SLAC MEMORANDUM

RP-RPG-210609-MEM-01

DATE: June 9, 2021

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FROM: J. Bauer (RPD), K. Lauer, S. Boutet (LCLS)

SUBJECT: **Be Lens/FEL Energy Interlock for LCLS MFX Instrument as of June 2021**

1. Summary

The hazard from focused diffracted FEL beam depends on the combination of the FEL energy and the focal length of the beryllium lenses at that FEL energy [1]. To reduce these hazards, an interlock will continuously compare the current FEL energy with the focal length of the inserted Be lens focusing optics, and will stop the beam if certain criteria are not met [2].

Memorandum RP-RPG-160914-MEM-01 [3] described the first implementation of such an interlock and is being superseded by this current memorandum by describing the implementation of this interlock as of June 2021. The changes to this interlock were discussed and approved in Ref. [4], but were not completed until now. Like Ref. [3], the memorandum presented here covers both hardware and software, administrative controls, and testing of the Be Lens Interlock (BLI).

2. Implementation

A schematic view is given in Figure 1 below.

Hardware

Inside XRT, **HPS Stopper S.5** is installed at 951.5 m (LCLS coordinates). The **XRT Be lenses**, used as pre-focusing lenses, are mounted downstream, at z position 983 m, in a holder with three lenses (or lens stacks) placed vertically on top of each other (Figure 2 middle). This holder is being moved into the beam via an actuator. Through the Transfocator EPICS panel, the users may request the actuator to move one of the Be lenses/lens stacks into the beam one at a time.

The **Be Lens Transfocator** (TFS) inside Hutch 4.5 holds up to ten Be lens/lens stacks on ten individual holders arranged in series along the beamline. Each holder is independently controlled by an actuator. Through the Transfocator EPICS panel, the user may request one or more of the ten lenses/lens stacks to be inserted into the beam simultaneously.

Attenuator 11 is one of 11 attenuators located close to each other in series, all 20 to 60 cm upstream of the XRT Be Lens (Figure 2 right, Figure 3). The first 10 attenuators are being used by experimenters, while Attenuator 11 (the thickest of the 11 attenuators) will be used only for the BLI. To ensure Attenuator 11 attenuates FEL energies of 2 keV to 25 keV sufficiently well, a 5 mm thick stainless steel plate will be attached at the downbeam end of 5 mm thick silicon [5].

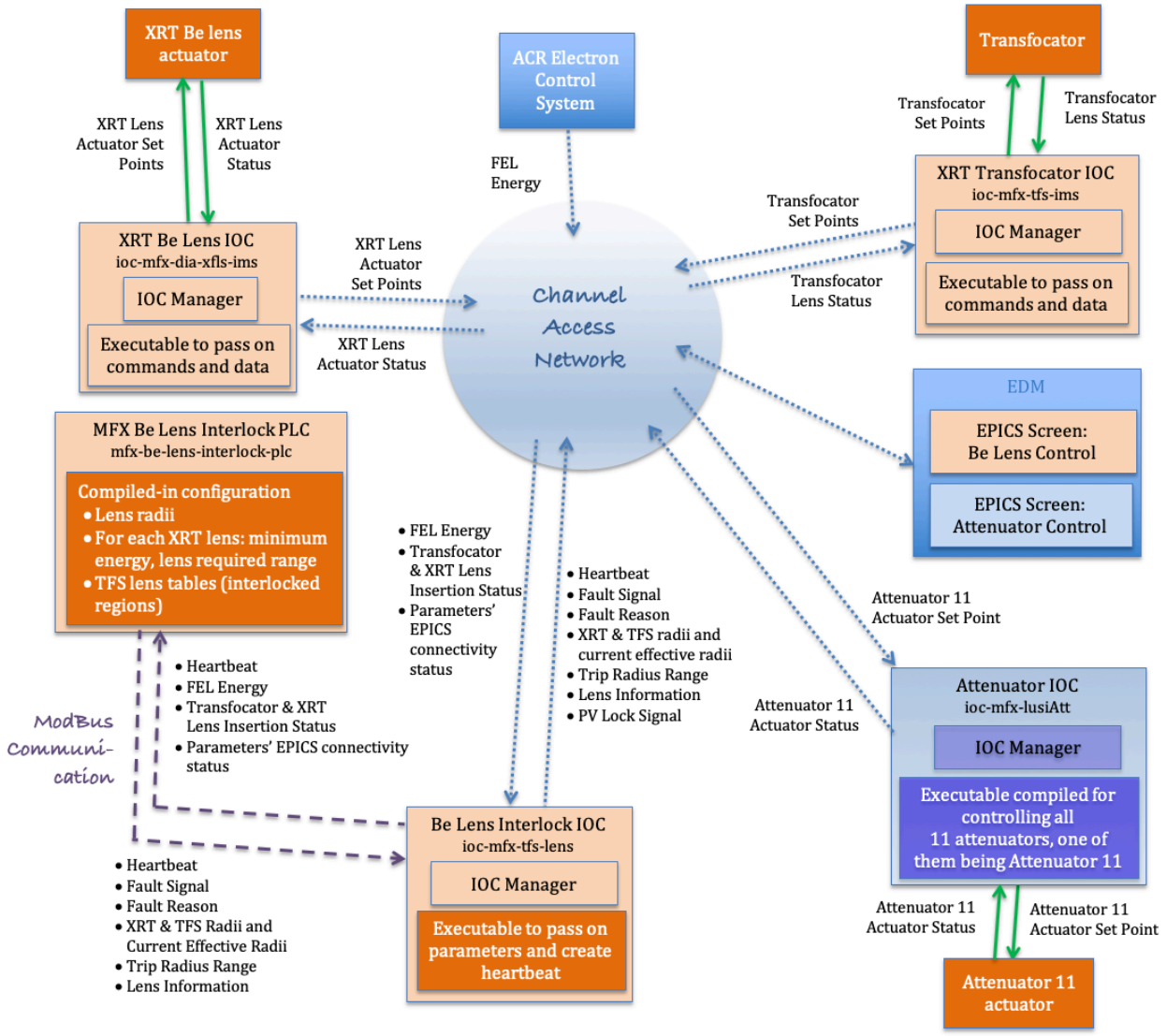

Figure 1: Schematic of Be Lens Interlock (light and dark orange) and its interaction with other and existing systems (blue). Dark orange parts are under Configuration Control (= RSWCF required for change).

Logic and Control Software

Based on the XRT and Transfocator actuator readbacks, **EPICS** determines the status, namely whether the holder is completely out of the beam ("out"), whether a Be lens is within a small range of the requested set point ("in"), or whether the holder is at an unknown location ("unknown"). These controls are needed independently of the interlock.

IOCs are a specialized computers that connect on one side to EPICS, on the other side to hard-ware controls and PLCs. The IOCs run a Logic Program Executable that is compiled from a common C source code with a specific Configuration File that sets up the interface and data transfer between the IOC and PLC.

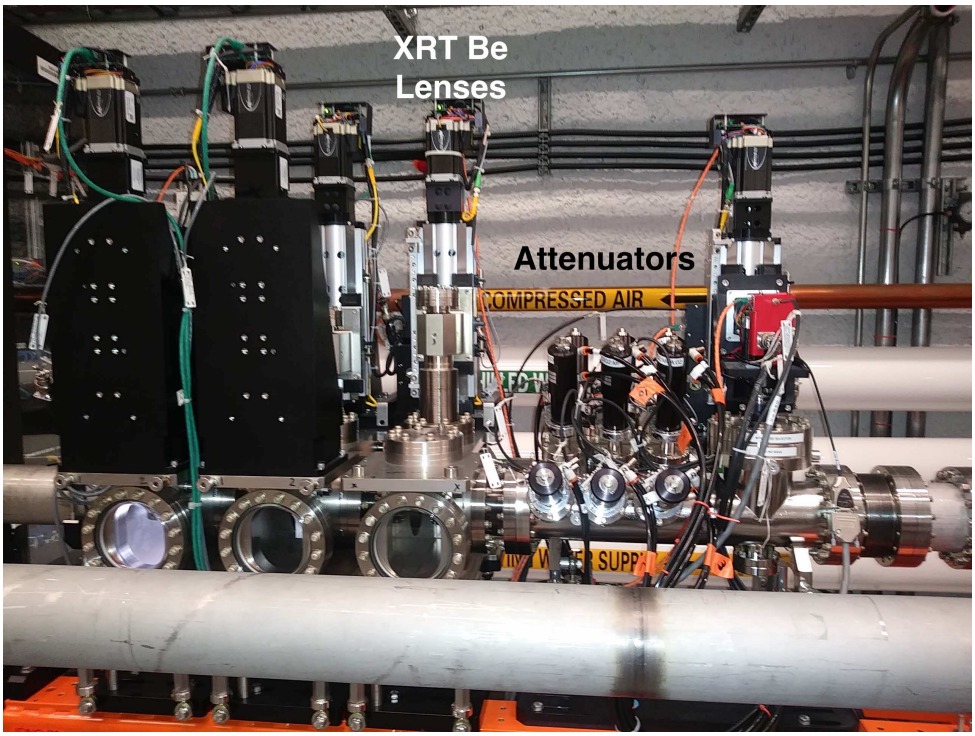

Figure 2: Set of 11 attenuator actuators just upstream of XRT Be lenses.

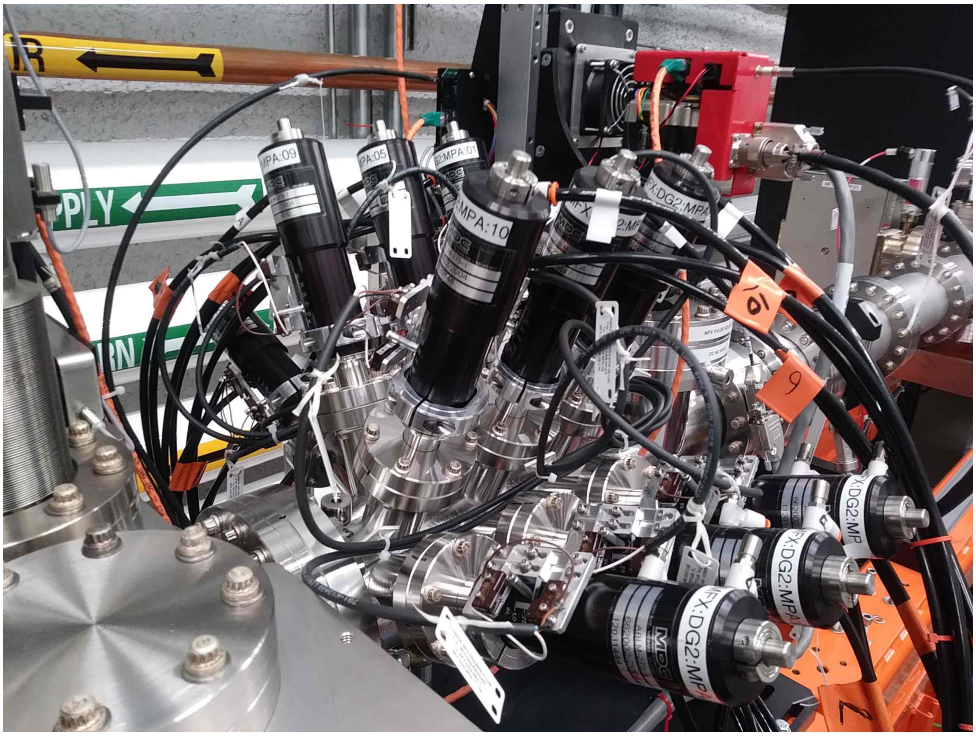

Figure 3: Closer view of 11 attenuator actuators upstream of XRT Be lenses.

The **IOC "ioc-mfx-tfs-lens"** connects EPICS to the **mfx-be-lens-interlock-plc** that runs the actual logic for the BLI. From information gathered from EPICS, the PLC code decides whether or not FEL beam is allowed into Hutch 4.5. As such, the core of the logic is present in the PLC. The attenuator and motion IOCs act as "glue" for sending and receiving information from the PLC to determine fault status, and also acting upon a fault signal. The IOC and PLC also exchange heart beats. If the heartbeat would stop from the other side, the system sends a fault signal to insert Attenuator 11.

Upon initialization, the PLC loads four tables that were generated based on the hazard analysis [2]. Each table lists the allowed effective transfocator radii for a given FEL energy. The four tables are for the first, second, and third XRT lens stacks in, and for all XRT lens stacks out.

The PLC program continuously monitors the following EPICS parameters:

- As FEL energy, the program uses EPICS PV SIOC:SYS0:ML00:A0627. The value is calculated by another program (unrelated to this interlock) from electron magnet settings and from Undulator settings. As the most widely used value for the FEL energy, any malfunction or significant discrepancy will be noticed quickly.
- The program reads the PVs that were listed in the Configuration File, *i.e.*, the PVs with the Be lens actuator status (in or out), along with the XRT lens status (which lens, if any, is inserted) and calculate the transfocator's effective radius[1] based on the lens states.

Based on this information, the program then decides whether beam into Hutch 4.5 is permitted:

Proper location of lenses:

- The XRT Be lenses are neither **out**, **nor** any one of the XRT Be lens is **in** → Beam **not** permitted
- **Any** Transfocator lens is **neither out nor in** → Beam **not** permitted

With all XRT Be lenses **out**:

- All Transfocator lenses are **out** → Beam permitted
- Effective radius of Transfocator lenses is **inside** range for given FEL energy → Beam permitted
- Effective radius of Transfocator lenses is **outside** range for given FEL energy → Beam **not** permitted

With a XRT Be lens **in**:

- No Transfocator lens **in** AND FEL energy **inside** disallowed FEL energy range for given XRT lens → Beam **not** permitted
- Effective radius of Transfocator lenses is **inside** range for given FEL energy and given XRT lens → Beam permitted
- Effective radius of Transfocator lenses is **outside** range for given FEL energy and given XRT lens → Beam **not** permitted

If the beam needs to be stopped, the PLC will send the "faulted" signal back through the BLI IOC and to **Attenuator IOC "ioc-mfx-lusiAtt"**, which controls the insertion of the actual atte-

[1] The calculation of the focal length uses the simple formula $1/r_{eff} = \sum 1/r_i$ to obtain the effective lens radius. It therefore does not take any spatial separation between the z locations of the lenses into account.

nuator material. At that time, the BLI IOC will issue a 'lock signal' for the EPICS PV of Attenuator 11, assuring that users will be unable to move the attenuator out of the beam while the BLI is tripped.

The PLC also passes all of the calculated information to the IOC and with this to EPICS:

- Faulted: whether or not beam is allowed
- Fault reason (heartbeat, table violation, min energy, TFS lens required)
- XRT, TFS radii and current effective radii
- Trip radius range
- Heartbeat

Additionally, previous faults are latched for future diagnosis.

Reaction Time

The IOC is evaluating the interlock as soon as it receives a changed EPICS input value. The MFX BLI PLC similarly evaluates any change signal from EPICS and the IOC within very short time (updates to and from the PLC are performed at 20 Hz). The shutdown chain then goes from this MFX Be Lens PLC to the actuator of Attenuator 11, which inserts the silicon plate within a fraction of a second.

Archiving

The important parameters for the interlock will be archived via EPICS to diagnose any problems encountered.

3. Discussion on Failure Modes

An interlock failure will not lead automatically to an unsafe situation, but only if improper settings would be accidentally chosen during the time of the failure and if a crystal in the beam path is oriented such that beam is Bragg-diffracted towards the hutch wall or roof.

While the system should work reliably and in a fail-safe way as possible, it does not need to meet the high requirements of a Radiation Safety Systems. Indeed, no device involved in the interlock is a device with a safety-rating for Radiation Safety Systems.

Failure of IOCs and PLCs:

- The Attenuator IOC, being regular Linux computers, might become unresponsive and therefore fail to put Attenuator 11 in. A failure of the IOC would, however, be noticed by a change in colors on the Attenuator EPICS panel. Since the attenuators are quite frequently used by experimenters, the IOC failure would be quickly noticed.
- A failure of the BLI IOC would also be noticed by a color change on the Transfocator EPICS panel. This would be noticed whenever experimenters would try to use the Be lenses.

  In the previous version of the interlock, a frozen BLI IOC would be detected by the PLC not receiving the regular heartbeat, leading the PLC to shut off beam. In this new version, this safety feature is precluded due to the shut-off path going from the PLC through the possibly frozen IOC.

- The MFX BLI PLC is less likely than an IOC to malfunction, but if the PLC would fail, the IOC would detect that the PLC heartbeat signal is missing and would initiate a fault. Additionally, such failure could be detected by the user, since the color of the Be Lens Interlock would not change on the Transfocator EPICS panel during lens movements.

Any errors in the encoder settings and readbacks will be caught quickly:

- If the encoder settings change by slow drifts in the motors or by accidental bumping, the FEL beam will likely no longer line up with the Be lenses and will instead miss or terminate at the Be lens holder. This would be a safe failure.
- If the FEL beam would by chance line up with a wrong lens, or if the expected encoder numbers would be changed by an unauthorized modification of the Configuration File, the users would quickly notice during beam setup that wrong Be lenses have been inserted. We note that beam setups are often performed with attenuated beam.
- Similarly, entries in the configuration file may be plain wrong (due to typos or misunderstandings). The Configuration Control and Testing plans will reduce the likelihood that MFX will operate with wrong entries, and if not, users would again quickly notice such a mistake during beam setup.

Thin attenuators have broken sometimes, but not thick ones like the one at Attenuator 11. Unlike other types of actuators, the pneumatic type of Attenuator 11 has not yet failed.

4. Configuration Control

1. A RSWCF will be required for any work on the beryllium lenses that are already installed or being installed in the beam lines. The RSWCF will require a verification that the configuration file has been updated to reflect any changes in Be lenses (focal length) and any change in lens location.

   A RSWCF will be needed to change Attenuator 11.

   The XRT Actuator, Transfocator, and Attenuator 11 assemblies will have stickers labeling them as Radiation Safety Items under Configuration Control.

   If a RSWCF is signed for placing a Be lens at a new z-location, the allowed operational limits will also need to be verified.

   A RSWCF will also be needed for changes to the code running on the MFX BLI IOC or on the MFX BLI PLC.

2. Updating code on the MFX BLI IOC or MFX BLI PLC requires password-restricted access to these units. At this time, only one person will have access (Ken Lauer, a member of ECS). The names will be listed in the yearly procedure. Additional personnel may be added per PCDS procedures as needed (no RP approval will be required), but the number of authorized persons must be kept as low as possible, to just a few, like 3 to 5 people. They must be aware of the purpose and configuration control on this system.

   No password will be required to access the code on the MFX Attenuator IOC. This IOC is crucial for operation, and additional PCDS personnel needs access for trouble-shooting. At the same time, the purpose of this IOC is very simple, refleced in simple code.

For the same reasons, no password will be required to access the code of the XRT lens and transfocator actuator IOCs.

3. The code for both the MFX BLI PLC and IOC carries statements that it is part of a safety interlock and that the LCLS Safety Office needs to be contacted before loading any executable. A warning has been added to the code of the MFX Attenuator IOC that Attenuator 11 may not be disabled.
4. The MFX BLI IOC Logic Program files, look-up tables, and the configuration file will be stored in the version control system GIT. Changes of any file will be documented by publishing a new release in GIT.

5. Testing Plans

1. The **certification** is being described in the latest revision of Ref. [6].
2. During any test, safety will be assured by either inserting a stopper upstream of the XRT lenses, or by inserting attenuators into the beam.
3. The certification needs to assure that for various suitable combinations of FEL energies and of Be lenses inserted into the beam the system does or does not trip as required by Ref. [2].

   The test may be performed in two steps:

   - First the logic in the PLC is tested by itself. For this, the EPICS PV inputs for the FEL energy and the inserted lenses are bypassed temporarily. An automated scanning routine will then be used to map out the phase space of FEL energy and effective radius, all the while recording trip status and reason. The output report the script must be provided in the test documentation. This test must be performed without the beam delivered to the MFX line, and a stopper (S4.5 or one upstream) must be inserted during that time.
   - The second part is done with beam (one single FEL energy suffices), and with real clicks on the EPICS panels. With attenuated beam visible on a YAG screen downstream of the Attenuator 11 location, the proper closure of Attenuator 11 will be tested for several combinations. It will also be verified that Attenuator 11 remains in the beam during a trip regardless of user requests on the Attenuator EPICS panel to extract the attenuator.
4. Quarterly tests will repeat the certification's part with beam on the YAG screen (for one single beam energy).
5. A full or partial certification will be required by RP after work on the interlock or on parts that the interlock depends on.

6. BLA Requirements

1. The test requirements will be described in the MFX BLA Running and Pre-running Conditions, and the test procedure [6] will be referenced there.

2. A BLA running condition will state that the Be Lens/FEL Energy Interlock needs to be operational during FEL operation (all stoppers enabled).

   If the system is found to be malfunctioning, the Safety Office needs to be contacted and operation with Be lenses will need to cease until other mitigations, as agreed-upon with RP, are in place. For example, a paper-based verification of meeting the operational limits may be required at each change of Be lens or FEL energy until the interlock is functional again.

7. Extension to Transfocator and to Other Hutches

Implementation of such interlocks is expected also for other hard X-ray instruments. This memorandum does not describe their specific implementations, but any new implementation will be similar to the MFX installation.

To obtain approval from RP for such future implementations or changes, LCLS will provide the necessary details to RP.

References

[1] SLAC Memorandum, *Optional Software-based Mitigation for Focused Diffracted FEL Beam Hazards at LCLS Photon Lines*, RP-RPG-160229-MEM-01, J. Bauer and J. Liu, February 29, 2016.

[2] LCLS Memorandum, *Estimation of the hutch wall burn-through hazard from Bragg-reflected focused SASE FEL generated by copper-linac beam in the LCLS-II hard x-ray undulator*, A. Prinz, June 12, 2020; data provided in e-mail Alyssa Prinz, "*Fw: MFX Interlock Numbers*" from January 5, 2021.

[3] SLAC Memorandum, *Be Lens/FEL Energy Interlock for LCLS MFX Instrument*, RP-RPG-160914-MEM-01, J. Bauer, T. Rendahl, S. Boutet, September 14, 2016.

[4] SLAC Memorandum, *RP Approval of Simplified Be Lens Interlock Design at LCLS MFX Instrument and other Hard X-ray Hutches*, J. Bauer, February 8, 2018.

[5] E-mail from A. Prinz to S. Boutet, J. Bauer, K. Lauer, S. Xiao, April 16, 2021, 6:52pm.

[6] LCLS Procedure SLAC-I-030-302-059-00, *MFX Be Lens/FEL Energy Interlock Certification Procedure*, K. Lauer, latest revision.

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