Photo-neutralization-based NBI systems for Nuclear Fusion Power Plants

Donatella Fiorucci[1], Alessandro Fassina [1]

[1] ENEA, National Agency for New Technologies, Energy and Sustainable Economic Development, Frascati Research Center, Via Enrico Fermi 45, 00044 Frascati – Rome, Italy

e-mail (speaker): donatella.fiorucci@enea.it

A key factor in realizing the first nuclear fusion power plant is the efficiency of the methods used to heat the plasma to the required temperature (~10^8 K). This is achieved through three primary techniques: the ohmic heating, along with two auxiliary methods—radiofrequency heating (RF) and neutral beam injection (NBI)—which become necessary once the plasma temperature exceeds the operational limit of ohmic heating (~ 10^7 K).
Ohmic heating works by driving an electric current through the plasma, generating heat because of the plasma electrical resistance, which decreases as the temperature increases. Radiofrequency heating utilizes electromagnetic waves tuned to specific frequencies to energize plasma particles, either through ion cyclotron resonance for ions or electron cyclotron resonance for electrons. Neutral beam injection involves accelerating ions to high velocities, neutralizing them, and injecting the resulting fast-moving neutral atoms into the plasma, where they transfer their energy through collisions.

Together, these methods enable plasma to reach the extreme conditions necessary to achieve and sustain fusion reactions. However, Electron Cyclotron Resonance Heating (ECRH) and Ion Cyclotron Resonance Heating (ICRH) systems face limitations related to their energy coupling with the plasma and the thermalization process between electrons and ions. Moreover, these systems must be placed close to the plasma, which requires advanced engineering solutions to mitigate excessive thermal loads.

In contrast, Neutral Beam Injection (NBI) offers significant advantages by allowing placement far from the plasma, reducing direct thermal stress on equipment, while still providing efficient plasma heating. This makes NBI a strong candidate to become the primary auxiliary heating system in future nuclear fusion power plants. However, current NBI systems exhibit limited performance, largely due to the low efficiency of ion neutralization method (i.e. gas neutralizers) [1], [2]. To address this limitation, photon-neutralization techniques have been proposed [2]-[4], offering the potential to attain complete neutralization.

The main challenge with photon neutralization lies in the low cross-section of the process, requiring extremely high optical power to achieve a significant neutralization rate. As a result, several techniques are being explored to generate optical power in the megawatt range while maintaining high wall-plug efficiency (exceeding 60%) of the overall NBI system [5]-[7].

This work presents an analysis of the proposed photon-neutralization techniques for application in the future NBI system of the first nuclear fusion reactor. Preliminary studies and experiments confirm the feasibility of photo-neutralization-based NBI systems. The next step is to secure efforts in R&D activities aimed at identifying the optimal photo-neutralization configuration and developing a full-scale prototype.

References

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