REVIEW OF STATE-OF-THE-ART DIAGNOSTIC PRESENTED AT BIW06 AND DIPAC07

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*The biennial **B**eam **I**nstrumentation **W**orkshop (BIW) and the also biennial Workshop on Beam **D**iagnostic and **I**nstrumentation for **P**article **Ac**celerators (DIPAC) are events for the exchange of the latest advances in the field of beam diagnostics and instrumentation to measure and analyse particle beams in all kinds of particle accelerators. This talk will review and summarize the main topics presented in 2006 and 2007 at these two major international workshops in this field. General instruments as well as very special topics will be discussed to give a comprehensive overview of state-of-the-art beam diagnostics around the world.*

I. INTRODUCTION

This talk will concentrate on those topics most frequently discussed during the two workshops. Obviously there were a lot more topics left out here. However, one can find all DIPAC presentations (and more) at the JACoW (**J**oint **A**ccelerator **Co**nference **W**ebsite; http://accelconf.web.cern.ch/accelconf). The selection of the following topics is my personal point of view and does not claim to be complete. The selection was driven by recent developments for new accelerator projects with their very special requirements on precise, reliable and fast instruments, but also by the wish to show real results of the discussed instruments. Measured results are important for the understanding of the potential of these devices. Therefore a detailed description of each instrument was left out but real measured numbers and results are given.

II. HIGH RESOLUTION BPM

Common to most of the planned or recently commissioned accelerators such as the new third generation synchrotron light sources (e.g. SOLEIL, DIAMOND, PETRAIII, ALBA, …), ultra-violet and X-ray free electron lasers (xFELs) (e.g. FLASH, LCLS, FERMI@ELETTRA, XFEL, …) and colliders (e.g. LHC, FAIR, SNS, ILC,…) is the need of reliable and high resolution Beam Position Monitors (BPMs). There are two main components, which defines the resolution of a BPM system: a) the Pickup and b) the processing chain of the signal. Ref. 1 gives an overview of different kinds of high resolution BPM Pickups at the DIPAC07. One of the most discussed types of BPM was the pillbox RF-cavity. Single shot resolutions of about 20 nm were reported. But note that most of these cavity-BPMs have a high Q-factor of some thousands at a resonance frequency of few GHz. That means that the cavity “rings” for about 1 µs before the signal decays and the next bunch may enter the cavity (Ref. 2, 3). However, Ref 4 reported already in 1998 a low Q (Q=130 at 5.7 GHz) cavity BPM with a resolution of 25 nm single shot which is capable of resolving high repetitive bunches up to about 10 MHz. R&D is still ongoing mainly for the next generation of linear accelerators such as xFELs and the International Linear Collider (ILC).

The other part of any BPM system is the electronic processing chain of a Pickup signal. Many aspects of this topic are discussed in a comprehensive tutorial of Ref. 5. Most of the new third generation synchrotron light sources now rely on a commercial digital readout system which provides high resolution as well as turn by turn output for fast orbit feedback. Orbit stabilization down to 20 nm rms at a bandwidth of < 10 Hz was reported in Ref. 6. At a higher bandwidth of 2 kHz the overall integrated noise (including beam movements) was about 1 µm. SOLEIL (Ref. 7) reported similar results with stabilized beams over 15h on a < 5 µm level, even with a large variation of beam currents by using the same commercial system. Some other Labs (ALBA, ESRF, PETRAIII, DELTA, …) had also reported results in view to use this or an upgraded version of the commercial system for an improved orbit stabilization in a sub-micron level.

III. RELIABILITY AND DAMAGE

The new high power or high brilliance beams in accelerators such as SNS, FAIR, XFEL, ILC or LHC have the power to seriously damage components of the accelerator. Even at running machines like TEVATRON, SPS or HERA the beam already had some serious impact on components (see Ref. 8). Therefore the new machines need to have a sufficient and reliable machine protection system in order to suppress serious damage and related long down times. An extreme situation will occur in the

LHC at top energy, where two 360 MJ beams have to pass collimator holes of about 9 mm^2. Ref. 9 gave a nice overview about the instrumentation challenges of this project. The beam loss monitor (BLM) system in particular is a crucial part of the LHC protection system with emphasis on reliability. The probability of damaging a magnet, the number of false alarms and the number of generated warnings has been derived with a fault tree analysis; the system failure rate and the availability have been evaluated using the Safety Integrity Level (SIL) approach. The probability of not detecting a dangerous beam loss was calculated to 10^{-3}, which corresponds to the SIL3 level. The analysis also includes the lifetime of the detector, which should be about 20 years as its exchange will be impossible in some locations due to high radiation levels. The expected radiation dose at some locations is several ten MGy per year. Beside redundant positioning of BLMs (3700 pieces) the whole digital signal chain of each BLM is doubled in order to increase their reliability, incorporating error-correction and –detection techniques and continuously monitoring the proper function of the BLMs. Subsequent studies and detailed analyses suggest the use of more reliable components, of redundancies in the system and of defined testing procedures where the reliability goals are only achievable with frequent testing procedures (Ref. 10).
This appears to be the first time in accelerator history that the reliability figures of a large system have been evaluated in such a detail. The use of a commercial software package (Isograph™) was noted to be most helpful.

IV. FEMTO-SECOND SYNCHRONIZATION

The operation of ultra-violet and X-ray free electron lasers (xFELs) require bunch arrival-time stability on the order of several tens of fsec between the X-ray pulses and laser pulses of external probe lasers, to take full advantage of the fsec-short X-ray pulses in pump-probe experiments. The following questions were pointed out in Ref. 11:

- What is the currently achievable signal jitter for a reference signal?
- How do we measure it and where does jitter in an FEL-based machine come from?
- How and to what level can we get rid of it?

In Ref. 12 it was pointed out that the 2005 Nobel Prize in Physics was awarded to John L. Hall and Theodor W. Hänsch "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique" (see Ref. 13). Ref. 12 claimed that this technology is *nearly* ready for application in the precision synchronization in accelerators. The precision of laser based optical atomic clocks is nowadays about 100 fsec / day (Ref. 13), and even an order of magnitude better on shorter time scales, which gives an idea of the achievable precision of the stability of a reference synchronization signal for accelerators.

The bunch arrival has to be measured in respect to such a synchronization signal to answer from where the jitter of the arrival time comes. But one can also measure the delay and sort it into slices to use this information for the pump-probe experiment results. Various interesting techniques were presented to determine the jitter-source along the accelerator. For this purpose a stabilized link has to be established to distribute the timing signal to the points of interest. A stability of 7.5 ± 1.8 fsec / 12 h with a drift of 25 fsec/12h was achieved by Ref. 14 for a 400 m long fiberlink loop while Ref. 12 reported a linear drift of 0.13 fsec/hour and a residual temperature drift of 1 fsec/deg C under laboratory conditions.

IV.A. Beam Measurements

In this section some beam measurements are discussed which achieved already sub-psec resolution just by using "standard" instruments, but with a clever setup of experimental conditions:

IV.A.I Bunch arrival time

A precise bunch arrival measurement in FLASH and its principal were reported in Ref. 15: A reference laser pulses traverse an electro-optical modulator which is driven by the signal of a beam pick-up. A change of the arrival time of the electron beam causes different modulation voltages at the modulator at the laser pulse arrival time. This leads to laser amplitude changes behind the modulator that are detected by a photo detector (see Fig. 1). With such a setup a single bunch jitter resolution of 30 fsec was achieved. A clear dependence of the arrival time from the beam energy was detected (≈ 1 psec/$2.0\cdot10^{-3}$ relative energy change) indicating one source of an arrival time jitter.

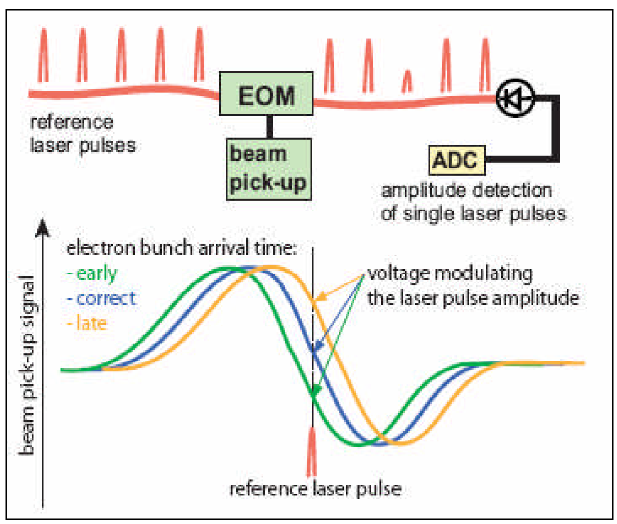

Fig. 1: Principle of the arrival time detection (from Ref. 15)

IV.A.II Energy Jitter

The energy jitter was measured at FLASH (Ref. 16) by using synchrotron radiation (SR) in the low energy bunch compressor at a high dispersion point. The horizontal profile of the bunch is imaged by a telescope onto a gated, intensified CCD camera. The energy distribution of the electron bunch with a residual energy spread of only a few keV shows a steep rising edge at high energies and a long low energy tail. This distribution is reflected in the horizontal profile as well (see Fig. 2).. Phase variations of the acceleration cavities change the tail distribution, while gradient variations of the acceleration cavities shift the entire profile (max. energy). To determine the energy stability, the offset value of a linear fit on the rising edge is used. Typically, an energy stability of $2.7\cdot10^{-4}$ is measured, where values as small as $1.5\cdot10^{-4}$ have been recorded. This corresponds to a bunch arrival jitter of about 140 fsec or 75 fsec, respectively using the formula given by Ref. 11 (first term only):

$$\Sigma_t^2 \approx \left(\frac{R_{56}}{c_0 \cdot A}\right)^2 + \left(\frac{C-1}{C}\right)^2 \left(\frac{\sigma_\phi}{c_0 k_{RF}}\right)^2 + \left(\frac{1}{C}\right)^2 \Sigma_{i,t}^2$$

Where Σ_1^2 is the arrival time jitter, R_{56}, A, k_{rf} and C are constants from machine settings, σ_A and σ_Φ are the amplitude and phase jitter and $\Sigma^2_{i,t}$ is the incoming time jitter. The first term (gradient) is about 5.5 ps/% at FLASH, the second term (phase) is about 2 ps/deg and the third term is about 0.05 ps/ps (incoming jitter).

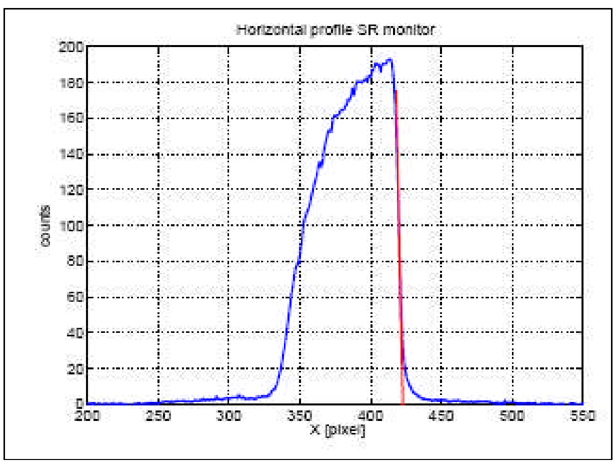

Fig. 2: Horizontal beam profile from the synchrotron monitor in the first magnetic chicane (from Ref. 17).

IV.A.III Phase Jitter

The phase jitter of an acceleration cavity RF is another source of arrival time jitter. For measuring it, an off-crest acceleration of the bunch is done to provide an energy chirp of the bunch. This leads to different compressions of the electron bunch in a magnetic chicane depending on the phase of the RF. The compression is monitored at FLASH (Ref. 17) using a diffraction radiator after the chicane and a pyroelectric sensor that records the emitted coherent Terahertz radiation power. The phase of the acceleration cavity was scanned to calibrate the compression monitor. The monitor signal varies strongly with the phase and the slope of the linear fit (1.44V/deg for the shown calibration) provides the calibration factor (see Fig. 3). The phase stability over 10 minutes was measured to 0.067^0 (≈ 134 fs). This value still includes beam injection jitter and the phase jitter of the RF gun, so the quoted value is an upper limit on the phase stability achieved by the low level RF regulation.

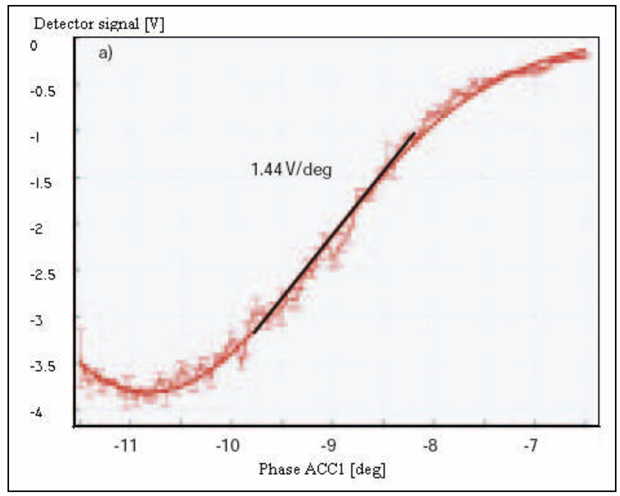

Fig. 3: Phase scan of acceleration module (from Ref. 17).

IV.A.IV RF Gun Phase Jitter

Another source of arrival time jitter was expected to come from the electron gun phase jitter. To measure the gun phase stability, a current transformer (toroid) for bunch charge measurements is used (Ref. 17). First, the gun phase of the RF cavity was scanned while recording the bunch charge. Operation of the gun phase close to the zero-crossing makes the charge-phase dependency strongest. The result of a scan shows a steep slope typically of 0.05 nC/deg (see Fig. 4). This provides a calibration and a direct measurement of the relative phase stability between the reference laser and the gun cavity. With a single shot toroid resolution of 2-3 pC/bunch, the phase jitter can be determined bunch-by-bunch with a precision of 0.05^0 (≈100 fs). The measured jitter of 0.064^0 (137 fs) still includes the photocathode laser arrival time jitter.

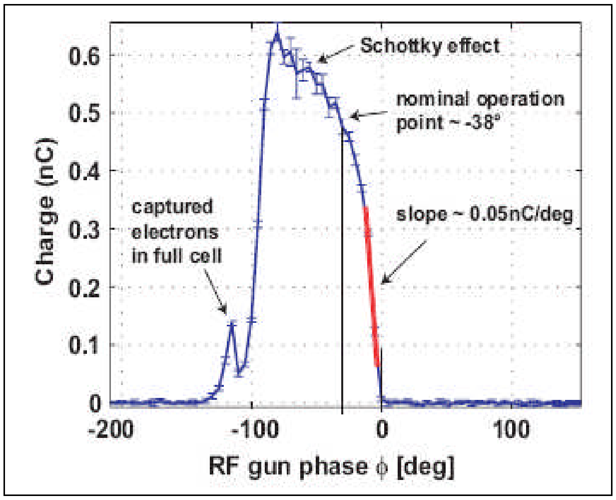

Fig. 4: Beam current versus gun phase (from Ref. 17)

V. SUB-PSEC BUNCH LENGTH MEASUREMENTS

Various techniques for bunch length measurements of compressed bunches of xFEL machines were presented at the workshops. Here are discussed three different types which had shown very impressive results.

V.A Transverse deflecting Cavity

The transverse deflecting cavity was originally used as a RF separator for secondary particles (1964, Ref. 18). It was named after its designers G. **Lo**ew, R. **L**arsen, O. **A**ltenmueller (LOLA). It has already been used for beam diagnostics at SLAC. This cavity is in operation in FLASH since 2005. It deflects the beam in vertical direction, while the RF phase of the structure is at zero-crossing when bunch is injected. The time varying deflection maps the longitudinal profile into the vertical coordinate and the appearing vertical distribution is readout by an imaging screen, like in a "normal" streak camera. The bunch image is taken from an off-axis OTR screen mounted 10m downstream of LOLA The filling time of the structure is sufficiently short that one bunch out of a macro-pulse with 1MHz bunch spacing can be measured. The resolution was determined to about 20 fsec, mainly limited by the beam size without RF-deflection. Since the screen also measures the horizontal beam size, this method enables for slice emittance determination just by measuring the horizontal slice widths. The emittance can then be measured either by a three screen method or by varying the quadrupole strength. By using a screen in a dispersive section with small β, the slice energy spread can also be measured (Ref. 19) (see Fig. 6 left). A resolution of ΔE=7.2 keV was achieved.

V.B Coherent Radiation Spectroscopy

Transition or synchrotron radiation is produced when the electron bunch passes a boundary of two media or a magnetic field. The shape of the radiation pulse is a "copy" of the electron bunch shape. When the bunch length is shorter than the observed wave length of the radiation the radiation becomes coherent. Its power is proportional to $N_{electrons}^2$. The measurement of the radiation spectrum gives information about the bunch length. The coherent spectrum can be obtained in a interferometer and its Fourier transform represents the particle distribution. The Michelson interferometer produces an interferogram of the radiation pulse which represents directly the autocorrelation of the particle distribution and thus the bunch length can then be derived immediately from the interferogram. Since there is no phase information, the pulse reconstruction may be carried out using the Kramers–Kronig analysis. A pyroelectric detector is the most convenient choice to use in the autocorrelation bunchlength measurement due to its small size and easy operation at room temperature. Measurements at JLab showed a resolution of about 130 fs rms (Ref 20).

The investigation of the longitudinal charge distribution in the electron bunches on a bunch-by-bunch basis is an important requirement for optimizing and improving the operation of the machine. This requires a single-shot device. A novel spectrometer was presented (Ref. 21) which permits the analysis of the radiation of single electron bunches in a broad spectral range and with high resolution (see Fig. 5). The new single-shot spectrometer uses diffraction gratings as dispersive elements and an array of pyroelectric detectors with multi-channel readout. The presented preliminary data was used to estimate the time profile of the bunches. Profiles with a leading peak in the bunch as short as 15 fsec were detected (Ref. 22).

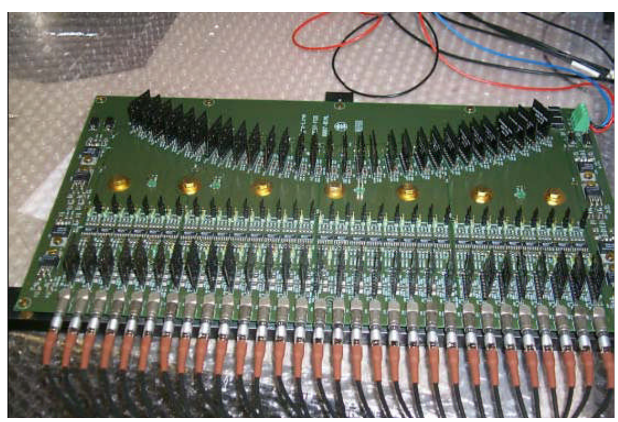
Fig. 5: Photo of the 30 channel pyro-line-detector of the single shot spectrometer (from Ref. 21).

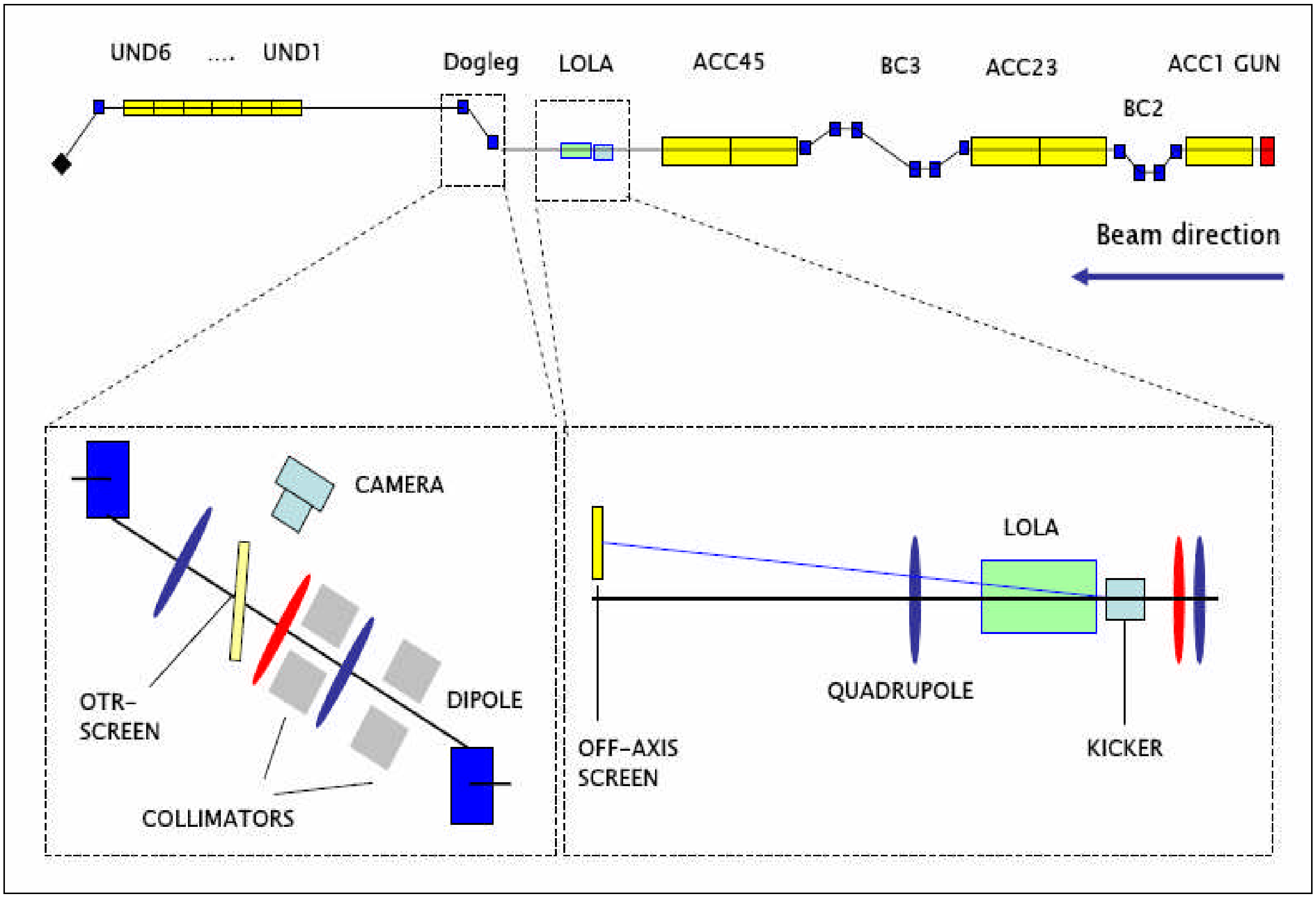

Fig. 6 bottom left: Slice energy spread measurement in a dispersive section of FLASH, Fig. 5 bottom right: Longitudinal profile and slice emittance measurement with an off-axis screen. Fig. 5 top: Schematic of the FLASH beam line (from Ref. 23).

V.C Electro Optical Sampling; Temporal Decoding

Another non-destructive single shot bunch length measurement technique using electro optical sampling was presented in Ref. 24. The longitudinal electric field profile of the electron bunch is obtained from the encoded optical pulse by a single shot cross correlation with a 35 fs laser pulse using a second harmonic crystal (temporal decoding).

The time structure of the electric field of the electron bunch (= longitudinal electric field profile) is encoded onto a chirped laser pulse by an electro optic crystal (ZnTe) which is located very close to the electron beam. In the electro-optic crystal a stretched laser pulse acquires a polarization proportional to the electric field of the passing electron bunch and therefore encodes its temporal structure. The polarization is then turned into an intensity modulation by an analyser. The intensity distribution is then sampled by a short laser pulse in a single-shot cross-correlator, using a second harmonic BBO crystal. A scheme of the setup is shown in Fig. 7 and the principle of the single shot cross correlator is shown in Fig. 8.

An electro-optical signal with 118 fsec FWHM (σ = 50 fsec) was observed (Ref. 24).

A comprehensive summary of the different methods for sub-psec bunch length measurements including more variations of electro optical sampling methods can be found in Ref. 25.

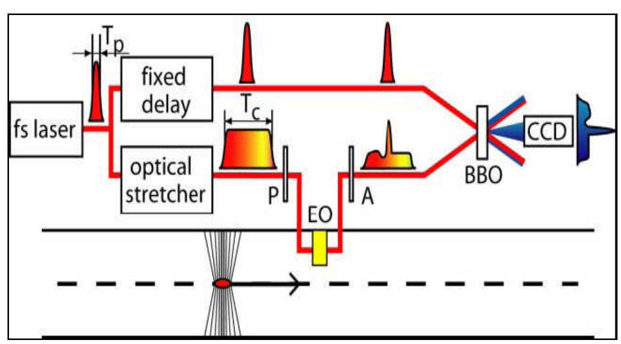

Fig. 7: Schematic setup of the single shot bunch length measurement technique using electro optical sampling (from Ref. 24).

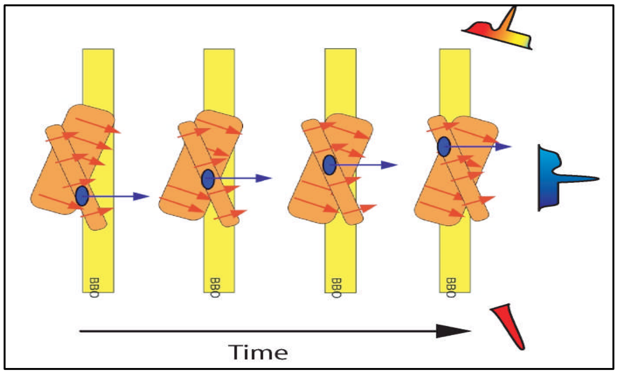

Fig. 8: Schematic of the single shot cross correlator (BBO) (from Ref. 26)

VI. CONCLUSIONS

A personal selection of state of the art beam diagnostic instruments presented at the last BIW06 and DIPAC07 was discussed. Topics presented here were high resolution BPMs (pickups and digital electronics), reliability issues of BLMs in view of potential damage of accelerator components, femto-second synchronization and jitter measurements and fsec bunch length measurements. The idea of this talk was to give a compressed overview over recent developments with the emphasis on measured results while details of the measurement, the instruments and techniques can be found in the adjacent references.

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