OPTIMIZATION OF ELECTRON BEAM AND LASER PULSE ALIGNMENT AND FOCUSING AT INTERACTION POINT FOR A COMPACT FEL BASED INVERSE-COMPTON SCATTERING X-RAY SOURCE*

P. Niknejadi†, J. M. J. Madey, University of Hawai‘i at Manoa, Honolulu, HI, USA

Abstract

In July 2015, the first beam of 10 keV X-rays from our FEL based inverse-Compton scattering X-ray source was detected. In this setup, 3 micron laser pulses at 2.856 GHz repetition rate from a free electron laser are collided head-on with 40 MeV electron bunches driving the laser. To attain our objective the ebeam was required to have 1) a tight focus at the X-ray interaction point, 2) vertical and horizontal envelopes matched to the downstream undulator, 3) minimized transverse dimensions for low ionizing radiation. Optimization of these quantities required information on the evolution of the beam profiles between the beam spot images on the available insertable screens, leading to the need for a simulator to accurately trace the beam profiles through the system. A simulator was developed and used to optimize the system Twiss parameters by comparing the effectiveness of the beam profiles computed by fitting the profiles to the experimental beam spot images along the beamline for different cathode positions. This method proved to be considerably more flexible and effective than the more traditional quadrupole scan technique. Summery of the designed system and results are provided.

INTRODUCTION

A novel high brightness 5-20 keV inverse-Compton x-ray source, Mark V (MkV), is under development at the University of Hawai‘i at Manoa (UHM). This system utilizes elements and concepts that are widely recognized and well understood yet have never been put to practical use in one place before [1]. Additionally, it can match requirements of spot size and divergence (etendue) of different applications. The final goal is to achieve a proof-of-concept experiment that produces a high average flux of monochromatic photons of 10 keV x-rays with $\mathcal{B} \sim 10^{15}$.

The components of MkV FEL were for the most part developed at Stanford. It was originally identified as the MkIII FEL as it was the third FEL system developed at Stanford. After its transfer to UHM, commissioning and upgrades the system is now called MkV. The MkV upgraded system is currently in use for the exploration of the physics as well as the research and development associated with Time Encoded Differential Absorption (TEDA) project. For this purpose the MkV is configured as an inverse-Compton scattering source that utilizes the infrared output of the MkIII FEL to produce photons in the x-ray regime with energies of the order of 10 keV. The main elements of MkV are: 1) a thermionic cathode electron source in a microwave gun injector, 2) a high power ITT Triton 2956 klystron powering the S-band Linac, 3) a transport system (diagnostic chicane (DC)), 4) Interaction Point (IP) scattering chamber, 5) an oscillator IR FEL set as a quasi-CW mode-locked laser, and 6) an optical resonator cavity. Once fully commissioned, the system is expected to be capable of producing high brightness photon beams with lower peak power. The current and future parameters of MkV are shown in Table 1 [2].

Table 1: MkV FEL Based ICS Experiment Parameters

Symbols & Parameters	Values or Range
RF / Electron Pulses	
f_{RF} RF Frequency	2.856 GHz
T_{RF} / T_e Macropulse Spacing	350 ps
I_{mp} Macropulse Current	~ 170 mA
τ_{mp} Macropulse Duration	4-8* µs
f_{mp} Macropulse frequency	4-10 Hz
$I_{\mu p}$ Micropulse Current	30-60 A
$Q_{\mu p}$ Micropulse Charge	60 pC
$\tau_{\mu p}$ Micropulse Duration	1-2 ps
$\mathcal{E}_e$ Electron Beam Energy	35-45 MeV
Laser Pulses	
λ_0 Laser Wavelength	3 µm
$\mathcal{P}_l$ Laser Power	8-16 MW
Interaction Point	
w_0 Beam Radius	30-100 µm
$\mathcal{F}$ Storage Cavity Finesse	2000*
$\mathcal{P}_s$ Stored Optical Power	~16* GW
Scattered X − rays	
$\mathcal{E}_\gamma$ X-ray Energy (Max)	10 keV
λ_γ X-ray wavelength (Max)	1 Å
$\mathcal{P}_\gamma$ X-ray Average Power	1* W
$\mathcal{B}_{ave}$ Average Brightness	10^{14}* photons per $\mathcal{A}$ [1]
$\mathcal{B}_{peak}$ Peak Brightness	10^{21}* photons per $\mathcal{A}$

*predicted values

MOTIVATION

The energy of the back-scattered photons in an ICS experiment is $\mathcal{E}_{\gamma'} \sim 4\gamma^2\mathcal{E}_\gamma$, for the set up at UHM, $\mathcal{E}_\gamma$ is the energy of the radiation from the FEL laser ($\lambda_\gamma \sim \frac{\lambda_u}{2\gamma_z^2}$)

$$\mathcal{E}_\gamma = \frac{2hc\gamma_z^2}{\lambda_u}, \tag{1}$$

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* Work supported by DHS-ARI grant: 2010-DN-077-ARI045

† pardis@hawaii.edu

[1] $\mathcal{A}$ represents unit sec × mm^2 × mrad^2 × 0.1%BW

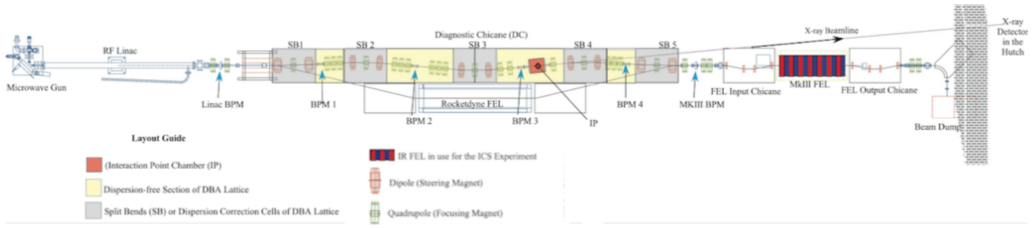

Figure 1: Annotated scale drawing of the MkV FEL beamline.

where γ_z is the γ-factor in the electron rest frame in the undulator on the z-axis. Therefore the energy of the photons from our ICS experiment has the following relation:

$$\mathcal{E}_{\gamma'} \sim \frac{8hc\gamma^2\gamma_z^2}{\lambda_u}. \tag{2}$$

The power of the x-rays backscattered by the electron beam is then proportional to the above factor and the arrival rate of the electrons. For a strong laser pulse and with an optimized interaction region we can get an estimate of the radiated x-ray photon flux that does not include the coherent effects. As the number of photons becomes large, a strong coherent laser pulse would act like an undulator. In this case, electron beam will micro-bunch which can result in coherent emission. In this case the x-ray brightness may be enhanced by several orders of magnitude [3, 4]. In this paper, we will discuss the electron beam diagnostic set up and method that led to detection of low flux 10 keV x-rays and briefly mention future plans that are expected to turn MkV to a coherent x-ray source.

ELECTRON BEAM REQUIRMENTS

The probability of a single photon scattered by ICS increases as the electron beam radius (w_0) gets smaller. Therefore it is essential to focus the beam to a waist at the IP. At the same time, since the same beam will be driving the FEL, over focusing the beam at the IP must be avoided to ensure non-linear and undesirable effects are not introduced. We studied this problem by means of simulation and then from the intuition gained based on the simulations; We present a simple yet elegant and effective solution that can be described by ray optics. Additionally, the electron beam must be centered on the DC's longitudinal axis in order for the photon and electron beam to collide with maximum cross section.

FINDING A MATCH SOLUTION

We described, in general terms, the electron beam requirements for our experiment. Here we identify what steps needed to be taken to obtain a beam with the said requirements. It is important to point out that the transport line (DC) of MkV (shown in Fig. 1) is complex. The beamline was designed not only to deliver a suitable beam to the undulator but also to allow for different experimental setups such as the one we are currently discussing. This design was based on the DBA lattice design used in rings. By alternating the direction of the bends the DBA lattice was adapted and successfully commissioned for our linear accelerator [5].

Longitudinal Alignment

The first requirement that needed to be satisfied was the longitudinal alignment. This was done by means of Beam Position Monitors (BPMs) and Transition Radiation (TR) screens. The BPMs and the TR screens were carefully calibrated. The BPMs show an offset value, when the offset is non-zero, the beam is no longer centered.

Transport Simulation Module (TSM)

An electron transport system can be described in terms of matrices. Although the matrix for DC is known, as it is a linear beamline without the periodicity of a ring, it does not have a real analytical solution. Prepackaged simulation codes are often used to describe such beamlines, but in our case, due to the high number of elements and constraints, this becomes a nonlinear problem. Therefore an in-house transport simulation module (TSM) was prepared. The TSM reads the current supplied to the magnets by the power supplies directly and calculates the beam parameters along the beamline to first order. The TSM was benchmarked, tested, and updated to represent the beamline geometry (DC matrix) accurately. Before the beamline turns into the reliable tool it is today, the following two elements has to be carefully considered.

Residue Fields With the TSM, we were able to reduce the complexity by means of the direct communication between the module and control elements. The set ups, however, were not exactly reproducible the next day. We discovered that this was due to the very small yet present residual field in the quadruples. We were able to eliminate this issue by installing degaussing coils on all magnets.

Initial Conditions A reliable estimate of the evolution of the beam along DC is only possible if the beam emittances and Twiss parameters are known accurately. Originally this measurement was done by performing quad scans. We realized, however, that if the beam is a match to the undulator, we can use the focusing properties of the undulator to estimate the emittance and β of the beam in the vertical direction (y).

Since there is no focusing in the horizontal (x) direction (when run without a microfocus at the IP), we can treat the beamline in the horizontal direction as a long drift line. A shorter version of the beam transport module was written in matlab to take the TR screen images for a run with a vertical focus and horizontal minimum in the middle of the undulator (based on image on $\pi/2$ screen) to find the emittances and Twiss parameters. The $\pi/2$ screen is strategically located before the chicane just before the undulator. The beam on $\pi/2$ is automatically reproduced in the center of the undulator.

A Ray Optics Model for the Microfocus

Once we had a stable beam and reliable information and control of its parameters, we used the ray optics model shown in Fig. 2 to implement the microfocus without jeopardizing the match to the undulator. We were able to accurately and reproducibly fulfill this requirement as a result of the discussed capabilities of TSM. An example of the optimized match recorded on the TR screen based on the predictions of the TSM is shown in Fig. 3.

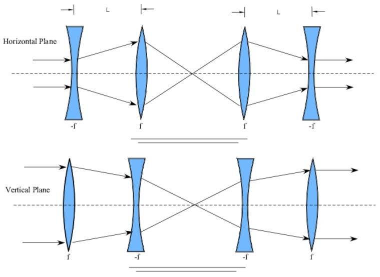

Figure 2: Ray optics model for the doublets around the IP demonstrates it is possible to achive a microfocus in both the horizontal and vertical direction and allows us to identify some of the required beam parameters for the initial condition (i.e. ratio of beam size in x to y.)

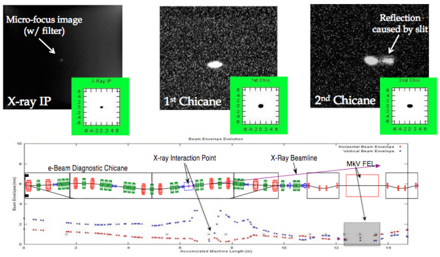

Figure 3: Comparison of the TSM prediction and beam profiles for an optimum match for the ICS experiment.

OUTCOMES AND RESULTS

Match and Alignment

The cathode position in the cavity gun, plays an important role in obtaining the best match solution for x-ray production. We found that when the gun's cathode was moved to a position at which the electron beam emerging from the linac was weakly convergent in both the vertical and horizontal planes, achieving all the beam requirements was possible. This was an unexpected yet valuable insight, because we were able to find the optimum cathode position (initial conditions) in advance and then have the flexibility and time needed to implement the solution for the electron beam and align the electron and the laser beam. An example of the ~ 70 micron beam aligned with the laser pulse is shown in Fig. 4.

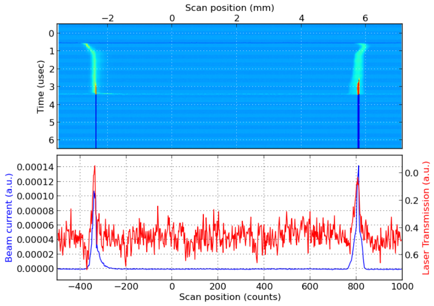

Figure 4: Wirescan of the microfocused electron beam and laser beam aligned. (The fully optimized laser for this run had a pulselength of 1.5 µs and energy of 2 mJ, however laser power was reduced, by detuning the cavity, factor of 4 to prevent damaging the wire.)

X-ray Measurements

The studies presented here led to successful detection of 10 keV x-rays from our FEL based ICS source. Although the background radiation in these data were moderate, by performing pulse height and width selection analysis, we were able to observe flux of ~ 10 or 20 photons per second (Fig. 5).

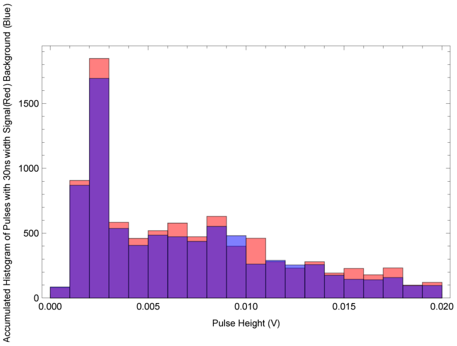

Figure 5: Example of photon counting when ~ 11, 10 keV photons per second were recorded.

CONCLUSION AND FUTURE PLANS

The results presented verify that we have met the requirement for focal properties and alignment of the beams. Future upgrades to 1) reduced the background, 2) increase the macropulse duration from 4 to 8 µs [6] and 3) commissioning of a 4-mirror optical cavity have been initiated to reach our final goal of making a coherent ICS source [2].

ACKNOWLEDGEMENT

We wish to thank the past and present members of University of Hawai'i Free Electron Laser Laboratory, whose contributions were integral to this work.

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