STATUS OF THE MARIE X-FEL ACCELERATOR DESIGN*

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Abstract

The Matter-Radiation Interactions in Extremes (MaRIE) facility is intended to probe and control the time-dependent properties of materials under extreme conditions [1]. At its core, the “MaRIE 1.0” X-FEL is being designed to deliver pulse trains of ~10^{10} 42 keV photons, with a minimum bunch spacing of 2.4 ns, enabling time-dependent studies particularly of mesoscale phenomena. The X-FEL accelerator is also intended to deliver a series of 2 nC electron bunches to enable electron radiography concurrently with the X-ray pulse train, so as to provide multi-probe capability to MaRIE.

In 2014, the reference design for the MaRIE X-FEL 12 GeV driver linac was changed from an S-band normal-conducting to an L-band superconducting linac to accommodate pulse trains up to 100 μs in duration. This paper does not present a complete solution for the MaRIE linac design; rather it describes our current reference design, achieved parameters, areas of concern and paths towards mitigation of identified issues.

REQUIRED PERFORMANCE

The MaRIE X-FEL is intended to generate coherent 42 kV X-ray photons using a 12 GeV electron beam. This places tight constraints on the electron beam slice emittance and energy spread. Table 1 lists the some of the major performance requirements for the MaRIE linac.

REFERENCE DESIGN

Design Overview

The MaRIE linac is a 12 GeV, superconducting electron linear accelerator based on the use of ILC-type cryomodules. The general layout is shown in Figure 1. The majority of the linac consists of ILC-type cryomodules [2] containing 1.3 GHz TESLA-type 9-cell cavities. The 3.9 GHz (3^{rd}-harmonic) modules [3] are located before the bunch compressors to provide for linearization of the longitudinal bunch profile prior to compression. Dual-chicane bunch compressors are located at 250 MeV and 1 GeV. Following the end of the linac the beam passes through an energy droop corrector [4], the beam switchyard (incorporating smooth-pipe dechirpers) and finally the undulators, with space reserved for in-situ diagnostics in each section.

Table 1: Major Performance Goals for the MaRIE Linac

Parameter	Units	Value
Beam energy	GeV	12
Linac frequency	GHz	1.3
Cavity gradient	MV/m	31.5
Max. macropulse duration	μs	100
Bunches / macropulse		10 – 100
Bunch charge, XFEL	nC	0.1 nominal 0.2 max
Bunch charge, eRad	nC	2
Intrabunch energy spread		$\leq 1\cdot10^{-4}$
Slice energy spread		$\leq 1.5\cdot10^{-4}$
RMS slice emittance	μm	≤ 0.2

Beam Source

The design assumes an 0.2 μm rms normalized transverse emittance at the undulator entrance, placing stringent performance requirements on the photoinjector. The MaRIE photoinjector is based on a modified PITZ design: a 1.6-cell normal-conducting structure resonant at 1.3 GHz, with a coaxial RF feed to promote field symmetry. The PITZ gun has obtained a normalized emittance of 0.2 μm at 100 pC [5] so its demonstrated performance represents a good starting point for the MaRIE injector.

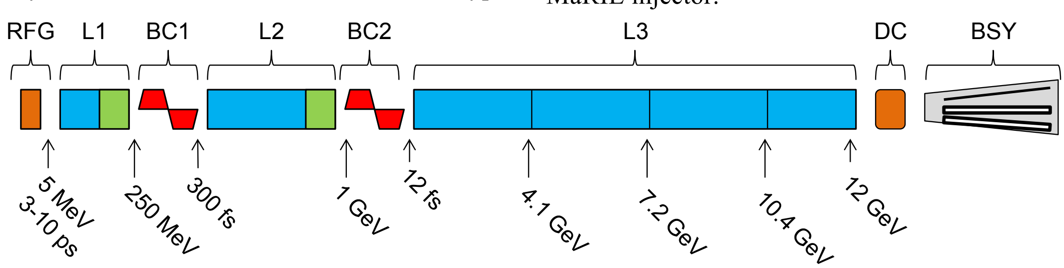

Figure 1: Schematic layout of the MaRIE linac. Room-temperature structures are copper-colored; 1.3 GHz superconducting in blue; 3.9 GHz superconducting in green. RFG is the photoinjector; L1-L3 are the three major sections of the MaRIE superconducting linac; BC1 and BC2 are the first and second dual-chicane bunch compressors; DC is the energy droop corrector; and BSY is the beam switchyard region.

The MaRIE gun design uses a redesigned solenoid with the axial magnetic field peak much closer to the cathode [6]. A very small laser spot is required to avoid

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excessive thermal emittance; to extract 100 pC, a long drive laser pulse is required, and the resulting peak current is 7 A. A plot of transverse emittance and beam energy vs. distance from the cathode is shown in Figure 2. OPAL [7] was used to perform the simulation.

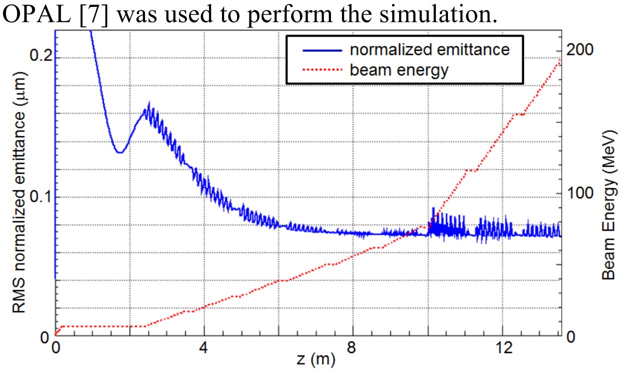

Figure 2: MaRIE injector emittance (blue) and beam energy (red) from the cathode to 200 MeV.

The planned electron radiography (eRad) injector would likely be a clone of this photoinjector, but would generate 2 nC micropulses. This injector would be followed by several cryomodules to bring the eRad beam to 250 MeV.

Linac & Bunch Compression

As shown in Figure 1, the MaRIE linac is conceptually broken into three sections. L1 captures the beam from the electron gun, accelerates it off-crest to 250 MeV and prepares it for compression in BC1. L2 provides an additional 750 MeV nominal energy gain and applies the required chirp for compression at BC2. In L3, the compressed beam is accelerated on-crest through an additional 11 GeV, to a final energy of 12 GeV.

The MaRIE linac contains two dual-chicane bunch compressors, BC1 and BC2 in Figure 1, located at 250 MeV and 1 GeV respectively. Given the requirement of a 3 kA, 12 fs (rms) beam at the undulator entrance, and a ~7 A beam from the photoinjector, the beam must be longitudinally compressed by a factor of 400 – 500:1. BC2 compresses the beam by 25:1, while BC1 applies a compression ratio between 16-20:1 depending on the bunch length from the injector.

The dual-chicane design is intended to help compensate for the effects of coherent synchrotron radiation on both the slice and projected beam emittance. Broadly speaking, the CSR wake introduces a time-dependent energy change along the bunch as it transits the chicane. Since the energy change occurs within the chicane, this results in a time-dependent dispersion error after the bunch exits the chicane, and an increase in the projected emittance. At sufficiently high compression ratios, the slice emittance is also degraded. By splitting the compression into stages, the dual-chicane design allows the time-dependent dispersion error introduced in the upstream chicane, to be at least partly mitigated by the downstream chicane; the effect is particularly noticeable at high compression ratios. Figure 3 shows a plot of the bend-plane slice emittance for single- and dual-chicane compressors operating at 57:1 for the same input beam, modelled using **elegant** [8].

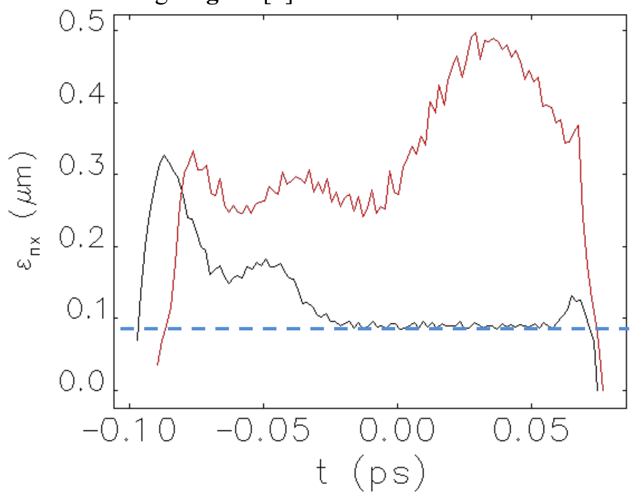

Figure 3: Bend-plane RMS normalized slice emittance for single- (red) and dual-chicane (black) compressors. Incoming beam energy was 250 MeV, R_{56} = -0.16m. The dashed blue line indicates the pre-compression slice emittance of 0.09 μm RMS.

Microbunching driven by longitudinal space charge is of concern in the MaRIE linac, where the beam is space-charge dominated up to an energy of ~ 5 GeV, as shown in Figure 4. Laser heaters, used to ameliorate μBI by increasing the beam energy spread near the injector, are now common design features on X-FELs; however, the tight energy spread requirement at the undulator, combined with the high bunch-compression ratio, makes the technique problematic for the MaRIE X-FEL linac.

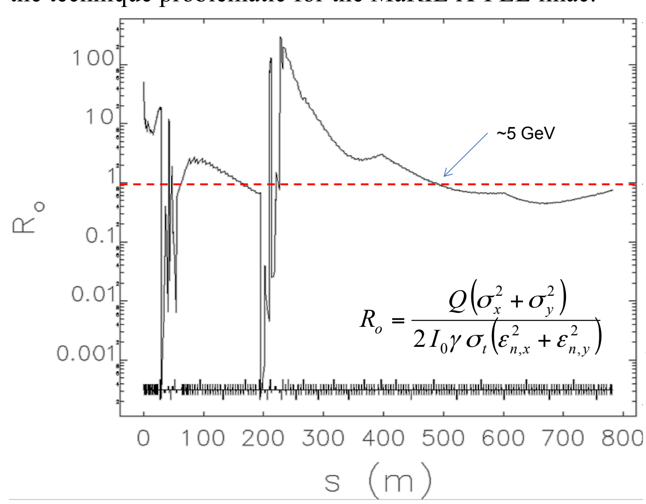

Figure 4: Space-charge impact parameter R_o vs. distance along the MaRIE linac. $R_o>1$ implies space-charge dominated beam transport.

The existing design incorporates a variation of the μBI mitigation scheme proposed in [9], using dispersion between the first and second bunch compressors. While this approach has helped, applying the method as prescribed would be problematic for MaRIE, and additional efforts will be required in this area.

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Preliminary studies indicate that moving the second compressor to 2 GeV will eliminate approximately half of the space charge-induced energy spread growth, but this requires further study to ensure other beam properties will not be compromised in the process.

Electron Radiography (eRad)

MaRIE will use 800 MeV proton radiography for imaging through very high areal density samples. Enabling ~12 GeV eRad allows for higher resolution radiography through intermediate areal density samples. eRad imaging is not particularly sensitive to either beam emittance or voltage [10], however, bunch charges of up to 2 nC are required to obtain good image contrast ratios.

One option for providing a 2 nC bunch for eRad is to use the last dipole of the second bunch compressor to merge a 250 MeV beam into the main MaRIE linac line. In this fashion, the 2 nC eRad beam can bypass the bunch compression required for the X-FEL drive beam. The eRad beam would accelerate on-crest in L3, for a final beam energy of 11.25 GeV.

Beam Switchyard

The beam switchyard performs three roles in the MaRIE design. First, it directs the electron beam towards one of two undulators. Second, if an electron radiography capability is added, the switchyard will provide passive separation between the 12 GeV X-FEL drive beam and the 11.25 GeV eRad beam. Finally, the switchyard must remove the residual chirp on the X-FEL drive beam remaining after the second bunch compressor.

The large apertures of the 1.3 GHz SRF cavities preclude the use of linac wakefields to perform this last task. Instead, small-diameter beam pipes in the transport lines to the undulators will provide this required function. LCLS-II will use a similar technique [11]. LCLS-II uses its 2 km bypass line to dechirp a 4 GeV beam, however, whereas MaRIE will have only 150 m to dechirp a 12 GeV beam with a larger absolute energy slew.

AREAS OF CONCERN

As noted in Table 1, MaRIE has tight tolerances on both the slice energy spread, and the variation of mean slice energy along the bunch. LSC-induced μBI causes difficulties with each of these; for instance, Figure 5 illustrates the variation of average slice energy spread along the bunch. Based on Table 1, the acceptable variation is approximately an order of magnitude lower. At present, reduction of the slice energy spread is our principal concern, followed by dechirping and emittance preservation through the post-linac transport lines.

FUTURE PLANS

The aforementioned linac design is a pre-conceptual reference design to enable cost and schedule estimation. This MaRIE design effort is internally supported by Los Alamos National Laboratory, and the design parameters presented here can be expected to change as MaRIE's operational requirements are refined. The design of the MaRIE linac will, of necessity, be modified to meet new requirements as they emerge.

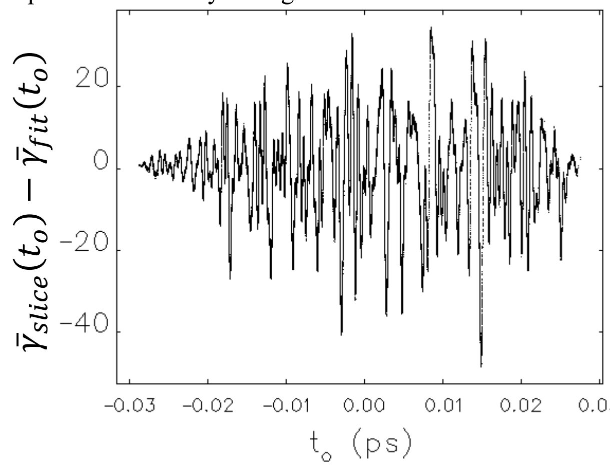

Figure 5: mean slice energy less mean bunch energy as a function of time along the bunch, at 12 GeV.

Future efforts will focus on development of a prototype photoinjector for MaRIE, mitigation of LSC-induced microbunching by techniques such as laser heating [12] as well as dispersion control, dechirping, multi-bunch effects, and emittance preservation through the transport lines and FEL. Tolerance / jitter studies will occur later in the design process.

ACKNOWLEDGEMENTS

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