FEL – ACCELERATOR RELATED DIAGNOSTICS

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Free Electron Lasers (FEL) present a unique set of beam parameters to the diagnostics suite. The FEL requires characterization of the full six dimensional phase space of the electron beam at the wiggler and accurate alignment of the electron beam to the optical mode of the laser. In addition to the FEL requirements on the diagnostics suite, the Jefferson Lab FEL is operated as an Energy Recovered Linac (ERL) which imposes additional requirements on the diagnostics. The ERL aspect of the Jefferson Lab FEL requires that diagnostics operate over a unique dynamic range and operate with simultaneous transport of the accelerated and energy recovered beams. This talk will present how these challenges are addressed at the Jefferson Lab FEL.

I. INTRODUCTION

The Jefferson Lab FEL team has gained a great deal of experience in operating high power FELs beginning with the successful commissioning of the JLab IR-demo machine in 1998. The demo has been operated with CW power as high as 2.4 kwatt until the JLab Upgrade installation began in 2001. (Ref. 1)

I.A. Machine Parameters

The comprehensive diagnostic suite enabled rapid commissioning of both the drive accelerator and the FEL. Table 1 shows design specifications and the realized performance of the IR Upgrade machine.

Table 1. IR Upgrade FEL Parameters

JLab IR FEL Electron Beam Parameters	Design	Achieved
Energy (MeV)	145	160
Bunch charge (pC)	135	270
Average current (mA)	10	9.1
Bunch length* (fs rms)	400	150
Norm. emittance* (mm-mrad)	30	7 (135pC)
Max. Bunch rep. rate (MHz)	74.85	74.85

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I.B. Free Electron Laser Parameters

The FEL has operated in a number of configurations with both electro-magnetic and permanent magnet wiggler and an assortment of different mirrors.

JLab IR FEL Laser Parameters	Design	Achieved
Wavelength (microns)	0.9 - 10	0.7 - 10
Bunch length (fs FWHM)	1000	150
Average Power (kW)	10@ < 2 μm	14.3 @ 1.6 μm
Beam quality (M^2)	< 2	Not meas.
Spectral bandwidth	FTL*	1.2 * FTL
Max. Bunch rep. (MHz)	74.85	74.85

Table 2. IR Upgrade FEL Parameters.
FTL is Fourier Transform limit

II. INJECTOR DIAGNOSTICS SUITE

The injector consists of a GaAs DC photocathode gun, a copper buncher Radio Frequency (RF) cavity, a booster with two 5-cell Superconducting RF (SRF) cavities and an injection chicane. The GaAs wafer is illuminated with a 75 MHz frequency-doubled, mode-locked Nd:YLF drive laser. Electron bunches with a nominal charge of 135 pC are generated when the photocathode is illuminated with the drive laser pulses, each 23 ps rms long. (Ref. 2)

II.A. Low Energy Design Considerations

The nominal operating voltage of the photocathode gun is 350kV (Ref. 3), therefore the drift space between the exit of the gun and the SRF cavity is kept to a minimum for minimizing emittance growth due to space charge effects. This region must also be long enough to accommodate the light box for the drive laser delivery to the photocathode, a zero-crossing buncher for compressing the electron bunches, two solenoid lenses for electron beam handling and a shielded beam viewer. There are also a number of ion pumps and steering coils in this ~1.5 meter region.

II.A.1. Beam Viewer at Low Energies

Optical Transition Radiation (OTR) (Ref. 4,5,6) is the method of choice for profile monitoring but is impractical at energies much less than 10 MeV. A Chromox (Ref. 7) view screen is currently used in the low energy region of the injector. This material is very sensitive but suffers from blooming, very long persistence and can be quite easily damaged from excess electron beam. When this screen is used the drive laser output is attenuated by a Neutral Density (ND) filter of Optical Density (OD2) (100x attenuation) to prevent damage.

In the JLab machine this sensitivity allows it to be used for 3 distinct functions;1. When the high voltage is brought up on the gun power supply this view screen is watched for evidence of field emission from the electrode assembly and for dark current coming off the photocathode, 2. This view screen is also illuminated from field emission coming our of the SRF quarter-cryomodule (Fig. 1), 3. The screen also acts as a profile monitor (but poor performance due to blooming & saturation) Each time the machine is turned on this screen is inserted and observed as a *health* monitor looking for changes in the field emission patterns.

There are plans to change this single Chromox screen out with a ladder assembly which would hold 3 different types of screens. These would be a phosphor coated thin Aluminum screen, a YAG crystal, and the Chromox flag.

II.A.2. Beam Loss at Low Energies

The energy is low enough in the region between the gun and the SRF cavities that the beam tube shields the conventional Beam Loss Monitors (BLMs). When running high currents (CW > 5mAmp) the ion pump current gives the best indication of loss. This loss would come from electron beam halo inherently created at the photocathode by drive laser scattered light and other sources like excessively long tail in the electron bunch due to the slow response time from GaAs cathodes.

II.B. Injector Transport Region

The nominal energy of the beam at the exit of the injector cryo-unit is 9 MeV. To properly set up the injector we need to measure the energy, energy spread, emittance and Twiss parameters. The beam position is also important so that it is possible to center in the various beamline elements. The bunch length is measured using the energy spread at full energy from the linac.

II.B.1. Injector set-up

With the gun voltage, laser spot radius and laser pulse length fixed, there are 8 degrees of freedom in setting up the injector. The upstream solenoid strength is set by minimizing vacuum rise at the exit of the gun. The second solenoid, located just upstream of the SRF cavities is set for emittance compensation, although it can be done only partially because the drift between the gun and the SRF cavities is not ideal for this purpose. The buncher phase is set to operate at zero-crossing while the gradient is adjusted by minimizing the energy spread to compress the bunch. Bunch length out of the injector is critical to minimize longitudinal space charge effects that could significantly decrease the FEL efficiency. Finally, the SRF booster is set to accelerate the electron beam to about 9 MeV/c. The upstream SRF cavity gradient is set to its maximum, presently limited by field emission. This cavity is operated on crest with respect to the drive laser RF cycle for maximum beam acceleration. The downstream cavity phase is set to 10 degrees off crest to longitudinally match the electron beam to the driver accelerator after injection. The gradient of this cavity is adjusted to compensate for the off-crest operation.

II.B.2. Injector Emittance Measurements

In the JLab FEL injector, the beam is space-charge dominated. The beam optics, which does not account for space charge effects, does not properly describe propagation of the beam in a drift space. The quadrupole scan emittance measurements would not be correct in this case. The multislit (Fig. 1) emittance measurement technique (Ref. 7) is used in the JLab FEL injector. The multislit mask is made of Niobium. The mask is 5 mm thick such that it scatters the 9 MeV electrons not passing through the slits to sufficiently large angles. The beam profile (beamlets) is imaged down stream on a phosphor coated screen. The essential part of the multislit emittance measurements in the JLab FEL is that the measurements also provide Twiss parameters. A frame grabber is used to digitize the live video signal, properly synchronized to the beam. The multislit emittance and Twiss parameters measurements are online measurements.

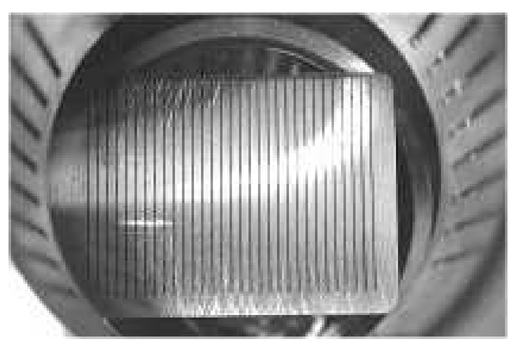

Fig. 1 Injector Multislit Mask

One important observation made during the measurements is that the transverse phase space distribution is very irregular. That part of the beam has Twiss parameters different from that of the rest of the beam. The multislit data contain enough information for the phase space distribution reconstruction. We are working presently to add such capability to the multislit measurements. The origin of the irregularity in the transverse phase space has not been understood completely and is presently under investigation

III. ENERGY RECOVERY LINAC DIAGNOSTICS

The JLab FEL relies heavily on OTR & CTR for the initial setup and machine studies for beam profile monitoring. During high power operation the synchrotron light monitors give a wealth of information about bunching, stability, and laser performance.

III.A. Shielded Beam Profile Monitor

Limiting the electron beam transport shunt impedance is crucial to both preserving the emittance of the beam and protecting the chamber from the RF heating from the short electron bunches. Figure 2 shows the internal of the monitor with the shield partially retracted.

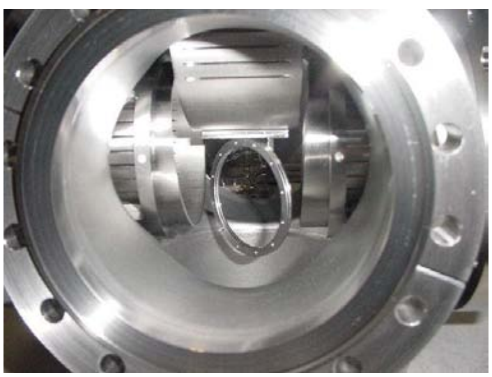

Fig. 2 The 3” shielded beam viewer (shield partially retracted) showing that it also has slots cut to allow for vacuum pumping.

There are a variety of materials used for flags installed on these monitors. Initially the monitors were setup with a 5 micron Aluminum foil (Fig. 3), these have the advantage of minimizing the radiation loading, but the disadvantage (for backward OTR) is that it does not possess a mirror like finish. Note the fiducial marks at $\pm$ 5 mm and $\pm$ 10 mm used to calibrate frame grabber system but no mark in the center as to not corrupt the beam image. As one chooses a thinner material trouble with handling and surface quality dominate the realized performance. The preferred material is now a 60 micron thick, polished, Silicon wafer. These also have a few Angstrom thick gold mask sputter on the surface that enables the frame grabber system to be calibrated for each individual profile monitor.

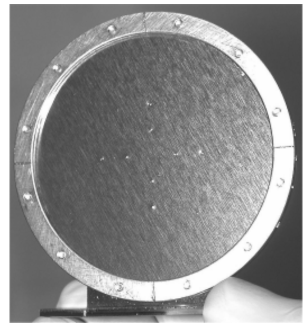

Fig. 3 Five micron thick Al flag (50mm dia.) with $\pm$ 5 & 10 mm pinhole fiducials for calibration

There are both alignment and collection issues that must be addressed when installing such a system. In the case of forward OTR (used in front of a bead magnet) neither the surface finish nor the alignment is crucial, however that is not the case for backward OTR. The most common use is a flag inserted at 45 degrees to the beam. In this case the surface finish of the material used can cause scatter of the signal and for high values of γ (~<200) the alignment is crucial. For initial setup the Jlab uses an alignment HeNe on axis with the electron beam and adjusts the angle of the flag and the deflecting mirror such that the HeNe spot is projected onto the bare CCD element.

There is also a 4” square Aluminum paddle that is used in the 10 MeV dump line. This is also phosphor coated since the beam is diffuse and at relatively too low of an energy for a sufficient OTR signal. Our phosphor techniques derive from Reference 8 & 9, and from techniques learned from the diagnostics team at DESY.

III.B. Beam Position Monitors (BPMs)

The BPM system is used for machine studies, to set up the accelerator for operations, and to monitor its performance (drift) in both low duty factor pulsed mode and during CW operation. In keeping with the philosophy of minimizing the shunt impedance presented to the beam we use shorted stripline BPMs in the areas with round beam tube and buttons where the transport is rectangular in shape. This technique provides an operator with a live updating non-invasive method of monitoring beam position.

The basic requirements for a BPM system are position accuracy < 100 microns over a modest range of beam currents for both pulsed and CW operation. With the understanding that a FEL/ERL will have large apertures, and a limited range in micropulse charge, these machines are setup to operate at a fixed charge while the micropulse rate is varied to increase the current. The majority of steering of the electron beam is done at moderate currents so this implies that a dynamic range of 40 dB is sufficient for this type of machine. The dynamic range is directly proportional to the current ranges that can be monitored so obviously the more dynamic range the better. Since a FEL/ERL can have numerous variations of pulse structures, a BPM system should respond the same regardless of the micropulse or macropulse rates.

Other capabilities that a modern system should posses would be the ability to monitor transverse motion in addition to position, capture enough data to reproduce the beam structure, and the bandwidth to measure pulse to pulse variations within a bunch. In order to monitor transverse motion there are 2 frequency ranges in that are of interest; few KHz and 10's of Hz and below. The faster motion would come from (electric field) problems within the RF or drive laser where the lower frequencies would be more indicative of power supply problems (magnetic fields). The capabilities to reproduce the beam structure would also allow for monitoring of transverse motion as well as view bunch structure changes. The bandwidth to measure pulse to pulse variations would allow for multiple beams to be monitored within a single beam line. This would also allow for steering changes or drifts within a specific bunch to be monitored and noted.

III.C. Synchrotron Light Monitors (SLMs)

The SLMs provide a crucial role as a non-intercepting beam profile monitor. During the design phase of this machine there were SLM ports located at all possible tangent points. The realization of some of these ports have been more difficult than others; in the large arc pi bends there has been a periscope bored through the iron pole pieces. (Fig. 4). These periscopes have also been fitted with a remotely switched mirror and optical transport system to pass the synchrotron light upstairs to a streak camera (Ref. 10).

Fig. 4 SML ports are located in Arc 1 and Arc 2 dipoles

There is also a port on the upstream side so one can properly align the camera. As with the beam viewers all of the SLMs have insertable ND filters of OD 1 and/or OD 2. With no ND filters inserted a 0.5 milliamp pulsed beam (250 microsec macro-pulse) (energy > 100MeV) the image is easily seen. To prevent the camera from being saturated when the machine is operating CW, at currents in excess of 5 milliamps, both the OD 1 & 2 are inserted giving an attenuation of x 1000. Figures 5 & 6 show a *grabbed* image of the live video from the second arc with *no lasing* and with *strong lasing.* Lower energy is shown to the left, that is the power that the FEL extracted from the electron beam. The energy acceptance of the accelerator is ~ 15%.

Fig. 5 This image is from the center of the second arc dipole. This is the nominal distribution of the beam without lasing.

Fig. 6 This is identical to Fig. 4 with the exception that the FEL is lasing quite strongly.

III.D. Beam Loss Monitors (BLMs)

The BLM system primary function is for the Machine Protection System (MPS) but it is a valuable tool to monitor very low (10^{-6}) levels of beam loss. The detector is a Hamamatsu 931B photomultiplier tube connected to a programmable high voltage power supply. Each of the analog outputs from the tubes connects through a 12 channel integrator/digitizer VME board. There is a fiber optic connection to the MPS for shutting down the beam in the event of dangerous levels of loss and each analog signal from the tubes connects to the Analog Monitoring System (AMS)(Ref. 11). The AMS allows remote connection of the signal to a scope for remote monitoring in the control room during operations and for machine studies. There are 24 active BLM heads located at likely loss points around the accelerator, and 6 floater heads that are not connected to the MPS and do not shut off beam.

The system is initially setup by directing 1 microampere of CW beam into these regions where a BLM head is located and remotely adjusting the head voltage (hence the tube's gain) until; the head trips off the electron beam. These voltages range from -500 to -1000 volts. This is done for each of the 24 heads and repeated at 6 to 12 month intervals.

The *floaters* are particularly helpful since the gain can be turned up and used for machine studies on beam loss. These heads are often located in a more exposed area than the interlocked ones (often the head location is partially shielded from an iron magnet or the vacuum chamber).

The wiggler has NdFeB magnets that are sensitive to the total radiation dose. In this case we have installed an ion chamber that kills beam when a given dose rate is exceeded. This dose is set at 300 RADS/hour for a 10 year wiggler lifetime. Typical operational values are much less than this.

IV. PHASE SPACE MANAGEMENT

Successful operation of an ERL-driven FEL requires delivery of a properly configured drive electron beam to the wiggler and the energy recovery of the exhaust beam after the FEL. This must be done while avoiding excessive beam loss in a high power FEL driver, losses must be at the 10^{-5} level or lower, and while avoiding any of a number of collective effects that can lead to beam quality degradation, instability, hardware damage, or beam scraping. These requirements demand well-controlled transverse (betatron) and longitundinal matching throughout the process of beam formation, acceleration, transport, beam delivery, and energy recovery.

IV.A. Betatron Match

In the JLab 10 kW FEL, betatron matching is provided via a number of multi-quadrupole telescopes and aided by a full set of diagnostics. Independent adjustment of the transverse phase space is available at injection into the linac, between the linac and the recirculator, within the recirculator up- and down-stream of the wiggler, and at reinjection for energy recovery. In each case, multiple beam viewers and synchrotron light monitors are used to determine beam spot sizes at numerous locations throughout the machine. A beam optics model (using Microsoft Excel as a compute engine) is then used to reduce the spot size data and evaluate beam emittance and beam envelope function behavior within the transport system. The model is then used to compute adjustments to the quadrupole settings to bring the observed beam behavior into closer compliance with design intentions. When reasonably well optimized, the FEL itself is used to establish fine-tuned values for the final quadrupoles matching the beam into the wiggler. A similar process is used to establish the energy recovery match. Beam viewers and modeling establish a reasonably well tuned configuration; beam loss monitors are then utilized to measure any remnant loss or scraping while running high power pulsed beam (e.g., 5 mA pulses of 1 msec duration at 60 Hz). Adjustment of the reinjection match eliminates measurable loss, leads to low radiation fields during operation and provides very low activation of beamline components.

IV.B. Longitudinal Matching

Longitudinal matching is similarly simplified by the extremely complete suite of available diagnostics. To provide the high peak current required for lasing, a longitudinal phase space rotation is performed. A long, low momentum spread bunch is injected and accelerated on the rising part of the RF waveform to introduce a phase-energy correlation (a "chirp"). The chirped beam is then compressed in length using the momentum compaction of the recirculator transport system. To ensure loss-free energy recovery, a similar process must be used to compress the very large exhaust energy spread from the FEL. The recirculator compaction is used to introduce a phase-energy correlation on the beam tailored to match the RF waveform during energy recovery ("rotate it back); this tuning is done through third (octupole) order in magnetic field and RF phase to ensure adequate performance. Variation of deceleration across the bunch length then compresses the energy spread from over 10 MeV immediately after lasing (at 115 MeV) to only a few hundred keV after energy recover (at 9 MeV). Successful execution of this phase space management scheme requires use of numerous diagnostics. A beam viewer at a dispersed location in the injection line provides momentum spread information; an SLM in a 180 degree dipole at full energy gives the full-energy momentum spread, which can be used to infer the injected bunch length. Verification of the accelerator phasing is performed using spectrometer measurements of the beam central energy as a function of phase with BPMs, and the lattice momentum compactions are directly measured and adjusted using a Beam Current cavity Monitor (BCM)-based phase-transfer function system. (Ref. 12)

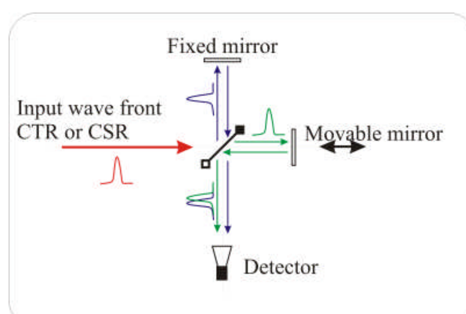

Fig. 7 CTR Bunch length monitor

Bunch length at the wiggler is monitored in four ways: a Martin-Puplett interferometer (Fig. 7, Ref. 13;

"Happek device") is used for beam tune-up; a THz spectrometer provides real-time monitoring of bunch length with high power beam; observations of the coherent enhancement of the beam momentum spread after full compression allows real-time tuning of the compression; and the FEL itself provides the most sensitive measurement of "optimal" compression. The phase transfer unction (M_{55}) system also certifies the momentum compactions of the arc downstream of the FEL; tune-up of the beam match to this transport is then performed in the energy recovery dump line itself, wherein the beam central energy is observed on viewers/with BPMs and adjusted using the recirculator path length, and higher order matching terms are set by iterative adjustment of trim quadrupoles, sextupoles, and octupoles so as to minimize the final momentum spread (as measured on a viewer in the dump/spectrometer line) while lasing at increasingly higher efficiency (with increasing higher exhaust energy spread). Fine tuning is done as with the energy recovery betatron match: beam loss is measured with BLMs and eliminated by appropriate trims on the compaction controls.

V. OTHER BEAM DIAGNOSTIC EXPERIMENTS

We have openly encouraged the use of this machine as a test bed for new concepts in diagnostics and to further exploit existing techniques. Here are a few examples.

V.A. Phase Noise & Energy Modulation

During the early commissioning and the operation of the FEL the laser efficiency dropped as the output power increased. This was the case for a number of different wavelengths. Investigating this efficiency drop-off with the electron beam average current we also have measured the electron beam phase noise and the fast energy modulations. The problem turned out to be absorbed power in the output coupler mirror causing distortions. The > 14 kWatt CW operation was achieved with cryogenically cooled mirrors (LN2).

The so-called phase noise is essentially a variation of the time arrival of the electron bunches to the wiggler. This was initially thought to be the cause of drop in efficiency since the accelerator is routinely operated with the RMS bunch lengths of about 150 fs. The amount of phase noise and/or energy modulation that the FEL can tolerate is defined by the net gain of the system.

The two effects are strongly connected in the FEL driver accelerator due to the Longitudinal Phase Space (LPS) transformation. The LPS transformation is a rotation of a long and low energy spread beam at the injector by ~90 degrees so the bunch length minimum is located in the wiggler. Under such a transformation an energy modulation in the injector would get transferred in to a phase modulation at the wiggler and a phase modulation in the injector would gets transferred in to an energy modulation at the wiggler.

Beam current monitor (BCM) cavities and Agilent E5052A Signal Source Analyzer (state of the art device designed for the phase noise measurements) were used for the phase noise measurements. The two cavities used for the measurements are installed at the injector (0F06) and upstream the wiggler (4F03). The BCMs are pill box cavities with the fundamental mode tuned to 1497 MHz.

In one set of the measurements the electron beam phase noise was measured as a function of average beam current in the range from 0.5 mA through 4.5 mA. As an example, Fig. 8 shows the phase noise spectra measured at the injector and in the vicinity of the wiggler side by side. Figure 8.a shows the spectra measured with 0.5 mA beam current and Fig. 8.b shows the spectra measured at 4.5 mA.

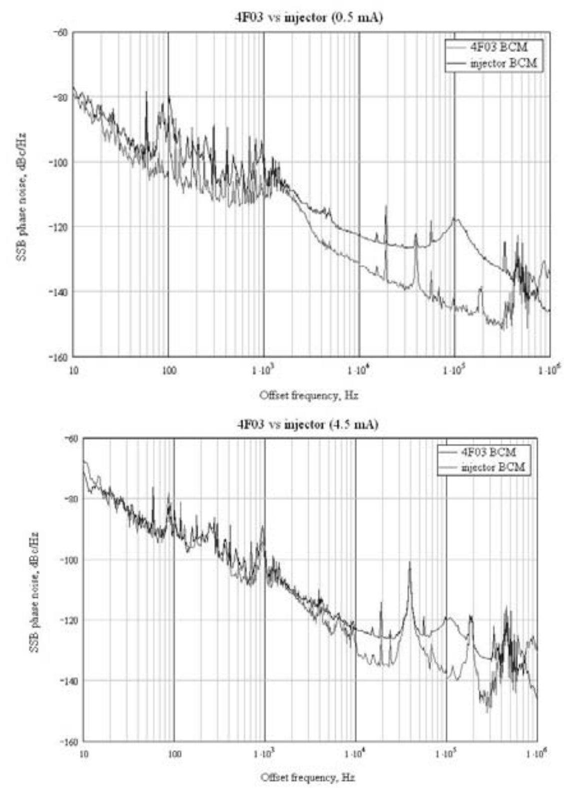

Fig. 8 a & b, Phase noise spectra at 0.5 & 5.0 mAmp

Our estimates are that the level of the energy modulation in the injector, which would lead to the phase modulation at the wiggler of a concern level, also would show up as a ~100 um beam position jitter at the dispersion section in the injector. Thus we would be able to detect such a motion very easily. The first result of the measurements was that there is no significant change in the energy jitter in the injector when the average beam current is increased form 0.5 mA up to 5 mA, so that there is no correlation between the FEL efficiency drop-off and the injector energy modulation. The second result was that beam motion we are measuring in the injector dispersion section is on the level of ~ 1 micron, i.e., much less that the level of concern. The same system was used to measure the fast energy modulations in the dispersion section right upstream of the wiggler. Here again we could not see any dramatic change in the energy modulation with the average beam current. Also the beam energy modulation which we have measured was extremely low and several times smaller that the intrinsic beam energy spread.

Making the above described measurements we could rule out the FEL efficiency drop-off due either the fast energy modulation or the phase modulation. It was in fact problems with the mirror coatings. We also have learned a lot about instrumentation and techniques necessary for this kind of beam study.

V.B. Streak camera measurements of the beam longitudinal phase space

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. We have established real-time LPS information without interruption to the accelerator operation. The design and construction of an all reflective optical transport has made it possible to make full use of the broadband synchrotron radiation and perform a high-efficiency dispersion-free measurement with a remote fast streak camera. The evolution of the longitudinal phase space can be observed live when the accelerating RF phase is tuned. For the measurement described here, the radiating electron bunches at the center of the 180 degree bend magnet (ARC1) are imaged through an optical transport that brings up the SR light to the streak camera entrance. The measured energy spread resolution is better than 0.05%. The streak camera is a Hamamatsu Synchroscan FESCA system with 700fs measured resolution. As an example, one measurement (*LPS vs. Linac Gang Phase)* is presented in Figure 9.

The phase relationship of the electron bunches relative to the linac gang phase is quantified using LPS measurement. 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 (Fig. 10), the bunches experience very little energy spread and the phase space is straight up with the least tilt. Another measurement shows an excellent linear chirp across the whole 2.3% energy spread range under normal FEL operating condition.

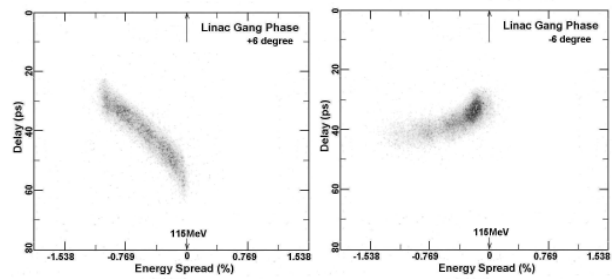

Fig. 9, Energy spread vs. Linac Gang Phase (± 6 degrees) Beam energy, 115MeV. Micro-pulse repetition rate: 9MHz. Macro-pulse, 1ms /60Hz. Charge, 110pC/bunch

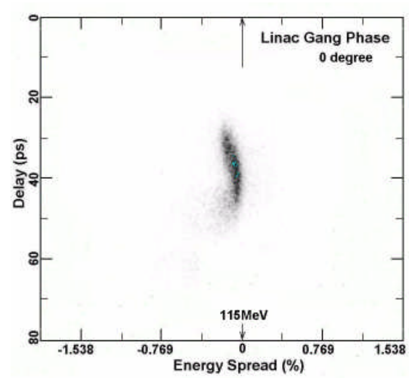

Fig. 10 Linac gang phase *On Crest*

V.C. Other Measurements

Optical Transition Radiation Interferometry (OTRI); Mike Holloway from Institute for Research in Electronics and Applied Physics at the University of Maryland led an effort this past year to examine the use of OTRI for emittance measurements (Ref. 15). This was installed in the little used strait-a-head dump line. The results of this experiment show great promise to enable one to separate the emittance of the core of the beam from the halo. Please see the reference.

VI. CONCLUSIONS

The diagnostics suites for both the IR-Demo & IR-Upgrade machines were optimized for minimizing risk not cost. We as a team faced many unknowns in the design and operation of this high power, CW ERL lasers. The extensive and varied diagnostics that were installed, commissioned and since upgraded were essential to our success.

VI.A. Lessons Learned

The injector diagnostics are crucial but difficult due to the low energies and the space constraints. One must decide whether you want to instrument the beam and in doing so sacrifice emittance or *fly blind*.

The Beam Loss Monitoring (BLM) system is the most important tool in both the initial commissioning and for routine operation of an accelerator. One should have the analog output available for viewing on a scope when threading beam in the machine.

The refinement and evolution of the OTR material has made a significant improvement on the quality of our measurements. The 80 micron Silicon wafers are a good step forward, especially considering the piece price of $10, but they are not optimal. Thinner wafers are expensive and fragile (10 micron @ $300). The alignment of the backward OTR flags is crucial for high gamma machines.

Alignment ports and Synchrotron Light Monitor (SLM) ports need to be designed into machines wherever possible. The SLMs must also be fitted with insertable attenuators to extend the dynamic range of the cameras.

A full function remotely controlled Video Distribution system and Analog Monitoring system are crucial to commissioning and operation of these machines. Often a camera is placed remotely to monitor anything from a meter to laser harmonics. We routinely (automatically) scan through all of the RF phase & gradients at the push of a button looking for an errant signal or oscillation.

VI.B. Desires Yet Unfulfilled

There still remain a few areas where we have been limited by either man power or money (or both). The main 2 are Multi-pass BPMs in the Linac & Phase Space Tomography of both the longitudinal and transverse phase space.

ACKNOWLEDGMENTS

I would like to first thank Fred Dylla & George Neil for their tireless efforts in working to get this facility established and secure funding for continued operation. A great number of people have worked tirelessly proposing experiments, building hardware & taking data to better understand this machine, a special thanks to Carlos Hernandez-Garcia, Shukui Zhang, Daniel Sexton, James Coleman, Tom Powers, Michael Holloway, and Mike Klopf.

There are also two colleges, no longer with us, that did much of the design and refinement of the hardware; Eric Feldl & Karl Capek. Their mastery & talents are sorely missed.

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