RF driven NBI sources towards ITER NBI

Stepwise development process defined by F4E

Neutral beam heating for ITER
- 33 MW power, two injectors.
- 1 MeV, 40 A Deuteron. 
  $\Rightarrow$ 285 A/m² extracted current density.
- Electron-ion ratio $s_1$ to protect the extraction system.
- Pulse length: 400 s, $Q=5$ baseline scenario.
- 3600 s, $Q=10$ advanced scenario.

IPP test facilities
- Early operational & physics experience supporting NBTF, ITER NBI and towards DEMO.

Operation of RF driven ion sources for NBI
- RF power up to 100 kW per cylindrical RF driver (volume: a few Iteras).
- Plasma cooled down ($T_e=10$ eV $\rightarrow$ 1 eV) by horizontal magnetic filter field.
- Gradients in electrostatic potential.
- Positive plasma grid bias potential for reducing co-extracted electrons.
- Grounded bias plate around PG for increasing non-biased surface.
- Production of $H$ at caesiated low-work-function surface of plasma grid.

Operation in deuterium

RF power variation for short pulses in deuterium and hydrogen:

Best deuteron pulse with ITER-relevant length (>400 s) done at ELISE till now:

Achievable performance in deuterium is limited by:
- Higher co-extracted electron current compared to hydrogen $\Rightarrow$ static effect.
- Co-extracted electrons can show a strong vertical asymmetry $\Rightarrow$ static effect.
- Temporal instability of co-extracted electrons and their symmetry $\Rightarrow$ dynamic effect.

ELISE focuses on development of advanced operational scenarios for long pulses in deuterium.

Reducing the co-extracted electrons

Modified magnetic field strength and topology:
- Typically in deuterium a stronger magnetic filter is used ($\pm4.6$ mT vs. $\pm2.8$ mT).
- Adding external permanent magnets enabled 3600 s pulses at ELISE at all.

Increased Cs evaporation:
- Possible to a certain extent only $\Rightarrow$ increased risk of HV breakdowns.

Symmetrizing the co-extracted electrons

Knobs close to the plasma grid:
1. Electrostatic potential
   - Successful test of internal potential rods.
   - Best solution: rods electrically connected to plasma grid, i.e. increasing biased surface.
   - Co-extracted electrons stabilized and symmetrized, also during long pulses.
2. Magnetic field
   - Apply potential to bias plate.
   - Reduction of extracted negative ions and electrons.
   - Makes possible a strong reduction of filter field strength.

Stabilizing the co-extracted electrons

Approach 1. “Cs overconditioning”
- Increase strongly caesium amount available for re-distribution during long pulses.
- $H_2$ enabled reproducible 1000 s pulses with 90 % of the ITER target for $\langle j_e \rangle$.
- Not a solution for $D_2$ due to increasing risk for HV breakdowns.

Approach 2. caesium evaporation directly onto the PG
- Initial tests conducted at BATMAN Upgrade of an “cesium shower”.
- Directed caesium evaporation works and suppresses the co-extracted $e^-$.
- Several technical details to be dealt with before application at ELISE.

Upgrade to CW operation

CW extraction is the ITER scenario and investigations at the test facilities are mandatory.

Conclusions

- Performance of ITER relevant long pulses in $D_2$ limited by static and dynamic effects regarding the vertical asymmetry and the amount of co-extracted electrons.
- Symmetrizing the electrons is important for operational safety of ITER NBI system.
- BATMAN Upgrade and ELISE give valuable insight.

Long deuteron pulses are still a challenge.
- Measures for the static and dynamic behavior of the co-extracted $e^-$ are mandatory.