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LCLS-II BEAM CONTAINMENT SYSTEM FOR RADIATION SAFETY*

C. Clarke†, J. Bauer, M. Boyes, Y. Feng, A.S. Fisher, R. Kadyrov, J. Liu, E. Rodriguez, M. Rowen, M. Santana-Leitner, F. Tao, J. Welch, S. Xiao, SLAC National Accelerator Lab, Menlo Park, USA
T. Allison, Trentronix, LLC, Hampton, USA
J. Musson, Jefferson Lab, Newport News, USA

Abstract

LCLS-II is a new xFEL facility under construction at SLAC National Accelerator Laboratory with a superconducting electron linac designed to operate up to 1.2 MW of beam power. This generates more serious beam hazards than the typical sub-kW linac operation of the existing xFEL facility, Linac Coherent Light Source (LCLS). SLAC uses a set of safety controls termed the Beam Containment System (BCS) to limit beam power and losses to prevent excessive radiation in occupied areas. The high beam power hazards of LCLS-II necessitate the development of new BCS devices and a larger scale deployment than previously done at LCLS. We present the new radiation hazards introduced by LCLS-II and the design development for the BCS.

INTRODUCTION TO LCLS-II

With the LCLS-II upgrade, the complexity and seriousness of potential beam generated hazards at the SLAC FEL facility expands greatly.

LCLS-II adds a second x-ray laser to the already established LCLS x-ray laser, which started operation in 2009 (Fig. 1). LCLS was the first hard x-ray laser and is used by hundreds of scientists each year to deliver 0.3 –13 keV x-rays at 120 Hz for imaging at the atomic level and visualisation of femtosecond-scale processes. LCLS-II will operate in parallel with LCLS, introducing new FEL capabilities to operate at up to 1 MHz with x-rays from 250 eV to 25 keV, utilizing Superconducting Radio Frequency (SRF) cavities at 1.3 GHz.

Each accelerator occupies one third of SLAC's existing linear accelerator tunnel. The electron beams traverse nearly 3750 meters of accelerator housing, cover an energy range of up to about 15 GeV for the LCLS (copper cavities) linac beams and above 4.0 GeV for LCLS-II SRF beams, and beam power of up to 250 kW for SRF beams. The SRF beams can simultaneously be sent to two different undulator lines and one additional dump line. The copper linac feeds the hard x-ray undulator only. Laser-like, high power x-ray beams are generated in the undulator lines by the electron beams and traverse another 300 meters to experiment "hutches". There are very many more complex configurations possible and expected in SLAC's future.

The new SRF linac runs CW, and the cryomodule cavities and the RF gun itself can generate beam hazards through field emission that can be captured and accelerated to high energies. Essentially there are six potential sources for beam related hazards after the LCLS-II upgrade that may be hard to distinguish from each other: Superconducting linac photo-current beam, field emission current generated by the RF Gun for the SRF linac, field emission current generated by superconducting cavities, secondary beam from SRF linac (FEL x-ray beam), copper linac photo-current beam, and secondary beam from copper linac (FEL x-ray beam).

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† cclarke@slac.stanford.edu

HISTORY AND DEVELOPMENT OF BCS

A Beam Containment System (BCS), as defined at SLAC, is a set of mechanical, electronic, and electrical devices that limit beam power and beam losses to prevent excessive radiation in occupied areas.

SLAC's original BCS was for the 2-mile long (up to 50 GeV) SLAC accelerator, which could generate nearly 1 MW average beam power and operated up to 8 beamlines. A significant event occurred where 30 W positron beam struck shielding resulting in 360 R/h dose rates outside the 1.8 m concrete shielding [1]. This illustrates the importance of containing the beam before it can hit shielding.

At SLAC, beam is contained with stoppers and protection collimators. A series of tests using 18 GeV electron beam at average powers ranging from 165 kW to 880 kW demonstrated the highly destructive capability of such beams; the rapid burn-through of materials used in the construction of stoppers and collimators (typically seconds if not faster) clearly demonstrated the need for "an extensive electronic system to prevent damage to mechanical devices and to detect onset of destruction" in addition to power monitors, errant beam monitors and burn-through monitors.

The conclusion to these studies was to define the requirements for BCS. The SLAC BCS control system consists of robust, overlapping and type-redundant fault detection devices and beam shut-off systems that provide three functions:

1. To monitor and limit the beam power in a beam line to the allowed value within the capability of the dumps and shielding
2. To limit the losses along a beam line that is operating to its allowed power
3. To protect beam containment devices from damage by sensing when a beam hits it with enough power to damage it

In response to excessive beam power, losses or the risk of damage to beam containment devices, the BCS shuts off the beam using redundant and diverse technologies.

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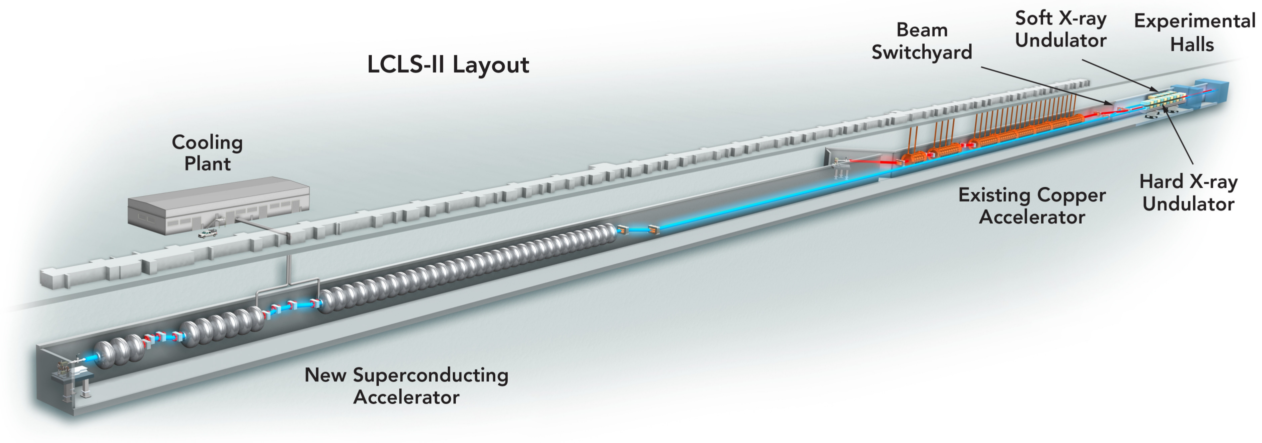

Figure 1: The SRF linac of the future LCLS-II X-ray laser (blue, left) occupies the first third of the existing SLAC accelerator housing. The existing LCLS copper linac (red, right) occupies the final third. Two undulators can be used to deliver x-rays to the experimental hutches. (SLAC National Accelerator Laboratory)

Because of the seriousness of the potential hazards, the systems must be tamper-proof, redundant and fail-safe, backed up by strict operational rules (that is, configuration control with regards to trip threshold values and device bypasses). Self-monitoring sensors are required where feasible to guarantee the continuity of the signal transmission path and to confirm the functionality of the processor.

These BCS design guidelines have withstood the test of multiple accelerator facilities hosted at SLAC. They have been formulated into a controlled document [2] that has been updated as new technologies are available and are applied equally to electron/positron beams as to secondary beams such as x-rays.

Although the linear accelerator shielding is designed for MW class beams, the LCLS FEL additions were shielded for beam power only up to 5 kW. With the LCLS-II upgrade they will contain two operating beamlines with power of up to 120 kW. In addition, the SLAC site has changed from a single-purpose laboratory to a site with multiple user facilities resulting in the presence of outside users bringing with it stricter regulatory limits. These factors increase the reliance on the BCS for LCLS-II.

BCS TECHNOLOGIES

In this section, we discuss the new technologies that are in development for LCLS-II BCS to detect potentially unsafe conditions and shut the beam off. Technologies that have been in use since the inception of BCS at SLAC (water flow interlocks, magnet current interlocks, etc.) are not discussed here but remain a part of BCS. The BCS is backed up by subsystems of monitors that can detect a burn-through of safety components, and by beam shut off ion chambers which detect radiation in occupied ares and operate through the Personnel Protection System (PPS).

BCS Controls Architecture

To begin, we will present the architecture within which the BCS sensors sit. BCS has historically been a series of (where possible) commercially available mechanical relays. More recently Siemens S7 safety programmable logic controller (PLC) solutions were developed for use in safety systems at SLAC. They have built-in redundancy, self-checking, extensive diagnostic monitors, and offer greater reliability over legacy hardware. The PLC and I/O modules would sit on a dedicated BCS network based on Profinet.

Some devices in BCS are required to shut the beam off much faster than 1 second, and these devices should remain hard-wired to the shut-off path. In such cases PLC solutions can provide a more supervisory role: reporting status, changing set-points, and managing device bypasses. The PLC system information can be available locally to accelerator operators.

Average Current Monitor

The BCS has Average Current Monitors (ACM) at the start of each beamline to limit beam current (and indirectly, beam power) to the approved values. The approved values depends on the power rating of the various dumps and the shielding through which the beams pass. It is expected to be increased in stages as the machine, diagnostics, and safety devices are commissioned. The proposed layout of ACMs is shown in Fig. 2.

Cavities have been proposed for the ACM sensor for LCLS-II. Compared to toroids, cavities have a low baseline drift, much better sensitivity, can detect dark current, and it is possible to continuously inject a pilot tone for constant sensor/system verification. The drawbacks for cavities are that they have to be temperature controlled and calibrated with beam against another calibrated beam device such as a Faraday Cup or toroid. Toroids can be calibrated using a

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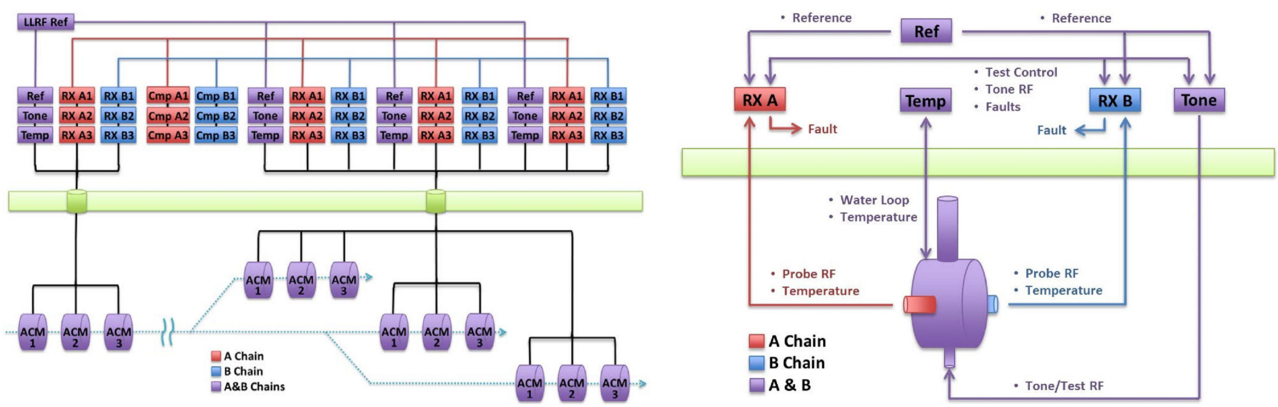

Figure 2: ACMs are located as triplets at start of linac and each beamline. It is recommended that two devices (each with pilot tones and redundant electronics chains) are employed with a third ACM cavity installed as a backup.

current source but only when beam is off and likely require frequent calibration due to baseline drifts. Specialized toroid electronics would also need to be developed to meet the accuracy, signal to noise ratio and dynamic range requirements. Therefore we are developing a cavity-based ACM device.

Each ACM cavity would have two probe ports that go to redundant (A and B) electronics chains. The A and B Receivers consist of the following main printed circuit boards (PCB): down converter board (a Fermilab LLRF down converter design), IF Digitizer and Signal Conditioner board, and FPGA Digital Signal Processing and Control board. The detected 1.3 GHz beam current signal will be compared to a limit for the absolute mode and the system will fault if the limit is breached. These Receivers will incorporate well established LCLS-II LLRF PCB and chassis designs.

Self-test is an important feature for the ACM. In order to constantly verify the end-to-end system functionality, a pilot tone that is 100 kHz off frequency from the 1300 MHz carrier can be continuously injected into a third test port of the ACM cavities. The chain A and B processing electronics compare the pilot tone signal fed to the cavity and the detected pilot tone signal as measured from the cavity to ensure that the system is functional and the cavity tune is not drifting. If the detected pilot tone signal drifts too far from the original then the electronics can generate a fault signal; this ensures that the ACM operates only with proper cavity tune.

The pilot tone generator could also produce a test signal to verify that the ACM will fault the BCS on an over-current.

FPGA use in ACM processing FPGAs are planned to be used in the signal processing for the Average Current Monitors. FPGAs are used in this capacity also at Argonne Light Source [3] and are widely used in accelerator Machine Protection Systems as well as in safety systems in aviation and nuclear power stations.

The SLAC BCS architecture for FPGA use for the ACMs includes two redundant logic controllers implemented on identical hardware. The LLRF BMB7 design by LBNL with Kintex-7 and Spartan-6 Xilinx FPGAs will be utilized. In the BMB7 board design, the communication and soft-processing logic is unloaded to a separate chip allowing the main FPGA do routine signal processing and avoiding peak loads and peak power dissipation.

Our approach is to have two separate programmers for the Chain A and Chain B FPGAs. We will also develop a single test bench for both chains by a third party, independent of the programmers. Safety standards do not require diversity in firmware to achieve the desired level; however there are concerns with regards to programmable devices in safety systems within the DOE Accelerator Laboratory complex. Industry practices commonly emphasize strict verification of the firmware rather than diversity of the firmware, however in practice in an accelerator laboratory environment, strict QA can be harder to enforce than programming diversity.

In addition to this diverse firmware implementation, each logic controller will use advanced safety design practices from Xilinx, such as the Soft Error Mitigation controller to monitor for Single Event Upsets (a common and most probable way of failure for programmable device) and generate a BCS fault if detected.

We will follow the IEC Functional Safety Standard IEC 61508. This provides guidance on how to implement software in a safety environment which can also be applied to firmware development.

Cherenkov Fibers to Limit Beam Loss

Shielding is the preferred mitigation tool for the prevention of radiation in occupied areas. The shielding at SLAC is designed to meet 25 rem/hr dose rates or 3 rem/event in a maximum credible incident. Below this level, shielding does not suffice and active controls are required.

Key to mitigating these risks is to cover the entire facility, with the exception of rare areas with sufficient earth shielding, with radiation monitors. Locations where beam loss is expected could be monitored with small, discrete radiation detector units; however this 4 km facility requires a more global solution that ensures coverage with the fewest sensors possible.

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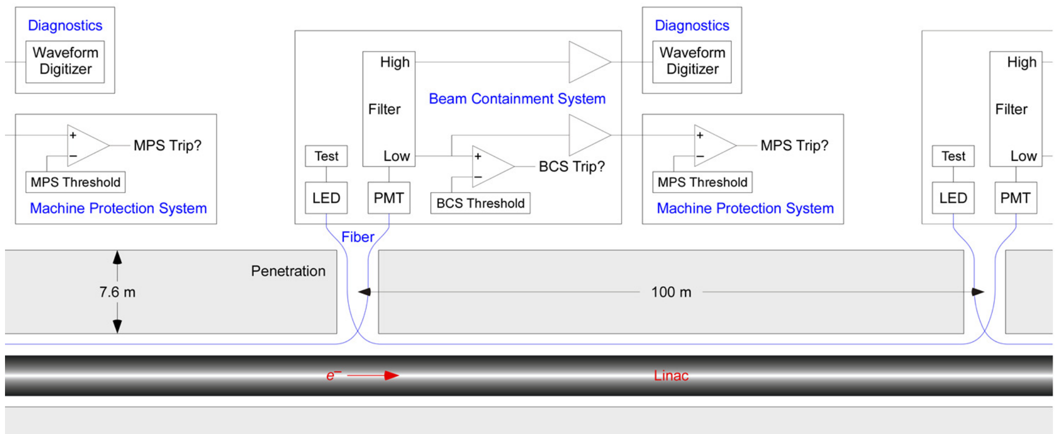

Figure 3: Fibers can cover hundreds of meters within the accelerator housing. A PMT at the downstream end detects Cherenkov light caused by radiation (beam loss). The signal is available for diagnostics as well as the generation of BCS and MPS faults.

Technologies were evaluated. These includes long ion chambers and ACM comparators. Long ion chambers (termed LIONs) have been used at SLAC since its inception [4]; however on this scale of deployment they would be expensive and unreliable due to the extensive gas system they require. In addition, the high repetition rate of LCLS-II means that the spacing between pulses is much shorter than the ion collection time in these devices. In an extended period of losses that are high but lower than the trip threshold, ions can build up between electrodes and screen the applied potential, reducing the collection of electrons and ions despite high losses [5]. ACM comparators would not meet sensitivity requirements to detect a few watts of beam loss using the same devices in the same locations as in the previous section.

We decided upon using Cherenkov emission in radiation-hard optical fibers [6] for our long beam loss monitors. A multi mode fiber with a 600 μm core was tested for radiation hardness up to 1.25 Grad for use in the LHC at CERN [7]. They found that radiation-induced fiber darkening resulted in high light attenuation below 380 nm and in the band 550 – 680 nm, moderate attenuation in the band 400 – 520 nm and "practically no attenuation above 700 nm". Based on these results, we decided to use an identical fiber material, a long pass optical filter at 680 nm and a red-sensitive silicon photomultiplier (SiPM) from Hamamatsu (H7422P-40). We integrate the SiPM signal and compare to a pre-set trip threshold to generate a BCS fault (Fig. 3).

As a conservative estimate, a fiber could be exposed to 25 MRad annual dose which, at 700 nm, results in below 3 dB attenuation. Operationally, we would set the trip threshold conservatively low to take into account expected changes to fiber transmission from radiation darkening and replace the fiber once it is 50%. At worst, this is replacement every year (for this conservative case). Replacing a fiber is straight forward and can be done in minutes with a "jetted" fiber technique using compressed air without requiring access to the accelerator housing.

The fibers and electronics can be checked routinely with a self-check mechanism to ensure they are operating correctly with an LED. The LED measures transmission through the fiber and can be used to generate a fault to test the trip mechanism.

Diamonds as Solid State Ion Chambers

Traditionally, ionization chambers have been used in SLAC BCS to protect beam containment devices from damage by sensing when a beam hits it with enough power to damage it. Modeling studies of ionization chambers indicate substantial uncertainty in their operation at high beam repetition rates and power. Scintillator or Cherenkov counters have been used at SLAC in non BCS applications. Cherenkov fibers will be a part of the LCLS-II BCS and can be used also for the protection of devices. However, diversity in beam loss technologies adds safety to the system therefore we are motivated towards solid state detectors for this device.

Diamond particle detectors, with their nanosecond time resolution, are a potential solution for fast beam loss detection. They have high radiation hardness, heat resistance, small size and don't require active cooling, making them relatively simple to install.

Diamond, because of its large resistivity, can be operated as a solid-state ionization chamber. A voltage is applied across a layer of diamond a few hundred microns thick. When a charged particle traverses the diamond, atoms in crystal lattice sites are ionized, promoting electrons into the conduction band and leaving holes in the valence band. On average, 36 electron-hole pairs are created in each μm of diamond traversed by a minimum ionizing particle. These charges drift across the diamond in response to the applied electric field producing a detectable electric signal.

We have been working with Cividec [8] to develop diamond detectors for use at SLAC. Experience Cividec has

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gained through diamond detector deployment at CERN is valuable such as the development of beryllium spring contacts to the diamond which are expected to survive 1 Grad, beyond the lifetime of the facility.

Self-checking of the diamond can be achieved by modulating the voltage applied across it at a known frequency and using a digital signal processor to monitor the amplitude at that frequency. UV flash lamps were also effective at producing a signal from the diamond; however in order to get enough signal, the flash lamp needed to be large and positioned directly against the sensor, making it a less convenient method than HV modulation.

Protection of Collimators with Photo-Diodes

The FEL x-ray beam can also damage safety components. The graphite-coated diamond disk, shown in Fig. 4, is on the upbeam side of the protection collimator and survives most LCLS-II operating conditions, but it can be damaged if extreme beam conditions are met.

In the event of a mis-steered beam striking the disk, the back-scattered X-rays can be detected by a 4-diode array positioned upstream of the diamond disk, generating a fault signal. The four X-ray diodes are divided into two groups connected to two independent circuits, providing the necessary redundancy for a BCS system. To detect the full energy range of the impinging X-rays, we have selected diode Model IRD-AXUV100Al from Opto Diode Corp.

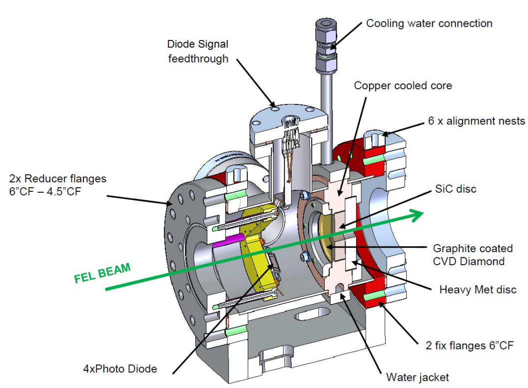

Figure 4: Components to the FEL Collimator. In-vacuum diodes detect scattered x-rays from a FEL beam mis-steer. (Engineer: Silvia Forcat-Oller)

Similar to the Cherenkov fibers, this lends itself to a simple self-check mechanism using an LED to periodically monitor the health of the X-ray diodes and the associated electronics.

Protection of Stoppers with Intensity Interlock

Unlike collimators, PPS stoppers need to be able to sustain FEL directly for an indefinite amount of time (PPS stoppers here act as insertable beam dumps to allow experimenters to access the x-ray hutch downstream). The solution to shut off the beam should FEL hit the stopper therefore cannot be applied. Instead, we plan to monitor the electron beam parameter (energy and bunch charge) and undulator gaps continuously, and shut-off the electron beams when FEL beams may potentially damage the CVD diamond layer on the PPS stoppers. This interlock is activated only when the PPS Stoppers could be in the beam path otherwise all FEL beams are permitted.

The trip threshold for this interlock is defined as the highest allowed temperature and is adjustable between 500°C to 2500°C. The trip threshold will be set conservatively at the beginning of operations. It may be raised when tests with the bootstrap processes demonstrate the safety at a higher threshold. The temperature is a function of electron bunch charge (as measured by a toroid) and FEL energy (which must be calculated from beam energy and undulator gap). The dangerous zone is the phase space of electron bunch charge and FEL energy within which the temperature will be higher than the limit. The calculations and comparison to the trip threshold can be done in a PLC.

This device is more complicated than most systems utilised in BCS and does not have a self-check mechanism however it is complemented with a burn-through monitor upstream of the PPS stoppers for a second layer of protection.

Fast Beam Shut-off

The BCS is required to shut off the beam using diverse technologies. The driving factor for the speed of the beam shut off is damage to safety components which can occur on a single shot (stress damage) with the onset of melting in milliseconds (in the case of the electron beam striking a collimator, stopper or beam dump). The BCS will include multiple beam shut off methods that work together on this timescale to ensure a safe and reliable system.

The fastest shut-off device proposed is an acousto-optic modulator (AOM) that is part of the delivered laser system for the LCLS-II injector laser. The AOM uses RF sound waves to deflect and extract the laser from the system. Without RF, the laser is undeflected into an internal laser dump and is not extracted. BCS can interrupt the RF to the AOM when there is a fault so that the laser power is internally dumped within microseconds. Overall our expected shut-off time using the AOM is expected to be less than 200 μs once signal time of flight, cabling and processing is taking into account, the dominant factor being the processing of the signals in the BCS relay and logic chassis.

CONCLUSION

LCLS-II sees a return to MW class electron beams for SLAC. The LCLS site, designed for a 5 kW beam, is repurposed leading to an increase of dependence on active safety systems. Existing SLAC standards for the beam containment system are followed. Due to new challenges in the scale of the deployment, dynamic range of the sensors required and faster response time required, technologies that have not been used in BCS at SLAC before are being developed. These include cavities, Cherenkov fibers, diamond detectors, photo-diodes and programmable devices such as PLCs and FPGAs.

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