Diagnostic Challenges at LCLS-II and Lessons Learned from LCLS-I at SLAC

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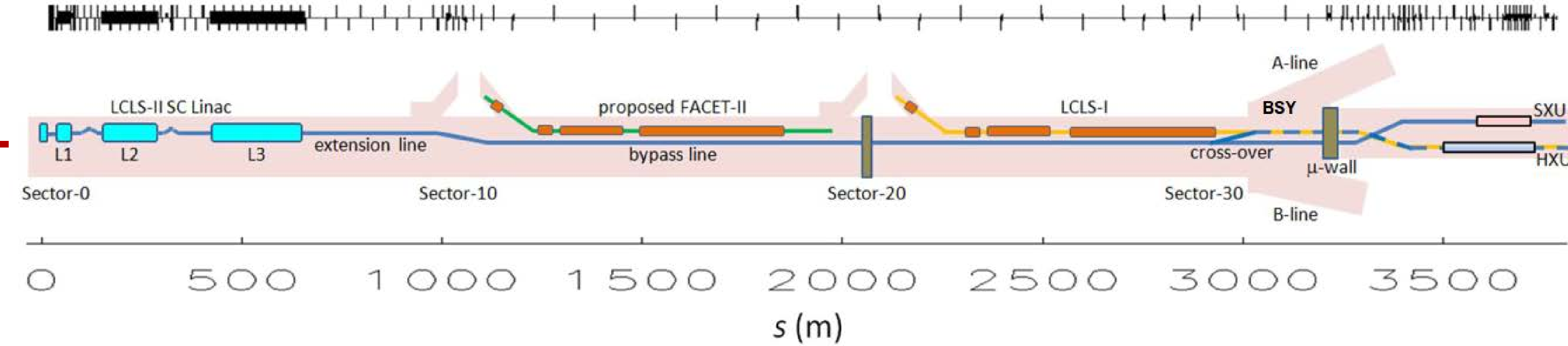
LELAND STANFORD JUNIOR UNIVERSITY · DIE LUFT DER FREIHEIT WEHT · 1891

Key diagnostic challenges at X-ray FELs

- High brightness, high peak current beams
  - Requires measurement of very small transverse beam sizes
  - And ultra short bunch lengths
- Add to this the requirements for new generation of superconducting CW linacs
  - High average beam power needs minimally invasive diagnostics
  - High repetition rates require high data acquisition rates
  - Diagnostics and instrumentation must be fully integrated with timing and machine protection systems

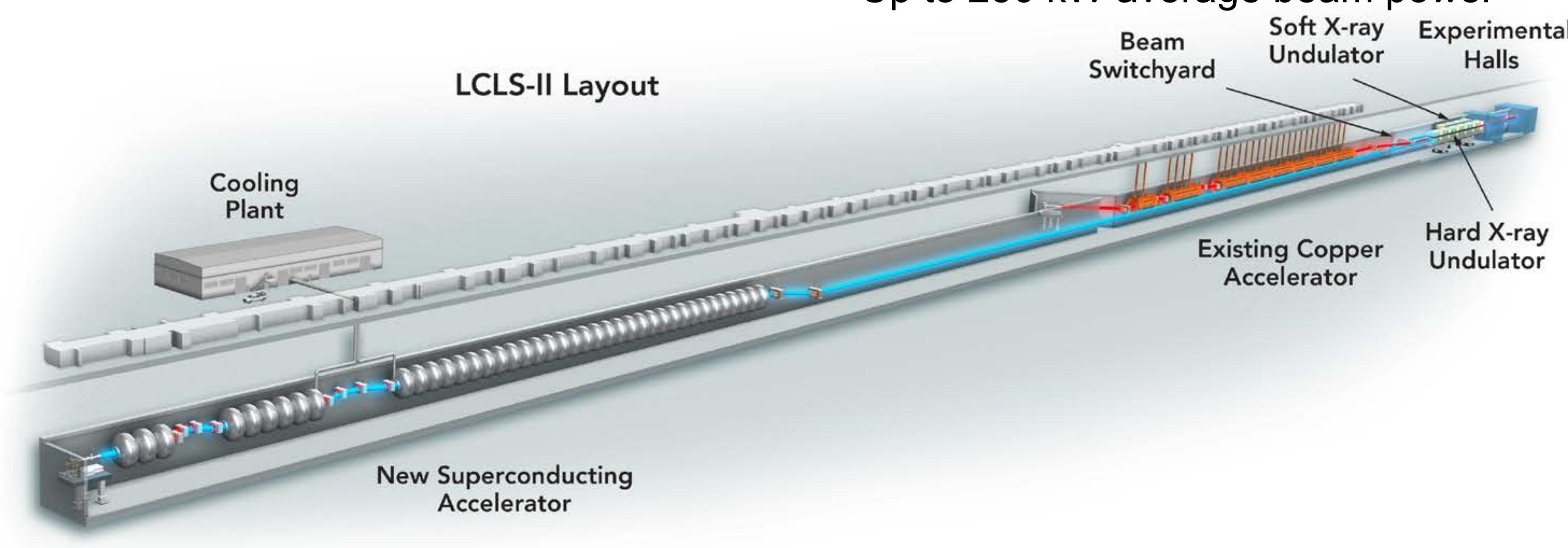


LCLS-I

- Warm, copper S-band pulsed linac
- 120 Hz single bunch repetition rate
- 3.5 to 14 GeV

LCLS-II

- Superconducting 1300 MHz CW linac
- Nominal 1 MHz bunch repetition rate
- 4.5 GeV
- Up to 250 kW average beam power



List of diagnostic devices for LCLS--II

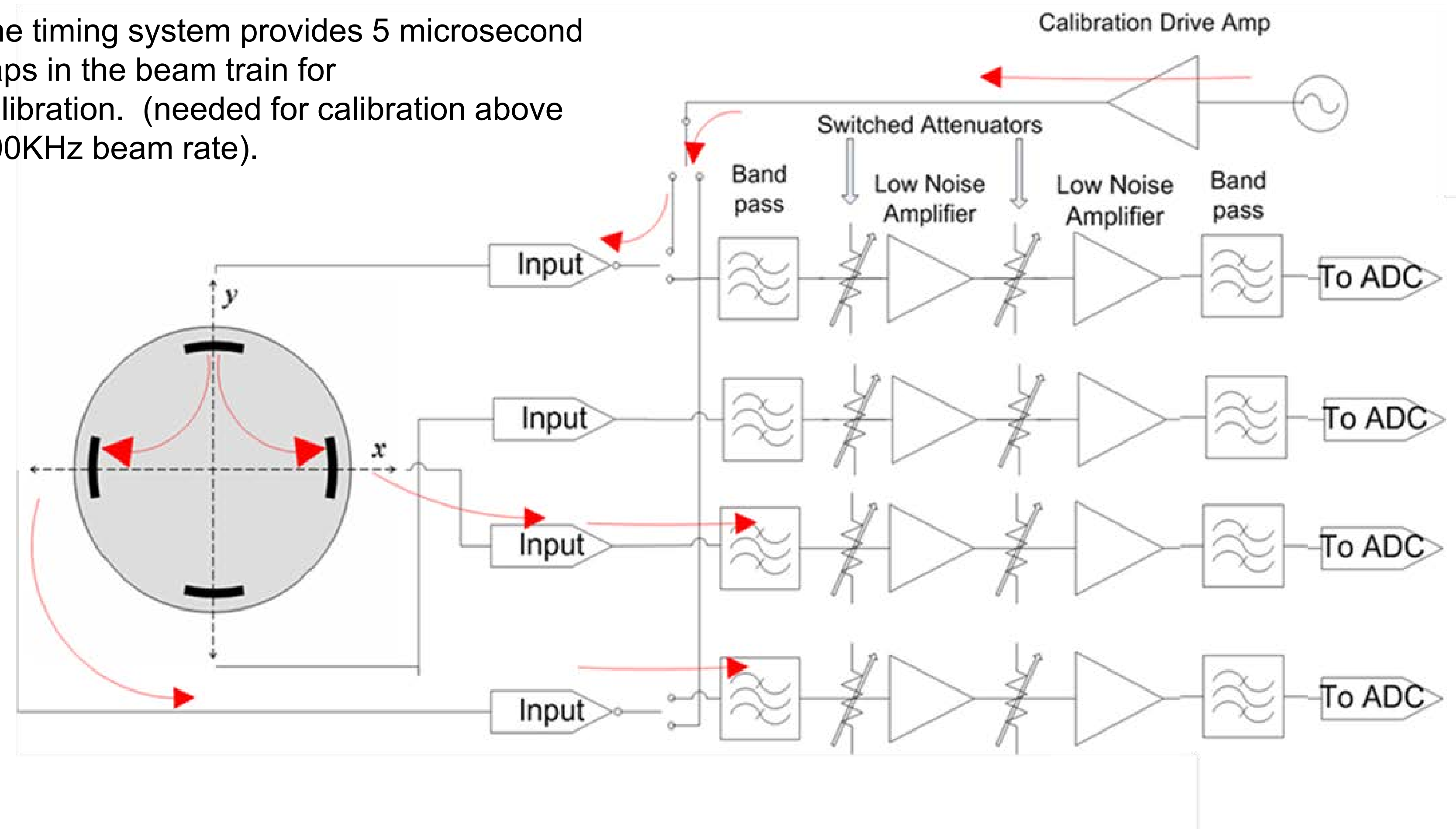
- **Beam Position Monitors (BPMs)** – (255, strip-lines, cavity, and cold-buttons)
- **YAG Screens** (6, *x* & *y* beam profile – thick screen)
- **OTR Screens** (14, *x* & *y* beam profile – sensitive to μ-bunching)
- **Wire-Scanners** (31, *x* or *y* beam profile – fast scans needed at ~0.3 m/s)
- **Transverse RF Deflectors** (1-3, allow time-resolved bunch measurements)
- **Rel. Bunch Length Monitors** (4, measures 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)

Beam Position measurement

- Continue to use stripline BPMs, as in LCLS-I
  - Eventhough resolution is limited to a few microns
  - 10's of microns at low 10 pC charge per bunch foreseen for LCLS-II
  - Not adequate for beam position jitter correction at wire scanners
  - But, they are 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

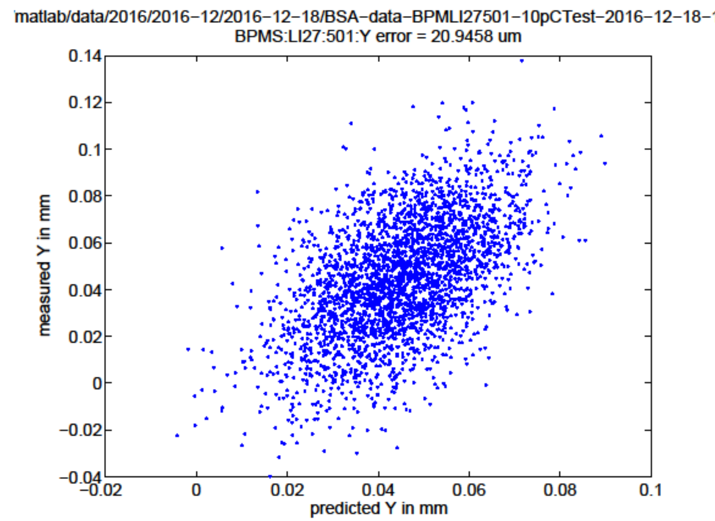
Stripline Signal Processing

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 LCLS1 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 LCLS1, 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 fro wire scanners at low charge. Would 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.

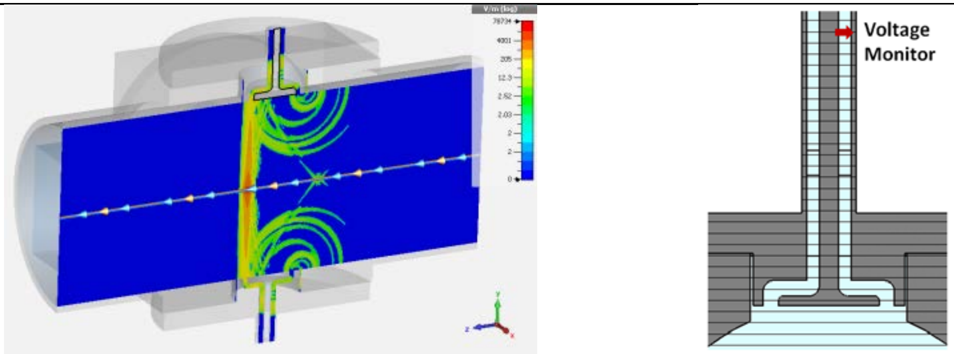


Figure 1. CST model of the button pickup (right) and a snapshot of the instant electric field induced by 1 mm bunch.

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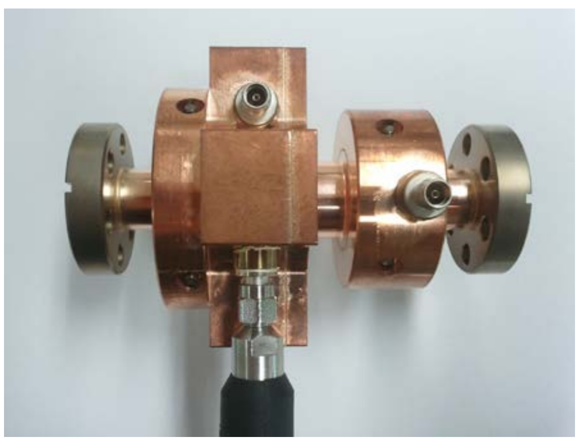
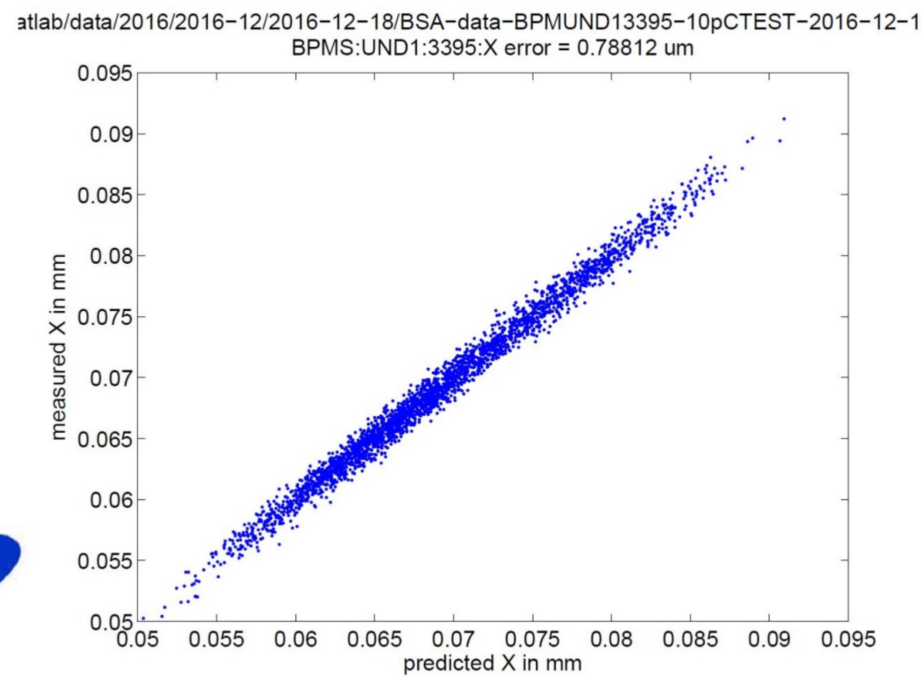
X-band RF Cavity BPMs

- 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



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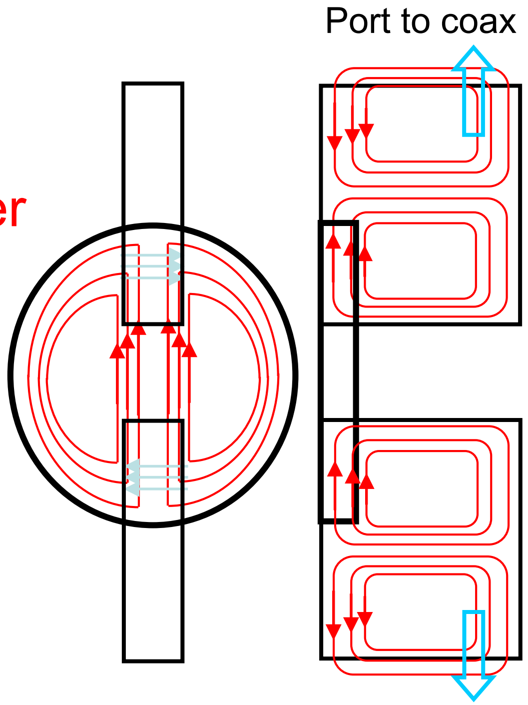
PAL

Original LCLS-I RF Cavity BPM Design Concept

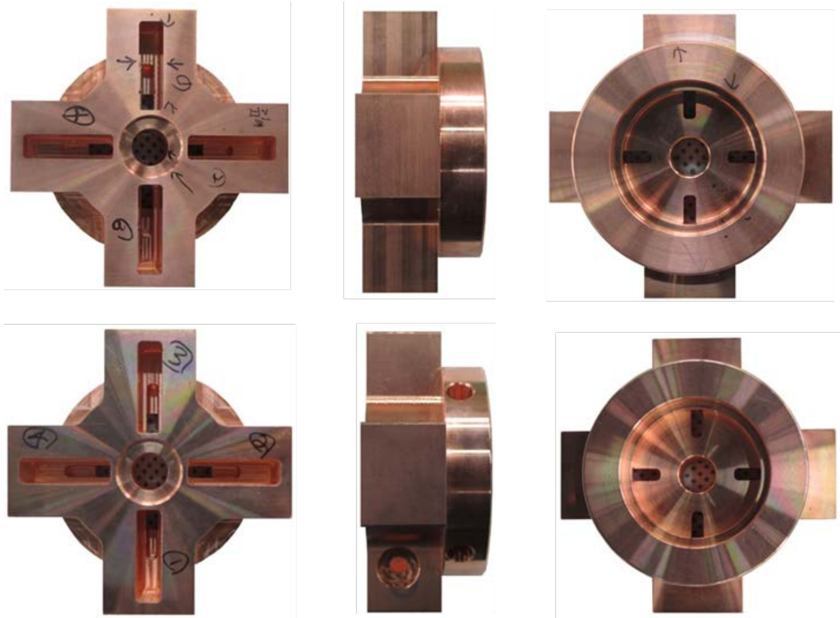
Z. Li

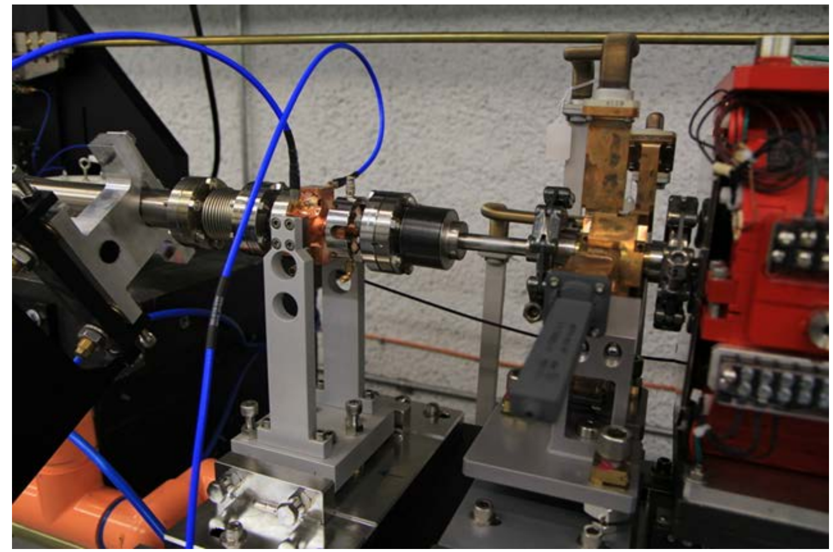
$$V(q,x) = qx\sqrt{Z_0 \frac{\beta}{1+\beta} \frac{\omega_0 k_{loss}}{Q_L}} \frac{1}{\sqrt{2_{ports}}}$$

- Dipole frequency: 11.424 GHz
- With Dipole Mode TM11 Selective Coupler
- Coupling to waveguide:
  - Radial magnetic field
  - Naturally couple to dipole mode
  - Does not couple to the monopole mode
- Beam x-position couple to vertical slot



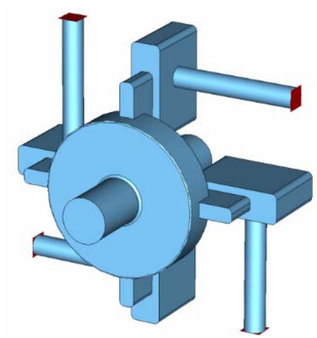
SLAC-Pohang X-band RF Cavity BPM Design For LCLS-II

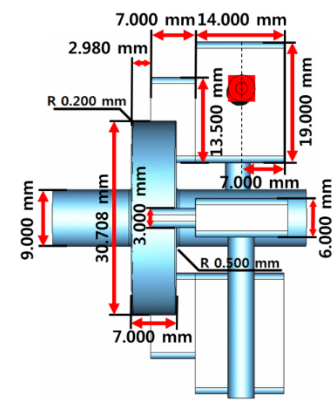




New Features:

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





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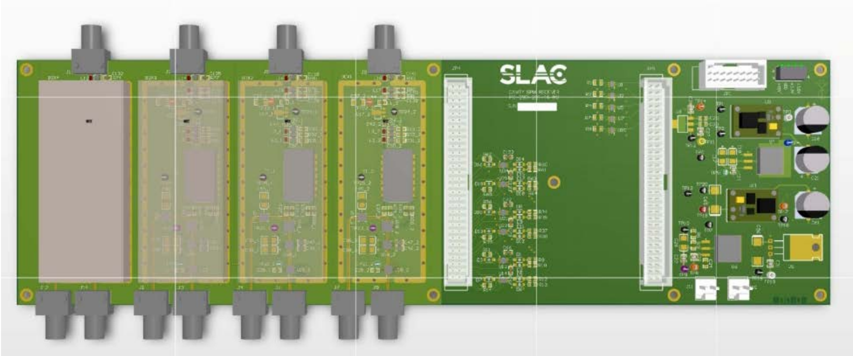
New SLAC Receiver Board and Chassis for LCLS-II

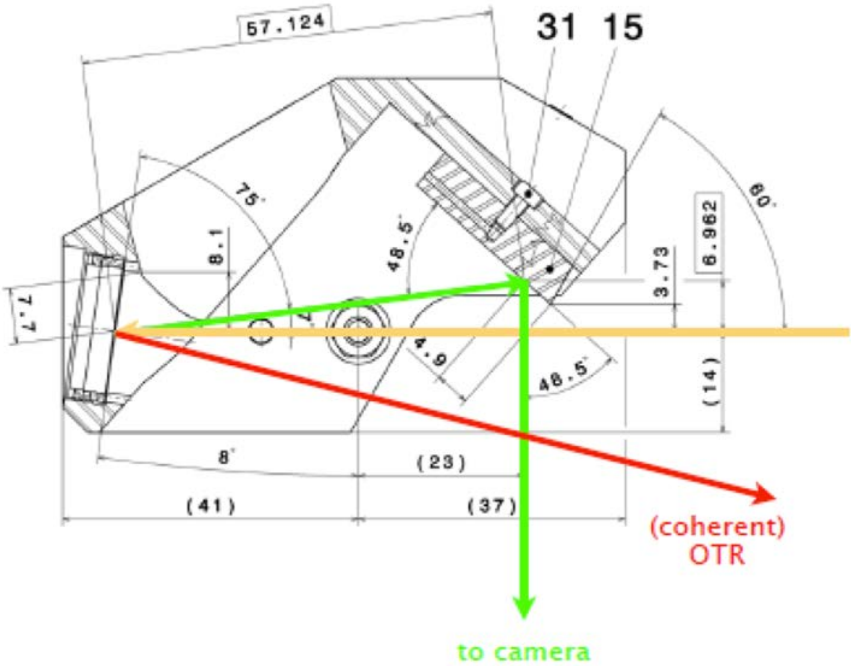


- Mounted beneath the BPM and connected by coaxial cable.
- Uses a monolithic IQ downmixer chip in place of the old Miteq waveguide mixer – Andrew Young

Beam size and emittance measurement

- Profile monitor screens enable single shot, invasive measurement of transverse intensity distribution
  - In FEL linacs very short, low energy spread beams give rise to microbunching instability
    - Worse in LCLS-II due to impedance of long transfer lines
  - Microbunches radiate nonuniform coherent optical transition radiation many orders of magnitude brighter than normal beam image.
  - Discuss ways to mitigate this
  - Screens will also not survive high repetition rate in CW machines
- Alternative is wire scans – projected beam size in one plane, averaged over multiple shots.
  - Wire speeds must be fast ~1m/s to survive high rate beams

COTR Suppression with the PSI Profile Monitor

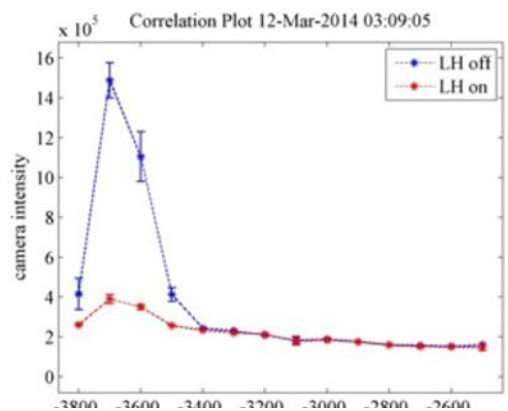


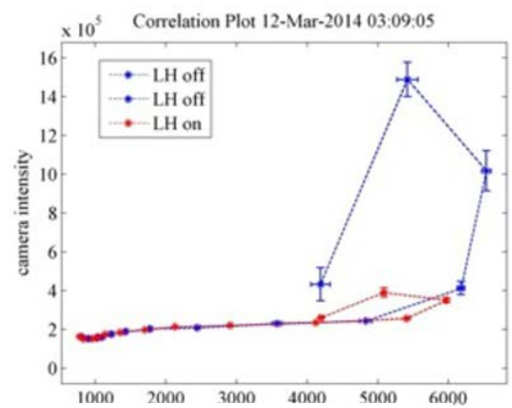
- Observe fluorescence from 30 μm YAG crystal while COTR is directed away from camera
- Observation at Snell angle to account for refraction in finite thickness crystal
- Camera image plane at Scheimpflug angle to maximize depth of field
- Developed by R. Ischebeck (PSI) and tested on the LCLS beam line

How Effectively was the COTR Suppressed?

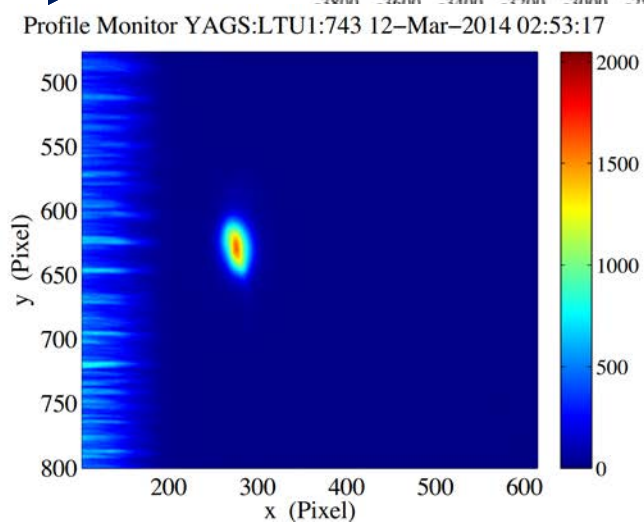
- The peak current is varied from 1 to 6 kAmp by adjusting the chirp upstream of the bunch compressor.
- Profile monitor has constant light output except at the shortest bunch length and the laser heater is off

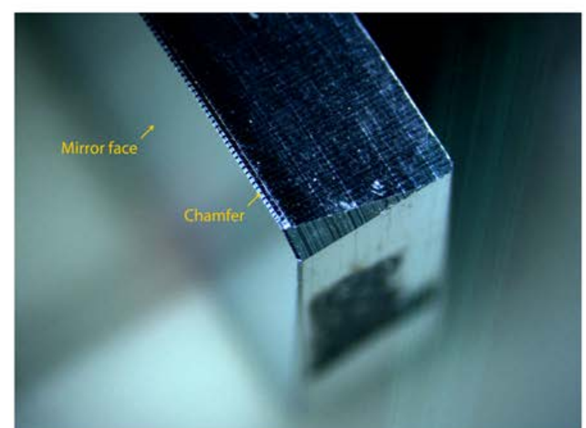
Camera intensity should be constant as bunch length is varied





Residual coherent diffraction radiation coming from the edge of the mirror





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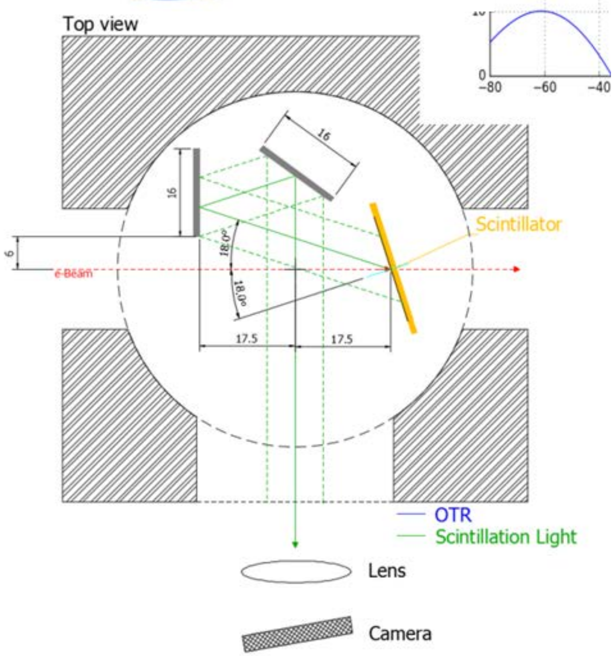
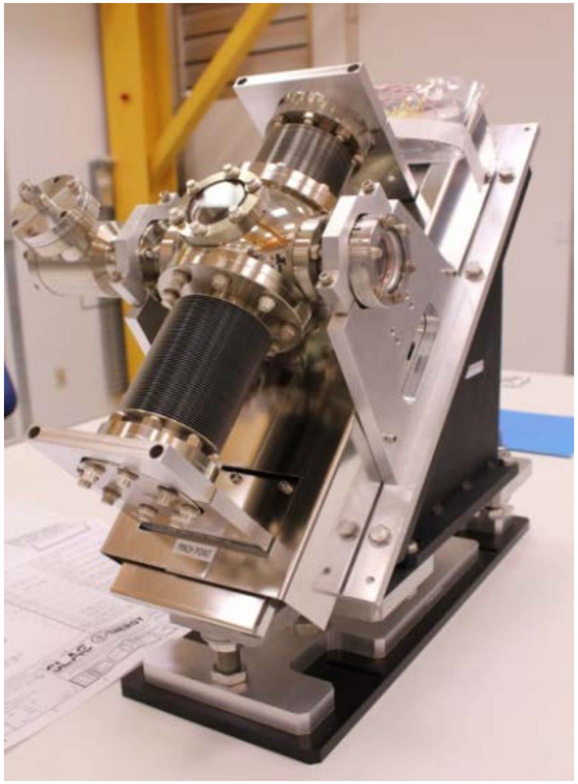
The Next Iteration in the Design comes from PAL

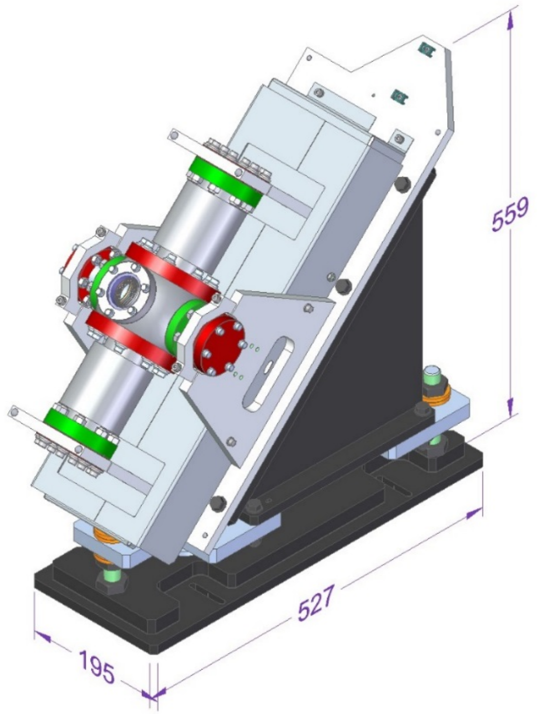
- The profile monitor design developed at Pohang Accelerator Laboratory uses two mirrors to increase the distance from the edge of the mirror to the beam from 3 mm to 6 mm while preserving the optimum viewing angles as used by PSI

- The PAL profile monitor will also be tested at LCLS this year



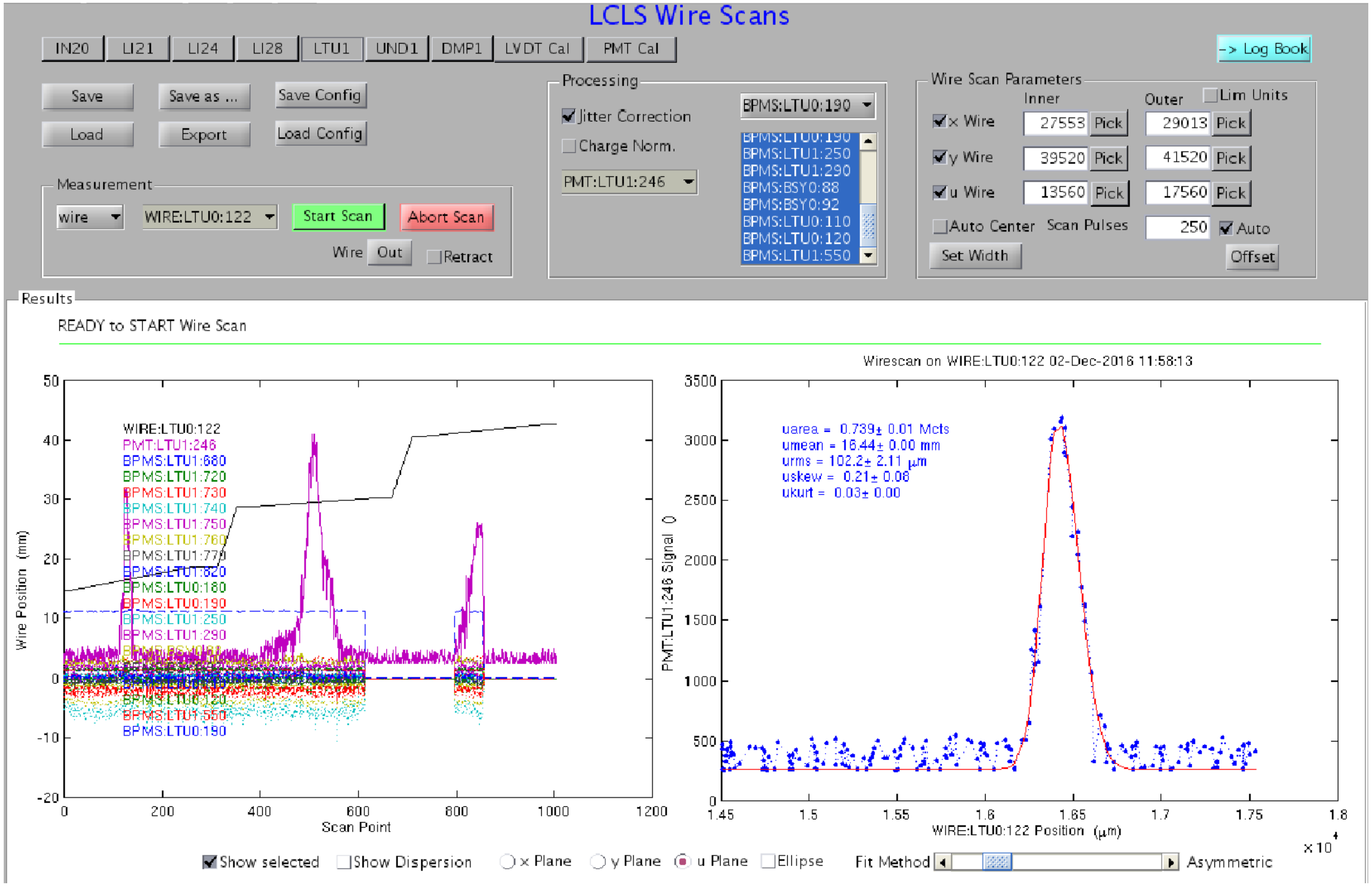
Fast Wire Scanners developed at LCLS-I





- Linear dc servo motor acting through dual bellows at 45°
- High speed significantly reduces emittance measurement and tuning time
- 1 MHz beam at LCLS-II requires 0.5 m/s wire speed

Slow speeds are also required depending on beam rate



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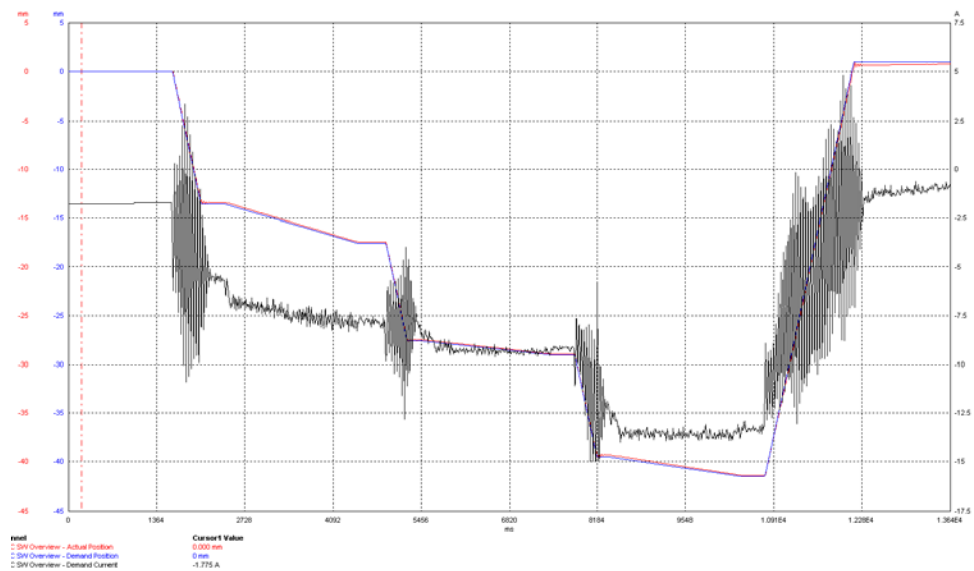
Operational lessons learned

- Stray magnetic fields from motor during acceleration 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



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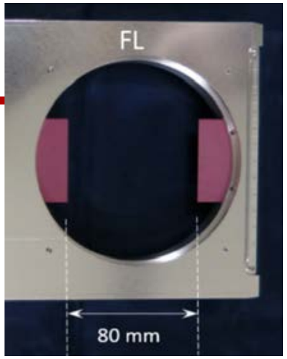
Beam Halo Measurements

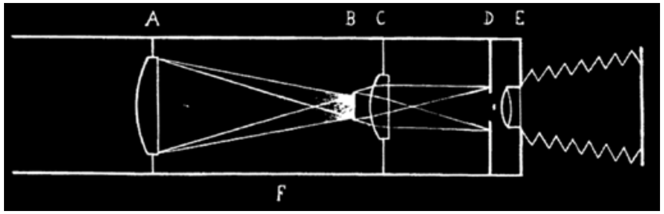
- Becomes an issue at LCLS-II
  - Significant fraction of beam power in a CW machine
  - Must be understood (diagnosed) and mitigated to prevent long term radiation damage to the undulator
  - Can occur with beam and without (dark current)
- Wire scanners can be used to profile halo
  - Raise sensitivity of wire scanner detector PMTs in halo only
  - Ideally wire spacing should be large compared to beam pipe radius in order to sample entire aperture.
- A. Fisher organized a Beam Halo Monitoring Workshop at SLAC in 2014
  - No shortage of good ideas to try at LCLS-II

Other halo measurements to try include -

- Partially intercepting screens or loss monitors
  - From Toshiyuki Mitsuhashi



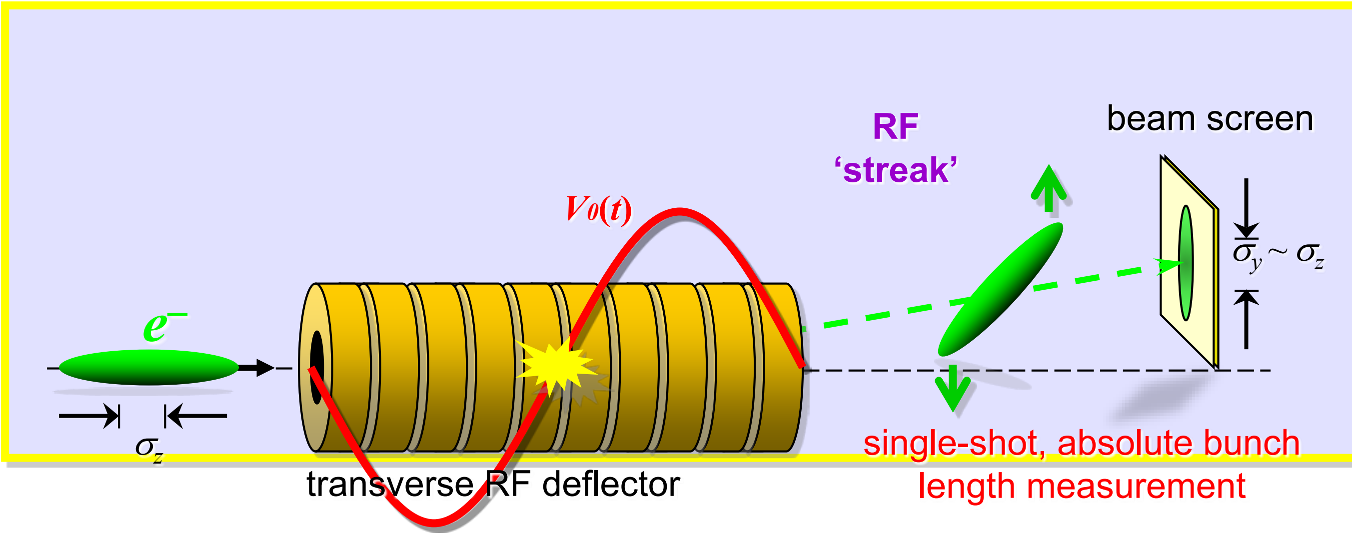
- Monitor synchrotron radiation and use a Lyot's Coronograph to block the core
  - Also extensively tested by T. Mitsuhashi



- Digital micromirror array
  - Jeff Corbett at SSRL

- Apodizer in the Fourier plane
  - Pavel Evuschenko at JLAB

Transverse Cavities are now a well-established longitudinal diagnostic



$$\sigma_{t,R} \propto \frac{\lambda_{rf}}{V_0}\sqrt{E\frac{\varepsilon_{N,x}}{\beta_x(s_0)}}$$

Temporal resolution improves with higher RF frequency

X-band TCAV: (before SLED)	
Frequency	11.424 GHz
Maximum kick	45 MV@35MW

HXR: *(14GeV)*	***SXR:*** *(4.3GeV)*
Calib.factor ~40, $\sigma_{t,R} \sim$ ***4 fs***;	*Calib. factor ~120,* $\sigma_{t,R} \sim$ ***1 fs***;

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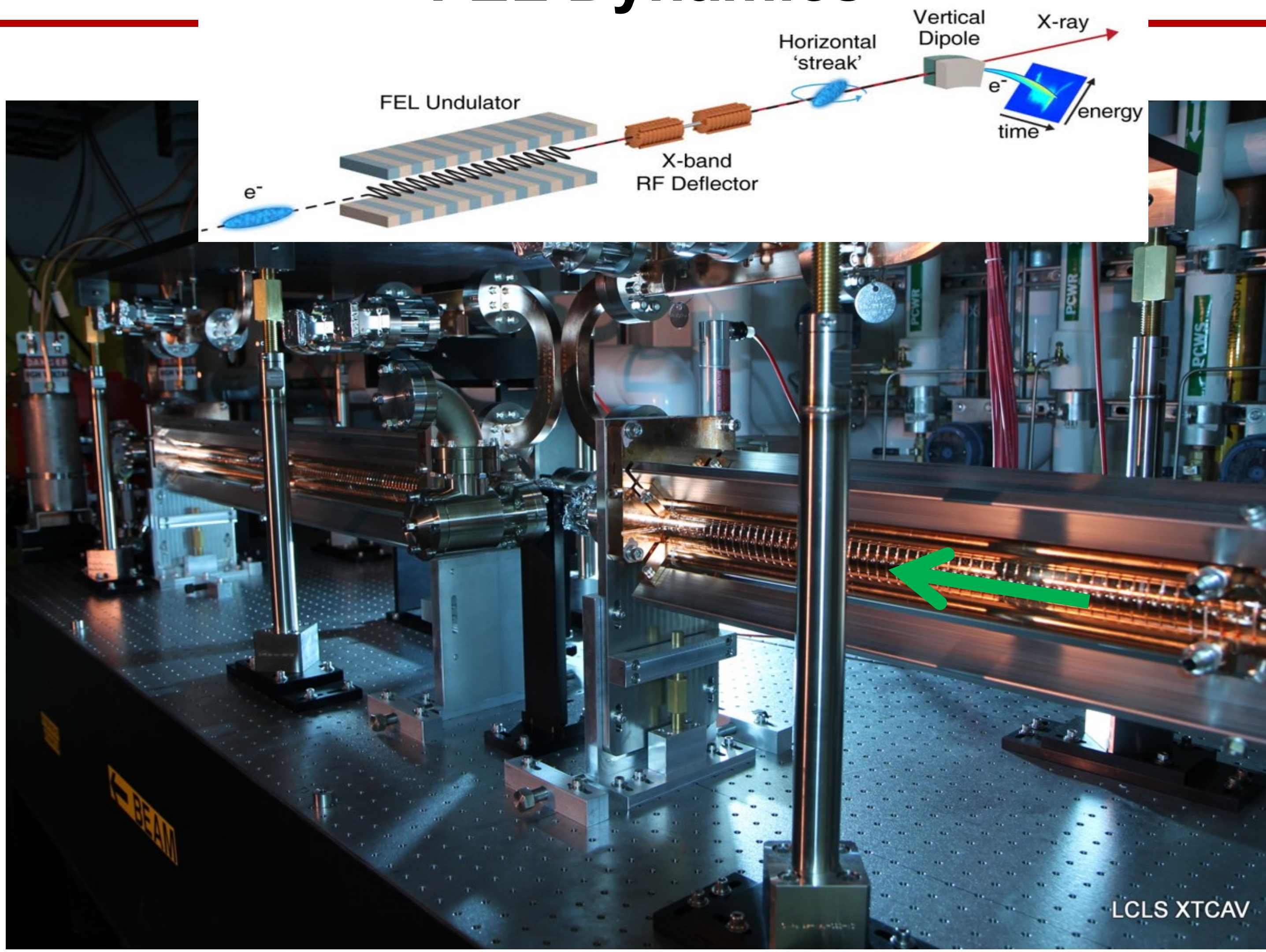
XTCAV downstream of Undulator reveals complex FEL Dynamics



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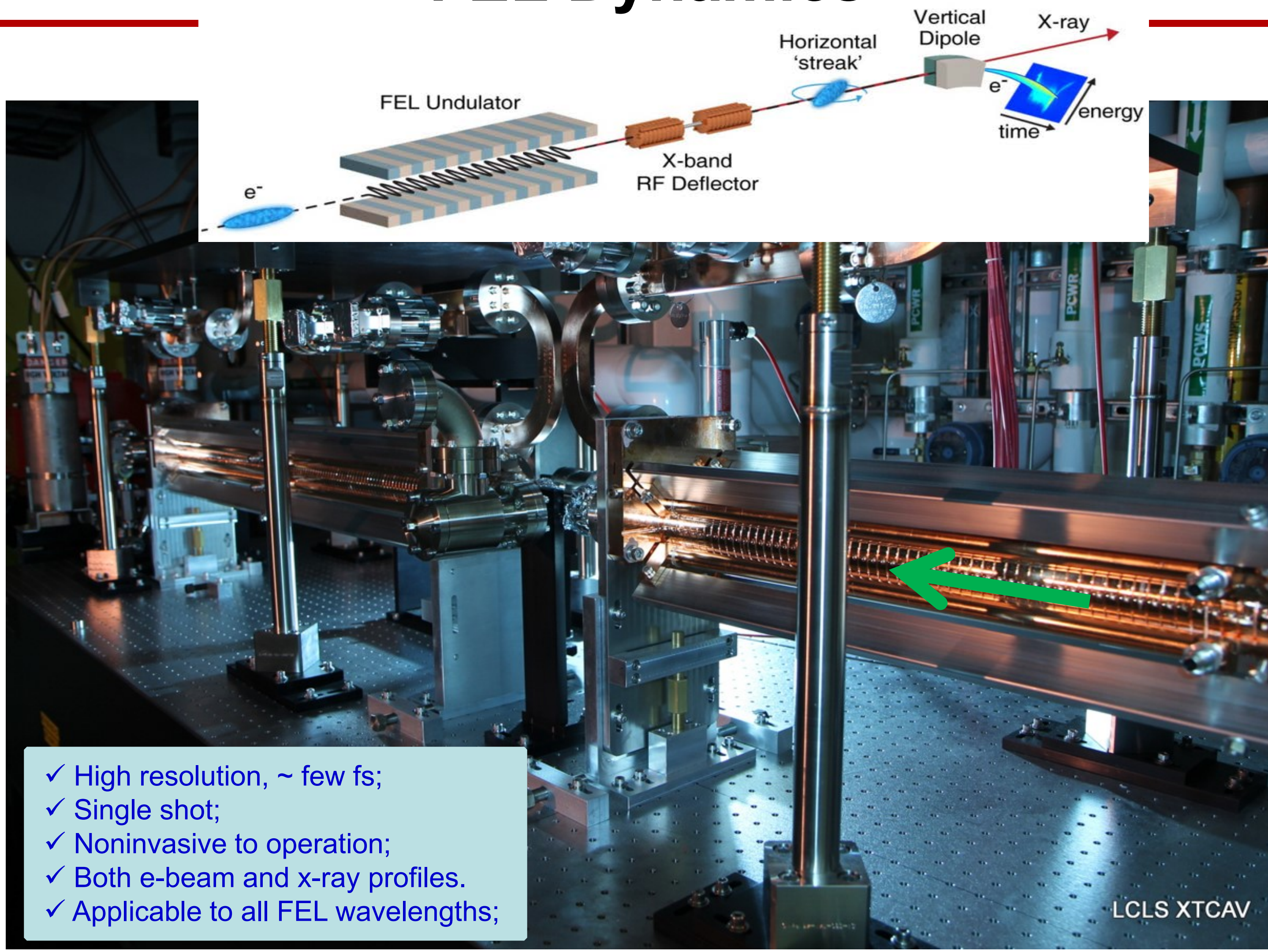

- ✓ High resolution, ~ few fs;
- ✓ Single shot;
- ✓ Noninvasive to operation;
- ✓ Both e-beam and x-ray profiles.
- ✓ Applicable to all FEL wavelengths;

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A Most Versatile Diagnostic!

- The XTCAV system is

  a ★★★★★ diagnostic tool

  at a $ $ $ $ $ price

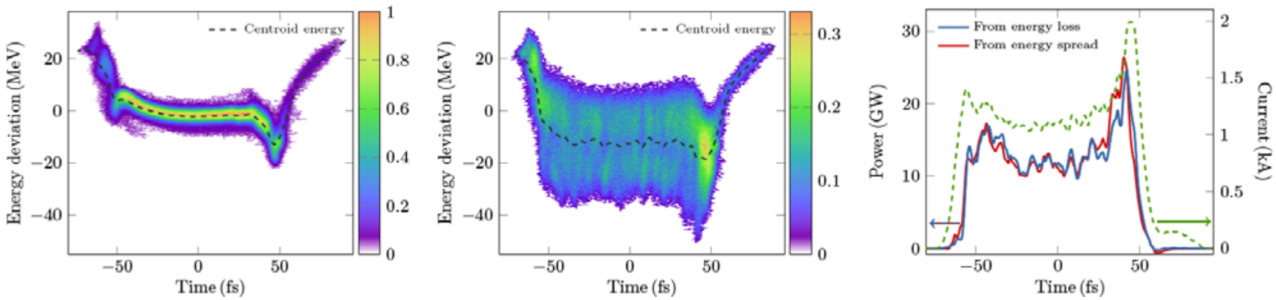
- Not in everyone's budget, but pays for itself in the long run
- Downstream of the undulator it is the only single-shot diagnostic that can reconstruct the x-ray photon beam temporal profile
- And allow a number of exotic pump-probe set ups for users

X-ray power temporal profile reconstruction

- **Two formulas compute profiles***

$$P_{\mathrm{FEL}}(t) = [\langle E \rangle_{\mathrm{FEL\ off}}(t) - \langle E \rangle_{\mathrm{FEL\ on}}(t)] \times I(t)$$

$$P_{\mathrm{FEL}}(t) \propto \left[\sigma^2_{E,\mathrm{FEL\ on}}(t) - \sigma^2_{E,\mathrm{FEL\ off}}(t)\right] \times I^{2/3}(t)$$



- Two formulae may disagree if…
  - Poor SNR (filters, camera settings)
  - Bad image processing
  - Glitchy moment calculation

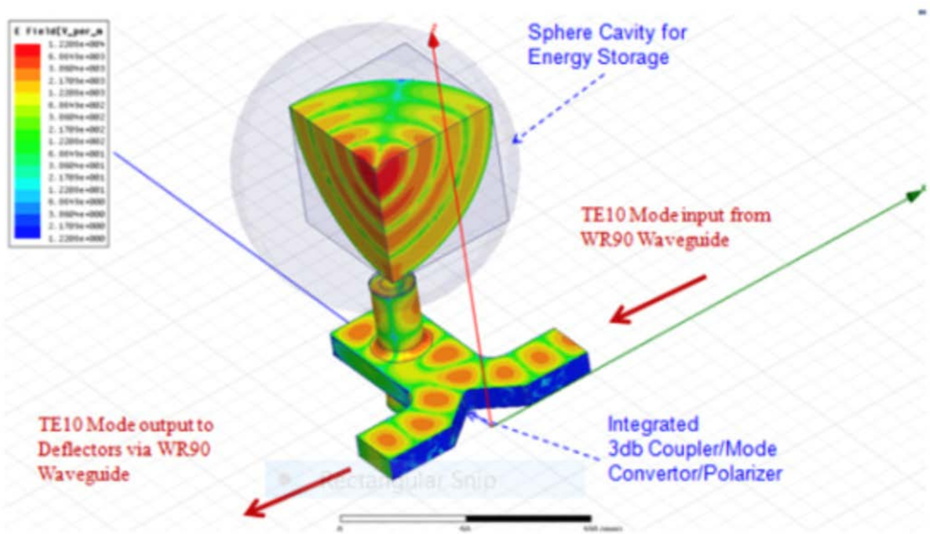
C. Behrens et al., Nat. Commun. 5:3762 (2014).
Y. Ding et al., PRSTAB 14, 120701 (2011).

- **Comparison is free "consistency check"**

*** T. Maxwell, *Proc. SPIE 9210*, X-Ray Free-Electron Lasers: Beam Diagnostics, Beamline Instrumentation, and Applications II, 92100J (2014).**

X-band SLED Cavity & Coupler Assembly- Juwen Wang
RF Pulse Compression Raises Peak Power by Factor 4

Doubled the resolution of the XTCAV system

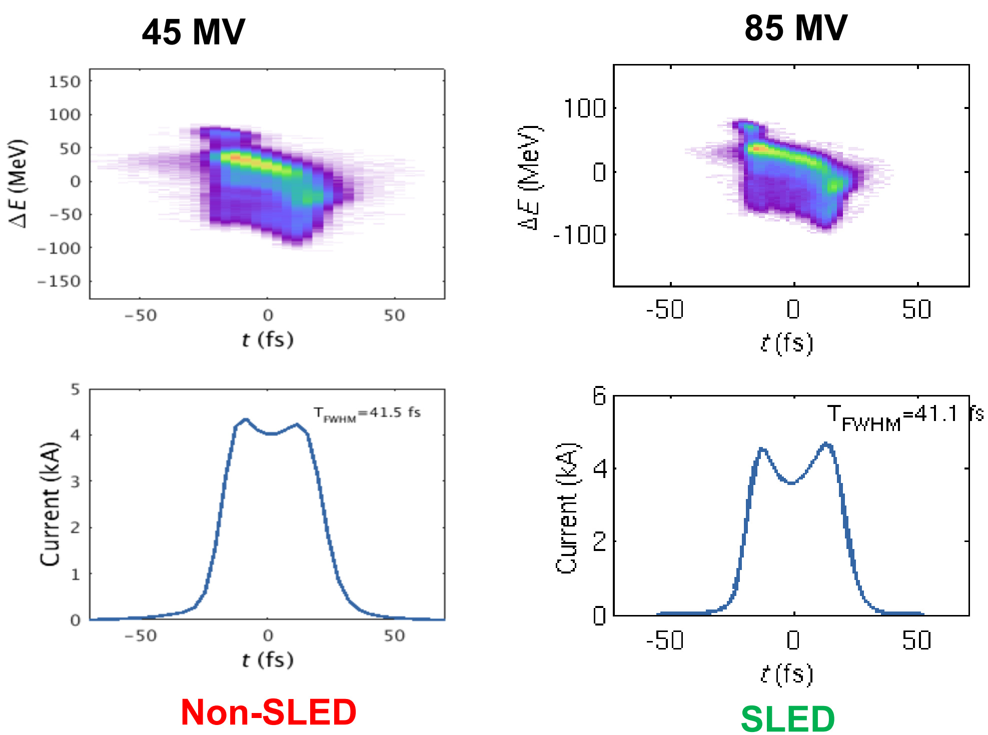


Sphere diameter < 12 cm

Final Brazed Assembly

J. Wang et al., "R&D of a Super-compact SLED System at SLAC", IPAC'16, MOOCA01.

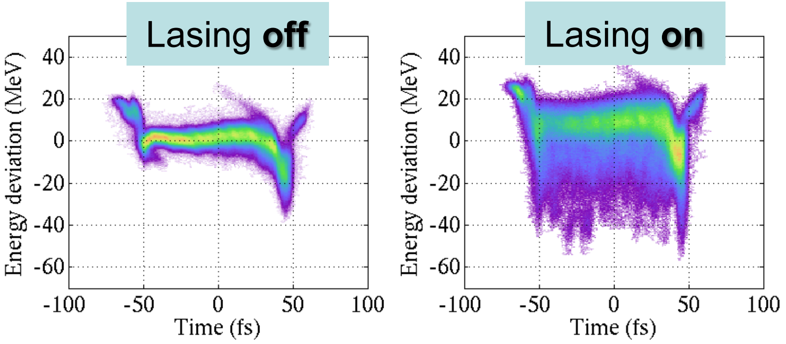
Beam Streaking enhancement with SLED mode



P. Krejcik et al., Sub-fs Resolution with the Enhanced Operation of the X-band Transverse Deflecting Cavity using an RF pulse Compression SLED Cavity, WEPG77, IBIC 2016.

XTCAV measures the lasing, and spoiling

Regular SASE,
Without foil



Y. Ding et al., APL 107, 191104 (2015)

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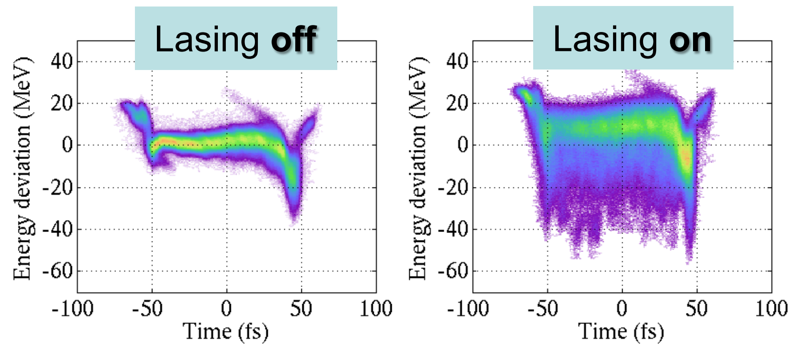
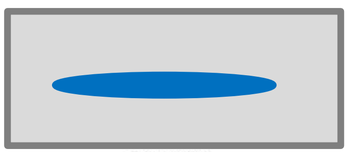
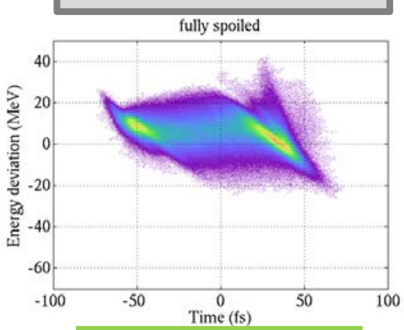


With foil





fully spoiled, no slot

Y. Ding et al., APL 107, 191104 (2015)

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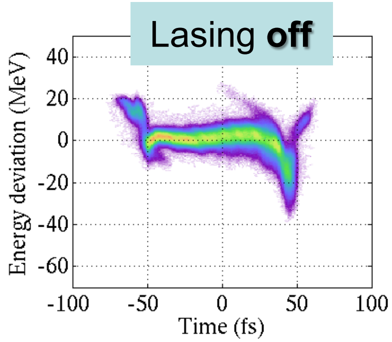
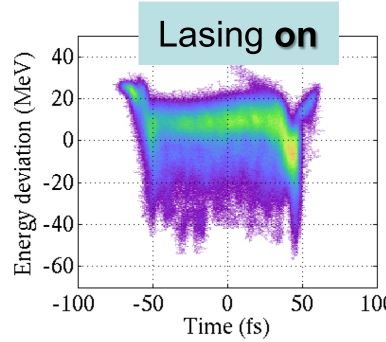
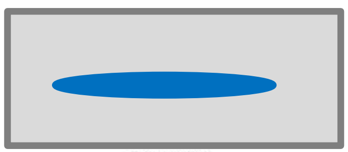
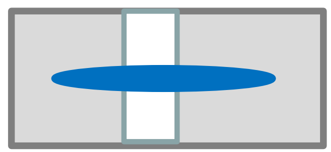
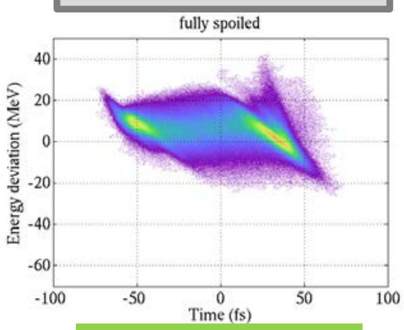




With foil







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Y. Ding et al., APL 107, 191104 (2015)

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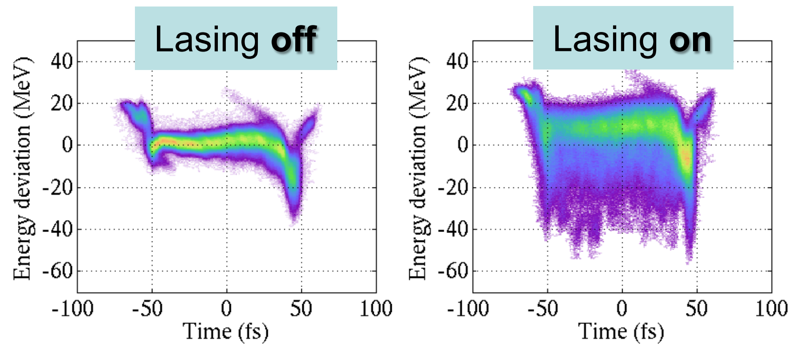
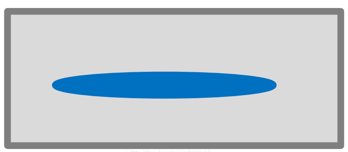
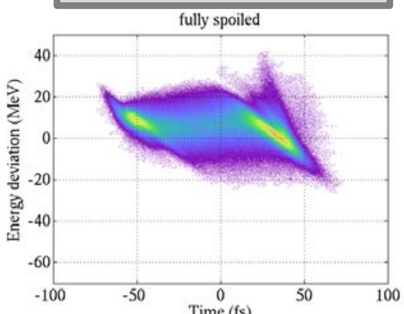
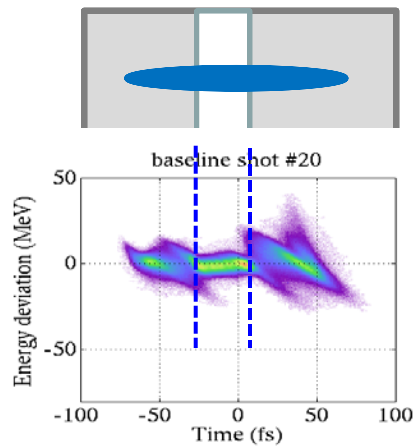


With foil





fully spoiled, no slot

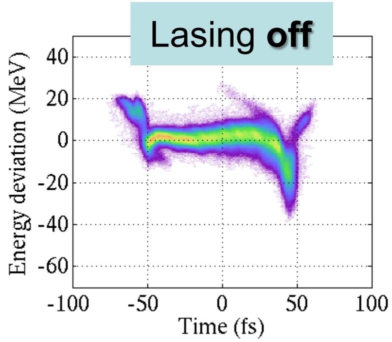


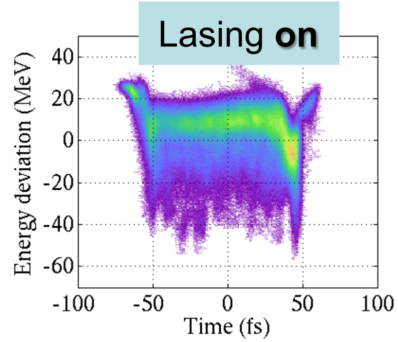
Lasing **off**, single slot

Y. Ding et al., APL 107, 191104 (2015)

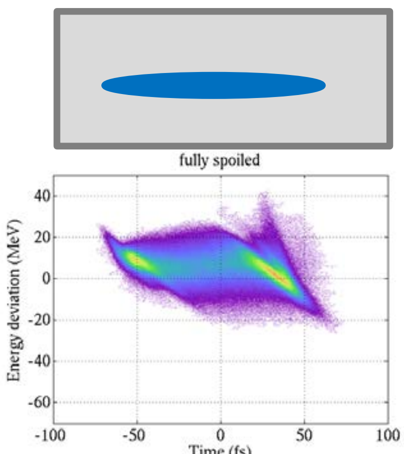
XTCAV measures the lasing, and spoiling

Regular SASE,
Without foil

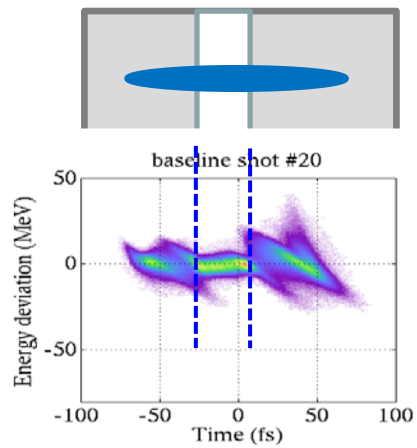




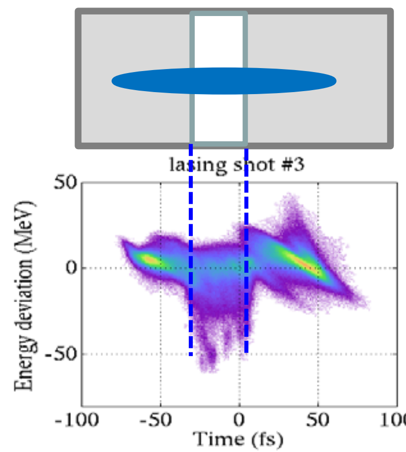
With foil



fully spoiled, no slot



Lasing **off**, single slot

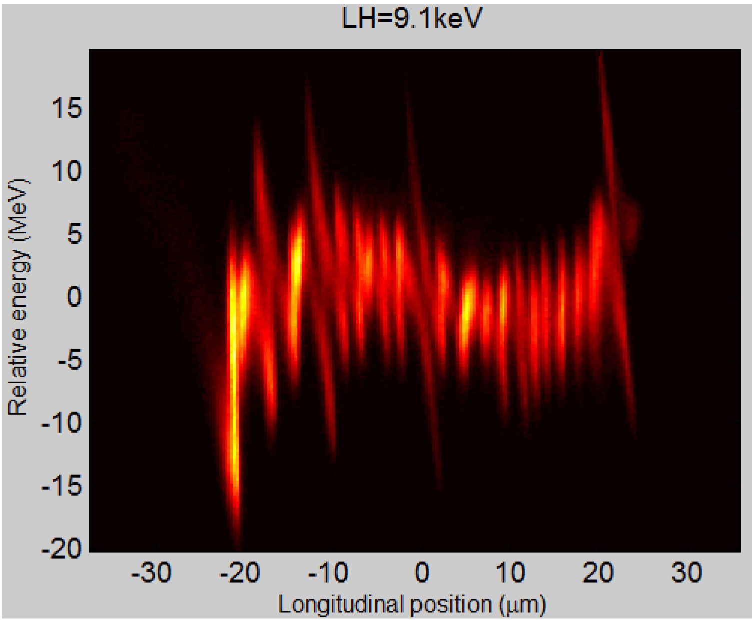


Lasing **on**, single slot

Y. Ding et al., APL 107, 191104 (2015)

Microbunching Measurements with the XTCAV

Laser Heater OFF

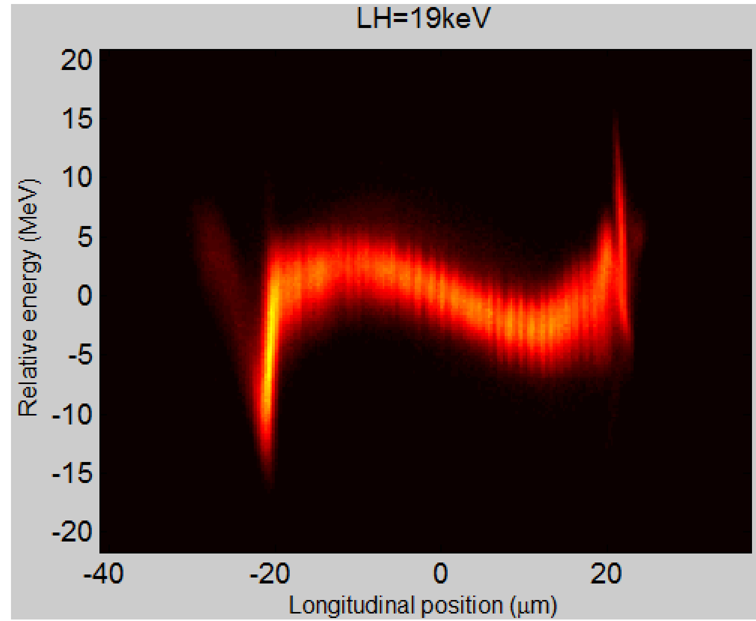


- Microbunches change shot to shot

Each microbunch generates coherent SR, DR and OTR at screens

Laser Heater ON

Add energy spread damp instabilities



- Microbunching is damped but not completely irradicated

D. Ratner et al., PRSTAB 18, 030704 (2015); J. Qiang et al., NaPAC 2016.

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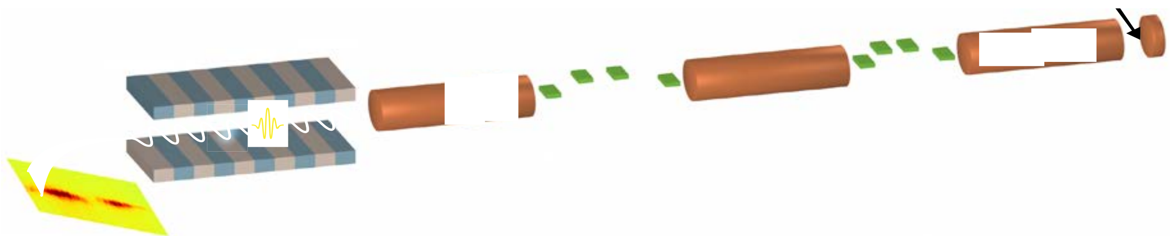
Twin-Bunch Two-Color FEL Operation for user pump-probe experiments



ΔE (MeV)

Twin-bunch takes full advantage of the XTCAV capability.

- Improve the peak power of 2-color SASE by a factor 20 at hard x-rays
- Allow 2 color self-seeding with large separation
- Allow x-ray pump/x-ray probe at high intensities

✓ **~10 fs pulse duration, over 1mJ pulse energy, pulse delay up to 150 fs.**
✓ **Up to 1% energy separation at HXR.**

(*A. Marinelli et al., Nature Commun. 6, 6369, 2015*)

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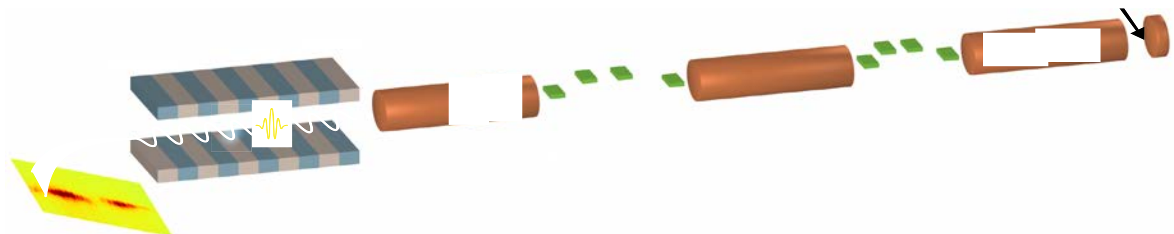

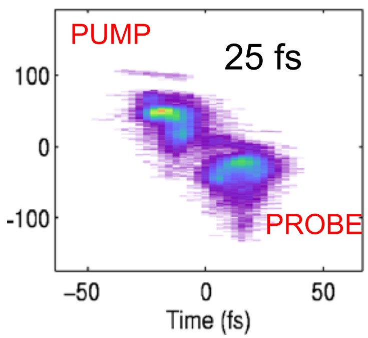

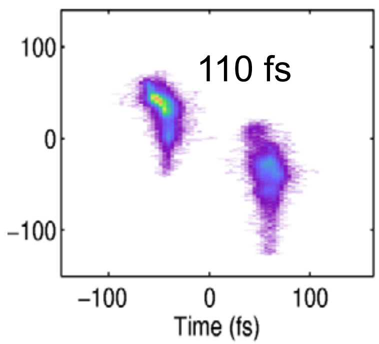

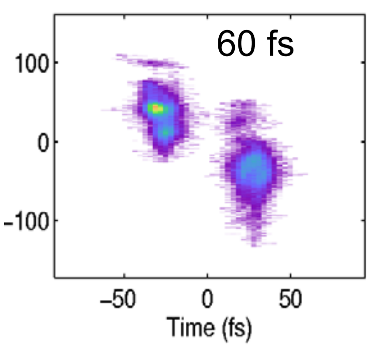

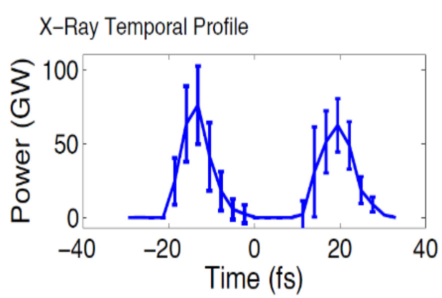

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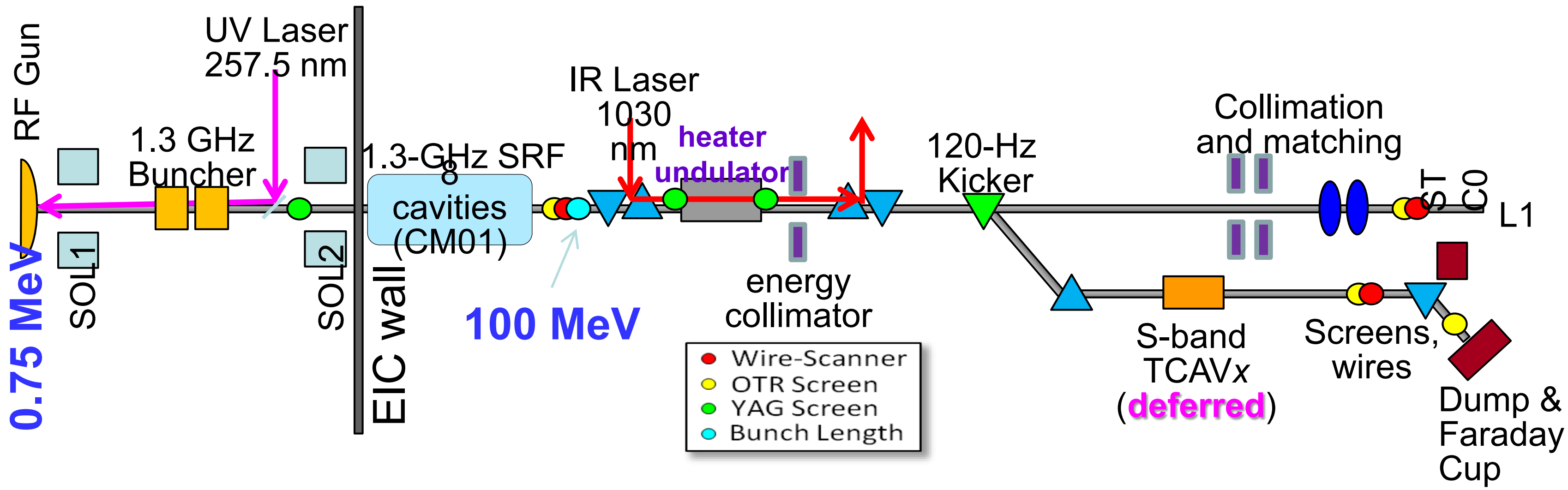
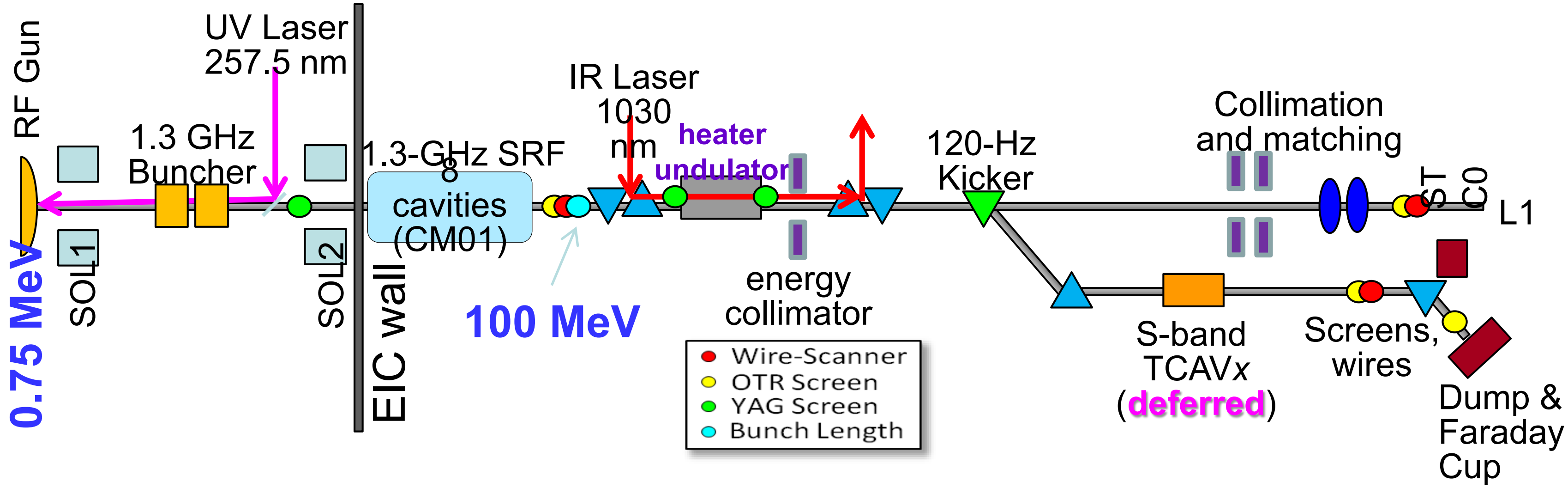
Pulsed deflector cavity for single bunches in a train of LCLS-II bunches



Pulsed deflector cavity for single bunches in a train of LCLS-II bunches

- Pulsed bypass line at the injector receives max of 120 Hz



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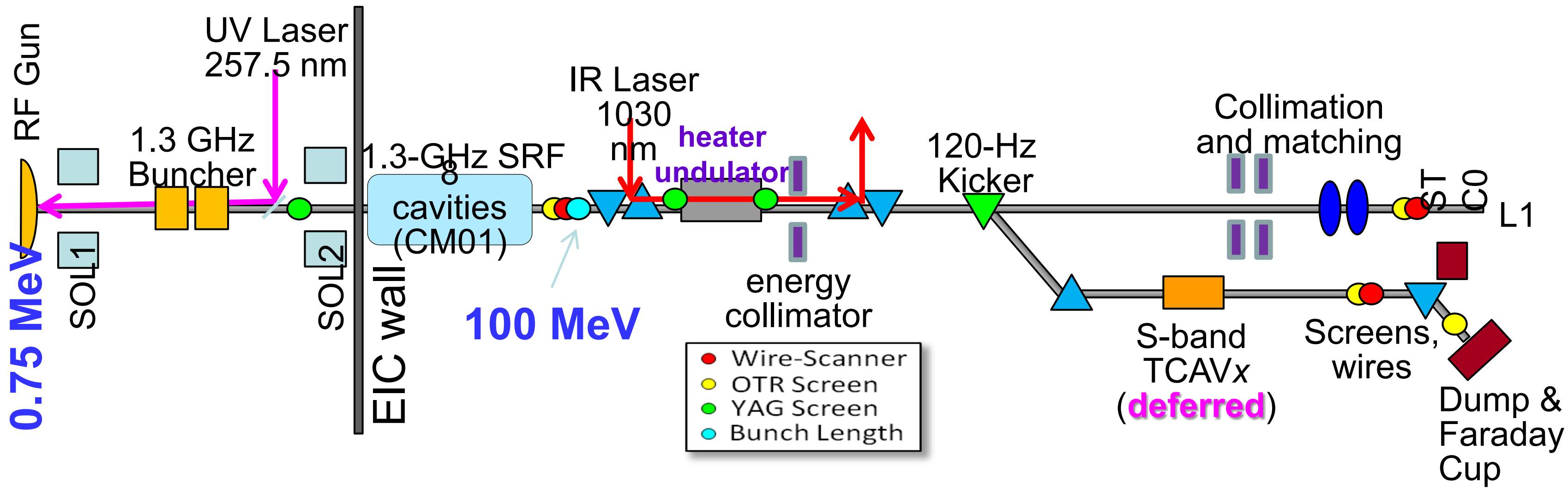
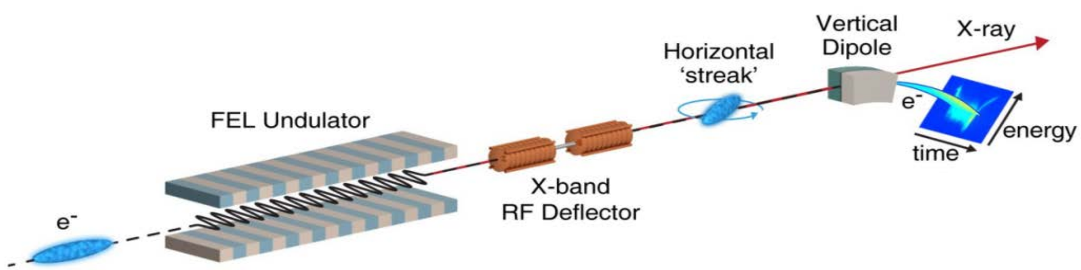


- Or, off-axis screen at the undulator dump



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What lies beyond streaking with an XTCAV?

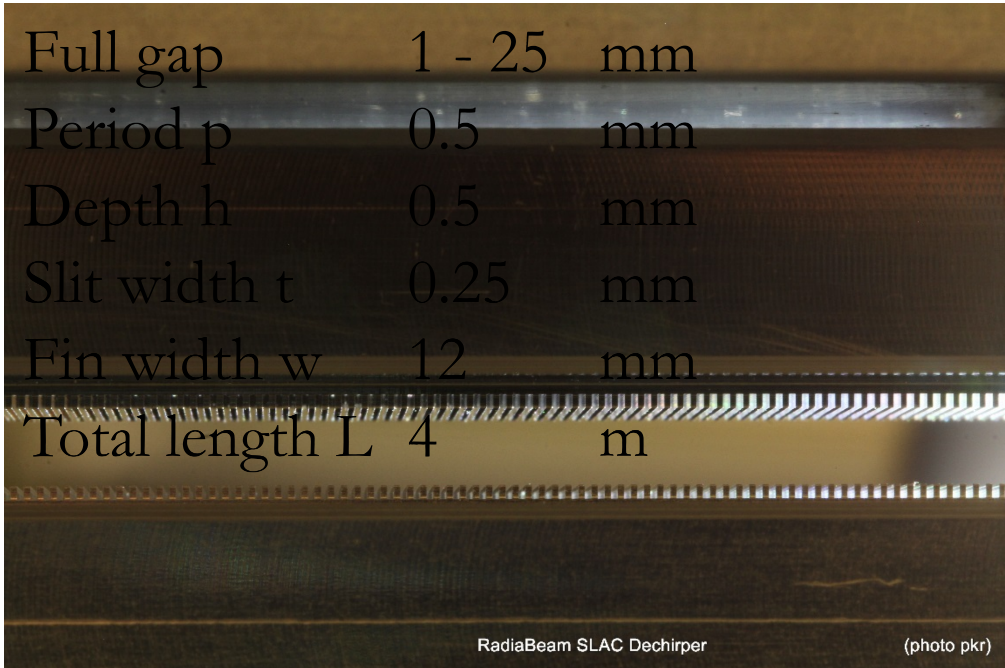
- Resolution may be limited by bunch arrival time jitter wrt to RF rather than the strength of the kick
  - Experience this already with SLED'ed XTCAV at low energies
- New ideas based on THz radiation may also be ultimately limited by beam stability
  - Any powerful transverse deflector can kick the beam out of the beam pipe and exceed allowable beam loss rates

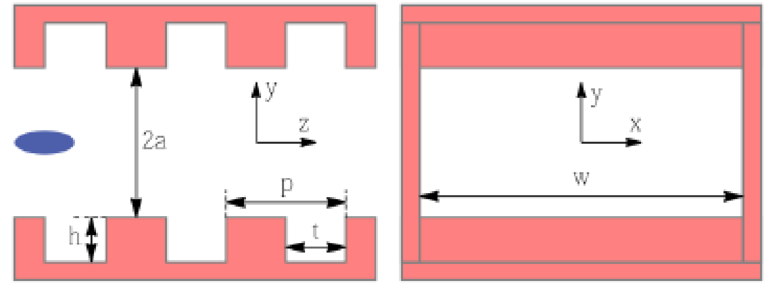
- Consider passive streaking schemes as an alternative for the next generation of attosecond beams

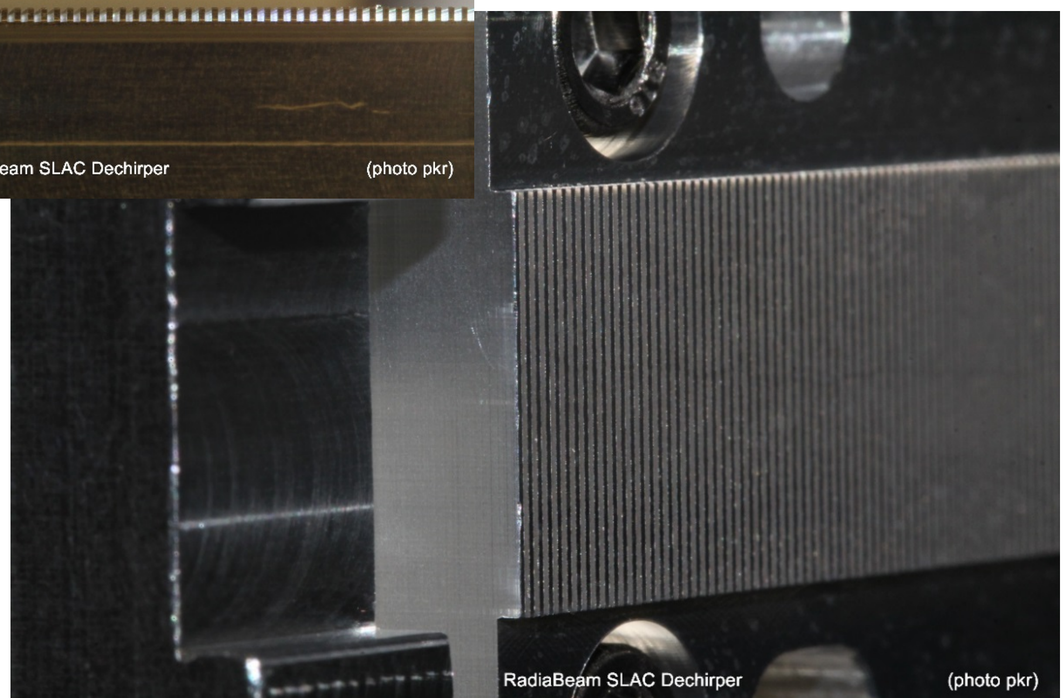
SLAC RadiaBeam Dechirper Installation at LCLS-I

Dechirper Jaws

Full gap	1 - 25	mm
Period p	0.5	mm
Depth h	0.5	mm
Slit width t	0.25	mm
Fin width w	12	mm
Total length L	4	m







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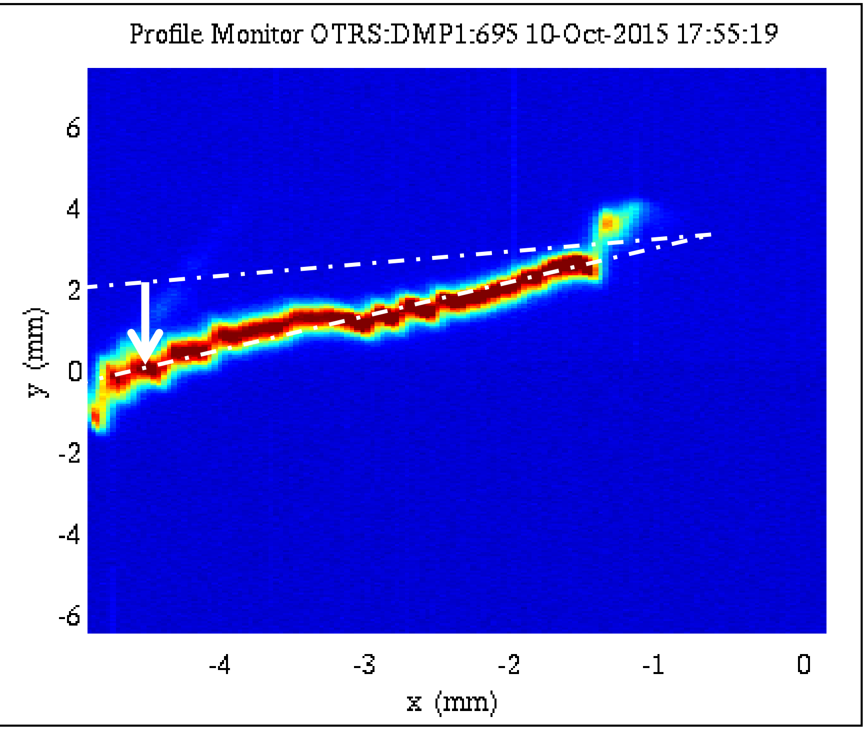
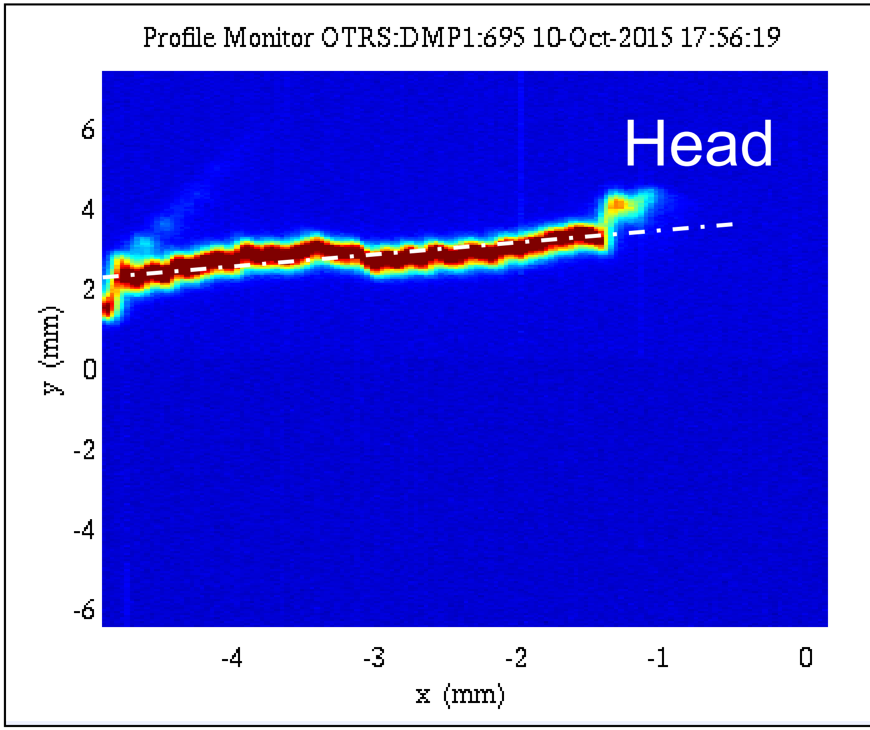
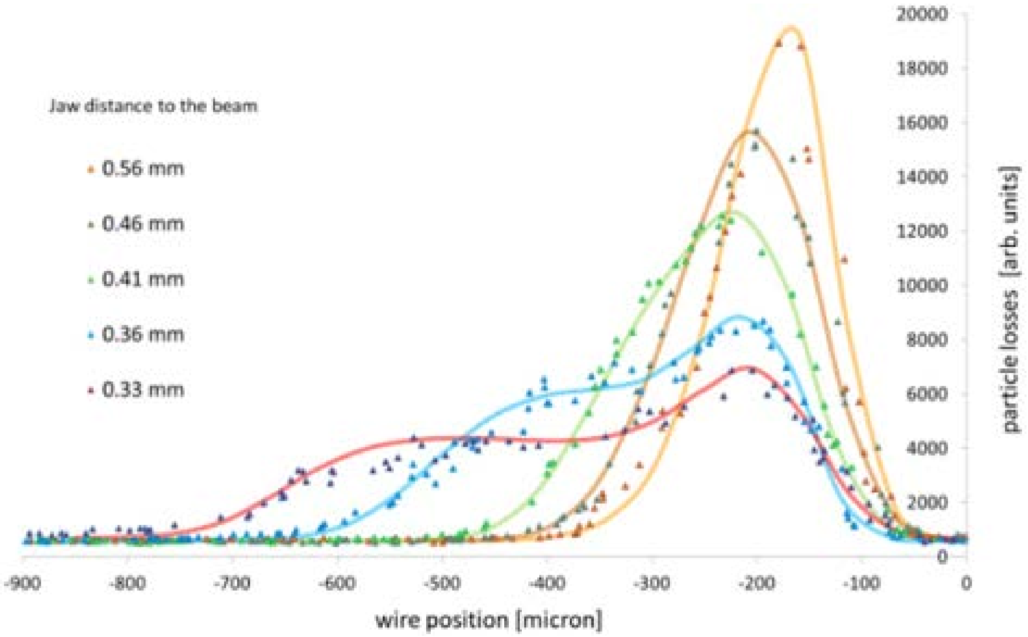
Symmetric Pair of Dechirper Jaws rotate bunch in longitudinal phase space and reduce energy spread

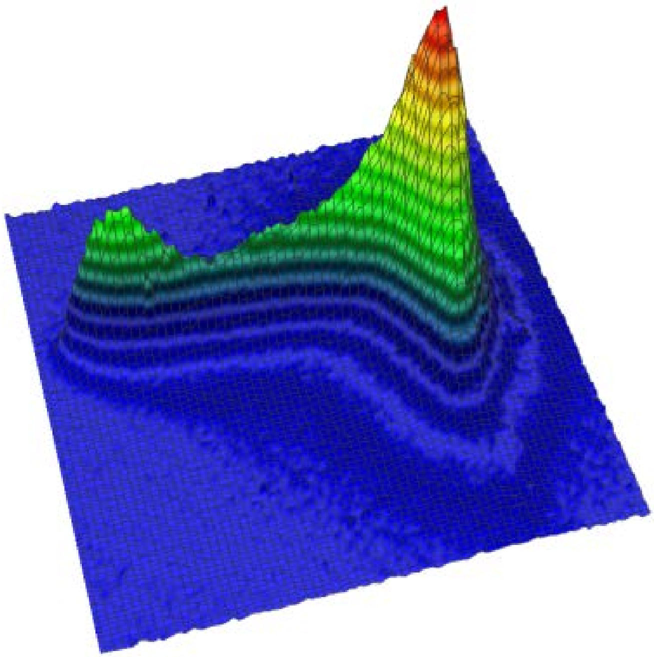




Measurements with XTCAV show rotation in longitudinal phase space as jaws are closed to 1 mm separation

Wakefield dipole kick from a single jaw will passively streak the bunch





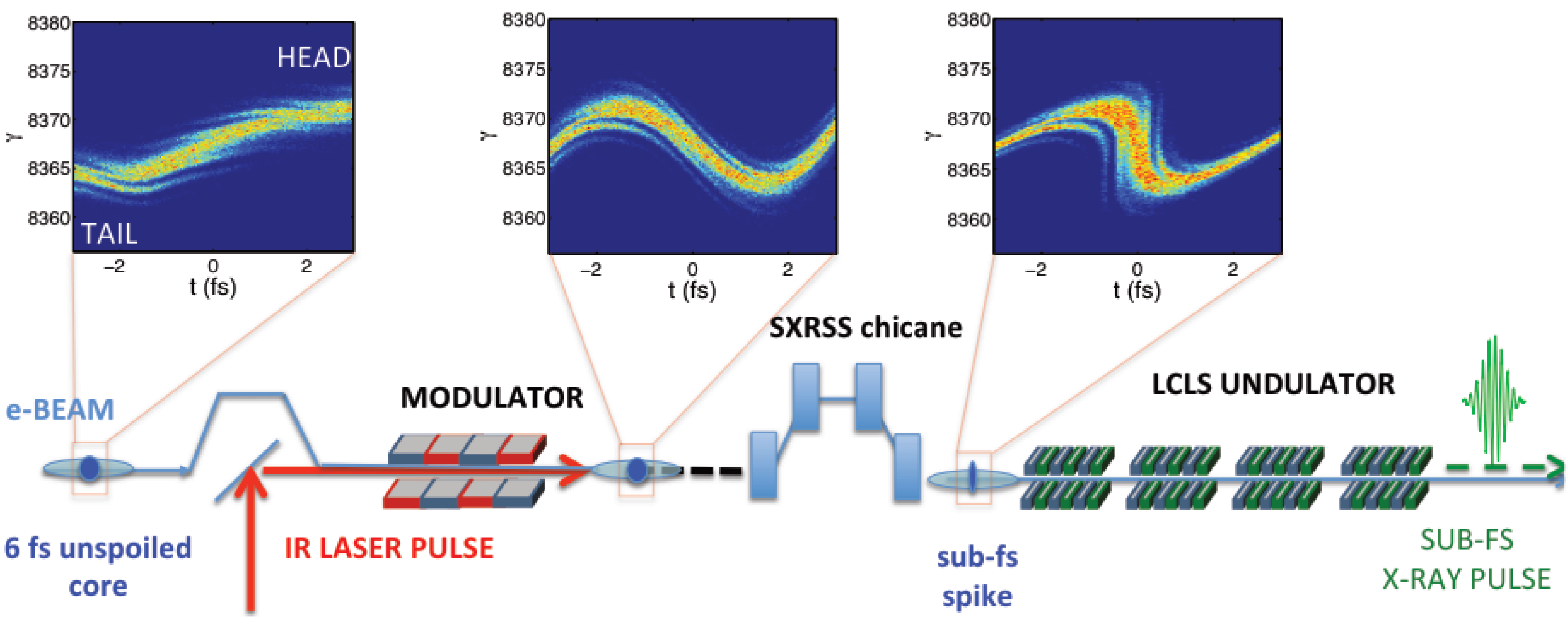
- Measured transverse profile and screen image as single jaw is moved to within 0.33 mm of the edge of the beam
- Streak is nonlinear but is not subject to beam jitter, and could reach sub-fs resolution

Dechirper for LCLS-II

- RadiaBeam is working with SLAC to develop a commercial water-cooled dechirper module
  - handles high average THz beam power dissipated at the jaws
- Second generation dechirper/passive streaker has refinements in
  - Cooling
  - Motor control
  - Alignment
  - Machine protection
  - diagnostics

Always shorter bunches!
towards attoseconds – XLEAP Project

- Led by A. Marinelli
- Laser modulates electron bunch energy in a short undulator
- Energy modulation => microbunching in a magnetic chicane



What about diagnostics??

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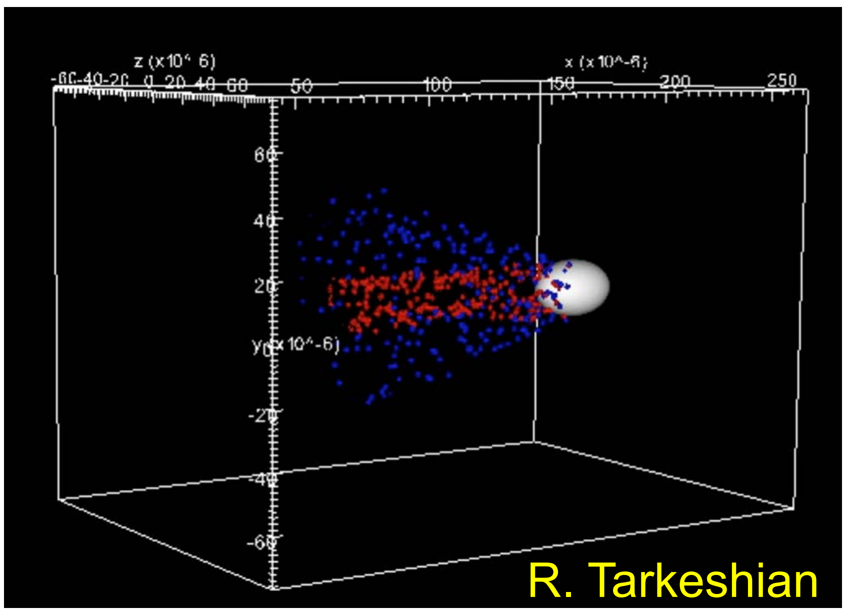
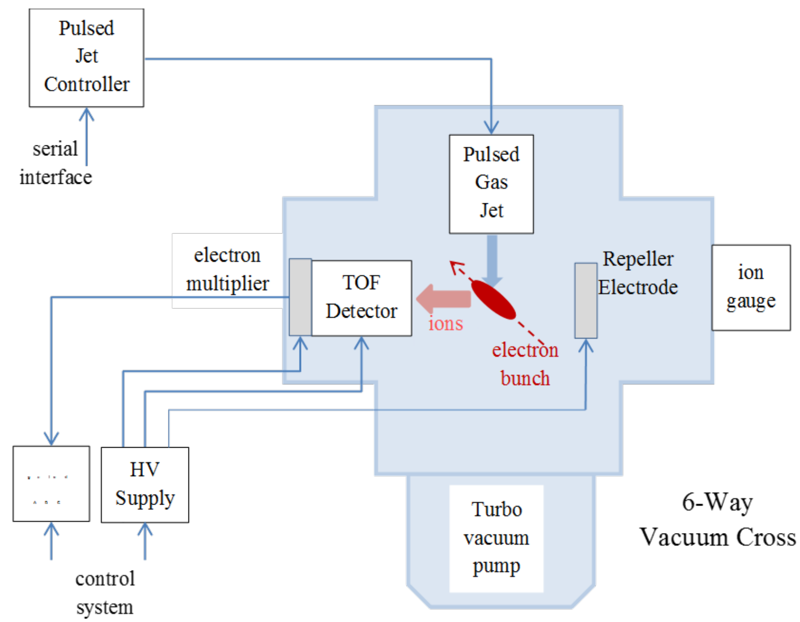
PSI Gas Jet Monitor tests at LCLS

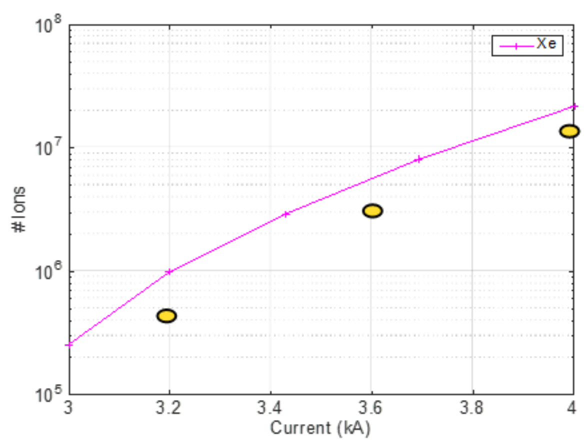
- Gas jet ionized by high electric field of very short electron bunch
  – the peak electric field proportional to $q/\sigma_x\ \sigma_y\ \sigma_z$
- Developed at Paul Scherrer Institute by
  – R. Tarkeshian (Univ. Bern), R. Ischebeck, V. Schlott

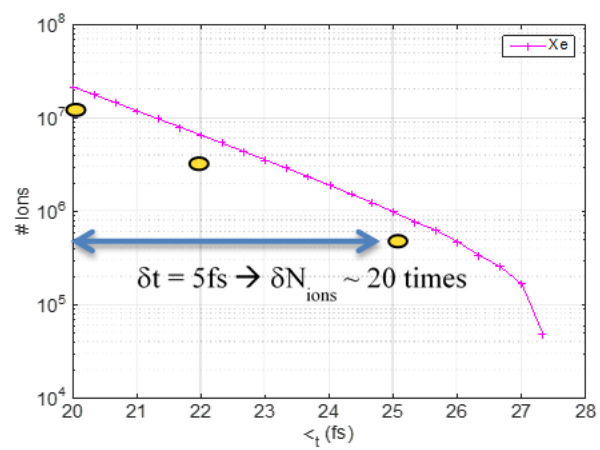




Goals of gas jet tests at LCLS

- Verify ionization yields with bunch properties
  - Initially with Xe gas, lowest ionization potential of 12.1 eV
- Exploit the sensitivity to ultrashort bunch phenomena on the XLEAP beam line at LCLS with attosecond bunches
- Forerunner for more exotic gas ionization diagnostics





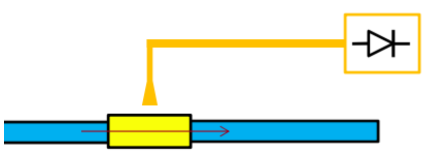
Bunch Length Detectors at BC1 & BC2

Diode detector at ceramic gap, BC1 (picosecond resolution)

1. Beam traverses ceramic vacuum pipe break
2. Sub-THz mircrowave horn+waveguide capture long-wave transition radiation (long bunches)
   - Attenuate & elongate radiation pulse
3. Sub-THz diode measures pulse intensity

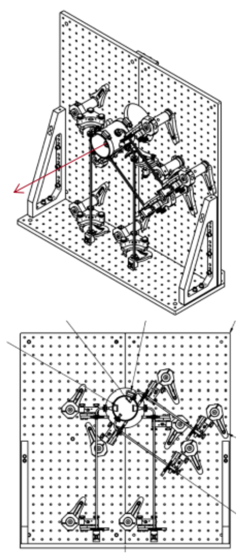
- Unlike pyro system, *narrow-bandwidth* measurement, good around single bunch length working point

+ Good sensitivity/dynamic range, less power managed



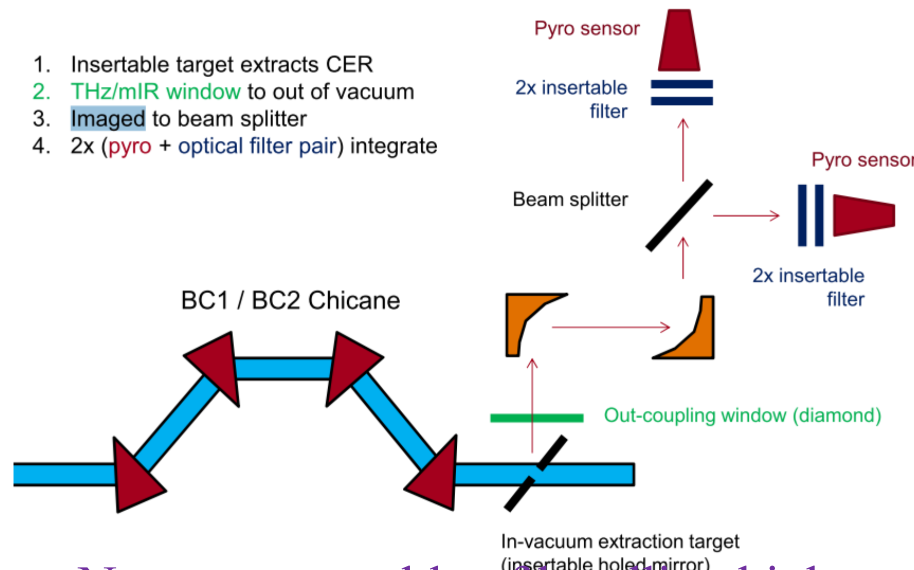
Recommend per location:
- 2 frequencies
- 2 diodes each
  (primary+redundant)

Minimum: 1 freq. x2 diodes



Pyro detector at BC2 (sub picosecond resolution)

1. Insertable target extracts CER
2. THz/mIR window to out of vacuum
3. Imaged to beam splitter
4. 2x (pyro + optical filter pair) integrate

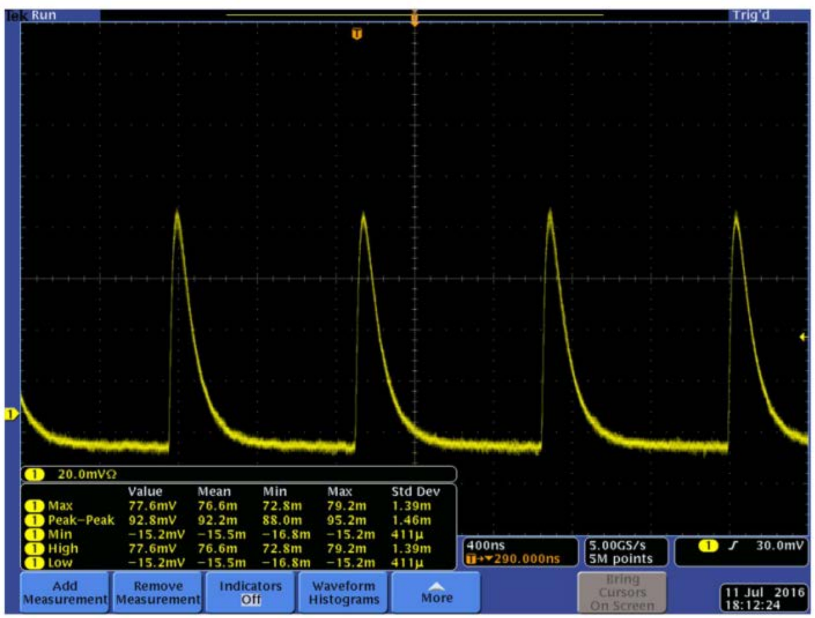


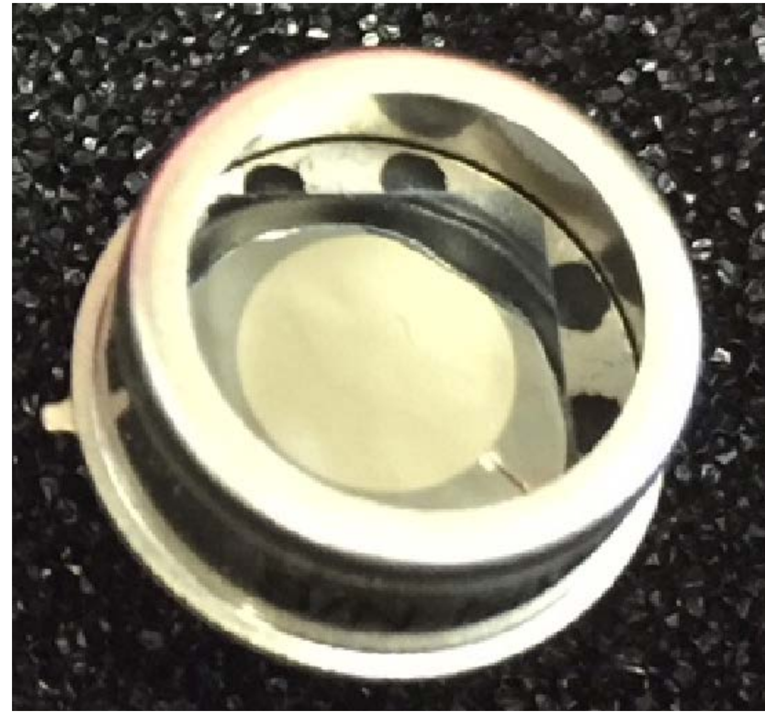
- New pyro capable of handling high average power at LCLS-II
- Also add scanning interferometer stage for calibration at LCLS-I

Gentec-EO Pryoelectric prototype sensor

- *Cleaner response to up to 1MHz*
- *Slightly improved sensitivity, same % noise*
- *4x higher average power (up to 6W for short duration) handling to cover all operating ranges of LCLS-II*

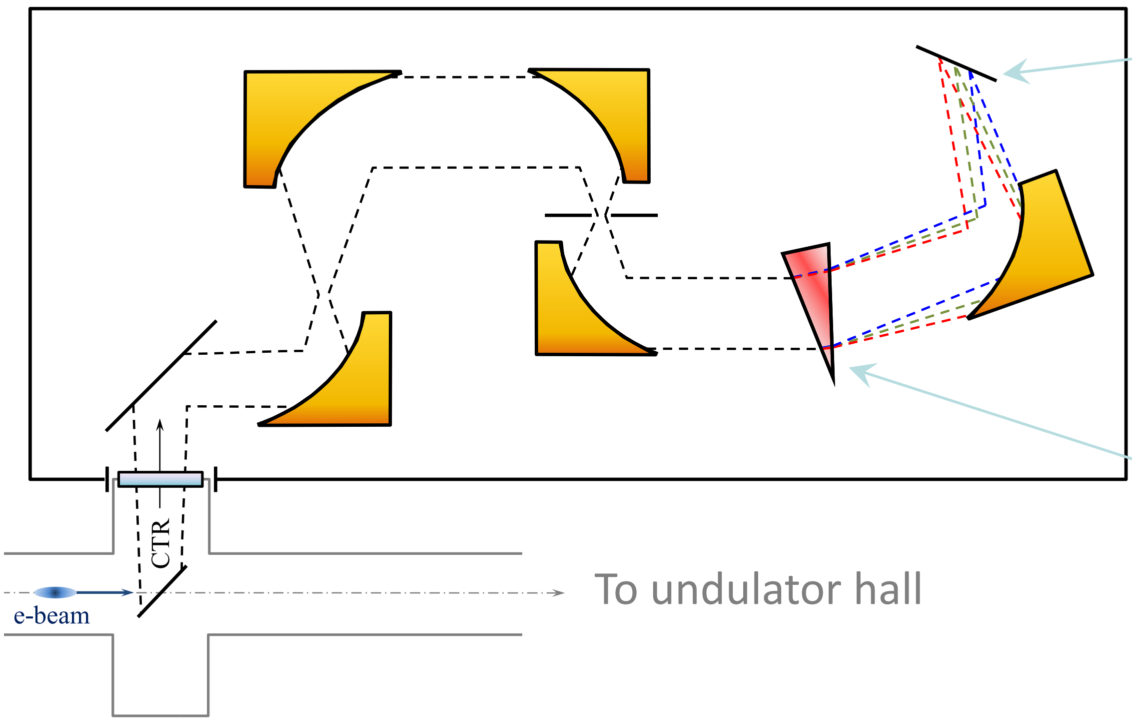
1 MHz (time base changed)

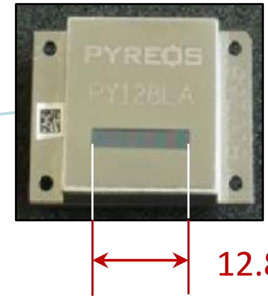




Pyroelectric detector prototype to operate at LCLS-II normal operating condition was developed by Gentec. Detector passed high power laser test to qualify for LCLS-II operation

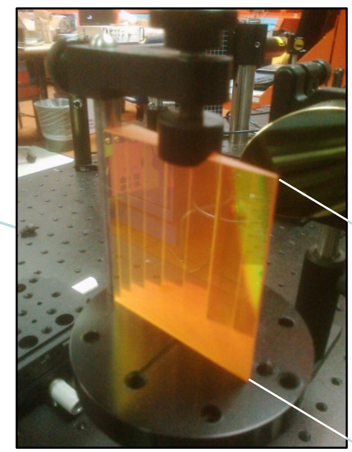
Mid-IR Spectroscopy Measurement of Bunch Length at LCLS - Tim Maxwell et al





Detector Array

12.8 mm



MIR Prism
(ZnSe shown)

60 mm

- Prism: 10º apex, KRS-5 (T = 0.6 – 40 μm) or ZnSe (T = 0.5 – 20 μm)
- Detector: Linear PZT pyroelectric array, 100 μm pitch
- Geometry: Design for 1-pix monochrom. illum. & 128-pix illum. w/ full BW
- Not foreseen for LCLS-II

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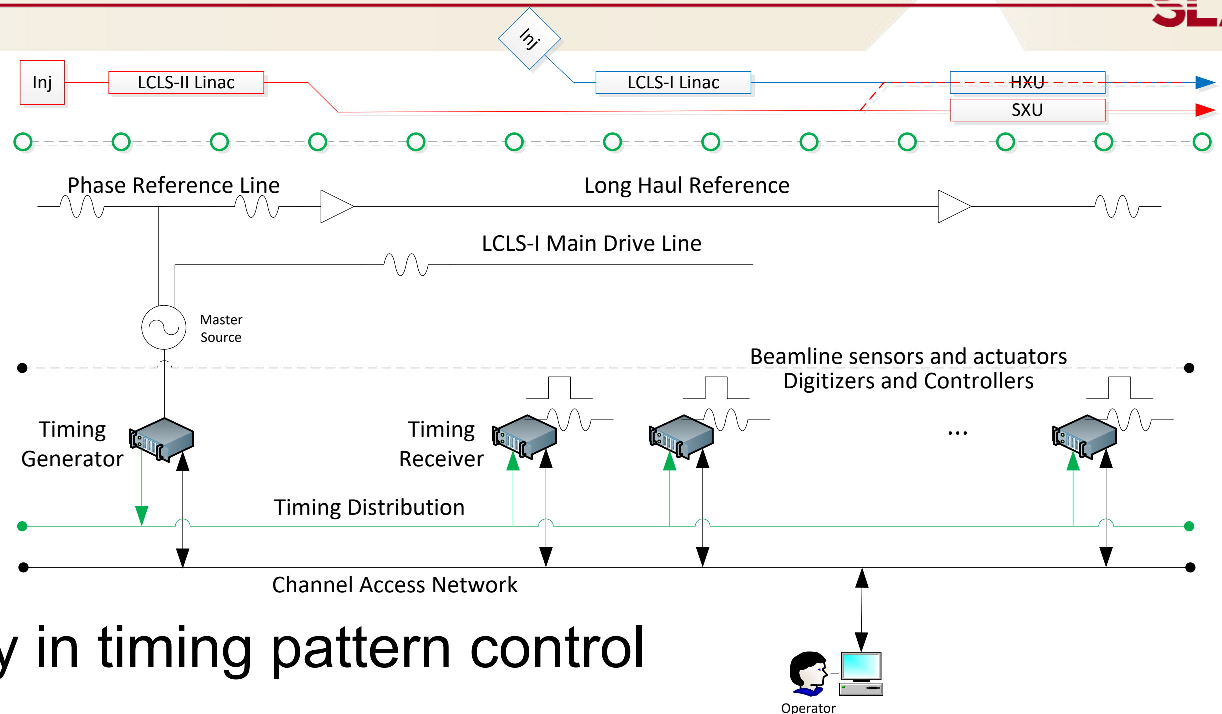
Further design details: *Int'l Beam Instrum. Conf. 2012*, Tsukuba, Japan, TUPA47

Beam loss monitors for LCLS-II
- see A.S. Fisher's talk TH1AB2

- Wire scanner detectors use long optical fiber distributed along beam pipe
- Loss monitors for machine protection cannot use gas detectors like the SLAC Protection Ion Chamber with 1 MHz bunch repetition rates
- Evaluate other
  - Long Beam Loss Monitors
  - Point Beam Loss Monitors
- Role of loss monitors in RF processing of SC cryomodules
- Integrated dose measurements with RADFETS
- New role for the Timing System in beam loss measurements

LCLS-II Timing System



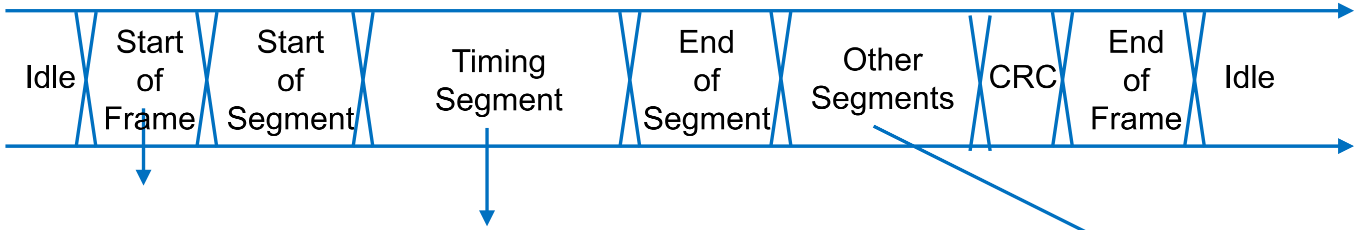
Phase Reference

Timing Distribution

- Need flexibility in timing pattern control
  - arbitrary bunch trains from 1 Hz to 1 MHz to multiple destinations
  - Beam synchronous data acquisition of single bunch data 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

Acknowledgements

D. Bohler, A. Brachmann, F.J. Decker, Y. Ding, P. Emma, A.Fisher, J. Frisch, M. Guetg, Z. Huang, A. Lutman, A.Martinelli, T. Maxwell, A. Novokhatski, J. Sheppard, M.Weaver, A. Young, J. Zemella

Thank You!

And also thanks to international collaborations with PAL, PSI, DESY ...

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20-24 August 2017 Grand Rapids, Michigan, USA

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