EVALUATION OF TEMPORAL DIAGNOSTIC TECHNIQUES FOR TWO-BUNCH FACET BEAM *

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Abstract

Three temporal diagnostic techniques are considered for use in the FACET facility at SLAC, which will incorporate a unique two-bunch beam for plasma wakefield acceleration experiments. The results of these experiments will depend strongly on the the inter-bunch spacing as well as the longitudinal profiles of the two bunches. A reliable, single-shot, high resolution measurement of the beam's temporal profile is necessary to fully quantify the physical mechanisms underlying the beam driven plasma wakefield acceleration. In this study we show that a transverse deflecting cavity is the diagnostic which best meets our criteria.

INTRODUCTION

The plasma wakefield acceleration experiments to be carried out at the FACET facility at SLAC will attempt for the first time to uniformly accelerate an electron bunch at gradients of tens of GeV/m using beam driven wakefields in a plasma [1]. This will be accomplished by creating a beam with a two-bunch structure; the driver bunch in front, driving the plasma wakefields, and the witness bunch a fraction of a plasma wavelength behind it. The magnitude and the uniformity of the accelerating gradient seen by the witness bunch will depend heavily on the relative longitudinal spacing between the two bunches, as well as the longitudinal profile of each bunch. In one set of experiments, we plan on investigating the effects of using a longitudinally "ramped" driver bunch, which is predicted to yield a substantially larger transformer ratio than that of a gaussian bunch [2]. It is thus important that we have a reliable temporal diagnostic device which can effectively resolve the two-bunch FACET beam on a shot-by-shot basis.

We considered three single-shot temporal diagnostic candidates in our study: a state-of-the-art streak camera, an electro-optic (EO) sampling system, and a transverse deflecting rf cavity (TCAV). Qualities such as the cost, size, and straight-forward interpretation of the signal will play into the ultimate decision as to which technology will be implemented. The two most critical criteria, however, are the ability to meet the required resolution for the FACET beam, and the reliability of the measurements taken.

The required resolution is determined by the structure of the two-bunch beam. The two-bunch structure is created upstream of the plasma in a chicane, where a notch collimator removes a section from the middle of the horizontally dispersed bunch. This transverse bifurcation is then translated into a longitudinal bifurcation downstream, after a phase space rotation through the chicane [1, 3].

For one typical example configuration of the FACET beamline, the nominal rms lengths of the driver and witness bunches are about $30\,\mu\mathrm{m}$ ($100\,\mathrm{fs}$) and $20\,\mu\mathrm{m}$ ($70\,\mathrm{fs}$), respectively. The peak-to-peak separation between them is about $140\,\mu\mathrm{m}$ ($470\,\mathrm{fs}$) [1, 3]. These values set the scale for our longitudinal resolution requirement. If we wish to resolve the longitudinal profiles of the individual bunches, then we require a resolution of about $10\,\mu\mathrm{m}$ ($30\,\mathrm{fs}$) or better. If we are satisfied to only measure the bunch separation, then the requirement is somewhat relaxed to around $50\,\mu\mathrm{m}$ ($170\,\mathrm{fs}$) or better.

STREAK CAMERA

Hamamatsu's Fesca-200 (C6138) is a top of the line streak camera that can resolve temporal features well below a picosecond [4, 5]. One of these cameras was brought to SLAC's LDRD laser lab where we were able to test its resolution capabilities. The test laser system was comprised of a $68\,\mathrm{MHz}$ SYNERGY PRO modelocked oscillator (Femtolasers Gmbh) and a Legend-Elite-HE USX Ti:Sa regenerative amplifier (COHERENT) with a central wavelength of $800\,\mathrm{nm}$ and a pulse length of $< 25\,\mathrm{fs}$, FWHM. The Fesca-200's spectral response range is $280 - 850\,\mathrm{nm}$, though its response is best at the IR end of the spectrum.

The typical FWHM for a single laser pulse was measured by the Fesca-200 to be $300 - 350\,\mathrm{fs}$, which is roughly an order of magnitude larger than the true pulse length. It is also about double the minimum value we require to resolve the peak-to-peak distance between the two bunches of the FACET beam, even after optimization of the slit width and gain parameters, and under the favorable conditions of our monochromatic ($60\,\mathrm{nm}$ bandwidth) IR light.

Due to this resolution limit, the Fesca-200, though perhaps the fastest streak camera available in the market today, is not well suited for single-shot temporal measurements in the regime of interest to FACET.

ELECTRO-OPTIC SAMPLING

An electro-optic sampling system was designed for use in LCLS by Fritz, *et al.* [6], which could also be suitable for use in FACET. The design of this new system builds upon

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the prior art in constructing and operating an EO system for SPPS [7].

A $100\,\mu$m ZnTe crystal would be used for finding the initial signal, and a $50\,\mu$m GaP crystal would be used for normal operation. ZnTe yields a stronger signal, but GaP provides better resolution because its effective cutoff frequency for the Fourier components of the signal is higher than that of ZnTe, allowing more fine detail of the signal profile to be preserved. The strength of the signal scales with the crystal thickness, but the resolution worsens with thickness. This is because the different Fourier components of the signal travel through the crystal with different phase velocities. If the distance of travel is too long, the signal becomes distorted and resolution is lost. If the crystal is too short, however, the reflected signal will begin to overlap with the true signal, destroying the resolution. A thickness of $50\,\mu$m for GaP and $100\,\mu$m for ZnTe was determined to be the optimum trade-off point between resolution and signal strength based on previous theoretical work [8] and our own calculations.

Numerical calculations were performed to predict the response of an EO system for a FACET-like two-bunch beam. The beam was assumed to be composed of two identical gaussian peaks of rms length $\sigma_{z,\text{bunch}} = 25\,\mu$m, separated by a distance $\Delta z = 140\,\mu$m. Each bunch is seen by the impinging laser pulse as a half-wave THz pulse. The magnitude of the THz peaks, about $400\,\text{V}/\text{nm}$, was determined by the assumed distance to the crystal, $5\,\text{mm}$, and the charge in each bunch, $Q_{\text{bunch}} = .75\,\text{nC}$. The crystal was assumed to be $50\,\mu$m of GaP. The laser pulse was assumed to be gaussian in shape, have a central wavelength of $780\,\text{nm}$, a diameter of $2\,\text{mm}$, and a FWHM pulse length of $60\,\text{fs}$, incident on the crystal at an angle of $30°$ from the surface normal vector. The signal was assumed to be extracted from the laser pulse using the so-called "balanced detection" technique [9].

Figure 1 shows the numerically calculated signal of the EO system overlaid on the input THz field as seen by the laser pulse. The details of the calculation were based on previous work found in [7, 8, 9, 10, 11]. Optical distortions from the transport of the laser pulse out of the vacuum chamber as well as experimental sources of noise have been ignored. The signal-to-noise ratio would be partially determined by the strength of the laser system employed.

Our calculations indicate that the peak-to-peak separation could be well resolved by the EO system. The individual bunch profile shapes are slightly less well preserved, however. In this case, where we have assumed two gaussian bunches, the widths of the bunches as seen in the EO signal are about 20% broader than the input THz pulses. We therefore take the resolution of the EO system to be approximately $30\,\mu$m. The dominant limitations on the resolution of an EO system are the optical properties of the crystal (particularly the cutoff frequency) and the precision to which these properties are known.

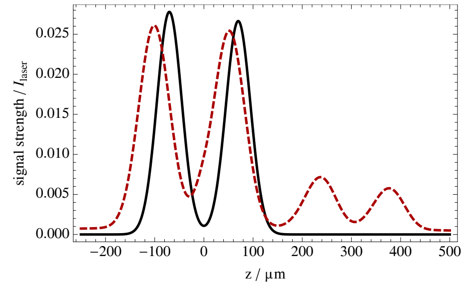

Figure 1: Calculated response of an optimized electro-optic system to a FACET-like two-bunch beam. The solid black line shows the THz field of the beam as seen by the laser pulse while traversing the crystal. The height of the THz field has been arbitrarily scaled. The dashed red line shows the final signal extracted using the balanced detection technique given as a fraction of the laser intensity incident on the EO crystal. The two right-most peaks are the reflected signal. Beam travels to the left.

TRANSVERSE DEFLECTING CAVITY

A transverse deflecting cavity system is comprised of one or more TCAVs, and a screen somewhere downstream. Because the vertical emittance of the FACET beam is expected to be an order of magnitude smaller than the horizontal emittance [3], and TCAV resolution is limited by spot size, it is advantageous that a TCAV system in the FACET beamline would deflect the beam vertically in the y-direction.

The vertical spot size on the screen for a gaussian bunch passing through a vertically deflecting TCAV is given by

$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_z^2 \beta_{y,T}\beta_{y,S}\left(\frac{eV_0}{pc}\frac{2\pi}{\lambda_{\text{rf}}}\cos\phi_{\text{rf}}\sin\Delta\psi_y\right)^2}\,, \tag{1}$$

where σ_{y0} is the nominal spot size in the absence of the TCAV, σ_z is the bunch length, $\beta_{y,T}$ and $\beta_{y,S}$ are the beta function values at the TCAV and at the screen, respectively, e is the charge of the electron, V_0 is the peak deflecting voltage, p is the beam momentum, c is the speed of light, λ_{rf} is the rf frequency, ϕ_{rf} is the rf phase, and $\Delta\psi_y$ is the betatron phase advance from the TCAV to the screen [12].

For the best resolution, the first term under the square root in Equation 1 should be much smaller than the second term. In that regime, the deflected spot size, σ_y, is linearly correlated with the longitudinal size, σ_z.

We define the longitudinal resolution as

$$\sigma_{z,res} \equiv 2\,\sigma_{y0}\Big/\left(\sqrt{\beta_{y,T}\beta_{y,S}}\frac{eV_0}{pc}\frac{2\pi}{\lambda_{\text{rf}}}\cos\phi_{\text{rf}}\sin\Delta\psi_y\right). \tag{2}$$

This number can be thought of as the ability to resolve the centroids of two transversely gaussian bunches of zero length separated by a distance $\sigma_{z,res}$, each with a transverse size of σ_{y0}.

For our calculations, we set $\phi_{\text{rf}} = 0$, and assume that $p = 23\,\text{GeV}/c$, $\sigma_{y0} = 17\,\mu$m, and $\beta_{y,S} = 18\,\text{cm}$ are fixed,

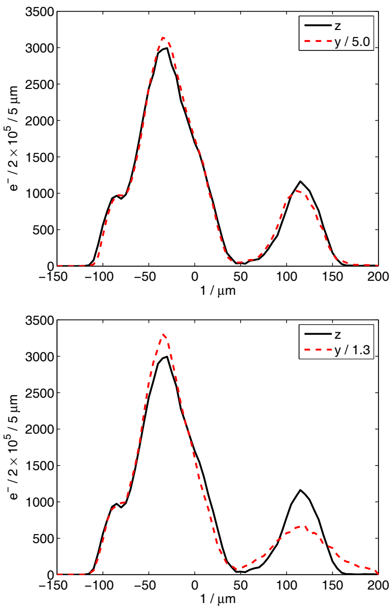

Figure 2: Final distributions of z (solid black line) and y (dashed red line) at screen downstream of X-band TCAVs (top) and S-band TCAVs (bottom) for a realistic FACET two-bunch beam simulated in Elegant [13]. Beam travels to the left.

leaving $\Delta\psi_y$, $\beta_{y,T}$, eV_0, and $\lambda_{\rm rf}$ as our free parameters. We thus want to maximize $(\sin\Delta\psi_y\sqrt{\beta_{y,T}}eV_0/\lambda_{\rm rf})$ to the extent allowed by our resources.

The best available options for FACET are travelling wave S-band or X-band TCAVs, with rf wavelengths of either $10.5\,\mathrm{cm}$ or $2.6\,\mathrm{cm}$, respectively. The maximum possible kick, eV_0, is determined by the cavity type, the available power, and the available space for the TCAV. The available space is determined by the density of elements in the beamline at a point with large β_y, approximately $\pi/2$ betatron oscillations upstream of the screen.

Given a power constraint of roughly $50\,\mathrm{MW}$ peak power, the most favorable location in the FACET beamline would provide a total kick of about $40\,\mathrm{MeV}$ ($50\,\mathrm{MeV}$) with average $\beta_{y,T}$ of about $1600\,\mathrm{m}$ ($1200\,\mathrm{m}$) for two $1\,\mathrm{m}$ X-band ($3.7\,\mathrm{m}$ S-band) structures, one mounted on either side of the final defocusing quadrupole in the dumpline. This location gives a phase advance to the screen (at the dump) of $\sin\Delta\psi_y = 0.70$. Evaluating Equation 2 for the parameters of the X-band and S-band systems gives a longitudinal resolution of $7\,\mu\mathrm{m}$ and $25\,\mu\mathrm{m}$, respectively.

The accelerator simulation codes Elegant [13] and Shower/EGS4 [14, 15] were used to simulate a realistic two-bunch beam in the FACET beamline using both the X-band and S-band TCAV setups. Figure 2 shows the final y and z distributions at the screen for each configuration. The $y-z$ correlation is significantly stronger for the X-band system, which is especially apparent in the distributions of the witness bunch (right-hand side of plots).

The simulation results confirm that the S-band TCAV system can resolve the peak-to-peak separation of the two bunches in the FACET beam, but it cannot not preserve the individual bunch shapes well. The X-band TCAV system, on the other hand, can both resolve the peak-to-peak separation and preserve the longitudinal profiles of the individual bunches. An X-band system, however, would be far costlier due to the new rf infrastructure that would be required, whereas the rf infrastructure for an S-band system is already in place near Sector 20 of the SLAC main LINAC, where the FACET experimental hall is located.

CONCLUSIONS

Based on our laboratory testing, numerical calculations, and simulations of the three single-shot temporal diagnostic devices, the X-band TCAV system is the best candidate for resolving FACET's two-bunch beam, with an estimated resolution of $7\,\mu\mathrm{m}$. Both the S-band TCAV system and the EO system could resolve the peak-to-peak separation of the two bunches in the FACET beam with estimated resolutions of $25\,\mu\mathrm{m}$ and $30\,\mu\mathrm{m}$, respectively, but would be unable to resolve the temporal profiles of the individual bunches themselves. Because the TCAV signal is more easily interpreted and because the reliability of the EO system is less well known, however, the S-band TCAV system would be the next preferred option after the X-band TCAV system. The Fesca-200 streak camera, though simple, compact, and reliable, is unable to achieve a resolution that would be of use to FACET.

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