MaRIE X-RAY FREE-ELECTRON LASER PRE-CONCEPTUAL DESIGN*

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Abstract

The proposed Matter-Radiation Interactions in Extremes (MaRIE) facility at the Los Alamos National Laboratory will include a 50-keV X-Ray Free-Electron Laser (XFEL), a significant extension from planned and existing XFEL facilities. To prevent an unacceptably large energy spread arising from energy diffusion, the electron beam energy should not exceed 20 GeV, which puts a significant constraint on the beam emittance. A 100-pC baseline design is presented along with advanced technology options to increase the photon flux and to decrease the spectral bandwidth through pre-bunching the electron beam.

XFEL REQUIREMENTS

The proposed Los Alamos MaRIE facility [1] consists of three experimental areas – the Multi-Probe Diagnostic Hall (MPDH), the Fission and Fusion Materials Facility (F^3), and the Making, Measuring, and Modeling Materials Facility (M4). MaRIE is intended to probe inside multi-granular samples of condensed matter with sub-granular resolution to study what determines bulk performance properties, to enable moving from measuring materials properties to controlling them. MPDH will provide the first X-ray imaging capability at high energy and high repetition rate with simultaneous charged particle imaging, allowing dynamic measurements on the same sample. F^3 will provide unique in-situ diagnostics and irradiation environments. The M4 facility will provide comprehensive, integrated resources for materials synthesis and control. The accelerator systems for MaRIE include both the 800-MeV LANSCE proton accelerator with a power upgrade and a 50-keV photon-energy XFEL, which will service all three experimental areas. Approximately 10^{11} X-rays per pulse with relative X-ray bandwidths no larger than 10^{-4} are needed to meet the scientific requirements of these facilities.

XFEL BASELINE DESIGN CONCEPT

The baseline MaRIE XFEL concept uses the SLAC National Accelerator Center LCLS XFEL [2] design scaled to 20 GeV with electron bunch charges of 100 pC. Based on LCLS experimental data, a beam emittance of 0.3 µm and an energy spread of 1.5 10^{-4} are assumed. Single-wavelength GENESIS [3] scaling simulations of XFEL performance as a function of bunch energy spread and transverse emittance are shown in Fig. 1, where all simulations were for a 20-GeV, 3.4-kA beam and where the undulator strength is given by a_w = 1.47. To convert the vertical axis in Fig. 1, there are 3.7×10^{10} 50-keV photons per GW and per nC of bunch charge, at a current of 3.4 kA. For example, a power of 10 GW leads to 3.7×10^{10} 50-keV photons for a 100-pC bunch (30 fsec). Strong focusing in the undulator was optimized for every set of beam parameters to maximize the photon flux.

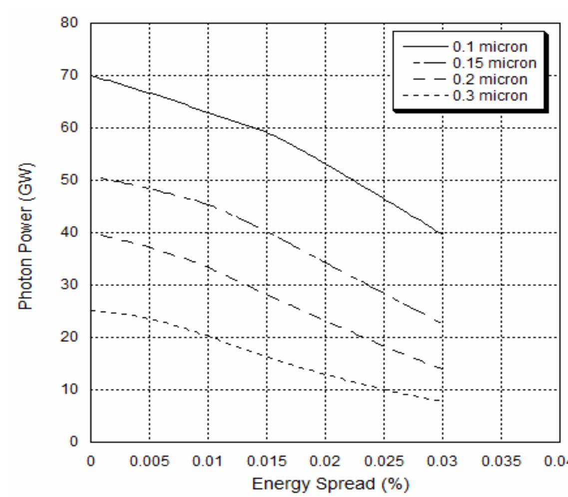

Figure 1: Time-independent GENESIS scaling simulations for the baseline MaRIE XFEL design.

Based on these simulations, we define a baseline design for a 0.3-µm, 100-pC bunch, with a 0.015% energy spread, which would produce 6×10^{10} longitudinally incoherent photons requiring an 80-m undulator. This operating point was chosen over using a 0.5-µm emittance, 250-pC bunch (also consistent with beam measurements at LCLS), which would produce slightly more (8×10^{10}) photons in a much longer 130-m undulator, partly because of the greater undulator length and partly because the transverse coherency drops significantly as the normalized transverse emittance exceeds $\beta\gamma\lambda_{x-ray}/\pi$ where γ and β are the usual relativistic factors [4]. Increasing the transverse coherency further by dropping the emittance to 0.15 µm (by using a bunch charge of 25 pC which would have a bunch length of about 2 µm) would reduce the photon flux too much. That short a bunch length may also introduce deleterious coherent synchrotron radiation (CSR) [5,6] effects not seen with the longer bunch lengths at LCLS (> 10 µm). Because of space constraints, the 20-GeV MaRIE baseline XFEL design requires an X-band accelerator, with an accelerating gradient of 50 MV/m (giving ~35 MV/m average real estate gradient).

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XFEL ADVANCED DESIGN CONCEPT

Using the baseline XFEL design as a starting point, we can consider both increasing the flux and generating increased longitudinal coherency using new concepts emerging at Los Alamos and other laboratories. New beam optics exploiting the properties of conserved canonical beam emittances, known as eigen-emittances, will likely lead to improvements in beam brightness [7,8]. Increased longitudinal coherency may result from a combination of pre-bunching the beam and staged high-gain harmonic generation (HGHG) sections [9,10].

Eigen-emittances

It is well known that a high-brightness photoinjector, with typical beam normalized emittances of $\varepsilon_{x,n} / \varepsilon_{y,n} / \varepsilon_{z,n}$ of 0.7/0.7/1.4 μm for a 500-pC bunch, can produce a total six-dimensional volume (here about 0.7 μm^3) significantly lower than the six-dimensional phase space volume required for this type of X-ray FEL (about 5 μm^3). However, the natural emittance partitioning into horizontal and longitudinal components is not optimal. A new technique based on changing the beam eigen-emittances at the cathode can allow photoinjector designers to control this emittance partitioning and, for example, to be able to reach beam emittances of $\varepsilon_{x,n} / \varepsilon_{y,n} / \varepsilon_{z,n}$ of 0.15/0.15/100 μm for a 500-pC electron bunch [8], which would be able to produce an order of magnitude higher X-ray flux than the baseline design. We have identified several optics architectures that might be able to reach this goal, facilitated by the fact that a beam with asymmetric transverse emittances performs nearly as well as one with equal emittances. When the product of the transverse emittances is kept constant, GENESIS analysis of asymmetric emittances for these parameters show that the X-ray flux is only decreased by about 15% when the transverse emittance ratio is as high as 4:1.

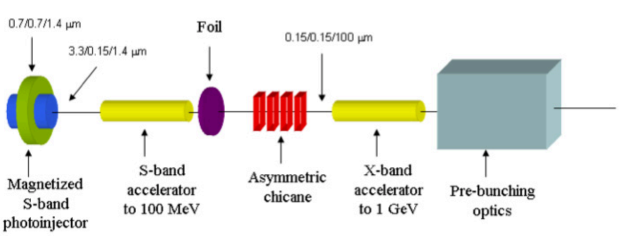

Figure 2: Possible optics configuration to achieve low eigen-emittances, using a flat-beam transform and beam attenuation in a wedge-shaped foil.

Eigen-emittances are conserved properties in the beam's phase space due to the Hamiltonian nature of electromagnetic acceleration and focusing, under the presence of linear forces. There are three eigen-emittances for a six-dimensional phase space, and their values are established when the beam is formed at the cathode. Though the eigen-emittances are invariant under linear Hamiltonian transport, their initial values can be changed, typically by means that result in correlations between the six phase-space dimensions of the beam matrix, as the beam is formed at the cathode. Once cross dimensional correlations are removed, the eigen-emittances are recovered as the beam emittances. The ability to form and manipulate the eigen-emittances is facilitated by recent work with flat-beam transforms (FBTs) [11-13] and emittance exchangers (EEXs) [14-16]. In a FBT, an axial field applied to the cathode results in beam correlations, that, when removed, lead to one transverse direction having a significantly smaller emittance. Upon exiting the magnetic field, the emittance in the other transverse direction increases while keeping the product constant. Specifically, if a photoinjector has an intrinsic emittance ε_0 and the field on the cathode leads to an angular momentum $\mathbf{L} = \frac{e|B_{cath}|R_{cath}^2}{8\gamma\beta cm} = \frac{1}{2}\left|\langle xy' - yx'\rangle\right|$ where c is the speed of light, m is the electronic mass, and R_{cath} is the cathode radius, the eigen-emittances are $\varepsilon_{eig,-} = \varepsilon_0^2 / 2\mathbf{L}$ and $\varepsilon_{eig,+} = 2\mathbf{L}$. Alternatively, in an EEX, one transverse emittance is swapped with the longitudinal emittance. One possible way to attain the required eigen-emittances is to have a cathode aspect ratio of 5.3:1 (where the initial x emittance is increased from 0.7 to 1.61 μm and the initial y emittance is decreased from 0.7 to 0.3 μm). A 3.3-psec long laser pulse with a tilt of 83° off normal incidence can provide the needed *x-z* coupling to produce an emittance split of 0.3/0.075/30 μm. An alternative approach is to use the configuration in Fig. 2. Consider a magnetized photoinjector FBT yielding an emittance split of 3.3/0.15/1.4 μm after recovery with three skew quadrupoles. The desired eigen-emittances can be created using a beamline element that can produce a correlation between horizontal position and energy in a non-symplectic way. A tapered foil is one possibility, as shown in Fig. 2. The horizontal emittance reduction for any such non-symplectic element is

$$\varepsilon_x = \frac{\left(\left(\frac{\Delta\gamma}{\gamma}\right)_{ind}^2 + \left(\frac{\Delta\gamma}{\gamma}\right)_{int}^2\right)^{1/2}}{\left(\frac{\Delta\gamma}{\gamma}\right)_{slew}} \left(\varepsilon_{ind}^2 + \varepsilon_{x,int}^2\right)^{/2} \qquad (1)$$

where *int* refers to the intrinsic bunch energy spread and emittance coming into the non-symplectic element, *slew* refers to the energy spread slew induced by the element correlated with horizontal position, and *ind* refers to the energy spread and emittance induced by the element. Due to induced energy spreads and emittances, a foil would likely only able to generate an emittance reduction of about a factor of ten, which still could lead to a significant emittance improvement to just over 0.2 μm in both transverse directions. As another example, a horizontally tapered wiggler field might achieve even lower transverse emittances by relying on non-symplectic incoherent synchrotron radiation.

Energy-Staged HGHG Sections

GENESIS simulations of SASE operation indicate a spectral bandwidth of about 5×10^{-4}. Some form of seeding is needed to achieve the required level of 10^{-4} or less. Recent work studying compression in an EEX has shown than an EEX can be used to generate a longitudinal microstructure with a wavelength shorter than 1 nm. Alternatively, a chicane, echo enhanced harmonic generation (EEHG) [17], or compressed harmonic generation (CHG) [18,19] can be considered for the pre-bunching optics in Fig. 2.

We have analyzed a staged HGHG architecture, shown in Fig. 3. The beam energy at which pre-bunching is done is limited by bunch lengthening from incoherent synchrotron radiation in the pre-bunching optics themselves. The logarithm of the decrease in harmonic current at a given wavelength scales to the fifth power of beam energy, seventh power of magnetic element bend angle, and inversely to the second power of the wavelength [20]. Conversely, smearing of the pre-bunched beam from the beam's own intrinsic energy spread is given by $\delta z = \frac{1}{\gamma'}\left(\frac{\Delta\gamma}{\gamma}\right)\left(\frac{1}{\gamma_0} - \frac{1}{\gamma_f}\right)$, where γ_0 is the beam energy at pre-bunching and γ_f is the energy to which the pre-bunched beam is accelerated [20], limiting how low a beam energy can be used for pre-bunching. One possible solution is to use a staged HGHG approach, where the beam is pre-bunched to a longer wavelength than finally needed. With an intrinsic energy spread of 0.005% and a gradient of 50 MV/m, a beam can be pre-bunched at 1 GeV with a wavelength of 4 Å and accelerated to a short undulator modulator at 5 GeV. This modulator induces a modest 4 Å energy modulation on the beam, which leads to a significant harmonic current at 1 Å after transport through a chicane. The beam is then accelerated to 10 GeV, where it drives a second short undulator modulator resonant at 1 Å, leading to a significant harmonic current at ¼ Å after a second chicane.

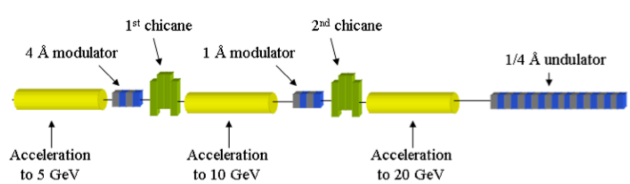

Figure 3: Energy staged HGHG configuration, with subharmonic modulators at 5 and 10 GeV.

Analysis has shown it is possible to maintain the pre-bunched beam structure as long as its rms size stays about 100 µm. The small size eliminates axial smearing from both the beam's transverse emittance and geometrical effects. The beam would be kept large in about the first third of the final undulator to generate a strong enough optical signal, then compressed to a matched rms size of about 10 µm for optimizing the X-ray output. Although this focusing would axially smear out the beam's micro-structure, the optical signal would maintain longitudinal coherency. Beam parameters for a sample case are shown in Table 1, which has been numerically calculated to have a spectral bandwidth of about 5×10^{-5}.

Table 1: Cascaded HGHG Parameters

Element		
EEX Pre-buncher	Harmonic current at 4 Å (%)	10
	RMS energy spread (%)	0.005
First HGHG	Peak energy modulation (MeV)	2.57
	RMS energy spread (%)	0.010
First chicane	R56 (nm/(Δγ/γ))	400.
	Harmonic current at 4 Å (%)	67.6
	Harmonic current at 1 Å (%)	16.1
Second HGHG	Peak energy modulation (MeV)	3.35
	RMS energy spread (%)	0.015
Second chicane	R56 (nm/(Δγ/γ))	55.
	Harmonic current at 1 Å (%)	52.5
	Harmonic current at ¼ Å (%)	10.9

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