LONGITUDINAL PHASE SPACE CHARACTERIZATION OF ELECTRON BUNCHES AT THE JLAB FEL FACILITY

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TJNAF, Newport News, VA23606, USA

Abstract

We report longitudinal phase space measurements of short electron bunches at the 10kW Free-Electron Laser Facility at Jefferson Lab using broadband synchrotron radiation and a remotely controlled fast streak camera. Accurate measurements are possible because the optical transport system uses only reflective components that do not introduce dispersion. The evolution of longitudinal phase space of the electron beam can be observed in real time while phases of accelerator RF components are being adjusted. This fast and efficient diagnostic enhances the suite of machine setup tools available to JLab FEL operators and applies to other accelerators. The results for certain beam setups will be presented.

INTRODUCTION

High power Free-Electron Lasers (FELs) require very short electron bunches. The picosecond electron bunches produced by the DC high voltage GaAs photoguns must be accelerated and compressed to femto-second time scale using RF and magnetic compressors (for example, RF buncher cavities, off-crest acceleration, drift spaces and magnet chicanes). Setting and maintaining proper phase of the electron bunches with respect to the RF fields in the accelerating linac is critical for effective bunch compression and high power FEL operation. Longitudinal phase space (LPS) measurements provide extremely valuable correlated information between the temporal position of the electrons and their longitudinal momenta. Knowledge of LPS and perhaps more importantly, its evolution with time, helps during machine setup. We report a convenient and non-invasive means to monitor LPS in real-time using synchrotron radiation and a fast streak camera. This work builds upon work reported previously [1], and is part of an ongoing effort to enhance the diagnostic capabilities at the JLab 10KW FEL Facility. In this paper, we describe the measurement technique and discuss the results obtained under different beam setups.

SYSTEM DESCRIPTION

Figure 1 shows a schematic overview of the Jefferson Lab 10kW energy-recovery FEL facility which has been described in detail elsewhere [2]. Electron bunches from the gun are accelerated to 115MeV using a superconducting RF linac and turned 180 degree using a Bates-style arc magnet (ARC1) toward the FEL wiggler magnet located midway between the high-reflector and output-coupler mirrors. The electron beam then passes through a second 180 degree arc magnet for energy recovery through the linac.

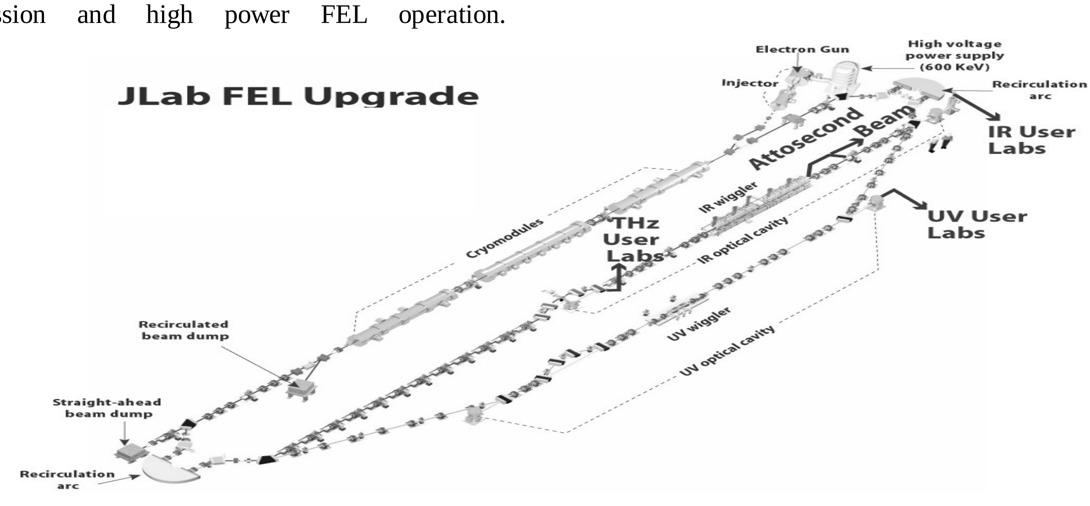

Figure 1: Layout of 10kW FEL facility at Jefferson Lab. The 1KW UV line is under construction. The linac consists of three cryo-modules. The ARC bending magnets are located at each end with ARC1 in the lower-left corner.

Managing the beam energy spread is critical for high current, high micro-bunch charge accelerator operation. In addition, it is particularly important to see how energy spread varies for the two states of accelerator operation: FEL on and off. As described in this paper, energy spread can be monitored non-invasively by monitoring the SR light emitted from the 180 degree bend magnets because electrons with lower energy travel a shorter radial path compared to electrons with higher energy. By monitoring the emission profile of the SR light in the horizontal plane, one can measure the size of the electron beam and therefore the beam energy spread.

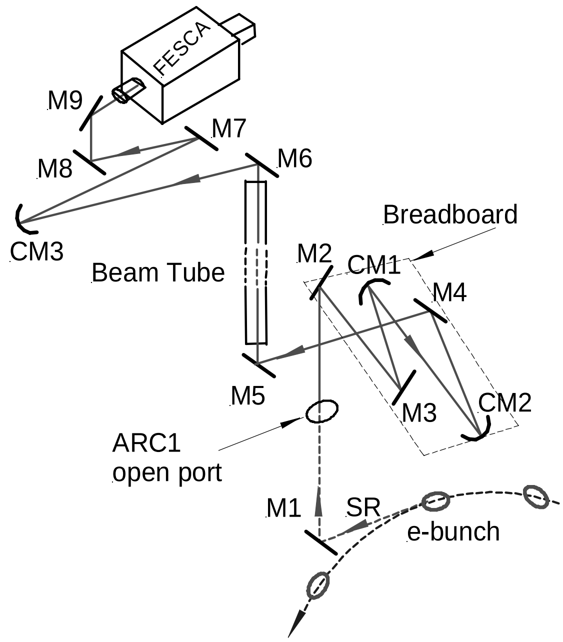

Figure 2: Schematic of the optical transport system (OTS). M, flat mirrors. CM, concave mirrors. Detailed description is given in the text.

For the measurement described here, SR light from the first 180 degree bend magnet (ARC1) was reflected upwards and out of the accelerator vault using an all-reflective optical transport system (Figure 2). The optical transport was designed to image-relay the bunch beam profile from outermost location of the beam orbit in ARC1 to the streak camera entrance slit. The SR light from the electron bunch is extremely broadband and it is important that transmission optics such as lenses are not used. Each mirror was coated with metallic coating to eliminate the dispersion effect. The three concave mirrors have radii of curvature of 200, 500 and 1000mm. Mirror M1 directs the SR beam from the bunch upwards through an open port to M2. The beam then reflects off several mirrors mounted on a small breadboard. The magnification can be adjusted by changing the distance between CM1 and CM2 in order to match the beam size to the camera cathode. The SR light propagates through a tube inserted into a penetration in the building floor. The final image at the streak camera was formed by the concave mirror CM3. A HeNe laser was available for rough pre-alignment of the system, but final alignment with SR light was time consuming, mostly because the distance between the bend magnet and the streak camera is long, more than 8m. Final optimization of the optical transport system was done with SR light during accelerator operations using several motorized mirrors.

The streak camera is a Hamamatsu Synchroscan FESCA system, the measured resolution is about 700fs. Having the streak camera outside the harmful environment of the accelerator vault is beneficial because sometimes local alignment of the camera must be performed, although data acquisition is completely remotely controlled.

MEASUREMENT AND DISCUSSION

Energy Calibration and Resolution

LPS measurements are presented on two-dimensional plots, showing energy spread along the temporal distribution of the electron bunch. Note however that what is actually measured is beam size versus the temporal distribution of the bunch. To convert beam size to energy requires calibration of the streak camera pixel display. This was accomplished using different beam energies and setups that provide minimum energy spread. Figure 3 shows five streak camera images for five different beam energies. The red curve is the initial energy set-point of 115MeV. The green (yellow) curve corresponds to higher (lower) with energy difference of 1.5%. The two peaks are separated by 391 pixels which yields a calibration factor of 0.00385% energy difference per pixel. Next, the pixel/energy resolution was studied using two energies separated by only 0.046%. The blue and pink peaks are separated by only 12 pixels but are clearly distinct. So the system resolution is definitely better than 0.05%.

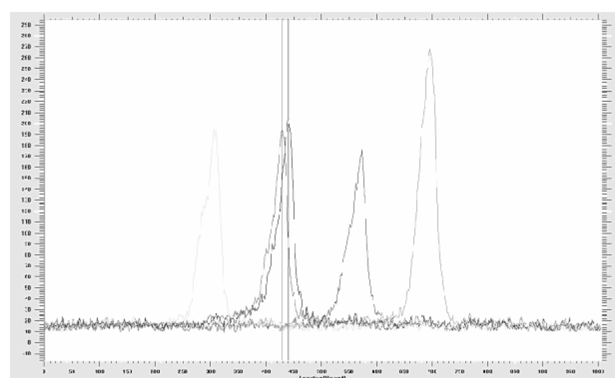

Figure 3. Streak camera images for five different beam energies. The yellow and green curves provide a calibration ratio, beam energy to pixel location. The pink and blue curves demonstrate the high degree of energy resolution of the system. The red curve is the nominal 115 MeV setpoint energy.

LPS vs. Linac Gang Phase

Production of high power FEL light requires off-crest operation of the accelerator. Deviations from this desired phase relationship may lead to reduced FEL output power. The phase relationship of the electron bunches relative to the linac gang phase can be quantified using LPS measurement and the SR light streak camera. This is dramatically evident in Figure 4 which shows streak camera data for different linac RF gang phases relative to on-crest operation. Each picture represents a snap-shot of data presented live within the FEL control room while the accelerator was running.

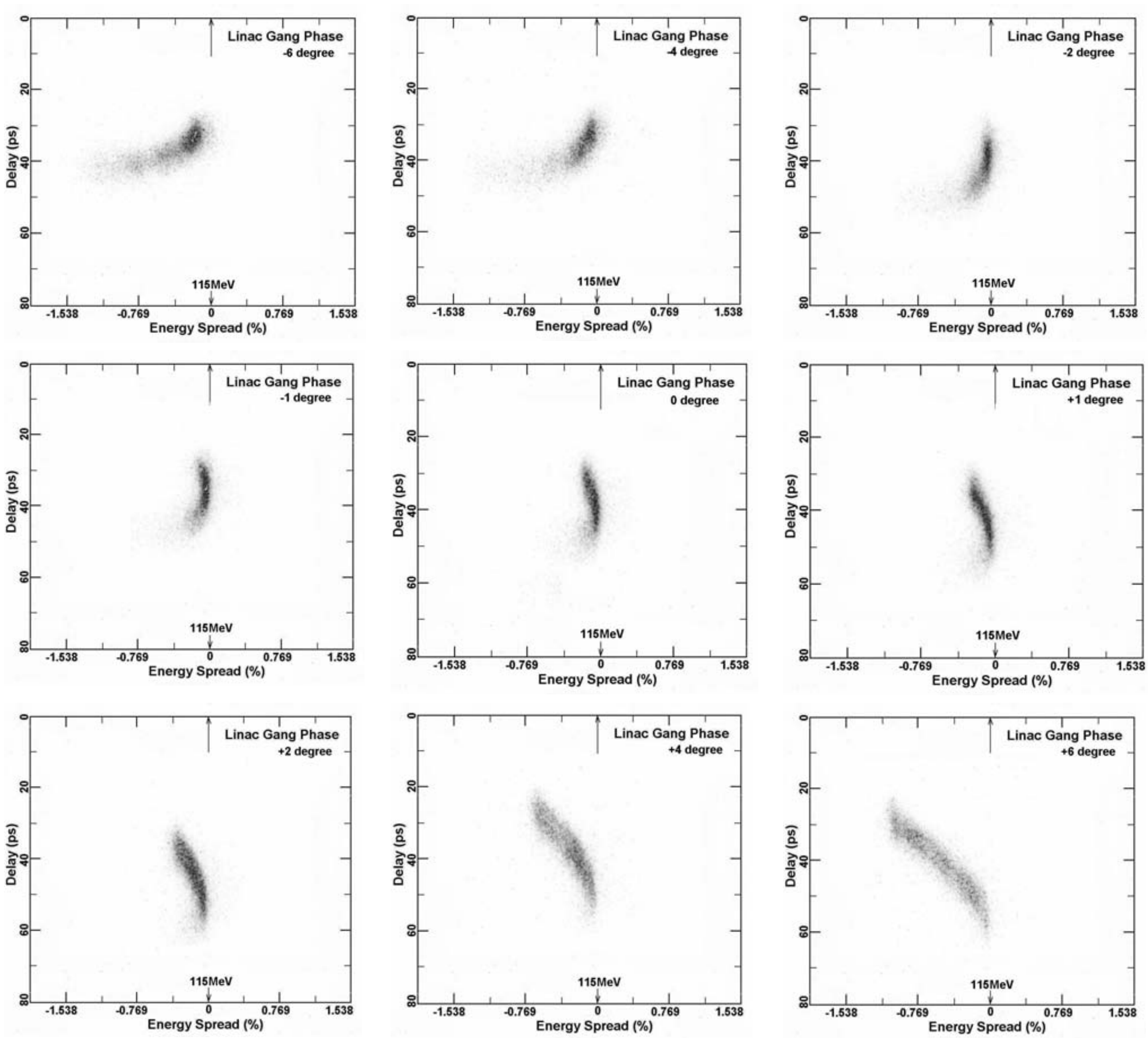

Figure 4: The LPS for different linac gang phase. Beam energy, 115MeV. Micro-pulse repetition rate: 9MHz. Macro-pulse, 1ms at 60Hz. Charge, 110pC per bunch.

From Fig.4, it is clear that the LPS can be quite different even if the bunches sit symmetrically on the two sides of the RF crest. This is the case when the phase angles are equal but have opposite signs. Apparently, a linear chirp and longer bunch length is obtained at 6 degree off-crest. At -6 degree off-crest, the bunch length becomes shorter but the shape is more like a banana, indicating high non-linearity. For on-crest operation, the bunches experience very little energy spread and the phase space is straight up with the least tilt.

LPS vs. Buncher Gradient

The whole injector of the JLab FEL facility consists of a high-voltage DC gun, a quarter cryo-unit followed by a transverse match section and an RF bunch compressor. The electron bunches from the photo-cathode initially have the same temporal length as the drive laser pulses but expand due to space charge effects. Passage through the quarter cryo-module also affects the electron bunch length. Optimum FEL operation requires the electron bunches be compressed before entering linac. We have observed that the gradient of the buncher can affect the phase space of the electron bunches. To investigate this phenomenon, we did LPS streak camera measurements while changing the buncher gradient (Figure 5).

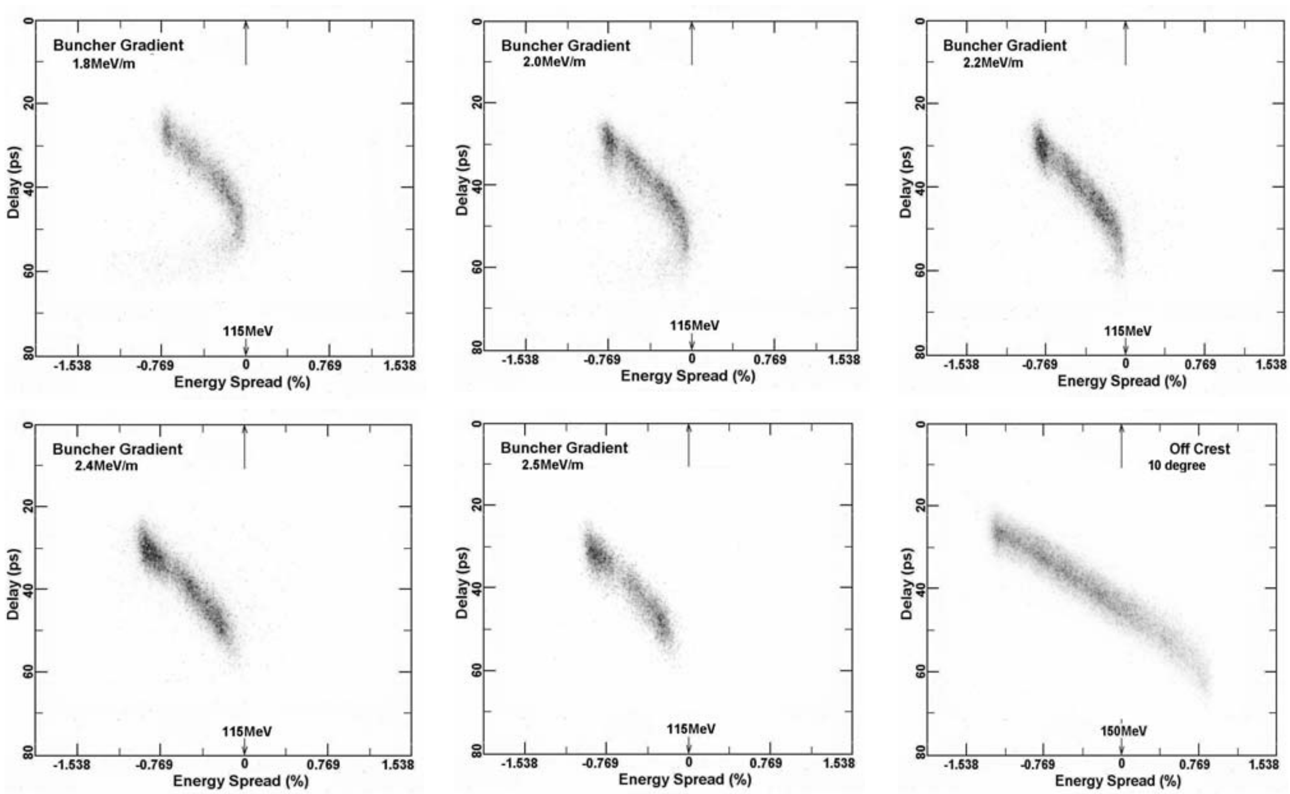

Figure 5: Longitudinal phase space for different buncher gradient. The beam energy, 115MeV. Micro-pulse repetition rate, 9MHz. Macro-pulse, 1ms at 60Hz. Charge, 110pC/bunch. The graph in lower right corner is explained in the text.

As the buncher gradient increases from low to high, the LPS trace gradually stretches out to become a linear chirp. The low energy head is basically preserved through the process while the curled tail disappears at 2.5MeV/m. The last graph in the lower right represents normal FEL operating condition. The excellent linear chirp can be seen across the whole 2.3% energy spread range.

A small part of the information at the two ends of the graph is lost, especially at low energy side of the plot. This is perhaps due to the limited energy window. This can be solved in the future by changing the optical demagnification at the expense of reduced resolution. We also used several band-pass filters with different bandwidth to see if there were dispersion effects induced in the optical transport. No difference was found with and without filters in the bean path, testament to the all-reflective nature of our design.

SUMMARY

We have established a diagnostic that provides real-time longitudinal phase space information without interruption to the accelerator operation. The longitudinal phase space was successfully measured with different linac gang phase and injector bunch gradient. The system was well calibrated with an energy resolution better than 0.05%. We are expecting to get better understanding on some important beam physics as we push toward high current beam and high power FEL on our facility in near future.

Acknowledgement

The authors would like to thank the FEL team, especially the I&C group. Thanks to M.Poelker for reviewing and extensive editing. This work is supported by the Office of Naval Research, Research, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, and by DOE Contract DE-AC05-84ER40150.

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