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Electro optical monitor final report

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Abstract:

In the CLIC two beam acceleration scheme the Main Beam must be precisely synchronized with respect to the RF power produced by the Drive Beam. Timing errors would have an impact on the collider performances. The Drive Beam phase errors should be controlled, by means of a feed forward system, within 0.1 ° (23 fs @ 12GHz) to avoid a luminosity reduction larger than 2%. A beam phase arrival monitor is an essential component of the system. As an alternative to a classical design using analogue electronic done in task 9.5.1., we pursue an approach using electro optical modulators. The advantage of this is its very high band width, it is measuring the arrival time of individual bunches with a potential resolution below 10 fs. The system was designed, manufactured and tested. As specified in the work package, the performance with beam was validated at the PSI injector.

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1. EXECUTIVE SUMMARY

The two beams acceleration scheme, basic feature of the Compact LInear Collider CLIC, asks for precise synchronization between the Main Beam and the RF power produced by the Drive Beam in order to keep the energy of the Main Beam constant at the delivery point. This problem exists in even stronger form in free electron lasers, where a tight synchronization between photo injector lasers, RF systems and other systems is required. We report on the design and performance of a bunch arrival time monitor (BAM) using a hybrid electro-optical approach.

It consists of a master laser oscillator distributing a train of optical pulses over a system of stabilized fibre links. Electrical pulses from ultra-wide bandwidth pickups are mixed with the optical signals using electro-optical monitors (EOM) to obtain the phase reference.

Two types of pickups have been developed and built as prototypes and tested with beam. The critical optical components of BAM have been tested with respect to their noise and drift behaviour. Special care was given to a localized thermal stabilization of the optical front end to minimize the long term drift, which is critical for FEL applications.

The full system has been tested with beam and was thoroughly characterized with respect to drift and jitter. The obtained resolution of 20 fs fits very well with the requirements for the CLIC drive beam CLIC.

2. INTRODUCTION

The Compact LInear Collider CLIC is based on the two beam accelerator scheme: the RF power produced in the deceleration of a high current electron Drive Beam is sent to 12 GHz RF sections to accelerate the Main Beam. The synchronization of the Drive Beam with respect to the Main Beam is mandatory in order to keep constant the main linac final energy. Errors in timing and intensity of the Drive Beam lead RF phase and amplitude errors in the accelerating sections with the consequence of effective gradient change. Final Main Beam energy errors, combined with limited beam delivery system acceptance, can cause loss of luminosity. The RF jitter tolerance is given by the limitation to less than 2% of the luminosity loss and by the negligible amount of the luminosity spectrum widening at collision.

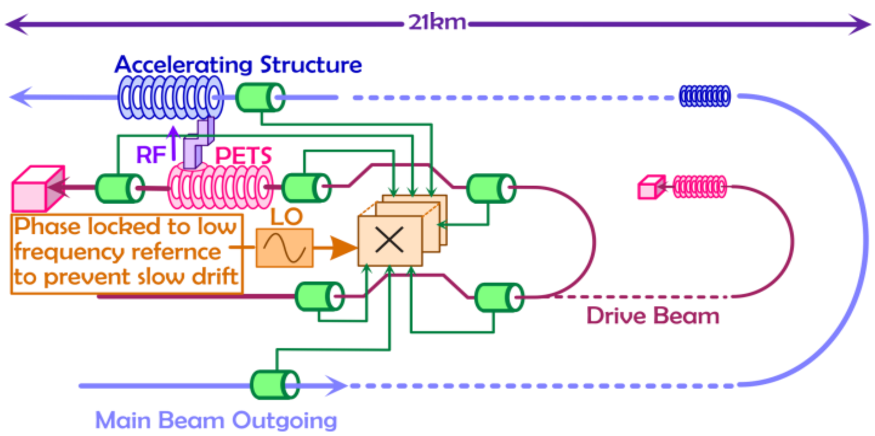


Figure 1: Overall CLIC layout with the placement of the detectors marked in green.

The CLIC single bunch RMS energy spread is of the order of $\sigma_E/E \sim 3.5 \cdot 10^{-3}$. Due to the previous considerations the relative energy variation must be less than $\sigma_{jitt}/E < 4 \cdot 10^{-3}$, corresponding to an effective gradient error of about $\Delta G/G \sim 4 \cdot 10^{-3}$. This means that the coherent error of the RF phase all along the main linac must remain below 0.1° at 12 GHz corresponding to a time jitter of 23 fs.

The synchronization between Drive Beam and Main Beam can be done with a feed-forward system that compares time measurements of both beams and then applies the proper phase correction to the Drive Beam. The front end of this system will consist of a monitor able to detect the bunch longitudinal positions. The accelerator scheme and the places where the phase measurements could be taken are illustrated in Fig. 1.

This is not an isolated problem of the CLIC project, it exists in even stronger form for free electron lasers. The lasing of an electron bunch depends in a highly nonlinear fashion on its properties; a tight synchronization of RF-cavities, the photo-injector laser and other auxiliary systems as seed and pump-probe lasers is required. This is done via a complex system using hybrid, electrical and optical techniques. For measurement and feedback, a so-called Beam Arrival Time Monitor (BAM) employing electro optical mixers to directly combine optical pulses from the synchronization system with beam signal, is used.

Since the CLIC test facility CTF 3 has no suitable infrastructure in terms of a high precision synchronization, it was decided to build and test the prototype monitor in the PSI injector. This facility is a 250 MeV S band linac using an RF gun as an electron source. It features an X-band phase space rotator structure, and a bunch compressor followed by a (yet to be installed) magnetic undulator. It serves as a test bed for critical accelerator related technology to be used in the SwissFEL free electron laser facility, whose construction started this year. To make the CLIC BAM prototype also suitable for application in a free electron laser, the specifications were complemented to require also an excellent long term stability (hours to weeks) as well as to allow high precision measurements at very low bunch charge down to 10 pC.

3. GENERAL LAYOUT

The so-called Bunch Arrival Time Monitor (BAM) is a part of a more complex optical system, which synchronizes diverse laser, RF and diagnostic stations, an environment available in the PSI injector (which is also the reason, that the prototype was developed for this machine). The core of the optical synchronization system is the master laser oscillator (MLO), a short pulse laser with a 180 fs pulse duration and 214 MHz repetition rate. The pulse train from the laser defines a time-scale to which the rest of the equipment is synchronized. The required frequency stability is in the order of 10^{-9}. The pulse train from the laser master oscillator is split and distributed over length stabilized fibre links to the clients, where the synchronization is made either optical via cross-correlation methods or electrical via laser to RF conversions. The bunch arrival time is registered as a near zero crossing overlap between a reference laser pulse and a large bandwidth pick-up signal induced by the electron beam [1, 2], which is measured by the electro-optical modulation of the laser pulses by the pickup signal. The mapping to time units is provided by a high-precision delay stage, equipped with a high resolution position encoder. The principle is shown in Fig. 2.

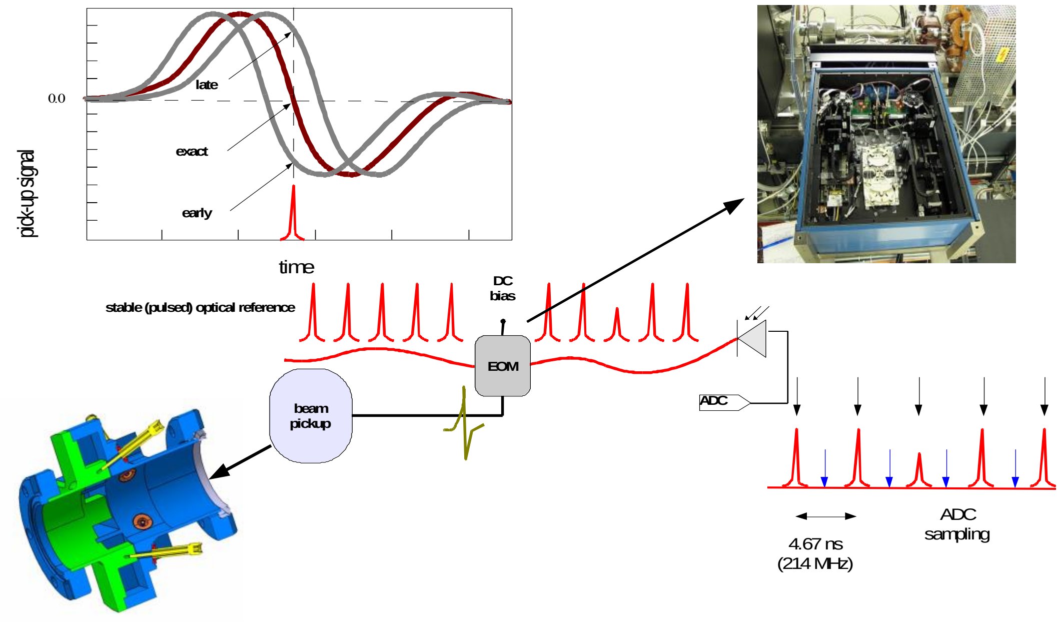


Figure 2: Measurement principle of the Bunch Arrival Time Monitor (BAM).

The development of a BAM prototype includes the design and assembly of one complete chain, consisting of the master laser oscillator, a length stabilized fibre link and the BAM front end. A layout of the system is shown in Fig. 3.

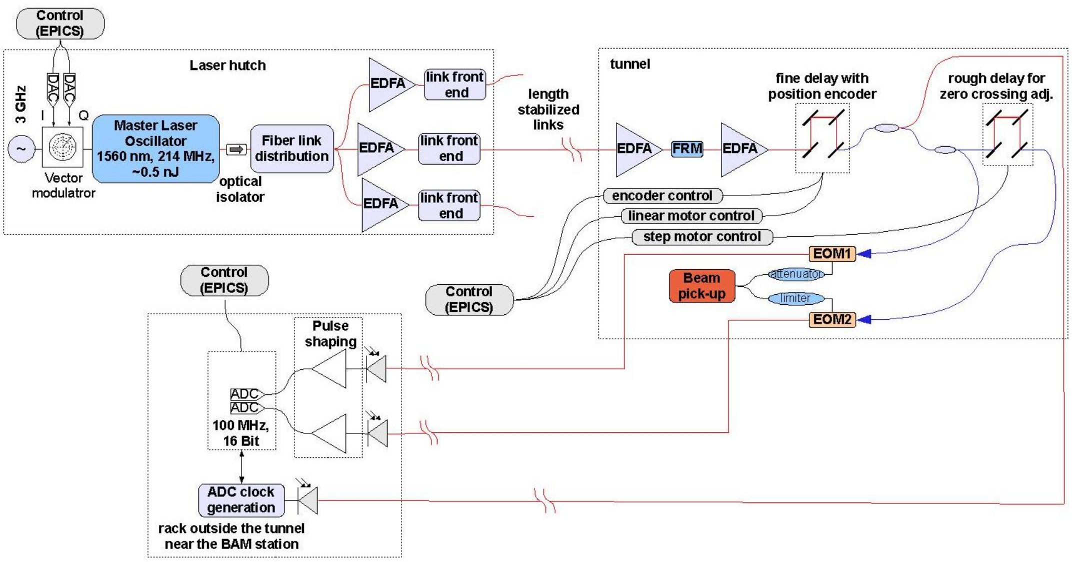
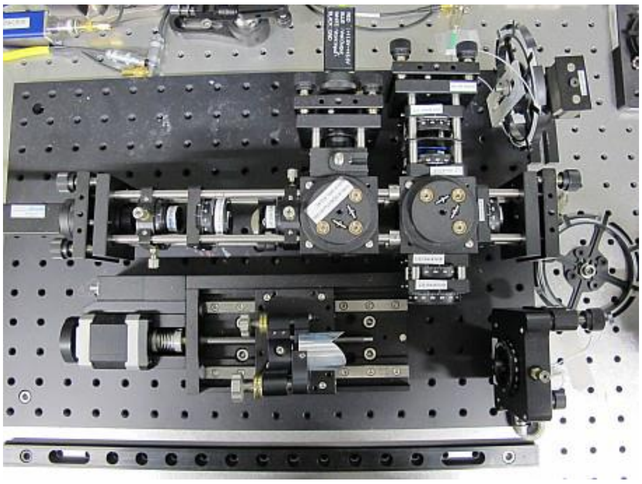


Figure 3: Block diagram of complete system including synchronization.

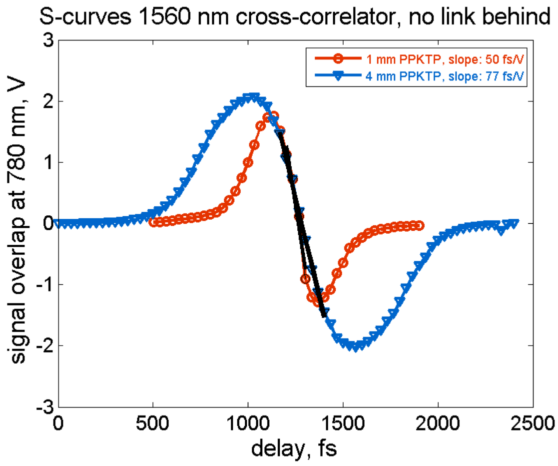
The master laser oscillator (MLO) is a commercial erbium-ytterbium solid state laser by the company OneFive. It operates at a central wavelength 1562 nm, has a bandwidth of 15 nm, a pulse length of 150-200 fs and a repetition rate of 214 MHz. The phase stability in the range of 1 kHz to 10 MHz has been measured as 3.3 fs (rms). Slow drifts of the MLO are compensated via a phase-lock-loop to a quartz phase locked oscillator (PLO) reference.

The length stabilized fibre links transmit the reference laser pulses to the end stations with a stability of less than 10 fs (rms). This is achieved by cross-correlating an incoming reference laser pulse with a partially reflected one from the link end. In a specially designed cross-correlator an error signal is produced, which drives a piezo-stretcher to compensate the fast changes (jitter), or a delay stage to compensate the slow variations (drift). The fibre links consist of standard single-mode fibre SMF28. To minimize the dispersion, pulse broadening pieces of a dispersion compensated fibre are used. A prototype optical cross-correlator for 1550 nm has been assembled and characterized under laboratory conditions.

To produce an error signal with maximum sensitivity to changes in the pulse overlap (link length jitter) with minimum amplitude fluctuations, the traditional layout of the PPKTP crystal (periodically poled potassium titanyl phosphate) was re-optimized. The new design takes into account the influence of the beam focusing, walk-off and group velocity delay. As a result, the length of the new crystal was reduced from 4 to 1 mm. The focusing was reduced to avoid the influence of the beam walk-off[1]. The crystal thickness was chosen such, that the group velocity delay between the two incoming pulses with orthogonal polarizations (Type II interaction) is optimum for the pulse swap inside the crystal, which eliminates the use of additional elements for group velocity adjustment. In addition, the output surface of the crystal is coated with a dichroic layer, thus eliminating the need for one of the external dichroic mirror.



Breadboard prototype



Measured optical cross-correlation signals from old and new (1mm) long PPKTP crystals

Figure 4: Optical cross-correlator for 1560 nm wavelength

A breadboard prototype of the cross-correlator was assembled and characterized in the laboratory. For these tests, there was no fibre link: the back reflection was done with a free space Ag mirror mounted on a translation stage to allow scanning of the pulse overlap. The incoming laser pulses were initially compressed with DCF to 230 fs in order to avoid any broadening in the coupling fibre collimator. Results for two PPKTP crystal lengths are shown in the Fig. 4. The error signals from the prototype cross-correlator show that the 1mm PPKTP crystal has the same efficiency as the 4 mm crystal, used in the original design. The slew rate with the shorter crystal is 25% steeper leading to a better resolution.

[1] In the periodically poled crystals, a quasi-phase matching scheme is used, which means that the idler beam walk off changes direction with each period. Despite the small poling period, the walk off can be 15%-35% of the beam radius, depending on the focusing. There is a tradeoff between efficiency gain due to high energy density in the focal spot and efficiency loss due to the walk off effect.

To avoid distortion of the reference laser pulses in the link and to provide enough power for the end stations, a proper power balance needs to be considered. After the MLO the laser pulses are split, which requires amplification either before splitting or for each separate link. The link front end consist of free space elements with important reflection losses, so, on one hand, the cross-correlator requires at least 30 mW for each pulse. On the other hand the power in link shouldn't exceed 100 pJ to avoid self phase modulation. At the link end the reference pulse is partly reflected – the first half returns to the cross correlator at the front end, the second enters the end station. All of this indicates the necessity of cascade amplification, the minimum number of amplifiers being three – one at the link front end, one immediately in front of the Faraday rotating mirror at the link end and one for the diagnostic station[2]. The amplifiers are erbium-doped ones (EDFA), which are standard for the chosen central wavelength. Due to the high number of devices needed for the 250 MeV injector and later on for the SwissFEL, commercial products are preferable. For a reduced complexity and higher flexibility, all EDFAs should have the same construction, independent of their position in the link. Their performance should be optimized by choosing the proper balance between seed and pump power. The difficulty in finding such a device off the shelf is not the amplification, which is moderate (6-10 dB), but rather the required high bandwidth (15-20 nm), the requirement for remote control and monitoring and finally the transparency for both propagation directions at the central wavelength.

The bunch arrival time monitor consists of a beam pickup, an optical station and acquisition electronics. The important parameter of the beam pickup is a wide band frequency response with minimum phase distortion, resulting in a high slew rate and a short duration of the pulse response. We tested two types of pickups, a button type pickup with small diameter tapered buttons having the advantage of an extremely wide bandwidth and a pickup using ridged waveguides with a more limited bandwidth but a stronger coupling to the beam. The optical station and the acquisition electronics are relatively straightforward. Apart from the fibre electro-optical modulators and the polarization maintaining fibres, the most critical part is the precision delay stage with position encoder, which provides the time scale. The resolution should be in the order of 1 fs. Such delay stages and encoders are available on the market, but the required robustness and long life time limits the choices. Among the linear stages with stepper motor, which otherwise offer perfect mechanical stability, very few companies meet the specifications for frequent movements over few millimetres, something reducing the lifetime of the device dramatically.

4. PICKUP

4.1. ELECTRICAL AND MECHANICAL DESIGN

The figure of merit in a pickup for a bunch arrival time monitor is the slew rate of the output signal, the steepness of the rise around a suitable chosen zero. The slew rate itself is determined by two parameters, the overall energy extracted from the beam and a very large bandwidth with minimum group delay variations.

[2] According to the latest reference distribution concept, the timing stability will be considerably improved, if for the first amplification stage one power amplifier is used immediately before the splitting to the different links, instead of amplifying the OMO pulses separately for each link. (see e.g. [4]). The other two EDFA amplification stages remain unchanged

An additional condition coming from the application for the SwissFEL is the operation in multi bunch regime. We should be able to distinguish individual bunches spaced at a distance of 28 ns (while the CLIC drive beam also features a bunch train, the capability to identify individual bunches is not necessary there).

We pursued two approaches. The first uses a button pickup of relatively small diameter. The button is essentially an integrated part of a 50 Ohms coaxial line and tapers smoothly into a coaxial feed-through, before transitioning into a K-type connector. While coupling weakly to the beam, the pickup geometry exhibits extreme wide-band behaviour with a bandwidth of roughly 80 GHz. The practical limitation comes from the vacuum feed-through used (Meggit #8538972), which is specified only up to 20 GHz. This type should be a good choice for high charge application (Q > 200 pC). Fig. 5 shows the pulse shapes and spectra for different lengths including the cable attenuation.

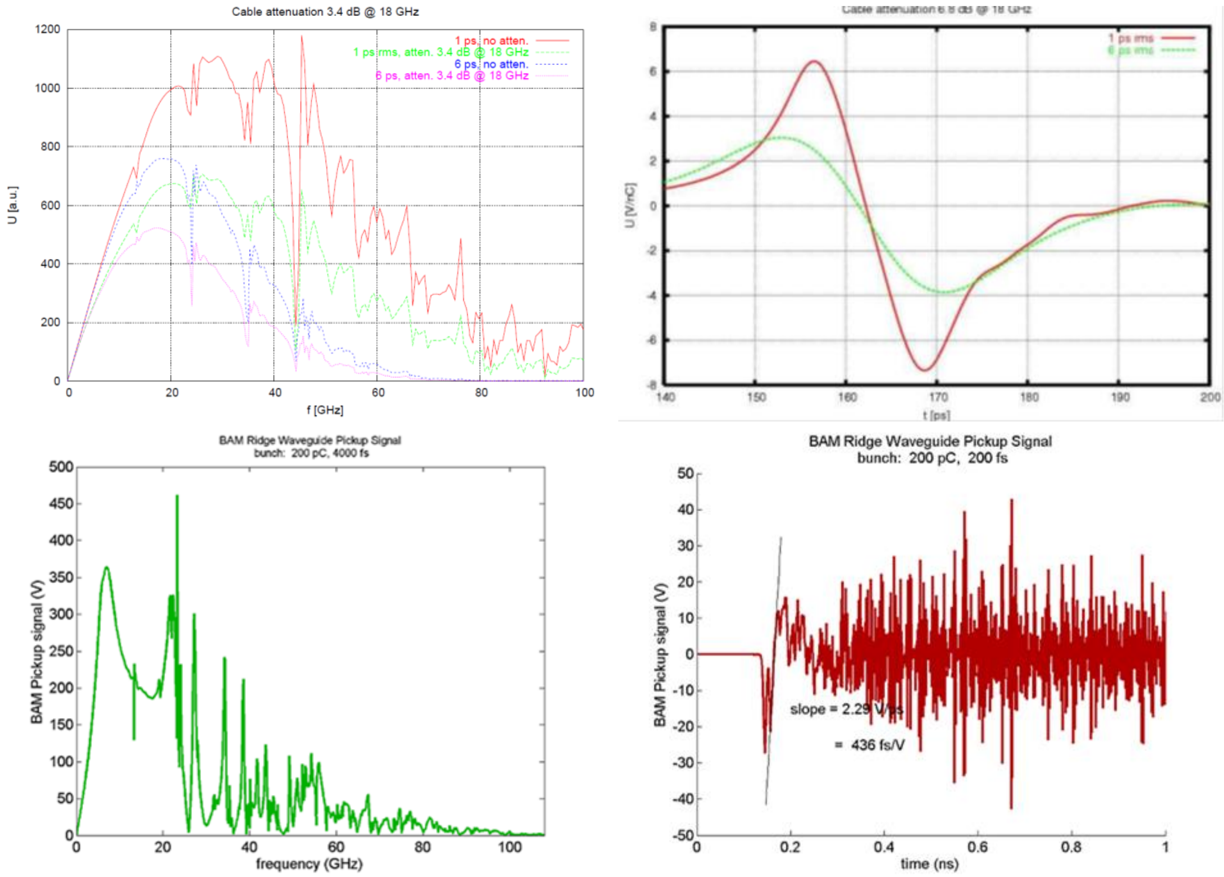


Figure 5: Output spectra and signals from beam – top: button pickup – bottom: ridged waveguide pickup

As an alternative geared to bunches with very low bunch charges of a few pico coulombs, we tested also a second pickup type, which puts the emphasis on coupling strength at the cost of the bandwidth. It uses ridged waveguides, which offer a large coupling aperture to the beam while still having acceptable bandwidth (16 GHz) and group delay variations. After a short section, there is a transition into a coaxial line leading into the combination of Meggit feed-through and connector used also for the button pickup.

Both, buttons and ridged waveguide (RWG) were mechanically integrated into one device. Fig. 6 below shows a CAD model of the device.

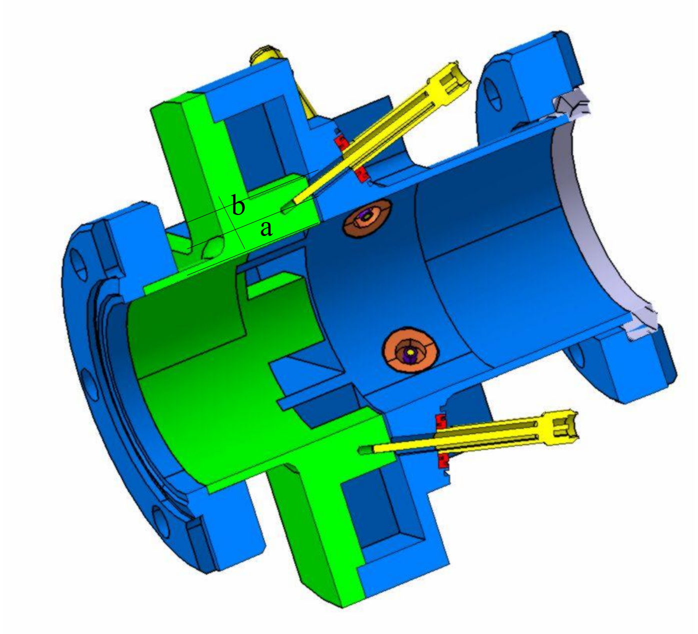


Figure 6: CAD model of device combining both button and ridged waveguide (RWG) pickup

4.2. BEAM TESTS

The pickup prototype was inserted in the beam line of the PSI injector, after the last accelerating section, at a short distance before the bunch compressor chicane. Fig. 7 shows the device.

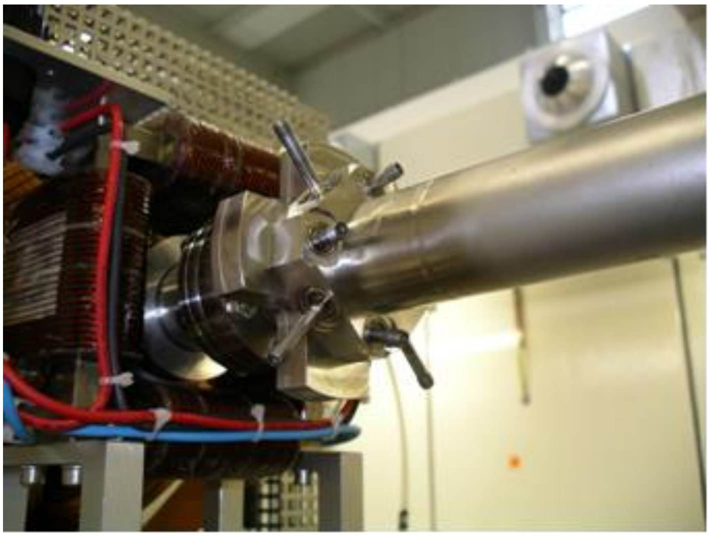


Figure 7: Pickup in the beam line

The RF front end between the pickup and the EOM is carefully balanced. High bandwidth and low temperature drift components are selected. An important aspect is the orbit dependence of the pickup signal, which we minimized by combining opposite pickup signals. In order to avoid any deterioration in the slew rate, this needs careful balancing of the group delays of cables and couplers. The group delay difference is kept constant with accuracy better than 50 fs within the measurement range 1 GHz - 1.5 GHz.

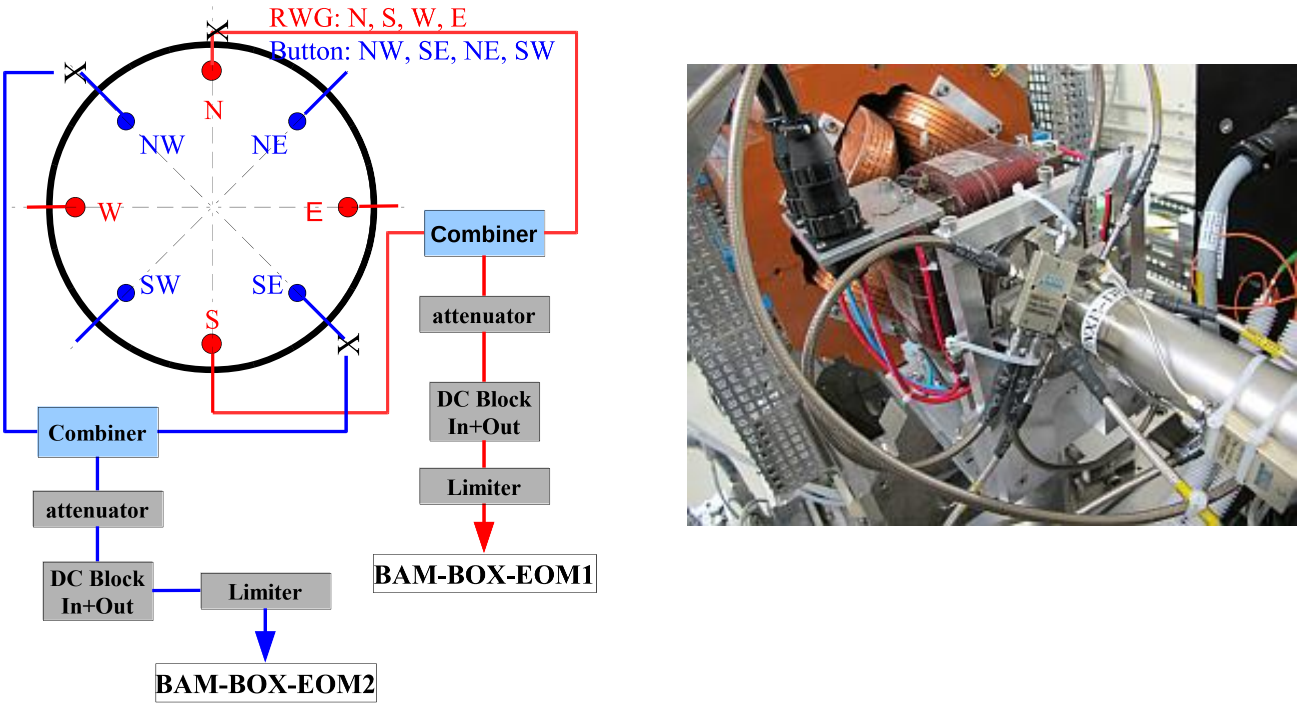
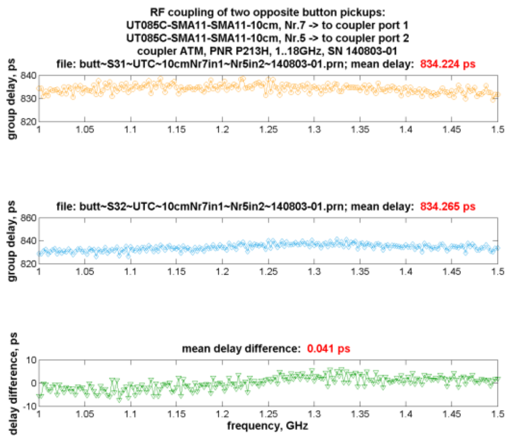
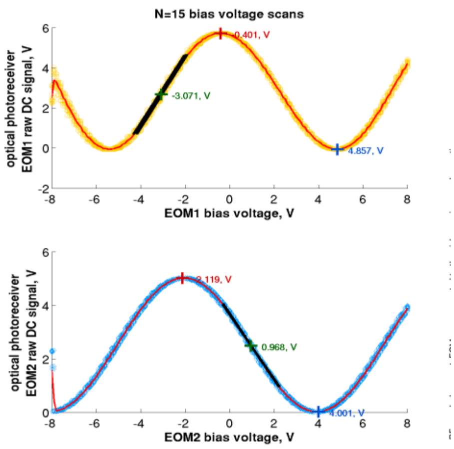


Figure 8: Block diagram RF front end, photo to the right



Group delay compensation of the pickup



EOM transmission curves

Figure 9: Electrical characteristics

To avoid ground loops from the accelerator beam pipe, the RF cables are insulated with double DC blocks. Additionally, the EOMs are galvanically insulated from the Front End base plate. A test with repetitive scans (*N*=15) of the EOM's bias while the magnets and the RF in the accelerator were on and the laser shutter was open (dark current), showed no variation in the EOM response curve, slope and working point position.

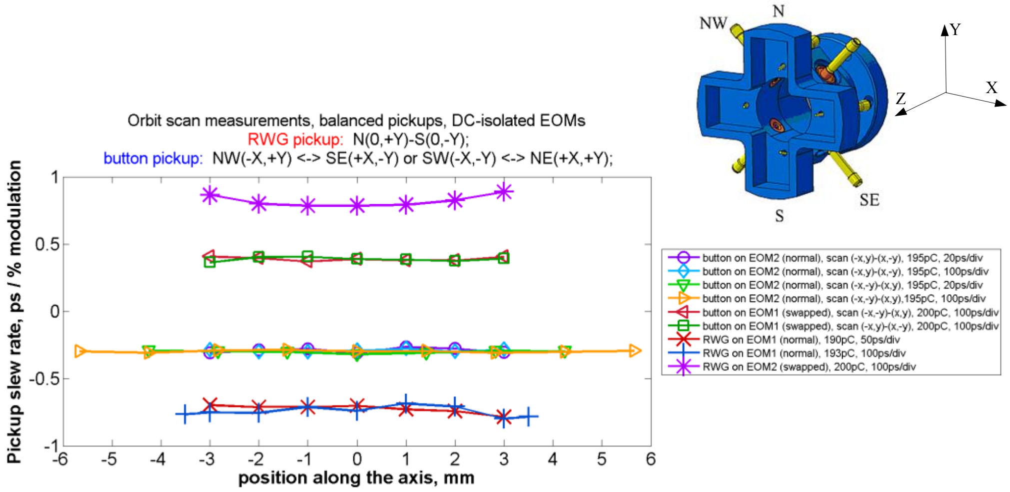
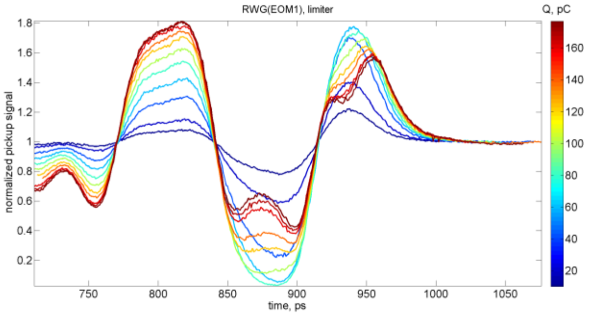


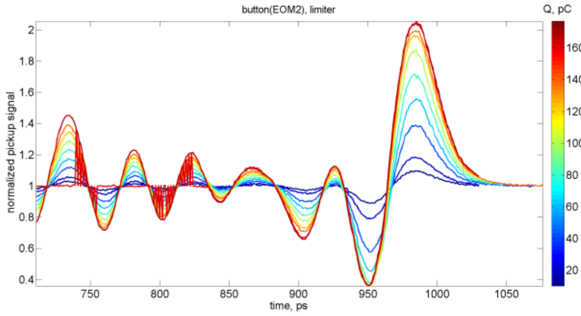
Figure 10: Orbit dependence of the pickup slew rate

The orbit scan measurements (Fig. 10) show the successful balancing of the RF front end: there is only negligible dependence between orbit and slew rate.

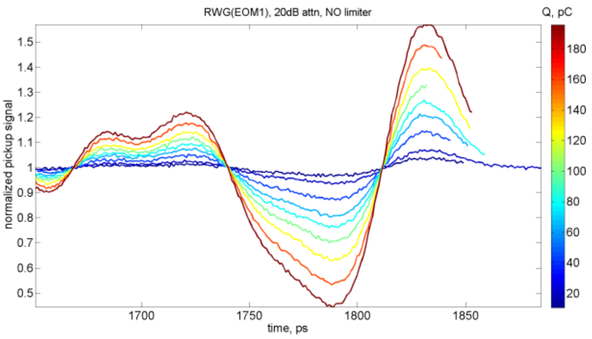
The EOMs are specified for input levels up to 5 Volts. Higher values lead to phase rotation and nonlinear distortion of the original pulse form. In order to avoid this effect, attenuators should be used despite of the drawback of a limited bandwidth decreasing the slew rate. As a protection against very high RF powers, which can damage the EOM, limiters were used.



RWG pickup with limiter (no attenuation)



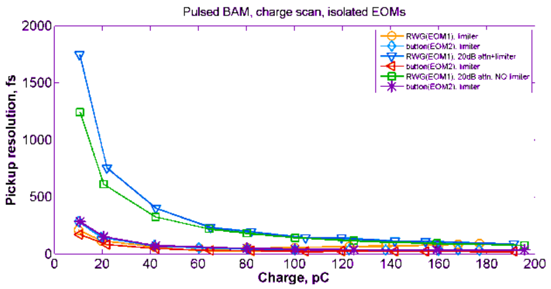
Button pickup



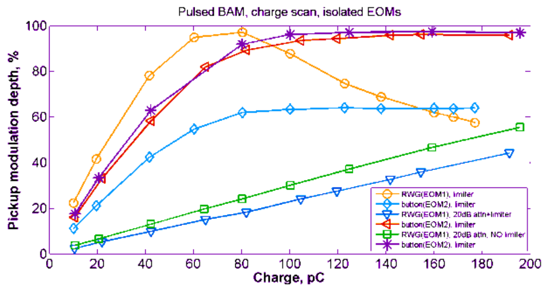
RWG pickup with 20 dB attenuator (no limiter)

Figure 11: Pickup response - each curve is taken with the BAM photo-receiver by changing the delay of the laser pulse relative to the pickup response with a vector modulator.

The charge scan measurement of the pickup signals reveals the typical effects of the attenuators and limiters. At 200 pC bunch charge, the stronger RWG signal requires 20 dB of attenuation in order to avoid over-rotation. For lower charge the attenuation should be reduced. Technically it is difficult to achieve online switching between different sets of attenuators to secure optimal performance. This leads to reduced sensitivity of the RWG at lower charge, for which it was designed. Comparing both pickups, the button version shows a better linearity with the charge.



Pickup resolution versus charge



Pickup modulation depth versus charge

Figure 12: Pickup performance versus charge

The best resolution achieved so far with the button pickup is 20 fs and for the RWG 85 fs. The ringing of the RWG pickup as well as its non-linearity makes it problematic for use in the BAM. The button pickup has a better resolution and should be optimized further to profit as much as possible of its intrinsic high bandwidth. Currently the bottleneck is the vacuum feed-through, which limits the bandwidth to 20 GHz. Optimized vacuum and RF design is under way in collaboration with two companies, BC-Tech CH and Microtest Inc., USA. Further potential for increasing of the BAM resolution is the use of 40 GHz EOM. Such EOMs exist off the shelf from e.g. Oclaro, Photline or GigOptic and are foreseen for test in the new BAM prototype.

5. OPTICAL SYSTEM

5.1. OPTICAL COMPONENTS

5.1.1. Master Laser oscillator

The master laser oscillator (MLO) is a commercial Er:Yb:glass soliton laser from the company OneFive, which operates at a central wavelength of 1562 nm and has a bandwidth of 13 nm. It has been thoroughly tested for continuous operation and shows constant phase noise stability of 3.3 fs (rms) in the range of 1 kHz to 10 MHz, reproducible over weeks. Phase locking to a rubidium reference has been demonstrated, autocorrelation and FROG (frequency resolved optical gating) traces have been recorded. Fig. 13 gives the measured autocorrelation curves and the corresponding Gauss- and $sech^2$ fits. The corresponding FWHM pulse lengths are 185 fs and 160 fs.

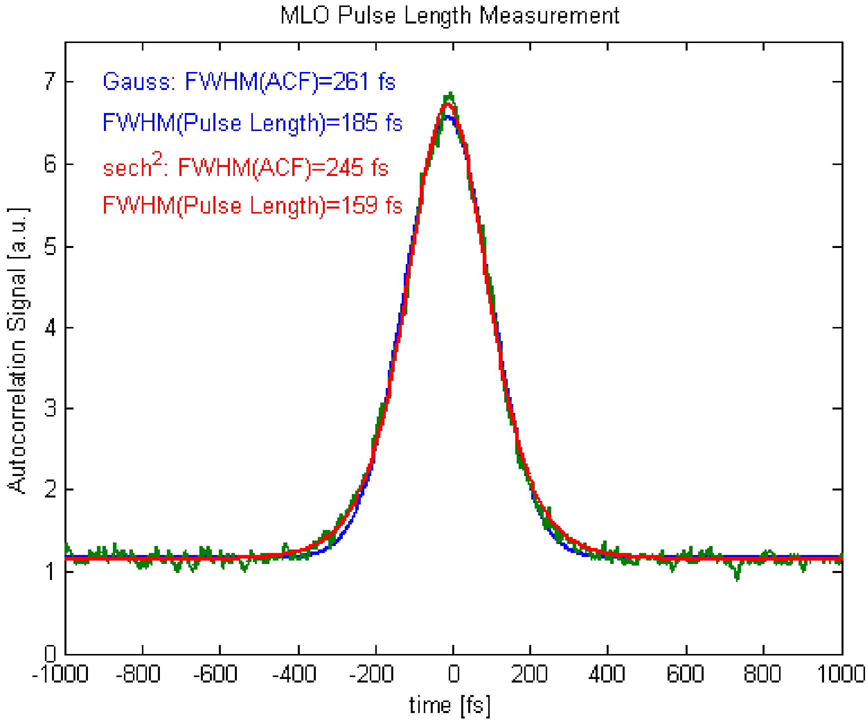


Figure 13: Spectrum of the master laser oscillator Origami-15 by OneFive

5.1.2. Erbium-doped Amplifiers (EDFA)

The distribution of the reference laser pulses from the link front end to the BAM station requires cascade amplification. The link design requires three Er-doped fibre amplifiers (EDFA). The first stage will be a power amplifier common for all links and will precede the link distribution. The design of this EDFA is still under consideration, but based on the experience from ELETRA, the provider of this power EDFA will be either Menlo systems or OneFive. The other two EDFAs in the cascade are compact and have the same design. Initially several providers, such as Menlo Laser, Calmar Laser, Keopsys and Photop, have been asked to deliver prototypes for testing. Among them only Menlo and Photop managed to meet the specifications. The product of Menlo was impractically bulky and expensive

The Photop EDFA has a very small footprint (70 mm x 90 mm), which allows integration of two such devices in the BAM optical front end. It has a bidirectional transmission, which is required for the optical fibre link. All the necessary operation parameters, such as the input and output powers in forward and backward direction, the device temperature are remotely monitored and controlled through an RS232 interface, for which Matlab and EPICS control routines have been implemented.

The Photop EDFA was tested for pulse length, spectrum and gain flatness. The results are shown in Fig. 14.

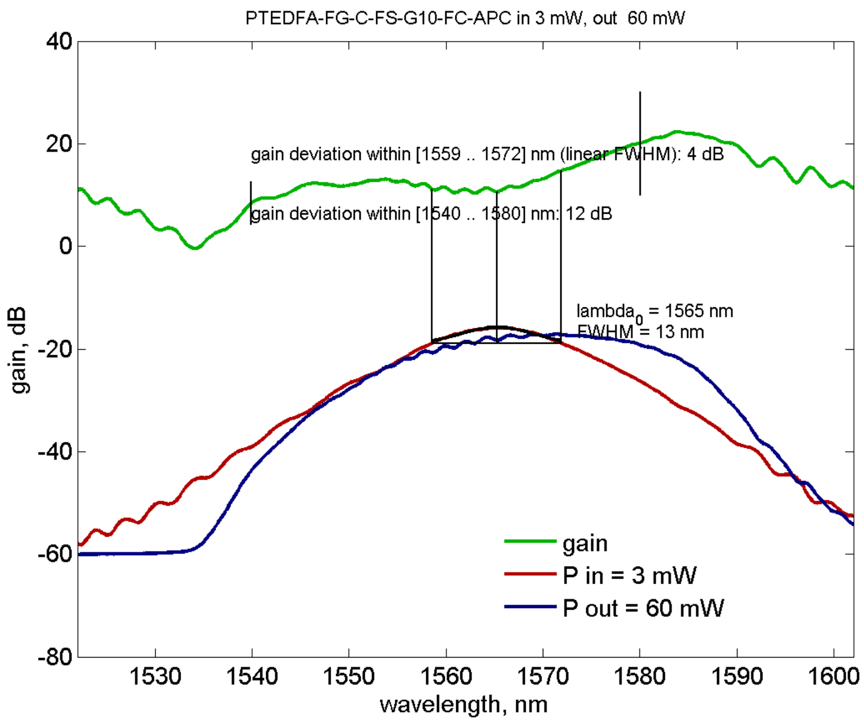


Figure 14: Spectra of the incoming (red curve) and amplified (blue curve) reference laser pulses of the Photop-EDFA in a forward direction. The gain curve is represented in green.

The device has a built in gain-flattening filter, which in principle stabilizes the gain to better than 1 dB in the range 1555-1565 nm. But this does not cover the full bandwidth of the MLO having a central wavelength of 1562 nm and a FWHM width of 13 nm. This results in a pronounced deviation from the gain flatness in the desired amplification range 1540-1580 nm of more than 12 dB. In addition, the pulse broadening in the EDFA is also considerable with more than 15 ps. The Photop EDFAs have the advantage that they are compact and allow easy integration in the BAM-Station. In addition their price is considerably less than that of the competitors. Based on the gained experience in a second iteration a shorter, high gain fibre was used. This has a double effect: on the one hand the gain is automatically flattened, without the necessity of an extra gain flattening filter. On the other hand the pulse is less broadened, which eases the recompression.

Initially, a second set of EDFAs was built in house using a short high gain Er-fibre from Liekki (ER80 8/125) omitting the gain flattening filter. The gain fibre lengths were 0.6m, 1m, 1.5m and 2 m. The design was similar to the one of DESY. With it, it was possible to recompress the pulse and we offered Photop to reuse the design for their products. In addition, we integrated four calibrated photodiodes to monitor the forward and reverse input and output powers. The design is shown in Fig. 15.

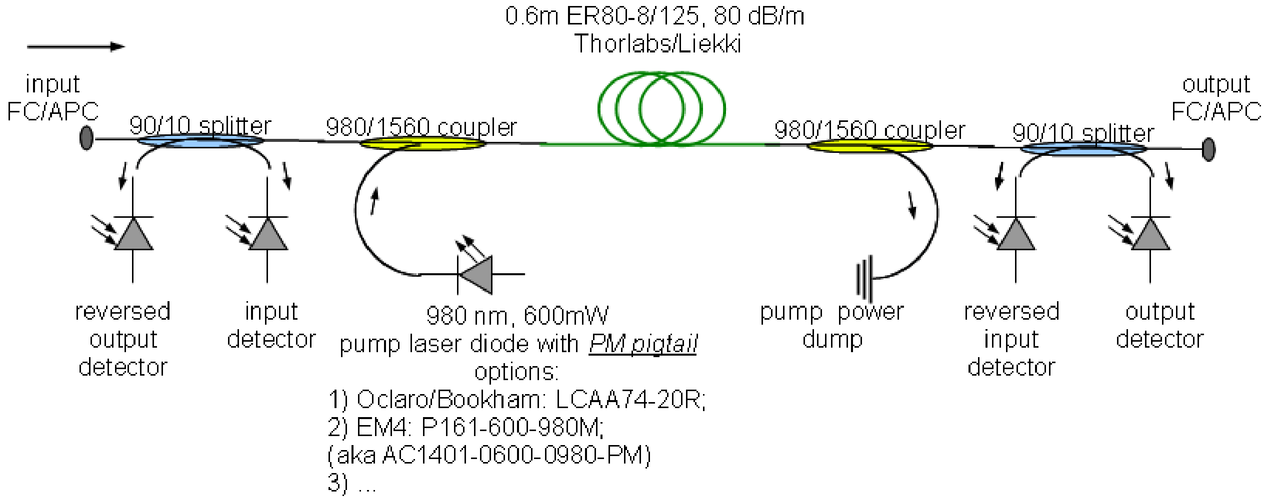
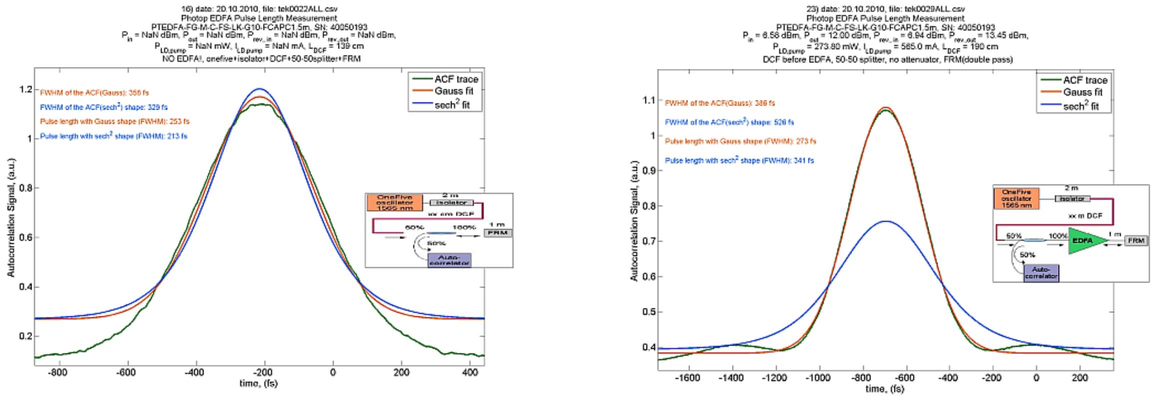


Figure 15: Design of the improved EDFA, commercially available by Photop

The possibility for pulse recompression after bi-directional pass in the EDFA has been tested in laboratory conditions [3]. Good pulse recovery of the original pulse length has been achieved with minimal change of the pulse form (side bands). Thus the dispersion compensation for an optical link has been verified.



Optical fibre isolator, splitter and FRM. Pulse length 213 fs (sech2)

Entire optical fibre path, including the EDFA. Pulse length 273 fs (sech2)

Figure 16: Dispersion compensation

5.1.3. Precision delay stage with position encoder for the BAM front end

The timing of the Bunch Arrival-Time Monitor is provided by a precision linear motor with a high resolution encoder, which allows scanning and high-accuracy positioning relatively to the pickup signal. Standard operation involve frequent movements over few millimetres – stringent mechanical requirements for the delay stage, which are best satisfied by a linear three-phase servo motor. This type of motor is susceptible to mechanical vibrations, influenced by the tolerances of rails and bearings and the stability of the periodic driver current. Therefore several stability and the accuracy tests have been performed. Stage stability is determined by the encoder period of 10 nm: a stationary state is achieved by a continuous oscillation between two neighbouring encoder positions. The position jitter added by the holding current is 8 nm (26 as) rms, measured in-loop. This result was verified by an out-of-loop measurement with a laser interferometer (Fig 17). During these measurements the motor was placed on an optical table, under power, but stationary. 10,000 points, corresponding to more than half an hour acquisition were recorded. Under these conditions, the position remained stable between two neighbouring encoder positions for 98% of the time.

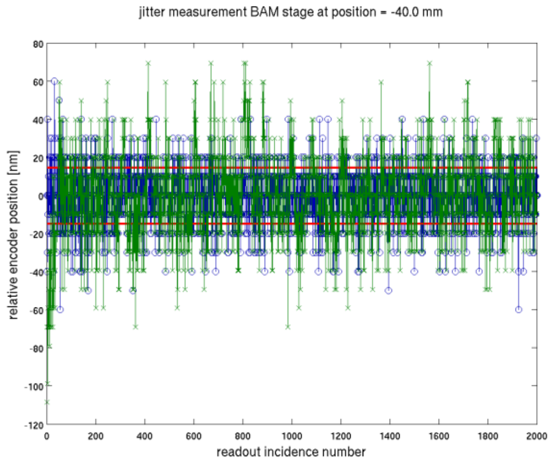
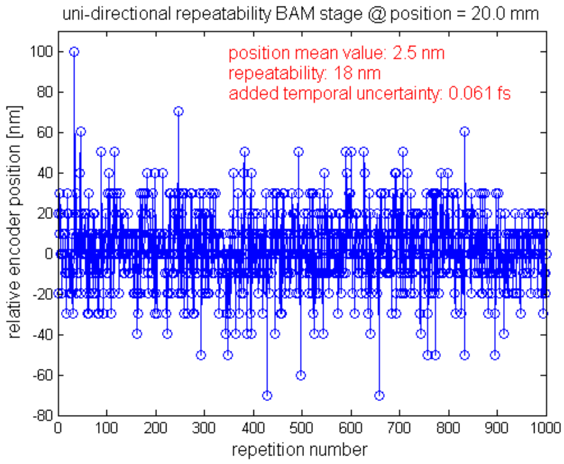
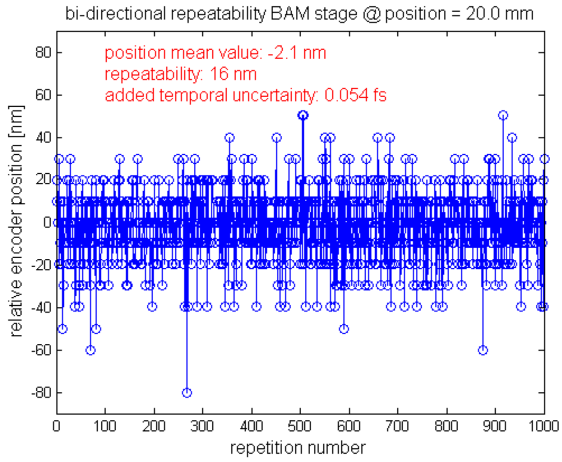


Fig 17: In- and out-of-loop stability measurement in stationary state. Additional Position jitter due to the holding current: 8 nm /26 as/ (rms)



Uni-directional repeatability – return to a target position (20 mm) from one direction.



Bi-directional repeatability – return to a target position (20 mm) from both directions.

Figure 18: In-loop characterization of the linear motor stage Parker MX80LT03.

In another set of measurements the uni-directional and bi-directional positional accuracy was tested in-loop. Here the motor was driven to a given position either from one side or from two opposite sides and the deviation from the target position was recorded. The results are shown in Figure 18. The motor was driven ±20 mm away from the target position and back to it. The rms repeatability was found to be 16 nm, which is a typical number for a variety of travel distances and also asymmetric approach from both sides; this corresponds to an added temporal uncertainty of 54 fs.

Another series of tests verified the specified mechanical straightness and flatness. Both parameters refer to the deviation perpendicular to the direction of travel in the horizontal and vertical plane. This can have an influence on the coupling of the laser pulses into the fibre collimator, which is an integral part of the BAM. For these measurements, a commercial system for precise angular measurements, a collimator ELCOMAT 2000, with measurement accuracy of ±0.25 arcsec (1.2 mrad) and resolution of 0.05 arcsec (0.24 mrad) was used. The producer specified flatness and straightness of the MX80LT03 linear motor stage is 5 mm. The measured peak to peak error in straightness was 6.5 mm and the flatness was 6.9 mm over the full travel range of 100 mm travel. Both values agree well with the passport data. These deviations are negligible for large aperture (~3-5 mm in diameter) fibre collimators. Knowing the flatness and straightness and the possibility to quantitatively measure them allows better mechanical design of future BAM stations.

The remote control of the linear motor stage in the BAM-station was implemented as follow. All parameters necessary for accurate movement as the driving method (sine or trapezoid), the homing method, velocity, acceleration, deceleration, encoder values etc. are accessible with Matlab through an RS232 serial port with ASCII commands. A set of driving routines has been written and tested. The influence of the readout and control over the accuracy has been tested and debugged.

5.2. OPTICAL FRONT END

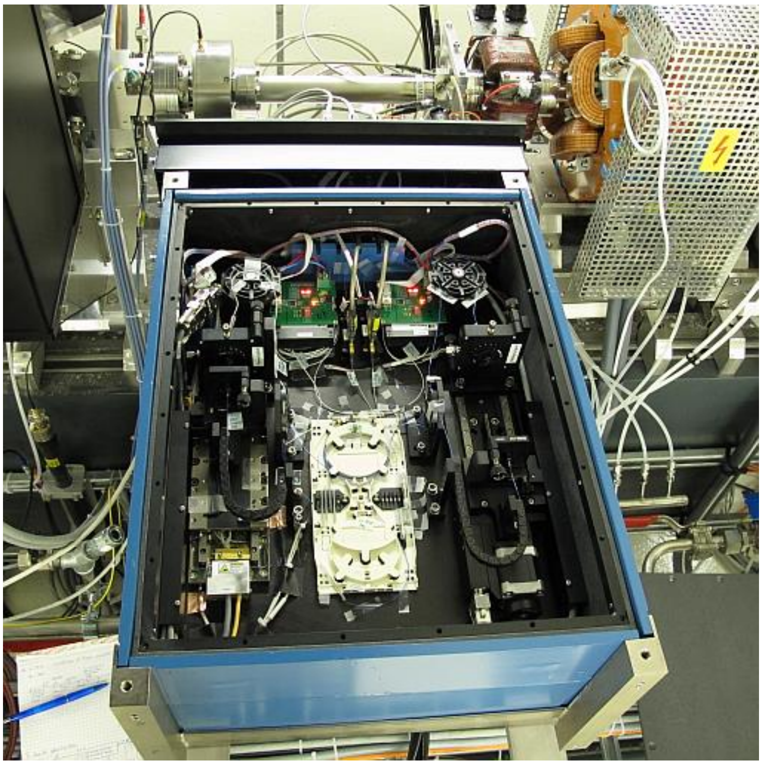


Figure 19: Opened optical front end

The optical front end, the so called BAM-BOX, contains the fibre optical and the opto-mechanical components necessary to measure the cross-correlation between the laser reference and the electron bunch. The end of the length-stabilized optical fibre link is also housed in the box: an EDFA (erbium-doped fibre amplifier) and a Faraday rotating mirror (FRM). The rest of the components are out-of-loop and therefore affected by temperature and humidity changes. Extreme care is taken to keep the fibre lengths short to minimize drifts. In addition the entire base plate is temperature stabilized which is also required because of the temperature dependent coupling of the optical fibre splitters (used to derive the clock signal and the reference for the two BAM channels) and the linear delay stage, responsible for an accurate BAM timing.

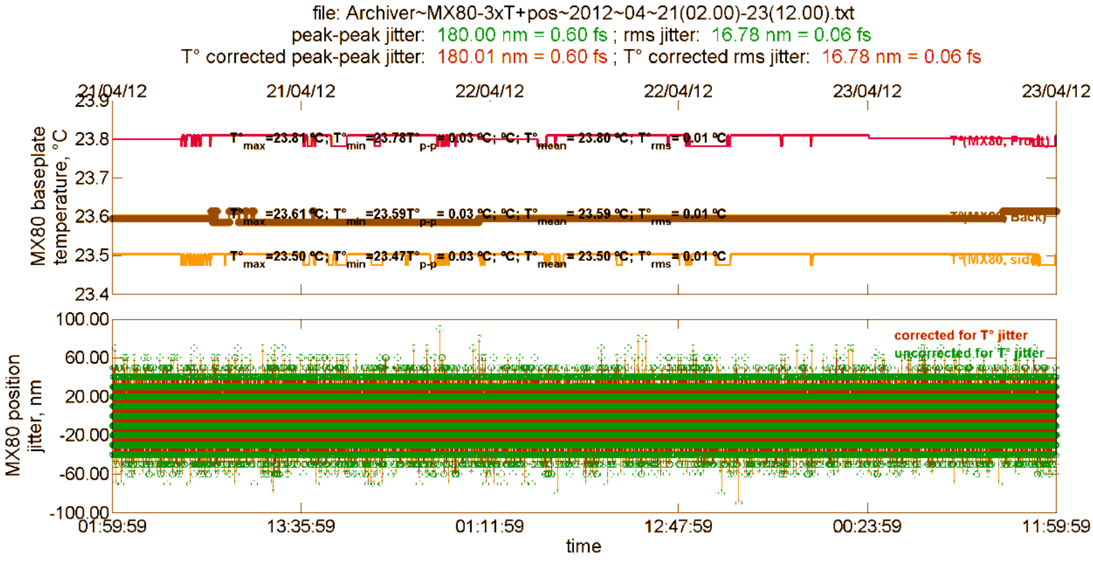


Figure 20: In-situ position jitter of the linear delay stage (optical front end mounted on the accelerator girder). The measured jitter over 3 days of 16.8 nm (60 as) rms, resp. 180 nm (600 as) pk-pk corresponds to the stability of the girder. The position was corrected for temperature (stability 0.03 K pk-pk) measured with three sensors around the stage.

Because of the free space components as the movable delay stages and the fibre path towards the optical photo receiver (PRX) outside the tunnel, the laser pulses need to be amplified with a second EDFA. The optical front-end prototype has two channels (two EOMs) with 10 GHz bandwidth, which were used to test and connect both pickup types – EOM1 to the RWG-pickup and EOM2 to the button pickup in order to characterize the signals. In normal operation only one pickup type (button) is needed. In this case one of the EOMs can be connected only with limiter to preserve the high resolution (< 5 fs over 20 ps dynamic range), and the other with an attenuator to provide a large (100 ps) dynamic range.

The task of the linear delay stage is not only to provide high timing accuracy but also to act as an actuator for the zero crossing feedback. Provided that the machine drifts for some reason, or that the bunch time of flight changes, e.g. by moving the magnetic chicanes, the delay stage should bring the overlap between the laser pulse and the pickup transient back to the zero crossing. Therefore the position dependent optical coupling in the delay stage was carefully optimized. Best results so far with $f = 1.9$ mm grin lens collimators, PM or SMF (divergence 5 µrad, beam diameter 0.5 mm), from Princetel were in the order of 0.3%/mm insertion loss. This should still be improved in future versions.

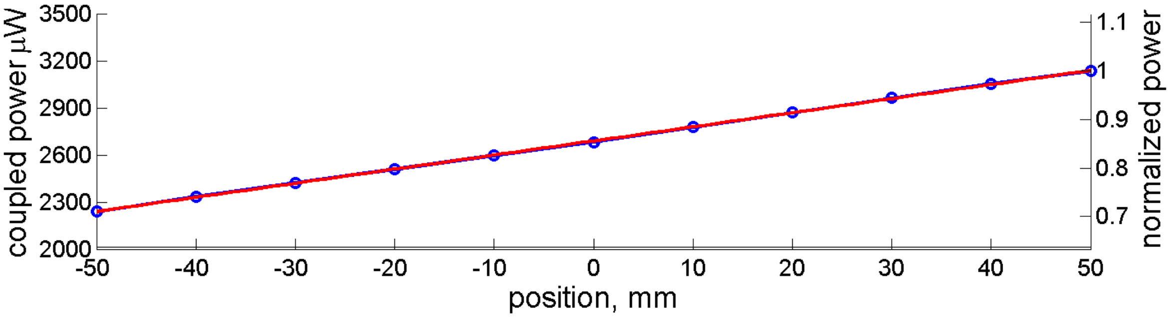


Figure 21: The position dependent optical coupling is ca. 30% over the entire travel range.

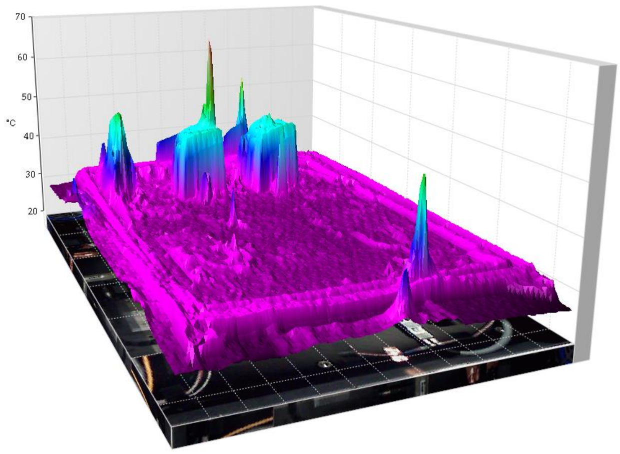
The coincidence of the zero crossing between the two BAM channels is provided by a second delay stage. This stage moves rarely, therefore the requirements for its robustness is not critical.

The front end is shielded against X-rays with 10 mm thick lead walls. To capture neutrons, a second hood of boron-doped polyethylene is added. Although the shielding is sufficient for the injector, the attenuation is only 1.5 dB relative to the surrounding environment (shortly before the BC). At that position the equivalent neutron dose at bunch energies of 230 MeV was measured to be 700 μSv/h, meaning that for higher energies a stronger shielding may be required.

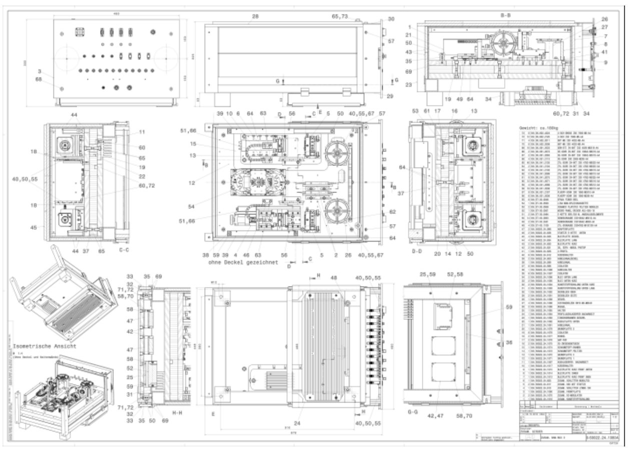
Front End improvement

In the first front end prototype several thermal sources - the two EDFAs and the controller of the linear delay stage – were mounted on the same base plate as the critical elements such as fibres, fibre couplers and the linear delay stage. In normal conditions the temperature of these sources is 10 K – 20 K higher than the control temperature. This makes the thermal regulation very difficult and energy consuming. In addition the cost of the front end increases, since 12 TEC elements are required for homogeneous heat extraction.

So in a second iteration, all thermal sources were housed in a separate compartment, which is isolated from the main volume. Only the surface below the critical components and not the entire base plate needs to be stabilized thermally.



Thermal image of the first prototype at full heat load and temperature regulation at 24°C



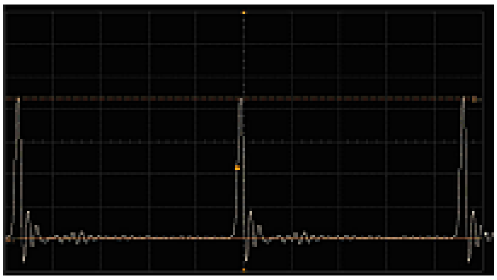
Second prototype with improved thermal performance

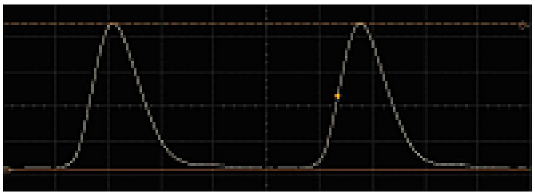
Figure 22: Front end prototypes

5.3. PHOTORECEIVER AND DATA ACQUISITION

5.3.1. Photoreceiver (PRX)

The BAM photo receiver, the back end of the monitor, is placed in a rack outside the accelerator tunnel. Its purpose is to transform the amplitude modulated laser pulses in an RF-signal, suitable for processing with a fast ADC card. The prototype has been designed by Stephan Hunziker at PSI.





Raw photodiode signals at the BAM PRX input *Pulse-shaped PRX signals fed to the ADC card*

Figure 23: Photodiode signals

The photodiodes used have a high intrinsic bandwidth, biased such as to minimize the photo receiver noise. The signals are band-pass filtered for low sampling jitter sensitivity: the interval between the pulses is broad and without ripples, the peaks are flat. After filtering, the signals are amplified by a broadband trans-impedance amplifier with high dynamic range. The ADC clock signal is also derived from the laser pulses, which are split in the BAM front end before the amplitude modulation and have the same delay relative to the pickup transient as the modulated pulses. This ensures, that the laser pulse, which is modulated by the electron beam appears always at the same ADC sample number, which aids in the analysis (more in section 6.3).

5.3.2. ADC card

The ADC card used was originally designed for the BPM system of the European XFEL[5]. It consists of a GPAC carrier board and an ADC mezzanine board. In the present BAM prototype a 12 bit ADC with 500 MHz sampling rate is used. For later BAM versions a 16 bit ADC card is foreseen, which will increase the resolution by a factor of 4.

The ADC trigger is received from the machine event receiver and is synchronous with the electron bunch. The 214 MHz clock is generated by the laser pulses and is delayed simultaneously with them either by the vector modulator for the laser reference, or by the delay stage in the BAM front end. Presently both the base line and the amplitude of the laser pulses are sampled by the same ADC channel at the double frequency (428 MHz). An internal PLO delay allows sampling on the maximum of the laser pulse.

Part of the available ADC range is already consumed by the offset of the photo diode signal, limiting the resolution. As part of the in house continuation of the project, a DAC front-end is under construction, which will allow to bias the PRX signals and to remove this offset, such that the laser amplitude is detected with the maximum number of available bits.

5.3.3. Data acquisition

Data acquisition is performed using Matlab scripts. The laser pulses are normalized shot-to-shot: each laser pulse is normalized to the previous one.

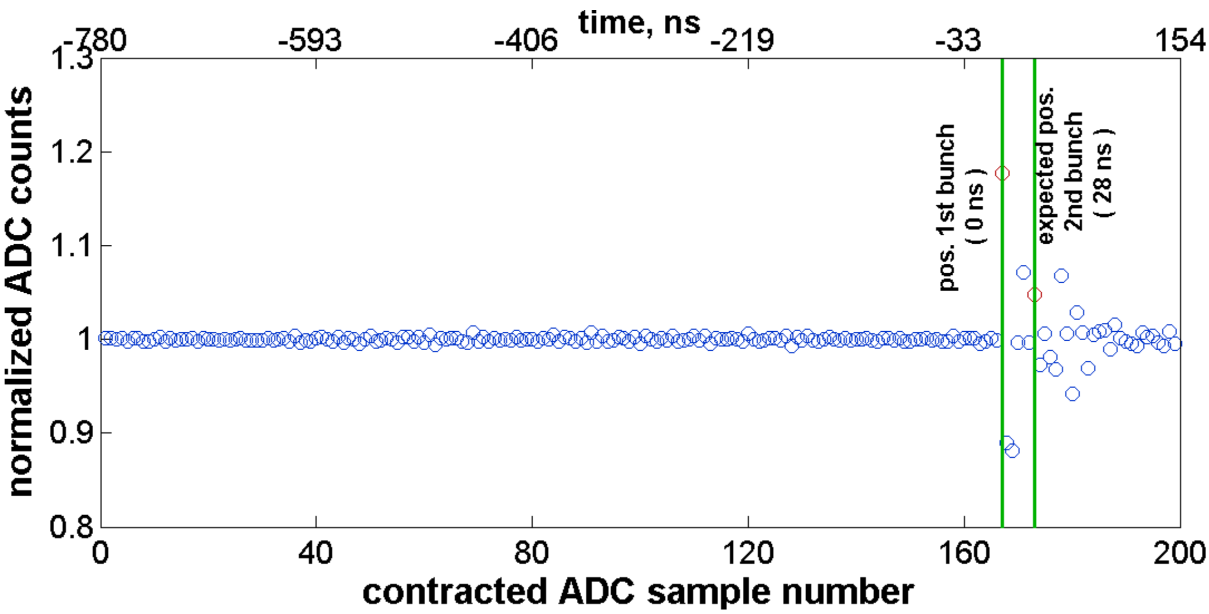


Figure 24: ADC data collected measuring an individual bunch.

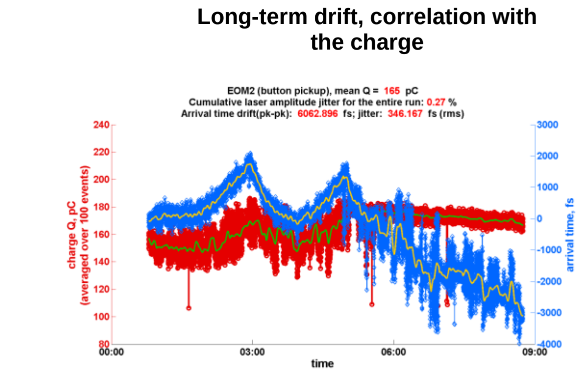
The ADC samples a large number of laser pulses, preceding the one modulated by the electron beam. The normalized residual laser shot-to-shot amplitude jitter is in the present system of an order of 0.25% - 0.27%. This laser amplitude jitter measurement is done continuously. Together with the slew rate of the pickup signal, obtained in a calibration run, this gives a continuous readout of the instantaneous BAM resolution.

Fig. 24 shows the raw ADC data collected single-shot from an individual bunch. Each point represents a normalized laser pulse. 150 pulses preceding the modulated pulse are used for online monitoring of the instantaneous laser amplitude jitter. The first modulated laser pulse, marked red, appears at the ADC sample number 167. The amplitude modulation of this laser pulse corresponds to the bunch jitter and drift. Because of the pickup ringing and wake fields also several following laser pulses are modulated. For the use in SwissFEL, this is somewhat undesired for the intended two-bunch operation. On the other hand with proper calibration the modulation of the following five laser pulses may be used for online charge measurement.

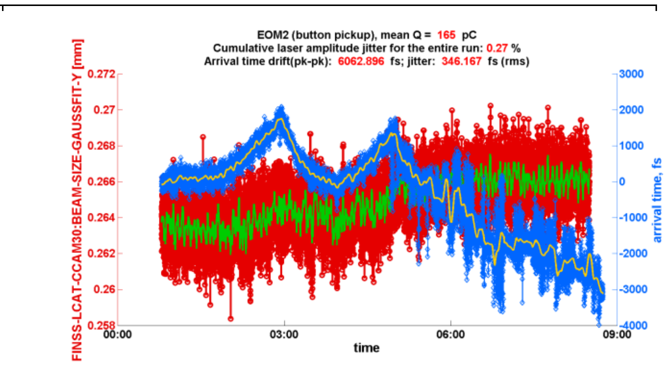
6. TEST OF FULL SYSTEM WITH BEAM

The entire chain – master laser oscillator, opto-mechanical front end, photo receiver and data acquisition electronics – are operational in the injector since the summer of 2012. The complete system except the link stabilization has been commissioned. Several sources of electromagnetic interference have been identified and eliminated. High level acquisition routines have been implemented and are continuously being optimized during operation. Long term drift runs have been made. Since the optical fibre link is still not commissioned, part of the measured drifts is due to length changes in the optical fibres. The influence of temperature and humidity on single mode fibres (SMF) is known as 40 fs/K/m and 12 fs/%RH/m. The expected influence for the first BAM station in SITF is then 200 fs/0.1 K and 600 fs/%RH. Given that the tunnel temperature is stabilized to within 0.1 K, the drift due to the optical fibres is caused primarily by humidity changes.

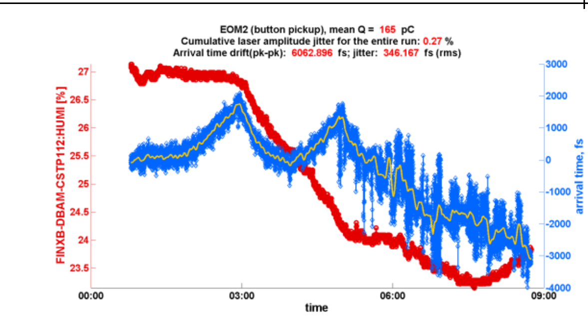
Due to its better slew rate giving resolutions of 20 fs to 50 fs, all drift measurements used the button pickup. For the first runs, no feedback for the zero crossing was used, meaning that, if drift and jitter exceeded 20 ps pk-pk, the BAM slope would be lost. An example of such a drift measurement with BAM is shown on Fig. 25. It should be noted that we did not have marked triggers from the event receiver of the timing system, so a bunch by bunch correlation of the BAM data with e.g. the charge measurements were not possible introducing artificial short term jitter over periods of few seconds. For long term drifts, this did not make any difference.



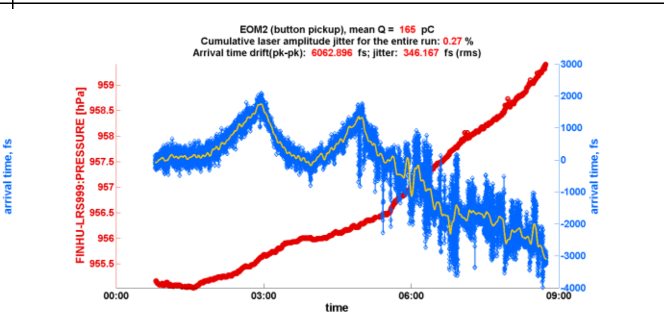
Correlation with charge



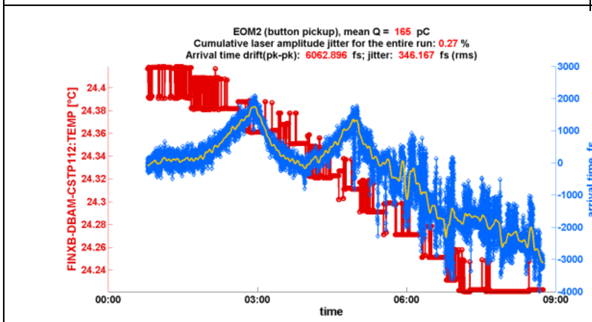
Correlation with laser spot size



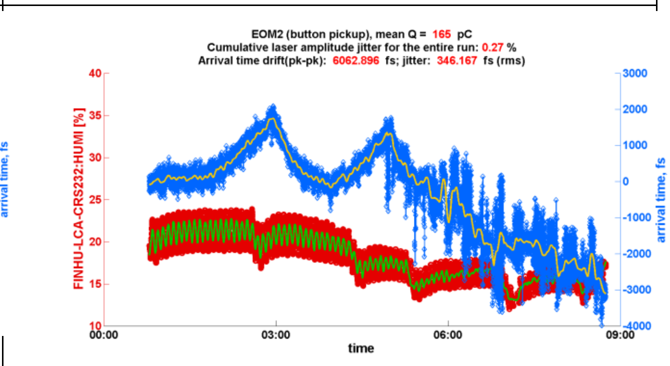
Correlation with tunnel humidity



Correlation with air pressure



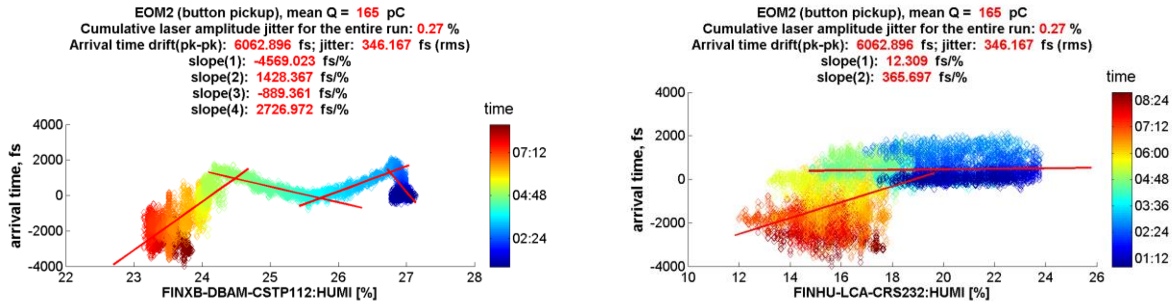
Correlation with tunnel temperature



Correlation with humidity in laser hutch

Figure 25: Drift of BAM without a zero crossing feedback.

Looking at the curves in Fig. 25, we see the following. During the first 6 hours there is a strong correlation of the drift with the charge. This correlation is also evident with the spot size of the gun laser on the cathode. The gun laser profile is not homogeneous. This irregularity drifts with time, leading to charge variations, which are detected with BAM. The drift during these first 6 hours is 3 ps, but has a very complex structure resembling the letter “M”. For example the turning points of this structure correlate with the humidity in the laser hutch, which although regulated, has peculiar jumps, detected also with BAM. The humidity in the tunnel is not regulated. There is a correlation between it and the drift during the last 3 hours of the measurement. The tunnel humidity changes during that time with 2%, which would lead to 1.2 ps fibre drift (non-stabilized fibres). The measured arrival time drift during that time is 6 ps, which means, that there are also other influences, beyond the fibre drift. A candidate would be for example the air pressure, which can affect the gun laser, but not the fibre-based optical reference system.



Correlation with the humidity in the tunnel | *Correlation with the humidity in the laser hutch*

Figure 26: Humidity correlation of the drift measurement with BAM without a zero crossing feedback.

Fig. 26 gives an idea of the drift of the monitor versus time (colour coded in the scatter plot) and humidity, that in the tunnel on the left and that in the laser hutch on the right. As mentioned before the theoretical humidity drift of the optical fibres of this particular BAM without active link stabilization should be approximately 600 fs/%RH_tunnel and 150 fs/%RH_laser hutch. The measured drift of 1430 fs, slope 2 between 03:00 and 03:40 o'clock, and -890 fs, slope 3 between 03:40 and 04:50 o'clock can be explained with drift of the fibres in the tunnel. But in the measurement, the humidity in the tunnel during that time interval does not change sign, whereas the arrival time-humidity correlation does. In other sections of the correlation curve, the measured drift is beyond the theoretical fibre drift. Therefore it is difficult to draw a definite conclusion where many different factors influence the drift simultaneously. Furthermore in the other sections of the correlation curve, the measured drift is beyond the expected fibre drift.

Similar effects can be seen in the correlation with the laser hutch humidity. There are two slopes: the first one between 00:30 and 04:45 o'clock is 12 fs/%RH and is far below the expected 150 fs/%RH. The second one is 365 fs/RH and can incorporate drift of the fibres. It is interesting to observe, that the time dependence of both the humidity in the laser hutch and the arrival time as in Figure 25 has the same complex structure, marking the turning points in the shape, but it is not repeated in the corresponding correlation curve in Fig. 26. This indicates that this peculiar shape is not due to a fibre drift, but due to the drift of another component, probably somewhere in the gun laser chain.

At the moment, it is yet too early to draw definite conclusions, more measurement data needs to be collected.

Drift measurements with zero crossing feedback

In order to keep the BAM acquisition on the pickup slope a zero crossing feedback is necessary. This feedback is done with the linear delay stage with high resolution encoder in the opto-mechanical front end (Section 4.2).

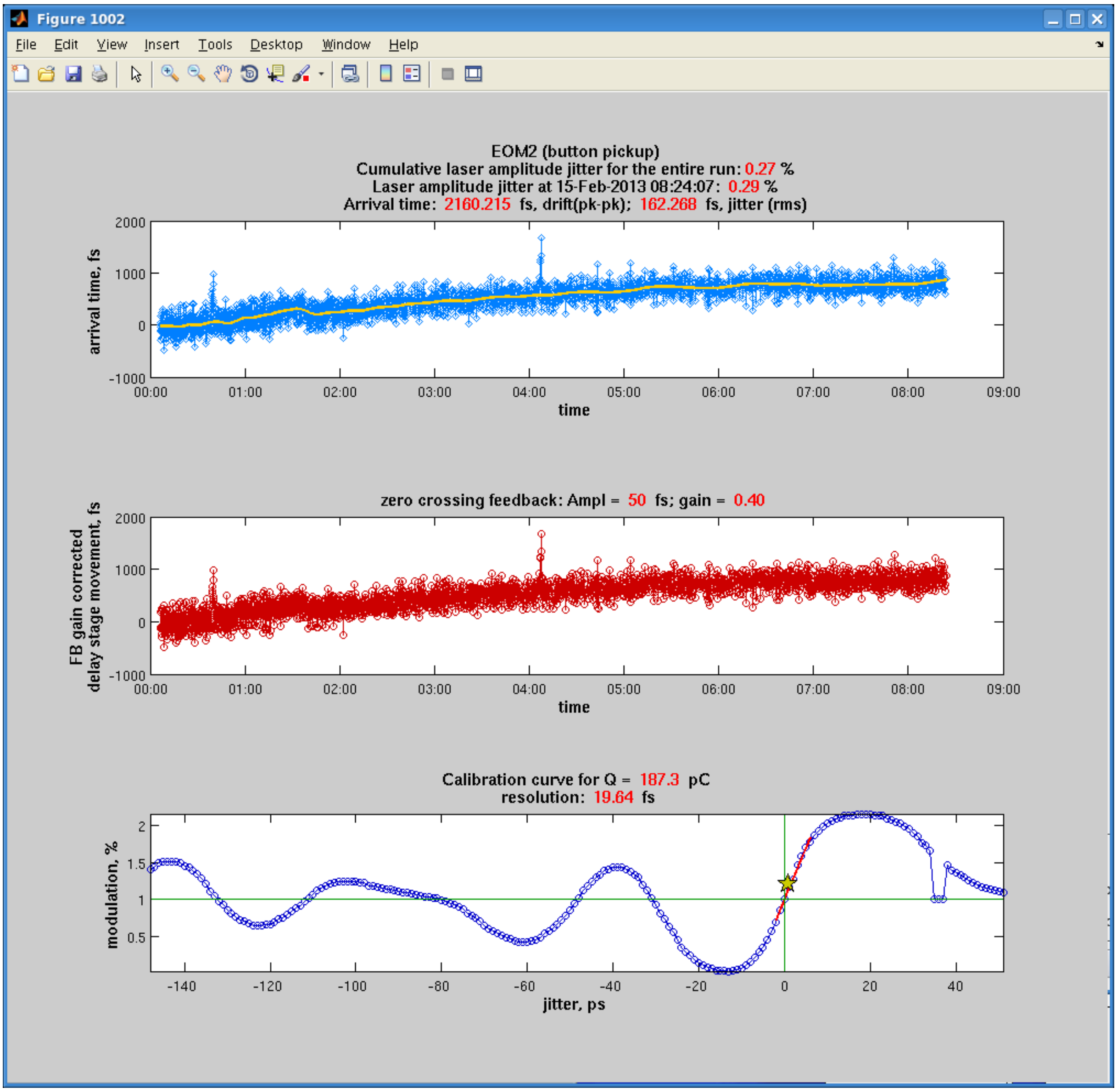


Figure 27: BAM acquisition panel

Presently the control panel for the bunch arrival time monitor is based on Matlab. After a fine scan of the laser pulse across the pickup signal with a vector modulator, the resolution and the calibration constant for the acquisition are determined. The resolution is determined by the instantaneous laser amplitude jitter of the non-modulated laser pulses and the slope of the modulation curve. The BAM server displays the arrival time in three ways (Fig. 27). The upper curve shows the time dependence of the arrival time, measured from the modulated laser pulse. The middle one shows the arrival time, derived from the delay stage used for the zero crossing feedback. When all parameters are taken into account, the displayed arrival time on both figures is the same. The lower curve displays the modulation slope, obtained by scanning the laser pulse across the pickup signal with a vector modulator. The time axis is rescaled, so that its origin is in the pickup zero crossing. The instantaneous arrival time is marked with a star, which moves across the modulation slope shot to shot. The positions of the arrival time, swept during the acquisition, are marked with a red line. Using such a display the operator is always sure, that the acquisition stays on the modulation slope. Further useful information is also displayed, such as the rms jitter and peak-peak drift over the entire acquisition, the instantaneous and cumulative MLO amplitude jitter, the feedback parameters (amplitude and gain) and the acquisition resolution. The feedback parameters can be changed on the fly during acquisition. The drift acquisition is archived every few hundred shots, or can stop automatically at a predefined time.

7. OUTLOOK

As planned for EuCARD, we have developed and built a prototype system for the measurement of beam phases and arrival time, which, assuming the presence of the necessary infrastructure (optical master oscillator with its distribution system) should be suitable for use in a future CLIC machine.

PSI pursues a second stage of development to optimize the performance of this device further for SwissFEL, which is its in-house free electron laser project. The development follows two main directions:

- Increased measurement resolution: Here the main limitation comes from the limited bandwidth of pickup and electro optical modulators. For EOMs, components with a larger bandwidth of 40 GHz are on the market and will be tested in the future. The ridged waveguide (RWG) pickup has shown an inferior performance compared to the button version, its development will be terminated. For the button pickup, the bottle neck is given by the vacuum feed-through used, which are only specified up to 20 GHz. We are trying to address this with a custom developed feed-through, which should accommodate frequencies up to 40 GHz. Simultaneously, we would like to address the problem of the ringing in the pulse response of the pickup, which in our opinion is due to the layout of the current feed-throughs.
- Integrate the monitor with the overall machine system; minimize (especially long term) drifts and jitters. In that respect, we plan to include the system into a beam based feedback system to stabilize the overall machine performance at the PSI injector, as well as later on in the SwissFEL facility.

8. PUBLICATIONS

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[2] F. Loehl, Optical Synchronization of a Free-Electron Laser with Femtosecond Precision, DESY-FLA, DESY-THESIS-2009-031, März 2009, 185pp, TESLA-FEL 2009-08

[3] V. Arsov, S. Hunziker, M. Kaiser, V. Schlott, F. Loehl, Optical Synchronization of the SwissFEL 250 MEV Test Injector Gun Laser with the Optical Master Oscillator, TUPA21, Proc. 33rd International Free Electron Laser Conference, Aug. 22-26 2011, Shanghai, China

[4] S. Hunziker, *Requirement specification for optical master oscillator amplifier and splitter*, FEL-HS84-058-1, internal note

[5] B. Keil et al., *A generic BPM electronics platform for European XFEL, SWISSFEL and SLS*, MOCB02, Proc. International Beam Instrumentation Conference IBIC 2012, Oct. 1-4 2012, Tsukuba, Japan

9. ANNEX: GLOSSARY

Acronym	**Definition**
ADC	Analog to digital converter
BAM	Beam Arrival Time Monitor
EDFA	Erbium doped fibre amplifier
EOM	Electro-optical Monitor
FRM	Faraday rotating mirror
FROG	Frequency resolved optical gating
MLO	Master laser oscillator
PLO	Phase-locked oscillator
PPKTP	Periodically poled potassium titanyl phosphate
PRX	Photo-receiver
RWG	Ridged waveguide
SMF	Single-mode fibre