Sub-millimeter Bunch Length Non-invasive Diagnostic Based on the Diffraction and Cherenkov Radiation

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Abstract. A layout for the investigation the coherent Cherenkov radiation from a dielectric target with a large spectral dispersion and the coherent diffraction radiation from a conducting screen as a tool for non-invasive longitudinal electron beam profile diagnostics are proposed for the 20–30MeV Linac at Shanghai Institute of Applied Physics (SINAP). In this paper the status of the joint experiment and future plans are presented.

1. Introduction
Non-invasive methods of the sub-millimeter bunch length diagnostics are very important nowadays for such facilities as free electron lasers with typical bunch lengths of some hundreds of femtoseconds. One of the ways to measure bunch length is based on coherent radiation that is generated at wavelengths comparable to, or longer than, the bunch length, when all electrons in the bunch irradiate more or less in phase. The intensity of coherent radiation is proportional to the square of the bunch population. The spectral distribution of the coherent radiation contains the information about the electron distribution in a bunch. Coherent Diffraction Radiation (CDR) and Coherent Cherenkov Radiation (CChR) are suggested as the mechanisms for coherent radiation generation due to their non-invasive nature.

2. Experimental setup
The future experiments will be performed at the facilities of the femtosecond accelerator in the SINAP. It generates a multi-bunch electron beam with 68 pC per bunch and 20–30 MeV energy electron beam. The main beam parameters are summarized in table 1.
To register a THz radiation the Golay Cell Type OAD-7 is proposed. This is the room temperature detector what makes it very attractive to use for accelerator physics and other application. It has excellent sensitivity and flat frequency response over a wide wavelength range. The detector parameters are presented in table 2.

**Table 1.** Electron beam parameters of SINAP linac facility

| Parameter                        | Value                               |
|----------------------------------|-------------------------------------|
| Electron energy                  | 20–30 MeV                           |
| Beam charge                      | 0.068 nC                            |
| Normalized emittance             | $\sim 10\pi$ mm·mrad               |
| Macro-bunch repetition           | 3.125–50 Hz                         |
| Micro-bunch repetition           | 2856 MHz                            |
| Macro-bunch duration             | 2–3 μs                              |
| Micro-bunch duration (FWHM)      | $\sim 250$ fs                      |

The linac consists of S-band thermionic RF gun, an alpha-magnet and the SLAC-type accelerating tube (figure 1). After pre-acceleration in the RF gun the electron beam is compressed by the alpha-magnet from few tens of picoseconds to few hundreds of femtoseconds. Then the electron beam is accelerated up to 20–30 MeV by the SLAC-type tube.

**Table 2.** Detector parameters

| Parameter                        | Value                               |
|----------------------------------|-------------------------------------|
| Optimal operating wavelength rage| $15 \div 1000$ μm                   |
| Response rate                    | 28 ms                               |
| Maximum signal input power       | 10 μW                               |
| System noise output @ 20 Hz      | $6.2$ μV·Hz$^{-1/2}$                |
| System optical responsivity @ 20 Hz | 29.7 kV/W       |
| Detector optical NEP (20 Hz)     | $208$ pW·Hz$^{-1/2}$                |
| Aperture diameter                | 6 mm                                |
| Window material                  | HDPE                                |
3. CChR for bunch length measurement

In conventional case Cherenkov Radiation (ChR) is emitted when the charge particle travels inside the medium with velocity that exceeds the speed of light in this transparent medium. The radiation cone in this case is defined by the following condition:

\[ \cos \theta = \frac{1}{n \beta}, \]

where \( \theta \) is the radiation angle, \( \beta \) is the electron velocity in the speed of light units, \( n \) is the refracted index.

ChR may also appear while a particle travels in the vacuum in a vicinity of the medium due to the fact that ChR is generated due to dynamic polarization of the medium by the charged particle’s electromagnetic field [1–3]. For the high-energy particles, the Lorentz-boosted electromagnetic field has the transverse dimension of about \( \gamma \lambda \) (\( \gamma \) is the particle Lorentz-factor, \( \lambda \) is the radiation wavelength).

If a dielectric medium has a frequency dispersion, the different wavelength would be radiated under different angles. One may change the complicated spectral measurements by more convenient angular ones in order to obtain bunch form-factor and the bunch length.

Target made from CsI will have large frequency dispersion in THz region [4]. Manufacturing such a Cherenkov target as prism one may obtain wide angular distribution that may be measured with good accuracy. The dependence of the CsI refractive index on the frequency from [4] is presented in figure 2.

![Figure 2. Refractive index dependence on frequency for CsI.](image)

To calculate the target geometry for arrangement of experiment it is needed to use the frequency dependence, the Cherenkov criterion and the Snell’s law. One may write \( \frac{d\eta}{dn} = \frac{d\eta}{df} \times \frac{df}{dn} \), where \( \eta \) is the observation angle, \( f \) is the frequency and \( n \) is the refracted index. To determine the target geometry, the maximum reasonable value of \( \frac{d\eta}{dn} \) should be used. The calculated \( \frac{d\eta}{dn} \) dependence on the angle of prism using the data from figure 2 is shown in figure 4. Thus, for the experimental target shown in figure 3 the optimal prism angle \( \alpha \) is equal to 45 degree.
There are many brands of the same dielectric material, which can differ from each other in a number of characteristics (e.g. content of admixture, fabrication method etc.), consequently, different brands may have different properties including the refractive index. For joint experiments three different dielectric targets were manufactured. Therefore we are going to measure the dielectric targets spectral dispersion in the THz region prior to start experimental research. The materials and dimensions of the targets are listed in table 3.

| Material        | Dimension a , mm | Height, mm | Angle α , degree |
|-----------------|------------------|------------|-----------------|
| Pure CsI        | 40               | 40         | 45              |
| Impure CsI (Tl) | 40               | 40         | 45              |
| PbF2            | 30               | 30         | 45              |

The theoretical angular distribution was simulated for parameters of the SINAP linac and characteristic of the CsI Cherenkov target using the universal model describing polarization radiation mechanism [5] (figure 5).

**Figure 3.** Experiment scheme.

**Figure 4.** Calculated $\frac{dn}{d\eta}$ dependence on the angle $\alpha$ of Cherenkov prism.

**Figure 5.** Calculated angular distribution of CChR from the CsI target for electron bunch energy 20 MeV, bunch length 75 μm and $\lambda = 0.04 \div 10$ mm.
4. CDR for bunch measurement

Diffraction Radiation (DR) appears when a relativistic charged particle moves in the vicinity of a medium (or target) with some impact parameter comparable to or smaller than the charged particle field area. The particle field polarizes the target atom thereby induced currents changing in time, which in turn give rise to DR.

Bunch length may be reconstructed from a coherent radiation spectrum. The interferometers, e.g. Michelson, Mach-Zender, Fabry-Perot, Martin-Puplett, which are used for this purpose are very cumbersome and expensive. The design of simple interferometer consisting of two CDR aluminium targets from both side of beam is suggested (figure 6). Moving one of these targets it is possible to measure some kind of interferogram without any additional spectrometer equipments.

The theoretical curves of interferograms measured by detector placed at distance 153.2 mm from CRD target were simulated using the developed DR model [6] (figure 7).

![Figure 6. Scheme of CDR interferometer.](image)

![Figure 7. Theoretical calculated interferograms for electron bunch energy 20 MeV, $\text{\lambda} = 0.04 \pm 2$ mm and different values of bunch length.](image)

Main part of information about the bunch length is grouped in the first oscillation of the interferogram. Therefore we may try to build a criterion for the bunch length estimation using this part of interferogram. If we define the interferogram function as $S(L)$, then the simplest criterion may be represented using the dimension theory as $\sigma_z = f(x)$, where $x = \left( \frac{S(L)}{\frac{dS(L)}{dL}} \right)_{L=L_{\text{max}}}$, $L_{\text{max}}$ is the value of variable $L$ in the point of maximal $\frac{dS(L)}{dL}$, $\sigma_z$ is the bunch length in Gaussian approximation of the longitudinal distribution of electrons in bunch, the function $f(x)$ is yet undefined.

For definition of this function we calculated the dependence $x(\sigma_z)$ from theoretical curves of interferogram in Gaussian approximation of the longitudinal distribution of electrons. Finally with a good accuracy was obtained $\sigma_z = x$.

5. Conclusion and future plan

In conclusion, it is worth pointing out that CChR generated by the ultra-relativistic electron bunch passing near a target with frequency dispersion and CDR generated by a DR target consisting of the two planar shifting halves seem to be a promising non-invasive mechanisms to estimate the length of bunch without additional spectrometers. The next step is to carry out experiments at the Shanghai linac facilities during May 2012.
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