PHYSICS REQUIREMENTS FOR LINAC STABILIZATION AND TECHNICAL SOLUTIONS

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Abstract

This paper gives a general overview of active and passive stabilization systems, which are mainly required for future X-FEL and high-energy linear colliders. Key physics criteria for beam stability for X-FELS and linear colliders will be introduced and resulting technical implications discussed. New and innovative approaches to the design and development of state-of-the-art linear accelerator components and stabilization systems will be reviewed, and recent results shown from selected prototypes and new machine installations.

INTRODUCTION

Achieving performance specifications of modern accelerators places narrow tolerances on a wide range of technical parameters. The location of magnetic optics elements in space, their field strengths, and particle energy all must remain within tight bounds.

Within the context of stabilizing beams with dimensions measured in microns, there are many potential sources of drift and jitter that must be taken into account.

Sources of drift and slow changes include air and cooling water temperatures, ground motion due to settlement and lunar cycles. Medium timescale disturbances include girder vibration excited by ground motion, cooling pipes, or mechanical pumps. Faster disturbances include power supply ripple, rf jitter, switching magnet jitter, etc.

In our discussion of linac beam stabilization, we will focus on four large-scale pulsed electron linacs: LCLS and the European XFEL (both x-ray photon sources); and ILC and CLIC (both linear colliders). Table 1 lists some of their main parameters [1-4].

Table 1: Main Linac Parameters

	ILC	CLIC	EU-XFEL	LCLS	
Max. Energy	2x 250	2x 1500	20	13	GeV
ML Length	2x 12	2x 21	1.6	1	km
Cavity type	S/C	N/C	S/C	N/C	
RF Freq	1.3	12	1.3	12 + 2.8	GHz
RF source	Klystron	Drive beam	Klystron	Klystron	
Pulse rate	5	50	10	120	Hz
Pulse length	970	0.15	650	--	µs
Bunches / Pulse	2670	312	3250	1	
Bunch length	300	44	25	20	µm
Bunch size	640 nm x 5.7 nm	45 nm x 0.9 nm	20-30 µm	37 µm	

S/C: Superconducting N/C: normal conducting

These represent the most recent generation of linacs: LCLS is in commissioning and XFEL is under construction; while ILC and CLIC remain in development and proof-of-principle stages respectively.

All four machines present significant technical challenges, in part due to their large scale and complexity. From a beam stabilization perspective, these include distribution of precision rf phase references to many locations over distances of kilometers to tens of kilometers and stabilizing beams with dimensions of nanometers.

This next section gives a brief overview of the four machines and discusses their performance and stabilization criteria. Some examples of technical solutions will also be discussed.

PHOTON SOURCES: LCLS AND EU-XFEL

For certain classes of photon user experiments, FEL-based sources such as LCLS and XFEL dramatically exceed the capabilities of storage ring light sources by:

- Peak brightness is many orders of magnitude higher than the present storage ring photon sources
- Sub-picosecond photon pulse lengths compared with 10's to 100's ps from storage rings
- Photon beams are transversally fully coherent

The ultra-short pulse lengths will make it possible to study the time evolution of chemical processes that occur in timeframes of 100's femtoseconds to picoseconds, while the high coherence will open up new classes of imaging experiments.

A comparison of peak and average brightness with other light sources is shown in Fig. 1.

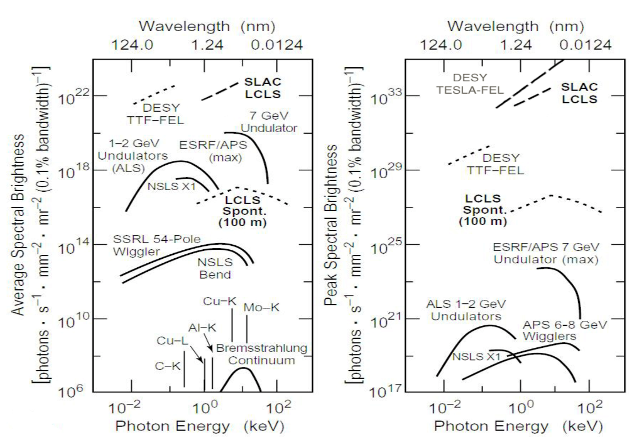

Figure 1: Average and peak brightness calculated for photon sources that are operating or under construction.

Lasing occurs through a process of Self-Amplified Spontaneous Emission (SASE). Referring to Fig. 2, synchrotron radiation is emitted in a narrow forward cone as the beam travels through the alternating magnetic field of a long undulator.

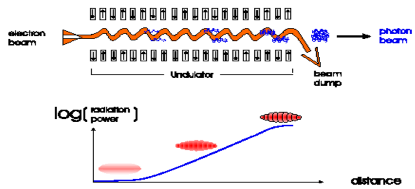

Figure 2: Principle of the FEL process.

The electric field of the synchrotron radiation density-modulates the electron beam longitudinally at the wavelength of the light (micro-bunching). Particles within an optical wavelength emit synchrotron light coherently, and consequently the intensity of the light grows as the square of the number of particles. The more intense light enhances the density modulation and the process grows exponentially until it reaches saturation after about ten gain-lengths of the undulator. The process requires high-energy electron beams with low emittance, high peak currents, and small energy spread.

A schematic layout of the XFEL accelerator is shown in Fig. 3 [5]. (A schematic layout of LCLS is shown in Fig. 8 to follow). Both XFEL and LCLS accelerators comprise an rf gun, followed by two bunch compressors and the main linac.

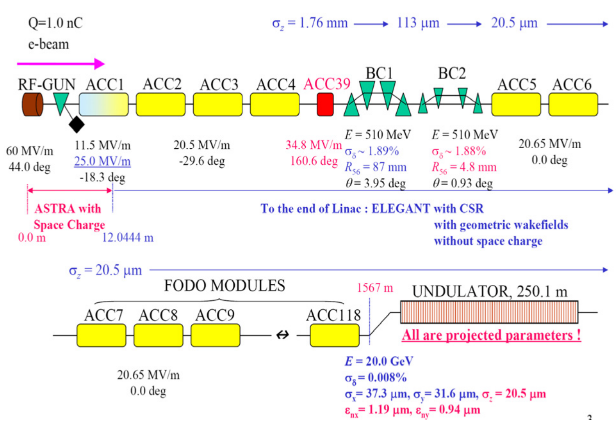

Figure 3: Schematic layout of the XFEL accelerator.

Stringent tolerances are placed on RF cavity phase and amplitude to achieve the necessary energy stability, bunch length, and peak bunch current. Example tolerances and sensitivities for XFEL are shown in Table 2 [6] and for LCLS are documented in the references [7]. Stabilizing pulsed cavity fields to the level of 0.01% and 0.01 degrees is state of the art. RF phase reference distribution to this level of performance goes beyond the state of the art.

Experiment techniques used by the ultra-fast science community place difficult timing and synchronization requirements on XFEL and LCLS. Pump-probe experiments require that the photon bunch and the pulse from a local pump laser to illuminate the sample with a precise delay of a fraction of the photon bunch duration. Synchronization to the 10's of femtosecond level is beyond the present state of the art.

Table 2: Example RF Tolerances & Sensitivities (XFEL)

	Sensitivity(p2p)	Tol. (p2p)	Tol. (rms)	Threshold
dT	± 0.729 ps	± 0.300 ps	0.100 ps	saturation length
dQ/Q	± 5.452%	± 3.000%	1.000%	saturation length
ACC1C1234 phase	± 0.133 deg	± 0.045 deg	0.015 deg	saturation length
ACC1C1234 dV/V	± 0.129%	± 0.045%	0.015%	arriving time
ACC1C5678 phase	± 0.072 deg	± 0.045 deg	0.015 deg	saturation power
ACC1C5678 dV/V	± 0.063%	± 0.045%	0.015%	arriving time
ACC234 phase	± 0.048 deg	± 0.045 deg	0.015 deg	arriving time
ACC234 dV/V	± 0.045%	± 0.045%	0.015%	arriving time
ACC39 phase	± 0.064 deg	± 0.045 deg	0.015 deg	saturation power
ACC39 dV/V	± 0.142%	± 0.045%	0.015%	arriving time
BC1 dI/I	± 0.013%	± 0.012%	0.004%	arriving time
ACC56 phase	± 0.721 deg	± 0.045 deg	0.015 deg	arriving time
ACC56 dV/V	± 0.913%	± 0.045%	0.015%	saturation length
BC2 dI/I	± 0.201%	± 0.012%	0.004%	arriving time
ACC78910 phase	±10.037 deg	± 0.045 deg	0.015 deg	SASE wavelength
ACC78910 dV/V	± 0.060%	± 0.045%	0.015%	SASE wavelength

LINEAR COLLIDERS: ILC AND CLIC

In recent years, high-energy physics experiments have explored the 100 GeV energy range using hadron colliders such as the Tevatron at Fermilab and lepton colliders such as LEP at CERN. Attention is now shifting to the TeV energy range, which will be first explored at the Large Hadron Collider at CERN. A widely anticipated result from the LHC is discovery of the Higgs Boson and validation of the so-called Standard Model of particle physics. While hadron colliders provide a wealth of physics through a broad spectrum of particle-particle interactions, lepton colliders provide precision measurements over a narrow spectrum of particle interactions. As such, information from both types of collider is necessary to develop a complete understanding of physics in the energy range. To complement the LHC, development is in progress for an e+/e- linear collider.

Present linear collider development efforts are converging on the International Linear Collider, which uses superconducting accelerating cavities to reach a center-of-mass energy of 500 GeV. As shown in Fig. 4, the ILC comprises the following major elements:

- Polarized electron source
- Undulator-based positron source
- Damping rings to develop very low emittance beams
- One or two bunch compressors
- Two counter-posing accelerating linacs
- Beam delivery systems to focus the beams and bring them into collision at the Interaction Point

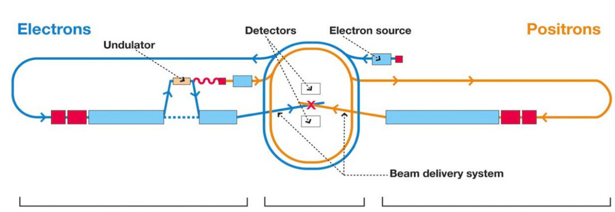

Figure 4: ILC top-level layout.

While it is anticipated that 500 GeV center-of-mass will be sufficient to explore the new physics of the Higgs, some theories that go beyond the standard model predict that energy well above 500 GeV might be required. A separate R&D effort is ongoing at CERN to prove and develop a novel linac concept with the intention of reaching center-of-mass energies up to 3 TeV. The Compact Linear Collider (CLIC) uses normal-conducting accelerating structures that receive their RF power from a second high power electron beam that travels parallel to the main accelerator (Fig. 5).

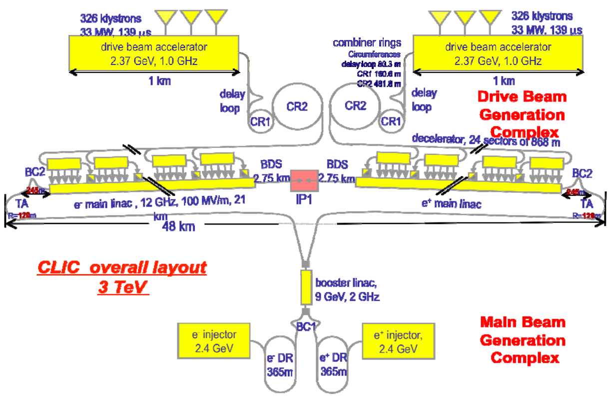

Figure 5: Schematic layout of CLIC.

Both the ILC and CLIC are of an unprecedented scale and complexity. For example, each ILC main linac has some 8,000 superconducting cavities housed in 1,000 cryomodules, powered by 320 10 MW rf klystrons. In the case of CLIC, the complexity is increased by the existence of the drive beam accelerators.

Stability challenges originate at the interaction point where the two beams collide. To achieve the highest luminosity, optics for the electron and positron beam delivery systems must be optimally matched at the IP, and the two beams must be synchronized to intersect perfectly at the IP. Tolerances for optics matching, arrival times, and trajectory errors must have impacts that are small, relative to the bunch dimensions.

A luminosity loss budget example for CLIC is shown in Table 3, clearly illustrating the degree of stability needed to stabilize nanometer-scale beams. Whether it is feasible to stabilize large structures to the sub-nanometer level is under study by the CLIC Stabilization Group [9].

Table 3: Example Luminosity Loss Budget for CLIC

Source	budget	raw tolerance
Damping ring extraction jitter	1%	
Magnetic field variations	?%	
Bunch compressor jitter	1%	
Quadrupole jitter in main linac	1%	$\Delta\epsilon_y = 0.4\,\mathrm{nm}$ $\sigma_{jitter} \approx 1.5\,\mathrm{nm}$
Structure pos. jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04\,\mathrm{nm}$ $\sigma_{jitter} \approx 200\,\mathrm{nm}$
Structure angle jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04\,\mathrm{nm}$ $\sigma_{jitter} \approx 170\,\mathrm{nradian}$
RF jitter in main linac	1%	
Crab cavity phase jitter	1%	$\sigma_\phi \approx 0.01^\circ$
Final doublet quadrupole support jitter	1%	$\sigma_{jitter} \approx 0.18\,\mathrm{nm}$
Other quadrupole jitter in BDS	1%	
...	?%	

EXAMPLES OF TECHNICAL SOLUTIONS

In this section, examples of technical solutions and approaches to meeting stabilization requirements will be discussed.

Precision Timing and Synchronization

A major challenge for large linacs is to implement a timing and synchronization system with the needed accuracy and stability:

- Ultra-stable RF phase references must be distributed over kilometer distances to multiple RF stations while maintaining the relative phase between stations and the absolute phase relative to the beam. Stability of the phase references must exceed the 0.01-degree stability required in the rf cavities
- ILC and CLIC require the electron and positron bunch arrival times at the interaction point to be synchronized within a fraction of a bunch length
- LCLS and XFEL pump-probe experiments require synchronization of the FEL photon bunch with a pump laser at the <10 fs scale

Significant progress is being made in developing methods for distributing ultra-stable phase references and in timing synchronization. Schemes for actively stabilized links using pulsed and CW lasers are being developed. An rf phase reference transmission scheme developed at LBL uses a CW laser modulated by rf (Fig. 6). Stability of <100 fs rms over 12 hrs has been reported for fiber lengths of 2 km [10].

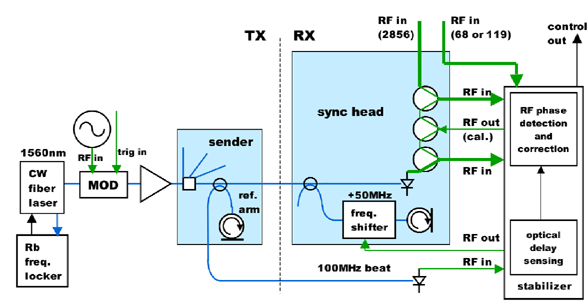

Figure 6: LBL optical RF distribution system.

Bunch arrival monitors using electro-optical sampling techniques provide a means to phase-lock a bunch train and to tag each bunch with an arrival time. Principles of the bunch arrival monitor (BAM) are shown in Fig. 7.

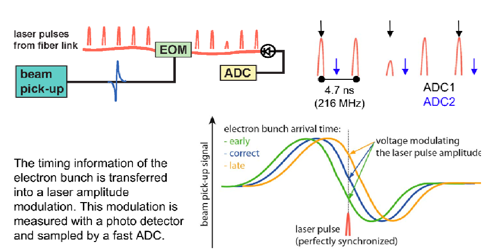

Figure 7: Bunch Arrival Time Monitor.

Reference laser pulses pass through an electro-optical modulator that is driven by the signal from a beam pick-up. Changes in the arrival time of the electron beam cause different modulation voltages at the laser pulse arrival time. The resulting change in laser amplitude is detected using a photo detector. The resolution of these devices is improving rapidly, and single-bunch measurement resolutions of <6 fs have been recently reported [11].

Time-tagging each bunch allows pump-probe experiments to identify bunches where the arrival time of the photon bunch is within the desired time window relative to the pump laser. Other ways to tag bunches with their relative arrival time is to correlate light from the pump laser and photon pulse using a streak camera.

LCLS Longitudinal Feedback System

A pulse-by-pulse longitudinal feedback system has been implemented in at LCLS to stabilize beam energy and bunch lengths [12, 13]. The overall topology is shown in Fig. 8. Beam energy is measured at the end of each linac section and regulated by adjusting the amplitude of the rf drive to the accelerating structures. Both phase and amplitude of the rf drive to the bunch compressors are regulated in order to stabilize both the beam energy and the bunch length.

Bunch lengths are measured using coherent synchrotron radiation in the chicanes of the two bunch compressors and energy is measured using high-resolution bpms after each section. Rather than implanting cascaded feedback loops around each linac section, all the feedback loops are integrated into a single global computation with multiple inputs and outputs.

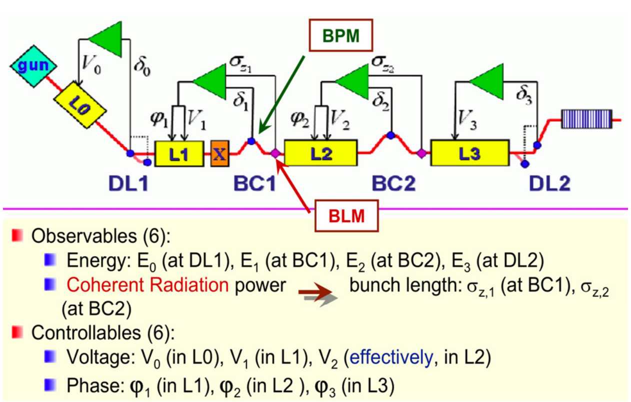

Figure 8: LCLS longitudinal feedback system.

With the longitudinal feedback on, energy stabilities of ~0.03% rms have been measured after each linac section, and peak bunch currents at BC1 and BC2 have been stabilized to ~5% rms and ~10% rms respectively.

Beam Position Monitors

Specifications for stability and precision of the undulator bpms are very demanding because of the micro-scale transverse beam sizes and pointing stability requirements of a fraction of the beam size.

Table 4 shows some key performance specifications for bpms in the undulator section of LCLS [14].

Table 4: LCLS bpm Specifications

Parameter	Specification
Transverse beam size	~37μm
Resolution	< 1μm
Offset Stability over 10hrs	< +/- 1μm
Offset Stability over 30days	< +/- 3μm

The bpms are x-band cavity type, and comprise a monopole TM010 reference cavity and a single TM110 dipole cavity for detecting both horizontal and vertical position. X-band signals are down-converted to an IF of 20-50 MHz before being digitized at 119 MHz. Mounting the bpms on precision mechanical movers has simplified the processes of calibration of bpm offsets and gains.

Single-shot resolutions of ~200 nm rms have been measured with a beam charge of 200 pC. Figure 9 shows an example vertical position scan when the bpm assembly is moved in 5-micron steps [15].

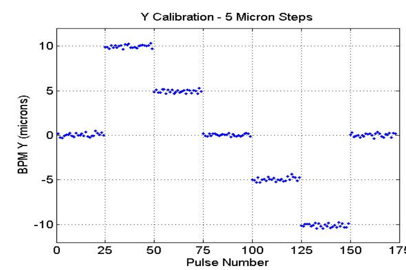

Figure 9: LCLS cavity bpm resolution measurement.

XFEL Intra-Train Transverse Feedback System

Stable SASE operation requires the electron and photon beams to be collinear in the undulators to within ~10% of the beam size (~3 μm rms), and therefore the electron beam trajectory must be stable through the undulators to the same order. Long bunch trains of the XFEL make it possible to implement intra-train trajectory feedback. Figure 10 shows the proposed topology for an XFEL intra-train feedback system, using two upstream and two downstream bpms to monitor the beam trajectory and two rf kickers to make position and angle corrections [16]. The feedback regulator will be implemented digitally.

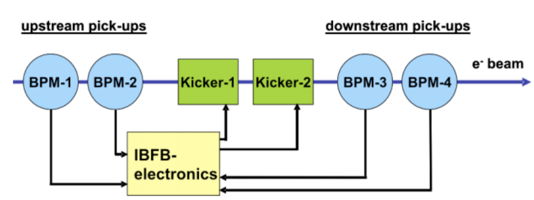

Figure 10: Proposed topology for XFEL intra-train feedback.

The proposed scheme computes the correction kicks using the upstream bpms and an optics model rather than using the downstream bpms in a more conventional feedback loop. This reduces latencies because cable lengths are shorter and also as correction signals are traveling in the same direction as the beam. At a slower rate, the downstream bpms are used to check and update the optics model based on the response to the applied kicks. A prototype system is currently being developed for testing on FLASH.

OUTLOOK

The latest generation of FEL based light sources, such as LCLS and XFEL present some significant technical challenges. The ILC and CLIC will present even greater challenges. Equally, significant progress is being made towards achieving the end-user requirements of LCLS and XFEL. Experience tells us, that as we start to meet the needs of accelerator users, even more challenging expectations begin to emerge. For example, just as we begin to develop the technology to provide femtosecond timing precision, there is already talk of experiments requiring attosecond-scale precision. It is this type of thinking and forward progression that keeps the field of diagnostics ever advancing.

REFERENCES

[1] XFEL Technical Design Report, DESY 2006-097, 2006
[2] LCLS Conceptual Design Report, SLAC-R-593, 2002
[3] ILC Reference Design Report, ILC-REPORT-2007-001, 2007
[4] CLIC 3 TeV Design and Parameters, CLIC-Note-764, 2008
[5] W. Decking, "Beam Stability Challenges at the European XFEL," Workshop on Beam Stability, Hamburg, Germany, 2004
[8] D. Schulte, "Some Stabilization Specifications," CLIC08 Workshop, CERN, Swizerland, 2008
[9] http://clic-stability.web.cern.ch/clic-stability/
[10] R. Wilcox, "Recent results of RF synchronization at LBL," Second Timing and Synchrotron Workshop, Trieste, 2009
[11] F. Loehl, "Beam Arrival Monitor Implementation Challenges," Second Timing and Synchrotron Workshop, Trieste, 2009
[12] P. Kreicik, "Feedback Concepts: Experience at SPPS, LCLS Plans," 37th ICFA Advanced Beam Dynamics Workshop on Future Light Sources," Hamburg, Germany, 2006
[13] P. Emma, private communication
[14] S. Smith "LCLS Cavity Beam Position Monitors" these proceedings.
[15] R. Lill, private communication
[16] B. Keil et al., "Design of an Intra-train Feedback System for the European XFEL," DIPAC 2007, Venice, Italy