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ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
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FEASIBILITY STUDY FOR A NOVEL PULSED NEUTRAL BEAM DIAGNOSTICS FOR TOKAMAKS

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НОВОСИБИРСК

I Introduction

Injection of a neutral beam to diagnose plasma parameters is widely used in controlled fusion research. The products of plasma/beam interaction give the information on the plasma density, temperature, impurity concentration, etc. Tracing of the subsequent behavior of the ions born from initial beam particles represents the essence of many of proposed schemes [1, 2, 3]. Recently, in [4] a novel promising method of this kind has been proposed. Fast ion bunches are to be produced in a tokamak by the oblique injection of a periodically pulsed neutral beam. If the temporal distance between the pulses is properly chosen, then it results in a strong increase of the density of the bunches near a certain resonant magnetic surface with the rational local q value. This occurs by virtue of stacking of the subsequent bunches near the resonant surface after several turns over large radius of a tokamak. Thus, it gives a tool for q-profile measurements. Dense ion bunch running around a tokamak can be used also for other diagnostics purposes, providing information on the structure of magnetic field, plasma fluctuations localized near the certain magnetic surfaces, etc. In [4], the estimations for parameters of the pulsed neutral beam required for this diagnostics have been formulated. To be applied to the conceivable experiment on a medium-scale tokamak, the neutral deuterium beam with a pulse length of 0.3 μs, a current of 100 A and an energy of as high as 80 keV is needed. The distance between the pulses of ~ 10 μs is required. The total number of pulses is supposed to be of order of 20, thus giving the entire pack duration of ~ 200 μs. We have studied different approaches to provide a pulsed neutral beam with aforementioned parameters which is to be incorporated into this diagnostics. This paper should be treated neither as an attempt to list all the possible solutions of the problem nor as a technical proposal. We are rather trying to show a technical feasibility of the diagnostics scheme and give an outline of possible ways for its further development to a concrete hardware. Since our aim was to assess the technical feasibility of the diagnostics, we tried to avoid yet unproven approaches. In this context we have tried to select those that would be composed of the parts already in hands.

II Overview of possible approaches

There is a long history of experimental study of the creation of ion beams for both diagnostics and heating purposes. Technology level achieved by now undoubtedly covers the requirements of 100 A, 80 kV ion source. For example, START-2 ion source [5] developed for a pulse plasma heating would be a good candidate for this role after some redesign of the ion optics to increase accelerating voltage from 25 to 80 kV. Then a problem arises how

to provide the series of short pulses from a continuous 200 μs beam. Below we will discuss a few possible approaches to that problem. Before proceeding to these we would like to make a remark concerning the diagnostics scheme proposed in [4]. Let consider the scheme when one observes the density distribution in travelling bunches over a cross section of a tokamak. By injecting the another neutral beam in this cross section (in principle, this role can be played by the initial beam itself) one can obtain an outflux of charge-exchange atoms which contains among others also a fraction of particles born from the bunches. These can be easily distinguished from background due to their well defined energy and angle. Reliable technique for particles energy analysis has been already developed (see, for example [1]). In particular, one can use a pinhole camera incorporated with ion optics sensitive to the particles energy which is capable to provide a plasma image formed by the escaping atoms with fixed energy [6]. Observation of their Doppler shifted lines excited during the charge-exchange collisions also may give a reliable data. On the other hand, then one would be able to reduce requirements to the injected diagnostics beam. In particular, the total beam current can be then reduced or it would became possible to use a single continuous pulse beam with sufficiently short raise time but not the multi-pulse beam. In the latter case, temporal evolution of the signals may provide additional data. Nevertheless, the multi-pulse character of the beam appears in many cases as a necessary attribute of the diagnostics scheme.

II.I Mechanical chopping

The first approach, that can not be skipped without special considerations, is a mechanical chopping of a continuous neutral beam by combination of a rotating disc and a motionless mesh both fitted with narrow slits for the beam passing through .

The frequency of rotation of order 1 kHz is routinely available so one can have the single pulse duration of order of 1 μs or so for $r=10$ cm rotation radius and a width of the slits of $\sim$0.5 mm.

Assuming the chopper deformations to be elastic (the permissible stress is then under $\sim 10^{-2}$ of the Young's modulus E) one can obtain the maximum chopper's gates velocity $\sim \sqrt{2E \times 10^{-2}/\rho}$, where ρ is the gating disc density. Preliminary estimations have shown that for a moderate current density in the beam ($\sim$0.3 A/cm^2) the chopper would be of too large area (and radius) to accommodate .00 A beam. Evidently, this approach becomes more attractive when the beam current is reduced (the same is valid for higher current densities of the beam). Other disadvantages of the chopper approach are at least 50% loss of the beam on the slits and clear difficulties in providing of required 10 μs intervals between the single pulses which appear due to the difference in the slit width and the beam diameter. Anyway, one may use this approach in specific experimental conditions especially if a shape of the beam envelope is not a critical issue. Obvious advantage of the approach is that it guarantees stability of the beam energy.

II.II Fast sweeping of the beam

A reliable but not very elegant approach is a use of a low inductive coil system to sweep ion beam on a small (of order of 0.1) angle. Initially the ion beam goes through the magnetic field of the coils and eventually hits a dump, but when for 0.3 μs the current in the coils drops to zero it starts to go through the collimator to a gas-cell and then enters a tokamak as an atomic beam.

Power supply for, say, a pair of one turn Helmholz' coils of 10 cm radius would be roughly 2.5 kA, 5 kV for 100 ns rise time. These parameters seems to be rather routine ones. Of course, further considerations are required to take accurately into account screening currents in the parts of the sweeping system.

II.III Modulation of extracting voltage

High voltage modulators for ion sources have a pulse front of order of a few μs that is determined by a capacity of the ion source (500 – 1000 pF) and a switching current available for modern switching elements ($\sim$ 1 kA per switch) [7]. We believe that a traditional scheme allows this time to be decreased to the needed 0.1 μs but it will be accompanied by an increased energy spread. Besides, there are also certain apprehensions that a multistage network that uses many parallel switches would be rather expensive and unreliable. Remaining are also the problems of compensation of the short ion bunch in the duct. To avoid them, one can sustain in the duct a small density plasma to compensate the beam space charge.

In this respect, more attractive seems the approach that uses modulation of a plasma density inside the ion source just at the plasma grid which will be discussed in the next section. Also possible is the partial modulation of accelerating voltage accompanied by further monochromatization of the beam energy (by 90 degrees bending magnet, for instance) if needed. Preliminary estimations show, that for the beam divergency of $\sim$1 degree it is sufficient to provide only 5% energy modulation. This version is distinguished by a reliable physics but seems to be rather complicated technically.

II.IV Modulation of Plasma Emitter

Since the plasma density over the emitting surface in the ion sources is of order of 10^{12}cm^{-3}, one can use grids with reasonable spacing and a size of the cells that subsequently repel ions and electrons to prevent the plasma entering into the accelerating structure. Potentials should be a few hundreds of volts or even less for characteristic parameters of ion source plasmas. Ions time of flight through the grids can be made negligible as compared to, say, 100 ns or less. A special negatively biased grid can be also used to absorb the ions. Similar manipulations have been already performed in the experiments described in [8]. Anyhow, further experimental efforts are needed to achieve adequate confidence in suitability of this scheme.

II.V Pulsed stripping target

The pulsed beam can also be realized on the basis of the negative ion source. One can use a negative ion beam instead of positive ions and neutralize the beam in a pulse photon stripping target. Negative ion source that can provide a multi-amperes beam has been recently developed at Novosibirsk [9]. Accessibility of the photodetachment technology [10] has been already displayed in experiments of Semashko et al. [11], who used a Nd-laser with moderate parameters. For a short pulse photoneutralizer requirements to a laser and to the resonator's mirrors are to be even reduced. In any case, 99.5% mirror reflectivity seems not a big problem for short laser pulses. Stability of the mirror properties is high enough if an absorbed energy is less then 20 J/cm^2. In optimal case, the photons are to move coaxially with the converted beam. The photodetachement cross section for $H^- + photon \rightarrow H^0 + e$ is $3 \times 10^{-17}\text{cm}^2$ for Nd-laser radiation [12]. Required parameters of

the target can be roughly estimated if the life time of photons in the target is considered to be negligible comparing to the beam particles time of flight along the target. This suggestion is rather realistic since the beam velocity is 3×10^8 cm/s $\ll$ velocity of the photons. For the sake of simplicity we also are neglecting by a laser pulse duration in comparing to the photon life time in the target. The target length of 100 cm is adequate to provide the single bunch of 0.3 μs duration. Fraction of neutrals after the stripping is $1 - \exp(-n_{\text{photons}}\sigma_{\text{detach}}LN)$, where L — is the target length and N — is a number of reflections from the mirrors inside the resonator (~20). This relationship can be also rewritten into somewhat different form suitable for estimations of required laser pulse energy [13]: $1 - \exp(-\frac{\text{laser pulse energy}}{\text{area}} \times \sigma_{\text{detach}} N/\hbar\omega)$.

The target density of order of 2.7×10^{13}photons/cm^3 is sufficient to convert ~ 80% of the beam into neutrals. Total energy content in the cell with the aperture of 100 cm^2 can be then estimated as $\sim 5.5 \times 10^{-2}$ joules. The lasers capable of delivering appropriate energy output with a pulse duration of ~30–50 ns are undoubtedly available. The resonator length, laser pulse duration, mirrors reflectivity and their locations should be properly chosen to provide the required lifetime of the target and envelope of the neutral beam pulse.

III Conclusions

We can say with reasonable confidence that all the approaches, listed here, would lead to creation of the efficient diagnostic hardware. In fact, a choice among them depends on the experimental conditions and parameters to be measured with the use of this diagnostics. The approach, that uses the photon stripping, is particularly interesting because of its capability to provide very short pulses. This may be sufficient reason for the choice in certain cases. Of course, we understand that all discussed above represents only initial consideration, and it will require much more efforts, including experimental ones, to obtain reliable equipment for the experimenting.

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