

# INFRARED DIAGNOSTICS INSTRUMENTATION DESIGN FOR THE COHERENT ELECTRON COOLING PROOF OF PRINCIPLE EXPERIMENT\*

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## Abstract

The Coherent Electron Cooling Proof-of-Principle experiment [1] based on an FEL is currently under construction in the RHIC tunnel at BNL. Diagnostics for the experimental machine [2] are currently being designed, built and installed. This paper focuses on the design of the infrared diagnostic instrumentation downstream of the three tandem 2.8 m long helical wiggler sections that will act on a 22 MeV 68 uA electron beam co-propagating with the 40GeV/u RHIC gold beam. The 14  $\mu\text{m}$  FEL radiation, or wiggler light, will be extracted from RHIC via a viewport in a downstream DX magnet cryostat and analysed by instrumentation on a nearby optics bench. Instruments concentrating on three parameters, namely intensity, spectral content, and transverse profile, will extract information from the wiggler light in an attempt to quantify the overlap of the electron and ion beams and act as an indicator of coherent cooling.

## INTRODUCTION

The success of Coherent Electron Cooling (CeC) experiment will depend largely on the effectiveness of the instrumentation available. This paper focuses on those instruments associated with measuring and characterizing the infrared light emitted by the wiggler that functions as an FEL and amplifier [3] in this arrangement of modulator, amplifier, and kicker sections. See reference [4] for an update of CeC beam cooling theory using this three-step process. Presented in this paper are details of the instruments that will be employed to measure the wiggler light. Also presented are low cost alternatives to readily available off the shelf instruments and some other low cost alternative solutions.

The construction of the CeC experiment is underway and has been segmented into three phases, each requiring an increasing number of electron beam instruments. As elaborated on elsewhere at this conference [4], the instrumentation for the wiggler's infrared radiation, or wiggler light, will only be installed as part of phases two and three (see Fig. 1). The wiggler sections will be appended to the injector beamline after the injector is commissioned in Phase 1. Phase 2 allows for the wiggler sections to be tested with the electron beam as a stand alone experiment in the RHIC tunnel, independent of RHIC operations, except for use of the cryogenic system.

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During this phase, a local optical bench will be installed downstream of the three wiggler sections. The instruments located there will receive the wiggler light through a ZnSe viewport in a downstream auxiliary port of the dipole magnet that brings the electron beam to the beam dump. The optics bench will be located in the RHIC tunnel to avoid the upfront cost of an optical beam transport back to the laser building, approximately 60m away. When the experiment moves into Phase 3, the wigglers will be installed into the RHIC beam path to allow co-propagation of the electron beam and the Yellow ion beam. In this phase, the optical instrumentation table may be relocated to a laser trailer installed outside the RHIC tunnel to avoid further exposure to high radiation levels in the tunnel. A modification of the DX magnet cryostat, responsible for splitting and recombining the RHIC blue & yellow counter circulating beams, will be made so that the wiggler light can propagate straight out between the two emerging (blue & yellow) beam pipes via a viewport. A sealed optical beam transport could be installed to bring the light from the viewport to the laser trailer.

## WIGGLER

The three helical permanent magnet wiggler sections are being constructed by the Budker Institute of Nuclear Physics. Table 1 summarizes the parameters of the electron beam and the wigglers.

Table 1: Wiggler & e-beam Parameters

e-Beam	Value
Energy	21.8 MeV
Charge per bunch	0.5 – 1 nC
Current (1nC), Avg / Pk	78 $\mu\text{A}$ / 60 – 100 A
Beam Power	1.7 kW
Bunch Length	10 ps
Repetition Rate	78.3 kHz
Wiggler	Value
Length (3 sections)	3 x (2.5 + 0.30 m)
Period ( $\lambda_u$ ) / poles	4 cm / 60 + 2.5 ea. section
Strength (K)	0.50
Wavelength ( $\lambda$ )	14 $\mu\text{m}$
Optical Power	250 nW – 250 mW

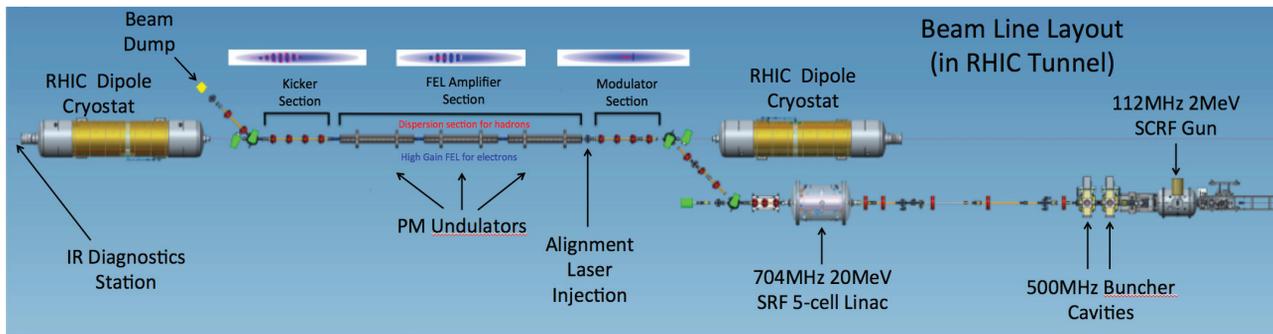


Figure 1: Layout of Phase 3 for implementation of the CeC experiment with the RHIC ion beam.

The three wigglers are due to arrive at BNL later this year. Window-frame corrector coils and 3-pole wiggler (phase shifter) coils are being provided to match the beam trajectory and the phase of the electron beam from one Wiggler section to the next. The position measurement of the electron beam is critical for sufficient overlap with the ion beam. Moreover, the phase of the electron beam entering each wiggler section must be adjusted to ensure proper alignment of the electron wave packets [5] created in the modulator section with the ion energy centers during the amplification process through the FEL.

To provide enough amplification of the imprinted pattern on the electron beam, an wiggler of a length surpassing fabrication capabilities was required. Therefore, three separate sections were proposed, each consisting of 60 poles, plus  $2\frac{1}{2}$  poles for matching; thereby comprising the 2.8 m length. The wigglers will receive an electron beam of  $\sim 10$  ps pulses at a repetition rate of 78 kHz, corresponding to the revolution frequency of the RHIC beams. This will allow a single bunch in RHIC to be cooled for comparison to the uncooled bunches during this proof of principle experiment.

The wiggler peak magnetic field strength, required to give the specified wiggler  $K$  parameter of 0.50 is calculated to be 0.134 T by the well-known equation (1) for the deflection parameter,  $K$ , below.

$$K = 0.934B(T)\lambda_u \text{ (cm)} \quad (1)$$

The coherent electron cooling theory calls for a dispersion section that imposes a time-of-flight dependence on the hadrons' energy in order for the kicker section to cool it [6]. As this proof of principle experiment is budget conscious, the experiment is designed such that the ion beam shares the same path as the electron beam through the wigglers where the effect on the ions is negligible. As the dispersion is still necessary, RHIC will operate its run with gold ions at an energy, less than typical, of 40 GeV/u for this dispersion to occur as the ions drift from the modulator section towards the kicker section.

As the electron beam passes through the wigglers, coherent radiation occurs and the system begins to behave as an FEL. The light emitted by the FEL will be an important feedback of both the position of the electron beam in the wiggler as well as the degree of overlap of the

electron and hadron beams. The light from the wiggler has a predictable wavelength that is given by equation (2) below.

$$\lambda = \frac{\lambda_u}{2\gamma^2} (1 + K^2) \quad (2)$$

Calculating  $\gamma$  based on the fact that the electrons must have the same velocity as the ions, at 40G eV/u, and using the  $K$  from (1), the expected wavelength is  $14\mu\text{m}$ . Moreover, numerical simulations were performed and presented earlier [2] showing the full spectrum. The viewport allowing the FEL IR light to exit the vacuum for analysis shall be constructed of ZnSe, allowing 70% transmission in the  $0.6 - 20\mu\text{m}$  infrared region. Also, the simulations predict a radiation pattern, 15 m from the FEL, to be circular with a 40mm diameter. Figure 2 below shows this result, also presented earlier [2].

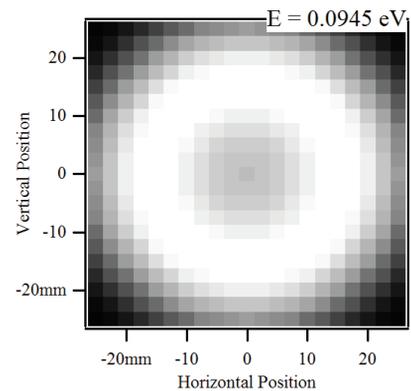


Figure 2: The transverse distribution of the optical power at wavelength corresponding to the maximum. The dip in the middle is due to the spiral electron motion.

## IR INSTRUMENTATION

Measuring the characteristics of the wiggler light will be made in the far infrared region, as the wavelength is  $14\mu\text{m}$ . Qualities such as intensity, position, and spectral content of the light contain information about the lasing and cooling process. Moreover, a widening of the fundamental spectral line in the wiggler light is expected during the cooling process.

The optical table down stream of the last dipole supports devices to measure optical power, optical beam

profile, and optical beam spectrum. A 5 mW HeNe alignment laser with a 10X adjustable beam expander, located 65 ft upstream, will be used with a surveyed monument on the table to align the optical components to beam center. The laser beam is injected into the beam pipe using a mirror on the backside of a beam profile monitor just upstream of the wiggler section.

### IR Power Measurements

The power from the IR light is expected to range from the 250 nW to 250 mW (spanning ~6 orders of magnitude depending on the amount of amplification, seeding, etc.). Two detectors will be used interchangeably during commissioning of the wigglers. A high bandwidth IR photodetector will be used, likely with a lock-in amplifier to improve S/N, to measure down to ~1 μW with a 1 MHz BW so as to capture the optical power measurements and look for variations from pulse to pulse in the 78 kHz beam. The other detector is a slower but offers a wider range of thermal power sensitivity.

The IR photodetector is from Vigo Systems, model PC-3TE, optimized for 2 – 14 μm and based on a (HgCd)Te semiconductor with optimized doping and sophisticated surface processing with a three-stage thermoelectric cooler and optically immersed to a high refractive index GaAs hyperhemispherical lens. This detector is packaged in a sealed TO-8 case with a BaF2 lens and integrated into model MIPAC-F-1 ac coupled transimpedance amplifier with a bandwidth of 1 MHz, shown in Fig. 3a.

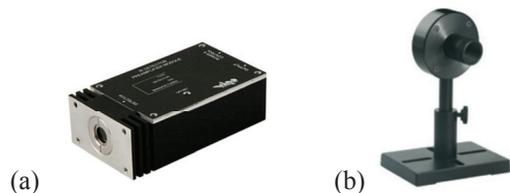


Figure 3: (a) 1MHz IR photodetector, (b) wide range thermal power sensor.

The thermal power IR detector, shown in Fig. 3b, is Ophir model 3A-UA-RS232\_AO-V-FC, with a power input range of 10 μW – 3 W, over 3 selectable gain settings on an integrated calibrated amplifier and 16-bit DAC with remote connection via serial link. It has a spectral range of 0.19 – 20 μm, with a 9.5 mm aperture and is used for average power measurements in CW mode with a response time of 1.8 seconds.

These power measurement sensors will likely be employed after the electron beam has been commissioned to operate in CW mode. The thermal power sensor signal will be digitized, asynchronously at a rate 1 Hz; whereas the photodetector will require synchronous digitization to acquire the measurements with each beam pulse.

### Direct Profile Measurements

We are considering using a pyroelectric crystal based digital camera to measure the IR beam profile. Spiricon offers a Pyrocam<sup>TM</sup> III, as shown in Fig. 4, with a 124

x124 array of 100 μm pixels on a 11.5x11.5 mm sensor. The IR beam transverse profile at the exit of the DX magnet cryostat viewport is expected to have a 40 mm diameter, as shown in Fig. 2. Thus a large LWIR lens (7 – 14 μm typ.) will be required to image the 40mm diameter beam. The model Pyrocam IV, as shown in Fig. 4, is a better option with a 320x320 mm array of 80 μm pixels on a 25x25 mm sensor but at a much higher price. The pyroelectric crystal in the integrating sensor is sensitive to very short pulses. However, once CeC begins operating in CW mode, the internal chopper option of the Pyrocam would be needed.

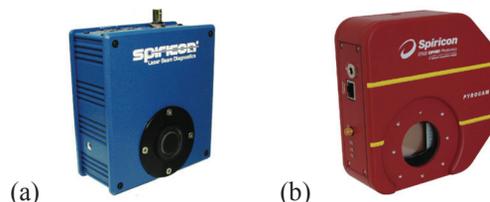


Figure 4: (a) Pyrocam III IR profile monitor, (b) Pyrocam IV IR Profile Monitor.

### Scanning Profile Measurements

In order to be conscientious of cost, an alternative scanning method of profiling is proposed using the IR power measurement detectors already purchased. Leveraging off of software development completed for the “pin-hole” e-beam profile measurements made at RHIC’s Electron Lens (eLens) project [7]; a two-axis scanner could move the power detector, covered by a pinhole mask, to create a map of the beam’s transverse profile. In the eLens, the electron beam is scanned over a pin-hole masked Faraday cup. Software controls the steering magnets and recreates the image from the array of collected charge data. Here, similar software can run stepper motors to scan the detector through the beam and reconstruct the image from the array of collected IR power data. Thus scan time for a 300 x 300 point array would be require ~35 sec (accounting for stepper motor drive speed and integrator & digitizer triggering). This will require a stable beam over the full scan period.

The scanning algorithm produces arrays of data in alternating horizontal line directions to avoid retrace time. Thus the software must massage the data back into a proper array and apply the step size scale factors to recreate the image with the proper scale. The existing software was developed to analyse the image intensity by identifying axes (X, Y & θ) through which to section the data for a profile plot. A sample beam image from eLens is shown in Fig. 5, representative of the round beam profile expected from CeC’s helical wiggler. A radius feature is implemented to find the full field of the beam based on a settable threshold (3 % typ.). This is shown as the satellites around the beam spot in Fig 4.

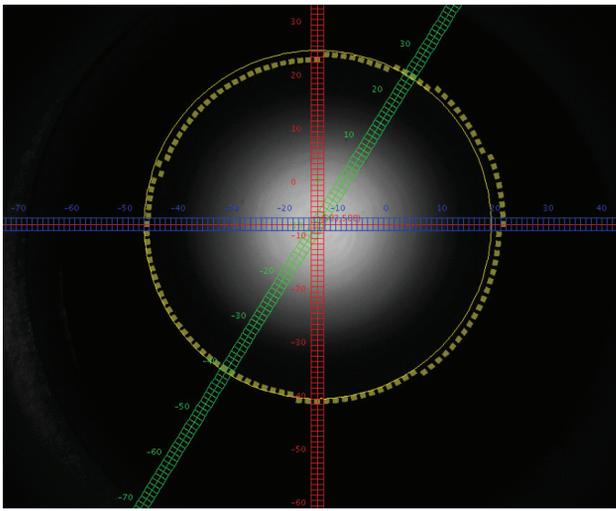


Figure 5: Representative beam spot for demonstrating profile measuring software.

Figure 6 shows the profile plots through one of the axes. The blue delimiting lines correspond to the full field (3 % typ.) point in the Gaussian tails. Each axis plot displays the calculated sigma, radius, and  $\chi^2$ .

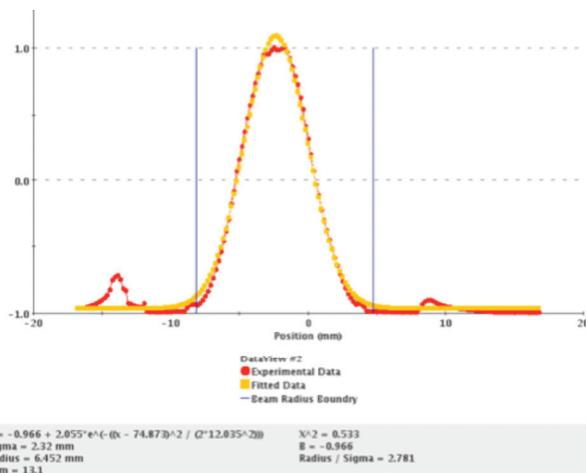


Figure 6: Screen shot of profile generated from the x-axis.

## FUTURE PLANS

Once the Phase 1 configuration is commissioned during the next several months and stable e-beam from the photocathode is measured by the instrumentation, we will proceed with Phase 2 where the 5-cell superconducting LINAC is added as well as the three wiggler sections and the high power beam dump, and associated instrumentation [4]. Once the full power of the FEL is demonstrated and the IR light is measured with the power meters, and optional profiling system, the dog-leg beam transport section will be added to allow the three FEL be relocated into the RHIC beam for Phase 3; where the coherent electron cooling process will be demonstrated with the RHIC ion beam.

## Spectral Measurements

As we advance in optimizing the coherent electron cooling process, it may become interesting to investigate, not only changes in the intensity and shape of the wiggler light, but also any changes in the spectrum. We expect to see variations in the spectral line width during the cooling process. We have considered the Acton VM-504 Spectrometer from Princeton Instruments configured with a 75-groove/mm grating centered around our 14  $\mu\text{m}$  wavelength. If we find that spectral changes occur in a manner that has some distribution over the 2D image, we may consider an imaging spectrograph, such as Princeton's IsoPlane SCT 320 with cutting edge resolution due to its zero astigmatism design.

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## REFERENCES

- [1] V. Litvinenko, et al., "Proof-of-Principle Experiment for FEL-Based Coherent Electron Cooler", WEOA3, proceedings of FEL2011, Shanghai, China, 2011.
- [2] D. M. Gassner, et al., "Coherent Electron Cooling Proof of Principle Instrumentation Design", WEAP01, proceedings of BIW2012, Newport News, VA, 2012.
- [3] V. Litvinenko, et al., "High Gain FEL Amplification of Charge Modulation Caused by a Hadron" MOPPH026, Proceedings of FEL08, Gyeongju, Korea, 2008.
- [4] D. Gassner, et al., "Coherent Electron Cooling Proof of Principle Stage 1 Instrumentation Status" THP093, These proceedings, FEL2014, Basel, Switzerland, 2014.
- [5] G. Wang, et al., "Influence of Electron Beam Parameters on Coherent Electron Cooling", THYB02, proceedings of IPAC 2012, New Orleans, LA, USA, 2012.
- [6] V. Litvinenko, et al., "Advances in Coherent Electron Cooling" THAM2HA02, Proceedings of COOL2013, Murren, Switzerland, 2013.
- [7] T. Miller, et al., "RHIC Electron-Lens Beam Profile Monitoring" TUPG039, Proceedings of BIW2012, Newport News, VA, USA 2012.