# Instrumentation and Controls for a High Repetition-rate Superconducting Linac

Tim Maxwell for the LCLS-II Collaboration

Tuesday, May 1, 2018

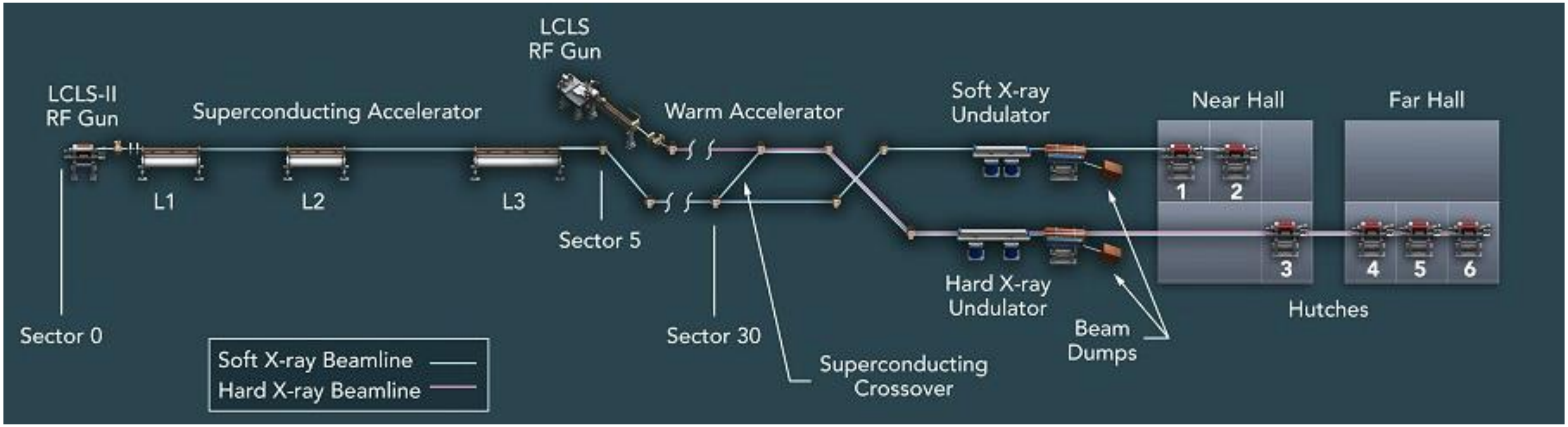
IPAC18

**TUZGBD1**

U.S. DEPARTMENT OF ENERGY Office of Science
BERKELEY LAB Lawrence Berkeley National Laboratory
Cornell University
Fermilab
Argonne National Laboratory
SLAC National Accelerator Laboratory
Jefferson Lab


Remove SLAC Linac from Sectors 0-10
New Injector & New Superconducting Linac
LCLS-II
New Cryoplant
SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB
Argonne NATIONAL LABORATORY
Fermilab
Jefferson Lab
Existing Bypass Line
New Transport Line
Two New Undulators And X-Ray Transport
Update Existing Experimental Stations
John Galayda (MOYGB2)

# LCLS-II Parameters




| *e*-beam Parameters | Copper Linac | Supercond. Linac |
|---|---|---|
| *Energy* | 3-16 GeV | **4 GeV** |
| *Max beam power* | 5 kW | **120 kW (per undulator line)** |
| *Max repetition rate* | 120 Hz | **0.929 MHz** |
| *Charge* | 250 pC, typ. | **100 pC, typ. (power limited)** |
| *Trans. emittance (normalized)* | 0.5 µm | **0.5 µm** |
| *Slice energy spread (RMS)* | < 0.02% | **< 0.02%** |
| *Peak current* | 1 – 5 kA | **0.5 – 1.5 kA** |

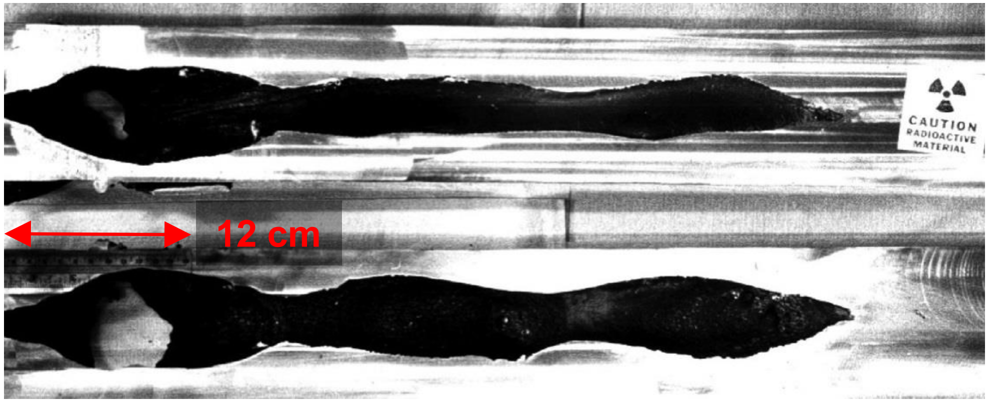
# The LCLS-II: Demanding diagnostics & controls

| | |
|---|---|
| *High power* | – kW- to MW-class *e*-beam (safety) |
| *High rate* | – Single-pass, μs spacing (fast readout) |
| *High complexity* | – Multiple beam destinations (controls) |
| *High brightness* | – Diagnostics for FEL-quality bunches |

# High Power
# Safety: The SLAC Beam Containment System (BCS)

Original SLAC BCS for 3 km, 50 GeV SLC linac w/ 8 beamlines

- Uncontained 30 W beam directly hit shielding produced 360 R/hr dose rates outside 1.8 m concrete
- Average powers from **165 to 880 kW** demonstrated the highly destructive capability of such beams:
  - Rapid burn-through of materials in collimators and PPS stoppers (~seconds)
  - Call for “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”




Picture: Test of copper stopper (52 $X_0$) after 9.5 s @ 880 kW, SLAC-PUB-1223 (1973)

BCS details: IEEE Transactions on Nuclear Science, Vol. NS-24, No.3, p. 1583 (1977)

*BCS slides courtesy Christine Clarke (SLAC)*

# BCS vs. MPS

Beam Containment is *not* Machine Protection

**Machine Protection** – Prevent damage to machine

**Beam Containment** – Prevent/detect radiation outside of predetermined safety envelope

# BCS Sensor Technologies Overview

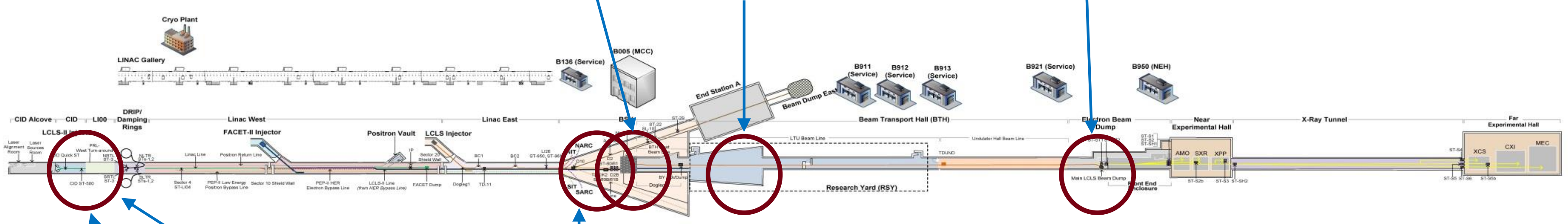
| Sub-system | Reason | # Units | In development | Existing |
|---|---|---|---|---|
| Average Current Monitors | Limit Beam Power | 12 | Sensor, electronics, FPGA | |
| Magnet Current Monitors | Limit Beam Power, Protect Safety Devices | 32 | | Sensor |
| Fiber Loss Monitors | Limit Beam Loss | 90 | Sensor, electronics | |
| Bremsstrahlung power monitor/BSOICs | Limit Beam Loss | 2 | Sensor, electronics | |
| 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, toroids |

# BCS Design Requirements

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

(1) Limits personnel dose outside of housing from mis-steered beams (**limits beam loss**)

(2) **Protects** the integrity of devices that contain the beam from damage e.g. PPS stoppers, beam dumps, collimators



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

(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

# What happens if a hazardous situation is detected?

Signal on Sensor

e.g. Beam Loss Monitor voltage increases

Signal beyond threshold

e.g. Voltage level above allowed level indicates high radiation loss

Shut off logic

Proposed methods:

Shut off Photocurrent

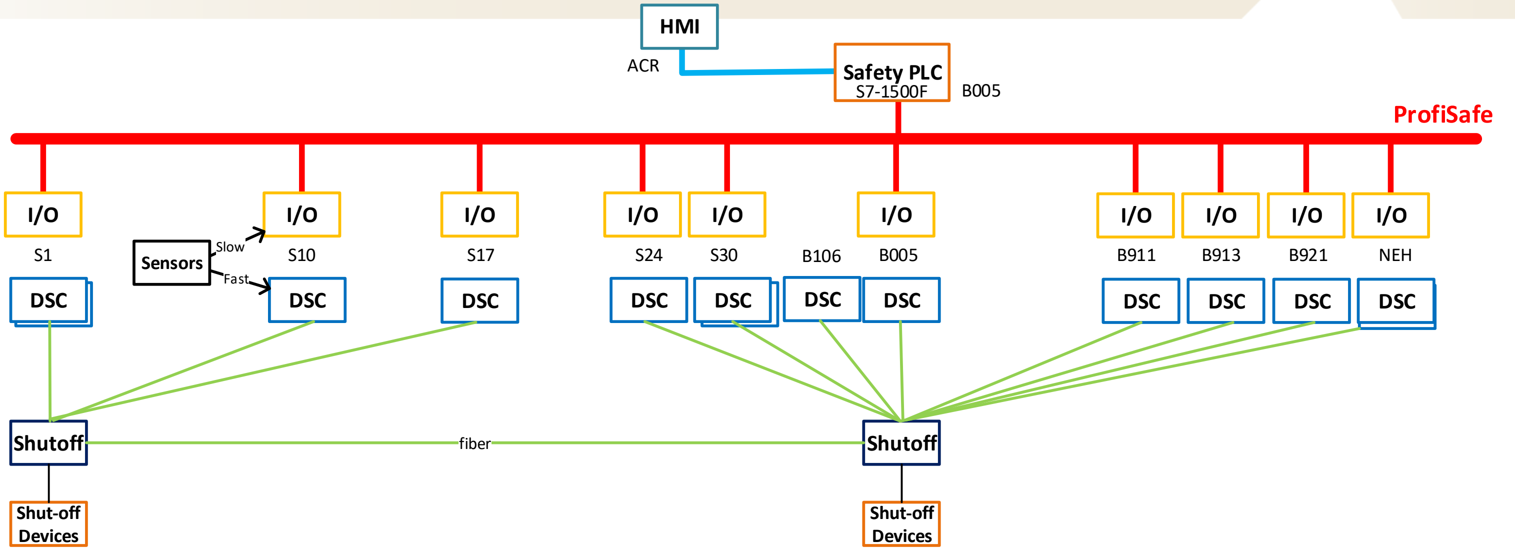
- Disable Acousto-Optic Modulator
- Disable Injector RF
- Close Laser safety shutters

Disable Gun RF

Shut down LCLS-Cu

Developing/testing multiple shut-off devices with diverse technologies

# Architecture

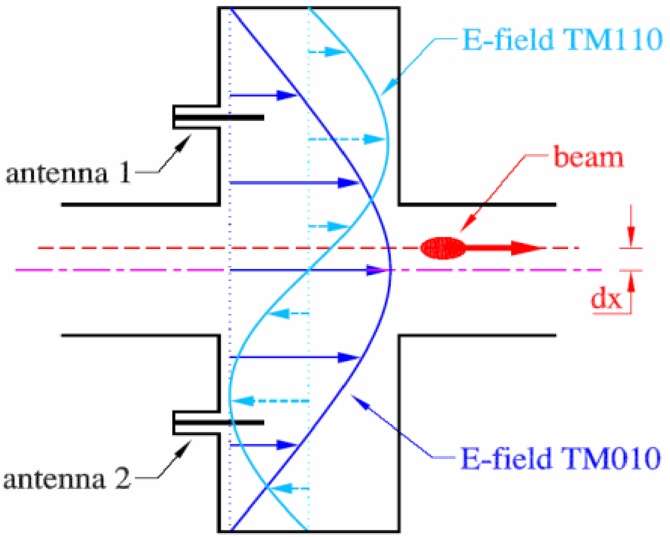



- Two ways to connect a sensor to shut-off path:
  - Direct copper or fiber connections for < 200 μs shut off time
  - To Safety PLC (Siemens S7) for < 1 second response time
- Desirable to use safety PLC where possible for improvements over custom built relays in maintenance and diagnostic availability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

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

# Average Current Monitors (ACMs)

- 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

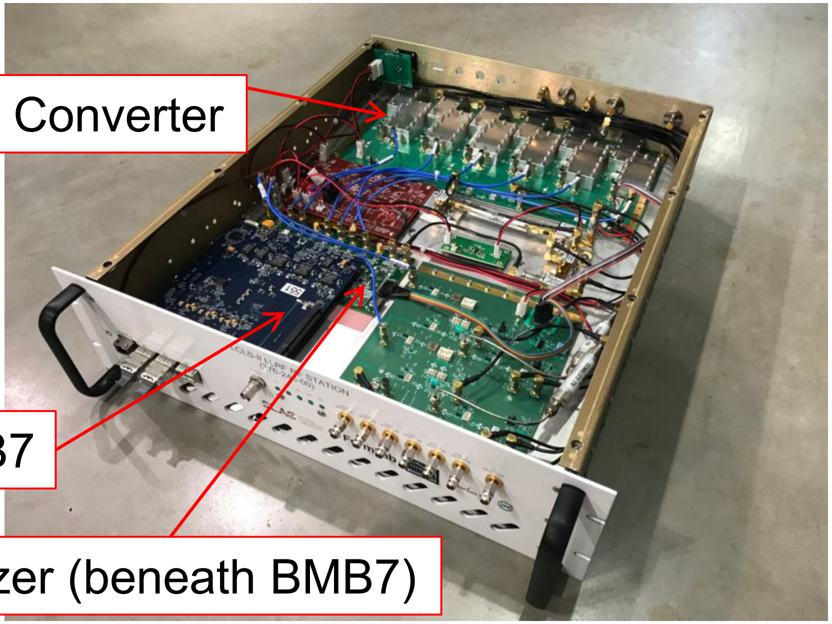

Beam Position Monitors, *Peter Forck, Piotr Kowina, Dmitry Liakin*

**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
- Xilinx Soft Error Mitigation Controller
  - Self-monitoring FPGA
- If measured current > allowed

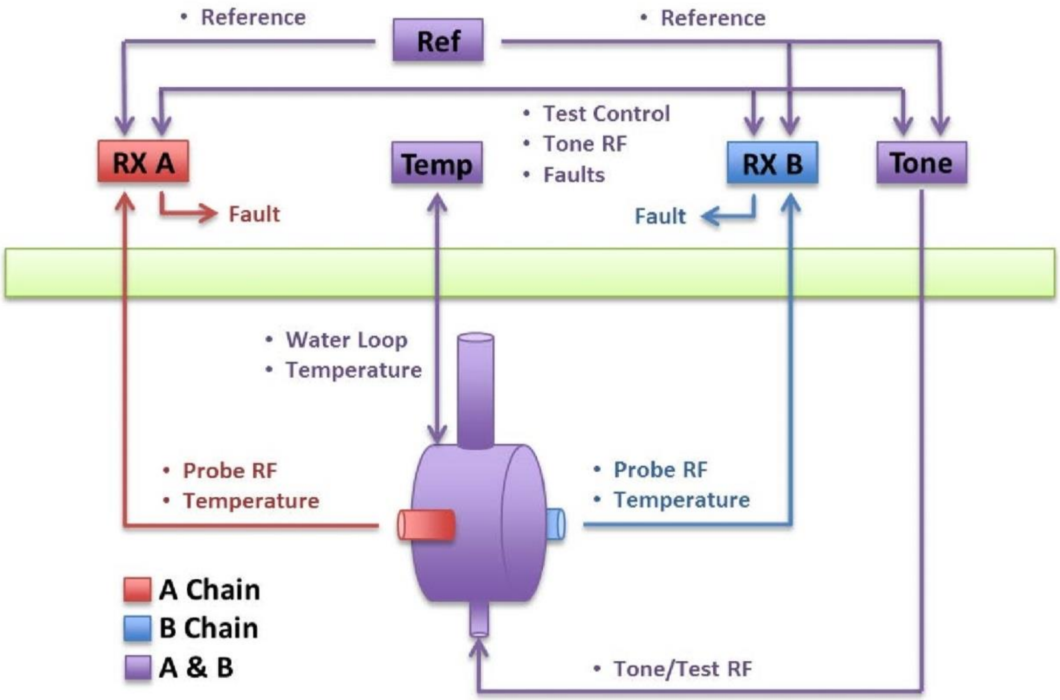
  → ACM fault




SLAC/JLab/FNAL/LBNL collaboration to develop ACM electronics /firmware

# ACMs Self-Monitoring

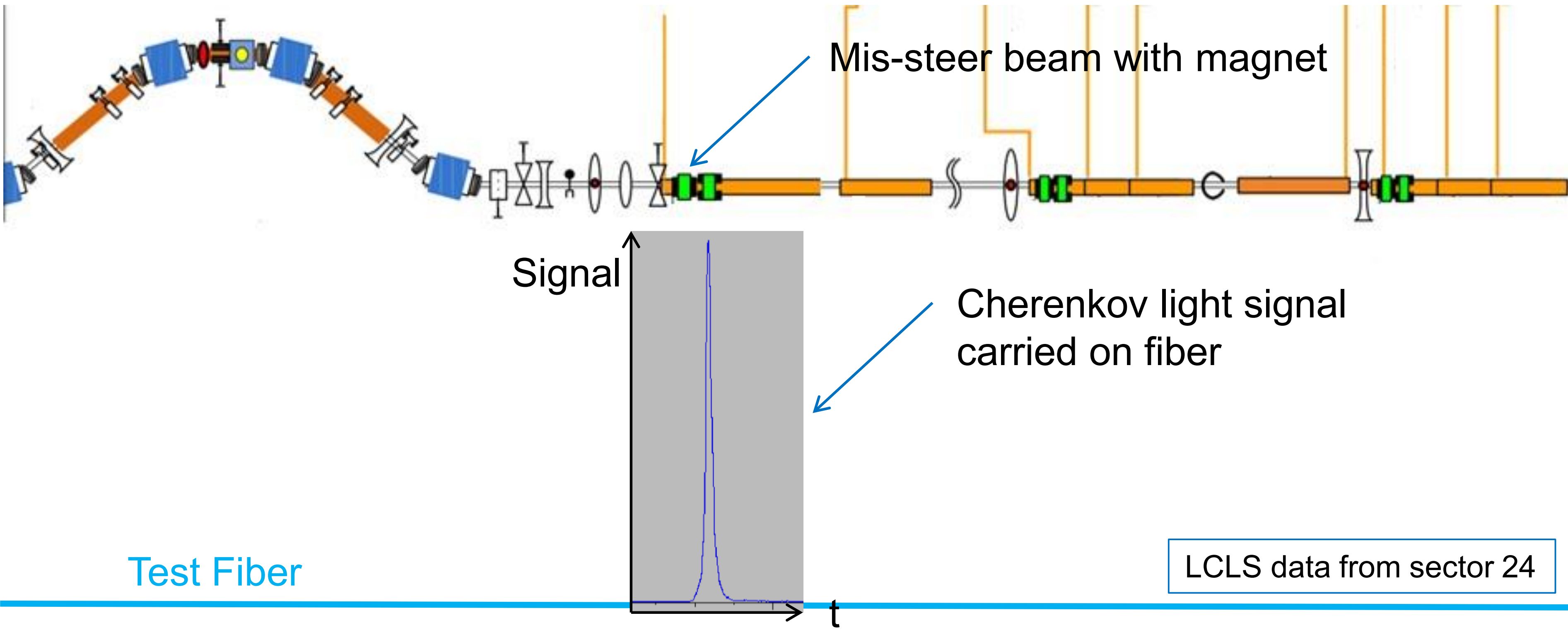
- Self test uses a pilot tone
- 100 kHz off frequency from 1300 MHz carrier
- Chain A, B electronics compare pilot tone feed to measurement from cavity
- If detected pilot tone signal drifts → ACM fault
- Pilot tone also used to verify ACM fault on over-current
- Temperature monitored




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

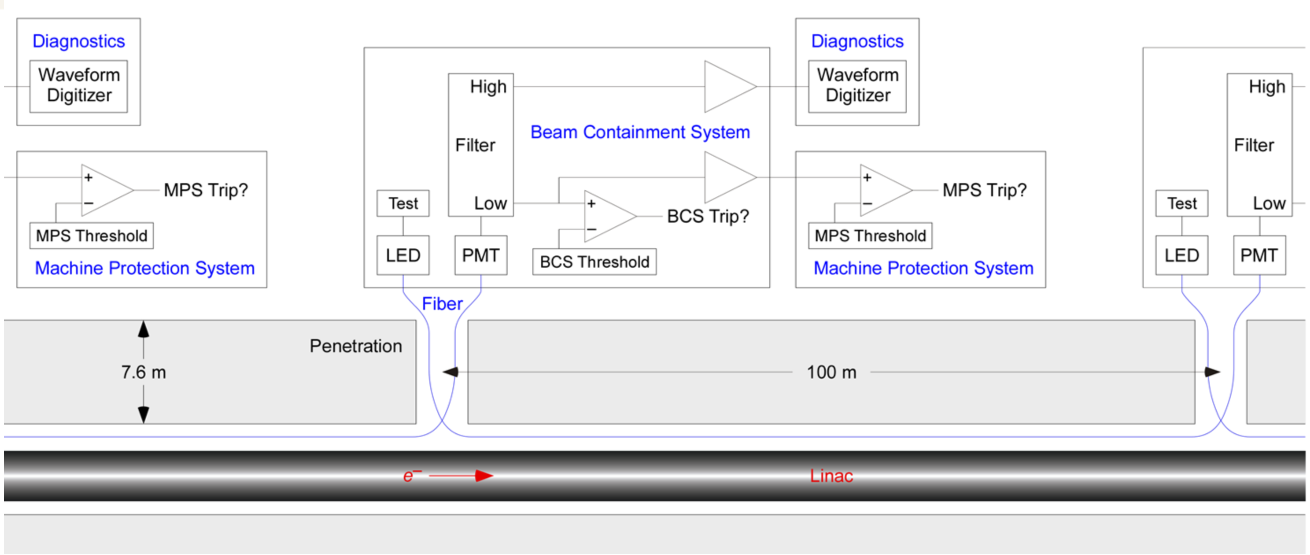
# Cherenkov light from irradiated fibers

- Particles from radiation showers generate Cherenkov light in fiber core
- 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

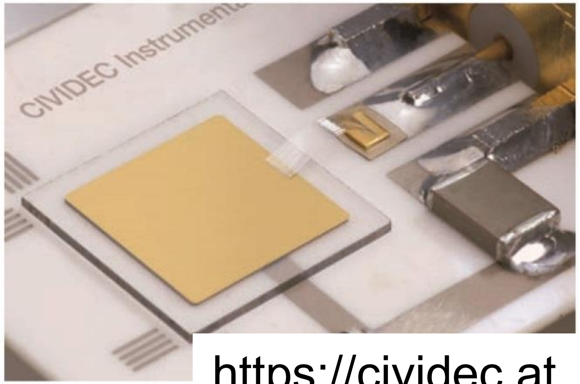
Developing fail-safe/self-monitoring implementation for Cherenkov fibers

# Diamond Detectors for protecting safety devices from e-beams

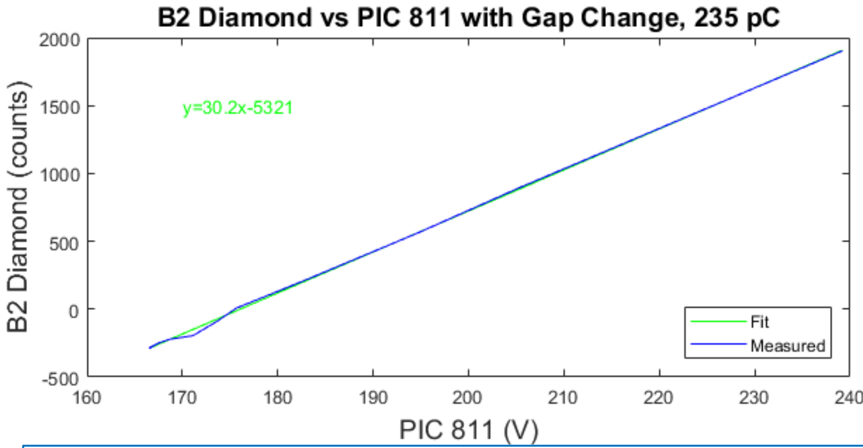
- At high power, collimators can be burnt through ~1s
  - Onset of stress damage in μs
  - Melting onset ~ms
- Burn-through triggers shut off with integrated monitor
  - Already a 3 rem event, one-use

→ 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



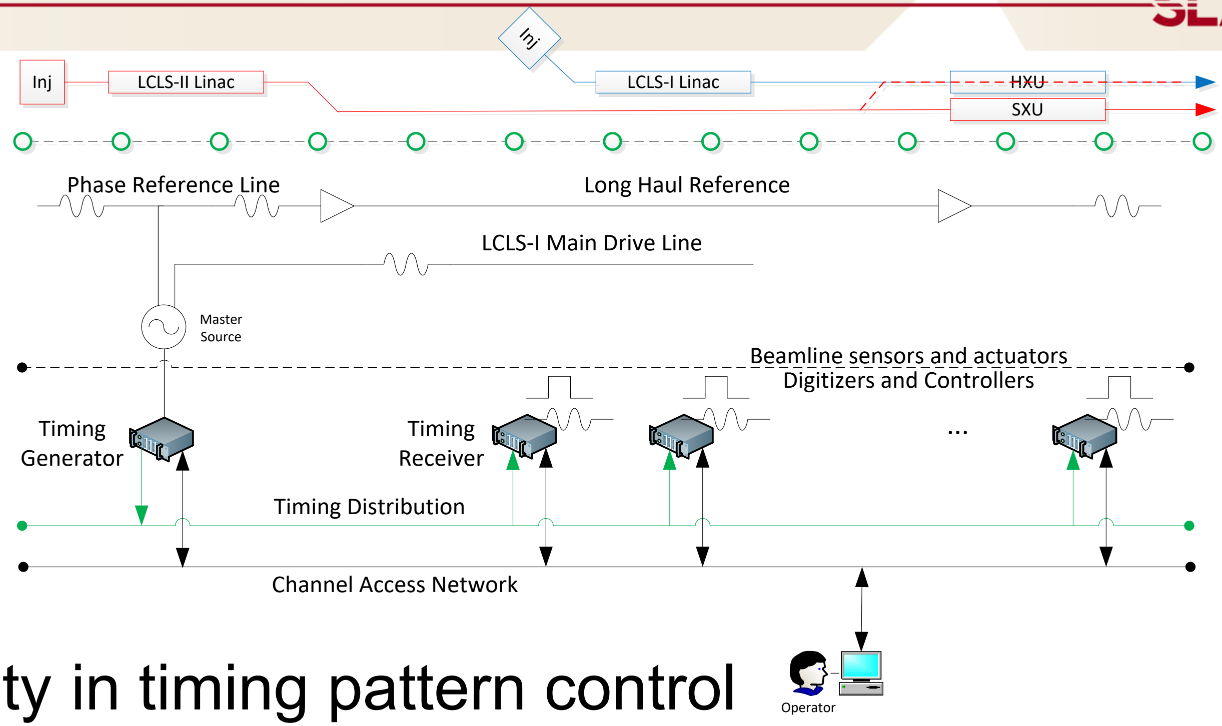

Cross-check with gas ionisation chambers at LCLS

Developing diamond sensors for localized detection of high power electron beam in undesired places

# *High Rate, High Complexity*
# LCLS-II Timing System

Phase Reference

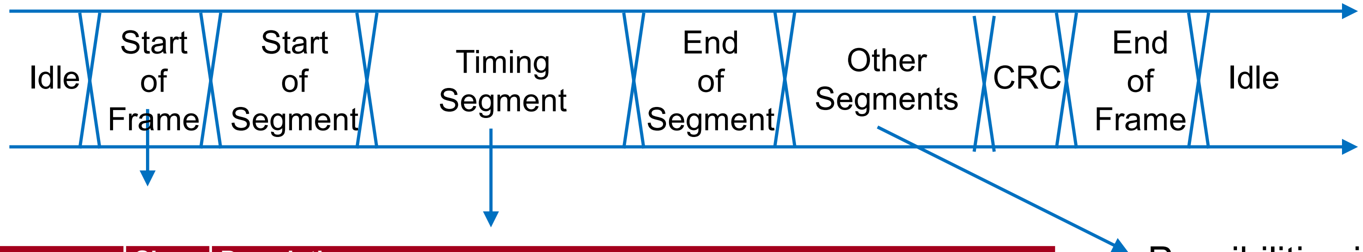
Timing Distribution




- Need flexibility in timing pattern control
  - Arbitrary bunch trains from 1 Hz to 1 MHz to multiple destinations
  - Beam synchronous data acquisition per bunch at 1 MHz
- Timing data now also includes expected bunch charge and other beam parameters - metadata

# Timing Pattern and Fast "Beam Loss" Measurement

Frame data is serialized as 186MHz of 16-bit words (+8b/10b encoding = 3.71Gbps)
Recovered clock is beam synchronous




| Field | Size | Description |
|---|---|---|
| PulseID | 64 | Unique, monotonic. Increments at base rate. |
| TimeStamp | 64 | Time since 1990 epoch. Increments at programmed step size |
| FixedRates | 10 | Fixed rate markers 0-9; one bit for each. |
| ACRates | 6 | Power line synchronized markers 0-5, one bit for each. |
| TimeSlot | 3 | 360Hz timeslot 1-6, persistent. Computed from TS1 input. |
| BeamRequest | 1 | Beam is requested from the injector. |
| Destination | 4 | Beam destination {HXL,SXL,D10,DL,InjSpec}. |
| ChargeInj | 16 | Bunch charge. |
| BeamEnergy | 4x16 | Beam energy at 4 locations. |
| BSA Control | 4x64 | For each buffer, initialize, average, acquire, finalize. |
| ControlSeq[0:17] | 288 | 16b control step data for each of 18 sequences. |
| +others | | |

Possibilities include:
Fast feedback,
DAQ Control,
LCLS-I Timing.

Fast control, acquisition commands, beam meta-data

- Allows diagnostic devices to e.g. instantaneously flag if measured charge on a single bunch does not agree with expected value for MPS

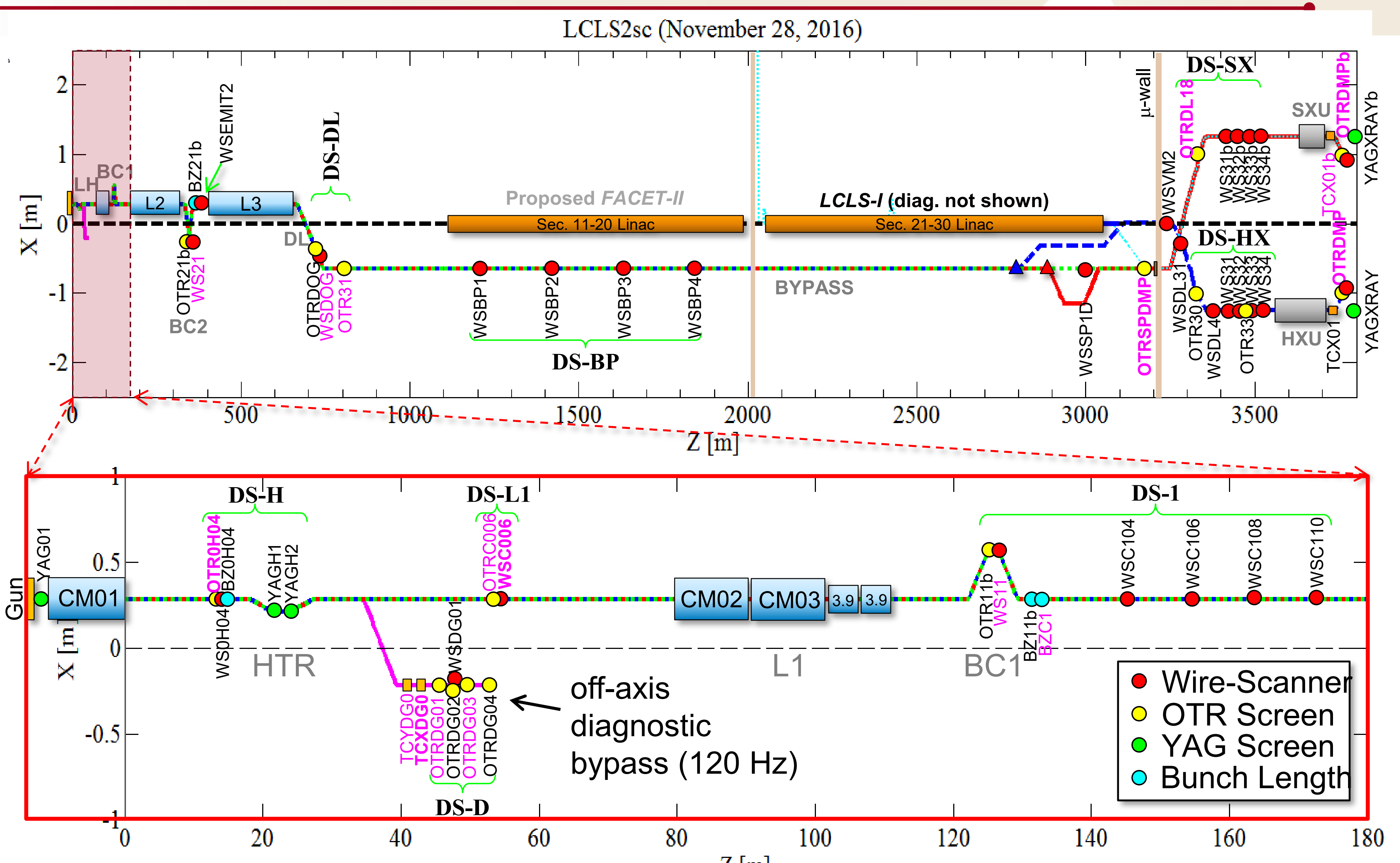
# *High Brightness* Diagnostic devices for LCLS--II

- **Beam Position Monitors (BPMs)** – (255, strip-lines, cavity, and cold-buttons)
- **YAG Screens** (6, *x* & *y* beam profile – thick screen)
- **OTR Screens** (14, *x* & *y* beam profile – sensitive to $\mu$-bunching)
- **Wire-Scanners** (31, *x* or *y* beam profile – fast scans needed at ~0.3 m/s)
- **Transverse RF Deflectors** (1-3, allow time-resolved bunch measurements)
- **Rel. Bunch Length Monitors** (4, relative bunch length for feedback)
- **Beam Loss Monitors** (BCS and MPS loss detection)
- **Micro-Bunching Detector** (not in baseline yet)
- **Beam Toroids** (< 2 MHz only – does not see gun dark current)
- **Average Current Monitors** (BCS, cavity based, new)
- **Faraday Cups** (2, absolute bunch charge – FC after gun temporary)
- **Bunch Arrival Time Monitors** (cavities, not in baseline yet)
- **RADFETs** (long term undulator loss management)

*Diagnostics slides courtesy P. Krejcik, P. Emma*

# LCLS-II $e^-$ Diagnostics Map

*Not included:* BPMs, Charge Monitors, X-ray diag's, Beam Loss Monitors




Slide courtesy P. Emma

# Beam Position measurement

Continue to use stripline BPMs, as in LCLS-I

- Even though resolution is limited to a few microns
- 10's µm at low 10 pC charge per bunch foreseen for LCLS-II
- Not adequate for position jitter correction at wire scanners
- But… less expensive than cavity BPMs

Added for LCLS-II

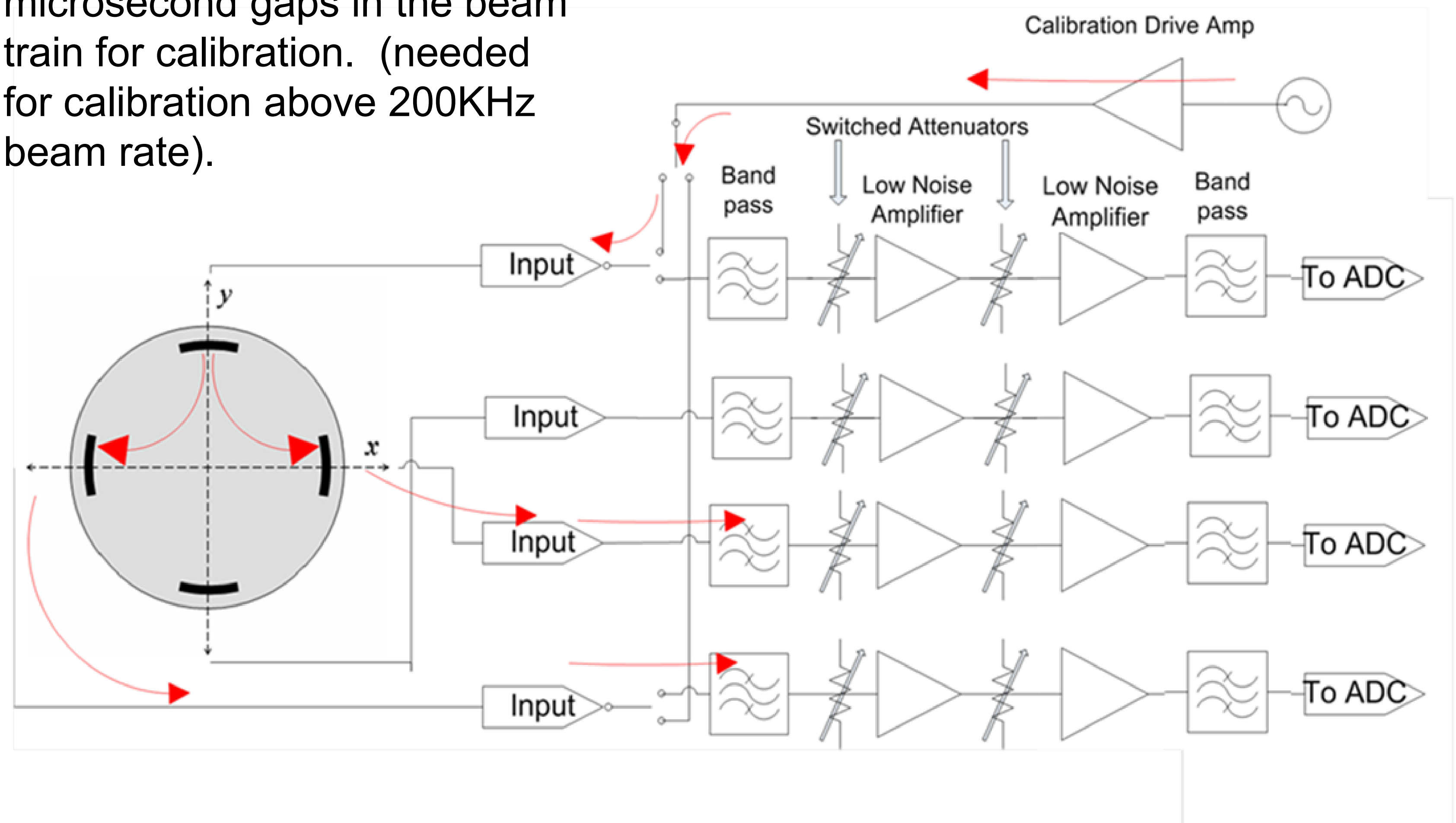
- Cold, button BPMs in the cryomodules

Improved for LCLS-II

- RF cavity BPMs used in the undulator region where submicron resolution is essential for beam-based alignment in the FEL

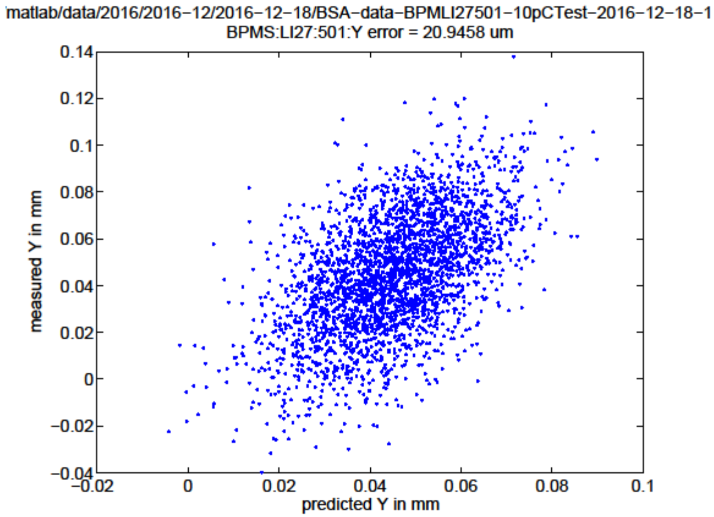
# Stripline Signal Processing

The timing system provides 5 microsecond gaps in the beam train for calibration. (needed for calibration above 200KHz beam rate).



# Beam Position Monitors – Stripline BPMs

- Same concept as existing LCLS BPMs
  - Strip signals ring a bandpass filter
  - Signals from all four channels digitized
  - Online calibration by injecting a pulse down one strip and reading induced signal in adjacent strips
    - Calibrates position center and sensitivity, but not charge
- Same 30MHz bandwidth as LCLS, but with faster digitizer and FPGA based processing for high beam rate
  - Better than the 30um resolution at 10pC spec
  - Resolution NOT good enough for jitter correction for wire scanners at low charge. (Need cavity BPMs for that.)



# Cold BPMs

- Fermilab design: 20 mm buttons
- Use Stripline Front-end electronics
- 200 um resolution at 10 pC

Lunin *et al* model button response for several versions of the button in CST Particle Studio reporting in IBIC 2014 paper TUPF18.

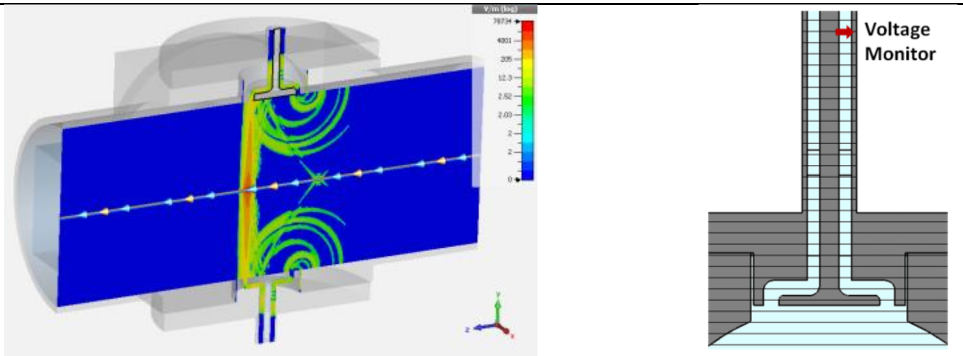
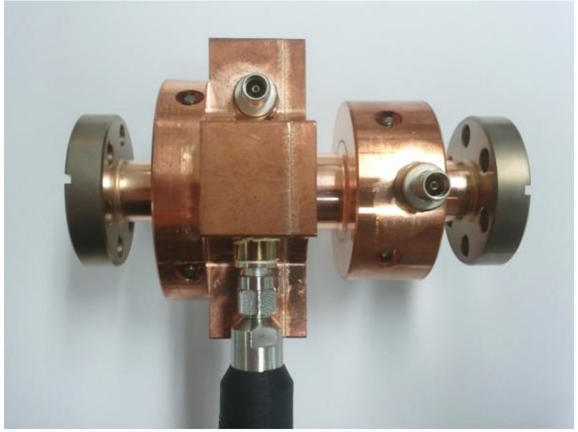


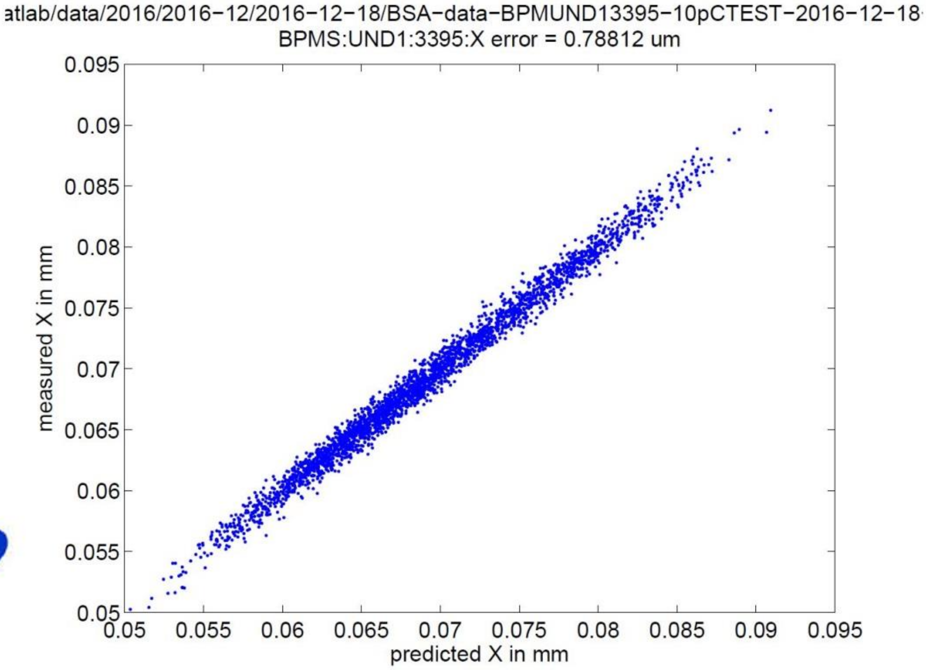

Figure 1. CST model of the button pickup (right) and a snapshot of the instant electric field induced by 1 mm bunch.

# X-band RF Cavity BPMs

- Cavity BPMs
  - Better resolution than Striplines,
  - ~1μm at 10pC (250nm in Undulator at 150 pC)
- Developed in collaboration with Pohang Accelerator Laboratory
- 11.424 GHz opertion insensitive to dark current from 1.3 GHz SC linac
- But at harmonic of multi bunches in S-band Cu linac

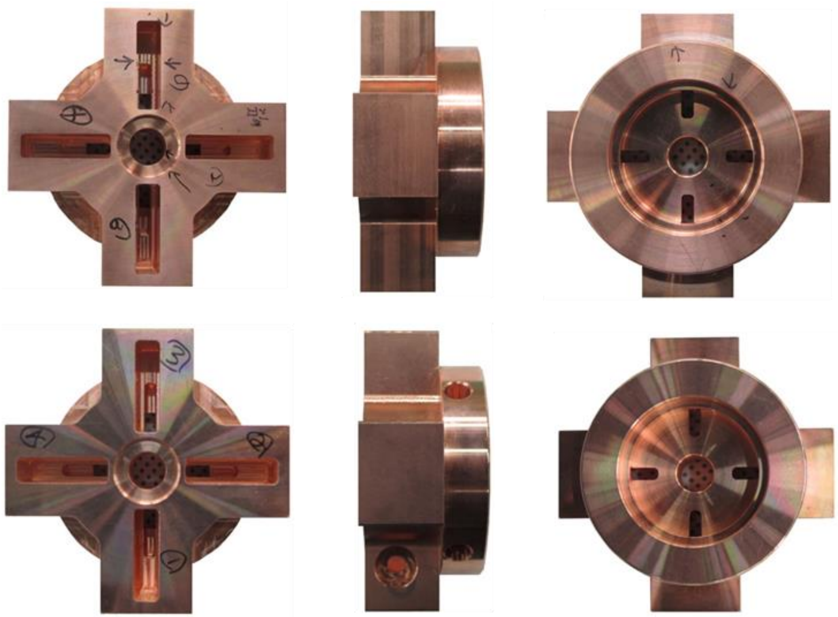


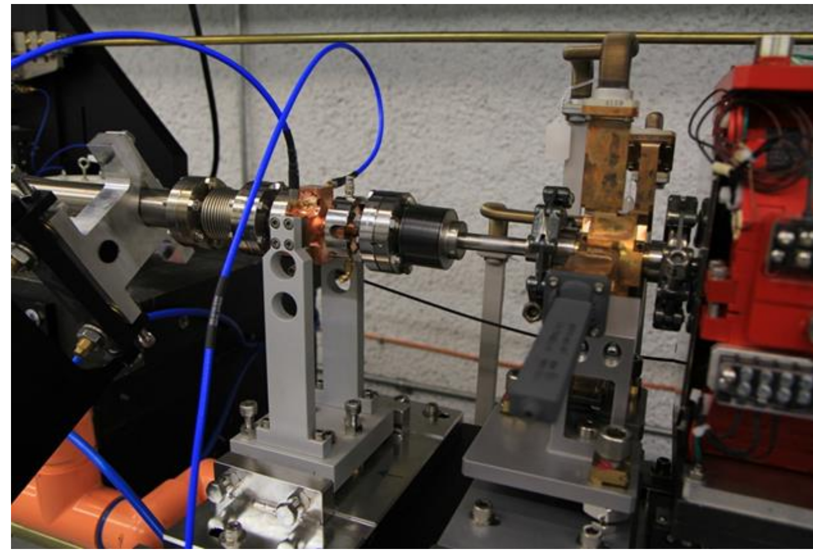
PAL X-Band Prototype



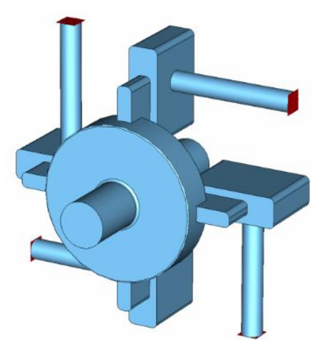
# SLAC-Pohang X-band Cavity BPM Design For LCLS-II

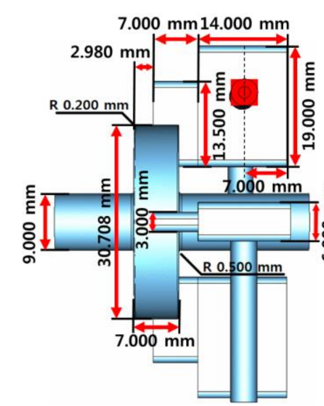






PAL
POSTECH

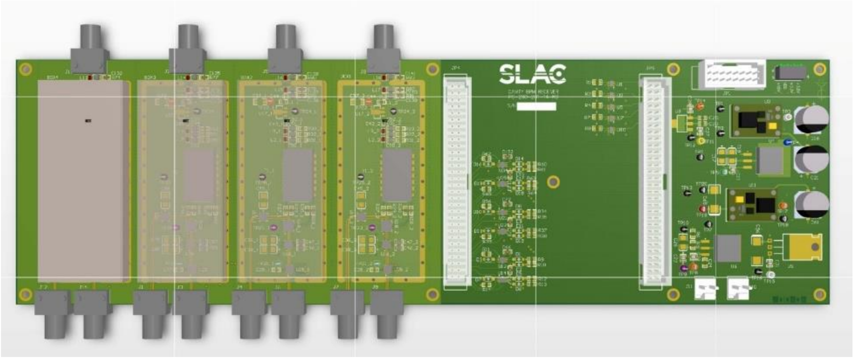





<u>New Features</u>:

- Abolish waveguide and windows
- Coaxial feedthroughs
- Simplified fabrication & tuner design
- Cavity freq centered on beam harmonic

# New SLAC Receiver Board & Chassis for LCLS-II




Mounted beneath the BPM and connected by coaxial cable.

Uses a monolithic IQ downmixer chip in place of the old Miteq waveguide mixer – Andrew Young

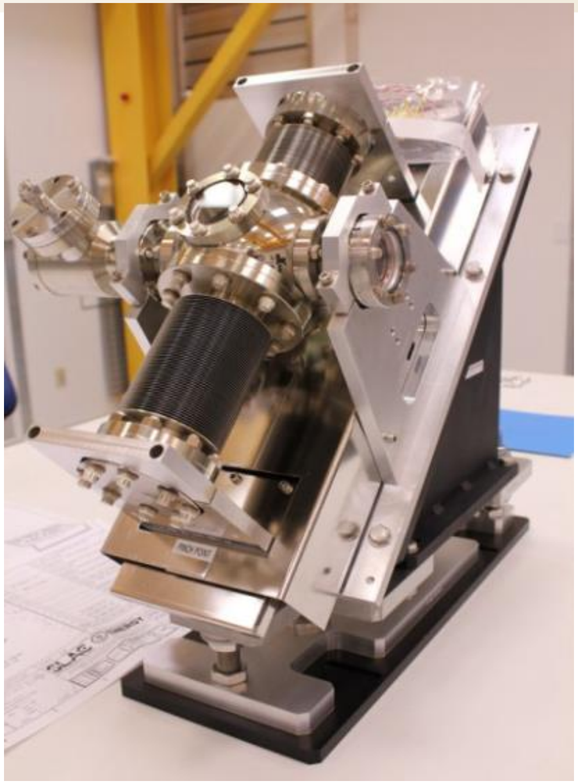
# Beam Size and Emittance Measurement

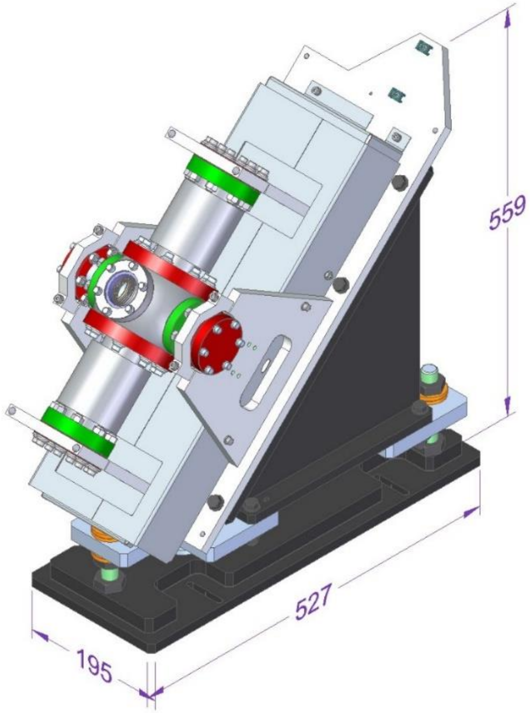
Profile monitor screens enable single shot, invasive measurement of transverse intensity distribution

- COTR
  - Highly compressed bunches produce coherent tails out into the optical range
  - In FEL linacs very short, low energy spread beams also give rise to microbunching instability
    - Worse in LCLS-II due to impedance of long transfer lines
  - Coherent spectrum radiates *C*OTR orders of magnitude brighter than normal beam image.
- Screens will also not survive high rep. rate in CW machines

Alternative #1: wire scans – projected beam size in one plane, averaged over multiple shots.

# Fast Wire Scanners
# Developed at the LCLS

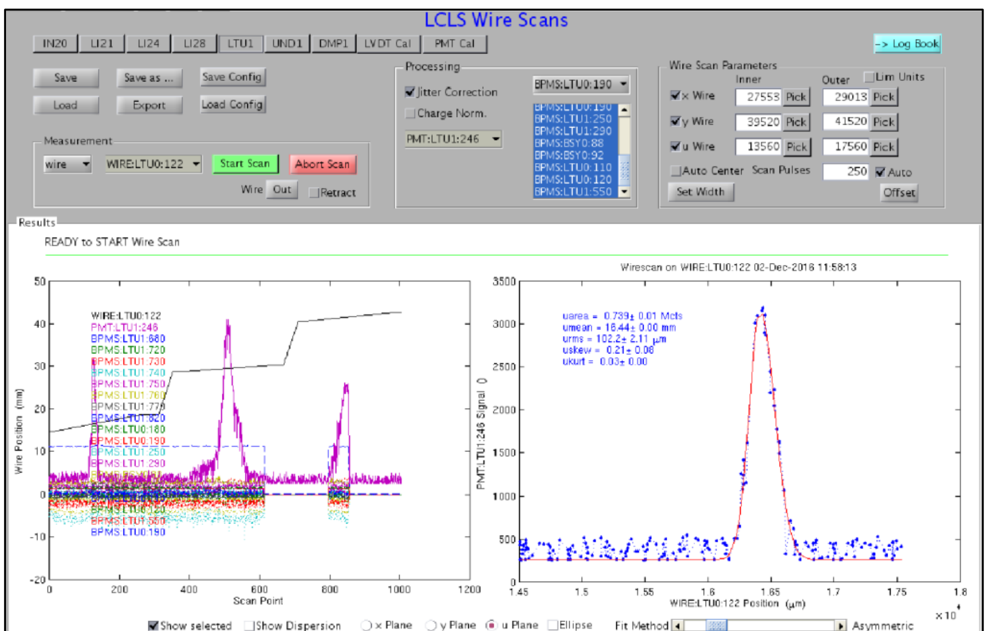


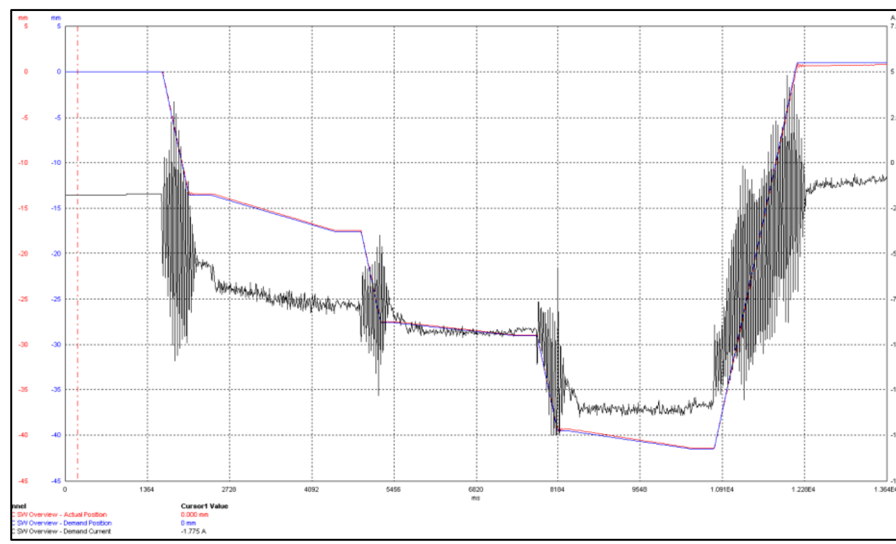



- Linear DC servo motor acting through dual bellows at 45°
- High speed greatly reduces emittance measurement and tuning time
- 1 MHz beam at LCLS-II requires 0.5 m/s wire speed
    - (but also possibility to be slow enough for lower rate, 10-100 Hz beams!)

# Operational Lessons Learned

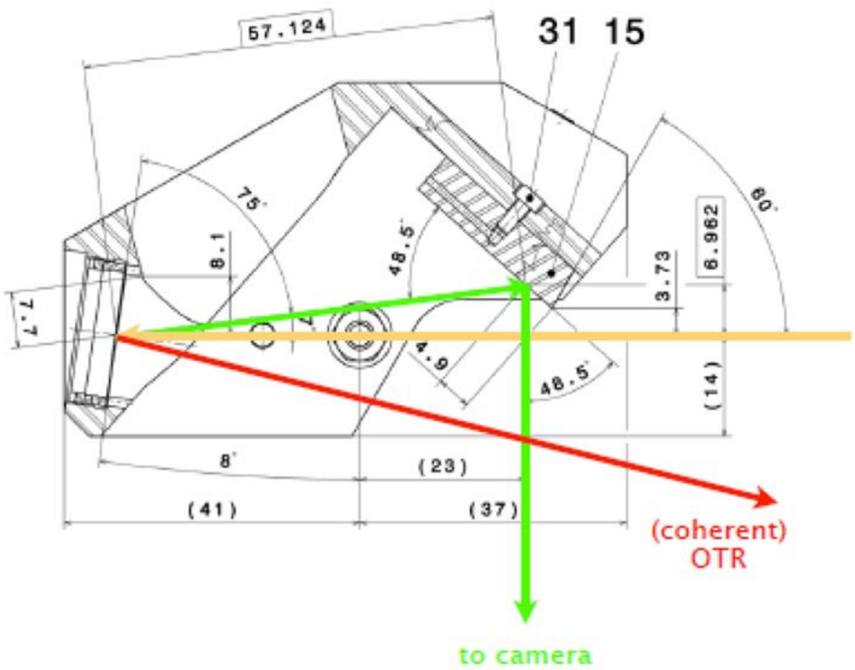
- Stray motor magnetic fields can disturb beam
  - Especially at low energy
  - Add mu-metal shielding
- Position encoder is read back synchronously with the beam
  - But also need to monitor motor current
  - PID servo loop can be unstable in regard to motor current
- Pulsed motor drive install req's careful ground loop analysis



# COTR Suppression with PSI Profile Monitor

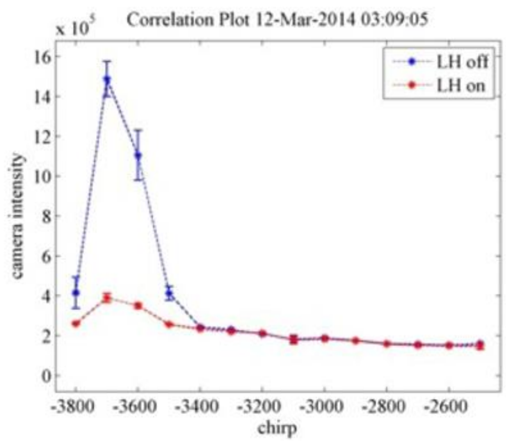
R. Ischebeck, *et. al*, PRSTAB **18**, 082802 (2015)

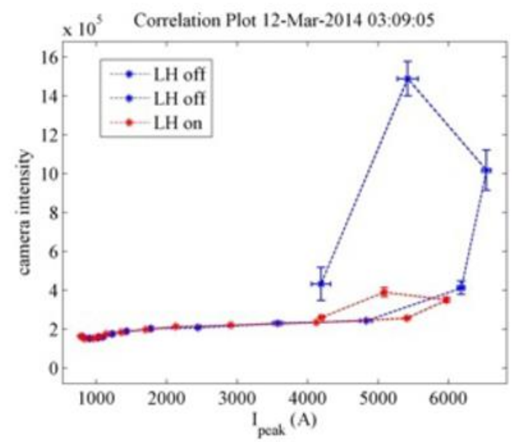



- View fluorescence from 30 mm YAG, COTR directed away from camera
- Observe at Snell angle to account for refraction in finite thickness crystal
- Camera image plane at Scheimpflug angle to maximize depth of field
- Developed by R. Ischebeck (PSI) and tested at the LCLS

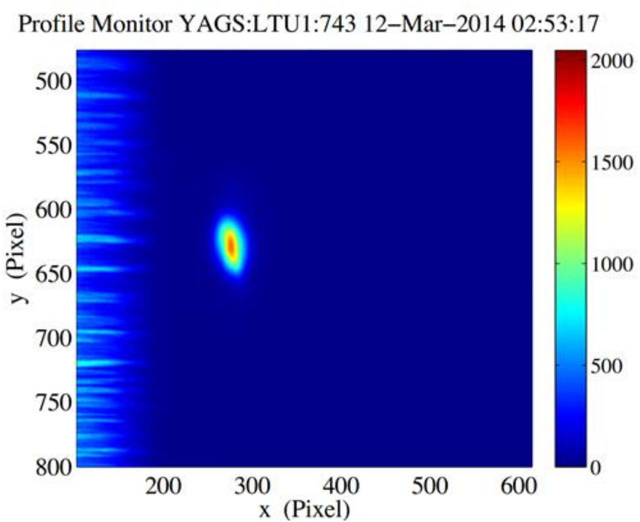
# Effectiveness of COTR Mitigation

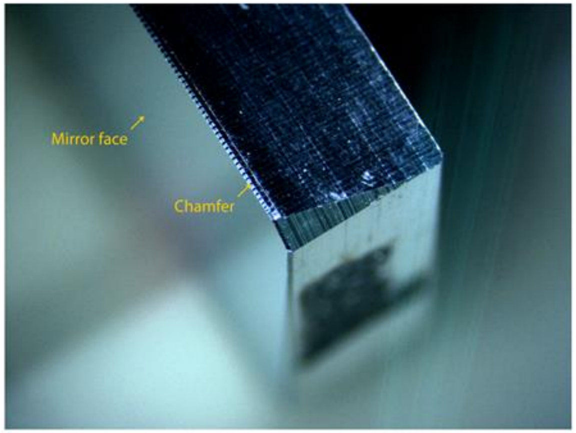
- The peak current varied from 1 - 6 kA via chirp upstream of BC2
- Camera image intensity ~constant except at shortest bunch length and the laser heater is off




Residual CDR from the edge of the mirror

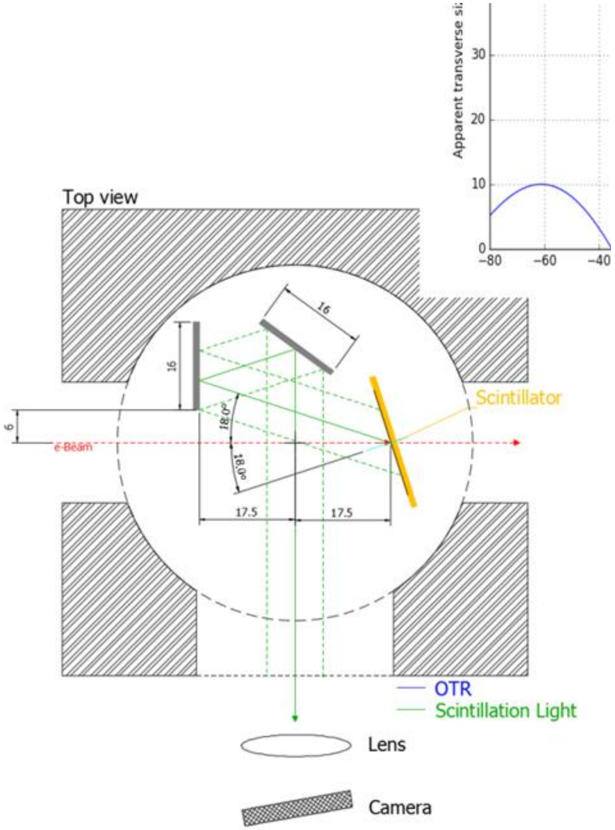


# Next Iteration from PAL

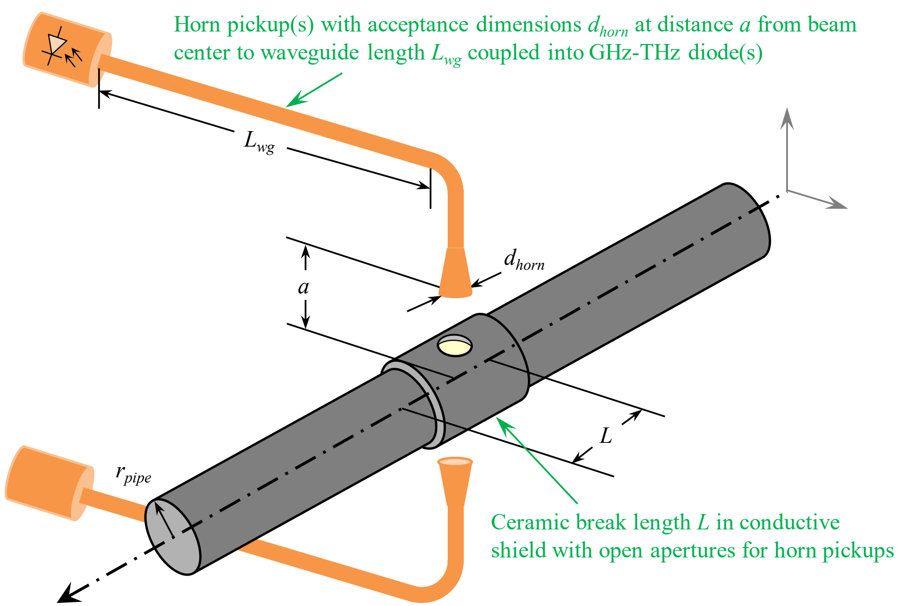
- The design developed at Pohang Accelerator Laboratory uses two mirrors to increase the distance from the mirror edge to the beam from 3 mm to 6 mm, preserving optimum viewing angles used by PSI

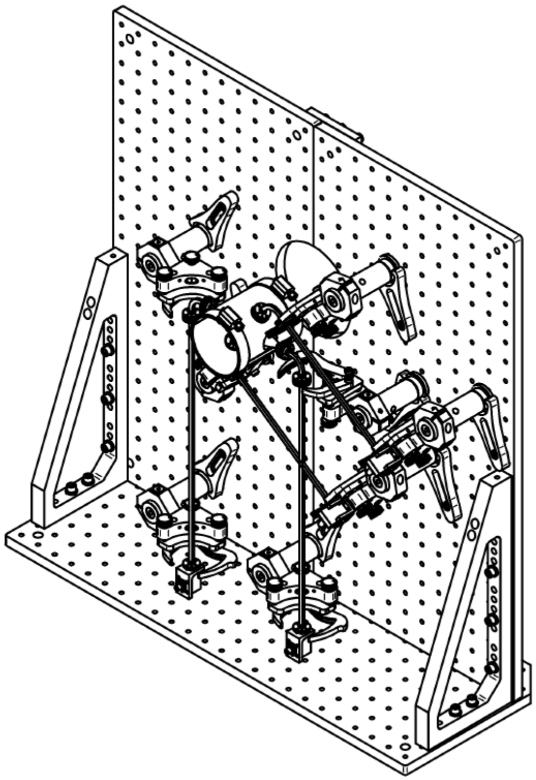
- The PAL profile monitor under testing at the LCLS this year



# Picosecond Relative Bunch Length Monitors (Injector buncher & BC1)

- Sub-THz, narrow-band pickup waveguides + diodes
- View through ceramic breaks
- Vacuum-side thin metallic coating on ceramic to avoid charge pile up
- 2 diode frequencies x 2 diodes each

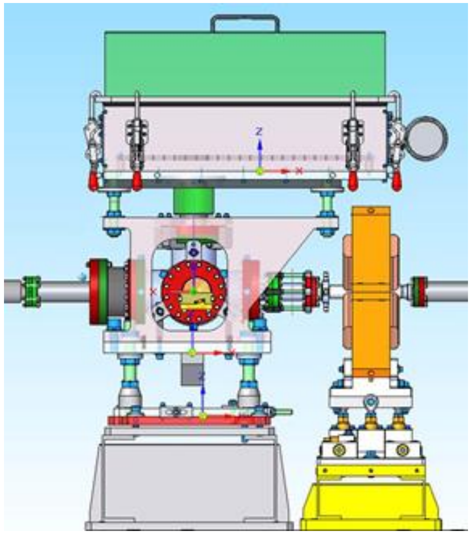


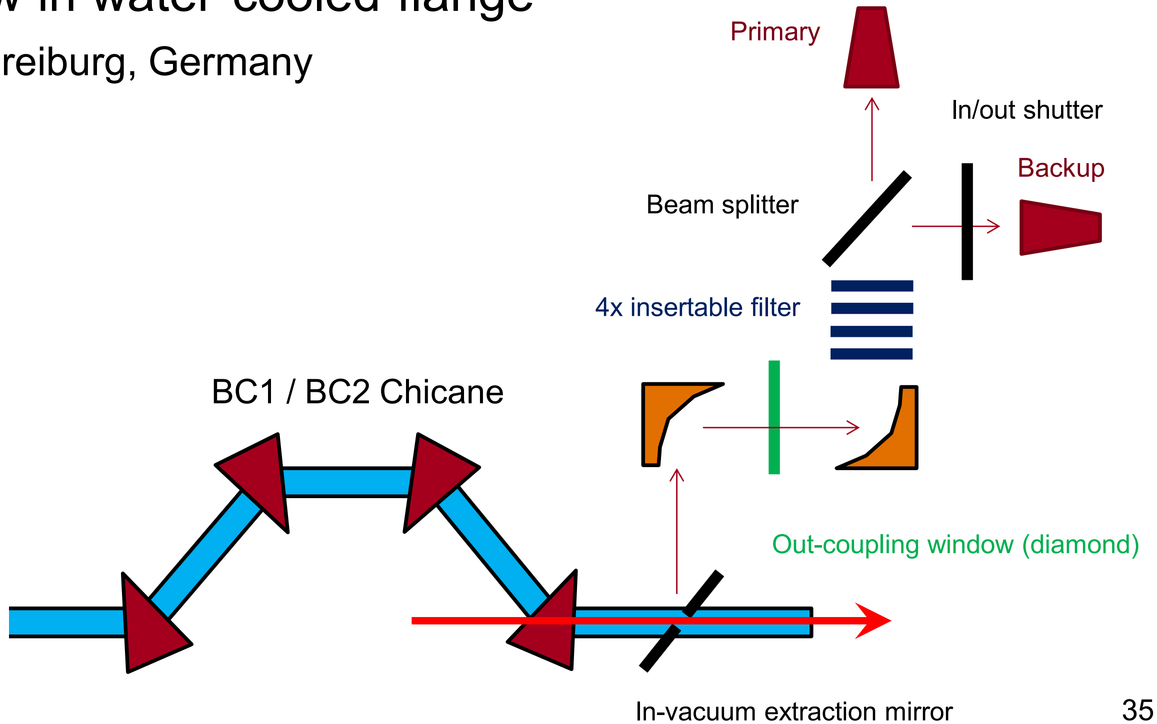



# Femtosecond Relative Bunch Length Monitors (BC1 & BC2)

Broadband coherent edge radiation detection

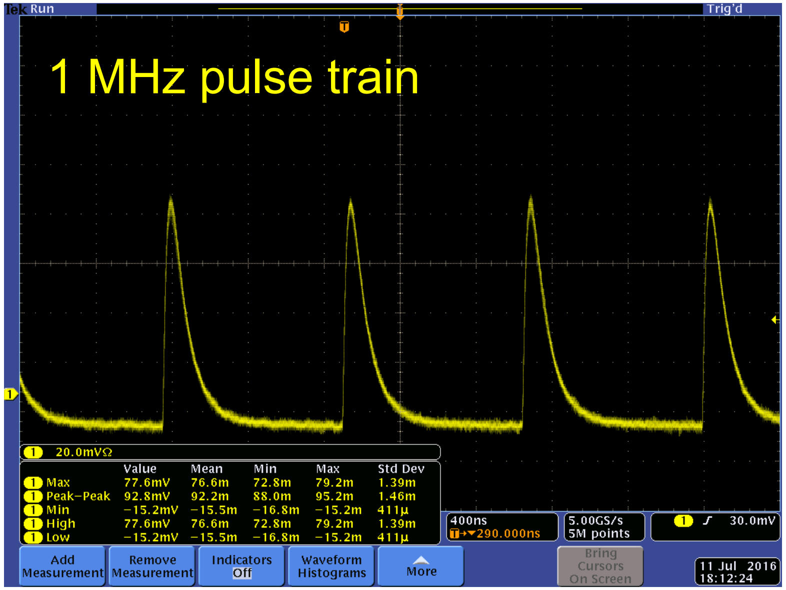
- Spectral control: 2x Long-pass filters
- Power control: 2x ND filters
- Redundancy: 2x Pyro detectors
- Copper, water-cooled extraction mirror
- 50 mm diamond window in water-cooled flange
  - *Diamond Materials*, Freiburg, Germany





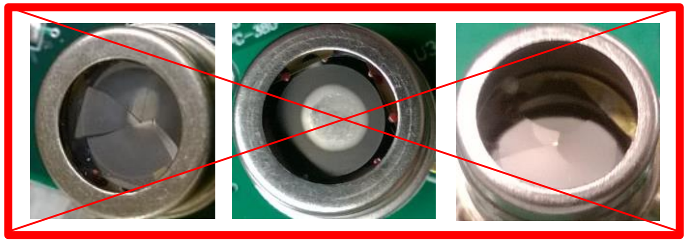
# Femtosecond Relative Bunch Length Monitors (BC1 & BC2)

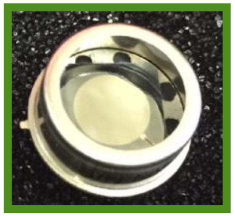
- Fast (250 ns) SLAC *Q-V* convertor/amplifier for detector
- High power & sensitivity pyros from ***Gentec-EO***
- Temperature monitored/interlocked
- MPS interlock to excessive peak signal fault
  - Protect pyro *and* other components from coherent radiation power in bends




*High-power, fs-pulse IR laser testing*

Misc. off-the-shelf articles





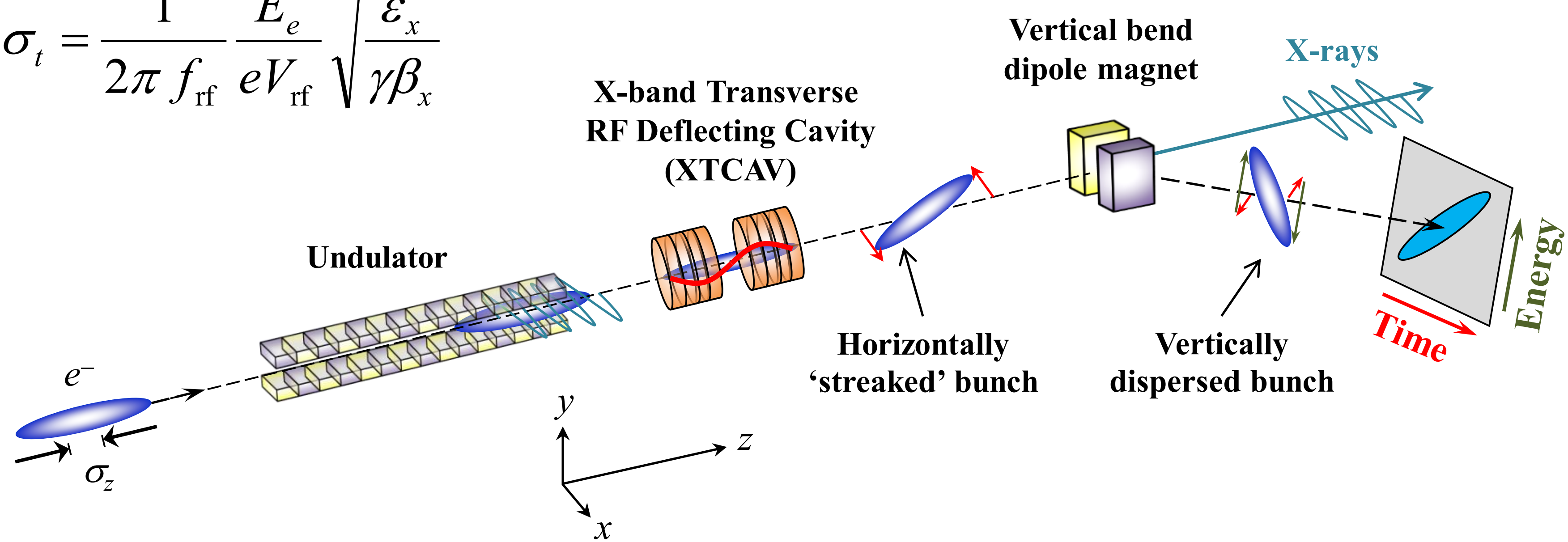
Custom Gentec-EO pyro
2 W sustained (40°C)
6 W maximum

# Transverse Deflectors

- Upstream diag. bypass deflectors not in baseline ($$$$$)
- LCLS-II *does* inherit another old friend…

The LCLS X-band Transverse Deflector w/ few fs resolution

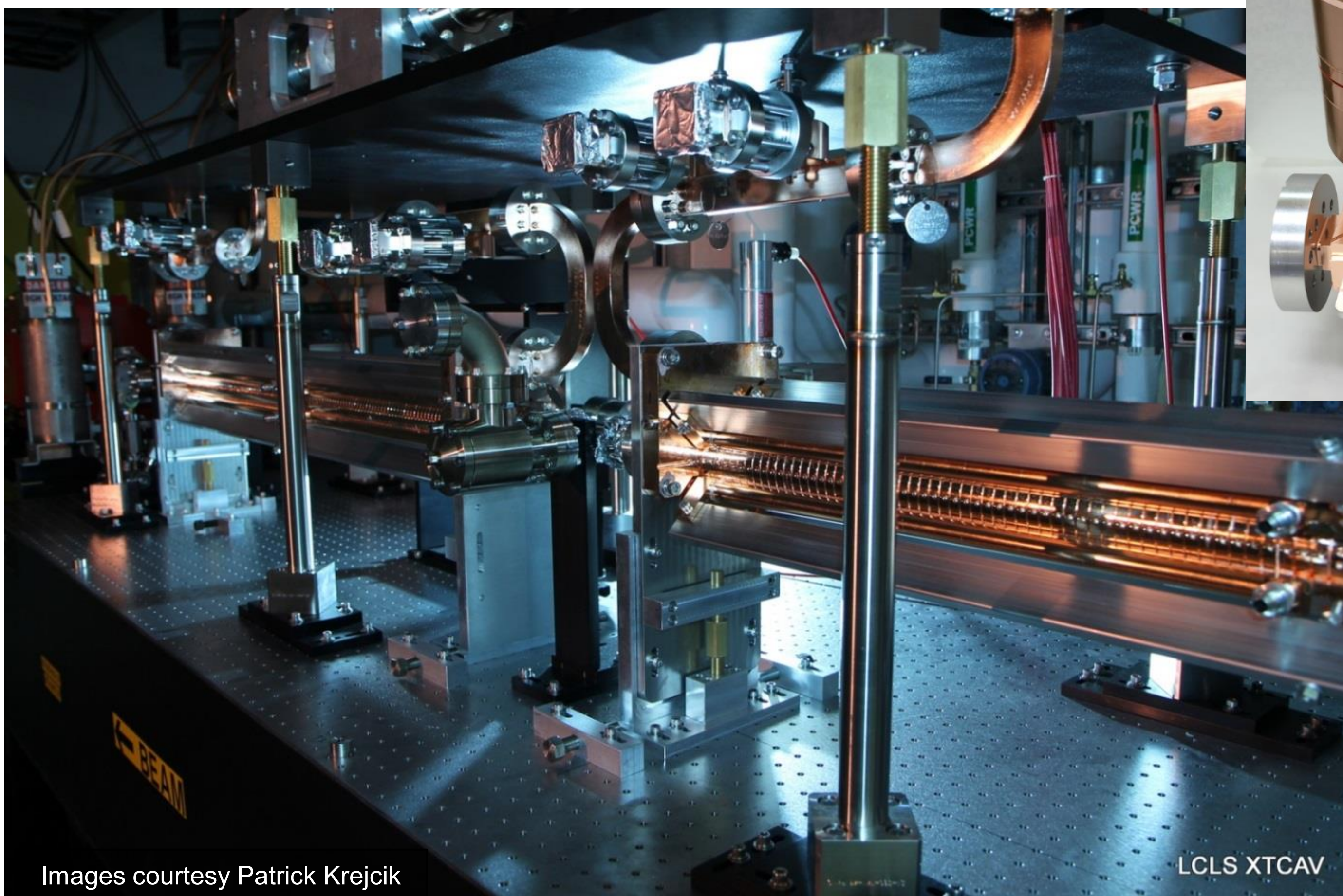
$$\sigma_t = \frac{1}{2\pi f_{\mathrm{rf}}} \frac{E_e}{eV_{\mathrm{rf}}} \sqrt{\frac{\varepsilon_x}{\gamma\beta_x}}$$

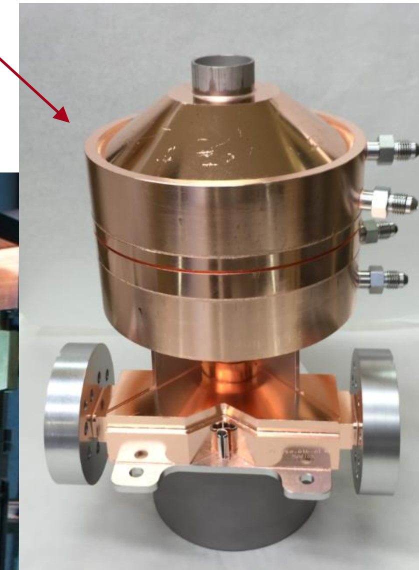


# Pulsed operation at up to 120 Hz

Plus compact (< 12 cm) X-band SLAC linac energy doubler

- J. Wang, *et al.*, IPAC 2016, MOOCA01

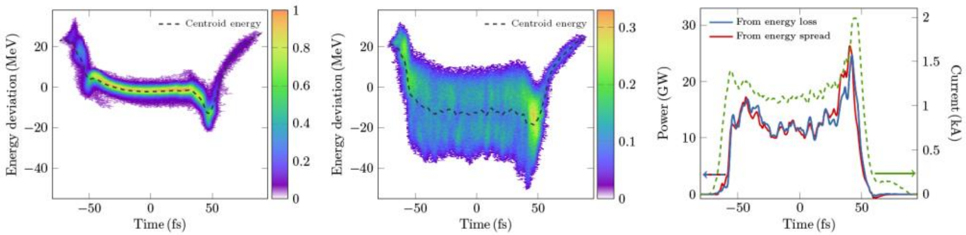


Images courtesy Patrick Krejcik

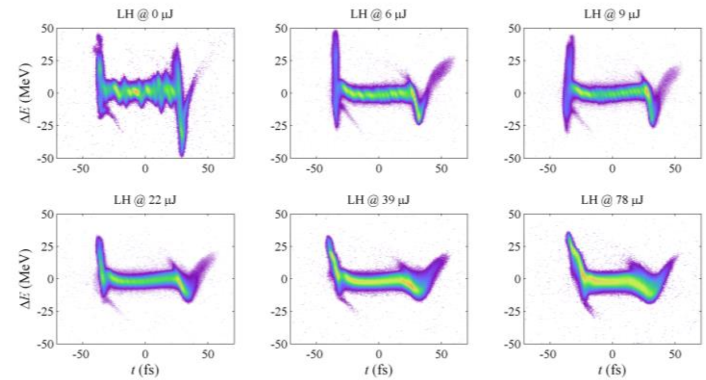
# Versatile tool to carry forward

### X-ray profile reconstruction




Proposed: Y. Ding, *et al.*, PRST-AB **14**, 120701 (2011)
Demonstrated: C. Behrens, *et al.*, Nat. Comm. **5**, 3762 (2014)
Applications: T. Maxwell, Proc. SPIE 9210, XFELs, 92100J (2014).

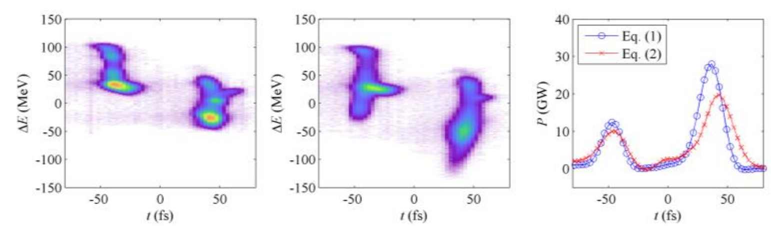
### Laser heater studies




D. Ratner, *et al.*, PRAB **18** 030704 (2015)

- HXR dump YAG screen to be relocated off axis
- Will operate XTCAV just off zero crossing to *kick* + streak beam to YAG
- Cu cavity pulses to pick bunches from higher bunch train rates

### Two bunch, two color modes




A. Marinelli, *et al.*, Nat. Comm. **6**, 6369 (2015)

# And more!

MOZGBD3 – N. Solyak (FNAL), *First LCLS-II Cryomodules: Issues & Solutions*

WEPML001,3,4 – J. Holzbauer (FNAL), *Microphonic Mitigation & Precision* $Q_0$ *Measurement/Tuning*

THYGBE3 – C. Serrano (LBNL), *RF Controls of High Loaded Q Cavities for the LCLS-II*

THPAK153 – X. Huang (SLAC), *Linac Optics Correction with Trajectory Scan*

# *Thank you!*

*Additional thanks to:*

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