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Laboratory Experiment for the Development of a Laser Neutralizer in View of DEMO NNBI

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Abstract. Laser neutralization of an accelerated negative ion beam is a promising alternative to the gas neutralizer of current NNBI systems. It has the prospect to boost the overall wall-plug efficiency of the NNBI system from currently about 28 % at ITER to about 60 % for the next step after ITER, a DEMO tokamak. Laser neutralization requires resonant coupling of a cw laser to an amplification cavity, which contains the ion beam. In the final stage, the amplified laser radiation of several hundreds of MW needs to intersect an ion beam cross section of ~ m^2 at energies up to 1 MeV. Such a sophisticated concept needs to be tested in small-scale at laboratory experiments. Challenges include the realization of covering the entire ion beam cross section, thermal lensing of the cavity mirrors due to the huge optical power loads as well as coupling to a cavity under vibrations due to vacuum pumps and possible interferences during ion beam extraction. Using a medium power laser (8 W), investigations regarding the influence of vibrations are performed on an independent optical table, while in a second step the application to an ion beam with reduced cross section (~ mm^2) and beam energy (~ keV) will be studied.

INTRODUCTION

For the ITER neutral beam injection system (NBI) neutralization of the accelerated negative ions will be achieved with a gas neutralizer. However, its neutralization efficiency is only at about 60 % [1], leading to a large amount of wasted power and thus to a decrease of the overall efficiency of the NBI system (presently at about 28 %). For a future steady-state DEMO tokamak that requires high neutral beam powers for current drive, the NBI system must achieve a wall-plug efficiency of at least 50 %. Therefore, alternative neutralization concepts have been discussed [2, 3] with the photoneutralizer being a promising candidate with which neutralization efficiencies of more than 95 % might be possible depending on the provided optical power. Together with the reduced pumping requirements in the absence of a gas target and the reduced requirements on the cooling of the ion dump, the wall-plug efficiency of the entire NBI system can be increased to roughly 60 % [2].

It was shown in [2] that the total circulating optical power needed for the neutralization of an accelerated ion beam power of 40 MW is of the order of several hundred MW. Therefore, the use of optical cavities is mandatory, reducing the initially required optical power by about $10^4 – 10^5$. One possible concept is to couple the laser light into an enhancement cavity that also contains the ion beam (neutralizer cavity) [4]. To achieve the envisaged neutralization efficiency, the wavelength of the narrow band laser has to be resonantly coupled to the cavity length (Pound-Drever-Hall locking technique [5]) and the laser beam within the cavity needs to intersect the ion beam at its entire cross section, which might be very large, e.g. around m^2 for ITER NNBI. Furthermore, coupling of laser, cavity and ion beam needs to be stable under enormous optical power loads at the mirrors, under vibrations from vacuum pumps, under neutron radiation from the torus, as well as during interaction with the ion beam itself.

Feasibility studies on this concept are performed at a laboratory testbed in small-scale, based on a medium power laser (1064 nm, 8 W). In order to investigate the influences of vacuum pump vibrations on the stability of the cavity locking, the optical system including the laser head and the cavity is installed on an independent optical table without connection to an ion beam in a first step. The second step will be the application to an ion beam at reduced parameters (energy ~ keV, cross section ~ mm^2). For an acceleration potential of 1 kV the laser power is calculated to be sufficient for a neutralization efficiency of up to 90 %. The further objective is to identify potential show-stoppers for a laserneutralizer-based NNBI system at DEMO.

OPTICAL SETUP

The total envisaged optical setup including the required optics for mode-matching and -locking is shown in figure 1 together with its realization on the vibration-isolated optical table (1.2 × 2.4 m).

The laser radiation is reflected off an adjustment mirror and is led through a double stage Faraday isolator that prevents back-reflected light from re-entering the laser head. Via a variable beam attenuator the optical power from the laser (driven at the nominal value of 8 W) can be adjusted without losing the characteristic parameters of the laser beam, such as beam width, divergence and direction. In order to couple the laser radiation into the optical cavity, the propagation of the laser beam has to be adapted to the envisaged propagation mode within the cavity (fundamental Gaussian mode, see figure 2). This is done by an optical mode-matching system that mainly consists of two high-quality lenses. The required properties of these lenses are determined by calculating the Gaussian beam propagation and adapting it to the requirements given by the fundamental mode of the cavity. The electro-optical phase modulator (EOM) modulates the laser frequency, creating sidebands in the frequency spectrum. This is required for the Pound-Drever-Hall (PDH) locking technique [5] described below. According to the horizontal polarization of the laser, the following polarizing beam splitter (PBS) transmits the laser light in forward direction. With the subsequent λ/4 waveplate the linearly polarized light is converted to circular polarization. Once mode-matching and -locking are achieved the laser light is coupled into the resonator.

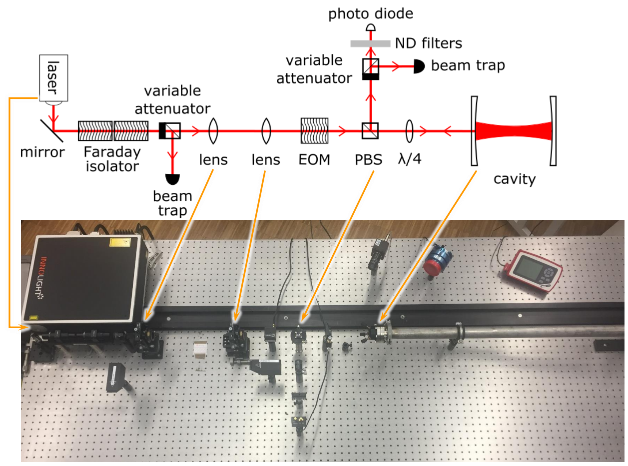

FIGURE 1. Schematic of the optical setup for mode-matching and -locking (EOM = electro-optical phase modulator, PBS = polarizing beam splitter, λ/4 = wave plate, ND = neutral density).

Even when the laser frequency ω_{laser} is locked to the resonance frequency ω_{cavity} of the cavity at least the modulated sidebands are reflected back from the entrance cavity mirror and are converted to vertically polarized light at the λ/4 waveplate. The beam splitter now directs the light towards the photo detector. Since without mode-lock the full laser power is reflected off the cavity, the laser needs to be attenuated before irradiating the photo diode to prevent damage. This is performed via another attenuator combined with neutral density (ND) filters. By mixing the signal from the photo detector with the original driver signal for the EOM and a low pass filter (LPF) a DC signal is created, the Pound-Drever-Hall error signal. This signals depends on the difference between the cavity resonance frequency and the laser frequency having different signs for $\omega_{\text{laser}} < \omega_{\text{cavity}}$ and $\omega_{\text{laser}} > \omega_{\text{cavity}}$. This can be used to tune the laser frequency to the cavity resonance via a PID controller and continuously track it to achieve a stable lock.

CURRENT STATUS

In order to meet Gaussian beam propagation within the cavity (see figure 2), beam profile calculations need to be performed by ray transfer matrix analysis using the complex beam parameter of the Gaussian beam [6]. With these, the waist of the beam as well as its position are determined depending on the characteristics of the input beam and the position and focal lengths of the two lenses used for mode-matching. Here, the beam waist to be achieved is given by the Gaussian mode of the cavity (410±2 µm). Thus, if the focal lengths (127.1 mm & 152.6 mm) and the position of the first lens are given, the corresponding position of the second lens can be calculated. Furthermore, the actual position of the beam waist along the optical axis is an output which is necessary for correct positioning of the cavity mirrors. Beam profile calculations significantly depend on the characteristics of the input beam at the first lens. Thus, the laser beam profile needs to be accurately measured and, furthermore, continuously checked throughout the set up procedure. A beam profiler is used for that purpose as it is capable of determining the beam width with a certainty of better than 3 % down to values of 20 µm.

The actual beam characteristics after the isolator and the attenuator (see figure 1) were checked in order to confirm the input beam for the mode-matching lenses and the appropriate lens positions were determined using ray transfer matrix analysis. Subsequently, the optical components for mode-matching and -locking (PDH optics: EOM, PBS, λ/4) were aligned and the final laser beam profile is measured. Figure 2 (a) shows the comparison of the measured profile with a calculated one (dashed line) using the initial laser beam without disturbance due to the optical components. The

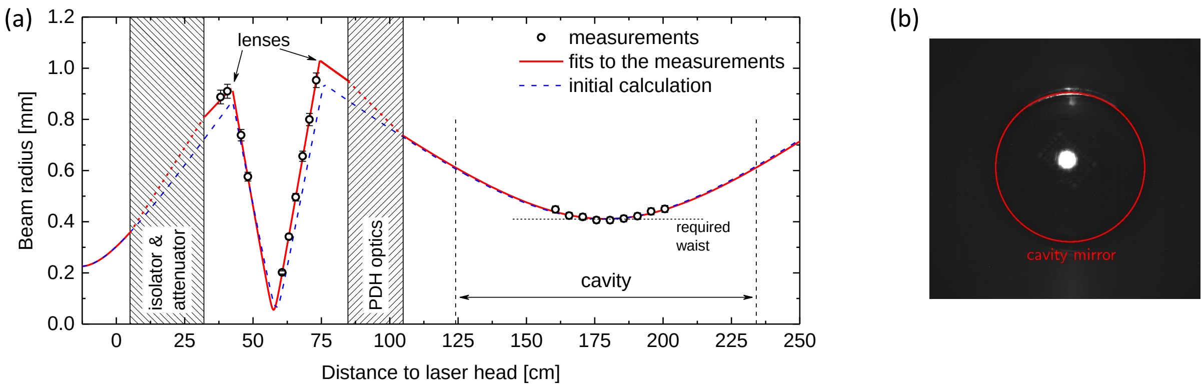

FIGURE 2. (a) Beam profile determined by measurements and compared with a calculated one neglecting the optical components. (b) Photograph of a coupled Gaussian mode within the cavity taken with a CMOS camera.

correct beam waist for Gaussian beam propagation at the position of the cavity is confirmed. Furthermore, it can be seen that the optical components result in an elongation of the optical path, since they consist of media with non-unity refractive index. This leads to wider (and narrower, respectively) beam radii than expected from propagation in air.

Finally, the cavity was installed at the appropriate position. It consists of two highly reflective mirrors (99.99 %) installed in adjustable mirror mounting flanges and a stainless steel tube connecting them (length 1.1 m). The tube moreover comprises the flange for evacuating the cavity. Optimal alignment of the cavity is confirmed by measuring the profile in the sidearm of the polarizing beam splitter, where the reflected beam is directed (see figure 1).

The success of alignment can be verified by positioning a CMOS camera behind the cavity. The result can be seen in figure 2 (b) where a coupled Gaussian mode within the cavity is shown. However, the mode is not constant, but it varies with time showing several different modes with a timescale of about 10 seconds. For locking the Gaussian mode and thus achieving the required amplification within the cavity, the laser frequency needs to be locked to the cavity resonance. This is to be achieved by the Pound-Drever-Hall lock (PDH lock) in the next stage.

CONCLUSION

A laboratory experiment for the development of a small-scale laser neutralizer in view of DEMO NNBI is set up, particularly addressing the influence of vacuum pump vibrations and possible interferences due to an ion beam within the amplification cavity. The aim is the experimental realization of a substantial, i.e. measurable, neutralization of a small negative ion beam (single aperture extraction) via a photo-detachment neutralizer utilizing an external optical cavity. Identification of potential show-stoppers along the way is another objective. The optical components including the amplification cavity are aligned on an optical table according to calculations of the beam propagation profile. The profile is verified by measurements and first Gaussian modes are observed within the cavity. Next step is to realize the feedback system in order to adapt the laser frequency to the cavity resonance. Via this Pound-Drever-Hall locking scheme stable continuous-wave coupling can be achieved. Afterwards, the cavity can be evacuated and coupling during vacuum pumping is studied. In a last step, the optical setup can be installed at a negative ion beam with reduced parameters.

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