HELICAL MICROBUNCHING OF A RELATIVISTIC ELECTRON BUNCH

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Abstract

An experiment to generate and measure the helical microbunching of a relativistic electron beam into a helix is described. Helical microbunching occurs naturally when an e-beam interacts resonantly at harmonics of the combined field of a helical magnetic undulator and an axisymmetric input laser beam, ie, the first stage of an optical klystron setup. The bunched beam may then be used to generate coherent emission of light with orbital angular momentum at the microbunching wavelength.

INTRODUCTION

An electron beam that undergoes the free-electron laser (FEL) instability becomes microbunched in density and energy at harmonic wavelengths of the resonant interaction field. For relativistic beams in modern FEL structures, the microbunching wavelength, λ_b, can span from the far infrared to Å length scales. Once the beam is bunched, it can then travel to a downstream radiator and emit coherent radiation at the microbunching frequency that retains signatures of the microbunching structure. It is most common, in modern devices, to generate microbunching that is purely longitudinal, such that the e-beam is "sliced" into axisymmetric pieces along its length. In such a beam there is no correlation between the transverse and longitudinal positions of an electron, and the subsequent radiation will reflect this symmetry (though the radiation distribution will certainly depend on the type of emission process). In certain types of resonant modulator interactions, however, a correlated microstructure can be imprinted on the beam modulation. In particular, a helical corkscrew-like structure has been predicted to occur naturally at harmonics of the interaction inside a helical undulator[1], such that the electron beam becomes coiled like a spring (or multiply twisted springs, depending on the harmonic). This geometry reflects the structure of the resonant ponderomotive phase bucket wherever the beam interacts collectively with gradients of the resonant field structure that are symmetric about the longitudinal axis. The helically modulated beam can then be used to radiate coherent light with an azimuthal phase, either through the high-gain FEL process in a downstream undulator[2] or from transition radiation (TR) from a metal foil[3], or by other radiative processes. This light carries orbital angular momentum (OAM)[4] due to an azimuthal component of the linear photon momentum, and may be used in a myriad of purposes[5]. Since the wavelength of the OAM radiation is set by the microbunching wavelength, which is tunable according to the beam energy (other other design parameters), this suggests a method of generating OAM light over a large range of wavelengths.

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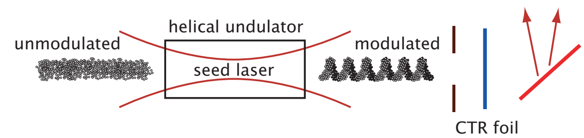

Figure 1: Experimental setup.

Here we describe experimental plans to investigate helical microbunching using a transversely gaussian (0^{th} order) CO_2 laser pulse and an electron beam in a short helical undulator (Figure 1). The undulator is tuned such that the λ =10.6 μm laser pulse is resonant with the second harmonic interaction of the 1.9 cm period undulator field with a 12.5 MeV e-beam (Table 1). The input laser spot is focused to a waist coaxial with the e-beam to produce a single-twist helix of the beam distribution. The structure of the beam will be diagnosed using coherent TR (CTR) from a metal foil immediately downstream. The helical phase of the radiation will be resolved interferometrically.

THEORETICAL MOTIVATIONS

This experimental proposal was borne from predictions of an analytic theory developed to describe the coupling and evolution of higher-order optical mode structures and the e-beam in an FEL[6]. The analytic model supposes that the e-beam modulation (with is assumed to be a cold, single-component plasma fluid) and the EM field can both be described by a superposition of transverse eigenmodes with discrete azimuthal dependence. In the presence of the field gradients, high-order effects lead to harmonic motion of the e-beam and thus coupling to frequency harmonics of the radiation field in a helical undulator. For an e-beam with negligible transverse betatron motion along the interaction length, the coupling between the different azimuthal modes at harmonics is

$$\mathbf{F}^{(h)}_{l_b,l_f} \propto 2\pi\delta_{l_f,l_b\pm(h-1)}. \tag{1}$$

where l_b (l_f) is the azimuthal mode number of the e-beam (field) and $\pm$ describes either a right (+) or left (-) handed magnetostatic undulator polarization. Thus, the second harmonic interaction (h=2) with a simple gaussian laser seed (l_f=0) in a short helical modulator will excite a $l_b = \mp 1$ helically microbunched beam, depending on the undulator polarization (Fig 1). We note that the coupling between the motion of the e-beam in the undulator and the input field is maximized when, for a fixed point in time,

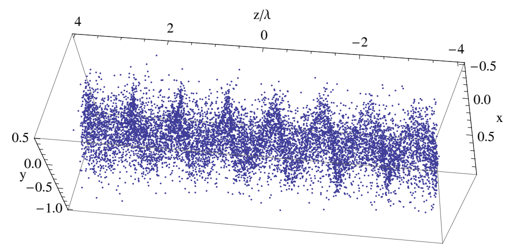

Figure 2: Section of e-beam calculated in TREDI for the parameters in Table 1 at the undulator exit.

Table 1: Experimental Parameters

Beam Energy	γ	25
Charge	Q	300 pC
Bunch length/size	σ_x, σ_z	250 μm, 300 μm
Norm. emittance	ϵ_n	4 mm mrad
Und parameter	K	0.58
Und period (12)	λ_w	1.9 cm
CO_2 wavelength	$\lambda \simeq \lambda_b$	10.6 μm
Laser spotsize	w_0	250 μm
Laser power	P	30 MW

the electric field of the circularly polarized input laser field evolves in the *opposite* sense as the magnetic field of the undulator.

The helical arrangement of the electrons stems from the adiabatic accumulation of phase as a function of the azimuthal coordinate. Since different portions of the electron beam encounter the peak of the field gradient at different positions along their circular orbits, they accrue an additional phase that corresponds to their position in the optical field. With axisymmetry of the gradient field, the single-twist helical arrangement therefore occurs naturally about the axis of a gaussian laser seed. This description applies in general to the resonant interaction in a modulator, and thus also extends directly to the coherent emission of intense radiation with a helical phase at harmonics of a helical undulator, since they are defined by the same coupling[7].

SIMULATIONS

Predictions from the analytic theory suggest that significant bunching can be achieved with only modest levels of input power, for the parameters described in Table 1. To check these results, numerical simulations have been performed using TREDI, a fully three-dimensional particle tracking code[8]. Results from simulation are in excellent agreement with the linear model description of linear bunching[1] provided that the bunching factor is small enough that the linear theory still applies ($b_{l_b}(z) < 40\%$). Beyond these values the linear theory is inadequate but still consistent with the main features of the simulations which show that the bunching into a helix can continue almost to unity, with negligible levels of microbunching into modes forbidden by the coupling "selection rule" in Eq. (1). A

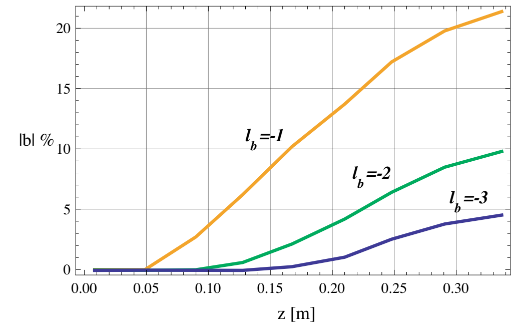

Figure 3: TREDI: Evolution of the azimuthal mode bunching factors along the interaction length. The undulator exit is at ∼26 cm, after which the drift allows the velocity modulation to turn into density modulations, and the bunching factors continue to increase.

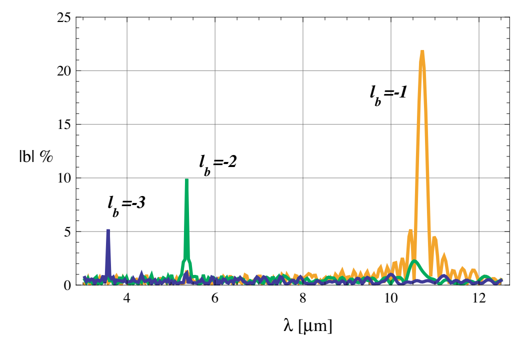

Figure 4: TREDI: Spectrum of the microbunching wavelength ∼10 cm from the undulator exit with 50000 particles.

section of the modulated beam just downstream of the undulator is shown in Fig. 2, where the helical structure is readily apparent. Simulations also indicate significant bunching into harmonics of the microbunching frequency as shown in Figures 3 and 4. The bandwidth of the bunching is quite narrow $\Delta\lambda_b/\lambda_b < 2\%$ at FWHM, even with the effects of emittance included.

To reveal the microbunching, it is standard practice to measure the CTR emitted when the e-beam strikes (or exits from) a metal foil[9, 10, 11]. This technique has been preformed previously with longitudinally bunched beams to determine both the frequency and amplitude of the modulation, but new methods are required to resolve the novel phase structure predicted by CTR theory for helical beams[3]. Given the levels of bunching predicted by simulations, the calculated CTR angular energy distribution for each of the bunching harmonics is shown in Fig. 5. Clearly the maximal signal is obtained for emission at the fundamental microbunching wavelength.

EXPERIMENT

Experiments will be performed at the NEPTUNE facility at UCLA, capable of delivering up to 500 pC at 14

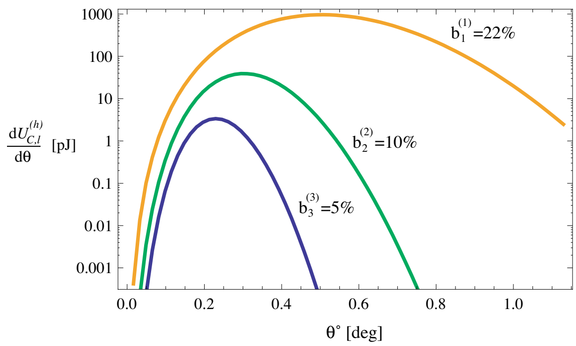

Figure 5: Calculated angular CTR distribution for the bunching factors predicted by simulations in Fig 4, for different harmonics (upper index) of the 10.6 μm microbunching wavelength and different helical modes (lower index).

MeV into the helical undulator in Fig 6. A 10.6 μm CO_2 laser pulse will deliver a 30 MW, 100 ps transversely gaussian seed focused to a waist to drive the harmonic microbunching process. A metal foil placed immediately downstream will allow measurements of the CTR emitted from the downstream side of the foil to eliminate the stray CO_2 signal, similar to the arrangement described in Ref. [11]. Since the predicted CTR signal energies are small ($U_{h,l} \leq 100$ pJ), resolution of the transverse intensity profiles is not an option and only the total signal energy can be measured. This is performed by focusing the CTR into liquid nitrogen cooled HgCdTe detectors. To reveal the helical CTR phase structure, a simple interferometric device is proposed in which the CTR signal is interfered with itself, or with a mirror image of itself with the phase helicity reversed (Figure 7). In the former case, the total power of the signal should vary with the delay in each detector (with the complementary varying signal appearing in the other detector). In the latter case however, one leg of the signal goes through an extra reflection such that the $l = 1$ input is interfered with an $l = -1$ beam resulting in two intensity lobes that simply rotate about the optical axis as a function of delay. The total power in this case is constant in both detectors, allowing one to differentiate the a helical phase from a flat phase which would vary in power with *both* arrangements.

ACKNOWLEDGMENTS

This research is supported by grants from Department of Energy Contract Nos. DOE DE-FG02-07ER46272 and DE-FG03-92ER40693 and Office of Naval Research Contract No. ONR N00014-06-1-0925.

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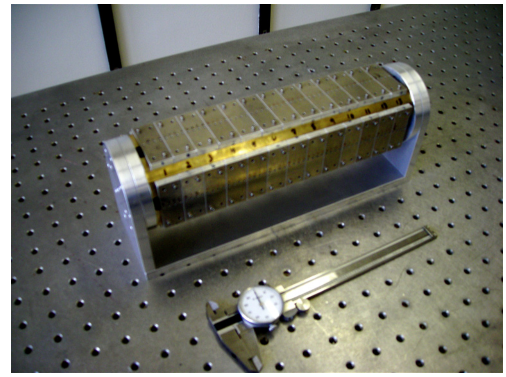

Figure 6: Helical undulator.

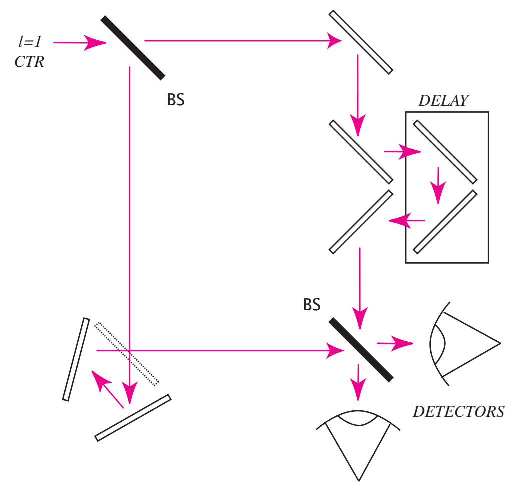

Figure 7: Simple interferometric scheme for resolving helical optical phase in the CTR. The mirror in the bottom left (dashed) is removable, allowing one path to experience either a single or a double reflection before encountering the second beam splitter (BS).

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