Title
Instrumentation and Diagnostics for High Repetition Rate LINAC-Driven FEL

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INSTRUMENTATION AND DIAGNOSTICS FOR HIGH REPETITION RATE LINAC-DRIVEN FEL

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Abstract

One of the concepts for the next generation of linac-driven Free-Electron Lasers (FEL) is a CW superconducting LINAC driving an electron beam with MHz repetition rates. The beam is then switched into an array of independently configurable FELs. The demand for high brightness beams and the high rep-rate presents a number of challenges for the instrumentation and diagnostics. The high rep-rate also presents opportunities for increased beam stability because of the ability for much higher sampling rates for beam-based feedbacks. In this paper, we present our plans for instrumentation and diagnostics for such a machine.

INTRODUCTION

A new class of fourth generation light sources makes use of LINAC-driven FEL for the production of intense and ultrashort X-ray pulses at high repetition rate [1-3].

Table 1: Electron Beam Parameters

	XFEL	Cornell ERL	NGLS
Beam Energy (GeV)	17.5	5	2.4
Bunch Charge (pC)	1000	77	300
Bunch Length (fs)	80	300	300
Beam Power (kW)	500	530	720
Bunch Rep. Rate (MHz)	4.8	1300	1

These machines are designed to accelerate bunches with extremely low emittance, length and energy spread up to the desired energy and inject them in long undulators to generate the X-ray pulses. For some applications the electron beam is aligned and synchronized with a seed laser in the undulator, or synchronized with a pump laser pulses in so called pump-probe experiments, where the FEL radiation is used to produce snapshots of atomic positions within a sample some time after it is excited with a laser pump pulse.

For the above reasons, this class of LINAC-driven FEL's depends on beam diagnostics capable of providing accurate measurements of the bunch (with typical resolutions)

- Transverse position (1 μm)
- Longitudinal position, or timing (~20 ps)
- Transverse dimensions (1÷10%)
- Projected emittance (0.1 μm normalized)
- Energy spread (0.1%)
- Length (1÷10%)
- Sliced emittance (10% slice, 0.1 μm normalized)
- Sliced energy spread (10% slice, 5%)

The higher repetition rate allows for performing these measurements in averaging mode, thus improving the signal-to-noise ratio, in a time comparable to single shot measurements in lower repetition rate machines. Furthermore, performing beam measurements, averaged or single shot, at higher repetition rate can be used to implement higher bandwidth feedback systems and achieve the greater level of beam stability necessary in FEL's.

Finally, the higher repetition rate makes it possible to "steal" bunches away from FEL production and perform sampled measurements with a much higher frequency.

On the down side, the much larger beam power presents challenges for the survivability of several types of diagnostic devices, when exposed to the full beam [4].

In this paper we discuss aspects of the instrumentation and diagnostics planned for the Next Generation Light Source proposed at Lawrence Berkeley National Laboratory.

NGLS ELECTRON BEAM CHARACTERIZATION

The Next Generation Light Source, a fourth generation light source proposed at LBNL consists in a 2.4 GeV superconducting LINAC, with 1.3 GHz CW 9-cell TESLA-like RF cavities (Fig.1).

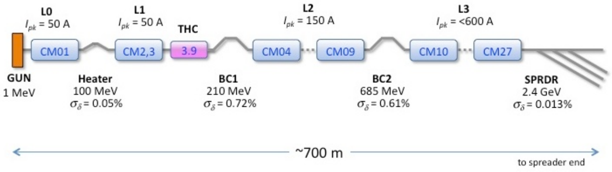

Figure 1. LINAC layout with energies, relative energy spreads (σ_δ) and peak currents.

The bunch length is reduced from the initial 900 μm, to about 350 μm after the first bunch compressor (BC1) to the final 100 μm after the second compressor (BC2). Transverse dimensions are between 200 μm (sigma) in the injector and 40 μm at the end of the LINAC.

At present, we plan to measure projected and sliced 6D phase-space at the end of the injector and at the end of the LINAC. Additionally, we will measure the projected transverse emittance in the LINAC, after the laser heater, between the two bunch compressors, and at the full 2.4 GeV energy. The energy and energy spread are measured

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in the bunch compressors, together with the bunch length. The bunch time of arrival is measured after the last cryomodule. Finally, the beam transverse position is measured using lower resolution stripline beam position monitors (BPM) for orbit control and feedback, and with cavity BPM's in correspondence of narrow gaps, where a higher resolution is necessary.

In general, most of the measurements listed above can be performed in a fully invasive mode, which can either be used during commissioning and machine development, or during user operations, on sampled fraction of the beam. Thanks to the NGLS beam high repetition rate, sampled measurements are in fact equivalent to the same measurements, which make use of the entire beam on lower repetition rate machines.

Another set of measurements can be realized in a minimally invasive mode, so that the quality of the beam is not disrupted. Those measurements, in most cases characterized by a very low intercepting cross section, can also take advantage of the higher repetition rate by building up higher signal-to-noise ratio (SNR) averages in a time span corresponding to a single bunch passage at lower repetition rates. Due to the CW nature of the accelerator, we can count on a certain degree of uniformity between different bunches, the more so when they are separated by a short time.

PROJECTED MEASUREMENTS

In this category we include all the measurements in which different parts along the bunch need not to be resolved.

Bunch Position

We plan to use stripline BPM's analogous to the ones currently being commissioned for the photoinjector test facility APEX [5]. These are shorted striplines, which can be matched to quadrupoles in a rather compact fashion, operating at 250 MHz. The present design yields a SNR for the raw signal of about 3 dB at low charge, with the desired resolution of about half the transverse beam size, and therefore need to be modified for single bunch measurements in that regime.

Where higher resolution is required, such as in the undulator narrow gaps and for laser and electron beams alignment, cavity BPM's will be used. These devices have demonstrated a resolution as high as 27 nm using C-band cavities [6]. In our case, where a more modest 1 μm resolution is sufficient, we plan using larger S-band cavities, which can withstand the full beam power thanks to their lower loss factor.

Transverse Emittance

In the injector, where the transverse bunch size is space-charge dominated, the emittance will be measured by electronically scanning the beam on a double slit system, similarly to what realized in the ERL photoinjector [7] and APEX. This system is obviously destructive, works in an averaging mode and cannot be used with full repetition rate and is reserved for commissioning and during accelerator physics shifts. For such a device the high repetition rate allows to collect a full scan at high SNR in a matter of a minute, even for very low bunch charges.

At higher energy, where the beam size is emittance dominated, we plan to use multiple transverse beam profile monitors with suitable betatron phase advance (60° for three screen, 45° for four screens) as summarized in Tab.2.

Table 2: Transverse Emittance Measurements in main LINAC.

Location	Energy (MeV)	$\sigma_{x,y}$ (μm)	Screens
Laser Heater	85	160,80	3
BC1	206	130,70	3
Collimator	2400	40,40	4

At present we are investigating using pulsed kickers to select a sample of bunch to measure slightly off-axis, thus avoiding possible damage of the beam profiler exposed to the full beam power.

Energy Spread

The bunch energy spread needs to be carefully controlled to optimize the compression process and it is also utilized as a control variable for the RF feedback system. The transverse beam size in the dispersive regions in BC1 and BC2 is dominated by the energy spread and its measurement will be performed analogously to the transverse emittance case.

Bunch Timing

NGLS generates x-ray pulses with durations as short as a fraction of a femtosecond. It is crucial to stabilize the bunch time of arrival to values sub-10 fs to optimize pump-probe experiments and seeded FEL operations. The bunch timing monitors will be integrated in the synchronization and the RF feedback systems. We are planning to use the amplitude modulation induced on a pulsed fiberlaser by means of an electro-optical modulator coupled to the bunch wakefield. This technique has been successfully demonstrated on FLASH [8] and is ideally suited to bunch-by-bunch monitoring of our 1 MHz beam.

SLICED MEASUREMENTS

We include all the measurements requiring resolving the properties of slices of the bunch along its longitudinal axis. Bunch length measurements are also included in this section since they can make use of the same hardware.

The key element of all sliced measurements is an RF transverse deflector, used to introduce a transverse displacement of longitudinal slices of the correlated to their position along the bunch [10]. Each slice is then analyzed separately, essentially with the same techniques already seen in the previous section.

We plan to install two deflecting structures: one at the exit of the injector, the other at the end of the LINAC. Their parameters, with voltages necessary for a longitudinal resolution equal to 10% of the bunch length are reported in Tab.3. At lower energy an S-band deflector at three times the LINAC RF frequency appears to be completely adequate, while at high energy, and with a much shorter bunch, we need to resort to an X-band deflector at eight times the RF frequency, with all the concerns deriving from its higher loss factor.

Table 3: RF Transverse Deflectors Parameters

Beam Energy	**Frequency**	σ_x	σ_z	V_{RF}
85 MeV	3.9 GHz	160 μm	870 μm	0.2 MV
2.4 GeV	10.4 GHz	40 μm	13 μm	4.5 MV

As already mentioned, it is possible to operate the deflectors at a reduced duty cycle, let's say 0.1%, still obtaining one thousand samples per second thanks to the beam 1 MHz repetition rate. This means each 10% slice could be averaged 100 times in one second, with a SNR improvement of 10 dB in the ideal case of perfectly identical bunches.

Particular attention needs to be paid to the deflector loss factor, which particularly in the case of the smaller aperture X-band deflector may cause an excessive thermal load for the deflector, due to the short bunch length.

We are in the process of evaluating available deflectors and, should the deposited beam power result too high, we could install the deflector downstream the spreader and the full power beam dump line, so that in no event it could be subjected to the 1 MHz beam at full bunch charge.

CONCLUSIONS

High repetition rate LINAC used to produce short bunches for free-electron laser based light sources are under construction of being planned at different facilities. This machines are characterized by unique working regimes with very short bunches and high repetition rates and the need of maintaining the lowest possible transverse emittance, energy spread and timing jitter throughout the acceleration process. The use of intercepting diagnostics commonly used in more traditional machine may present special challenges, due to the elevated beam power. On the other hand, the high repetition rate is beneficial to the use of minimally invasive diagnostics, when measurements can be performed in averaging mode and a sufficient degree of machine stability has been achieved, by using wideband feedback systems.

We have presented an overview of the diagnostics currently being studied for the NGLS, which we believe exemplifies many of the characteristic aspects of this class of fourth generation light sources.

ACKNOWLEDGMENT

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