Beam Profile Measurements Using Nonimaging Gamma Optics*

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Abstract

High energy photons produced from bremsstrahlung foils, Compton scattering or beamstrahlung from high energy e^+e^- collisions can be used to measure beam profiles using nonimaging optics. We describe the method and its limitations (resolution, backgrounds etc.), as well as the apparatus required to implement it. Data from a low energy test run is described as well as other possible applications such as a 250+250 GeV linear collider and possible experiments with existing beams.

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1. Introduction

Linear colliders require very small beams at the interaction point to permit efficient collisions between the electron and positron bunches. Designs of the Next Linear Collider (NLC) assume that the beams can be a few nanometers in one dimension[1], while the Final Focus Test Beam (FFTB) at SLAC has already produced beams with a height of 70 nm[2]. The difficulty of producing and maintaining these beams means that diagnostics must be developed which will be able to measure them accurately on a bunch to bunch basis.

Perhaps the single most important measurement for optimizing the luminosity of the linear collider is the bunch position and profile in the small dimension. Such measurements are complicated by a number of factors, including the high power density of the beam and the relative inaccessibility of the interaction point. Optical diagnostics cannot be used since the beam is much smaller than the wavelength of visible light, and the aspect ratio is large, which means that the electric and magnetic fields near the bunch are primarily a function of the larger dimension.

At present there are a number of methods proposed which might produce measurements of beams suitable for linear colliders. Shintake[3] has proposed a system which looks at the modulation of Compton scattered photons as the beam is steered across the peaks of a standing wave. This method may be adequate for 70 nm beams but is considerably more difficult for beam sizes of a few nanometers. A system proposed by Chen and Buon[4] looks at the angular distribution of heavy ions produced by beam ionization. The angular distribution of e^+e^- pairs[5], disrupted electrons and beamstrahlung photons[6] have also been discussed for measuring the aspect ratio at the interaction point of a collider.

In the discussion below we consider the operation of the system, the results of a test run and possible applications, with emphasis on the special advantages of this method.

2. Method

2.1) Introduction

The proposed method is basically a pinhole camera, modified for high resolution using high energy photons[7][8]. An image can be produced using a pinhole camera if the pinhole is smaller than the object being observed. With the very small beam sizes expected in electron colliders it is difficult to use two sided pinholes so we use a modification with one sided collimator where the image profile is produced by differentiating the distribution of photons in the shadow edge or penumbra as shown in the upper part of Fig. 1. This is fully discussed from the standpoint of geometric ray optics in the next section and the Appendix.

2.2) Ray Optics

A modification of this system using a tilted slit can produce a profile of each bunch if the x and y profiles of the beam are uncorrelated. This assumption is most valid at the final focus where the rms spot sizes $\sigma_{x,y}$ are required to be smallest and are typically quite asymmetric. This may be tested by scanning another variable slit (not shown) orthogonal to the first. This slit can also control intensity and resolution like a cats eye. The lower half of Fig. 1 shows a schematic layout of a system that permits measurements of the longitudinal (z or t) and vertical (y) distributions, assumed smallest here, of every bunch in a closely spaced train of bunches.

In this mode of operation, the profile of beam transmitted through the slit is equivalent to scanning the slit through the penumbra. At one end, the slit looks past the primary collimator at the source, at the other end of the slit, the collimator almost fully shadows the source. The tilt and position of the slit can be used to control the magnification and aim of the system.

This technique can, in principle, also be used to give time information, since Cherenkov photons would maintain the time structure of the beam and are effectively produced from a slit source, permitting the use of a streak tube, perhaps without an additional input slit. The ultimate time resolution of this method, perhaps 200 fs for the Hamamatsu FESCA-500, would be given by the time resolution of the streak camera, generally quoted as FWHM = 2.35 times the standard deviation[9]. Better resolution can also be obtained from streak cameras using traveling wave rather than electrostatic deflection tubes[9].

As shown in the Appendix, assuming x and y are uncorrelated, a single profile measurement with an inclined slit determines the density $\rho(y,y')_{y' \sim \text{const}}$ at the point of conversion, where y' is the slope of the photon or electron. However, to completely measure transverse-transverse or transverse-longitudinal correlations we need additional constraints or knobs, e.g. we discussed x, x' correlations and the addition of another orthogonal slit. It is also possible to scan the beam rather than the slit, although this may be less accurate. The streak camera in Fig. 1 clearly allows us to extract information about bunch length, profile and y, z correlations which are extremely important for wake effects on bright beams in narrow channels.

For asymmetric final focus systems where the beta functions satisfy the relation ($\beta_x^* \gg \beta_y^*$), it is also important to insure that there is no beam blowup from anomalous dispersion in the y direction and that the leading order chromatic effects of the strong final quads are properly corrected. We would also like to measure correlations such as y, δ and y, y', δ , where δ refers to the particle energy spread. If the apparatus is moved vertically, one can map the complete beam ellipse in a number of scans, permitting measurements of chromatic contributions and nonlinear effects which are not accessible on the median plane. Fig. 2

illustrates the use of this system to measure chromatic effects. In this case, higher or lower momenta are focused behind or in front of the focal point for the central momentum, giving beam ellipses which are sheared to the right or left of vertical. By measuring the profiles off axis it is possible to directly measure this effect by comparing the width measured at large y' with measurements at $y'=0$. Measurements at $\pm y'$ and $y'=0$ are probably required to avoid confusion with other correlations.

Because we assume ray optics with high energy photons, we ignore any errors due to folding the outgoing photon divergence ($\gamma^{-1} \sim 0.01$ mr) which is small compared with the electron divergence ($y' \sim 0.5$ mr). Multiple scattering effects in solid bremsstrahlung converters are also small. The effects of beam self focusing can be comparable to the beam divergence when observed off the median plane and must in general be corrected[7].

2.3) Resolution

The resolution of such a system can be evaluated using Fresnel integrals[10]. For monochromatic light with wavelength λ , the width of the diffraction image is given by

$$y = v \sqrt{b\lambda(a+b)/2a},$$

which, in the limit $a \gg b$, becomes

$$y = \sqrt{b\lambda/2},$$

where a is the distance from the collimator to the detector and b is the distance from the collimator to the object as shown in Fig 3. The function v is a constant of diffraction used to integrate the Cornu spiral, and $\Delta v = 1$ corresponds to about two standard deviations. From these expressions it is evident that the resolution is optimized when the collimator is as close to the photon source as possible, and the highest energy photons are used for the measurement.

The discussion above assumes that elastic and inelastic scattering from the primary collimator is negligible. This is assumed since the collimators would consist of thick (20 radiation lengths), high Z material and inelastic photon scattering through showers would require production of e^+e^- pairs with multiple scattering and subsequent bremsstrahlung which produces secondaries with a much larger solid angle than the acceptance slit of the detector, which could be as small as the beam size multiplied by the magnification.

The resolution for real beams with a large momentum spread must be obtained using the whole photon spectrum, as described in reference [7], and shown in Fig 3c). In a Monte Carlo calculation, this is done by incoherently summing the contributions of the diffraction image weighted by the detected photon spectrum. This sum tends to smooth out the bumps on one side of the diffraction image and give a smooth curve somewhat similar to a

gaussian with oscillations on one side. We define a resolution function as the derivative of the sum of contributions from all energies. The shape of this function depends on the spectrum of photons, with the width roughly given by $y \approx \sqrt{b\lambda/2}$.

2.4) Detector, Rates, Backgrounds

In order to detect the beam it is necessary to convert a significant number of primary electrons into high energy photons which can carry information about the initial electron phase space distribution. These high energy photons must be subsequently converted to low energy photons which can be detected in sufficient numbers to produce useful distributions. The high energy photons which are not detected will tend to produce backgrounds.

In a linear collider environment there are primarily three ways of producing the high energy photons from primary electrons: conversion with a bremsstrahlung target, Compton scattering from intense laser pulses and beamstrahlung, i.e. synchrotron radiation from the fields at the interaction point of a linear collider. These spectra are shown in Figure 4. Both beamstrahlung and bremsstrahlung produce many more low energy photons than high energy photons, so it is necessary to use a detector which has low efficiency at low energies and high efficiency at high energies.

A number of methods for weighting high energy photons more than low energy photons are possible. In order to be detected, photons must be converted to charged particles, and magnetic deflection of charged secondaries, calorimetry or multiple scattering can be used to weight the detected photon according to energy. For example, if a detector is placed in the forward direction, multiple scattering will remove low energy particles and the overall efficiency as a function of detector thickness and photon energy can be as shown in Figure 5. For thicknesses of about $t \sim 3 - 6$ radiation lengths the detection efficiency becomes roughly proportional to E_γ which cancels the E_γ^{-1} dependence of the bremsstrahlung spectrum, increasing the energy of the detected photons and increasing the resolution of the system.

The number of detected high energy photons for a given primary beam is given by the number of primary electrons times the efficiency for producing and transmitting equivalent photons through the slits, combined with the efficiency for producing secondary e^+e^- pairs and Cherenkov photons, which can be detected in a camera, from these pairs.

Since the photon beam being measured is produced by a high energy electron beam which must be dumped nearby, and perhaps upstream, there are a number of sources of background due to the dumped electrons. In addition to the dumped electrons, however, high energy photons hitting the slits also produce showers and secondaries which can be detected as backgrounds. The magnitude of these backgrounds has been evaluated by Monte Carlo techniques using the EGS4 code.[11] The results of these calculations can be

summarized in Figure 6, which show that narrow slits can transmit photon beams through the slot while essentially absorbing the shower created if the beam hits either collimator jaw. Transmitted particles are mostly first generation secondaries produced very close to the slit opening. The angular distribution of these secondaries is given by the aspect ratio of the slit and the distribution of the source of secondaries in the jaws is roughly given by the radiation length times the aspect ratio of the slit or the angle of emission. For a single sided primary collimator the effective depth of the initial photons in the jaw of a collimator is $\delta \sim L_R \theta$ where the radiation length, L_R , is 0.0032 m for W and the angle θ is roughly $\sigma_y / b = 10^{-7} \text{ m} / 10 \text{ m}$, giving values of δ on the order of $10^{-10} - 10^{-11} \text{ m}$.

2.5) Apparatus

The collimators themselves are tungsten blocks polished flat on the face that defines the beam. Optical polishing techniques can produce and measure surfaces which are flat to better than a few nm with comparatively conventional techniques[7]. Positioning of these components within $\pm 25 - 100 \text{ nm}$ can be done with computer controlled micrometer technology, and positioning at finer levels can be done with piezomovers.

Since the resolution of this method is potentially much better than the scale of earth motions, which is $\sim 100 \text{ nm}$ at low frequencies, we have considered the use of seismometers to correct for seismic motions in the frequency range of 0.1 to 10 Hz. The frequency sensitivity of this system is determined by the seismic wavelength. At low frequencies, $f < 1 \text{ Hz}$, defined here as $< v/l$, where v is the velocity of sound in the ground (about 400 m/s), and l denotes the dimensions of the system (perhaps about 20 - 200 m), the whole apparatus tends to move together, and at high frequencies ($f > 10 \text{ Hz}$), the amplitudes of ground vibrations tend to be small. This system is most sensitive to ground vibrations whose wavelength is roughly the size of the apparatus.

In order to measure the spectrum of seismic noise, we used a STS-2 seismometer to measure seismic spectra at Argonne.[12] The seismometer was mounted on a large steel block which was in turn mounted on bedrock. A FFT was used to convert the time domain data, obtained at 76 Hz, to frequency domain, with the results shown on Figure 7. Peaks are due to 60 Hz noise aliased to 12 Hz and to 30 Hz noise from air conditioning and motors, and the IPNS accelerator running nearby. The peak around 0.1 Hz is seen in all sensitive seismometers and is attributed to waves hitting beaches around the world. In order to verify the operation and calibrate the device we mounted the seismometer on piezoelectric movers which we were able to excite small amplitude oscillations at 1 - 10 Hz to provide a calibrated motion of about 1 nm.

The camera for imaging the photon beam from the slit consists of a Hamamatsu V4183U two stage, gated image intensifier which has single photon sensitivity, in optical contact with a Hamamatsu S3902 MOS linear image sensor.[9] The image sensor is managed locally by a Hamamatsu C4070 Driver/Amplifier card. This detector is interfaced to

CAMAC by a single-width module, the Camera Controller, which provides all the control and readout functions required. The 8 bit CCD has 512 channels with a dynamic range of 256. This system is thus capable of producing profiles of light over six orders of magnitude in signal intensity, down to single photons.

On receipt of a NIM level signal, EVENT IN, or CAMAC request, the storage sites in the linear image sensor are strobed into the Camera Controller, buffered, and digitized by an eight bit Analog Devices AD7569. The data words are written to FIFO and remain there awaiting data acquisition through CAMAC. A Status Register which may be written/read via CAMAC is provided in the Camera Controller, and bits in the Status Register initiate start of scan, indicate end of scan, FIFO empty, and FIFO full. This allows scan to be initiated by CAMAC, and allows CAMAC to poll or check status. Various diagnostic functions are provided; for example, FIFO may be written as well as read by CAMAC to permit diagnostic tests of FIFO.

The CAMAC crate is interfaced to a 486 clone computer by a DSP 6001 CAMAC controller, and the data acquisition code, which is written in C, runs under LabWindows, providing useful online histograms and plots. The data acquired through CAMAC is written to disk in the computer and may subsequently be analyzed off-line. A block diagram of the Data Acquisition System is shown in Figure 8. In beam tests only the optical data acquisition channel and the encoder motors for positioning the collimators were used, however the other hardware in the figure is functional and has been operated separately.

3. Experimental test

In order to test the system we set up an experiment at the MIT / Bates 1 GeV electron linear accelerator. We used slits to define a beam source 25 μm high and were able to use the detection optics to measure the beam profile.

The geometry is shown in Figure 9. Just before the beam dump, a thin window was used to produce a bremsstrahlung spectrum of gammas with a maximum energy equal to that of the beam, 799.1 MeV. This electron beam was then collimated using a pair of tungsten blocks ground flat on one face and separated by 25 μm shims. Following this we assembled a system consisting of a single sided collimator and a slit constructed with optically flat tungsten mirrors separated by shims, both remotely controlled by encoder motors with a minimum motion of about 0.1 μm . These elements, which defined the beam, were followed by a detector which consisted of a pair converter (a 1.25 cm W plate), a Cherenkov radiator (10 cm air), a periscope and the image intensified camera. The collimators were surveyed in using a transit and levels and this alignment was then checked using the beam. In fact, the initial alignment was excellent, so that the first pulse seen was within a few microns of the ideal beam line.

Scans were taken with the active stripe of the CCD camera oriented with parallel to the detector slit and perpendicular to the detector slit, the latter orientation permitted measurement of the effective width of the Cherenkov source, as well as the distribution of background light. Scans were taken while moving the position the front collimator, and with the beam dumped at the front collimator and the final slit. Typical data are shown in Fig 10., where the image intensifier was operated with a microchannel plate voltage of 1550 V, which gave about 1/10 of the maximum gain of the maximum possible gain. The observed width of a point Cherenkov source should be $\sim 0.5 l \sin(\theta_C) / \sqrt{2} = 0.8$ mm, where l is the length of the Cherenkov radiator and θ_C is the Cherenkov angle.

The primary background seemed to be due to light uncorrelated with the beam transmitted by the slit. Additional shielding around the first collimator and stopping the beam from reaching the slit both reduced the background intensity. The source of this background thus seemed to be showers produced at the primary collimator and slit, creating secondaries which produced Cherenkov radiation in the periscope. Since the slits were mounted with commercial movers and the volume of the sensitive region of the periscope was large, (2 m long and 10 cm in diameter at the largest point) it was difficult to shield this background completely.

With the beam dumped at the first collimator, it was possible to look at "single" photons in the camera, and thus to normalize the camera sensitivity. Using the primary beam energy and intensity, a calculation of the fringe field of the dump magnet, the radiator thickness, as well as slit widths, and pair conversion and Cherenkov efficiencies calculated by Monte Carlo, we were able to calculate the size of the signal which should be seen in the detectors. The primary uncertainty in this calculation is the initial direction of the electron beam after the ~ 1.2 mrad deflection in the fringe field before the gamma converter, which is larger than the multiple scattering angle of the electrons in the radiator. The expected signal size agreed with the observed signal within this uncertainty.

A plot of the beam profile as measured by the system is shown in Fig 11. As the beam intensity changed somewhat during the run, and we had no precise beam intensity monitor, we normalized the intensity of beam through the slit to the background, which seemed to be proportional to the beam intensity. Since the limiting resolution in this application is $0.1 \mu\text{m}$, the measurements errors are determined by statistics. Profiles are obtained by differentiating the intensity as a function of collimator position. The magnitude of errors due to normalization of the beam intensity, and to statistical error in the signal is difficult to determine independently.

4. Possible Applications

A number of applications are possible. The system was originally proposed as a method of looking at final focus spots at a linear collider which can be tested at the FFTB at SLAC, but the implementation should be fairly inexpensive.

4.1) Measurement of Compton Scattering Source

A beam of high energy Compton scattered photons is produced at the FFTB using an electron beam with $\sigma \sim 20 \mu\text{m}$, and a $\sim 1 \text{ TW}$ laser beam focused down to $\sigma \sim 2 \mu\text{m}$. The precise shape of this overlap can be measured using this system as that shown in Figure 12. Two collimator systems can be incorporated in the dump line, the primary, single sided, collimator immediately following the last bending magnets $\sim 19 \text{ m}$ from Compton source, and the diagnostic slit just before the beam dump diagnostics, $\sim 35 \text{ m}$ from source. Since the existing pair spectrometer and gamma calorimeter cannot be blocked for long periods it will be necessary for both collimator and slit should be mounted on movable stages to raise them above or below the beam when downstream components are in use.

The Compton source has dimensions determined by the laser spot, and divergence determined by the $1/\gamma = 10^{-5} \text{ rad}$ opening angle of the Compton photons and the electron beam divergence at the waist, which is tuned to be much smaller than the $1/\gamma$ opening angle. The beam size downstream is small, $\sigma < 0.5 \text{ mm}$, and the power density is high. The number of photons / pulse would be large, ($\sim 5000 \gamma/\text{pulse}$). The diffraction limit on the resolution of this system would be about 16 nm .

4.2) Profile measurements at the FFTB IP

If a 0.1 radiation length target is inserted at the final focus of the SLAC / FFTB, the bremsstrahlung beam can be used to measure the profile at the IP. With a $46 \text{ GeV } e^-$ beam the diffraction limit on the resolution at the IP should be $\sim 32 \text{ nm}$ with the collimators as described in the section above. The collimator placement is not ideal, since the magnification is less than one, and the likelihood that backgrounds would be large due to the location of the detectors inside the dump shielding, however it should be possible to produce useful measurements of the 60 nm beam focus. Roughly 300 high energy gammas / pulse should be detected with a slit equal to the diffraction limit, giving perhaps 3000 Cherenkov photons in the detector which should be sufficient to produce a useful plot of the beam profile for individual bunches.

Implementation of this option would require the installation of a movable foil at the final focus of the electron beam. The thickness of this foil would be $t \sim 2 \beta_y \sim 0.1$ radiation lengths $\sim 0.200 \mu\text{m}$, which implies the foil should be dense, perhaps tungsten, gold or platinum.

4.3) Measurements at a $250+250 \text{ GeV}$ Linear Collider

The proposed system should also be flexible and useful for measurements of the small spots and high energy beams associated with the Next Linear Collider (NLC). The system could be used with foils or lasers to measure the properties of single beams using

bremssstrahlung or Compton scattering, or using beamstrahlung from beam-beam interactions to make passive measurements of the parameters of the collisions at the IP. The diffraction resolution is determined by the minimum distance between the IP and the first collimator, and we assume this could be ~ 10 m, since the beam would be passing through final focus and beam dump quadrupoles. The minimum distance at which such a collimator could operate is determined almost entirely by power loading and thermal deflection of the collimator surface, since the photon flux alone would be in the range of ~ 10 kW / mm².

The dimensions associated with the linear collider permit detection systems which could include elaborate magnetic deflection or focusing, however using a simple detector consisting of a pair converter and radiator to give a detection efficiency proportional to E_γ would give a good diffraction resolution. In this case a nonlinear optical resolution function, approximately measured by an equivalent standard deviation, would be about $\sigma \sim 5.0$ nm for Beamstrahlung, 3.6 nm for bremssstrahlung and 2.6 nm for Compton gammas as shown in reference [8].

5. Conclusions

High energy gamma optics should provide a means to produce high resolution beam profiles using photons from either bremssstrahlung, beamstrahlung or Compton scattering. Using nonimaging optics, the profiles of penumbras from collimators in the forward direction can, in principle, produce single bunch, time resolved measurements which should be useful in a variety of applications. This method may have the highest resolution of any method proposed for the final focus or interaction point of a linear collider.

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Appendix

As shown in Fig. 13, suppose $y_{max} > r$ with $2r$ the aperture or pinhole diameter. In the figure we consider 3 lines that bound the phase space. Clearly, the angular acceptance of the slit is $y'_{acc} < y'_{max}$ as seen from the center, solid line. If we monitored the beam profile on either slit surface (dot or dashed) we would get an essentially equivalent result except for a non-inverted image if the off-axis profile remains the same. Scanning the slit vertically can also measure this or, correspondingly, by rotating the horizontal slit about the longitudinal direction as shown in Fig 1, we can get the same information from a single bunch without a slit scan if there are no x, y correlations.

If $y'_{max} \gg y'_{acc} = r / a$, then the center, solid line in Fig. 13 rotates toward the vertical and we get the pinhole camera profile in Fig. 1, i. e. $\rho(y, y')_{y' \sim 0}$. Vertical control of the slit or rotation, as in Fig. 1, then measures $\rho(y, y')$ using vertical slices at different y' . With sufficient control over the vertical location c and the size of the aperture r , we might then expect to measure higher order y, y' correlations. Notice that because the same situation applies in the other transverse direction, x , another movable orthogonal slit with variable aperture can also measure x, x' correlations but this appears to require multiple beam bunches and therefore an electron bunch current monitor for normalization.

Now, let's suppose that $r > y_{max}$ and $y'_{max} \gg y'_{acc}$ again. In this case we again measure the transverse beam profile $\rho(y, y')_{y' \sim 0}$ when the slit and beam are aligned on one another i.e. nothing essential changes from the first example if a is large enough to give a better magnification *if* we impose some additional upstream collimation. To get the same result with improved magnification, the collimation slit needs to be small compared to y_{max} which is a constraint we need to avoid. If, however, we now remove the top or bottom half of this collimator so that $r \gg y_{max}$ but keep the second unchanged, then we measure $\int dy [\rho(y, y')_{y' \sim 0}]$. This is the equivalent of the modified pinhole camera for $y' \sim 0$ in Fig 1. If we also rotate the slit relative to the jaw and scan the jaw vertically, we effectively measure $\rho(y, y')$ for a bunch, if the time between bunches is large compared to the streak camera resolution Fig 1. Further, the aperture of the second slit can be $r_2 \gg y_{max}$ which is important for nm beam sizes and the high energy photons that need to be attenuated. Without the second slit one has to scan the jaw in very small steps for reasonable resolution with a potentially large background from 'off angle' rays.

Figure Captions

- Figure 1, The technique, using a bremsstrahlung target, a tilted slit to give single bunch measurements and a streak camera for time resolution.
- Figure 2, The measurement of chromatic effects using off axis profiles.
- Figure 3, The geometry for diffraction from a single slit, showing the intensity $F(v)$ for the shadow.
- Figure 4, The spectrum of beamstrahlung, bremsstrahlung and Compton scattering.
- Figure 5, The efficiency of detecting Cherenkov photons from a heavy pair converter followed by a 10 cm air radiator.
- Figure 6, Showers in slot collimators.
- Figure 7, The seismic noise spectrum showing a calibration signal at 2 Hz.
- Figure 8, The data acquisition system.
- Figure 9, The geometry of the test at Bates / MIT
- Figure 10, The CCD image of the Cherenkov source, showing a "single" photon signal.
- Figure 11, The measured profile and its derivative, showing the beam profile.
- Figure 12, A possible geometry at the for profile measurements at the FFTB.
- Figure 13 Phase space optics for slits.

Pinhole camera

$$I'(y') \sim I(y)$$

Single sided collimator

$$I'(y') \sim \int_0^y I(y) dy$$

Streak Camera

Compton/Bremsstrahlung
Beam Profile Monitor

Bremsstrahlung
Radiation or Compton
converter

Primary
Collimator

Slit

Converter

dl/dx

$I(x)$

Dump

e^-

Final focus

Primary Collimator

Slit

Fix Colors
putseturn

Data Acquisition System