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ILC Laser-wires

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Abstract

Laser-wires will be one of the essential components within the arsenal of beam diagnostics that will be required at the ILC. One of the challenges is to achieve micron-scale laser-spot sizes in order to be able to scan micron-scale transverse electron bunch profiles. Another challenge is to achieve very fast scanning in order to determine the bunch profile at several points within the ILC bunch train. These challenges are discussed in some detail and an overview of ongoing R&D provided.

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1 Introduction

The laser-wire (LW) uses a finely focused laser beam to scan across the ILC electron bunches. Compton scattering events are then recorded by counting the high energy photons (or degraded-energy electrons) downstream of the LW interaction point. The count rate as a function of laser-position then provides the electron bunch profile.

LWs for the ILC are currently being tested in international R&D projects; one at the PETRA ring at DESY [1] and two complementary projects at the ATF facility at KEK. The first of the KEK experiments [2] is located in the ATF damping ring (DR) and uses two optical cavities (one for scanning in the vertical dimension and the other for the horizontal) to amplify the incoming continuous wave (CW) laser-light. The almost-CW nature of the electron bunches in the DR makes this a relevant technique because each bunch can be scanned many times while it is still within the DR; such a technique would therefore also be relevant to the ILC DR. The second of the KEK experiments has just been installed at the ATF extraction line. In the extraction line, just as in the ILC linac or beam delivery system (BDS), the bunches trains are "single pass" with large (~300 ns) inter-bunch spacing. This means that a CW laser is no longer appropriate and a high-power pulsed system is required.

Using a convention where z is along the electron beam direction, y is the vertical and x is along the laser-beam direction, the light intensity of the laser has the form

$$I_\ell(x,y,z) = \frac{I_0}{2\pi\sigma_\ell^2}\exp\left[-\frac{y^2+z^2}{2\sigma_\ell^2}\frac{1}{1+x^2/x_R^2}\right] \tag{1}$$

where $\sigma_\ell = M^2\lambda f_\#$ and the Rayleigh length: $x_R = 4\pi\lambda M^2 f_\#^2$; λ is the wavelength of laser light and M^2 is the transverse mode quality factor of the laser (an ideal diffraction-limited laser would have $M^2 = 1$); in the following we take $M^2 \sim 1.3$. $f_\#$ is the usual f-number for optical systems and is given by $f_\# = D/f$ where D is the diameter of the LW final focus lens and f is its focal length; throughout we use the conventions of Ref [3]. The opening angle between the centre of the diverging Gaussian beam and its e^{-2} intensity cone is given by $1/f_\#$, which is 1 rad (or 57°) for $f_\# = 1$; developing an f/1 optical system for use at a beam-line is the subject of challenging and ongoing R&D.

Assuming the electron beam has a simple Gaussian form, with $\sigma_x = A\sigma_e, \sigma_y = \sigma_e$ (A is the horizontal/vertical aspect ratio) and using the fact that the electron longitudinal bunch length (~300 μm) is long compared to the laser spot-size (~ 1 μm), the overlap integral between the laser intensity and the electron charge distribution is then proportional to:

$$\varepsilon(\Delta_x,\Delta_y)=\int\frac{dxdy}{(2\pi)^{3/2}}\frac{1}{A\sigma_e^2\sigma_\ell}\left[1+\left(\frac{x-\Delta_x}{x_R}\right)^2\right]^{-\frac{1}{2}}\exp\left[-\frac{x^2}{2A^2\sigma_e^2}-\frac{y^2}{2\sigma_e^2}-\frac{(y-\Delta_y)^2}{2\sigma_\ell^2}\left[1+\left(\frac{x-\Delta_x}{x_R}\right)^2\right]^{-1}\right] \tag{2}$$

where Δ_x and Δ_y are the horizontal and vertical relative displacements of the electron and laser beams. For a well aligned LW, Δ_x should be zero as is assumed in the following. The effect of the laser Raleigh range is to produce non-Gaussian tails in the scanning profile, as is apparent in Figure 2, where the results of the overlap integral are shown for a 1μm in *y* by 100μm in *x* (A = 100) electron bunch with laser light wavelength λ = 532 nm. As a result of this effect the f-number must be tailored to the specific electron bunch aspect ratio *A*. At the ILC, the aspect ratio is of order 10; larger aspect ratios may be expected at CLIC.

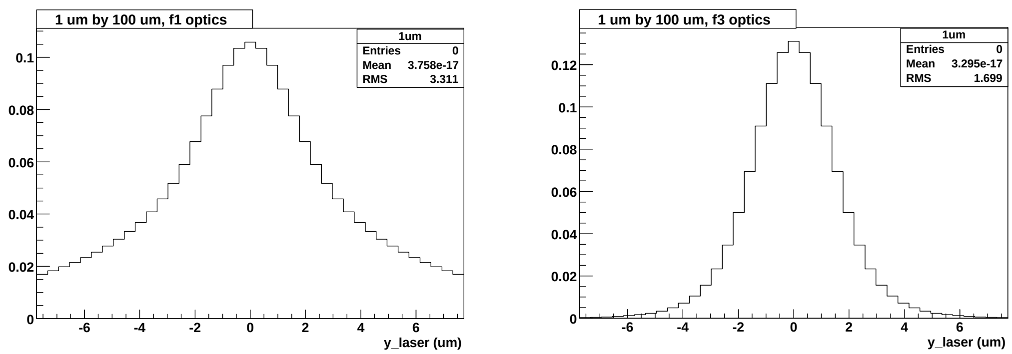

Figure 2: Results of the overlap integral in Eqn. (2) for a 1μm *y* by 100μm *x* electron bunch and λ = 532 nm, as a function of Δ_y (with Δ_x = 0). Left: f/1 optics. Right: f/2 optics.

The integral Equation (2) was performed numerically for a range of parameters of interest at the ILC and the results are shown in Table II, assuming the Thomson cross section to produce 2900 events per laser-pulse when Δ_y = 0; the number 2900 provides a statistical error δ_m of approximately 1% in the profile measurement using 5 laser shots per profile scan. The laser-power factors needed to compensate for the decrease in Compton cross section compared to the Thomson (low energy limit) one are given in Table I; a factor of about 5 is typical for ILC-relevant parameters.

	λ=1064 nm	λ=532 nm	λ=355 nm	λ=266 nm
E=250 GeV	2.4	3.3	4.2	5.0
E=500 GeV	3.3	5.0	6.3	7.7

Table I: Factors of laser power required in order to compensate for the decrease in the Compton cross section

An emittance measurement also requires knowledge of the laser pointing stability and instantaneous laser power. Knowledge of the electron beam parameter errors is also crucial, including the local β-function, the bunch transverse jitter, the residual dispersion at the LW location and the electron beam energy spread; these electron beam parameter errors may end up dominating the emittance measurement. The discussion is limited here to the systematic error from the laser beam profile: define $r \equiv \sigma_\ell / \sigma_e$ and $\delta \equiv \delta\sigma/\sigma$ with the subscripts e, m, ℓ referring to the electron bunch, the measured raw profile, and the laser spot respectively. The electron bunch error is then $\delta_e = \sqrt{\delta_m^2 (1+r^2)^2 + \delta_\ell^2 r^4}$ so $r = \sqrt{\delta_e / \delta_\ell}\left[1 + O\left((\delta_m/\delta_e)^2\right)\right]$. If δ_e <~2.5% (for a 5% emittance measurement) and $\delta_\ell \approx 0.1$, then there results the requirement that $\sigma_e >\sim 2-3\sigma_\ell$. Achieving small laser spot-sizes is therefore essential because the necessary length of the BDS diagnostics section is proportional to the β-function, which in turn is proportional to σ_e^2.

σ_e (μm)	A	$f_\#$	σ_ℓ (μm)	x_R (μm)	P(MW)
1	1	1	0.69	8.7	1.8
1	10	1	0.60	8.7	1.8
1	100	3	2.1	78	4.0
2	1	1	0.69	8.7	4.2
2	10	1	0.60	8.7	5.0
2	100	3	2.1	78	12
3	1	1	0.69	8.7	6.4
3	10	1.5	1.0	20	7.6
3	100	4	2.8	140	17
5	1	1.5	1.0	20	24
5	10	1.5	1.0	20	26
5	100	5	3.5	220	50

Table II: Optimal values (based on statistics only) of f-numbers for various electron bunch vertical sizes and aspect ratios of interest at the ILC, assuming a laser wavelength λ = 532 nm and M^2 = 1.3. Also shown are laser waist sizes at the LW interaction point and the instantaneous laser power P required to produce 2900 Compton events at the central point of the scan, assuming the Thomson cross section (only valid for low energy electrons). The Compton power factors for representative ILC energies (and various possible laser wavelengths) are given in Table I.

2 Conclusion

LWs for the ILC present a number of challenges that are being met head-on by a set of ongoing R&D projects. One of the key LW technology goals is the achievement of micron-scale spot-sizes, which requires challenging low f-number optics design and lasers with high quality transverse-mode. Different LW technologies are relevant to different parts of the ILC; the DR could employ a CW LW based on optical cavities, such as is already in use at the ATF, whereas the BDS will need a high-power pulsed laser system. Such pulsed systems could also be used in the linac, provided the laser light can be transmitted to the beam-pipe either at specific locations between the cryo-modules or through a set of specially designed cryo-modules; this is the subject of ongoing study.

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