The status of negative ions R&D for Fusion Applications

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In several research fields, ranging from neutron generation to synchrotron accelerators, sources of negative ions are used to obtain powerful beams with high brightness. In future nuclear fusion devices, neutral beam injection (NBI) systems are expected to play a key role in plasma heating, current drive, energy gain and configuration control. In particular at the dedicated Test Facility under advanced realization in Padova (Italy) the design and realization of the prototype injector of the ITER NBI is carried out as the outcome of an international R&D programme devoted to this project.

In this contribution an overview of the main issues on negative ion physics for fusion applications and the present status of the related R&D carried out at the Test Facility are presented. The most outstanding open issues are reviewed focusing on experiments and simulations aimed to improve the understanding of the physics of negative ion beams, including generation, extraction, acceleration and neutralization. All these processes involve atomic and molecular phenomena as well as a complex dynamics of molecules, negative and positive ions and electrons which is described for each process as listedin the following

The generation of negative ions is discussed by illustrating the main production mechanisms and the beneficial effects of caesium addition. For this purpose the results of recent studies based on rigorous ab-initio Molecular Dynamics are presented which allow a quantitative understanding of the processes by which Cs atoms are deposited and adsorbed on the surfaces of high performance metals highlighting the implication for optimal Cs management.

The extraction of negative ions is discussed focusing on the effect of the magnetic field in filtering the most energetic electrons and therefore increasing the amount of negative ions in the extraction region.

The acceleration is discussed focusing on the phenomena of space charge compensation of the accelerated beam taking into account the gas distribution and interaction of beam particles with secondary particles as well as the production of secondary and back-streaming particles. It is found that both space charge and beam optics are strongly influenced by the presence of background gas the flow of which has been simulated in molecular regime taking into account the full three-dimensional geometries of the multi-aperture extractor and accelerator electrodes. In particular it has been found that the effect on the negative ion beam optics is the accumulation of heavy positive ions in the potential well of the beam, until they overcompensates the negative charge, resulting in a focusing of the beam as it crosses the drift region as shown in fig.1.

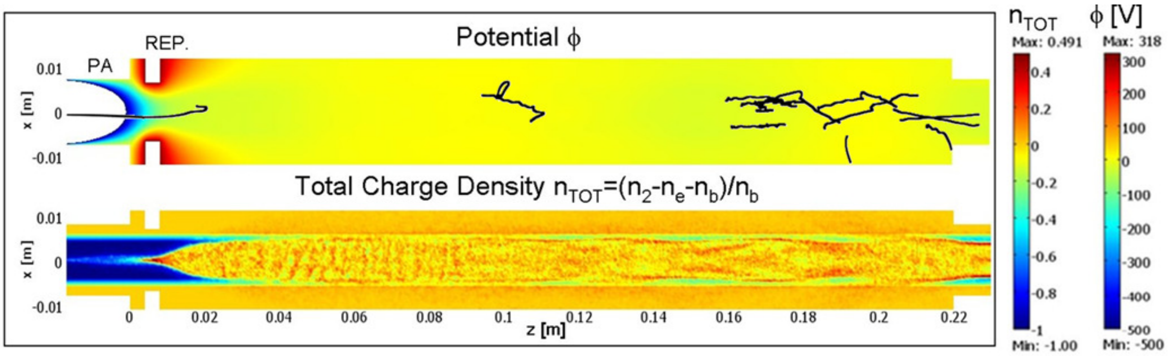

Figure1. Stationary state of the space charge compensation of a negative hydrogen beam: total density and potential maps are shown: n_2, n_e and n_b are the density of the H_2^+, the electrons and the beam respectively. Some examples of ion trajectories are reported in black.

Finally an overview of the ITER NBI design focusing on the optimization of physical requirements and technological constraints is presented. Given the complexity of the processes involved and the unprecedented parameters required by the ITER NBI system (40 A current and 1 MV acceleration for 1 hour) , the design of the new generation of neutral beam injectors has been developed using an integrated approach which allows all the relevant physics and engineering aspects to be taken into account simultaneously. For this purpose and in order to increase the reliability of the NBI design, the latest advances in physics understanding and in modelling have been extensively benchmarked to experimental results in existing fusion facilities and applied to the design of the high power beams for ITER, where the physical requirements have to meet the engineering constraints and additional issues regarding the obtainment of a high degree of uniformity, in terms of particle density and beam divergence, over the cross-section of large-area beams. Two-dimensional and three-dimensional numerical codes have been developed, tested , benchmarked and applied. An example of the trajectories of the negative ions and of the other particles involved is shown in fig. 2 for the ITER NBI accelerator.

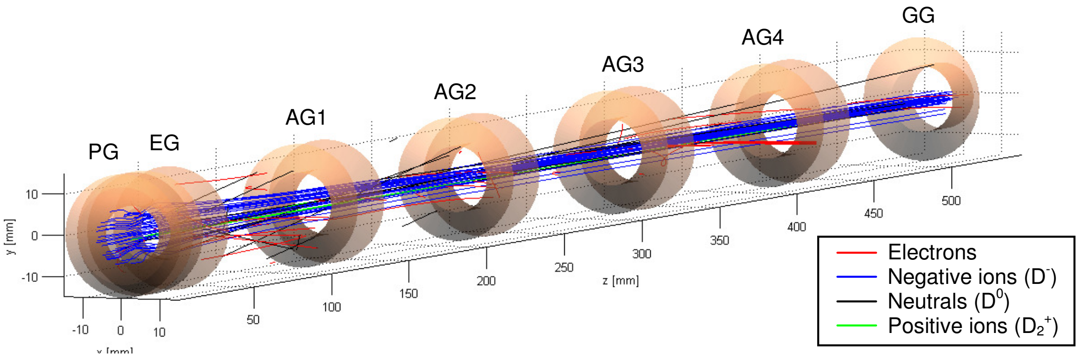

Fig. 2 – Numerical simulation of the trajectories of negative ion beam and of secondary particles generated by stripping and surface reactions.

As a result of this approach, new design solutions have been identified and introduced in the accelerator design and their application discussed taking into account different operating scenarios.