BUNCH-COMPRESSOR TRANSVERSE PROFILE MONITORS OF THE SwissFEL INJECTOR TEST FACILITY

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Abstract

The 250 MeV SwissFEL Injector Test Facility (SITF) is the test bed of the future 5.8 GeV SwissFEL linac that will drive a coherent FEL light source in the wavelength range 7-0.7 and 0.7-0.1 nm. Aim of the SITF is to demonstrate the technical feasibility of producing and measuring 10 or 200 pC electron bunches with normalized emittance down to 0.25 mm.mrad. A further goal is to demonstrate that the electron beam quality is preserved in the acceleration process, in the X-Band linearizer and the magnetic compression from about 10 ps down to 200 fs. The SITF movable magnetic bunch-compressor is equipped with several CCD/CMOS cameras for monitoring the beam transverse profile and determining the beam energy spread: a YAG:Ce screen and an OTR screen camera at the mid-point of the bunch compressor and a SR camera imaging in the visible the Synchrotron Radiation emitted by the electron beam crossing the third dipole. Results on the commissioning of such instrumentations, in particular in the low charge limit, and measurements of the beam energy spread vs. the compression factor will be presented.

INTRODUCTION

The SwissFEL project aims at the construction of a 5.8 GeV electron linac driving a coherent FEL light source in the wavelength regions 7-0.7 and 0.7-0.1 nm. The relative compact size of the facility (the SwissFEL total length is about 700 m, linac+undulators+experimental area) being a constraint for the linac energy performance, high brilliance features are imposed to the electron source by the lasing condition. Projected emittance 0.65/0.25 mm.mrad and longitudinal length of 25/2 fs (RMS) at the undulator are indeed the design parameters of the 200/10 pC electron bunches of the SwissFEL [1]. In the two different charge operation modes of the SwissFEL, sequences of two electron bunches separated in time by 28 ns will be produced at a repetition rate of 100 Hz by a photocathode gun and accelerated by S-band Travelling Wave (TW) accelerating structures (injector section) up to 330 MeV and, finally, by a C-band TW linac up to the final energy of 5.8 GeV. Thanks to a magnetic switchyard and a further accelerating section (up to 3.4 GeV), two different undulator lines will be simultaneously electron-supplied at 100 Hz: the hard X-ray undulator line (ARAMIS) and the soft X-ray undulator line (ATHOS). The electron beam, produced at the cathode of the RF gun by a Ti:Sa laser with a flat-top longitudinal profile (3.6/10 ps FWHM), will reach the undulator after a two-stage longitudinal compression by means of two magnetic chicanes. The magnetic compression scheme foresees an energy chirping of the electron beam, achieved in the S-band injector, and a longitudinal phase space linearization performed by a couple of X-band cavities upstream the first magnetic chicane.

The preparatory phase of the future SwissFEL is carried out at the 250 MeV SwissFEL Injector Test Facility (SITF). This is composed of, see Fig. 1: a Copper photo-cathode and a Standing-Wave (SW) S-band 2.5-cell RF gun accelerating a 10/200 pC electron bunch up to 7.1 MeV/c at a repetition rate of 10 Hz; four S-band TW RF structures accelerating the beam up to a maximum final energy of 250 MeV; a compression section composed of a X-band cavity (under installation) and a magnetic chicane; finally, downstream a SW S-band 5-cell Transverse Deflecting Cavity (TDC), a FODO section and an energy spectrometer where both the transverse and the longitudinal phase spaces of the electron beam are experimentally characterized. Goal of the experimental activity so far performed at the SITF is to check the reliability of the key components of the future accelerating machine, to optimize the procedures to experimentally characterize the electron beam parameters, to demonstrate the feasibility of an electron source with the required high brilliance quality and, finally, to show that the high quality features of the electron beam are preserved by the X-band linearizing scheme of magnetic compression. The campaign of measurements carried out so far at SITF established and consolidated several measurement techniques of the beam projected and slice emittance measurements for both the charge operation modes and of the longitudinal phase space, for instance. The outcome of this experimental work [2, 3] confirmed that the extremely high beam quality constraints required by the SwissFEL design can be achieved. The bunch compressor is one of the key components of the future SwissFEL whose main diagnostics have been recently commissioned or is under commissioning as in the following described.

BUNCH-COMPRESSOR DIAGNOSTICS

The vacuum chamber of the magnetic bunch compressor (BC) is a flexible structure composed of two arms and a central part whose rigid components are joined together

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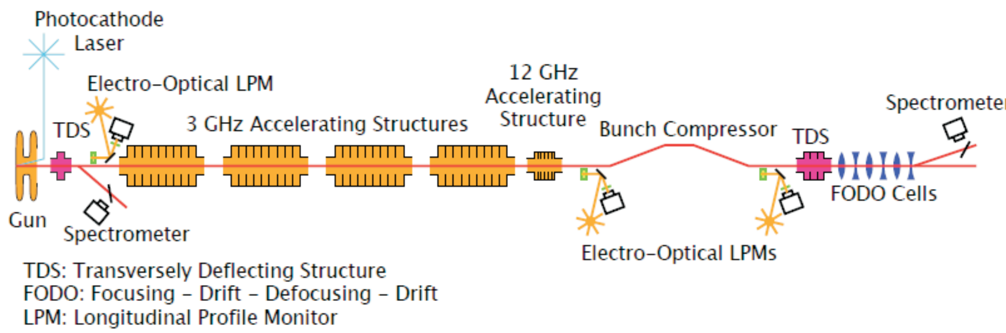

Figure 1: Schematic layout of the 250 MeV SwissFEL Injector Test Facility (SITF).

by vacuum-bellows (see Fig. 2). The central part of the BC vacuum chamber, mounted on a movable girder together with the two central dipoles of the chicane, can be horizontally shifted with respect to the accelerator beam axis by means of a micro-meter stepping-motor. The BC acceptance of the dispersive trajectories ranges continuously from 0 to about 404 mm, corresponding to a BC bending angle between 0° and 5°. The BC is equipped with diagnostics measuring charge, center-of-mass, transverse and longitudinal distribution of the electron bunch and phase jitter of the beam. Charge and position in the transverse plane of the electron beam can be measured by Beam Position Monitors (BPM): Resonant Strip Line (RSL) (7 μm resolution 5-500 pC) are located upstream and downstream the first and the fourth dipoles of the chicane [4]; Cavity BPM, also installed in the BC arms, are under commissioning [5]. Bunch Arrival-time Monitor [6] (BAM, resolution better than 5 fs, SwissFEL specifications) are installed upstream and downstream the BC to measure, respectively, the phase jitter of the beam due to both the gun and the laser arrival time and to the S-band accelerating structure in off-RF-crest operations. A single shot monitoring of the electron bunch length can be provided by pyrodetector monitors detecting in the THz the synchrotron radiation (CSR) emitted by the fourth dipole of the chicane and the coherent diffraction radiation (CDR) produced, just after the BC, by a 1 μm thick Ti foil with a circular hole of diameter 5 mm. A couple of Electron Optical (EO) monitors are also installed upstream and downstream the BC. They will be used for on-line monitoring the compression and the bunch shape with a resolution of 200 fs. At the BC, bunch length measurements can be obtained from a spectroscopic analysis of the CSR performed by a Martin Puplett Interferometer equipped with a bolometer.

The transverse profile of the electron beam can be monitored at the entrance of the third bending dipole of the chicane and in the mid symmetry plane of the BC. The visible Synchrotron Radiation (SR), emitted by the electron beam at the third bending dipole of the BC, can be imaged by a CMOS-Camera located below the vacuum chamber between the third and the fourth dipoles thanks to a couple of in-vacuum and out-vacuum mirrors forming a vertical translation stage for the SR light. The set-up of the SR out-coupling mirror guarantees the transmission of the full SR light spot within a range of the BC bending angle between 3° and 5°. The CMOS-Camera, equipped with a 300 mm focal length lens (AF-S Nikkor 300 m f/2.8G ED VR II), can image the SR light spot with a projected pixel size resolution of 0.040 mm. A YAG:Ce and an OTR view screen allows the monitoring of the beam transverse profile at the mid symmetry plane of the BC. Both view-screens can be vertically inserted in the central vacuum chamber of the BC by a step-motor feed-through. The YAG:Ce screen (0.3 mm thick and 45° vertically tilted with respect to the machine axis) can be imaged by a vertically oriented CCD camera that is located below the BC central vacuum chamber. This CCD camera, equipped with a 45 mm focal length lens (Nikkor 45 mm f/2.8D ED), can resolve the beam transverse profile with a projected pixel resolution of 0.115 mm. The BC OTR screen, normally intercepting the electron beam, emits a backward light pulse that can be imaged by a second CMOS camera whose optical set up is almost identical to the SR one and specularly symmetric to it with respect to the BC mid plane. The backward OTR light spot can be imaged by a CMOS camera with a 300 mm focal length lens and projected pixel size resolution of 0.049 mm (under commissioning). At the nominal bending angle (4.07°) of the SITF magnetic chicane, the BC transverse profile monitors are designed to measure the relative energy spread ($\Delta E/E$) with an expected resolution of: 1.2×10^{-4} (SR-monitor); 1.5×10^{-4} (OTR-monitor); 3.5×10^{-4} (YAG-monitor). The sCMOS cameras (PCO.Edge) are connected via a CAMERLINK-Fiber bridge to a PC with a 64-bitWindows operation system. The CCD camera (Basler SCOUT) for the YAG screen is connected via a direct GigE-Link to a similar PC described before. The cameras synchronization is done with a TTL-puls generated by the event based timing-system (Micro Research Finland). The software (IOC/EPICS) controls the camera via the vendor software interface and delivers the picture over EPICS or saves the pictures directly to a filesystem.

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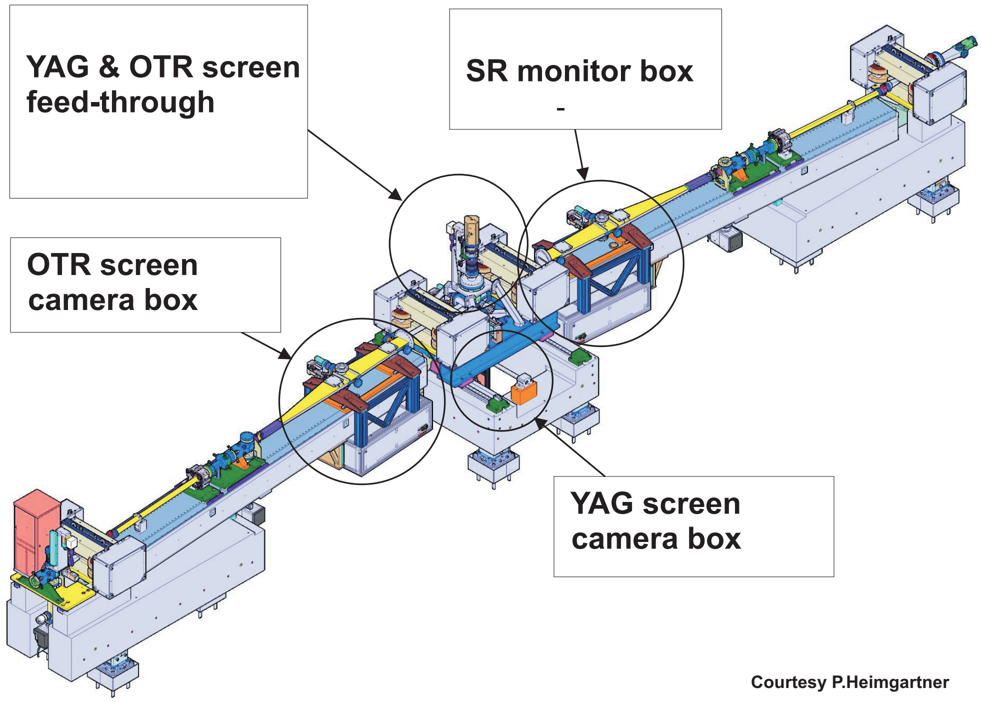

Figure 2: The SITF Bunch Compressor layout with Transverse Profile Monitors

MEASUREMENTS AND RESULTS

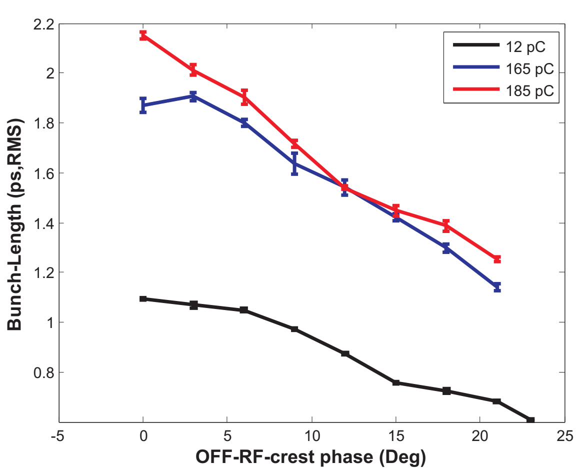

Figure 3: Bunch-Length measurements vs. compression at 12 pC, 165 and 185 pC.

The BC transverse profile monitors of SITF were commissioned in both the 10 pC and the 200 pC operation modes. A Ti:Sa laser pulse with a nominal flat-top longitudinal profile (3.6/10 ps, FWHW) is the photo-cathode laser used at SITF for 10 and 200 pC operations. A Nd:YLF laser with a nominal Gaussian longitudinal profile (2.7 ps, RMS) is also available for machine operations at SITF. According to the compression scheme designed for SITF, the electron beam is chirped in energy by running off-RF-crest the last two TW-structures of the injector and operating the magnetic compression at a nominal bending angle of 4.07° of the magnetic chicane, corresponding to a horizontal dispersion function of about η_x=331 mm. In order to preserve the matching of the magnetic optics with the beam during the compression scan, the beam energy is maintained to a constant value lower than the nominal one (230 MeV instead of 250 MeV) so that the forward RF power to the last two TW accelerating structures can be accordingly increased as a function of the off-RF-crest phase. During the compression operations, the transverse size of the electron beam in BC can be measured on-line and continuously by the SR monitor and in a destructive way by the YAG and the OTR monitors. The relative energy spread can be finally determined from the measured horizontal beam size σ_x from:

$$\sigma_x = \sqrt{\sigma_{x,0}^2 + \left(\eta_x \frac{\Delta E}{E}\right)^2} \qquad (1)$$

where $\sigma_{x,0} = \sqrt{\epsilon_x \beta_x}$ is the natural betatron size of the electron beam.

A campaign of measurements aiming at studying the per-

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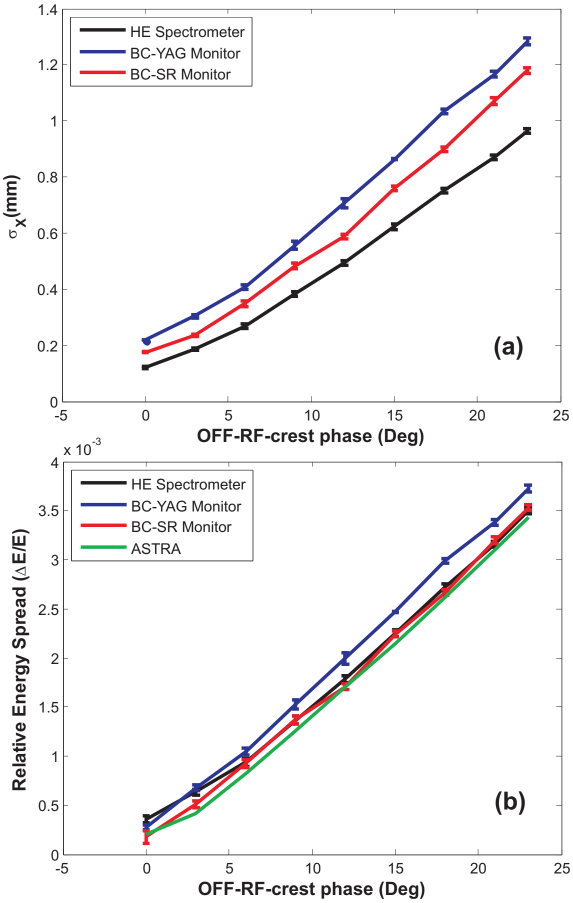

Figure 4: Beam Energy 230 MeV, bunch charge 12 pC. (a) Horizontal beam size vs. off-RF-crest phase measured in the High Energy Spectrometer, BC-YAG Monitor, BC-SR Monitor. (b) Resultant Relative Energy Spread in comparison with numerical results.

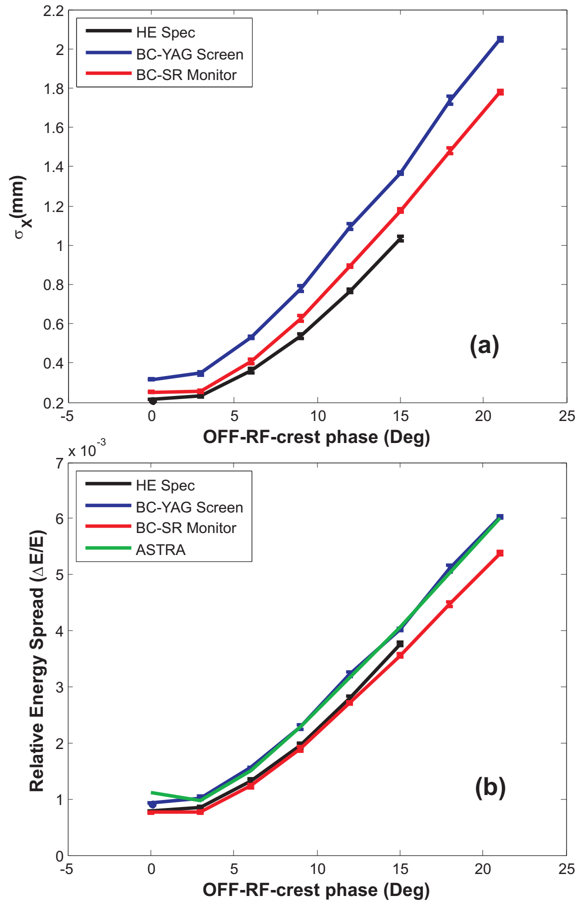

Figure 5: Beam Energy 230 MeV, bunch charge 165 pC. (a) Horizontal beam size vs. off-RF-crest phase measured in the High Energy Spectrometer, BC-YAG Monitor, BC-SR Monitor. (b) Resultant Relative Energy Spread in comparison with numerical results.

formance of the compression scheme was carried out at SITF. As a function of the compression factor (i.e., as a function of the off-RF-crest phase of the last two accelerating structures of the injector), the transverse profile of the electron beam was measured in the BC by means of the YAG and SR monitors. In parallel, the electron bunch length was measured by means of the TDC as well as the beam energy spread in the high energy (HE) spectrometer. TDC bunch-length measurements were done streaking the beam onto a view screen where the vertical betatron phase advance maximizes the TDC resolution. In the bunch-length measurements as well as in the HE spectrometer measurements, a YAG:Ce screen (0.2 mm thick and 45° horizontally tilted with respect to the beam axis) and a CCD camera with a projected pixel size of about 0.023 mm were used.

Bunch compression measurements were performed with a bunch charge of 12 pC (Ti:Sa laser, flat-top profile) and 165 and 185 pC (Nd:YLF laser Gaussian profile). As a function of the off-RF-crest phase of the last two accelerating structures of the injector (compression), the beam transverse profile at the BC, the bunch length by means of the TDC and the energy spread at the HE spectrometer were measured in a row. Results of the measurements of the bunch length (Fig. 3) and of the horizontal beam size (BC YAG and SR monitors and HE spectrometer) are reported in Figs. 4(a), 5(a), 6(a). From the measured values of the beam transverse size (BC YAG and SR monitors and HE spectrometer), the corresponding values of the relative energy spread of the beam were determined via Eq.(1) and compared with numerical simulations of a beam tracking code (ASTRA, [7]), see Figs. 4(b),5(b), 6(b). In the analysis of the experimental data, Eq.(1) was used neglecting the natural betatron size of the beam except in the case 12 pC. In the 12 pC operations, the signal-to-noise ratio of the SR monitor was checked by reducing the light intensity with a 10% density filter with a performance of appreciable sensitivity of the monitor in the low compression regime.

The measured results of the beam transverse size and bunch length, reported in Figs. 4(a), 5(a), 6(a) and (Fig. 3), respectively, are RMS values. These values were obtained by using a noise-cut routine of the camera images of the

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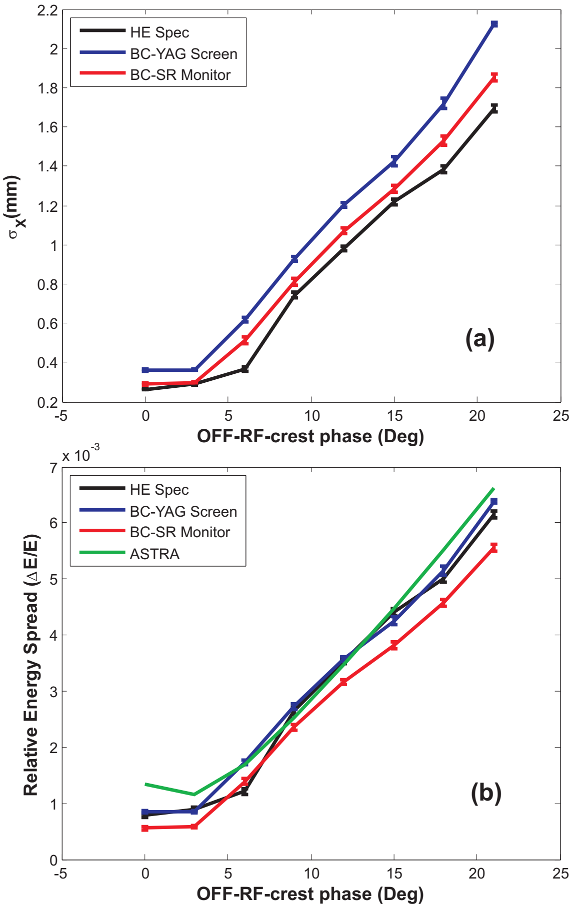

Figure 6: Beam Energy 230 MeV, bunch charge 185 pC. (a) Horizontal beam size vs. off-RF-crest phase measured in the High Energy Spectrometer, BC-YAG Monitor, BC-SR Monitor. (b) Resultant Relative Energy Spread in comparison with numerical results.

beam profile. An adaptive region-of-interest is used to mask the noise not related to the beam spot. This is achieved by an intermediate smoothing of the image and then a comparison with a certain threshold. Pixels above the threshold in the intermediate image are considered to be beam related in the original image [8]. For the beam transverse profile analysis, a 10% noise-cut threshold was settled on a basis of a check of different threshold values and of a comparison with results of a Gaussian fit when possible. For the bunch-length analysis, a cut-threshold of 6% was defined. In the numerical simulations of the beam energy spread, the values of the laser profile at the cathode of the RF gun were set according to the TDC measurements of the bunch length (see Figs. 3): i.e., 1.1 ps (RMS, 12 pC); 1.9 ps (RMS, 165 pC); 2.2 ps (RMS, 185 pC).

On the basis of a comparative analysis of the experimental characterization of the relative energy spread vs. compression, the resolution performance of the BC SR monitor can be evaluated. In particular, in the case 12 pC, the SR monitor shows to have a very good sensitivity to small variations of the energy spread energy. The relatively high value of the projected pixel size (0.115 mm) of the YAG monitor in the BC strongly affects the resolution and the precision of such a device. Finally, numerical simulations and experimental data are in a good agreement, in particular, in the 12 pC case, where the role of space-charge effects in the numerical model of the beam tracking is less important compared to the high charge case. Further measurements and studies on modeling the beam dynamics are foreseen.

CONCLUSIONS

The BC transverse profile monitor were successfully commissioned in SITF. The commissioning results confirmed the high resolution performance of the SR monitor in determining the relative energy spread of the electron beam in comparison with instrumentation already in operation at SITF. The experimental characterization of the beam energy spread vs. compression is also in agreement with expected results from numerical simulation of beam tracking codes. Moreover, the sensitivity of the SR camera in monitoring the beam transverse size of the beam has been checked to extend far below the 10 pC charge value of the SwissFEL specifications. Further steps towards routine operations of the BC transverse diagnostics will be the commissioning of the OTR monitor and more extensive comparative studies of the energy spread monitors of SITF. The improvement of the energy spread resolution of the BC YAG camera by replacing the 45 mm focal lens with a 85 mm focal lens is also foreseen.

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