Optimized in-situ window cleaning system by laser blow-off through optical fiber

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Abstract. An optimized in-situ window cleaning system by laser blow-off through optical fiber
has been developed on the basis of a feasibility study previously presented. The beam generated from a Q-switched Nd:YAG laser (up to 330mJ output energy, pulse duration 5ns FWHM with 10Hz repetition rate) is launched into a high damage threshold optical fiber (Ø=1mm) through an f=80mm lens kept in a sealed box at 1mbar pressure. The fiber output is focused on the coated surface of a vacuum window previously exposed to the plasma of the RFX-mod experiment. We investigate the energy density threshold necessary to ablate the impurity deposition substrate: above threshold a single laser pulse recovers $\sim$95% of the window transmission before its exposure to the plasma, while below it the efficiency of the cleaning process is too poor. The system so conceived can clean completely the largest window on RFX-mod ($10^4$mm$^2$ surface) in about 20minutes. We also present first results obtained firing the laser directly on a bundle of small core diameter fibers, showing performance similar to those attainable with commercial products.

1. Introduction
In present fusion devices impurity deposition processes, due to plasma wall interaction, affect vacuum windows used by optical diagnostics: for a Thomson scattering (TS) diagnostic, the window optical transmission degradation causes a distortion of the spectral transmission curve, which corresponds to a systematic underestimation of electron density $n_e$ and to a misevaluation of electron temperature $T_e$. In the specific case of the main TS diagnostic installed on the modified Reversed Field eXperiment (RFX-mod) this impurity deposition mainly affects the signal level, gradually increasing the minimum density operational limit of the diagnostic[1]. To cope with this problem, an in-situ window cleaning system by laser blow-off, carrying out the laser radiation through an optical fiber, has been developed on the basis of a feasibility study previously presented [2].

2. The laser–fiber system
The Brilliant Easy laser from Quantel is used. This is a TEM$_{00}$ Q-switched Nd:YAG laser, with 1064nm wavelength, 10Hz repetition rate, less than 50microrad pointing stability and 0.5mrad beam divergence. The energy of the 6mm diameter beam can be varied from 330mJ with 5ns pulse duration FWHM to 25mJ with 12ns FWHM, acting on the time delay between the Q-switch and the flashlamp.
(Δt_{FLQS}). In Figure 1 we report the available combination of pulse duration and energy with respect to the Δt_{FLQS}. The pulse duration was measured with a 1ns response time photodiode read by an oscilloscope; the energy was measured with an optical energy meter and a thermopile detector, with 1.2kHz sampling rate. This energy range was scanned to determine the power threshold level in the cleaning process of the impurity layer.

![Figure 1](image_url)  
**Figure 1.** The output energy and the pulse duration FWHM of the Quantel Brilliant Eazy laser with respect to the Q-switch and the flashlamp.

The laser beam is then coupled to the Φ=1mm optical fiber through a lens with focal length f=80mm, which focuses the beam ~10 mm before the fiber entrance face (not on the entrance face to avoid damages on the fiber face). The focal length matches the 0.36 numerical aperture (NA) of the fiber and the Φ=6mm beam. In case air breakdown occurs at the focus with lower NA fiber, the focal length should be chosen such as the NA is matched and the dimension of the breakdown spark is minimized: the longer the focal length, the longer the spark tube (l ∼ l^2) and the higher the risk of damaging the fiber surface [3]; the lower the focal length, the shorter the distance of the fiber surface to the beam waist. In our case, on the basis of calculation reported in [3], the expected spark cylinder has L=2.14·θ/d·f^2=0.2mm length and D=2·λ/3.14·f/d = 10µm diameter (θ is the beam divergence and d the beam diameter on the lens). In order to avoid air spark in front of the fibre, a sealed box has been built (400x200x200 mm^3): the laser is launched into the fiber at 1mbar pressure. The laser beam enters the chamber though a BK7 vacuum window; an optical fiber feedthrough guarantees the vacuum seal allowing using the fiber to exit the vacuum chamber. Collimation between the laser beam and the fiber axis is done in atmospheric pressure, with the box open, running the laser at low energy (25mJ with 12ns FWHM). At the fiber output, two f=50mm lenses are used to first collimate the beam and then focus it onto the dirty surface of the window; two HR mirrors are used to deflect it to the desired direction. The beam hits the impurity substrate on the fused silica collection window from rear (i.e., passing through the window). The energy density on the window surface is varied changing the distance between the last lens and the window (i.e., varying the spot size) bewareing the laser is not focused inside the window in order to prevent any damage. This layout is compatible with the use on RFX-mod of an in-situ window cleaning remotely-controlled system: the collimated beam will be moved across the window surface and focused on the dirty surface from outside the RFX-mod vessel.

A damage energy threshold test was first done on a standard Φ=1mm fused silica fiber (silica core / silica cladding): as the energy output exceeds 45mJ with 8ns FWHM (5.6 MW/mm^2), the probability of melting the fiber is quite high (in the first 20 laser pulses): the damage is in the first 15cm from the fiber entrance face, since the damage occurs at the first reflections on the inner core/cladding interface where the beam energy is mainly absorbed. Below this threshold the laser causes no damaging. In order to further reduce the damage probability in case of spurious events (the laser is operating in the most unstable region of the curve shown in Figure 1), a Φ=0.94mm fiber with a high energy damage threshold (10 MW/mm^2) is used, manufactured by SEDI industries: this ensures almost a two-fold safety factor. Below this threshold, output energy from the fiber is found to be 50%-70% of that measured at its entrance (depending on the alignment accuracy and position of the fiber with respect to the launching optics), so that 80-100mJ in entrance are enough to obtain the required 40mJ.
3. Results

The system has been tested on two fused silica windows used in the main TS system [4] on RFX-mod; they have been removed in July 2009, after four months of exposure to various types of plasma discharges (RFP, helical RFP and Tokamak configurations) and wall conditioning treatment (one boronization and 20 - 60min daily He-glow discharges). The major oblong window was found to be almost completely darkened while the circular one only partially (see dashed black lines in Figure 2): the transmission was respectively 5%-30% and 60%-80% the transmission of the clean window. The laser launching system was configured so that the fiber output energy was ~40mJ in 8ns (5 MW).

The spot size on the dirty surface of the window was $\varnothing=2.5\text{ mm}$, corresponding to an average energy density of $\sim 8\text{ mJ/mm}^2$ (1 MW/mm$^2$). The window was moved with a step motion of 1mm perpendicularly to the laser beam: several regions of $20\times 5\text{ mm}^2$ area have been cleaned, each with different laser pulses per step, and their transmission function has then been measured.

With this set-up, a single pulse provides a recovery of 90%-97% of the initial transmission (see Figure 2 a-b) and increasing the number of pulses improves the results only of few %. Comparing the transmission recovered with a single pulse in the oblong and circular windows, the single pulse efficiency is more pronounced in case of thinner impurity substrate (circular windows), and so the need of further pulses. A relevant result is that in case of a too low energy density, the first pulse is not capable of recovery more than 60-70% of the initial values, and even further pulses per position cannot significantly improve the result. This indicates of the existence of an energy density threshold above which the cleaning process should be performed. This is more evident progressively reducing the laser energy without varying the spot size: with half energy density ($\sim 4\text{ mJ/mm}^2$ in 8ns), a single laser pulse produces a circular spot on the oblong window which shows a cleaner central region ($r=0-0.5\text{ mm}$ and $\sim 90\%$ of the original transmission) surrounded by a partially cleaned anular region ($r=0.5-1.5\text{ mm}$ and $\sim 60\%$ of the original transmission): the energy density in the central region is still above the threshold, while outside is below, and even with several laser pulses the transmission in this outer region does not exceed $\sim 80\%$ of the original transmission. Without a beam profiler we cannot estimate the shape of the beam at the fiber output: in the worst case of a Gaussian beam we can assume a FWHM of about $1.5\text{ mm}$ at $40\text{ mJ}$ (the entire cleaned spot), and the threshold energy value is estimated to be between 5 and $10 \text{ mJ/mm}^2$ in 8ns (again, 0.6-1.2 MW/mm$^2$). This also shows that the beam shape is an additional aspect that must be considered; an homogeneous beam is preferable because it allows to fine tune the beam energy above the impurity substrate ablation threshold value without changing the area of the cleaned surface: the tail and the top of a Gaussian shaped beam would be below the ablation threshold or above the damaging threshold respectively.

The system so conceived is more performing than those previously proposed in [2]: a $2.5\text{ mm}$ spot size, with 10Hz repetition rate and the high energy output from the fiber, make it more attractive for its application to in situ window cleaning. The time required to clean the entire oblong major window of RFX with a single pulse / step and 1mm steps is only about 15 minutes, while it is 75minutes with 5 pulses per position (plus time required for motions, estimated to be 5 minutes): this is much less than 2 days of work required to replace the window (assuming an already vented vessel) or the 14 hours previously estimated with the less optimized laser-fiber system in [2].

Similar results can be obtained also launching the laser directly into the fiber with 330mJ energy pulse (e.g., running the laser at full energy), without a focusing lens, since the 1mm fiber partially collects the energy of the $\varnothing=6\text{ mm}$ beam, providing about $40\text{ mJ}$. As a general statement, it would be preferable to exploit all the laser output power, with the constraint of staying below the damage threshold of optical fibers. On the basis of this idea, a different strategy suitable for cleaning larger optics consists in firing the laser straight onto a bundle of fibers covering the entire beam diameter: in order to estimate the energy lost in the fibers interspaces we have tested a $\varnothing=7\text{ mm}$ fiber bundle ($38\text{ mm}^2$), made of $\varnothing=40\mu\text{m}$ fibers. Running the laser at full energy, $160\text{ mJ}$ output energy is obtained from the bundle because of the loss in the interspaces (30%), reflections at both ends (10%), and damages into the fiber (10%): on a $25\text{ mm}^2$ spot area, a single pulse is sufficient to recover 90% of...
the nominal window transmission, as expected from the energy density value on the window surface (7mJ/mm\(^2\) energy density in 5ns, or 1.3 MW/mm\(^2\)). A further advantage of this fiber bundle is that the output shape is square and not circular, so that the voids between two adjacent cleaned regions are negligible: a longer step can be adopted, so that the square shape can increase the cleaning speed by about 50%. With this technique, the time required to clean a surface is estimated to be more dependent on the beam motion time, i.e. 5 minutes. The extracted power is comparable with that provided by commercial products, such as the Laserblast from Quantel: the basic model works at 50Hz, with 160mJ output at 25ns, corresponding to 6.4MW/mm\(^2\). The main limits for our system is the repetition rate of the laser and the output energy which could be simply overcome with a new laser and a more transmissive fiber bundle respectively (200mJ at 100Hz in 10ns FWHM could be obtained). The most powerful Laserblast model provides 330mJ at 120Hz, which seems much further from our results; nevertheless the extracted energy density of 5-50 mJ/mm\(^2\) is in the same range we obtain.

![Graph showing transmission change](image)

**Figure 2.** The transmission change for the major oblong and circular collection windows of the RFX-mod Main TS system after plasma operations and cleaning procedure with laser 1, 3, 5 pulses per step.

### 4. Future plans

A remotely controlled motion system will be designed, produced and tested on the basis of the Quantel laser actually available at Consorzio RFX focusing its beam onto the single high damage threshold fiber. Concurrently, on one side further tests will be done on a small diameter fiber bundle with higher transmission to verify the potential of this configuration and to make it more attractive for large optical surfaces used in large fusion devices such as JET and ITER. On the other side, first tests will be performed to verify the application of the laser blow-off cleaning technique also on metallic surfaces: damage tests will be first accomplished on clean surfaces, and then cleaning procedure will be applied to coated surfaces.

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