# The Next Step in a Development of Negative Ion Beam Plasma Neutralizer for ITER NBI.

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**Abstract.** Injectors of deuterium atom beams developing for ITER plasma heating and current drive are based on the negative ion acceleration and further neutralization with a gas target. The maximal efficiency of a gas stripping process is 60%. The replacement of the gas neutralizer by plasma one must increase the neutral yield to 80%. The experimental study overview of the microwave discharge in a multi-cusp magnetic system chosen as a base device for Plasma Neutralizer realization and the design development for ITER Neutral Beam Injectors are presented. The experimental results achieved at a plasma neutralizer model PNX-U is discussed. Plasma confinement, gas flows, ionization degree were investigated. The plasma in the volume 0.5m$^3$ with density $n_e$~10$^{18}$ m$^{-3}$ has been achieved at power density 80 kW/m$^3$ in operation with Argon.

## 1. Introduction

To provide an effective stripping of $D^-$ beam PN plasma linear density have to be at a level of $n_e l$~2-3 10$^{19}$m$^{-2}$. As the plasma neutralizer (PN) must be able to replace the gas neutralizer in the ITER Neutral Beam Injector (NBI) of the reference concept its length, $l$, is defined and equal to 3-4m. So the necessary plasma density in neutralizer should be $n_e$~5-7·10$^{18}$m$^{-3}$. The 3D multi-cusp magnetic wall configuration has been chosen for PN plasma confinement system [1]. An electrodeless microwave discharge at a low gas pressure (10$^{-2}$Pa, $H_2$, $Ar$) has been used to generate a plasma in the multi-cusp configuration. After some preliminary experiments the large volume (0.5m$^3$) model PNX-U was constructed to proof of principle of the proposed PN scheme. The first results of the experiments have been presented at IAEA Conference in Yokohama [2]. The experiments were continued to get the more comprehensive database for PN ITER NBI design. Plasma confinement, gas flow and ionization degree were investigated. H-mode of operation with plasma density exceeded the critical one (for 7GHz-microwave source) has been got. Some diagnostics were prepared and installed additionally. Namely: diagnostic $H^-$ beam injector (10–100mA, 350kV); local passive spectrometry for visible spectrum region; laser fluorescence diagnostic for local measurements of ionization degree in experiments with Argon plasma. A microwave interferometer, probes, calorimeters and ultraviolet/soft X radiation detector were used as well as ion and electron multi-grid end loss analyzers (ELA).

## 2. PNX-U installation and diagnostic

*Figure 1* shows PNX-U magnetic field configuration and the coils arrangement. The magnetic system consists of cylindrical side part and two end parts: a front one and a back one. The side part is arranged with ring coils connected in pairs with interchanging current direction from pair to pair. The inner diameter of the side part coil is 0.6m. The ends closing of the formatted multi-cusp magnetic system is fulfilled with transition to a ring coil of reduced diameter and finally on the axis to a coil of a racetrack form. The large part of experiments was fulfilled at dc coil current in the range of 2.5–2.7 kA. Two tangential microwave inputs are located at gaps between coils of a co-current pair to prevent large plasma flow to a launcher. The diagnostic laser radiation is injected through a magnetic slit.

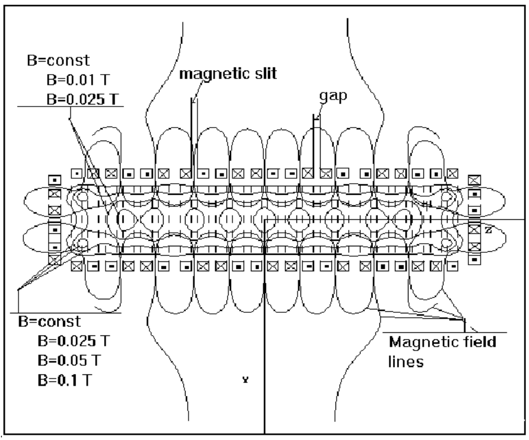

*FIG.1. PNX-U magnetic field configuration, 2.5kA*

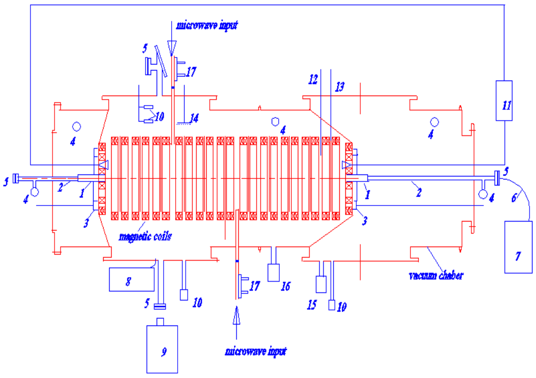

*FIG.2 The diagnostics displacement*

The schema of diagnostic system is shown on *FIG.2*. The PNX-U vacuum chamber is divided into three parts with two partitions. The central part and the right one have their own independent vacuum pumping with turbo-molecular pumps. The left part is evacuated via edge side windows and axial hole. There are two collectors of axial plasma flows at the front and the back ends (1) and two circular collectors at the end ring slits (3). All collectors are water-cooled and are used for calorimetric measurements and are electrically insulated. Each of the ring collectors is divided into two independent parts to estimate a vertical uniformity of the plasma flows. Each of the collectors can be biased with different potentials. This allows to get their probe-like characteristics and in particular to measure a full ion current to each of the collectors. The axial gas-boxes are connected to pressure gauges with tube (2). This gives a possibility to measure gas pressure variation in the collectors during plasma flowing at different conditions. Pressure gauges on *FIG.2* are marked as (4); the optical windows for the spectrum measurements are marked as (5). Plasma linear density is measured with 4-mm microwave interferometer (11). The horns are oriented along the installation axis via the right window. The left window is used for diagnostic $H^-$ beam to measure the line density, $n_e l$, too. A retarding potential method is used to measure plasma parameters with ELA (10). These analysers give a possibility to get an information about electron or ion mean energy and plasma potential in different parts of the installation. The plasma particles go into ELA along magnetic field lines. The ELA-MA1 “sees” the particle flow coming from the periphery of the magnetic system. The ELA-MA2 “sees” the central region. The magnetic field lines lead particles to ELA-MA3 from more deep region (up to 0.1m from the axis) than to ELA-MA4 (up to 0.2m from the axis).

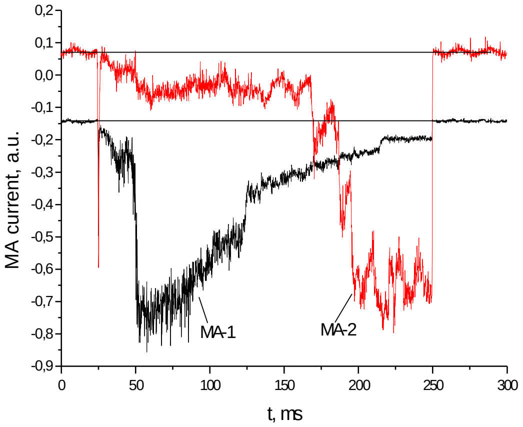

*FIG.3 Oscillogram of the ELA ion current. $U_+$= 0 V, $U_-$= -300 V.*

*Figure 3* demonstrates typical oscillograms of a full ion current ($U_+$=0V) for ELA-MA1 and ELA-MA2. One can see that during the pulse (0.23s) a transition to improved plasma confinement was occurred. The plasma density and electron temperature were measured locally with movable Langmuir probes (marked as (12), (13) on *FIG.2*). The arrangement of immovable Langmuir probes (14) was situated behind the side magnetic slit. Ten probes are displaced across the slit plasma flow to measure profiles. The probe ion current oscillograms for “central” and “peripheral” interception are shown on *FIG.4*.

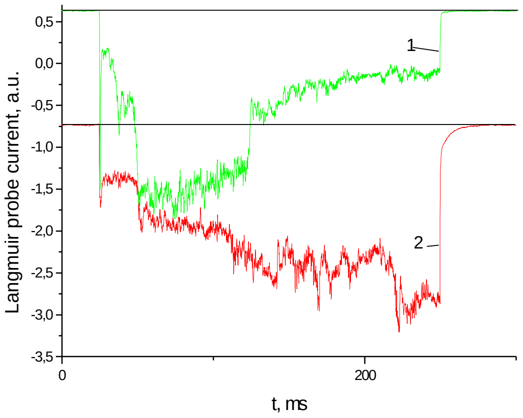

*FIG.4 Oscillograms of Langmuir probes (14). $U_L$= -50 V. 1- peripheral region, 2- central plasma region.*

There are marked also on *Fig.2* fiber light guide (6); the monochromators for emission spectroscopy and for laser-induced fluorescence (LIF) technique (7), (8); laser irradiation system for LIF diagnostic (9). The total light intensity is measured by photo-multiplier (15); gas composition is analyzed by mass-spectrometer (16); microwave directional couplers (17) measure the incident and reflected microwave power.

## 3. Overview of experimental results

The main experimental results can be listed as follows:

- Use of piezo-valve for an additional gas puffing gave a possibility to get a steady-state H-mode of operation with $n_e = 1.5 n_{cr}$ . An Ar plasma with $n_e l$=2 $10^{18}$m$^{-2}$ ($n_e$=$10^{18}$m$^{-3}$) was generated at average injected microwave power density 80 kW/m$^3$.

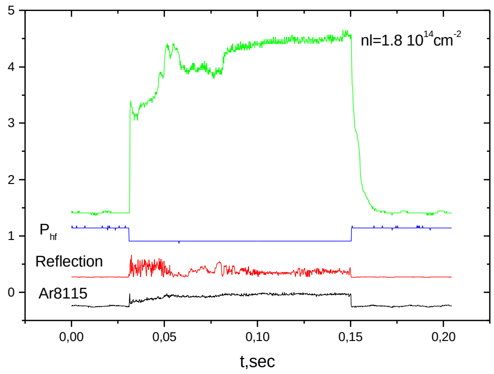

*FIG.5 The H-regime signal oscillograms: $n_e l$ interferometer, $P_{hf}$ the injected microwave power, reflected power, Ar line intensity,*

- Significant improvement of plasma confinement in compare with à simple magnetic case was achieved during microwave injection. It can be explained by ambipolar potential barrier in cusp slits because of ECR heating of electrons.
- An average ionization degree $n_e/n_g$=0.25. It is non-uniform in radial direction and achieves a value not less than ~40% near plasma axis i.e. in the region which is important for beam neutralization.
- In case of PNX-U operation with hydrogen the plasma density was 1.5-2 times less than with argon.
- Low electron temperature ~8eV and ion temperatures ~5eV were observed near plasma axis. The electron temperature on the plasma periphery (in slits) is larger, ~20eV. This phenomenon can be explained by ECR heating on the periphery and volume radiation cooling.

## 4. PN-ITER design

The status of experimental achievements at PNX-U in compare with the designed and with the necessary for PN ITER parameter meanings is demonstrated Table 1 below. The super-conducting PNX-SU installation is the proposed intermediate step. The requisite for PN-ITER plasma parameters should be obtained on PNX-SU. The calculations, based on PNX-U results, have predicted the microwave power level of 700kW for PN-ITER with deuterium. The use of Ar as processing gas can give the additional possibilities (radiation cooling of electrons, multi-charged ions, and high ionization degree) for power decrement and plasma density increment. The complementary investigation of such “radiation discharge” on PNX-SU installation is necessary. The future experiments have to specify in particular the working gas. Figure 6 shows the PN-ITER design (is shown the front view). Two large rectangular opening are used for negative ion beams entrance. The common magnetic shield of NBI line is shown too.

TAB. 1: MAIN PARAMETERS OF PLASMA NEUTRALIZERS.

| | PNX-U | | PNX-SU | PN ITER |
|---|---|---|---|---|
| | Experiment | Design | | |
| Plasma length, m | 2 | 2.2 | 2.5 | 3-4 |
| Plasma volume, m$^3$ | 0.5 | 0.5 | 1 | 6 |
| Linear density, m$^{-2}$ | $\sim 2\cdot 10^{18}$ | $1.4\cdot 10^{18}$ | $1.3\cdot 10^{19}$ | $2\cdot 10^{19}$ |
| Plasma density, m$^{-3}$ | $1\cdot 10^{18}$ | $0.7\cdot 10^{18}$ | $5\cdot 10^{18}$ | $\sim 7\cdot 10^{18}$ |
| Ionization degree | 0.4 | ~0.2 | 0.4 | 0.4 |
| Microwave power, kW | 50 | 50 | 150 | 700 |
| Frequency, GHz | 7 (*klystron*) | | 24 (*gyrotron*) | |
| Magnetic system | *copper* | | *super-conducting* (*NbTi*) | |
| Magnetic field in slits, T | 0.36 | 0.5 | 1 | 1 |

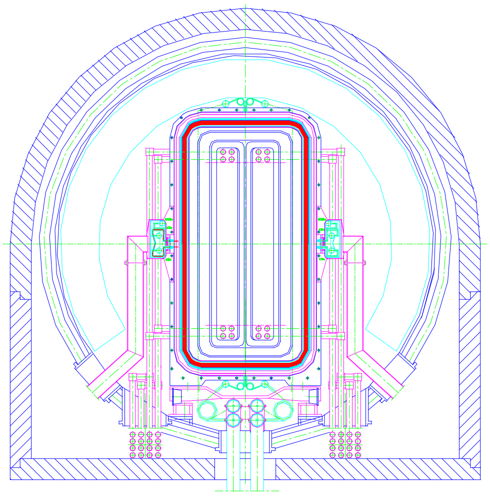

*Fig.6. PN-ITER design*

## 5. Conclusion

The experiments have shown that the cut off plasma density can be easily provided in the multi-cusp configuration with microwave near wall ECR discharge at a low pressure. The potential improvement of the magnetic cusp confinement allows obtain the plasma density more than the cut off one at smaller input microwave power. The high ionization degree can be achieved at a low plasma electron temperature and acceptable microwave power. The radiation type argon discharge in multi-cusp magnetic configuration was investigated. PN could be integrated into existed ITER NBI design.

## References

[1] ITER Design Description Document, N 53 DDD 15 97-11-30 W 0.2 (1998).

[2] SKOVORODA, A.A., “Plasma neutralizer for ITER injector”, IAE-5544/6, Moscow (1992)

[3] ZHIL’TSOV, V.A., KLIMENKO, E.YU, KOSAREV, P.M., KULYGIN, V.M., et al., “The development of a negative ion beam plasma neutralizer for ITER NBI”, Nuclear Fusion **40** (2000) 509; Fusion Energy 1998 (Proc.17th Int. Conf. Yokohama, 1998), IAEA, Vienna (1999) (CD-ROM file ITERP2/04).