ULTRASHORT BUNCH LENGTH DIAGNOSTIC WITH SUB-FEMTOSECOND RESOLUTION

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Abstract

Fourth generation light sources require the observation of sub-picosecond bunches with femtosecond resolution for successful operation and beam characterization. In this paper, we report on the conceptual design of a novel technique to achieve sub-femtosecond temporal resolution of high brightness bunches. The technique involves the coupling of the electron beam to a high power laser in an undulator field, which is optimized to maximize the angular deviation of the bunch. The beam angular components are imaged on a distant screen yielding a sweep across angles in one dimension. The addition of an x-band deflecting cavity downstream of the undulator creates another sweep of the beam, in the perpendicular dimension. The temporal resolution of the bunch is dependent on the seed laser wavelength and the spatial resolution of the screen. Initial calculations show that for a CO_2 laser (T$\sim$30fs) and a phosphor screen ($\sim$50μm spatial resolution), the longitudinal resolution is approximately l/200th of the laser wavelength, or $\sim$150 attoseconds.

INTRODUCTION

The Linac Coherent Light Source (LCLS) [1], and other next generation light sources and user facilities, employ magnetic chicane bunch compressors, or velocity bunching techniques [2], to achieve short pulses without compromising transverse emittance quality. These facilities require the ability to observe sub-picosecond bunches with a resolution on the order of tens of femtoseconds. The measurement of these short pulses with ultra-short time resolution is essential for successful beam operation, performance optimization, and benchmarking to computational models. Also, the attainable resolutions are essential to study phenomena on the ultrashort length and ultrafast time scales (e.g. space-charge driven microbunching instability that has recently led to observation of coherent optical transition radiation [3]).

Present bunch length diagnostics rely on electro-optical techniques [4], deflecting cavities [5], or deconvolution of the frequency spectrum of emitted radiation sources [6, 7], but are limited to resolutions of $\sim$10fs. The UCLA-RadiaBeam collaboration has designed a concept to surpass the femotsecond barrier and develop a diagnostic that can attain a temporal resolution on the order of 100 attoseconds. The bunch length diagnostic scheme utilizes a novel technique of coupling the electron beam to a high power laser to enforce an angular modulation in the beam. The angular modulation is observable, with standard beam profile imaging techniques, on a distant screen. The sweep traced out by the beam on the screen is proportional to the beam bunch length. The proposed scheme provides a temporal resolution on the sub-fs scale.

The diagnostic consists of a few-period undulator, a high-power polarized laser, and an RF deflecting cavity. The undulator and laser electric field provide the angular modulation on time scales of a fraction of the laser wavelength (λ=10.6μm for CO_2), while the RF deflector (λ_{RF}=2.6cm for x-band) provides a slow resolution yielding detailed information about the beam longitudinal characteristics (Figure 1).

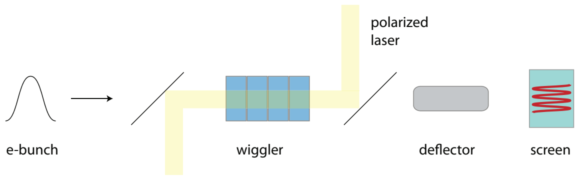

Figure 1: Conceptual schematic to measure ultrashort bunches. The undulator provides the coupling between the particles and the laser mode, creating an angular modulation in the beam (horizontal dimension). The RF deflector provides a much slower angular modulation perpendicular to the modulation generated by the laser (vertical). A snake-like pattern is observed on a downstream screen. The total length of this curve corresponds to the beam bunch length.

BUNCH LENGTH DIAGNOSTIC

The design of the bunch length diagnostic is constrained to available space at the Neptune facility which is approximately 1.5m after the final focusing triplet (Figure 2). The diagnostic line consists of the planar undulator, two mirrors with holes for copropagating the laser and allowing the beam to pass, the deflecting cavity, and a phosphor screen with appropriate imaging.

The Neptune facility has a history of exploring laser-electron interactions and recently demonstrated harmonic microbunching [8] using a similar undulator. The operating parameters of the Neptune facility are given in Table 1.

Undulator

The diagnostic scheme is based on the interaction between a CO_2 laser and an electron beam in a planar un-

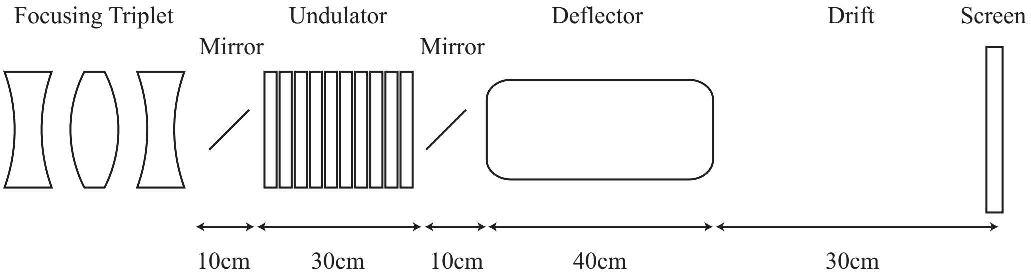

Figure 2: Layout of the experiment with approximate distances at the Neptune laboratory. The entire line is constrained to 1.2m after the focusing quadrupoles.

Table 1: UCLA Neptune Parameter Table

Beam Energy, E	12.3 MeV
Undulator Parameter, K	1.8
Undulator Period, λ_u	3.3 cm
Undulator Length, L_u	33 cm
Laser Wavelength, λ	10.6 μm
Laser Power, P_L	$\leq$200 MW

dulator field. The angular modulation of an electron beam interacting with the TEM$_{10}$ Hermite-Gaussian laser mode in the presence of a planar undulator field is given by [9]:

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

where ct is the coordinate along the bunch, K is the undulator parameter, P_L is the laser power, $[JJ]$ is the sum of Bessel function dependent only on K, and f is a function dependent on the undulator length, L_u, and Rayleigh length, z_0. Using the UCLA Neptune laboratory parameters (P_L=200MW, K=1.8, E=12MeV), the maximum angular modulation (Eqn. 1) of the beam due to the interaction is $\Delta x'$ =2.2mrad. For a screen placed 80cm away from the undulator exit (Figure 2), the beam sweeps out a horizontal line that is 3.5mm long. A traditional electron detection diagnostic (such as Ce:YAG, phosphor, or micro-channel plate), has a spatial (granular or pixel) resolution on the order of ~30μm [10]. Therefore the electron horizontal sweep (~15fs total) across such a screen has a temporal resolution of ~150 attoseconds.

Achieving such a temporal resolution using the electron beam-laser interaction is novel and innovative for a bunch length diagnostic. However, it does restrain its applicability to real-world beams because beams shorter than 15fs have yet to be realized. The shortest available beams created using ultrafast lasers are on the order of tens of fs, while practical bunch lengths (using compression schemes) are on the order of sub-ps [11]. Practical service to real-world beams requires one additional step in the diagnostic scheme - the deflection of the beam in the perpendicular direction to resolve the slow component (sub-ps). This is achievable with the addition of an RF deflecting cavity downstream of the undulator. Preliminary calculations using a novel x-band structure (λ_{RF}=2.6cm, V_{def}=8MV), show that the sweep along the slow dimension is approximately $\Delta y'$=0.8mrad for a screen placed 50cm away from the center of the cavity (see next section).

Deflecting Cavity

One challenge of converting a beam angular modulation into a spatial observable on a screen is the fact that the electrons would retrace their sweep if the motion were restrained to one plane, as it is with a planar undulator. To address this issue, an angular kick is imposed on the beam in the perpendicular (vertical) dimension, with a much longer, or slower, resolution. The RF deflecting cavity is a suitable choice for the implementation of this trajectory deviation. In the previous section, it was shown that the total sweep across the horizontal plane is 15fs. The vertical sweep (beam centroid-centroid position) can be analogously determined using values from a novel x-band traveling wave deflecting cavity. The angular deflection in the vertical dimension is given by [12]:

$$\Delta y' = \frac{1}{\gamma mc^2}\frac{2\pi}{\lambda_{RF}} eV_{def}\Delta z, \quad (2)$$

where λ_{RF} is the RF wavelength of the cavity, V_{def} is the deflecting voltage, and Δz is the separation of the centroid position along the path of the trace (for 10.6μm CO$_2$ lasers, this value is 5μm). For an X-band traveling wave deflector (XTD), λ_{RF} =2.6cm, and with some additional modifications to the existing design, V_{def} can reach a value of ~8MV [13]. Using these parameters, we determine that the vertical angular sweep is $\Delta y'$=0.8 mrad. Referring to the distances of Figure 2, the distance from the center of the cavity to the screen is 50 cm. This corresponds to a vertical separation of 400μm from beam centroid-centroid on consecutive sweeps.

For acceptable vertical resolution, the full beam size must be smaller than this vertical separation. This imposes another constraint on the system, namely the beam spot size focusing (discussed in the next section).

The deflecting cavity for this experiment has a parameter set similar to one currently being built (Figure 3), with testing, installation, and commissioning planned at the Brookhaven National Laboratory Accelerator Test Facility

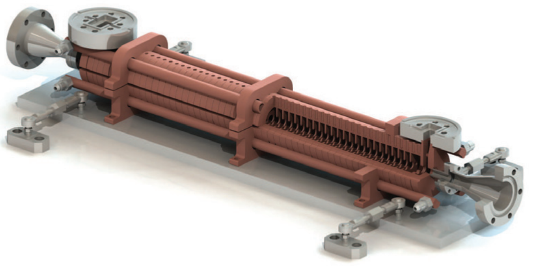

Figure 3: A rendering of the x-band traveling wave deflector produced by RadiaBeam with planned installation at the Brookhaven National Laboratory Accelerator Test Facility. A similar type deflector is considered for this bunch length diagnostic scheme.

[14]. Although some modifications will be needed to install into the Neptune beamline, the overall lengths and voltage requirements are roughly equivalent.

Beamline Optics

To completely resolve the beam the separation between sweeps must be significantly greater than the rms beam size otherwise a smearing effect would make the data incomprehensible. The beam emittance, and thus transverse rms size, must be small enough (in both transverse dimensions) such that the consecutive sweeps across the screen are resolvable. The focusing system is constrained to ∼1m for practical implementation and prototyping; therefore, the focal length of the focusing array (i.e. the quadrupole triplet) must be on the order of 1m, and placed just upstream of the undulator. This constraint is achievable within the existing infrastructure of the UCLA Neptune facility.

In the prior section we demonstrated that a vertical beam centroid separation of 400μm is readily achievable with the assumed deflector parameters. Now we consider that $\Delta y > 8\sigma$ for adequate resolution (i.e. 8 times the rms beam size). Practically, in the following calculations, we require a beam width of 8σ separation across each vertical center sweep. This corresponds to a beam size of $\sigma^\star$=50μm, at the screen. The corresponding β-function is given by

$$\beta^\star = \frac{\gamma\sigma^\star}{\epsilon_n}, \tag{3}$$

where ϵ_n is the normalized emittance of the beam (ϵ_n=1×10^{-6}m-rad for the Neptune beam). This corresponds to a $\beta^\star$=6cm at the screen. From Figure 2, the distance from the focusing triplet to the screen is approximately 1m (i.e. the focal length is f=1m). The initial β-function is given by,

$$\beta_0 \approx \frac{f^2}{\beta^\star}, \tag{4}$$

which corresponds to β_0=20m. For self-consistency, the initial beam size that corresponds to this value is σ_0=900μm. These beam spots are achievable in the Neptune facility with existing infrastructure [15].

CONCLUSIONS

Preliminary calculations of a novel bunch length diagnostic scheme show that a temporal resolution of ∼150 attoseconds is readily achievable with the current parameters at the UCLA Neptune facility. The diagnostic line operates on the laser-electron beam interaction in a planar undulator field coupled with a deflecting cavity to provide a two-dimensional sweep of the beam across a phosphor screen. The length of the sweep is directly proportional to the beam bunch length.

Future efforts will be directed at decoupling the transverse and longitudinal components of the beam, such as in the optical replica scheme [16], to generalize the applicability of the experimental findings for higher energy facilities and more complicated bunch distributions.

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