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FACET-II RADIATION SAFETY SYSTEMS DEVELOPMENT

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Abstract

Facility for Advanced Accelerator Experimental Tests (FACET)-II is an upgrade of the FACET. It uses the middle third of SLAC's 2-mile long linear accelerator to accelerate the electron beam to 10GeV, with positron beam to be added in the Stage 2 of the project. Once the first stage completes in late 2019, it will be operated as a Department of Energy (DOE) user facility for advanced accelerator science studies. In this paper, we will describe the Radiation Safety Systems (RSS) design and implementation for the FACET-II project. RSS including Personnel Protection System (PPS) and Beam Containment System (BCS). Though both systems are safety critical, different technologies are used to implement safety functions. PPS uses Siemens PLC as the backbone for control but legacy CAMAC for data acquisition; while BCS develops customized electronics for faster response to protect safety devices from radiation induced damage, and depends on VME I/O modules for operational data communication.

INTRODUCTION TO FACET-II PROJECT

FACET used first two third of the SLAC's two mile long linear accelerator to generate high density beam of electrons and positrons. The initial motivation for constructing FACET was plasma wakefield acceleration, but the operation results shows that it achieved far more than that.

In 2016, FACET completed its mission to make way for the LCLS-II project, which takes up the first one third of the accelerator originally taken by FACET. The new FACET-II will be a major upgrade over the previous FACET, taking up the middle one third of the accelerator. The beam energy of the FACET-II is 10GeV with the repetition rate up to 30Hz.

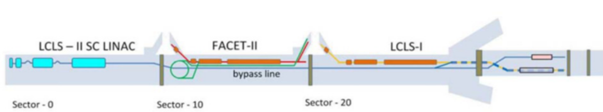

Figure 1: Schematic layout of FACET-II.

This project will be implemented in two stages. In the first stage, a new photoinjector and two bunch compressor in the linac will be restored; and a new positron damping ring with injection and extraction line will be installed in the second stage.

As the radiation hazards assessment completed by radiation protection physicists is based on the stage 1 baseline design, we will limit our discussion in this paper only for this baselined design. Modification of the accelerator and associated experimental area of FACET-II later may require additional modification of the radiation safety systems, and is beyond the scope of this paper.

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Key parameters of the FACET-II project are listed in Table 1. As this paper is focused on the radiation safety aspects of the project, only those parameters related to radiation safety are listed in the table.

Table 1: Key Parameter of FACET-II [1]

Parameter	Unit	Nominal	Range
Rep Rate	Hz	30	1 - 30
No. of bunches/pulse	-	1	1
Bunch charge	nC	2	0.5 - 5
Final beam energy	GeV	10	4 - 13
Final peak current	kA	72	10 - 130
Final beam power	W	600	2 - 1950

A detailed illustration of the FACET-II beamline layout and the RF accelerating structure is shown in Figure 2:

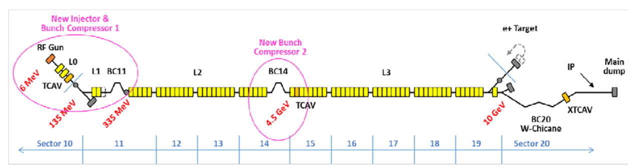

Figure 2: FACET-II accelerator layout.

RADIATION SAFETY SYSTEMS

In SLAC, major radiation hazard is ionization radiation, which comes from electron or positron beam. In addition to the passive shielding, Radiation Safety Systems (RSS) are designed and deployed to further mitigate the risk. RSS include two active control systems built on two distinct principles:

- Personnel Protection System (PPS): keep people away from beam
- Beam Containment System (BCS): keep beam away from people

Although two systems are both safety critical, but they are designed to prevent/mitigate radiation risk for different hazardous scenarios. As a result, the response time required and the technology deployed are significantly different.

The subject of PPS is people, whose movement is slow. Therefore, the typical PPS response time is in terms of seconds. In SLAC's recent engineering practice, a 5 seconds response time has been specified for the worst case scenario, as the real response time of PPS may differ case by case, depending the location of the fault and the signal transmission path to the shutoff devices. Radiation protection physicists are required to use this time constant in their radiation risk assessment. Mechanical engineers are also required to put sufficient material behind the BTM correspondingly in the case of burn-through.

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BCS's primary functions are to detect abnormal beam loss during operation, as well as to protect critical beamline devices whose failure have personnel safety consequences. According to this functional definition, the BCS's device protection function is identical to that of the Machine Protection System (MPS). The difference on device protection between two systems lies in that protection of beamline devices by BCS limits to those safety critical devices whose failure may bring enormous risks to people. Examples of these devices include beam stoppers used as safety token for downstream access, and safety collimators used in ray trace study. Rigorous configuration control and periodic proof testing are important characteristics lacking by MPS but are critical to those safety devices.

Historically, due to the high beam power of the SLAC's beam program, BCS was required to shut off the beam in a very short time, usually in terms of tens of milliseconds. In recent years, as the beam power of LCLS or FACET has been significantly reduced, a 600ms response time has been adopted to pave the way for adoption of safety PLC in BCS.

Particular for FACET-II, existing control infrastructure of FACET will be utilized to the maximum extent to lower the project cost. For this reason, PPS will continue using the legacy Siemens S7-315F PLC system as the backbone for control and data acquisition. BCS still uses customized electronics with modernization of some chassis only.

BCS DEVELOPMENT

FACET-II BCS makes substantial simplification to that of the FACET, as the linac length has been reduced by half. The main architecture keeps unchanged but with less sensors/devices and modernization of some chassis.

BCS Shutoff Path

Any fault from BCS sensors/devices will inhibit the production of beam. The FACET-II BCS has three independent shutoff paths to remove the radiation hazards:

1. The Gun Solid State Sub-booster must be put into a "STANDBY" timing. This inhibits the photoelectrons from the FACET-II cathode being captured and accelerated into the linac structures downstream.
2. Linac Sub-boosters must be put into a "Staggered Standby" timing state. This prevents acceleration of photoelectron beam or dark current.
3. A dedicated laser safety shutter must be inserted to prevent the Injector laser from striking the FACET-II photocathode and generating photoelectrons.

To be specific, devices involved in those three independent shutoff paths are:

- Two new Sub-Booster Trigger Chasses (SBTC) will be installed in Sector 10 for the Gun RF shutoff and L0Ab/L0Bb RF Shutoff respectively. The newly designed SBTC chassis uses CPLD logic components to improve the performance.
- Existing Sub-booster Interface (SBI) in each sector from Sector 11 to Sector 19.
- A Commercial-Off-the-Shelf (COTS) laser safety shutter and the associated shutter controller. Those products are supplied by nmLaser Inc. The controller will be installed in an enclosure in the Injector Vault on the wall, and the shutter will be installed on the laser table.

BCS Requirements

In the previous FACET BCS, there are beam loss monitors and beam current monitors installed in the beginning of the accelerator and BC1. In this project, after beam loss assessment, we request the project to seal the penetrations (from the gallery above the ground to the underground accelerator tunnel) to eliminate the needs for radiation loss monitors. Thus avoiding the LION (Long Ion Chamber) system as well as the instrument gas system. In addition, we request a more thorough analysis on the "maximal creditable beam", so that exactly scenarios under which the maximal beam power can be generated are analyzed as well as the possibility. Through this detailed assessment, it is concluded that the max creditable beam energy from FACET-II is still within the limit that the Main Dump can take, thus avoiding a complicated Average Current Monitoring (ACM) system.

With the simplified BCS requirements, the active control system components are distributed in Sector 19 and Sector 20 experimental area (as shown in Figure 3). These sensors belongs to three categories:

- Beam loss monitor: including Protection Ion Chamber (PIC) for point beam loss detection, and Long Ion Chamber (LION) for line beam loss detection.
- Pressure switch to monitor the instrument gas, which is used by PIC/LION sensors.
- Flow switches to monitor the cooling water to beamline components with energy deposition, e.g. Beam Stoppers, Main Dump.

Figure 3: FACET-II BCS beam loss monitor layout.

BCS Electronics and System Design

Signal from PIC/LION sensors is processed in the PIC/LION chassis, where the signal will be conditioned, integrated and compared with pre-determined trip thresholds (in terms of mV) to determine if the excessive beam loss has occurred. On the output path of the PIC/LION chassis are dual redundant OK/Fault dry contact switches.

With all of BCS inputs are OK/Fault type switch signals, another customized chassis, e.g. Digital Summary Chassis (DSC), will act as "AND" logic gate to summarize all kinds of sensors' OK/Fault condition and output to the shutoff

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chassis. This chassis is designed to accept 16 input channels and can be daisy-chained in case more input channels are required.

The shutoff chassis will issue three permissive signals to shutoff devices. As this chassis was originally developed for transmitting the signal over longer distance, the output voltage is -48VDC and is not compatible with newly developed electronics. For this reason, A redundant solid-state and electromechanical relay pair is used to convert the permissive signal to +24VDC permit signals for shutoff devices.

Similar to other accelerator control projects, one of the challenges is cable plant design. The hub for SBI control in each linac sector, the interface to linac timing system, and the future FACET-II operations are located in three different locations, where are exactly the three generations of accelerator operation centers at SLAC, e.g. CCR (Central Control Room), MCC (Main Control Center) and ACR (Accelerator Control Room). In the system design, we utilize the new safety network infrastructure to migrate some hardwired signal to Ethernet, and re-configure the freed out cable connections to eliminate the need for new long haul trunk cable.

In Sector 10, a remote I/O drop of the Master Beam Control (MBC) will be added to provide the "Beam ON/OFF" command and fetch the status back to ACR. The reset signal will also be provided through the remote I/O. The block diagram of BCS is shown in Figure 4 below:

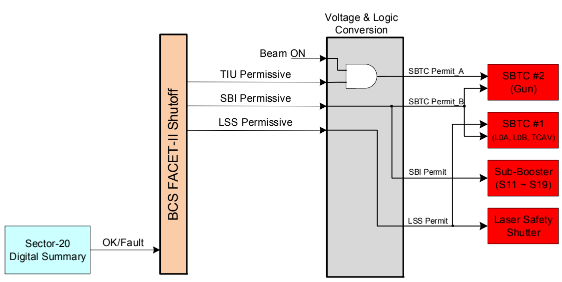

Figure 4: FACET-II BCS block diagram.

PPS DEVELOPMENT

FACET PPS was named as "Global West" for its physical location; and LCLS PPS is called "Global East". As the new LCLS-II Superconducting Linac takes up the west end of the tunnel, the FACET-II PPS will be denoted as "Global Middle" to reflect this change.

Siemens S7-315F PLC was adopted in PPS as part of efforts to modernize safety system built from electromechanical relays. The system can be classified into two tiers: zone level and system level.

In the zone level, the legacy relay based system is mainly unchanged. The zone level PPS is responsible for following functions:

- Zone search: operators will swipe through the tunnel to make sure that no people are in the tunnel before bailing the zone from "Permitted Access" to "No Access" and turning on the beam
- Lighting and audio/visual warning: indicate if the local radiation/electrical hazards are ON, and provide audio/visual warning for people inside the accelerator tunnel
- Access Control: enable people to enter/exit the accelerator with keys as safety tokens; or without keys in emergent situations.
- Emergency Off buttons to stop the beam.

In the middle section of accelerator, zone level PPS are mainly unchanged from old days. Those systems are still relay based with some electronic chassis for dedicated functions such as set-entry loop, secure loop etc. System level PPS has been migrated to PLC system to enable/disable global radiation generating devices, and shut off the beam in the case of safety violation.

For the FACET-II project, radiation generation devices are defined in following groups:

- Gun/L0-A/L0-B/TCAV RF: Modulator (MOD) 10-2, 10-3, 10-4, 10-5.
- Accelerating RF Power Supply: Variable Voltage Substations (VVS) VVS-5, VVS-66, VVS-7, VVS-9.
- Accelerating RF Modulators: 19-1/2/3/4/5/6, 20-4A/4B/3C.

There are two sets of stopper are defined within the scope of FACET-II. In SLAC, the stopper in the "generalized" sense include insertable stoppers and bend magnets which can deflect the beam. Those two stopper sets are:

- Stopper set in Positron Vault for the beam to the Positron Target: Extraction Line stoppers EXT-ST1, EXT-ST2; Extraction horizontal bend EXT-HBEND
- The backward beam stopper RST1F and two bend magnets BX01F, BX02F.

With the radiation hazard sources and the beam stopper sets identified, the function of system level PPS can be defined as:

- Get the PPS zone "Radiation Ready" status from S10 Injector Vault, linac Sector 10 to Sector 20
- Get the PPS zone "Radiation Ready" status from LCLS Global East PPS for Sector 20 and all the way to BSY
- Enable all radiation generation devices and remove the backward beam stopper set when the PPS zones are "Radiation Ready"
- The Positron Vault stopper will be inserted before the area is accessible.
- The backward beam stopper should be inserted before the Injector Vault is accessible.

Three Beam Shutoff Ion Chambers (BSOICs), supplied by Thermo Fisher, will be installed to detect the above the normal radiation to those accessible areas to protect people. These devices are complement to those beam loss monitors (PIC or LION) of BCS, but focus on those locations people have access during the normal operation. The usual trip set-point is 10mrem/hr.

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- BSOIC in the Sector 10 Injector Vault close to the exit: its trip will shutoff FACET-II beam
- BSOIC in the entrance to the Positron Vault: its trip will insert the Positron Vault stopper set
- BSOIC in the S20 Injector Vault: its trip implies that the beam from FACET-II lost the containment and needs to be shut off.

BSOIC chassis developed at SLAC will be responsible for transmit the OK/Fault signal from processing unit of BSOIC to PPS, and get the activate/bypass command by the system level PPS according to the accelerator operation information and the zone access state. The BSOIC chassis also re-route the analogue readout to EPICS for data achieving purpose.

System Level PPS exchanges two critical information with the zone level PPS through so-called “secure loop” and “set entry loop”.

“Secure Loop” is a current loop pass through Sector 10 all the way to Sector 20 and its status will be read into PPS safety PLC in CCR. It is a sum up signal of all area “Radiation Ready”, so when the loop is made up, it implies that the middle section of the linac is searched, secured and ready for the beam. The safety PLC will combine this information with the downstream S20- BSY “Radiation Ready” status to determine if all the areas are ready for the FACET-II beam.

On the other hand, “set-entry” loop will summarize all the relevant VVS OFF status and send to PLC to inform the system that the radiation hazards are OFF and it is safe to bail to the “Permitted Access” state and allow people to access the accelerator tunnel.

There are safety functions of the system level PPS such as enable the keybank to release the key for access, yellow-magenta radiation warning lights etc.

The FACET-II system level PPS is implemented with Siemens S7-315F safety PLC with both safety and non-safety I/O modules. The safety portion of the PPS is dual-redundantly configured to ensure the safety integrity. The PLC configuration diagram is shown in the Figure 5.

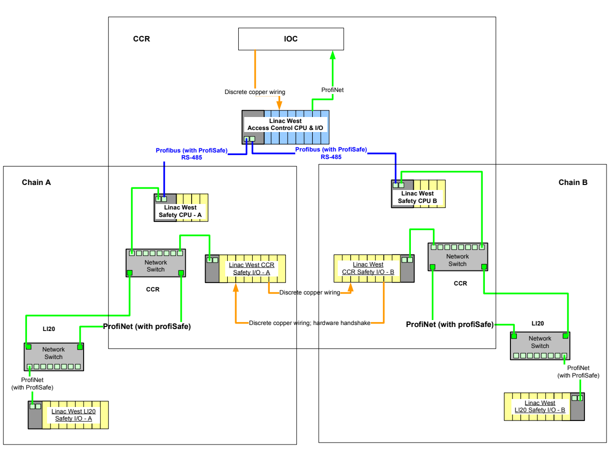

Figure 5: FACET-II PPS PLC architecture diagram.

CONCLUSION

In this paper, we briefly discuss the Radiation Safety System (RSS) requirements and design for the FACET-II project. Both PPS and BCS are discussed as part of the RSS. In PPS design, the previous PLC architecture is retained, but the interface to new radiation generating devices will be added or modified. As the half of the FACET PPS devices have been removed by the LCLS-II construction, the corresponding modifications are necessary to make the system level PPS complete again.

For BCS, the system has been significantly simplified due to passive shielding and the reduced quantity of sensors required. The system architecture keep unchanged with modernization of some hardware, which include newly re-designed SBTC chassis and the COTS laser safety shutter.

REFERENCE

[1] “Technical Design Report for the FACET-II Project at SLAC National Accelerator Laboratory”, SLAC, CA, United States, Rep. SLAC-R-1072, Aug. 2016.