Correction of high spatial frequency errors on optical surfaces by means of Ion Beam Figuring

M. Ghigo [1], R. Canestrari [1,2], D. Spiga[1], A. Novi [3]

[1] INAF-Osservatorio Astronomico di Brera - Via Bianchi 46 23807 Merate (Lc) Italy
[2] Università degli Studi dell'Insubria - Via Valleggio 11 22100 Como (Co) Italy
[3] Galileo Avionica - Via A. Einstein 35 50013 Campi Bisenzio (Fi) Italy
Email: mauro.ghigo@brera.inaf.it rodolfo.canestrari@brera.inaf.it daniele.spiga@brera.inaf.it andrea.novi@galileoavionica.it

ABSTRACT

The Ion Beam Figuring is a well known technique able to correct shape errors on optical surfaces with high accuracy. The size of the ion beam dictates strongly the higher spatial frequencies that can be corrected on the optical surface. The correction of small optics of some cm in diameter or containing high spatial frequencies can be very time consuming or impossible. A system that permits the Ion Beam Figuring of small optical components has been developed in the Astronomical Observatory of Brera (INAF-OAB). It has a small ion beam size and large removal rate. The system employs a concentrator able to force the broader beam emitted from an ion source into a smaller spot having large removal rate. The concentrator is placed between the ion source and the optical surface to be figured and doesn't influence the long term stability of the source. It consists of a conical cavity in which is injected the beam extracted from the grids of the source. The grazing incidence angle of impact of the ions with the walls of the cone ensure a very low level of sputtering of the cone material and meanwhile permits the creation of a very small spot removal function having large removal rate. To demonstrate its functionality a number of test optics has been figured using this system with very good results.

Keywords: Ion Beam Figuring, IBF, removal function, spatial frequencies, removal rate, focusing grids, conical concentrator, etching rate.

1. INTRODUCTION

The technique of the Ion Beam figuring (IBF) uses a beam of Argon ions that is able to remove material. The beam is moved with variable speed, to correct the residual errors remaining on an optical surface after the conventional lap polishing processes. This technique permits to obtain optical surfaces of very high quality, in terms of shape departure from the theoretical one, and it is probably the best corrective process for optics among those available nowadays. The surface errors that can be corrected depend strongly from the dimension of the ion beam that typically has a near Gaussian shape. The systems now on the market offer ion beam sources capable to mount different ion optic grid sets to accommodate for the different possible applications: focusing grids, parallel or divergent grids, to obtain ion beams accordingly. Typically the ion beam sizes generate from these grids options range from 20 to 100 mm FWHM or more. Are also available ion beam sources that can figure optical surfaces extremely small[1] (few mm or less) having beams with FWHM of few hundred microns, used for applications in microlithography or in photonics. It has been observed instead a lack of ion beam systems suitable for the figuring of optical surfaces having dimensions between 50-100 mm down to 10 mm in diameter. When there is the need to correct optical surfaces having these dimensions or to correct larger optics having high spatial frequencies errors, the correction became impossible or too much time consuming. This happens because the ion beam sizes available are the same or larger than the details to be corrected.

In the Astronomical Observatory of Brera (INAF-OAB) is located an Ion Beam Figuring facility[2] having an ion source with two separate graphite grid sets, a 30 mm and a 15 mm diam hole pattern (Fig. 1). The facility can figure optics up to 500 mm in diameter and is provided with a Veeco 30 mm ion source with hollow cathode. The beam neutralizer is separated from the source and has a hollow cathode too. The source can be moved along the XY axes for figuring optics up to 350 mm and for larger optics a polar configuration permits to rotate the optical surface meanwhile moving the X axis only, to translate the source along the radius.

During the present study it has been developed a system capable to concentrate the ion beam emitted from the source, generating a small beam dimension (FWHM of 7-5 mm or less) that permits the correction of small optical surfaces or

Optical Manufacturing and Testing VII, edited by James H. Burge, Oliver W. Faehnle, Ray Williamson,
Proc. of SPIE Vol. 6671, 667114, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.734273

errors with high spatial frequencies. This goal has been reached by means of a metallic concentrator having a shallow conicity angle of the cavity so to receive almost grazing angle impacts from the Argon ions of the source. The ion beam emitted from the acceleration grids is directed through the lower and larger opening of the conical cavity. Due to the impact of the ions against the inner walls of the device, an elevated concentration of ions is present on the upper opening that has a smaller diameter. The dimensions of the ion beam generated in this way are essentially linked to the dimensions of the exit opening of the cavity and to the distance of the optical surface respect to this opening. Even if conceptually simple, this principle has been demonstrated to be viable and valid. It presents advantages respect to other methods actually used for the generation of reduced size ion beams. The use of this technology of concentration for the IBF can permit the figuring of small size optics having very high shape requirements.

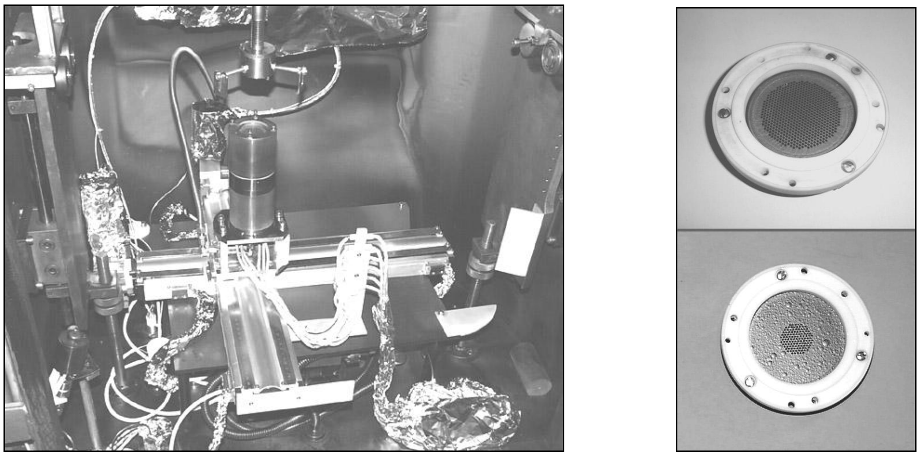

Fig. 1) Ion Beam Figuring facility with different ion optic grid sets

2. PRESENT TECHNIQUE USED FOR BEAM SIZE REDUCTION

As an example of the methods that nowadays are used for the reduction of the size of the ion beams in the field of IBF, is here cited the system that employs a diaphragm to shield and reduce the ion beam size. This technique, well known in literature, is commonly used to limit part of the ion beam and permits to a smaller part of the beam itself to hit the optical surface under figuring. Essentially, a screen with a hole, made in a material having a low sputtering rate when exposed to the ion beam (for example graphite), is placed at a certain distance from the grids of the source. It's clear, as visible in Fig. 2, that the method reduces effectively the diameter of the ion beam. This technique has been used also with the IBF facility presently in INAF-OAB during the figuring of small optical surfaces gaining hence experience about this approach.

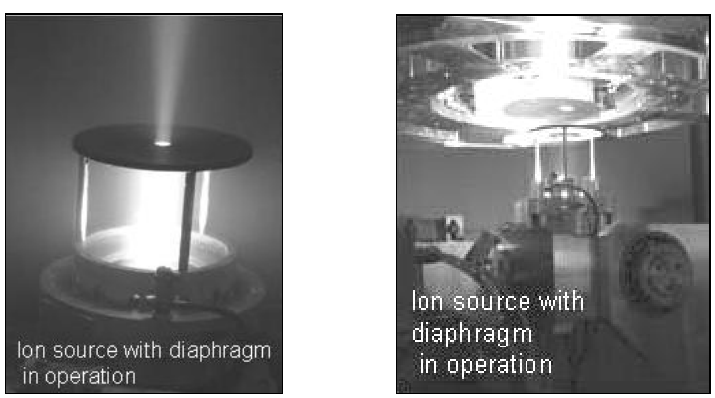

Fig. 2) Examples of use of diaphragms for IBF (Credit[3]: IOM-Leipzig)

The use of diaphragms to reduce the beam dimensions during the figuring of the optics presents however some disadvantages. The material of the screen, even if made with a substance having low removal rate, is anyway sputtered by the beam and is deposited onto the optical surface under figuring, creating on it a thin coating. In this process hence a certain quantity of material is deposited (from the screen on the optic) and contemporary a certain quantity of material is removed (from the optic under figuring). This fact can potentially induce an error in the final result of the figuring because the mathematical solution (the dwell time matrix) computed for the correction and applied during the task, generally doesn't take in account these particular physical problems. If the thickness of the deposit is sufficiently thin, the final results don't differ too much from the searched result but it will be obtained anyway a lesser correction to that theoretically possible. Sometime it will be hence necessary to iterate a second or third corrective cycle. The contaminating coating deposited on the optical surface must be also removed at the end of the figuring. Depending from the material used for the screen this coating will be more or less difficult to remove, for example, using a chemical bath. This is possible for example if metals are used for the diaphragm permitting an easy removal of the sputtered material. The use of metals for the diaphragm has the advantage that the sputtered material can be easily removed but it creates another type of problem. We don't have to forget in fact that the material of the screen is also sputtered backward on the graphite grids of the ion source. If this material is electrically conductive like a metal, the conductive film that buildup on the grids could create an electrical short after hours of operation, forcing a stop to the figuring process for their cleaning.

Another aspect to be kept in consideration concerns the power of the ion beam and its removal rate. If we compare the removal rate in the peak of an unobstructed ion source with that of the same source shielded with a diaphragm, it's clear that the shielded beam has a much lower removal rate. As example we can cite some indicative data: our source with the 30 mm grid setup and working with a 50 mA beam has a removal function of 40 mm FWHM. It has in the peak of the Gaussian (on BK7 glass at 100 mm of distance) a removal rate of 1.2 nm/sec. If we now shield the source with a diaphragm having a hole of 5 mm, the removal function is reduced to a dimension of 10 mm FWHM but the removal rate become of 0.04 nm/sec, i.e. 30 times weaker. This translates in a large increase of the working times.

The conclusion that can be drawn from all these considerations is the following. The use of diaphragms is a technique normally used to reduce the dimensions of the removal function of an ion beam. Yet this technique is not optimal in the sense that it has a series of limitations connected to the contamination of the optic under figuring and the grids of the source with the material of the diaphragm. Furthermore (and probably more important), whereas a strong reducing factor is used to obtain a small removal function, it brings to a reduced removal rate of the beam that translate in longer working times.

3. DESCRIPTION OF THE CONCENTRATOR

Aim of the present study was to obtain a workable system for the figuring of small optical surfaces producing an ion beam having a small removal function with high removal rate and long temporal stability of the source. This technique could be defined as "Concentration and filtering of the ion beam".

The technical solution here proposed (Fig. 3) use a normal Kaufman ion beam source with hollow cathode and grids in graphite. The separate neutralizer uses also a hollow cathode. The ion beam generated is concentrated in a very intense small spot thanks to a hollow cone made in a ferromagnetic material placed above the extraction grids and at an adjustable distance of the order of 10 mm. The entrance cavity of the cone has a size larger than the diameter of the grids and hence the length of the cone is dictated by the conicity angle and the diameter of the upper aperture. The ions emitted vertically from the grids will hit the tilted walls of the conical cavity. These walls are smooth and polished and have a low microroughness to reduce the sputtering of the material. The angle of impact of the ions will be maintained very low, almost at grazing incidence, with few degrees of conicity. This fact too permits to further reduce the sputtering of the material that could be deposited onto the optic under figuring. Another feature has been also implemented on the concentrator and it acts as a "filter" for the metallic nanoparticles that are extracted from the concentrator walls from the impacts of the Ar ions. A high intensity anular magnet is placed on the top of the ferromagnetic cone so that these particles are extracted from the beam before hitting the optical surface.
The tests executed during the development of this concentrator have been made using the ion source with the 15 mm grid set and are based on a conical cavity made in Iron, having a base entrance diameter of 25 mm, length of 90 mm and upper exit aperture with diameter of 10 mm. The inclination angle of the inner conical cavity was of about 4 degrees. The distance between the upper aperture and the optical surface was typically of 20-25 mm.

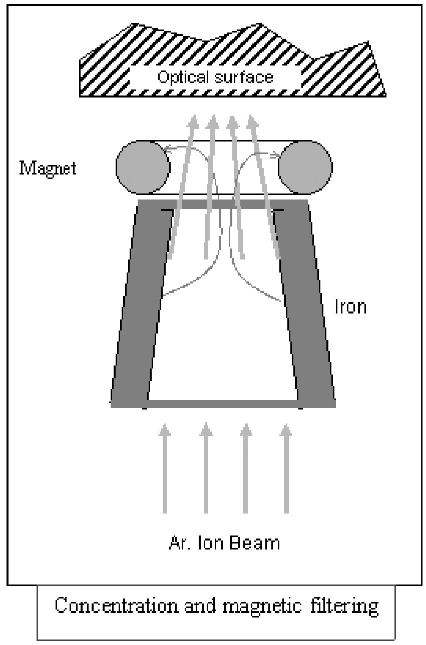

Fig. 3) Conceptual scheme of the ionic concentrator

The values cited for the present prototype have been obtained simulating the system with a ray tracing program and assuming that the Ar ions, even if provided of charge and hence having the tendency to repel each other, would have behaved essentially in a ballistic way because of their mass and the short travel necessary to reach from the grids the surface of the optic. As we can see, even in the limits of this modeling, the resulting shape of the simulated near Gaussian removal function (Fig. 4) was qualitatively in agreement with the real removal function (Fig. 7) obtained with the concentrator.
We now pass to analyze the several characteristics of this concentration method.

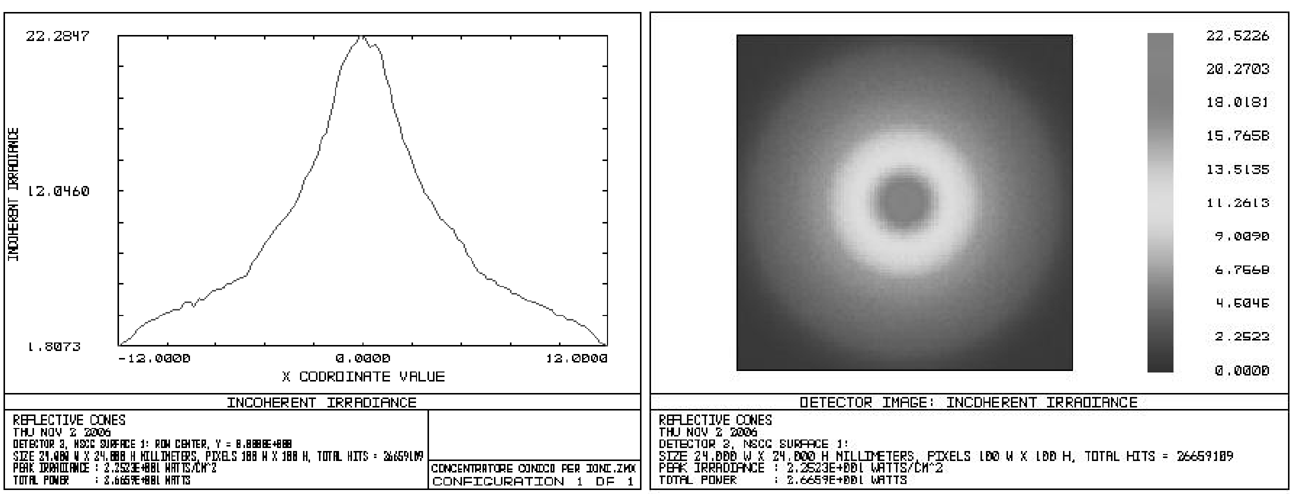

Fig. 4) Simulation of the ionic concentrator spot profile. The FWHM is of 6 mm

The use of a metal for the material of the concentrator offers the opportunity to remove quickly, with a chemical attack, the thin metallic coating that should anyway be sputtered from the concentrator walls. Around ten second has been necessary in order to remove the few nanometers thick layer deposited on the worked samples using hydrochloric acid. The strong magnetic field produced from two powerful ring-like Neodymium magnets, placed on the exit side of the concentrator, has a double effect:

- To capture a significant portion of the few metal sputtered from the inner surface of the cone, as a result of the collisions of the Argon ions with its inner walls, limiting the number of those which will hit the optical surface (filtering).
- Act as a magnetic lens on the Argon ions helping focusing them further.

It has been observed that the Iron of the concentrator does not come sputtered backward on the grids and does not contaminate them. Essentially all the sputtered metal (that is in a very small amount) exits from the upper side of the concentrator. This fact ensure that the grids never go in short circuit during long figuring runs and therefore the beam is extremely stable in the time. Multiple figuring cycles have been made on various optical samples without need to clean the grid assembly.
In order to quantify the capability to filter magnetically the material of the concentrator, it has been executed a static test using the concentrator with the magnets and without magnets. We wanted to seen if the amount of material sputtered on the optical surface changed in the two cases as it would have been in case of a proper functioning of the principle of the magnetic filtering. To such scope a 50 min static run has been made with the concentrator with magnets placed below a glass sample. Successively a second run without magnets has been executed on another sample for as many minutes. From a comparison between the thickness of the coating of Iron deposited on the two samples it has been measured that the magnetic filtering reduces of more than 30% the Iron that is deposited for the same exposure time to the beam. The thickness of the Iron coating was however extremely small also in the case without magnets and of the order of 2-3 nanometers for 50 minutes of static work. Although the Iron does not come totally filtered and removed from the beam, it is interesting to note that the proof of principle has given positive outcome and that the magnetic field effectively removes from the ion beam a part of the sputtered metal. Increasing the power of magnets could in principle bring to a more effective filtering.

A recent deeper analysis of the sputtering phenomenon has indicated that a critical angle of incidence of the Ions exists, under which the phenomenon theoretically is completely cancelled. Such angle depends from the atomic mass of the material of the concentrator and from its atomic sublimation heat that is the minimal amount of energy necessary to detach an atom from the surface. Moreover it depends also from the mass of the Argon ion and from its kinetic energy.
In the case under study, for the Iron it has been estimated that such angle is of approximately 2.7 degrees. The fact that the concentrator prototype had an angle of 4 degrees also justifies the presence of a minimal amount of sputtered material. A method to eliminate the sputtering would be therefore to create an Iron concentrator with an angle of 2.7 degrees or less. Obviously this implies a greater length of the concentrator having the same exit opening as before. Alternatively it could be possible to use a ferromagnetic material different from the Iron, having a greater atomic weight Z.

We will now estimate the ion beam concentration capability of the device and the removal rate that can supply. In order to obtain this, a removal function has been performed with the prototype realized and visible in Fig. 5 and Fig. 6.

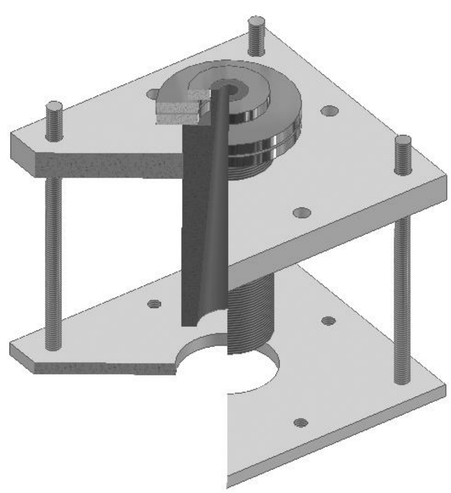

Fig. 5) Drawing of the ionic concentrator

After having realized and installed the system (mounted above the ion source), several tests have been carried out in order to verify the degree of concentration and the removal capability of the ion beam. One of these tests is shown in Fig. 7 where is shown a removal function realized onto a flat Silicon Carbide sample kept at a distance of 25 mm from the upper aperture of the concentrator. The removal function test was made exposing the sample for 30 minutes to the concentrated beam produced by the 15 mm grid set.

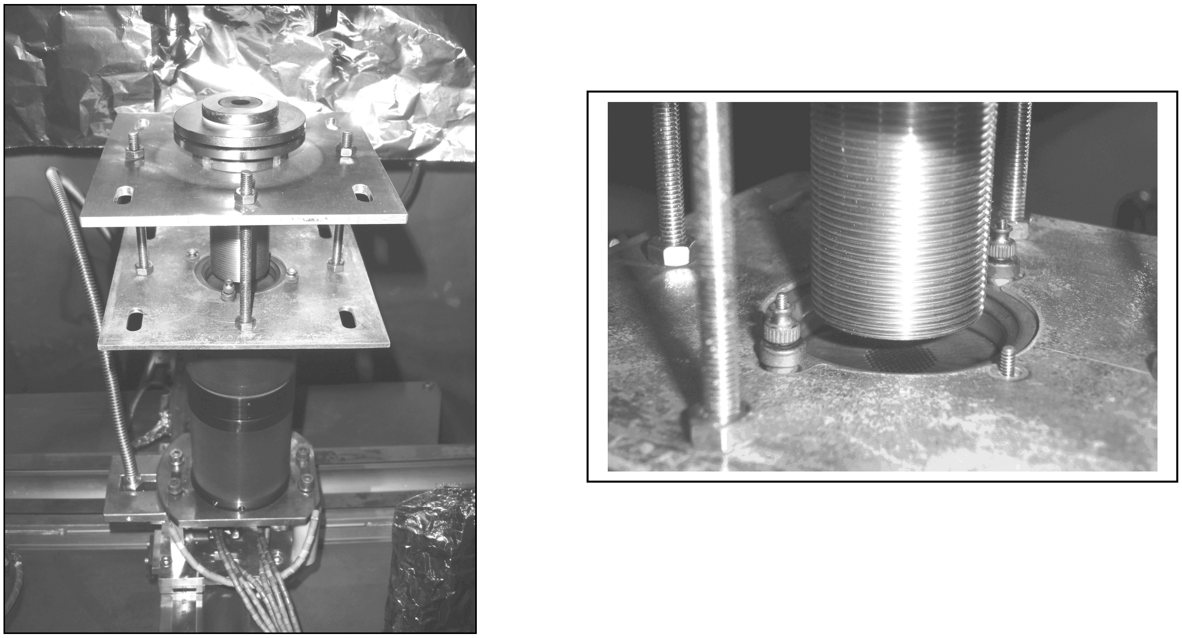

Fig. 6) Ionic concentrator prototype installed above the ion source with 15 mm grids

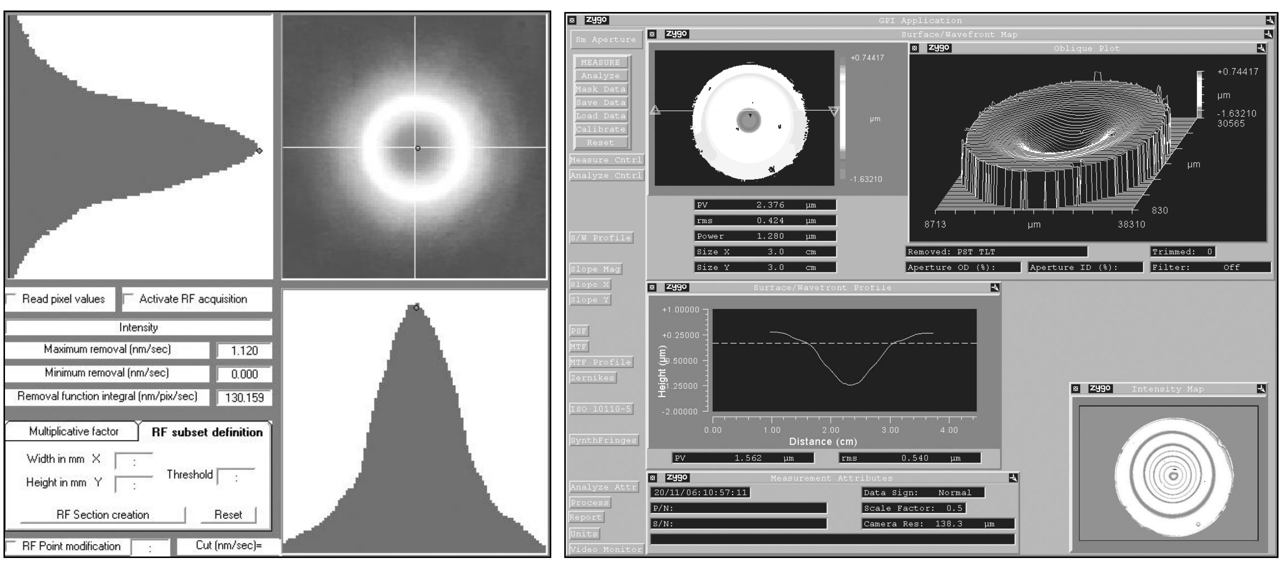

Fig. 7) Example of a removal function made on a SiC sample

The profile of the ion beam thus obtained shows a near Gaussian form with a removal rate in the peak equal to 1.12 nm/sec and width FWHM of approximately 7 millimeter.

The result obtained is extremely interesting because the removal function is decidedly of small dimensions, having a diameter of approximately 6 millimeter FWHM. Further, it possesses a removal rate quite large and of 1.12 nm/sec that is confrontable with that obtainable in the peak of the Gaussian employing the 30 mm grids mounted on the ion source. It must be remembered that instead this test was performed with the 15 mm grids, than normally in this case remove about 0,3 nm/sec. This means that the effect of the concentrator has magnified of approximately 4 times the removal rate of the beam emitted from the grids. On the contrary, a diaphragm would have reduced the removal rate in a significant way.
The removal rate obtained in this example is in our opinion rather elevated for a so small removal function size and is, to our knowledge, not easily reachable with the present techniques on ion beams of these dimensions. Its availability can allow the very accurate optical working of small optics and in short working times.

An aspect to keep in consideration for future implementations of this technique for optical corrections, regards the figuring of curved surfaces, concave or convex. In such case, since the distance of the surface under figuring from the concentrator change according to the position, is necessary a system of movimentation in Z of the ion head so as to maintain constant the distance between the optical surface and the exit opening of the concentrator. It must to be kept in mind that the beam is focused and therefore the removal function changes quickly varying the distance concentrator-optical surface.

Reassuming, the advantages supplied from this concentrator are the following ones:

- The concentrator allows to obtain a removal power elevated with nearly Gaussian form of the removal function (concentration of a factor of 4 in the present prototype). On the contrary the technique of shielding today employed reduces the removal rate.

- It permits to have a small removal function (FWHM of 6-7 millimeter or less) so to be able to figure small dimension optics. A further reduction of the dimension of the upper exit aperture should permit smaller removal functions.

- It permits to keep under control the sputtering of the material of the concentrator since this last one depends from the coning angle. Moreover, the thin deposited layer is metallic and can be removed very easily from the optical surface through chemical attack.

- The concept of magnetic filtering in order to further reduce the sputtering has been demonstrated experimentally viable and improvable, increasing the intensity of the used magnets.

- There is no contamination of the grids from back-sputtering of the material of the concentrator and therefore the ion beam has a stable behavior in the time. This contamination happens instead with the technique of the shielding.

- The use of materials having larger Z for the concentrator has the potential to allow to obtain a compact system totally free from sputtering and possibly eliminate thus the use of the magnets.

4. RESULTS OF THE IBF TESTS

As an example of figuring performed with the concentrator, are here described some Ion Beam Figuring corrections made on optical surfaces in SiC and Zerodur® carried out through the concentrator mounted on the ion source with 15 mm grids. These figuring, together to others carried out but not shown here, demonstrates the effective capability of optical figuring of this system.

For the first figuring the concentrator has been used on a flat sample in sintered SiC on which was deposited a cladding in SiC PECVD (Plasma Enhanced Chemical Vapor Deposition). These depositions are made in order to produce mirrors in Silicon Carbide in which the substrate is a type of SiC less valuable (and less expensive). Depositing then a layer of 100-200 micron of' a more valuable SiC that can be polished to a high degree, permit to realize a mirror of high quality in SiC. The surface of the sample was elliptic with dimensions of 97x 69 mm In Fig. 8 is visible the map of the surface loaded in the computation program of the dwell time matrix. Initially the surface had a PV of 278 nm and an rms of 43 nm. The goal was to bring the flat surface to a value rms of 10 nm.

For this figuring a working cycle of 2.4 hours was foreseen. The used removal function is the one visible in Fig. 7 where is also shown the interferogram executed for the measurement of the relative footprint etching. As it is visible, in 30 minutes of static run a peak material of 2,01 microns was removed, translating in a removal rate of 1.12 nm/sec. The sample used for the removal function determination was circular, in SiC, with a diameter of 25 millimeter and covered with SiC PECVD like the sample to be figured. After the figuring of this test sample the interferometric measure of the surface has supplied a PV of 144 nm and an rms of 15 nm. The surface is therefore passed from 43 nm rms ($\lambda/14$) to 15 nm rms ($\lambda/42$) @632.8 nm. As it is visible from the interferometric map of the worked surface (Fig. 9 right) the two initially present lateral lobes on the surface (Fig. 9 left) have been removed completely and the figuring has gone near to reach the theoretical value in a single run of 2.4 hours.

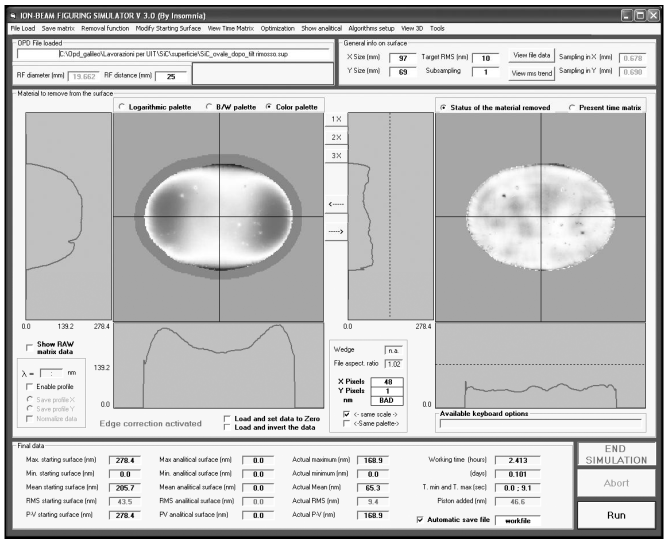

Fig. 8) Software for the time matrix computation

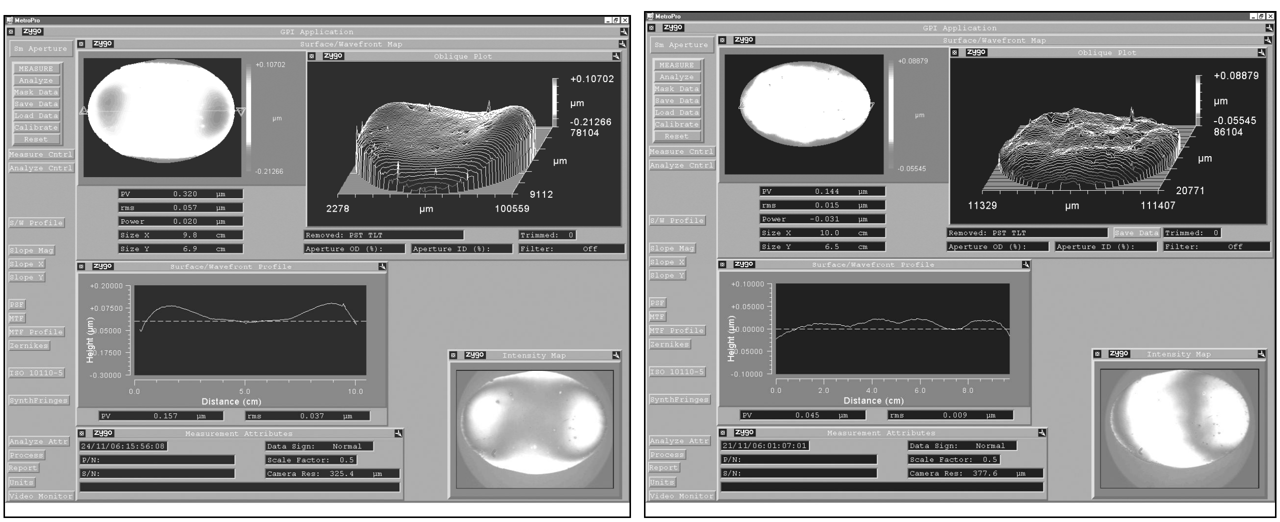

Fig. 9) Interferometric map of the surface before and after the figuring

The following ion figuring processes were made on three elliptical mirrors in Zerodur®. These figuring were made not on test samples but instead on a set of mirrors making part of instruments under manufacturing. The Astronomical Observatory of Brera has a long time collaboration with Galileo Avionica (GA), a Finmeccanica Company that is the Italian leader in Avionics, Airborne Systems and Electro-optics. Galileo Avionica has a privileged access to the IBF facility in INAF-OAB following an agreement stipulated with the Observatory and in the years it has contributed to its development. Recently it has been necessary to figure with IBF a set of three small mirrors in Zerodur® that will be used in the optical path of the LLT telescopes (Laser Launching Telescope) that GA is manufacturing. These telescopes are used to generate a synthetic star at around 90 Km of altitude (exciting a Sodium layer there present) to be used as reference star from the adaptive optics of the last generation telescopes. The three small elliptical mirrors have dimensions of 40 x 56 millimeters and are placed in the optical train of the 50 cm diameter telescopes as indicated in Fig.10.

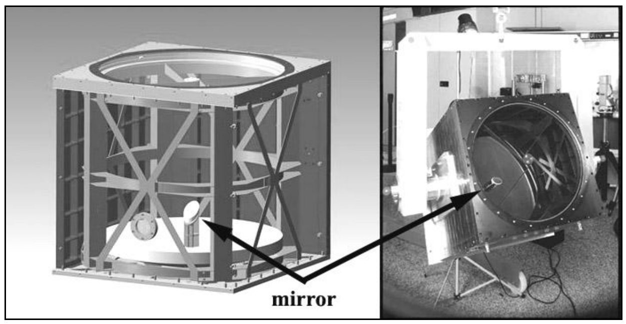

Fig. 10) Laser Launching Telescope

The dimensions of these mirrors were too small for an appropriate use of the grid sets available in our facility. The 15 mm grid set has a removal function of about 20 mm FWHM that is too large for these mirrors. Hence it was decided to use the concentrator for their figuring. Only the results for the first mirror will be here described more in detail. The complete results for all the three optical surfaces that has been figured are summarized in Tab. 1

The first mirror had an initial surface with a PV of 67 nm and an rms of 11 nm. The dwell time computation determined a working time of 42 minutes to reach 3.8 nm rms. After the figuring the resulting surface obtained had a PV of 31 nm and an rms of 4.1 nm, approximately a third of the initial value and essentially identical to the theoretical value. The determination of the removal function on the Zerodur® supplied a removal rate in the peak of 0.13 nm/sec. This value was intentionally held low using a smaller than usual value for the beam current on the power supply, because of the small quantity of material to be removed. In Fig. 11 are shown the interferometric maps of the surface, before and after the figuring.

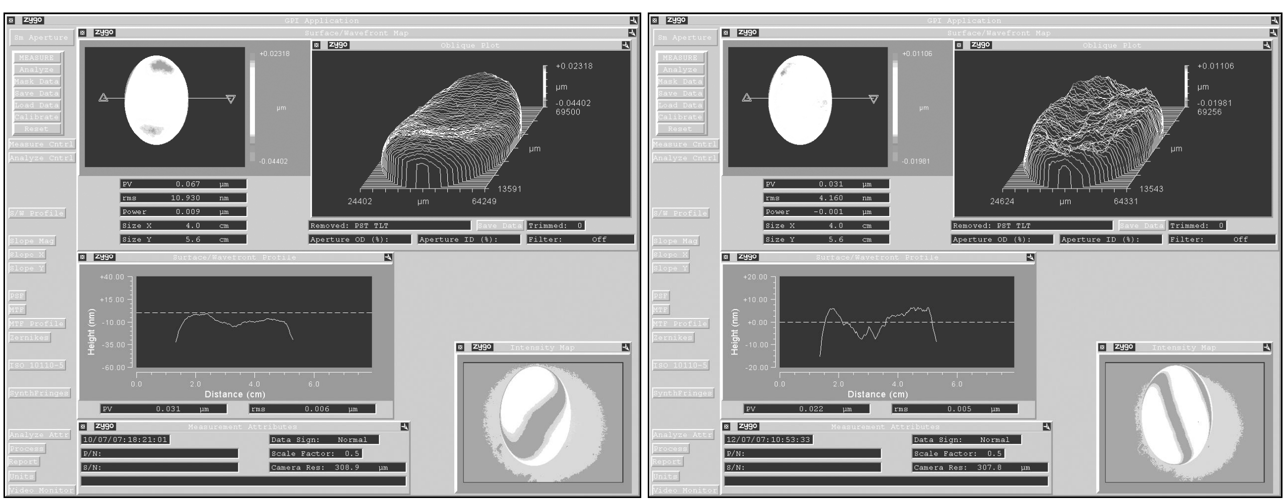

Fig. 11) Interferometric map of the surface before and after the figuring

In the following table are summarized the results obtained after the figuring of all the three mirrors. These results confirm that the Concentrator permit the figuring of small optical surfaces that couldn't be corrected with the same ion beam not concentrated.

Mirror	**Start values (nm)**		**End values (nm)**	
	PV	**Rms**	**PV**	**Rms**
M1 (n5)	67	11	31	4.1
M2 (n4)	53	8.7	36	4.5
M3 (n7)	48	8.7	30	4.1

Tab 1) Ion Beam Figuring results of three LLT mirrors

5. CONCLUSIONS

During this study it has been investigated the possibility to concentrate the ion beam emitted from an ion source with the aim of reduce the dimension of the removal function and to allow the figuring of optical surfaces of small dimensions not otherwise machinable with normal ion optics grid sets. An innovative technique of concentration of the ion beam has been developed that take advantage of a conical concentrator made in a ferromagnetic material and of a magnetic filtering system able to remove partially (or in toto) from the ion beam the material of the concentrator eventually sputtered. In this way the optical surface under figuring is worked with an intense ion beam of small dimensions and in the meantime is only slightly contaminated by the material of the concentrator. The contamination can anyway be easily removed through chemical attack. The acquired experience with such a figuring system and the good results so far obtained induces to think that the operational principle is valid. It has been observed that the ion source does not suffer of the presence of the concentrator from the point of view of the reliability and of the operational continuity. The ion figuring of optical surfaces, made coupling the concentrator to the 15 mm grids available in INAF-OAB, has given excellent results demonstrating the capability of the concentrator to figure small surfaces down to 40 mm in size (in these tests) and within very tight specifications. A strong point of this approach is related to the good removal function obtainable that is comparable with that one generated in the peak with the set of 30 mm grids also available in INAF-OAB but has a diameter (in the setup used) typically of 6 mm FWHM. This combination between good removal power and small dimension of the ion beam is a not usual and interesting characteristic in the ambit of the Ion Beam Figuring technique.

A patent concerning the ion beam concentration method for IBF described in this article has been recently deposited.

6. REFERENCES

1) Prashant M. Shanbhag, Michael R. Feinberg, Guido Sandri, Mark N. Horenstein, and Thomas G. Bifano "Ion-beam machining of millimeter scale optics", 1 February 2000 / Vol. 39, No. 4 / APPLIED OPTICS
2) M. Ghigo, P. Conconi, E. Antonello, G. Pareschi, "Accurate ion beam figuring of field correctors for optical and UV space instrumentation", Proc. OPTRO 2005 International Symposium, (2005)
3) Axel Schindler, Thomas Hansel, Andreas Nickel, Frank Frost, Peter Seidel, Wilfried Frank, Georg Bohm, Thomas Arnold, Renate Fechner, Nasser Razek "Ion Beam and plasma jet techniques for precision figuring and polishing", OptoNetWorkshop – May 16-17, "Ultra Precision Manufacturing of Aspheres, Freeforms and Microstructures", (2006)