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# PHIL : PHoto Injecteur au LAL

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# Bunch Length Measurement Consideration

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**Abstract**: Tremendous progress has been made in the measurement techniques, either in time domain or in frequency domain, of micro bunch length in the past decade. Streak cameras are widely used in time domain measurements, which can directly determine the longitudinal bunch charge distribution by detecting the light pulse from the electron bunch through various radiation mechanisms. The PHIL is a new electron beam accelerator at LAL. This accelerator is dedicated to test and characterize electron photo guns and high frequency structures for future accelerator projects. This paper presents the measurement consideration of the bunch length for PHIL using streak camera techniques with picoseconds resolution. Pulse shape of the electron single bunch is measured via Cherenkov radiation emitted in a sapphire disk. Optical parameters of the optical measurement system will be optimized based on much experiment and numerical analysis in order to achieve a picoseconds time resolution.

## 1 Introduction

Since measurement of charge is a standard measurement, the bunch length becomes the key issue for ultra short bunches. Recent developments in physics and technology open an exciting world of very short sub-picosecond bunches [1]. The production and tuning of these short bunches is crucial to the performance of the future linear colliders and FELs, but the measurement of such ultra-short bunches is an interesting challenge itself[2][3][4].

For bunch lengths in the range of picoseconds, a streak camera can be performed for measurements[5][6]. But shorter bunches require special techniques. Streak cameras currently do not have the necessary resolution. There are many different methods now available. They include high-power RF transverse deflecting structures that streak the beam in the accelerator allowing the bunch length to be observed on a profile monitor[7][8]. Electro-optic crystal diagnostics use the electric field of the electron bunch to modulate the light emitted by high-bandwidth, femtosecond visible lasers thereby allowing one to recover the bunch length[9]. Coherent synchrotron radiation from dipole magnets can also be detected in a terahertz band at wavelengths comparable to the bunch length[10][11].

The PHIL is a new electron beam accelerator at LAL[12]. This accelerator is dedicated to test and characterize electron photo guns and high frequency structures for future accelerator projects. This machine has been designed to produce low energy (E<10 MeV), small emittance (10pi mm.mrad), high current (charge 2nC/bunch) electrons bunch at low repetition frequency (rep<10Hz). Successful optimization and improvement of the performance of PHIL as well as comparisons between experimental results and theoretical analyses (simulation results) will strongly depend on the ability of beam diagnostics, especially on the measurements of transverse emittance and longitudinal phase space. Therefore, the measurement of micro bunch length is very important for PHIL.

## 2 Bunch measurements methods

### 1) Streak camera

A streak camera provides a direct and convenient way to measure bunch length. The streak camera is also a single-shot time domain technique and is a device for a direct measurement of the longitudinal bunch charge distribution[13][14][15]. In 1997, Alessandro Variola and his colleagues used the Cherenkov radiation and Streak camera for a bunch length measurement on the TTF at DESY[16]. Using streak camera for electron beam bunch length measurement involves production and imaging the optical radiation for the streak camera[17].

Many effects could introduce significant error in sub-picosecond measurement, such as dispersion of the optics; bandwidth of the filter and the finite size of the source. For short electron bunch length measurement, the synchronization between the streak camera and accelerator RF system could significantly improve the experiment. Space charge effect inside the streak camera tube limits the dynamic range of the measurement and the achievable sweeping speed limit the temporal resolution.

The temporal resolution of streak cameras is limited mainly by the transit time dispersion of the photoelectrons as they travel from the photocathode to the deflection plates. It is also limited by the spatial resolution, and the deflection speed of the streak plates. For sub-picosecond time resolution, space-charge effects may also limit the time resolution, and thus limit the dynamic range[18][19].

There are a new method which can potentially improve the temporal resolution of a streak camera down to 100 femtoseconds(10fs)[20]. This method uses a time-dependent acceleration field to lengthen the photoelectron bunch, significantly improving the time resolution as well as reducing the time dispersion caused by initial energy spread and the effects from the space charge forces[21].

**2) RF deflecting cavity**

It becomes very challenging for conventional techniques such as streak cameras to resolve bunch lengths of a few hundred femtoseconds. RF cavity operating in the $TM_{120}$ mode (deflecting cavity) is another time domain measurement device. It has been used in many laboratories for low energy beams. The high frequency field in the cavity gives a phase dependent transverse kick and the longitudinal distribution of the bunch is converted to the transverse distribution on the screen after drifting a distance. This is the most direct method of measuring the bunch length and gives high resolution[22][23].

The method was first mentioned and carried out some years ago. In 1969, a deflector-resonant cavity working at $TM_{120}$ was used to measure the bunch length and charge distribution at LAL[24]. The measurement provided a measurement of the bunch length with a value of 3deg 30mn (FWHM, figure 5 of the article). That represents about 3.2 picoseconds. At SLAC, the traveling-wave detecting cavity (LOLA) that was designed for particle separation in the 1960s was used here and it was reported in 2000 that a bunch with the length 20 ps was measured[25]. Recently, the structure was again used in LCLS[26]. INFN has designed a 9-cell S band standing-wave detecting cavity to measure their 150 MeV bunch[27], while UCLA has made an X-Band standing-wave structure to diagnose the beam with the energy of 15 MeV[28].

Good resolution of the RF deflecting cavity comes from two important sources. One is the space charge effect which is negligible at high energy, second is small geometric emittance of the electron beam. RF deflecting cavity enjoys many advantages over streak camera. It can be self calibrated; single shot to produce longitudinal profile of the electron bunches. It can be used for non-destructive timing jitter measurement of the electron bunches combining with beam position monitor, and can measure the longitudinal phase space of the electron beam in the dispersive beam line.

Using shorter wavelength RF power source, or using superconducting RF cavity (high Q, such as B-factory crab cavity), femto-seconds resolution can be realized by the RF deflecting cavity with a high resolution beam profile monitor[29].

**3) RF zero-phasing methods**

Recently there has been increasing interest in applications of very short electron bunches. Accurately measuring bunch length and profiles becomes essential for characterizing, commissioning, and operating such short bunch machines[30]. The RF zero-phasing method is the only technique that is able to measure bunch length and longitudinal density distribution in the femtosecond regime.

The shortest bunch for proposed and existing accelerators is around 100fs (rms). Bunch length measurement is essential to develop and operate such accelerators. Such measurement also plays a crucial role in developing and advancing new techniques such as the coherent radiation method. Recently developed frequency domain techniques measuring coherent radiation spectra are not able to uniquely determine bunch shape and length[31][32][33]. The RF zero-phasing technique has been used to measure longitudinal distributions and bunch lengths of picosecond bunch. Good consistency was found between measurement and simulations[34][35][36][37][38].

An electron bunch length as short as 84fs (rms) has been measured in CEBAF[39][40]. This is the first accurate bunch length measurement in the regime of less than 100fs, and the zero-phasing is the only technique that has demonstrated such a capability. Now, the resolution of zero-phasing methods is about 10fs, but it is a destructive method and requires additional acceleration structure[41].

**4) Electro-Optic methods (EO)**

Electro optic methods to modulate ultra-short laser pulses using the electric field of a relativistic electron bunch have been demonstrated by several groups to obtain information about the electron bunch length charge distribution[42].

Conventional laser technology has succeeded in producing and characterizing visible light pulses with the time structure that is well matched to these electron beam requirements[43]. The bridge between the two systems exists in the form of electro optic (EO) crystals whose birefringence properties are modulated by the electric field of the electron bunch to be measured[44]. The transmission of polarized light through an EO crystal is in turn modulated and the problem of measuring an electron bunch length is thereby transformed into one of measuring the duration of a light pulse[45].

The EO detection method is resolution limited by the phase slippage that occurs from the slight difference in propagation velocity for the sub-millimeter radiation from the bunch. It is expected that improvements in EO detection techniques will go hand-in-hand with progress in the generation of ultra-short electron bunches over the next few years.

**5) Coherent radiation methods (CSR, CTR, CDR)**

As electron beam bunch length getting shorter, the shielding effect from beam pipe is reduced, so coherent radiation from small electron bunches getting stronger [46]. The coherent radiation contains the bunch length information. Longitudinal form factor is none negligible only when radiation wavelength is comparable with the bunch length. After initial experimental observations of coherent radiation in Tohoku University of Japan and Cornell University[47][48], Fourier spectrometer using Michelson interferometer was successfully used at Stanford University[49] to measure hundred femto-second long electron pulse train. This technique can be treated both in time domain and frequency domain; the width of the interferogram is the auto-correlation of the coherent radiation, which can be used directly to estimate the electron beam bunch length. The spectrum of the coherent radiation can be obtained by Fourier transforming the interferogram. The bunch length information from coherent radiation can be extracted using Kramers-Kronig relation. Good agreement was observed between streak camera measurement and coherent radiation technique at University of Tokyo [50].

Interferometric technique has demonstrated many advantages, such as simplicity, cost effective and no fundamental limit in its resolution. Recently, holographic Fourier spectroscopy technique was suggested for single-shot measurement, and to eliminate mechanical constrain. The detector bandwidth and calibration of the measurement are two main challenges as electron bunch length getting shorter for coherent radiation technique.

## 3 Streak camera applications on PHIL

### 1) Streak camera principle

The principle of a streak camera is illustrated in Figure 1 and Figure 2.The heart of it is the streak tube which converts the information in the time domain to a spatial domain. A light impulse will hit a photocathode which will cause the emission of photo-electrons inside the tube. This so-created electron bunch contains the same time structure as the impinging light pulse. The electrons are electrically focused and accelerated towards the other extremity of the tube where they will hit a phosphor screen. The electrons will, however, have been deflected vertically by an electric field during their transit through a pair of deflection plates. This deflection field has an ultra-fast time slope. These causes the electrons in the bunch to be deflected differently, the «first» emitted electrons will hit the phosphor screen at the bottom and the «latter» electrons higher-up. The intensity profile along the stripe-like image (a «streak») left on the phosphor screen gives the time profile of the input light impulse [51].

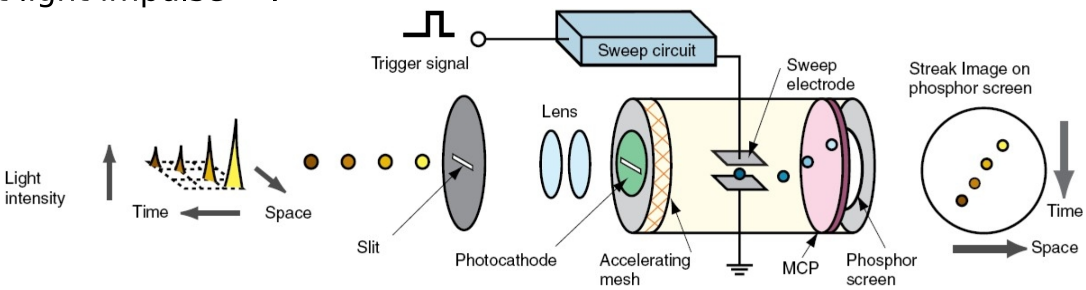

Fig.1: Operating principle of the streak camera

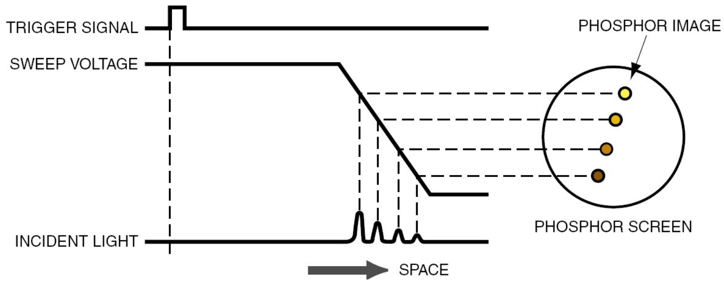

Fig.2: Operating timing principle

**2) Cherenkov radiation**

Cherenkov radiation is electromagnetic radiation emitted when a charged particle (such as an electron) passes through an insulator at a constant speed greater than the speed of light in that medium. The atoms of the medium are polarized by the charged particles, which then turn back rapidly to their ground state, emitting prompt radiation. The characteristic blue glow of nuclear reactors is due to Cherenkov radiation. It is named after Russian scientist Pavel Alekseyevich Cherenkov, the 1958 Nobel Prize winner who was the first to characterize it rigorously [52].

Cherenkov radiation is commonly used in experimental particle physics for particle identification. One could measure (or put limits on) the velocity of an electrically charged elementary particle by the properties of the Cherenkov light it emits in a certain medium. If the momentum of the particle is measured independently, one could compute the mass of the particle by its momentum and velocity (see Four-momentum), and hence identify the particle.

The simplest type of particle identification device based on a Cherenkov radiation technique is the threshold counter, which gives an answer as to whether the velocity of a charged particle is lower or higher than a certain value ($v0 = c / n$, where c is the speed of light, and n is the refractive index of the medium) by looking at whether this particle does or does not emit Cherenkov light in a certain medium. Knowing particle momentum, one can separate particles lighter than a certain threshold from those heavier than the threshold [53].

**3) Experimental consideration**

Since the energy of the electron beam at PHIL is less than 10MeV, standard optical transition radiation technique produces just a low number of photons which are irradiated in a large solid angle [54]. For the measurement of the micro bunch length at PHIL, the Cherenkov radiation mechanism is used to convert the electron beam information into a photon beam at visible light wavelengths.

In order to obtain adequate photon yields after the long photon beamline we will use Cherenkov radiators to convert the information of the electron beam into a photon beam. The drawing of PHIL beamline is illustrated in Figure 3. The produced photon bunches are transported through a ~17 m long beam line to an optical room and are then detected by a Hamamatsu streak camera.

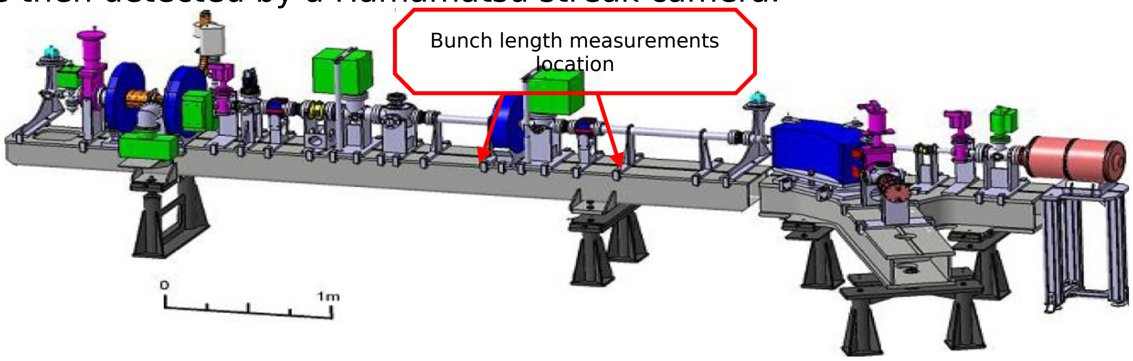


Fig.3: A drawing of the beamline on PHIL

For analyzing charge distributions of electron bunches, the electrons pass through a Cherenkov radiator and emit photons. The produced visible light has to be transmitted from the tunnel through beam line to the optical room where it will be measured by a used streak camera. The streak camera is currently located in the laser room, which is 17 meters away from the machine. This quite long distance associated with the streak camera type used might be a limitation for the minimum signal level that can be detected. This device and the optical transport system have to be accurately studied in order to determine the feasibility and the accuracy of such measurement.

**4) Optical design**

The density of yielded photons at PHIL is not so high and the light is not a point source but a cone with Cherenkov angle. Furthermore, the Cherenkov light covers broadband wavelengths, even in the visible range, the optical elements and air in the long transport line may normally bring about chromatic effect and other aberrations. Therefore, the transport system should have a high light collection and transmission efficiency. The beam line should also be designed to have a high degree of optical correction and low transit time spread due to the difference of the light path. The dispersion within the optical wavelengths should be small. It is the idea to combine the whole system out of highly corrected subsystems near to diffraction limit. This should lead to a moderate optical resolution of the whole system, which will be remarkable higher as for a design consisting only of single lenses or achromats.

The first lens should have a high aperture to collect a maximum of light, whereby the focus length has to match to the port geometry. This light should not be lost by absorption and vignetting in the subsequent elements. Therefore, the number of optical elements should be minimized. Finally, the output focal length and aperture should match the slit of the streak camera and its input optical system. The light is projected in a focus on the slit to maximize the number of photons penetrating the small slit. This light concentration in the focus is limited by the entrance aperture of the lens in the streak camera, which performs the image of the slit onto the photo cathode. The width of the slit right at the entrance of the streak camera should be chosen under the trade between the requirement of the time resolution and the signal-to-noise ratio.

Furthermore, space charge effects in the streak tube have to be avoided by appropriate setting of the optical system. For the high temporal resolution, narrow width of bandpass filters are usually needed in the measurement in order to avoid the pulse broadening due to optical dispersion in the lens and air.

The trigger driving the streak camera will be generated from the master oscillator. The time jitter between the RF (laser) and the camera should be as small as possible. Therefore, the phase stability of the gun is also very important for the bunch length measurement.

## 4 Conclusion and outlook

Cherenkov radiators with streak camera to measure the picosecond electron single bunch with high time resolution will be established at the PHIL of LAL. The choice and evaluation of the slit width of the camera and the optical band-pass filter are performed with the picosecond time resolution. The long light transport line is optimized to have a high collection efficiency, high transmission, low aberration and low dispersion. The experimental setup will be installed in the near future.


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