

SPPS

Sub-Picosecond Electron Bunch Length Measurements at SLAC

Patrick Krejcik

R. Akre, P. Emma, K. Gaffney, J. Hastings, M. Hogan, J. Wu (SLAC),
R. Ischebeck, H. Schlarb (DESY, Hamburg),
P. Bucksbaum, A. Cavalieri, D. Reis (U. Michigan),
P. Muggli (USC)

26TH INTERNATIONAL
FREE ELECTRON LASER CONFERENCE
& 11TH FEL USERS WORKSHOP



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FEL2004, Trieste

Motivation for Bunch Length & Timing Diagnostics

- FELs rely on short bunches for high peak current
- Longitudinal distribution reflects bunch compression dynamics and tuning
- RMS bunch length measured on a single pulse is used to stabilize linac RF phase and amplitude
- Characterize timing jitter in the bunch
- Measure pulse-by-pulse arrival time with respect to pump-probe laser for users

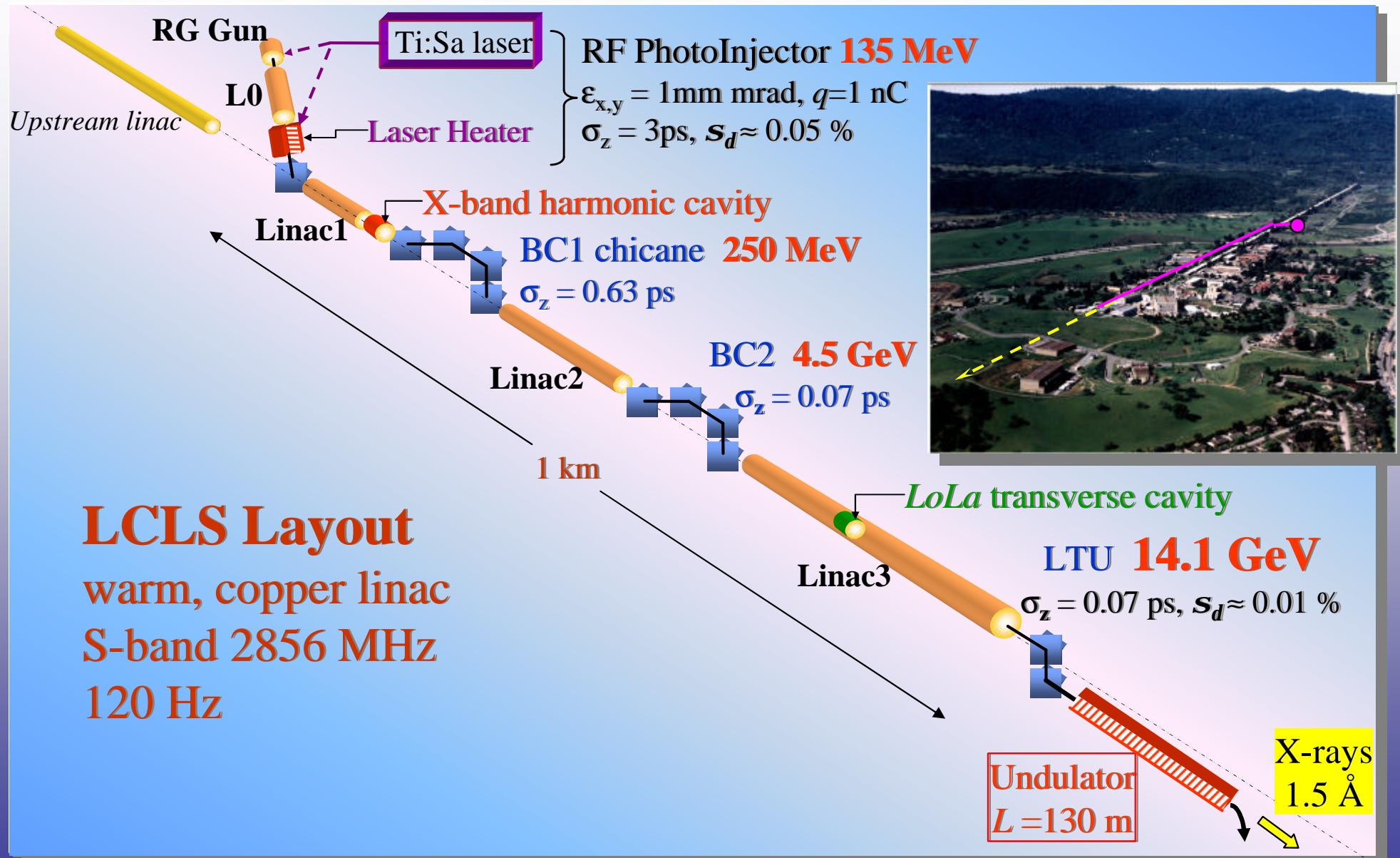
SLAC Program

■ The Linac Coherent Light Source, LCLS Project

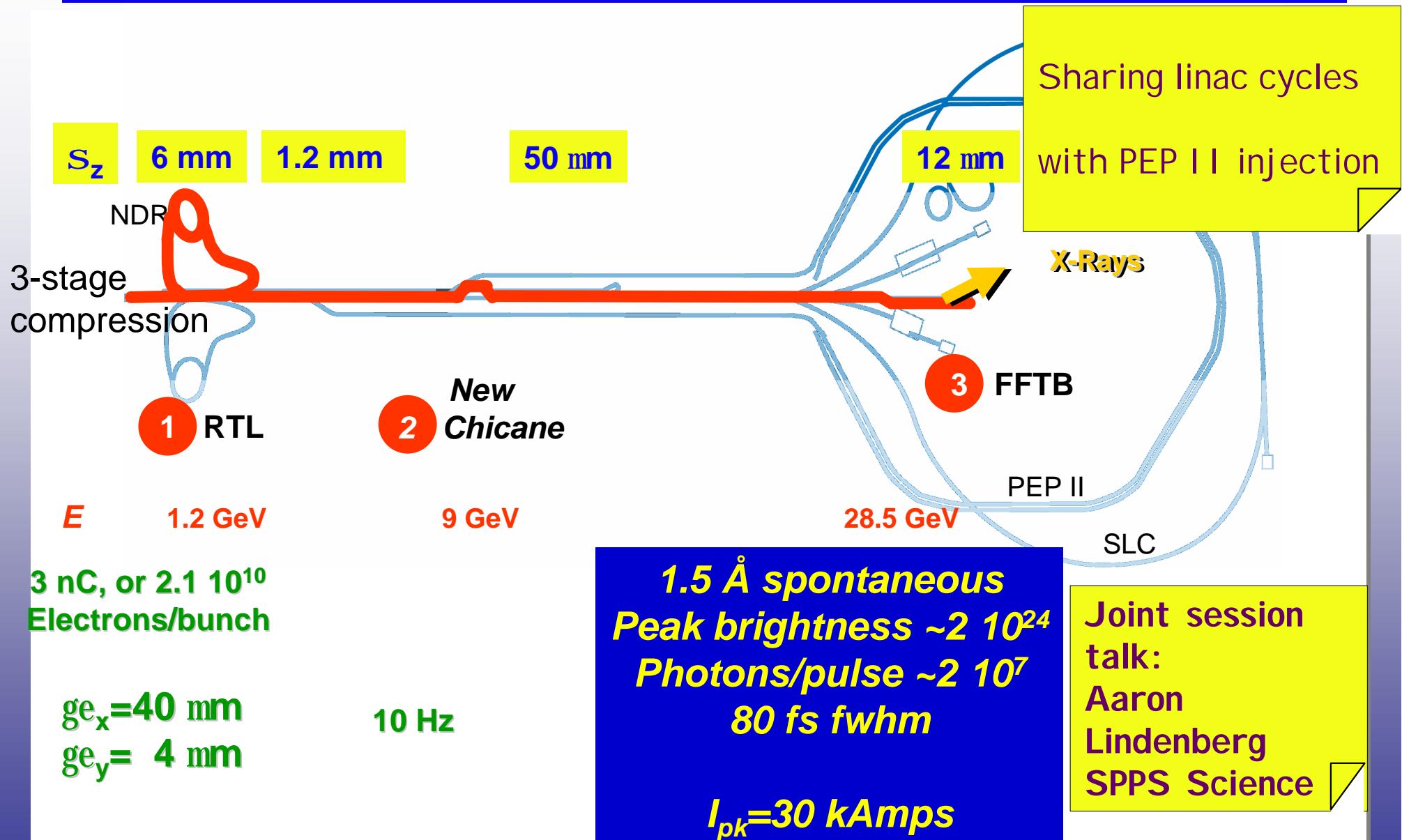
- Project start date 2005
- Deliver X-rays in 2008

■ The Sub Picosecond Pulsed Source, SPPS Project

- Commissioned in 2002
- Produces 1.5 Å spontaneous radiation using
- ~80 femtosecond fwhm pulses 28.5 GeV electrons



SPPS compresses existing linac beam



Diagnostic challenges

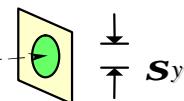
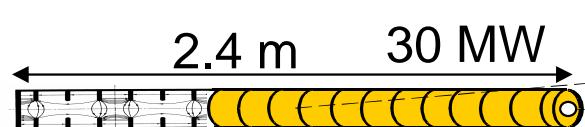
Measurement

- Measurement of ultra-short bunch profiles
- Shot-by-shot measurement of bunch length
- Bunch timing measurement

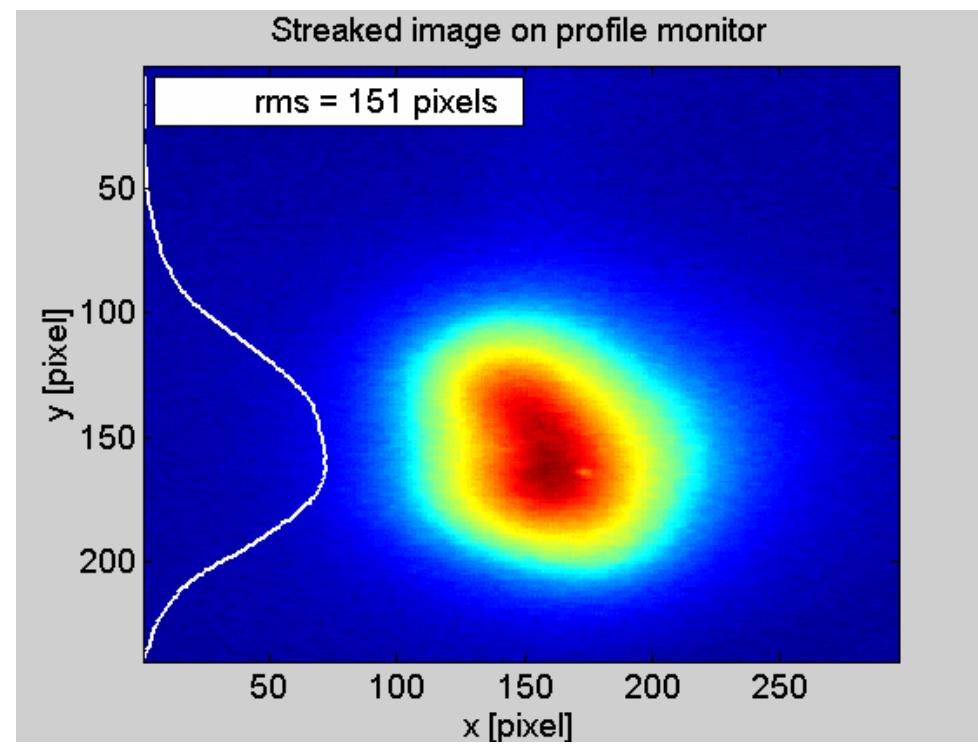
Devices

- RF transverse deflecting cavity “LOLA”
- Terahertz coherent spectral power measurement
- Coherent radiation autocorrelation
- Electro-optic bunch profiling

Bunch Length Measurements with the RF Transverse Deflecting Cavity



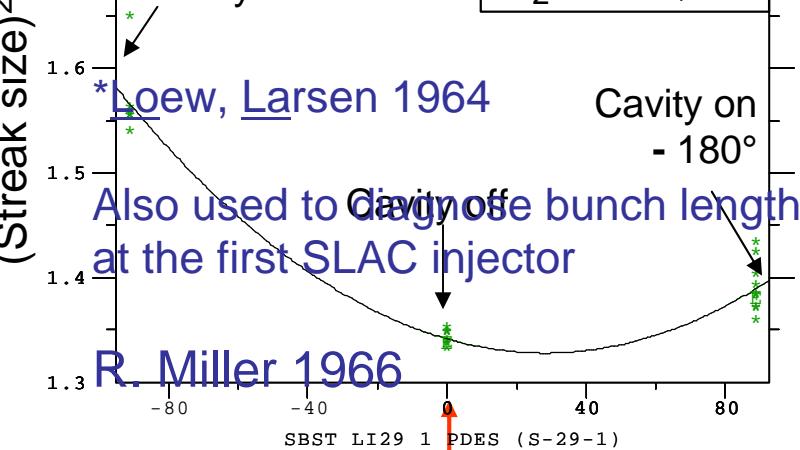
Bunch length reconstruction
Measure streak at 3 different phases



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

An S-band DLW structure with a TM₁₁₁ transverse deflecting mode at 285.6 MHz

$A =$	1.6696E-02	$\text{STD DEV} =$	1.3536E-03
$B =$	28.23	$\text{STD DEV} =$	1.094
RMS Fit	132.2	$\text{STD DEV} =$	23.63
ERROR			



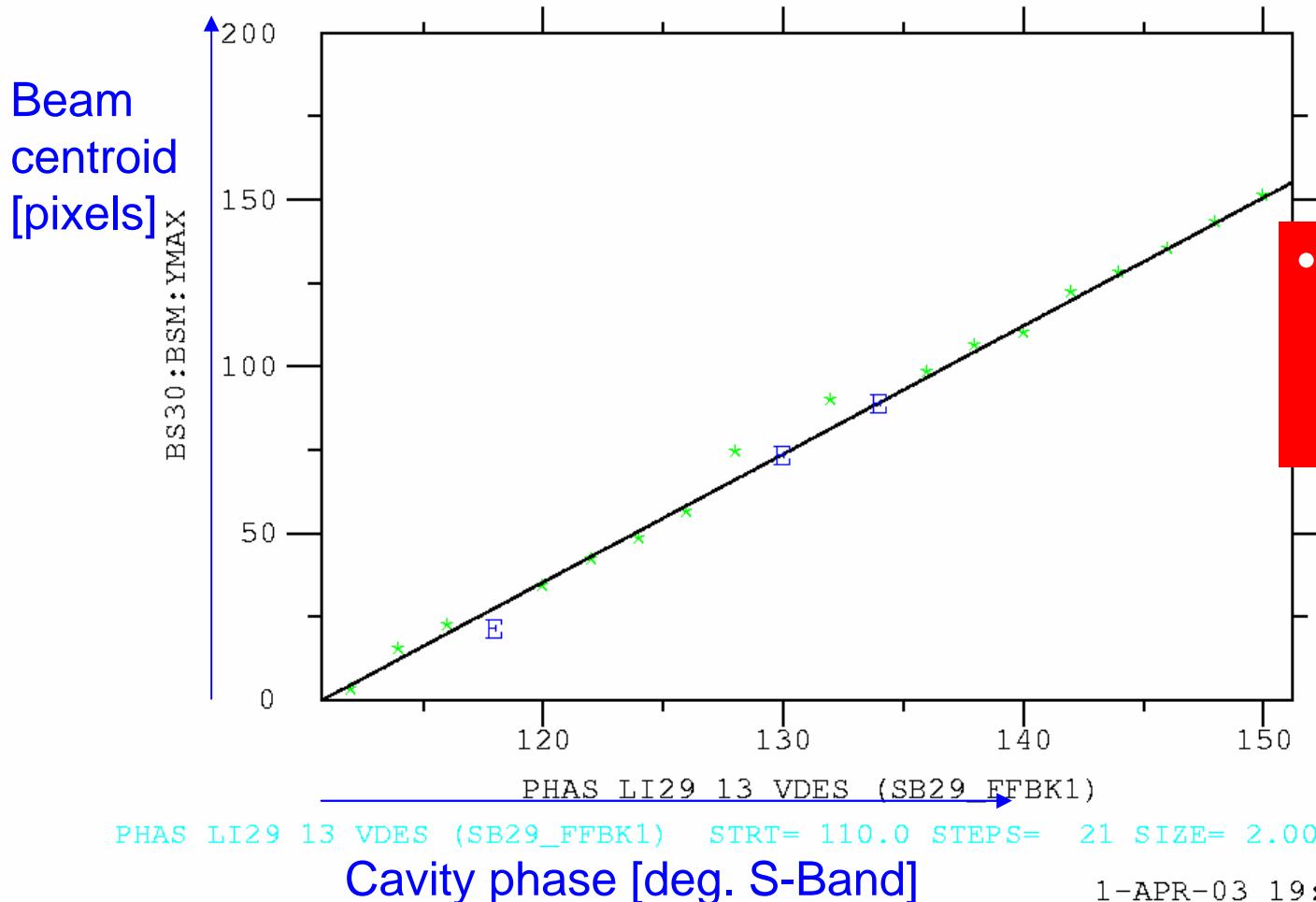
Asymmetric parabola indicates incoming tilt to beam

P. Krejcik

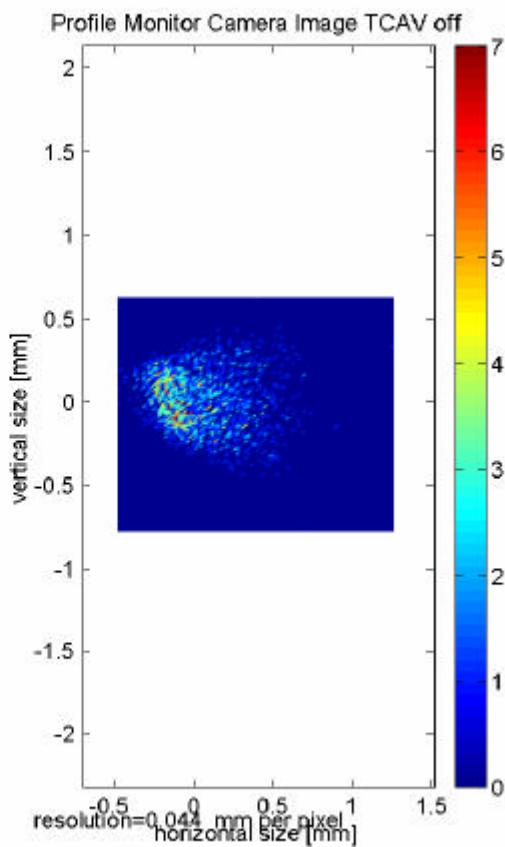
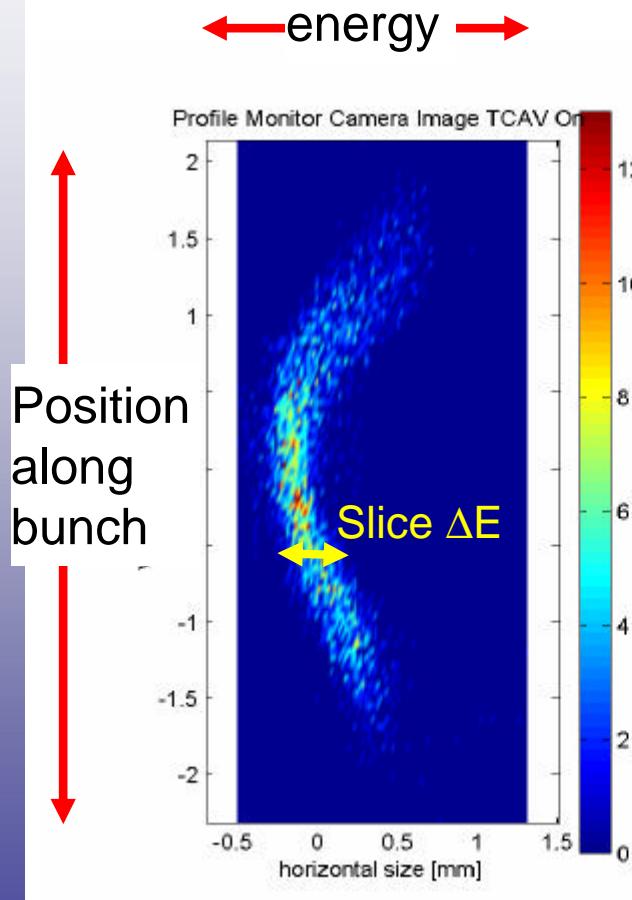
pkr@slac.stanford.edu

Calibration scan for RF transverse deflecting cavity

A = 3.848 STD DEV = 6.6705E-02
B = -426.6 STD DEV = 8.818
RMS FIT ERROR = 3.116



OTR Profile Monitor in combination with RF Transverse Deflecting Cavity



Simulated digitized video image at LCLS Injector DL1 beam line

Slice energy spread is the relevant parameter for FELs

Coherent radiation from the electron bunch

■ Frequency domain

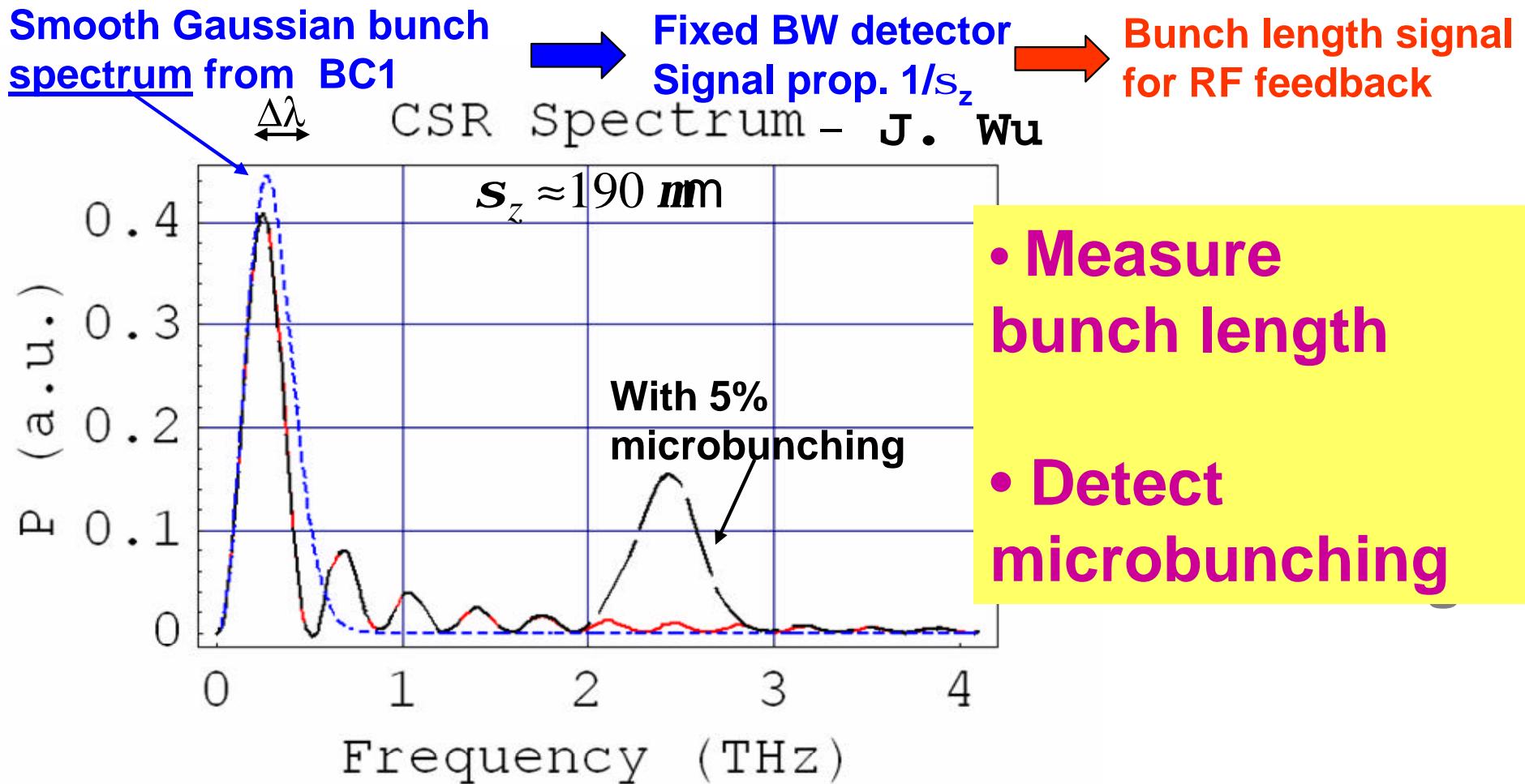
- Spectral power in a fixed bandwidth
- Spectrometry
- Autocorrelation

■ Time domain

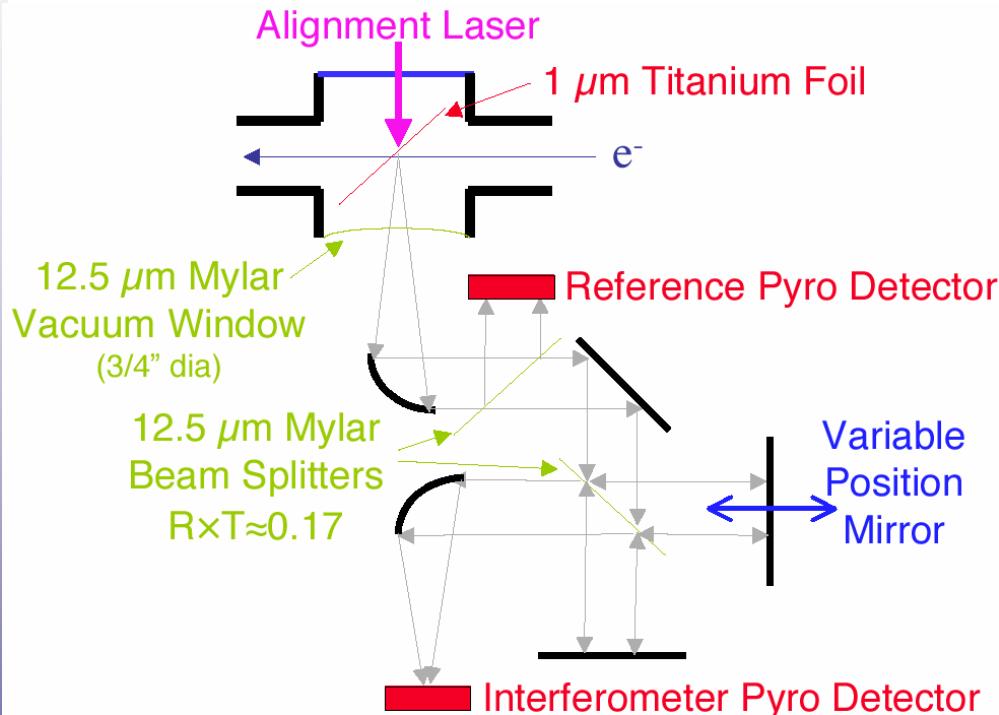
- Electro optic sampling
- Measured directly near the bunch
- Or transported out of the beam line

Diagnosing Coherent Radiation

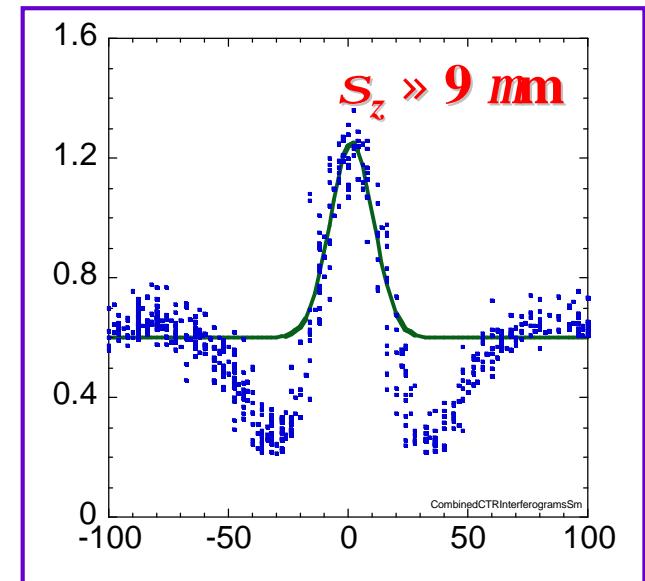
1. spectral power



Diagnosing Coherent Radiation 2. autocorrelation



Transition radiation is coherent at wavelengths longer than the bunch length, $\lambda > (2\pi)^{1/2} \sigma_z$

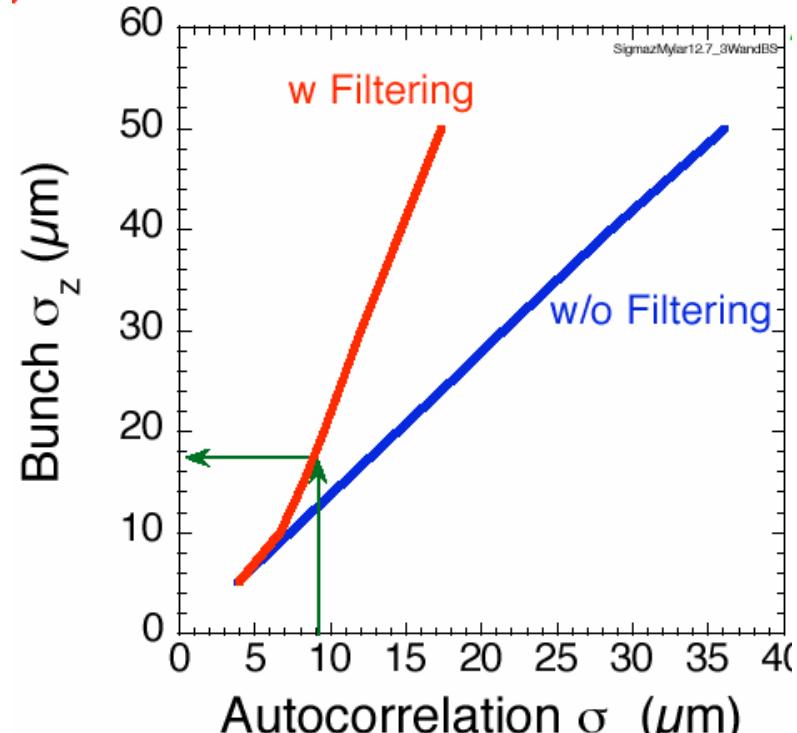
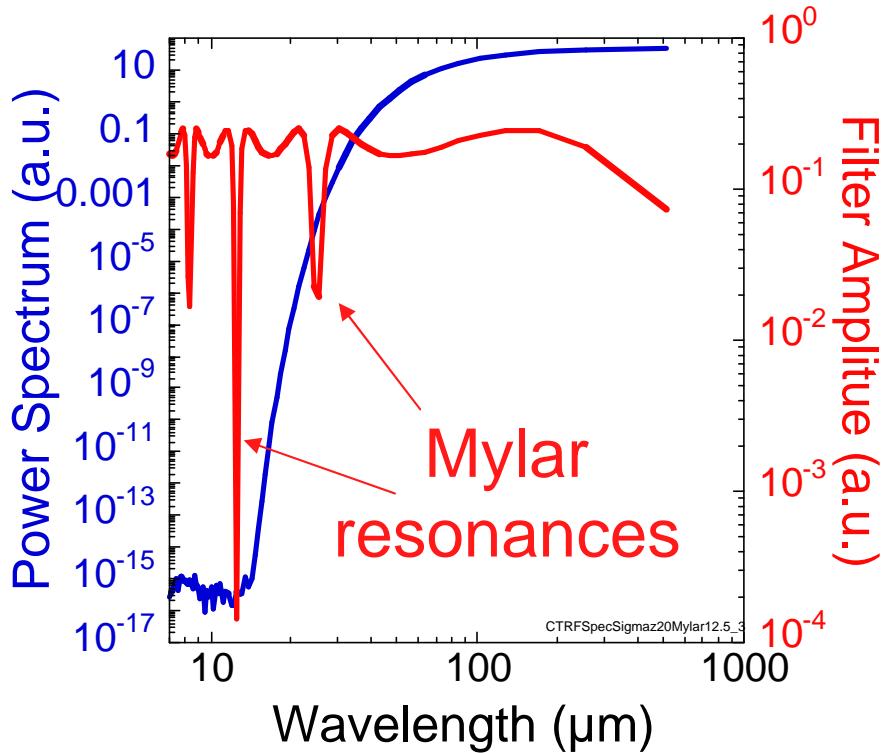


Limited by long wavelength cutoff and absorption resonances

SLAC **SPPS** measurement:
P. Muggli, M. Hogan

Transport issues for THz radiation

Simple model: Gaussian, $\sigma_z=20 \mu\text{m}$, $d=12.7 \mu\text{m}$, $n=3$ Mylar window+splitter

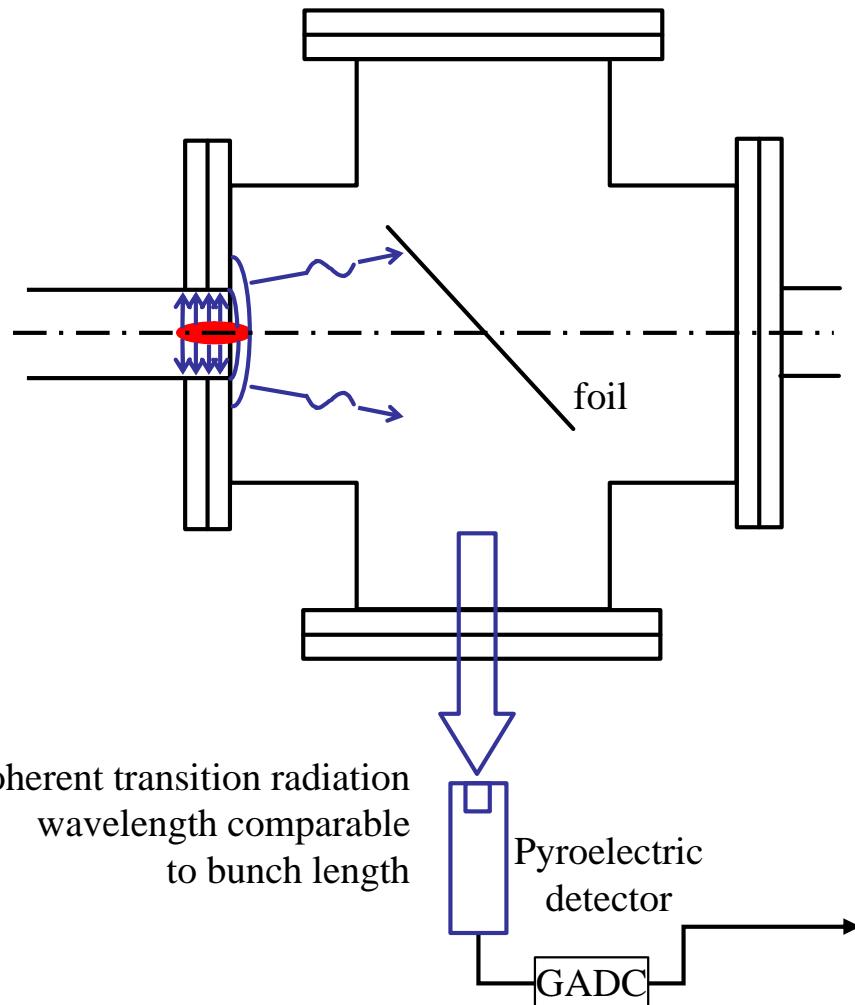


- Fabry-Perot resonance: $\lambda=2d/m$, $m=1,2,\dots$
- Signal attenuated by Mylar: $(RT)^2$ per sheet

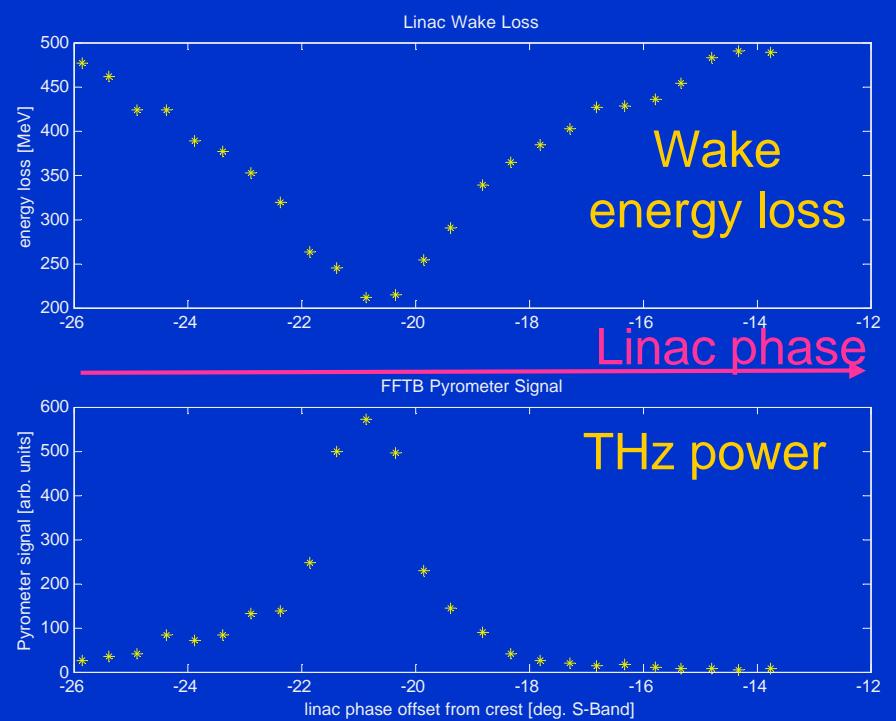
P. Muggli, M. Hogan

- Modulation/dips in the interferogram
- Smaller measured width:
 $s_{\text{Autocorrelation}} < s_{\text{bunch}}$!

Bunch length scan performed while observing spectral power with THz detector



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

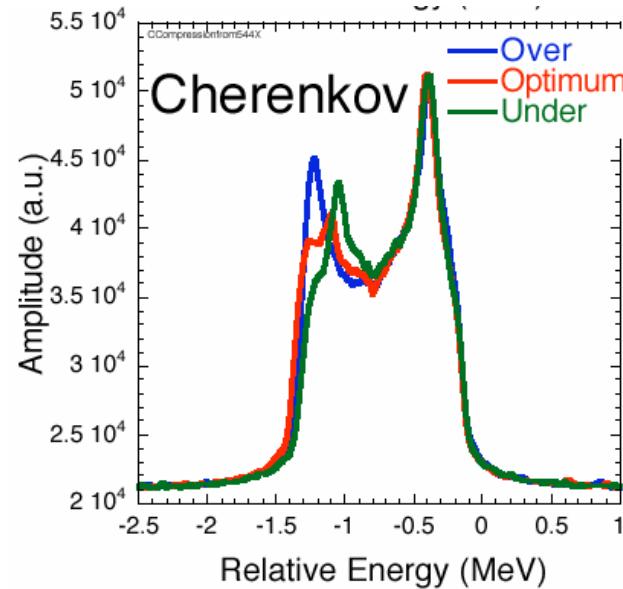


Diagnosing Longitudinal phase space: Energy spectrum versus Bunch length signal

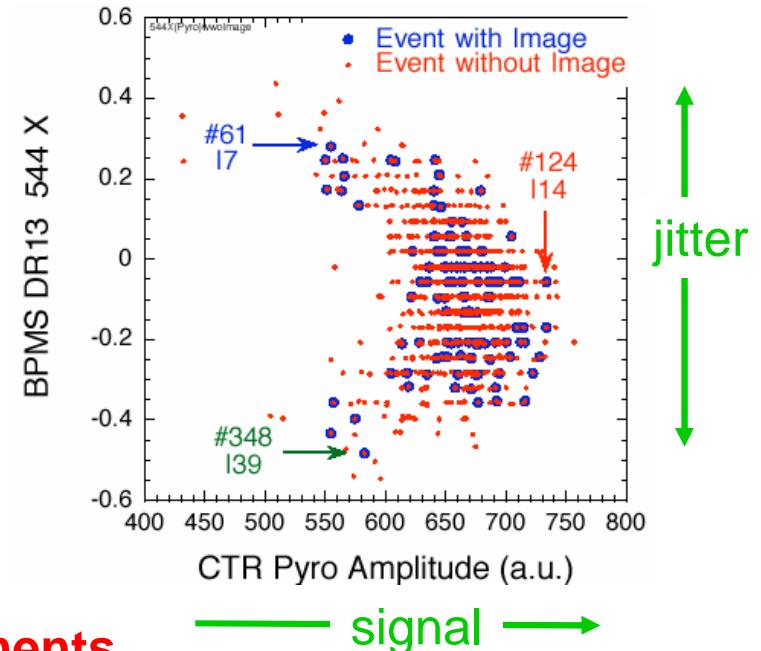
- Muggli, Hogan et al

Jitter in the compressor phase:

Resulting energy profile



Corresponding bunch length signal

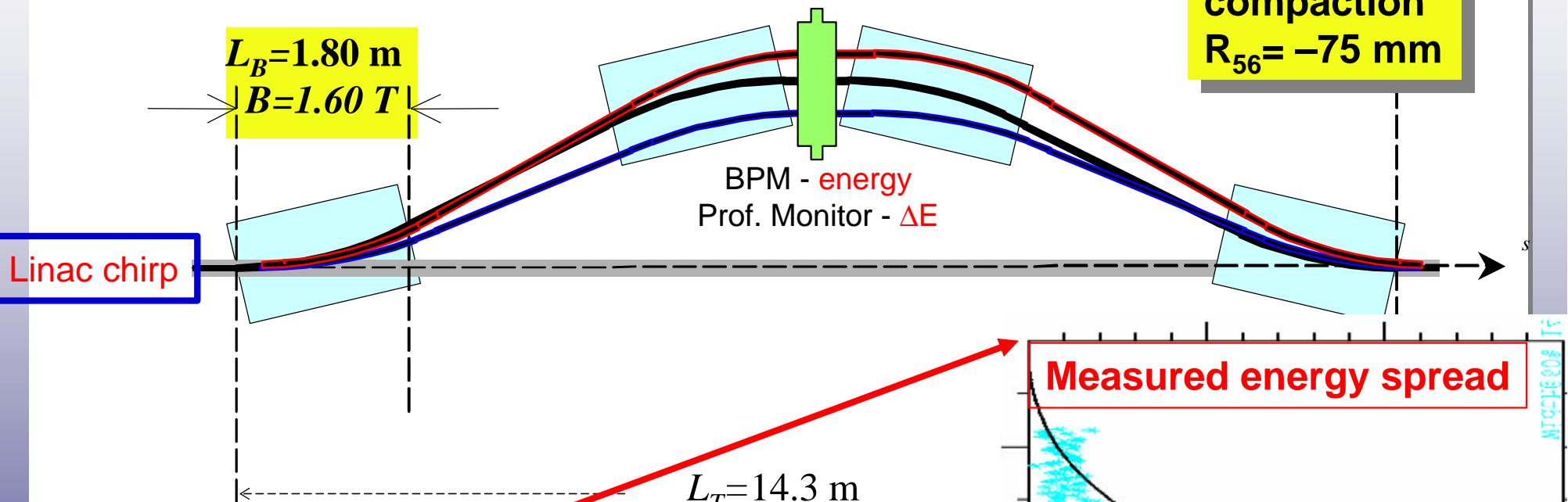


Single shot measurements

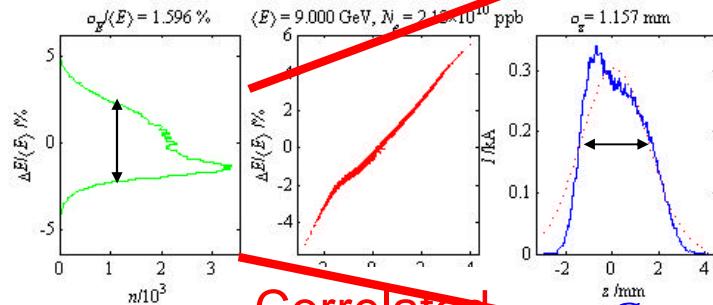
SPPS Four Dipole Chicane

9 GeV

Momentum compaction
 $R_{56} = -75 \text{ mm}$



S_d
1.6%

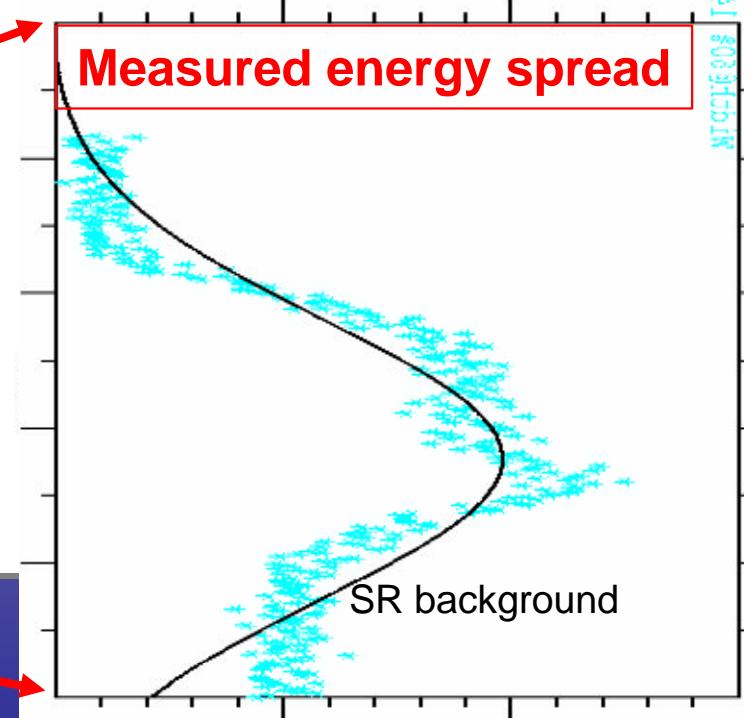


Correlated
energy
spread

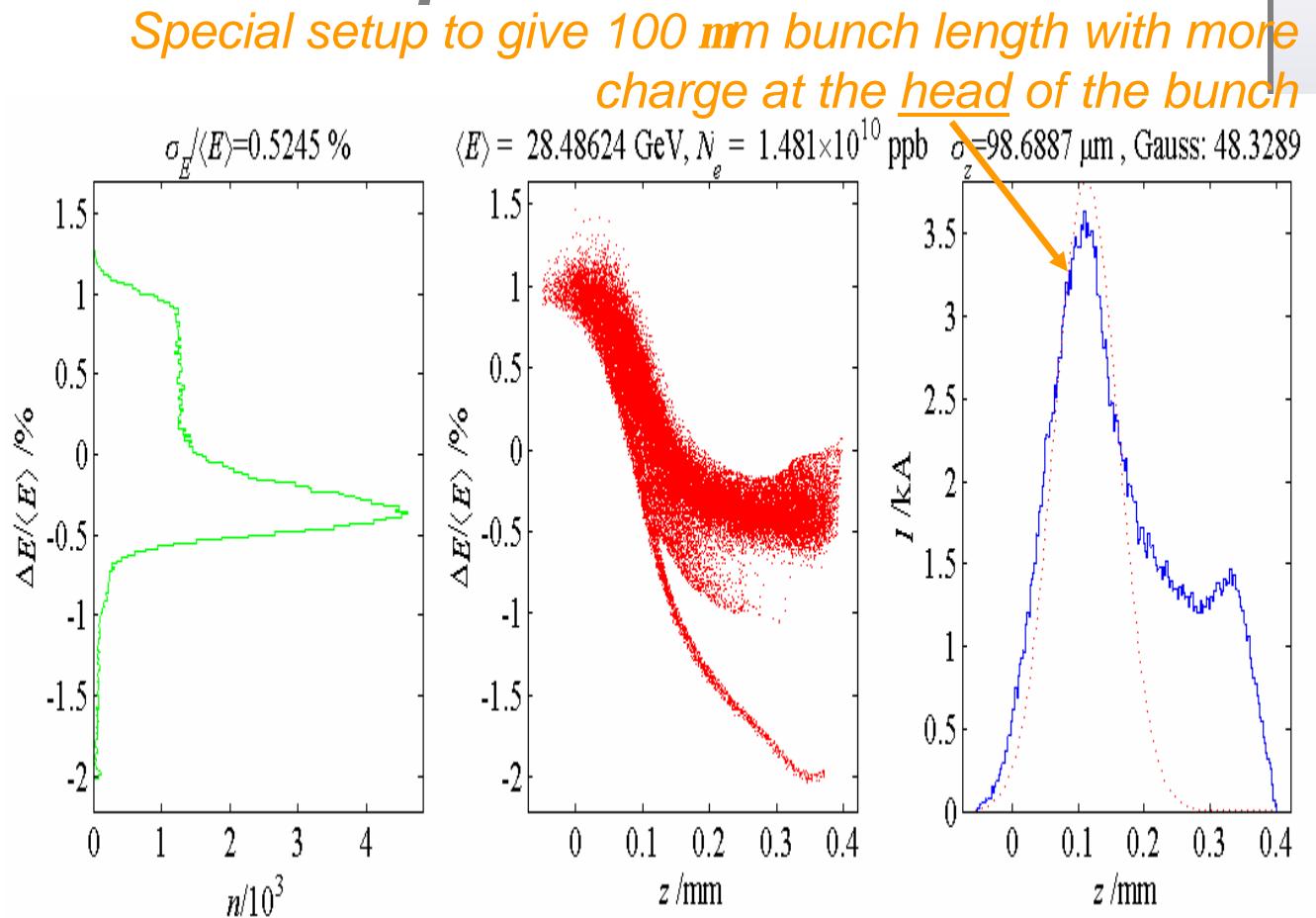
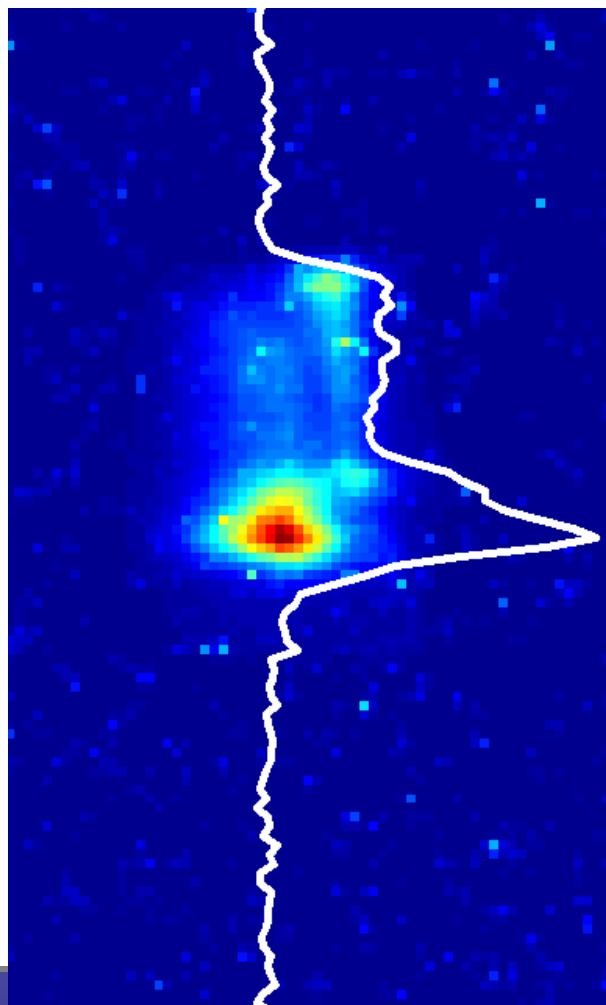
S_{η}
1.2 mm

Aug. 30 - Sept. 3,
FEL2004, Trieste

Measured energy spread



Measured and predicted energy spread from wakefield chirp in SPPS



Aug. 30 - Sept. 3,
FEL2004, Trieste

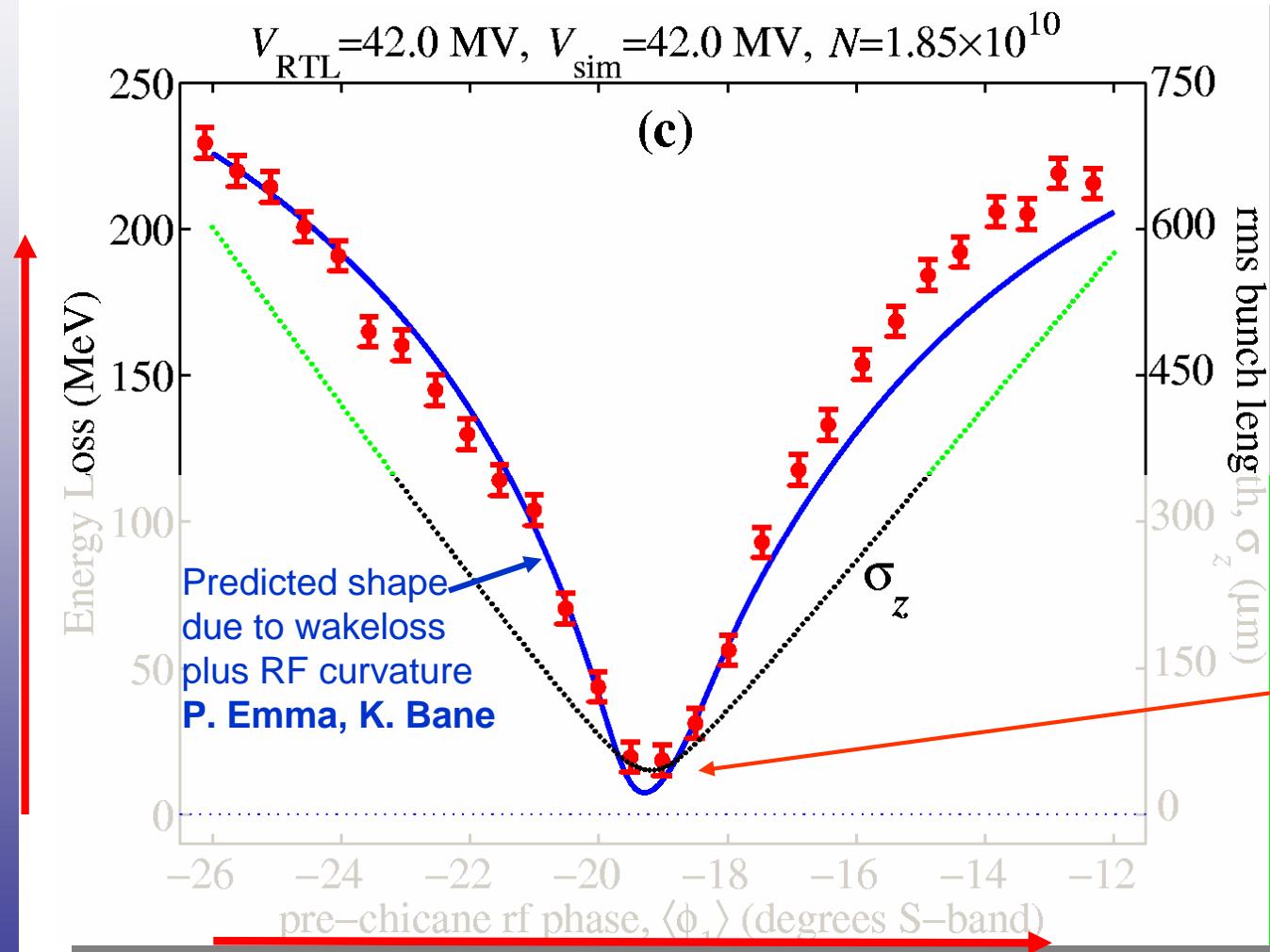
Measured at end of linac

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- Wakefields change not only the energy spread in the bunch
- But also the centroid energy of the bunch
- Fast means of determining relative bunch length



Relative bunch length measurement 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
For bunch length s_z

Coherent radiation from the electron bunch

■ Frequency domain

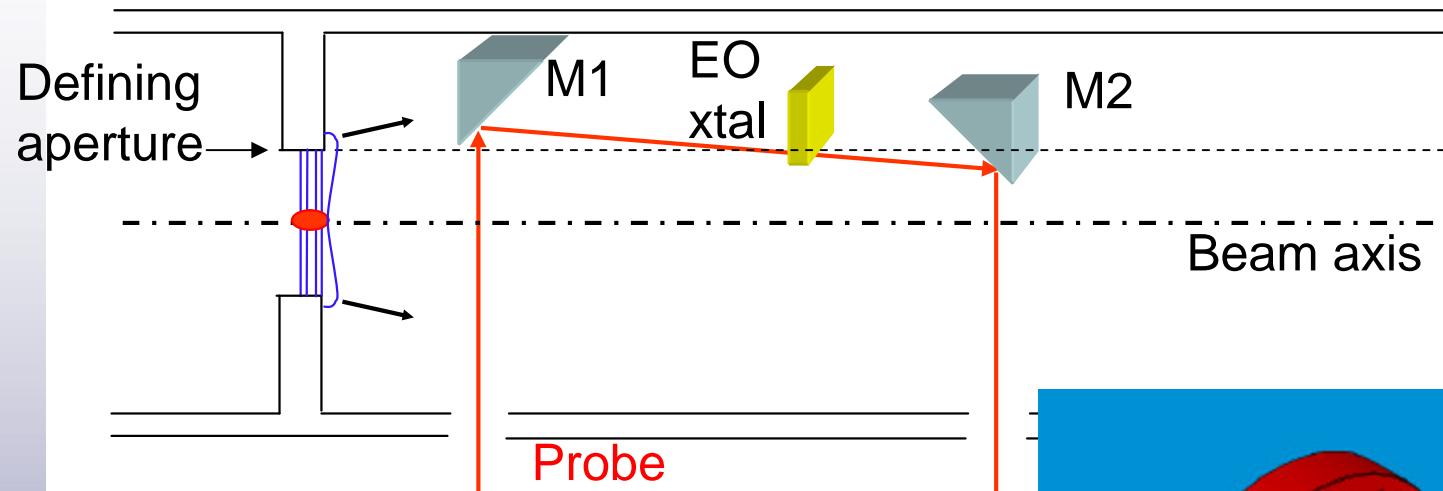
- Spectral power
- Spectrometry
- Autocorrelation

■ Time domain

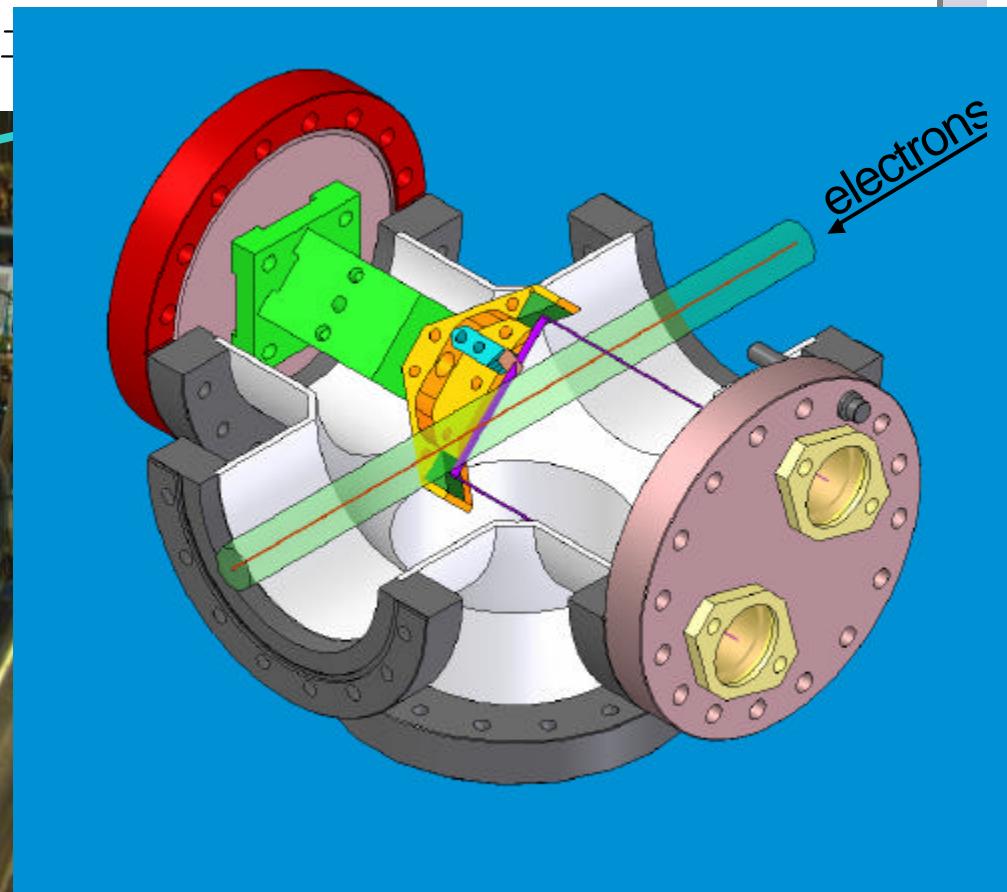
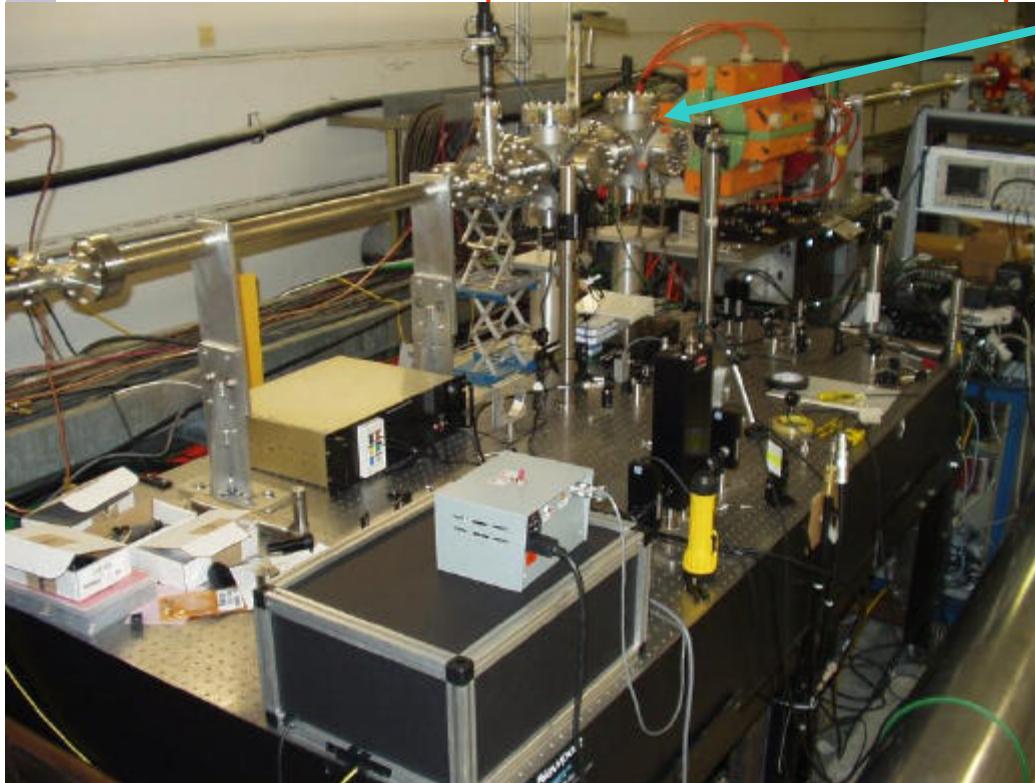
- **Electro optic sampling**
- Measured directly near the bunch
- Or transported out of the beam line



SPPS Electro Optic Bunch Length Measurement

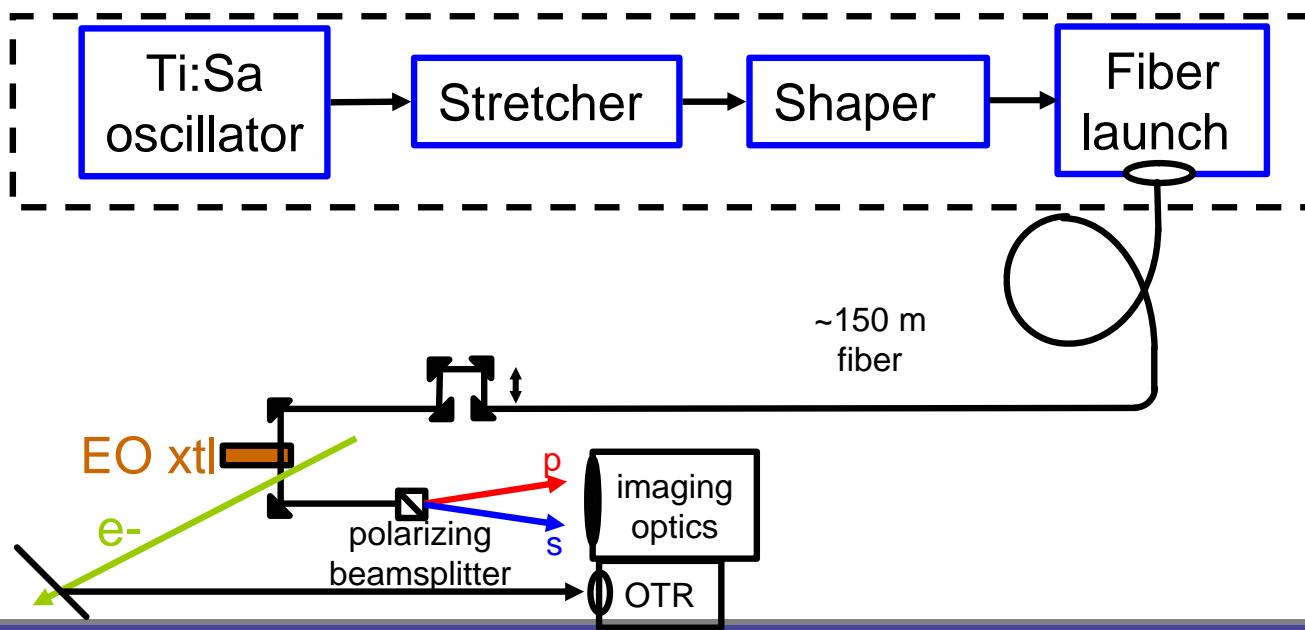


Geometry chosen to measure direct electric field from bunch, not wakefield
Modelled by H. Schlarb



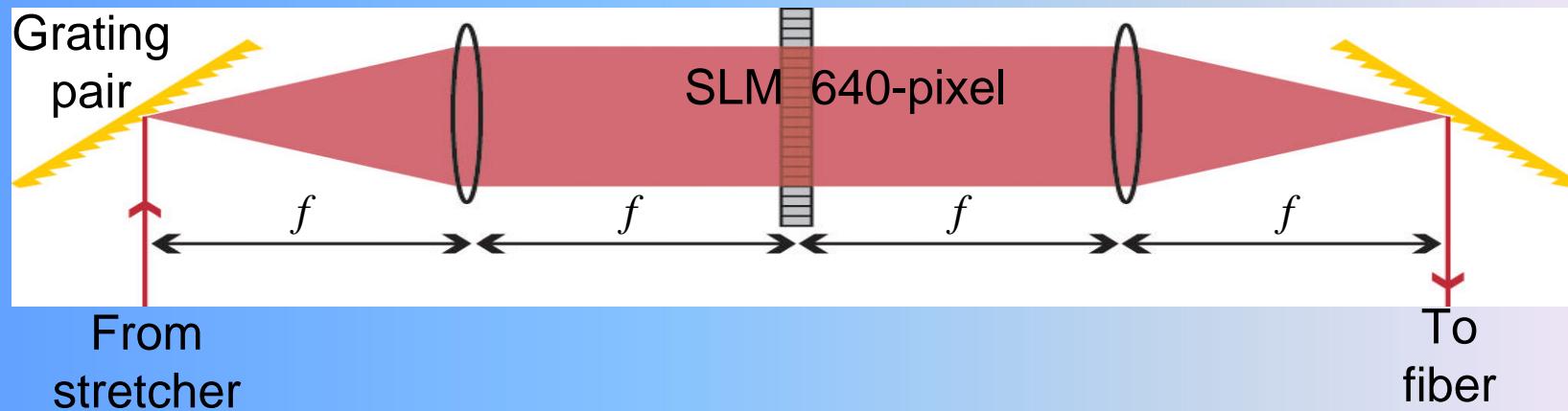
Features of the SPPS Electro Optic Setup

- Compressed pulse from the users pump-probe Ti:Sa laser oscillator
- Transported low power pulse over ~150 m fiber to the electron beam line
- OTR provides coarse timing



Features of the SPPS Electro Optic Setup

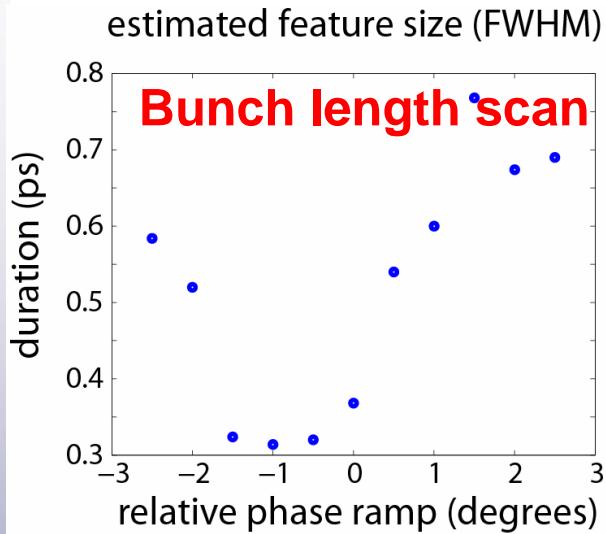
- Fiber incorporated in pulse compression setup including compensating fiber dispersion with a spatial light modulator
 - Cavalieri et al, FOCUS Group U. Michigan



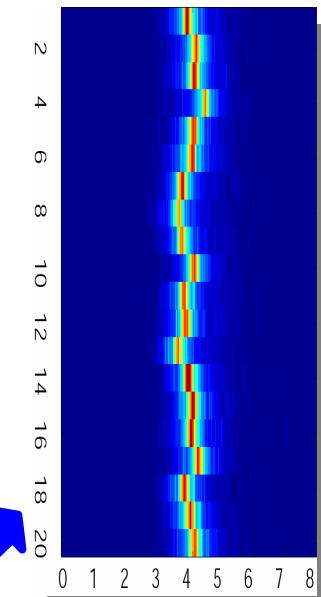
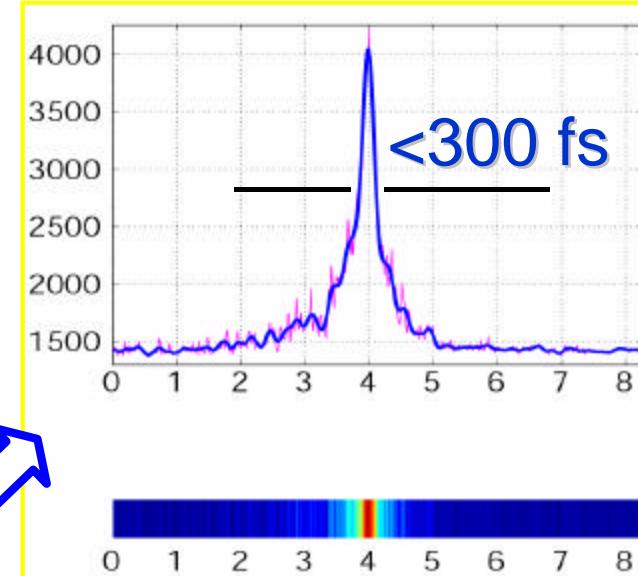
Features of the SPPS Electro Optic Setup

- Crystal mounted close to electron beam
 - Avoid wakefields from smaller apertures
- ZnTe crystal:
 - 200 um thick
 - EO coefficient,
 - phase match,
 - phonon resonances

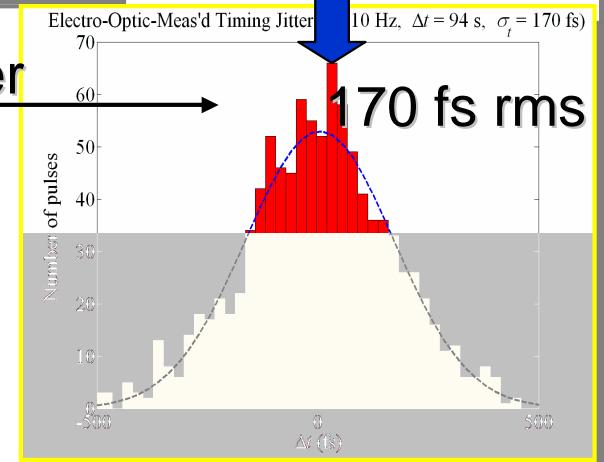
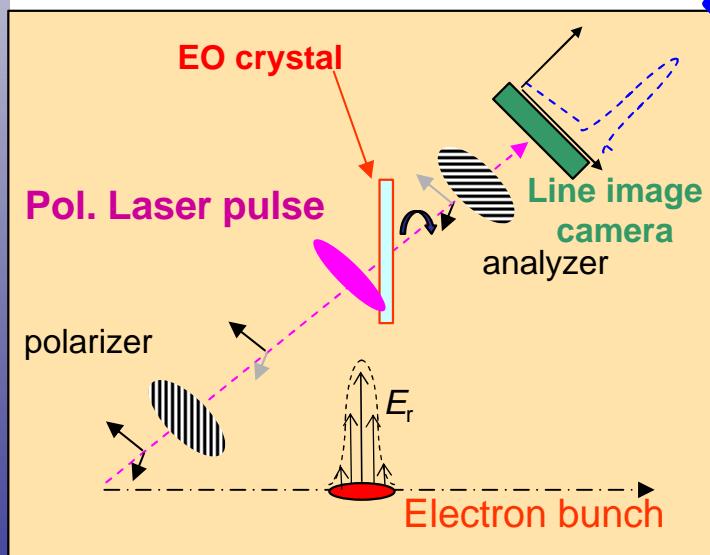
Electro-Optical Sampling at SPPS – A. Cavalieri et al.



Single-Shot



Timing Jitter



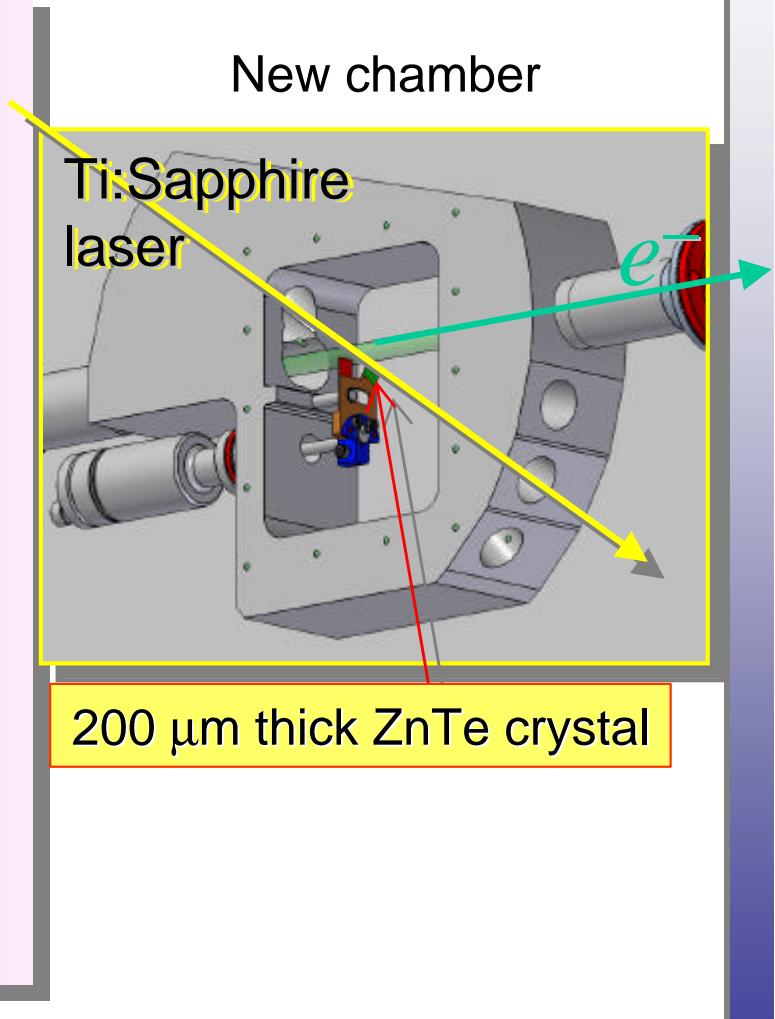
Electro optic resolution limits

- Spatial imaging resolution limits time resolution
- Crossing angle determines width of time window and temporal resolution
- Resolution limit then set by crystal thickness and the phase velocity mismatch
- Crystal material chosen to minimize phase mismatch

Electro optic resolution limits

Future experiments

- Smaller crossing angle
 - Smaller angle magnifies time coordinate on spatial axis
 - But reduces the time window to accommodate beam jitter
- EO polymer films
 - Strong EO coefficient
 - May not last long
- Higher laser power cross correlation techniques (Jamison et al)
 - Laser amplifier located near beamline

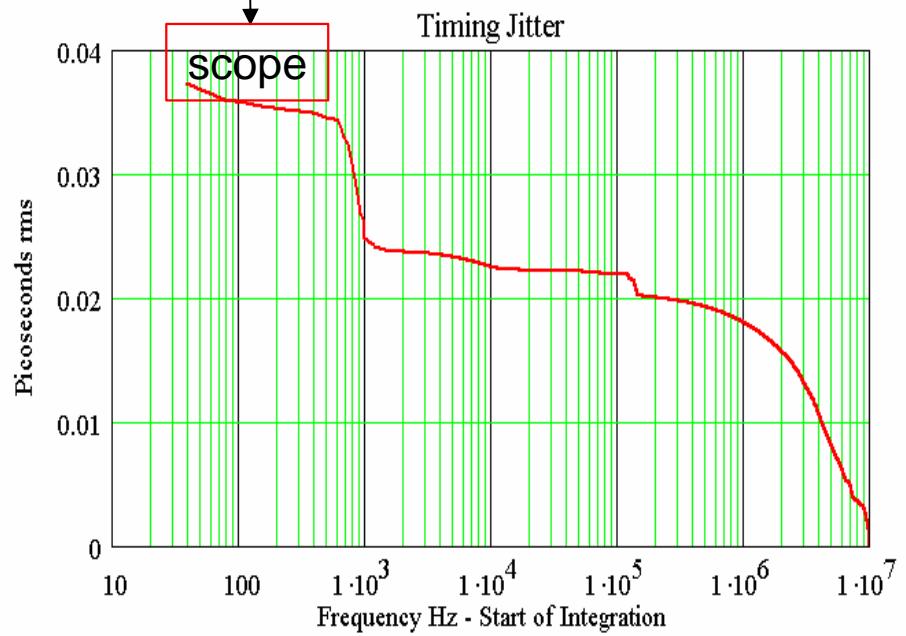
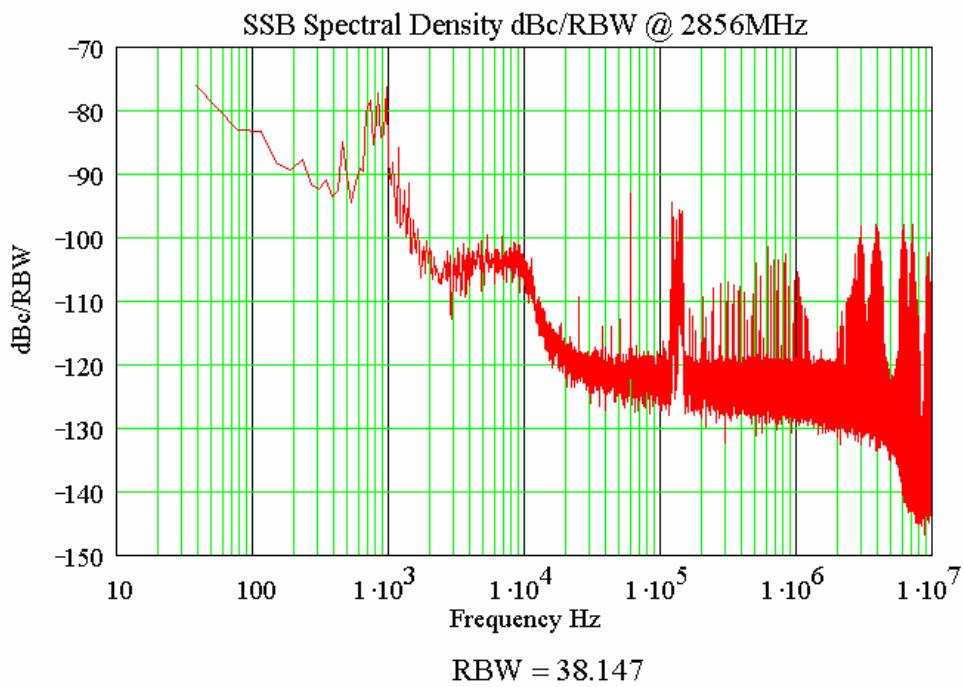
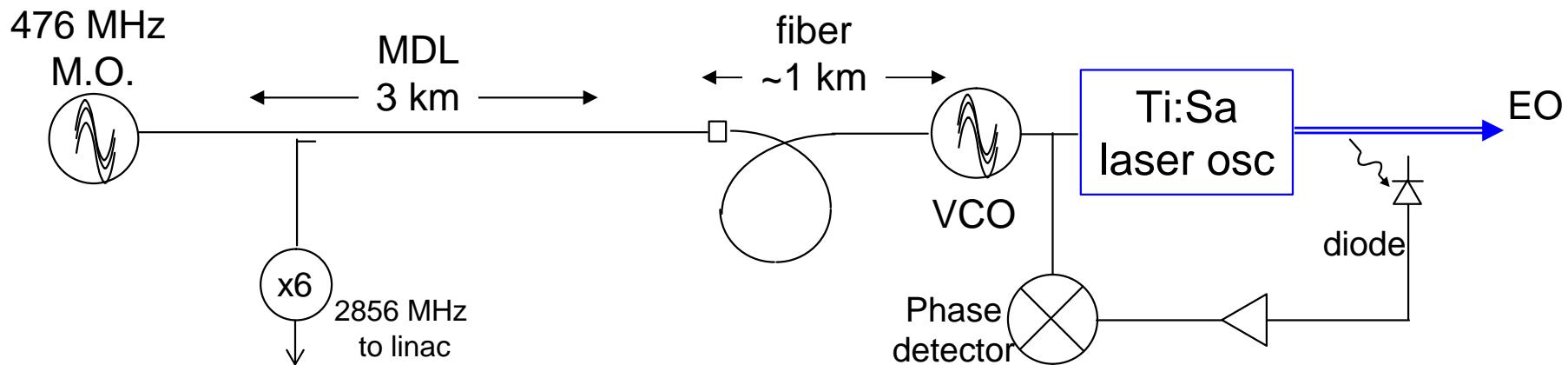


Synchronization of the Laser timing

■ Jitter in the laser timing effects

- Electro optic bunch timing measurement
- Pump-probe timing for the users
- Enhancement schemes using short pulse lasers

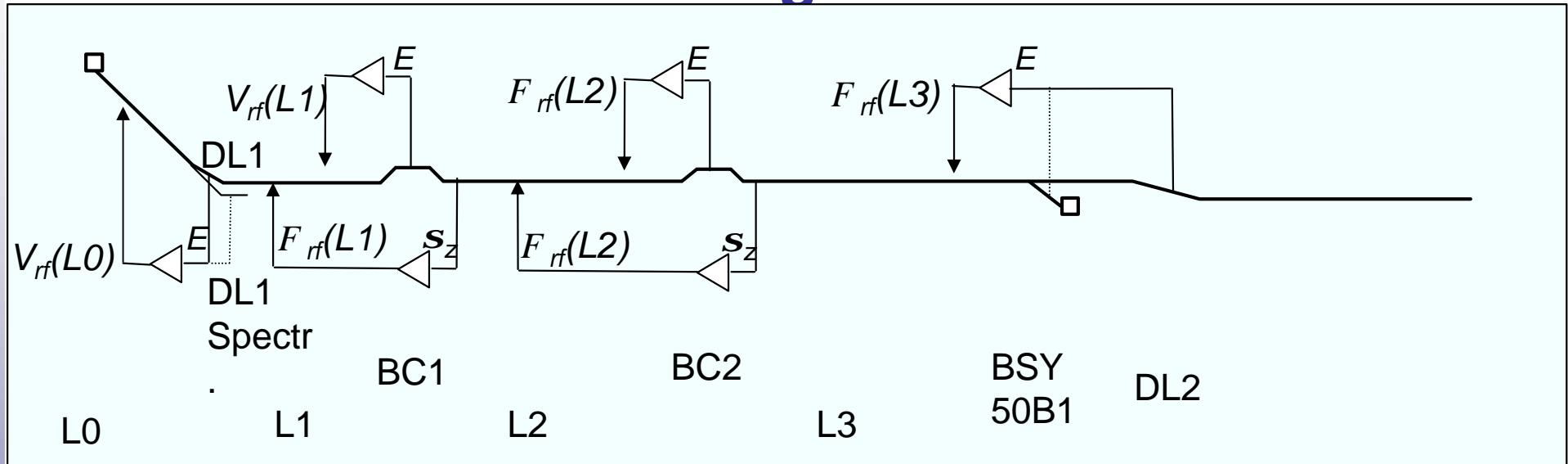
SPPS Laser Phase Noise Measurements – R. Akre



Bunch Length Feedback Systems

- Responds to fast signal from THz power monitor
- Controls amount of energy chirp by changing linac RF phase
 - While energy feedback holds energy constant!

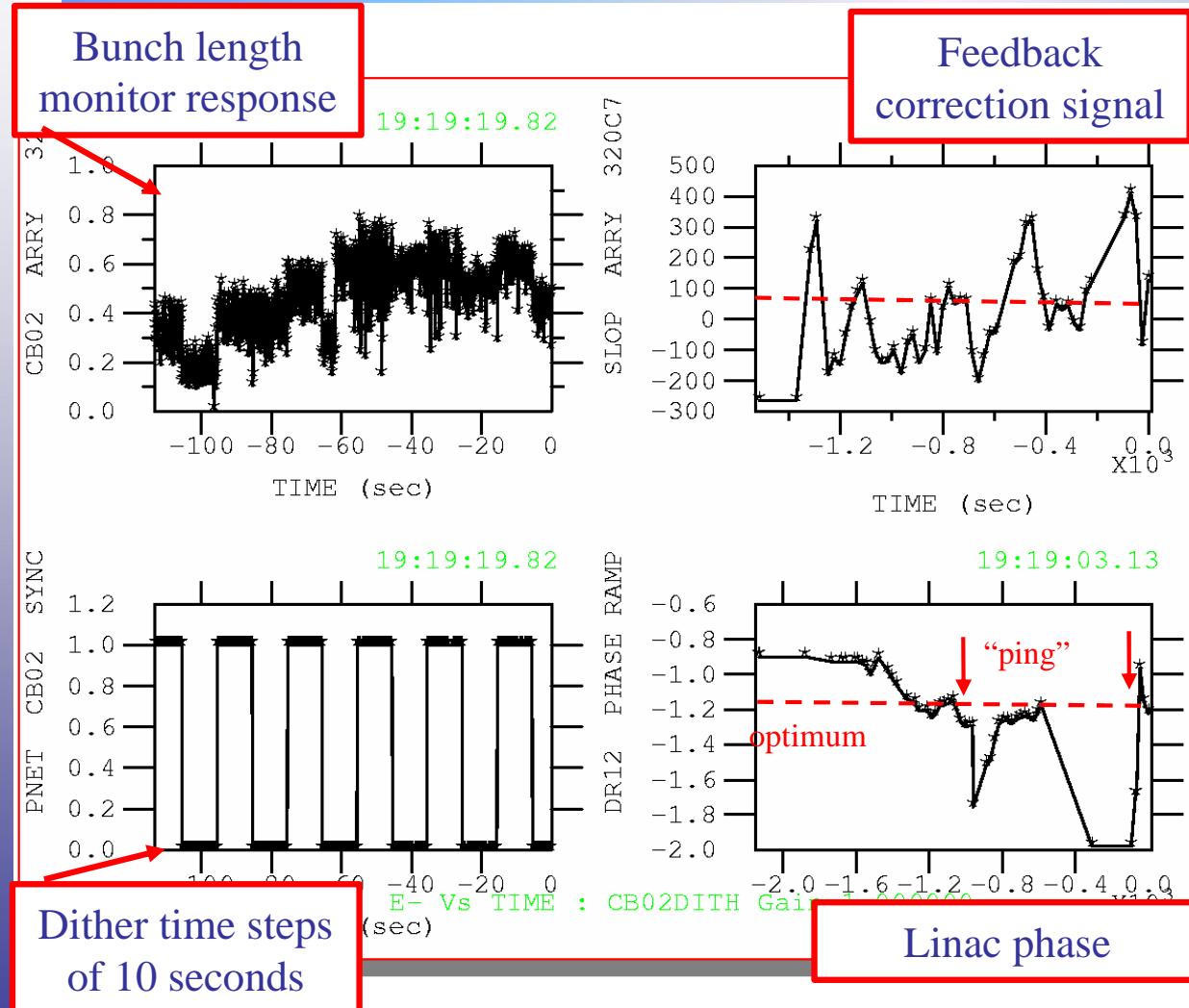
Required Feedback Loops for Energy and Bunch Length in LCLS



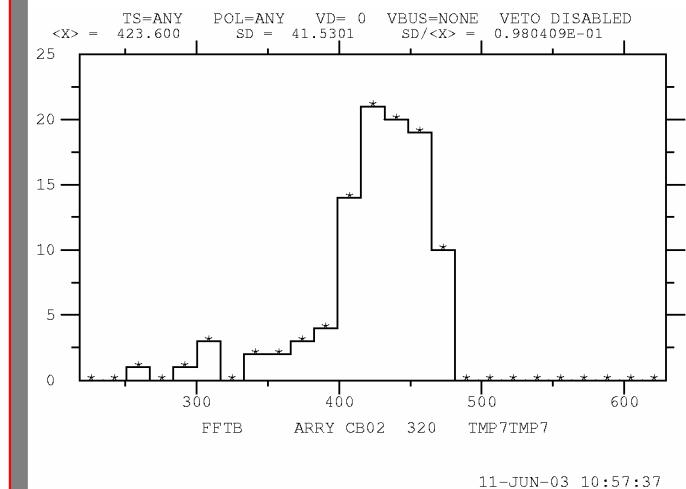
- 4 energy feedback loops
- 2 bunch length feedback loops
- 120 Hz nominal operation, <1 pulse delay

- Feedback model (J. Wu)
- PID controller (proportional, integral, derivative)
- Cascade control for sequential loops (off-diagonal matrix elements)

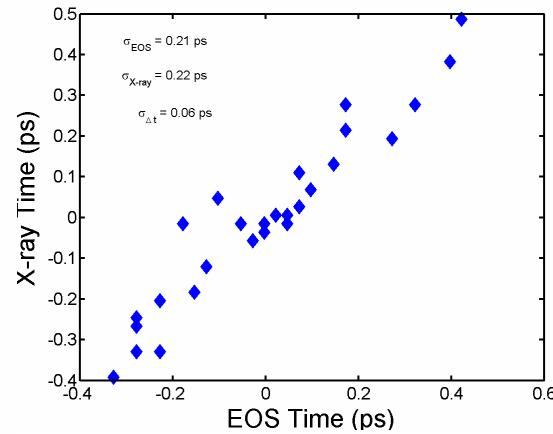
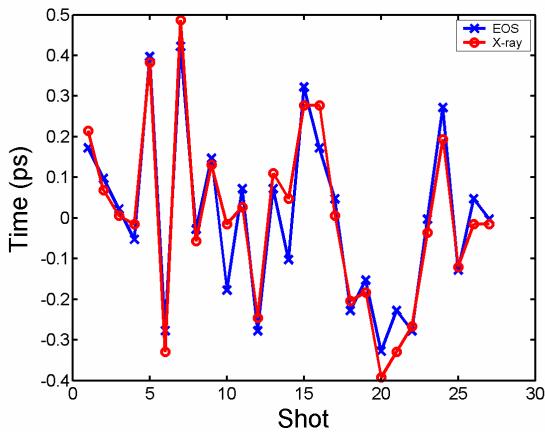
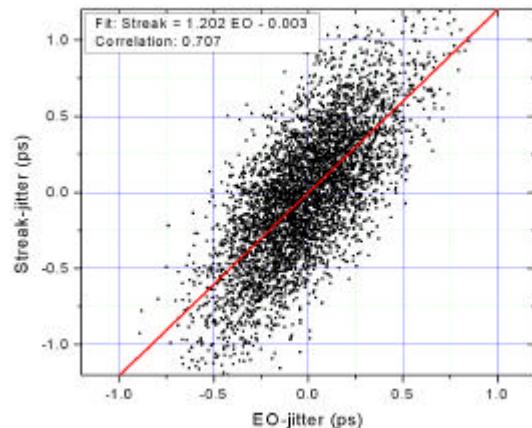
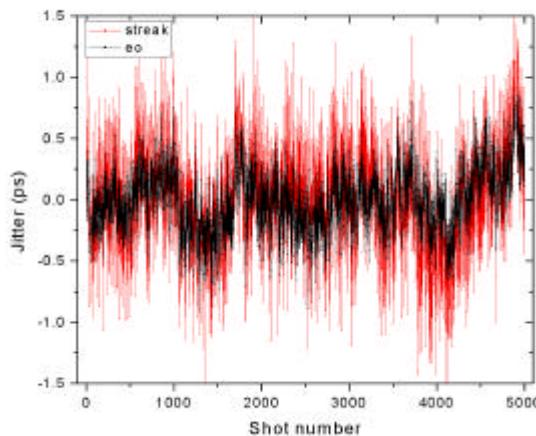
Dither feedback control of bunch length minimization at SPPS – L. Hendrickson



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



Correlating e-beam measurements to X-rays



1. Electron beam arrival time measured with EO correlated with X-ray arrival time measured on a streak camera

A. MacPhee, LBL

2. correlated with X-ray arrival time measured with pump-probe melting

See also
Joint session
talk:
Aaron Lindenberg
SPPS Science

Bunch length diagnostic comparison

Device Type	Invasive measurement	Single shot measurement	Abs. or rel. measurement	Timing measurement	Detect μ bunching
RF Transverse Deflecting Cavity	Yes: Steal 3 pulses	No: 3 pulses	Absolute	No	No
Coherent Radiation Spectral power	No for CSR Yes for CTR	Yes	Relative	No	Yes
Coherent Radiation Autocorrelation	No for CSR Yes for CTR	No	Absolute (2 nd moment only)	No	No
Electro Optic Sampling	No	Yes	Absolute	Yes	No
Energy Wake-loss	Yes	No	Relative	No	No

Bunch length and timing measurements at SLAC/SPPS are a collaboration with

SLAC

DESY

Univ. of Michigan

Univ. of S. California

**and the SPPS Science collaboration
encompasses many more institutions**