Experimental realization of non resonant photon neutralizer for negative ion beams. Concept of neutralizer for big NBI systems

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Abstract. Concept of photon neutralizer for large ITER like NBI system has been proposed. The use of proposed concept allows beam neutralization with significantly lower requirements to radiation quality in comparison with resonance schemes, also there is no need for complicated stabilization and tuning system.

INTRODUCTION

A traditional approach to produce a neutral beam from the negative ion H^-,D^- beam for further application for plasma heating or neutral beam assisted diagnostics is its neutralization in a gas or plasma target which detach the excess electrons. However, these approaches have a significant limitation on efficiency in particular at particle energy above 100 keV. For heating injectors with the 1 MeV beam [1] the maximal limit neutralization efficiency in the gas and plasma targets are 60% and 85% correspondingly [2], which considerably affects the overall efficiency of the injectors. It happens due to accompanying process of ionization to positive charge. In addition, application of these neutralizers is associated with complications including the deterioration of the vacuum conditions due to gas puffing.

Photodetachment of excess electron from a high-energy negative ions is an attractive method of the beam neutralization. Such method does not require a gas- or plasma-puffing into the neutralizer chamber; it does not produce positive ions. The photodetachment cross section is well known (see, for example, [3]). It has a wide resonance, which practically overlaps the visible and near IR spectrum. This approach has been proposed in 1975 by J.H. Fink and A.M. Frank [4]. Since than time a number of projects of photon neutralizer have been proposed. As a rule, they are based on an optic resonator similar to Fabri-Perot cells. This needs the very high reflectance mirrors, powerful light source with thin line and very precise tune of all the optic elements. For example, the reflectance of mirrors should be not less than 99.96%, the total laser output power is to be 800 kW with output intensity about 300W/cm^2 and the laser bandwidth should be less than 10^4 Hz in the scheme considered in [5]. Optimized by authors of [6] geometry have reduced the laser power down to a few kW, but they need narrower laser line less than 100 Hz. A realization these parameters of laser together is very difficult problem. In addition the technique of optic elements stabilization is required [6], which similar to used in large gravitational experiments [7].

The alternative approach to photoneutralization has been demonstrated [8]. It is based on adiabatic photon confinement between reflective concave mirrors. This paper presents a conceptual design of a neutralizer for large neutral beam injection systems, also some problems of such an approach are considered.

PRINCIPAL SCHEME

A photon target [4-9] simplified diagram is shown in Figure 1. Negative ions crossing the region occupied by radiation undergoes to the photodetachment. The growth of the flow (equivalent current density) of neutrals in a photon accumulator is described by the following equation:

$$j_0(z) = j_-(0)\left(1-\exp\left(-\frac{\sigma c}{V\hbar\omega}\int_0^z W dz\right)\right) \quad (1)$$

where $j_-(0) = n_-(0)V$ is the negative ion flow density at the entrance to the target; V is the ion speed; W is the density of the energy of photon gas; σ is the cross-section of the photodetachment; z is the coordinate along the beam; $\hbar\omega$ is the energy of a single photon. As differentiated from resonance scheme with separated laser beams in

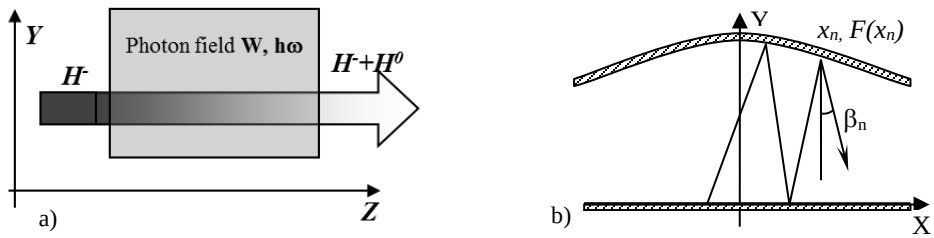

FIGURE 1. a) Schematic diagram of photon neutralizer; b) 2D scheme of adiabatic photon trap.

neutralization region and injection through high reflective mirror, in the proposed concept there is extended area of space occupied by photons injected through small holes. The principal 2D scheme of such photon target is presented by Fig.1b. As can be seen, with each reflection from the upper mirror, a photon gets an increment in the horizontal momentum towards bigger distance F to the lower mirror. As a result, the ray will bounce off the open ends of the trap, where the distance between the mirrors is less, and return to the center, where this distance is maximal, of course, provided that β_n, the angle of deviation of the movement direction from the vertical in center of the trap, is small enough. More detailed mathematical model and conditions of photon confinement are described in [9].

For ion beam neutralization the photon accumulator is combination long cylindrical mirrors with spherical or toroidal ends, as it shown in Fig 2. Success experiments on neutralization with such photon target have been carried out in [8]. For large ITER like NBI system the following parameters can be elected (See fig.2). The distance between mirrors is 6 meters. The neutralization zone width is 0.4 m. The cylinder mirrors radius of curvature is 5 m. The curvature radii of toroidal ends are 5 m and 20 m. The laser injection is realized through three groups of small holes

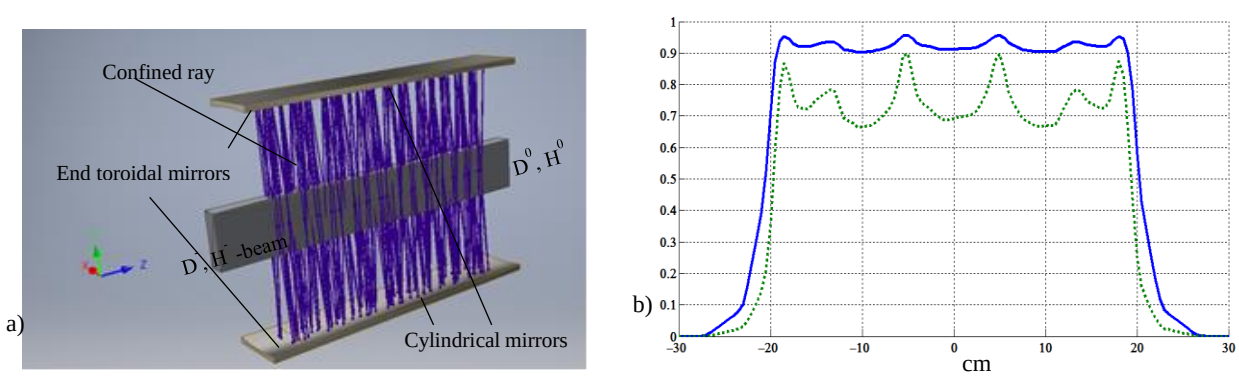

FIGURE 1. a) Layout of big photon neutralizer b) profiles of radiation intensity (doted) and neutralization (solid) at injection power 310 kW.

in mirrors. First group is located in 19 cm from middle vertical plane. Their laser beams has angular spread about 0.2 degree. The second group is located in 17 cm, has 1 degree spread. The third is respectively 8 cm and 3 degree. The total power is distributed on groups in proportion 0.3:0.4:03. The mirror reflectance is taken 0.9995. The averaged along Z-axis intensity profile obtained with using ZEMAX code is shown by dotted line in Fig.2b. As can be seen the

confinement region has sufficiently sharp boundaries. The calculated in simulation the total circulating in target radiation power corresponds to formula

$$P = P_{las} / (1 - R), \tag{2}$$

that confirms the confinement of photon trajectories between mirrors. Substituting calculated intensity in (1) as multiplication cW, we compute the neutralization degree. It is presented in Fig.2b by solid line. At calculating the total injection power is taken 310 kW. As seen the photodetachment exceeds above 90 %. Industrial fiber laser can provide up to hundred kilowatts of radiation power [10]. Their typical efficiency is about 30%. Thus no problem with radiation sources in comparison with resonance approaches.

TECHNOLOGICAL DISADVANTAGES AND ADVANTAGES

Let us consider more important difficulties. Firstly it is large mirror area. Clearly, manufacturing such single mirror is impossible. It have to be combined from sufficiently small elements. The main problem is creation of the multilayer dielectric films with high requirements of uniformity. At present the several manufacturers are ready to consider dimensions about 50x50 cm^2.

The second problem is mirror stability toward neutron or other particle flux. As for neutron load the tests [11] have demonstrated that mirrors with titanium and zirconium dioxide films can withstand fluence of 10^{19} n/cm^2. Taking into a count the neutron flux at outside NBI ducts order10^{12} $n \cdot cm^{-2}s^{-1}$ [12] the mirrors ca be used at least several years.

Other particle flow will produced due to scattering high energy particle (neutrals, ions) on residual vacuum particles (of order 10^{-2} Pa[13]). A Simple estimation leads to load ~10^9 $cm^{-2}s^{-1}$. Although this is significantly lower than possible neutron flux, it is probably the defects and vacancies in dielectric film and substrate will being more rapid created due to stronger interaction between charged bombarding particles and atoms of mirror. This issue needs experimental research. Probably significant improve the vacuum conditions the will be needed. Note that the calorimetry will be possible only at shielded mirrors i.e. without neutralization.

The third problem is powerful cooling system for mirrors. The average heat flow does not exceed 10 W/cm^2. It does not seem an insurmountable problem despite large total radiation power.

Advantages are as follows: the source of radiation with extremely high requirements to radiation quality is not needed; There is no need for an very complicated system of resonator elements stabilization; There is no need for a substantial modification of the negative ion beam generator to drastically reduce the width (a few cm) of the stream; The feasibility of such an approach with comparable accumulation coefficients in the target experimentally confirmed [8].

ACKNOWLEDGMENTS

The study was funded by a Russian Science Foundation grant (project No. 14-50-00080).

REFERENCES

1. R. Hemsworth et al. Nucl. Fusion., **49**, 045006 (2009)
2. G. I. Dimov and G. V. Roslyakov. Nucl. Fusion., **15**, 551 (1975).
3. L.M.Branscomb, and S.J.Smith, Phys. Rev. Lett., **98**, 1028 (1955).
4. J.H. Fink, A.M. Frank. Photodetachment of electrons from negative ions in a 200 keV deuterium beam source, Lawrence Livermore Natl. Lab., UCRL-16844 (1975).
5. M. Kovari, B. Crowley. Fusion Eng. Des., **85**, 745–751 (2010).
6. A. Simonin, Jocelyn Achard, K. Achkasov et al. Nuclear Fusion, **55** , 123020 (2015).
7. Acernese F. et al Class. Quantum Grav. **32**, 024001 (2015).
8. S.S. Popov et al. AIP Conference Proceedings **1869**, 050005 (2017); http://doi.org/10.1063/1.4995786
9. S.S. Popov et al. preprint https://arxiv.org/ftp/arxiv/papers/1703/1703.10777.pdf
10. http://www.ipgphotonics.com/47/FileAttachment/YLS-100000+Datasheet.pdf
11. I.I. Orlovskiy, K.Yu. Vukolov, Fusion Eng. Des., **74,** 865–869(2005).
12. P. Pereslavtsev et al. Fusion Eng. Des., **98–99,** 1585–1588 (2015).
13. Dremel M et al. Nucl. Fusion **49** 075035(2009).