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*

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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*

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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*

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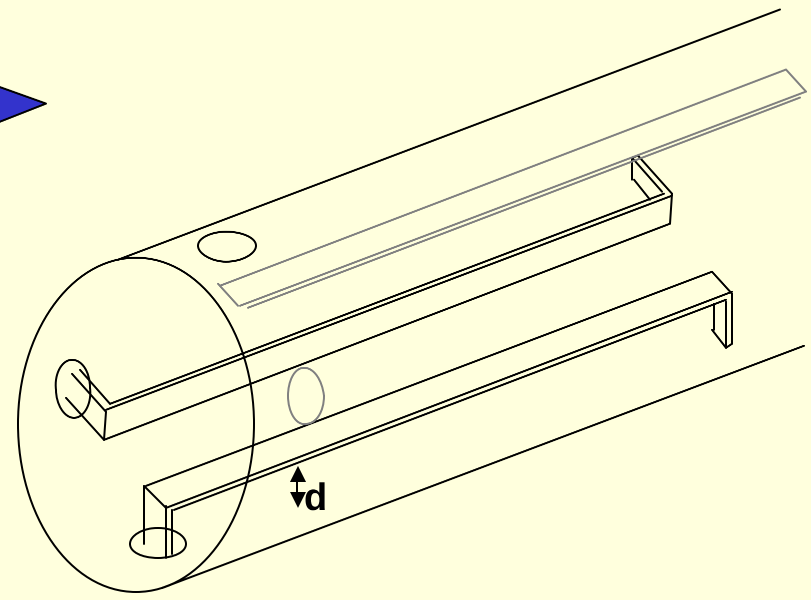
Status of beam position monitors

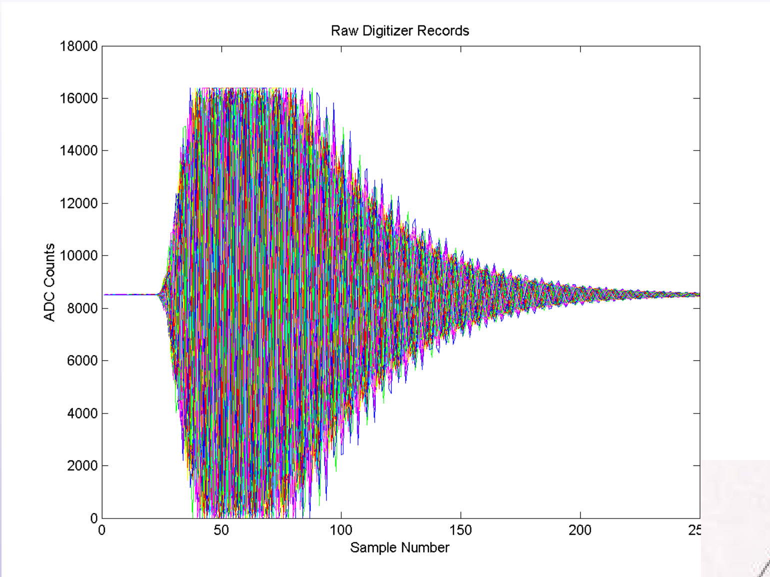
- *Injector-Linac-LTU*
  - *Stripline bpms*
  - *0.2 – 1 nC*
  - *5 mm resolution*
  - *Requires new modules*
    - *To be designed.*
  - *New stripline BPMs to be fabricated for chicanes*
    - *20 um res. for 1 - 0.2 nC in a 3 cm x 10 cm chamber*
  - *New stripline BPMs to be fabricated for the LTU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

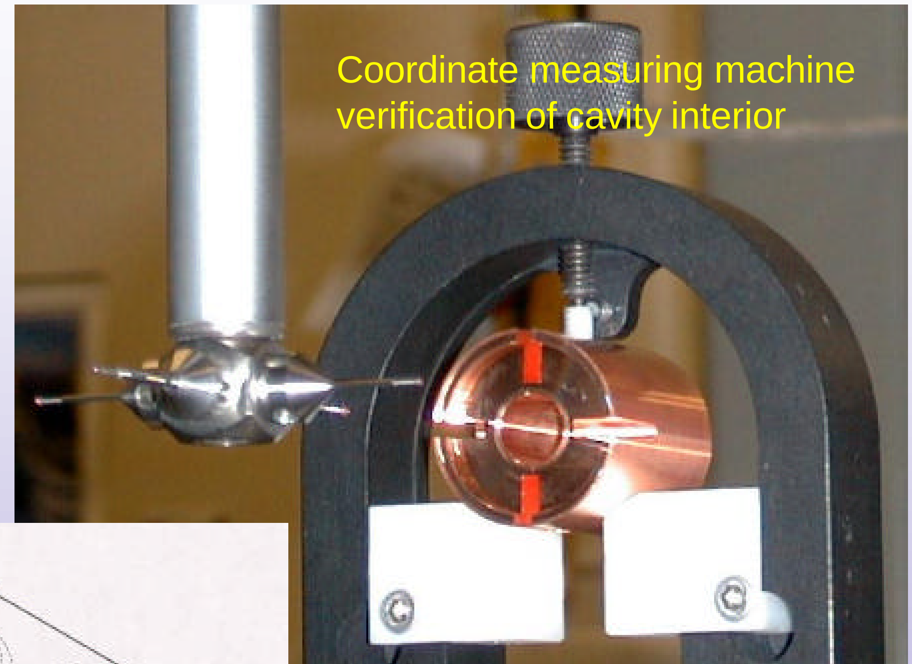


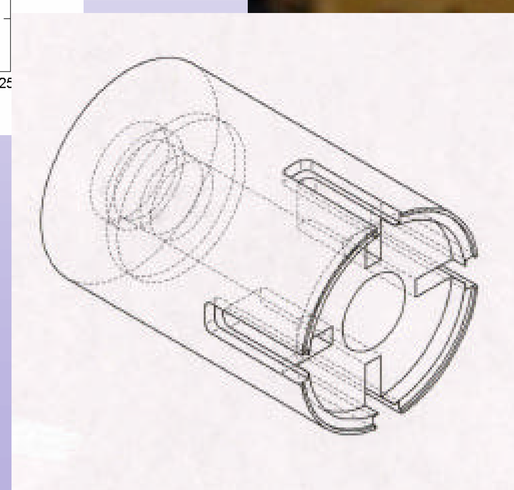
- *Aligned to* mechanical *center of quadrupoles*
- *Systematic offsets from variations in* **d**

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

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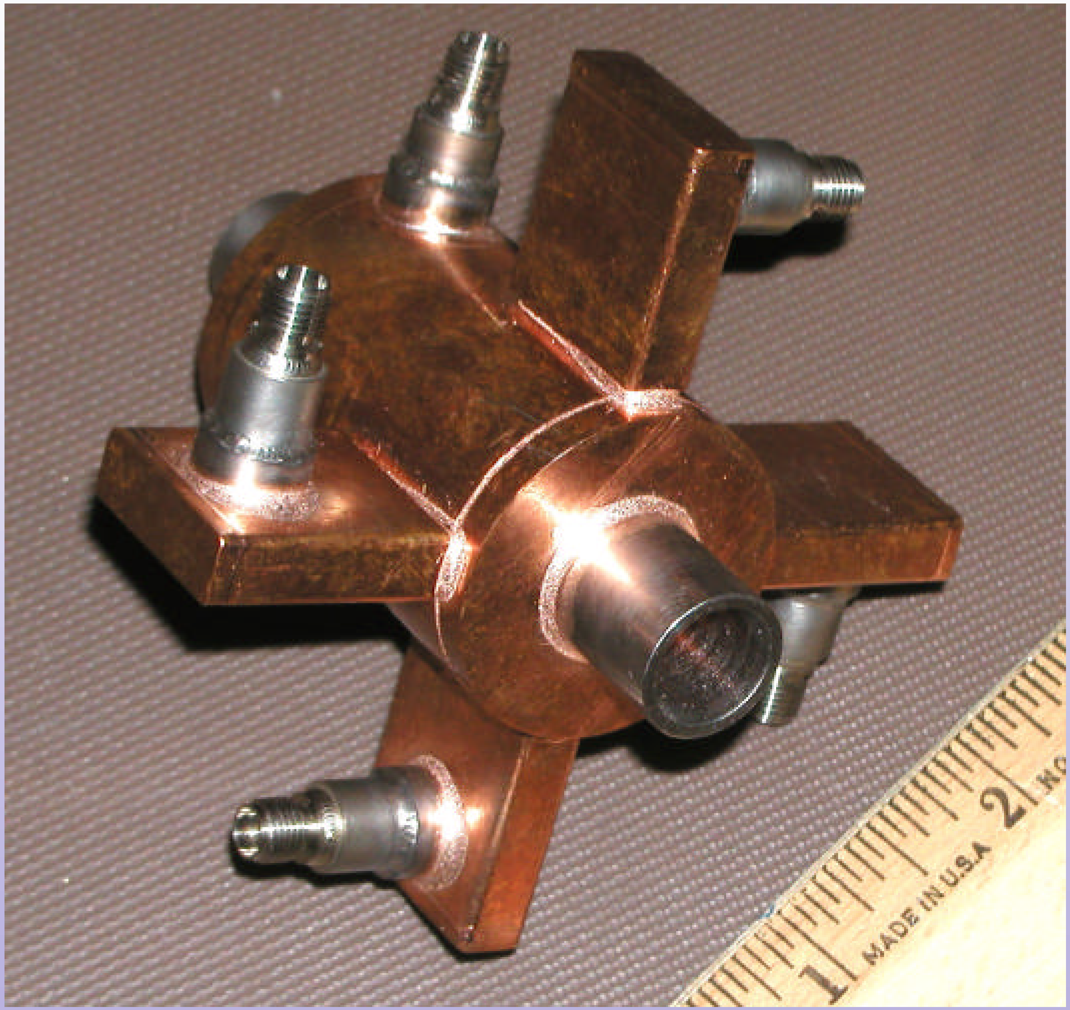
SLAC X-band cavity BPM – Steve Smith



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

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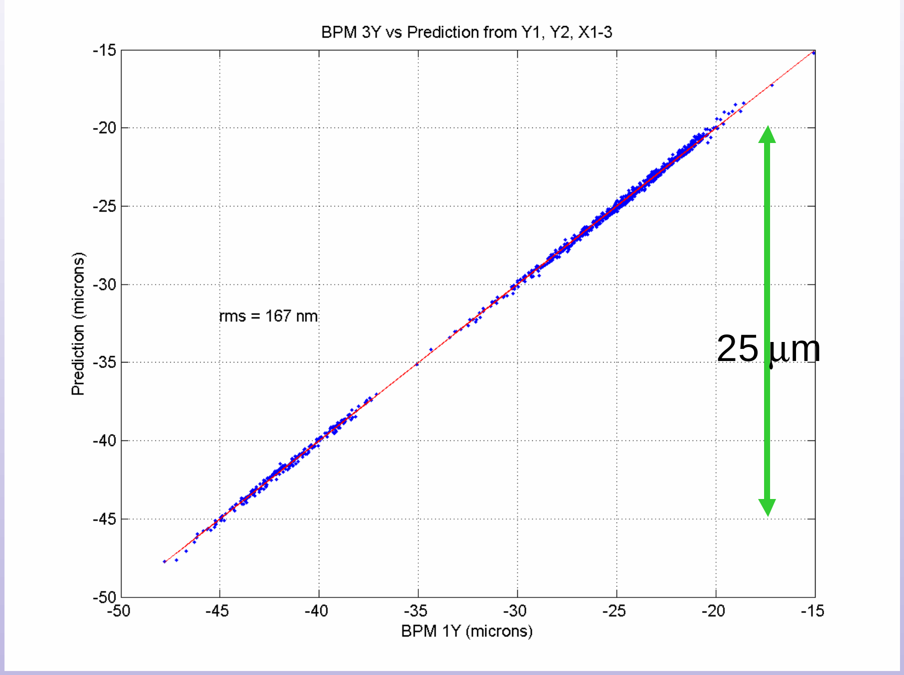
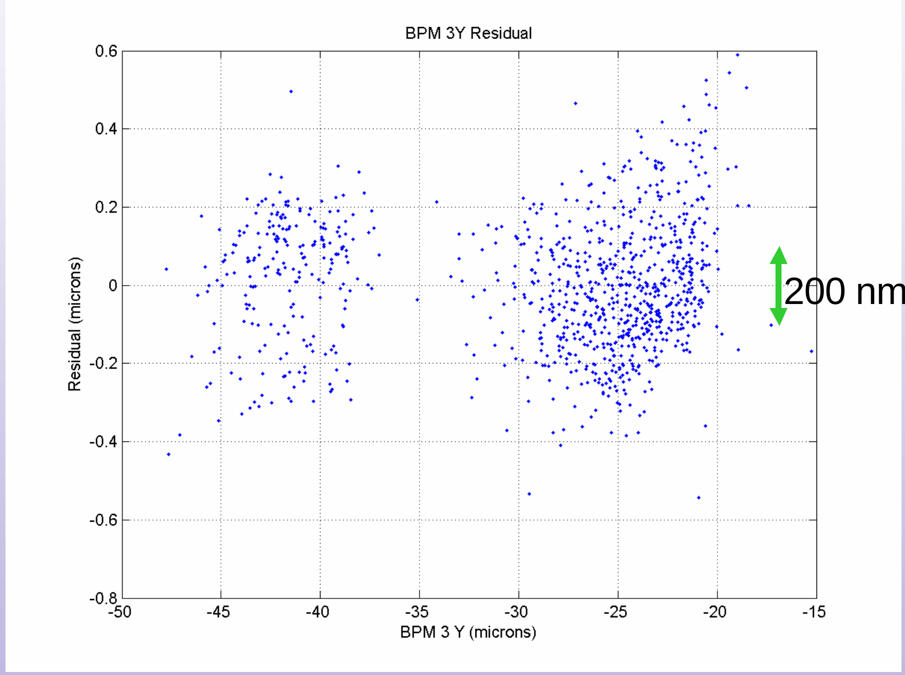
Cavity BPM R&D at SLAC – Steve Smith preliminary beam calibration data from a C-band cavity at ATF





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

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

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*

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*

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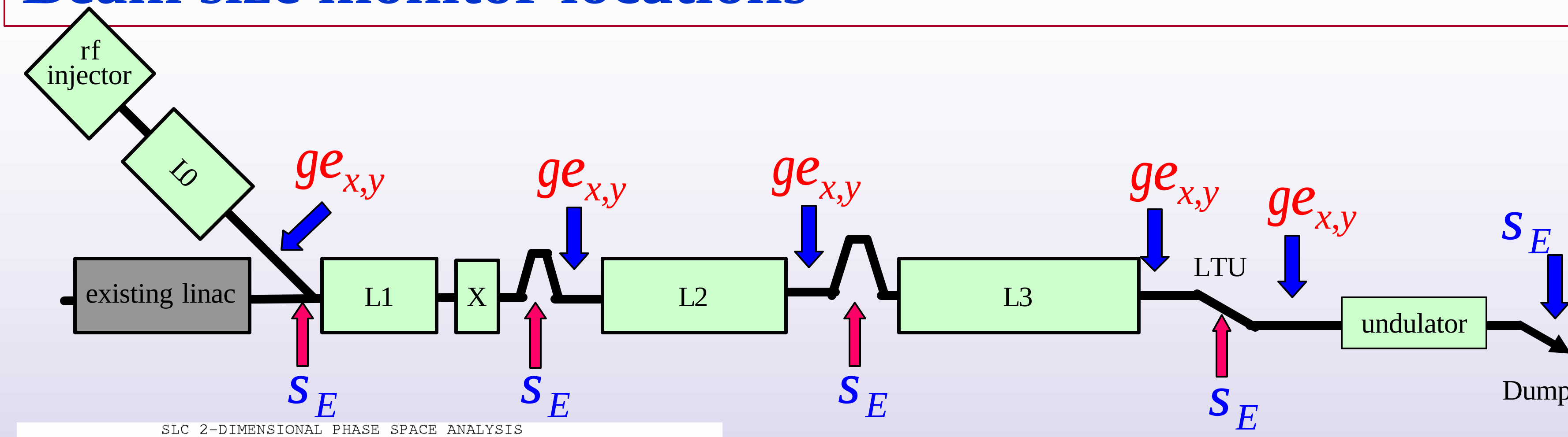
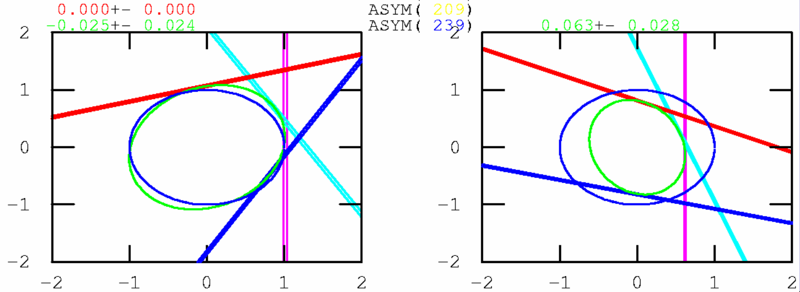
Beam size monitor locations





SLC 2-DIMENSIONAL PHASE SPACE ANALYSIS
DATA NOT SAVED IN DATABASE BECAUSE TIMER FLAG IS TURNED OFF

LI02 X-PLANE ELEC		LI02 Y-PLANE ELEC
3.214+- 0.068 (3.000)	EMITTANCE(mE-5)	0.151+- 0.004 (0.300)
3.273+- 0.076 (3.000)	BMAG*EMIT(mE-5)	0.159+- 0.006 (0.300)
1.018+- 0.006 (1.000)	BMAG	1.056+- 0.014 (1.000)
-0.076+- 0.030 (0.000)	BMAG_COS	-0.279+- 0.021 (0.000)
-0.172+- 0.028 (0.000)	BMAG_SIN	0.158+- 0.058 (0.000)
14.378+- 0.429 (15.282)	BETA (m)	5.468+- 0.128 (7.179)
-3.345+- 0.099 (-3.369)	ALPHA	0.568+- 0.066 (0.526)
449.958+- 8.999 (443.700)	SIG(119)(um)	59.342+- 1.187 (96.170)
252.750+- 5.055 (230.385)	SIG(133)(um)	77.259+- 1.545 (127.452)
336.788+- 6.736 (324.875)	SIG(148)(um)	50.716+- 1.014 (68.189)
0.000+- 0.000 (0.000)	SIG(209)(um)	0.000+- 0.000 (0.000)
329.471+- 6.589 (352.409)	SIG(239)(um)	35.574+- 0.711 (44.644)
2.163+- 0.013	INTENSITY	2.131+- 0.050
.2614240	CHISQ/DOF	.3497621
0.021+- 0.025	ASYM(119)	-0.075+- 0.043
0.078+- 0.026	ASYM(133)	-0.092+- 0.040
0.000+- 0.035	ASYM(148)	-0.275+- 0.034
0.000+- 0.000	ASYM(209)	
-0.025+- 0.024	ASYM(239)	0.063+- 0.028

4-wire emittance reconstruction example from linac sector 2

$\gamma\epsilon_y$ = 1.5 μm

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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*

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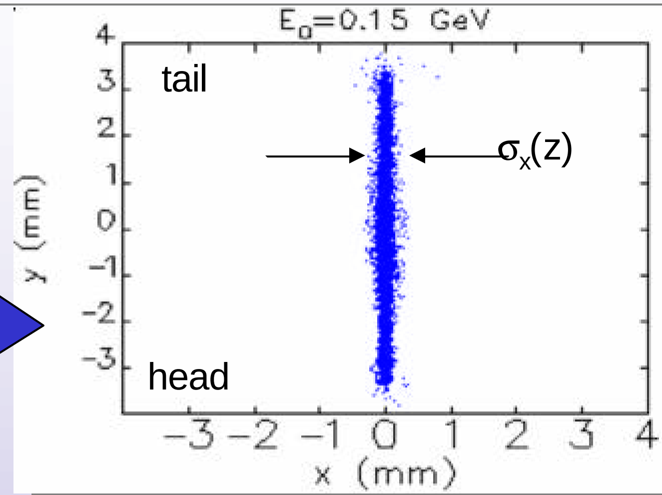
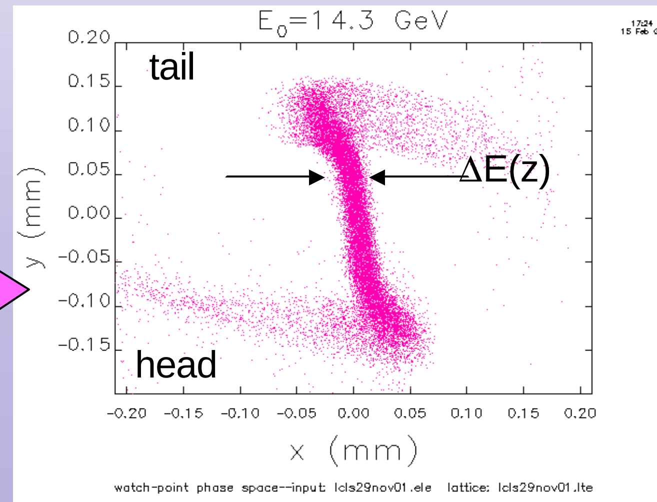
Slice parameters from transverse RF deflecting cavity

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

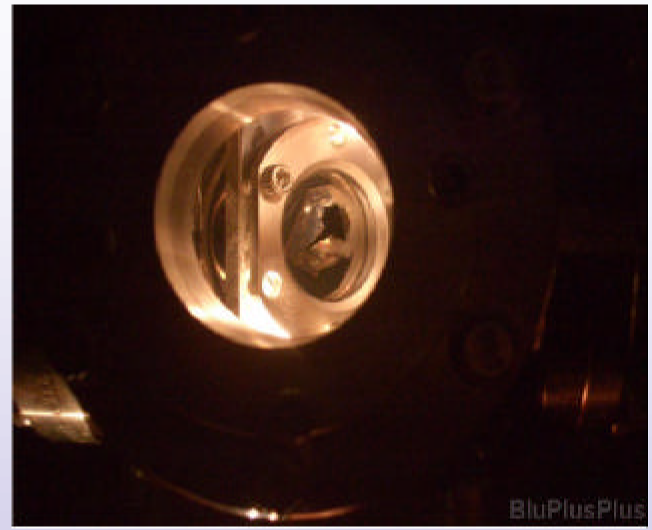


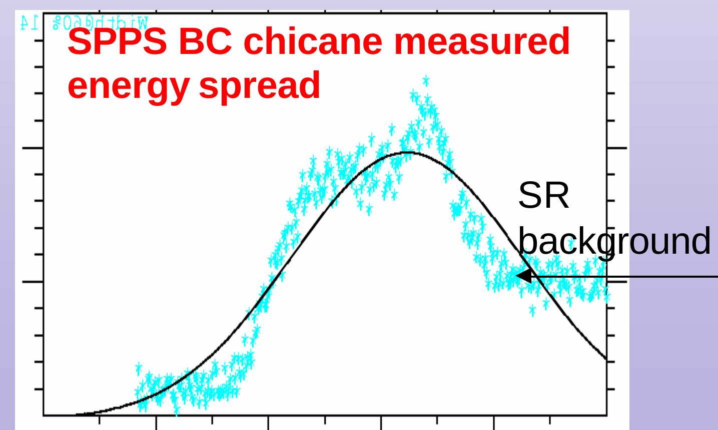
- *OTR screen down stream of the Tcav. At a horizontal dispersion location, large h_x, small b_x, can measure slice energy spread*



Profile Monitors

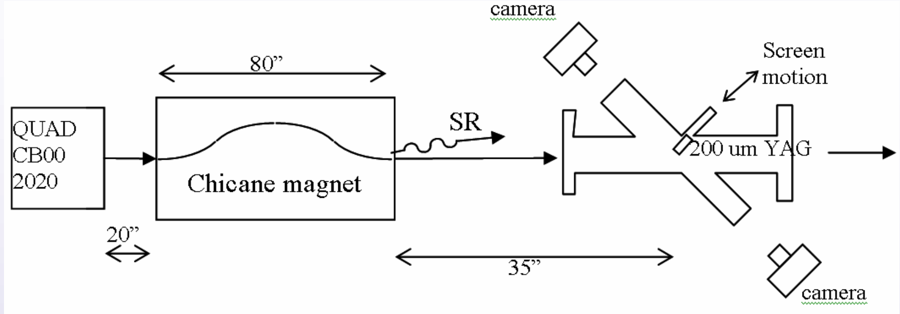
- Technical challenges
  - Small beam size requires precision, remote optics + digital video ($'s)
  - Stretching a thin, low Z foil flat
  - Avoiding punctures
  - Block synchrotron radiation from bends bends with polarizers

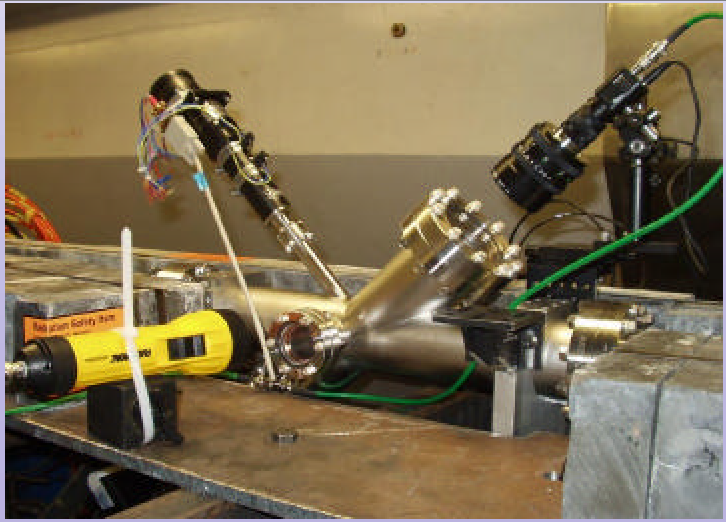




Profile Monitors for Synchrotron Radiation

- *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*



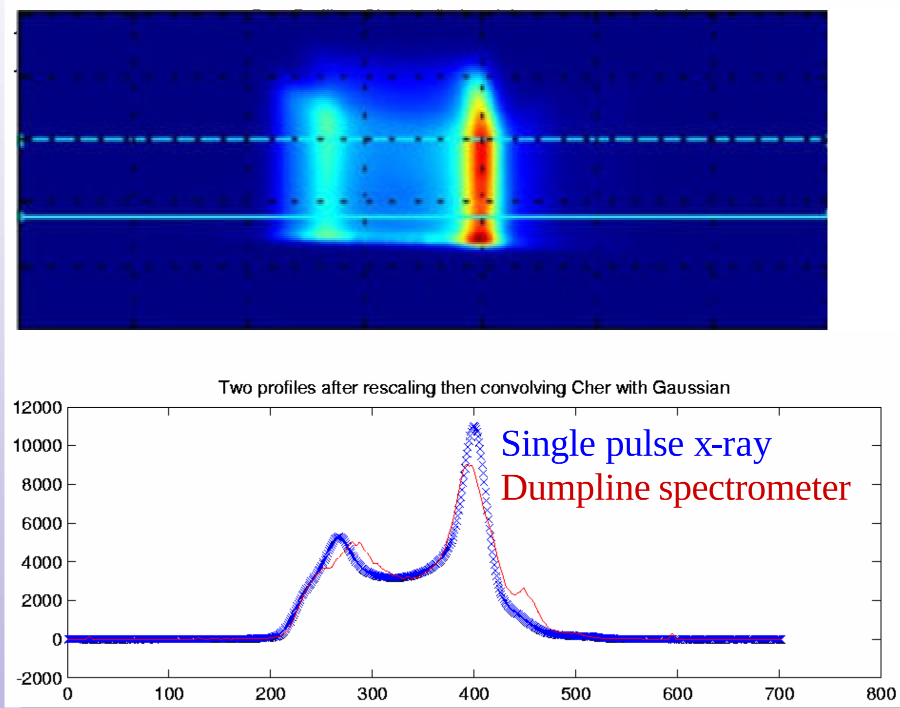


- *Also serves as CSR monitoring port*

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

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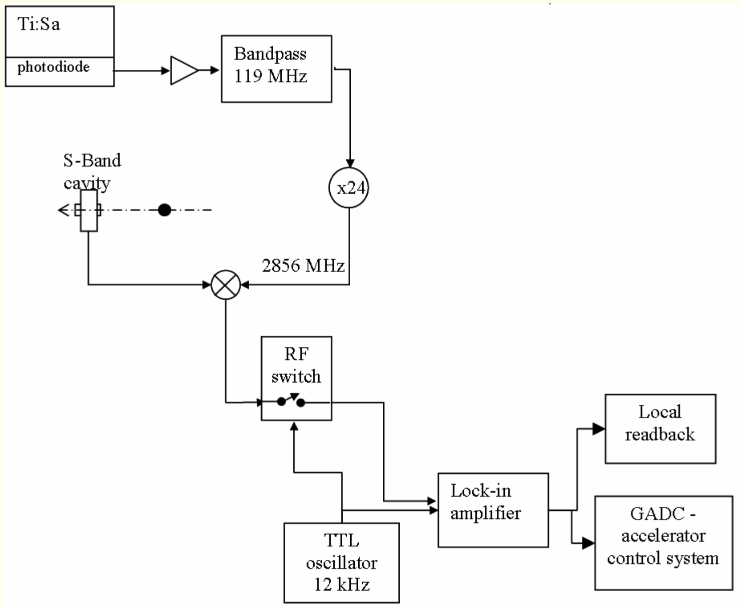
Conventional diagnostics and their upgrades

- *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*



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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*

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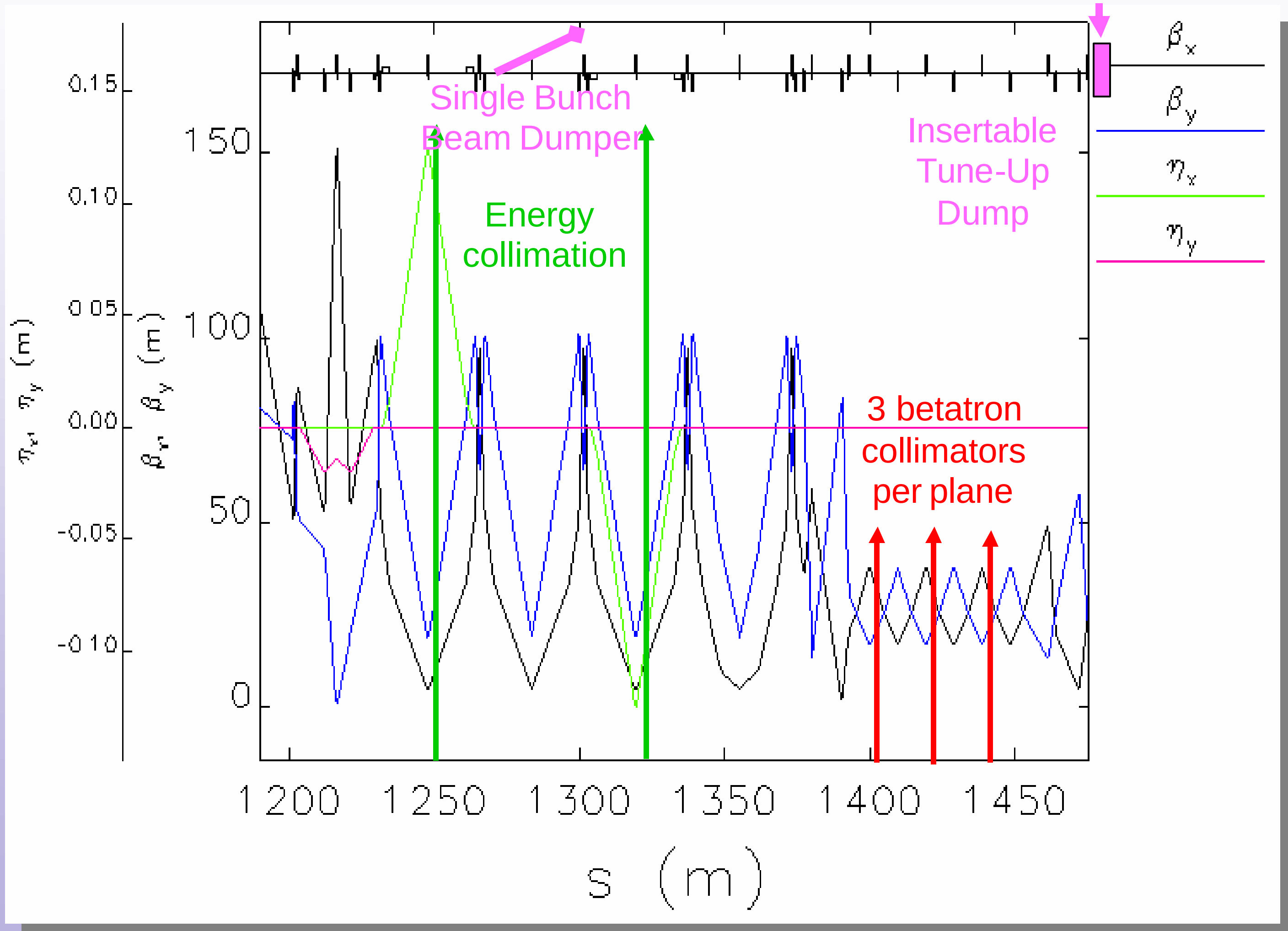
Linac To Undulator beamline diagnostic & collimation section



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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*

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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*

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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

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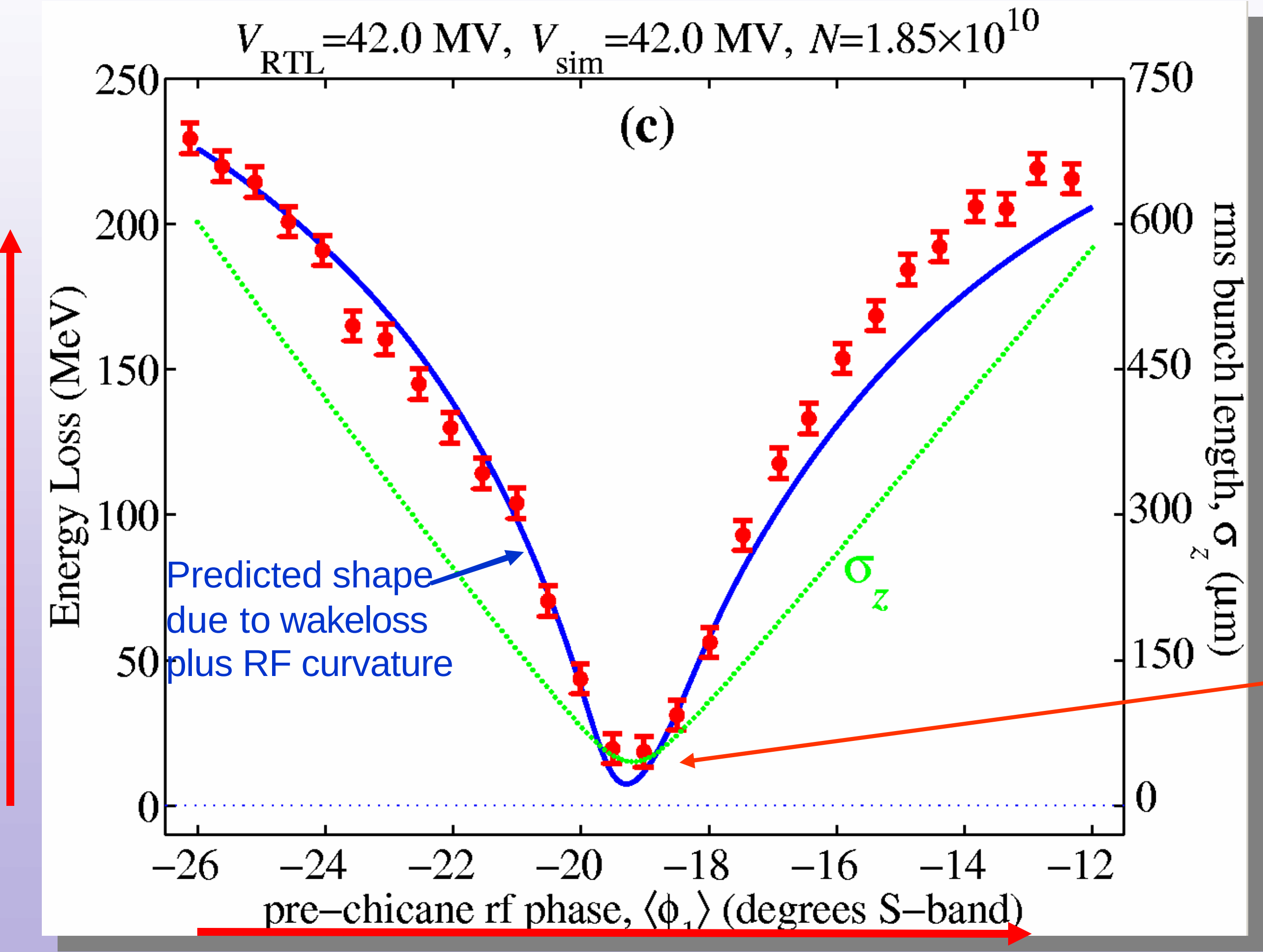
Relative bunch length measurement at SPPS based on wakefield energy loss scan



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 $_z$___

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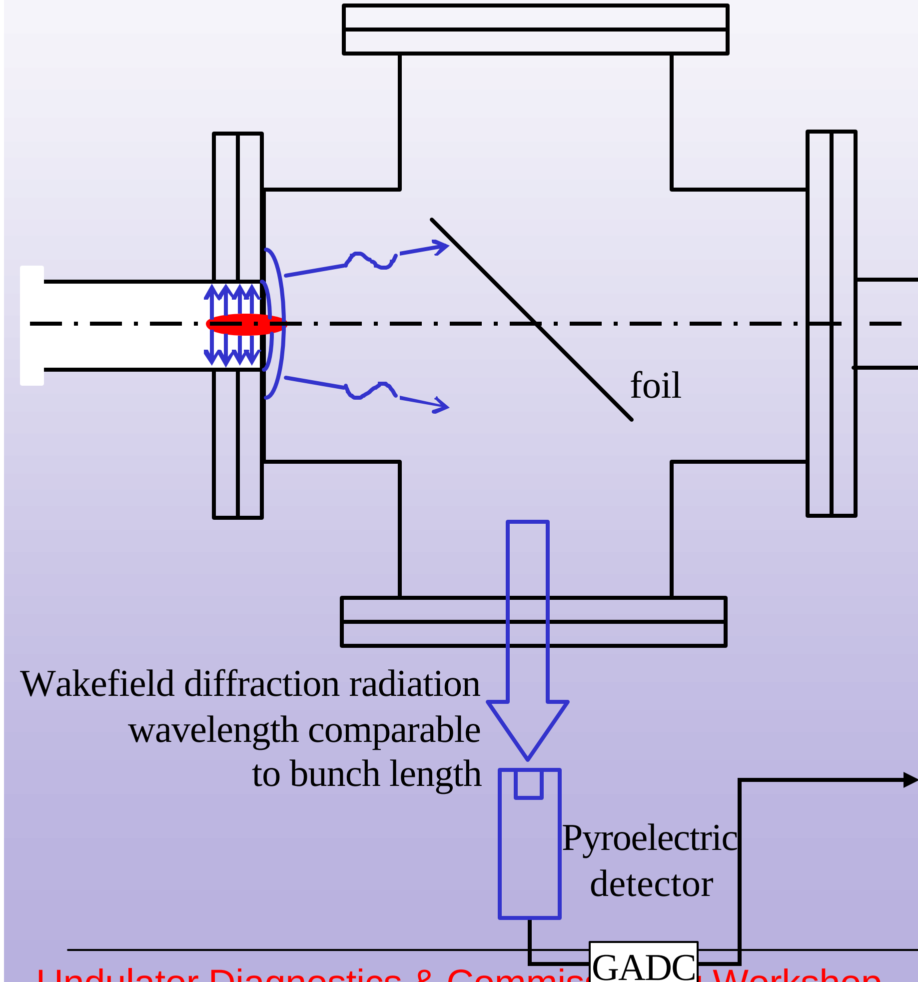
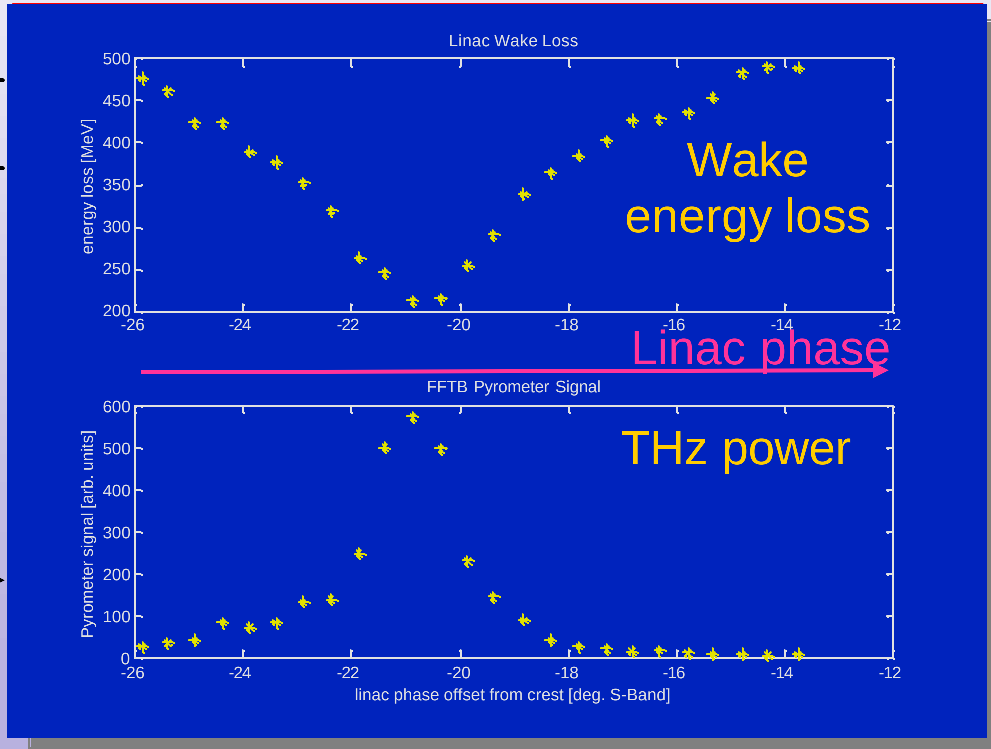
Far-Infrared Detection of Wakefields from Ultra-Short Bunches



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



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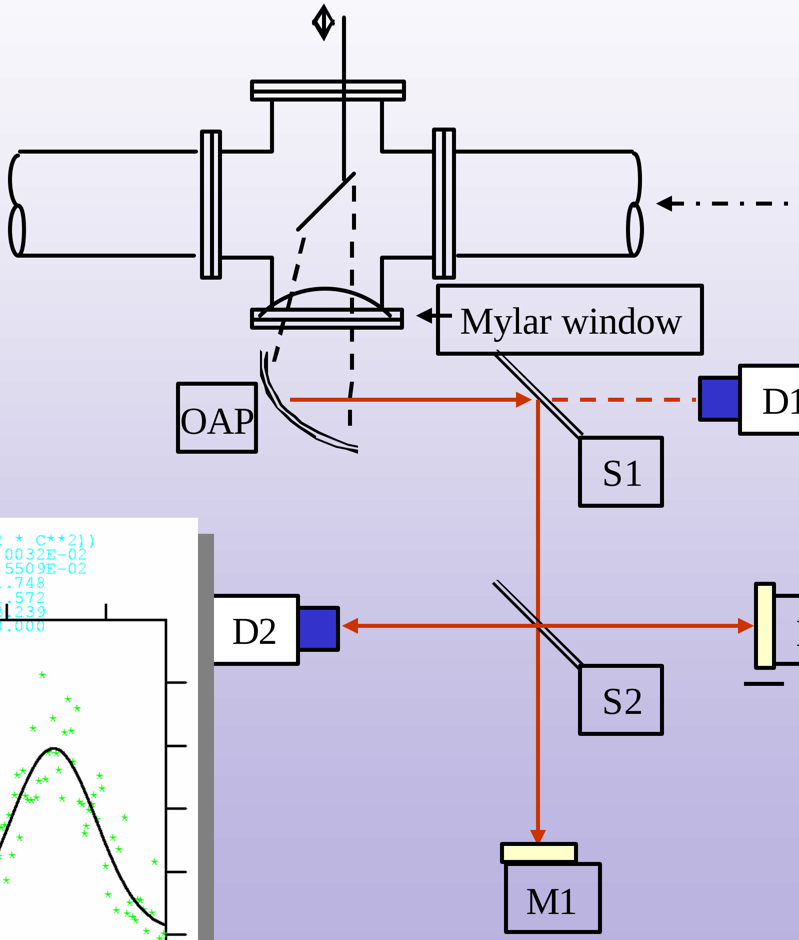
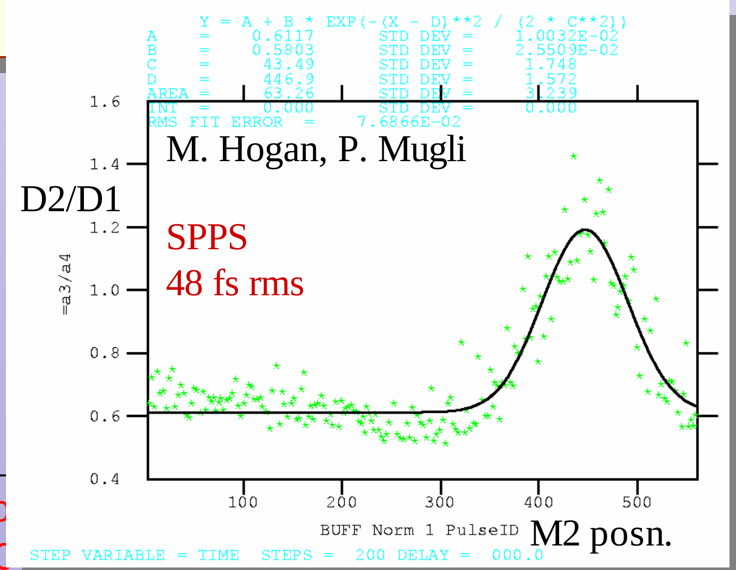
Absolute bunch length determination

- *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*





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CTR Measurements

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*

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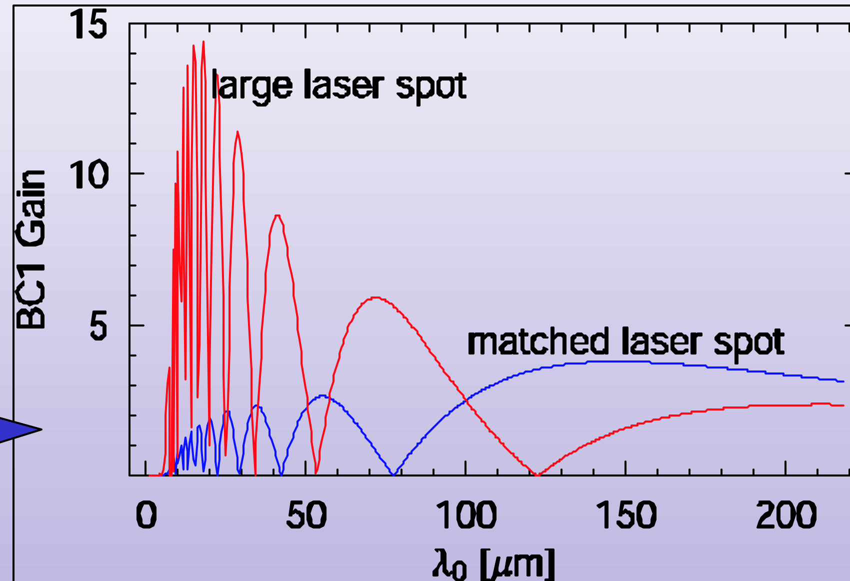
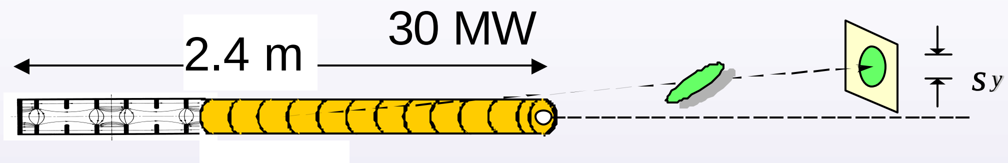
CSR THz radiation from diagnostic chicane

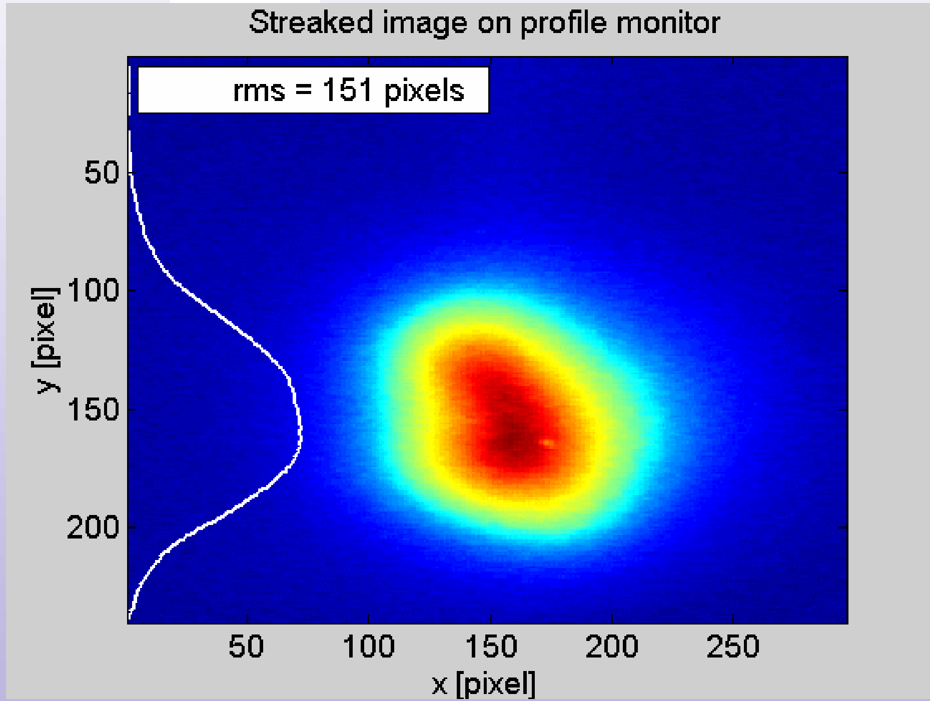
- *THz spectral power diagnoses relative bunch length*
- *CSR spectrum reveals spikes in bunch length distribution*
- *Spikes due to microbunching instability arising in the BC chicanes also seen in CSR spectrum*



Z. Huang:
expect to observe microstructure at λ_0/comp.fact

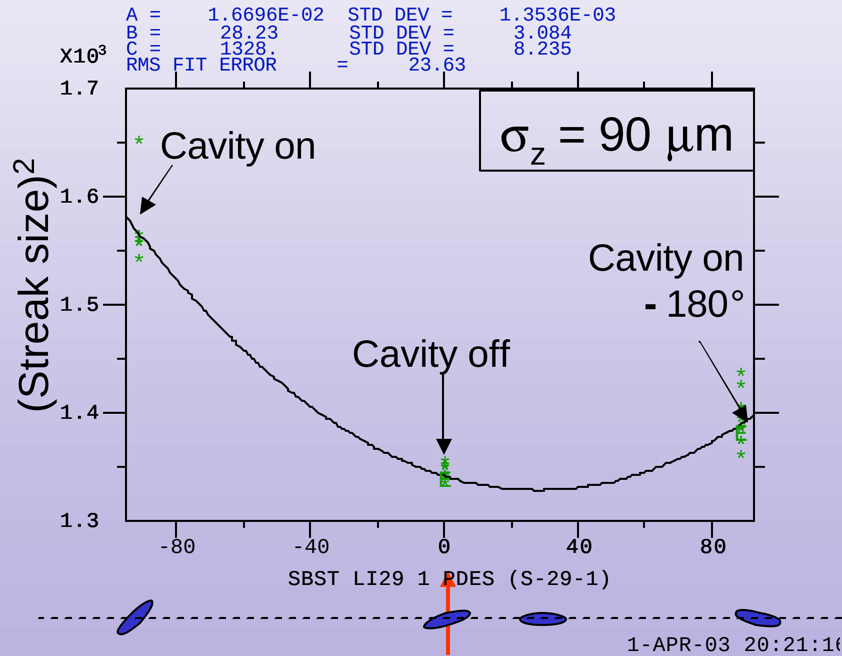
Bunch Length Measurements with the RF Transverse Deflecting Cavity

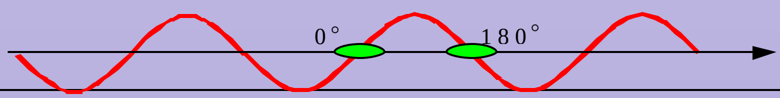




Bunch length reconstruction
Measure streak at 3 different phases

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





Asymmetric parabola indicates incoming tilt to beam

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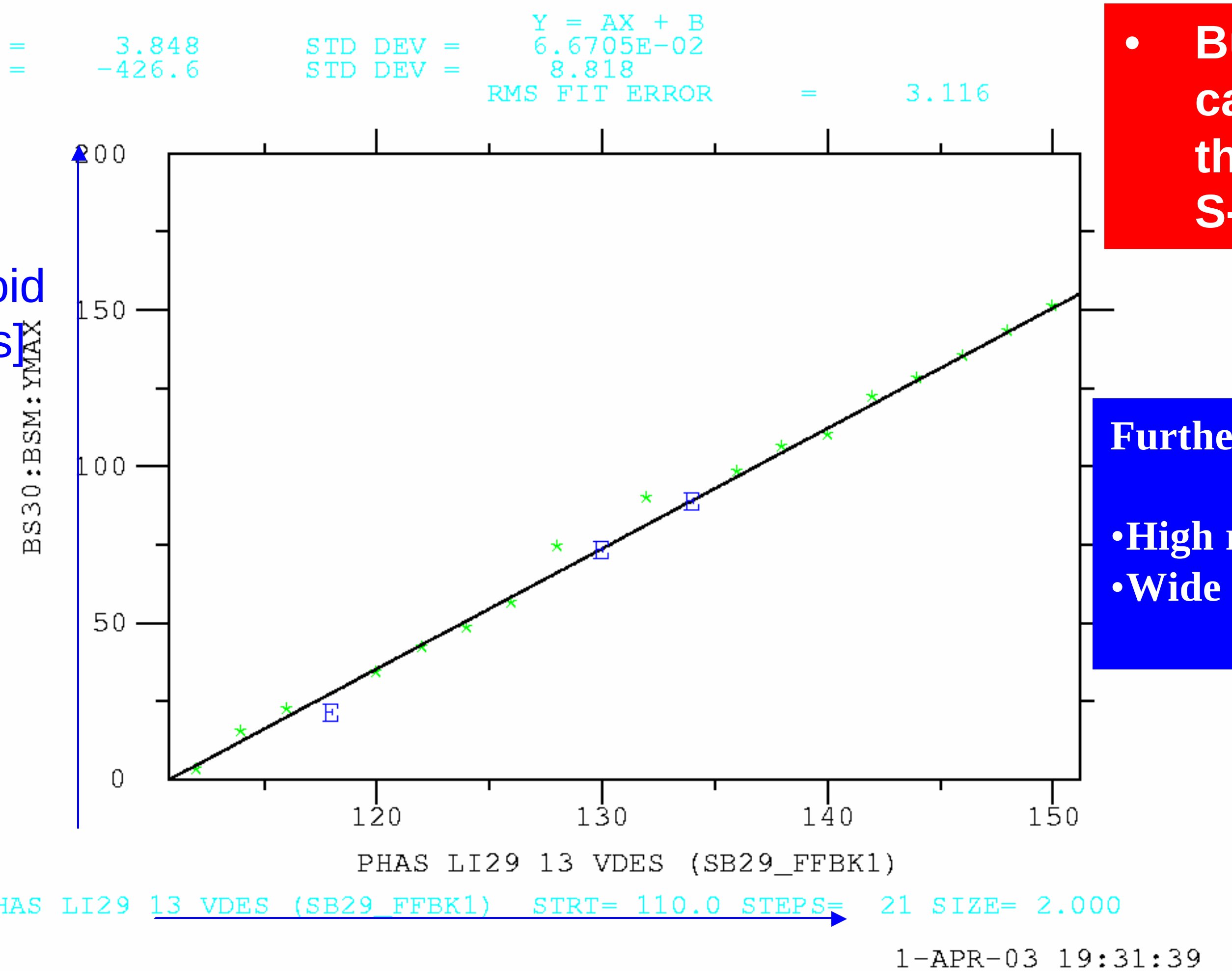
Calibration scan for RF transverse deflecting cavity

Beam centroid [pixels]



Cavity phase [deg. S-Band]

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

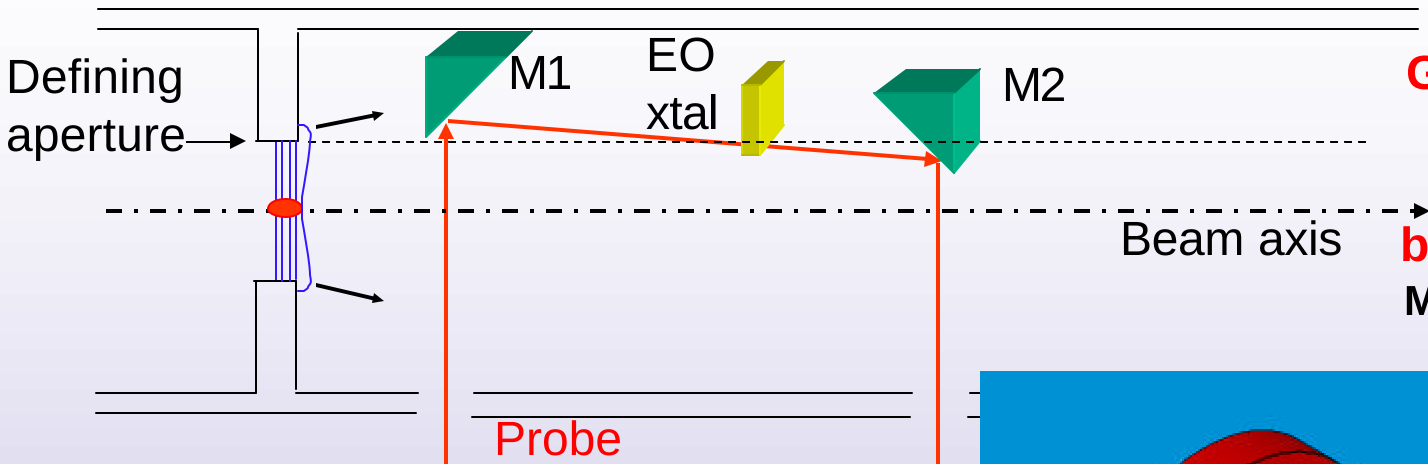
Further requirements for LCLS:

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

Bunch length and timing diagnostics

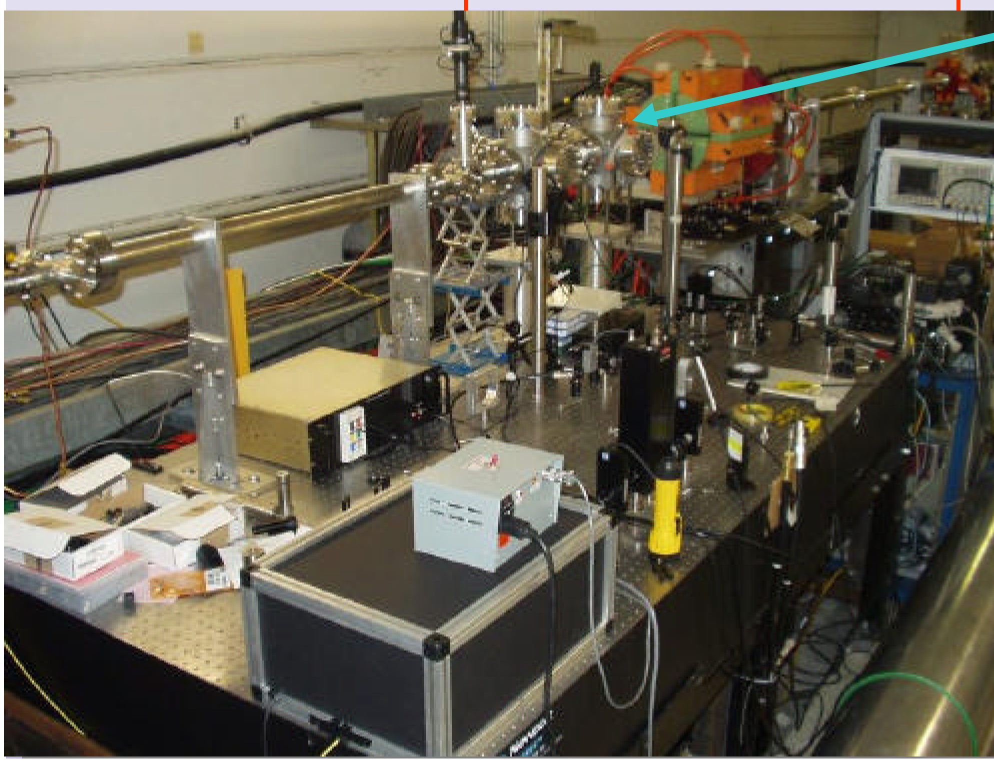
- *Absolute bunch length determination*
  - *Single shot electro optic pump probe measurement*
    - *Transforms the problem of measuring short electron bunch length to measuring a short pulse of laser light.*
    - *Electro-optic process is inherently fast, < 2 fs*
    - *Time resolution is dependant 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*

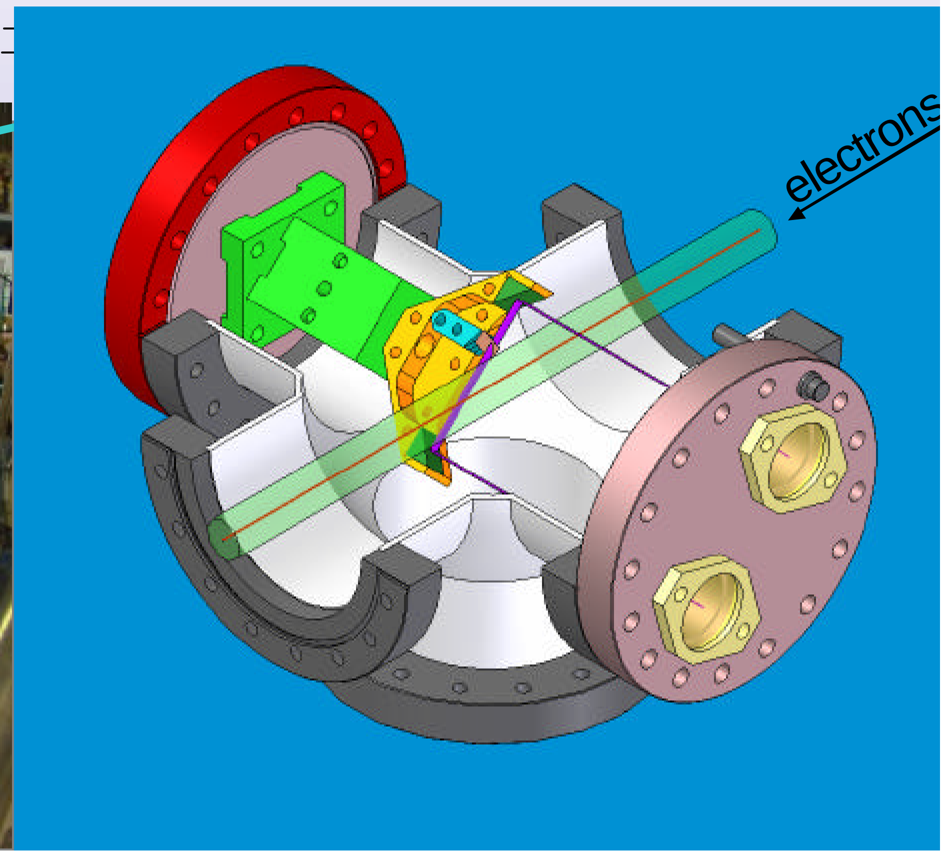
Electro Optic Bunch Length Measurement



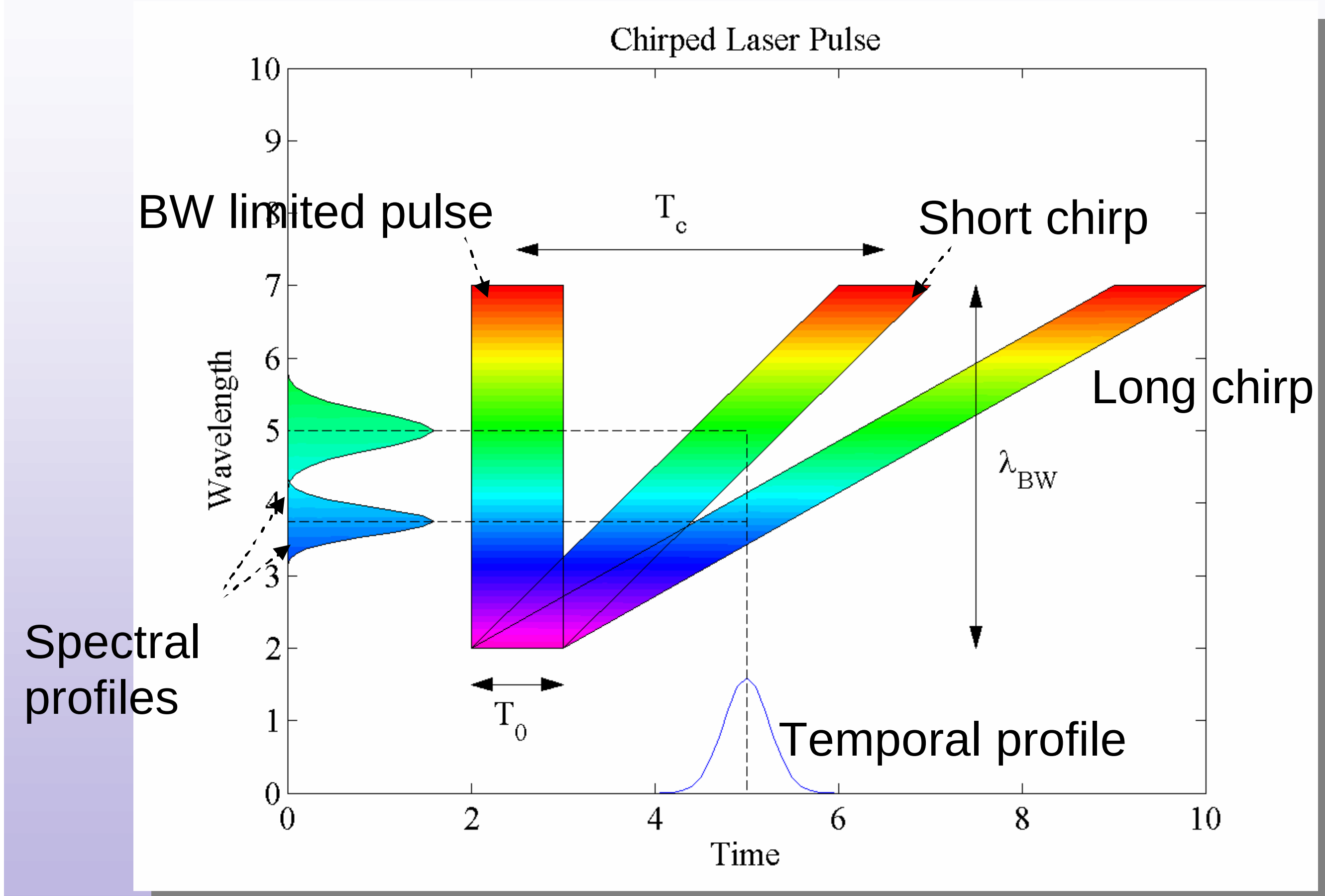
Geometry chosen to measure direct electric field from bunch, not wakefield

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

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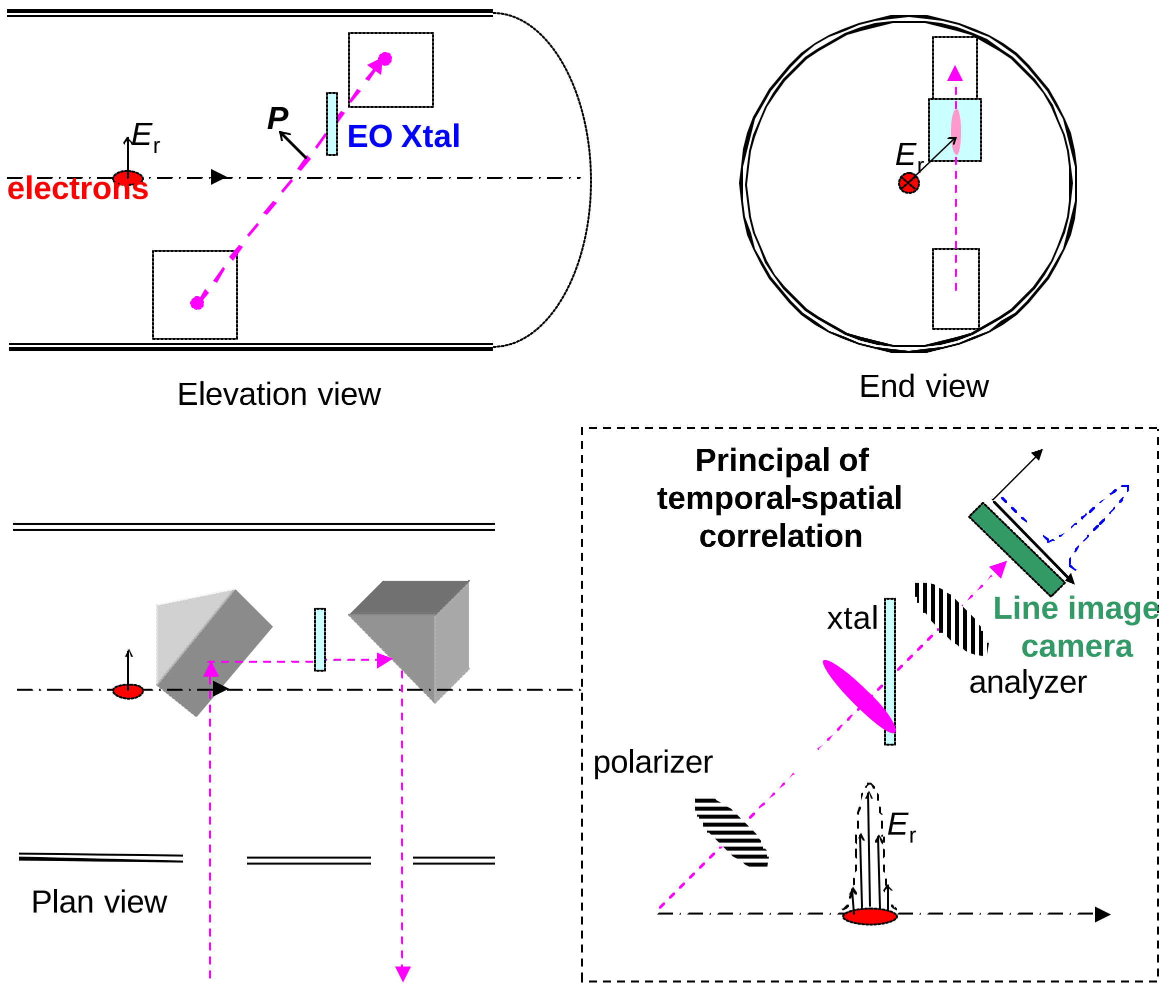
Temporal to spatial geometry under test at SPPS



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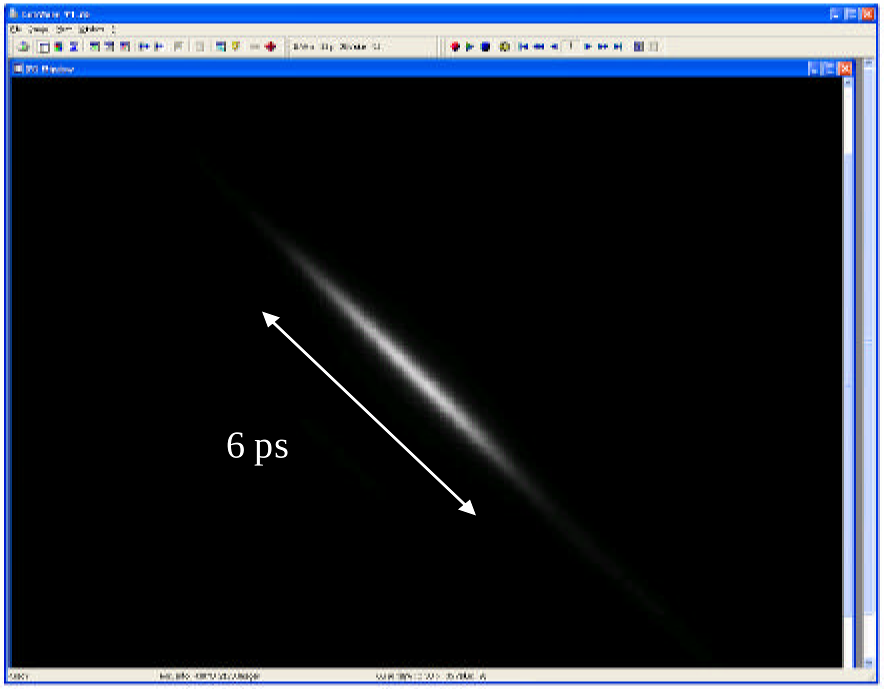
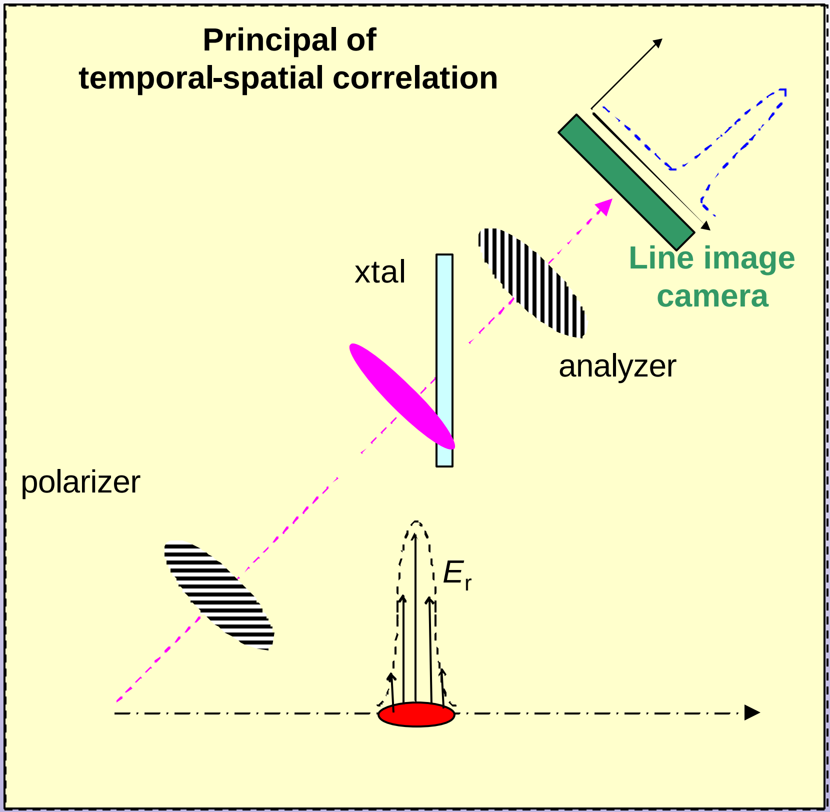
SPPS Electro Optic bunch length measurements – Adrian Cavalieri et al

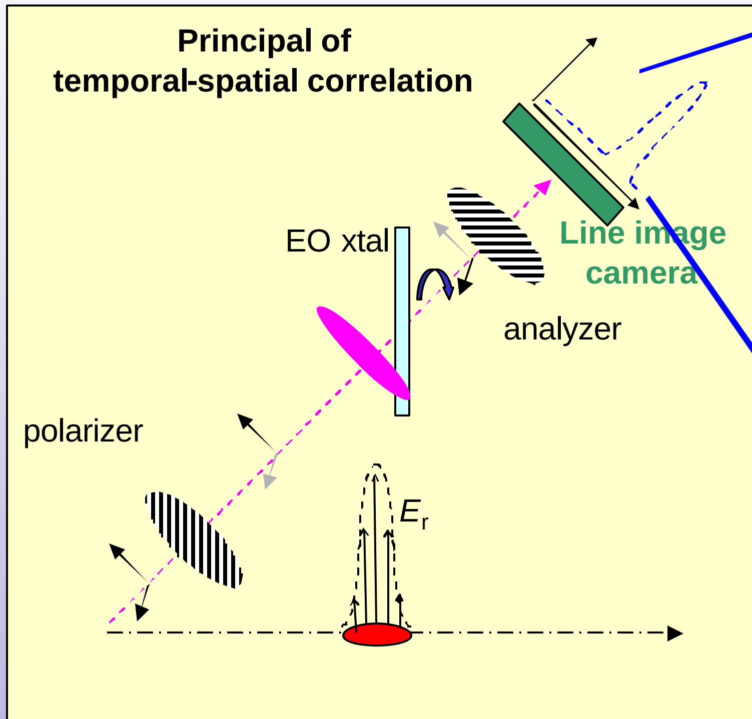
Spatial profile of beam focused along time axis, total sweep only several picoseconds

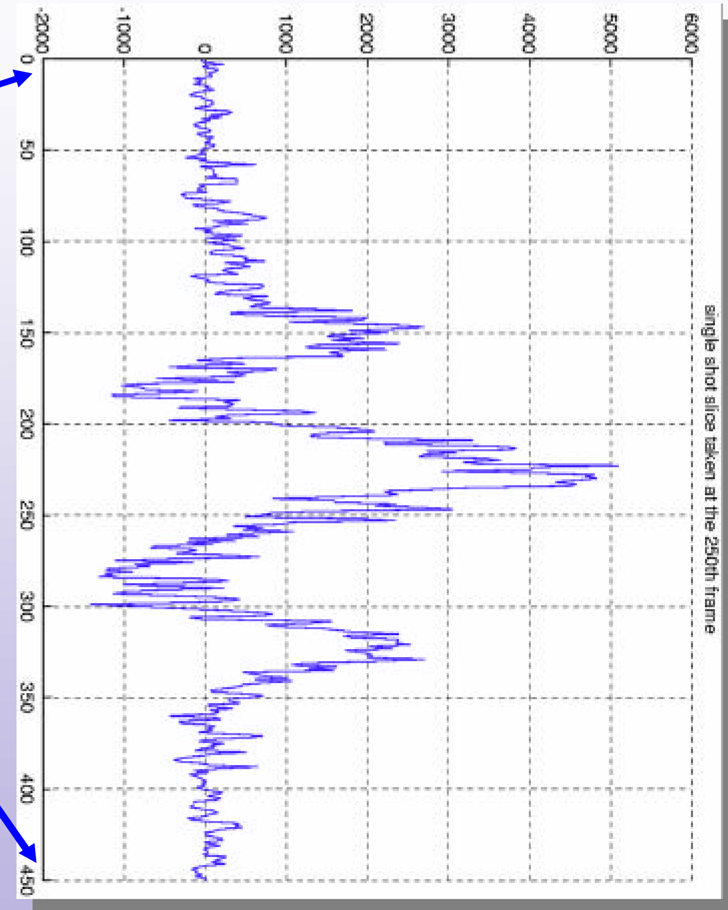




SPPS - EO signal vs time and single bunch – Adrian Cavalieri et al

- 0.5 mm ZnTe crystal





- multiple peaks indicate multiple rotations of polarization vector

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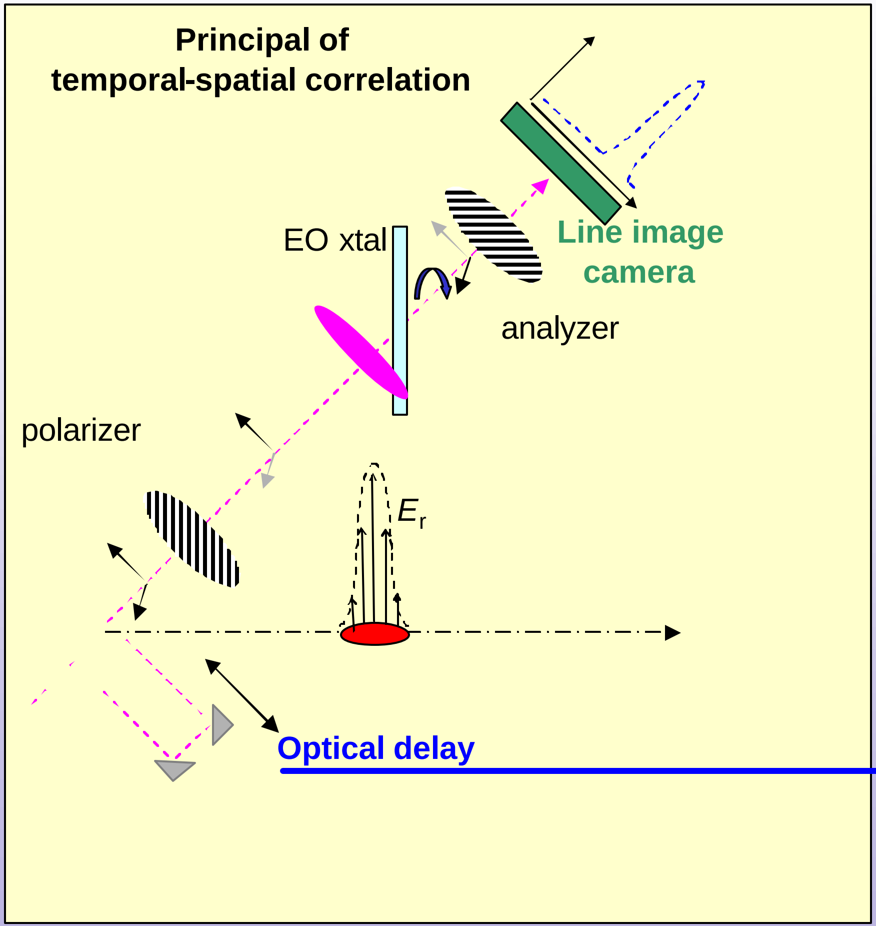
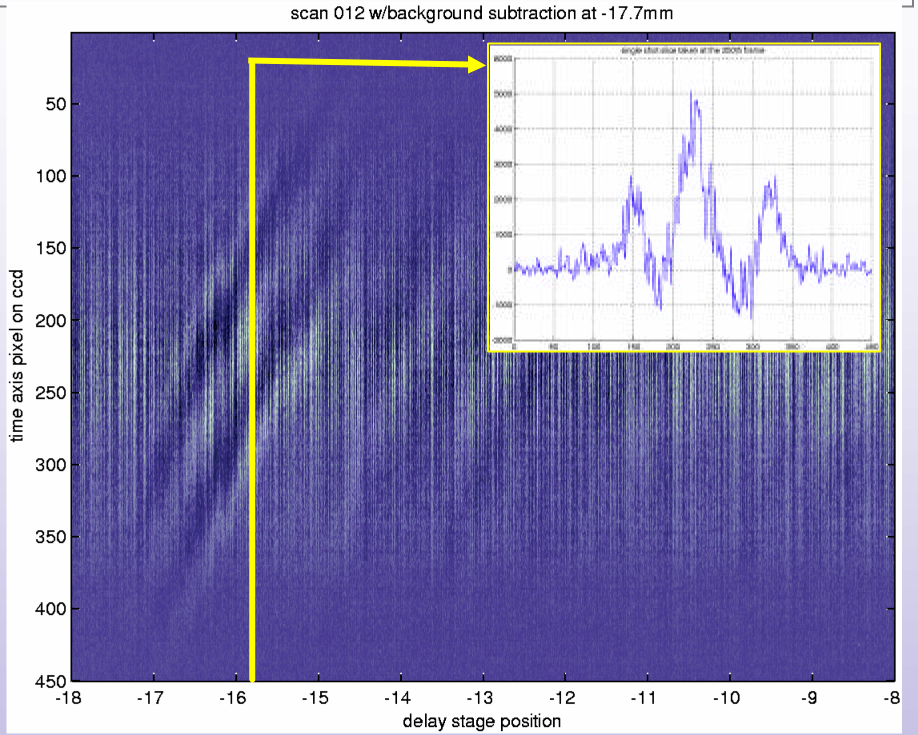
SPPS - time sequence of multiple EO images





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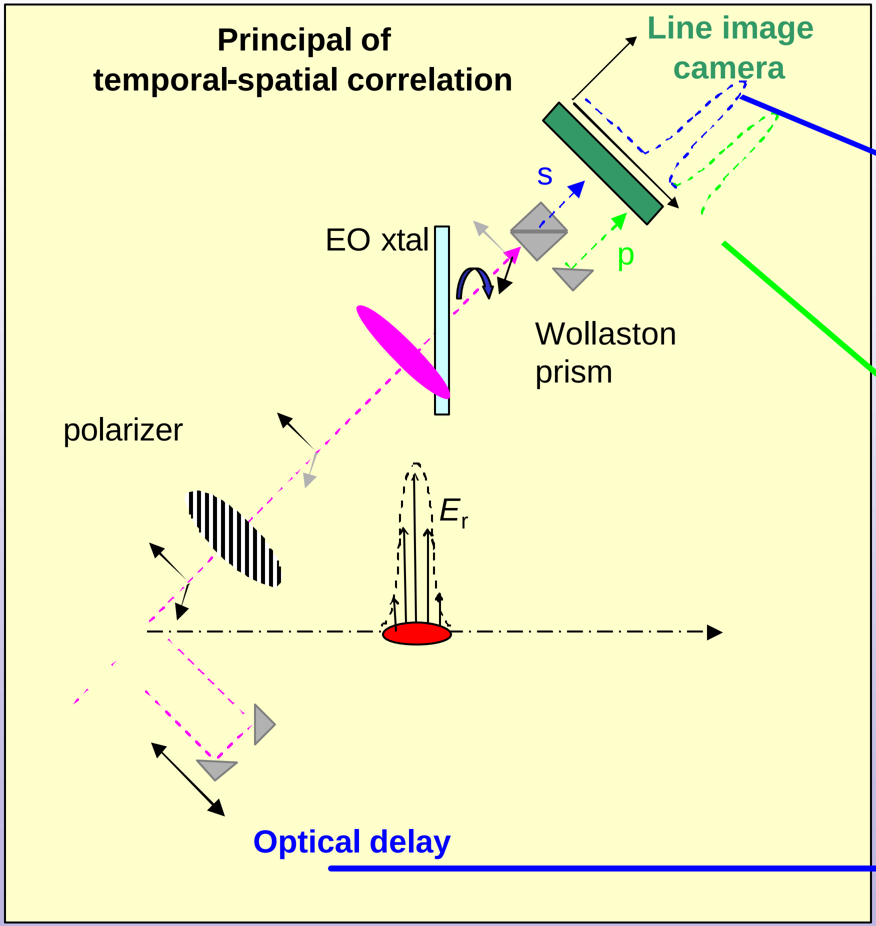
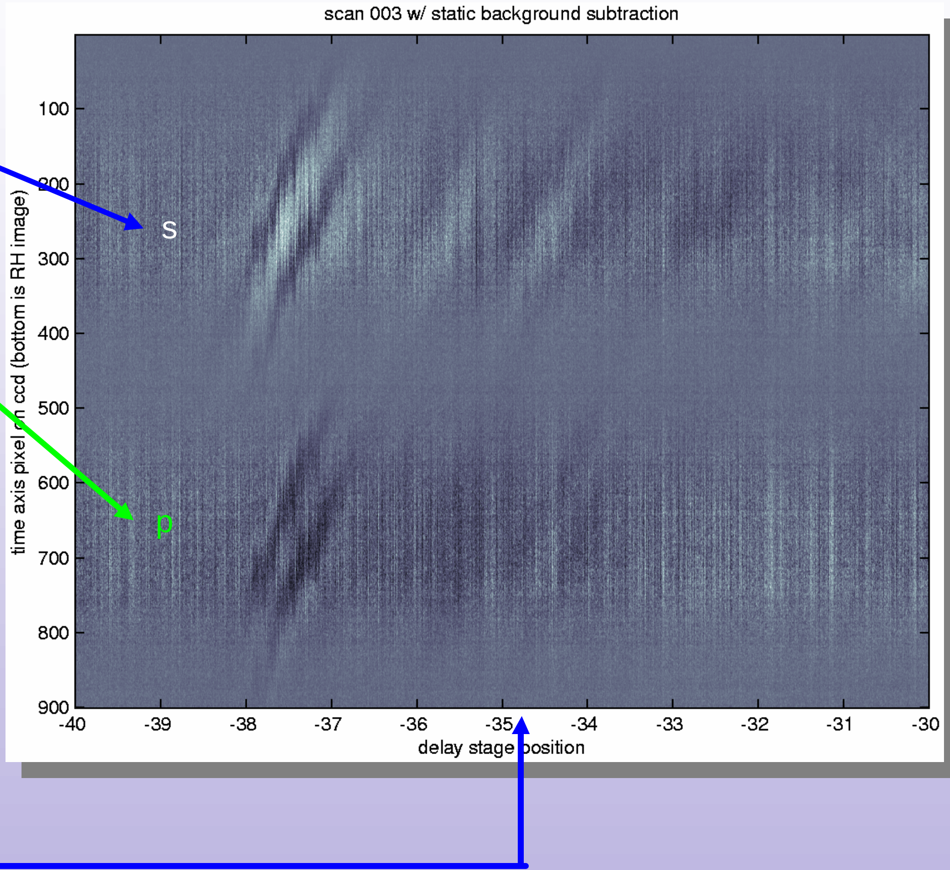
SPPS - time sequence of multiple EO images





Note wakefields after passage of the bunch

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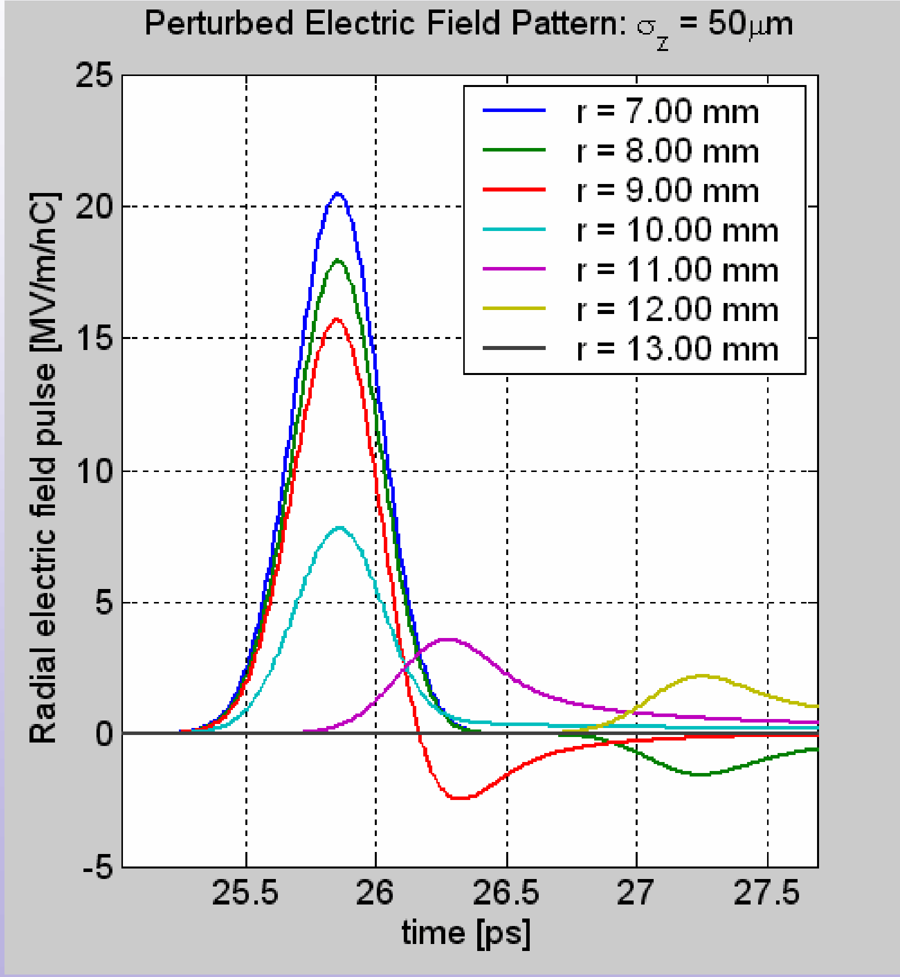
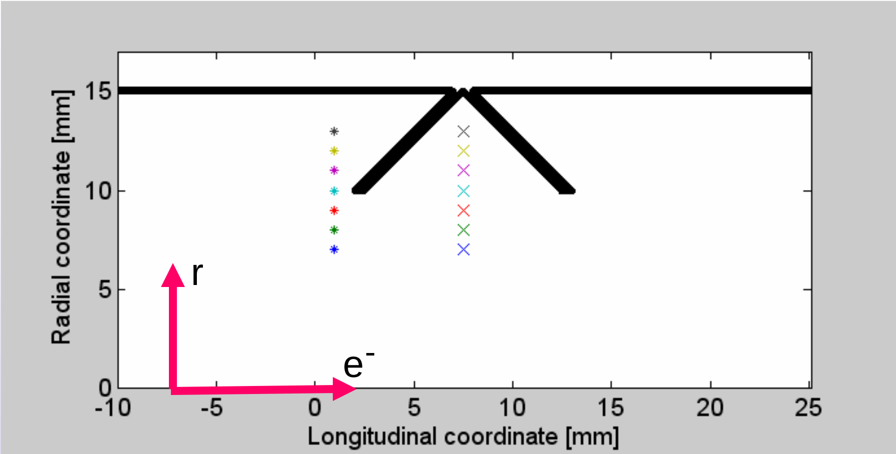
EO resolution limit due to wakefields – H. Schlarb





•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.

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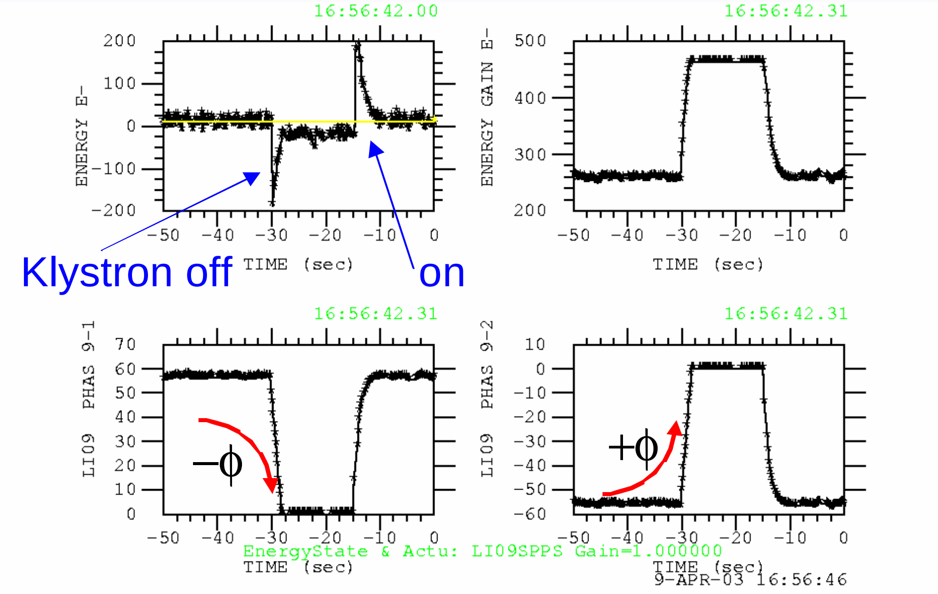
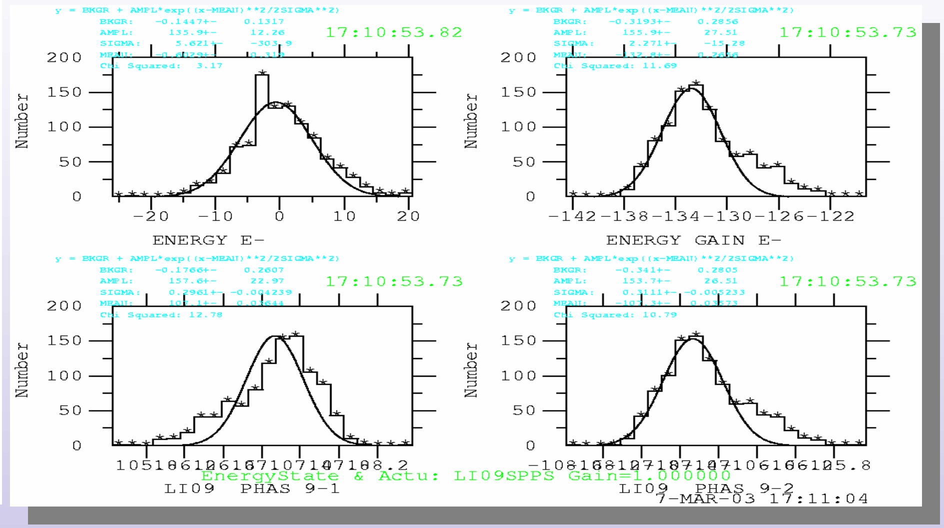
Feedback implementation

- *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)*

Energy feedback



Klystron 1
Klystron 2



Energy feedback at SPPS chicane responding to a step energy change

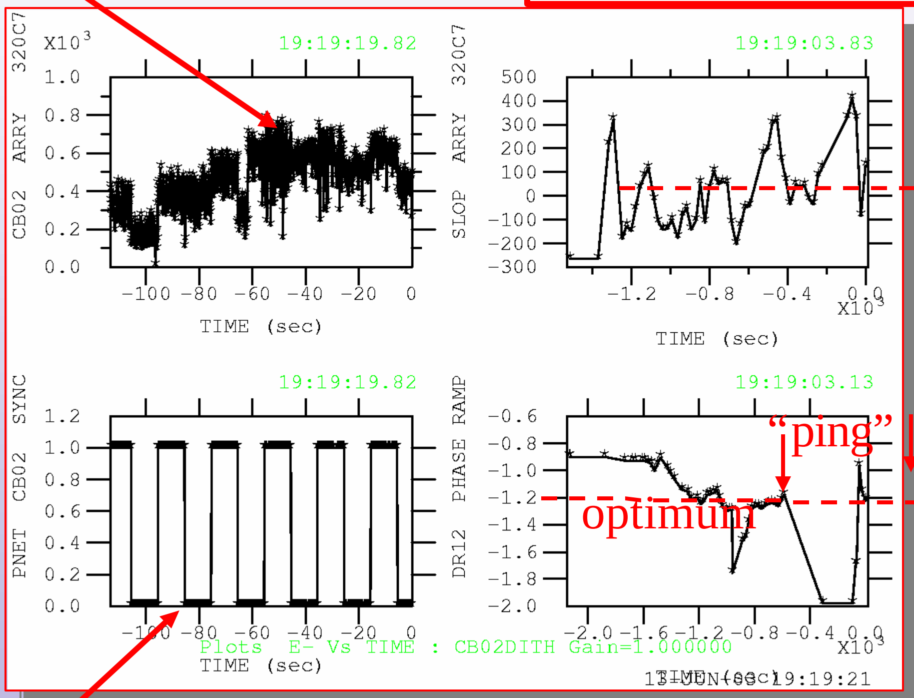
Energy measured at a dispersive BPM,
Actuator is a klystron phase shifter

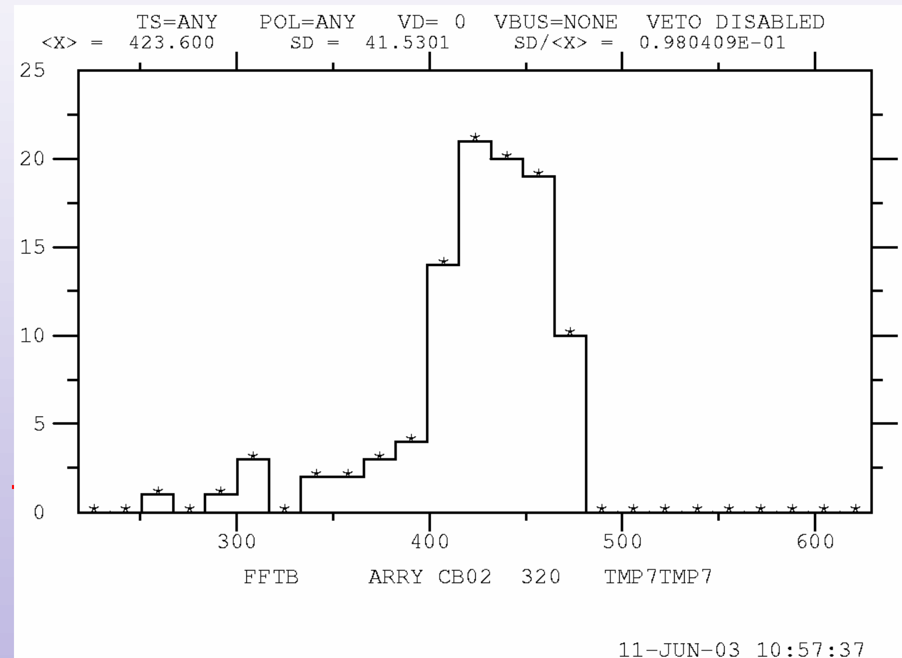
Energy jitter measured from chicane feedback system 5.6 MeV rms 0.06%

Dither feedback control of bunch length minimization - L. Hendrickson

Bunch length monitor response

Feedback correction signal





Dither time steps of 10 seconds

Linac phase

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

Conclusions

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*

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