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A beam-shaping system for TIMEX beamline

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ABSTRACT

FERMI@Elettra is a Free Electron Laser (FEL) user facility currently under construction at Sincrotrone Trieste in Italy. It will provide a spatially coherent and transform-limited photon beam in the sub-ps regime, covering the VUV/Soft X-ray range (from 100 down to 1.33 nm). Thanks to its high fluence this 4th generation light source will be able to create and probe warm dense matter (WDM) inside the TIMEX end-station. Since the WDM state has a short lifetime (a few ps), measurement of basic physical quantities, such as temperature and density, is a challenge and new approaches are needed. For this reason a new method has been proposed for measuring temperature using a slowly responding pyrometric probe (Principi et al., 2010 [1]). However, the technique does require the spatial photon beam profile to be properly shaped at the sample. This can be done using an active optic (i.e. a deformable plane mirror) placed before the elliptical focusing mirror. Ray-tracing simulations and metrology measurements on a prototype have been performed and the results are presented here.

1. Introduction

The FERMI@Elettra user facility is a 4th generation light source with high brilliance and short pulse length with a Gaussian temporal structure. It is currently under construction at Sincrotrone Trieste. It is based on a High Gain Harmonic Generation (HGHG) scheme employing multiple undulators that up-shift the frequency of an initial seed signal (pulsed laser) in a single pass. This will provide radiation that is almost ideally transform-limited and fully spatially coherent [2,3]. Pulse duration, bandwidth and wavelength of the output radiation will be tunable. Two undulator chains will be employed: FEL1 covering the wavelength range from 20 to 100 nm (down to 6.7 nm in third harmonic) and FEL2 from 4 to 20 nm (down to 1.3 nm in third harmonic). The main parameters are reported in Table 1.

The first section of the photon transport system is the Photon Analysis Delivery and Reduction System (PADReS) [4], mostly dedicated to the diagnostic of photons on-line and shot-by-shot. It will include the Shutters, the Beam Defining Apertures (BDA), the Beam Position Monitors (BPM), the Intensity Monitors (I0), the Gas Absorber (GA), the Energy Spectrometer and the Transverse Coherence Diagnostics. After PADReS the following four beamlines will be installed: TIMER (TIME-Resolved spectroscopy of mesoscopic dynamics in condensed matter), DiPROI (Diffraction and PROjection Imaging), LDM (Low Density Matter) and TIMEX (TIme-resolved studies of Matter under EXtreme and metastable conditions) (see Fig. 1).

2. TIMEX: ultrafast TIme-resolved studies of Matter under EXtreme and metastable conditions

The main aim of the TIMEX project [5] is the development of a versatile end-station, suitable for time-resolved, pump and probe experiments in matter, under controlled extreme conditions. The FEL beam will be used as a pump and/or probe for ultrafast (reflectivity, transmission, scattering) studies mainly concerning (i) generation of WDM, (ii) transitions occurring in stable, metastable and excited states under transient high-temperature/pressure conditions and (iii) ablation phenomena and ultrafast surface transitions. To achieve these goals the end-station will take advantage of a focused FEL beam with micrometric size, which will ensure the necessary photon flux and fluence for high temperature experiments up to the WDM regime (1–10 eV typical temperature) [6]. The end-station will be equipped with suitable diagnostics, including a long-distance microscope for fine alignment and a pyrometric probe [1], ultrafast laser super-continuum probes for pump-and-probe reflectivity/absorption measurements and a transmission detector in the VUV/Soft X-ray range.

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2.1. Beamline basic design

After the delay-line shared with DiPROI and LDM (see Fig. 1), a plane mirror will reflect the radiation to an ellipsoidal mirror that is going to focus it about 1.4 m downstream into the TIMEX end-station. Since the two undulator chains will have different lengths, the position of the beam waist is different if FEL1 or FEL2 is used. In fact the waist of FEL1 beam will be 7 m downstream of that of the FEL2. Since TIMEX will use the same focusing ellipsoidal mirror for both sources (see Table 2), the performance of the beamline will be slightly different if working with shorter wavelengths (covered by FEL2) or longer ones (covered by FEL1). In particular the system has been designed in order to guarantee the highest photon density (and therefore fluence) in the high energy range (i.e. when using FEL2) without compromising too much the performance at lower energies. For this reason the source distance of the ellipsoidal mirror has been chosen to be 61.5 m corresponding to the theoretical distance from FEL2 waist and the center of the focusing mirror's chamber. In this way, a Gaussian spot is expected at the TIMEX experimental chamber perfectly focused for FEL2 photons and slightly defocused for the FEL1 ones. The source properties have been simulated by the FERMI@Elettra Machine Physics Group with GINGER and GENESIS codes [7]. The electron bunch has been propagated within the last undulator since saturation occurred. There the photon emission was estimated to be maximum and it has been considered as the beam waist. The expected spot at focus has been simulated with the SHADOW code [8] having considered the geometrical characteristics of the FEL source, the alignment tolerances and 1 μrad rms slope error of the mirrors (see Table 3). The ray-tracing results, the reflectivity and the angular acceptance of every optical element have been used to calculate the flux and fluence per pulse at the target (see Table 3).

Table 1
Expected output parameters of FERMI@Elettra for the two undulator chains FEL1 and FEL2. The geometrical properties of the source have been simulated with GINGER and GEANT codes. The constant source size for each FEL is an estimation and will be tested experimentally.

Parameter	**FEL1**	**FEL2**
Wavelength (nm)	20–100	4–20
Pulse length rms (fs)	40–100	<100
Bandwidth rms (meV)	~20–40	~20–40
Polarization	Variable	Variable
Peak power (GW)	1–5	~1
Photons per pulse	$\sim 2\times10^{14}$ at 100 nm	$\sim 1\times10^{13}$ at 10 nm
Peak brightness (Ph/s mm^2 mrad^2 0.1% bw)	$\sim 6\times10^{32}$	$\sim 10^{32}$
Source size, FWHM (μm)	290	140
Divergence rms (μrad)	50 at 40 nm	15 at 10 nm

2.2. Beam-shaping

As already mentioned, in the basic design solution, the spot at focus will have the Gaussian distribution whose size is close to the product of the size at source times the de-magnification factor $M=q/p$, where p and q are, respectively, the source distance and focal length. In order to measure the temperature of the sample with the pyrometer, the tails of the beam must decay following a hyperbolic secant law [1]. For this reason the beam must be reshaped so as to redistribute the irradiance of the beam. Since FERMI@Elettra will operate in the VUV/Soft X-ray range, beam-shaping will be possible only by means of reflective elements with a well defined modified profile. These peculiar figures can be calculated by numerical solution of a differential equation, whose inputs are spatial distribution of the incoming radiation and the one needed at focus [9–11]. For the TIMEX beamline, not including the mirror's figure errors, an optical element with a Lorentzian-like shape (replacing the plane mirror) is needed to obtain the desired distribution at focus. The mirror's shape can be parametrized as follows:

$$L_\alpha(A,\gamma,x_0)=\frac{A\gamma^{\alpha-1}}{\pi\left[(x-x_0)^\alpha+\gamma^\alpha\right]}$$

Table 2
Requirements for the TIMEX focusing ellipsoidal mirror.

Parameter	Value
Source distance p (m)	61.5
Focal length q (m)	1.4
Incidence angle α (°)	2.5
Tangential slope error rms (μrad)	<1
Sagittal slope error rms (μrad)	<5
Coating	Ir (50 nm)
Surface roughness (nm)	<0.3

Table 3
Beam parameters at the sample position for TIMEX end-station, calculated by considering the source parameters, the geometrical and reflectivity losses of all optical elements considering 1 μrad rms slope errors on the mirrors.

Wavelength (nm)	FEL	Harmonic	Spot size$_{FWHM}$ (μm × μm)	Flux (Ph/pulse)	Fluence W/cm^2
1.7	2	3rd	3.0 × 3.0	5.9×10^{8}	3.0×10^{13}
3.3	2	3rd	3.2 × 3.1	3.4×10^{9}	7.6×10^{13}
4	2	1st	3.3 × 3.1	1.9×10^{11}	2.9×10^{15}
6.7	1	3rd	5.1 × 5.1	2.2×10^{10}	8.0×10^{13}
10	2	1st	3.3 × 3.0	6.9×10^{12}	4.5×10^{16}
20	2	1st	4.2 × 3.7	2.8×10^{13}	5.8×10^{16}
20	1	1st	6.1 × 5.7	6.5×10^{12}	5.9×10^{15}
60	1	1st	6.7 × 5.7	5.4×10^{13}	1.4×10^{16}
100	1	1st	7.1 × 6.7	1.1×10^{14}	1.4×10^{16}

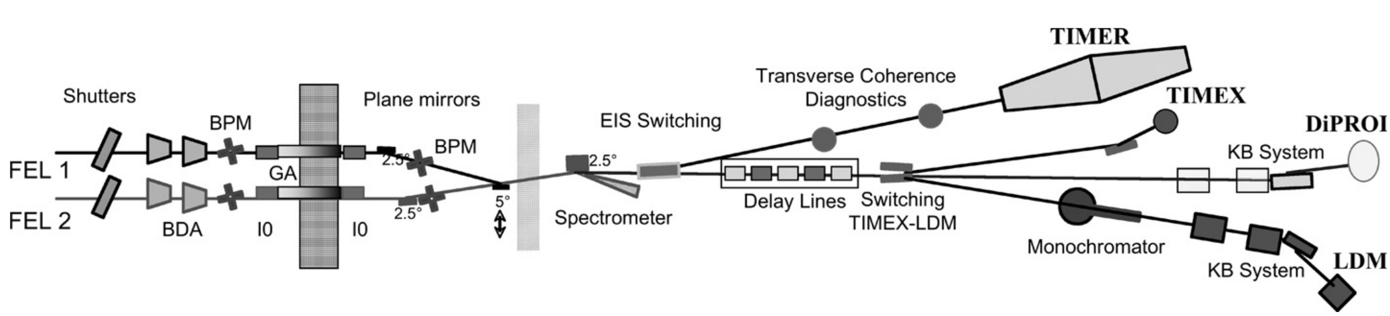

Fig. 1. Photon transport system layout. Propagation direction is left to right. The left portion of the figure up to the energy spectrometer comprises the PADReS section, dedicated to photon diagnostics, which is followed by the four beamlines (TIMER, TIMEX, DiPROI and LDM).

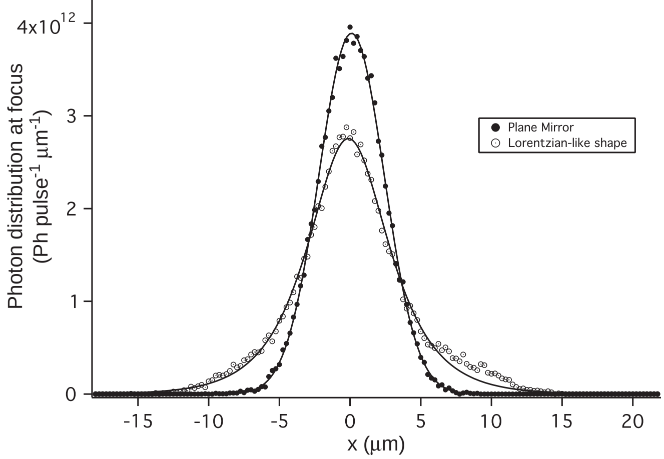

Fig. 2. Horizontal distribution of the expected spot at focus for a wavelength of 40 nm with and without the calculated Lorentzian-like mirror profile. The histograms have been integrated with a step size of 0.25 μm. The shaped beam has been fitted with the distribution wanted at the focus with parameters $a=3.88\times10^{12}$, $x_h=0.11$ μm and $w=3.27$ μm.

where A is an amplitude coefficient, x_0 the center of symmetry of the profile, γ the scale parameter that specifies the Half-Width at Half-Maximum (HWHM) and α is an even number. For $\alpha=2$ the mirror has a Lorentzian shape. Ray-tracing simulations with SHADOW code have proved that this calculated shape with a relative variation in amplitude Peak-to-Valley (P_tV) of hundreds of nanometers from the initial flat mirror profile is needed to change the beam distribution at focus. Fig. 2 shows a ray-tracing result: it reports two histograms of the spot at focus in the case of 40 nm wavelength radiation with and without the calculated Lorentzian-like induced deformation. The spot obtained with the basic design is well fitted by a Gaussian function while the one obtained with the calculated shape is well fitted by the function

$$f(x)=\frac{a}{\cosh\left[(x-x_h)/w\right]}$$

(i.e. the one needed for the temperature measurements) where a is an amplitude, x_h the center of symmetry and w is a scale parameter. It can be seen that the central part of the beam has still enough fluence to create the WDM and the tails exhibit the desired intensity distribution.

3. Mirror prototypes

The active mirror consists of a Si substrate with some piezoelectric patches glued on its back side. When voltage is applied on the piezos these will react with contraction/expansion and the forces will be transferred to the substrate that will consequently bend. The tests have been done by using different substrates with various number of piezoelectric patches separated 1 cm from each other. A floating power supply (HVPS MAS-III) [12] developed in-house has been used to apply the needed voltage to the piezos. Delivering up to 500 μA (at 2000 V), with its 16 channels (4 channels/module), the system has been especially designed to drive piezoelectric bendable mirrors. The piezoelectric patches have been purchased from PI and the used model is P-876.SP1 DuraAct™ transducers.

3.1. ACT software and LTP measurements

The Elettra Long Trace Profiler (LTP) [13] has been used to measure the shape of the prototypes. The mirror was clamped at both ends, restricting the measurable portion of the mirror to 320 out of 400 mm in the longitudinal direction. The mirror has first been measured with a sampling step of 2 mm at its reference position (no voltage applied to the piezos). A set of eight more measurements has been performed in order to check the response of the substrate to specific piezo action (see Fig. 3). These results have been used to calculate the interaction matrix needed to evaluate the voltages to be applied to every piezo in order to bend the mirror into the desired shape. To do this the Adaptive Correction Tool software (ACT) has been used. The ACT has been originally developed in order to optimize either the shape or the slope residuals of a Piezoelectric Bimorph Mirror (PBM) [14]. As a first step, the ACT software calculates the interaction matrix of the mirror using the least squares approach. It then uses the interaction matrix in order to calculate the voltage to be given at each electrode to shape the mirror as close as possible to a wanted profile. This iterative procedure converges very quickly to reach the needed Lorentzian-like mirror deformation relative to the initial reference shape (see Fig. 4). During the tests it has been seen that the dynamic range of the system is of the order of 1 μm, wide enough to reach all the possible desired shapes. The stability of the used piezoelectric patches has been measured and it has been seen that, over a few days, the maximum deviation is less

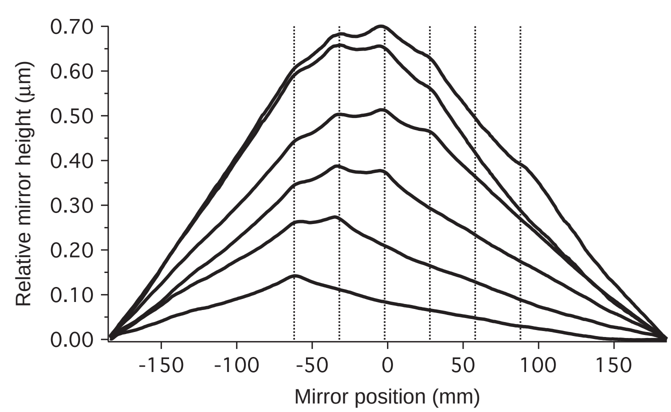

Fig. 3. Calibration measurements of the first glass prototype necessary to realize the interaction matrix of the mirror used by the ACT software. The vertical lines show the position of the piezoelectric patches glued on the rear face of the mirror.

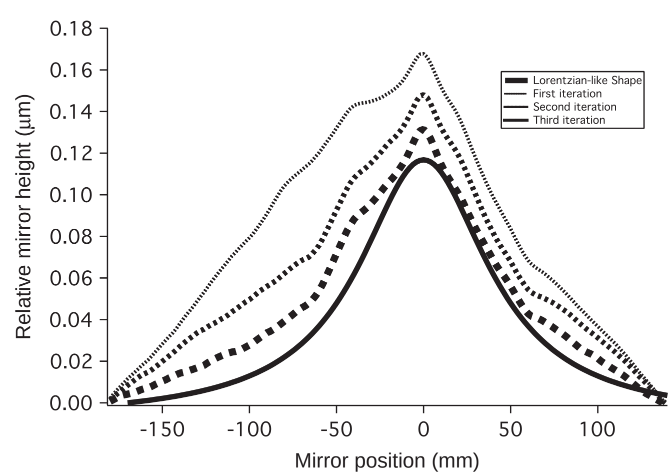

Fig. 4. Relative height measurements of the Si prototype made with the LTP. In just three iterations of the applied voltage to the piezos, the shape of the mirror has become closer to the desired one.

than 3 nm P_tV including the LTP stability. Due to the poor mirror quality (these were just prototypes to test the system functionality), there are some residual structures in the mirror's figure present in every measurement. Such errors are not present in the good quality substrate (already purchased from Zeiss), which will permit us to obtain exactly the desired profile.

4. Conclusion and outlooks

The tests on the prototypes have been successfully completed, giving us all the necessary information to realize a real mirror, including the realization of the desired shapes. Calculations will be done using commercial programs in order to solve the beam-shaping differential equations (see Ref.[9] for more details) and find the optimal theoretical mirror shape. The final 400 mm long Si substrate will have eight piezos glued on to its rear face and a clamping system that permits 380 mm of usable length. A system to prevent mirror twist is incorporated into the mirror holder, which is similar to that used in the FERMI bending mirror [15]. The optimal profile of the active mirror will be calculated considering also the figure errors of the previous and following optical elements (all measured by the Elettra LTP) in order to correct as much as possible the presence of the unwanted aberrations of the spot at focus. The TIMEX beamline is scheduled to be installed and have first light during April 2011.

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