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Design and mockup tests of the RING photo-neutralizer optical cavity for DEMO NBI

P. Vincenzi, A. Fassina, L. Giudicotti, R. Pasqualotto

Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA) Corso Stati Uniti 4 - 35127 Padova, Italy

High energy Neutral Beam Injection (NBI) is one of the methods being considered to heat EU DEMO plasma. A major issue of present NBI systems is the limited efficiency of the gas neutralizer (for ITER NBI ~55-60%), which impacts on the overall system efficiency. An attractive method, but still undemonstrated at full performances, is the photo-neutralization of the negative D-ion beam, with an expected neutralization efficiency for a full-scale DEMO NBI up to 70-90%.

A possible scheme for photo-neutralization is named RING (Recirculation Injection by Nonlinear Gating) where a laser second harmonic is generated and trapped within a non-resonant optical cavity. A mock-up of the optical cavity is being operated in Consorzio RFX with a low repetition rate Nd:YAG laser (f=10 Hz, λ=1064 nm) to study the feasibility of the RING concept and its potentiality for a full-scale NBI photo-neutralizer. The 2nd harmonic generation efficiency has been measured using a set of 3 Lithium Triborate (LBO) crystals in a disk configuration, confirming the non-linearity of the process with the total crystal thickness. Losses during the 2nd harmonic recirculation in the cavity have been measured in order to estimate the optical cavity performance and to consider further improvements to increase the optical cavity photon accumulation.

Keywords: DEMO, NBI, photo-neutralization, negative ions, optical cavity

1. Introduction

Neutral beam injection (NBI) is currently one of the most used systems to provide auxiliary power to the plasma, with the main aim of plasma heating. ITER foresees the use of 2 neutral beam (NB) injectors, with an injected power up to 33 MW [1]. NBI is being considered also for the future EU DEMO reactor [2]. ITER and DEMO NB systems are characterized by the injection of neutral particles at energy in the order of 800-1000 keV, originated from a negative ion beam, and neutralized before entering in the plasma. A major issue for the NB systems conceived nowadays is the limited efficiency of the gas neutralizer, based on electron stripping of the weakly bound electron of the negative ion in a low pressure gas. The low efficiency of this process (e.g. for ITER NBI, the gas neutralizer efficiency is ~55-60% [3]) impacts adversely on the overall system efficiency, insufficient for future reactors.

Alternative solutions for neutralization are under investigation, and one of the most promising seems to be the neutralization of negative Deuterium ions (D^-) by photon impact (photo-detachment of the electron or "photo-neutralization"): $D^- + h\nu \rightarrow D + e^-$. The photo-neutralization takes place into an optical cavity, where a sufficient amount of laser photons interacts with the D^- beam. The frequency of the laser is chosen to maximize the photo-neutralization cross section. The theoretical neutralization efficiency can reach 100%, and it is expected to be 70-90% for a full-scale, high energy, DEMO NBI, depending on available optical power and

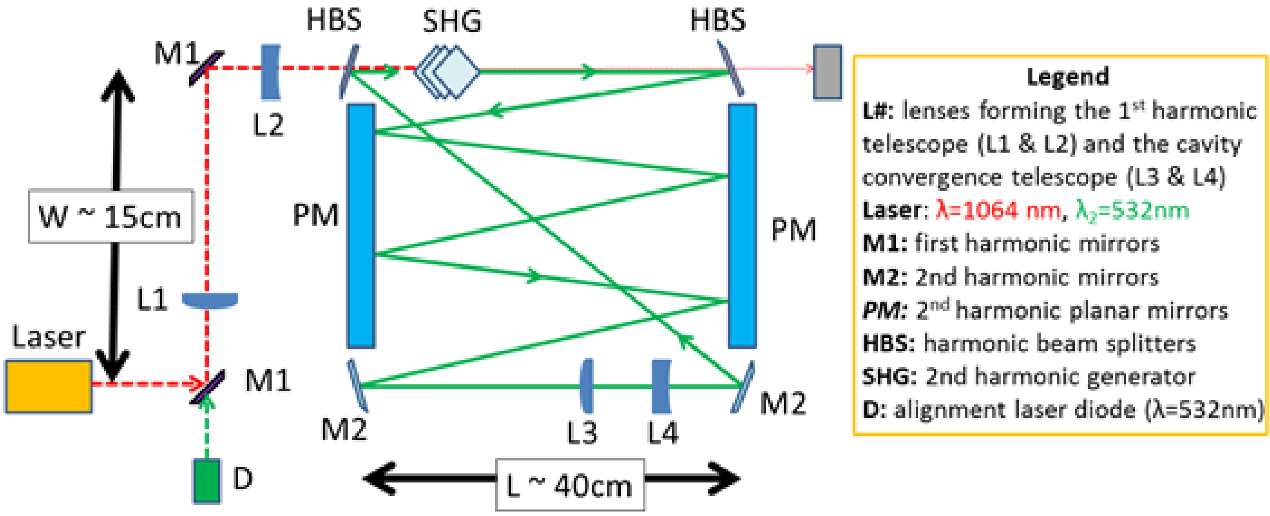

Fig. 1. Cavity mockup optical scheme

author's email: pietro.vincenzi@igi.cnr.it

the optimization of the interaction volume between the negative ion beam and photons.

Various photo-neutralizer concepts are being studied. A scheme based on a Fabry-Perot high finesse resonator is being developed at CEA [4]. Recent experiments with a medium finesse cavity demonstrated the photo-neutralization of ~50% of a low energy H^- beam [5]. At Budker institute, a non-resonant adiabatic photon trap has been used to obtain a photo-neutralization efficiency up to 98%, with a low energy D^- beam [6].

A different concept for a non-resonant optical cavity is being developed in Padova, at Consorzio RFX. A description of this scheme and of the mockup recently built in Padova is reported in section 2. Section 3 describes the operation of the cavity with a low repetition rate laser and results on the optical cavity performances. Conclusions and future work are reported in section 4.

2. Description of the optical cavity mockup

The optical cavity for photo-neutralization studied at Consorzio RFX is named RING (Recirculation Injection by Nonlinear Gating) [7]. The feasibility of a full-scale RING photo-neutralizer has been firstly investigated by means of numerical simulations in [8]. In this scheme, the second harmonic of a laser is generated by a non-linear crystal and trapped within a non-resonant optical cavity. Unlike resonant cavities as Fabry-Perot [4], non-resonant concepts relax the requirements on the laser radiation quality and occupied volume, at the price of higher laser power. With respect to the non-resonant adiabatic trap developed at Budker institute and described in [6], where the laser enters the cavity from an aperture, RING concept prevents laser injection losses, since the laser 2nd harmonic experiences a closed cavity. The intensity of 2nd harmonic, while multi-refolded in the cavity, decays exponentially due to optical losses on the mirrors and on the second harmonic generator (the non-linear crystal). The figure of merit of the cavity performance is the number of roundtrips of the 2nd harmonic photons, which depends on the optical losses. In the full-scale RING photo-neutralizer proposed in [8], ~100 roundtrips were estimated for high neutralization efficiency (90%) of a high energy D^- beam.

In order to estimate the losses, to verify the behavior and the thermal stability of the second harmonic generator (SHG), and to test the optical and mechanical stability of the concept, a small scale mockup of the cavity has been built in Padova [9], and it is sketched in fig. 1. The mockup is operated with a low repetition rate Nd:YAG laser (f=10 Hz, λ=1064 nm, with a second harmonic at λ_2=532 nm). The photo-neutralization cross section for a hydrogenic negative ion beam with the second harmonic of a Nd:YAG laser is close to $3{,}1 \cdot 10^{-17}$ cm^{-2}, i.e. ~75% of the maximum cross section (reached at λ~850 nm) [10]. Despite the non-optimum matching in wavelength, the choice of a Nd:YAG laser is nonetheless favorable due to the higher available power and lower costs of this technology.

The peculiar characteristic of this optical cavity scheme is the presence of a 2nd harmonic generator, which is formed, in the cavity mockup, by 3 plates of a LBO crystal (20mm x 20mm x 1.5mm each), shown in fig. 2. The crystal is divided in several plates in order to dissipate efficiently the heat, caused by the laser passage. This design is required in a full scale neutralizer in order to allow an efficient cooling. In the available mockup, the laser power is low and the crystal dissipates the heat in air. The 2nd harmonic generation efficiency η_{SHG} is expected to depend on the square of the crystal thickness and linearly on the laser intensity, as shown in [11]:

$$\eta_{SHG} = C^2 L^2 \frac{P}{A}, \quad C^2 = 2\omega^2 \eta_0^3 \frac{d^2}{n^3} \qquad (1)$$

where P/A is the laser intensity, L is the total crystal thickness, C is a constant depending on the refraction index *n*, the light angular frequency ω, the material second order susceptibility *d*, and the free space impedance $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$.

In the mockup, two telescopes (1st harmonic telescope and cavity convergence telescope, see fig. 1) have been positioned to control the laser beam divergence, with the aim of having a shallow refocus of the beam at each passage, avoiding hot spots on the optical materials. The beam transversal dimension is an important parameter, since the 2nd harmonic generation efficiency depends linearly on the laser intensity (W/m^2). The 1st harmonic diameter on the SHG is about 1-1.5 mm. The cavity is delimited by two lines of mirrors, including two parallel

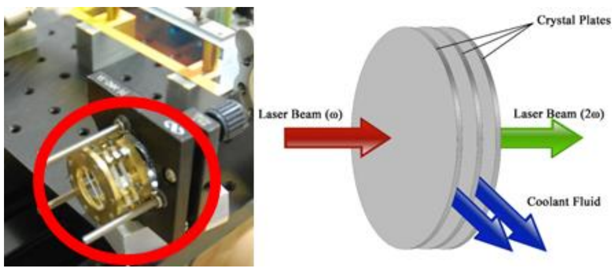

Fig. 2. Details of the 2nd harmonic generator in the mockup (left) and a sketch from [8], (right) showing the 3 plates of the LBO crystal, designed to allow fluid cooling.

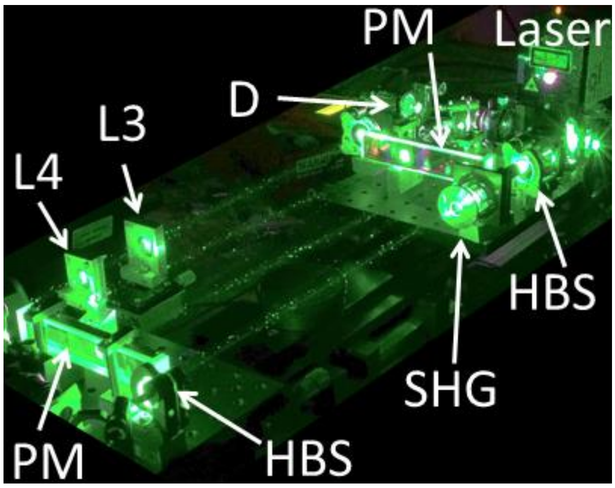

Fig. 3. The optical cavity mockup in operation. The 2nd harmonic (green light) path inside the cavity is clearly visible.

flat mirrors of 100 mm length at 400mm distance. The 1st harmonic enters (and exits) the cavity passing through a harmonic beam splitter (dichroic mirrors -HBS-), which instead reflects the 2nd harmonic. The 2nd harmonic is reflected for a total of 8 times per roundtrip, with a photon path length of ~3.2 m travelled in 10.8 ns.

3. Operation of the cavity and performance measurements

So far the cavity has been conservatively operated at low laser energy (below 100 mJ), in order to reduce the risk of optical damages in the SHG crystal. Low laser energy impairs on the SHG efficiency, but since we are not neutralizing any beam in the current setup, the photon intensity in the cavity is not a figure of merit at the moment. The optical alignment of the cavity appears not to be critical, and repeated measurements tuning different optical elements have been possible. We have been able to control the beam divergence obtaining an almost parallel laser beam. A picture of the cavity in operation is shown in fig. 3, where it is possible to see the path of the 2nd harmonic beam (green light) reflected inside the cavity.

Table 1. 2nd harmonic generation efficiency measurements with a pyroelectric energy meter, pulsed laser input at 30.4 mJ nominal energy (1st harmonic). Expected SHG efficiency from eq. 1 in the rightmost column.

Crystal plates	tot. crystal thickness [mm]	SHG efficiency %	SHG eff. % from eq. 1
1	1.5	1,83 ± 0,18	1,71
2	3	5,25 ± 0,62	6,85
3	4.5	11,78 ± 1,16	15,41

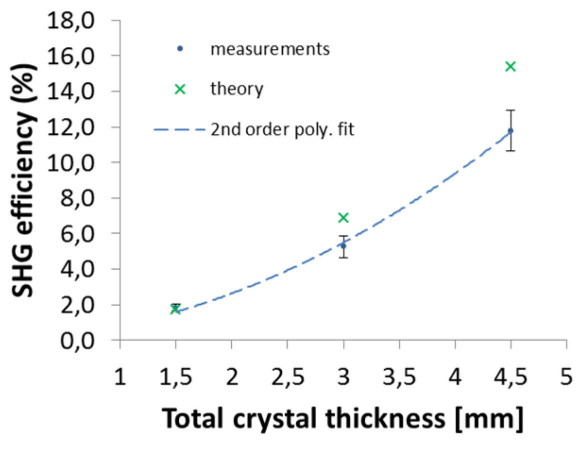

Fig. 4. Second harmonic efficiency as a function of crystal thickness ("theory" from eq. 1).

The first step has been to verify the 2nd harmonic generation, whose efficiency is expected to depend on the square of the crystal thickness (eq. 1). In our case we have a set of 3 crystals in a disk configuration (fig. 2), and laser wavefront coherence has to be maintained among the crystal surfaces. Measurements with 1, 2 and 3 crystal plates (1.5mm thick each, separated by 1.5 mm air) have been performed with a pyroelectric energy meter placed inside the cavity, averaging over 100 laser pulses. Results, summarized in table 1 and plotted in fig. 4, show a quadratic dependence of the SHG efficiency on the total crystal thickness. The verification of the quadratic dependence is a non-trivial result since each plate of the crystal is separated from another. The theoretical value calculated with eq. 1 is also reported, assuming a laser spot on the crystal with a diameter of 1 mm and a laser pulse duration of 25 ns.

We have also measured the SHG efficiency as a function of the laser intensity, changing the laser energy at the same pulse duration and laser beam transversal dimension. We confirmed the linear dependence of the SHG efficiency with the laser intensity. In a full-scale RING photo-neutralizer as proposed in [8], (with higher laser intensity and thicker crystal) the SHG efficiency is expected to saturate at ~70%.

A radiometer has been used to quantify the power losses after every passage of the light of the alignment laser diode (λ=532 nm) on an optical element of the cavity. The planar mirrors show very low losses, undistinguishable from measurement noise. The SHG and the HBS show losses in the order of ~5%. The two tilted mirrors M2 in fig. 1 reflect ~93% of the laser beam. The majority of the losses happens in the cavity convergence telescope, which loses almost 42% of the light. For this reason we foresee to substitute the telescope lenses, and also to install customized mirrors for not-normal reflections to further improve the performances.

In order to measure the figure of merit of the cavity performance, which is the number of roundtrips done by the 2nd harmonic photons, a fast Si pin photodiode has been installed to track the pulse decay as a function of time. The photodiode looks at the transmitted light from the back of the planar mirror in correspondence of a light spot of the 2nd harmonic reflection (the light spots on the planar mirror are visible in fig. 3). To reduce the losses and collect a strong enough signal, we have removed the cavity convergence telescope, at the price of having a slightly divergent light beam. The photodiode is screened by a 1st harmonic filter and a laser diffuser, used in order to level out the intensity on the photodiode sensitive area, because of the changes in the 2nd harmonic beam diameter roundtrip after roundtrip. With the available laser, we have been limited in the reduction of the pulse length, and therefore we have been not able to separate in time the signals of each roundtrip of the 2nd harmonic on the oscilloscope. We have anyway estimated a number of ~10 roundtrips in the cavity, dividing the FWHM of the convoluted pulse decay signal (the "duration" of the trapped 2nd harmonic) with the photon roundtrip time previously calculated (10.8 ns). This value is in agreement with a photon life-time of ~140 ns estimated from simple analytical calculations in [9], assuming an average reflection index R=0.99 for all the optical elements (and excluding the losses on the telescope). With the foreseen installation of new optical materials we expect to obtain a higher number of roundtrips, in the order of 20-40.

4. Conclusions and future work

The photo-neutralization of a hydrogenic negative ion beam can be a solution for NBI system low efficiency in the path towards DEMO.

At Consorzio RFX, a non-resonant optical cavity for photo-neutralization (RING concept) is being studied. The peculiarity of this scheme is the trapping of the 2nd harmonic of a laser beam, generated by a non-linear crystal. A mockup to test the feasibility of this scheme has been built: the cavity has been operated with a low repetition rate Nd:YAG laser and characterized through several measurements. The 2nd harmonic generation and its dependence on the total crystal thickness and laser intensity have been verified in a disk configuration, with a set of 3 crystal plates, designed to better dissipate the heat of the laser pulse. The optical alignment of the cavity and the control of the beam divergence are not critical, and the setup is mechanically stable. The losses on each optical element have been estimated, and we foresee to substitute some elements with customized objects to improve the cavity photon accumulation. The figure of merit of the optical cavity performance is the number of roundtrips done by the 2nd harmonic photons. We have estimated ~10 roundtrips, in agreement with previous analytical calculations. As diagnostics, in addition to a pyroelectric energy meter and a fast Si pin photodiode, we plan to employ a CCD camera to track the beam envelope. We aim to further improve the optical cavity performances and complete its characterization in order to assess the potentiality for actual photo-neutralization.

Acknowledgments

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