Beam Monitoring and Conditioning Working Group IV Report

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Abstract. The highlights of Seventh Advanced Accelerator Concepts (AAC) working group IV (Beam Monitoring, Conditioning and Control at High Frequencies and Ultrafast Timescales) are presented in this report. The talks given at the working group covered wide range of subjects of beam monitoring. They including a new technique of measuring sub-picosecond electron beam bunch length, optical stochastic cooling experiment, timing jitter measurement of photocathode injector, and proposed experiment of measuring micro-bunching of IFEL accelerator. Working group IV also carried out extensive discussion on the longitudinal and transverse emittance characterization of short (sub-picosecond) low emittance (normalized rms emittance < 1 mm-mrad) electron beam, and beam diagnostics requirements for Muon collider.

I. INTRODUCTION

With successfully experimental demonstrations of first generation of laser plasma[1], Inverse Cerenkov[2], and Inverse Free Electron Laser (IFEL)[3] accelerators, generation and characterization of ultra-short, low emittance electron beams for the future laser accelerators now become one of the major challenges for advanced accelerator research. The proposed X-ray FEL by SLAC and DESY also have similar requirements. The charge of the working group IV at Seventh Advanced Accelerator Concepts (AAC) is to discuss the resent developments in Beam Monitoring, Conditioning and Control, and identify critical areas of future research.

The works reported in the working group IV is first summarized in this report. Three discussion secessions were held on longitudinal emittance measurement, transverse emittance characterization, and Muon collider beam diagnostics. Following sections reflected my personal view of the discussion. There are many important developments in beam diagnostics are not discussed in our working group due to both the time limitation and participants' interests, such as nanometer beam size measurement [4] and sub-micrometer beam position monitors [5].
II. SUMMARY OF WORKS REPORTED

Table 1 summarized the subjects covered by the talks presented in working group IV. The three talks on the transverse emittance measurement discuss three different techniques of emittance measurement. J. Power of ANL [6] discuss how using quad scan technique measuring the emittance for space-charge dominated beam. Including space charge effect in the envelope equation instead of traditional matrix formula, the measurement agreed reasonably well with the beam emittance.

Table 1: Summary of the talks presented at working group IV.

<table>
<thead>
<tr>
<th>subject</th>
<th>Number of talks</th>
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<tbody>
<tr>
<td>Transverse Emittance Measurement</td>
<td>3</td>
</tr>
<tr>
<td>Pulse length and longitudinal emittance</td>
<td>4</td>
</tr>
<tr>
<td>measurement and technique</td>
<td></td>
</tr>
<tr>
<td>Beam Conditioning- Optical Stochastic Cooling</td>
<td>1</td>
</tr>
<tr>
<td>Timing Jitters Measurement</td>
<td>1</td>
</tr>
<tr>
<td>Muon Collider Beam Diagnostics</td>
<td>1</td>
</tr>
</tbody>
</table>

Using transition and diffraction radiations for electron beam diagnostics were review by R. Fiorito [7]. The basic properties of TR and DR were first discussed, comparing with synchrotron radiation, the angular distribution of TR and DR are much broad, so the spatial resolution of TR and DR are mainly determined by the collection angle of the imaging optics. He presented preliminary data of OTR image from CEBAF 3.25 GeV beam. Data presented are consistent with wire scanner measurement and optical resolution limited, and smaller than self diffraction limits.

Four talks presented covered techniques of measuring wider spectrum of pulse length and longitudinal emittance. Y. Liu of UCLA presented an experimental scheme of measuring micro-bunches (<15 fs) produced by Inverse Free Electron Laser (IFEL) accelerator [8]. M. Uesaka of University of Tokyo discussed technique of using S-band linac and magnet compression system to produce sub-picosecond electron pulse and pulse length measurement using streak camera [9]. He pointed out the advantage of the streak camera for short pulse length measurement, such as the pulse structure and direct longitudinal emittance measurement in the dispersion region. D.H. Dowell of Boeing presented his experiment of measuring longitudinal phase space of 144 MHz photocathode RF gun at Bruyeres-le-Chatel [10], he reported first observation of longitudinal beam break up caused by the space charge effect in a RF gun. M. S. Zolotorev of LBNL
discussed a new technique of measuring short electron beam pulse length [11], the technique based on measuring the visibility fluctuation of incoherent radiation interference fringe and statistical analysis to reconstruct the pulse shape. The main advantage of this technique allows the measurement carried out in the visible and x-ray region, where sensitive detectors are readily available.

The only paper discussed beam conditioning was given by A. A. Zholents of LBNL. He first discussed basic principle of transit-time method of optical stochastic cooling [12] and its advantages, it can cool both transverse and longitudinal phase space simultaneously with wider band-width comparing microwave stochastic cooling. An experiment is under construction at LBNL to test the tolerance of optical stochastic cooling on the synchronization and phase mixing.

Other talks presented in the working group are timing jitter measurement in the RF gun injector and beam diagnostics requirements for Muon collider. R. Fernow of BNL gave an outline of the future Muon collider and basic beam parameters. The discussed followed the talk focused on the emittance measurement and background produced by the Muon decays. Emittance on-line monitoring is critical for the success of the Muon collider, the main challenge in Muon beam diagnostics is the large number of electrons produced by the Muon decay \((10^7)\) and the background associated with for both beam position and profile measurement. The author discussed four different techniques of measuring timing jitters of photocathode RF gun injector, the timing jitters resolution of 0.5 ps has been experimentally demonstrated using quarter-wave length beam position monitor [13].

III. SURVEY OF SUB-PICOSECOND BUNCHLENGTH MEASUREMENT TECHNIQUES

To facilitate discussion about sub-picosecond electron bunch length measurement, table 2 summarize the electron bunchlength requirements for various frequency linacs and laser accelerators based on the requirement of the energy spread smaller than a few percents. For FEL, wakefield control and other beam dynamics studies, the bunch shape and longitudinal emittance is also the important issue for consideration.
Table 2: Typical pulse length for advanced accelerator applications.

<table>
<thead>
<tr>
<th></th>
<th>Time Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-band Linac</td>
<td>500fs - 10 ps</td>
</tr>
<tr>
<td>30 GHz Linac</td>
<td>100fs - 1ps</td>
</tr>
<tr>
<td>90 GHz Linac</td>
<td>&lt;200 fs</td>
</tr>
<tr>
<td>X-Ray FEL</td>
<td>≈100 fs</td>
</tr>
<tr>
<td>CO₂ Based IFEL, ICA</td>
<td>&lt;15 fs</td>
</tr>
<tr>
<td>Plasmas Based Laser Accelerators</td>
<td>10 fs - 1 ps</td>
</tr>
</tbody>
</table>

Table 2 shows that bunchlength required for most advanced accelerators and X-ray FEL applications in the range a few femto-seconds to sub-picosecond, the techniques either demonstrated or have the potential measuring the sub-picosecond bunchlength are discussed in the remaining part of this section.

Time Domain: The only technique in the time domain now has the capability of measuring sub-picosecond pulse length is streak camera, the state of art streak camera is represented by FCS-200 streak camera manufactured by Hammmasu, it has resolution of 200 fs (FWHM). Using streak camera for charge particle beam measurement involved first production of radiation, and image the radiation onto the streak camera. Many forms of radiation, such as synchrotron radiation, Cerenkov radiation and transition radiation, can be used to produce the bunchlength information of the beam. Care must be taken for sub-picosecond measurement, such as dispersion of the optics and the source effect must be minimized. Transition radiation is the choice for very short bunch length measurement because of its promptness. For sub-picosecond measurement, synch-scan streak camera is required. Streak camera has played an important role in short bunch length characterization in both circular[15] and linear accelerators[16], its measurement is direct and single shot, it is capable of measuring the charge distribution within the bunch. It can also measure the longitudinal phase space if the radiator located in the dispersion region. The main disadvantage of the streak camera is that it is an expensive equipment, it requires large amount of charge and small dynamics range. Using RF deflector technology, it is believed that streak camera resolution will reach 50 fs (FWHM) in a few years.
Frequency Domain: Techniques considered in the frequency domain can be further divided into coherent and incoherent radiation.

Coherent Radiation: The total radiation power generated by a bunch of N charge particles can be expressed as,

\[ I_{\text{co}}(\omega) = I(\omega)[N + N(N-1) F(\omega)] \]  

where \( I(\omega) \) is the single electron radiation power and,

\[ F(\omega) = |\int d\mathbf{r} S(\mathbf{r}) e^{ikr}|^2 \]  

is the Fourier transform of three-dimensional beam distribution \( S(\mathbf{r}) \). The first part of Eq(1) is the incoherent radiation and second part is coherent radiation. It is coherent radiation contains the bunch length information, and coherent radiation wavelength is comparable with the bunch length. There are two techniques used coherent radiation to extract electron beam bunch length information. The first one use the auto-correlation method proposed by W. Barry of CEBAF to measure the bunch length, a Michelson interferometer with one arm on the movable translation stage was developed at Stanford, the interferogram is the direct measurement of the bunch length [16]. It was reported as short as 100 fs (rms) bunch length was measured with resolution of 30 fs [16].

Another way of extract bunch length information from coherent radiation is the frequency analysis using Kramers-Kronig relation [17], by measuring the coherent radiation over wide frequency range, it is possible to extract both the amplitude and the phase information of the radiation source applying a Kramers-Kronig relation to the spectrum form factor to find the minimum phase. The reported resolution of frequency analysis techniques is on the order of 50 fs [18]. Using coherent radiation to obtain the bunch length information has many advantage, such as its simplicity and demonstrated capability in sub-picosecond to femtosecond resolution. Since radiation usually range from mm to IR, the detector will be major challenge for advanced accelerator applications due to small number of electrons (10^7).

Incoherent Radiation: Fluctuational Interferometer technique discussed in the previous section [11] measuring the incoherent radiation interference fringe visibility fluctuation to extract the bunch information. Since the radiation must be incoherent, the working spectrum will be in visible and x-ray regions, and measurement could be single shot. This techniques will be soon tested at beam test facility of LBNL.

All frequency domain techniques are limited by the bandwidth of the detector and optical system, the reconstruction bunch information suffers the incompleteness of the information, and hence the detailed structure of the bunch distribution maybe lost. It is very important in the near future to compare the
frequency domain techniques with streak camera measurement in the sub-picosecond scale experimentally.

**RF deflector cavity and Linac based techniques:** RF cavity operating in the TM_{110} mode have been used for electron beam bunch length measurement in many facilities [19,20]. The principle of using RF deflector cavity for bunch length measurement is similar to the streak camera. The fields of the cavity can be described by,

\[
E_x = E_0 \cos\left(\frac{\pi x}{a}\right) \sin\left(\frac{2\pi y}{d}\right) \cos \omega t
\]

\[
H_x = -\frac{\lambda}{d} E_0 \cos\left(\frac{\pi x}{a}\right) \cos\left(\frac{2\pi y}{d}\right) \sin \omega t
\]

\[
H_y = -\frac{\lambda}{2d} E_0 \sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{2\pi y}{d}\right) \sin \omega t
\]

where \(a\) and \(d\) are \(x\) and \(y\) dimensions of the cavity, on axis particles pass through the cavity suffer a vertical (\(y\)) kicker, and the amplitude of the kick depends on the relative phase between the cavity RF fields and the particles. The angular kick will translate into vertical displacement after a drift distance, hence by measuring the beam size increase in vertical dimension we can obtain the bunch information of the particles. One of the advantage of using RF kicker cavity is that it can be very accurately calibrated by varying the phase of the RF and measuring the centroid variation of the beam [20]. The resolution of the RF kicker cavity depends on the location (beam optics) of the cavity and the emittance of the beam, sub-picosecond resolution were reported for both L-band and S-band cavity[19,20].

There are several techniques to obtain electron beam bunch information using the RF linac. The energy spread of the beam near the beam crest can described by,

\[
\frac{\Delta E}{E} = \frac{1}{8} \Delta \phi^2
\]

where \(\Delta \phi\) is the electron beam bunch length measured in the RF phase spread. A technique developed at BNL accelerator test facility using linac can measure the charge distribution within the bunch with half picosecond resolution [21]. The linear energy chirp was first produced by dephasing the linac about 30 degree from the crest, and the chirped electron was pass through a dipole magnet and energy selection slit, the opening of the slit and the beam emittance determine the resolution. The distribution of charge was measured by a beam position monitor after the energy selection slit as the different sections of the beam were passed through the slit by varying the linac phase. This technique has the advantage of large dynamics range, hence can measure the detailed structure of the bunch.

Another technique of using linac to measure the electron beam longitudinal phase space using tomographic technique [22]. The energy spectra of the electron
beam were taken as the function of the relative phase between the beam and accelerating field, the longitudinal phase space of the electron beam was reconstructed using inverse Radon Transform technique. With the energy resolution of 0.1%, the resolution of the bunch length can be 250 fs.

**Laser based techniques.** With the dramatic increase in peak laser power, electron pulse length measurement based on the interaction between the electron beam and laser field, i.e. Compton scattering becomes more feasible[23]. The two techniques have been proposed are laser micro-probe[24] and Shintake laser heterodyne method[25]. Femtosecond laser with delay line was used to probe the electron pulse structure, if the laser pulse much smaller than the electron beam pulse length, the detected x-ray flux variation as laser relative the beam timing was varied give the longitudinal distribution of the electron beam. Experiment has demonstrated this technique has the sub-picosecond resolution [24]. The timing jitter between the laser and electron beam and transverse electron beam size are main limitation of resolution.

Another technique proposed by Shintake using two laser beams with different frequencies to generate the intensity modulation (beam wave), normal incident electron beam will produce x-ray flux due to Compton scattering, the fluctuation depth of the x-ray gives the Furies spectrum of the injected bunch. Scanning the frequency of the one laser allows measurement of wide spectrum of the bunch. All laser based techniques not only require powerful laser, but also laser number of electrons due to the small cross section of the Compton scattering process.

**IV. BEAM PROFILE MONITORING AND EMITTANCE MEASUREMENT**

Emittance is one of the fundamental parameters characterizing the charge particle beams. It determines the final spot size in the linear collider and the wave length of the X-ray FEL will be operating, emittance characterization always plays an important role in all accelerators development. In advanced accelerator research community, emittance measurement will become more critical for second generation laser acceleration experiment; for example, emittance preservation in the plasma based accelerators will determine its potential applications, and ultra-low emittance (normalized rms emittance < 10^{-8} mm-mrad) is required for structure based laser accelerators. There are many excellent reviews and lectures on the concepts and measurement techniques on the emittance [26,27], I will devote rest of this section on the importance of accuracy of emittance measurement and brief discussion on the several commonly used emittance measurement techniques.
The importance of emittance and accurately determine the emittance can be best illustrate using x-ray FEL application. To operate a FEL, the geometric emittance of the electron beam must satisfy the following conditions,

\[ \lambda = \frac{\lambda_w}{2\gamma^2} (1 + K^2 + \gamma^2 \theta^2) \]

\[ \lambda = \frac{\varepsilon}{4\pi} \]

where \( \lambda \) is x-ray wavelength, and \( \varepsilon \) is the geometric emittance. And using \( \varepsilon = \varepsilon_n / \gamma \) and FEL resonance condition, we have,

\[ \varepsilon_n = \frac{4\pi \lambda_w}{2\gamma} \]  

(5)

The gain of single pass FEL \( G \),

\[ G \propto B^{1/3} \approx 1/\varepsilon_n^{2/3} \]  

(6)

where \( B \) is the beam brightness. Equations (5) and (6) show that the beam energy and gain of FEL almost inverse proportional to the normalized beam emittance. Since the beam energy is linear proportional to the linac length, and the wiggler length is inverse proportional to the gain of FEL, the cost uncertainty of linac and wiggler is directly proportional to the uncertainty of the emittance measurement.

Since all transverse emittance measurement techniques involve determining both the beam spot size and its divergence angle. So accurately measuring emittance requires good accuracy in measuring both the spot size and angle. We can classify emittance measuring techniques two categories. The first one are usually involves measuring the beam profile only, such as multi-screen method, quadrupole magnet scan and pinhole method. The accuracy of emittance measurement are directly proportional to the resolution of the beam profile monitor, typical on the order of 50 \( \mu \)m. Using transition radiation, wire scanner and YAG crystal [28] may improve the beam profile resolution to the order of 10 \( \mu \)m. The accuracy of emittance measurement based on beam profile measurement also depends on the special arrangement because the divergence of the beam is derived from the beam profile information. For example, in three beam profile monitor techniques, the emittance measurement accuracy is directly determined by the separation between the beam profile monitors and the beam waist location [29]. Another good example is the quadrupole magnet scan techniques, the minimum spot size measured is directly proportional to the emittance, the divergence of the beam is basically determined by quadrupole current far from the minimum spot size. To measure the small divergence, the spot size of the beam image must be varied significantly, this require not only good resolution of beam profile monitor, but also large dynamic range. A 10 to 12-bit CCD camera with pixel size on the order of a few micron is needed for quadrupole magnet scan technique.
The second type of emittance measurement techniques can measure both the beam profile and angular divergence simultaneously. Such as transition radiation, diffraction radiation, synchrotron radiation and laser scattering. One of most successful technique so far developed for emittance measurement is the two-foil interferometer. It using optical transition radiation (OTR) to measure the beam profile while using interference pattern to measure the angular distribution[7]. The angular resolution of 100µrad was measured experimentally.

V. Acknowledgments

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VI. References

6. J. Power, these proceeding.
9. M. Uesaka et al, these proceeding.