The ITER Neutral Beam Injectors (NBI) [1] will constitute essential tools for thermonuclear plasma heating and diagnostic. The operation of such injectors involves the generation and acceleration of focused negative ion beams (with a current up to 40 A and voltage up to 1000 kV), which are neutralized before entering the plasma. In order to avoid the negative ion trajectories to be deflected by the stray poloidal magnetic field of the Tokamak, an active magnetic compensation system is needed in addition to passive magnetic shields. A prototype of the ITER heating NBI, named MITICA, is presently under construction in the PRIMA test facility in Padova [2]. Magnetic sensors will be positioned near the main components (ion source, accelerator, neutralizer and residual ion dump), so as to provide specific signals for driving the active compensation coils, for the interlock and protection system and also for beam diagnostic. These sensors shall be robust, vacuum-compatible, radiation-hard and capable of steady-state operation, with a sensitivity better than 0.02 mT and a measurement range of ~ 10 mT [3]. Flux-gate magnetometers [4] appear to be good candidates for this task, especially because their sensing part, not containing semiconductor devices, can be constituted of radiation-hard materials. In addition, they have good sensitivity and, being their operation based on AC signals, they are immune to Thermally-Induced and Radiation-Induced Electro-Motive Forces effect [5] and to the integration drift typical of pick-up coils during long-pulse operation.

However, commercial flux-gate sensors, which are normally used for geomagnetic survey and defence applications, demonstrate very good sensitivity, but their measurement range is insufficient, i.e. about 2 orders of magnitude lower than the requirement. Moreover, they are not vacuum-compatible and rad-hard, as they include a front-end electronic circuit (necessary for signal conditioning) enclosed together with the sensor in the same package. The feasibility of a flux-gate sensor for the ITER NBI application first has been explored using a numerical model of the hysteresis in the core [6] to describe the relationship between the externally applied magnetic field $B_{ext}$ and the second harmonic of the output signal.
The numerical simulations indicated that, by a suitable choice of the core material and geometry, it is possible to increase the measurement range. Several experimental tests have then been carried out using a prototype flux-gate sensor as shown in fig. 1. The experiments confirmed that the 2\textsuperscript{nd} harmonic of the sense signal shows a good linearity with the externally applied magnetic field up to 8 mT, provided that the sinusoidal excitation frequency is not higher than \(\sim 500\) Hz. However, if the external field \(B_{\text{ext}}\) was increased and then reduced, a sort of "decalibration" of the sensor was taking place, so that the 2\textsuperscript{nd} harmonic of the output signal was slightly different in the ascending and descending leg of the curve, as shown in fig. 2. The phenomenon was very well repeatable and has been attributed by the authors to a residual magnetization of the short (transverse) legs of the core.

This issue has been solved by acting a "demagnetization" of the core, consisting in temporarily increasing the sinusoidal excitation current, decreasing it to zero and then setting it again to its original value \((\sim 0.05\) A), so that also the transverse legs of the iron core could be demagnetized. By applying this "demagnetization" procedure before each measurement, the prototype sensor produced a very well repeatable output signal. When the "demagnetization" procedure is applied (orange line in fig. 2) the sensor behaviour appears to be very satisfactory, the sensitivity is of the order of about 10 mV/mT, at an excitation frequency of 120 Hz. The response time of the sensor (including the time necessary for "demagnetization") is compatible with the measurement bandwidth required for the feedback control of the active shielding of the ITER NBIs, which is of the order of 1 Hz.

Fig. 2: amplitude of 2\textsuperscript{nd} of output voltage \(v_{\text{sense},2}\) during experiments with external field \(B_{\text{ext}}\) varying from -5 mT to +5 mT, peak excitation current was 50 mA at 120 Hz.

References