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New generation mirror systems for the ESRF upgrade beamlines

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Abstract. The construction of new beamlines defined in the ESRF upgrade program, requires high performance optics, for which thermal and mechanical stability will be of the utmost importance. Solutions for optimizing drifts and thermal gradients, as well as vibration free positioning have been analysed. This has led to new opto-mechanical engineering able to implement generic solutions for the optics, such as new architecture for flat or bent mirrors, multilayer monochromators, and a new generation hexapod for toroidal mirrors. Vertical incidence fine tuning within 200 nrad, as well as horizontal reflection resolution in the range of 50 nrad, has led to the development of different movers and positioning mechanisms. A review is presented, considering the different design validation stages and laboratory commissioning and showing performance achieved on the very first upgrade beamlines.

1. Introduction

The ESRF engineering groups (Instrument Support and Development Division - ISDD) have been designing mirror systems for many years and valuable operating experience in has been accumulated through beamline maintenance and repairs – strong and weak points have been identified. The new demanding characteristics of the ESRF upgrade provided the ideal occasion to implement design changes driven by this past experience. The two most critical issues addressed in new mirror systems for the ESRF upgrade were vibration sensitivity and thermal stability. Depending on the required degrees of freedom, there are two basic designs: a) the granite bench (G-bench), based on sliding granite benches in order to optimise vibration sensitivity requirements, b) a new improved hexapod. Mirror pointing requirements were defined below 200 nrad, leading to the development of specific dual closed loop incidence tuning. Fine tune positioning nano flexures were developed for use in UHV, close to the optical elements.

2. Design requirements, thermal and mechanical stabilities (see Table 1)

The upgrade mirror performance requirements were defined firstly from scientific specifications. Beamline Technical Design Reports [TDRs], describe the optimised optical layout, (ray tracing, spectral analysis, coherence preservation, etc...) and evaluate the thermal load, absorbed power and predicted slope error. Derived from these parameters, the main engineering challenges were:

- Strong limitation of thermal drift, leading to fast thermal response time.
- High level of mechanical stability (minimising vibration).
- Ultra fine UHV angular tuning whilst preserving the above stability concepts.

X-ray beam drift is essentially caused by the thermal bending of the mirror supporting parts. This can be limited by applying the thermal wave diffusion model: bending is proportional to the ratio A/B in which $B = \frac{k}{\rho C_p}$ and $A = \frac{\alpha}{k}$ (α = coefficient of thermal expansion, ρ = density, C_p = specific heat and k = conductivity). Minimising this ratio optimises fast thermal reaction. Typically A/B=2 for aluminium,

and 50 for invar. B represents thermal diffusivity and A is the main cause of thermal bending, i.e. angular drift.

$$\frac{A}{B} = \frac{\rho C_p \alpha}{k} = \frac{\alpha \rho C_p}{k^2}$$

This concept leads to designing with high conductivity materials, such as aluminium rather than lower expansion materials such as invar or stainless steel. Any positioning parts close to the optics are therefore made from aluminium. Figure 1 shows how the thermal response time was improved between two mirror systems on the same beamline, one performed in 2008 from the old design, the second in 2011 from the recent commissioning of the UPBL11 first upgrade mirror.

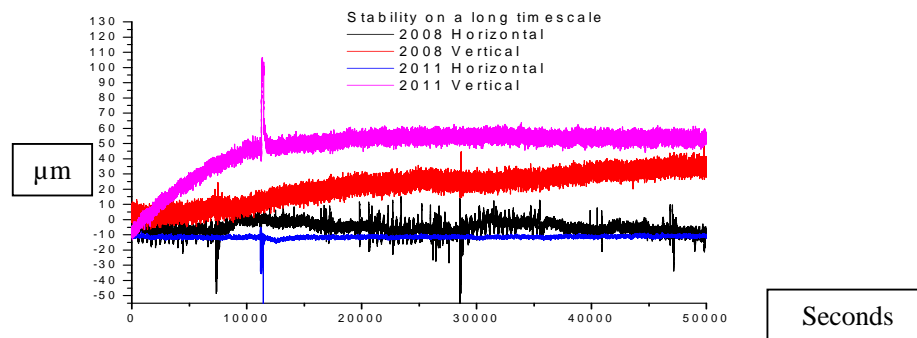


Figure 1. Thermal drift measurement at ID24. The first mirror is illuminated, a BPM located 20 m downstream measures the beam position (H and V) versus time. An identical experiment was done in 2008, with the old mirror. The second measurement was made in 2011, with the new mirror system. Pink plot (vertical position) shows faster thermal stabilisation time.

Table 1. Generic design series of mirrors for the ESRF upgrade programme

Beamline	Optic Name	Reflection Plane H:Horz V: Vertical	Absorbed Power [watt]	Distance To Sample [m]	Reflecting surface aspect	Architectural Solution G-Bench: Hexapod
UPBL 11 (ID24)	MIR-w ^a	V	850	50	Flat	G-Bench
	DMIR-w ^a	H	850	45	Flat-Flat	G-Bench
ID06	DMIR-m ^c	H	~	30	Flat-DR:20	G-Bench
UPBL6 (ID20)	MIR-m ^b	V	~	20	ToR	Hexapod
	MIR-w ^a	V	700	30	FR:15	G-Bench
UPBL4 (ID16)	ML Mn-w ^d	H	160	155	FR:2000	G-Bench
	DMIR-w ^e	H	660	135	Flat-DR:1000	G-Bench
ID10	DMIR-w ^e	H	400	30	Flat-Flat	G-Bench
	DMIR-w ^e	H	625	60	Flat-Flat	Hexapod
UPBL7 (ID32)	MIR-m ^b	V	~	50	FR	Hexapod
	MIR-m ^b	V	~	40	FR	Hexapod
	MIR-m ^b	H	~	30	FR	Hexapod

UPBL9a (ID02)	DMIR-w ^a	H	800	60	Flat-Flat	G-Bench
UPBL1 (ID01)	DMIR-w ^a	H	900	125	Flat-Flat	G-Bench
	ML Mn-w ^d	H	200	115	Flat-Flat	G-Bench

^a MIR-w : Single white beam mirror.	FR : Fixed radius [m]
^b MIR-m : Single monochromatic beam mirror.	DR : Dynamic radius [m]
^c DMIR-m : Double monochromatic beam mirror.	SphR: Spherical radius [m]
^d ML Mn-w: Multilayer monochromator.	ToR : Toroidal
^e DMIR-w : Double white beam mirror.	~ : Monochromatic beam

The technical layout is shown in figures 2 and 3. Although heavy masses are connected to the optic, the stiffness to mass ratio is preserved, such that vibration modes are never below 70 Hz.

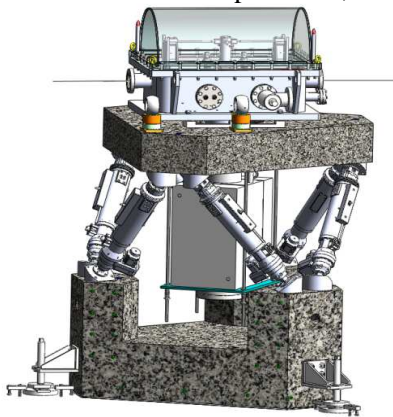


Figure 2. New generation hexapod (UPBL6 toroidal mirror)

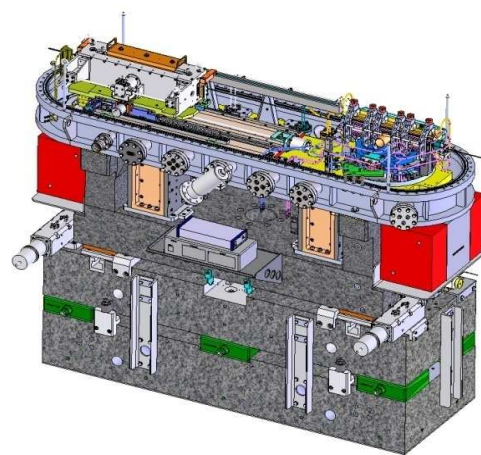


Figure 3. New granite bench (G-bench) generation (UPBL4 double mirror)

3. Mirror actuators designed for positioning optics

Most of the upgrade optics are either coated for energy filtering or multilayers. Stripe change consequently requires transversal mirror movements (typically 50mm). In addition, alignment movements and fine tuning incidence are mandatory. Hence two translations and two angular adjustments are almost systematically needed. The larger movements are ensured by mechanical jacks providing excellent resolution (typically 5 μm). Vertical movement and vertically reflecting incidence - the most critical for optimal performance - are ensured by a pair of specifically developed elevators optimised for excellent vibration quality, the so called “TZ generic mover”. These are able to achieve an incidence resolution of 200 nrad and a vertical step size of only 6 nm.

4. Designing UHV fine tuning movements

White beam mirrors are generally bulky objects requiring cooling absorbers all around their reflecting surface and are as such the principal source of beam instability. They must therefore be equipped with a fine angular tuning system in which an accurate and well defined axis of rotation is essential. For masses typically around 30Kg, vibrating modes under 70 to 100Hz should not be measurable. We have developed two rotating piezo or stepper driven adjusting stages as shown in Figures 4 and 5.

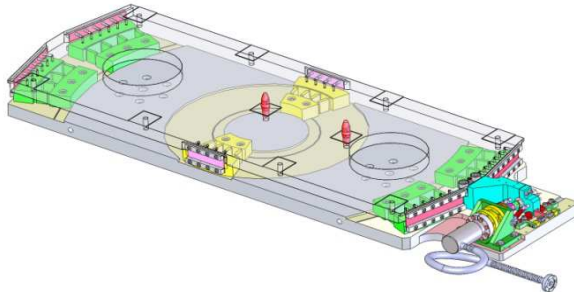


Figure 4. 1m long rotating table designed to adjust long optics in the μ rad range using an encapsulated stepper motor actuator. It employs a circular flexure hinge guiding system.

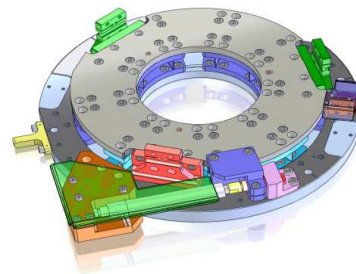


Figure 5. A 200 and 300 mm \varnothing fine tune table was designed for reaching 50 nrad angular resolution. It uses a piezo feedback positioning loop. Guiding is ensured through flexure leaf springs.

5. Software and hardware feedback loop together - dual loop feedback positioning

Fine incidence tune is operated in closed loop, exploiting a dual feedback concept: A first long distance loop, composed of a beam position monitor (BPM) close to the sample (50 to 150 m from the mirror), aims to define by means of a specific algorithm, a set point for the piezo controller at a rate of 1 Hz. The second, hardware based loop is equipped with a piezo or stepper actuator and a local position sensor. For the piezo version (figure 5), a Physik Instrumente E753 controller drives a P 844-50 actuator, and reads a D100 capacitive sensor. The larger table (figure 4) uses a stepper motor driven by the standard ESRF ICEPAP controller. To date, only the hardware loop has been tested. Angular resolutions of 200 nrad for the stepper actuator and 50 nrad (close to the measurable limit) for the piezo version have been achieved. The software loop (BPM) is currently being tested.

6. New generation hexapods

In cases where optics require more than 4 degrees of freedom (such as for toroidal mirrors) parallel type architecture (hexapod) offers distinct advantages. In-house designed hexapods for mirror positioning have been used since 1994 at the ESRF and 18 such systems are currently in operation. In order to cope with the very high thermal stability, vibration stability and resolution required for the ESRF upgrade beamlines, a new hexapod for mirror positioning has been developed in collaboration with Symétrie [1], who have a strong experience and design maturity in this field.

To reduce thermal drifts and vibration amplification and to improve resolution, the new design incorporates reduced length, high stiffness high resolution jacks with external motors, associated with high stiffness low friction ball joints. The measured stiffness of the new hexapod is twice as high as that of the existing ESRF hexapod. Vibration and thermal stability measurements are in progress. The measured linear and angular resolutions are $0.1\mu\text{m} / 0.1\mu\text{rad}$ respectively.

7. Lab testing and vibration qualification

Almost all the design work was systematically validated by vibration testing and precision metrology prior to qualification. Several prototypes were required, especially to attain vibration performance objectives. The ESRF Instrumentation Services and Development Division has dedicated resources to upgrade instrumentation projects, allowing high performance generic mirror systems to be created.

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[1] B. Hromadka(*), T. Roux(*), L. Eybert-Berard, P. Marion: New generation ESRF hexapod, (internal design report), (*): Symétrie (Nimes-France).