CONCEPTUAL DESIGN OF A 20 GeV ELECTRON ACCELERATOR FOR A 50 keV X-RAY FREE-ELECTRON LASER USING EMITTANCE EXCHANGE OPTICS AND A CRYSTALLOGRAPHIC MASK*

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Abstract

At Los Alamos National Laboratory we are actively exploring the feasibility of constructing a 50-keV x-ray free-electron laser. For such a machine to be feasible, we need to limit the cost and size of the accelerator and, as this is intended as a user facility, we would prefer to use proven, conventional accelerator technology. Using recent developments in transverse-to-transverse and transverse-to-longitudinal emittance exchange optics [1,2], we present a conceptual 20-GeV conventional electron accelerator design capable of producing an electron beam with a normalized transverse emittance as low as 0.15 μm, a root-mean-square (RMS) beam length of 80 fs, and an RMS energy spread of 0.01%. We also explore the possibility of introducing a crystallographic mask into the beam line. Combined with a transverse-to-longitudinal emittance exchange optic, we show that such a mask can be used to modulate the electron beam longitudinally to an integral of the x-ray wavelength. This modulation, combined with the very low transverse beam emittance, allows us to not only generate 50-keV x-rays with a 20-GeV electron beam, but also drastically decrease the length of the required undulator.

INTRODUCTION

The Matter-Radiation Interactions in Extremes (MaRIE) facility, a materials science resource to be built at Los Alamos National Laboratory, consists of three components: the Multi-probe Diagnostic Hall (MPDH), which will allow simulatneous x-ray scattering and proton radiography, the Fission and Fusion Materials Facility, which will create extreme radiation fluxes, and the M4 Facility, which will be dedicated to <u>m</u>aking, <u>m</u>easuring, and <u>m</u>odeling <u>m</u>aterials.

The MPDH will contain two separate accelerators: a proton accelerator for proton radiography and a 20-GeV electron accelerator that will drive a 50-keV x-ray free electron laser (X-FEL). The choice of a 50 keV X-FEL was made because MaRIE seeks to probe *inside* multigranular samples of condensed matter that represent bulk performance properties with sub-granular resolution. With grain sizes of tens of microns, “multigranular” means ten or more grains, and hence samples of a few hundred microns to a millimeter in thickness. For medium Z elements, this requires photon energies of 50 keV or above. This high energy also serves to reduce the absorbed energy per atom per photon in the probing, allowing for multiple measurements on the same sample. Additionally, interest in studying transient phenomena implies a very bright source, such as an X-FEL.

Currently we are in the very early stages of design for the 50-keV X-FEL. Here we present a conceptual design of the 20-GeV electron accelerator.

CONCEPTUAL ACCELERATOR DESIGN

We wish to keep the energy of our electron accelerator as low as possible for two main reasons: cost and the quantum fluctuation limit that becomes increasingly problematic as the beam energy increases [3]. How low we can reduce the beam energy is mainly constrained by the beam emittance we can achieve. By employing recent developments in beam phase space manipulation techniques, we believe that we can meet the emittance requirements for our X-FEL at a beam energy of 20 GeV [1, 2, 4, 5].

Beam Parameters

In the absence of optical guiding, the normalized beam emittance is constrained by:

$$\frac{\epsilon_{norm}}{\gamma} \leq \frac{\lambda_{xray}}{4\pi} \tag{1}$$

where γ is the usual beam relativistic parameter and $\lambda_{xray} = 0.0248$ nm for 50 keV x-rays. The X-FEL also defines the longitudinal beam properties. Required electron beam parameters are shown in Table 1.

Table 1: Required Electron Beam Parameters at Undulator

Parameter	Value
Energy	20 GeV
Charge	250 pC
Bunch Length (FWHM)	80 fs
RMS Energy Spread	0.01 %
ϵ_{norm} Longitudinal	100 μm
ϵ_{norm} Transverse	0.15 μm

Accelerator Layout

With current electron injector technology, it would be difficult at best to achieve the required transverse beam quality directly. However, as has been pointed out previously [1], modern photoinjectors produce beams with a

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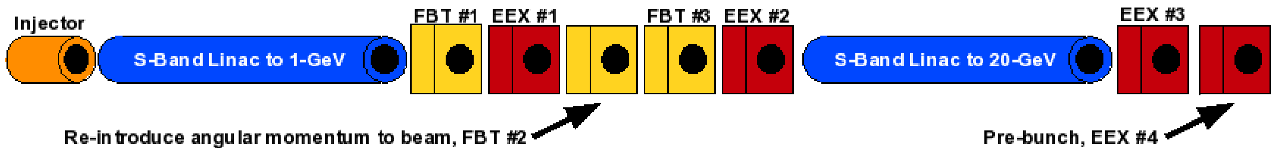

Figure 1: Block layout of MaRIE X-FEL accelerator.

longitudinal emittance that greatly surpasses what is required for our X-FEL. With a proper choice of beam line optics, we can manipulate the six dimensional phase space to reduce the transverse emittance at the expense of the longitudinal dimension, where we have a large emittance budget. The key to our scheme is the use of multiple flat beam transformers (FBTs) [2, 4, 5] and emittance exchange optics (EEXs) [1]. Figure 1 shows a crude block diagram of our current thinking for the MaRIE X-FEL accelerator. We will describe the various components below.

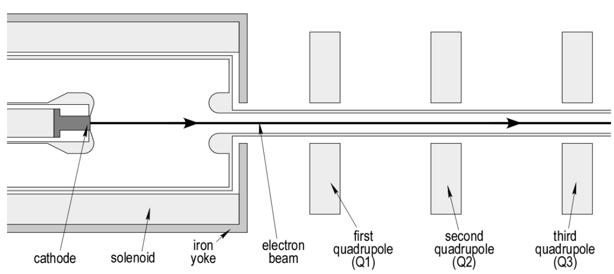

Figure 2: Schematic of flat beam transformer (FBT).

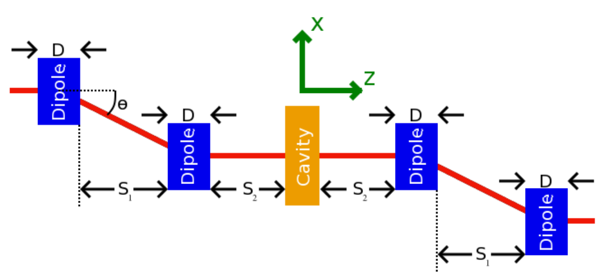

Figure 3: Schematic of emittance exchange optic (EEX). The cavity operates in a transverse deflecting mode.

Figure 2 is a schematic of an FBT optic. Angular momentum, defined by:

$$L = \frac{eB_{cath}R_{cath}}{16\beta\gamma c m_e} \tag{2}$$

where B_{cath} is the magnetic field on the cathode, R_{cath} is the cathode radius, β and γ are the usual relativistic parameters, c is the speed of light and m_e is the electron mass, is introduced into the beam. With three properly placed skewed (rotated 45°) quadrupole magnets, we can remove the angular moment and shift emittance from one transverse plane to the other according to:

$$\begin{aligned} \epsilon_x &= \frac{\epsilon^2_{intrinsic}}{2L} \\ \epsilon_y &= 2L \end{aligned} \tag{3}$$

where $\epsilon_{intrinsic}$ is the residual emittance of the beam absent the emittance due to L and we assume $L \gg \epsilon_{intrinsic}$ [2, 4, 5].

As depicted in Figure 2, we introduce angular momentum at the cathode. However, since we can subsequently remove this momentum utilizing an FBT, we maintain that the reverse is also true and we can re-introduce angular momentum to the beam using an FBT. This allows us the freedom to peform multiple shifts of emittance between the transverse planes and is key to our accelerator concept.

Figure 3 is a schematic of an EEX optic. Here we utilize two doglegs and a transverse deflecting cavity (or cavities) to create an optic with a first order transfer matrix of the form (neglecting the y plane) [1]:

$$\mathbf{M}(\eta,\xi,L) = \begin{bmatrix} 0 & 0 & -\frac{L}{\eta} & \eta - \frac{L\xi}{\eta} \\ 0 & 0 & -\frac{1}{\eta} & -\frac{\xi}{\eta} \\ -\frac{\xi}{\eta} & \eta - \frac{L\xi}{\eta} & 0 & 0 \\ -\frac{1}{\eta} & -\frac{L}{\eta} & 0 & 0 \end{bmatrix} \tag{4}$$

$$\begin{aligned} \eta &= \sec^3(\theta)\tan\left(\frac{\theta}{2}\right)\{S_1[1+\cos(\theta)] \\ &\qquad + D[1+\cos(2\theta)]\} \\ \xi &= -2D\beta^2\theta\csc(\theta) \\ &\quad + \frac{S_2 + \{2D\gamma^2 + S_1[1+\gamma^2\tan^2(\theta)]\}\sec(\theta)}{\gamma^2} \\ L &= S_1\sec^3(\theta) + 2D\sec(\theta) + S_2 \end{aligned} \tag{5}$$

where β and γ are the usual relativistic parameters and the other parameters are defined by Figure 3. The matrix of Eq. 4 self-evidently transposes the x and z phase spaces.

In our design (Figure 1), the accelerator will utilize a conventional 2856 MHz photoinjector. An S-band accelerating section will then take the beam up to an energy of 1 GeV. At this point we employ several FBT and EEX optics to manipulate the beam phase space. We then accelerate the beam to 20 GeV and utilize two final EEX optics to introduce beam pre-bunching, which will be describe in the next section. Table 2 lists the estimated emittance of the beam at important points in the machine.

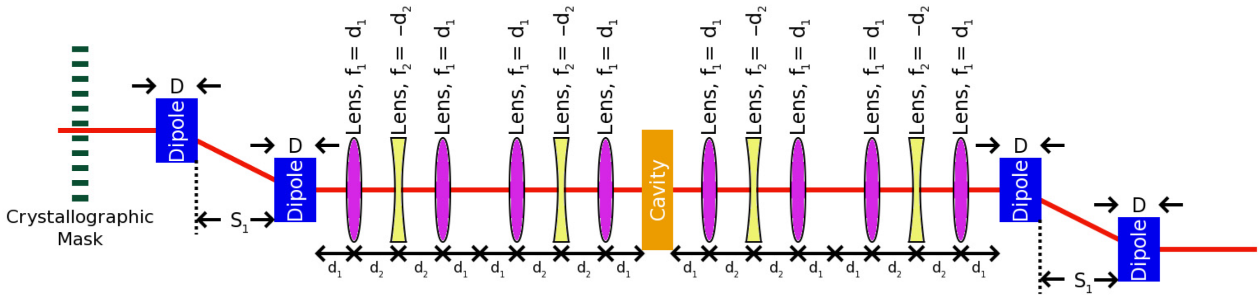

Figure 4: Schematic of emittance exchange optic with crytallographic mask for beam pre-bunching. The addition of the quadrupoles in the drift before and after the cavity allow us to make the term $M_{32} = 0$ in Eq. 4. Alternatively, the quadrupole lattices could be located in the drifts between the dogleg dipoles.

Table 2: Beam emittance at various points in the beam line in Figure 1. Here we have separated the angular momentum, L, from the intrinsic emittance. All values should be considered approximate.

Component	L[μm]	$\epsilon_{\mathbf{x}}[\mu\mathrm{m}]$	$\epsilon_{\mathbf{y}}[\mu\mathrm{m}]$	$\epsilon_{\mathbf{z}}[\mu\mathrm{m}]$
Injector	2.5	0.7	0.7	1.4
FBT #1	0	5	0.1	1.4
EEX #1	0	5	1.4	0.1
FBT #3	0	70	0.1	0.1
EEX #2	0	0.1	0.1	70
EEX #2	0	70	0.1	0.1
EEX #3	0	0.1	0.1	70

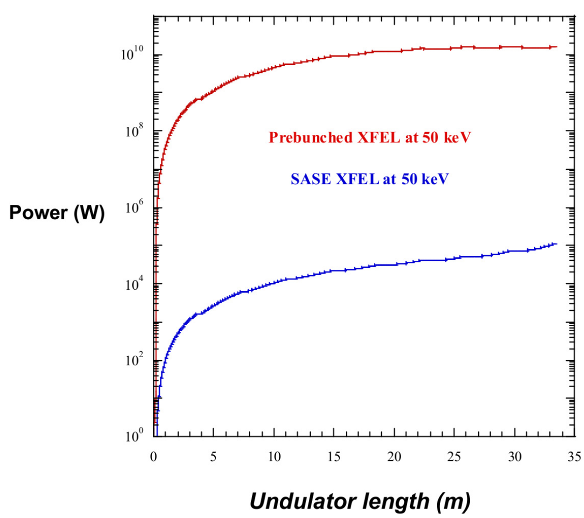

Figure 5: Simulated X-FEL output power versus undulator length for an electron beam pre-bunced to the x-ray wavelengh and a non-bunched electron beam at 35 GeV.

CRYSTALLOGRAPHIC BEAM MASKING

Simulations show us that we can vastly improve the performance of our X-FEL by pre-bunching the beam to some integral of the FEL wavelength. This is shown in Figure 5 where we plot the X-FEL power versus undulator length for a pre-bunched beam and a non-bunched beam. The difference is dramatic and suggests a possible path to further cost and size reduction of our system.

We intend to explore the possibility of beam pre-bunching using a crystallographic mask [6] and a modified EEX optic, as depicted in Figure 4. The addition of the quadrupoles allows us to set $M_{32} = 0$ in Eq. 4 so that we directly map the mask in Figure 4 to the z dimension.

SUMMARY AND CONCLUSIONS

We are only at the beginning of our MaRIE X-FEL concept and we will flesh out our design with hard numbers and numerical simulations over the next many months. A few outstanding questions (among many) we need to address.

- Can we achieve the emittances we desire with FBTs and EEXs?
- Once we achieve our emittance goal, can it be preserved?
- What is the effect of CSR in the EEX sections?
- How effective is the crystallographic mask? Will it survive?
- Will inchorent CSR effects wash out our beam pre-bunching?

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