Short Bunch Beam Profiling

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Abstract

The complete longitunal profiling of short electron bunches is discussed in the context of 4th generation light sources. The high peak current required for the SASE lasing process is achieved by longitudinal compression of the electron bunch. The lasing process also depends on of the preservation of the transverse emittance along the bunch during this manipulation in longitudinal phase space. Beam diagnostic instrumentation needs to meet several challenges: The bunch length and longitudinal profile should be measured on a single bunch to characterize the instantaneous, peak current along the bunch. Secondly, the transverse emittance and longitudinal energy spread should be measured for slices of charge along the bunch. Several techniques for invasive and noninvasive bunch profiling will be reviewed, using as examples recent measurements from the SLAC Sub Picosecond Photon Source (SPPS) and the planned diagnostics for the Linac Coherent Light Source (LCLS). These include transverse RF deflecting cavities for temporal streaking of the electron bunch, RF zero-phasing techniques for energy correlation measurements, and electro-optic measurements of the wakefield profile of the bunch.

Paper not received

(See slides of talk on following pages)

6th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators
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Mainz, Germany
Invited Talk IT06

SHORT BUNCH BEAM PROFILING

P. Krejcik
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Introduction

Motivation for short bunches in 4th generation light sources (LCLS, TTF2 …)

- Self Amplified Spontaneous Emission (SASE) requires high charge density to reach saturation
  - Gain length reduced with higher peak current
- Experimenters seek the highest temporal resolution for stroboscopic images of molecular reactions
- The short, ultra-bright SASE radiation pulse destroys the molecule but image can be retrieved if it was taken quickly enough

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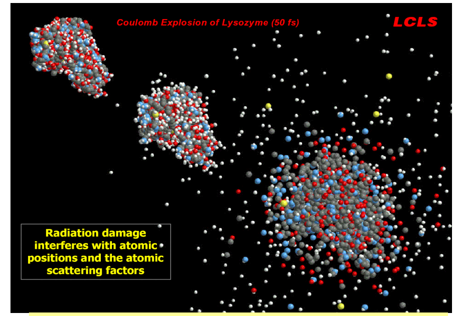

Courtesy Janos Hadju, *Structural Studies on Single Particles and Biomolecules for LCLS*

… Introduction

Short bunches also finding applications in High Energy-Density beam experiments

- Plasma-wakefield experiment E164 at SLAC
  - Beam-plasma interaction scales as $1/\sigma_z^2$
- Laboratory astrophysics experiments
  - Utilize the extreme peak fields associated with the high peak current in a short bunch
- Beam-matter interactions

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Short Bunches at SLAC

- The Linac Coherent Light Source, LCLS
  - An X-Ray FEL starting construction ~2005 80 femtoseconds rms
- The Sub Picosecond Particle Source, SPPS
  - A bunch compression scheme in the existing linac
  - Experiments with short electron bunches
  - And short-pulse spontaneous X-Rays from an undulator 30 femtoseconds rms
- Many laboratories around the world are contributing to progress in this burgeoning field

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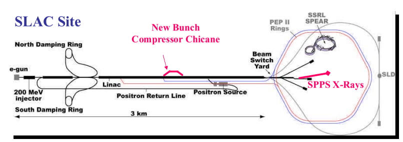
SPPS



- Fast-track project using existing linac beam
- Extensive opportunities to test short bunch technology

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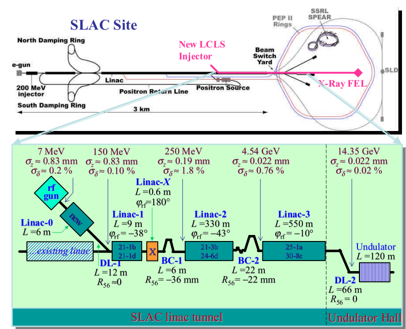

Bunch Length Profiling Techniques

- Transverse RF deflecting cavity
  - Setup and measurements
- Electro Optic techniques
  - limits to resolution for extremely short bunches
- Chirp, or induced correlated energy spread
  - Transforms bunch length into energy spread
- Relative measurement techniques
  - Wakefield energy loss scan
  - Measurement of CSR power spectral density
  - Measurement of THz radiation from wakefields as CDR
  - Auto correlation of COTR using interferometry

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Review of Techniques

- Quantifying σ_z
  - Both relative and absolute measurements
- Bunch length charge distribution
- Slicing up the bunch and measuring
  - *Energy spread, transverse emittance* along the bunch
- Relevant because FEL SASE depends on local parameters of slice that is lasing

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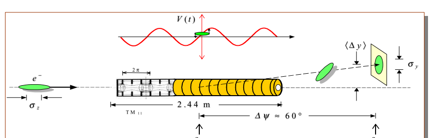
RF deflecting cavities

- Brief description of principal
- Example of measurements taken in SLAC linac
- Comparison with simulation of its use in the LCLS



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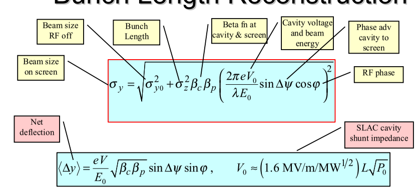
Transverse Deflecting Cavity Bunch Length Reconstruction



$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi e V_0}{\lambda E_0} \sin \Delta\psi \cos\varphi \right)^2}$$

$$\langle \Delta y \rangle = \frac{eV}{E_0} \sqrt{\beta_c \beta_p} \sin \Delta\psi \sin\varphi , \qquad V_0 \approx \left(1.6\ \mathrm{MV/m/MW}^{1/2}\right) L \sqrt{P_0}$$

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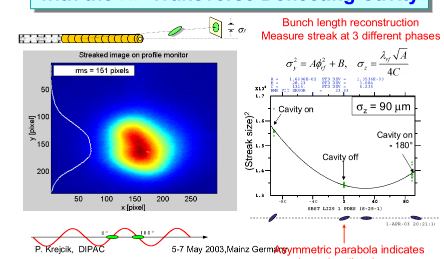
Bunch Length Measurements with the RF Transverse Deflecting Cavity



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

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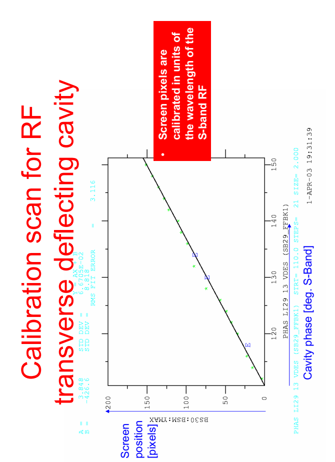
Calibration scan for RF transverse deflecting cavity
Screen pixels are calibrated in units of the wavelength of the S-band RF
Screen position [pixels]
Cavity phase [deg, S-Band]
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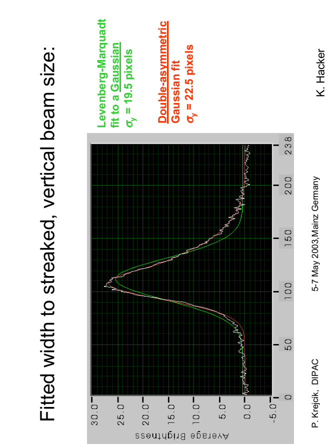
Fitted width to streaked, vertical beam size:
Levenberg-Marquadt fit to a Gaussian
σ_y = 19.5 pixels
Double-asymmetric Gaussian fit
σ_y = 22.5 pixels
Average Brightness
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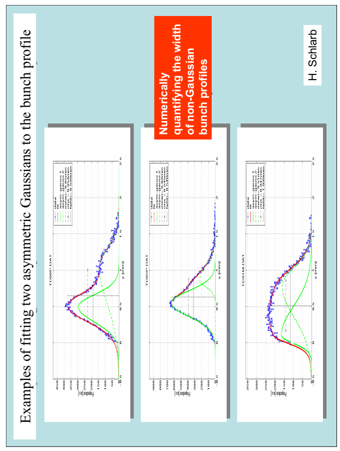
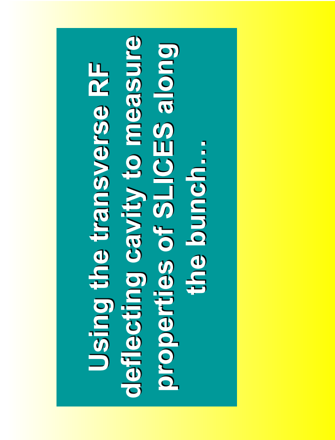
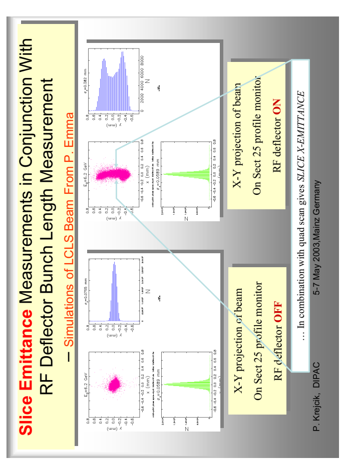
K. Hacker


Examples of fitting two asymmetric Gaussians to the bunch profile
Numerically quantifying the width of non-Gaussian bunch profiles
H. Schlarb


Using the transverse RF deflecting cavity to measure properties of SLICES along the bunch…


Slice Emittance Measurements in Conjunction With RF Deflector Bunch Length Measurement
– Simulations of LCLS Beam From P. Emma
X-Y projection of beam
On Sect 25 profile monitor
RF deflector OFF
X-Y projection of beam
On Sect 25 profile monitor
RF deflector ON
… In combination with quad scan gives SLICE X-EMITTANCE
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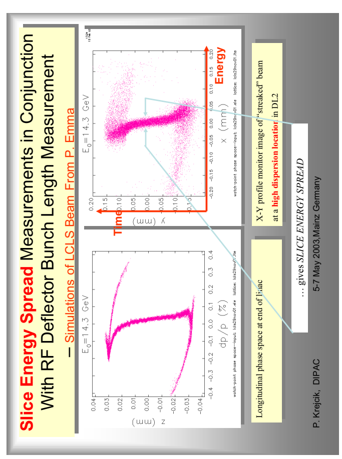
Slice Energy Spread Measurements in Conjunction With RF Deflector Bunch Length Measurement
– Simulations of LCLS Beam From P. Emma
Time
Energy
Longitudinal phase space at end of linac
X-Y profile monitor image of "streaked" beam at a high dispersion location in DL2
… gives SLICE ENERGY SPREAD
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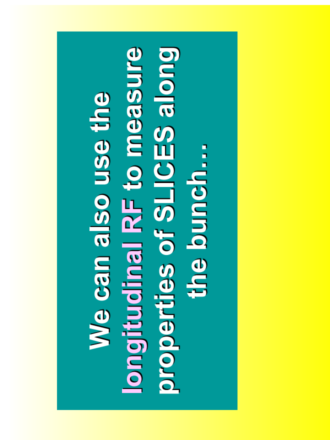
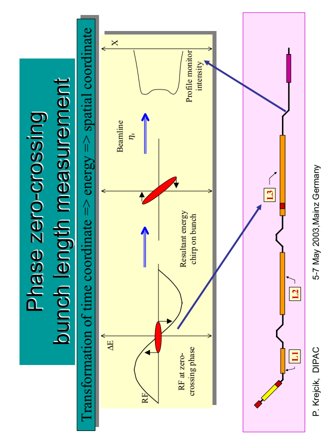

We can also use the longitudinal RF to measure properties of SLICES along the bunch…


Phase zero-crossing bunch length measurement
Transformation of time coordinate => energy => spatial coordinate
RF at zero-crossing phase
Resultant energy chirp on bunch
Beamline
Profile monitor intensity
L1
L2
L3
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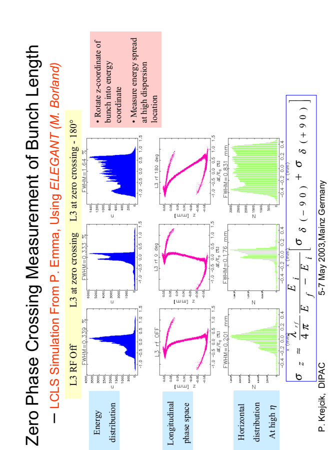
Zero Phase Crossing Measurement of Bunch Length
– LCLS Simulation From P. Emma, Using ELEGANT (M. Borland)
Energy distribution
Longitudinal phase space
Horizontal distribution At high η
L3 RF Off
L3 at zero crossing
L3 at zero crossing - 180°
• Rotate z-coordinate of bunch into energy coordinate
• Measure energy spread at high dispersion location
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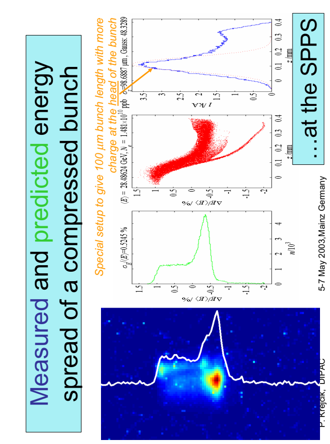
Measured and predicted energy spread of a compressed bunch
Special setup to give 100 µm bunch length with more charge at the head of the bunch
…at the SPPS
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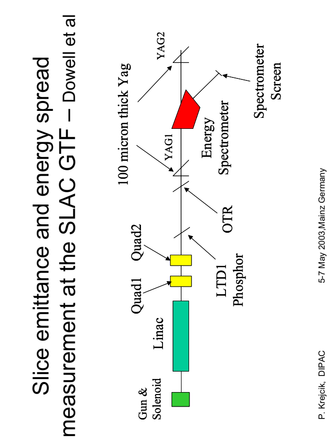
Slice emittance and energy spread measurement at the SLAC GTF – Dowell et al
Gun & Solenoid
Linac
Quad1
Quad2
LTD1 Phosphor
OTR
YAG1
100 micron thick Yag
YAG2
Energy Spectrometer
Spectrometer Screen
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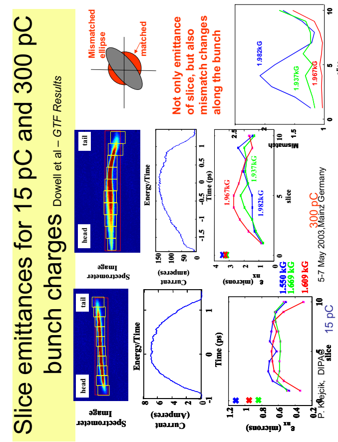
Slice emittances for 15 pC and 300 pC bunch charges Dowell et al – GTF Results
Spectrometer Image
Current (Amperes)
Time (ps)
slice
15 pC
300 pC
Mismatched ellipse
matched
Not only emittance of slice, but also mismatch changes along the bunch
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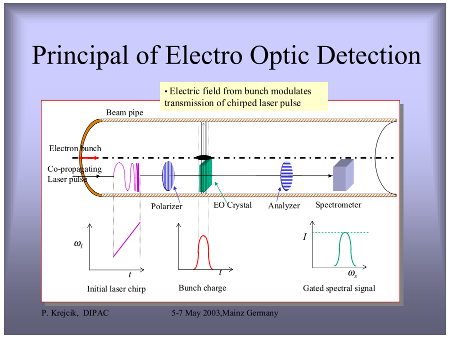
Principal of Electro Optic Detection
• Electric field from bunch modulates transmission of chirped laser pulse
Beam pipe
Electron bunch
Co-propagating Laser pulse
Polarizer
EO Crystal
Analyzer
Spectrometer
Initial laser chirp
Bunch charge
Gated spectral signal
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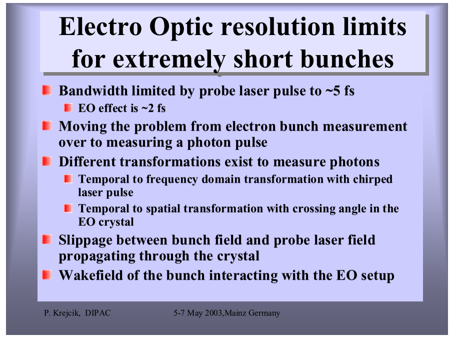
Electro Optic resolution limits for extremely short bunches
Bandwidth limited by probe laser pulse to ~5 fs
EO effect is ~2 fs
Moving the problem from electron bunch measurement over to measuring a photon pulse
Different transformations exist to measure photons
Temporal to frequency domain transformation with chirped laser pulse
Temporal to spatial transformation with crossing angle in the EO crystal
Slippage between bunch field and probe laser field propagating through the crystal
Wakefield of the bunch interacting with the EO setup
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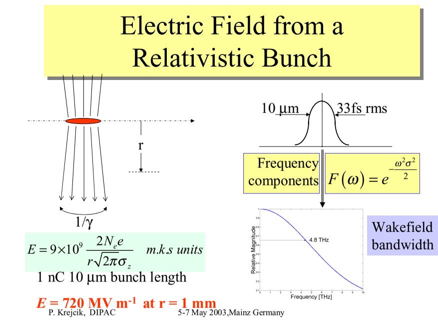
Electric Field from a Relativistic Bunch
r
1/γ
$E=9\times10^9\frac{2N_e e}{r\sqrt{2\pi}\sigma_z}$ m.k.s units
1 nC 10 μm bunch length
E = 720 MV m-1 at r = 1 mm
10 μm
33fs rms
Frequency components
$F(\omega)=e^{-\frac{\omega^2\sigma^2}{2}}$
Wakefield bandwidth
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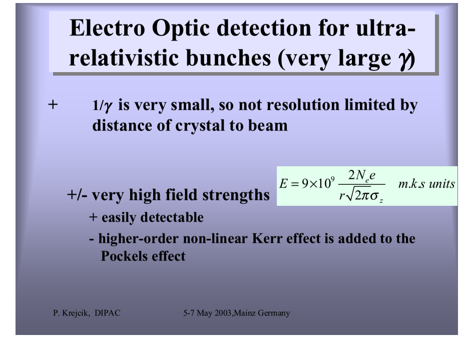
Electro Optic detection for ultra-relativistic bunches (very large γ)
+ 1/γ is very small, so not resolution limited by distance of crystal to beam
+/- very high field strengths
$E=9\times10^9\frac{2N_e e}{r\sqrt{2\pi}\sigma_z}$ m.k.s units
+ easily detectable
- higher-order non-linear Kerr effect is added to the Pockels effect
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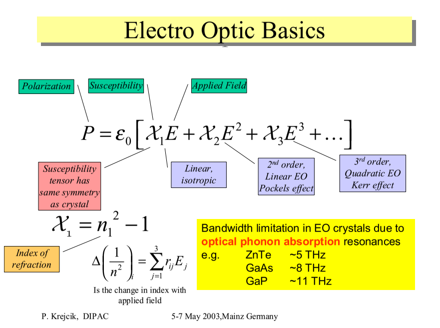
Electro Optic Basics
Polarization
Susceptibility
Applied Field
$P=\varepsilon_0\left[\mathcal{X}_1E+\mathcal{X}_2E^2+\mathcal{X}_3E^3+\ldots\right]$
Susceptibility tensor has same symmetry as crystal
Linear, isotropic
2nd order, Linear EO Pockels effect
3rd order, Quadratic EO Kerr effect
$\mathcal{X}_1=n_1^{\ 2}-1$
Index of refraction
$\Delta\left(\frac{1}{n^2}\right)_i=\sum_{j=1}^{3}r_{ij}E_j$
Is the change in index with applied field
Bandwidth limitation in EO crystals due to optical phonon absorption resonances
e.g. ZnTe ~5 THz
GaAs ~8 THz
GaP ~11 THz
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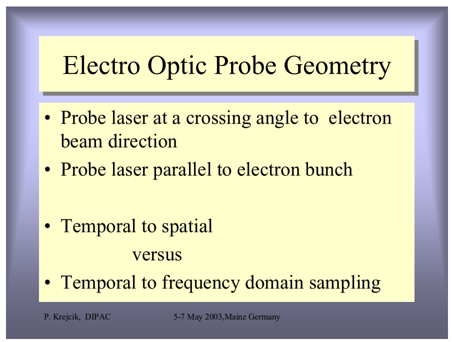
Electro Optic Probe Geometry
• Probe laser at a crossing angle to electron beam direction
• Probe laser parallel to electron bunch
• Temporal to spatial
versus
• Temporal to frequency domain sampling
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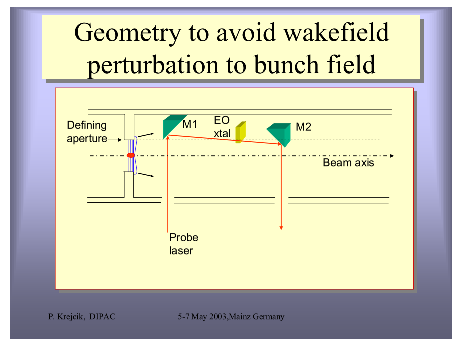
Geometry to avoid wakefield perturbation to bunch field
Defining aperture
M1
EO xtal
M2
Beam axis
Probe laser
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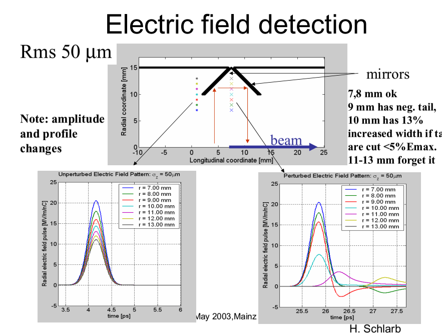
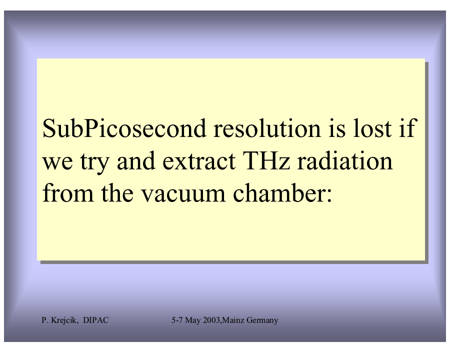

Electric field detection
Rms 50 μm
mirrors
beam
Note: amplitude and profile changes
7,8 mm ok
9 mm has neg. tail,
10 mm has 13% increased width if tails are cut <5%Emax.
11-13 mm forget it
H. Schlarb


SubPicosecond resolution is lost if we try and extract THz radiation from the vacuum chamber:
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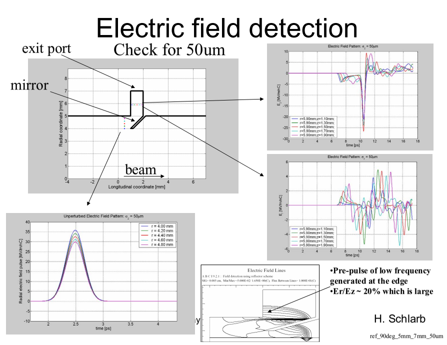
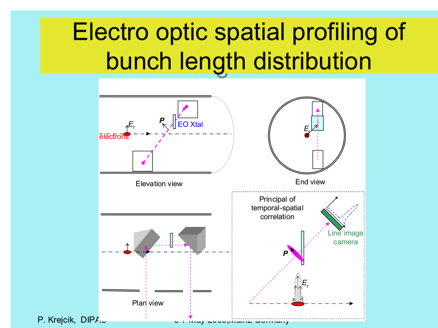

Electric field detection
Check for 50um
exit port
mirror
beam
•Pre-pulse of low frequency generated at the edge
•Er/Ez ~ 20% which is large
H. Schlarb


Electro optic spatial profiling of bunch length distribution
EO Xtal
Elevation view
End view
Principal of temporal-spatial correlation
Line image camera
Plan view
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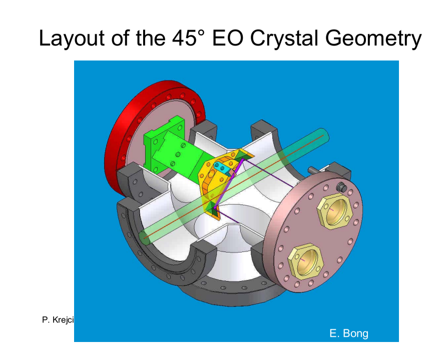
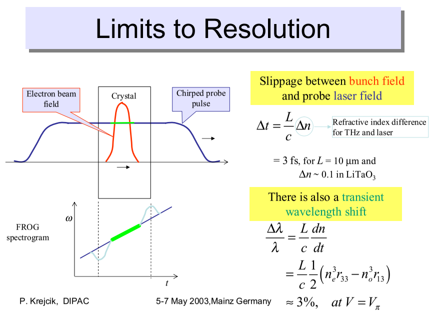

Layout of the 45° EO Crystal Geometry
E. Bong


Limits to Resolution
Electron beam field
Crystal
Chirped probe pulse
FROG spectrogram
Slippage between bunch field and probe laser field
$\Delta t = \frac{L}{c}\Delta n$
Refractive index difference for THz and laser
= 3 fs, for L = 10 μm and Δn ~ 0.1 in LiTaO3
There is also a transient wavelength shift
$\frac{\Delta\lambda}{\lambda} = \frac{L}{c}\frac{dn}{dt} = \frac{L}{c}\frac{1}{2}(n_e^3 r_{33} - n_o^3 r_{13}) \approx 3\%, \quad at\ V = V_\pi$
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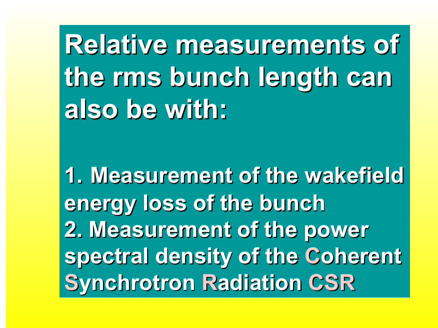
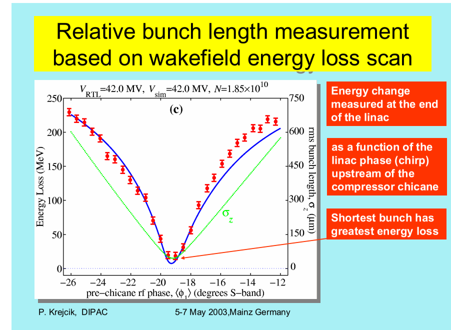

Relative measurements of the rms bunch length can also be with:
1. Measurement of the wakefield energy loss of the bunch
2. Measurement of the power spectral density of the Coherent Synchrotron Radiation CSR


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
Energy Loss (MeV)
rms bunch length, σz (μm)
pre–chicane rf phase, ⟨φ2⟩ (degrees S–band)
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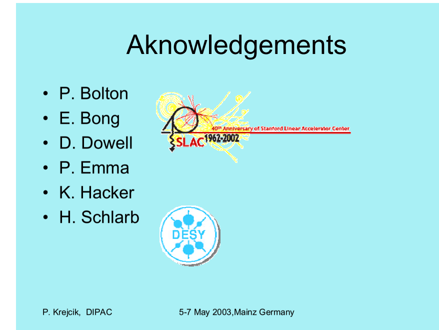
Aknowledgements
• P. Bolton
• E. Bong
• D. Dowell
• P. Emma
• K. Hacker
• H. Schlarb
SLAC
1962-2002
DESY
P. Krejcik, DIPAC
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