MaRIE – INSTRUMENTATION & CONTROL SYSTEM DESIGN STATUS AND OPTIONS*

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Abstract

Los Alamos National Laboratory has defined a new signature science facility, Matter-Radiation Interactions in Extremes (MaRIE) that builds on the existing capabilities of the Los Alamos Neutron Science Center (LANSCE). It will be the first multi-probe materials research center to combine high-energy, high-repetition-rate, coherent x-rays with electron and proton-beam charged-particle imaging to perform in-situ measurements of a sample in extreme environments. At its core, a 42-keV XFEL will be coupled with the LANSCE MW proton accelerator. A pre-conceptual design for MaRIE has been established. Technical risk reduction for the project includes an injector test-stand that is currently being designed. New accelerators are either planned, under construction, or currently in operation around the world, providing opportunities for the MaRIE project to leverage the instrumentation & controls (I&C) efforts of these facilities to minimize non-recurring engineering costs. This paper discusses possible MaRIE I&C system implementation choices and trade-offs, and also provides an overview of the proposed MaRIE facilities and the current design.

BACKGROUND

X-ray imaging is unique, both because of the penetrating power of x-rays in solid matter - as Wilhelm Rontgen discovered in 1895 - and because x-ray wavelengths are short enough to resolve the interatomic spacing in matter via diffraction - Max von Laue's discovery in 1912. Those properties allow scientists to push forward fundamental physical sciences and to find major applications in structural imaging, from new commercial drugs to jet turbine blades [1].

Los Alamos National Laboratory's proposed Matter-Radiation Interactions in Extremes (MaRIE) experimental facility is slated to introduce the world's highest energy hard x-ray free electron laser (XFEL). The MaRIE 42-keV XFEL, with bursts of x-ray pulses at up to gigahertz repetition rates for studying fast dynamic processes, will help accelerate discovery and design of the advanced materials needed to meet 21st-century challenges [2].

MaRIE FACILITY

The MaRIE facility will include a 12-GeV linac to provide a suite of measurements designed to investigate the performance limits of materials in extreme environments. One of MaRIE's most powerful tools will be the ability to multiplex an x-ray FEL, electron, and proton radiography onto a target material to study dynamic events as they develop. The existing LANSCE proton linac will be used to provide proton radiography (pRad) [3]. The MaRIE electron linac will be built in a new tunnel north (right side in the figure) of the existing LANSCE proton linac tunnel as shown in Fig. 1 [4].

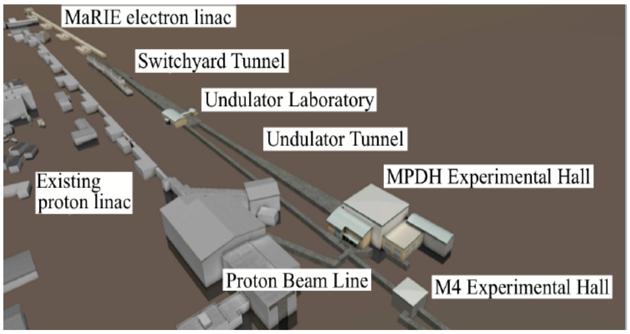

Figure 1: MaRIE Facility Layout.

OTHER XFELS

Besides the planned MaRIE XFEL facility in Los Alamos, New Mexico, USA, next-generation light sources also exist in Europe, Japan and elsewhere in the USA. X-ray facilities are being constructed at LCLS in California, SACLA in Japan, the European XFEL in Germany and the SwissFEL. The operating principles of these facilities are very similar. Electrons are first accelerated to high energies and then made to generate high-intensity x-ray laser light. LCLS and SACLA rely on conventional accelerator technologies. The European XFEL will use superconducting technology [5].

MaRIE BEAM REQUIREMENTS

The MaRIE electron beams consist of micro pulses for an XFEL undulator and micro pulses for electron radiography (eRad). A special feature of the MaRIE facility is the ability to provide unevenly spaced XFEL and eRad micro pulses distributed over a macro pulse of up to 100 µs. The macro pulse repetition rate is 60 Hz. Each XFEL micro pulse includes up to 0.2 nC of charge. Each 100-µs-long macro pulse can include up to 30 XFEL micro pulses. Each eRad micro pulse includes up to 2 nC of charge. Each 100 µs long macro pulse can include up to 10 eRad micro pulses. The spacing between micro pulses is determined by the experimental needs. The minimum spacing for each eRad micro pulse is 25 ns, while the minimum spacing for each XFEL micro pulse is 2.5 ns [4].

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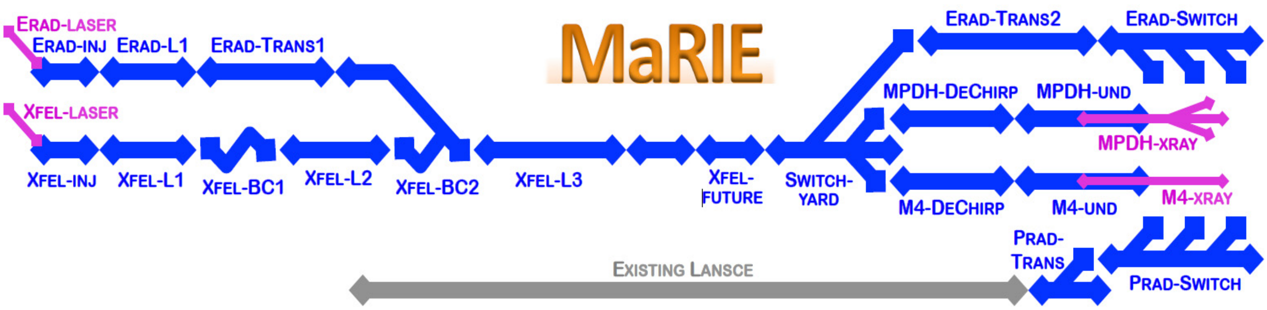

Figure 2: MaRIE Beamline Layout [6].

MaRIE BEAMLINE LAYOUT

The MaRIE XFEL and eRad micro pulses are produced and accelerated by separate injectors and initial injector linac sections. Both injector linac sections include an injector and L1 linac section. The XFEL side includes two bunch compressors and a short L2 linac section. The outputs of these parallel beamlines feed the L3 main linac as shown in Fig. 2. A switchyard at the end of the L3 linac splits the XFEL and eRad beams off to go through undulators or directly to the target [4].

Photo Injector Region

Current plans suggest a 1.3 GHz normal conducting photo injector (PI) for long pulse (100 µs) operation and a 60 MV/m gradient cathode for both the eRad and XFEL [7]. The photo injector design is similar to the PITZ design used at the Photo Injector Test facility in Zeuthen, also used at FLASH [8] and will be used for the European-XFEL [9]. Following each injector are two superconducting cryo modules (CM1 & CM2) operating at 1.3 GHz for the purpose of capturing the beam from the PI and introducing energy slew for bunch compression BC1. Cryo modules 3 & 4 will operate at 3.9 GHz for the purpose of linearizing the beam energy slew for bunch compressor (BC1). BC1 will provide x20 compression at about 400 MeV. An overview of the injector region is given in Fig. 3 [6].

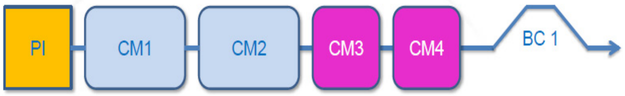

Figure 3: MaRIE Injector Region Layout.

Linac

The MaRIE linac will use proven RF cavity designs. Four hundred sixty cavities will be of the 1.3 GHz TESLA type used in the FLASH [8], LCLS-II [10] and European XFEL [9] projects. The L2 linac includes 78 of these cavities and the L1 linacs each include 11 of these cavities. Like the International Linear Collider (ILC), the 460 TESLA cavities are run at an average cavity field of 31.5MV/m [11]. The 22 third-harmonic linearizer cavities will be of the 3.9-GHz type used in the FLASH linearizer [8]. Each L1 linac includes 7 of these cavities and the L2 linac includes 8 of these cavities. The average cavity gradient is 20 MV/m [4].

Undulator

The MaRIE facility is expected to have two matching undulator beam lines each leading to a different experimental facility. An underlator line is shown in Fig. 4. The first undulator line will go to the Multi-Probe Diagnostic Hall (MPDH). Each end-station in this hall will receive simultaneously eRad, pRad and XFEL beams. The second experimental facility will be the Making, Measuring, Modelling, Materials (M4) facility with potentially 3 end-stations. The undulator lines will produce greater than 2 x 10^{10} 42-keV photons in each 33-fs pulse from a bunch length of 10µm.

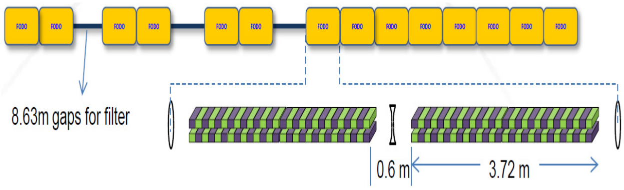

Figure 4: MaRIE Injector Region Layout.

The undulators planned for MaRIE are similar to the SwissFEL U15 undulator. Fourteen alternating focusing and defocusing quadruple lenses forming a FODO magnetic focusing lattice make up each of the undulator lines. Each 0.6 m break between undulator segments will house two gate valves, a beam position monitor, a phase shifter, a permanent magnet FODO quad and an adjustable alignment quad [12].

ACCELERATOR CONTROL SYSTEMS

Requirements

The demands on modern accelerator control systems are increasing from year to year. Today's operator and operations physicist require more and more information in real-time in order to minimize start-up time, maintain optimal beam parameters, predictively intervene to minimize beam down time and to recover quickly from off-normal events.

Given that an accelerator facility lifecycle consists of several different stages, the control system must be modular, scalable, and incrementally upgradeable.

Expansion of the control system to accommodate the installation of the accelerator and beamlines from early testing, through commissioning, and during the life of the facility should not impact the control system performance.

Today's Accelerator Control Systems

Today's accelerator control systems are a combination of a wide variety of commercial/industrial and custom made hardware and software solutions. Early accelerator controls deployed in-house custom solution as this was often the only choice. Over the years this has dramatically changed. Today more and more industrial and commercial based control system solutions are available and have become the first choice for control system engineers. The spectrum of these industrial and commercial products reach from uniquely dedicated hardware products with software configurable solutions for standard implementations to custom software solutions in highly adaptable hardware.

On a related note, over the past decade accelerator control system integration with facility related systems has become more common. Control systems for cryogenics, tunnel cooling and ventilation, etc. monitoring are needed and should be well-integrated because of their tight coupling to accelerator operation. It only recently has been felt there was a need for integrating the water distribution, building heating, etc. as well.

MaRIE CONTROL SYSTEMS

The scope of the MaRIE project likely requires a multilab collaboration with other facilities that have expertise in many of the systems required for MaRIE. Similarities between MaRIE and other XFEL facilities have been pointed out in this text. The expectation is that some of these systems could be delivered as turnkey subsystems (i.e. Cryo Plant System, Cryo Module Systems, High Power and/or Low level Radio Frequency System, Undulator System …) and later integrated with the overall facility control system. However, past experience has also shown that some of the subsystems and associated equipment were delivered by partner labs or industrial partners without their control system and were equipped in-house later with the control system product of choice. In the following we discuss the pros and cons (pros of a turnkey systems are in most cases closely tied to the cons of the in-house solution and vice versa) for a turnkey system.

Turnkey System vs In-House Solution

A turnkey system is a system that has been customized for a particular application. Turnkey systems include all the hardware and software, installation, start-up assistance, training, etc. for a subsystem with little or no involvement of the host facility (in this case MaRIE) until the system is accepted.

The pros of using a turnkey include:

- One responsible supplier will provide all the project management and become the single interface to the host facility. This frees the host facility from dealing with many individual contractors to achieve the same result.
- Suppliers most likely have already developed a control system solution for a particular subsystem which could save design / engineering costs.
- Turnkey system providers (subject matter experts) often have a better understanding of what is required to make a system work which in turn increases the cost certainty for the project.
- When working with one responsible authority, one would expect to have one warranty to secure the quality and craftsmanship of the subsystems to be delivered.

The cons of using a turnkey system include:

- Having a single responsible supplier usually means a higher management fee for this type of service which could be equivalent to hiring independent consultant(s) or permanent staff.
- Most likely the turnkey system needs to be integrated into one holistic control system which may require extensive integration work.
- In-house personal likely need extensive training due to the lack of being involved during the engineering design phase.
- Higher maintenance cost due to the possible wide variety of hardware and software solutions used across the host facility for different turnkey systems.
- Timely response to pending problems may be difficult due to lack of on-site subject matter experts.
- Reduced opportunity to develop in-house capabilities and knowledge base that could be beneficial for future projects at the host site.

Systems Engineering

A project of the scale of MaRIE will likely take delivery of many turnkey systems. To successfully integrate these systems a strong systems-engineering approach is needed as early as the beginning of the project.

A model should be developed to investigate and determine the required data flow, direction, performance, and need of synchronization between the individual systems.

Prime candidates for a turnkey system may be those that can operate in a stand-alone fashion or those that have limited interaction with the rest of the control system.

Before deciding to work with a turnkey system provider it is necessary to evaluate the technical expertise

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available within our organization. For instance, if we have resources that could do the work, it may be better to take advantage of these in-house resources rather than outsource the work to a turnkey provider.

However, once a decision is made in favor of a turnkey system several things should be kept in mind in order to avoid any difficulties down the road.

- Be mindful about changing interface requirements in the future as the facility goes through its lifecycle stages.
- Insist on having access to all system documentation and software. Proprietary implementation may lead to the inability to make required changes in the future.
- Require the use of industry standards whenever practical which will make upgrading and interfacing easier in the future.
- Like the rest of the control system, turnkey systems should be designed with a modular upgrade path in mind.
- Test early, test often. Take advantage of prototypes, simulators, emulators, and any other way to let everyone involved get an early look at the system. Make sure tests prove that the supplier satisfies the requirements.

Integration

Given the range of demands (controls, data acquisition, data management, data analysis, …) on information technology in an accelerator facility one solution may not fit all needs. Coupled with individual preferences of the controls engineers it is more than likely that extensive integration work will need to be done. Given these facts integration should be planed for accordingly.

MaRIE PROJECT FUTURE

Over the last several years the MaRIE project has gained more and more momentum with the likelihood of gaining official US Department of Energy (DOE) project status soon. The first critical project milestone to be met will be approval of the project mission need, Critical Decision Zero (CD-0). In anticipation of an approved CD-0, the MARIE project team has developed a project schedule and cost estimate based on the facility layout presented in this paper. Furthermore, independent reviews have validated our scientific and cost/schedule bases.

To further reduce project risk a detailed technology maturation plan has been developed for MaRIE that includes an injector test stand based on an existing Advanced Free Electron Laser test facility at the LANSCE user facility.

CONCLUSION

MaRIE is a promising project that will require a multilab collaboration. In this environment, the control system's ability to be upgradable, scalable, extendable, and allow the integration of many turnkey systems will be essential to the success of the project. Implementing turnkey solutions is not necessarily always the best choice for a project like MaRIE. To determine whether a turnkey solution is a viable option, there are a number of important considerations to take into account which have been discussed in this text.

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