TECHNOLOGY MATURATION FOR THE MaRIE 1.0 X-FEL*

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Abstract

Los Alamos National Laboratory is proposing a high-energy XFEL, named MaRIE, to meet its mission needs. MaRIE will be required to generate coherent 42+ keV photons, and, due to space constraints at the LANSCE accelerator complex at Los Alamos, MaRIE's design electron beam energy is 12 GeV. This combination places significant restrictions upon the MaRIE electron beam parameters, in particular the transverse emittance and energy spread at the undulator entrance. We are developing approaches to meet these requirements, but these often require solutions extending beyond the current state-of-the-art in X-FEL design.

To reduce overall project risk, therefore, we have identified a number of key experimental and modeling / simulation efforts intended to address both the areas of greatest uncertainty in the preliminary MaRIE design, and the areas of largest known risk. This paper describes the general requirements for the MaRIE X-FEL, our current areas of greatest concern with the preliminary design concept, and our corresponding Technology Maturation Plan (TMP).

INTRODUCTION

The Matter-Radiation Interactions in Extremes (MaRIE) facility is intended to provide unprecedented time- and space-resolved measurements on multiple scales, but with particular emphasis on mesoscale phenomena in dense materials such as metals at up to GHz measurement rates [1]. The MaRIE concept leverages the existing LANSCE 1-MW, 0.8-GeV proton accelerator [2] for multi-probe measurement capabilities.

MaRIE 1.0 is the initial implementation of the MaRIE facility, and includes at its core a 42-keV X-ray free-electron laser (X-FEL) driven by a 12-GeV superconducting linac. The X-FEL must be co-located with the existing LANSCE facility to fully realize the multi-probe promise of MaRIE; however, this imposes several constraints on the overall design of the MaRIE X-FEL linac, in particular the length available for the accelerator, over and above the stringent beam quality required by the 42-keV photon energy goal.

Electron beam radiography (eRad) is a highly desirable option for MaRIE. While most of our initial modelling and simulation work has focused upon the requirements for the X-FEL, the option to support eRad operations should not be precluded by the MaRIE linac design. Emittance and bunch length are not critical parameters for eRad bunches, but eRad requires bunch charges of 2 nC, and the MaRIE linac must be capable of providing both eRad and XFEL bunches within the same macropulse.

While our initial design simulations indicate the MaRIE linac design is feasible, we have identified several areas of particular concern where the performance of the MaRIE driver linac must be extended beyond the current state-of-the-art. A technical maturation plan (TMP) has been developed to explore the relevant physics and ameliorate risk early in the MaRIE project.

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REQUIRED PERFORMANCE

MaRIE requires an extraordinarily bright electron beam in order to drive the SASE process to saturation within the X-FEL. (While the eRad beam should not be challenging to generate, copropagating it with an X-FEL drive beam raises additional questions and concerns. However, the MaRIE TMP is currently focused primarily on the challenges surrounding the X-FEL design.) Table 1 summarizes the parameters and performance requirements for the MaRIE linac.

Table 1: MaRIE Drive Linac Performance Requirements

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
X-FEL bunch charge	nC	0.1 nominal 0.2 max
eRad bunch charge	nC	2
Intrabunch energy spread		$\leq 1 \cdot 10^{-4}$
Slice energy spread		$\leq 1.5 \cdot 10^{-4}$
RMS slice emittance	μm	≤ 0.2
RMS bunch length	fs	12

IDENTIFIED KEY RISK AREAS

The MaRIE beam requirements at the undulator drive requirements for the remainder of the linac. While based on existing technology to the extent feasible, MaRIE's performance requirements demand beyond-state-of-the-art performance in several areas.

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The MaRIE Technology Maturation Plan (TMP) [3] identifies the following areas of risk: photoinjector emittance; long-range wakes; coherent synchrotron radiation (CSR)-induced emittance growth; correlated energy spread reduction; longitudinal space charge and microbunching; emittance preservation; and distributed seeding.

The TMP calls for the risks to be addressed by a series of experiments where possible, as well as enhanced modelling and simulation (M&S). The subsections below describe the particular concerns identified for each risk area, and briefly discuss the remediation strategies. Generally, all experimental approaches will also include modelling and simulation.

Photoinjector Emittance and Energy Spread

MaRIE requires an 0.2 μm RMS normalized slice emittance at the undulator at 100-pC bunch charge. While recent results from PITZ indicate this level of performance is achievable directly from the injector [4], we must allow for degradation of the emittance as the beam is accelerated and compressed. Therefore the MaRIE photoinjector has a target emittance goal of 0.1 mm RMS at a bunch charge of 100 pC, inclusive of thermal emittance. Assuming a copper cathode with thermal emittance of ~0.6μm/mm [5], this implies a sub-mm emission spot. In turn, to keep emission current density low enough to avoid space-charge-induced beam quality degradation, a relatively long bunch must be generated, on the order of 10 – 20 ps with flattop emission. Finally, as discussed below the beam at the photoinjector must have a slice energy spread of less than 3.6 – 7.2 keV, depending on the bunch length, or on the order of 0.1%. The present MaRIE photoinjector design concept is, essentially, a PITZ-type photoinjector with a reconfigured solenoid, to provide better focusing earlier, as illustrated in Figure 1.

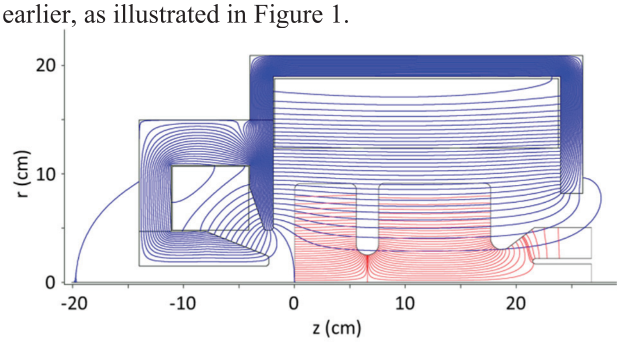

Figure 1: MaRIE photoinjector, showing RF cavity based on the PITZ design (red field contours) with a new solenoid design (blue contours).

To reduce technical risk associated with the photoinjector design, we are proposing construction of a full-scale MaRIE RF photoinjector and solenoid to validate the baseline performance assumptions. We are also proposing additional cathode R&D focused on thermal emittance reduction; this would help relax requirements on the emission spot size, with concurrent reduction in bunch length from the photoinjector and relaxation of the linac bunch compression requirements.

Long-Range Linac Wakefields

The requirement for a 100-μs beam pulse duration drives the selection of superconducting technology for the linac; in particular, TESLA-type cavities and cryomodules are used in the conceptual design. The overall space constraints drive a target accelerating gradient of 31.5 MV/m (based on cavity, not overall real-estate, gradient). We view this as aggressive but possible; the baseline MaRIE concept also includes length contingency in case this gradient is not achievable.

The flexible bunch pattern incorporates a minimum spacing of 1 RF period between X-FEL driver bunches, and also should accommodate 2-nC eRad bunches being accelerated in tandem with the X-FEL drive beam, but with greater intra-bunch spacing. The interaction of a variable-spacing, variable-charge bunch train with cavity short- and long-range wakefields must be well-understood, including effects of and tolerances on cavity alignment. While short-range wakes are now well-understood [6,7], long-range wakes require additional exploration.

A series of drive / witness beam experiments can be conducted on existing TESLA-type modules [8] to thoroughly map out the long-range wakefields in a typical module, complemented by modelling and simulation via the Lucretia code [9]. This experiment will also help determine requirements for cavity and module alignment tolerances for MaRIE.

CSR Emittance Growth and Chirp Control

At 12 GeV, a relative energy spread of 0.015% equals 1.8 MeV. A starting bunch length of 10 – 20 ps (quasi square pulse) requires an overall bunch compression ratio of 250 – 500:1 to obtain the required 12 fs RMS bunch duration at the undulator.

The MaRIE design incorporates multiple compression stages, nominally at 250 MeV and 1 GeV with compression ratios of 25:1 and 10 – 20:1, respectively. These energies were chosen based on the potential for mitigation of net energy spread increase [10], and also to reduce net energy spread increase at the end of the linac, as the linac energy can be changed to tune the FEL wavelength.

Each compression stage is nominally a 2-chicane compressor, designed to help mitigate the time-dependent kick in the x'-t plane induced by CSR effects within each chicane [11,12]. Initial optimization studies indicate a single dual-chicane compressor can provide up to ~50:1 compression without significant slice, and greatly reduced projected, emittance degradation; for instance, Figure 2 shows the difference in t-x' phase space between a conventional 4-dipole chicane and a dual-chicane compressor for a 57:1 compression ratio. However, such an arrangement has not as yet been experimentally tested.

The dual-chicane compressor provides considerable flexibility in how each compressor is tuned; other approaches such as the Z-bend or zig-zag [13] and the 5-dipole compressor [14] are also of interest and will be

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further explored in modelling and simulation as part of the overall MaRIE design optimization effort.

As part of the general CSR mitigation strategy, the compressors are set to somewhat undercompress relative to the chirp; however, this leaves a residual chirp on the beam. At a final compressed duration of 12 fs, using an RF-based dechirper is infeasible. Since the accelerator structures do not provide a sufficiently strong short-range wake to dechirp the beam, a dedicated dechirping system such as the one in [15] is planned for installation in the switchyard between the end of the linac and the undulator entrance.

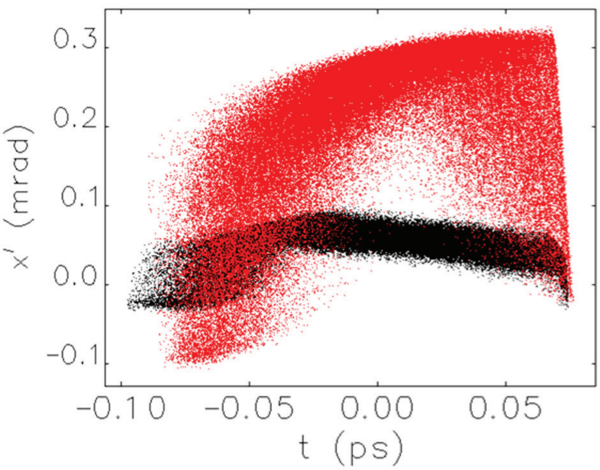

Figure 2: **elegant** [20] simulation of t-x' phase space for a 57:1 compression ratio with a single (red) and dual (black) chicane compressor.

We propose constructing a full dual-chicane compressor at a suitable test facility to map out the performance space of the dual-chicane design. The chicane will also provide a compressed beam for experiments with corrugated and smooth-wall dechirpers.

Longitudinal Space Charge and Microbunching

The high compression ratios at relatively low beam energies, combined with the low energy spread of the beam, tend to drive longitudinal space charge (LSC)-induced microbunching and associated energy spread growth. Indeed, in the baseline design for the MaRIE linac, the beam is space-charge dominated [16] along a large fraction of its length (see Figure 3). In particular, a significant fraction of the energy spread growth occurs between 1 and 2 GeV. At present, the growth in uncorrelated energy spread is the main point of concern for the MaRIE linac reference design, as it exceeds the tolerances presented above. The longitudinal phase space at the end of the MaRIE linac is shown in Figure 4 below.

The now-traditional method for dealing with LSC in X-FEL driver linacs is inclusion of a laser heater at the front end of the linac [17]. Typical laser heater designs, such as that at LCLS-I, impart too large an energy spread on the beam and thus cannot be used in MaRIE. Operating existing laser heaters at low energy tends to lead to a "trickle heating" effect [18], resulting in a greater, rather than lower, final energy spread. While it is possible a "low-energy" laser heater can be designed specifically for MaRIE, and will be part of our design effort, it is prudent to consider other means of ameliorating LSC in MaRIE. These include maintaining a larger beam radius in sections of the linac currently in the space-charge-dominated regime, and introducing controlled residual dispersion along portions of the linac [19].

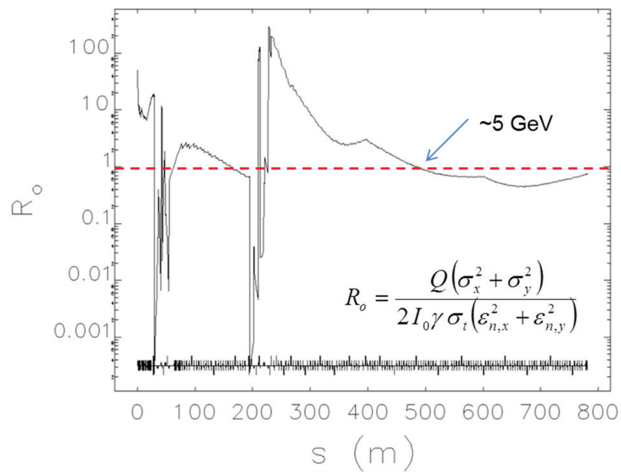

Figure 3: Space charge impact parameter along the MaRIE linac. R_o > (<) 1 implies space-charge (emittance) dominated beam dynamics.

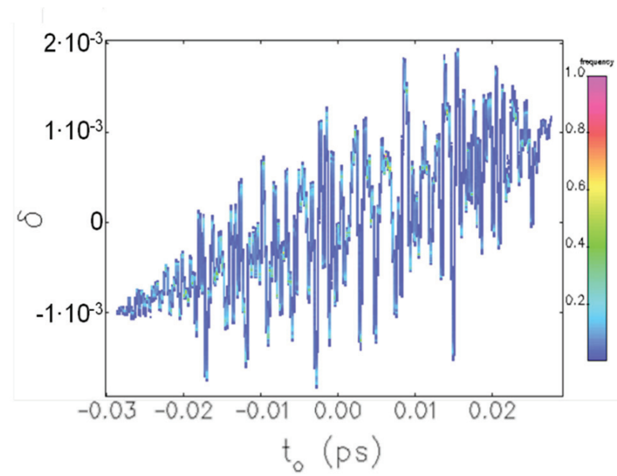

Figure 4: Longitudinal phase space at the end of the MaRIE linac.

Most of these techniques can be tested at existing facilities to a greater or lesser extent; with the exception of a low-energy laser heater, which may require a new undulator or drive laser, hardware costs should be minimal.

Modelling and simulation will also play a critical role in mitigating this area of concern; for instance, further optimization of the bunch compressor placement along the linac is warranted. Also, at the present time **elegant** [20] is our primary modelling tool for the MaRIE linac. **elegant**'s space charge model is longitudinal only; our modelling and simulation strategy includes extending the use of the OPAL code [21] beyond the injector, as it can be

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used to include true 3-D space charge effects along the entire linac.

Emittance Preservation and Distributed Seeding

Generation and preservation of the low-emittance beam is discussed above for specific areas of concern; here, we refer to a general effort to improve the fidelity of the start-to-end modelling of the MaRIE linac, including detailed design of the beam switchyard area between the linac and undulator lines, and beam transport along the undulator.

The distributed seeding (DS) technique [22] is intended to improve the stability of the X-FEL output while reducing its bandwidth. DS makes use of chicanes within the undulator line to serve as time delays; the effects from these chicanes, such as CSR-induced energy spread and emittance growth, must be incorporated into the general modelling of electron beam transport along the undulator.

Both of these areas of concern will be addressed by modelling and simulation. Ideally the DS concept would be experimentally explored, but doing so would require significant modification to an existing SASE-FEL.

CONCLUSIONS

The current reference design for the MaRIE linac appears to meet most of the criteria presented above, with the residual slice energy spread being a notable exception. While aggressive, most of the assumptions in the design are based on proven SASE-FEL linac technology. The MaRIE TMP is intended to buy down risk early in the project by placing additional emphasis on areas identified as being of particular concern. This will be done, wherever feasible, by a combination of experimental and modelling / simulation. We believe the work to be done is interesting from both the standpoint of fundamental accelerator physics as well as technology maturation and improvement, and welcome discussions regarding collaboration in these and related areas.

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