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Direct generation of NBI plasmas in TJ-II with lithium-coated walls

In contrast to the fully inductive scheme used in tokamaks, plasma start-0up in stellarators is commonly achieved by launching electron cyclotron resonant (ECR) or ion cyclotron wave (ICW), thus creating a target plasma for high-density plasmas heated by neutral beam injection (NBI). In large devices, however, direct start-up by unaided injection of the heating beams has been proven to be feasible, as reported in the Large Helical Device (LHD) and, only for well-conditioned walls, in Wendelstein 7-AS (W7-AS) [1, 2]. Microwave-assisted start-up, at 2.45 GHz, was also recently reported in Heliotron-J [3], and ICW heating was successfully applied in CHS [4]. In TJ-II, ECR injection at 53.2 GHz at the second harmonic is routinely used to produce target plasmas for NBI coupling. The effect of initial neutral pressure on the resulting delay of the gas breakdown with respect to the nominal time of ECR injection was addressed in a previous paper [5], with typical values of 2–10 ms. A kinetic model, including atomic and molecular processes for the injected H_2, was successfully applied to the results. Furthermore, the effect of wave polarization on plasma start-up was also addressed [6].

The TJ-II stellarator has been operating at CIEMAT (Madrid) since 1997, and different heating schemes and wall condition scenarios have been applied for the generation of hot plasmas [7]. Since 2007, a new kind of first wall coating, produced by boron deposition followed by lithiation, has been applied. This wall conditioning technique was a key to achieving full-power NBI plasmas under good density control conditions, not possible with boron coatings alone [8], as well as transition to H mode confinement. Since 2012, a liquid lithium limiter (LLL) based on the Capillary Porous System (CPS) design replaced one of the former carbon limiters, and very recently the second C limiter has been replaced by another LLL. Two NBI systems (E_b = 35 kV), delivering up to 600 kW each, are coupled to the machine in opposite directions to compensate for induced currents in the plasma. In the present experiments only one of the NBI sources was used (co-direction). Due to the close coupling to the vacuum vessel, neutral gas from the neutralization box leaks into the plasma as the NBI is launched. In addition, the interaction of the beam with the wall opposite to it releases extra gas, depending on beam power and wall conditions.

The magnetic configuration of TJ-II plasmas involves four main magnetic field components, two of them (CC and HX) produced by the central coil system [9]. For the magnetic configuration used here, with B_T = 0.95 T at the magnetic axis, the steady-state values of the CC and HX currents are10 kA and 4.8 kA, respectively. These currents are produced in a 250 ms ramp-up time. The associated toroidal electric fields induced are 2.8 and 1 V/turn, respectively, corresponding to a total induced toroidal field of 0.35 V/m, at the lower limit of those used for ohmic break-down in tokamaks [10]. However, nested magnetic surfaces are produced in TJ-II at times well before (~200 ms) the plateau is reached.

Three gases were tried for the formation of the target plasma: H_2, He, and Ar. They were puffed during the ramp-up phase, at different delays with respect to the NBI

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time, yielding typical pressures at the vacuum chamber of ~ 10^{-5}–10^{-4} mbar. NBI power scans were also tried, from 400 to 600 kW. Several H_α monitors, with submillisecond time resolution and located at different toroidal positions, were used to characterize the delay in start-up, together with the other plasma diagnostics routinely used in TJ-II operation.

First attempts to directly generate NBI plasmas were made with an unconditioned first wall. Strong production of hard X rays was seen, especially when gas was injected some hundred milliseconds before the plateau phase at 1000 ms. Although chord-integrated electron densities on the order of 10^{12}–10^{13} cm^{-3} were recorded by the interferometer, no sustained plasma heating by NBI alone was found. Figure 1 shows one of these cases. The results were the same when H_2 was replaced by He as the pre-filling gas. Under these wall conditions, it was found that any extra gas injected during the early phase of plasma breakdown led to the production of strong high-energy X-ray (HXR) emission without any improvement in the coupling of the NBI energy to the target plasma. Thus, direct NBI was used alone as both particle and energy source. A sweep in NBI injection times during the ramp-up phase of the CC and HX coil currents was performed, spanning the last 200 ms of the current ramp-up. The results indicated optimized conditions (low HXR generation, short delay time to plasma breakdown) for NBI launch times between 960 and 980 ms.

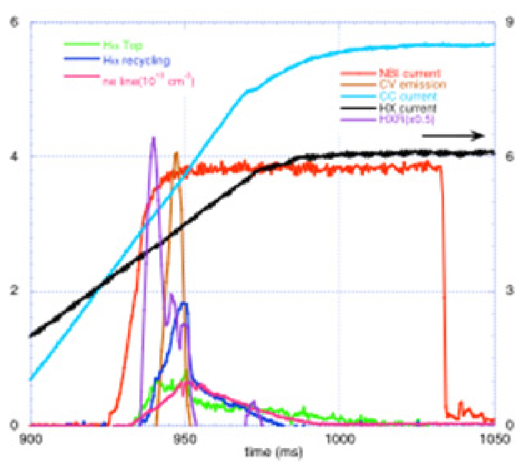

Fig. 1. Start-up with unconditioned walls.

This situation changed dramatically after full conditioning of the TJ-II walls by boronization followed by lithiation. Base pressures in the range of 1–2 × 10^{-7} mbar were readily achieved after the conditioning, mostly due to the gettering of residual water and oxygen by the deposited films. Figure 2 shows one example of plasma start-up by NBI with well-conditioned walls. The delay between the onset of the H_α signal located on top of the NBI-wall interaction area (beam dump) and the rise of the electron density is negligible. Also, typical traces indicative of hot plasma production were seen at times ~20 ms after the NBI time. Central electron temperatures T_e ~ 320 eV at chord densities of n_e ~ 4 × 10^{13} cm^{-3} are routinely obtained for NBI nominal powers of P_{NBI} ~ 550 kW. Thomson scattering profiles of the NBI-generated plasmas are basically identical to those obtained earlier in target plasmas with ECR heating (ECRH).

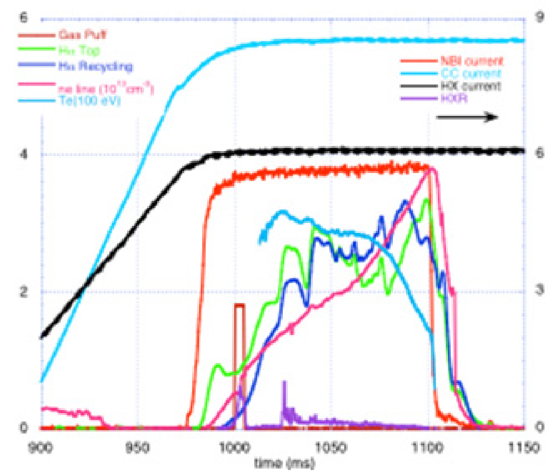

Fig. 2. Start-up with fully conditioned walls.

To date, this new scheme for plasma start-up has allowed for 2-beam NBI operation at total nominal injected powers up to 800 kW, chord-integrated densities up to 8 × 10^{13} cm^{-3}, and diamagnetic energy contents up to 4.5 kJ. Scans in B_T have led to successful plasma production up to B_T < 0.6 T, thus opening the possibility of physics studies under conditions free from the ECRH resonant field constraint. Finally, the toroidal electric field when the NBI gas is actually injected (onset of H_α, top signal in Fig. 2) is at least a factor of 5 lower than that produced earlier in the ramp-up phase. Very recently, the use of the ohmic heating circuit for inducing toroidal electric fields of magnitude comparable to those actually required (less than 10^{-1} V/m) has proven successful for plasma breakdown at times within the nominal plateau time (t >1000 ms), possibly helped by the remaining hot electrons accelerated during the last stages of the current ramp-up.

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