Towards long-pulse and continuous positive-ion-based neutral beam injection

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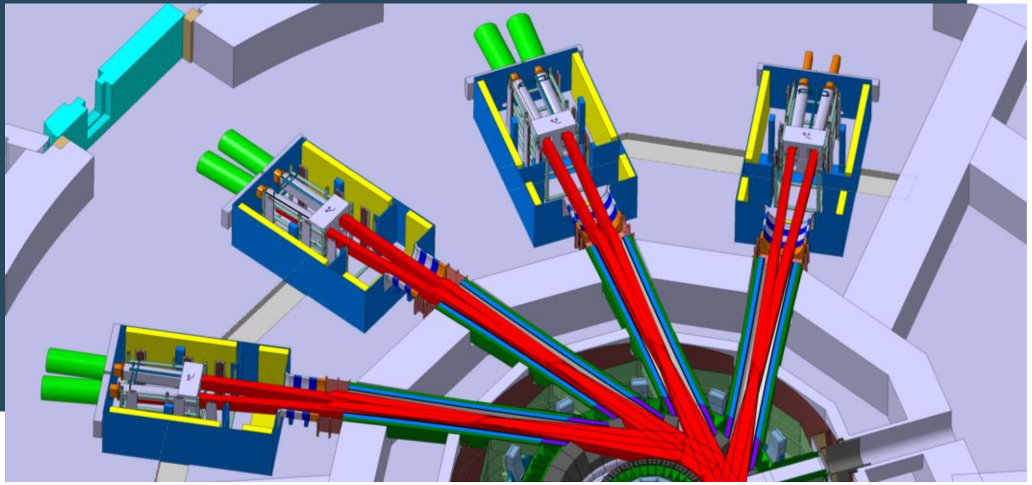

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Outline

- Why long-pulse positive ion based (P-) NBI?
- Present status of P-NBI experience and technology
- VNS NBI as case study
  - Transmission
  - Everything related to gas – reionization, feed gas, pumping
  - Energy (“wall-plug”) efficiency
  - Active cooling
  - Residual ion dump erosion
  - Remote maintenance philosophy
- Conclusion

Example 1: EURO*fusion*'s Volumetric Neutron Source

- Small tokamak with beam-driven D–T fusion.
- So far: feasibility study concluded.
- Main mission: test functional breeding blankets under reactor-relevant neutron fluxes and fluences.
- Neutral beam injection (NBI) provides
  - most of the fusion rate
  - fully non-inductive current drive for steady state.

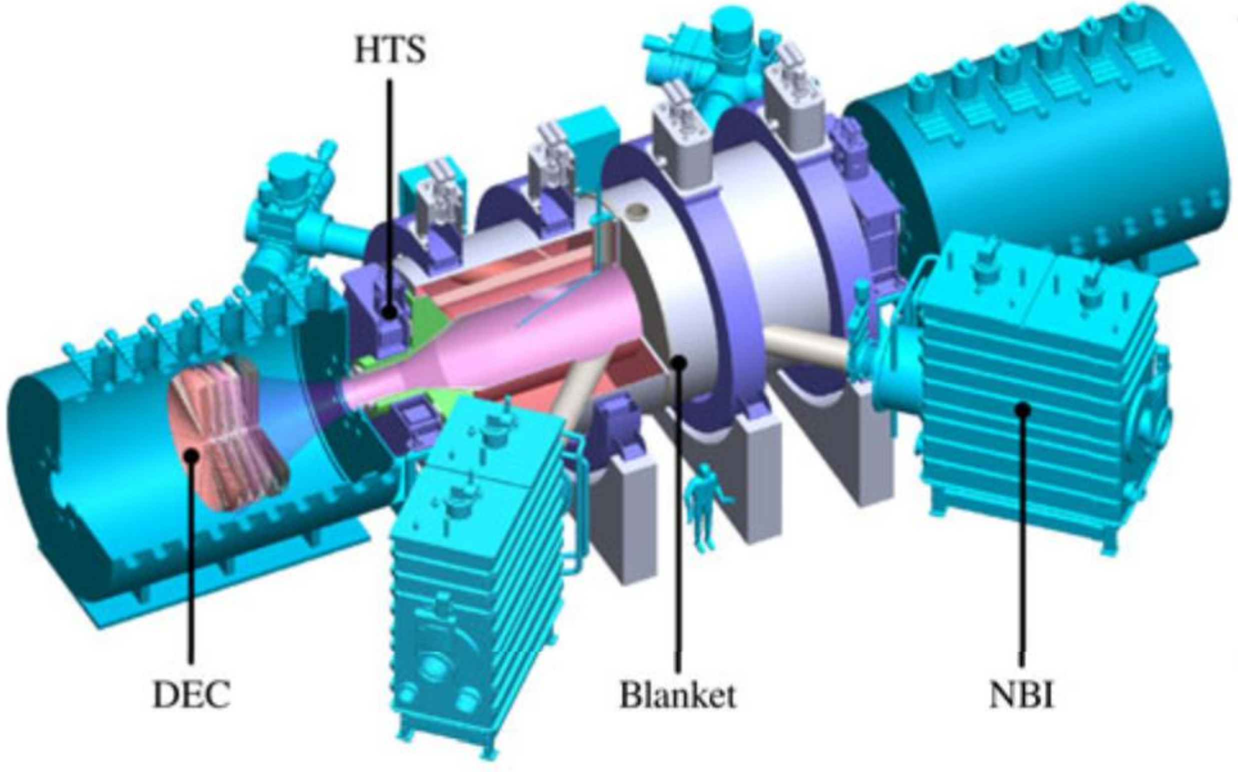
VNS requires 42 MW of continuous 120 keV deuterium NBI.

At 120 keV (only) positive-ion-based NBI can be used.

Advantage: No Cs, 10 × higher current density, good reliability record especially with RF ion sources.

VNS main parameters	
R_0	2.53 m
a	0.5 m
B_t	5.4 T
I_p	1.76 MA
P_{fus}	29 MW
P_{NBI}	42 MW
E_{beam}	120 keV
Plasma isotope	T
NBI isotope	D
Neutron wall load	≤ 0.5 MW/m^2
First wall lifetime dpa	30–50

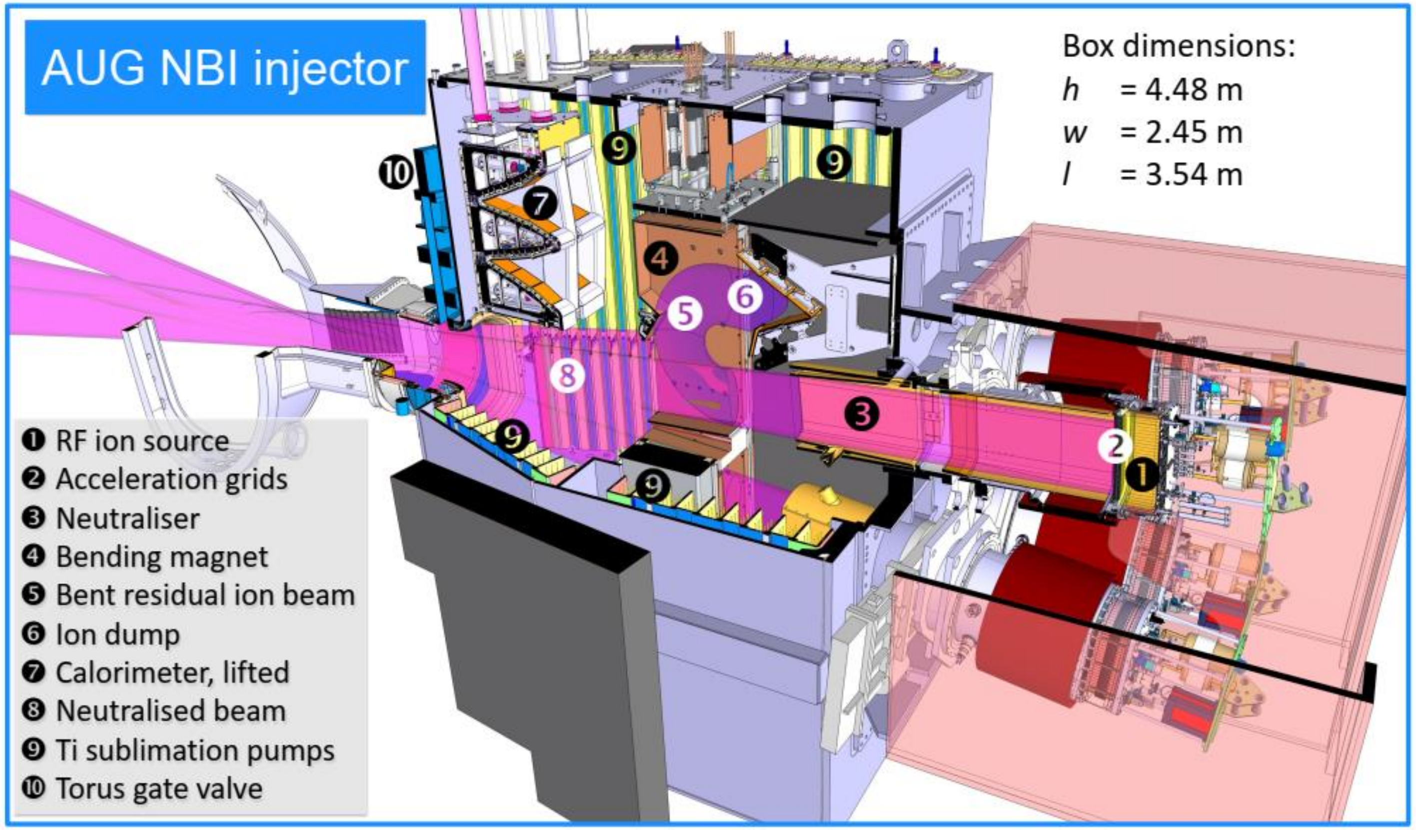
Example 2: Realta's High-Field-Mirror BEAM



	WHAM	BEAM
Q_{DT}	~ 0.05	~ 1
β	0.3	0.3
L_p (m)	2.0	8
a_0 (m)	0.12	0.30
a_M (m)	0.025	0.10
R_M	20	10
B_0 (Tesla)	0.85	2.5
B_M (Tesla)	17	25
E_{NBI} (keV)	30	100
P_{NBI}(MW)	< 1	10
T_i (keV)	17	80
T_e (keV)	2.5	10
n_{20} (m^{-3})	0.3	1
τ_p (sec)†	0.15	0.25
$nT\tau$ ($10^{20} m^{-3}$·keV·sec)	0.7	20
pulse length (sec)	< 2	> 5
kA·m of HTS tape	$\sim 10^4$	4.3×10^5
Cost of tape ($M)	~1	40

C.B. Forest *et al.*, J. Plasma Phys. 90 (2024) 975900101

Present status of P-NBI experience and technology

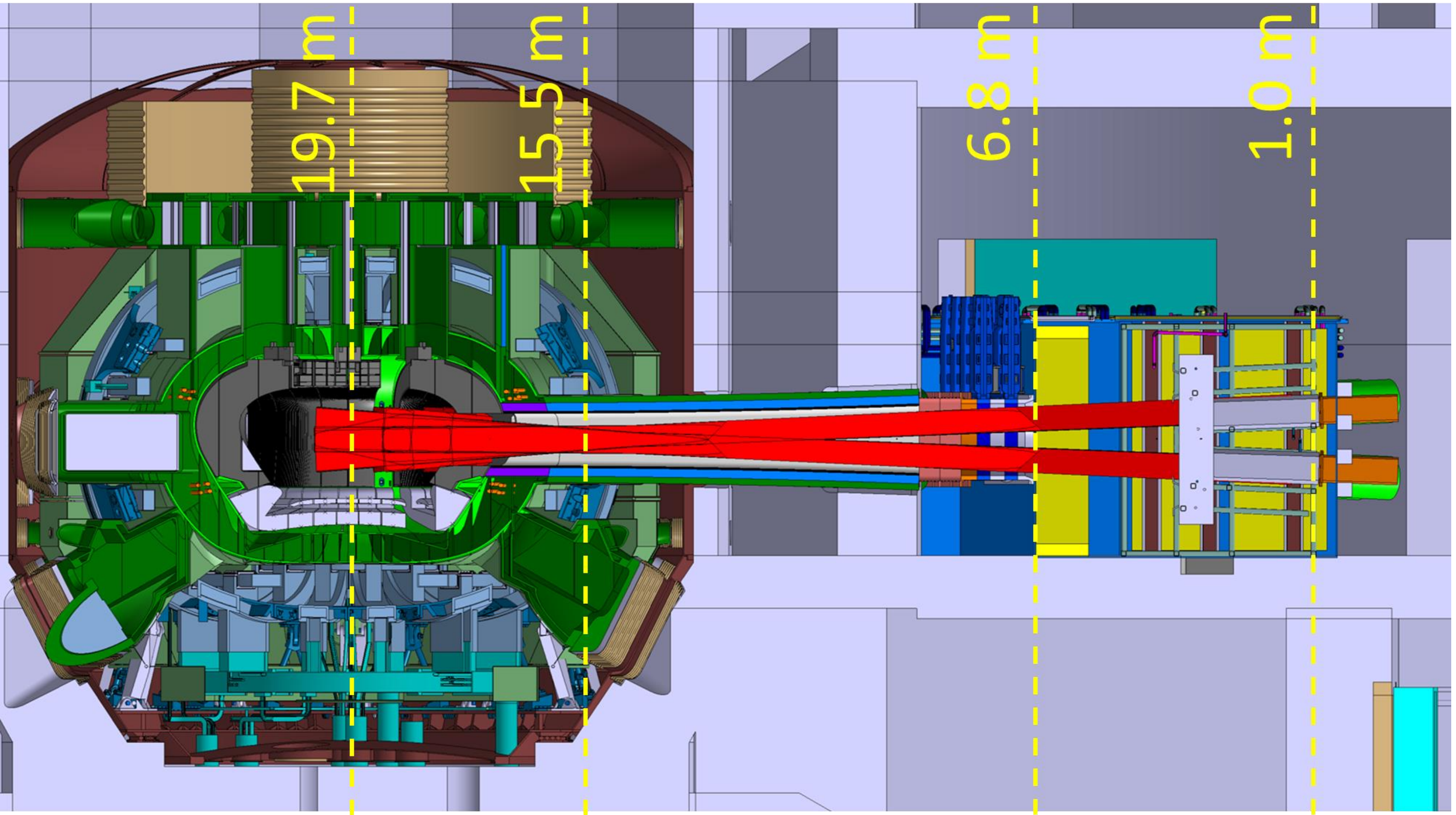


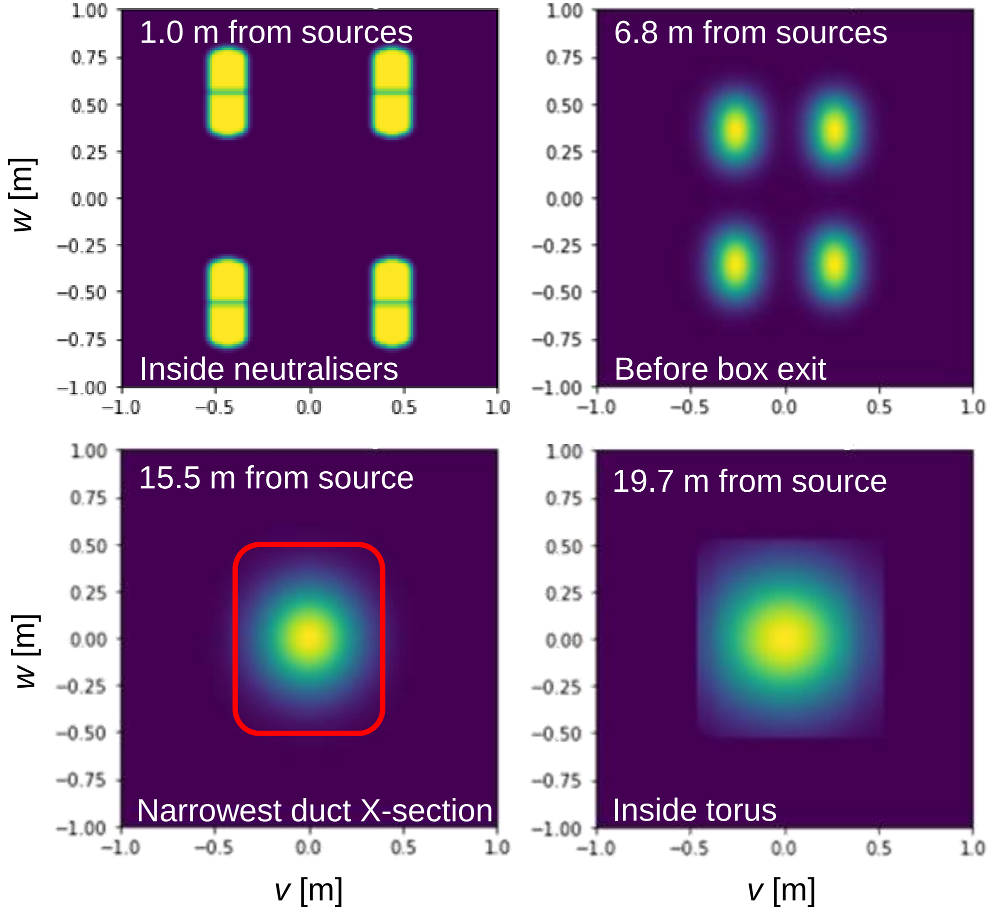
	Cycles	Cumulative beam-on time
AUG NBI	< 30 000	22 h
GLADIS**	270 000	770 h
VNS NBI in 10 FPY	**22 000**	**65 000 h**

**High heat flux component test facility that uses the beam from a NBI ion source that is smaller than, but technologically similar to the AUG RF ion sources.

Case study: VNS NBI

Transmission

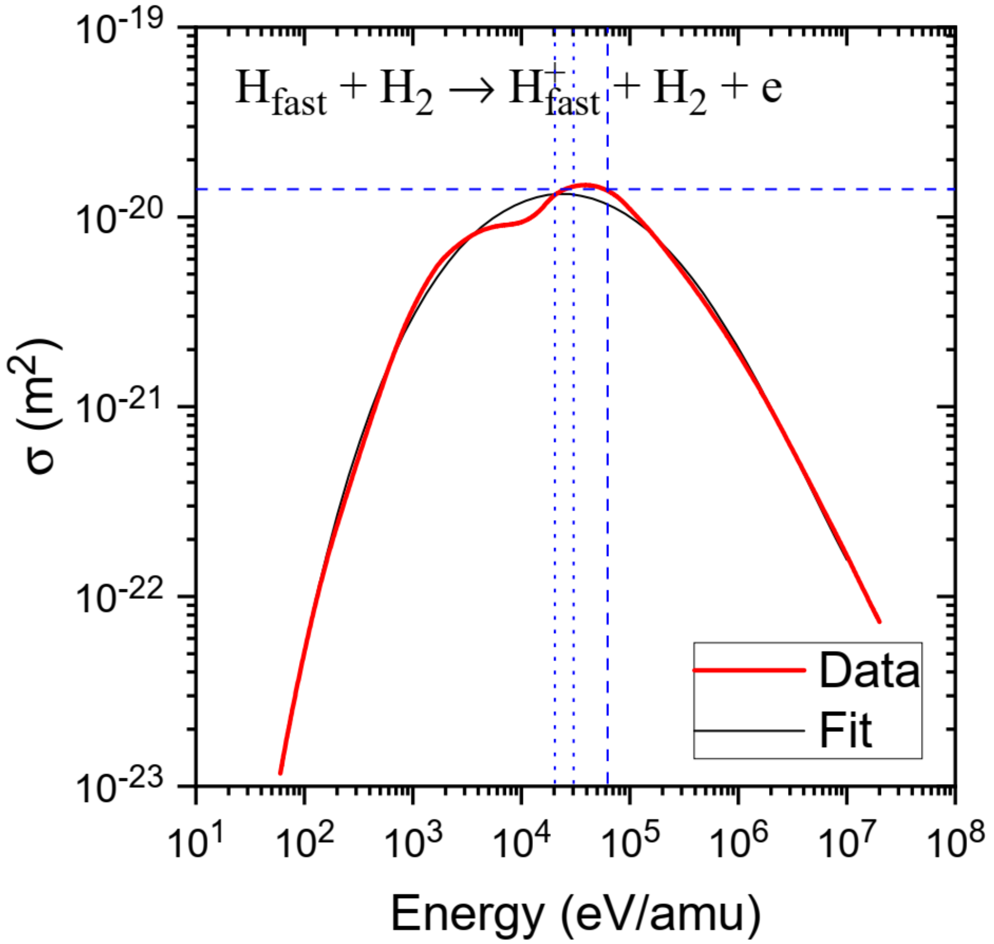




- Small device, but neutron shielding does not scale → long beamline.
- Beamlet divergence $\langle v_\perp \rangle / v_{||}$ is larger for slower beams (~ 0.7° for 120 keV D).
- TF and PF coils as well as NBCD requirement for tangential injection restrict duct cross section.

→ **87 % geometric transmission**

Reionization

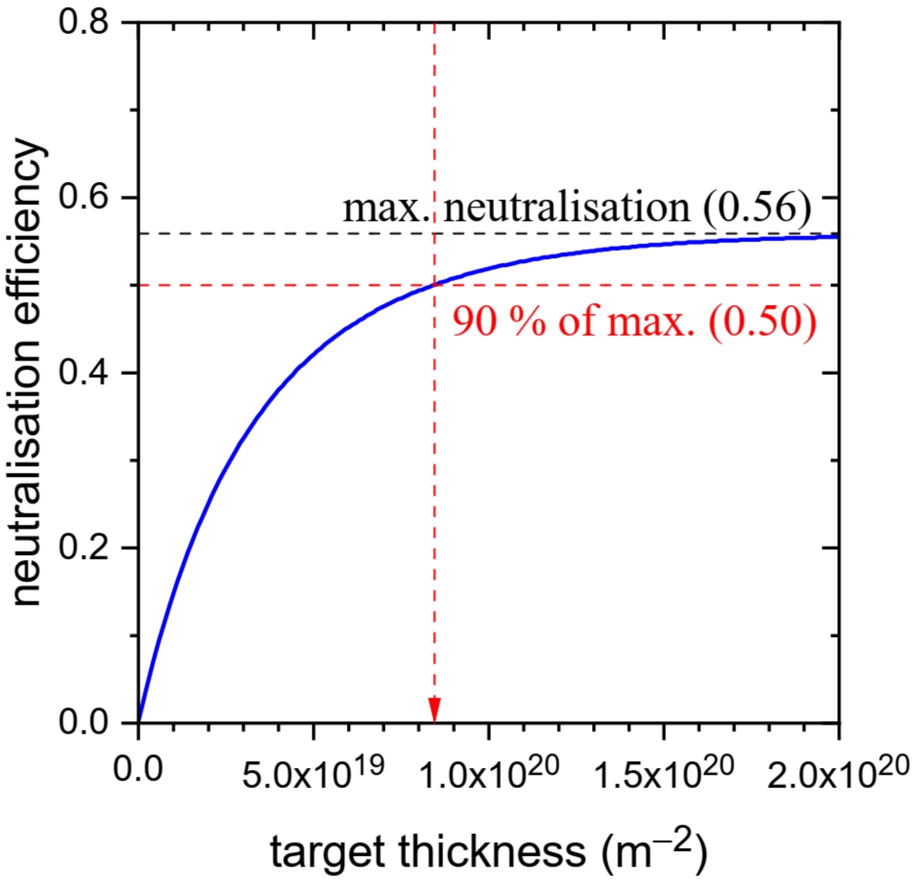


C.F. Barnett *et al.*, Report ORNL–6086 (1990)

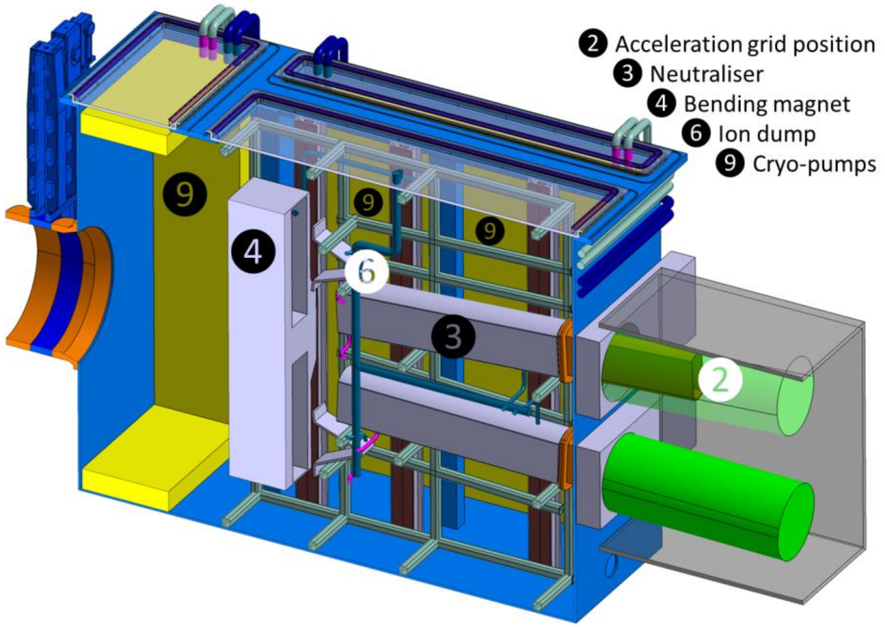
- 120 keV D^0 (and 60/40 keV energy fractions) are around the maximum of the ionization cross section!
- 4.4 % beam loss by ionization per every 10^{-5} mbar background gas.

➢ **For < 10 % reionization losses average duct pressure needs to be < 2 × 10^{-5} mbar!**

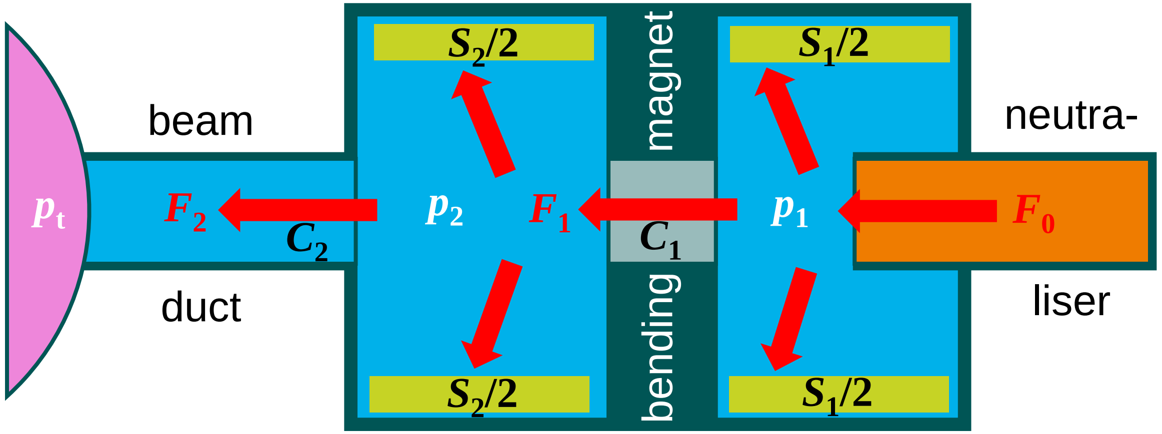
Required feed gas flow



- Neutralisation via charge exchange $D^+ + D_2 \rightarrow D^0 + D_2^+$
- Target thickness required for 50 % neutralisation: 8.5×10^{19} m^{-2}
- Achieved with 25 mbar L/s per source (~ 45 % converted to beam) in 4 m long neutraliser = twice the length of AUG neutralisers.
- Total feed gas flow 100 mbar L/s = half of AUG NBI

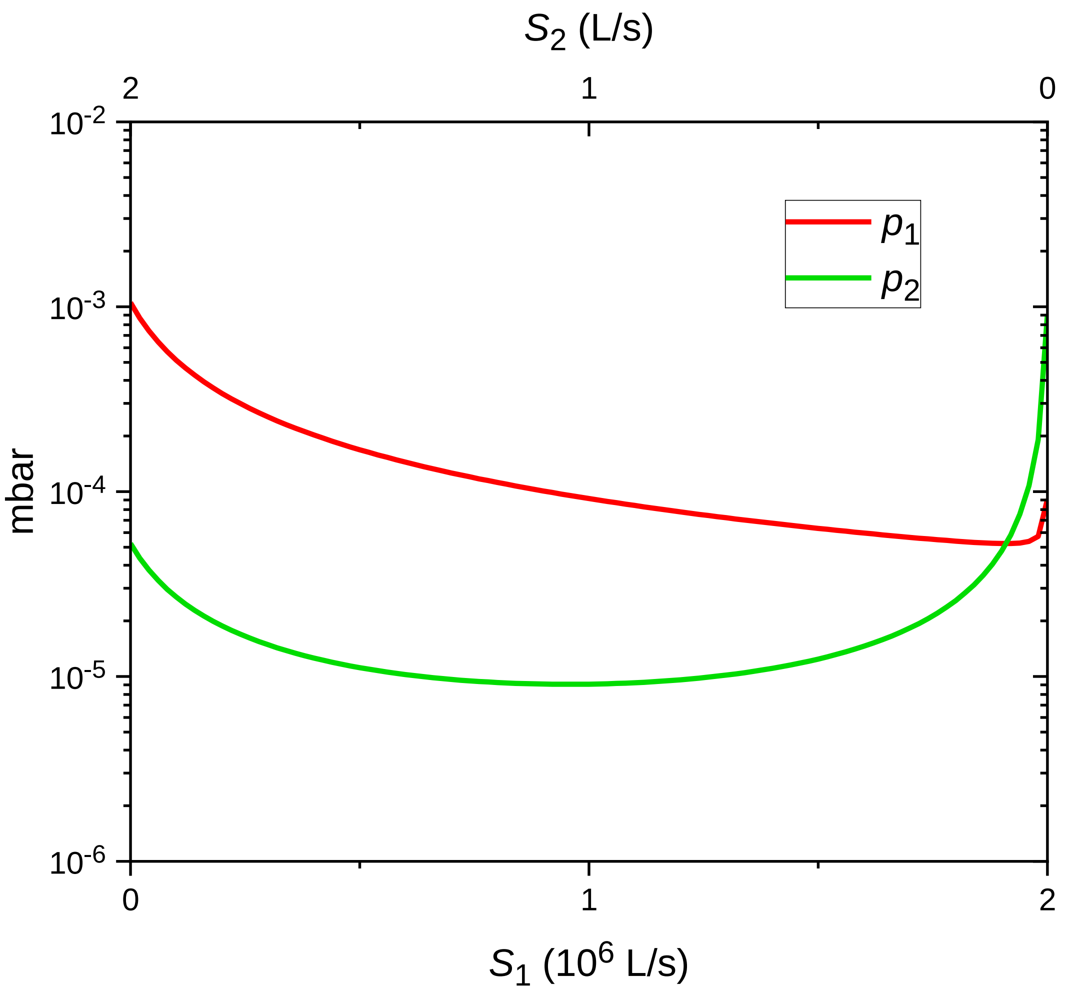


Pumping



Differential pumping

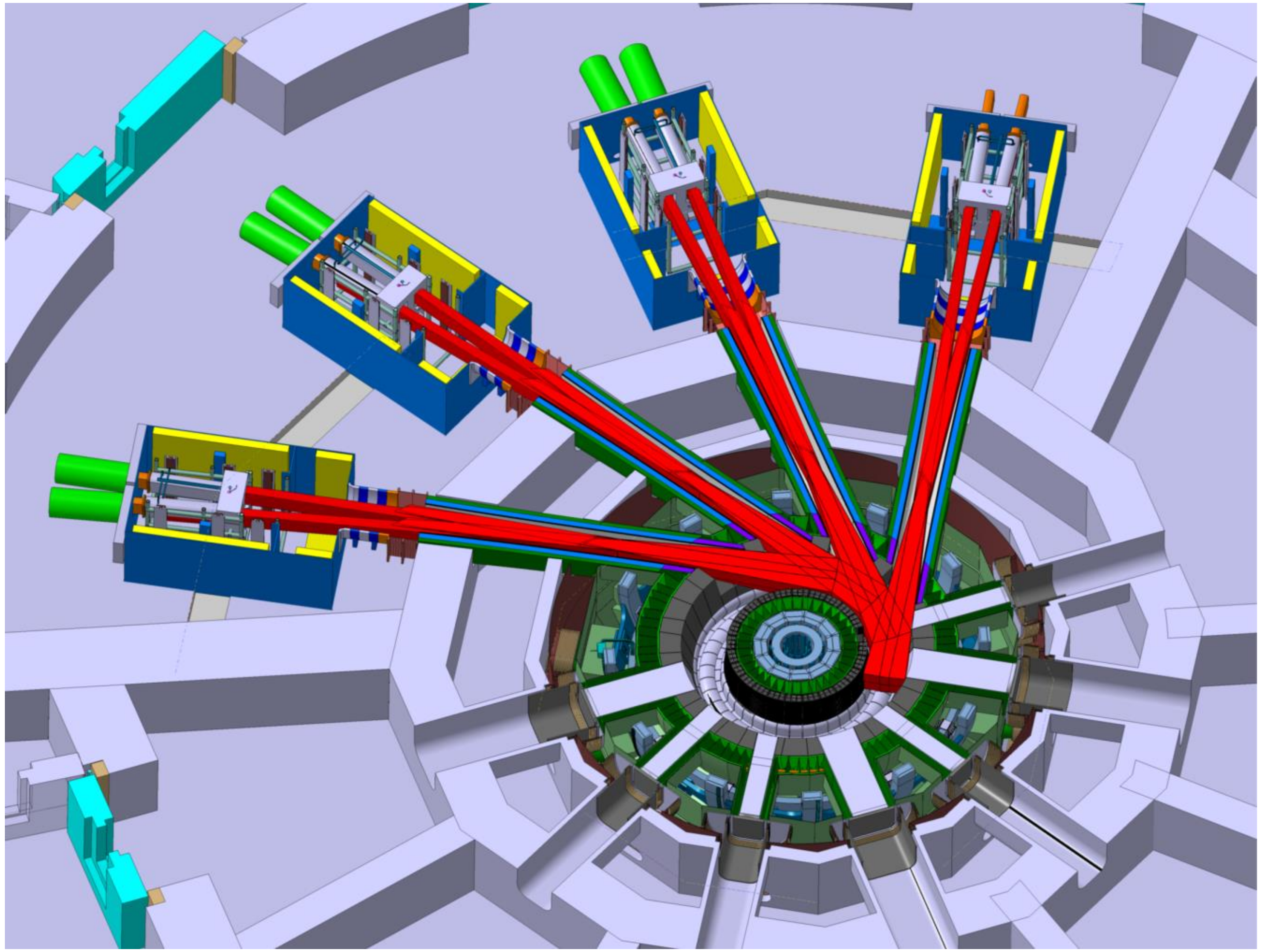
F_0	100	mbar L/s
$S_1 + S_2$	2×10^6	L/s
C_1	1×10^5	L/s
C_2	1×10^4	L/s
p_t	1×10^{-6}	mbar



Box exit pressure < 2×10^{-5} mbar achievable with total pumping speed of ~ 2×10^6 L/s → feasible.

Cyclic operation and pump regeneration

- Conservative explosion safety limit: in case of air leak with sudden release of adsorbed hydrogen from cryopumps **hydrogen partial pressure must remain below 16 mbar** = 40 % of explosion limit.
- 70 m^3 box volume and 100 mbar L/s feed gas flow $\rightarrow$ **max. 3.1 h operation.**
- **Concept: 4 injectors, cyclically 3 operating, 1 regenerating**
- $\rightarrow$ 1 h for cryopump regeneration
- NBI cryopumps constitute one of the bigger T inventories.



Efficiency

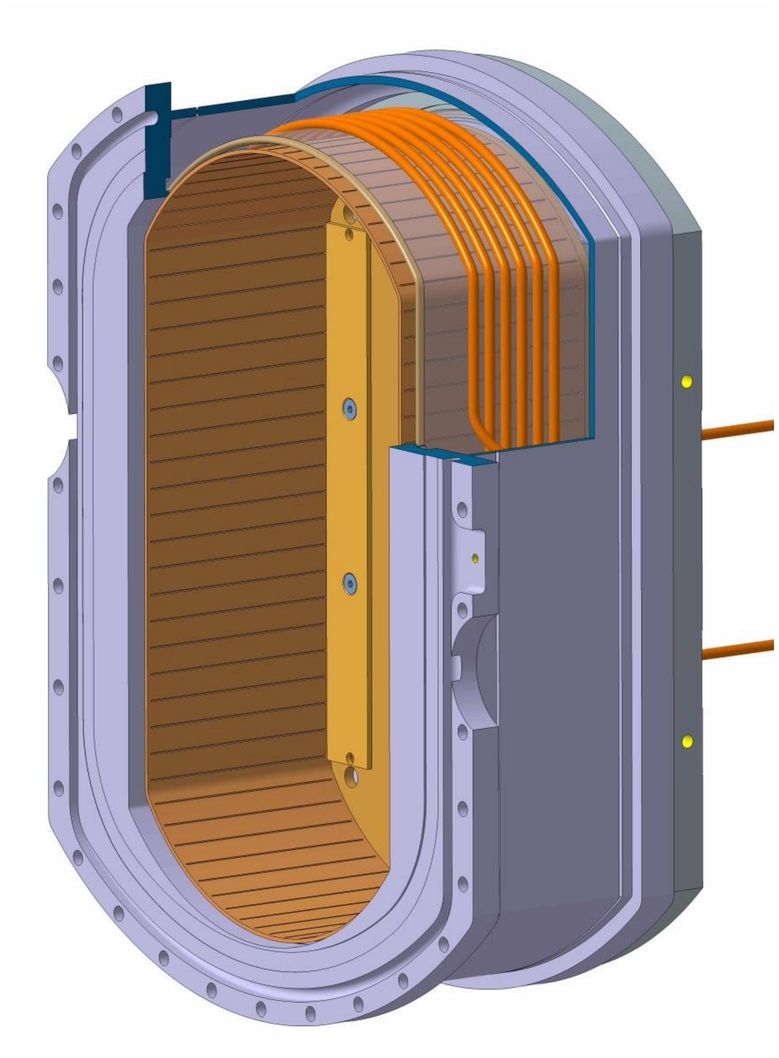
	Efficiency	Power
Injected power per injector		**14.00 MW**
Geometric transmission	0.87	
Reionisation transmission	0.90	
Neutralisation efficiency	0.50	
Accel. power supply efficiency	0.95	
Acceleration gross power		**37.55 MW**
RF generator power consumption		0.44 MW
Cooling system power		0.18 MW
Cryo Pump Power		3.42 MW
Total power consumption per injector		**41.59 MW**
Wall-plug efficiency	0.34	
VNS NBI gross power		124.76 MW

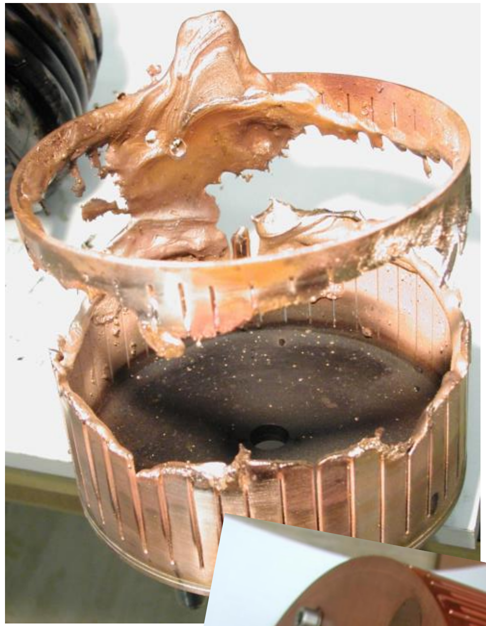
Option: Residual Ion Energy Recovery

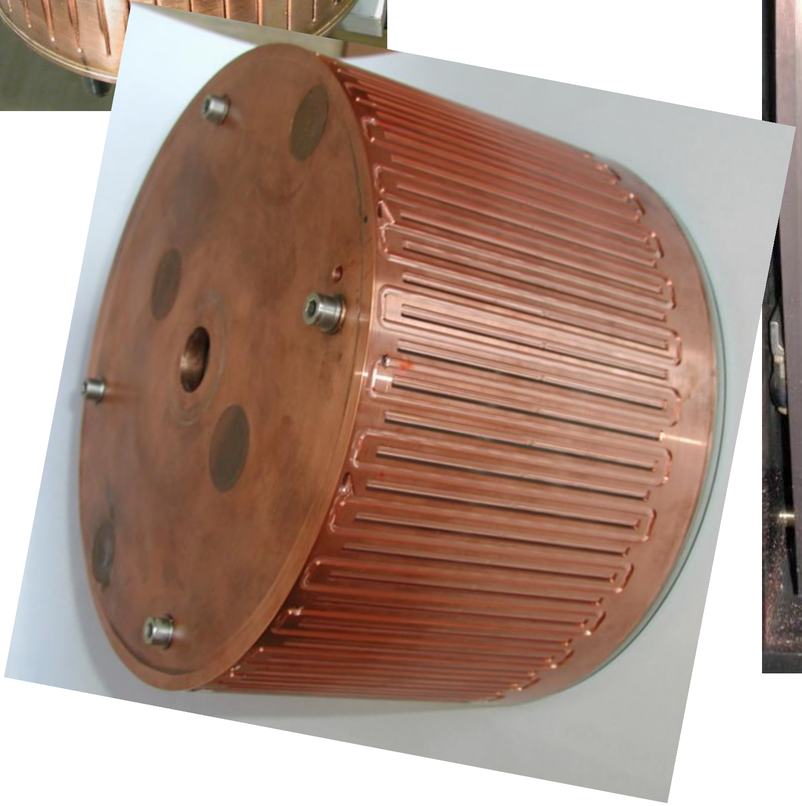
Reclaiming part of the kinetic power of the residual ions by electrostatic deceleration could improve the wall plug efficiency $\rightarrow$ to be studied in detail.

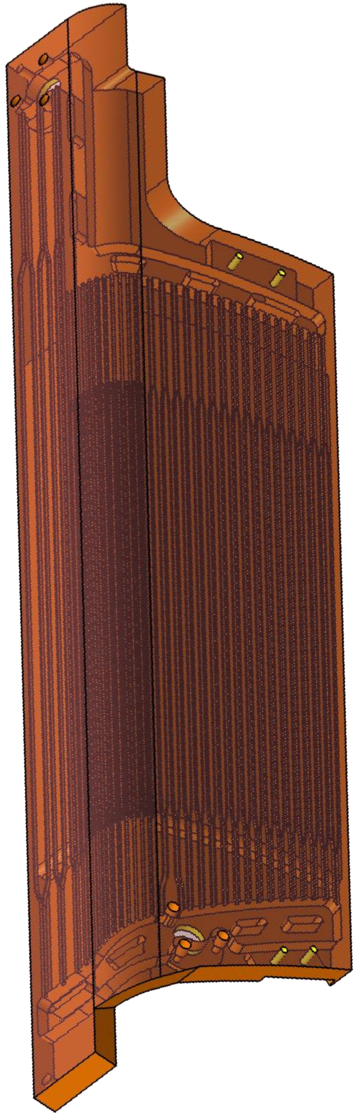
Active cooling

- Active cooling required for every component that sees beam or source plasma power.
- Solutions exist; have to be adapted.

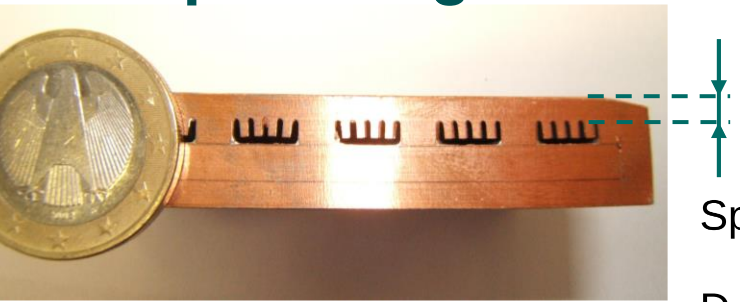








Sputtering



3 mm

Sputtering yield

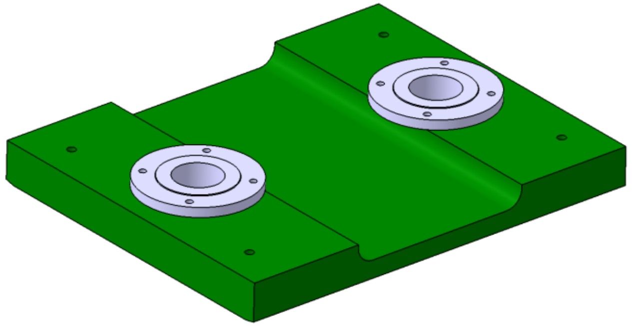
D → Cu: 6 × 10^{-3} ... 1 × 10^{-1}

D → W: 2 × 10^{-3} ... 2 × 10^{-2}

Time to erode 1 mm

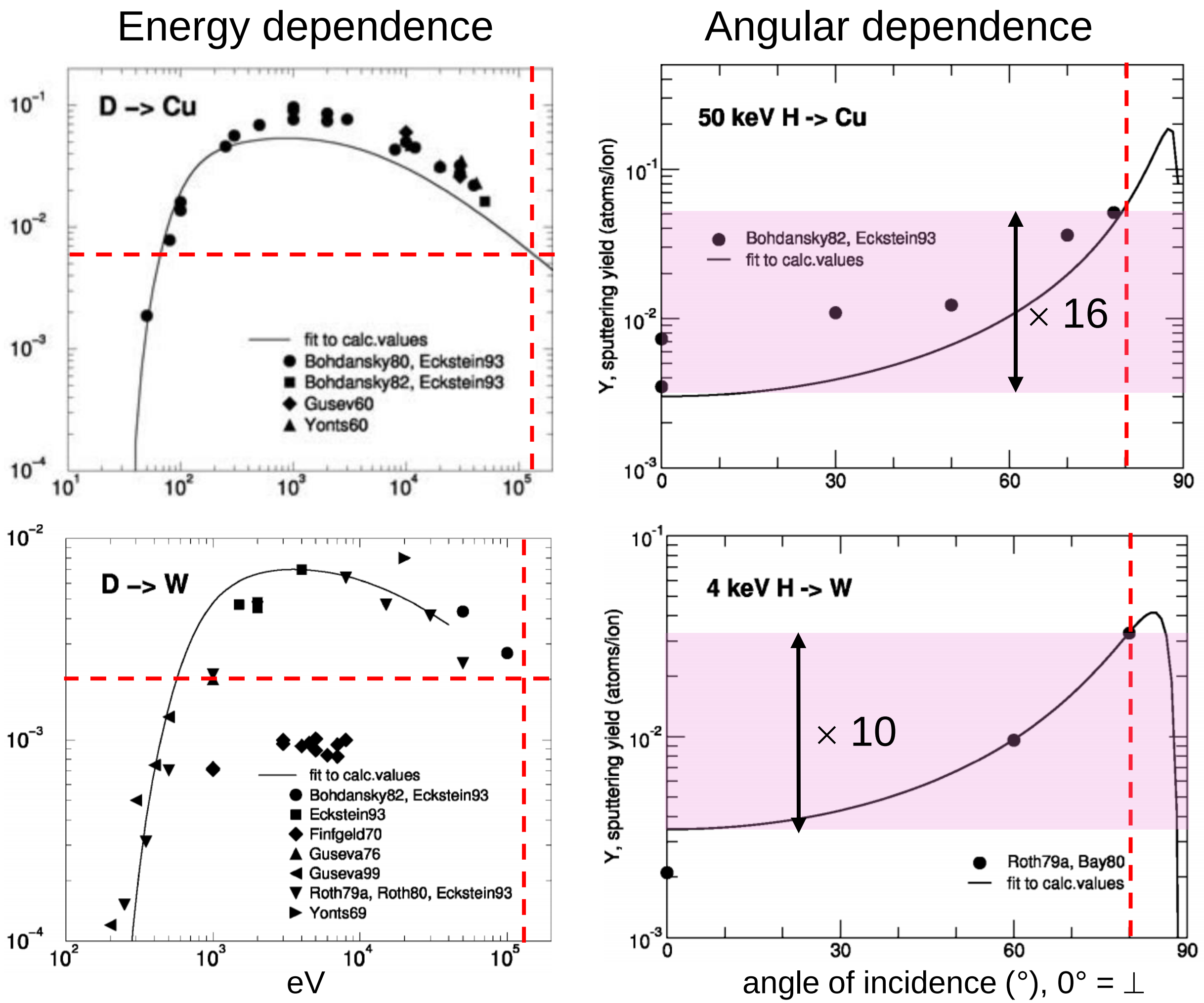
D → Cu: 6 ... 100 days

D → W: 25 ... 250 days



Different solution required

- Different target design, e.g. tungsten monoblocks.
- Lower peak heat fluxes through different deflection geometry.



W. Eckstein, “Sputtering Yields” in Behrisch & Eckstein, “Sputtering by particle bombardment”, Springer, 2007

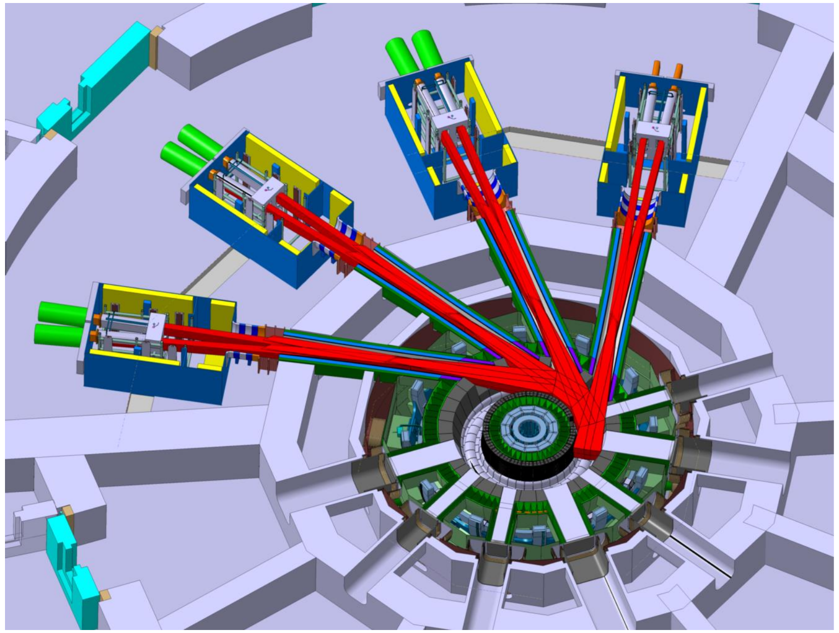
Remote maintenance and redundancy

Redundancy

- VNS can run with less NBI power at reduced plasma current and fusion power/neutron flux.

General remote maintenance philosophy

- In case of scheduled or non-scheduled maintenance of an NBI injector: replace entire injector with a spare to keep VNS downtime short.
- Injectors moved between NB cell and remotely located active maintenance facility (AMF) on a rail and turntable system.
- In AMF:
  - Only standardized tasks; replacement of entire components, not replacement/repair of individual parts.
  - HV conditioning in AMF; no calorimeter in injector.

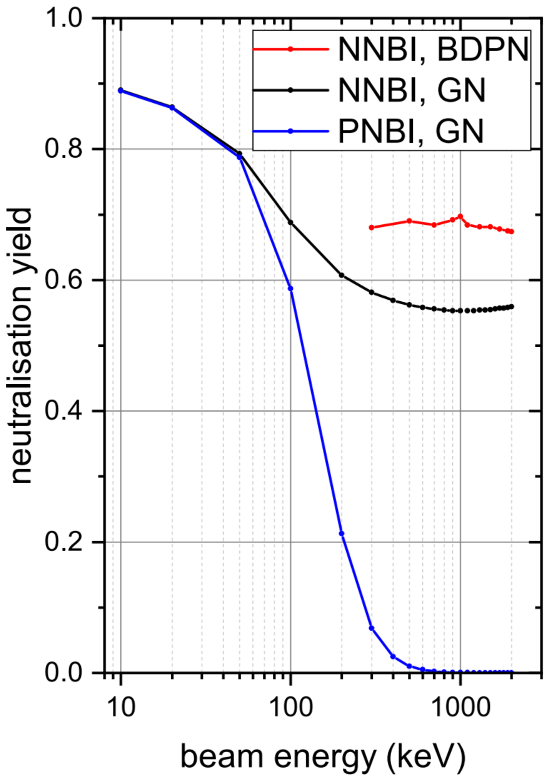


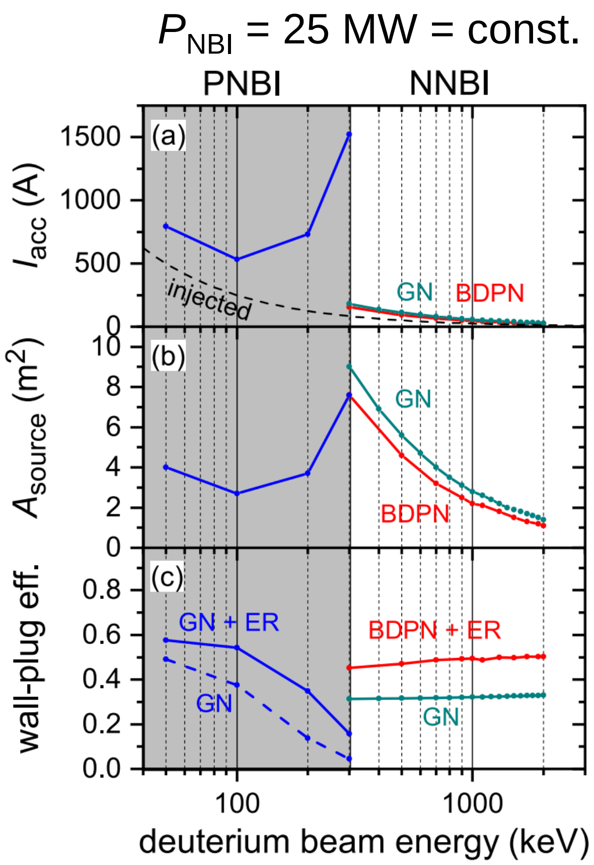
Conclusions

- Reliable operation of P-NBI systems with RF ion sources has been demonstrated over hundreds of thousands of cycles and > 1 month of cumulative operation.
- The main challenges are
  - Uninterrupted NBI despite need for cyclic regeneration of getter pumps.
  - Keeping reionization at an acceptable level.
  - Unprecedented operation times → Erosion of residual ion dump targets and other components.
  - Remote maintenance concept & concrete RM-compatible design.
- All required technical solutions for continuously operated P-NBI do in principle exist, but need to be tested over meaningful times. → Long-pulse test stand, prototype beamline
- Not addressed in this talk:
  - Effect of neutron irradiation on NBI components, e.g. permanent magnets, insulators ...
  - Efficiency improvement through energy recovery

Backup Slides

P-NBI vs. N-NBI





C. Hopf *et al.*, Nucl. Fusion **61** (2021) 106032

- P-NBI with RF sources uses neither filaments nor Cs and is practically maintenance-free and very reproducible.
- P-NBI extracts 10 times more current density than N-NBI.
- P-NBI is the only reasonable choice below 300 keV D because of size.

VNS tritium inventories

Tritium inventory in		D beams/ T plasma	T beams/ D plasma
Isotope Separation	g	386	222
Torus cryopumps	g	85	10
NBI cryopumps	g	19	179
Pellet injector	g	23	1
Sum outside T storage	**g**	**518**	**413**