

Low loop voltage start-up of the TEXTOR-94 discharge with ICRF and/or NBI assistance

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Low loop voltage start-up of the plasma current is desirable in tokamaks like TEXTOR-94 to avoid high voltage and fast transient forces induced in the OH coil system. For superconducting reactor-scale devices, the initial loop voltage will necessarily be limited (e.g. $\approx 0.3\text{V/m}$ in ITER). Except maybe if the initial magnetic configuration is highly optimized (stray field compensation, minimum-B formation), start-up assistance will be mandatory, and in any case will make the start-up phase more robust and reliable. Waves in the ion-cyclotron range of frequencies (ICRF) have been recently successfully used for this purpose in TEXTOR-94. [1,2]

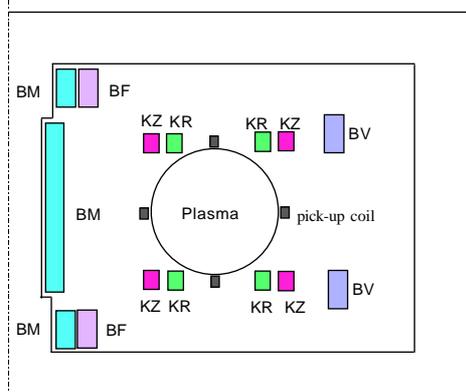


Fig.1 Poloidal field coil system in TEXTOR

TEXTOR-94 is a medium size ($R_0=1.75$ m, $a=0.46$ m) circular cross-section tokamak. The vacuum vessel is a continuous resistive shell, with a total toroidal resistance of 1.55 m Ω . The OH system, shown in Fig.1, comprises an iron core and consists of magnetizing (BM) and outer poloidal coils. The BV coils are used for equilibrium control whereas the KZ and KR coils allow fast position control. The BF system controls the plasma shape and is suited for stray field compensation during start-up. In order to maximize the pulse length, the flux swing of TEXTOR-94 was increased, leading to operation with saturated iron core. This gives rise to stray fields in the plasma volume, which have to be properly compensated for successful low-voltage start-up.

Required values of the current in the BF coils were calculated for different values of the magnetizing current (BM) by a 3-D code and confirmed by electron beam measurements at the center of the plasma volume. During the start-up phase, the voltage is produced by ramping down the BM current. This leads to a drastic variation in stray field, which has to be compensated to allow successful start-up. The compensation is performed by the fast KZ system controlled by signals from vertical field pick-up coils located around the plasma volume.

However, even for the best possible compensation, a higher voltage is required for start-up as compared to the non-saturated iron core operation. For normal start-up, the required high voltage is produced by switching a resistor into the magnetizing circuit. This

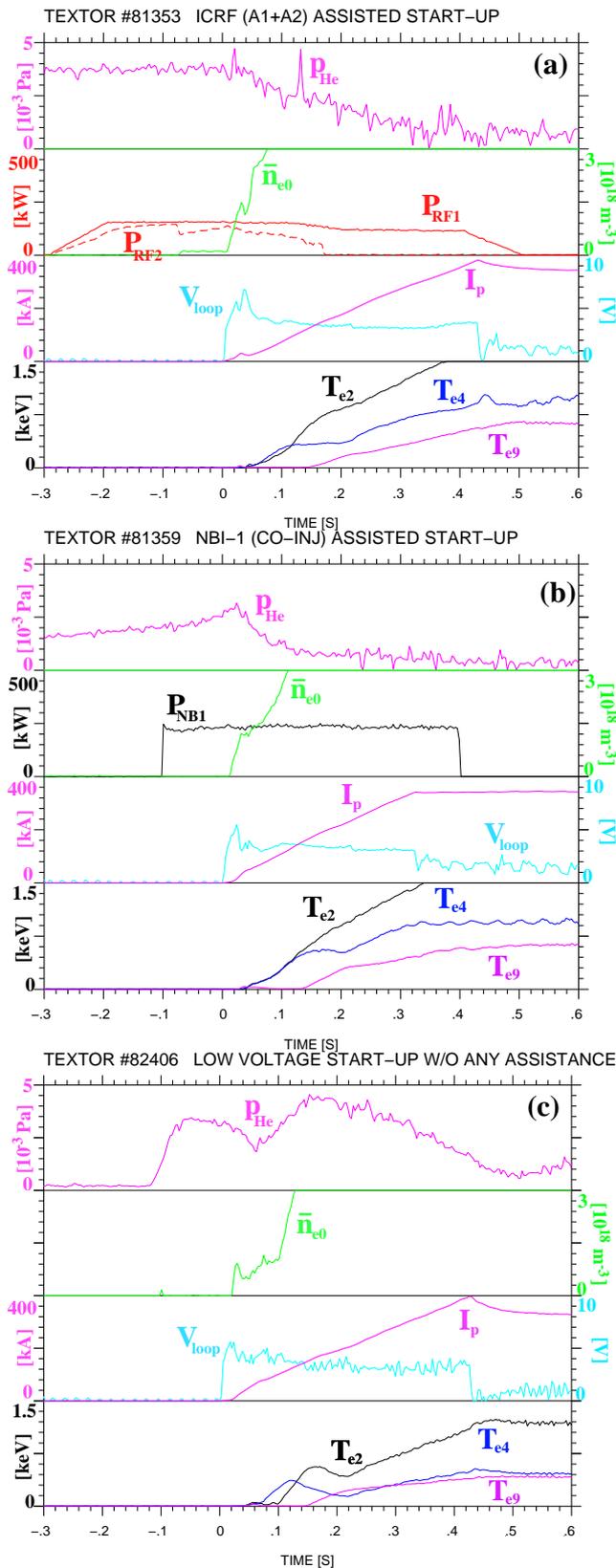


Fig.2. Three shots with low loop voltage start-up (a) with ICRF-assistance, (b) with NBI-co assistance and (c) without assistance. T_{e2} , T_{e4} , T_{e9} is resp. T_e (ECE) at $R=1.75, 1.56, 2.08$ m; $p_{He}+p_D \approx 3.5 \times 10^{-3}$ Pa for all shots.

operation is sensitive to faults and causes mechanical stresses to the machine. The idea is to avoid this high voltage phase by using for start-up assistance at lower voltages the auxiliary heating systems available in TEXTOR-94, namely ICRF or NBI.

Successful low voltage start-up with ICRF pre-ionization and ramp-up assistance has been reported earlier [2,3]. Fig.2(a) shows a recent shot at low loop voltage with RF-assistance. Note the plasma formation ($\bar{n}_{e0} > 10^{17} \text{ m}^{-3}$) due to RF at $t < 0$. Experimental results indicate that after careful compensation, stray fields ($|B_{\perp}| \leq 5$ G) are no longer the bottleneck. Rather we suspect that the difficulty in achieving reliability is the sensitivity of the start-up to machine conditions (in particular wall) and impurity content. On shot days where the machine conditions were rather poor (following leaks or due to spurious impurity injection,...), start-up was very difficult to achieve, while a careful and lengthy conditioning of both machine and antenna allowed again successful RF-start-up, with a central inductive electric field $E(0) \approx 0.32$ V/m. The accessible helium prefill pressure range was investigated. Successful ICRF-assisted start-up was achieved in the range $(1 - 4) \times 10^{-3}$ Pa.

In order to increase the robustness of the low voltage start-up, neutral beam only (NBI-Co: D, co-injection) and combined RF-NBI target plasma production have also been attempted. For the first time NBI-assisted low voltage plasma current initiation was successfully achieved in TEXTOR-94 (with $E(0) \approx 0.34$ V/m). Beam start-up operates reliably at $P_{NBI} = 200$ kW. We choose to run the beam at low energy (25kV) but at full beam width, to increase the number of fast particles and have a larger beam volume for the same power. Such an NBI-assisted discharge is shown in Fig.2(b). No plasma seems to be created by the beam alone ($t < 0$), or at least the density is so low that it cannot be detected by the interferometer ($\bar{n}_{e0} < 210^{16} \text{ m}^{-3}$). The plasma is created from the moment V_{loop} is

applied and the beam helps the ionization and the current ramping, possibly also contributing some non-inductive part to the total plasma current I_p . At this low beam power, the shine-through is not a problem. It is about 40% without plasma and drops to 20% with plasma. With the beam duct open, there is a continuous flow of D_2 such that, even without He prefill, the initial pressure is 2.3×10^{-3} Pa. NBI start-up operates reliably in these conditions, as well as at higher pressure $< 6.8 \times 10^{-3}$ Pa. Start-up at the latter value of the pressure did not succeed.

In principle, combined ICRF + NBI pre-ionization was expected to be even more

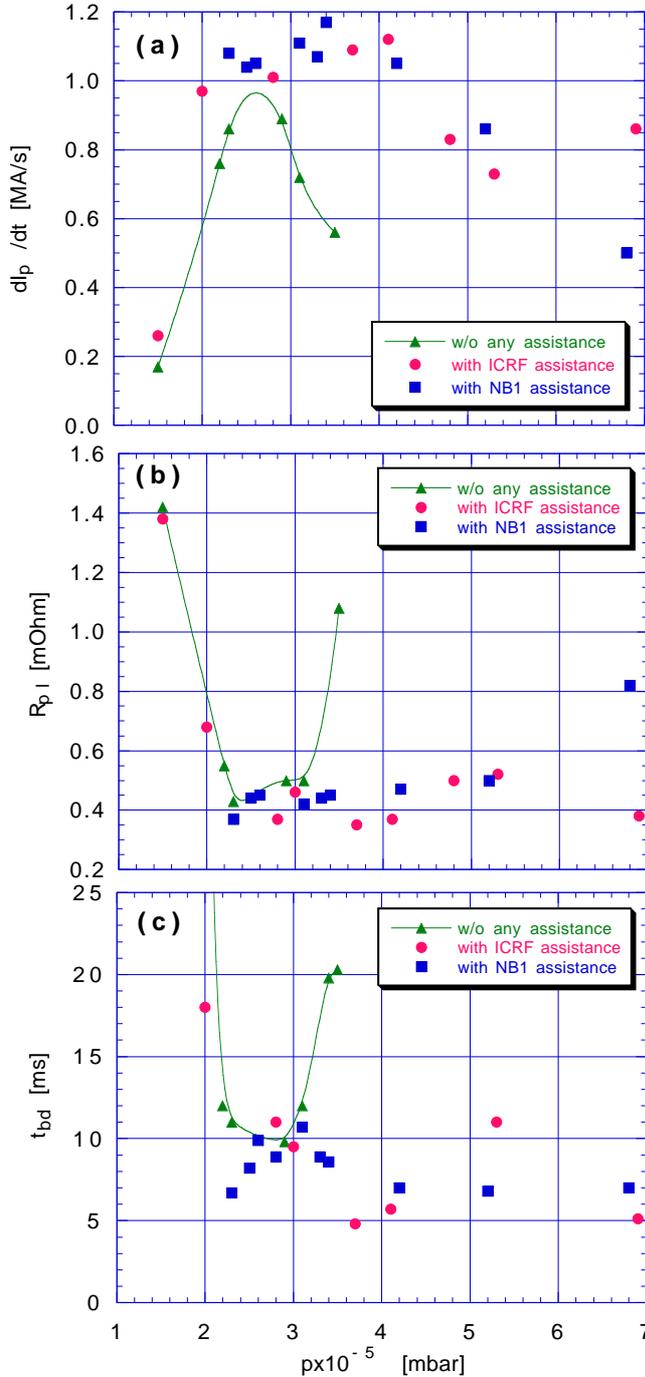


Fig.3. (a) Current ramp, (b) Resistance of the plasma column, and (c) Plasma current initiation delay, versus pressure. The quantities (a) and (b) are averaged over a 3 ms interval around $t=20$ ms.

robust and efficient than either of them separately. However, two attempts to use combined RF and beam were unsuccessful. Although the target plasma produced at $t < 0$ was possibly even denser than with RF alone, the plasma current did not start. This may be due to the fact that this plasma was produced much earlier than $t=0$ and moved to the inboard side of the machine before the onset of the loop voltage.

At the end of each of the RF start-up campaigns, at least one shot was devoted to trying low voltage start-up without assistance ($E(0) \approx 0.45$ V/m). Until recently, this was always unsuccessful, leading to the provisional conclusion that start-up assistance was necessary, although start-up was achieved without assistance in DIII-D at even lower $E(0) \approx 0.25$ V/m [4]. In the last campaign, in a shot with NBI-assistance, the beam came too late ($t=0.018$ s). Nevertheless, the current started normally, demonstrating that low voltage start-up without assistance was indeed possible. Unassisted start-up was then further attempted and successfully achieved as shown in Fig.2(c).

The performances of low voltage start-up without assistance or with ICRF or NBI-co are compared in Fig.3. The quantities shown relate to the early stage of the current ramp. Generally speaking, the pressure range for successful current initiation is significantly broader with assistance than without, especially at higher pressure. The current ramp rate is larger with assistance and the plasma column electrical resistance is smaller. Points with a resistance larger than 1 m Ω correspond to cases where start-up failed and the resistance is essentially that of the resistive shell. From the point of view of current ramp rate and plasma resistance,

ICRF and NBI assistance have similar performance. On Fig.2, one can observe, in cases (b) and (c) that current ramping is delayed by 10-15 ms with respect to the application of V_{loop} (at $t=0$). On the contrary, in case (a) current ramping starts immediately. Figure 3(c) compares these time delays for the different scenarios versus pressure. Although the statistics is rather scarce, the trend seems to be that current initiation is somewhat prompter with assistance, while, given the scatter of the data, NBI and RF perform similarly. Concerning the place where the plasma forms, it is well known that with OH alone, the plasma tends to start at HFS where the electric field is largest. This is also observed in TEXTOR-94 with low loop voltage while NBI-assistance and even more RF-assistance tend to initiate the current near the center of the vacuum vessel.

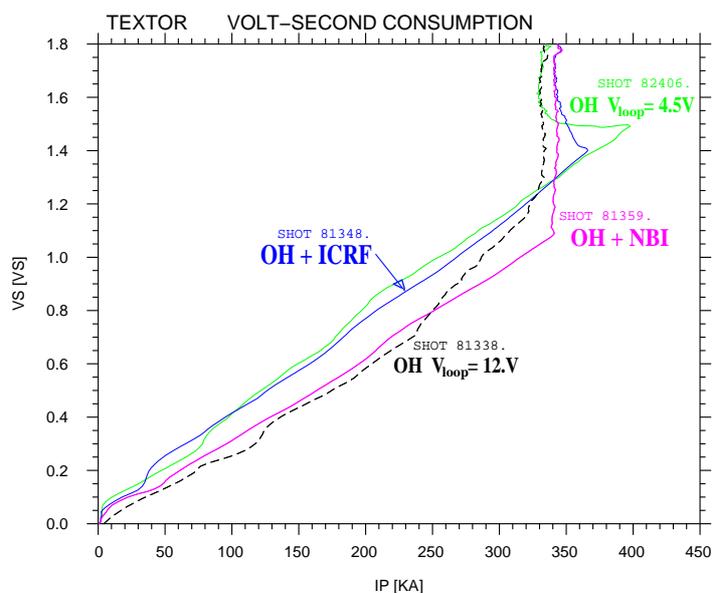


Fig.4. Volt-second consumption versus plasma current for different types of start-up scenarios. For ICRF and NBI assistance the auxiliary power is 200kW (from source). The case with 12V loop voltage is the normal start-up of TEXTOR-94.

The impact of start-up assistance on volt-second consumption is not very large. Fig.4 shows two extreme cases with a significant Vs saving in the case of NBI assistance (approximately 0.2Vs) and no saving with ICRF assistance. For comparison a shot with normal (12V) loop voltage start-up is also shown. In the case of RF start-up, it was shown earlier [3] that up to 0.15Vs can be saved by suitably programming the density ramp rate. If the gas puffing used to rise the density is delayed, the density remains low during the first current ramp-up phase (50-80 ms) and the Vs consumption is reduced. This is usually accompanied by a burst of ECE signals which might reflect the generation of runaways during this phase. With early gas puffing, the density rises immediately, the ECE burst does not occur and the Vs saving is reduced or non-existent. This might point to a possible positive effect of runaways helping to build-up the current in the early phase of the discharge.

In summary, we have now succeeded in TEXTOR-94 to start-up the discharge at low loop voltage with ICRF assistance ($E(0)=0.32$ V/m), with NBI assistance ($E(0)=0.34$ V/m) and without any assistance ($E(0)=0.45$ V/m). Surprisingly, this did not succeed with combined ICRF+NBI (2 attempts), but it is conjectured that it was due to premature plasma formation and subsequent loss of equilibrium. Assisted start-up appears in many respects more robust than unassisted one. The achievement of the latter is in line with results obtained in other machines. Finally, it is noted that a closer examination of the role of runaways might be useful for optimizing the early current ramp phase.

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