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AN OVERVIEW OF THE MaRIE X-FEL AND ELECTRON RADIOGRAPHY LINAC RF SYSTEMS

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Abstract

The purpose of the Matter-Radiation Interactions in Extremes (MaRIE) facility at Los Alamos National Laboratory is to investigate the performance limits of materials in extreme environments. The MaRIE facility will utilize a 12 GeV linac to drive an X-ray Free-Electron Laser (FEL). Most of the same linac will also be used to perform electron radiography. The main linac is driven by two shorter linacs; one short linac optimized for X-FEL pulses and one for electron radiography. The RF systems have historically been the one of the largest single component costs of a linac. We will describe the details of the different types of RF systems required by each part of the linacs. Starting with the High Power RF system, we will present our methodology for the choice of RF system peak power and pulselength with respect to klystrons parameters, modulator parameters, performance requirements and relative costs. We will also present an overview of the Low Level RF systems that are proposed for MaRIE and briefly describe their use with some proposed control schemes [1].

THE MaRIE FACILITY

The MaRIE facility will include a 12 GeV linac to provide a suite of measurement devices 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) [2]. The MaRIE electron linacs will be built in a new tunnel north of the existing LANSCE proton linac tunnel as shown in Figure 1.

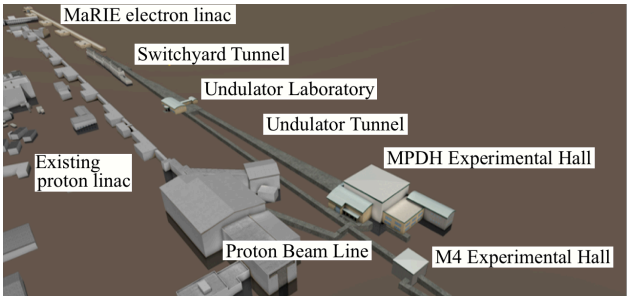

Figure 1: MaRIE Facility Layout

MaRIE BEAM REQUIREMENTS

The MaRIE electron beams consist of micropulses for an X-ray FEL (XFEL) undulator and micropulses for electron radiography (eRad). A feature of the MaRIE facility is the ability to provide unevenly spaced XFEL and eRad micropulses distributed over a macropulse of up to 100 μs. The macropulse repetition rate is 60 Hz.

Each XFEL micropulse includes up to 0.2 nC of charge. Each 100μs long macropulse can include up to 30 XFEL micropulses. Each eRad micropulse includes up to 2 nC of charge. Each 100μs long macropulse can include up to 10 eRad micropulses.

The spacing between micropulses is determined by the experimental needs. The minimum separation between micropulses is determined by the time for cavity wakefields to decay. The minimum spacing after each eRad micropulse is 25 ns, while the minimum spacing after each XFEL micropulse is 2.5 ns.

COMBINATION LINAC DESIGN

Linac Layout

The XFEL and eRad micropulses are produced by and accelerated on separate injectors and initial linac sections. Both sections include an injector and L1 linac section, but the XFEL side also includes two bunch compressors and a short L2 linac section. The outputs of these parallel beamlines feed the L3 main linac as shown in Figure 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.

RF Cavity Details

The MaRIE linacs will use proven RF cavity designs. Four hundred sixty cavities will be of the 1.3 GHz TESLA type used in the FLASH [3], LCLS-II [4] and European XFEL [5] projects. The L3 linac includes 360 of these cavities. 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 [6].

The 22 third harmonic linearizer cavities will be of the 3.9 GHz type used in the FLASH linearizer [3]. 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.

For beam diagnostics, the facility will use three transverse deflection cavities (TCAV) at 1.3 GHz and one normal conducting, traveling wave TCAV at 11.4 GHz.

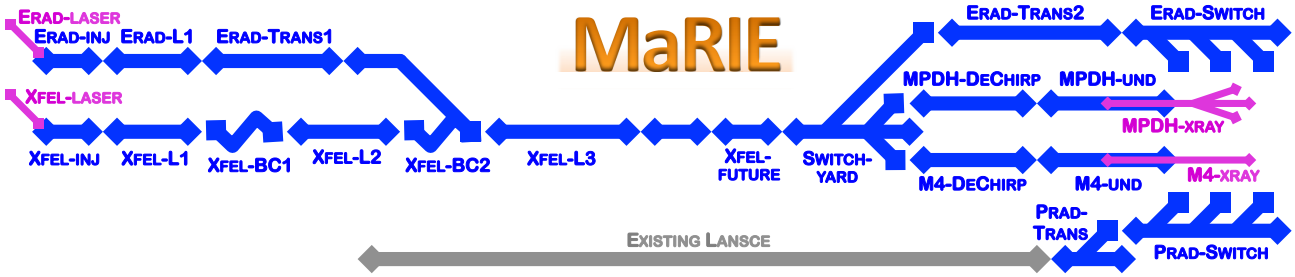

Figure 2: MaRIE Beamline Layout

RF SYSTEM DESIGN

Driving the 1.3 GHz TESLA Cavities

Even though the TESLA cavities are run at 31.5 MV/m, the lighter beam loading (relative to the ILC) allowed for optimization of the RF coupling to minimize the required RF powers for a range of possible cavity fill times [7]. Longer cavity fill times require less peak power. When beam pulse time is added, the question becomes a trade-off between klystron peak output power and klystron RF pulselength. The klystrons considered were limited to those with proven performance, so the power vs. pulselength trade-offs were not curves but discrete steps.

Trade-offs were also made between the cost savings of higher power klystrons and the cost penalties of the other RF system components. The geometry of the linac layout played a role in that at least every other cryomodule includes a quadrupole magnet, reducing the number of cavities from 9 to 8 in that cryomodule.

When the trade-offs were compared, a 6 MW, 1000 μs pulselength multi beam klystron (MBK) was chosen as the best compromise to drive the TESLA cavities. In the L2 and L3 linacs, each 6 MW RF station consists of at 6 MW, 1.3 GHz klystron split 24, 25 or 26 ways. The splits were done such that each klystron drove all the cavities in three adjacent cryomodules. By setting the cavity risetime to 900 μs (the maximum RF pulsewidth less the beam pulsewidth), the available the RF power was minimized to 173 kW when cavity coupling is set to produce a cavity external Q factor of 2.9E6. In the case of a 26 way split, 12% waveguide loss leaves ≥18% control margin.

In each L1 linac the eleven TESLA type cavities are driven by a single 6 MW system.

Driving the 3.9 GHz Linearizing Cavities

An 80 kW, 3.9 GHz klystron with a pulselength of 2000 μs was selected. By setting the cavity risetime to 1900 μs (the maximum RF pulsewidth less the beam pulsewidth), the available the RF power was minimized to 3.4 kW when cavity coupling is set to produce a cavity external Q factor of 1.9E7. The linearizing 3.9 GHz cavities in the L1 linacs are driven in sets of 7 and the 3.9 GHz cavities in the L2 linac are driven in a set of 8. The 3.9 GHz waveguide is more lossy, but over 75% control margin remains after a waveguide loss of 40%.

Injector RF System

The two photoinjectors operate at 1.3 GHz. Each normal conducting injector has a fill time of 10 μs and requires 5.28 MW of 1.3 GHz RF power at the cavity. Total required RF pulse length is 110 μs.

A standard 10 MW, 1.3 GHz klystron run at 110 μs pulselength is chosen for each injector to account for a 12% waveguide loss and a generous control margin. The klystron size was largely driven by the availability of klystrons with proven performance in at this pulselength and power level.

1.3 GHz TCAVs

The short pulse requirement of the TCAVs allows the use of a standard short pulse 20 MW, 1.3 GHz klystron. The klystron pulselength of 3 μs is more than the rise time of the copper TCAV.

Each of three normal conducting 1.3 GHz transverse deflecting cavities (TCAVs) requires 14.25 MW of RF power at each cavity input. The total required RF pulse length is <1 μs.

11.4 GHz TCAV

A normal conducting 11.4 GHz TCAV requires 13 MW of RF power at the cavity input. The total required RF pulse length is <1 μs. The short pulse requirement of the 11.4 GHz TCAV allows the use of a SLAC 50 MW, 11.4 GHz klystron [8]. The klystron pulselength of 1.5 μs is more than the rise time of the copper TCAV.

Modulator Choices

The klystrons and modulators will be located in a klystron gallery above the new electron linac tunnel. This allows ample space for the modulators, transmitters and klystron tubes. Based on their proven reliability [9] and recent demonstrations of 1% pulse flatness [10], Spallation Neutron Source (SNS) style modulators were chosen to drive all 19 of the 6 MW, 1.3 GHz linac transmitter systems. Collaborative work is planned with ORNL to further improve pulse flatness and repeatability.

The four short-pulse RF klystrons will be driven by commercially available short-pulse modulators with demonstrated performance.

LLRF

The LLRF system is being design based on the modular Micro TCA technology (MTC.4), which has recently been developed at DESY [11]. The MTC.4 approach offers a powerful and flexible solution with unprecedented LLRF performance: stability of <0.01% in amplitude and <0.01° in phase. While the injectors and TCAVs will be individually controlled, most of the MaRIE cavities will be vector-sum controlled in groups, ranging from of 8 up to 26, depending on their location and number of cavity types (1.3/3.9 GHz).

The LLRF algorithms will include standard I/Q control approaches as well as more advanced adaptive techniques. While the spacing pattern of the pulses can be irregular, it is determined well before each beam pulse. The LLRF system will utilize model-independent adaptive techniques [1], including adaptive feed forward to compensate for the expected beam loading based on previous beam pulses. Model-independent techniques will be utilized to optimize overall machine performance despite uncertainties and coupled time-varying components (misalignments, thermal drift, phase drift, power ripple, etc.…).

CONCLUSIONS

The MaRIE facility will complement the existing LANSCE pRad facility by the addition of a 12 GeV electron linac to drive an X-ray FEL and perform electron radiography. The main electron linac in the MaRIE design is driven by two shorter linacs; one short linac optimized for X-FEL pulses and one for electron radiography. The linac cavity choices followed the ILC design [6], but the lighter beam loading was leveraged to reduce the RF system cost per cavity. A total of 460 RF cavities in the linacs are driven by 27 RF systems. Four cavities require shorter pulses (1.5 - 3 μs) and 454 require long pulses (110 - 2000 μs).

The selections of RF systems are based on minimizing RF system costs and waveguide splitting and control costs. The external coupling factors of the 452 superconducting cavities were chosen to minimize the required RF power for the chosen given cavity fill times [7]. Cavity fill times were limited by the maximum pulselengths of candidate RF generators. The mandate to choose RF generators with proven performance made the trade off of peak output power and pulselength a step function rather than a smooth curve, simplifying the choice of RF generator size.

Nineteen out of 27 of the RF systems are designed to produce 6MW, 1.3GHz, 1000 μs RF pulses. Three of the 27 produce 80kW, 3.9 GHz, 2000μs pulses and two of the 27 produce 10MW, 1.3GHz, 110μs RF pulses. All three types of the long pulse RF systems will be driven by SNS style modulators [9,10]. Adaptive feed forward systems are used to compensate for variable spacing between beam micropulses over the 100μs long beam macropulse. Macropulses are repeated at 60 Hz to match one of the most common proton radiography rep rates.

The short pulse RF systems include three RF systems designed to produce 20MW, 1.3 GHz, 3μs pulses and one designed to produce 50MW, 11.4 GHz, 1.5μs pulses. These short pulse RF systems are used to drive transverse deflection cavities for beam diagnostics. The four short-pulse RF systems will be driven by commercially available short pulse modulators with demonstrated performance and reliability.

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