Max-Planck-Institut für Plasmaphysik

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Neutral beam injection for fusion reactors: technological constraints versus functional requirements

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Motivation

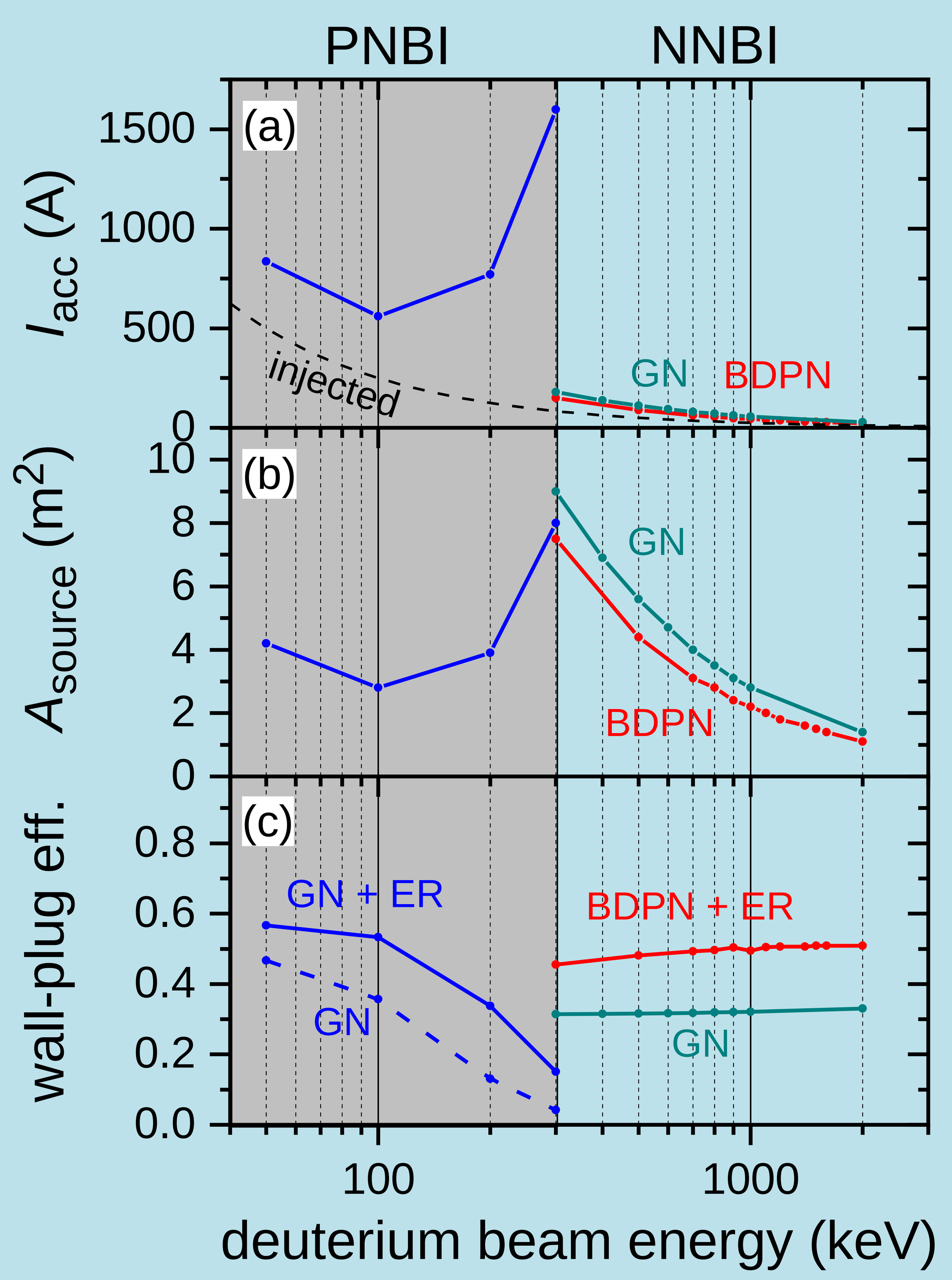
- Neutral Beam Injection (NBI) can serve various different functions on a fusion reactor: heating, current drive, inducing rotation, fuelling
- Different functions have different NBI requirements regarding
  - beam energy
  - beam power
  - energy efficiency (wall-plug efficiency)
- These parameters are correlated and determine injector size and complexity.

➢ **When foreseeing NBI in a reactor scenario, one has to check the feasibility and implications of the chosen NBI parameters for the NBI design.**

Conclusions

- **Energy efficient NBI requires advanced neutralisers and/or energy recovery**
  - ➢ **esp. required for NBCD in fully non-inductive scenarios**
- **Wall plug efficiency > 50 % could be possible with PNBI ≤ 100 keV and with NNBI**
- **Beam energies between 200 and 450 keV are rather unattractive for powerful NBI due to impractical source and hence injector size**
- **NBI to induce rotation is possible with PNBI, but very low beam energy combined with high power results in overly large injectors.**
- **Plasma ramp-up with technically simpler, positive-ion-based low-energy neutral beams < 200 keV is promising and should be investigated in detail**

Technological constraints



Dependence of key design figures on beam energy for a 25 MW beamline

PNBI: required extracted current increases above 100 keV due to decreasing neutralisation yield

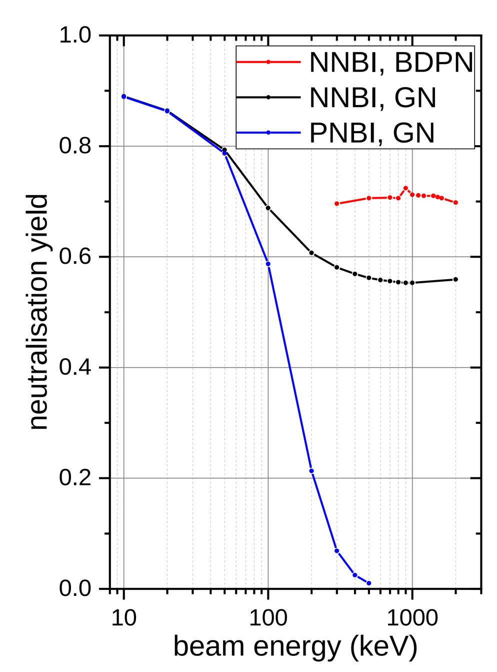
Both, PNBI and NNBI injectors become impractically large at energies 200–450 keV

Wall plug efficiency ≥ 50% possible with PNBI ≤ 100 keV with ER, and with NNBI using BDPN + ER

Two flavours of NBI

PNBI (positive ion based, e.g. on AUG, JET …)
- Positive ions extracted from an ion source.
- Neutralised in a gas neutraliser.
- Neutralisation yield decreases strongly with beam energy.
- Proven high reliability at nominal parameters

NNBI (negative ion based, e.g. on ITER, JT-60SA)
- Negative ions from ion sources with Cs evaporation
- Neutralisation yield ≥ 55 % in gas neutraliser
- 10 times lower current density than PNBI
- Temporally stable operation with low co-extracted electron current challenging due to Cs management



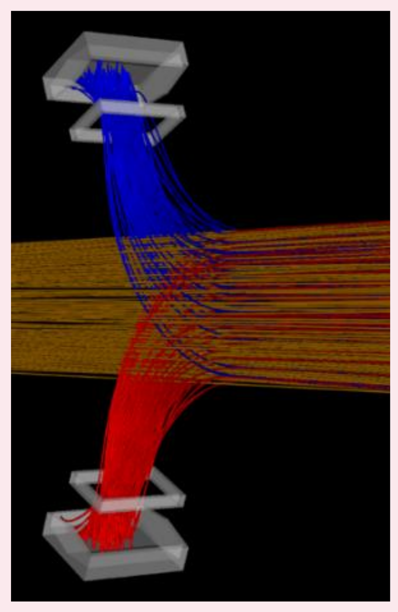
Ways to improve wall-plug efficiency*

*injected power/el. power to operate NBI

Status (ITER)
0.27 = 0.55 (neut. yield) × 0.50 (all other losses)
➢ Reduce residual ion losses

Photoneutralisation (photo-detachment of second electron)
- Highest possible neut. yield (theoretically 100%)
- Technologically not ready (lasers, cavities …)

Beam Driven Plasma Neutraliser (BDPN) [6]
- Beam ionises neutraliser gas (no added complexity)
- Stripping due to charged species enhances neutralisation
- Neutralisation yield > 70 % predicted



Particle tracking simulations in an energy recovery system: the negative (blue) and positive (red) residual ions are deflected out of the neutral beam (yellow) by a transverse magnetic field and collected on biased electrodes at 5 % of their initial kinetic energy.

Energy recovery (ER)
- Recover kinetic energy of residual ions by electrostatic deceleration to ~ 0.05 E_0

NBI for current drive in non-inductive tokamak and burn control

Typical requirements:
- Beam energy ≥ 1000 keV [1, 2]
- Power >≈ 50 MW [3] for burn control and 100–200 MW [1, 2] for NBCD
- Highest possible wall plug efficiency, esp. for CD as system is continuously operated

➔ **Needs NNBI**

➔ **Requires advance neutralizer (e.g. photoneutraliser or BDPN) and/or energy recovery**

NBI for toroidal rotation (improved confinement, QH mode)

Typical requirements:
- Beam energy 35–100 keV [2, 4]
- Power 10–75 MW [2, 4]
- High wall plug efficiency, as system is continuously operated

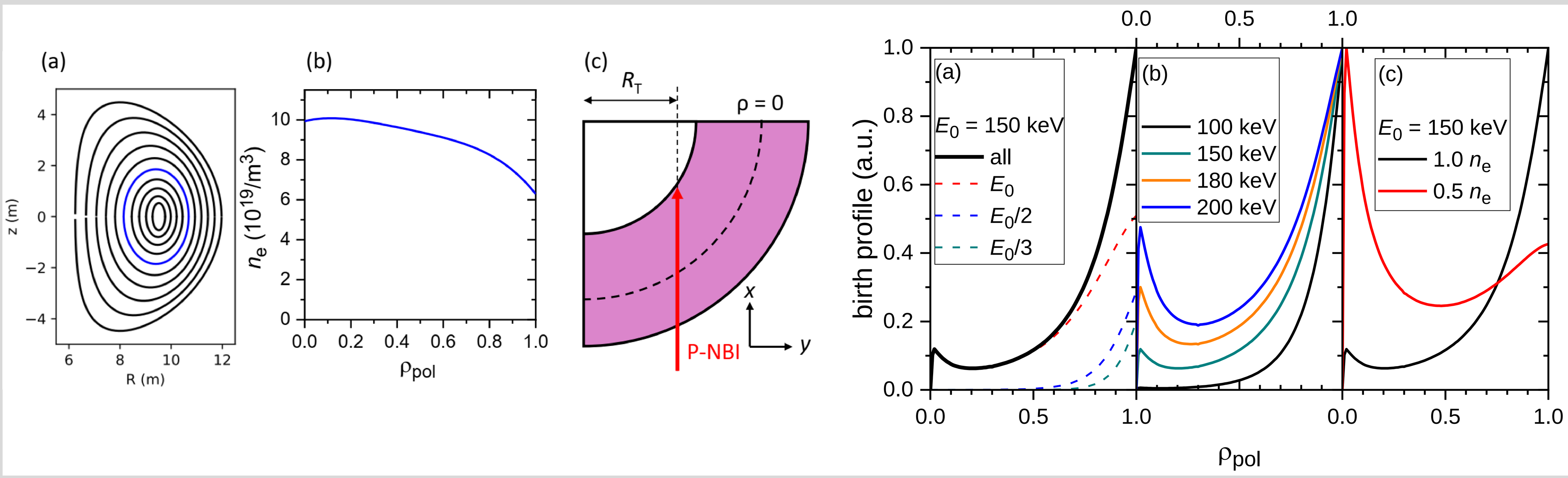
➔ **Generally possible with PNBI (using energy recovery)**

➔ **Combination of very low beam energy and high power (e.g. 35 keV/75 MW) results in very large system(s)**

NBI for plasma ramp-up

Motivation
- The EU DEMO baseline assumes ECRH as the only heating system, but it is not clear whether ECRH alone can heat the ions sufficiently for ramp-up.
- If NBI is needed only for ramp-up, an NNBI system is disproportionately complex.

➢ **Question: Can a much simpler PNBI be used for this function?**



Parameters
- Equilibrium and density extracted from Ref. [5] ((a) and (b))
- Injection geometry: R_T = 4 m in midplane, spread from z = – 0.3 to 0.3 m (c)
- Beam composition: E0 : ½E0 : ⅓E0 = 0.7 : 0.2 : 0.1

➢ **Ramp-up with low energy beams < 200 keV should be investigated in detail**

Birth profiles (NBI-born ions per unit volume)

(a) Profiles of the three energy components and total profile for 150 keV

(a+b) Profiles are peaked at the edge, but

(b) **For 150 keV and above central deposition is not zero.**

(c) At reduced density (scaled by 0.5 to simulate heating early in ramp-up) the 150 keV profile peaks centrally

[1] G. Giruzzi et al., Nucl. Fusion 55 (2015) 073002
[2] P. Vincenzi et al., Fus. Eng. Des. 163 (2021) 112119
[3] R. Wenninger et al., Nucl. Fusion 57 (2017) 016011
[4] X. Jian, Nucl. Fusion 57 (2017) 046012
[5] P. Vincenzi, submitted to Plasma Phys. Control. Fusion (2021)
[6] E. Surrey and A. Holmes, AIP Conf. Proc. 1515 (2013) 532

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