ALL-OPTICAL FEMTOSECOND TIMING SYSTEM FOR THE FERMI@ELETTRA FEL

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Abstract

FERMI@Elettra, a 4th generation light source under commissioning at Sincrotrone Trieste, Italy, is the first FEL facility to use an all-optical system for femtosecond timing and synchronization over the entire facility ranging from the photo-injector, linac, FEL and beam-line end stations. The system is a unique combination of state-of-the-art femtosecond timing distribution systems based on pulsed and CW stabilized optical fibre links. We describe the details of this unique system and present the performance to date.

INTRODUCTION

FERMI@Elettra is the Italian fourth generation synchrotron light source [1] based on the seeded Free Electron Laser (FEL) scheme. The first branch line, named FEL1, is presently under commissioning [2,3] and significant milestones had been reached with the wavelength of the seeded FEL reaching down to 32nm at 100µJ of pulse energy.

One key system of the accelerator is the timing system, which includes the generation and distribution, with femtosecond accuracy, of the phase reference signal to all the time critical accelerator systems and of the machine trigger [4]. The measured typical phase noise of the phase reference signal, as delivered to the various end stations,, is <20fs_{RMS}.

The FERMI@Elettra timing system has been presented in detail last year at the Beam Instrumentation Workshop 2010, in Sante Fe [5]. In this paper, a review is presented on the design of the FERMI@Elettra timing system as well as recent results on the measured global longitudinal stability of FERMI@Elettra.

The FERMI@Elettra project started back in early 2002 with brainstorming discussions, internally to the Laboratory of Sincrotrone Trieste. The first internal Conceptual Design Report (CDR) has been produced at that time.

After a first analysis of the main characteristics of the new machine, it appeared evident that the implementation of this new machine would have called for several break-through if compared to the state of the art present at that time in our Laboratory. As a matter of fact, the timing system, i.e. the generation and distribution of a femtosecond level phase reference signal all over the facility, was included in the list of the needed break-throughs, since then.

So, we started the design of the new timing system with no legacy to existing already installed systems on site, from scratch.

GENESIS OF THE FERMI@ELETTRA HYBRID TIMING SYSTEM

After some initial studies and brainstorming sessions, including literature search, we got in touch with the FEL Community in the summer of 2004 when two main events took place. The *11th Beam Instrumentation Workshop* [6] took place in Knoxville (TN,USA) in May, 3-6. Later on, the *ICFA Future Light Sources Workshop on XFEL Short Bunch Measurement and Timing* has been organized at SLAC in July [7]. During those events we got familiar with femtosecond electron bunches and the associated longitudinal stability issues. Also, several results from “proof of principle” experiments were there presented, showing that handling and measurement of femtosecond bunches was possible indeed.

During those events in 2004, we also met Colleagues already active in the field we would have been soon starting several fruitful collaborations with. Among these, we would like to mention here: H, Schlarb and A. Winter from DESY, P. Krejcik from SLAC, J. Staples, R. Wilcox and J. M. Byrd from LBNL and O. Ilday who, by that time, was at MIT/RLE working in prof. F.X. Kaertner's group. Since then, we have been in regular contact with most of them for several years: without their competence and availability our final result could have been much different.

The above mentioned preliminary efforts and activities took the form of an executive project when the FERMI@Elettra *Technical Optimization Study* (TOS) started back in 2005. It was at that time that collaborations on timing, with LBNL [8] and MIT [9], were formalized. Together with the overseas colleagues we outlined possible solutions for the timing system of FERMI@Elettra.

Since the beginning, the two proposed systems, both demonstrating in the laboratory very good results, were competing for the final choice: the system developed by LBNL (*CW optical timing* in the following) and the one developed by RLE at MIT (*Pulsed optical timing*). Given the exceptional level of performance (jitter and drift well below 100fs) delivered by both systems, it would have been really difficult for us to made up our minds on which one to adopt. And, in fact, we did not as we went for an original approach, which we called the *hybrid timing*

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system. A new and original timing system, embedding both the *pulsed* and *continuous wave* optical timings for the phase reference distribution, has been conceived.

The rationale for this choice is based on technical considerations the first one being the extremely good level of performance of both systems. Secondly, some of the systems to be synchronized operated natively in a pulsed mode (lasers and diagnostics) whereas others operated in a CW or quasi-CW mode (mainly the Linac klystrons).

Finally, during the above mentioned *TOS*, the already developed and demonstrated (at the SNS) digital *Low Level Radio Frequency* (LLRF) system by LBNL appeared to be one viable option to stabilize the FERMI@Elettra klystrons. During its optimization for FERMI@Elettra, the LLRF system has been more and more deeply embedded to the LBNL CW optical timing distribution system.

A part from purely technical issues, keeping on board the FERMI@Elettra timing team both the MIT and LBNL Colleagues, significantly improved our overall efficiency, in terms of the system development time, providing in the end to the FERMI@Elettra timing system a superior flexibility and redundancy. W have installed today almost two parallel systems, as we have two parallel back-bone networks for the phase reference, which any system could in principle be switched to.

Finally, also a European expert group on femto-second timing systems grew during the FP6 EUROFEL Design Study [10], coordinated by DESY. In this joint effort, 16 European organisations developed a deep knowledge in some of the key technologies required for the design and construction of next free electron laser sources.

WHY OPTIC?

The main reason for going optical i.e. using optical components and cables for signal transmission originates from the superior performances of optical devices used for the transmission of the phase reference signals and for the stabilization of the links rather than a superior stability of optical cable. Optical cables do provide superior electro-magnetic noise immunity that has to be traded off with poorer radiation hardness, which is not an issue on low average power machines like FERMI is.

Going optic also opened up to the designers the availability of high reliability components from the optical communication market. Actually, optical communications are one application area where ultra-high speed (> tens of THz) electronics and optics merged so effectively.

The optical communication media, i.e. fibre optics (*FO*) plays another key role in their successful deployment to our Community, mainly due to their high density (channel per mm^2) and, as said, intrinsic superior EM noise performance.

The only remaining still critical issue of FO deployed to accelerators, i.e. the limited radiation hardness, has been addressed in our application and it can be if not solved at least mitigated, either with the adoption of radiation-hard fibres (only in radiation intensive environment) or with careful FO layout (out of direct radiation line-of-sight) or with successive FO cables substitution, which can be easily implemented with the so called *blown fibres cabling system* which has been adopted for FERMI@Elettra.

At the time of the design of the FERMI@Elettra timing system, it was not obvious that using only optic cables for the routing of the signals throughout the facility would have been the best solution to go. During topical workshops we have arranged in the past few years at Elettra with the active collaboration of many Colleagues, more conservative approaches have been proposed as well, where back-up coaxial cables should have been laid down, just in case.

The installation of the different sub-systems and components of the timing system followed the main FERMI@Elettra installation plan and so we could accommodate for some delays in the construction and installation of the FERMI timing system. To say that when back in summer 2009, the commissioning of the FERMI@Elettra photo-injector started, we were synchronizing the Photo injector and its laser plus few Linac sections also using some COTS components [5]. These proved to be very reliable, providing very good performances; on few non critical klystrons these are still in operation.

As mentioned earlier and after a suggestion from a Desy colleague, we adopted the so called *blown-fibre* cabling system [5], which proved to really meet the specifications in terms of optical properties, cabling time and density of channels/mm^2, leading to a redundant number of installed optical links per end station.

THE FERMI TIMING SYSTEM SPECIFICATIONS

The basic idea behind the FERMI@Elettra timing system is to deploy all the demonstrated state of art technologies, available at the moment we started our effort, for the generation and the distribution of an ultra-stable phase reference signal over stabilized optical lines to meet the specifications, while keeping it as simple as it could be.

It is worth noting here how a timing system like the one we are dealing with in this paper is not an absolute clock system (no GPS need nor atomic clock), which by the way will work perfectly well. It is not an absolute stability we need for this application; we just need an ultra stable relative timing system with a typical and the stability is observed in microseconds time windows every N millisecond, N depending on the machine repetition rate. Currently FERMI@Elettra operates at 10Hz and N is equal to 100ms. An upgrade to 50Hz is scheduled for next year and N will become 20ms. Talking about repetition rates we need also to mention the so called *time structure* of the beam. FERMI@Elettra is a pure single bunch accelerator (one single bunch every N ms), pretty much the same as the LCLS. At DESY (FLASH, X-FEL) they are typically operating with bunch trains (with a

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separation of each micro bunch down to 200ns for the XFEL) at different repetition rate within the macro period of ms. This "multi bunch" operation mode poses different requirements on the timing system too.

Global Choices

Given the above mentioned criteria, the most obvious choice was to generate and distribute as *ultra-low phase noise signal* directly the S-band accelerating structure frequency (f_{RF}=2,998.010MHz) and to set the repetition rate of the various lasers to a sub-multiple values of f_{RF}, namely 78.895MHz for the photo injector and seed lasers (i.e. $f_{RF}/38$) and 157.790MHz for the *Optical Master Oscillator*. The phase noise of this reference signal has to be lower than $10fs_{RMS}$ in the 100Hz-10MHz frequency offset range (see later paragraph on this topic).

Timing System Layout

All the critical equipments of the FERMI@Elettra timing system are housed in the timing hutch, a temperature controlled (24±0.3°C) laboratory located adjacent to the accelerator tunnel and next door to the photo-injector laser hutch. Thanks to the outstanding performance of our optical stabilized links and to the good (24±0.5°C) overall temperature stability of the FERMI@Elettra facility, we can stably feed the phase reference signal to the far most end stations of FERMI@Elettra, i.e. the *seed laser hutch*, the in-tunnel *Bunch Arrival Monitor* located at FEL1 entrance and the *user laser hutch* (d≅300m). These are exactly the end stations with most stringent requirements in terms of jitter and drift (≈10fsRMS). So, it would have make more sense to locate the timing hutch close to the end of machine tunnel, rather feeding the photo-injector laser with a long link. But system installation progressed with the civil construction work and the photo-injector area has been released for occupancy almost one year in advance compared to the user hall.

From the timing hutch, we distribute the phase reference to all the end stations by means of bundle of blown fibres. Each end station receives either 4 or 8 fibres in a single bundle of which, by design, we use two as a maximum which accounts for our flexibility basically at no extra cost except for the optical connectors which for some fibres will be installed at a later stage.

It is worth mentioning here that the trigger signals are distributed with the Event System [11] over a dedicated fibre network.

Optical Switchboard

In summary, pretty much the like in the 40's years of the previous century, the telephone centrals relied on the *telephone switchboard*, the FERMI@Elettra timing system benefits from an *optical switchboard* were in principle any optical signal can be routed to any end station in minutes. This feature greatly expands the flexibility of our timing system as we can both deliver new signals to new end stations as well as set-up back up solutions in a very short time.

Phase Noise Issues

In our effort of defining the specification for the FERMI@Elettra timing system, our first exercise was defining what, or how much, is it *ultra-low* phase noise. At the beginning we defined the phase noise too stringently; let's see why. While our colleagues from the physics group were performing the global machine sensitivity studies coming up with numbers for the allowed jitter budget for the different machine systems (S-band & X-band plants and lasers), we deepened our knowledge about jitter being not so familiar with the femtoseconds and the associated measurements techniques.

A very powerful instrument, called *Signal Source Analyzer* (SSA) was available at that time by Agilent and so we got one. In order to reach the femstosecond ranges this instrument measures the phase noise in the frequency domain with a very low noise floor. Actually, the SSA measures the amplitude of the sidebands at a given offset frequency from the carrier frequency and presents the data in a typical curve. Then, by applying the definition of phase noise integral, the SSA computes how much total RMS time jitter is present on the given carrier ($f_{CARRIER}$ = *3GHz* in our case), displaying also the whole phase noise curve. Last, but not least: to compute the integral of the phase noise components offset from the carrier, the user needs to define for the SSA the integration interval, say *10Hz to 10MHz*.

Let's focus ourselves for a while on what this interval means from the physical point of view. Using the number of our example, it indicates that over the frequency offset spectrum of interest (10Hz to 10MHz) the 3GHz carrier (period of τ=330ps) has several phase noise components whose amplitude is typically lower than 100dB than the carrier itself. The SSA also tells us how fast these phase noise are, i.e. for a phase noise component in the spectrum at 20Hz offset, its period is 50msec.

In practical terms, rather than looking only at the absolute value of the phase noise integral, we need to compare the starting frequency of the integration interval to the *time-of-flight* of our machine, i.e. the time window over which we do really need the femtosecond stability, to see whether that phase noise components could spoil the stability in the glimpse of the time-of-flight. For FERMI@Elettra, the time-of-flight (time interval from the electron bunch generation on the photo-cathode surface to the FEL light pulse hitting the sample) is roughly 1μs being the machine 300m long.

Based on the above considerations, we restricted the phase noise measurement interval in the specifications from the original: *10Hz to 10MHz* to the current *100Hz to 10MHz*. This choice had a significant impact on the Reference Master Oscillator we adopted, budget wise

Just as a numerical example considering, on a 3GHz carrier signal, a 100Hz phase noise component with significant amplitude at -80dBc, will reach a maximum peak deviation of 5.39fs after 2.5ms (at π/2), but 2μs later (i.e. after one time-of-flight) the amplitude is 0.00667fs, if

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computed from the maximum rate of change point (zero crossing).

THE FERMI@ELETTRA TIMING SYSTEM

As mentioned in the Introduction, the FERMI@Elettra timing system has been presented in detail elsewhere [3] so here we briefly report its basic features. In Fig. 1, a schematic block diagram of the FERMI@Elettra timing system is presented with its main components indicated. The upper dashed box in Fig. 1 represents the timing hutch where all the generator and transmitters are located.

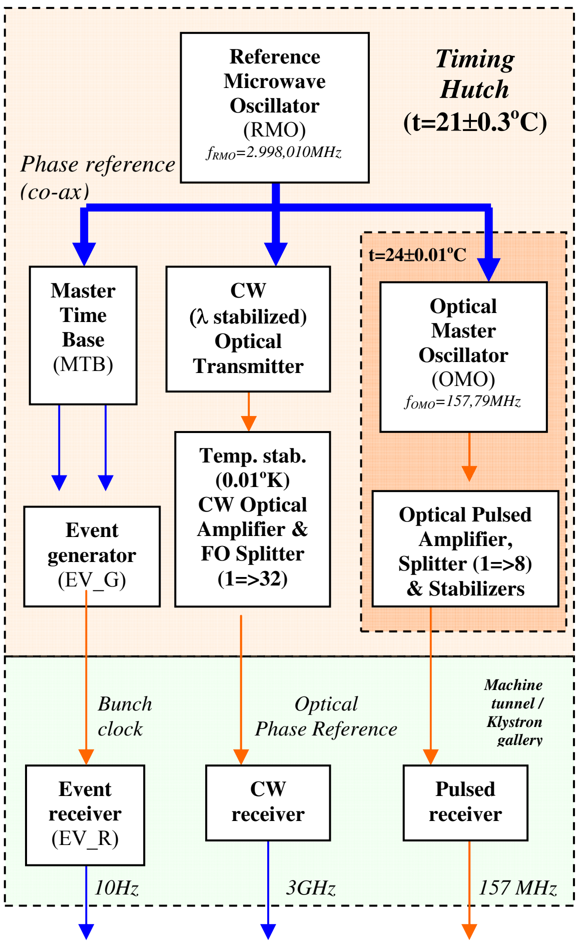

Figure 1: Basic block diagram of the FERMI@Elettra timing system. Blu lines indicate coaxial cables; orange lines, optical fibres. Temperature stability of the timing hutch and of individual systems is stabilized to 0.01°C.

The main systems indicated in Fig. 1 and located in the timing hutch are:

- the reference microwave oscillator (**RMO**)
- the pulsed optical master oscillator (**OMO**)
- the pulsed optical amplifier and splitter
- the pulsed links stabilization system
- the CW phase reference sender
- the master time base (**MTB**)
- the Event generator (**EVG**)
- the patch panels of the fibre cabling

The timing system started to operate in July 2009, for the 1st commissioning period of FERMI@elettra and it going to be completed by 2011.

The Reference Microwave Oscillator

The reference micro-wave oscillator [12] is a 3GHz oscillator (f_{RMO}=2,998010GHz) is in operation since 2009 and underwent several upgrades [13] to improve its reliability rather than the phase noise which was very low since the beginning. Currently, the phase noise level is 7.8fs_{RMS} [100Hz-10MHz].

The core of the timing system is the phase reference system (presented in the following) that distributes the phase information with fs accuracy.

Ancillary Systems

Besides the phase reference systems, there are some ancillary systems which have been described in [5]. Among these, there is the master time base (MTB) which generates the bunch clock (1, 5, 10 and 50Hz) and the laser coincidence clock at 78MHz. These signals are distributed to the end stations by means of the Event system on dedicated fibre optical cables.

Then, as said earlier, we have developed in-house a CW phase reference system (both transmit and receive units) by using a COTS DFB laser TX/RX pairs to transmit over FO an optical carrier amplitude modulated by the RMO signal at 3GHz. These units proved to be very important at the early days of commissioning and they are still in operation on some klystrons, till the end of 2011.

PHASE REFERENCE SYSTEMS

In a Linac-based FEL facility like FERMI@Elettra, the systems needing a femto-second synchronization are:

- the Linac, the S-band klystrons (accelerating and deflecting) and X-band (longitudinal phase space linearizer);
- the lasers: photo-injector, seed and user's ones;
- the femto-second longitudinal diagnostics, like the Bunch Arrival Monitor (BAM) and the Electro Optical Sampling (EOS) station;

The phase reference generation and distribution systems provide to the end-stations the phase reference with femto-second jitter and drift.

It is worth mentioning here how the allowed amount of phase noise differs for the above cited systems; for FERMI@Elettra according the jitter sensitivity studies, the values range from the <70fs_{RMS} of the Linac accelerating voltage to the <15fs_{RMS} of the seed and user lasers; same applies for the drift (8h.).

As presented above for the distribution of the phase reference the FERMI@Elettra timing system relies on both the CW optical phase reference system by LBNL and the pulsed one, developed and demonstrated by MIT/DESY.

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The Pulsed Optical Phase Reference System

The pulsed optical timing system is represented in Fig. 2; it has been specifically engineered for FERMI@Elettra by MENLO Systems Gmbh [14].

The optical master oscillator (**OMO**) is a *soliton* fibre laser [5] working at a repetition rate of 157.790MHz (S-band÷19). For its femtosecond phase locking to the phase reference signal the innovative *Balanced Optical Micro-wave-Phase Detector* (**BOM-PD**), designed by the group at MIT [15], has been adopted.

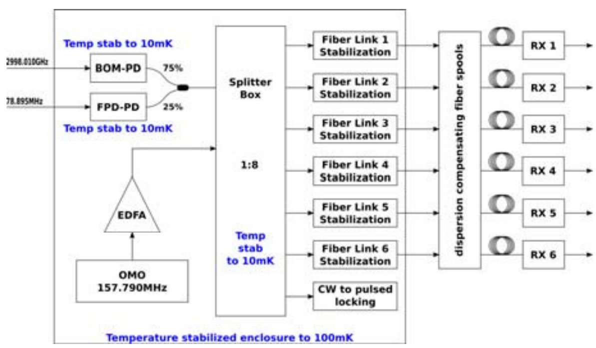

Figure 2: Pulsed optical timing system; the components, inside the box on the left, are temperature stabilized, down to 0.01°K.

The path between the OMO and each FLS is entirely in fibre; the dispersion compensation assures the shortest pulses in front of the link cross-correlators.

The path length variations are actively compensated by the combined action of a piezo-mirror, on the short time scale, and a motorized translation stage, for the drifts.

At the remote end of the stabilized link there is the receiver with a link amplifier to overcome the losses in the link and a 10% reflecting *Faraday Rotator Mirror*. The link stabilization is performed up to this point, resulting in a highly flexibility and compact solution.

The measured performances of the pulsed optical timing system are well within the specifications of FERMI@Elettra. The phase noise of the OMO, locked to the RMO by means of the BOM-PD, is as low as 11.6fs$_{RMS}$ [100Hz-10MHz] whereas the long term (2weeks) drift of one stabilized link relative to a local pulsed phase reference has been measured to be well below 10fs, namely 5.3fs$_{RMS}$.

The Continuous Wave (CW) Phase Reference

The relative time stability of the different RF plants of the Linac is a key element to the overall stability of the accelerator i.e. to the quality (energy spread) of the electron beam. Such a relative stability is achieved by adopting one digital LLRF controller per Klystron (15 in total), all sharing an ultra stable phase reference signal.

The digital LLRF system, developed at LBNL [16] has been adopted for FERMI@Elettra. In this system, the distribution of the phase reference is accomplished by means of CW optical links [17] where the phase reference signal is encoded onto an optical carrier. Peculiar to this design, a novel concept has been adopted where the drift of the link is measured with fs accuracy, but is not compensated for. Rather, the measured drift value is periodically added as a digital delay in the LLRF loop. By doing so, any moving part has been omitted for improved reliability.

Currently, nine klystrons are fitted with the full CW optical timing system with a 32 channel sender unit feeding the links and nine individual Sync Head / Link stabilizer pairs to drive local LLRF controllers.

The completion of the whole Linac klystrons, including the 12GHz X-band plant, is scheduled in 2011.

BUNCH ARRIVAL MONITOR

In order to verify quantitatively the performances of the timing system and, ultimately, of the whole accelerator (LLRF and lasers synchronization plus overall stability) we make use of the Bunch Arrival Monitors (BAM) stations which we have installed on the Linac. According to the formula below presenting the various contributions to the bunch jitter, downstream a bunch compressor

$$\sqrt{\langle\Delta t^2\rangle} \approx \frac{R_{56}}{c}\sqrt{\left(\frac{\partial\delta}{\partial V}\bigg|_{\phi=\phi_0}\right)^2\langle\Delta V^2\rangle + \left(\frac{\partial\delta}{\partial\phi}\bigg|_{V=V_0}\right)^2\langle\Delta\phi^2\rangle + \frac{\langle\Delta B^2\rangle}{B_0^2} + \frac{\langle\Delta t_{in}^2\rangle}{C^2}}$$

where

$\sqrt{\langle\Delta V^2\rangle}$: RF voltage jitter in Linac 1

$\sqrt{\langle\Delta\phi^2\rangle}$: RF phase jitter in Linac 1

$\sqrt{\langle\Delta B^2\rangle}$: dipole power supply jitter

$\sqrt{\langle\Delta t_{in}^2\rangle}$: initial time jitter (from photoinjector

the dominant factors are the jitter of the photo-injector (reduced though by the compression factor) and the phase jitter of the RF plant creating the longitudinal energy correlation within the bunch itself. Therefore in our measurements we used the BAM station located downstream of BC1.

The BAM developed for FERMI@Elettra is based on the original idea of the DESY advanced diagnostics group [19]. We think that this diagnostic is one of the most brilliant use of the optical pulsed timing as it is making direct use of the stabilized optical pulses to sample the bunch arrival time.

At first, a prototype BAM system has been designed, assembled and tested with beam [20] on the laser heater location (up stream of BC1). These tests clearly demonstrated both BAM idea potentiality as well as some critical issues.

A further optimization work, leading to a continuous performance improvement, has been performed during the final installation of the BAM station at Bunch Compressor 1 (BC1 BAM) by Leon Pavlovic and Fabio Rossi.

Leon carried out a successful design review of the back-end unit with particular emphasis on the mitigation of the electro-magnetic noise issues, both irradiated and conducted, rather severe in our Linac environment.

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Fabio, being in charge of the optical timing systems, provided in tunnel the optical stabilized pulses to the front–end unit of sufficient amplitude for the Mach Zenhder modulator to operate correctly.

To operate the BAM on the real beam a coarse and fine time alignment of the electron bunch signal, obtained from the BAM pick-up, to the nearest optical pulse from the stabilized link is needed.

To perform the coarse time alignment Leon designed and built the "spaghetti box". It is a remotely controlled coaxial delay unit implementing a maximum delay equal to the time separation of the OMO laser pulses i.e. 12ns in steps of 600ps. This delay unit has been installed in the tunnel, directly on the pick-up signal cable. The name originates from its appearance (see Fig. 3) and from the fact that FERMI@Elettra is located in Italy.

Figure 3: The programmable coaxial delay unit, nicknamed "spaghetti box", as it appears once the box is open; the origin of its name is quite obvious, at least in Italy.

Once inserted the spaghetti box on the BAM pick-up signal path to the BAM Front-end, the time alignment was found with a reasonable effort. Then by using the optical delay line (600ps long) fitted to the front-end unit the fine alignment has been performed. The same optical delay line is also routinely used for the on-line calibration of the BAM slope (see Fig. 4) and to centre the optical pulse on the zero crossing of the slope the BAM pick/up signal.

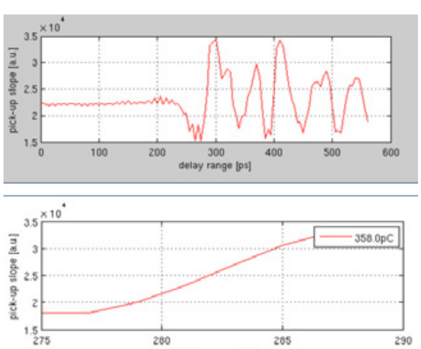

Figure 4: (Top) The BAM pick-up signal sampled by scanning the OMO pulse over it, with the optical delay line (±300ps) fitted to the BAM Front-end. Bottom: the steep slope used for the calibration, assures a ±5ps linear window around the zero crossing, resulting in about 1200 counts /ps.

As evident from the formula reported above, the BAM pick-up signal, generated by the electron bunch, carries out the information on the time jitter and drift of the photo-injector and of the upstream Linac plants, particularly the ones of klystron K3, used to create the energy dependence in the bunch. The BAM pick-up signal amplitude modulates the OMO optical pulses, in the BAM Mach-Zehnder modulator, distributed to the BAM end-station, carrying the total time jitter and drift of the pulsed optical timing (OMO, OMO locking, splitter and stabilized link).

Therefore by comparing at the BAM station the relative time position of these two physical events with adequate resolution (<10fs$_{RMS}$ is our BAM system measured resolution) we were able to quantify the global FERMI stability from the photo/injector to downstream the first bunch compressor. Typical values are <80fs as long term average value over hundreds of Linac shots which are well within the FERMI specifications.

In Fig. 5 below, a 10 minutes continuous acquisition from the BAM station located downstream of BC1 is shown. The average value of arrival times is 74fs.

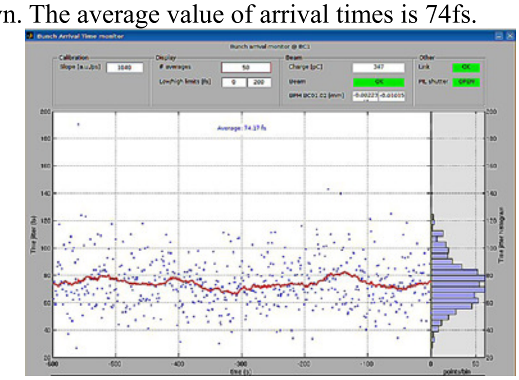

Figure 5: A 10 minutes continuous acquisition from the BAM station located downstream of BC1; each dot represents the rms value from 10 single shot acquisitions. The average value is 74fs.

Another BAM measurement taken at BAM BC1 station is shown in Fig. 6, where two simultaneous acquisitions are shown.

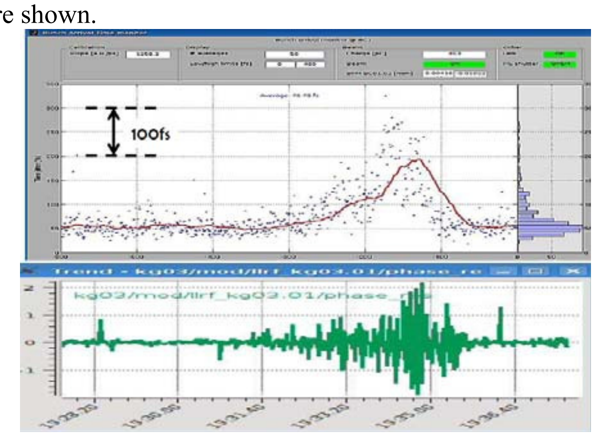

Figure 6: (Top) BC1 BAM acquisitions while klystron 3 phase was becoming temporarily instable (bottom). Total time window is roughly ten minutes.

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The lower plot shows the RF phase noise in klystron3 which become temporarily rather instable; the total time window in Fig. 6 is ten minutes. The upper plot shows the resulting increase in jitter due to the klystron 3 instability.

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