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# High Precision Tungsten Cutting for Optics

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## Abstract

Coded Masks provide the Signal Multiplexing tools for the High Energy Instrumentation of the INTErnational Gamma Ray Astrophysics Laboratory (INTEGRAL) ESA Project addressed to fine imaging of celestial gamma ray sources. Milestones on its development are described in the paper by *Reglero et al* in this Seminar.

The aim of this paper is to summarise the results obtained during the INTEGRAL Masks development programme on implementing the HURA and MURA Codes on Tungsten plates of different thickness. Hard scientific requirements on pixels size and location tolerances (tenths of microns over large areas –1$\text{m}^2$- and thickness from 0.5mm to 60mm) required the set up of a dedicated programme for testing cutting technologies: Laser, Photochemical Milling, Spark Machining and Electro Discharge Wire Cutting.

After a very intensive test campaign the Wire Cutting process was selected as the optimum technology for code manufacturing . Accuracies achieved on the code cutting fulfil scientific requirements. In fact, they are 5 times better than required. Pixel size and centroids location accuracies of 0.01mm over a 1$\text{m}^2$ area have been obtained for the 10,000 pixels on IBIS, 100 pixels on SPI and 24000 pixels on JEM-X Masks.

Comparative results among different cutting technologies are also discussed.

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**Keywords:** Tungsten, Densimet, High Energy Astrophysics, imaging, INTEGRAL, Electrodischarge Wire Machining

## 1. The Coded Masks on INTEGRAL Satellite

The *Astronomy and Space Science Group (GACE)* of the University of Valencia was the responsible of the design and developement the Coded Aperture Systems (Coded Masks) for the ESA Mission INTEGRAL. The three high energy instruments on Satellite (Spectrometer SPI, Imager IBIS and X-Ray Monitor JEM-X) use Coded Masks to become imagers in the gamma ray domain. An overview of the INTEGRAL Coded Masks operation principle and performances is presented in *Reglero et al* in this Seminar.

The main function of the Coded Masks is to perform spatial multiplexing of the incident radiation. The Masks are basically matrixes of opaque and transparent pixels, following a bidimensional pattern, each of the holes acting as an individual pinhole camera. The image on the detector plane is therefore the convolution of the sky image and the code pattern. Each Mask use a different code pattern, optimised for the scientific goals of the instrument. The performance of the Masks acting as Spatial Multiplexing Systems depend to a great extent on the accuracy of the code elements position and size.

Tungsten (pure or alloyed) was the baseline material chosen to implement the codes because of both its high density and large atomic number which provides the required stopping power (opacity) in the gamma and X-ray energy ranges.

The main parameters for the Mask Code Patterns are:

*IBIS Coded Mask:*

- Material: Densimet 18
- Code pattern: MURA 53x53, four times repeated (symmetry 180°). See Figure 1a.
- Pixel Size: Square, $11.2x11.2mm^2$
- Total Nr of Pixels: 95x95; 50% transparent / 50% opaque
- Total Coded Area: $1064x1064mm^2$
- Code Thickness: 16mm

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*SPI Coded Mask:*

- Material: Densimet 18
- Code pattern: HURA 127 elements; 64 transparent, 63 opaque (symmetry 120°). See Figure 1b.
- Pixel Size: Hexagon, 60mm side to side
- Total Coded Area: 780mm diameter
- Code Thickness: 30mm

*JEM-X Coded Mask:*

- Material: pure Tungsten
- Code pattern: HURA 22501 elements (symmetry 120°)
- Pixel Size: Hexagon, 3.3mm side to side
- Total Coded Area: 535mm diameter
- Total Nr of Pixels: ~23500; 25% transparent / 75% opaque
- Code Thickness: 0.5mm

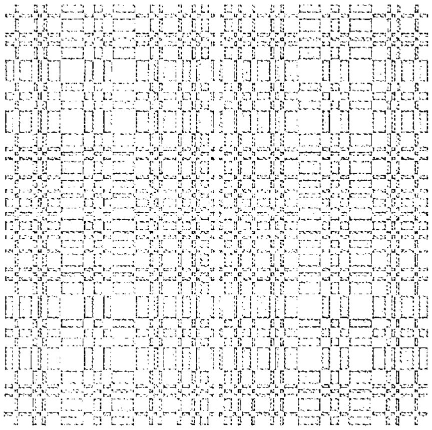

Figure 1a. IBIS Mask Code pattern

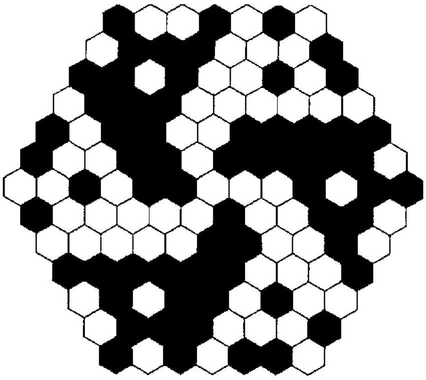

Figure 1b. SPI Mask Coded pattern

For further information see (1)

Strong requirements were defined for the code parameters at the beginning of the project (1994) in order to fulfil the instruments scientific goals (angular resolution, source location accuracy and sensitivity). These requirements define the performance of the Masks as Optical Systems, and refer mainly to two aspects:

- *Position and size* of the code elements, defined by the code manufacturing process and code integration into the Mask Assembly
- *Transparency/Opacity* of the hole/opaque pixels in the instrument energy range. Deviations from its theoretical values (0/1) induced by the presence of support structures need to be characterizes in detail.

Tables I, II and III summarise the *pixel position* and *size* scientific requirements (deviations from theoretical values) altogether with the those imposed to the codes cutting process itself, before their integration in the Mask Assembly. Error budgets are quite demanding in order to achieve the required final precision for the full Mask Assembly.

The *IBIS Mask Code* was machined in four individual W 16mm thickness plates, with hard requirements in pixel position (±0.075mm) and size (0.1mm).

| | Mask Requirements | | Code Manuf. Requirements | |
|---|---|---|---|---|
| | Position | Size | Position | Size |
| Y | ±0.15mm | 0.1mm | ±0.075mm | 0.1mm |
| Z | ±0.15mm | 0.1mm | ±0.075mm | 0.1mm |

Table I. IBIS Mask scientific and manufacturing requirements (pixel position and size)

The *SPI Mask Code* was machined in individual W 30mm thickness blocks (1, 2 or 17 hexagons each one). The manufacturing requirement (±0.025mm) refers to these blocks dimensions.

| | Mask Requirements | Code Manuf. Requirements |
|---|---|---|
| | Total Position | Total Size |
| Total in plane | ±0.15mm | ±0.025mm |

Table II. SPI Mask scientific and manufacturing requirements (pixel position and size)

The *JEM-X Mask Code* hexagons are machined in a very thin (0.5mm) Tungsten sheet. Centroid pixel position (±0.06mm) and pixel size (±0.01mm) requirements are quite demanding for more than 5400 hexagonal holes.

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| | Mask Requirements | | Code Manuf. Requirements | |
|---|---|---|---|---|
| | Position | Size | Position | Size |
| Y | ±0.2mm | 0.01mm | ±0.06mm | 0.01mm |
| Z | ±0.2mm | 0.01mm | ±0.06mm | 0.01mm |

Table III. JEM-X Mask scientific and manufacturing requirements (pixel position and size)

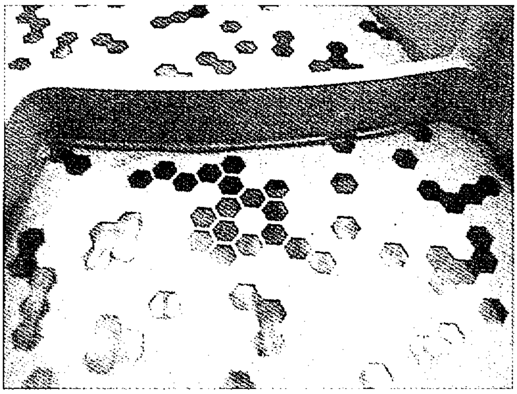

Figure 2. JEM-X Mask code detail: "island"

## 2. Cutting Technologies.

One of the milestones of Coded Masks development carried out from 1995 to 2000 was *to define the cutting optimum technology* for the Code machining. The main constraint for the optimal cutting technology selection was the *extremely high accuracies* needed for the pixel position, size and geometry. As it is shown in Tables I, II and III, the manufacturing accuracies should be better than 0.1mm over Tungsten plates larger than 500mm, having several thousands of pixels. The standard machining processes for hard materials like Tungsten were not prepared to obtain these accuracies in such large areas.

Another challenging problem was the machining of the *JEM-X Code* on a 535mm diameter plate of only *0.5mm thickness*. The code of JEM-X (~5400 hexagonal holes 3.3mm side to side) includes "islands" (opaque hexagons surrounded by transparent holes) joined to the plate by 0.4mm thickness ribs (see figure 2). The selected machining process must avoid the presence of

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microcracks coming from the manufacturing process in a very fragile coded plate.

In all cases, after the manufacturing and assembly of the Coded Masks, they had to pass through a hard *Qualification Test campaign*, in order to prove their capability to survive INTEGRAL launch and operation environments, maintaining their scientific performances. These tests include Vibration tests (more than 12g inputs) and Thermal Vacuum and Cycling (from –60°C to 45°C).

Technologies tested were: *LASER cutting*, *Photochemical Milling*, *Electrodischarge Milling* and *Electrodischarge Wire Machining*. Main advantages and disadvantages of each method are summarised in the following paragraphs.

### 2.1. LASER Cutting.

*BENEFITS:*

- Low cost
- Good accuracy, regular hexagon shapes

*PENALTIES*

- Material damage: cracks due to overheating
- Material mechanical and thermal properties affected
- Recasting

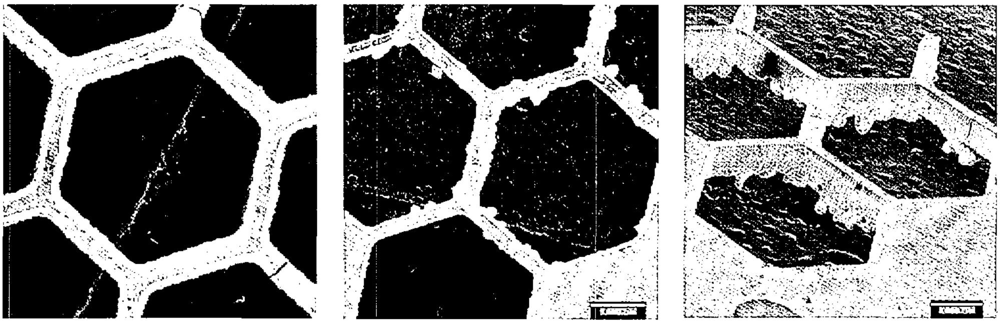

Figure 3. *LASER cutting*. JEM-X Code sample, hexagons with 0.4mm ribs. On the left, cracks on the ribs can be observed. On the centre and right pictures rests of materials along the ribs are clearly shown. Microphotographs from ICMUV facilities.

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## 2.2. Photochemical Milling.

*BENEFITS:*

- Low cost
- Material properties not affected

*PENALTIES:*

- Poor accuracy in pixel dimension and shape
- W high resistance to chemical milling
- Photoresin: difficult to resist the acid required for Tungsten.

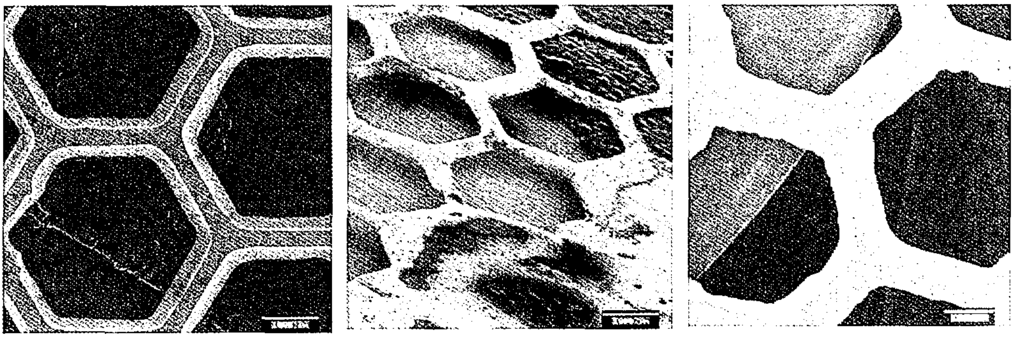

Figure 4. *Photochemical Milling.* JEM-X Code sample, hexagons with 0.4mm ribs. A poor geometrical finishing is clearly seen in the three pictures. Inhomogeneities and shapes Microphotographs from ICMUV facilities.

## 2.3. Electrodischarge Milling.

*BENEFITS:*

- Good accuracy, regular hexagon shapes
- Minimum material damage

*PENALTIES:*

- Large uncertainty in pixel position
- Quick wearing of electrodes
- Several electrodes required to comply accuracy requirements
- Expensive

## 2.4. Electrodischarge Wire Machining (EDWM).

*BENEFITS:*

- Splendid accuracy of hexagon shapes and positioning
- Minimum material damage
- Flexibility to improve pixel accuracy (multiple passes)

*PENALTIES:*

- Expensive
- Time machine consuming

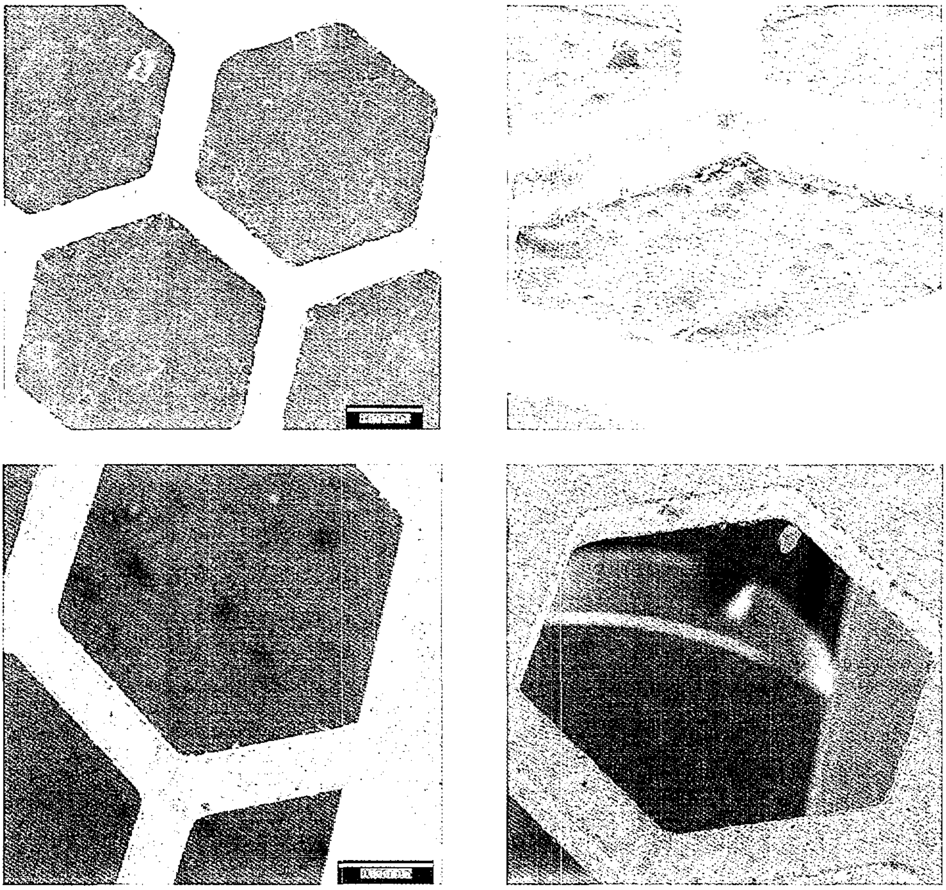

Figure 5. *Electrodischarge Wire Machining.* JEM-X Code samples, hexagons with 0.4mm ribs. Good finishing in the pixel wall and pixel regular shapes are clearly seenn.

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The EDWM was the technology selected to implement the Codes of the three INTEGRAL Masks. More information about the EDWM can be found in (2). The Code plates for the Coded Masks Development Models (DM), Qualification Models (QM) and Flight Models (FM) have been manufactured by this method, with increasing successful results in the Spanish company *Mecanizados Ginés.*

Main parameters of the wire cutting are the following:

- Wire Diam: 0.25mm
- Wire Material: Cu (Zn coating)
- Voltage: -80/-100V
- Cutting speed: 2.2 to 2.5mm/min
- Dielectric: Distilled water
- Nr. of cutting hours (one JEM-X Code): ~500

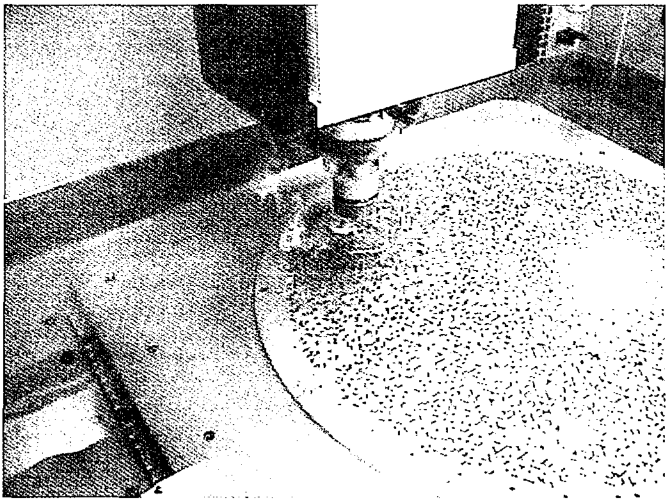

Figure 6. Cutting of the JEM-X code by Electrodischarge wire machining. More than 5000 hexagonal holes 3.3mm side to side.

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# 3. FM Masks Results on Pixel Size and Position.

The results on pixel size and position obtained in the implementation of the INTEGRAL FM Masks codes are presented hereafter, compared with both scientific and manufacturing requirements.

## 3.1. IBIS Mask Results.

a) Plates Manufacturing (all pixels measured)

| | | Required | Std Dev(σ) | Max Dev |
|---|---|---|---|---|
| Pixel Position | Y | ±0.075mm | *0.010mm* | 0.030mm |
| | Z | ±0.075mm | *0.015mm* | 0.040mm |
| Pixel Size | Y | 0.1mm | *0.010mm* | 0.060mm |
| | Z | 0.1mm | *0.010mm* | 0.060mm |

Table IV. IBIS Mask pixel position and size results, after code machining.

b) Mask Assembly (16 control pixels measured)

| | | Required | Std Dev(σ) | Max Dev |
|---|---|---|---|---|
| Pixel Position | Y | ±0.150mm | *0.030mm* | 0.040mm |
| | Z | ±0.150mm | *0.030mm* | 0.050mm |

Table V. IBIS Mask pixel position and size results, after Mask assembly.

Detailed IBIS Mask results can be found in (3) and (5). Main conclusions can be summarised as follows:

- The results obtained are 5 times better than required.
- Stability of the IBIS Mask as an optical system: no significant deviations have been found before and after environmental tests at INTA

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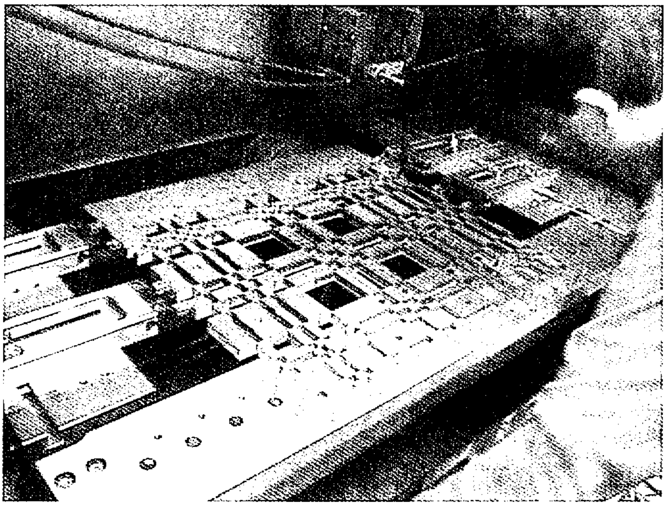

Figure 7. IBIS Code plate cutting by Electrodischarge Wire Machining.

## 3.2. SPI Masks Results.

a) Plates Manufacturing (all pixels measured)

All Code blocks (1, 2 & 17 hexagons) are within manufacturing tolerances (±0.025mm).

b) Mask Assembly (all pixels measured)

| | Required | Std Dev(σ) | Max Dev |
|---|---|---|---|
| Total in plane Pixel Position | ±0.150mm | 0.020mm | 0.080mm |

Table VI. SPI Mask pixel position and size results, after Mask assembly.

Detailed results of SPI Mask scientific performances can be found in (4) and (6). Main conclusions can be summarised as follows:

- The results obtained are 7 times better than the scientific requirements
- Stability of SPI Mask as an optical system: no significant deviations found before and after environmental tests at INTA

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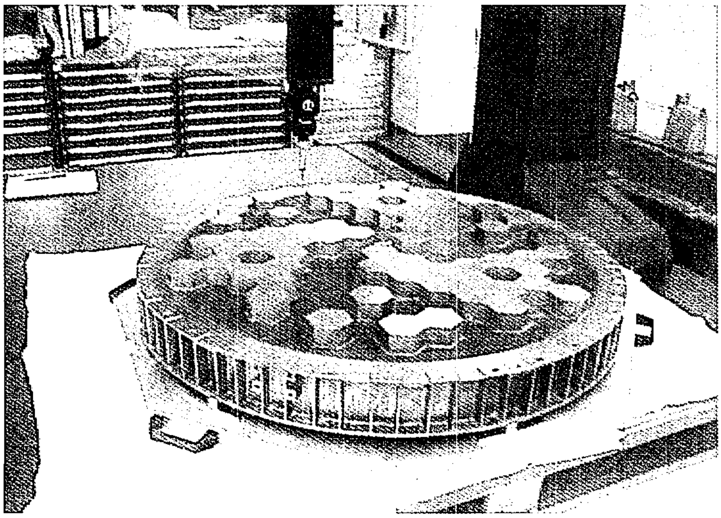

Figure 8. Dimensional Control of the SPI FM Coded Mask

### 3.3. JEM-X Mask Results.

a) Plates Manufacturing (200+200 pixels measured)

| | | Required | Std Dev(σ) | Max Dev |
|---|---|---|---|---|
| Pixel Position | Y | ±0.060mm | *0.015mm* | 0.030mm |
| | Z | ±0.060mm | *0.015mm* | 0.030mm |
| Pixel Size | Y | 0.01mm | *0.005mm* | 0.010mm |
| | Z | 0.01mm | *0.005mm* | 0.010mm |

Table VII. JEM-X Mask pixel position and size results, after code machining.

b) Mask Assembly (100+100 pixels measured)

| | | Required | Std Dev(σ) | Max Dev |
|---|---|---|---|---|
| Pixel Position | Y | ±0.2mm | *0.025mm* | 0.060mm |
| | Z | ±0.2mm | *0.025mm* | 0.050mm |

Table VIII. IBIS Mask pixel position and size results, after Mask assembly

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Detailed JEM-X Mask results can be found in (7) and (8). Main conclusions can be summarised as follows:

- The results obtained are 8 times better than the scientific requirements
- Stability of JEM-X FM Masks as optical systems: no significant deviations found before and after tests

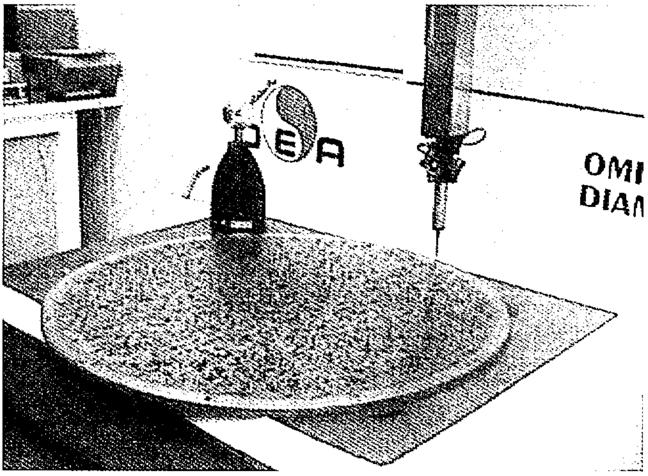

Figure 9. Dimensional Control of the JEM-X FM code plates after their machining.

## 4. Conclusions.

An extensive programme on testing technologies for high precision Tungsten cutting in large areas was carried out from 1995 to 1998 by the Spanish team involved in the INTEGRAL ESA Mission (GACE, SENER, INTA and Mecanizados Ginés): LASER, Photochemical Milling, Spark Machining and Electrodischarge Wire Machining. The EDWM was selected as the optimum technology.

Qualification and Flight Models for the four Mask Assemblies (SPI, IBIS and JEM-X) demonstrate the high accuracy achieved in the code cutting and geometry. Code elements size and shape fulfil scientific requirements. In fact they are 5 times better than specified.

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Qualification and Acceptance Tests carried out at INTA proved the stability of the code positioning under extreme conditions (12g input acceleration; –60ºC to +45ºC), exceeding requirements by a factor 8. EDWM has demonstrated its capability to produce fine Tungsten plate cutting to implement new Optical Systems for High Energy Astrophysics.

## Acknowledgements.

We would like to thank more than 14 European industries that have participated in the Masks development, with special mention to our Prime Contractor SENER, test facilities team at INTA, our Tungsten supplier PLANSEE and its representative in SPAIN Technalloy.

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