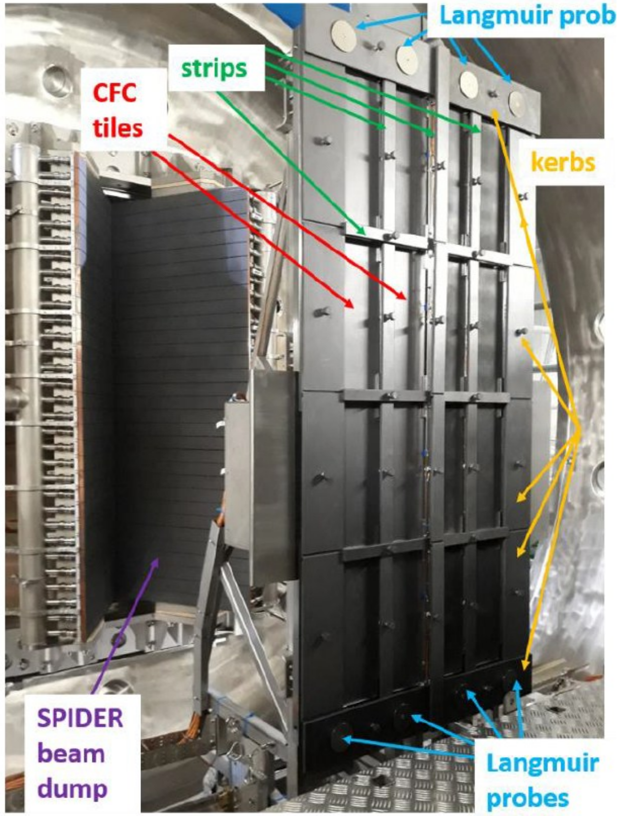
CFC inertial calorimeter

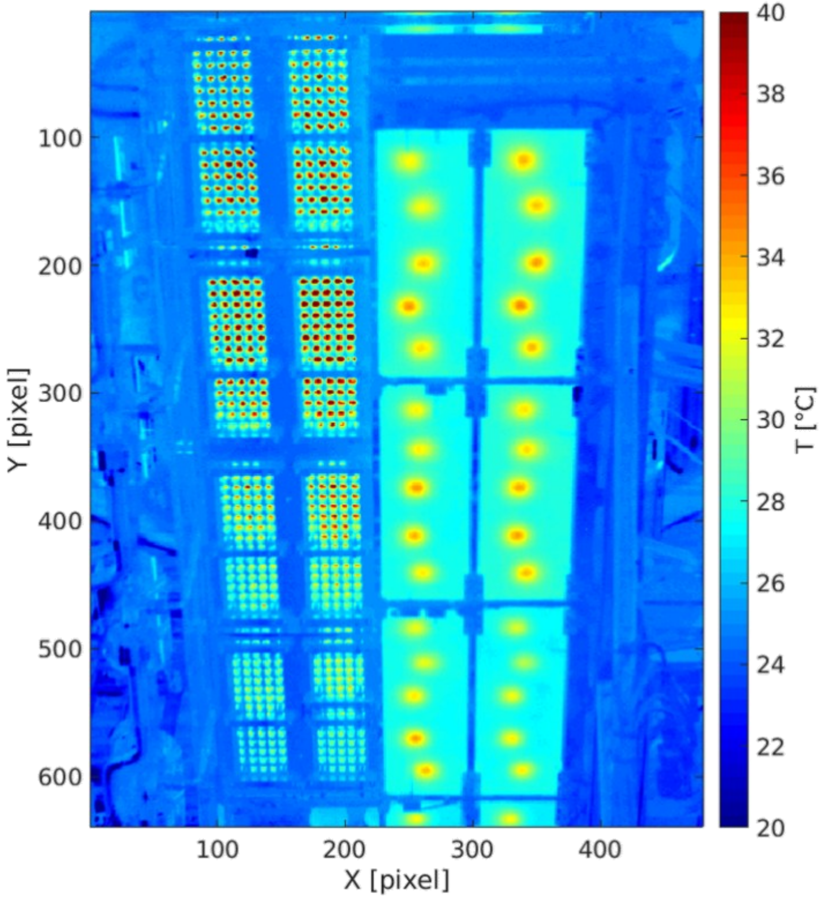
Carbon fibre composite blocks used as calorimeter.

- When exposed to a short beam pulse, CFC tile temperature distribution reaches equilibrium in the fibre direction (beam direction) within few second.
- Footprint of the beam is practically "frozen" and infrared imaging can be used to derive power density distribution.

Properties of the diagnostic:

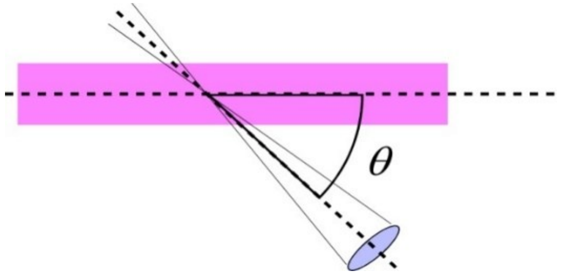
- Short pulses
- High spatial resolution: 1-2 mm
- Accuracy: <10%





Example with isolated beamlets

Doppler shift spectroscopy



Light emission from interaction between beam particles and residual gas molecules:

- Target emission
- **Beam emission**

$$\frac{\lambda}{\lambda_0} = 1 + \varepsilon - \sqrt{\frac{\varepsilon(\varepsilon+2)}{\varepsilon+1}} \cos\theta, \quad \varepsilon = T / m_o c^2 \quad T, \ beam\ energy\ (J)$$

Line intensity ratio ⇒ species composition

Line width ⇒ beam divergence, optimum perveance

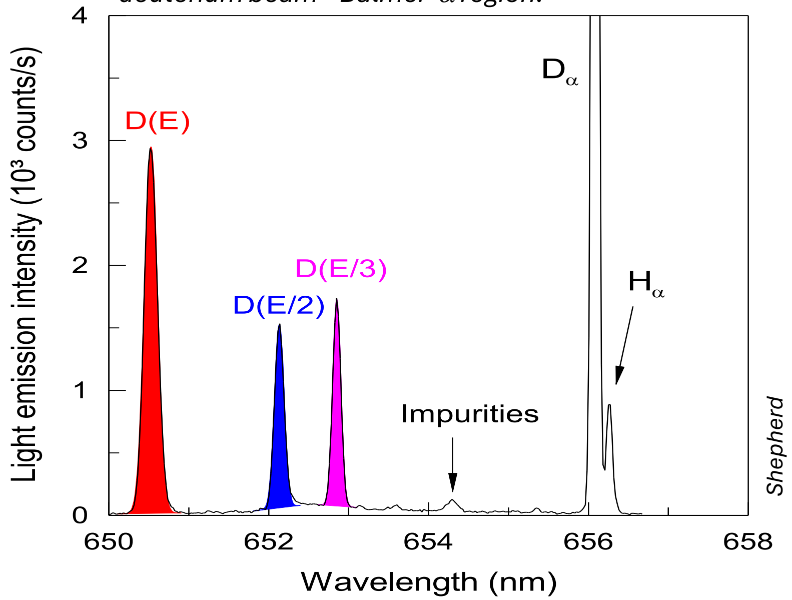
Line shape ⇒ accelerator losses

Spatial resolution ⇒ beam profiles, non-uniformity

A. Shepherd

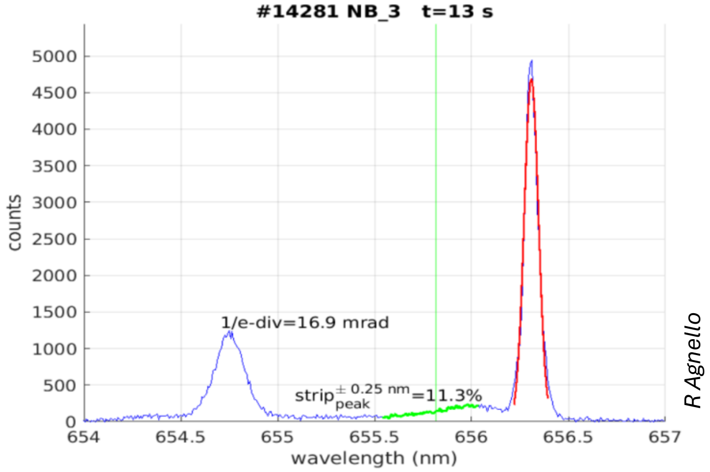
P-NBI

Optical emission spectrum of 142 kV/ 30 A deuterium beam - Balmer-α region.



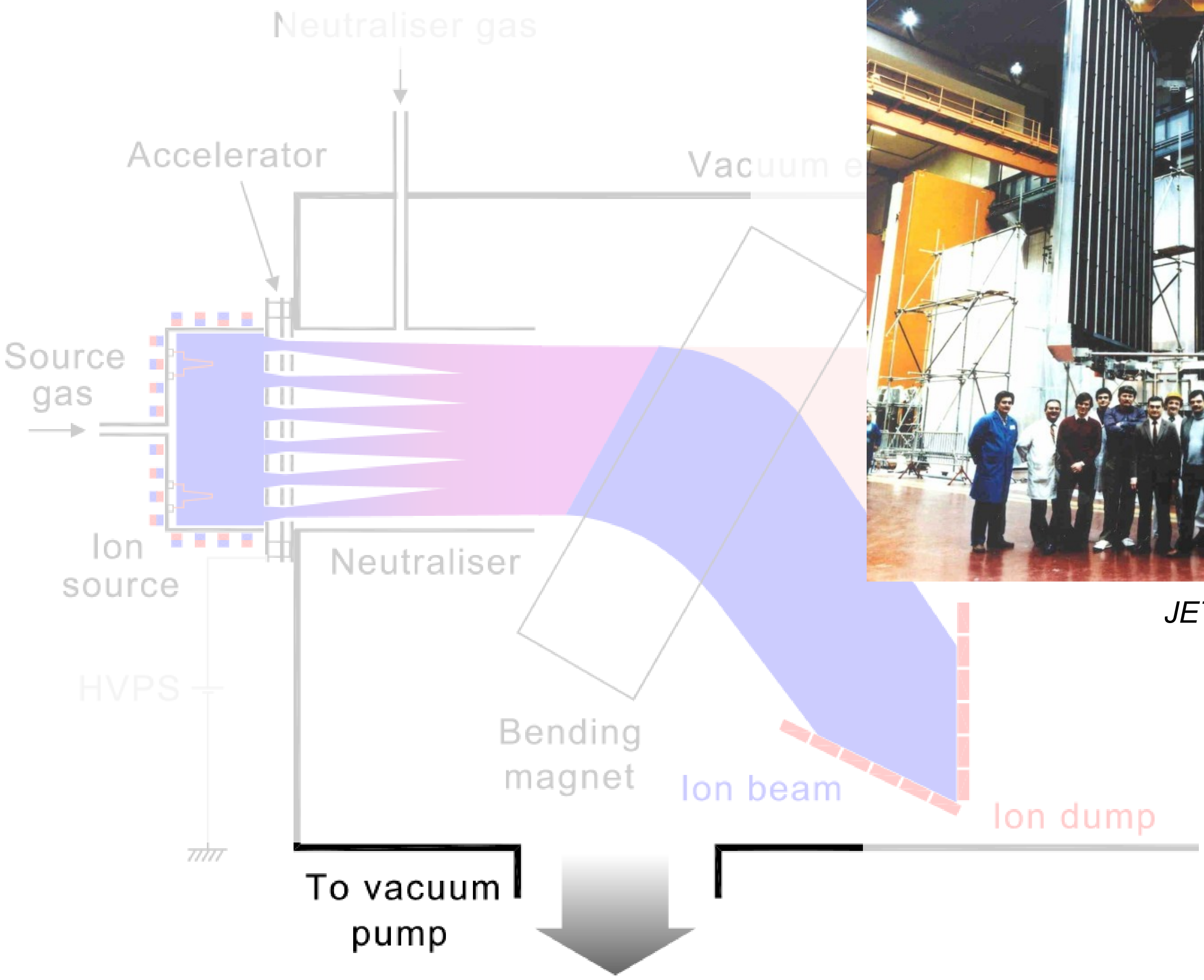
N-NBI

Optical emission spectrum of hydrogen negative ion beam - Balmer-α region.



R Agnello, measurements in SPIDER

Pumping system



JET NB Injector cryopump

JET NBI (H_2)[1]
S=8000 m^3/s
Q=25 Pa·m^3/s
p=5·10^{-3} Pa

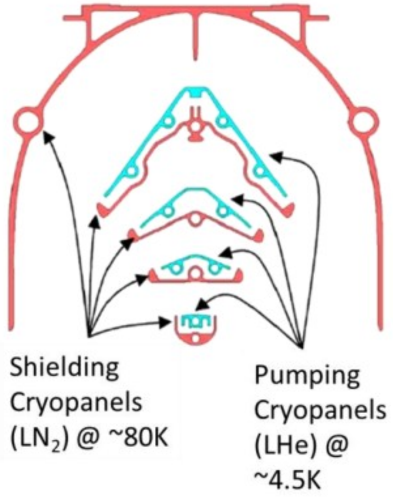
One of the two cryopanels of MITICA

ITER NBI (H_2)[2]
S=4700 m^3/s
Q=48 Pa·m^3/s
p=3·10^{-3} Pa

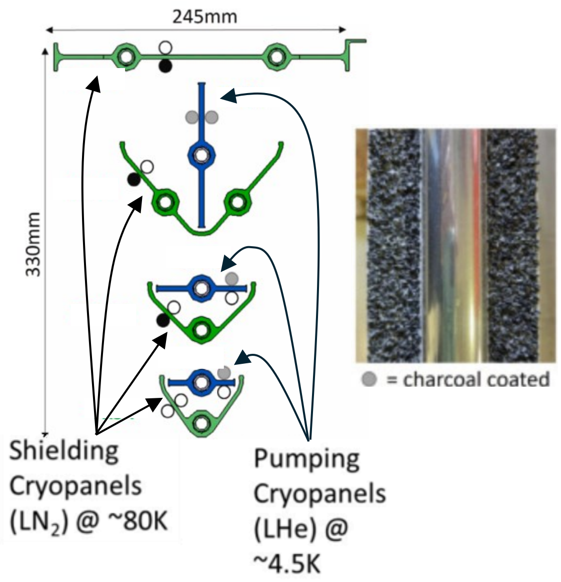
[1] G Duesing, Vacuum **37** 309-315 (1987)
[2] M. Dremel, et al, Nucl Fus **49** 075035 (2009)

Cryopump design and requirements

JET cryopump
- A = 40 m^2
- S = 8000 m^3/s
- Q = 25 Pa·m^3/s
- p = 5x10^{-3} Pa



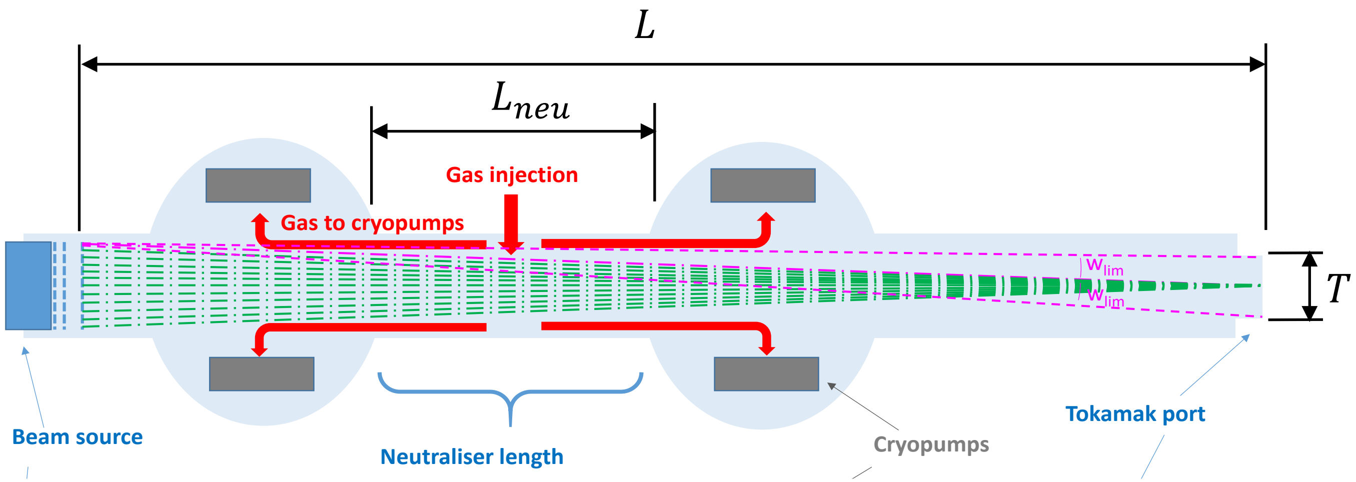
ITER cryopump
- A = 38 m^2
- S = 4700 m^3/s
- Q = 48 Pa·m^3/s
- p = 3x10^{-3} Pa



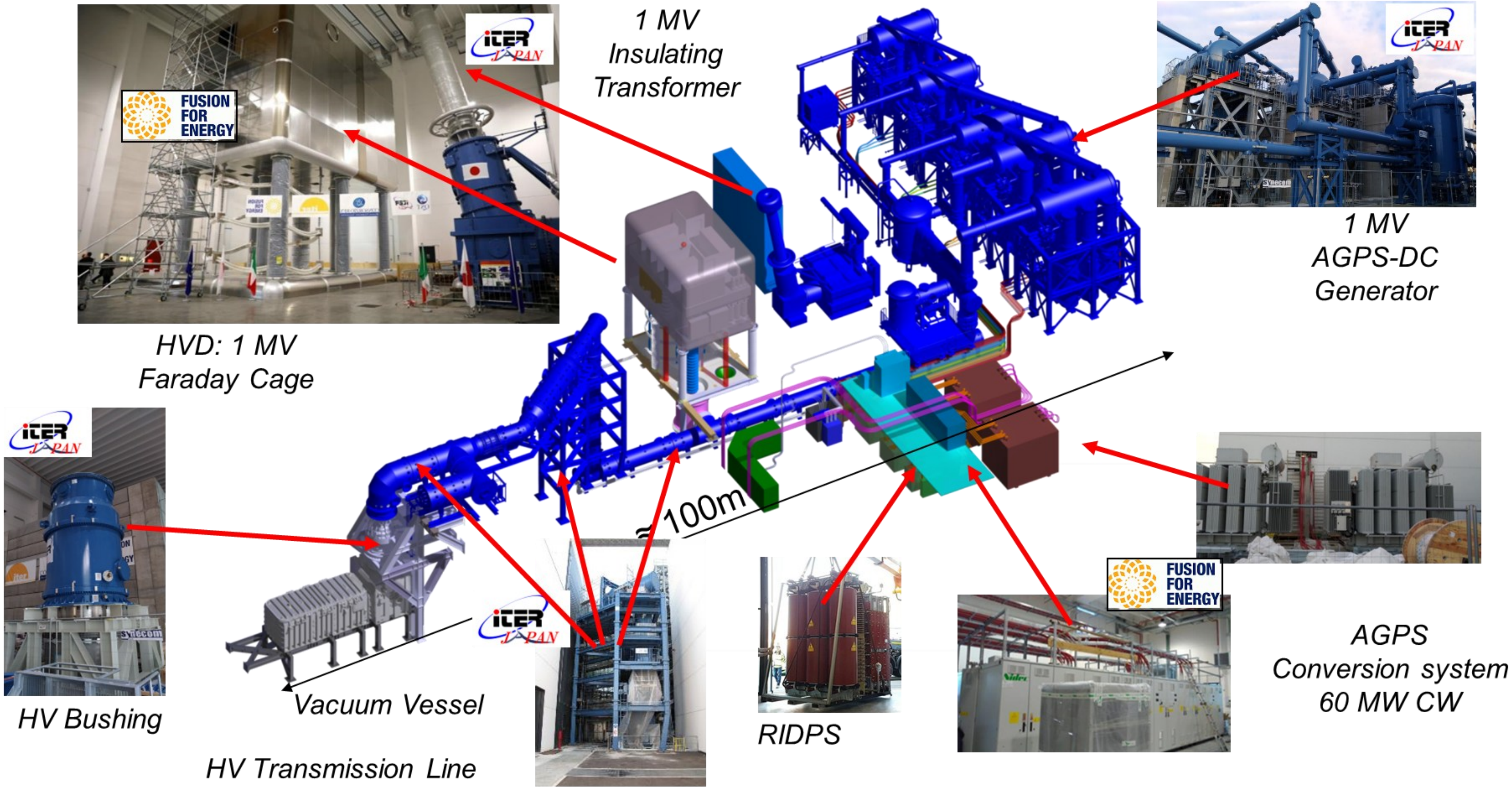
J Buckerfield,et al., Fus. Eng. Design 215 (2025) 114991

Requirements given by neutraliser gas:

- Required gas throughput at the neutraliser reads: $$Q \propto \frac{1}{(L_{neu})^2}$$
- Due to cryopump limited capacity, the operation time is inversely proportional to Q
- Because of the beam divergence ω, the transmitted power F decreases with the total beamline lenght: $$F \propto \mathrm{erf}\left(\frac{T}{2 \cdot L} \cdot \frac{1}{\omega}\right)$$



Power supplies



Summary and ITER perspective

Neutral beams offer:

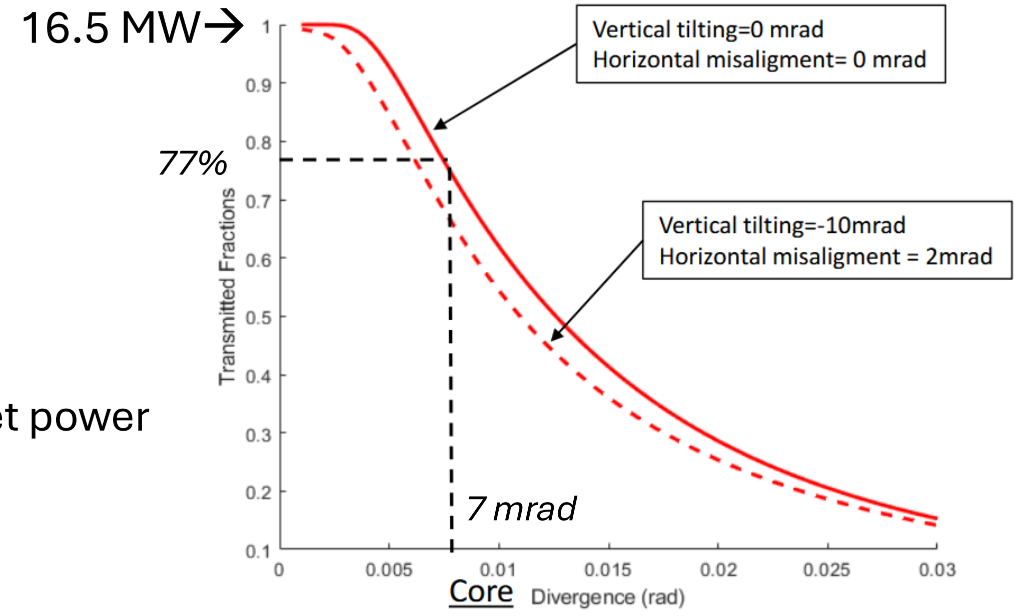
- Flexible and powerful heating method (high total power, long pulses, power waveforms, beam position)
- Ease of coupling to plasma. No upper limitations regarding plasma density
- High reliability
- Complex, robust and well-established technology

Disadvantages:

- Low efficiency at present (but negative ion precursor is better)
- Expensive

ITER Heating neutral beam developments:

- RF-based sources confirmed linear dependence of ion current against discharge power.
- Rather uniform beam pattern on calorimeter.
- Voltage holding up to 870 kV verified (without beam)
- Achieving <u>low divergence and proper beamlet aiming</u> to achieve target power



Acknowledgement

My thanks to the teams in the Neutral beam test facility, IO, laboratories and DAs helping us and working on the systems mentioned in this presentation.

Università degli Studi di Padova

Students in Thesis and Internship

6 courses in Bachelors and Master programmes dedicated to Fusion Science and Engineering

PhD in “Fusion Science and Engineering” since 2006
~10 PhD students/year

Post doc and young researcher- grant

Thank you!

Neutral Beam Injectors

22nd May 2025 – Joint ICTP-IAEA Fusion Energy School
International Centre for Theoretical Physics – Trieste

prof. Emanuele Sartori

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

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