LCLS-II

# Beam Containment System for Radiation Safety

The 60th ICFA Advanced Beam Dynamics Workshop

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SLAC NATIONAL ACCELERATOR LABORATORY

BERKELEY LAB Lawrence Berkeley National Laboratory

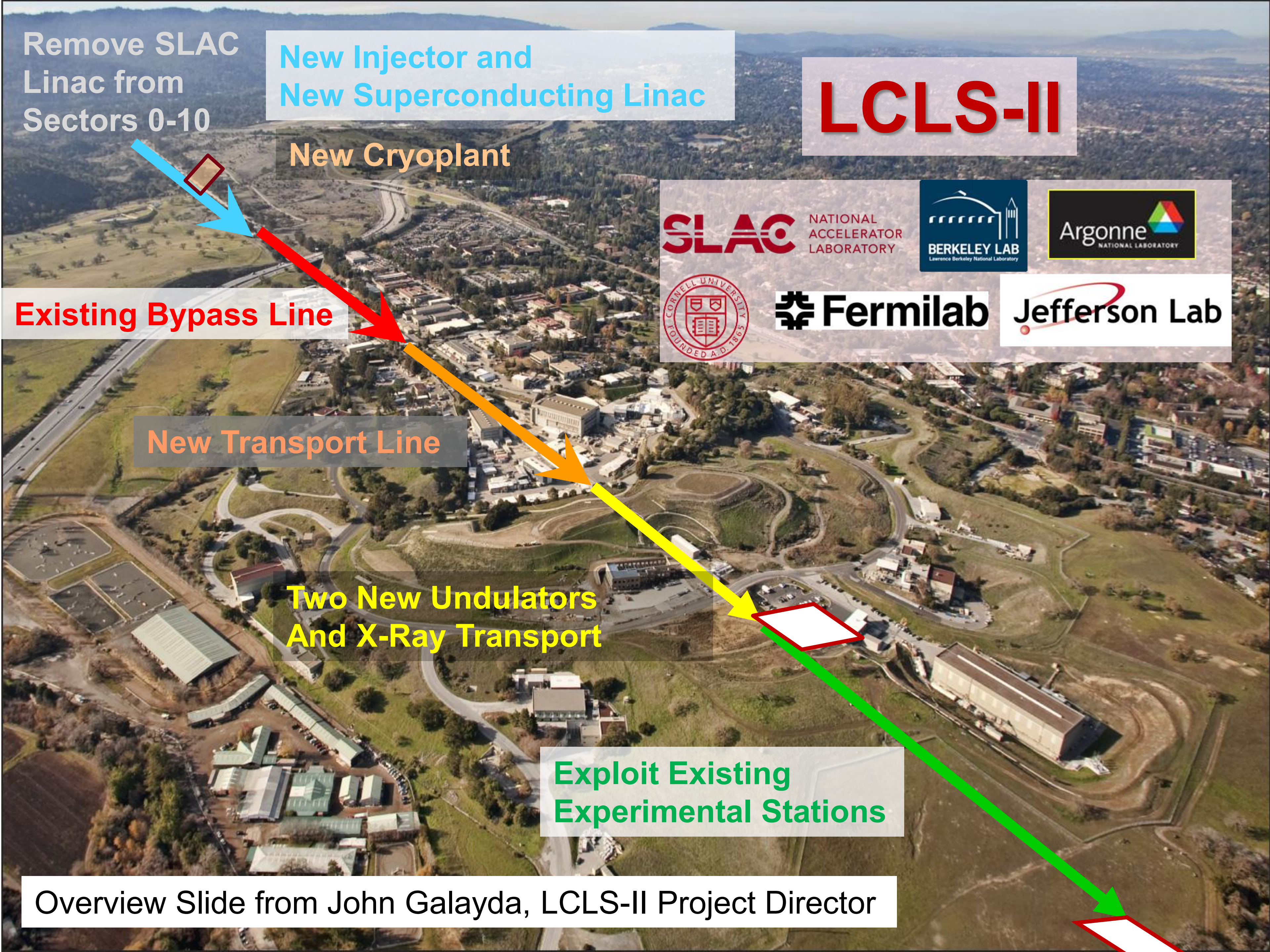
Argonne NATIONAL LABORATORY

CORNELL UNIVERSITY FOUNDED A.D. 1865

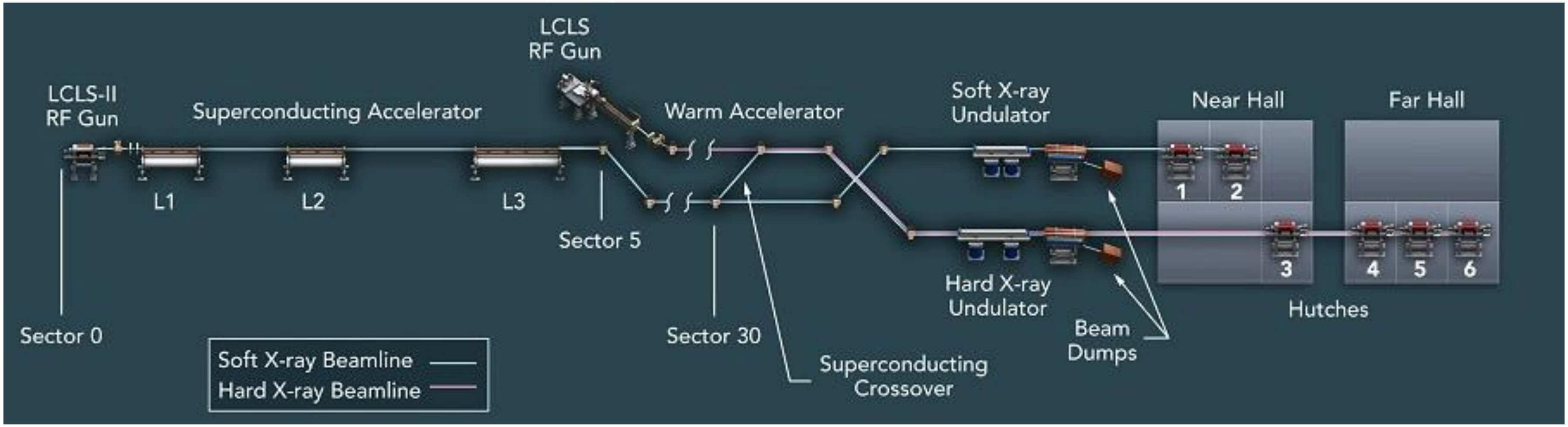
Fermilab

Jefferson Lab

U.S. DEPARTMENT OF ENERGY Office of Science


Remove SLAC Linac from Sectors 0-10
New Injector and New Superconducting Linac
LCLS-II
New Cryoplant
SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB
Argonne NATIONAL LABORATORY
Existing Bypass Line
Fermilab
Jefferson Lab
New Transport Line
Two New Undulators And X-Ray Transport
Exploit Existing Experimental Stations
Overview Slide from John Galayda, LCLS-II Project Director

# LCLS-II Power and Complexity



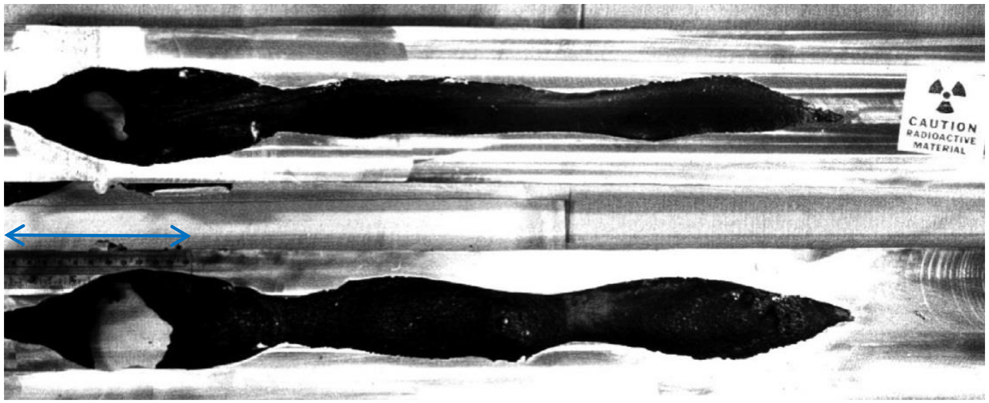

- LCLS FEL facility was designed for 5 kW beam power
- LCLS-II can run 250 kW
- FEL beams from the x-ray undulators are hazards
- Hazardous conditions could also be from CW field emission from gun or cavities

→ Multiple hazard sources to shut-off

LCLS-II introduces increased risk to the existing FEL facility

# History of Beam Containment System

12 cm




Picture: Copper Stopper (52 $X_0$)
after 880 kW 9.5 s
SLAC-PUB-1223 (1973)

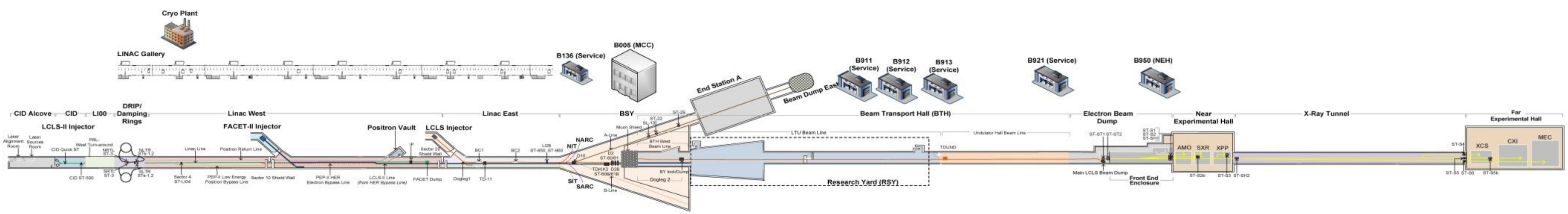
BCS post-analysis:
IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

- SLAC's original BCS was for 2-mile long (up to 50 GeV) SLAC accelerator ~900 kW beam power and 8 beamlines
- Uncontained beams that directly hit shielding results in 3.6 Gy/hr dose rates outside concrete
  - This stresses importance of using collimators/local shielding with beam interlocked monitors
- 18 GeV electron beam at average powers ranging from 165 to 880 kW demonstrated the highly destructive capability of such beams
  - Rapid burn-through of materials used in the construction of stoppers and collimators (~seconds)
  - Need “an extensive electronic system to prevent damage to mechanical devices and to detect onset of destruction”
  - Resulting BCS was “Reliable and essential to the operation of high-powered interlaced beams being delivered to a number of different experimenter beamlines”

SLAC has a verified set of BCS guidelines for MW Linacs

# BCS Design Requirements

- BCS should consist of overlapping and type-redundant fault detection devices and beam shut-off systems to serve four purposes:



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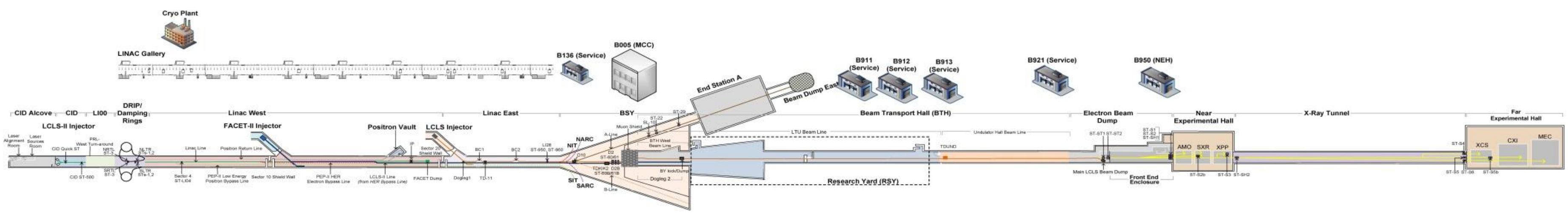

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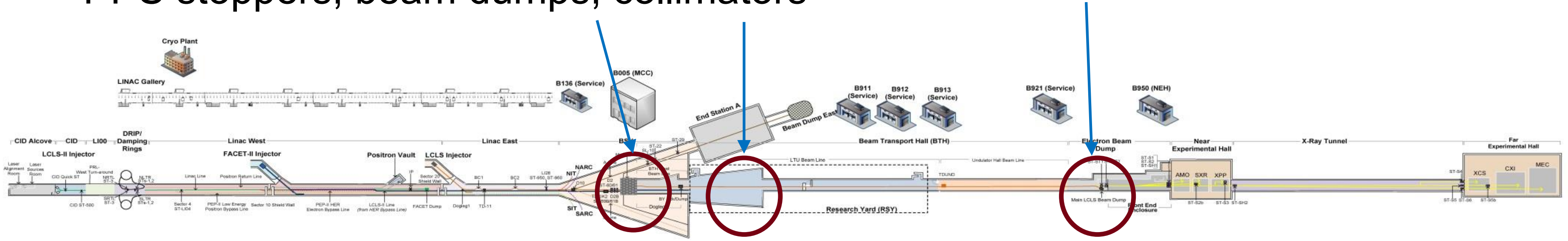

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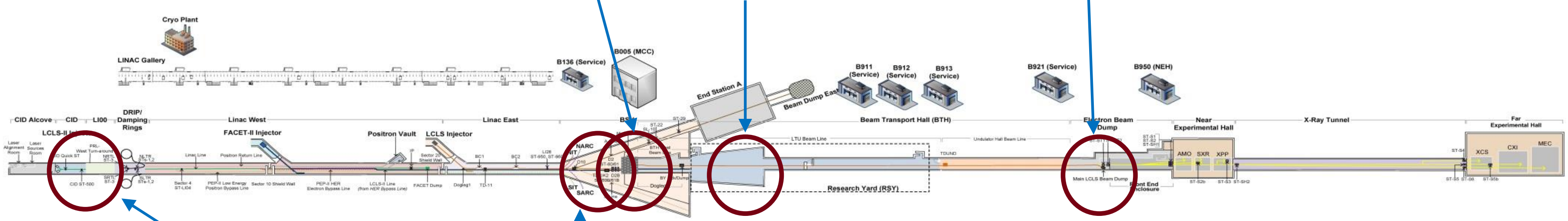


(3) **Limits beam power** and keeps it within designated safe channels

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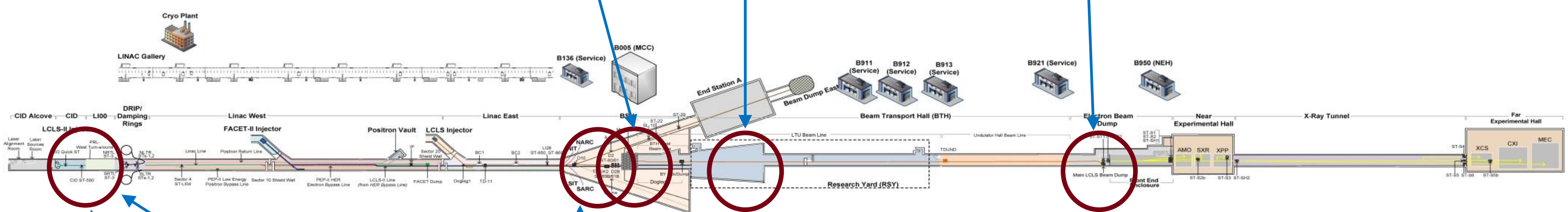


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(4) Acts to **turn the electron beam off** if an unsafe condition arises

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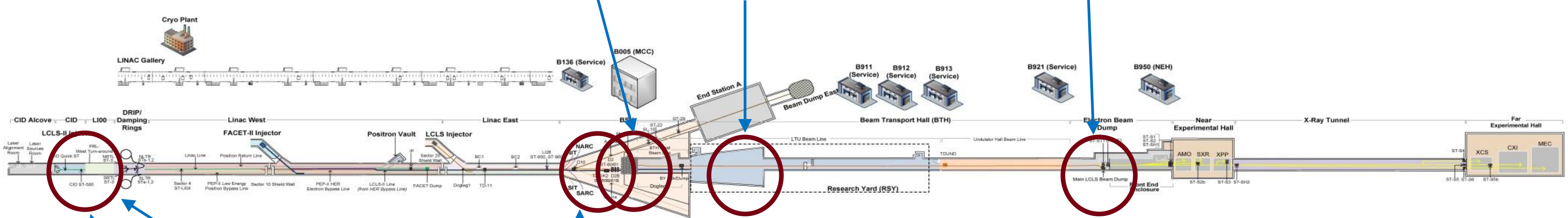


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(4) Acts to **turn the electron beam off** if an unsafe condition arises

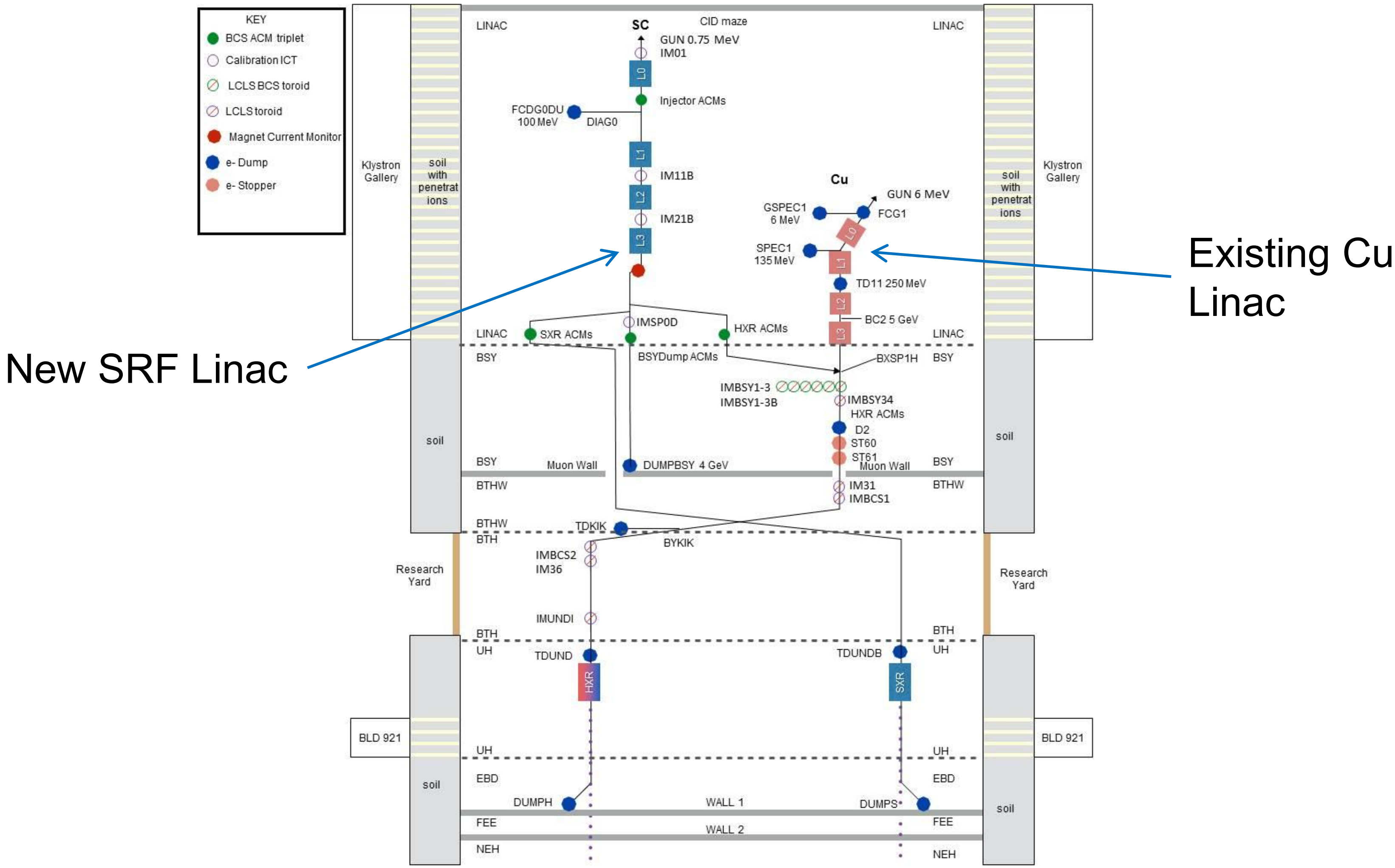
- BCS devices must be: Tamper-proof | Configuration Controlled | Documented | Self-monitoring where feasible | Fail safe | Reviewed

# BCS Sensor Technologies Overview

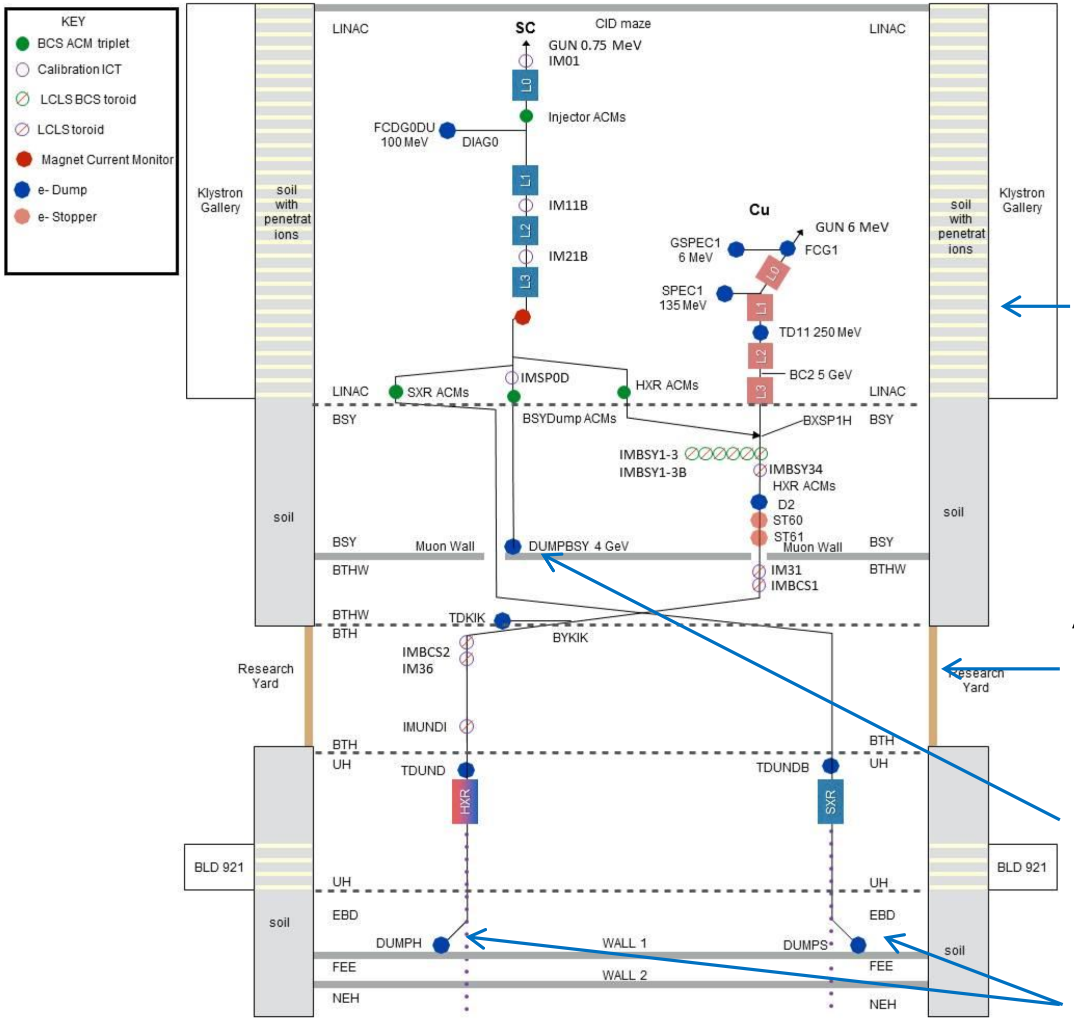
| Sub-system | Reason | # Units | In development for SLAC BCS | Existing |
|---|---|---|---|---|
| Average Current Monitors | Limit Beam Power | 12 | Sensor, electronics, FPGA | |
| Fiber Loss Monitors | Limit Beam Loss | 90 | Sensor, electronics | |
| Bremsstrahlung power monitor/ BSOICs | Limit Beam Loss | 2 | Sensor, electronics | |
| Magnet Current Monitors | Limit Beam Power, Protect Safety Devices | 32 | | Sensor |
| Cooling Water Panels | Protect Safety Devices | 12 | | Sensor |
| Diamond Loss Monitors | Protect Safety Devices | 122 | Sensor, electronics | |
| Rastering monitor | Protect Safety Devices | 1 | Electronics | |
| FEL Collimator diodes | Protect Safety Devices | 18 | Photo-diode, electronics | |
| BCS Absorber diodes | Protect Safety Devices | 1 | Photo-diode, electronics | |
| FEL Intensity Monitor/Interlock | Protect Safety Devices | 1 | PLC, gap monitor | Magnet current monitor sensors, |

We will discuss some of the new technologies for SLAC BCS that are in development

# LCLS-II Layout



# BCS Limitation of Beam Power



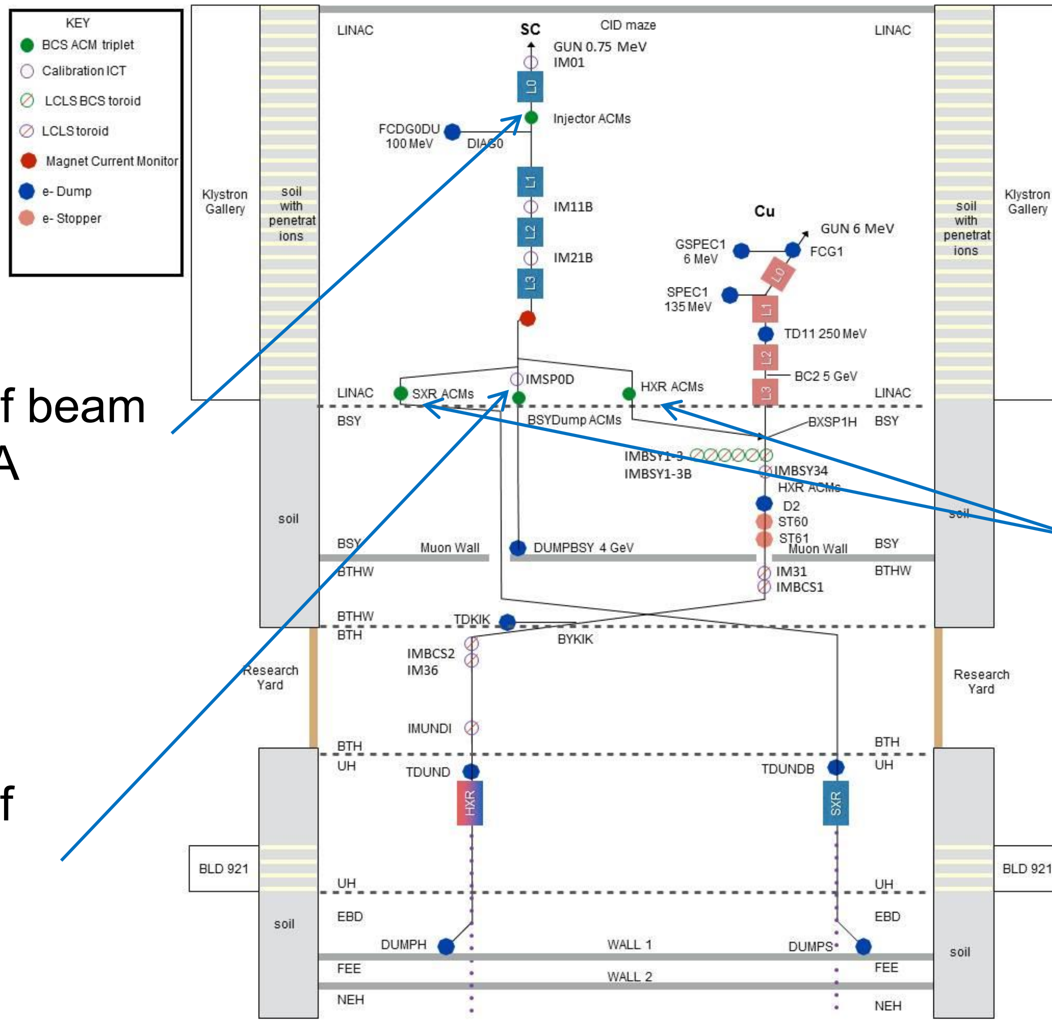

Allowed up to 1.2 MW

Allowed up to 120 kW/beamline

Dump allows up to 250 kW

Dump allows up to 120 kW

# BCS Limitation of Beam Power




Average current of beam limited to < 300 μA

Average current of beam limited to < 62.5 μA

Average current of beam limited to < 30 μA

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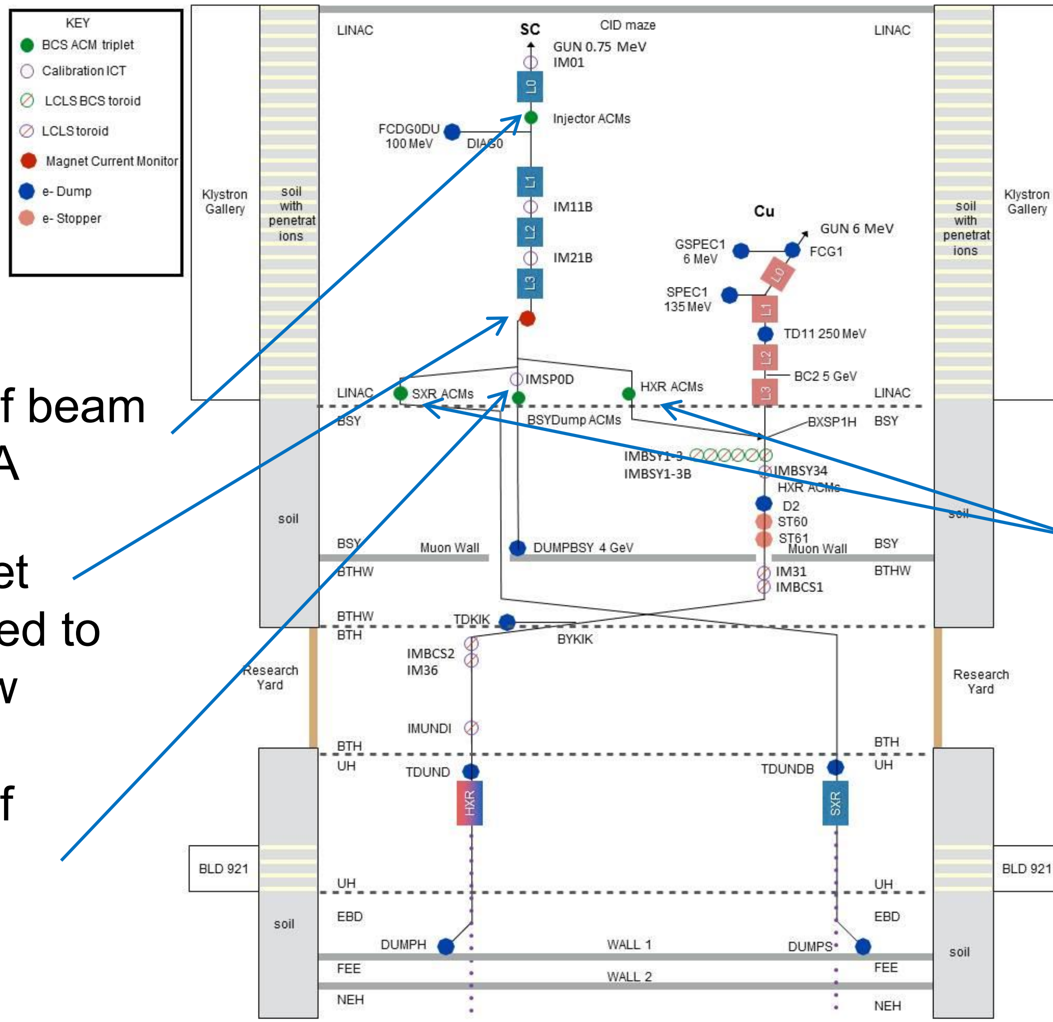



Average current of beam limited to < 300 μA

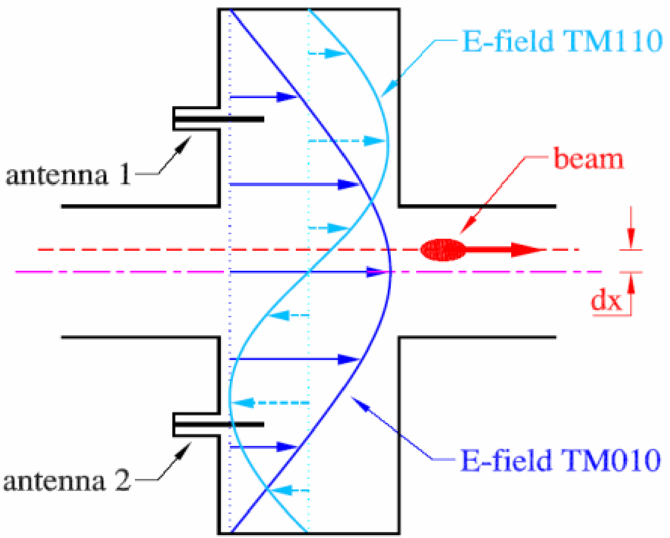
Dog-leg magnet current restricted to 4 GeV or below

Average current of beam limited to < 62.5 μA

Average current of beam limited to < 30 μA

# Average Current Monitors (ACMs)

- We are developing a cavity based solution to measure average current of the beam
  - Based on similar devices used at Jlab
- Electric field of beam passing along axis of cavity excites resonator modes
- Monopole mode is proportional to the bunch charge
- Part of field energy is extracted through probes
- Two probe ports go to redundant Chain A Chain B electronics for signal processing
- Cavity Pros
  - Low baseline drift
  - Good sensitivity
  - Can detect dark current
- Cavity Cons
  - Needs to be temperature controlled
  - Calibration needs to be against other diagnostics

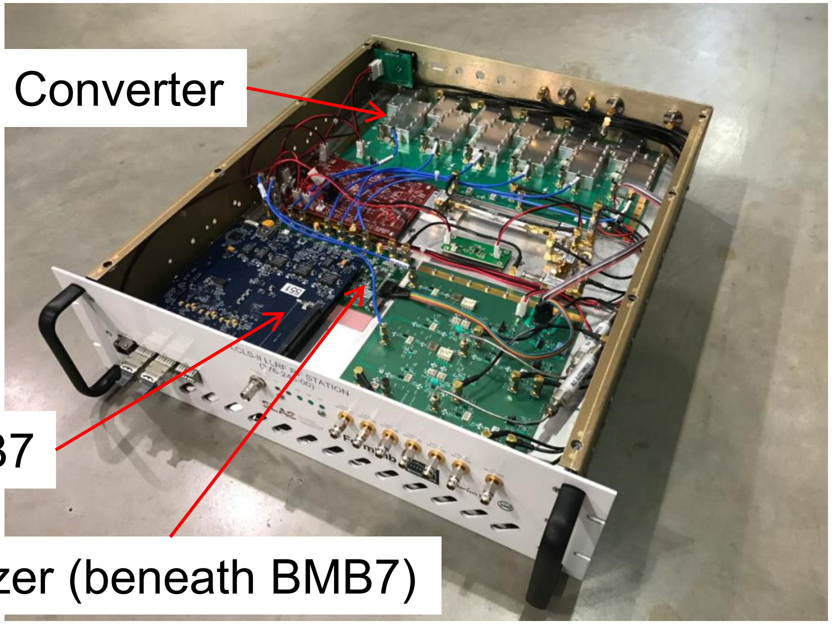

Beam Position Monitors, *Peter Forck, Piotr Kowina, Dmitry Liakin*

We are developing cavity-based average current monitors for BCS

# ACM Signal Processing

- ACM Chassis modified from LCLS-II LLRF Chassis
- Fermilab LLRF down converter design
- BMB7 FPGA design from LBNL
- FPGA will have separate programmers for Chain A Chain B FPGAs
  - Work from same specification
  - Diversity in firmware
  - Test bench developed by independent party
- Uses Soft Error Mitigation Controller from Xilinx
  - Self-monitoring FPGA
- If measured current > allowed

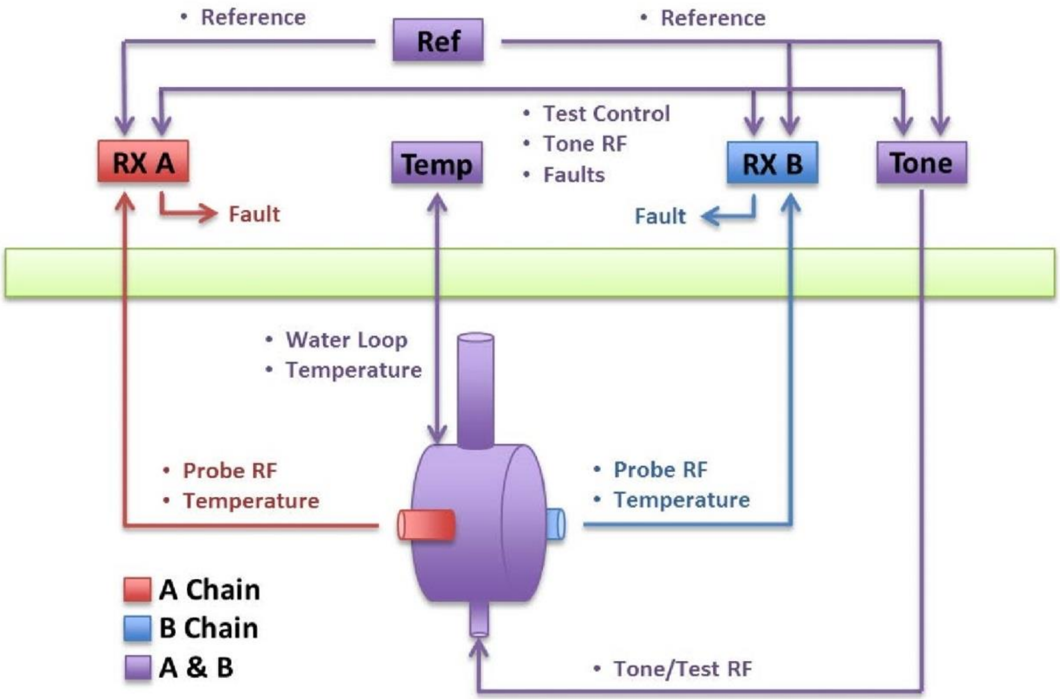
  → ACM fault




SLAC/JLab/Fermilab/LBNL collaboration to develop ACM electronics and firmware

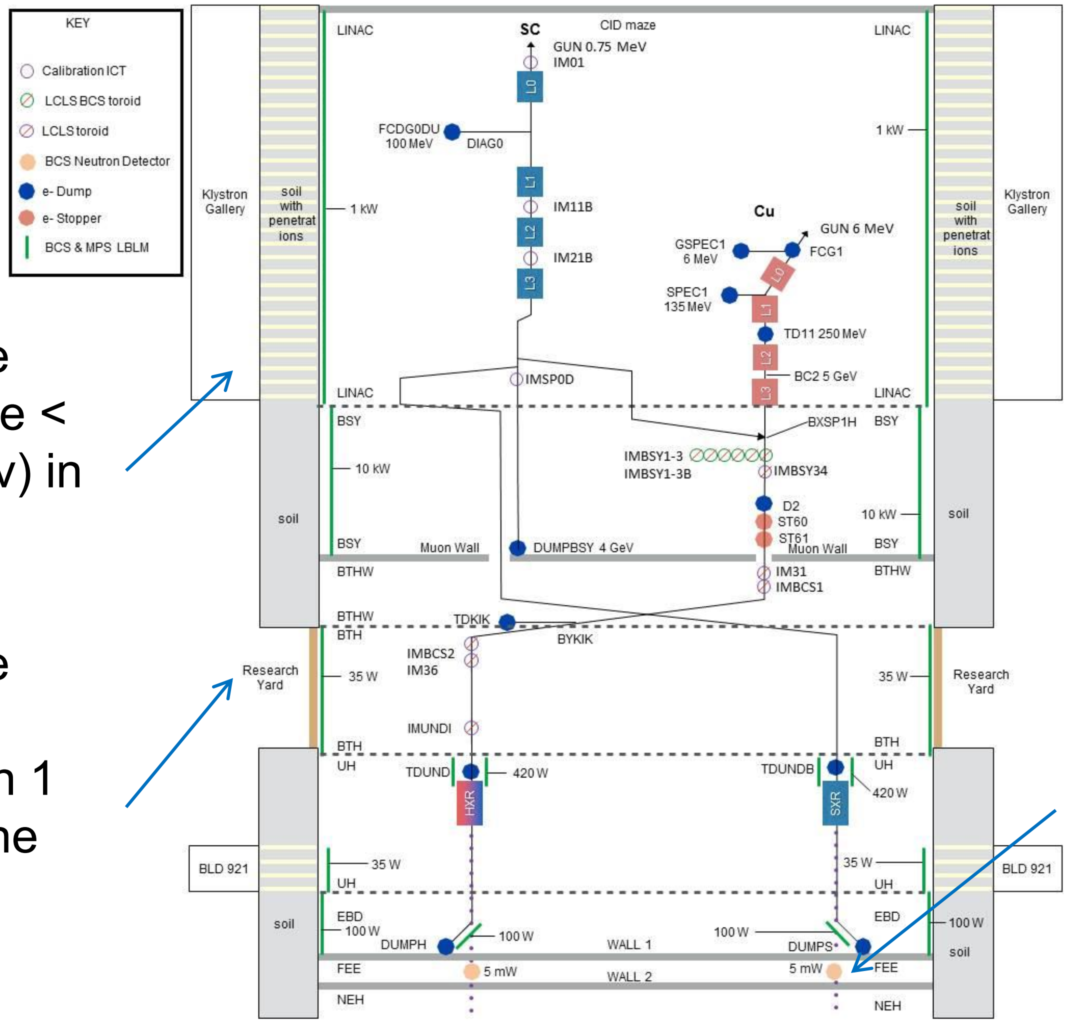
# ACMs Self-Monitoring

- Self test uses a pilot tone
- 100 kHz off frequency from 1300 MHz carrier
- Chain A B electronics compare pilot tone feed to measurement from cavity
- If detected pilot tone signal drifts → ACM fault
- Pilot tone also used to verify ACM fault on over-current
- In addition, temperature is monitored




The ACMs under development will be self-checking: continuous monitoring of pilot tone provides end-to-end verification

# BCS Limitation of Beam Loss




Losses must be limited to ensure < 5 mrem (50 μSv) in 1 hour for area classification*

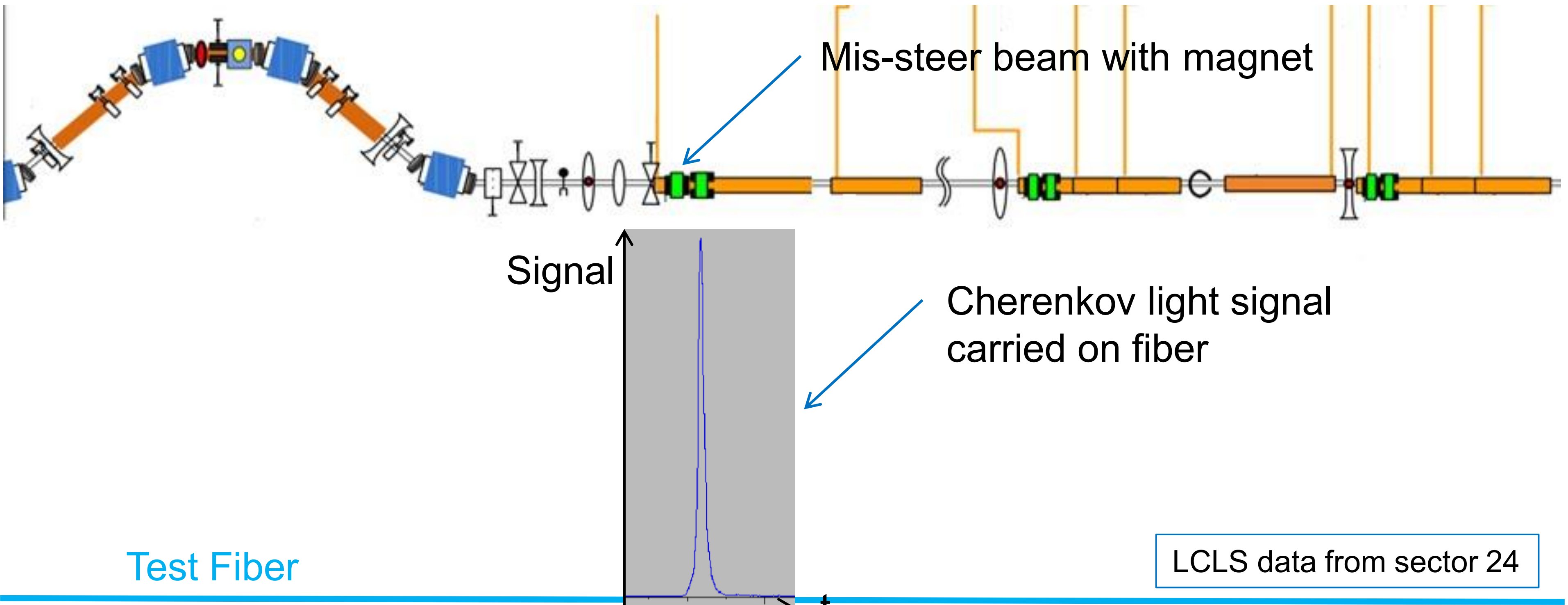
Losses must be limited to < 0.5 mrem (5 μSv) in 1 hour for skyshine and area classification*

Forward going secondary radiation limited to meet annual dose limit to users

* By meeting area classification, this helps meet annual dose limits for personnel

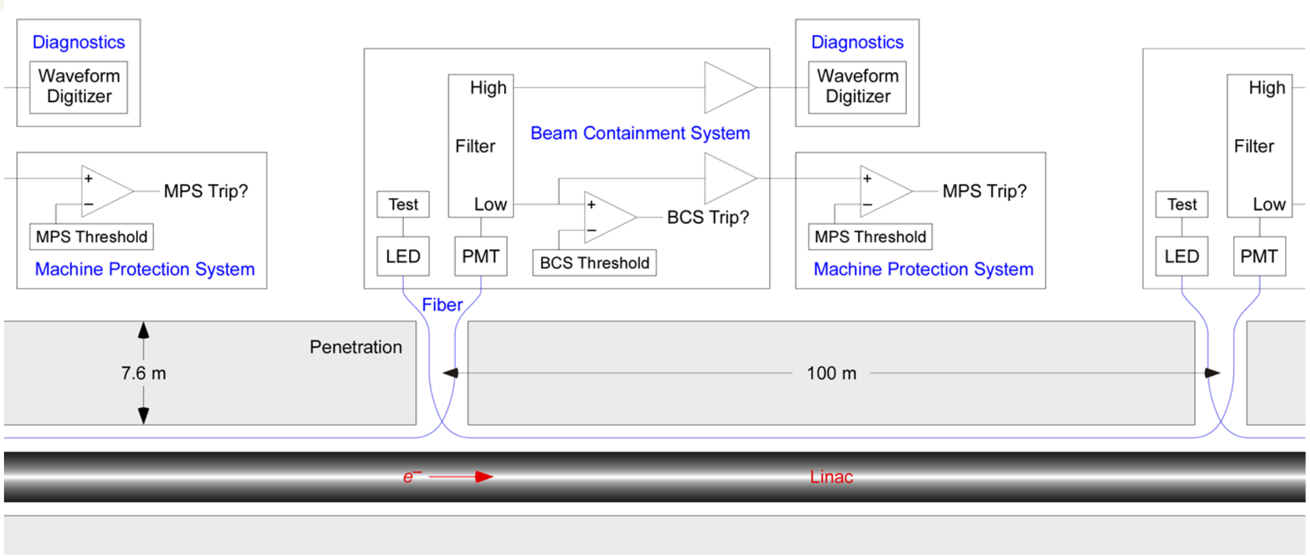
# Cherenkov light generated in fibers from radiation

- Particles from radiation showers generate Cherenkov light in fiber core
- The light can be trapped and transported in the fibers over ~100 - 200 m




We are developing Cherenkov-fiber detectors for BCS to sense potentially hazardous levels of radiation

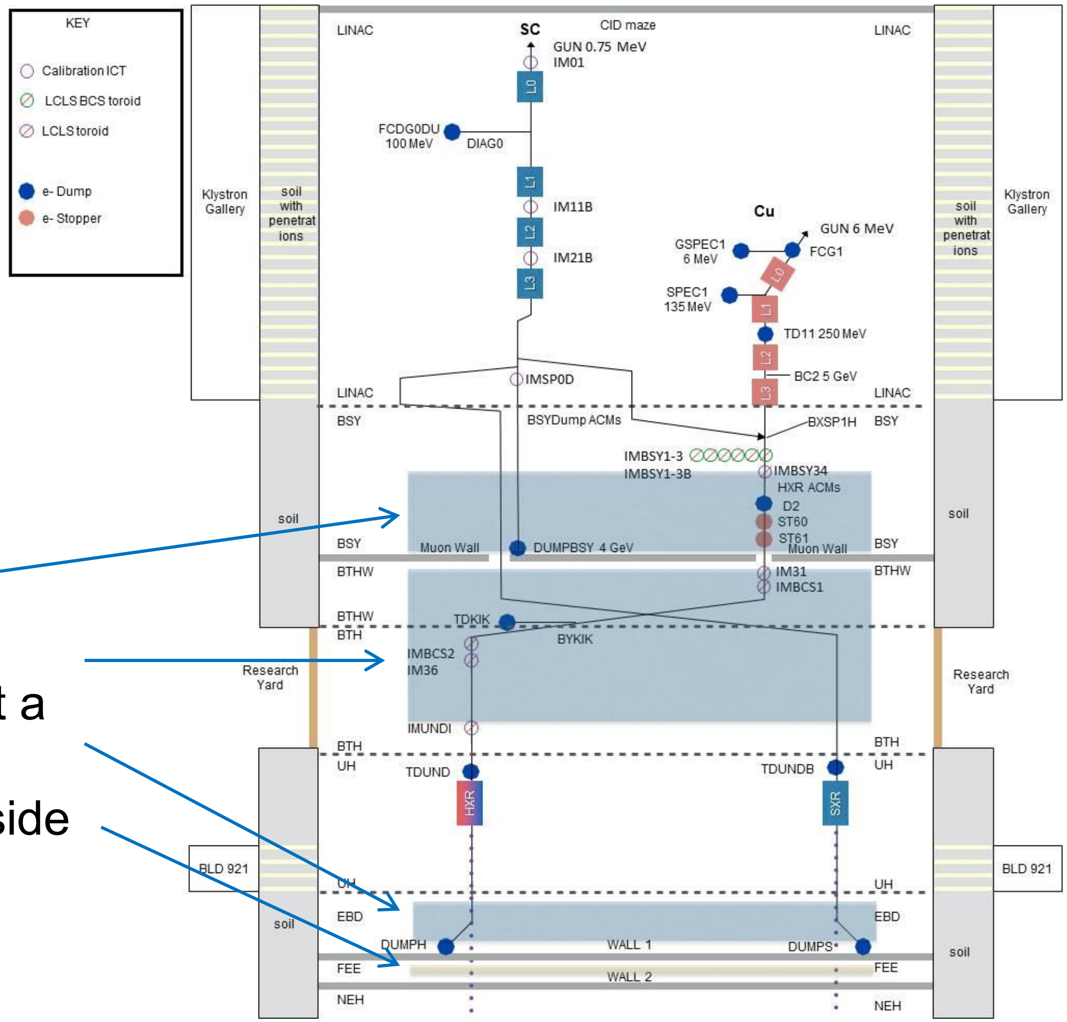
# Cherenkov Fiber Deployment




- Cherenkov light detected with PMT and integrated in electronics
- If signal > pre-set trip threshold, then → Fault
- Known issue: Fiber darkens with radiation
  - CERN studies show practically no attenuation above 700 nm
  - We mitigate radiation damage effects by using red filter and PMT
- Self-monitoring can be achieved with a red LED at upstream end to produce “keep alive” signal

We are developing a fail-safe/self-monitoring implementation for Cherenkov fibers

# BCS Collimator Protection




Local shielding ("collimators") intercept beams before they can hit a wall behind which personnel may reside

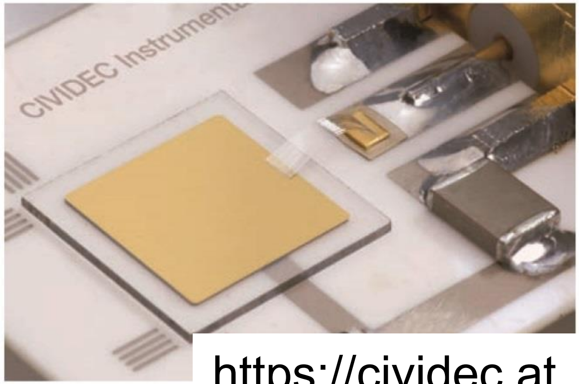
Note: up to 100 kRad/h (1 kGy/h) dose rate consequence from direct hit of beam on shielding

# Diamond Detectors for protecting safety devices from e-beams

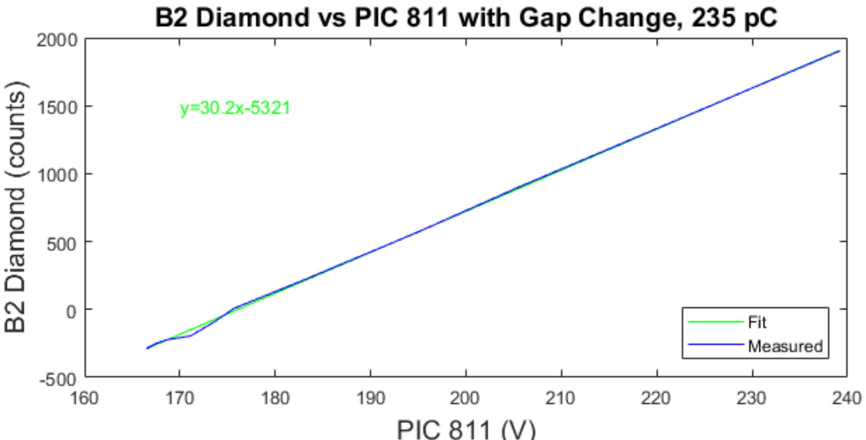
- At high power, collimators can be burnt through ~1s
  - Onset of stress damage in μs
  - Melting onset ~ms
- Burn-through triggers shut off with integrated monitor
  - Already a 3 rem (30 mSv) event, one-use

→ Need to terminate as fast as possible

- Diamond detectors with a voltage applied across them act as a solid state ionisation chamber
  - Nanosecond time resolution
  - Radiation hardness
  - Heat resistance
  - Simple deployment (no gas or cooling)
- Modulating the HV produces a signal for self-check




https://cividec.at

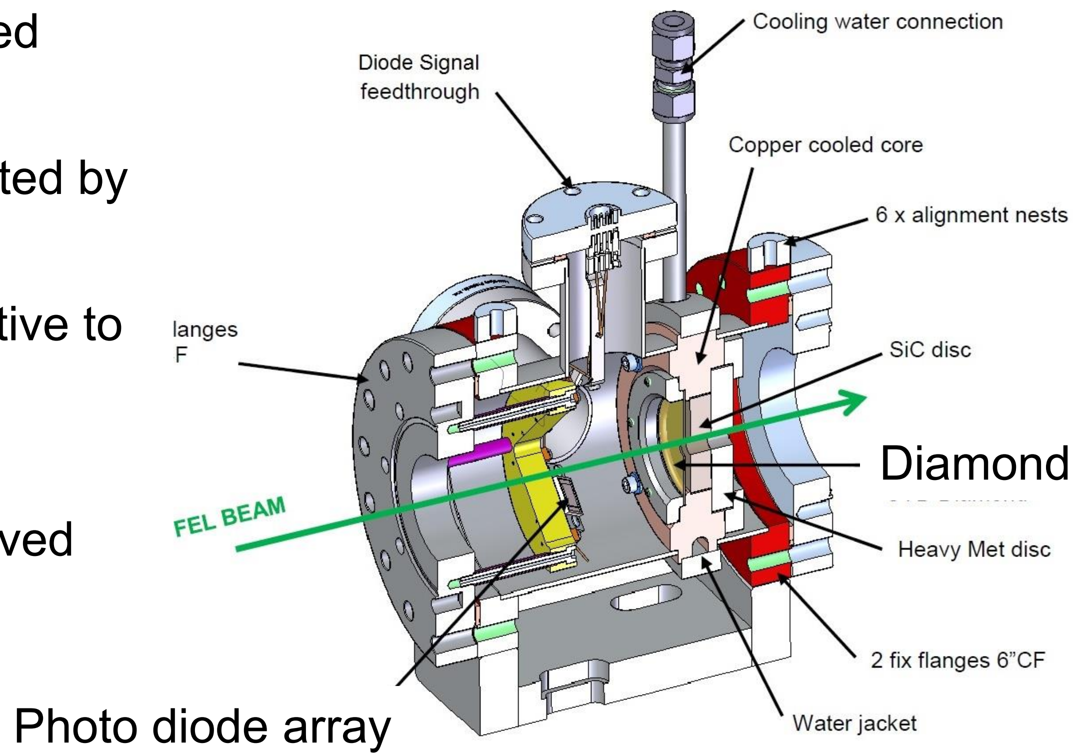



Cross-check with gas ionisation chambers at LCLS

We are developing diamond sensors to detect high power electron beam in undesired places

# Photo-diodes for protection from X-rays

- FEL protection collimators protected with graphite-coated diamond disk
- Back-scattered X-rays detected by photodiodes
- Photo-diodes selected sensitive to full X-ray energy range
- Self-check of diodes and processing electronics achieved using LED

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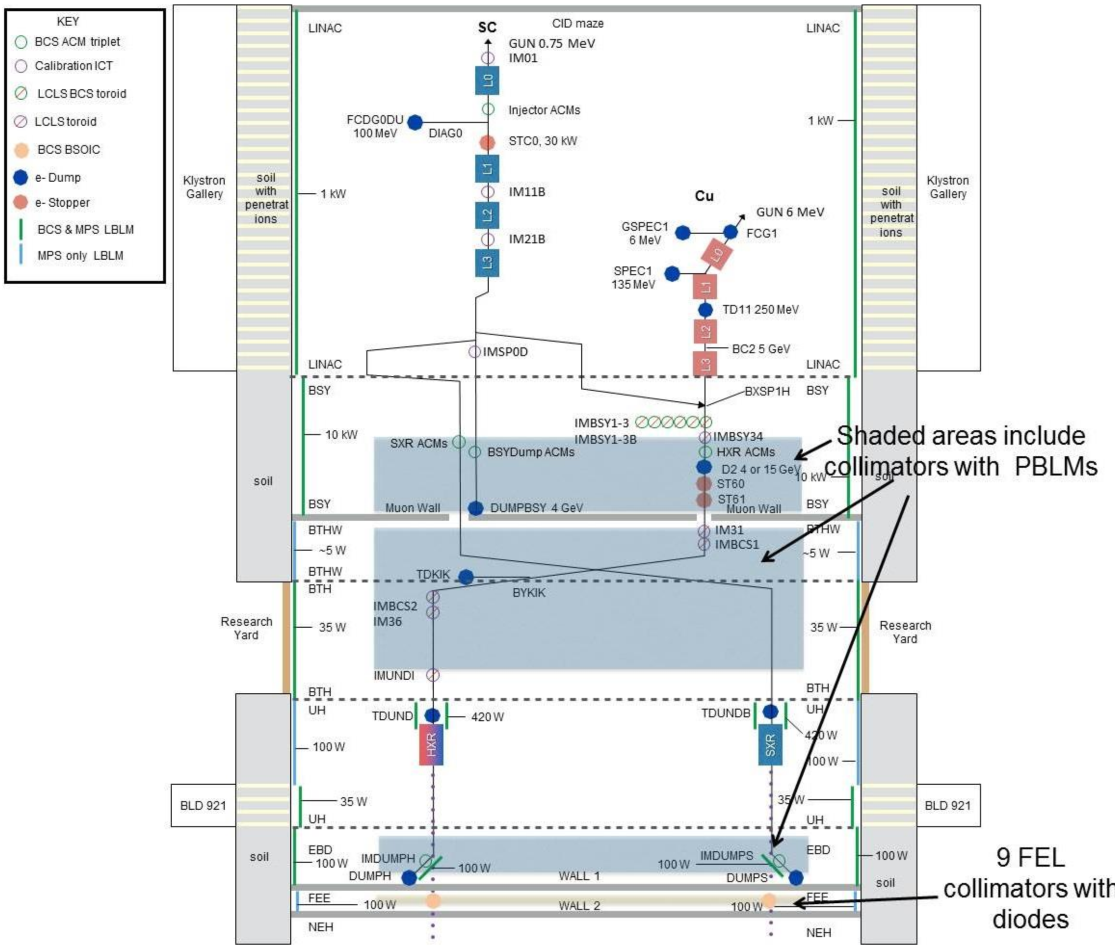
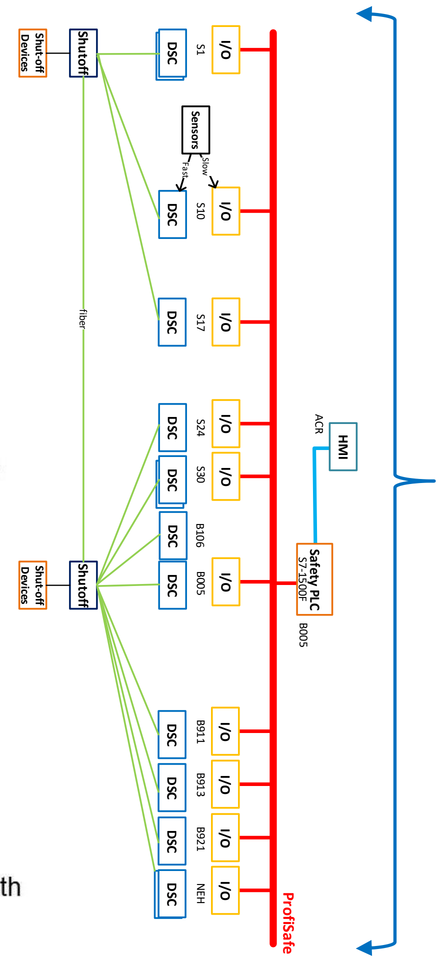
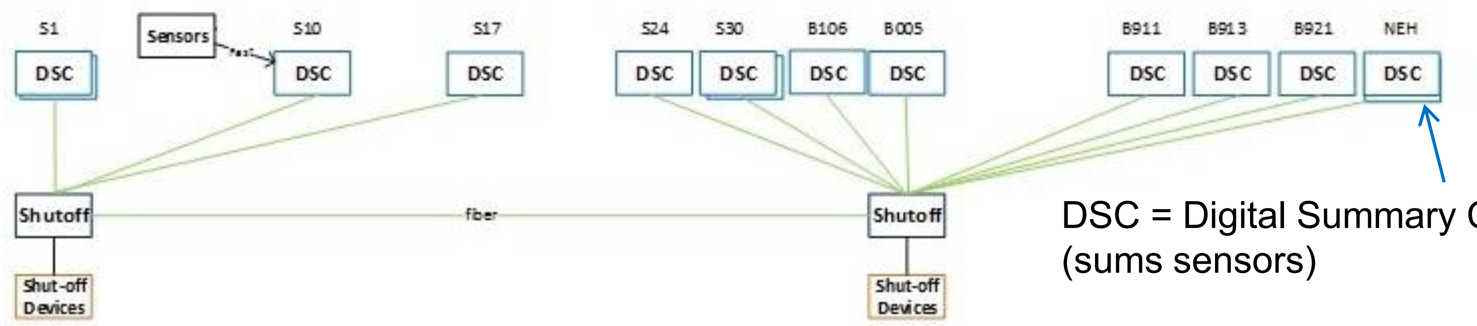
# Globally distributed control system




Sensor inputs spread over 4 km length of facility

# Architecture




DSC = Digital Summary Chassis (sums sensors)

- Two ways to connect a sensor to shut-off path:
  - Direct copper or fiber connections for < 200 μs shut off time

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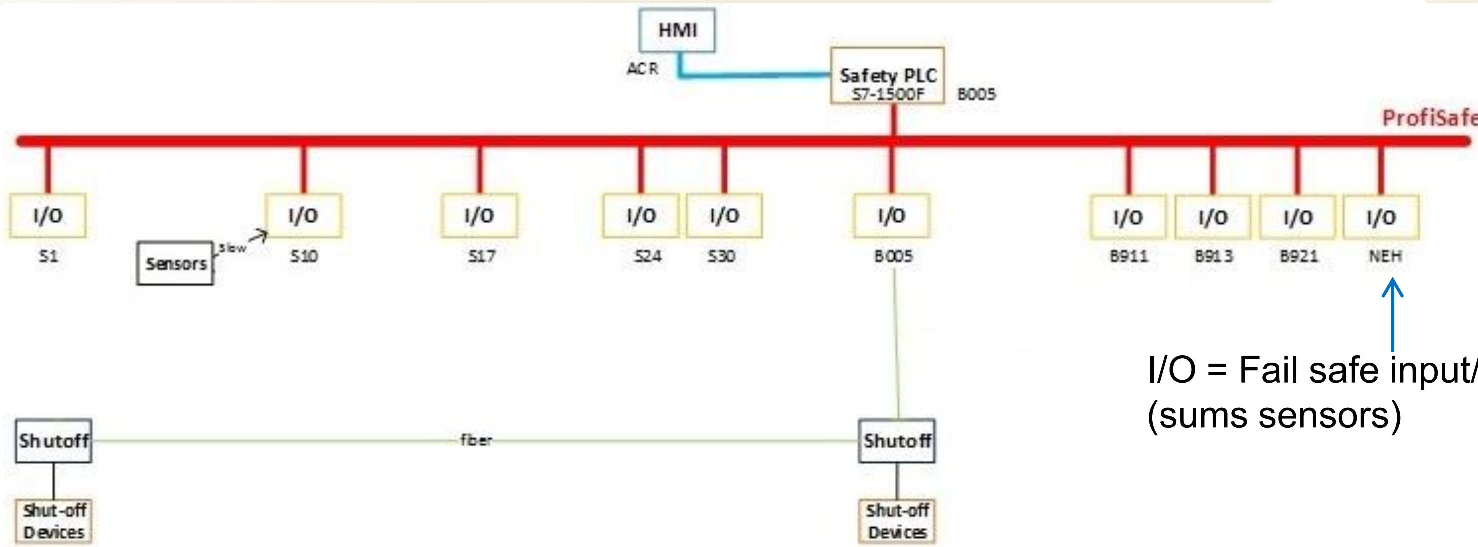


I/O = Fail safe input/output module (sums sensors)

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  - To Safety PLC (Siemens S7) for < 1 second response time

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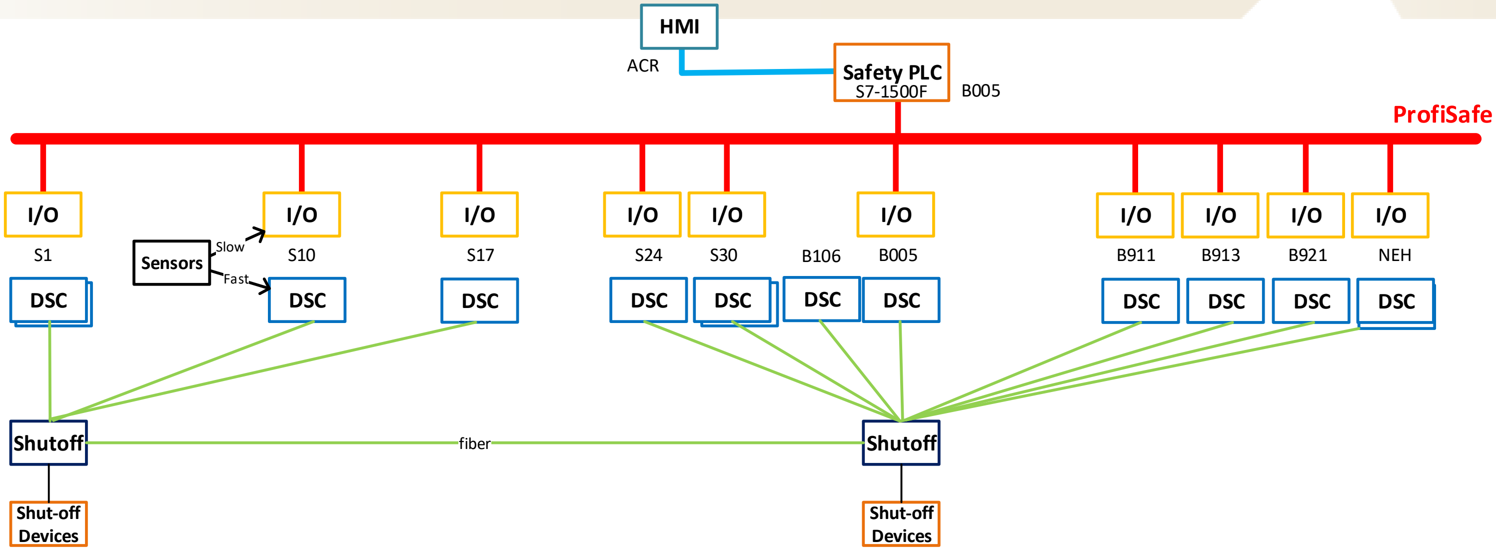


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  - Direct copper or fiber connections for < 200 μs shut off time
  - To Safety PLC (Siemens S7) for < 1 second response time
- Desirable to use safety PLC where possible for improvements over custom built relays in maintenance and diagnostic availability in control room
- Two chain redundancy in implementation at each level

Architecture spans full 4 km complex and can perform shut-off < 200 us

# Summary

- LCLS-II has greater beam related hazards than LCLS
- BCS requirements developed at SLAC to address the risk
- Beam Containment (Controls) System performs multiple functions to mitigate beam related risks
  - Limits beam power
  - Limits radiation levels outside of housing
  - Protects safety hardware
  - Turns off the beam when there are beam hazards
- It is global across whole machine from Injector to Experiment hutches
- Technologies not used in BCS before are being developed
  - Cavities with FPGA processing
  - Cherenkov fiber beam loss monitors
  - Diamond beam loss monitors
  - Photo-diode X-ray monitors
  - PLCs