DIAGNOSTIC CONCEPT FOR HIGH-RESOLUTION TEMPORAL PROFILE MEASUREMENTS

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Abstract

The diagnosis of the temporal profile and length of high brightness electron beams is very important in advanced accelerator facilities and next generation light sources. A novel diagnostic scheme to reach temporal resolutions exceeding 1 femtosecond has been studied recently [1]. The scheme entails imposing an angular modulation on the electron beam by interaction with a high power laser in an undulator field. A subsequent deflection in the orthogonal dimension, provided by an RF cavity, generates a streak on a downstream screen. The observable pattern is now correlated to the beam longitudinal profile. In this paper, we present a test case for this scheme using the parameters of the Brookhaven National Laboratory Accelerator Test Facility (BNL ATF). The components of the proof-of-principle experiment are presented.

INTRODUCTION

There are a variety of techniques to measure the bunch length and profile of high brightness electron beams. There are many measurement techniques in the frequency and/or time domain, such as the autocorrelation of emitted coherent radiation from short bunch beams [2, 3], RF deflectors [4], and the optical replica synthesizer [5]. These methods are robust and well-studied however they are limited in temporal resolution to ~10 fs. Extending the resolution down to sub-fs scales is challenging but feasible under the appropriate conditions.

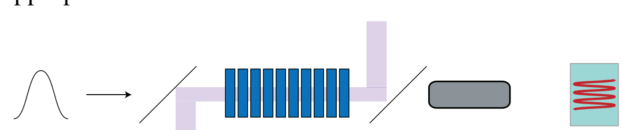

Figure 1: Layout of the diagnostic scheme. The electron beam interacts with a high power laser, operating in the TEM_{10} mode, in an undualtor field imposing a modulation on the beam. The RF deflector provides a vertical streak to resolve this modulation on a distant screen. The transverse distribution on the screen is sinusoidal and directly correlated to the bunch length of the beam.

Recent analytical and simulation work has demonstrated that achieving sub-fs temporal resolution is feasible using an enhancement to an existing RF deflector [1]. This scheme is described in detail in Reference [1] and summarized here. An angular modulation that is sinusoidally dependent on the beam bunch coordinate is imposed based on the interaction between a high power, long-wavelength laser operating in the TEM_{10} higher-order Gaussian mode and a high-brightness electron beam. The interaction takes place in a few-period planar undulator. The angular modulation of the beam is given by [6]

$$\Delta x' = \frac{2K}{\gamma^2}\sqrt{\frac{P_L}{P_0}}\,[JJ]\,f(L_u, z_0, \mu)\sin(ks_0+\phi) \quad (1)$$

where, K is the undulator parameter, γ is the relativistic Lorentz factor, $k = 2\pi/\lambda$ is the laser wavenumber, P_L is the laser power, s_0 is the initial beam bunch coordinate, ϕ is the phase, $[JJ] = J_0(K^2/(4+2K^2) - J_1(K^2/(4+2K^2)$ and f is a function that depends on the undulator length, L_u, the laser Rayleigh range, z_R, and the beam detuning ratio, μ. It is important to note that the amplitude of the modulation scales as $\sim \sqrt{P_L}/\gamma^2$ which are optimization parameters for the design of the proof-of-principle experiment.

An RF deflector immediately downstream provides a streak in the orthogonal dimension, allowing the resolution of the sinusoidal modulation on a distant screen. The angular coordinate is converted to a position on the screen. The bunch coordinate is correlated to the trace along the sinusoidal curve, in contrast, the RF deflector alone provides a streak where the bunch coordinate is correlated to the transverse coordinate.

The temporal resolution is determined by the amplitude of the imposed angular modulation. It can be formally written as

$$\Delta t = \frac{\epsilon_n}{\gamma\sigma ckA} \quad (2)$$

where ϵ_n is the normalized transverse emittance, σ is the rms transverse beam size, A is the amplitude of the modulation defined in Eqn 1.

The limits of the temporal resolution have been studied for the beam and laser parameters at the UCLA Neptune facility and the SLAC NLCTA facility and shown that Δt can reach 200fs with use a low-emittance beam and a high-power, long wavelength laser [1]. The proof-of-principle experiment has been planned for the BNL ATF where similar analysis shows that sub-fs temporal resolution is achievable with the available beam parameters.

BNL ATF TEST CASE

The Brookhaven National Laboratory Accelerator Test Facility (BNL ATF) incorporates a high-brightness electron beam for advanced acceleration applications. The nominal operating charge is 500pC, with an energy variable from 44-90MeV and normalized emittance of 1mm-mrad. The BNL ATF also employs a high-power (GW-TW class) CO_2 laser for experiments in laser-electron beam interactions The BNL ATF also has the x-band RF infrastructure for a transverse deflecting cavity in place to study the diagnostic scheme. The parameters used for the Elegant [7] simulations in the BNL ATF scenario are listed in Table 1.

Table 1: Parameters used for Elegant Simulations

Parameter	Value
Beam Energy	44 MeV
Charge	500 pC
Normalize Emittance	1 mm-mrad
Undulator Peak Field	1.06 T
Undulator Period	3.0 cm
Undulator Parameter	3.0
Unulator Length	30 cm
Laser Power	300 MW
Laser Wavelength	10.6 μm
Deflector Voltage	8 MV
Deflector Wavelength	2.6 cm

The laser parameters used in simulations are conservative and the BNL ATF has demonstrated the generation of TEM_{10} mode in prior inverse Cerenkov acceleration experiments [8]. The undulator parameters are chosen to match the resonant condition for the beam energy and laser frequency. In this case, the undulator is similar to the Linac Coherent Light Source (LCLS) at SLAC (3cm period, 1.06T peak field). However, the number of periods required for the interaction is only 10 corresponding to a total length of 30cm. For this parameter set, simulations show that the angular modulation has a peak amplitude of ~0.2mrad (Figure 2).

The transverse deflecting cavity parameters are identical to the cavity that will be installed at the BNL ATF in 2012. The cavity has a total length of 46cm and operates at x-band frequency ($\lambda_{RF} = 2.6$cm). The beam operates at zero-crossing to streak the beam i.e. correlate longitudinal position to transverse. After modulation with the laser in the undulator, the beam is deflected in the cavity and transported to a distant screen. A simulated image of the transverse distribution on the screen is shown in Figure 3. For the BNL ATF parameters, the resolution as defined in Eq.2 is approximately 600 attoseconds. Note this distribution is similar to the distributions shown in Ref. [1].

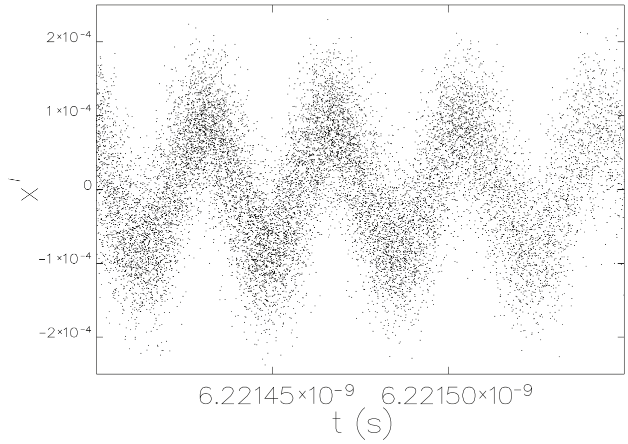

Figure 2: Angular modulation of beam after interaction with laser in the undulator (simulation). The peak amplitude is 0.2mrad.

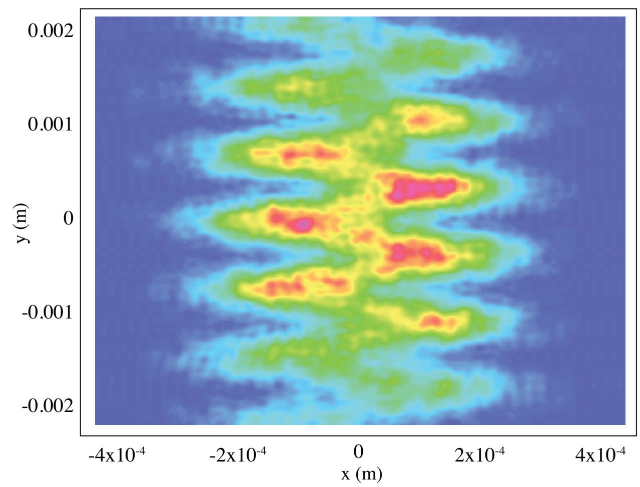

Figure 3: False-color transverse distribution at the observation screen (simulation). The bunch coordinate is encoded onto the sinusoidal trace in transverse space.

CHALLENGES AND CONCLUSIONS

The temporal profile of the beam is encoded in the sinusoidal curve and provides an enhanced resolution over the deflector alone if a few constraints are met. First, the beam size at the screen must be smaller than the unperturbed beam size at the screen due only to a drift. The angular modulation must be larger than the intrinsic beam divergence. This may require the use of collimators for specific examples. For the BNL ATF simulation studies, a 100μm collimator is placed at the entrance of the undulator to effectively reduce the emittance, and beam spot size, in order to resolve the pattern. This reduces the transmission of the total charge to the screen to about 10%, or 50pC, which is still observable using standard imaging optics. In addition, the laser wavelength must be long enough to allow adequate resolution of the pattern on successive sweeps. This is why the CO_2 (period $\simeq$30fs) laser is considered for practical application of this scheme.

The resolution is not linear throughout the screen. In fact, at the turning points of the sinusoidal curve, the resolution is not better than a deflector alone. This is due to a smearing effect caused by the beam size. Resolution enhancement is provided only at the near-linear part of the pattern. In order to mitigate the "low-resolution", one would need to shift the phase by $\pi/2$ to move the beam from the turning points, to the "high-resolution", near-linear part of the trace. For a CO_2 laser, this corresponds to a shift of $\sim$15fs, which is within the jitter fluctuations of most systems anyway. Successive data acquisition at multiple shots, with random phases, can recreate the longitudinal profile with very high resolution.

Other practical considerations include the generation of the TEM_{10} mode at high power. The suppression of the fundamental (TEM_{00}) mode is essential because any leakage of this mode may cause regenerative amplification that would smear the desired effect. Also, the diagnostic system used to resolve the observation screen should have adequate spatial resolution using optical transition radiation (OTR) screens or scintillators. For the BNL ATF case, the spatial resolution should be better than $\sim 15\mu$m.

The diagnostic scheme described has the ability to improve upon the temporal resolutions provided by the state-of-the-art x-band deflectors to beyond the femtosecond level. The proof-of-principle experiment planned for the BNL ATF has the potential to demonstrate <fs resolution with available hardware and minor improvements. A main drawback of the scheme is that in its current state it is only applicable to low-moderate energy beams ($\gamma < 200$) due to the scaling of the modulation with $1/\gamma^2$. Methods to overcome this limitation and employ this scheme for GeV beams are presently being considered.

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