REVIEW OF STREAK CAMERAS FOR ACCELERATORS : FEATURES, APPLICATIONS AND RESULTS

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Abstract

In the last decade Streak Cameras have found an increasing number of applications in particle accelerators permitting both precise measurements and instructive visualisations of beam characteristics and behaviour that can not be obtained from other beam instrumentation.

These applications have been driven by both new developments and features of Streak Cameras, and by innovative methods in optical configurations and timing systems.

First a review of all the features of a Streak Camera system is presented, with focus on the dual axis functionality, the repetition rate and the detection sensitivity. Also the intrinsic limitations like the time resolution and synchronisation jitter will be discussed.

Then results obtained at a large number of accelerator institutes will be presented, covering both typical applications and more specific work of special interest.

1 FEATURES AND FUNCTIONALITY

1.1 Basic Concept

The input for the streak camera instrument is an ultra fast light signal (a pulse with picosecond structure). In accelerators this light source can be synchrotron light, optical transition radiation, FEL emitted light, or from lasers associated with the accelerator. The photon energy may cover the entire IR to hard X-rays spectrum.

Its output is a two-dimensional image containing pictures (streaks), their analysis (intensity profile) reveals the time structure of the input signal.

For the streak camera to work it needs a synchronisation or trigger signal for the High Voltage (HV) ramp that performs the conversion in the streak tube of the time domain input signal into spatial domain output signal. [1]

At the front end of the streak tube photons hitting the photo-cathode will cause back-side emission of photo-electrons. These are accelerated and focussed, generally by electric fields through a number of electrodes or plates, to a phosphor screen at the other end of the tube. The time structure of this photo-electron bunch is identical to that of the light impulse. A set of plates in the streak tube makes it possible to deflect this bunch. If the HV signal applied to these plates is a fast ramp, and well timed with the motion of the bunch through these plates, then the electrons in the head of this bunch will be deflected differently than those in the tail of the bunch. It can be easily shown that the profile of the spatial image (the ‘streak’), obtained from reading the phosphor screen with a CCD camera, represents the temporal profile of the light impulse.

1.2 Dual Sweep or Dual Time axis extension

The dual sweep axis is a very important extension to a basic streak tube functionality. It requires a second set of deflection plates oriented perpendicular to the plates used for the fast time-space conversion. [1]

Applying a ‘slow’ HV ramp deflection to these plates equips the streak camera with a dual time axis : In addition to the ultra fast sweep (typically 500ps full scale) there is now a ‘slow’ (typ. 100ns to 10ms) sweep at right angle. In the two-dimensional output image of the streak camera (read out by a CCD camera with say, 20ms integration time) these dual times axis are now very conveniently represented as horizontal (slow) and vertical (fast).

This dual time axis allows one to obtain numerous streak images in the same output image if the light input signal and its fast sweeping is repeated. If the slow time scale on the dual axis is well adapted to the repetition frequency then the individual streaks of consecutive light impulses will be staggered (horizontally) next to each other. This allows the visualisation and the measurement of the (slow) time evolution of characteristics of the ultra fast light signal such as duration, profile, and phase stability. [2-9, 15-17, 21-22, 24-32]

1.3 Synchroscan mode for High Repetition rates

In order to fully benefit from this dual time axis it is important that the fast sweeping can be repeated at a suitable frequency. For the needed HV deflection signal, that is correctly timed and stable in phase with the repetitive light impulses, two kinds of operation modes exist:

1) Synchroscan operation : The deflection signal is a sinusoidal HV of a high but fixed (pre-tuned) frequency somewhere in the 50-250MHz range. The needed electric trigger signal is in particle accelerators or storage rings generally obtained from the master source of the RF cavity, at the same frequency or at a sub-harmonic. The attainable phase stability (jitter) is good : 2ps or less. It can even be improved further by internal phase-locked loops, and the trigger signal can be optical (e.g. from a laser oscillator) through the use of special pin-diodes. The range of available sweep speeds and their linearity is somewhat limited but usually more then sufficient.

2) Repetitive Single Shot : Compared with the synchroscan mode the range of sweep speeds is larger and faster, their repetition rate is freely selectable but only up to a few KHz and generally the jitter is worse (>10ps).

1.4 Optical Configurations

For applications where only the longitudinal dimension (S, time) is of interest the input light beam is usually truncated transversely (i.e. pinhole or slit). However, with suitable arrangements in the input optics, the light source object's information in the two-transverse dimensions can be pre-served in the image focussed onto the photo-cathode. [2, 3, 8, 29]

A correct magnification of the source object, and possibly a re-orientation is needed to adapt the image spot to the size limitations of the camera's photo-cathode (usually in the order of 0.2 X 10mm). Further arrangements like the duplication and rotation of images, and timing delays in combination with the use of the dual time axis, make it possible to obtain measurements of all the three dimensions (X, Z, S) of numerous consecutive bunches in the same output image.

The so recorded individual 'streaks' in this output image can now reveal ultra-fast phenomena in the transverse size and position (both horizontally and vertically) and time structure of an electron bunch over a number of consecutive turns.

In this configuration the spatial domains will have a resolution limitation caused by the diffraction, generally very severe for visible light and the small transverse beam dimensions of most accelerators. The X-ray streak cameras do not suffer from this but the needed optical arrangements are obviously more complex. [9-13]

1.5 Limitations to performance characteristics

The tubes' intrinsic time resolution is mainly limited by two factors : the tube design (spatial resolution of the imaging quality, maximum sweep speed attainable) and the energy spread of emitted photo-electrons which causes time dispersion. The latter is dependant of the photo-cathode material and the strength of the electric accelerator field of the photo-cathode. [10, 13]

The mutual repulsion of the photo-electrons in the same bunch can also cause non-negligible time dispersion (known as space-charge effects). To avoid this effect the number of photons in a given light pulse have to be kept below a certain level. But operating a streak camera at this level means that the statistical noise will impose a limitation on the Signal-to-Noise ratio of the measurement data. This flux level decreases exponentially with the pulse duration of the input signal and it means that the data quality (or S/N ratio) decreases strongly for single shot measurements of short light pulses. If the light source itself is repetitive and stable in phase then poor data quality can be improved by accumulation. However, unless a perfect synchronisation between the input pulse and the streak camera's trigger exists, i.e. non-negligible jitter, the measurement results would be false.

The jitter of modern systems in the synchroscan mode is in the order of the intrinsic time resolution (1-2ps) which is negligible to the pulse lengths to be measured in most accelerator applications (30-200ps fwhm).

However, the ultra-fast streak cameras (below 1ps) suffer seriously from the above limitations. Poor data quality of single shot measurements (due to the space charge limitations) would make accumulation necessary. The required stability (jitter-free) synchronisation for this accumulation has attained performances of 500fs, better than most tube's intrinsic time resolution. [10] However, in some of the fastest streak tubes developed (i.e.<500fs) the improvement of this intrinsic resolution is obtained by the use of extremely high extraction & acceleration fields (>50KV/cm) which are often pulsed to avoid HV break-down. But in a repetitive mode of operation a small fluctuation of these pulsed HV amplitude causes large time dispersion and consequently does not allow any accumulation without loss of time resolution.

The present technology of streak cameras does not allow measurement of the ultra fast time characteristics (<500femtosec) of certain accelerator projects. [14]

The sensitivity of a streak camera can be defined as the number of input photons (that hit the active part of the photo-cathode) required to produce an increment in the scale of the output signal. It is largely determined by the QE of the photo-cathode for a given photon energy. For most visible light streak cameras this value is around 10% for the typical alkali materials.

But for X-ray photons this value is much less and is often a serious limitation in the signal/noise ratio of measurement results. In the search for more sensitive materials CsI has been found to yield better results then Au, KBr and KI. [10, 12] In contrast to the streak tubes for visible light which are hermetically sealed, the X-ray streak cameras have an open input structure, with an independent and reliable vacuum system, that permits the exchange of photo-cathodes, and therefor also adaptation to a certain type of measurement (photon energy).

Other factors that determine the streak cameras' sensitivity are the tube's transmission, the gain of the phosphor screen, the transmission of these phosphor photons to the CCD, the DQE of the CCD, and the noise of the analog & digital read-out electronics of this CCD. In most visible light systems today a MCP intensifier with adjustable gain permits increasing the sensitivity to the detection level of a single photo-electron in the tube.

Important additional features in today's systems are the electronic gating or light shutter possibilities. They permit to visualise only certain specific time slots out of the total light input flux. This helps extracting phenomena like partial instabilities that would otherwise be overshadowed. The fast gating is usually achieved with the MCP intensifier while additional slower gating is possible on the photo-cathode, which together can give high extinction rates.

2 APPLICATIONS AND RESULTS

2.1 Bunch Length Measurements

In many synchrotron light sources and electron-positron colliders the measurement of the electron beam bunch length has been carried out for different operations and conditions like current per bunch, RF accelerating voltage, momentum compaction values, electron energy and use of harmonic cavities. [15-23]

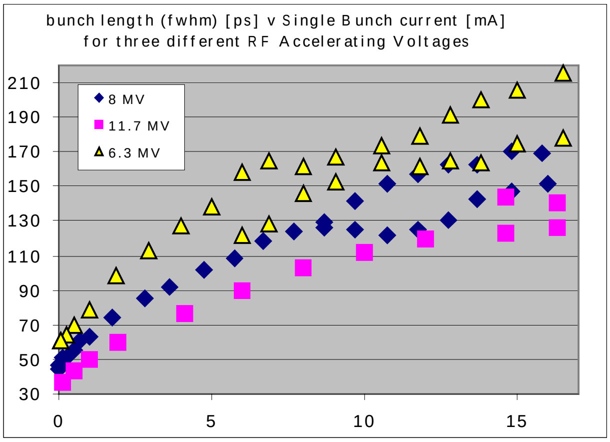


Fig.1 bunch length at the ESRF for 3 RF Voltages, note the regime of fluctuating bunch length at higher currents

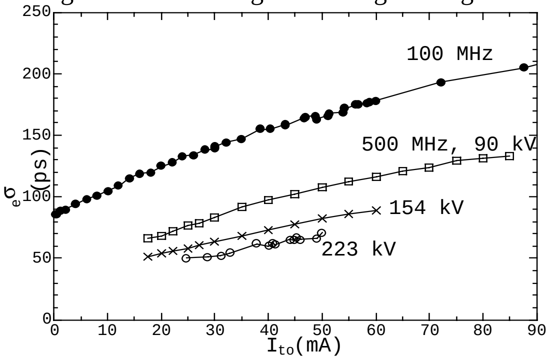


Fig.2 : bunch length at Super-ACO for the 100Mhz cavity alone and with the 5th harmonic cavity (for 3 RF Volt.)

The broadband impedance of a machine can be probed with the results of increasing bunch length with current per single bunch and the analysis of the slope of the asymptotic curve. (figs. 1&2) The same results permit to some extent a verification of techniques, models and simulations on the accelerator's impedance. At higher currents the potential well distortion becomes apparent by the asymmetric bunch profile. [26]

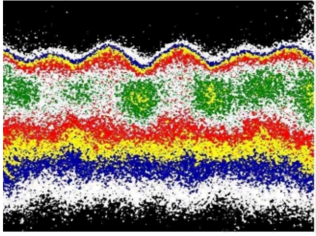
In the regime of microwave instabilities the threshold can be assessed, and in particular the onset of rapid fluctuations of the bunch length (but at stable RF phase, see fig. 3a) if a dual time base streak camera is used.

The latter makes it also possible to first verify that no longitudinal instabilities or bunch length fluctuations exist; then to reduce the photon flux per light impulse well below the threshold of space charge effects; and then to subsequently average, in the signal treatment of the obtained image, over all measured streaks in order to obtain good quality data, i.e. sufficient S/N ratio.

The operation of machines in the quasi-isochronous regimes (α=0) have shown that at medium to high currents the bunch length is independent of momentum compaction and energy. [17-19]

2.2 Longitudinal (In-) Stability Measurements

The measurement of longitudinal phase and stability of the bucket(s) in an accelerator with respect to the phase of the RF master source is a major feature of most of today's streak cameras that operate with synchroscan and dual time base. Higher Order Modes caused in the cavities drive coupled bunch instabilities that can be clearly visualised on the streak cameras output. (fig. 3b)



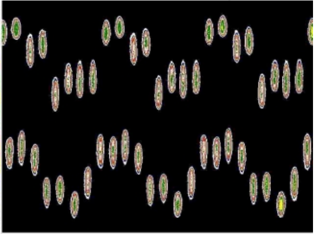


Fig.3a (left) : ESRF at low α : bunch length fluctuation
Fig. 3b (right) : ESRF HOMs causing longit. instabilities

The dual time base covering a very wide range of time-scales allows a convenient adjustment to the speed and frequency of the phenomenon under study. In all the pictures of figures 3 to 5 the slow time axis is represented horizontally.

Fast phase transients linked with the RF cavities mode of operation under both homogeneous and partial filling modes can be precisely monitored (fig.4a). [21, 22, 26] The measurement of injection transients and the subsequent optimisation of the injected beam phase and energy with respect to that of the Storage Ring help to limit radiation background. (fig.4c). [7, 25]

The effects of amplitude and/or phase modulation of the voltage of the RF cavity have been studied in detail (fig.4d) with benefits in beam lifetime and suppression of longitudinal coupled bunch instabilities. [24, 27] They give a good knowledge of the methods to apply Landau damping to cure HOM instabilities. The identification of HOM-modes (dipole, quadrupole, partial, mixed, etc.), with or without higher harmonic cavities, and following adjustments to cavity temperature (fig.5a) or use of feedback system have been carried out. [15, 16, 26, 32] Studies of the nature of HOMs with idle cavities tuned at impedances leading to Robinson instabilities have allowed the development of analytical models describing the features of the mechanism (fig.4b). [28]

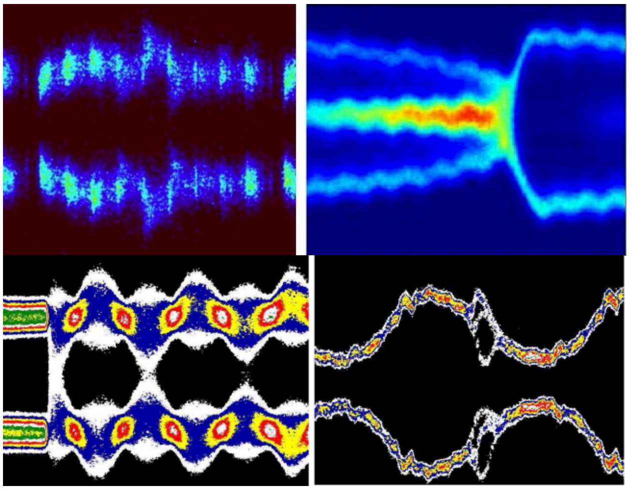


Fig.4a (top-left) PEP-2 HER: phase jumps in center of 1658 bunch train fill , fig.4b (top-right) Spear: full cycle of bunch filamenting with cavity tuning at Robinson instability, fig.4c (bottom-left) ESRF: longitudinal oscillations of the beam at injection into the Storage Ring, Fig.4d (bottom-right) : ESRF phase jumps with the beam undergoing RF Voltage modulation to obtain Landau damping

2.3 Free-Electron Laser characterisation

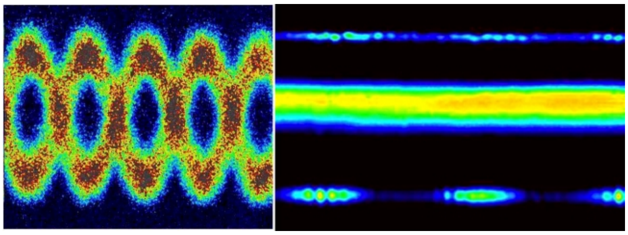


Fig.5a (left) : ELETTRA, longitudinal behaviour under cavity temperature adjustments, fig.5b (right) : Super-ACO, FEL-light (top & bottom) and Synchrotron light (centre) seen with the 500MHz harmonic cavity operated

The performance of Storage Ring based FELs depends much on the bunch length and longitudinal phase stability of the electron beam. Streak cameras are used to verify and adjust the longitudinal alignment of the optical resonator, to measure the pulse length and its stability, and to observe various effects of coupling, detuning and interaction between the electron bunch and the FEL light pulse. Both sub-structures in the light pulse and macro-temporal behaviour can be studied, while the effects of feed-back systems can be assessed. [30-34]

2.4 Ultra-Fast Transverse Motions

If, as described in 1.4, the transverse dimensions of the light source object are preserved and suitably imaged on the photo-cathode by an adapted optical set-up then motions in these planes can be observed with the same ultra-fast time resolution. With even more sophisticated optics side- and top-views 'streaks' can be generated in the same output image of the same bunch over many turns. This facilitates the detection of correlation between simultaneously occurring ultra-fast beam motions and beam size variations in all 3 dimensions (fig.6b). [2, 3]

Alternatively slower movements in the nanosecond scale like those in fig.6c can also be easily visualised. [29]

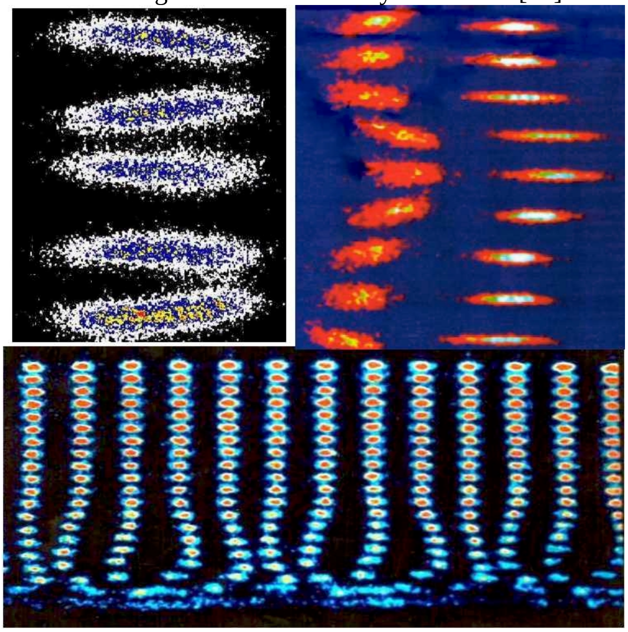


Fig.6a (left) : ESRF five turns of single bunch showing vertical Head-Tail instability,
Fig.6b (right) : LEP top & side views of bunch over 9 turns showing vertical Head-Tail effects, transverse motions and bunch length fluctuations,
Fig.6c (bottom) : APS horizontal coherent motions at trail of the 60ns filling pattern over 13 turns

2.5 Measurements on and with LINACs

Recent work and developments on S-band Linacs, possibly used with laser photocathodes to drive X-ray FELs based on the SASE principle, have used streak cameras for the characterisation of the longitudinal parameters of the beam. The light signal here is obtained through Optical Transition Radiation or Cherenkov light by the application of screens or gas chambers.

It can serve for tuning the bunching sections, surveying the sequence of the micro bunches, assessing the length and shape of the bunch, measuring the synchronisation between Laser and electron beam, and even measuring the longitudinal phase-space distribution of the electrons in single shot mode. [35-38]

2.6 Synchronisation in Pump-Probe experiments

A number of ultra-fast time-resolved X-ray scattering experiments can now benefit from both a high brilliance X-ray source, like those provided in 3rd generation synchrotron light sources, and state-of-the-art ultra-fast laser and detector technology. [39, 40, 41] In such an experiment a broad X-ray pulse (typ. 100picosec) probes the structure of the sample under study while an ultra-short (typ. 100femtosec) laser pulse (λ=200-1000nm) triggers an ultra-fast reaction in it. The latter becomes apparent by a modification of the diffracted X-ray beam.

An X-ray streak camera having this beam centered on its photo-cathode will measure the broad probe pulse while the ultra-fast modulation contained in it will be detectable within the time resolution limits of the streak camera. These experiments require high quality data to discern relatively weak signals within it which make operation in repetitive, accumulation mode imperative.

Technological research aims at optical triggering of quasi perfect synchronisation with the laser and at X-ray streak tube technology with sub-picosec resolution. [10]

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REFERENCES

[1] http://usa.hamamatsu.com/sys-streak/operating
http://www.photek.co.uk/Photochron.htm
http://www.photonetics.com/products/pages/
[2] E.Rossa et al, "Real Time measurements of bunch instabilities in LEP in 3 dimensions using a Streak Camera", EPAC-92, Berlin, p.144
[3] E.Rossa "Real Time Single Shot 3-dimensional measurement of picosec photon bunches ", BIW-94, Vancouver, AIP proceed. 333, p.148
[4] K.Scheidt, "Dual Streak Camera at the ESRF", EPAC-96, Sitges, p.1624
[5] M.Ferianis, "The ELETTRA Streak Camera : Set-up & First Results", DIPAC-99, Chester UK, p.69
[6] J.Hinkson et al, "Commissioning of the ALS dual-axis Streak Camera", PAC-97, Vancouver
[7] J.M. Byrd et al, "Non-Linear logitudinal dynamics studies at the ALS", PAC-99, New-York
[8] A.Lumpkin et al, "Observations of transverse beam-size instabilities for a high current bunch fill pattern in the APS storage ring", PAC-99, New-York
[9] A.Lumpkin et al, "First Multi-GeV particle beam measurements using synchroscan and dual-sweep X-ray Streak Camera " BIW-98 Stanford, p.214
[10] K.Scheidt, G.Naylor "500fs Streak Camera in 1KHz accumulation mode with optical -jitter-free-synchronization", DIPAC-99, Chester UK, p.51
[11] T.Hara et al, "Observation of Hard X-Ray pulses with a highly sensitive StreakCamera", SRI-2000
[12] T.Hara et al, "Performance of a CsI photo-cathode in a hard X-ray Streak Camera", submitted to Review of Scientific Instruments
[13] Z.Chang et al, "Demonstration of sub-picosec X-Ray Streak Camera", Appl. Phys. Lett. 69 (1) July 1996
[14] J.Suguhara et al, "Comparison of Femtosec Electron Beam Diagnostic Methodology", PAC-99, NewYork
[15] M.Ferianis et al, "Observation of Beam Stability and Bunch Length in ELETTRA using a Streak Camera", this EPAC-2000 conference, code WEP5b11
[16] W.Anders, Bessy Berlin, private communication
[17] ESRF Machine Dedicated Time studies no.34/96
[18] A.Ropert, "Probing some of the isues of 4th generation Light Sources at the ESRF", EPAC-96, Sitges, p.632
[19] M.Hosaka et al, "Longitudinal Beam Dynamics on a Electron Storage Ring with negative momentum compaction factor", APAC-98
[20] R.Holtzapple et al, "Streak Camera measurements of the longitudinal distribution with multiple bunches in CESR", PAC-99, New-York
[21] A.Lumpkin, "Time Resolved Imaging of Electron and Positron Beam at APS", PAC-97, Vancouver
[22] A.Fisher et al, "Streak Camera Measurements of the PEP-2 High Energy Ring", BIW-98 Stanford, p.471
[23] A.Burns et al, "Bunch Length Measurements in LEP", DIPAC-99, Chester UK, p.56
[24] S.Sakanaka et al, "Improvement in the beam lifetime by RF phase modulation at KEK-PF Storage Ring", Physical Rev. Spec. Top. Vol. 3, 050701, May 2000
[25] ESRF Machine Dedicated Time studies no.21/98
[26] Beam Instability. Workshop ESRF March 2000, www.esrf.fr/machine/machine.html
[27] O.Naumann, "Landau Damping of Longitudinal Multi-Bunch Instabilities in Electron Storage Ring", PhD thesis, TU Berlin - ESRF
[28] C.Limborg, J.Sebek, "Measurement and Simulations of Longitudinal Relaxation Oscillations induced by HOMS ", PAC 1999 NewYork
[29] B.Yang et al, "Characterising Transverse Beam Dynamics at APS Storage Ring using a Dual-Sweep Streak Camera", BIW-98, Stanford p. 229
[30] M.E. Couprie et al, "Interdependence of the electron beam excitations with the FEL stability on the Super-ACO storage ring", Nucl. Instr. Meth. A 429, 159-164 (1999)
[31] R.Roux, M-E.Couprie et al, "Dynamics of the Super ACO FEL measured with a Double Sweep Streak Camera", EPAC-96, Sitges, p.739
[32] R.Roux, "Dynamique et Conditions de Stabilité du LEL de Super-ACO", These de Doctorat de l'Université Paris 6, 28-1-1999
[33] H.Hama et al, "Microscopic study on Lasing Characteristics of the UVSOR Storage Ring FEL", NIM A 375 (1996) p.32
[34] H.Quick et al, "Longitudinal Alignment and Experience with the Optical Resonator of Felicita", 21st Internat. FEL Conf., Hamburg, August 1999
[35] Y.Ogawa et al, "New Streak Camera system for the KEKB LINAC", APAC-98
[36] A.Lumpkin et al, "High Brightness beam diagnostics for the APS Linac", PAC-99, New-York
[37] T.Kozawa et al, "Generation of Ultra-Short Electron Pulse at ISIR L-Band LINAC for Subpicosec Pulse Radiolysis", APAC-98
[38] M.Uesaka et al, "Precise measurement of a subpicosec electron single bunch by the femtosec streak camera", NIM A406 (1998), p371-379
[39] Y.Tanaka et al, "Timing Control of picosec Laser to Spring-8 Synchrotron Radiation Pulses", Rev Sc. Instr. Vol.71, No.3, March 2000
[40] J.Larsson et al, "Ultrafast X-Ray Diffraction using a Streak Camera detector in averaging mode", Optics Letters Vol. 22, No. 13, July 1997
[41] M.Wulff et al, "Studies of disordering in semi-conductors using time resolved X-Ray diffraction", ESRF Expt. July 1999, HS-798, report No. 990817