Status of Electron Beam Diagnostics

January 19, 2004

- *Review of electron beam diagnostics in the context of undulator commissioning*
- *Electron beam commissioning in readiness for undulator tests*
- *Electron beam diagnostics during FEL tuning*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Electron beam characterization

- *Measurement of 6D phase space*
  - *Transverse emittance*
  - *x, y only - no special effort made to measure coupling*
    - *round beams and no intentionally rolled beam lines*
  - *Bunch length and energy spread*
- *Beam centroid measurements*
  - *Energy*
    - *Is absolute energy calibration essential?*
    - *Only as good as bend field strength calibration, e.g. in the dump line.*
  - *Beam orbit*
    - *Requirement for absolute position measurement*
    - *Versus relative orbit – use beam based alignment*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

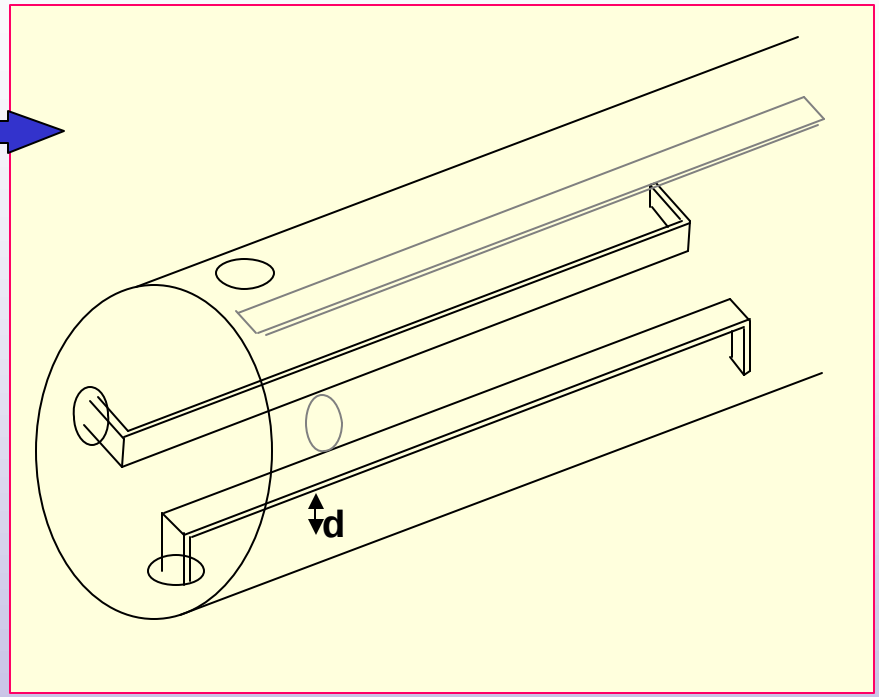
Electron beam monitoring

- *Electron beam changes due to FEL*
  - *Beam energy due to ISR*
  - *Energy spread from SASE*
  - *Microbuching not directly observable, except through x-ray spectrum*
- *Beam drifts due to upstream changes*
- *Minimize changes with feedback*
  - *Changes are never zero,*
  - *even with perfect feedback in a dynamic system*
- *Monitor pulse-to-pulse jitter in the beam*
- *Monitor instabilities in the beam*
  - *Diagnose CSR microbunching*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Status of beam position monitors

- *Injector-Linac-LTU*
  - *Stripline bpms*
  - *0.2 – 1 nC*
  - *5 mm resolution*
  - *Requires new modules*
    - *To be designed.*
  - *New stripline BPMs to be fabricated for chicanes*
    - *20 um res. for 1 - 0.2 nC in a 3 cm x 10 cm chamber*
  - *New stripline BPMs to be fabricated for the LTU in addition to existing FFTB BPM*
  - *Last 8 LTU BPMs redundant with undulator-style cavity BPMs*
    - *1 um resolution at 0.2 nC*

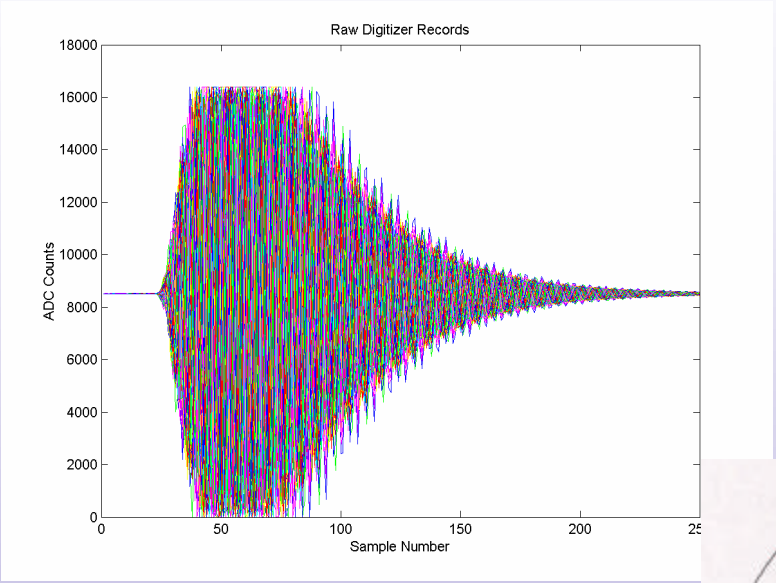


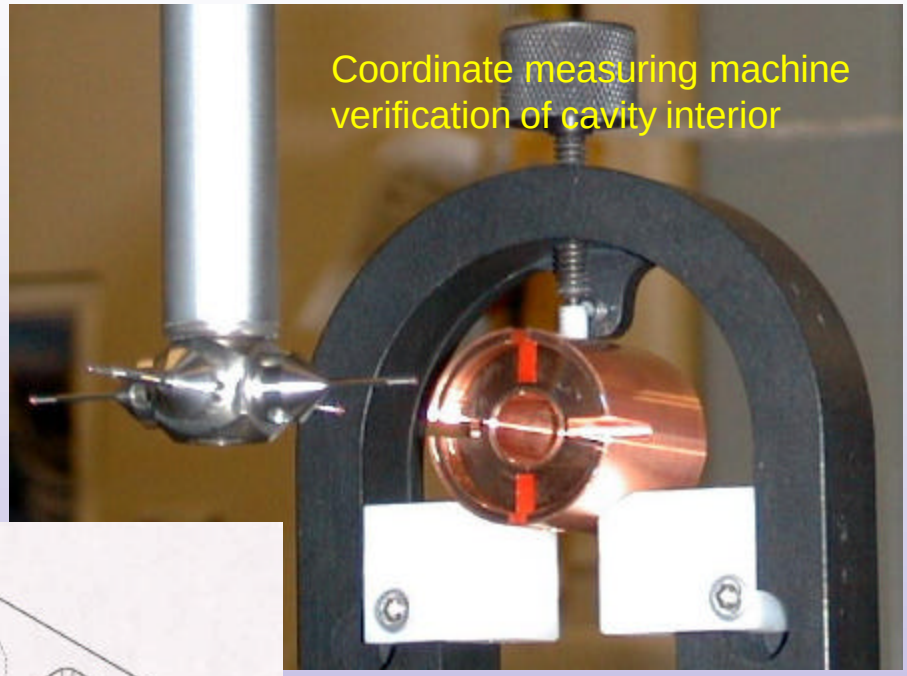
- *Aligned to* mechanical *center of quadrupoles*
- *Systematic offsets from variations in* **d**

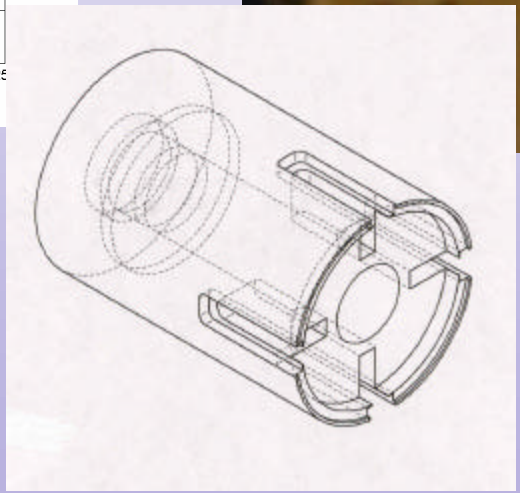
Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Cavity beam position monitors in the undulator and LTU

R&D at SLAC – Steve Smith





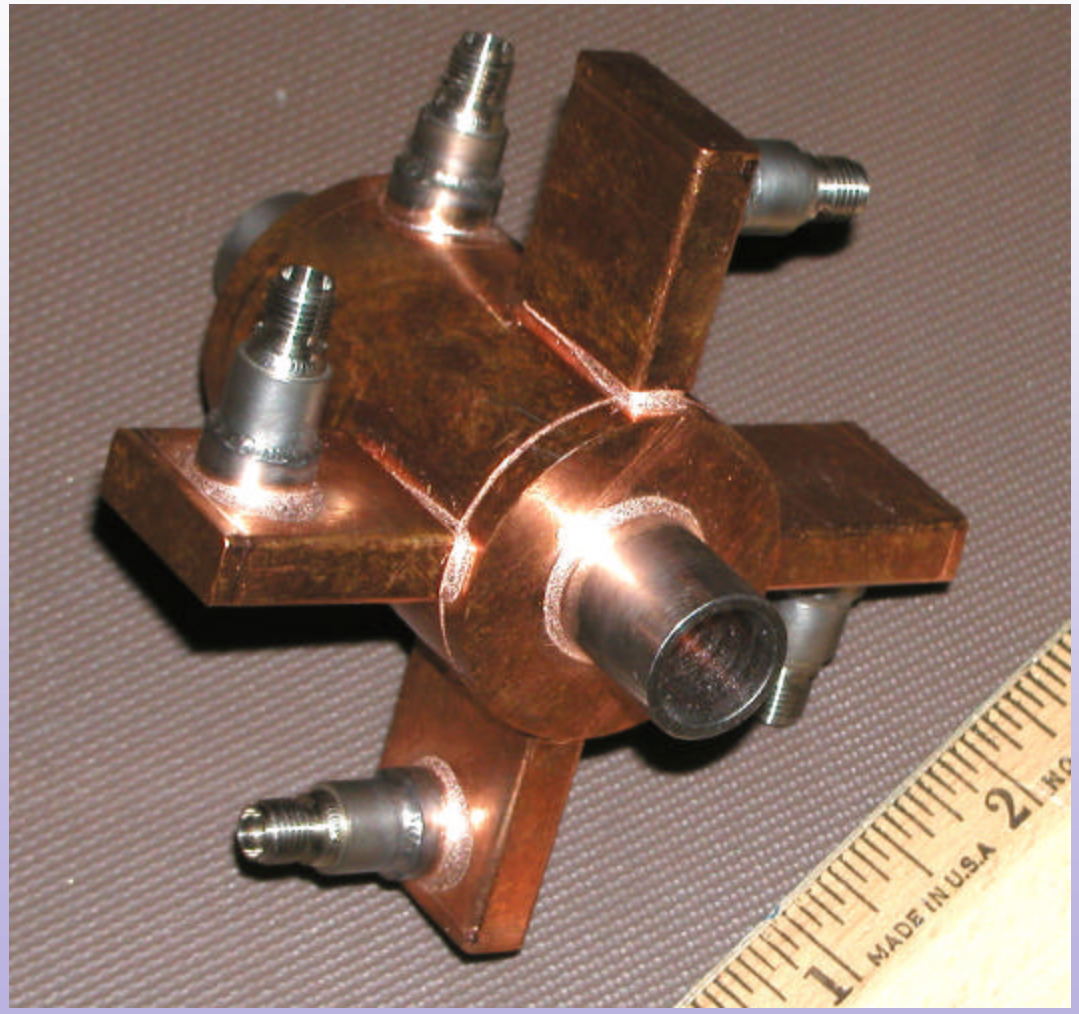


- Raw digitizer records from beam measurements at ATF

- X-band cavity shown
- Dipole-mode couplers

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

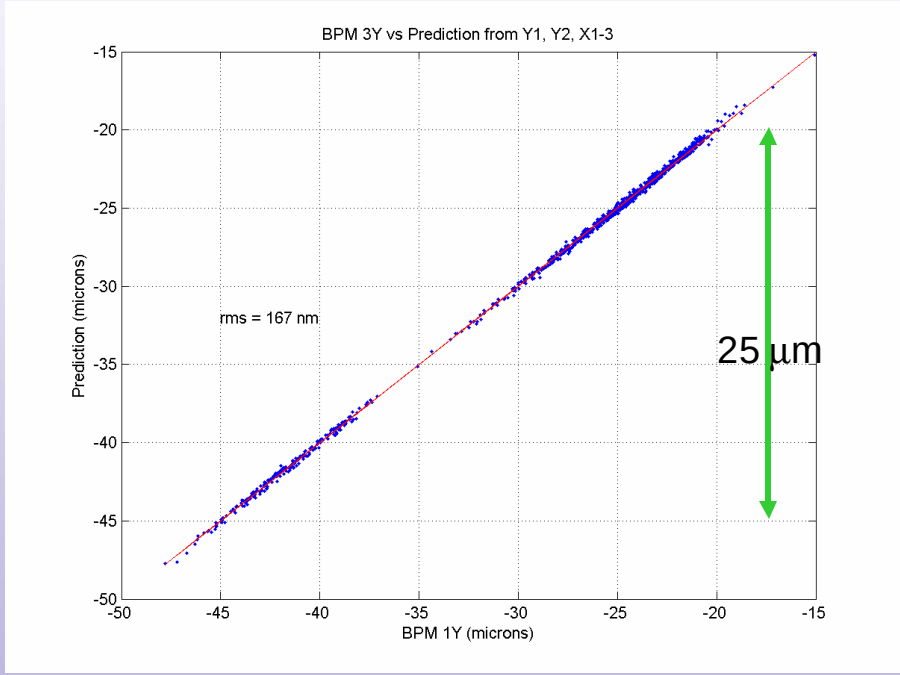
SLAC X-band cavity BPM – Steve Smith

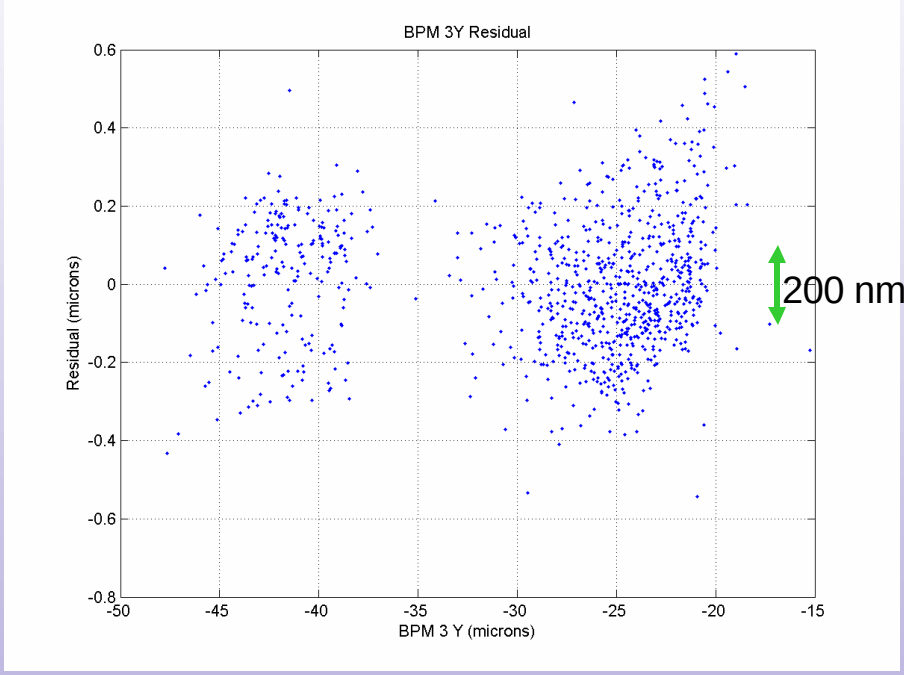


- *Mechanical center of RF BPM well correlated to electrical center – more accurately than for stripline BPMS*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Cavity BPM R&D at SLAC – Steve Smith
preliminary beam calibration data from a C-band cavity at ATF





- cavity BPM signal versus predicted position
- bunch charge 1.6 nC

- plot of residual deviation from linear response
- << 1 µm LCLS resolution requirement

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

BPM Controls issues

- *Timing pulse identification*
  - *Allows all BPMs to be read on the same beam pulse*
    - *Single pass machine each pulse is different*
- *120 Hz readback*
- *Ring buffer for all BPM readings extending back last ~1000 pulses*
  - *MPS trips can be traced to orbit excursion*
  - *RMS orbit jitter can be historied every ~1000 pulses*
- *Application software linked to optics model*
  - *Real-time orbit fitting displays*

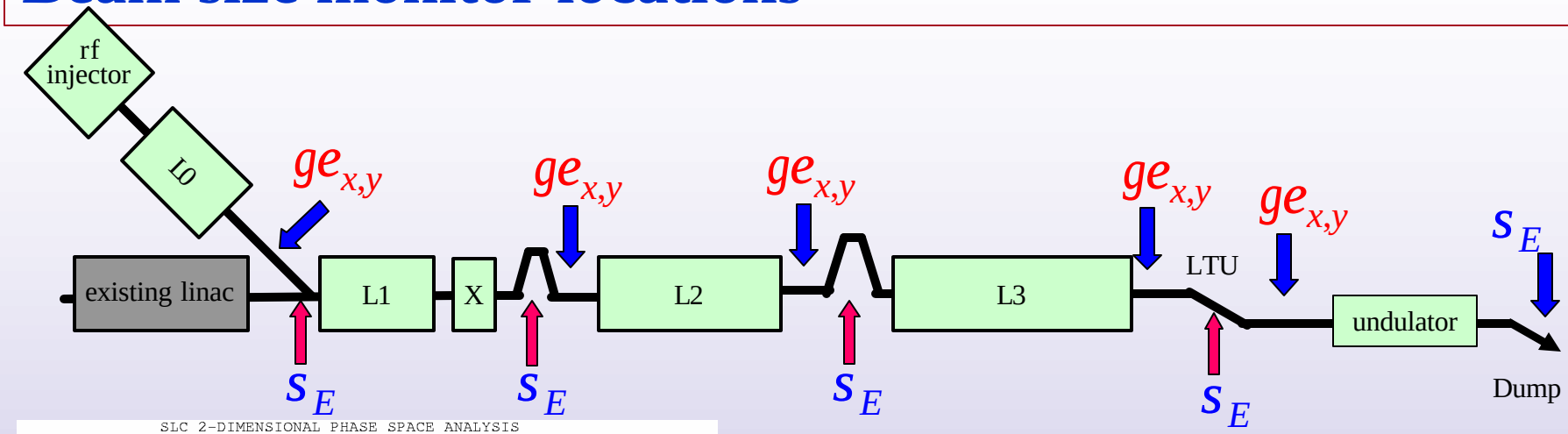
Patrick Krejcik, LCLS
pkr@slac.stanford.edu

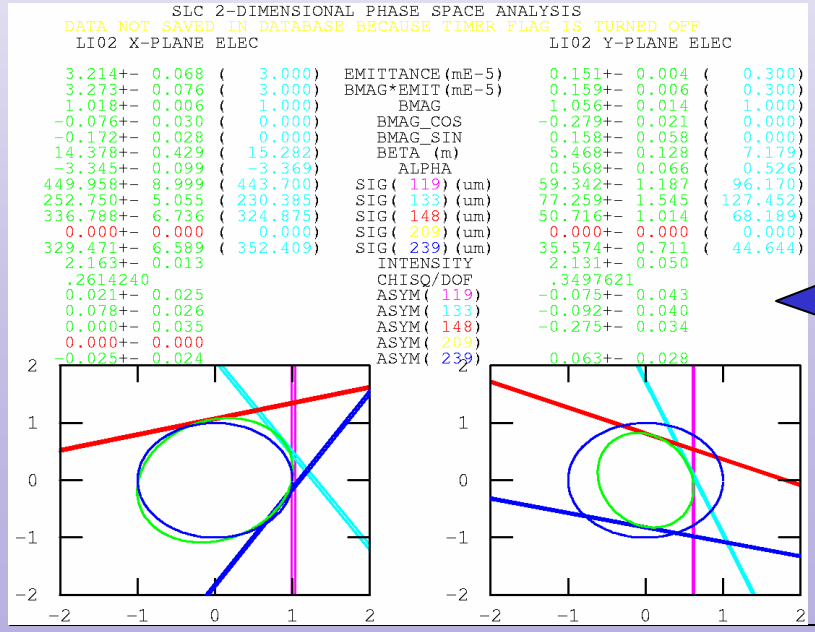
Beam size monitors

- *Wire scanners*
  - *Used throughout SLC, essentially noninvasive*
  - *Technical challenges are*
    - *Small beam size dictates small wire*
    - *Range of beam charge 0.2 – 1 nC,*
      - *compromise between signal to noise and saturation*
      - *Signal to noise from linac dark current*
    - *Low beam charge operation dictates high Z wire material*
    - *Beam loss considerations in front of undulator dictates low Z*
  - *Groups of 4 wire scanners for emittance reconstruction*
  - *Measure average,* projected *emittances in x and y*
  - *Matching section at end of LTU verifies emittance and beta match at undulator entrance*
  - *However, no room in the dump beam line for zero dispersion location*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Beam size monitor locations





4-wire emittance reconstruction example from linac sector 2

ge_y = 1.5 μm

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

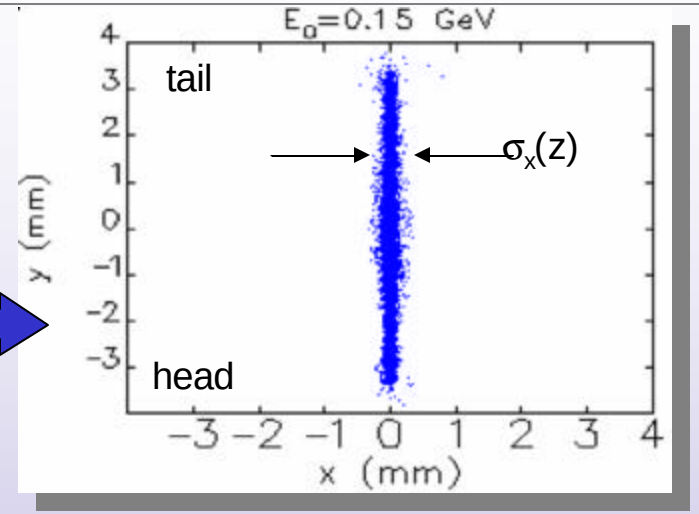
Beam size monitors

- *Profile monitors*
  - *Except for injector, use thin foil OTR screens*
  - *Technical challenges are*
    - *Small beam size requires precision, remote optics + digital video ($'s)*
    - *Stretching a thin, low Z foil flat*
  - *Measure single pulse x & y beam profiles*
  - *Acts as emittance spoiler , but beam still transported to dump*
  - *Energy spread profile in high dispersion locations*
    - *Injector inflector, chicanes, LTU dogleg, dump line*
  - *Single pulse slice emittance diagnostic (invasive)*
    - *in conjunction with transverse RF deflecting cavity*

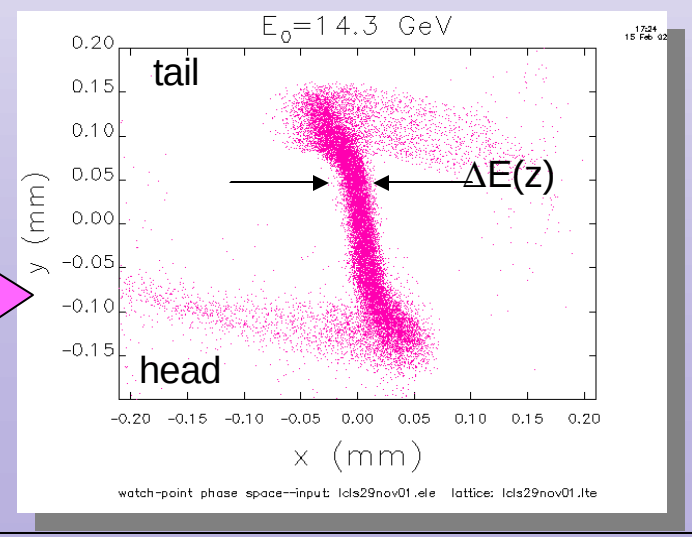
Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Slice parameters from transverse RF deflecting cavity

- *OTR screen down stream of the Tcav. can be used in conjunction with a quadrupole scan to measure horizontal slice emittance*



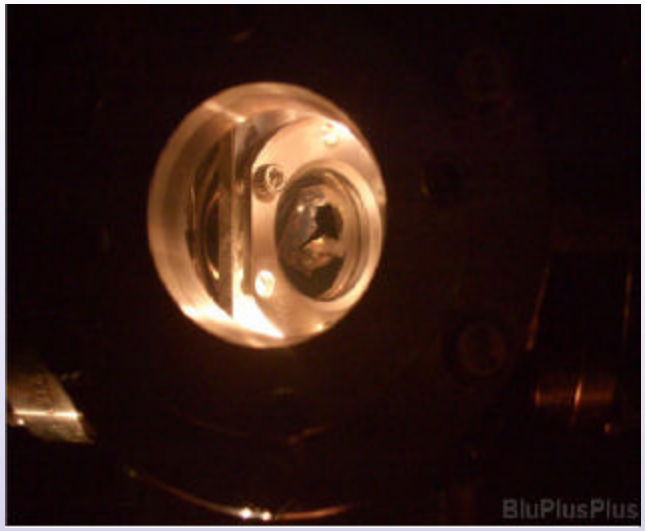
- *OTR screen down stream of the Tcav. At a horizontal dispersion location, large h_x, small b_x, can measure slice energy spread*



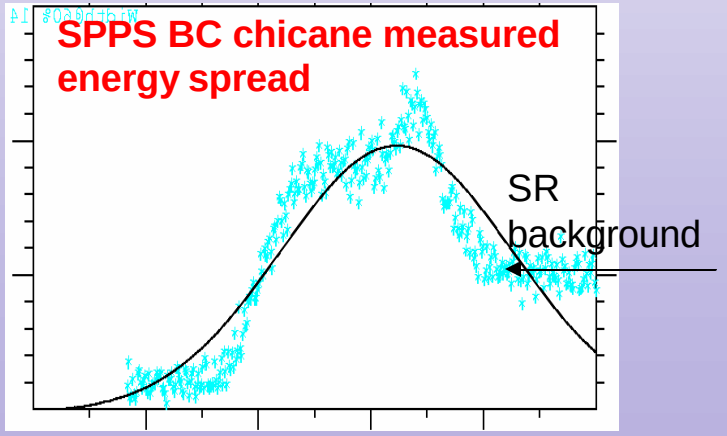
Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Profile Monitors

- *Technical challenges*
  - *Small beam size requires precision, remote optics + digital video ($'s)*
  - *Stretching a thin, low Z foil flat*
  - *Avoiding punctures*



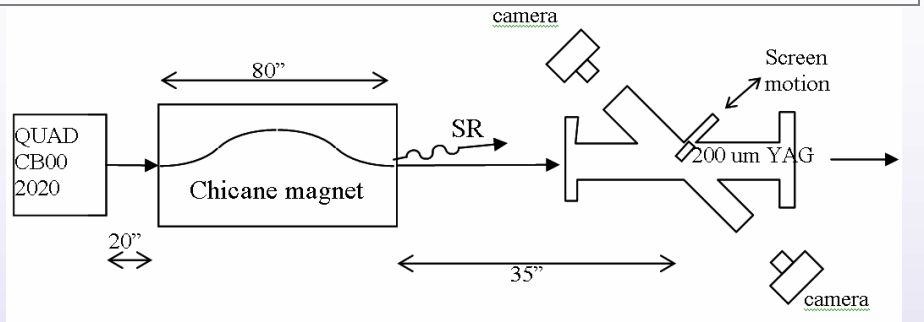
  - *Block synchrotron radiation from bends bends with polarizers*

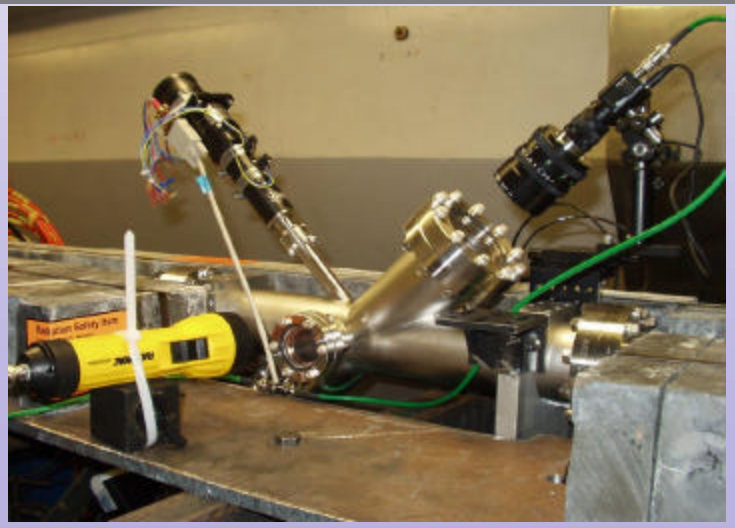


Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Profile Monitors for Synchrotron Radiation

- *single shot projected energy spread*
- *Generated from vertical chicane wiggler in a horizontal dispersion region*
- *ISR strikes an off-axis screen*
- *Optical resolution set by divergence of x-rays, filter out low energy x-rays with foil and use thin fluorescent crystal*





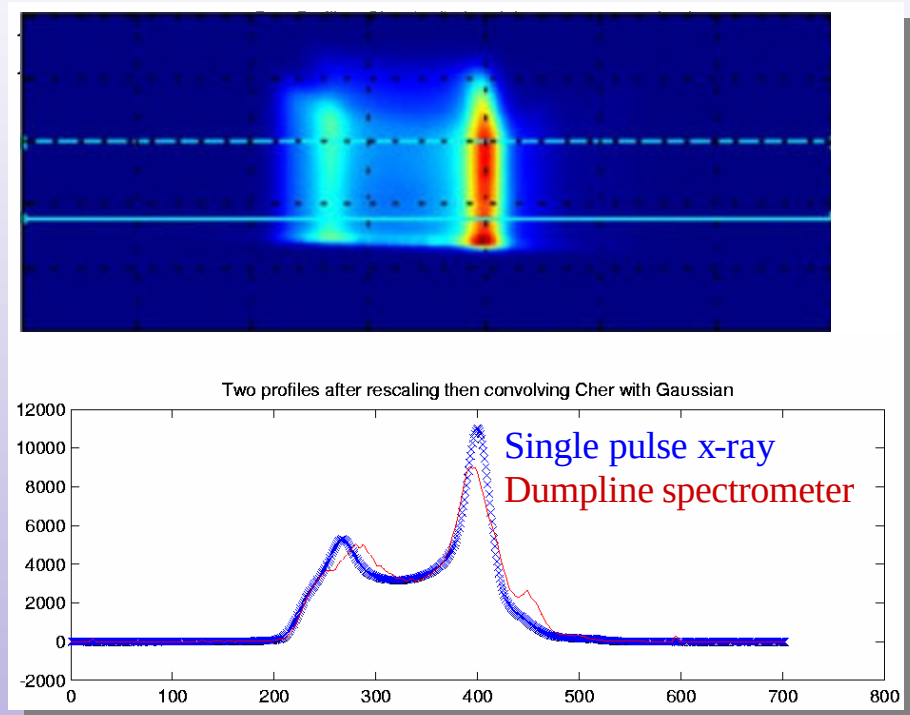
- *Also serves as CSR monitoring port*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Synchrotron Radiation:

- *Lattice optimized for high DE resolution: low b_x, high h_x*
- *real-time, noninvasive energy spread monitor*
- *single shot projected energy spread*

SPPS Measurement

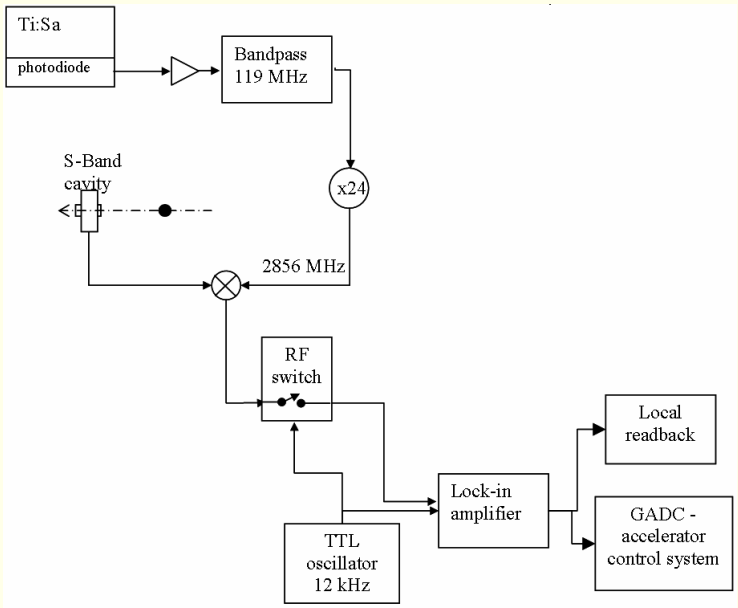


Compared to energy spread at dump spectrometer

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Conventional diagnostics and their upgrades

- *Beam Phase Monitors*
  - *Use linac style S-band monitor cavities*
  - *Measure pulse-to-pulse phase jitter*
  - *Subject to thermal drift so can't use for feedback control of phase*
    - *Thermal stabilization technology (as required for the undulator) may make this possible in the future.*
  - *Beam phase can be measured w.r.t.*
    - *RF distribution*
    - *Laser from injector or at experiment*



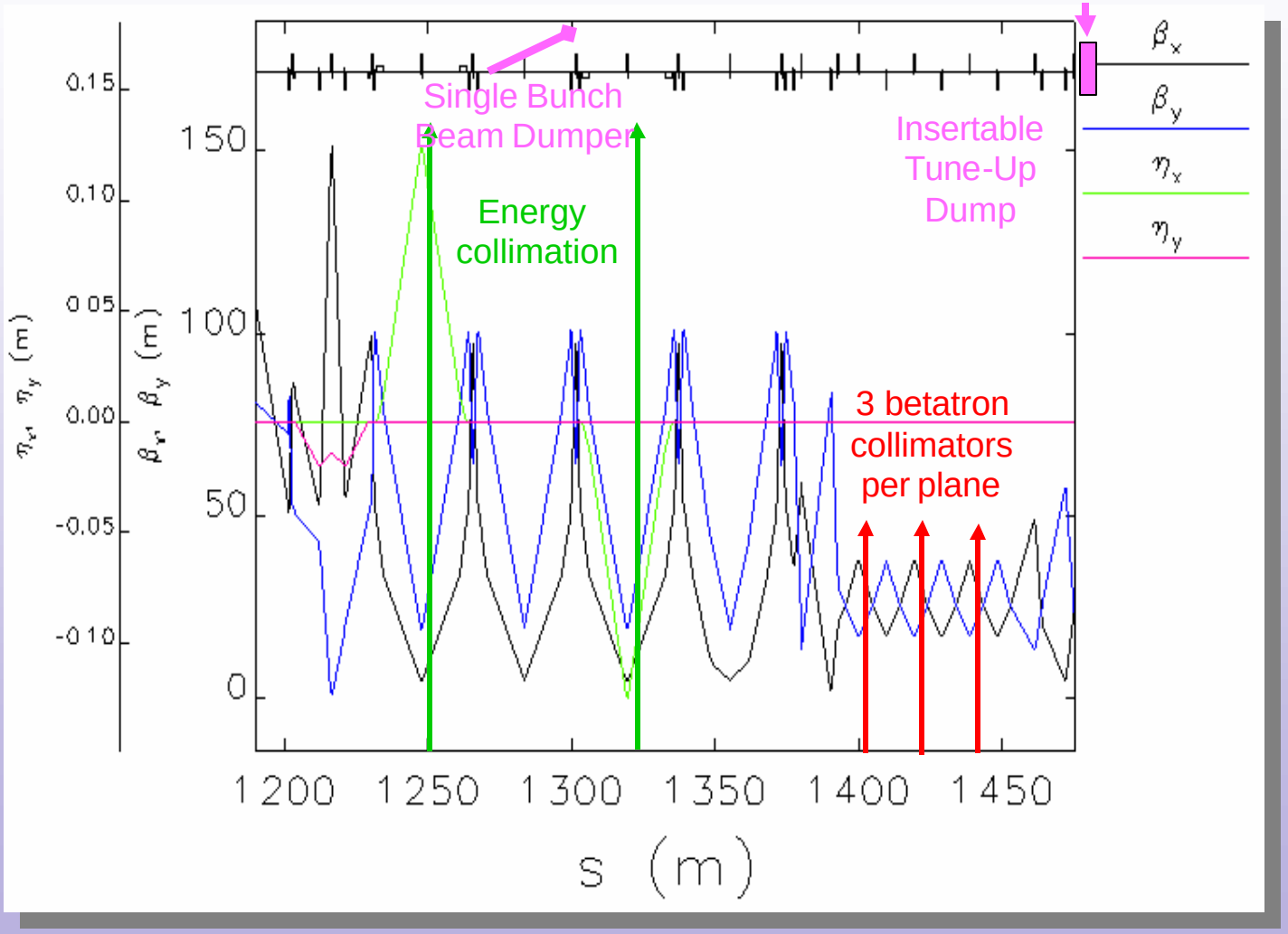
Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Collimation and Machine Protection System

- *Collimation*
  - *Movable energy collimator in each chicane*
    - *Diagnostic, and later for foil slits*
  - *Pair of adjustable energy collimators in the dog-leg bend of the LTU*
  - *Three x & y adjustable collimators in the matching section of the LTU*
    - *Two betatron phases and one clean-up in each plane*
- *Beam Loss Monitors*
  - *PLIC cables along the length of the undulator*
  - *Protection Ion Chambers at*
    - *collimation section in LTU*
    - *Between undulator modules*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Linac To Undulator beamline diagnostic & collimation section



Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Beam Rate Limiting

- *Single bunch beam dumper (SBBD)*
  - *Linac beam up to the dog-leg bend in the LTU can be maintained at 120 Hz*
    - *Favorable for upstream stability and feedback operation*
  - *Pulsed magnet allows*
    - *Single shot, 1 Hz, 10 Hz, 120 Hz down the LTU line*
    - *Failure in pulsed magnet will turn off beam at gun*
- *Tune-up dump at end of LTU*
  - *Optional second stopper at end of dummy line (radiation?)*
  - *Max. 10 Hz to tune-up dump*
  - *Stopper out will arm MPS for stopping beam with the SBBD*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Beam Rate Limiting

- *Conditions that will stop the beam at the SBBD*
  - *Tune-up dump at end of LTU is out,* **and***:*
  - *Beam loss at detected by either by PLIC along the undulator chamber, or by the PIC's between the undulator modules*
  - *Invalid readings from undulator*
    - *Vacuum*
    - *Magnet movers*
    - *BPMs*
  - *Energy error in the LTU*
  - *PIC's at the collimators*
  - *Launch orbit feedback failing*
  - *Magnet power supplies for some key elemets*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Bunch Length Measurement

Absolute bunch length profile measurements

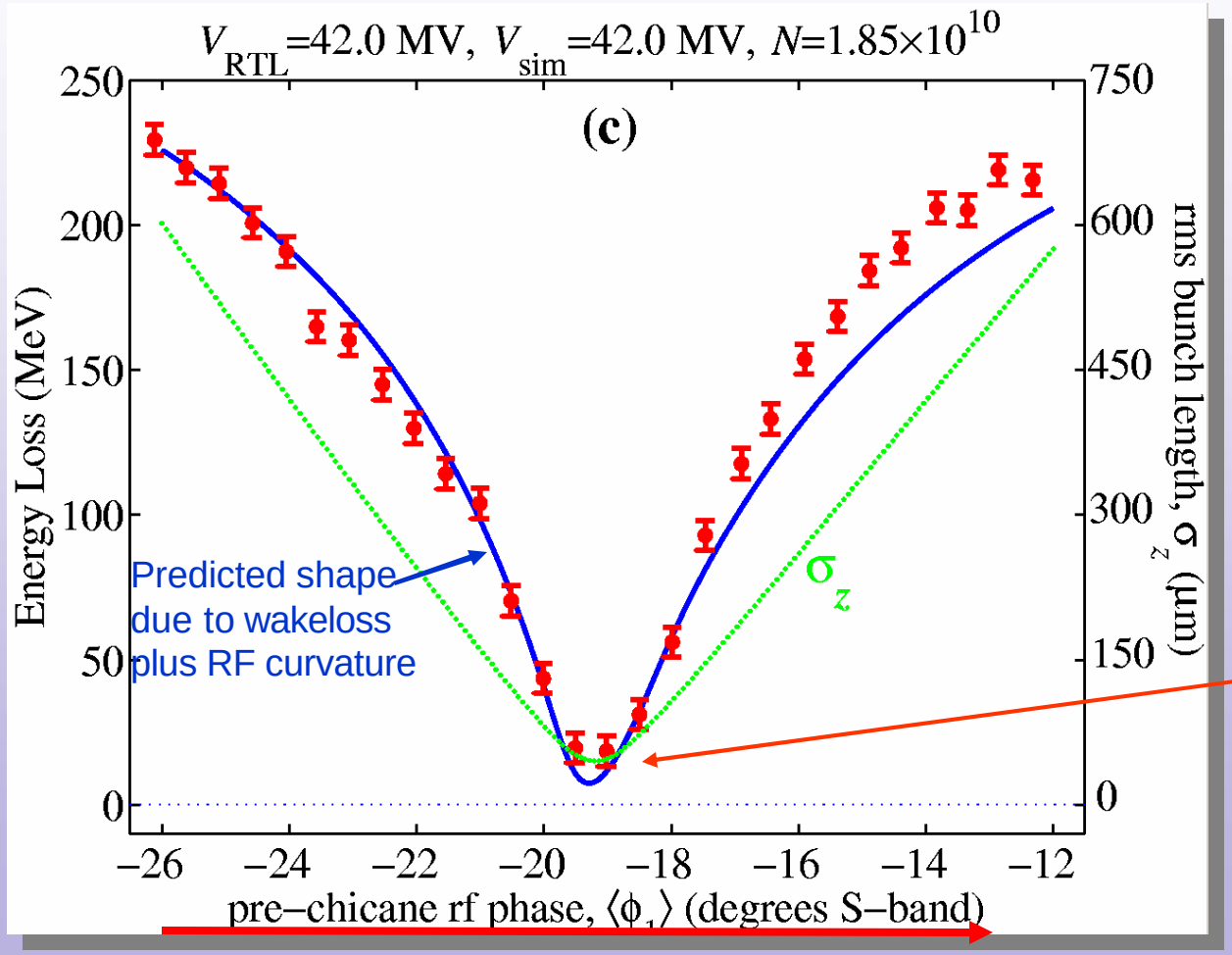
- *RF transverse deflecting cavity*
  - *1 Hz pulse stealing*
  - *3 pulse measurement*
- *Electro optic longitudinal profile and timing measurement*
  - *Single pulse*
- *Autocorrelation measurement from CTR*
  - *Average, 2nd moment*

Relative measurements of rms bunch length

- *THz power level measuremnts from Coherent TR, DR, SR*
  - *Prompt, single pulse*
- *Longitudinal wakefield energy loss*
  - *Invasive, fast scan*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Relative bunch length measurement at SPPS based on wakefield energy loss scan



Energy change measured at the end of the linac

as a function of the linac phase (chirp) upstream of the compressor chicane

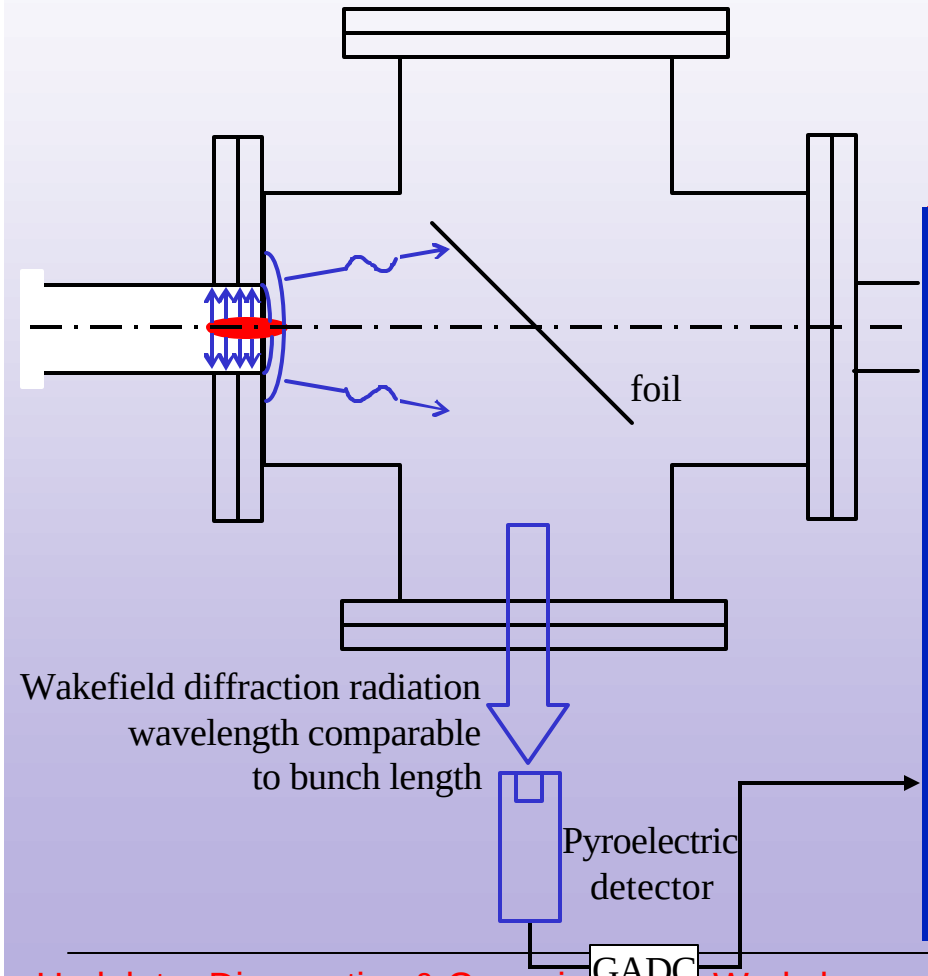
Shortest bunch has greatest energy loss

Predicted wakeloss___ (EMMA)

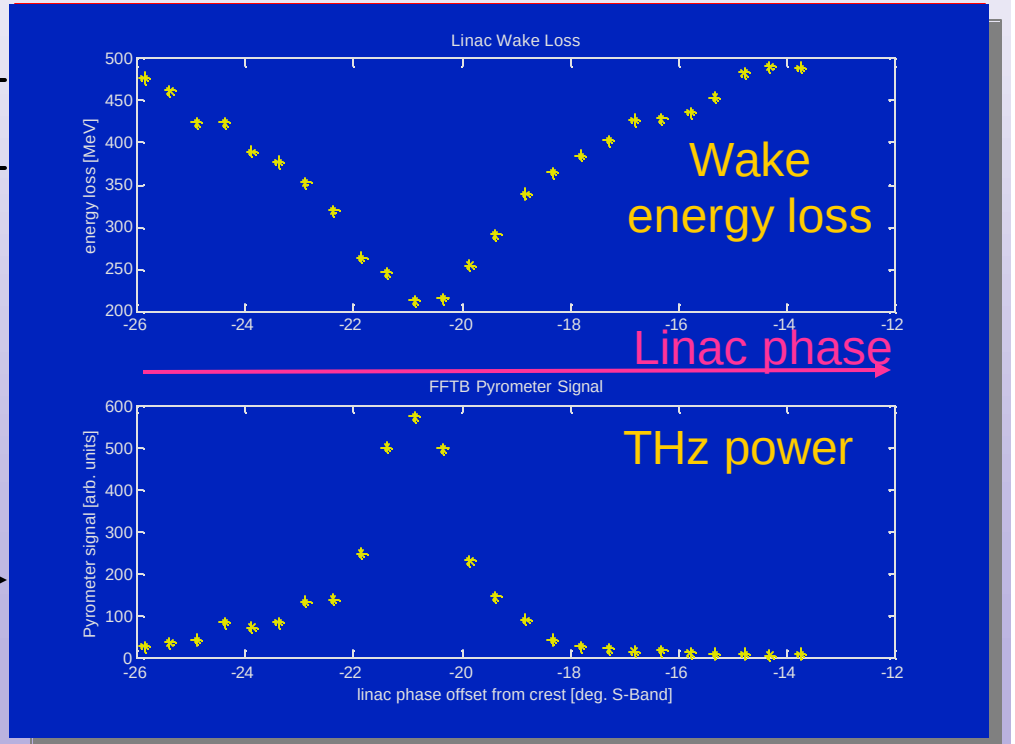
For bunch length s_z___

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Far-Infrared Detection of Wakefields from Ultra-Short Bunches



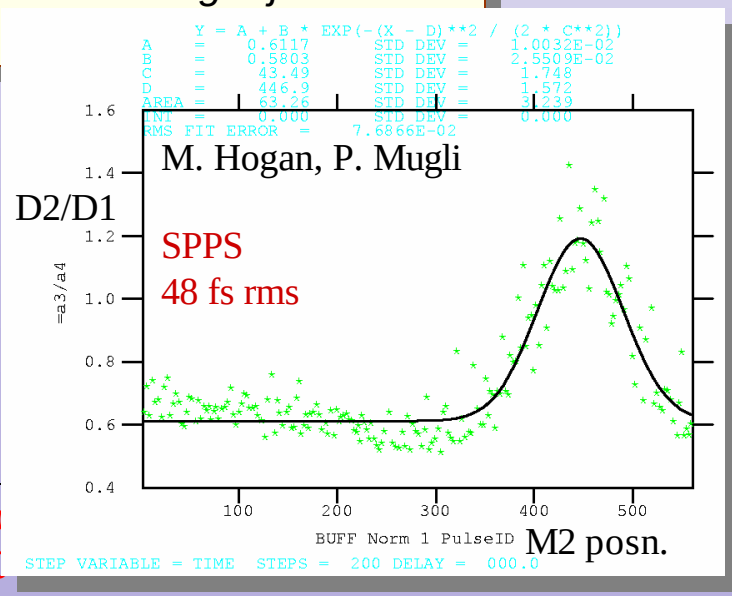
Comparison of bunch length minimized according to wakefield loss and THz power

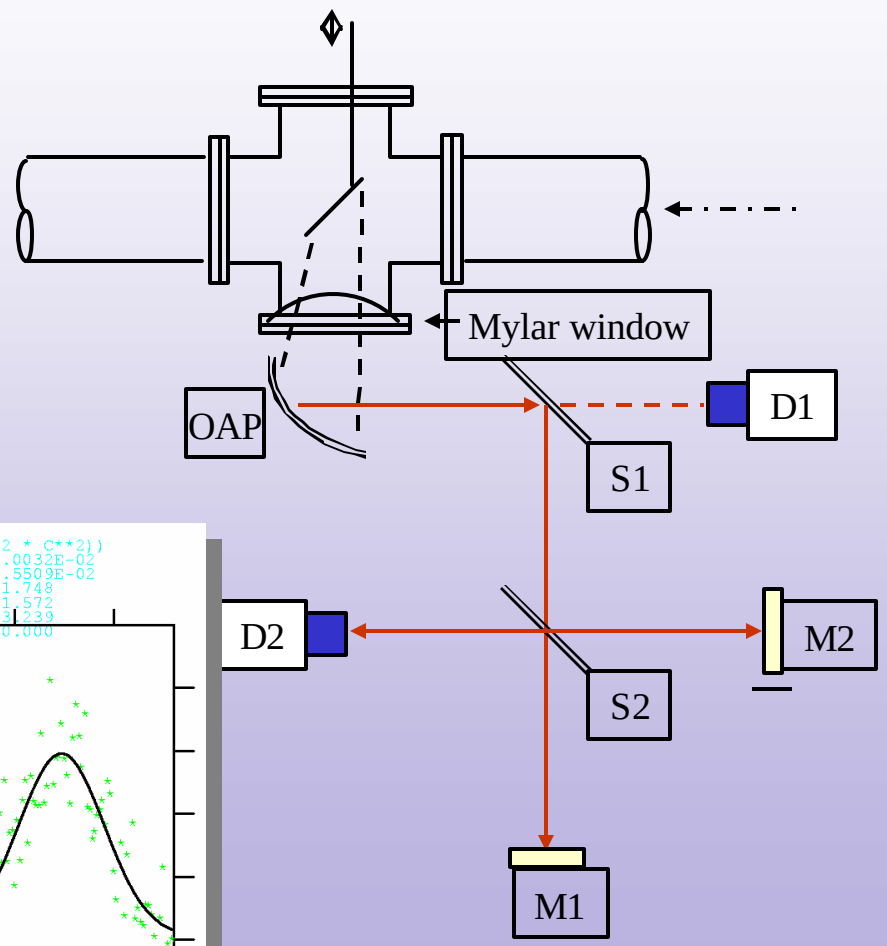


Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Absolute bunch length determination

- *Average bunch length from CTR autocorrelation*
  - *Radiation from the OTR screen is focused into an interferometer*
  - *One arm of interferometer is movable, so two profiles are swept through each other*
  - *Measured bunch length is calibrated in microns of arm motion*
  - *Averaged over many pulses, so integrates any bunch length jitter*





Patrick Krejcik, LCLS
pkr@slac.stanford.edu

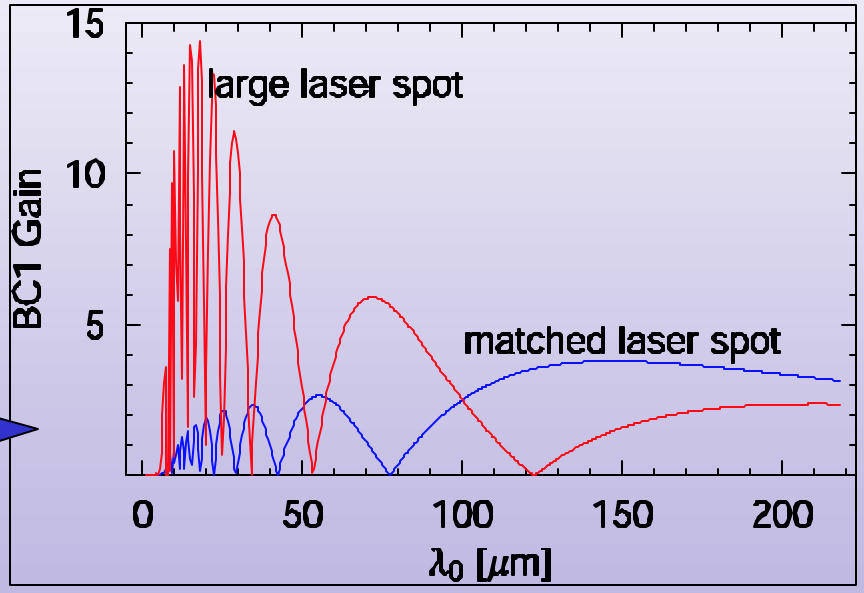
CTR Measurements

- *Technical challenges*
  - *Intercepting thin foil (OTR) versus foil with hole (ODR)*
  - *Wavelength response of vacuum window*
    - *Fused silica*
    - *Mylar foil vacuum window*
    - *Window diameter*
  - *Wavelength response of water vapor*
    - *Dry nitrogen blanket*
  - *Detecting power at several wavelengths*
    - *Tune to arbitrary bunch length, not the minimum bunch length*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

CSR THz radiation from diagnostic chicane

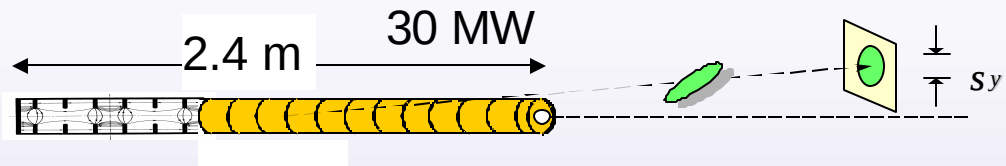
- *THz spectral power diagnoses relative bunch length*
- *CSR spectrum reveals spikes in bunch length distribution*
- *Spikes due to microbunching instability arising in the BC chicanes also seen in CSR spectrum*



Z. Huang:
expect to observe microstructure at l_0/comp.fact

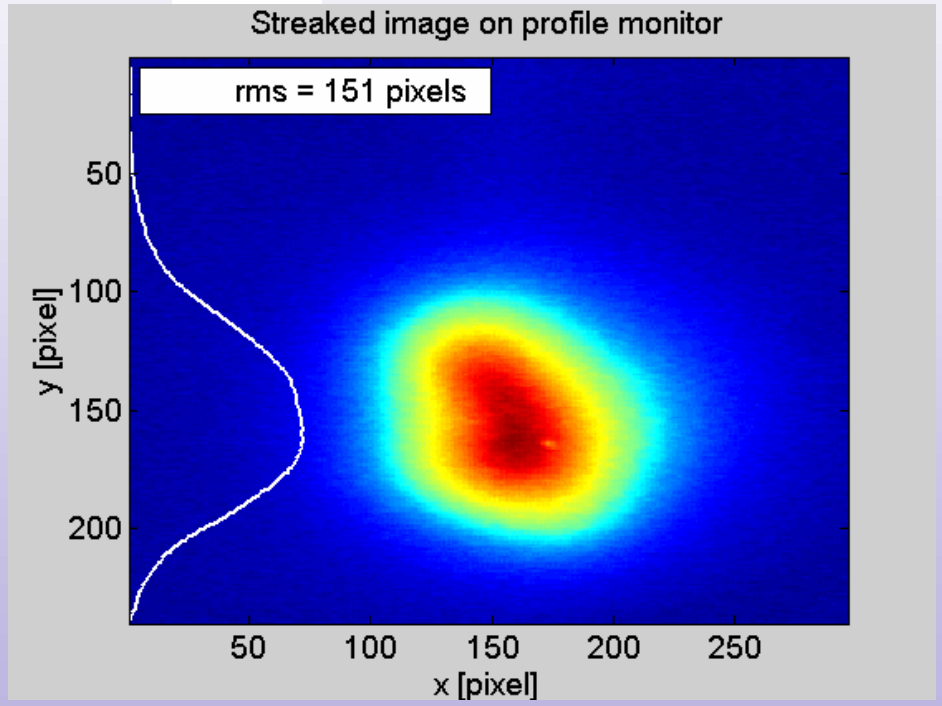
Patrick Krejcik, LCLS
pkr@slac.stanford.edu

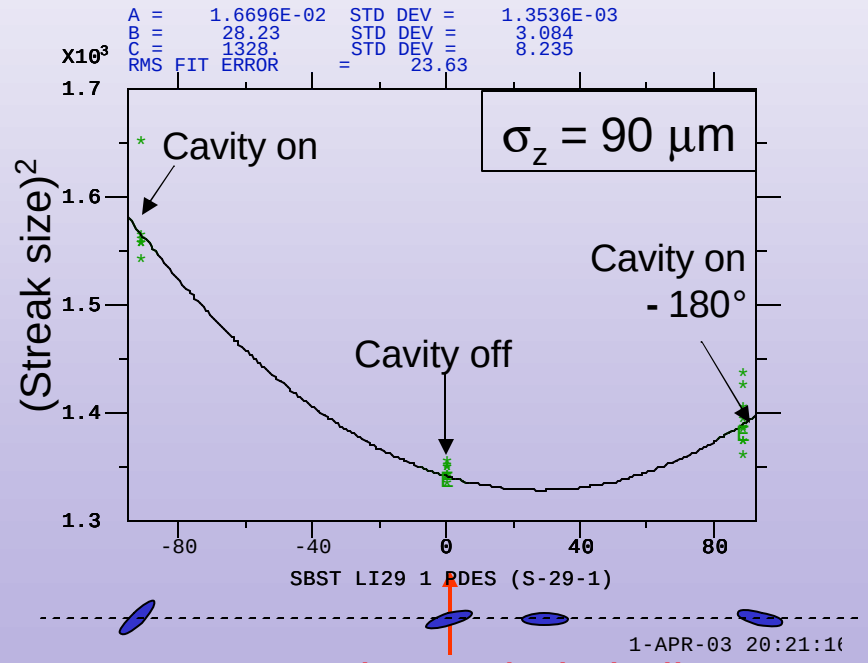
Bunch Length Measurements with the RF Transverse Deflecting Cavity

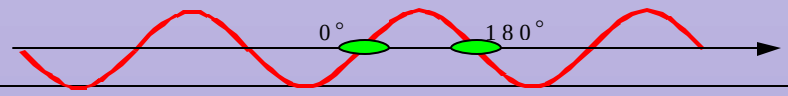


Bunch length reconstruction
Measure streak at 3 different phases

$$\sigma_y^2 = A\phi_{rf}^2 + B, \quad \sigma_z = \frac{\lambda_{rf}\sqrt{A}}{4C}$$



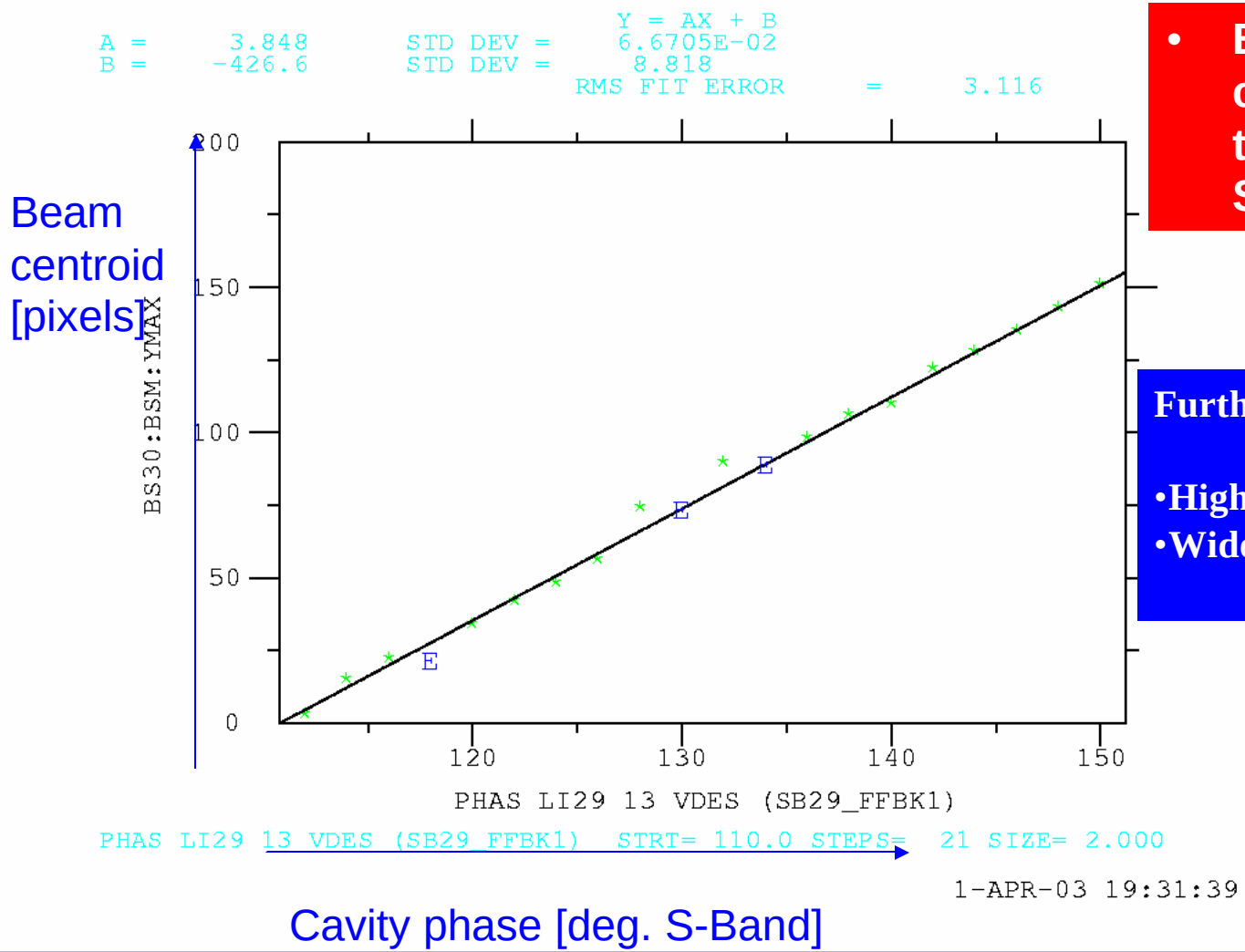




Asymmetric parabola indicates incoming tilt to beam

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Calibration scan for RF transverse deflecting cavity



- **Bunch lenght calibrated in units of the wavelength of the S-band RF**

Further requirements for LCLS:

- **High resolution OTR screen**
- **Wide angle, linear view optics**

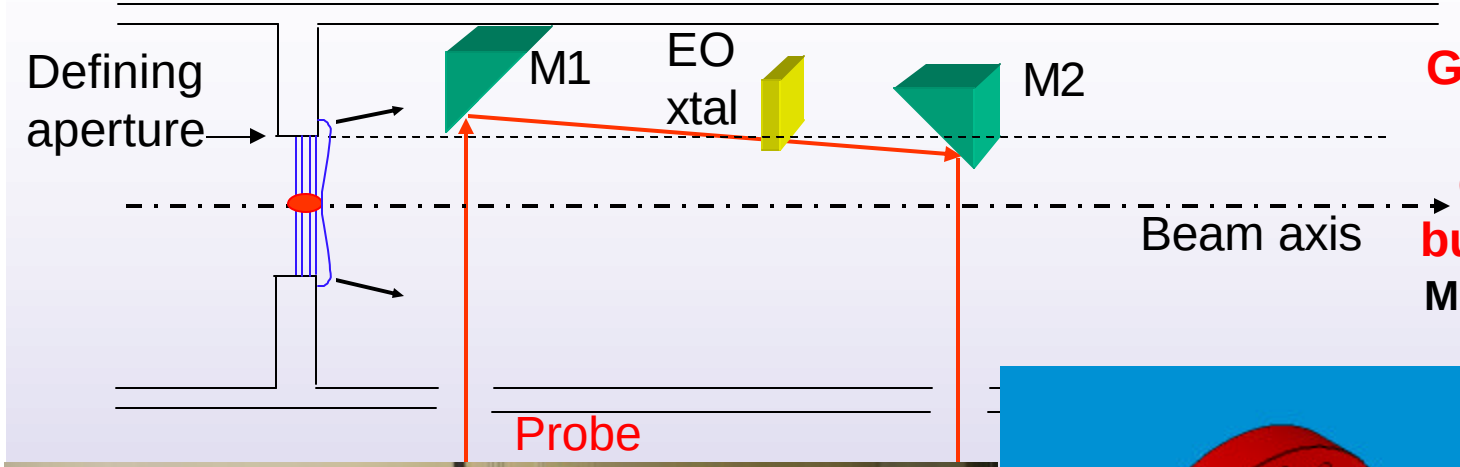
Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Bunch length and timing diagnostics

- *Absolute bunch length determination*
  - *Single shot electro optic pump probe measurement*
    - *Transforms the problem of measuring short electron bunch length to measuring a short pulse of laser light.*
    - *Electro-optic process is inherently fast, < 2 fs*
    - *Time resolution is dependant on crystal geometry and laser BW*
    - *Investigating two geometries at SPPS*
    - *Femtosecond laser systems are complex*
    - *Innovation at SPPS is transport a compressed beam to the e- beamline with a long fiber*

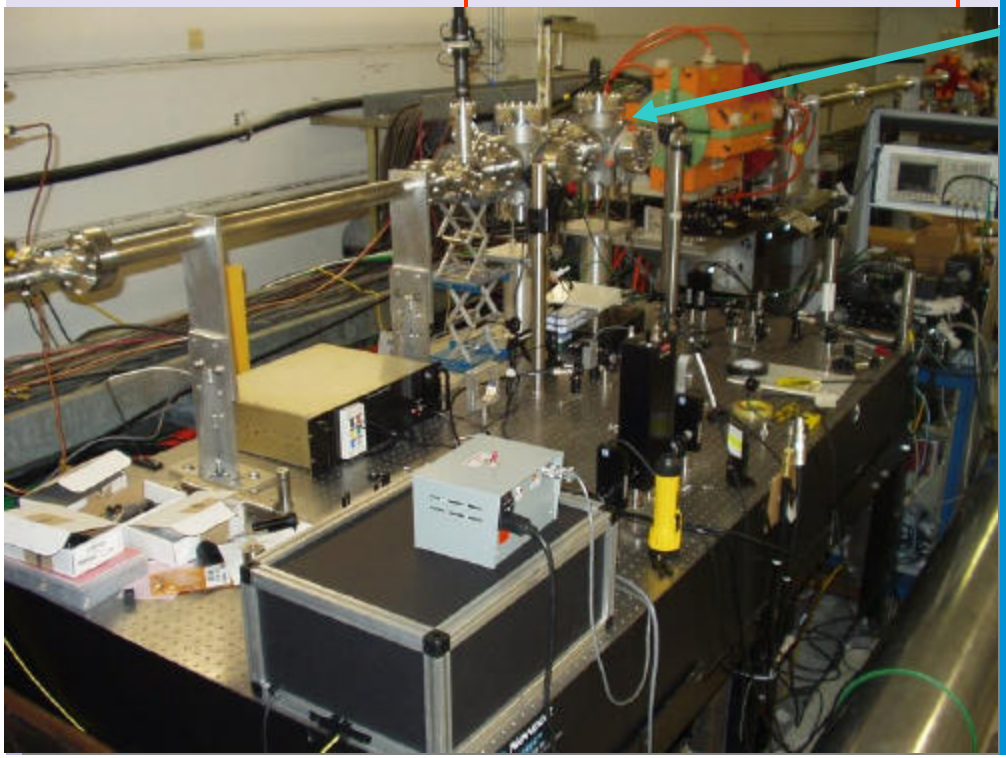
Patrick Krejcik, LCLS
pkr@slac.stanford.edu

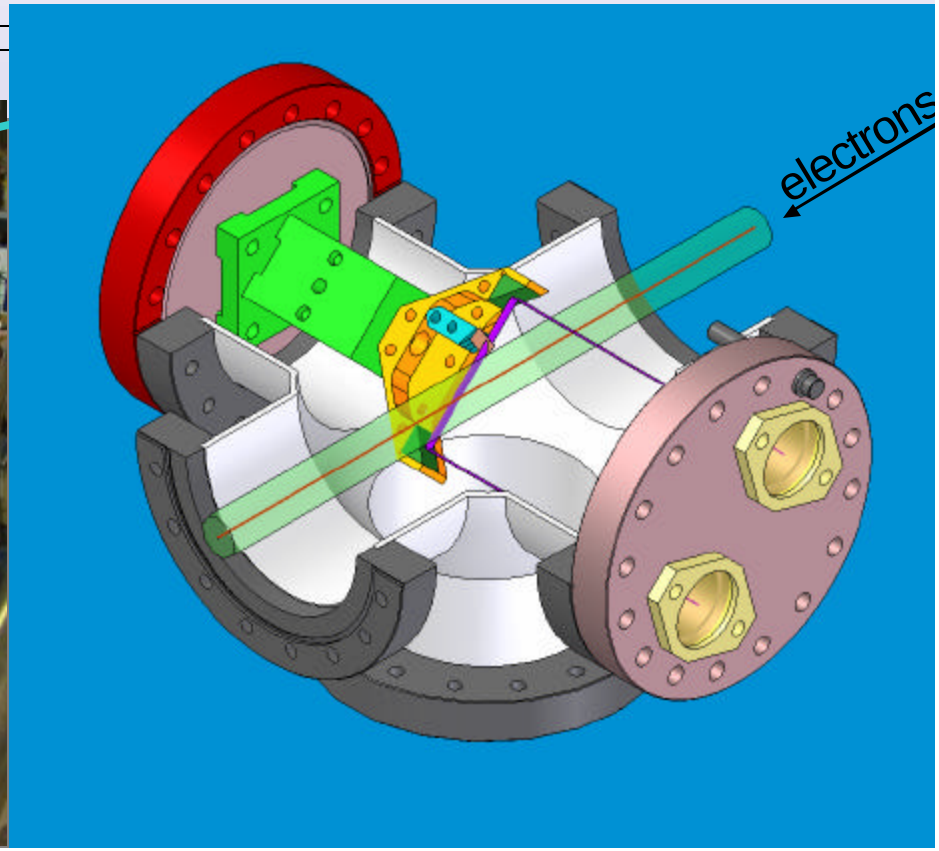
Electro Optic Bunch Length Measurement



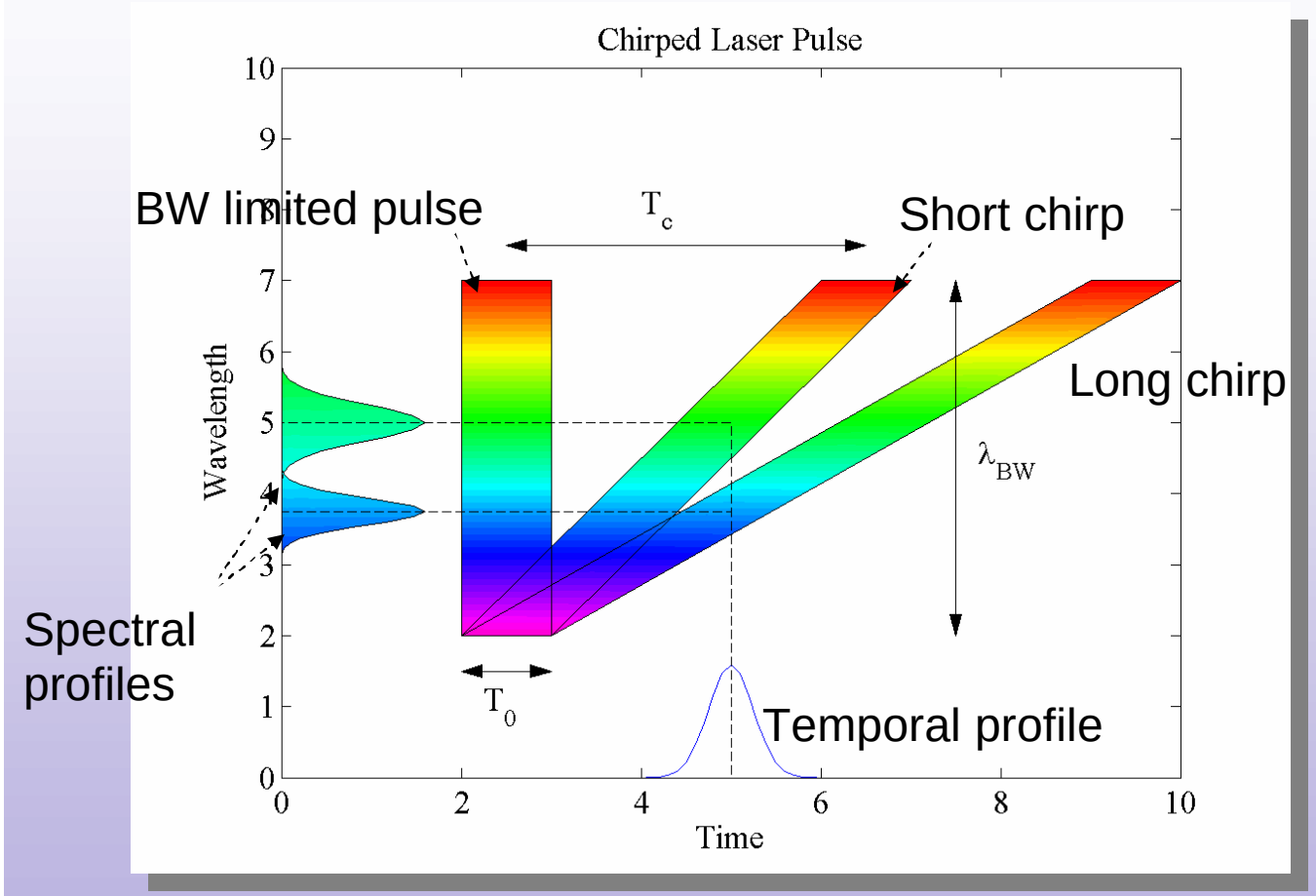
Geometry chosen to measure direct electric field from bunch, not wakefield

Modelled by H. Schlarb





Resolution limit in temporal-to-spectral translation



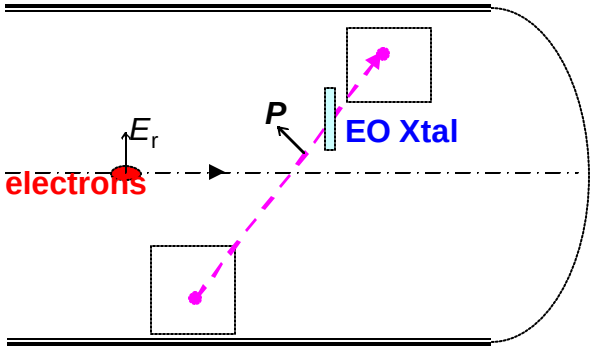
$$T_{res} = \sqrt{T_0 T_C}$$

However, recent work shows this limit can be overcome with noncollinear cross correlation of the light before and after the EO crystal

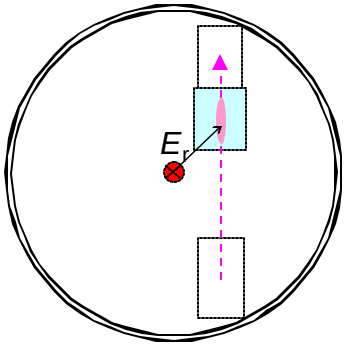
S.P. Jamison,
Optics Letters, 28, 1710, 2003

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

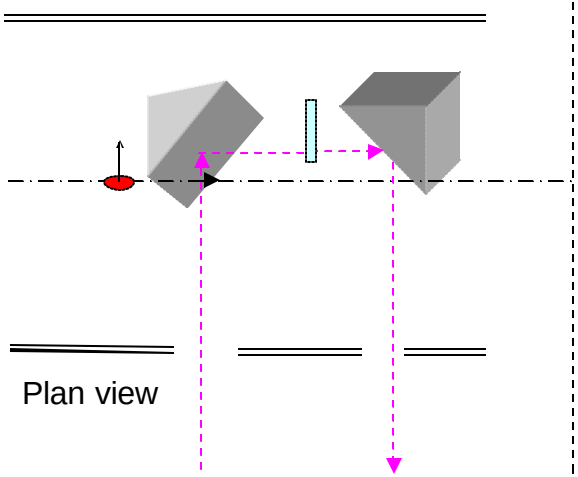
Temporal to spatial geometry under test at SPPS



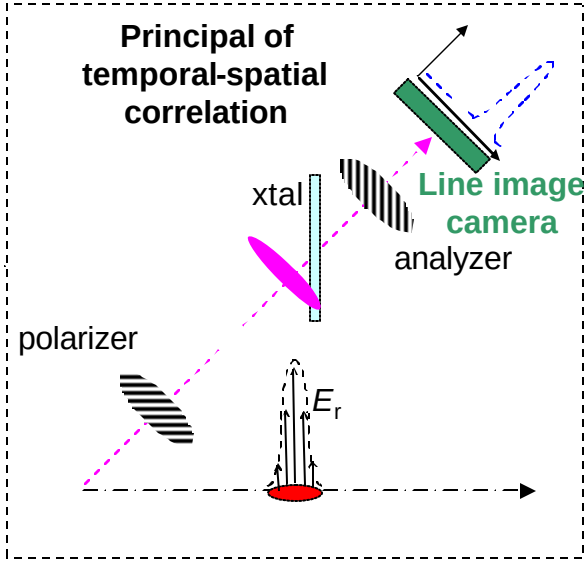
Elevation view



End view



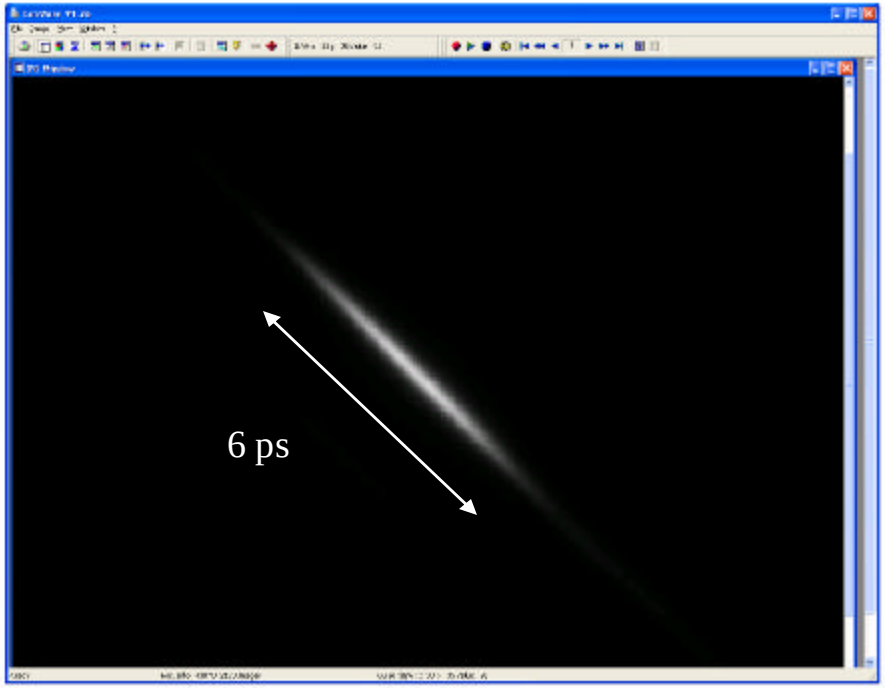
Plan view

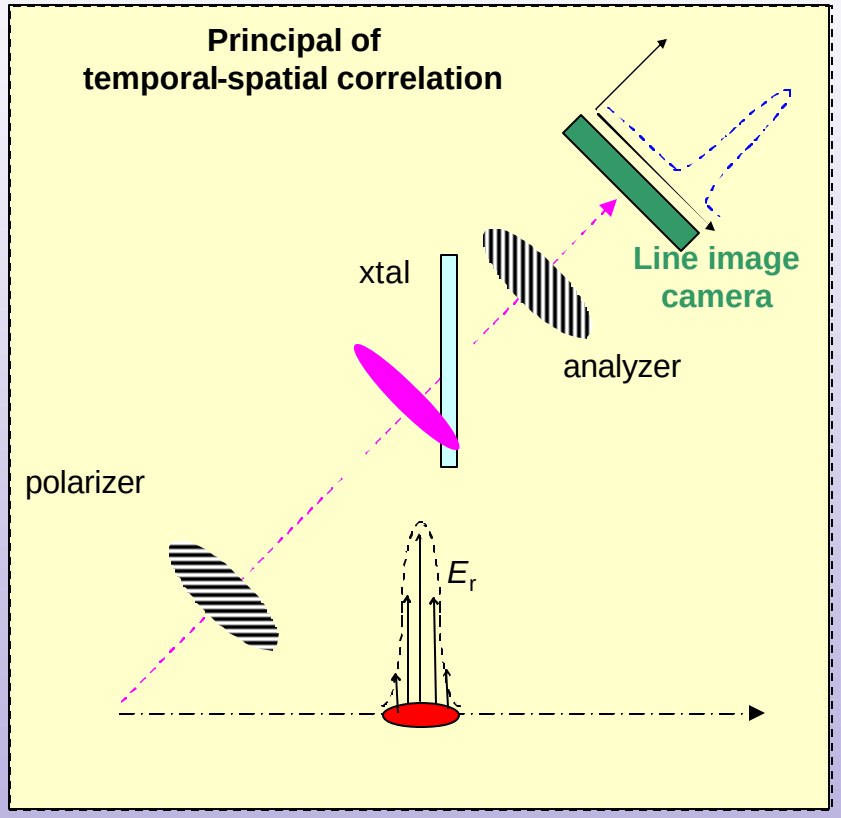


Patrick Krejcik, LCLS
pkr@slac.stanford.edu

SPPS Electro Optic bunch length measurements – Adrian Cavalieri et al

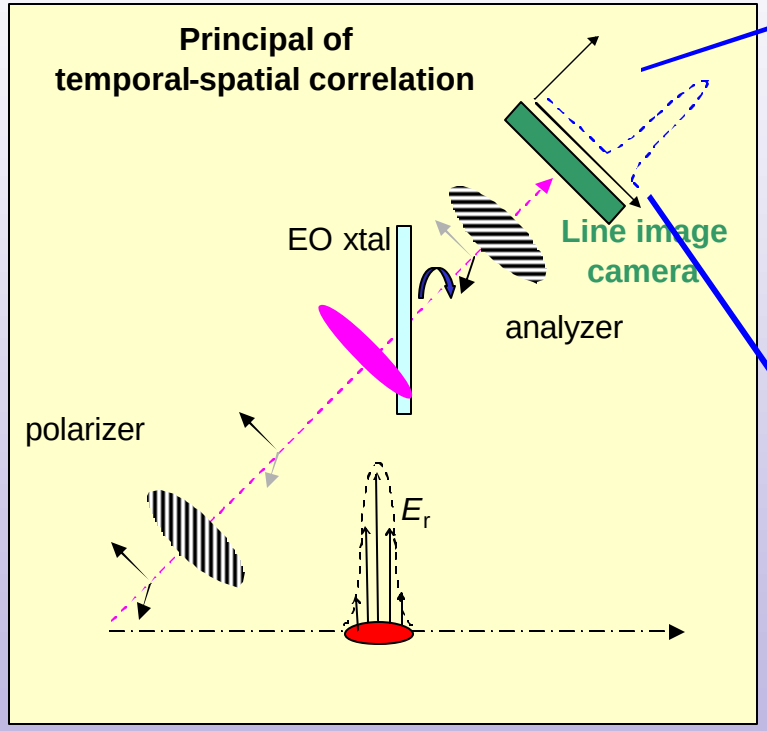
Spatial profile of beam focused along time axis, total sweep only several picoseconds

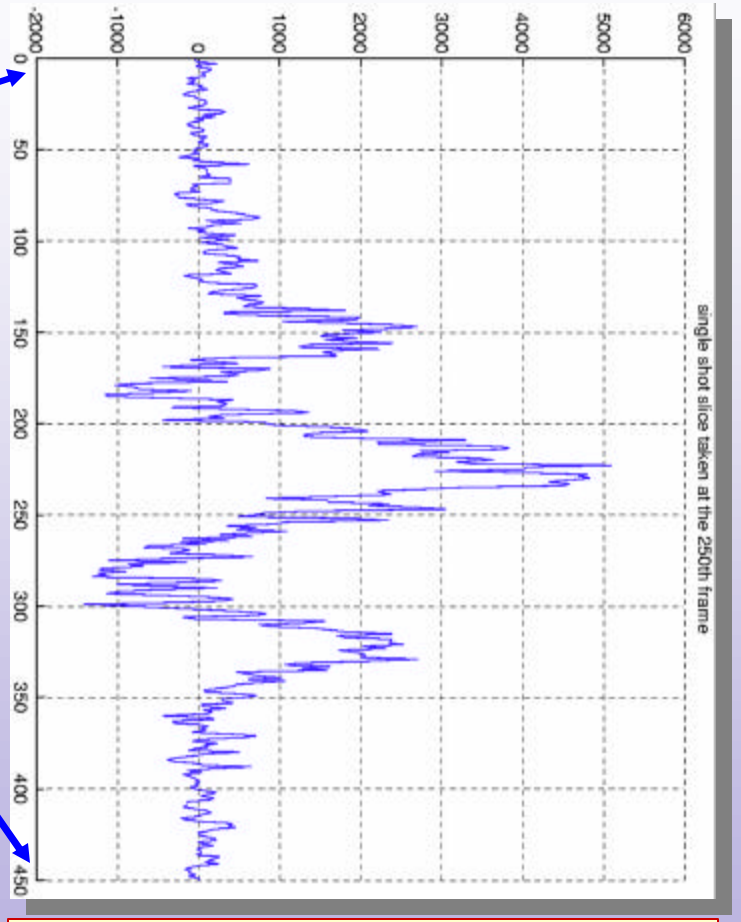




SPPS - EO signal vs time and single bunch – Adrian Cavalieri et al

- 0.5 mm ZnTe crystal

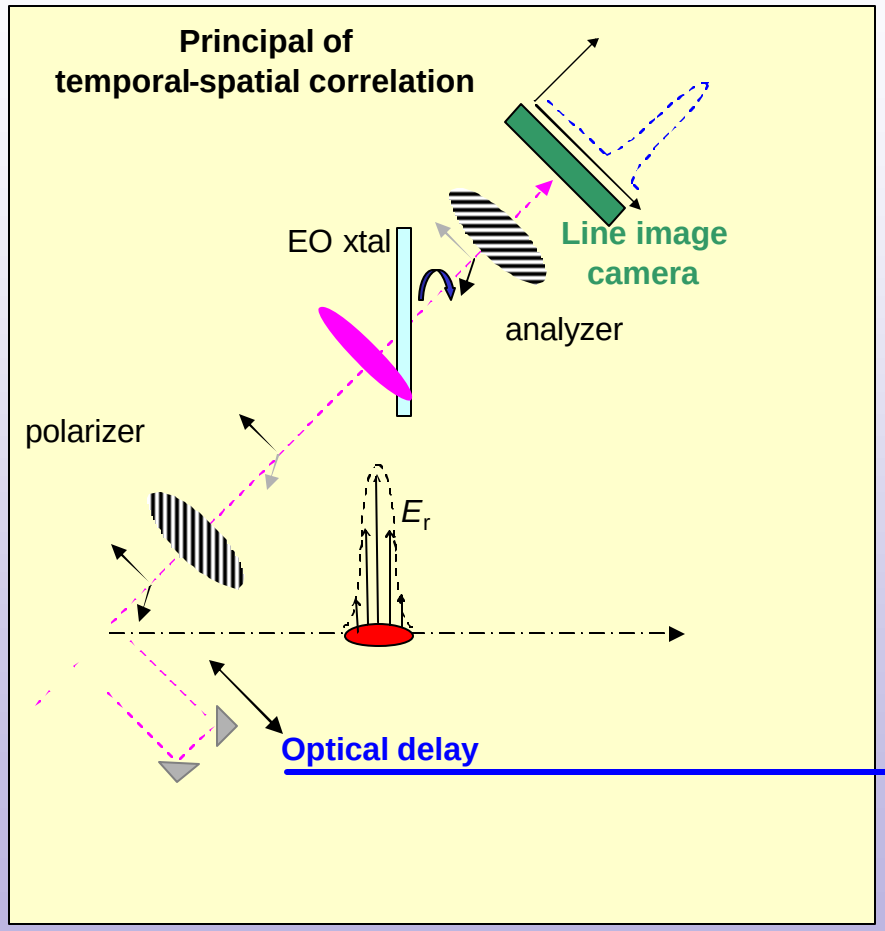


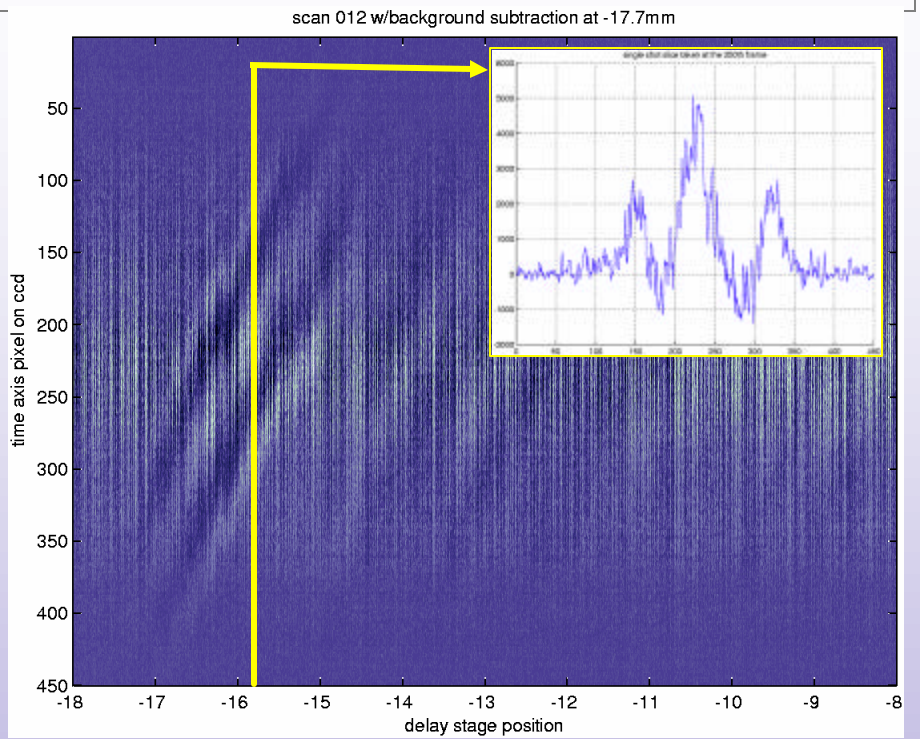


- multiple peaks indicate multiple rotations of polarization vector

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

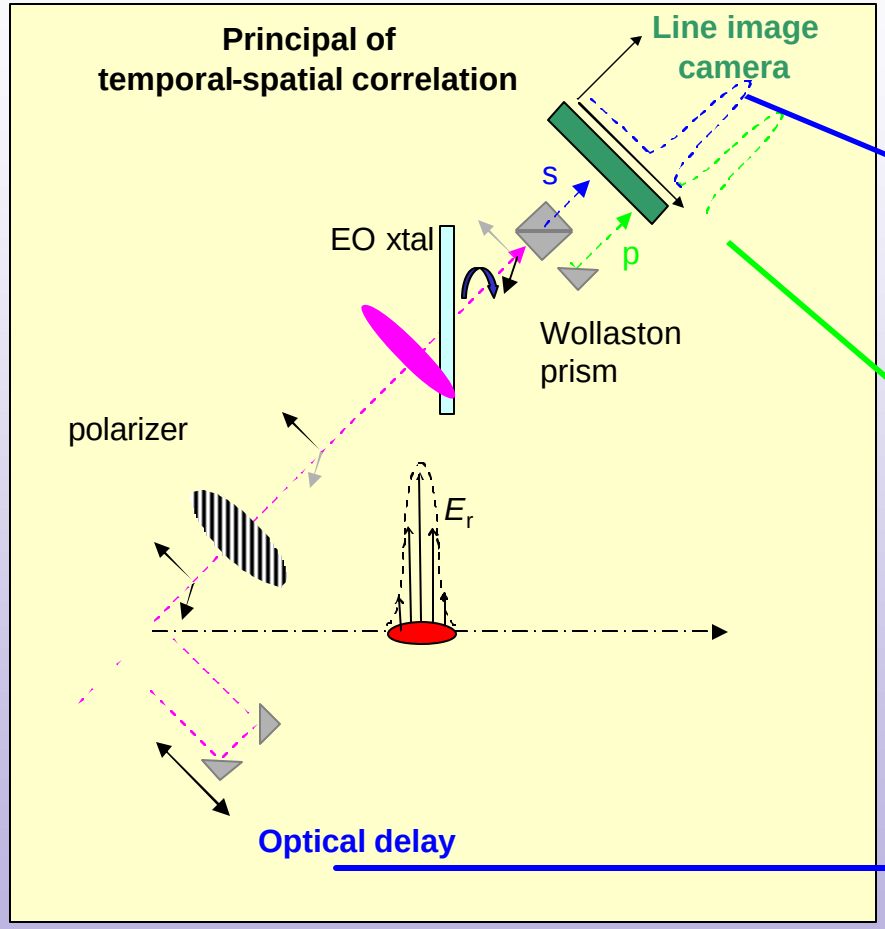
SPPS - time sequence of multiple EO images

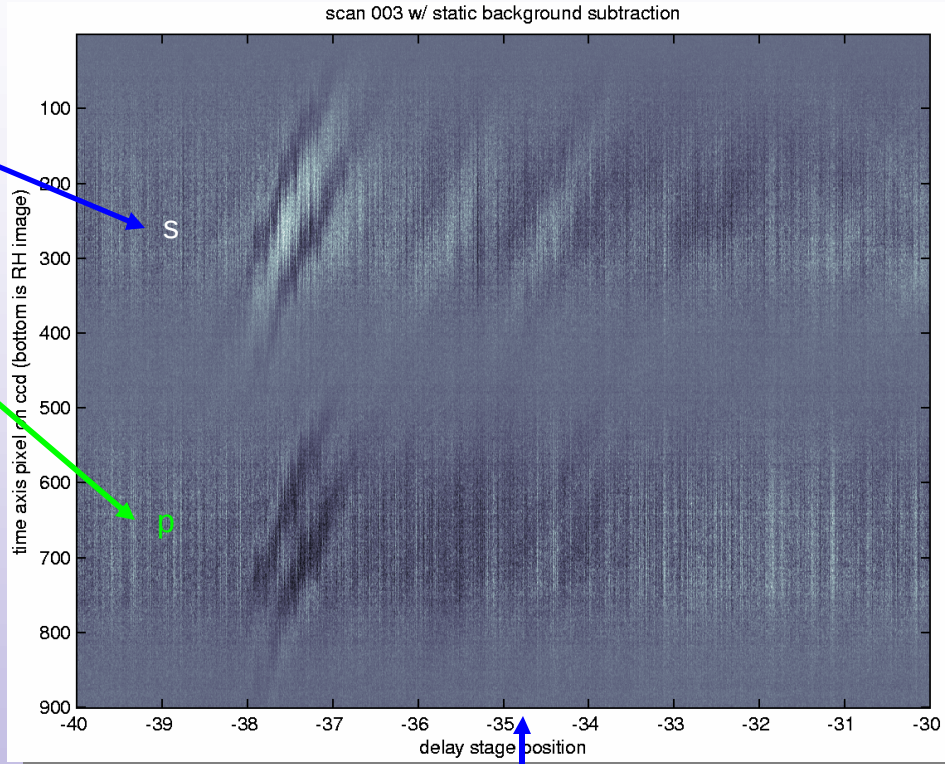




Patrick Krejcik, LCLS
pkr@slac.stanford.edu

SPPS - time sequence of multiple EO images

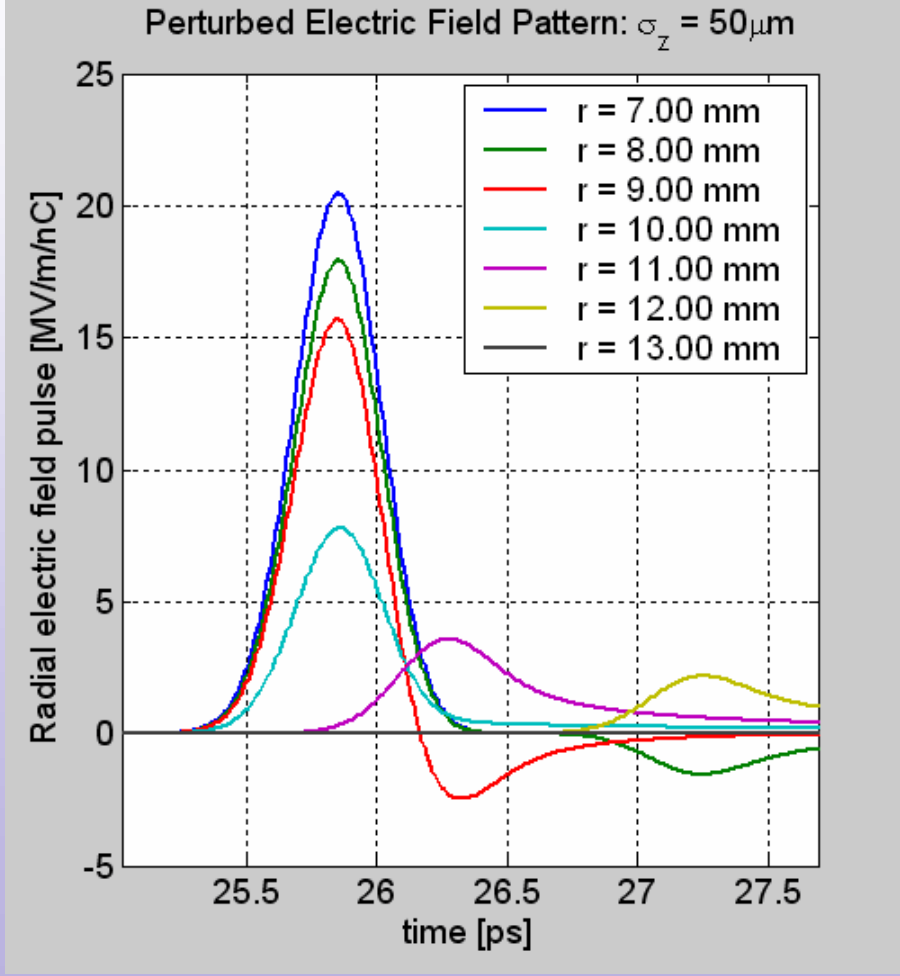


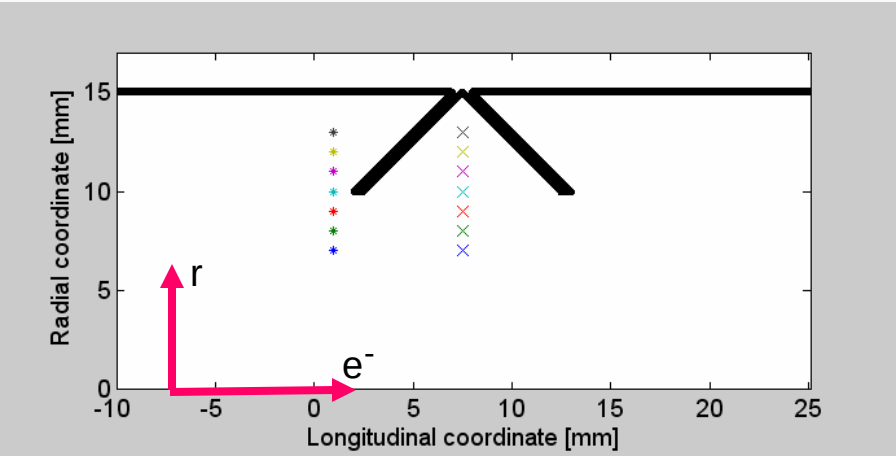


Note wakefields after passage of the bunch

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

EO resolution limit due to wakefields – H. Schlarb





- Apparent change in σ_z when measured at increasing radii relative to the aperture from the edge of the laser mirror
- negligible perturbation if EO crystal is closer to beam than mirror edge.

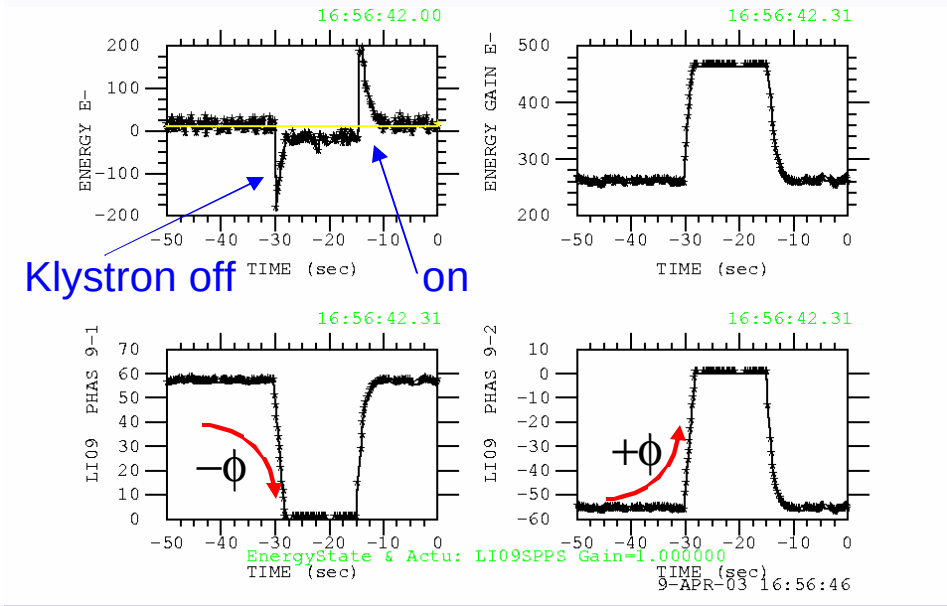
Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Feedback implementation

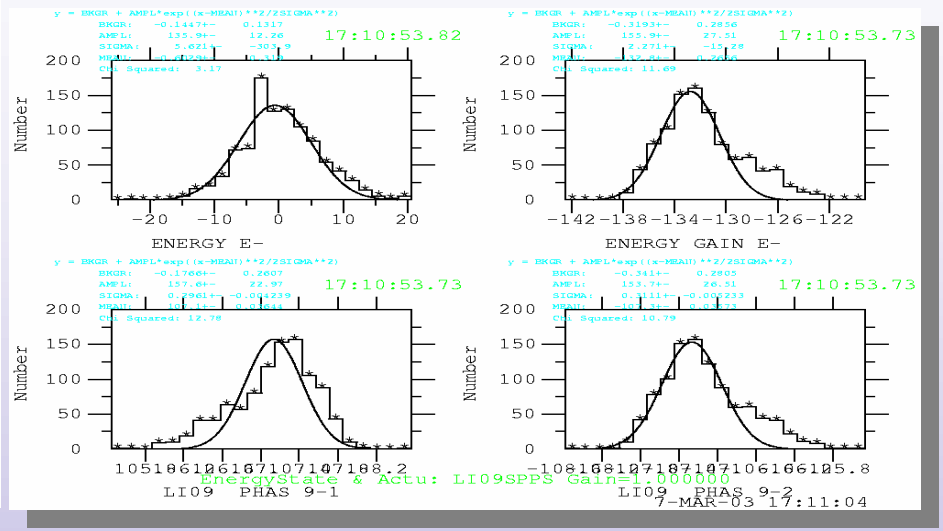
- *Pulse-to-pulse control of*
  - *Orbit position & angle, energy*
    - *as in SLC*
  - *beam phase,*
    - *Necessary, for example, to measure orbit after RF deflecting cavity to maintain cavity at zero phase crossing*
  - *bunch length*
    - *Use relative signal strength from OTR THz spectral power measurement*
    - *Demonstrated at SPPS with dither feedback to minimize bunch length*
    - *Needs power measurement at several THz wavelengths to tune to arbitrary bunch lengths*
    - *Decouple longitudinal feedback requirements*
      - *Energy feedback maintains constant energy at the BC chicane*
      - *Bunch length feedback controls the linac phase (energy chirp)*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Energy feedback



Klystron 1 Klystron 2



Energy feedback at SPPS chicane responding to a step energy change

Energy measured at a dispersive BPM, Actuator is a klystron phase shifter

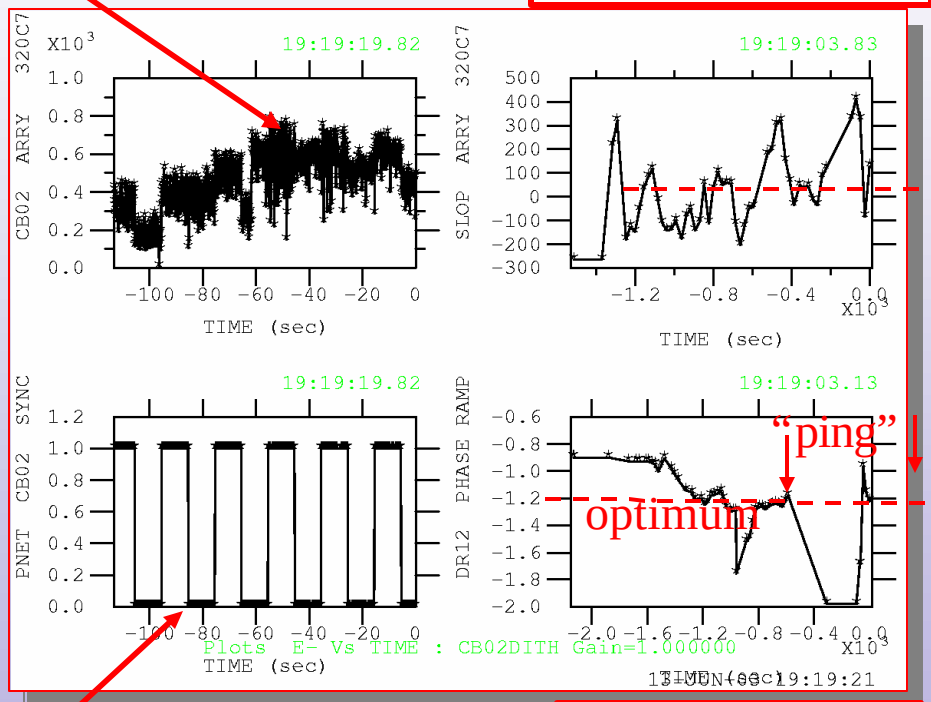
Energy jitter measured from chicane feedback system 5.6 MeV rms 0.06%

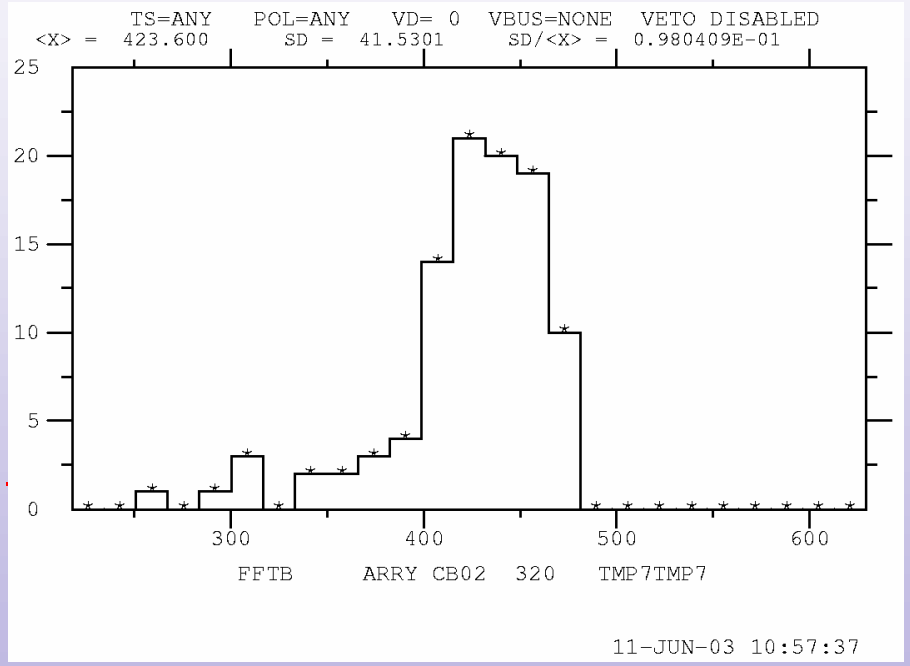
Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Dither feedback control of bunch length minimization - L. Hendrickson

Bunch length monitor response

Feedback correction signal





Linac phase

Dither time steps of 10 seconds

Jitter in bunch length signal over 10 seconds ~10% rms

Patrick Krejcik, LCLS
pkr@slac.stanford.edu

Conclusions

- *Upgrades to conventional diagnostic instrumentation*
- *We rely on several new and complex bunch length and timing diagnostics*
  - *Development work on these has started at SPPS*
- *Feedback is an essential part of maintaining stable tuning*
- *MPS is integrated into diagnostics and feedback requirements*

Patrick Krejcik, LCLS
pkr@slac.stanford.edu