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Performance analysis and application study of a laser enhancement cavity for photo-neutralization of Negative Ion Beams

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Abstract: Photo-neutralization of negative ion beams is now regarded as a promising concept to enhance plasma heating system efficiency of negative ion based neutral beam injection in large fusion experiments. In this work we describe a photoneutralization scheme currently under test at Consorzio RFX based on the trapping of the second harmonic of a Nd:YAG laser in a closed loop optical cavity. In this work the system performances are analyzed with respect to optical layout and optical losses, in order to identify an optimal configuration, as well as to validate a simple numerical model. The latter is developed to assess the photo-neutralization degree achievable once the system is applied to the NIO1 negative ion beam facility in Padova. In particular, the study defines the requirements of pumping laser energy and repetition rate. A parallel analysis, regarding the application of a resonating enhancement cavity to NIO1, is presented and a comparison between the two approaches is discussed.

Keywords: Plasma diagnostics - interferometry, spectroscopy and imaging; Plasma diagnostics - probes

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Contents

1 Background

Negative ion based neutral beam injection (NBI), along with RF heating, is widely used in fusion experiments as a plasma heater and a driver of plasma current. Currently, negative beam neutralization is obtained by means of electron stripping on a background gas; it shall be noticed that the neutralization efficiency is limited by the production of positive ions from neutrals. The importance of this loss channel rises with beam energy.

In order to overcome the intrinsic efficiency limits of gas and plasma neutralizer and to limit the pumping requirements, photoneutralization (PN) of negative ions has been investigated as a possible alternative concept. Photoneutralization of negative ion beams is technologically challenging, requiring high levels of optical power (in the MW range, for typical geometries [1]); these can be obtained only coupling a coherent source with an enhancement cavity (E.g. a optical resonator).

In the following are examined two possible approaches for a photoneutralizer setup in the NIO1 facility [2]: one based on laser Second Harmonic recirculation (RING, see [3]), the other based on a resonating optical cavity.

2 Photoneutralizer mockup

The photoneutralization scheme currently under test at Consorzio RFX is based on laser Second Harmonic Generation (SHG) and trapping in a non-resonant folded cavity [4] (figure 1). A 10 ns, 10 Hz, 300 mJ Quantel Nd Yag laser is fired through a telescope and a dichroic mirror inside a folded closed cavity. A layered lithium triborate (LBO) crystal inside the cavity convert most of the beam energy from first (1064 nm) to the second (532 nm) harmonic. Being the cavity mirrors transparent to the first but not to the second harmonic, the second harmonic light cannot escape and is trapped within the cavity; the latter is stable with respect to small misaligments thanks to the presence of a refocusing element (a concave mirror which can be paired with a divergent lens to tailor the effective power of the system, bottom in figure 1).

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The light intensity decreases as a function of loop number as a result of reflection losses on mirrors and absorption losses on the refractive elements (LBO crystal, lens if any).

The Second Harmonic Generation (SHG) efficiency is measured by placing a pyroelectric energy monitor inside the cavity. The pulse decay time can be inferred by recording the waveform of light transmitted through the mirrors and collected by two fast photodiodes.

The photodiodes cannot be exposed directly to the portion of the beam transmitted by the mirror in order to make the light power measurement independent from the beam dimension, which is not constant as the pulse is decaying. Hence one photodiode is coupled with a light diffuser (right in figure 1) and one with a miniature integrating sphere (left in figure 1), whose purpose is to mitigate the effect of light intensity variation on the photodiode active area.

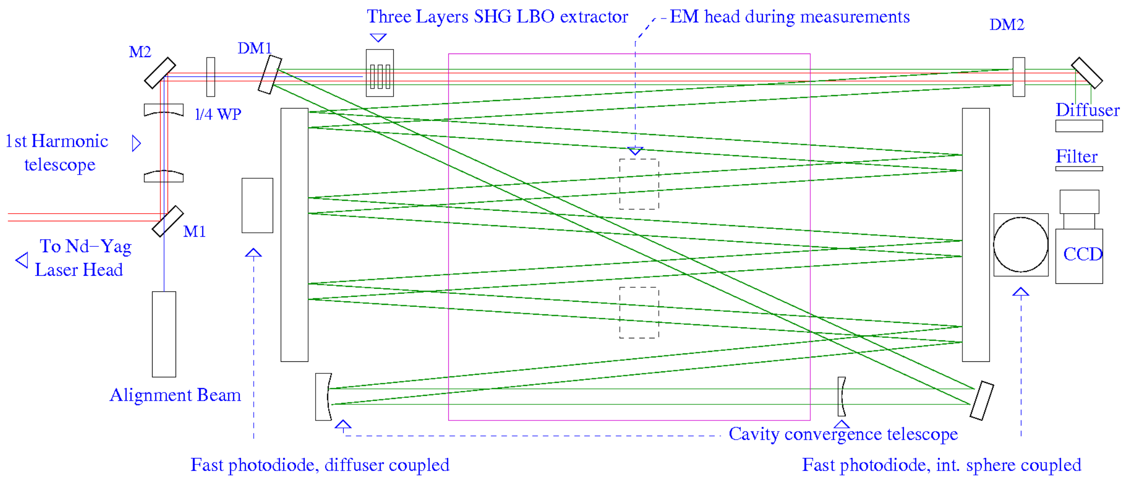

Figure 1. Layout of the RING photoneutralization cavity mockup: laser beam enters from the left and is frequency doubled inside the multi-folded cavity. A pair of dichroic mirrors ensure second harmonic trapping, letting the fundamental harmonic to pass through. The magenta rectangle defines the foreseen negative ion interaction region; the distance between the two mirror rows is 400 mm

2.1 Cavity operation and model validation

Since the pulse decay time is the figure of merit of the cavity, it is crucial to quantify loss channels and to optimize the optical setup. In particular, excessive refocusing leads to pulsations in beam diameter and to the possible presence of hot spots on mirrors, insufficient refocusing to vignetting losses.

Figure 2 displays at the top the beam profiles imaged in the light transmitted by one mirror at the variation of refocusing power, at the bottom the fast photodiode waveforms referring to the same configurations. The variation in beam diameter at the top is not related to variations in the pulse decay time (bottom), which lies in the range of 2–2.5E−7 s; it is hence expected that vignetting losses are negligible and the losses are dominated by transmission and scattering on the reflective surfaces.

Left, measured pulse decay time for the same configurations. The three setup are equivalent; a modulation in the red curve shall be noticed as a result of beam diameter pulsation

The light completes a cavity loop in 10 ns (roundtrip time), being reflected 10 times. Hence, a pulse decay time of 20 roundtrips (200 ns) corresponds to a decrease of about 5% per roundtrip,

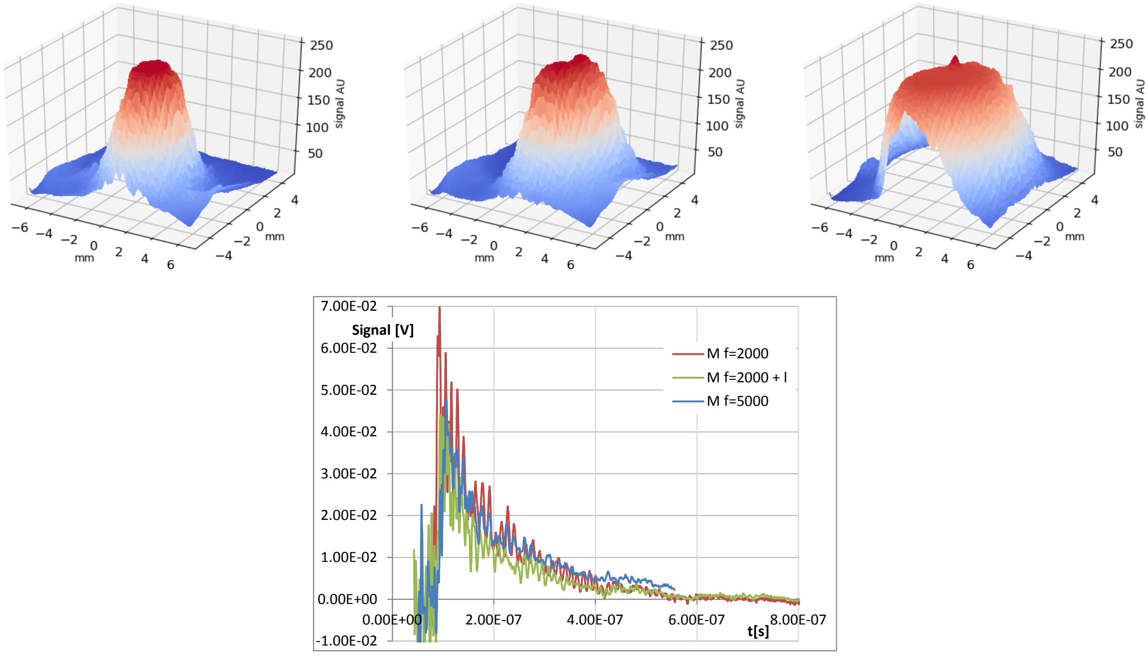

Figure 2. Top, variation of the intra cavity beam profile with different refocusing setups; field size is 20 mm. From left, single concave mirror $f = 2$ m, concave mirror $f = 2$ m + divergent lens $f = 3$ m, single concave mirror $f = 5$ m.

or 5E−3 loss per surface; the resulting average reflectivity is 99.5%, compatible with the mirrors specifications. This value is compatible with a measured mirror transmission of about 2E−3, once scattering and absorption losses are taken into account.

A pulse decay time of 200 ns is still insufficient for the application on NIO1. In order to assess quantitatively the PN performances of the cavity on the NIO1 facility, the SHG extraction and laser propagation has been modeled taking into account beam dimension and intensity, LBO conversion and absorption losses, mirror diameters and curvatures [5]. The pulse decay curves shown in figure 3 are in good agreement with the measured loss times, once the losses on each surface have

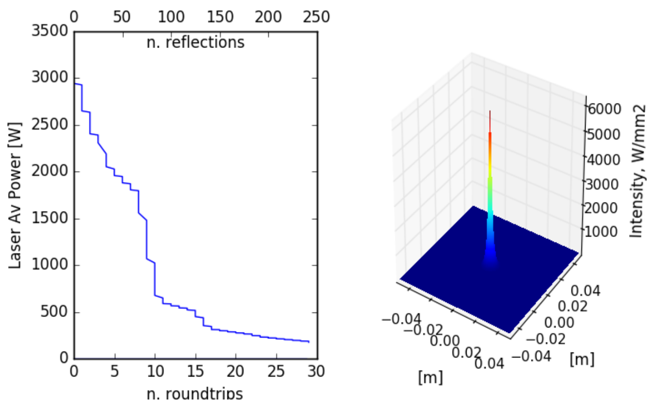

Figure 3. From left: laser average power as a function of number of reflections and number of roundtrips. Right, average power passing through the SHG crystal.

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been set to 5E−3, and so the spot size (right). Details in the pulse decay traces are related to the residual presence of vignetting losses.

3 Requirements on laser source for NIO1 operation

Being the RING concept intrinsically transient, application to the NIO1 beamlets requires a higher repetition rate, in order to keep the cavity continuously pumped, or at least to operate it with a duty cycle high enough to discriminate and quantify the presence of neutrals. Moreover, pulse length must be kept as short as possible in order to decrease the SHG thickness and reduce the cooling requirements on the LBO crystal.

NIO1 source features 9 beamlets in 3×3 arrangement, each one 6 mm wide. Beam energy is 10 kV and target current 10 mA. In a photo-neutralization experiment, only one line of 3 beamlets will be operated, the lower being the laser-beam interaction cross section, the higher the laser intensity at the same power level.

In the considered scenario, a 1 MHz, 100 ps, 1E−4J pulsed laser is used; moreover, a slightly higher efficiency is considered, lowering the mirror losses from 5E−3 to 2E−3 (99.8% reflectivity), still within the commercially available range. The foreseen results in terms of PN rate is shown in figure 4, showing that values in the range 0.25 could be achieved. A further increase can be obtained by further cavity refolding or by raising mirror reflectivity.

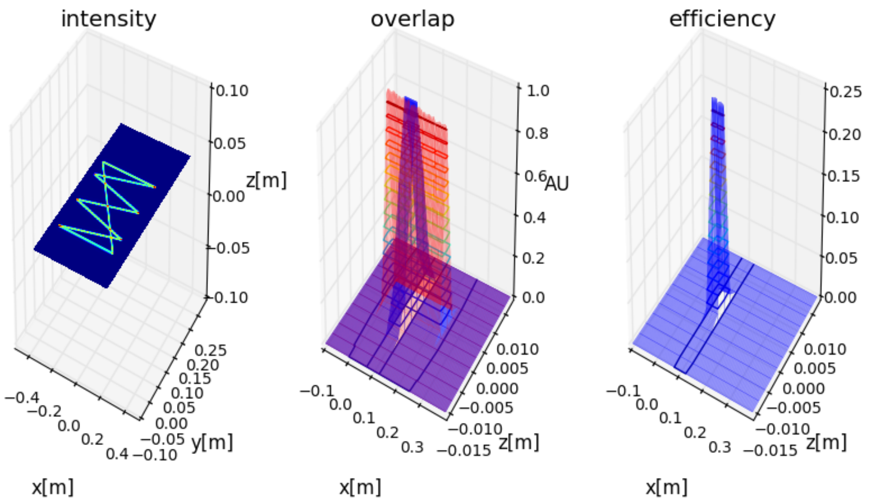

Figure 4. From left, light intensity contour map in the plane containing the negative ion beam. NIO1 beamlets direction follows the y axis. Middle: overlap between negative ion beam (blue) and radiation field (red) in the plane perpendicular to negative ion Beam. Right, contour plot of overall photoneutralization efficiency.

4 Comparison with optical resonator

Analytically, the power required to achieve saturation level in a single-pass photo-neutralizer can be expressed as [1]:

$$P_s = \frac{hc\nu d}{\sigma_{PN}\lambda}$$

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where d is the overlap dimension thickness between laser beam and ions beam, λ the laser wavelength and σ_{PN} the photo-neutralization cross sections [6]. Substituting for d = 2 mm,v = 1.38E6 m/s, P_s = 388 kW. In the case of an optical resonator, no second harmonic conversion is required; on the other hand, the resonance condition requires close matching between one of the resonator longitudinal modes and the laser one. Considering an input laser power 100 W mode matched at 1064 nm, the required enhancement factor is 4000, corresponding to a resonator finesse of 1.25E4.

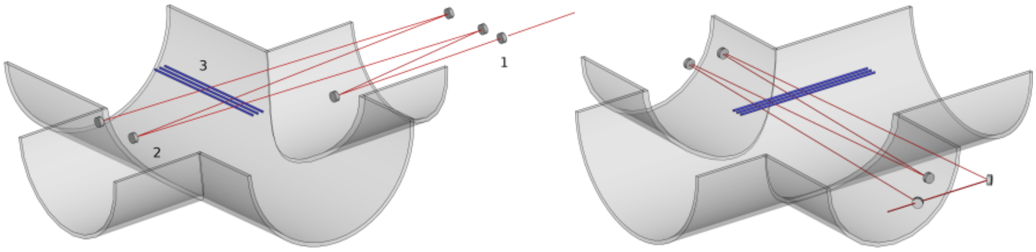

Figure 5. Possible layouts for an optical resonator cavity photoneutralizer. On the left, the laser beam enters the cavity via a matching telescope (first two mirrors, 1) and crosses the beamlets (3) times being reflected by flat mirrors (2). On the right, annular cavity concept, composed by 5 mirrors. Here the matching of the cavity on the input beam divergence can be obtained by varying the cavity length, in particular tuning the position of the convergent mirror (the 3rd from input). Annular cavities works with travelling waves instead of standing waves, reducing the risks of interference spots on mirrors

Figure 5 shows a possible layout for NIO1 geometry: a 3 folds cavity intercepts the beamlets, being coupled with the feeding laser by a matching telescope; a matching telescope is required to adapt the laser beam divergence to the one required by the injection in the resonator cavity [7]. Multiple passages are required in order to achieve a proper overlap of the laser beam with the negative ions beamlets, being the laser diameter smaller than the beamlets. A possible alternative involves the use of an annular cavity [7], which could mitigate the risk of interference spots on the mirrors; in this case in fact the resonator hosts a travelling wave instead of a standing one.

5 Conclusions

The NIO1 test facility can be exploited as a testbed for negative ion beam phot-neutralization experiments. In particular, photoneutralizers based both on a optical resonator and on second harmonic trapping are in line of principle feasible, depending on the availability of a proper laser source; as expected, optical resonators offer higher enhancement factors. Ongoing work concerns the cavity design optimization, the reduction of optical losses and the construction of a proper setup for photo-neutralization rate measurement.

Acknowledgments

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