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

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Introduction

Atomic powerful sources will be used as a source of heating of the plasma in future fusion reactors. To achieve high effectiveness of neutral injection the target with high neutralization efficiency is necessary in such systems. Currently, the main approach to neutralize the ion beams is to use a gas target, the efficiency of which at high energies (1 MeV) does not exceed 60% [1]. In addition, these approaches significantly affect the vacuum conditions and the appearance of impurities in the beam. A possible solution to the transformation of the negative ion beam to atomic one with high efficiency without flaws is a "photon trap", as the basic process of this method is based on the photodetachment of an electron from a negative ion. The use of the mechanism allows neutral atoms yield close to 100% [2].

Quasi-stationary photoneutralization based on the adiabatic photon trap

The trap consists of two complex surfaces composed of individual cylindrical and spherical mirrors with a typical size of 50 mm and a radius of curvature of 250 mm such, that multiple reflections of beams and their adiabatic retention (Fig. 1) [3]. Input laser radiation takes place through the aperture (d = 300 m) in one of the mirrors.

In the work applied dielectric mirror segments with a reflection coefficient 0.997, which allows radiation to accumulate several hundred times. The radiation pumping employs industrial ytterbium fiber laser with an output power up to 2kW and long wave 1069nm.

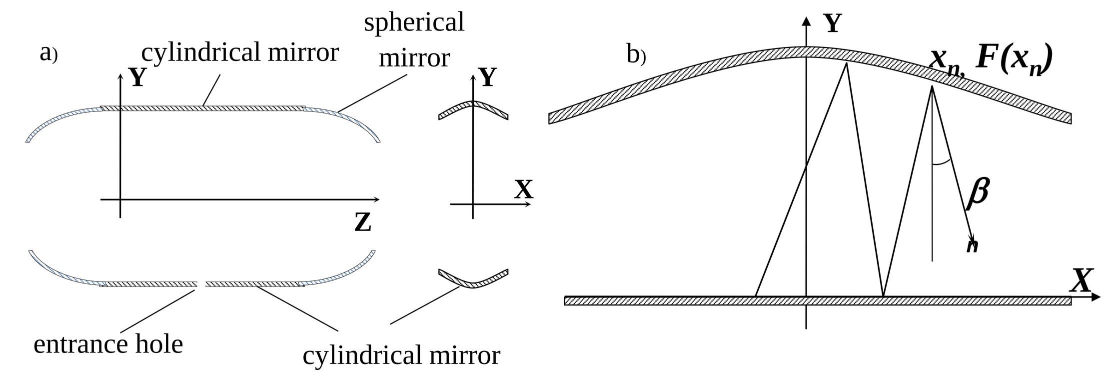


Fig. 1. **Scheme of nonresonance photon trap (a) and its action (b).**

Confinement of photons in such a trap is based on the adiabatic conservation $F(x)\cos(\beta) = const$ at stability condition [3]

$$F(0) < R\cdot(\cos\beta_{max})^2$$

Numerical simulation

To evaluate the applying of non-resonant converter, was carried out numerical calculation for the laser injection capacity of 2 kW and an energy H⁻ ions - 10 keV. Coefficient reflectance is selected not the maximum - 0.995. Simulation of the neutralization process shows an encouraging result for the experiment on a real beam (Fig. 2).

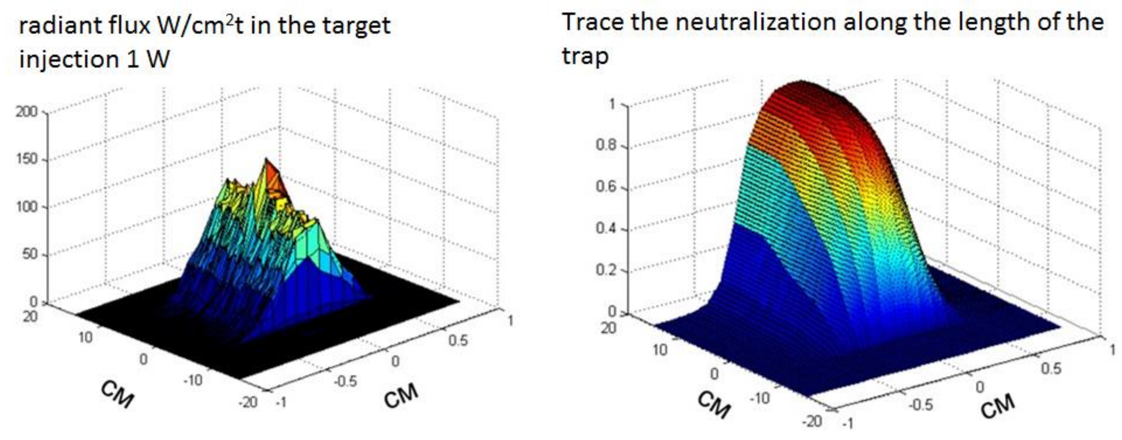


Fig. 2. **Modeling photo neutralization of negative ions.**

Scheme for the neutralization experiment H^- and D^- in an adiabatic optical trap

For carry out the experiment at measuring the coefficient of neutralization in the quasi-stationary photon exchange target, was made a special installation the stand is shown in Fig. 3.

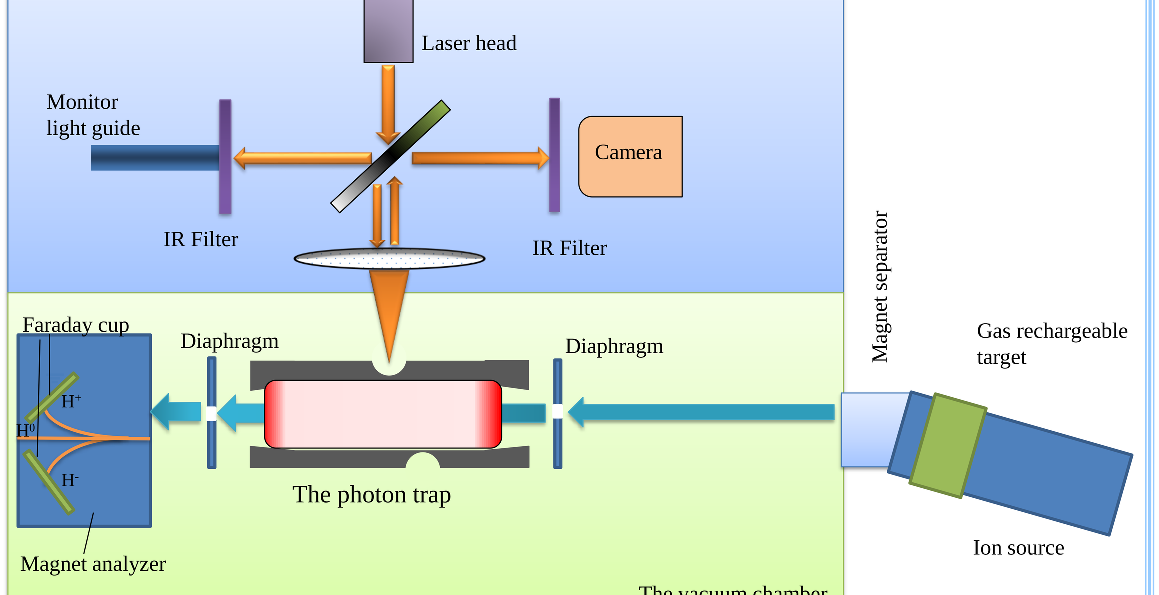


Fig. 3. **Experimental setup.**

The stand includes a system input laser radiation in photon target, a beam injector DINA-4M (E=6÷12keV), and the system of Registration of the charged components. Laser radiation is focused by a lens into the inlet target. Aligning the laser radiation is carried fast SDU camera, fixing the position of the laser spot near the hole. At minimum power the laser spot is aimed at the inlet via the translator of the focusing lens.

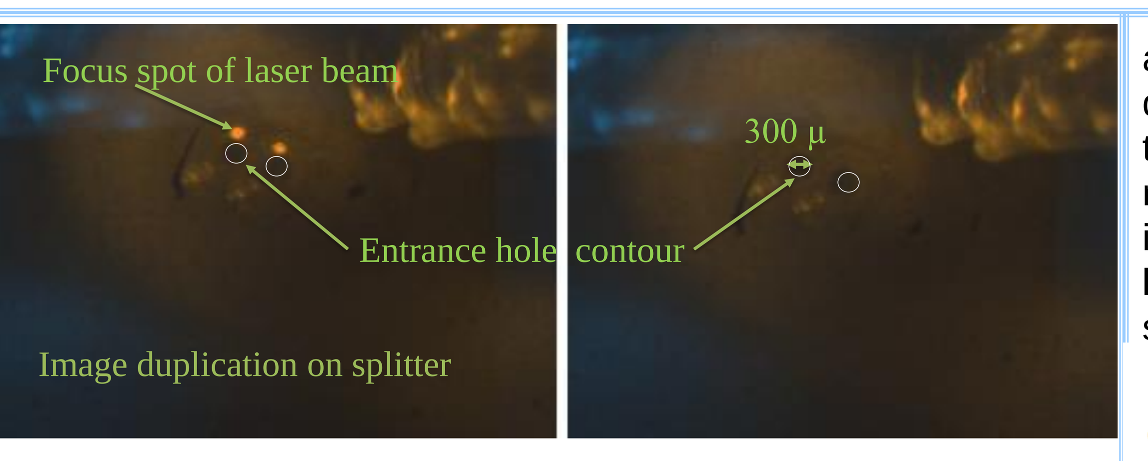


Fig. 4. **Aiming of the laser beam. (a) – missing ; (b) – hit.**

Inner view of the vacuum chamber with optical breadboard on wich the photon target and the diagnostic of particle beam are placed is shown in Fig. 5. The diaphragms with wide of 2 mm is located before and after the target, to isolate a narrow beam area corresponding area of neutralization.

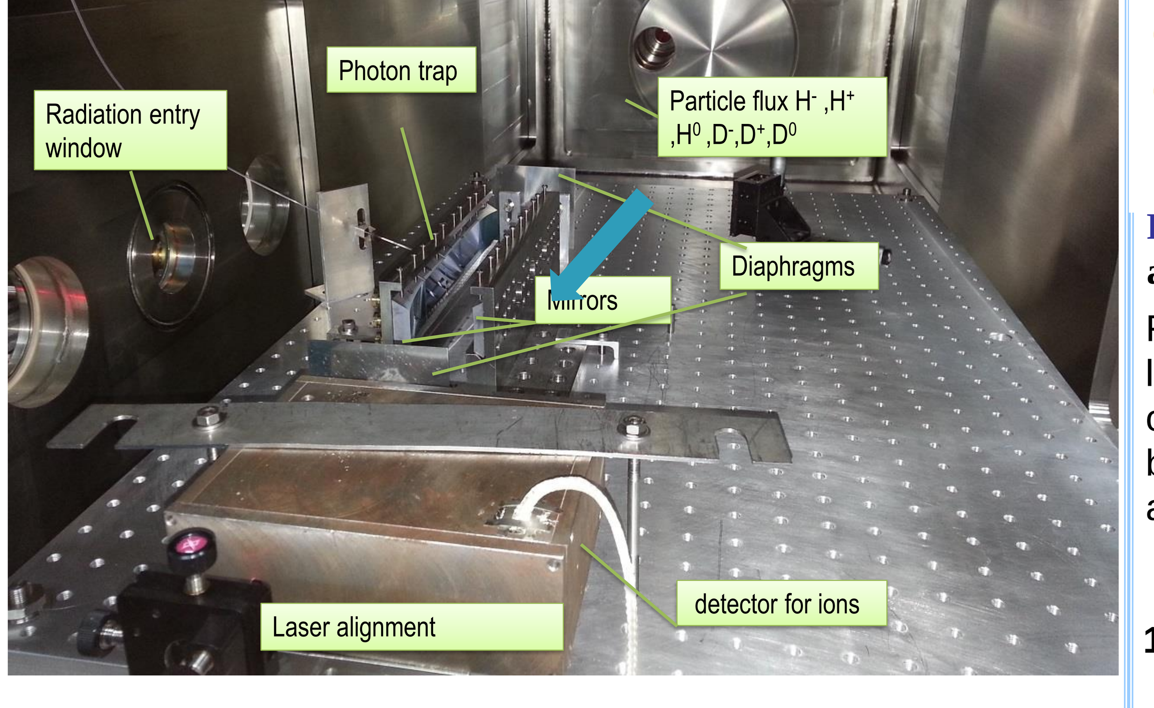


Fig. 5. **Photo of the vacuum part of the experimental set up.**

The level of current negative ion having a fractions of microamperes, is detecting particle analyzer.

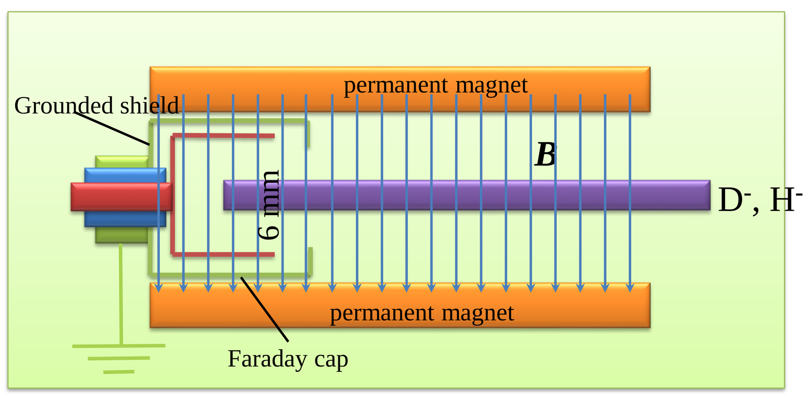
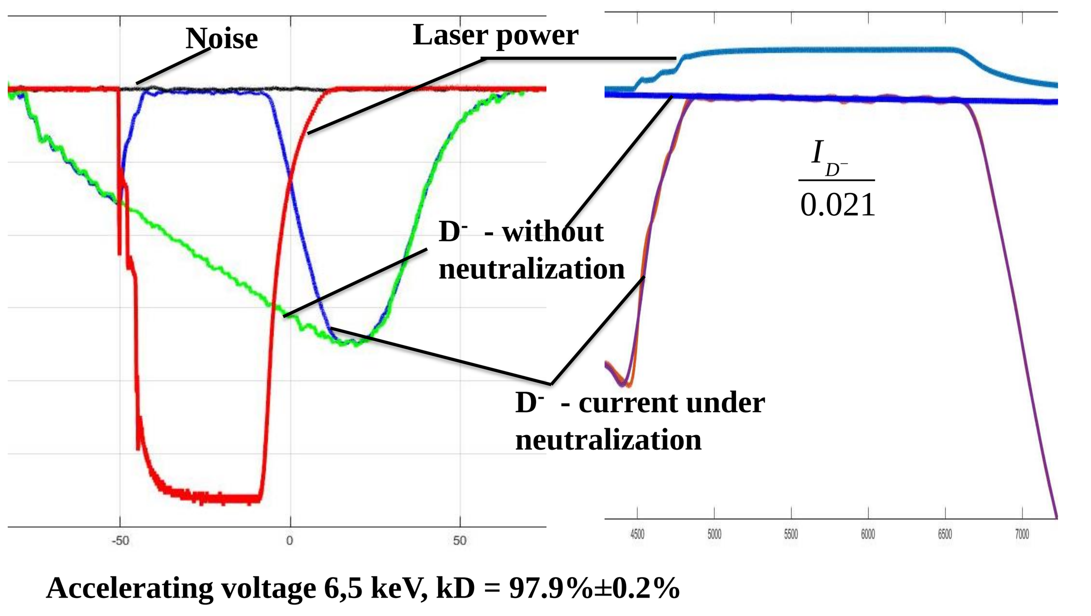


Fig. 6. **Scheme of detectors for negative and positeve ions.**

Main experimental Results

The degree of neutralization is determined by the ratio of signal current to the signal enabled without laser in target. The experiments were conducted at an energy of particles 6,5 - 12 keV, working gas of hydrogen and deuterium.

Fig. 7 shows the D^- beam waveform without neutralization (green), neutralized beam (blue) at an energy of 6.5 keV, the laser light (red) and electromagnetic noise (black). In this series of experiments, the maximum neutralization coefficient is k=98 %.



Accelerating voltage 6,5 keV, kD = 97.9%±0.2%

Fig. 7. **Oscillograms in experiments on neutralization D^- beam (a). The same waveforms averaged on 100 shots and scaled (b).**

Concept for big ITER-like NBI system

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 through small holes in mirrors is divided into three groups. 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.

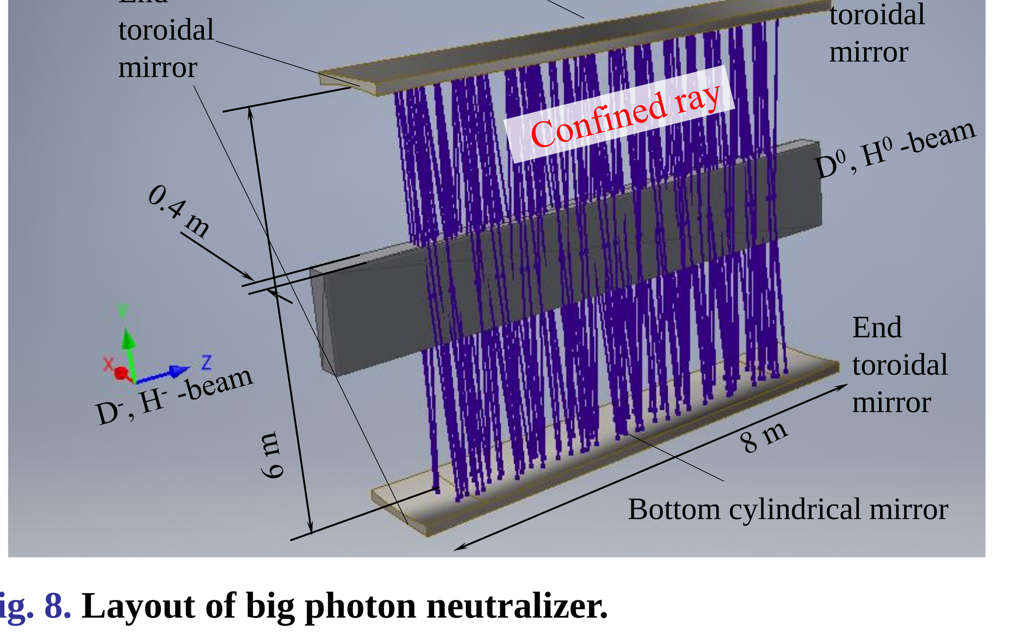


Fig. 8. **Layout of big photon neutralizer.**

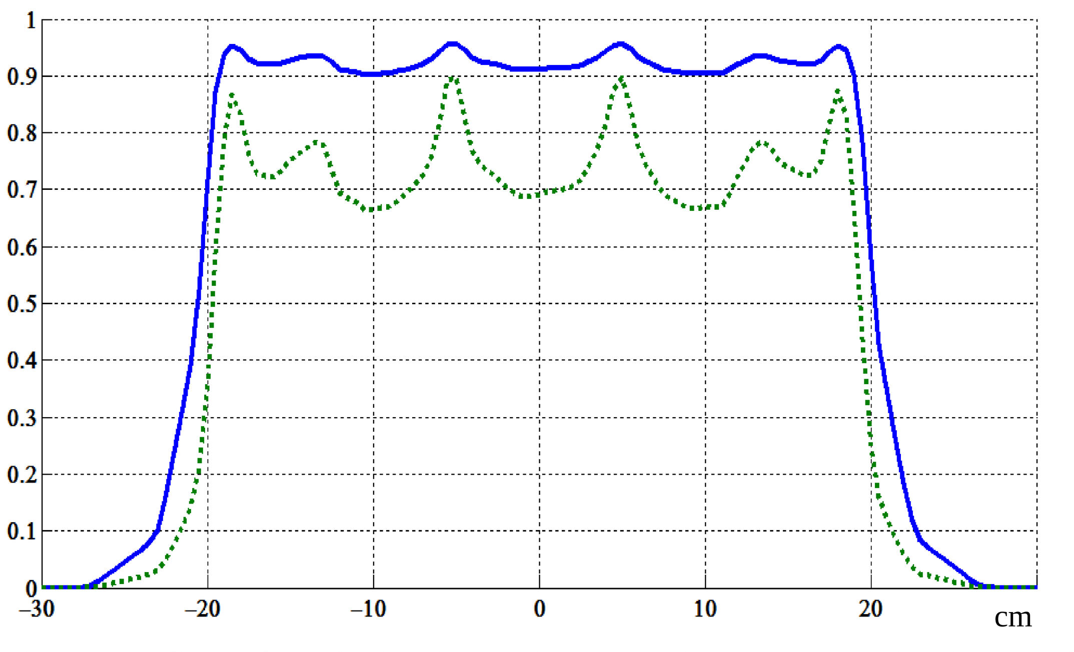


Fig. 9. **Profiles of radiation intensity (doted) and neutralization (solid) at injection power 310 kW.**

For radiation injection the powerful (above 100 kW) commercial lasers with wall plug efficiency 30% are allowable [4]. The efficiency of NBI as ratio of neutral beam power P_0 to sum of negative ion beam power P_- ~40 MW and laser energy consumption P_l/η_l is above 90%.

Technological problems

1. **Large mirror area**. 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** cm².
2. **Mirror stability toward neutron or other particle flux.** As for neutron load the tests [5] have demonstrated that mirrors with titanium and zirconium dioxide films can withstand fluence of **10^{19}** n/cm². Taking into a count the neutron flux at outside NBI ducts order**10^{12}** n·cm⁻²s⁻¹ [6] 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[7]). A Simple estimation gives load ~**10^{9}** cm⁻²s⁻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. This issue and also effect of electrons detached from negative ions 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.
3. **Cooling system for mirrors.** The average heat flow does not exceed **10** W/cm². It does not seem an insurmountable problem despite large total radiation power.

Advantages

1. **Radiation sources availability.** The source of radiation with extremely high requirements to radiation quality is not needed.
2. **Very complicated system** of resonator elements stabilization is not needed.
3. **A substantial modification** of the negative ion beam generator to drastically reduce the width (a few cm) of the stream is not needed.
4. **The possibility** of such approach with comparable accumulation coefficients in the target experimentally confirmed.

Conclusion

Carried out experiments confirm high potential of nonresonance photon target method for effective neutralization of negative ion beams. This photon accumulator can be pumped by the commercial fiber laser. However for creation large neutralizer for example ITER neutral heating system [1] or Tri Alpha Energy Inc. heating device [8], it is required manufacturing big mirrors of complicated shape. A mirrors stability under high energy atom, ion, electron flows is very important issue. But on the other hand we get simplifying and reduction in cost of radiation source, positioning and stabilization system for optic elements.

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