PRE-CONCEPTUAL DESIGN REQUIREMENTS FOR AN X-RAY FREE ELECTRON LASER FOR THE MARIE EXPERIMENTAL FACILITY AT LANL*

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Abstract

The MaRIE (Matter-Radiation Interactions in Extremes) experimental facility will be used to advance materials science by providing the tools scientists need to develop materials that will perform predictably and on demand for currently unattainable lifetimes in extreme environments.[1][2] The MaRIE facilities, the Multi-Probe Diagnostic Hall (MPDH), the Fission and Fusion Materials Facility (F^3), and the Making, Measuring, and Modeling Materials (M4) Facility will each have experimental needs for one or more high-energy x-ray beam probes. MPDH will also require access to an electron beam probe. These probe beams can be created using a 20-GeV electron linac, both to serve as a source of electrons and as a driver for a set of up to five x-ray undulators for the high-energy x-rays. Because of space considerations at the facility, a high-gradient design is being investigated that will use a normal-conducting linac and X-band RF systems. Experimental requirements are also calling for relatively long pulse lengths, as well as interleaving high- and low-charge electron bunches. This paper will provide an overview of how an XFEL would address the scientific requirements for MaRIE.

INTRODUCTION

The evolution of materials research drives towards a new era that will focus on the ability to manipulate and control materials on scales from the atomic to the continuum. MaRIE will address that frontier by providing unique capabilities in matter-radiation interactions and extreme environments to enable future materials-centric science and discovery. MaRIE will provide a comprehensive set of co-located tools to realize transformational advances in materials behavior, response, and fabrication. The MaRIE facilities, the Multi-Probe Diagnostic Hall (MPDH), the Fission and Fusion Materials Facility (FFMF), and the Making, Measuring, and Modeling Materials (M4) users drive the requirement of the addition of a 50-keV XFEL. These facilities will enable dynamic probing of material on previously inaccessible time and length scales, will provide intense radiation environments, and will provide the ability to characterize and synthesize new materials. MaRIE will utilize a significantly power-enhanced LANSCE linac [3], coupled with a challenging 50-keV XFEL to achieve the research goals. The XFEL will be driven by a 20-GeV electron linac. This paper describes the required operational parameters of the electron linac.

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MARIE PHOTON REQUIREMENTS

Temporal Requirements

MaRIE requires intense short-pulse coherent light pulses to make sub-picosecond, high-resolution images of high-Z materials. The most stressing temporal pulse requirements are set by dynamic event measurements. These measurements will require a series of images taken over a few-microsecond duration. The time duration to obtain an image is set by motion blur and the fastest rate of change of material structures, and result in pulse lengths that must be less than 0.1 ns. Given that a typical sample being measured has a unique granular configuration, each experiment will be a stand-alone measurement and so data cannot be the superposition of images taken from a series of samples. The minimum number of images to fully characterize a dynamic measurement is on the order of 100.

Photon Energy Requirements

The two types of x-ray imaging being considered for MaRIE are radiographic imaging and diffractive imaging. Radiographic imaging is like that used in medical imaging and only requires that the attenuation be small enough to let a measurable amount of x-rays exit the sample. Diffractive imaging only uses the coherently scattered photons and is limited to lower energy photons, compared to photon energy acceptable for radiographic images, since the diffraction is inversely proportional to the photon energy. Obtaining high-resolution images with shorter detector stand-offs is easier at lower photon energies. From a practical standpoint, the highest photon energy that can give the required imaging resolution is less than 80 keV. The minimum photon energy is set by the density, atomic number, and thickness of the materials of interest. The most difficult materials of interest to penetrate are the actinides, such as uranium. Figure 1 shows both the energy absorption and the coherent scattering of high-energy x-rays in two materials that reasonably span the materials of interest for MaRIE. The energy absorption gives the material heating from the x-rays which sets a limit on the maximum pulse intensity and number of pulses needed to avoid sample damage.

Intensity Requirements

The peak intensity is set by the above minimum pulse duration and photon absorption and scattering, and the number of photons to produce a high-resolution image. Calculations taking the above factors into account give a minimum requirement of ~ $5x10^{10}$ photons/image.

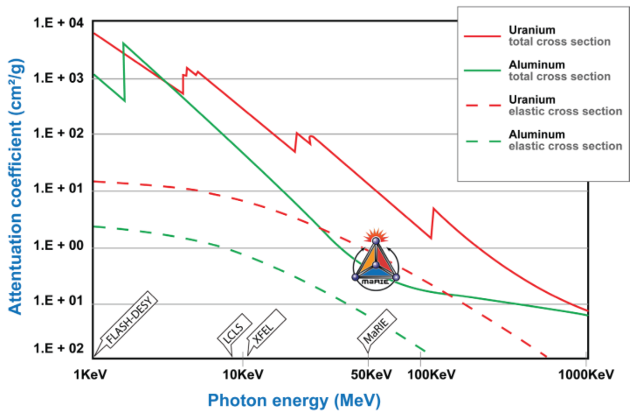

Figure 1: Photon absorption and coherent scattering coefficients for uranium and aluminium.

Beam Divergence

The requirements on the x-ray beam divergence are set by detector stand-off distances (minimum of 4 meters), diffractive imaging resolution requirements (< than 0.1% energy spread), and the lack of x-ray focusing optics that can maintain the optical phase-front quality. The combination of these factors leads to a divergence requirement of less than 20 microradians.

Physical Limitations of Site

The proposed site of the XFEL is that of the Los Alamos Neutron Science Center (LANSCE), located on top of a mesa. This site location, along with additional constraints to be able to deliver the other probe beams, limits the length of the 20-GeV electron linac. Since an XFEL is very sensitive to the electron beam quality and beam quality is negatively impacted by bends, using limited bend angles requires going to high cavity gradients. The proposed site at LANL has only approximately 600 m of length available for the linac and the associated XFEL hardware.

Requirements Summary

The light source requirements for the MaRIE MPDH, FFMF, and M4 experimental facilities were developed through a series of user workshops. These requirements are summarized in Table 1. The light source requirements given in this table are the requested performance parameters and may exceed the capabilities of the planned light source, but do serve as the ultimate performance goals. Also, the FFF facility has a radiographic requirement for imaging nuclear reactor fuel pins. Due to the high Z and approximately 1-cm thickness of a fuel pin, up to 400-keV photons are required. However since these are radiographs and do not rely on diffraction, coherence is not required; so a short undulator section, as compared to the XFEL undulator, can be used to generate these photons from the 20-GeV electron beam. The XFEL photon parameters and the major experimental requirements that set these parameters are:

- Photon energy – set by gr/cm^2 (the areal density) of sample and atomic number
- Photon number for an image – typically set by signal-to-noise in detector and size of detector
- Time scale for an image – fundamentally breaks down to transient phenomena, less than ps, and semi-steady state phenomena, seconds to months
- Bandwidth – set by resolution requirements in diffraction and/or imaging
- Beam divergence – set by photon number loss due to stand-off of source/detector or resolution loss in diffraction
- Source transverse size/transverse coherence – the source spot size will set the transverse spatial resolution, if transversely coherent then this limitation is not applicable so transverse coherence can be traded off with source spot size and photon number
- Number of images/repetition rate/duration – images needed for single shot experiments/image rep rate/ duration of experiment on sample
- Repetition rate – how often full images are required
- Longitudinal coherence – 3D imaging
- X-ray polarization - required for some measurements
- Tunability – time required to change the photon energy a fixed percentage

REFERENCE XFEL DESIGN

The baseline reference design is shown conceptually in Figure 2 [4]. It is based on either directly-measured or modest extensions of measured performance of the highly successful LCLS XFEL [5].

Our FEL simulations show an expected photon production rate of ~ 6x10^{10} x-rays from a 20-GeV electron beam with the following parameters: 100 pC charge per bunch, 30 fsec pulse length, 3.4 kA peak current, 0.015% energy spread, and a 0.30 mm-mrad emittance. The x-ray spectral bandwidth is estimated to be less than 10^{-3}.

Table 2 lists the baseline reference design parameters as well as the stretch performance goals for the XFEL linac structure. The reference design column consists of a self-consistent set of operational parameters for the XFEL electron linac. The advanced design column gives the desired maximum performance for each cell individually and is independent of the other rows. The color code for the table cells is: the parameters highlighted in green are based on straight-forward extensions of performance obtained at existing facilities; the parameters highlighted in yellow have not been demonstrated, but should be resolvable with more development; and those parameters highlighted in red are beyond state-of-art and will be challenging to reach.

The 20-GeV electron beam may be used for high-resolution radiography, and so the radiographic electron beam requirements have been added. Although the radiographic emittance requirements are not difficult to attain, ~1000 mm-mrad, the number of electrons required for an image is much more than that required for the XFEL, and the wakefields from higher bunch charge might impact the performance of the XFEL.

Before proceeding into final design for the XFEL, the following performance extensions should be demonstrated: Interleaving of 0.1 nC pulses with 1 nC pulses, detailed source-to-end simulations of the baseline 11.4 GHz design including tolerance/error studies, the generation of 1.5 microsecond long RF pulses, and establishing break-down stand-off limits in X-band structures.

SUMMARY

The need for a 50-keV coherent light source for the MaRIE signature science facility at Los Alamos is firmly rooted in strong user-developed science and diagnostic-probe requirements. These requirements form the motivation for the proposed 50-keV XFEL. A 50-keV XFEL driven by a 20-GeV electron linac appears to be feasible based on reasonable extrapolations of demonstrated performance at existing accelerators and FELs.

Table 1: The Light Source Requirements for the MaRIE MPDH, FFMF, and M4 Experimental Facilities

	MPDH	FFMF		M4	
Energy/Range (keV)	50	~10 to >50	10 to 400	0.1 to 1.5	10 to 50
Photons per Image	10^{11}	10^{11}	10^{9}	10^{9}	10^{11}
Time Scale for Single Image	50 fs	>1 s	0.001 s	10-500 fs	50 fs
Energy Bandwidth (ΔE/E)	10^{-4}	10^{-4}	10^{-3}	10^{-4}	10^{-4}
Beam Divergence	1 μrad	1 μrad	<10 μrad	<10 μrad	1 μrad
Transverse Coherence or Spatial Resolution	TC	TC	1-100 μm	TC	TC
Single Pulse No. Of Images/Duration	100/1.5μs	-	-	-	-
Multiple-Pulse Repetition Rate/Duration	120 Hz/day	0.01Hz/mo.	60 Hz/s	1 kHz/day*	10 Hz/days
Longitudinal Coherence	yes	yes	no	yes	yes
Polarization	linear	linear	no	linear/circular	linear
Energy Tunability (ΔE/E/unit time)	2%/pulse	fixed	fixed	10%/s	10x/day

*Assumes a 0.17 μs long RF pulse, keeping the average RF power approximately the same.

Table 2: XFEL Linac Reference Design Parameters.

Linac Parameter	Reference	Advanced
Energy	20 GeV	20 GeV
Linac frequency	11426 MHz	2856 MHz
Linac type	Room Temperature Cu	Room Temperature Cu
Cavity gradient	50 MV/m	70 MV/m
Bunch compressor 2	22 m	200 m
RF pulse duration	1.5 μs	1.5 μs
RF pulse rise time	0.1 μs	0.1 μs
RF peak power	50 MW	70 MW
RF Repetition rate	120 Hz	120 Hz
# RF tubes	268	273
Accelerator active length	400 m	286 m
Length from injector to linac end	482 m	546 m
Beam duty factor	0.0085%	0.017%

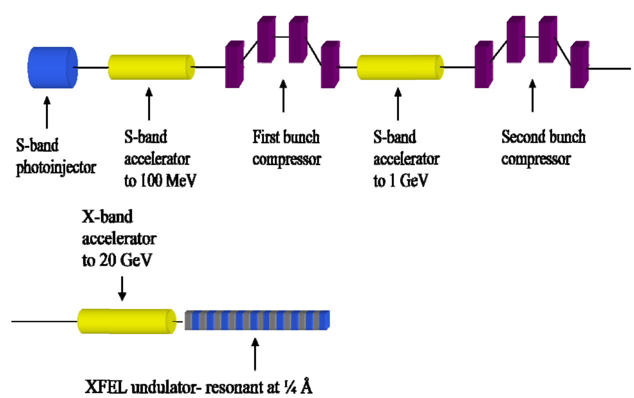

Figure 2: Conceptual layout of the 20-GeV X-band electron linac that will drive the50-keV XFEL.

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