MaRIE

(**Ma**tter-**R**adiation **I**nteractions in **E**xtremes)

MaRIE X-Ray Free-Electron Laser Pre-Conceptual Design

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LANL

R. Ryne

LBNL

MaRIE builds on the LANSCE facility to provide unique experimental tools to meet this need

First x-ray scattering capability at high energy and high repetition frequency with simultaneous charged particle dynamic imaging

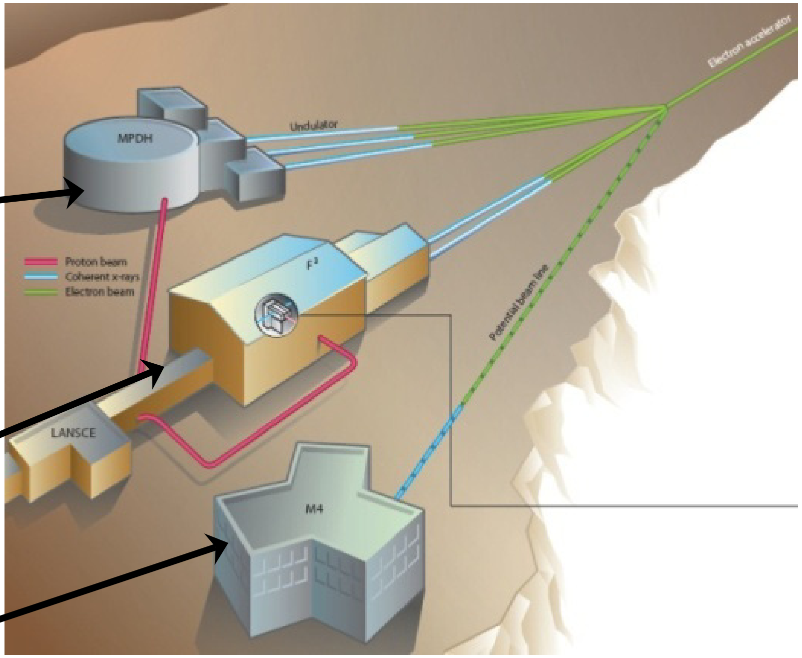
(**MPDH**: Multi-Probe Diagnostic Hall)

Unique in-situ diagnostics and irradiation environments beyond best planned facilities

(**F³**: Fission and Fusion Materials Facility)

Comprehensive, integrated resource for materials synthesis and control, with national security infrastructure

(**M4**: Making, Measuring & Modeling Materials Facility)



- **Accelerator Systems**
  - Electron Linac w/XFEL
  - LANSCE proton accelerator power upgrade
- **Experimental Facilities**
- **Conventional Facilities**

MaRIE will provide unprecedented international user resources

MaRIE photon needs can be met by an XFEL that is technically feasible and affordable

	MPDH	FFF		M4	
Energy/Range (keV)	50	<10 - >50	10-400	0.1-1.5	10-50
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
Trans. coherence (TC) or spatial res.	TC	TC	1-100 μm	TC	TC
Single pulse # of images/duration	100/1.5 μs	-	-	-	-
Multiple pulse rep. rate/duration	120 Hz/day	0.01 Hz/mo.	60 Hz/secs	1 KHz/day	10 Hz/days
Longitudinal coherence	yes	yes	no	yes	yes
Polarization	linear	linear	no	Linear/circular	linear
Tunability in energy (ΔE/E/time)	2%/pulse	fixed	fixed	10%/s	10x/day

- Photon energy - set by gr/cm^2 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/rep 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
- Polarization - required for some measurements
- Tunability – time required to change the photon energy a fixed percentage

XFEL Beam Energy Must 20 GeV or Less, With Tiny Emittances

Beam energy is typically chosen because of two constraints:

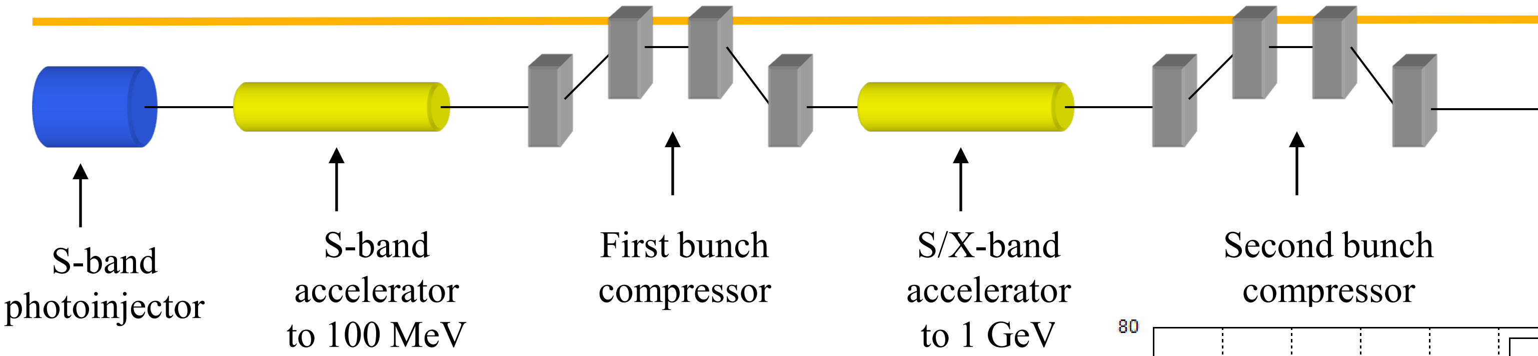
$$\frac{\varepsilon_{beam}}{\gamma} = \varepsilon_{lab} \leq \frac{\lambda_{x-ray}}{4} = \frac{\lambda_{wiggler}}{8\gamma^2}\left(K^2+1\right)$$

The choice for beam energy (γ) is dominated by the beam emittance, not wiggler period (which can go down to 1 cm)

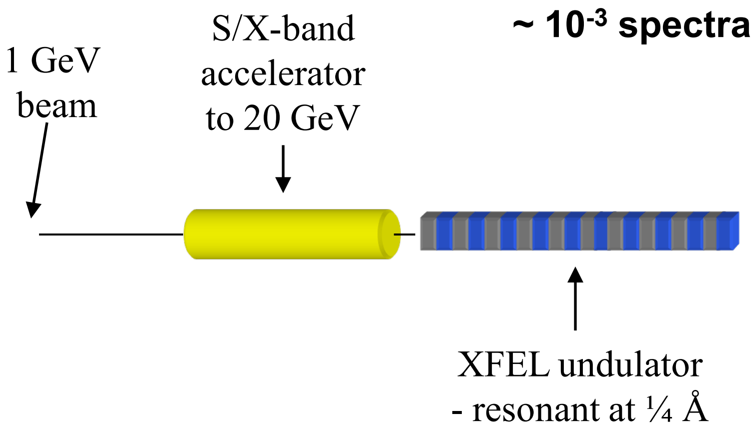
Energy diffusion limits how high the beam energy can be (~ 20 GeV), puts a very extreme condition on the beam emittance (ideally ~ 0.15 μm)

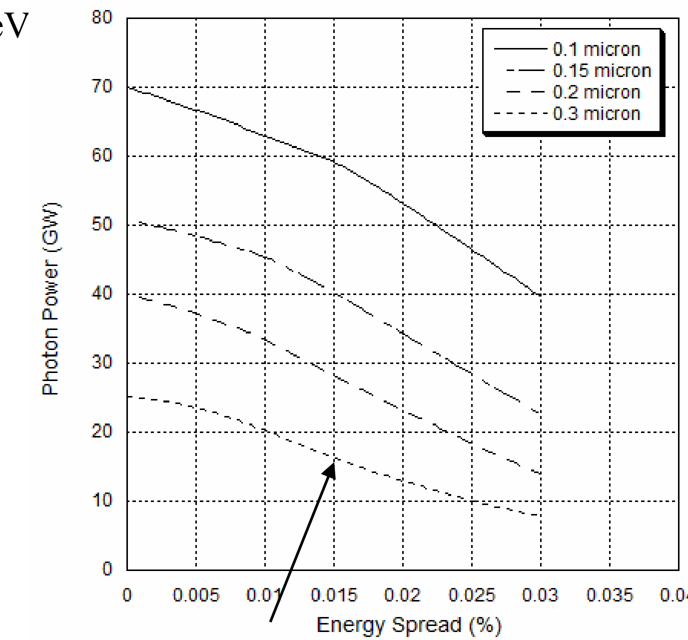
$$\left\langle \frac{d}{dz}\left(\delta\mathcal{E}\right)^2_{QF} \right\rangle = \frac{55 e\hbar\gamma^4 r_e^2 B_w^3}{24\sqrt{3} m_e c}$$

Reasonable Baseline Design – 100 pC, Extension of LCLS



17 GW, ~ 4 10^{10} X-rays
~ 10^{-3} spectral bandwidth





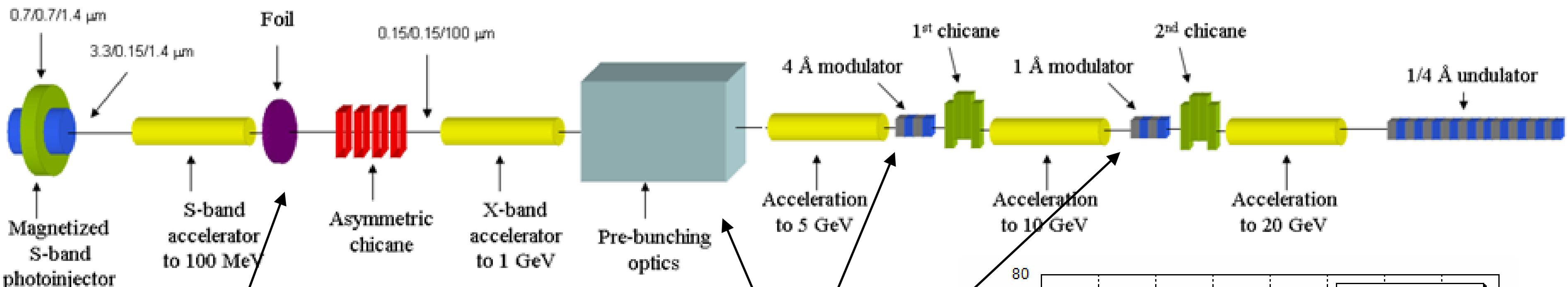
100 pC, 30 fsec, 3.4 kA,
0.015% energy spread
0.30 μm emittance

The Baseline MaRIE XFEL is a Reasonable Extrapolation of Demonstrated LCLS Performance

	UNIT	LCLS	MARIE baseline
Wavelength	Å	1.5	0.248
Beam energy	GeV	14.35	20.017
Bunch charge	pC	250*	100 **(500)**
Pulse length (FWHM)	fs	80*	30
Peak current	kA	3.0*	3.4
Normalized rms emittance	mm-mrad	0.3-0.4	0.3 **(0.15)**
Energy spread	%	0.01	0.015
Undulator period	cm	3	2.4
Peak magnetic field	T	1.25	0.93
Undulator parameter, a_w		2.48	1.47
Gain length, 1D (3D)	m	(3.3)*	5.7 (6.4)
Saturation length	m	65	85
Peak power at fundamental	GW	30*	13
Pulse energy	mJ	2.5*	0.48
# of photons at fundamental		2×10^{12}*	6×10^{10} **(10^{12})**

**Y. Ding, HBEB, 11/09*

Advanced Design Concepts – 500 pC, Based on New Ideas

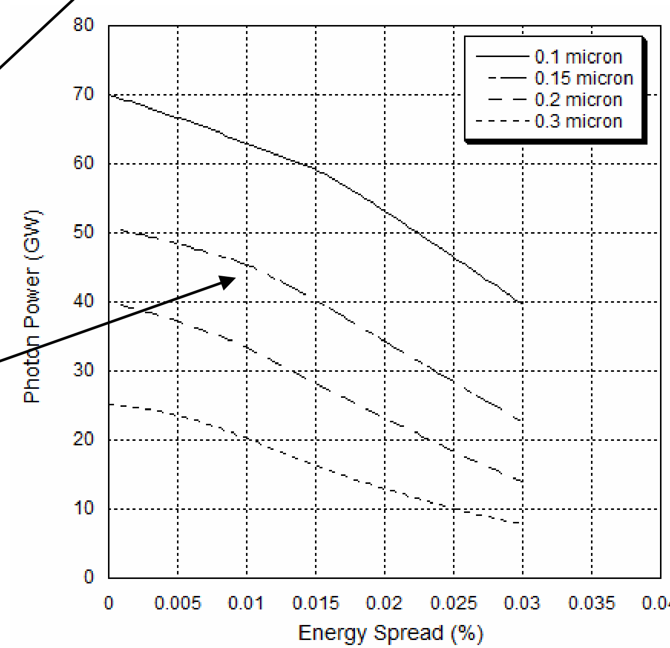


Pre-bunching beam at 4Å and energy-staged HGHG sections

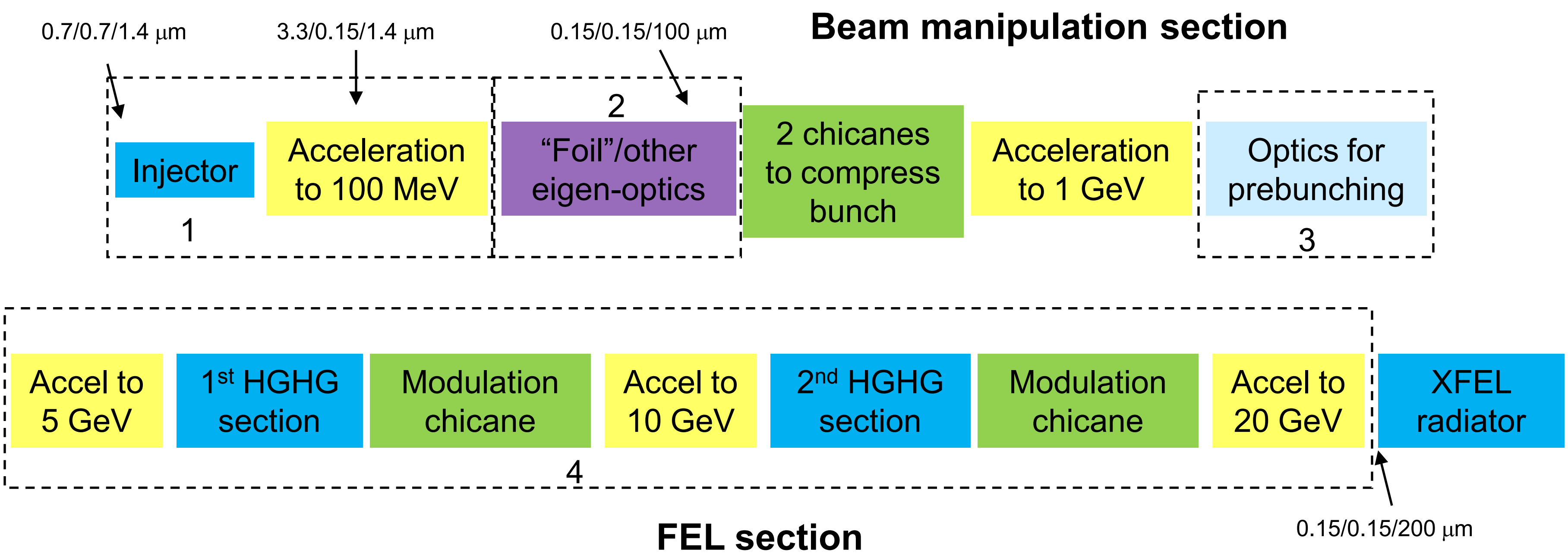
Using eigen-emittances to lower transverse emittances

500 pC, 150 fsec, 3.4 kA,
0.01% energy spread
0.15 μm emittance

40 GW, 9 10^{11} X-rays
~ 10^{-5} spectral bandwidth



MaRIE Advanced XFEL Block Diagram Components



1. Can we keep the longitudinal emittance low?
2. Will this work? Foil? Transversely tapered undulator?
3. Can we make optics linear enough to pre-bunch? Should use optically self-seed?
4. Can we design this section so the harmonic current is preserved?

We Have Thought About Four Ways to Get Low Emittances

1. Thin pancake with axial field

2. Asymmetric beam with laser tilt

3. Magnetized photoinjector and nonsymplectic foil/undulator (using ISR)

4. General three-dimensional couplings

We are currently evaluating these options

We typically consider an “ideal” photoinjector with nominal emittances (x,y,z) of 0.7/0.7/1.4 μm, with target eigen-emittances of 0.15/0.15/30 μm, but 4:1 ratio in final transverse emittances almost as good

(z-emittance can actually be as high as 200 μm)

The problem comes down to how low the energy spread (and longitudinal emittance) can be maintained

Foil Idea May Work, Stimulating Other Concepts

We nominally start with a magnetized photoinjector to get $\varepsilon_{x,n} / \varepsilon_{y,n} / \varepsilon_{z,n}$ = 3.3/0.15/1.4 μm

Non-symplectic element separates issues and simplifies design.

Induced angular scattering and increased energy spread limit effectiveness, still might get factors of ten improvement

Intrinsic energy spread and emittance

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

$$\varepsilon_{z,final} = \gamma\left(\frac{\Delta\gamma}{\gamma}\right)_{slew} \sigma_z$$

You can do an exact eigen-emittance recovery, if you wish, but it's hard, prone to second-order effects, and you don't need to – simple asymmetric chicane works fine

$$M_{\text{s-chicane}} = \begin{pmatrix} 1 & L_1 & 0 & \eta_1 \\ 0 & 1 & 0 & 0 \\ 0 & \eta_1 & 1 & \varepsilon_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & L_2 & 0 & -\eta_2 \\ 0 & 1 & 0 & 0 \\ 0 & -\eta_2 & 1 & \varepsilon_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & L_t & 0 & \Delta\eta \\ 0 & 1 & 0 & 0 \\ 0 & \Delta\eta & 1 & \varepsilon_t \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$L_t = L_1 + L_2$$

$$\Delta\eta = \eta_1 - \eta_2$$

$$\varepsilon_t = \varepsilon_1 + \varepsilon_2$$

$$\Delta\eta = 0.049 \text{ m}$$

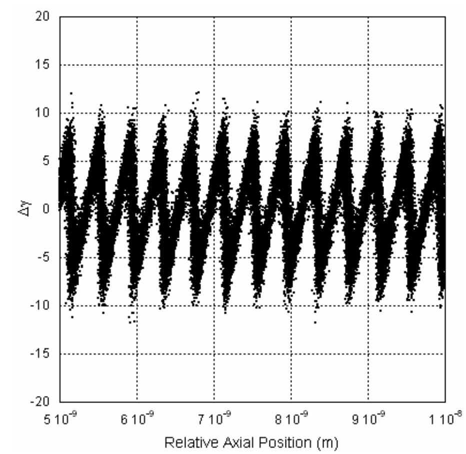
$$\varepsilon_x^2 \varepsilon_z^2 = \varepsilon_{x0}^2 \varepsilon_{z0}^2 + \eta^2 \left(\varepsilon_{x0}^2 + \varepsilon_{z0}^2\right) \left\langle x_0'^2 \right\rangle \left\langle z_0'^2 \right\rangle + \eta^4 \left\langle x_0'^2 \right\rangle^2 \left\langle z_0'^2 \right\rangle^2$$

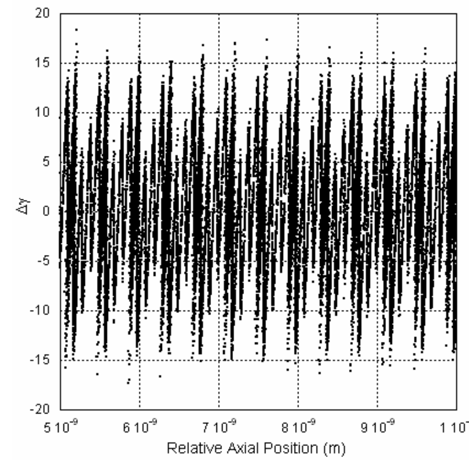
The growth in the product of the emittances of only about 1%.

Spectral Bandwidth Decreases from 10^{-3} to 5×10^{-5} with Cascaded HGHG (here all at 20 GeV, unoptimized)

EEX Pre-buncher	Harmonic current at 4 Å (%)	10
	RMS energy spread (%)	0.005
First HGHG (4 Å)	Peak energy modulation (MeV)	2.57
	RMS energy spread (%)	0.010
First Chicane	R56 (Å/(Δγ/γ))	4000.
	Harmonic current at 4 Å (%)	67.6
	Harmonic current at 1 Å (%)	16.1
Second HGHG (1 Å)	Peak energy modulation (MeV)	3.35
	RMS energy spread (%)	0.015
Second Chicane	R56 (Å/(Δγ/γ))	550.
	Harmonic current at 1 Å (%)	52.5
	Harmonic current at ¼ Å (%)	10.9

Can optically seed also





More Technical Details:

- Eigen-emittance oral talk (Duffy) 14:30 today (Beam Dynamics IV)
- WEP033 – “Using an Emittance Exchanger as a Bunch Compressor”
- WEP034 – “Beam Masking and Its Smearing due to ISR-Induced Energy Diffusion” (Yampolsky)
- THP162 – “Simulations of XFEL Output from Beams Conditioned with Emittance Partitioning and Electron Pre-Bunching” (Marksteiner)

MaRIE Overview Posters:

- THP045 – “Proposed Facility Layout for MaRIE” (O’Toole)
- THP163 – “Pre-Conceptual Design Requirements for an X-Ray Free-Electron Laser for the MaRIE Experimental Facility at LANL” (Sheffield)