FUTURE DEVELOPMENTS IN ELECTRON LINAC DIAGNOSTICS*

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Abstract

The next generation of electron linacs will fill two different roles:

1. ultra-low emittance, very high power accelerators for linear colliders and

2. ultra-short bunch, high stability accelerators for SASE X-ray production.

In either case, precision control based on non-invasive, reliable, beam instrumentation will be required. For the linear collider, low emittance transport is an important concern for both warm and superconducting linacs. Instrumentation will be used for control and diagnostics will be used to validate emittance preserving strategies, such as beam based alignment and dispersion - free steering. Tests at the KEK ATF and the SLAC FFTB have demonstrated the required performance of beam position and beam size monitors. Linacs intended for FEL's will require precision bunch length diagnostics because of expected non-linear micro-bunching processes. A wide variety of devices are now in development at FEL prototypes, including TTF2 at DESY and SPPS at SLAC. We present a review of the new diagnostic systems.

INTRODUCTION

The last ten years have seen unprecedented growth in electron linac technology development, driven by two main forces: 1) development of ultra-short pulse single pass free electron lasers (FEL) [1] and 2) development of high energy linear colliders (LC) [2]. The underlying physics for these machines has been well understood for 10 – 20 years and the intervening time has been devoted to demonstrations of key subsystems, such as accelerating structures, high-brightness beam generation and related instrumentation. In this paper we review 3 types of beam instruments that play a significant role in this work: 1) sub-micron resolution cavity beam position monitors (BPM's), 2) laser-based profile monitors (laserwires), and 3) bunch length monitors based on deflecting structures.

Demonstration of new beam instrumentation requires substantial accelerator test facilities to provide beams with smaller dimensions, higher brightness and greater stability. Indeed, the development of the instrumentation and the performance of the test facilities are strongly linked. Each is needed to validate and support the operation of the other and this is what has happened at the SLAC Final Focus Test Beam (FFTB) [3], the KEK Accelerator Test Facility (ATF) [4] and the DESY TESLA Test Facility (TTF) [5]. Since starting operation in the mid-1990's, these machines have been used to demonstrate 1) demagnification beyond that needed for the LC (FFTB), 2) generation of ultra-low emittance beams (ATF) and 3) generation of ultra-short pulse saturated ~100nm FEL radiation (TTF). Each of these tests has boosted and allowed aggressive development of related FEL/LC projects.

ULTRA-HIGH RESOLUTION BEAM POSITION MONITORS

The development of high resolution beam pickups for bunched electron beams lags substantially behind proton machine pickups, typically used for un-bunched (or weakly bunched) beams. Those devices, developed roughly 30 years ago for use with broad-band stochastic cooling, typically operate near the thermal, black-body radiation limit and are often cryogenically cooled in order to extend that limit as far as possible. In contrast to the needs of Schottky - signal based devices; most electron machine BPM requirements have been well served by devices that operate well away from the thermal noise limit. This is no longer true.

Third generation light sources require sub-micron resolution and stability, which is achieved using multi-turn digitization schemes that average over many hundreds of thousands of turns [6]. The Stanford Linear Collider (SLC) linac BPM system had 10 micron single reading resolution and an absolute precision of about 5 times larger [7]. This level of performance was well matched to the requirements of the machine. A good, practical way to interpret resolution requirements (r) in an LC or FEL is the view them in units of the beam size. Of course, the size of the vacuum chamber is also critical, so that the two key parameters are: 1) $j=r$/beam size and 2) $p=r$/vacuum chamber diameter. In operational terms, j allows the determination of sources of beam instability (such as poorly performing magnet power supplies or collective effects) with precision that is good compared to the beam's own emittance. In the SLC, with typical beam sizes of 50 µm and a one inch diameter beam tube, 10 µm resolution worked well for the identification most instability sources [8]. At the LC, with expected beam sizes almost 50 times smaller, and a larger beam tube, resolution performance must be substantially improved. Typical beam tube sizes in the FEL will be smaller. Table 1 summarizes these parameters, illustrating the challenge of the next generation linacs.

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Beyond the beam size and beam vacuum chamber size, there are several more critical performance parameters: 1) the loss factor of the pickup, 2) the monopole suppression factor, 3) the system bandwidth and 4) the dynamic range. The loss factor must be optimized between collective effects, such as transverse impedance wakes, and needed signal strength. The thermal noise power P_n depends on the system bandwidth in a simple way $P_n=ktb$ (where k is the Boltzmann constant, t is the temperature in degrees K and b is the system bandwidth). The cryogenic linac, with large beam inter-bunch spacing, is well adapted for a narrow band position monitor system, using cavity BPM's with a ~100ns decay time. For the cavity BPM engineer, the most important component of P_n is the electronic noise figure.

A system with roughly appropriate parameters, but with a rather large loss factor, has been tested several places [9] and we present here results from tests now underway at the ATF, using the damped, extracted ATF beam. The system uses C-band TM110 dipole mode cavities, designed and constructed at the Budker Institute, coupled to a simple two stage heterodyne down-mixer. The final IF mixer output is repeatedly sampled by a 100 MHz 14 bit commercial digitizer. Table 2 lists the parameters of the test cavity BPM system.

Table 1: BPM performance parameters, achieved and suggested, based on the practical rule (j ~ 0.2). The first four rows in the table describe the BPMs typical of the machine. The last row lists the performance parameters of the system presently in test at ATF. The sensitivity scaled to the vacuum chamber size, p, is excellent at the test system at ATF, but the loss factor of the BINP cavity BPMs is too large for use in an LC linac.

Machine	typical beam size (μm)	Beam tube diameter (mm)	bunch spacing (ns)	suggested/achieved resolution (μm)	j (= r/σ)	p (= r/d)
SLC	50	25	60	10	0.2	5e-4
ATF	5	25	2.8/330	1	0.2	4e-5
LC	1	75	330	.2	0.2	3e-6
FEL (LCLS)	1	10	-	.2	0.2	1e-4
ATF test (see below)	5	20	-	0.02	0.004	1e-6

Table 2: Parameter table for the BINP cavity BPM system

Parameter	
Cavity dipole mode frequency	6426 MHz
1/angular frequency	7.4 mm
Intermediate IF	476 MHz
Final IF	23 MHz
Cavity gap length	10 mm
Coupling β	1 (not known exactly)
System gain	48 dB
Electronic bandwidth	20MHz
Noise figure	3 dB
Loss factor	3.9e10 Joules/C^2/mm^2
mV/nm at 1e10	1
electronic noise (rms)	1mV
Electronic dynamic range	20 μm
Estimated resolution (preliminary)	15 nm

An RF cavity BPM with operating angular frequency close to one over the bunch length and with a gap near this same characteristic length is subject to additional complications associated with the so-called 'transit time effect' and the bunch's own tilt or y-z correlation [10]. This signal appears in phase quadrature with the basic radial offset signal and must be properly accounted for in any high performance cavity BPM system. Table 2 shows the magnitude of these effects at ATF, where they are large and can be studied in some detail. Figure 1 shows typical signals from the system, showing a nominal IF signal along side a more peculiar one. The top part of the figure shows a nominal decaying exponential, typical of most beam pulses. A reference cavity is used to determine the phase (sign) and normalize the pulse amplitude, here about 1e10 particles / bunch. The scale is approximately 350 ADC counts (peak amplitude) per micron. In this example case the beam is about 300 nm from the electrical center of the cavity (if the offset is purely axial). The bottom half of the figure shows a beam pulse with a smaller offset – perhaps less than 100 nm – but with a very large offset in the other plane (x) showing coupling between the TM modes. This figure also clearly shows the monopole transient.

In order to study BPM performance in the presence of 1) expected performance beyond our ability to hold a set of BPMs still with respect to each other, 2) transit time effects and 3) limited dynamic range beyond our ability to perform ab-initio alignment, we constructed an extremely stiff flexure-based mover system with full 6 degrees of freedom that can support a set of three BPMs. This device is used for precision displacement calibration. Three BPMs is the minimum number required to determine system resolution using a zero-constraint linear regression fit. Figure 2 shows typical performance of the system at ATF. The figure shows the residual (actual-predicted) vertical beam position measurement over a sequence of beam pulses during which the BPM mover is adjusted in one micron steps. The width of the distribution of data points roughly indicates the resolution, in this case around 16 nm. Effects related to stray field fluctuation, thermal stability, beam energy pulse to pulse jitter and wake fields are under analysis as of December 2004.

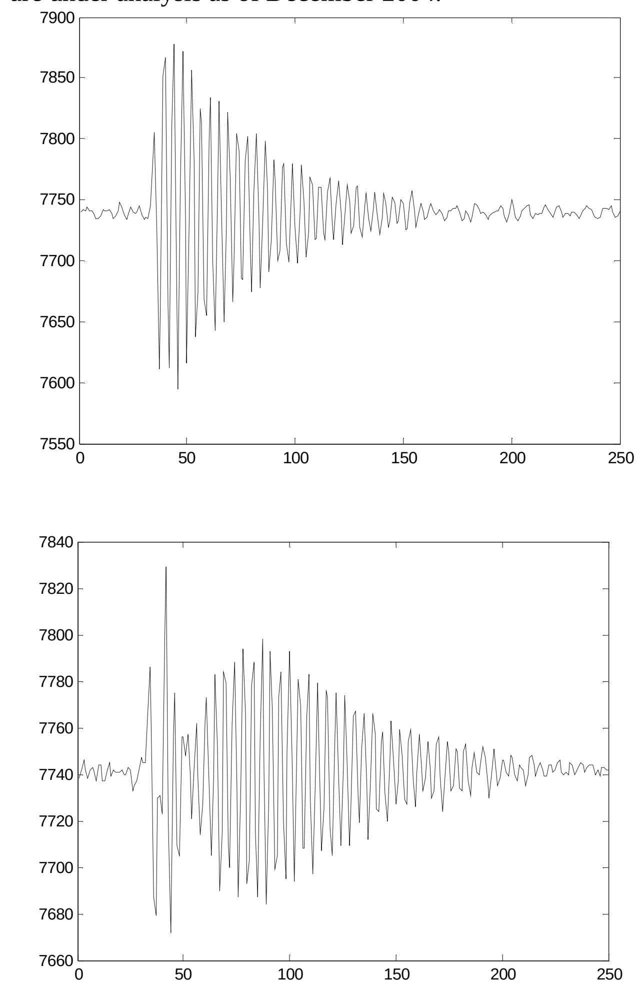

Figure 1: Sample IF waveforms from the ATF/BINP/SLAC cavity BPMs. The vertical scale is ADC counts and the horizontal scale is sample number of the 100 MHz sampling ADC.

An important use of precision beam position monitors is in the energy spectrometer device planned for the LC beam delivery section [11]. Such a device must have good resolution and stable long-term electrical and mechanical offsets. While the detailed spectrometer performance parameters have not yet been set, we expect the ATF system to be capable of proving cavity BPMs for this purpose.

LASER-BASED PROFILE MONITORS

Both the FEL and LC performance depend strongly on the beam phase space, and the ability to transport cleanly generated beams long distances through precisely matched lattices. The job of matching and compensating collective effects in a single pass system is quite different in practice from the similar task in a third generation light source storage ring. While precise, high resolution BPMs are, in both cases, the most important beam instrument for this purpose, in a single pass machine a second system is needed to verify that the job has been adequately done and to serve a tool for finishing the job. This was demonstrated at SLC [12], where sophisticated BPM-based optics tuning procedures were backed up by groups of wire scanners, typically four each, to allow full transverse phase space determination between major subsystems (damping ring, linac, arcs and beam delivery) [13]. At the peak SLC performance, however, three effects showed the inadequacy of filamentary wire scanners: 1) the wire was too fragile and cumbersome to replace when broken [14] and 2) the presence of the wire in the beam, however transient, generated too many secondaries and degraded particles to allow continued high power operation and finally (perhaps most importantly) 3) the wires could not be made small enough for accurate measurements of the low emittance beam. The latter was especially important as the machine performance moved to another regime where new effects made more precise measurements critical.

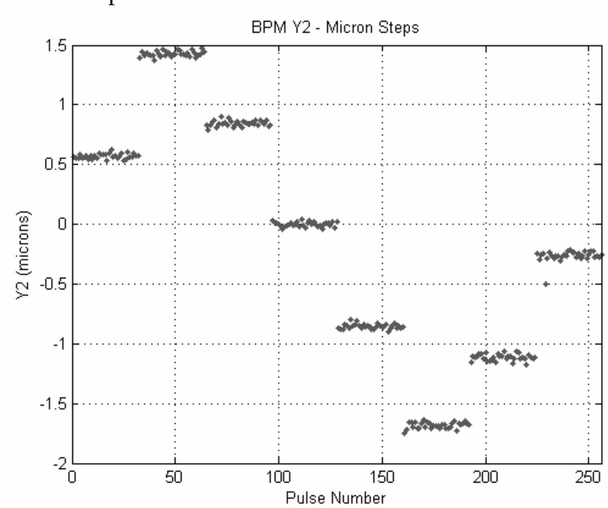

Figure 2: Preliminary cavity BPM data from a sequence of pulses at ATF, showing the difference between the predicted (using adjacent BPM's) and actual reading as the support struts were moved one micron steps. Some mover mechanical backlash (~150nm) is clearly visible.

These effects forced the development of a more complex, but much more powerful beam size monitor, one based on Compton scattering of the particle beam with a finely focused laser beam. The laser beam is not material so it cannot be trivially broken, its power can be adjusted remotely, allowing the number of degraded particles to be reduced if circumstances require and it can be focused to well below the typical 1 μm beam size. Key technical issues are 1) the degraded particle (or neutral beam) detector, 2) the stability and calibration of the laser beam itself and 3) the large number of mechanical and operational issues associated with the laser, its controls, transport line and optical focus system.

It is important to consider two ‘resolution’-like performance parameters: 1) the dynamic range of the system, i.e. the range of beam sizes can be effectively measured, and 2) the real resolution of the system, i.e. the reproducibility of the instrument given identical particle beam conditions. Table 3 lists these for some beam profile monitors. It is important to understand system requirements, especially for 2), because tuning procedures will depend critically on this and it may be very advantageous to develop devices with good resolution.

Table 3: Performance parameters for selected wire scanners and laserwires

Laserwire	σ_l	σ_e	P_l/wire mat’l	Resolution
SLC wires	NA	50	W/C/SiC	10%
SLD	.35	.8	100 MW	20%
ATF	5	5	1000 W	1%
PETRA	50	80	10 MW	

Several such systems have been built and tested and it seems that laserwires will become an effective tool [15]. The challenge of stabilizing the laser, perhaps at the expense of optical beam power, has been met by the ATF group who built the most heavily used laserwire system to date. This device has been the subject of several written thesis reports and remains subject to active development while at the same time proving critical for understanding ATF performance. Figure 3 shows a typical scan, illustrating the extreme stability of the system. Recent developments include a ‘pulse-stacking’ system that allows a substantial increase in peak power with fixed average power.

BUNCH LENGTH MONITORS

The performance of an FEL depends very strongly on the peak bunch current. As beam bunches are made shorter (10 μm σ_z) this is fresh territory for machine operation in several ways, a substantial world-wide RD effort is underway to prove practical ways making 1) accurate, 2) relative (high resolution) or 3) simple ways of bunch length estimation. This topic, along with a related topic of understanding bunch timing, has been central to a series of recent ACFA workshops which provide a comprehensive picture of the state of the art. Here we describe only one such system; that based on high power transverse deflecting structures.

What transverse deflecting structures lack in simplicity, they make up in precision. The principle of operation is simple, namely that a strong correlation between y (or x) and z, of well known amplitude is generated and then a y (or x) image is viewed using a conventional video – based profile monitor. The technique was first used almost 40 years ago, but has recently been revived as the need to make bunches shorter than 1 mm arose. Two such structures have been recently installed [16] and are either in use or in commissioning. At the DESY TTF, a 4 m long S-band structure, capable of monitoring 10 μm σ_z was installed in late 2003 and is now being commissioned. Table 4 shows the performance parameters of the system. First results are expected in early 2005.

Table 4: Performance Parameters of the TTF transverse deflecting structure ‘LOLA IV’

Power	18 MW
Length	3.7 m
Peak deflecting Voltage	25 MV
Wavelength	105 mm
Incoming vertical beam size	300 μm
Differential kick /μm	40 μm
Required phase stability	0.1 ps

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