A COLD FOCAL PLANE CHOPPER FOR HERSCHEL-PACS — CRITICAL COMPONENTS AND RELIABILITY

R. Hofferbert¹, D. Lemke¹, O. Krause⁵, U. Grözing⁵, A. Böhm¹, W. Bollinger², J. Katzer²

¹ Max-Planck-Institut für Astronomie (MPIA), Königstuhl 17, D–69117 Heidelberg, Germany
(correspondence: hofferbert@mpia.de, Tel 49-6221-528261, Fax 49-6221-528246)
² Carl Zeiss, Carl-Zeiss-Str. 22, D–73447 Oberkochen, Germany

ABSTRACT

A chopper acts as an optical switch within the entrance optics of the PACS instrument onboard the ESA Space Observatory HERSCHEL to discriminate the light of faint celestial sources from a large background flux, which is basically due to the thermal radiation of the only moderately cooled 3.5m-telescope (≈ 80K). This chopper primarily consists of a small electrically driven tilting mirror with a high position accuracy for the full range of elongations up to ±9° to be operated at 4K with a power dissipation of less than 4mW. At a chopping frequency of up to 10Hz in square wave modulation scheme a duty cycle of 80% is to be achieved. After a pre-development phase at MPIA, which resulted in an optimized and cold tested prototype, the industrial optimization and implementation of the PACS chopper started in 2000 in a cooperation with the company Zeiss (Oberkochen).

We focus on the new design of the chopper and its critical components, including the recently developed double-stage flexural pivots as high reliable bearings of the chopping mirror axis. The monolithic CuBe2 layout has to resist vibration loads of up to 45g during the launch of the ARIANE 5 carrier and to guarantee for an accurate motion in a cryogenic environment during a lifetime of at least 3 years in space, which corresponds to 630 Mio cycles of the chopper. Other components like the cryomotor and the rotor will be considered with respect to the selection of optimal materials, the reliability of mechanical linkages and the compensation of thermal stresses within the whole multi-material chopper assembly.

I. HERSCHEL SATELLITE

In 2007 ESA will launch the HERSCHEL satellite (formerly known as FIRST) as another cornerstone mission of its “Horizon 2000 long term programme” [1]. This multi-user device will be the biggest and most powerful infrared observatory of its time. With a wavelength coverage between 60 and 670μm it will be sensitive especially in the far-infrared and submillimeter region, thus exploring radiation in a very unknown range of the electromagnetic spectrum. Scientific objectives, which will be addressed by HERSCHEL, range from the exploration of the distant universe and the question how first stars and galaxies were born, across the formation of planetary systems up to the investigation of our own solar system.

HERSCHEL’s payload module is basically composed of a 3.5m Cassegrain telescope radiatively cooled to T ≈ 70-90K and three scientific instruments (HIFI [2], SPIRE [3] and PACS [4]) sitting in the corresponding focal plane inside a 1.7K cryostat filled with 2160l of superfluid helium, see Fig. 1. At a total mass of roughly 5.300kg and a length of about 11m, HERSCHEL will be launched in a pickapack configuration together with the PLANCK satellite (cosmic microwave background survey, [5]) by an ARIANE 5 carrier. After a transfer period of 3 month both will be separated and operated individually at the 2nd Lagrangian, 1.5 Mio km away from earth in the anti-sunward direction. HERSCHEL is specified as a multi-user, high accuracy pointed observatory with a lifetime of at least 3 years.

PACS, the Photodetector Array Camera and Spectrometer [4], is one of the three scientific instru-
ments. It offers two principal observation modes in the range between 60 and 210µm:

- Imaging photometry, using 2 bolometer detector arrays with 32 × 16 resp. 64 × 32 pixels, allowing for simultaneous observation in two bands with a FOV of 3.5′ × 1.75′ and a sensitivity of 5 mJy (5σ, 1 hour).

- Spectroscopy, using 2 photoconductor detector arrays with 25 × 16 pixels each (Ge:Ga, stressed and low-stressed), covering a FOV of 50″ × 50″ at a resolution of 175 km/s with a sensitivity of down to 2.5 × 10⁻¹⁶ W/m² (5σ, 1 hour).

In comparison to its very successful predecessor ISO [6], ESA’s “Infrared Space Observatory”, which was operated between 1995 and 1998, HERSCHEL-PACS features a roughly one order of magnitude higher sensitivity per pixel for compact celestial sources at a drastically increased number of pixels and a higher angular resolution.

**II. PACS CHOPPER**

Since the primary mirror of the HERSCHEL telescope is only moderately cooled to a temperature around 80K, a small tilting mirror at 4K, the chopper, located right within the entrance optics of PACS, will act as an optical switch to discriminate the light of faint celestial sources (down to 10⁻¹⁶ W) from the orders of magnitudes larger background flux. In addition the PACS chopper is specified to allow for in-orbit calibration of the whole camera by switching flux from internal black bodies onto the detector arrays. Both demands can be fulfilled, if the tilting mirror is driven at different elongations using appropriate modulation schemes. The full list of requirements for the chopper as adapted for an optimized operation of PACS itself [7] can be seen in Fig. 2.

Note, the critical items are given by a duty cycle of 80% in square wave modulation scheme at 10Hz driving frequency with an accuracy of 1 arcmin across the whole deflection range of 4.1°, to be achieved at 4K with only 4mW of total power consumption. Those stringent requirements together with its location in the entrance optics of PACS, making it a single point failure source of the whole experiment, demand a high degree of reliability and accuracy for the chopper and its critical components.

In a two year pre-development phase at MPIA the technical feasibility of such a cryogenic mechanism has been demonstrated, yielding an optimized and cold-tested prototype [8–10], which at least fulfilled the given functional requirements as given in Fig. 2. In Fig. 3 the principal design of the advanced prototype can be seen:

<table>
<thead>
<tr>
<th>Dimensions envelope</th>
<th>125 mm X 80 mm X 40 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>≤ 300 g</td>
</tr>
<tr>
<td>Mirror optical performance</td>
<td>( &lt; 150 \text{ nm} )</td>
</tr>
<tr>
<td>flatness</td>
<td>( &lt; 50 \text{ nm} )</td>
</tr>
<tr>
<td>roughness</td>
<td>( &lt; 98% )</td>
</tr>
<tr>
<td>reflectivity</td>
<td>( &gt; 98% )</td>
</tr>
<tr>
<td>Mirror size</td>
<td>26 mm x 32 mm</td>
</tr>
<tr>
<td>moving axis</td>
<td>( \leq 0.1 \text{ mm} )</td>
</tr>
<tr>
<td>sharp edges</td>
<td>10° wedge shaped</td>
</tr>
<tr>
<td>Chopper inclination</td>
<td>( \pm 0° - 4.1° )</td>
</tr>
<tr>
<td>a) operation</td>
<td>accuracy ( \pm 1 \text{ arcmin} )</td>
</tr>
<tr>
<td>b) calibration</td>
<td>accuracy ( \pm 2 \text{ arcmin} )</td>
</tr>
<tr>
<td>Modulation function</td>
<td>a) operation</td>
</tr>
<tr>
<td>b) calibration</td>
<td>arbitrary waveform</td>
</tr>
<tr>
<td>Frequency ranges</td>
<td>0 Hz ... 10 Hz, adjustable</td>
</tr>
<tr>
<td>For real time</td>
<td>square wave</td>
</tr>
<tr>
<td>Electronic condition</td>
<td>zero position ( \pm 1 \text{ arcmin} )</td>
</tr>
<tr>
<td>Service life</td>
<td>approx. 20 G</td>
</tr>
<tr>
<td>Vibration load</td>
<td>45 g RMS</td>
</tr>
<tr>
<td>Sinus random</td>
<td>15 g RMS</td>
</tr>
<tr>
<td>Lifetime</td>
<td>6 years, operation 33% of time</td>
</tr>
</tbody>
</table>

FIG. 3. Design of the advanced MPIA chopper prototype.

The mirror is an integral part of the rotor (one blank, Al 6061 T6), which also carries two driving magnets (Vacodym 344 HR), a position sensor magnet (Vacodym 344 HR) and mounting bushings for two flexural pivots. The latter in general provide for both, a frictionless bearing as well as a linear restoring force. This embedded, free swinging rotor is actuated by three alternating driving coils leaving only a small air gap for the moving permanent magnets on the rotor. To account for a very accurate deflection measurement, which is also important for controlling the externally pre-shaped modulation function of the rotor, a newly developed position sensor (closed Ultraperm/Cryoperm core with magnetic flux sensitive semiconductor fieldplates) picks up the signal of the moving position sensor magnet. Further information about design and functionality of this position sensor can be found in [11].
To demonstrate the achieved performance and accuracy of the advanced MPIA prototype, Fig. 4 presents the nominal square wave modulation function at 10Hz with a maximum deflection of 4.1° and a duty cycle of even more than 80% as measured in the cryovacuum at 4K. The attached table compares critical operational parameters, indicating that the prototype exceeds specification.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chop throw [°]</td>
<td>9</td>
</tr>
<tr>
<td>Chop frequency [Hz]</td>
<td>10</td>
</tr>
<tr>
<td>Position accuracy [arc sec]</td>
<td>60</td>
</tr>
<tr>
<td>Power dissipation [mW]</td>
<td>4</td>
</tr>
<tr>
<td>Duty cycle [%]</td>
<td>80</td>
</tr>
</tbody>
</table>

FIG. 4. Cold-measured modulation function of the advanced MPIA prototype and a comparison of specified and achieved physical properties. While curve a) is measured under closed-loop control, curve b) was recorded in a feed-forward loop without control.

Based on this prototype phase at MPIA, the development of a space-qualified chopper Flight Model (FM) for HERSCHEL-PACS has been finally commissioned to the company ZEISS in 2000. Their project philosophy is defined by

- the adoption of the MPIA prototype concerning functionality and performance,
- optimization with respect to lifetime and launch conditions,
- the fabrication of four models, including two test-specimen (lifetime test, qualification test),
- the space qualification of all components and the whole unit,
- the preparation of a complete documentation as demanded by ESA and
- supervision of the whole project by industrial system engineering and quality assurance.

A technical drawing of the PACS chopper as elaborated during the ZEISS design phase together with a photography of the corresponding hardware can be seen in Fig. 5.

III. CRITICAL COMPONENTS OF THE PACS CHOPPER

We will now focus on the design, manufacture and testing of critical components of the PACS chopper like the flexural pivots, the driving coils and the rotor. Special emphasis will be put on the selection of optimal basic materials, the reliability of linkages and the compensation of thermal stresses within the whole multi-material chopper assembly. All sub-level verifications serve as preparation for the assembly of the Lifetime Model (LM), which will be hard-tested soon.

A. Flexural Pivots

Flexural pivots present an optimal solution to construct maintenance-free bearings with one axis of rotation for the cryovacuum. The possibility to run
them friction-less without any lubricant makes them superior to any other type of suspension. The mechanical principle basically rests on two or more cylindrical stages in a suspension unit, which are only coupled and positioned to each other by a system of embedded crossed blade springs providing both, bearing as well as restoring force. Figure 6 shows a typical realization, which has been used in the advanced MPIA prototype.

FIG. 6. Typical design of a flexural pivot (model: Lucas 5005-800), which has been used in the advanced MPIA prototype.

Three different kinds of loads have to be considered:

- Fatigue during the whole lifetime of the satellite mission. Verification of this feature is the main goal of the lifetime test. Mainly the choice of material determines this item.

- Mechanical stress during the launch. This feature has been addressed in a detailed FEM model structural analysis of the chopper and the flexural pivot as its most critical mechanical subcomponent. Here also the limiting loads and the eigenfrequencies of the flexural pivots have been determined. To avoid any damage caused by shock loads during the launch, the chopper will be additionally equipped with an electro-mechanical launch lock mediated by electrically shortened motor coils. Tests of these items are also part of the LM verification phase.

- Thermal stress due to cryogenic shrinkage of different materials. Not only the embrittlement of certain raw materials at low temperatures but also the mechanical interplay with other materials had to be considered. Furthermore, this also determines the kind of linkage between components (screwing, cluing, etc.).

All those considerations led to a trade-off phase at the ZEISS laboratories and the present layout of the PACS chopper flexural pivots, see Fig. 7.

![cut view](image1)

FIG. 7. Results of the ZEISS trade-off for the PACS chopper flexural pivots. The whole investigation bases on a detailed FEM model structural analysis using typical grids as shown in the lower part (PACS Type 2A/2B in cut view). For comparison also the properties of the ISOPHOT chopper [12], which flew on the ISO satellite, are given. Eigenfrequencies are labelled by (FP) for flexural pivot excitations and (R) for rotor excitations, respectively.

While the advanced MPIA prototype used commercial, modularly composed, stainless-steel flexural pivots Lucas type 5005-800 (Fig. 6), the lifetime resp. launch requirements demand an optimized geometrical design [13] with respect to spring rate, bending stresses and load capacity. Therefore, on the one hand side a monolithic layout has been foreseen favoring CuBe2 resp. TiAl6V4 as raw material, both of which are suitable for individual geometrical structuring by wire eroding (EDM). The basic advantages of monolithic vs. modular-type manufacturing is the prevention of parasitic strength enhancement at taut points of the spring blades as well as a hysteresis-free momentum - angle of deflection characteristics.

On the other hand, a design with crossing spring blades unseparated on the axis of rotation has been
preferred. This guarantees internal prevention of a moving axis during deflection and therefore crucial reduction of additional stress by perturbing torque.

Anyway, since the stiffness or spring rate \(d\) (in Nm/rad) of an unseparated flexural pivot is in linear approximation 4 times larger than for a separated in the same dimensions \([14]\),

\[
d_{\text{unsep}} = \frac{2}{3} E \frac{W T^3}{L} = 4 \cdot d_{\text{sep}} , \tag{1}
\]

the maximum deflection \(\hat{\phi}\) is in the same way reduced by a factor of 4,

\[
\hat{\phi}_{\text{unsep}} = \frac{1}{4} \frac{\sigma L}{2 E T} = \frac{1}{4} \cdot \hat{\phi}_{\text{sep}} . \tag{2}
\]

Here, the properties \(L\) (length), \(T\) (thickness) and \(W\) (width) define the geometry of the blades, see Fig. 7, while \(E\) (modulus of elasticity) and \(\sigma\) (fatigue strength) characterize the used raw material. This in general enforces to choose long and thin blades for applications with large deflection angles as in the case of the PACS chopper. Now, an additional design feature had to be implemented to account for the disadvantageous factor of 4 and to again relax the bending stress loads of the bearings: A double-stage design divides the full range of elongations of at least \(\pm 9^\circ\) into two substages with half the deflection each, both of which are connected by an intermediate connecting bar or coupling rod. Figure 8 gives an impression of this double-stage design and the way it could be nowadays manufactured by wire EDM.

![Fig. 8. The monolithic, unseparated, double-stage flexural pivot presents the final result of the sophisticated design phase at the ZEISS laboratories. The photograph shows a first prototype, which has been manufactured from one blank of CuBe2 raw material in EDM (Electrical Discharge Machining, i.e. wire eroding) technique.](image)

Although the titanium type spring is superior in capacity against vibration loads during launch and presents higher safety factors during lifetime cycling, it is exposed to drastically enhanced thermal stress during cooldown as linking element between chopper rotor and housing, both made out of Al 6061 T6, see Fig. 7. Since the present design does only allow for limited mechanical compensation, CuBe2 was the only suitable solution and hence the baseline for the PACS chopper (Type 2A).

In a series of experimental investigations the physical properties of those finally realized flexural pivots have been analyzed. Although the structural analysis clearly points out capability against quasi-static loads of 56g, which correlates to roughly 45g taking into account an ESA specific vibration load safety factor of 1.3 for components inside PACS, see Fig. 7, the blade thickness of first prototype flexural pivots were increased from 40 to 50\(\mu\)m, also to somewhat relax the manufacturing process. Although this enlarges the power dissipation and reduces the lifetime safety factor of the chopper by about 10-15%, the load capacity is drastically enhanced due to the \(T^3\)-dependency in Eq.(1). Optical measurements indicate thickness variations of only 2\(\mu\)m across the whole lengths and widths of several blades. Using a balance with implemented flexural pivot as bearing element, the stiffness of the spring could be measured with different test masses at different lever arms. This yields \(0.50 \pm 0.02\)Ncm/rad, which is in good agreement with the FEM-analysis for the 40\(\mu\)m-blades scaled by the \(T^3\)-law of Eq.(1), which gives \((0.54 \pm 0.06)\)Ncm/rad for the (50\(\pm\)2)\(\mu\)m-blades.

In a final step a set of measurements has been performed to check for the load capacity of the springs using a Zwick material testing machine (type 1484 WN:074797). According to the increased blade thickness, also the specified quasi-static load emerging from the FEM-analysis, see Fig. 7, has to be rescaled using the \(T^3\)-dependency. This results in a new value for the 50\(\mu\)m-blades of \(\approx110\)g for each flexural pivot resp. \(\approx220\)g for the total setup with two bearings (both values again to be reduced by the above mentioned vibration load safety factor of 1.3).

To simulate this specified quasi-static load on the chopper, two prototype flexural pivots were mounted in a jig and laterally exposed to a tuneable force. In two sequences the springs were either symmetrically or asymmetrically loaded (with up to 85% portion on one of the two sides). The recorded force vs. displacement diagrams indicated up to forces of 12N, which corresponds to a quasi-static load of 120g at a rotor mass of 10 grams, a very linear behavior and a full restoration after force decrease without any damage and only a slight hysteresis, see Fig. 9. In the asymmetrical case the linear region ended approximately at 12N, first damage via inelastic buckling of the spring blades could be observed beyond 22N. This is also in very good agreement with the specified 220g as mentioned above.

Additional experimental investigations also tested the rupture limit of the blades themselves. For this purpose the coupling rod inside the flexural pivot has been exposed to tensional forces of up to 500N with respect to the housing of the flexural pivot, see Fig. 10.
Test case 1 (symmetric) | 2 (asymmetric)
--- | ---
Force F | 6N (60g at rotor mass = 10gr) | 12N | 12N | 18N | 22N
Displacement a | (13±1)µm full restoration | (33±1)µm full restoration | >41µm end of linear range | >84µm non-linear buckling

FIG. 9. Setup and results of the load capacity tests using the ZEISS prototype flexural pivots with 50µm-blades.

FIG. 10. Setup used for the rupture tests. On the left the flexural pivot can be seen in the jig, which is mounted in the material testing machine on the right, exposing up to 500N of tensional forces to the blades.

Damage only occurred in the case of asymmetric tension across the rod, thus defining the rupture limit of the used material.

After this static tests verifying the critical item "quasi-static load" of the flexural pivots, a whole bundle of experimental investigations will be devoted to launch vibrations between 5 and 100Hz (sine excitations) and between 20 and 2000Hz (random excitations). Those values could also be derived from the FEM structural analysis of the chopper, yielding limiting loads of 30g (sine) and about 18g rms (random), which are based on the mentioned 56g quasi-static load for the 40µm-blades. Verification of those items will be mainly part of the qualification tests on the PACS chopper QM, which are also planned for the second half of this year.

B. Driving Coils

In contrast to the flexural pivots the driving coils of the cryomotors were already optimized with respect to the chopper specifications during the prototype phase at MPIA [8–10]. Not only the design but also the choice of different raw materials were subject of detailed investigations, including e.g. a full electromagnetic FEM simulation of the whole actuator unit using the MAFIA package. Results of these simulations were in perfect agreement with cryogenic measurements defining a driving mechanism, which is understood in every physical detail like specific torque, power dissipation and stray field characteristics. This allowed for instance to operate the whole chopper in a feed-forward loop (curve b in Fig. 4) without any control unit, i.e. position sensor, since the desired modulation function can be directly converted into an exciting voltage via the electrical properties of the cryomotor and the mechanical, also well-known properties of the rotor.

ZEISS had to address important modifications to guarantee a reliable and space-qualifiable design. The principle task comprised (a) to properly issuing a procedure of how to manufacture and assemble every single part of the motor block ("the recipe") and (b) to further optimize the whole unit with respect to the choice of raw and bonding materials ("the ingredients"). Main drivers of this optimization process are on the one hand a further reduction of the power consumption basically mediated through Ohmic losses in the coils and eddy currents in the cores. On the other hand a sufficient thermal coupling of all components towards the housing, i.e. heat sink of the chopper, has to be guaranteed. In contrast to the MPIA prototype, where the motor chassis was realized as an integral part of the chopper housing, ZEISS preferred an exchangeable motor block made from polished Al 6061 T6, which could be modularly mounted and dismounted from the rest of the unit. Here, wide mounting feet equipped with shrinkage compensated screws (via Invar washers) account for an optimal thermal coupling. A detailed drawing of this final state can be found in Fig. 11.

FIG. 11. Final outcome of the cryomotor design according to ZEISS.

The recipe for the coils as mediator of the driving magnetic flux looks as follows: Cryoperm 10 (Vaku-
umschmelze), which defines an optimal raw material for magnetic applications with high permeabilities ($\mu_r \gtrsim 10^5$) and high saturation fields ($B_s \gtrsim 0.9T$), both at very low temperatures around 4K, has been used to produce laminated cores with typically 112 sheets of 100$\mu$m thickness, clued and encapsulated with Stycast 1266 layers of approximately 10$\mu$m. The corresponding manufacture process has been optimized by a dedicated procedure, which is known from circuit board etching: Pre-cutting of the Cryoperm sheet material, removing of the insulation and chemical abrading of the surface (nitric acid, 50%), rinsing and drying, applying of photosensit, exposing to UV light, processing with NaOH, removing the photoresist with KOH, etching with FeCl$_3$ and final rinsing and drying. The manufacture process is completed by a homogeneous cluing of all sheets inside a pressing tool and an outgassing sequence in vacuum to exclude embedded air. In a subsequent fine milling the core edges are finally prepared for coiling the very thin (80-100$\mu$m) high purity (5-6N) wire (970-1020 windings, aluminum resp. copper).

Furthermore, a slight lateral oversizing of the cores, see Fig. 11, guarantees an appropriate guiding of parasitic stray field in the outer regions of the motor block. This not only prevents the actuator from a non-linear torque vs. current behavior, but also reduces eddy losses in the aluminum chassis of the motor block. Finally, a Vespel cap also equipped with shrinkage compensated screws covers the chassis and cares for a sufficient mechanical stress to fix the coils during cooldown.

Concerning installation and adjustment, the chopper rotor can be regarded as the most important sub-component of the whole assembly. Due to its high number of interfaces to (i) the incident optical beam, to (ii) the housing via two flexural pivots, to (iii) the actuator via two driving magnets and to (iv) the position sensor via another fieldplate magnet, only a monolithic realization (Al 6061 T6) based on an optimized geometrical design could guarantee the necessary stiffness and compactness for the desired dynamical behavior. A monolithic construction is also necessary to allow for a precise alignment of the flexural pivots as rotor suspensions towards the chopper housing.

Although the MPIA prototype already presented a well-advanced development, certain modifications were necessary to comply with the present chopper specifications:

- While the prototype rotor was constructed on the baseline of a circular mirror with 25mm of diameter, the present PACS design demands an elliptical mirror with 26mm×32mm. This slightly increases mass and momentum of inertia ($MoI$), thus the geometry had to be adapted constituting a somewhat different lightweight concept on the mirror back (cross members instead of honeycombs).
- The driving and sensor magnets (Vacodym 655 TP) were slightly changed with respect to size and position above the rotor axis to coincide with the modified driving resp. position sensor unit.
- The bushings at the rotor ends have been well-adapted to the new double-stage flexural pivots. Here another shrinkage compensation feature has been foreseen: While on the housing side the flexural pivot will be fixed by a screwed clamp again with compensating washers, see. Fig. 5, the counterpart stage will be clued into the rotor bushing (using Stycast 1266). Within this bushing a small gluing gap of 2mm length allows to reduce lateral stress between the strongly shrinking aluminum ($\alpha = \Delta l/l = -420 \cdot 10^{-5}$) and the more weakly shrinking CuBe2 ($\alpha = -320 \cdot 10^{-5}$).
- Apart from those changes, which basically optimize rotor performance during the nominal
operation with typical angular accelerations of up to 20000 rad/s² during the mirror transitions, the ZEISS design in particular had to address optimization with respect to the launch conditions. In this context the FEM model structural analysis focused on two important requirements: (a) Eigenfrequencies of the rotor have to be far beyond the principle resonance frequency of the PACS instrument ($f_0 \approx 125\text{Hz}$) to avoid resonant amplification during the launch and (b) to reduce vibration excitations of the chopper and to improve the launch lock mechanism the rotor needs to be equipped with a tuneable balancing system, which might be adjusted and fixed even after the assembly of the rotor-bearing system.

The result of this considerations as part of the development phase at the ZEISS laboratories can be found in Fig. 13, the eigenfrequencies are given in Fig. 7. Beside design drawings also a photography of the corresponding hardware and a list of the fundamental properties are shown. The hardware manufacture turned out to be an enormous challenge for the MPIA mechanical workshop as the whole chopper did. The strict compliance of precise annealing processes before (6h at 215°C, slow cooling to ambient temperature) and after (8h at 180°C, very slow cooling to ambient temperature) the machining of the coarse structure and a very skillful handling during the fine structuring yielded a nearly perfect rotational symmetry between the mirror axis and the two flexural pivot bushings with a mechanical error of only about 1µm.

In a final step the mirror surface has been diamond milled and gold coated at the ZEISS workshops. Optical measurements on two rotors yielded very promising surface conditions with worst case values of 88nm/81nm rms of flatness (before/after the coating) and approximately 10nm rms of roughness at a typical coating layer thickness of 200nm, compare Fig. 2. Figure 14 presents the completed rotor ready for the implementation of flexural pivots and magnets and the final adjustment in the PACS chopper housing.

IV. CONCLUSION

Three most critical components, namely the flexural pivots, the cryomotor and the chopping rotor have been investigated with respect to design and choice of optimal raw materials. Their behavior and interplay during the launch and under cryogenic operation has been analyzed and verified in numerical simulations and first experimental component tests. This resulted in a completely new monolithic, unseparated, double-stage design for the flexural piv-
ots, which could be technically realized in a wire EDM process on CuBe2. Static tests on first prototype springs indicated the expected high load capacity and a proper functionality under nominal conditions. The cryomotor coils were optimized using a new and sophisticated manufacture procedure for the cores. Finally, also the rotor was subject to some important changes with respect to the MPIA prototype. Beside optimizing its balancing features with respect to a larger mirror and the specified launch conditions, also the optical processing of the mirror surface has been completed within specification.

The next milestone in this development will be the functional test phase of the complete chopper unit followed by a 2.5 month lifetime cycling at approximately 100Hz to simulate the specified 3 year lifetime of HERSCHEL-PACS. Before this cycling the PACS chopper LM will be exposed to vibration loads simulating the launch of the ARIANE 5 carrier. Experimental setups for both test phases can be seen in Fig. 15. With completion of the verification phase in fall 2001, the reliability, accuracy and performance of the PACS chopper will be demonstrated.

V. ACKNOWLEDGMENTS

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[11] O. Krause, ”Magnetoresistive position sensors for cryogenic space applications”, these proceedings resp. 9th ESMATS poster session.