## STATUS OF PLASMA NEUTRALIZER DEVELOPMENT

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Plasma is more effective stripping target than the gas one [1-3]. Figure 1 represents dependence of the stripping efficiency on ionisation degree in Hydrogen and Argon plasmas. Zero ionisation degree corresponds to gas target.



Fig. 1. Negative ion stripping efficiency (vertical axis) depend upon the target thickness (horizontal axis) and ionization degree (parameter) for different targets: A)  $D_2$  - target; B) Ar – target.

It can be seen that rather high ionisation degree should be provided at total target thickness of  $2.10^{19}$  m<sup>-2</sup> to get  $k \ge 0.8$ . Practical attempts to create a steady state operated plasma neutralizer for thermonuclear investigations were unsuccessful for a long time [4-8]. The main reason of that is lot of qualifying standards some of which seems to be mutual exclusive at first sight. The Table 1 the main requirements to possible ITER NBI Plasma Neutraliser (l=3m, plasma volume 6 m<sup>3</sup>) are collected:

## Table I.

The basic requirements to PN ITER

N	Parameter	Value
1	Target thickness / Plasma density	$2 \cdot 10^{19} \text{m}^{-2} / 0.7 \cdot 10^{19} \text{m}^{-3}$
2	Ionization degree	>0.3
3	Power density for plasma production	<0.2MW/m <sup>3</sup>
4	Beam divergence	<5·10 <sup>-3</sup> rad
5	Operation mode	Steady state

The first two requirements are defined by elementary processes and given sizes of the PN ITER. The third one follows a necessity of low energy consumption for plasma generation in compare with the energy gain because of the k increasing. The fourth one is the limit to additional beam divergence, which could be introduced by neutraliser. Moreover, the fifth one is defined by reactor operating mode. The items 2 - 4 are specific for PN namely.

The third requirement can be fulfilled if the cold plasma energy confinement time  $\tau$  will be more than 1 ms. Such a  $\tau$  in magnetic confinement systems can be achieved only at high magnetic fields (more than 0.1 T). But a magnetic field of such a value should result a very large beam divergence.

Other requirement, to get a plasma of high ionization degree at a low electron temperature, is also not so simple.

Thus in is necessary for ITER-scale PN to get a plasma of a large volume and high ionization degree with density  $\sim 10^{19} \text{m}^{-3}$ , at electron temperature  $\sim 10 \text{ eV}$ ,  $\tau \ge 1 \text{ms}$  and fulfill the low divergence conditions at confined magnetic field.

#### 2. Backgrounds

Plasma neutraliser based on multicusp magnetic trap of a large volume with 3D magnetic wall and microwave ECR discharge plasma generation was proposed in [9]. All the problems listed above were solved in principle. Proof-of Principle experiments were fulfilled [10-18] and full scale ITER-related PN design was done [12,14].

Different magnetic configurations with 3D magnetic wall could be technically arranged with permanent magnets or coils [9,10,13]. A principal difference between these two possibilities is that in permanent magnet system case all magnetic lines are coming through the magnet poles and rests on a metal surfaces while in case of coil system they can go by. Thus there is a possibility to arrange plasma flow dumps, so called "gas boxes" to diminish thermal load to walls and to control plasma recycling.

An acceptable plasma confinement time can be got in a multicusp if a closed electron drift will be provided [9,19]. It can be reached with rather smooth laying of coils or permanent magnets at all PN walls. It is necessary of course to arrange windows for beam and microwave passing through.

Nonelectrode ECR discharge is the best way to provide steady state plasma generation in magnetic field. The main advantages of such a type plasma generator are as follows: 1) microwave power is absorbed only by electrons (ionising agent) 2) extremely low gas pressure can be sufficient 3) energy deposition can be strongly controlled.

Ionization degree in PN near axis region, where D<sup>-</sup> beam have to be stripped, will be close to one. While plasma is generating in periphery region of PN where ECR conditions exists and gas puffing is providing, the question about plasma propagation into near axis region is arising.

## 3. PNX-U Experiment

All the ideas, mentioned above had to be proved experimentally. Let us list the main

items should be checked:

- Energy confinement time scaling;
- Specific power cost of steady state operation, power balance;
- Plasma ionisation degree;
- Mechanism of PN volume plasma infilling, plasma uniformity;
- Electron and ion densities and temperatures, its special distribution;
- Multi-charged ion generation (for Argon);
- Choice of working gas, gas recycling, gas boxes influence;
- Plasma density limitation at ECR plasma generation;
- Cross magnetic field plasma losses.

All the items were investigated at PNX-U. Multicusp magnetic system of the PNX-U forms a 3D magnetic wall (see Fig.2). At the same Fig.2 magnetic force lines and lines of equal magnetizing force are shown.

The PNX-U magnetic system consists of side cylindrical and two edge parts. The side part is formed with coaxial ring coils of rectangular cross section. Those are coupled in pairs with an opposite current direction in neighbour pairs. The side coil inner diameter is 60 cm. Each edge element of the system is formed with two coils. The first one have a ring form of smaller diameter in compare with the side coils. The second one is of elliptic (race track) form. That gave a possibility to have two beam windows at each of the edges (Fig.3.). Full inner length between two edges 2.2 m



Fig. 2. PNX-U magnetic system



Fig.3. Edge coils configuration.

It is possible to divide conditionally all the plasma confinement volume into two parts, inner one, where Argon ions are not magnetized, and a peripheral one, where the magnetizing condition  $\rho_i/L < 1$  ( $L=B/\nabla B$ ,  $\rho_i$ - ion gyro- radius) is fulfilled. The central region radius is about 15 – 20 cm.

PNX-U magnetic system is displaced in a cylindrical vacuum chamber of 1.2 m diameter and of 4 m length. (See Fig.4.). Two inner partitions (across the axis) have divided the vacuum

chamber into three "gaseous insulated" volumes, two of which have independent pumping. All edge magnetic slits were closed by gas boxes to prevent plasma flows into the edge parts of the vacuum volume. All three parts of the volume are communicated through the beam windows only. The central volume is divided by magnetic coils into inner part (plasma confinement volume) and the outer one (between the coil system and vacuum wall). Plasma can flow there through the side magnetic slits. The external volume communicates with the plasma one via magnetic gaps as well. That gaps were used for diagnostics and microwave inputs (Fig.4).



Fig.4. PNX-U and diagnostic displacement scheme.

1,2 – edge gas boxes, 3 – probes for side slit plasma flows measurements,4-vacuum bulbs, 5-laser windows, 6-probe system for plasma flow measurement, 7-monochromator, 8-monochromator for laser fluorescence,9-eximer laser, 10-magnetic analyzer, 11 – 4mm interferometer, 12 – multi-grid analyzer,13- time of flight (TOF) analyzer, 14- incident and reflected microwave power measuring device.

Two tangential microwave power inputs [13] are displaced in gaps between pairs of side coils. The transversal magnetic field in the gaps prevents direct plasma flow to the antennae.

Diagnostic disposition is demonstrated on the Fig.5. Two gas boxes are disposed at each of the edges to intercept plasma flows to axis and circular apertures (See Fig.2,3). The boxes are water cooled (to measure coming power calorimetrically) and electrically insulated (to measure ion current when a correspondent potential is applied).

Plasma linear density, *nl*, is measured with 4-mm microwave interferometer; its antennae are displaced at windows of opposite edges (Fig.3).

Ion energy spectrum in slit plasma flows was measured with retarding field multi-grid analyzers. Magnetic and TOF analyzers were used for mass and charge composition investigation after ion acceleration up to 1 - 1.5 keV.

Movable Langmuire probes were situated at magnetic slits and gaps to measure plasma density and electron temperature distributions, plasma potential and plasma oscillations as well.

Argon ion temperature distribution was measured with laser spectroscopy method [19]. The spectroscopy apparatuses displacement could be seen at Fig.5.



Fig.5. The spectroscopy apparatuses displacement in PNX-U cross section 1 –laser ray; 2 –quartz window; 3 –scanning system lens; 4 –light guide;
5 –monochromator; 6 –photo multiplier; 7 –to filing system;8 –vacuum chamber; 9 –magnetic coil

Diagnostic laser ray passes through a magnetic slit (See Fig.4.) A fluorescent radiation collects with lens 3 of a special optic-mechanical unit that provides line of sight scanning and focuses the collected light at a light guide input. Another edge of the light guide is coupled with a monochromator slit. Space resolution along the laser ray is 4 cm, the transversal one  $\sim 0.3$ mm. The scanning system was used also for chord measurements of argon atoms radiation in plasma. Monochromator 7 (Fig.4) served for a control of plasma radiation at chosen spectra lines.

An incident and plasma reflected microwave power measurements were provided with directed beam splitters 14.

#### 4. Experimental results

The installation specification and Argon plasma parameters have been got during last experiments with two klystrons are demonstrated in Table III. Maximal total power was limited by breakdowns in antennae at presence of plasma. [15,18]. Calorimetric and bolometric measurements demonstrate that, when plasma density exceeds the cut off one for used microwave generator frequency, the most part of the microwave power has been applied to the antennae. When a gas pressure exceeds 0.05 Pa, the discharge has been started just right at a microwave input. We'll discuss below the right operation modes only: the microwave discharge should be separated from the antennae system.[18].

Parameter	Experiment
Magnetic system size: length/diameter	2.2m / 0.6m
Magnetic slits number	15
Total slits length	~50m
Plasma volume	$0.5m^{3}$
Magnetic field in slits	0.36T
Magnetic field operation mode	steady state
Microwave generator	klystron
Microwave frequency	7GHz
Microwave power per one klystron	50kW
Klystron number	2

 Table III. PNX-U Specification and Plasma Parameters

Klystron operation mode: duration/period	0.5s / 5s
Target thickness, <i>nl</i>	$0.2 \cdot 10^{19} \text{m}^{-2}$
Plasma density	$10^{18} \text{m}^{-3}$
Electron temperature: center/periphery	~10eV / ~20eV
Ion temperature	~10eV
Plasma potential	~+30V
Average degree of ionization	>0.9
Power density	$0.1 \mathrm{MW/m^3}$
Working gas	Ar
Gas pressure	10 <sup>-5</sup> ÷10 <sup>-4</sup> torr

Typical dependence of averaged plasma density on microwave power input is given on Fig.6. The density is limited at a level of cut-off one which is about  $0.6 \cdot 10^{18} \text{m}^{-3}$  for used generator frequency. Maximal observed plasma density didn't exceed  $1 \cdot 10^{18} \text{m}^{-3}$ .



Fig.6. Typical dependence of averaged plasma density on microwave power input .

An average density dependence on injected Argon amount is shown at Fig.7. There is an optimal gas letting in amount; that is defined by absorbed microwave power space distribution reorganization. As was noted above most part of it is deposited at the antennae if gas amount is above of a critical one.[18].



Fig.7. Average plasma density versus gas input

Radial plasma density distribution measured with a movable probe in magnetic gap at "near critical" conditions is shown on Fig.8.



Fig.8. Plasma density radial profile in magnetic gap.

Usually the profile is rather flat (or even with some downtrend toward the axis) up to radial point  $\sim$ 12 cm and then goes to zero at 22 – 25 cm. Fig.10 demonstrates a radial plasma density distribution on a periphery and just behind a magnetic plug (magnetic plug is located at 35 cm) in a magnetic slit. It can be seen that plasma density is less of order of value in plug region in compare with central point.

Optical measurements (Fig.4,5) in central part of the trap with a laser fluorescence method have demonstrated that an  $Ar^+$  distribution function is Maxwellian and the ion temperature is minimal at the axis (Fig.10).



Fig.9. Radial plasma density profile along a magnetic slit in periphery region.



Fig. 10. Ion temperature,  $T_i$ , radial distribution.

The multi-grid analyzers investigation of the plasma flows out of the magnetic slits have showed significant positive plasma potential. The potential value is varying from slit to slit in a range 15 – 50 V. Ion current cut off curve (see Fig 11) demonstrates that ion energy distribution function is close to the Boltzmann one and plasma potential  $\Phi$  is ~30 V. Note that the analyzer is mainly registries the ions coming from the central plasma region. The ion temperature is rather close to value measured with laser scattering (See Fig.10). The electron temperature was measured with probes is close to the ion temperature and rises to periphery (to ECR region) [11].

An Argon atom coming from the wall (and being at wall temperature) will be ionized at a distance  $\ell a \sim 3$ cm. That is much less than the plasma radius *R*. Only fast Argon atoms, with a temperature of order  $\sim 10$ eV, which are generated at a periphery because of charge exchange in a layer of  $\ell a$  thickness, can reach the central region. It is not large amount and the central part of plasma is highly ionized because of that.



Fig.11. Grid analyzer ion current cut off curve.

Chord measurements of Argon atom optic radiation were fulfilled for wave lengths of 750 nm and 565 nm with the optic scanning system (Fig 5). The radiation intensity radial distribution was calculated using Abel conversion. Collision – radiation model was used for the data processing. The result shows that the plasma ionization degree at the central region is close to unity [16].

Plane Langmuire probes displaced behind the magnetic system coils (probes 3 on Fig. 2) were used to measure the total ion current to the side slits. An azimuth probe width was 6 mm; cross slit length was chosen large enough to intercept all the plasma flow cross section.



Fig.12. Side slits ion current distribution. - without edge gas boxes, □ - with edge gas boxes.

Such probes were displaced at different azimuth points of some slits. Total ion flows to the gas boxes were also measured. The measurements gave a possibility to learn an ionisation balance of the plasma. Azimuth flow homogeneity was not worse than ~10%. Significant nonuniformity (factor 2 - 3) was observed in flow sharing between the slits. Fig.12 presents the ion flows to the side slits at presence and absence of edge gas boxes. Ion flows to the edge slits diminish without gas boxes simultaneously with edge plasma density diminishing. That could be explained by two microwave inputs locality (in central part of the trap) and relatively low "communication" between different cusps of the trap. Use of the gas boxes increased the linear density at equal status, made the discharge more stable and reproducible.

Total ion flow through all the slits (including the edges) was varied in range 15 - 40 A depending on gas and power inputs. The ion flow orders of value exceeded the gas flows of external input and pumping. Gas recycling is a determinant for stable discharge maintenance.

Plasma losses at the coil cases were measured in special experiment. Flat probe system (Fig.4) was displaced at inner side of the coils namely for this purpose. The probes crossed a magnetic gap and both nearest slits. The experiment result is presented on Fig. 13, which shows that practically all ion flow is coming through the magnetic slits. It corresponds to measured plasma boundary at distance  $\sim$ 25 cm from axis in gap mid plane (Fig.4) which is located at extreme magnetic line, which crosses a coil case surface



Fig.13. Ion flow profile along the inner magnetic coil boundary Collectors 1,2,3 and 14,15,16 are located at magnetic slits, the others – at inner side of coils.

Magnetic and TOF analyser measurements of plasma flows have demonstrated a presence of multi-charged Argon ions (See Fig. 14) .  $Ar^{++}$  ion flow increased and  $Ar^{+}$  decreased correspondingly with microwave power input increasing.

Significant level of low frequency oscillations of floating potential and ion saturation current on Langmuire probes were observed in all the cusps of the system. The typical spectrum of the oscillations is demonstrated on Fig.15. The fluctuations indicate a possible mechanism of plasma transportation from periphery to central region of the trap. Maximal level of the fluctuations is observed namely at the periphery.



Fig.14.  $Ar^+$  and  $Ar^{++}$  fractions in ion flow versus microwave power.



Fig.15. Spectrum of floating potential oscillations.

# 5. Discussion

PNX-U operational modes are mainly defined by two parameters: gas and microwave power inputs. Namely that define discharge type, confinement character, maximal plasma density, temperature, potential and fluctuation characteristics.

The maximal plasma density is close to the critical one and can exceed it in special experimental conditions not more then 1.5 times. The critical plasma density 0.6  $10^{18}$ m<sup>-3</sup> is achieved just at 15 KW of microwave power input. Therefore, the necessary specific power is rather small: 0.03 MW/m<sup>3</sup>. Energy loss balance at maximal microwave power input of 40 KW and maximal achieved linear density *nl*=2.10<sup>18</sup>m<sup>-2</sup> is shown in Table 6. Large value of reflected power is result of operation at overcritical plasma density. Significant part of the losses is the result of microwave dispersion throughout the vacuum chamber. This happened because of a large area of slits and gaps through which the microwaves came to the outer part of vacuum volume (~3m<sup>3</sup>). Namely plasma losses are about 16 KW and defined by radiation and plasma flows in equal degree. The balance pointed to existed reserve of power costs diminishing.

Energy confinement time estimations give us value ~0.5 ms being in acceptable agreement with the scaling (1). In [11] was found that there are operating modes with improved plasma confinement (potential confinement) in PNX-U. Ion confinement time in the trap center at that mode is so increased that the ion (not only electron) thermalization became possible. The observed isothermal plasma with  $T_i \sim T_e \sim 10$  eV can be evidence of such a confinement. Multi-charged ions in coming out plasma flows also are evidence of such a confinement. However, energy transfer to central region of the system while Microwaves are skinned at periphery and radiation coming from that region cools the plasma needs to be specially investigated.

Power	kW
Klystron microwave power	+40
Reflected microwave power	-8
Charged particles losses	-8
Radiation losses (light+neutrals)	-8
Diffused microwave power	-16

**Table 4.** Power balance in PNX-U

The experiments have shown (Fig.6,8) that concave plasma boundary goes along the last magnetic force line which don't cross coil case und passed a magnetic slit (Fig.9, 14). At the same time all Argon atoms are ionized at periphery and the question is: how the central part of the system could be filled with highly ionized plasma. The answer could be as follows: plasma generation and heating in periphery going down magnetic field creates conditions for chute (or flutter) mode of instability. The low frequency fluctuations were observed let us a possibility to suppose that the radial density profile is forming mainly by two factors: turbulence transport and radial potential distribution. The last one in his turn is defined by mechanism of the periphery ECR heating and radiation ion cooling in central region [11].

Thus, as appears from the experimental results there are two plasma confinement regions in the multi-cusp with the ECR discharge plasma generation. The central one, which is filled with highly ionized, thermalized, homogenous plasma with non-magnetized ions. That can be used for negative ion stripping. The periphery, near wall region, is the place of electron heating, gas ionization, the place of a high turbulence, which provides plasma transport to the central part of the system.

Plasma density and general volume in PN of ITER (or DEMO) scale should be order of value larger than in PNX-U (See Tables 2 and 3). To increase the critical density up to necessary value is possible with slit magnetic field increasing by factor 3 with correspondent microwave frequency increasing. The volume enlarging gives energy confinement time increasing (1)  $\sim 8$  times. If power losses are proportional to plasma density, then the necessary specific power will not exceed the accepted one (see Table 2). Note that in reality the radiation losses should be less taking into account a self-absorption in a large volume.

The high ionization degree was measured in PNX-U will be naturally in full-scale PN conditions as well. Design of PN for ITER NBI, was done during EDA, took into account also the gas boxes efficiency [12,13]. Almost full gas blocking inside the PN volume and using Argon instead of Deuterium lets to diminish gas flow to beam line and get more (~2 times) maximal density at stable discharge parameters [10, 11].

The possibility to get a multi-ionized Argon plasma can't increase the neutralization efficiency, but lets diminish the necessary line density by factor  $\sim 2$  [9].

The experimental investigations, calculations and design developmental works demonstrate that the PN scheme on the base of multi-cusp magnetic trap with periphery ECR plasma generation is found rather perspective for further development as an element of N-NBI for full-scale fusion systems.

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