

## Deterministic ion beam figuring of Si spheres

Th. Arnold, F. Pietag

*Leibniz-Institut für Oberflächenmodifizierung (IOM), Permoserstr. 15, 04318 Leipzig, Germany*

[thomas.arnold@iom-leipzig.de](mailto:thomas.arnold@iom-leipzig.de)

**Keywords:** Ion beam figuring, sphere surface correction

### Abstract

In the framework of the Avogadro project isotopically enriched  $^{28}\text{Si}$  spheres had been manufactured as artefacts for the assessment of various physical quantities including the sphere volume which finally leads to a very accurate determination of the Avogadro constant  $N_A$ . The Avogadro constant is an important input datum for the redefinition of the unit of mass, the kilogram, on the basis of a fundamental physical constant. During the recent measurement campaign it has turned out that one of the main contributions to the overall uncertainty of  $N_A$  is the sphericity error and consequently the interferometric volume measurement. Since chemical-mechanical polishing has reached its limits with respect to form accuracy due to the sensitivity of material removal rate to crystal orientation it has been proposed to use Ion Beam Figuring (IBF) for further reduction of sphericity error from currently 50 nm PV to values <10 nm PV. The main challenge of this task is the deterministic machining of a surface with such a high symmetry and no significant features like edges or fiducial marks. In the paper we present the new concept and realization of a multi-axis ion beam figuring machine dedicated for sphere correction. We discuss aspects of alignment procedures in order to relate the ion beam footprint to the sphere surface. Results of process dwell time simulations will be shown. Since, at the beginning and end of processing the ion beam must act instantaneously to prevent unwanted etching during tool approach and departure, fast electrical beam switching is employed.

### 1. Silicon spheres

Isotopically enriched  $^{28}\text{Si}$  single crystal silicon spheres with nearly perfect spherical shape have been identified as suitable artefacts for volume and mass determination in the course of the accurate measurement of  $N_A$  [1]. Two of such spheres with diameter

of approx. 93.7 mm and a mass of 1 kg have been fabricated so far. Final polishing has been conducted by PTB, Germany. The ultimate roundness achievable on such spheres depends mainly on the mechanics of the grinding and polishing process. Recently, it has turned out that crystal orientation finally determines the local material removal in polishing. Deviations from ideal roundness are in the order of 30-50 nm peak to valley. The sphere volume is determined by measuring diameters using a spherical Fizeau interferometer developed at PTB [2]. Those interferometer measurements contain systematic errors partly originating from retrace errors due to shape deviations of the sphere under test. Since the uncertainty of the volume measurement contributes to the overall measurement uncertainty of the Avogadro number  $u_{NA}$  by nearly 60%, it is necessary to reduce the roundness error below 10 nm peak to valley in order to achieve the required relative uncertainty  $u_{NA} < 2 \times 10^{-8}$ .

## 2. Ion beam figuring machine

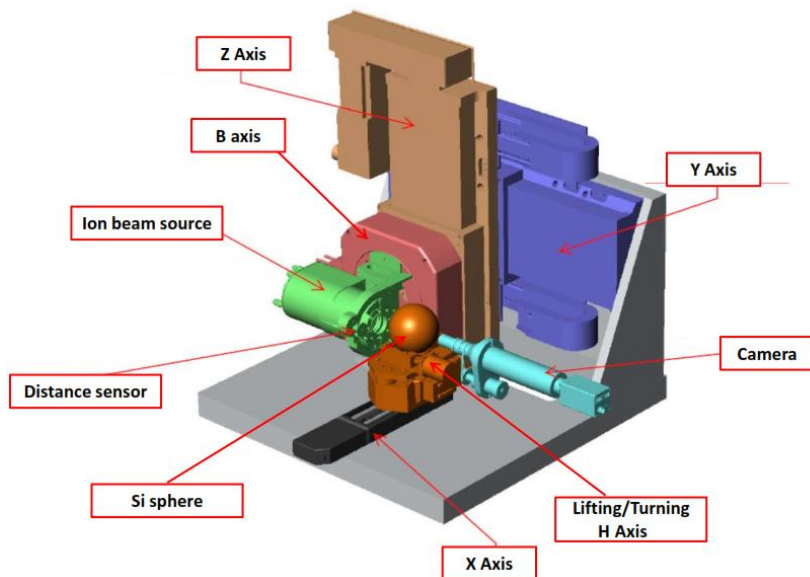


Figure 1: Ion beam figuring system for Si sphere correction (courtesy of NTG GmbH, Gelnhausen Germany)

Ion beam figuring (IBF) is an established machining technique for optics fine correction on nanometer scale [3]. It is based on surface atom physical sputtering by low energy ions (500 – 1000 eV) directed to the surface.

Together with NTG GmbH a new IBF machine has been designed and built for sphere correction. The system comprises 3 linear and 3 rotary axes mounted in a vacuum chamber. Fig. 1 shows a sketch of the motion system. The sphere rests on direct driven rotary stage A which rotates it around its vertical  $z$ -axis. The ion beam source is mounted on a Y,Z,B stage group which allows to conduct meridional movements with respect to the sphere. With this configuration every point of the upper hemisphere can be reached by the ion beam under normal incidence angle. Furthermore, a voice coil driven lifting mechanism together with a 3 point roller stage H can raise the sphere from its bearing and can turn it over around the  $y$ -axis to make the lower hemisphere accessible. The X stage serves for aligning the sphere in  $x$  direction and for positioning the attached beam current probe with respect to the ion beam. The argon ion beam is generated by a standard 40 mm diam. RF driven beam source equipped with multigrid-system for beam extraction, a neutralizer filament for injecting electrons into the positive space charge of the ion beam and an annular graphite aperture for beam size confinement to approx. 4 mm FWHM of the Gaussian beam. Accurate alignment of the Si sphere related to the ion beam is done both with the help of a high resolution microscope camera attached at the body of the X,A stage group as well as with an optical distance sensor mounted in parallel to the ion beam source. With the help of thin laser written fiducial marks at three different positions on the Si sphere the dwell time matrix is aligned with respect to machine coordinate system. Extraordinary care has been exercised to minimize concentric run-out of turning and rotation axes, since they largely determine the reproducibility of sphere positioning and thus the machining accuracy.

### **3. Deterministic machining**

Deterministic correction techniques utilize the dwell time method, where the centerpoint of the tool rests for a certain time  $t$  on a surface position depending on the local topography height in order to remove material locally. Based on sphere radius measurements provided by PTB with spatial resolution of approx. 0.5 x 0.5 mm and a footprint of the ion beam etched on a spherical surface a modified deconvolution

algorithm in 2-D space is employed to calculate the corresponding dwell times for all measuring points. A typical error topography and a theoretical residual error is shown in Fig. 2. Other than an ordinary optical workpiece surface with distinct boundaries a sphere is a closed manifold without any boundaries, which makes it necessary to regard the continuity condition on the calculation domain edge. For the same reason the typical raster path employed for surface machining is not applicable here since a line feed cannot be easily performed outside a clear aperture. Instead, we have chosen a tool path following an Archimedean spiral with constant distance between successive turns providing continuous line feed and preventing abrupt deceleration or acceleration of the axes. The spherical spiral is discretized by supporting points with the same arc length distance as the distance in meridional direction, which correspond to the pixel basis length of 0.5 mm of the surface measurement. The motion velocity over an arc length is determined by interpolation of the dwell time matrix and coded in G-code. Since only one hemisphere is accessible in one step, the machining starts on the equatorial position and ends in the vicinity of the first pole. In order to prevent high rotational speeds at pole positions the pole itself is not covered. Prior to the machining of the second hemisphere the Si sphere is lifted, turned upside down and put down on its bearings on the A axis. Total net machining time accounts for approx. 3-4 h for the full sphere.

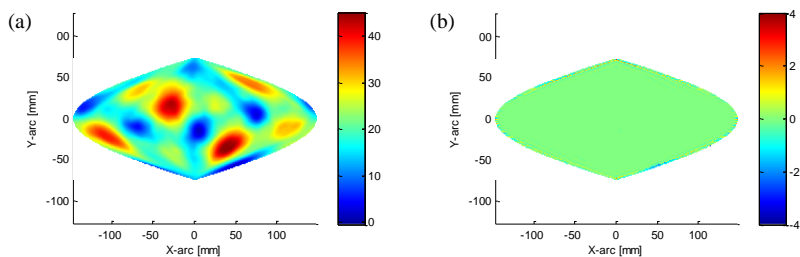


Figure 2: a) Error topography: 43 nm PV, 7.95 nm RMS. b) theoretical residual error after IBF 7 nm PV, 0.20 nm RMS plotted in sinusoidal projection

### References:

- [1] B. Andreas et al. *Metrologia* **48** (2011) S1–S13
- [2] G. Bartl et al., *Metrologia* **48** (2011) S96–S103
- [3] T. Arnold et al, *NIM A* 616 (2010) 147–156