Measurements of Short Bunches at SPPS and E-164X

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OUTLINE

- Motivation
- CTR Interferometry*
- Bunch energy spectrum measurements
- Application to E-164X
- Conclusions

*C. Settakorn, PhD thesis, Stanford (2001).

MOTIVATIONS

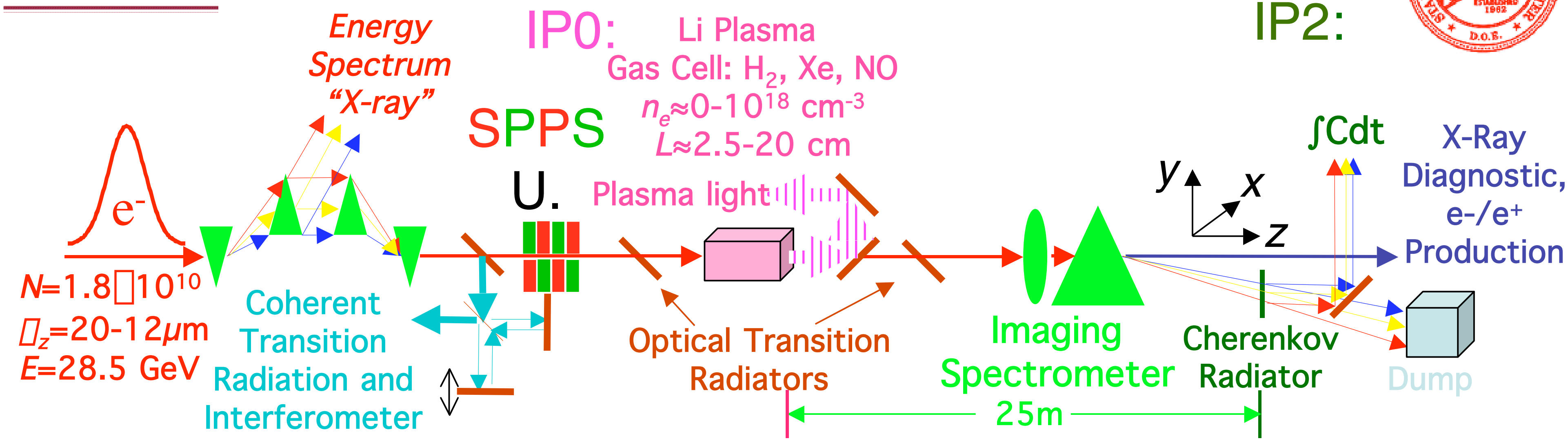
- Length of SLAC ultra-short bunches was never measured!

- In E-164X plasma wakefield acceleration (PWFA) experiment, the accelerating gradient increases as $1/\sigma_z^2$ with matching plasma density increasing as $1/\sigma_z$

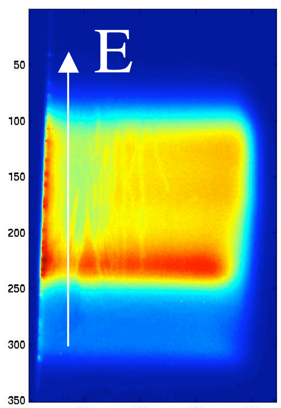
- Bunch incoming energy spectrum and CTR energy varies significantly from bunch to bunch (especially at 1 Hz rep. rate)

- Outcome of E-164X …

EXPERIMENTAL SET UP



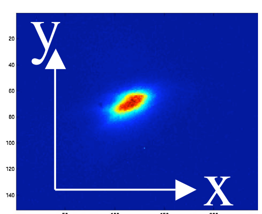
- X-ray Chicane



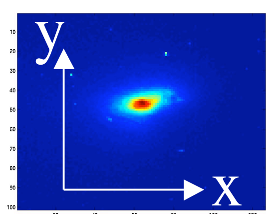
-Energy resolution ≈60 MeV

- Optical Transition Radiation (OTR)

Upstream



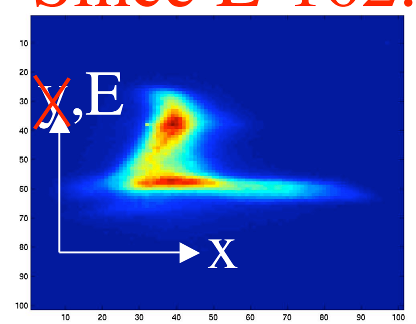
Downstream



-1:1 imaging, spatial resolution ≈9 μm

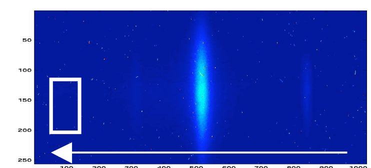
- Cherenkov (aerogel)

Since E-162:



- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV

- Plasma Light



TRANSITION RADIATION

- Transition Radiation (TR) becomes Coherent (CTR) for $\lambda>\sigma_z$, with intensity $\approx N^2/\sigma_z$, N the number of e$^-$/bunch of length σ_z
- CTR spectrum extends from for $\sigma_z<\lambda<\infty$, (i.e., broad spectrum in the IR/FIR)
- CTR spectrum amplitude given by the bunch form factor $f(\omega)$, i.e, the Fourier transform of the longitudinal charge distribution squared (neglecting transverse variations, in the forward direction of observation).

$$I_{total}(\omega) \cong N I_e(\omega)\left[1+(N-1)f(\omega)^2\right]$$

<< for $\omega<2\pi c/\sigma_z$

$I_e(\omega)=|E(\omega)|^2$, the TR for a single electron

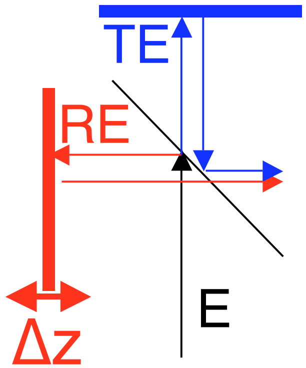
$$f(\omega)^2 = e^{-(\omega\sigma_z/c)^2} \text{ for } E_r(z) \qquad n(z) = \frac{1}{\sqrt{2\pi}\,\sigma_z} e^{-z^2/2\sigma_z^2}$$

(Gaussian bunch)

- CTR carries longitudinal bunch shape information at long λ's

ITERFEROMETER/ AUTOCORRELATOR

- Radiation field in the 2 arms of the interferometer with a time of flight difference $\tau=2\Delta z/c$:



$$E_{ref.} = RTE(t)$$
$$+$$
$$E_{var.} = TRE(t+2\tau/c)$$

T, *R* transmission and reflection coeff. of beam splitter
Note: T=T(ω), R=R(ω) !

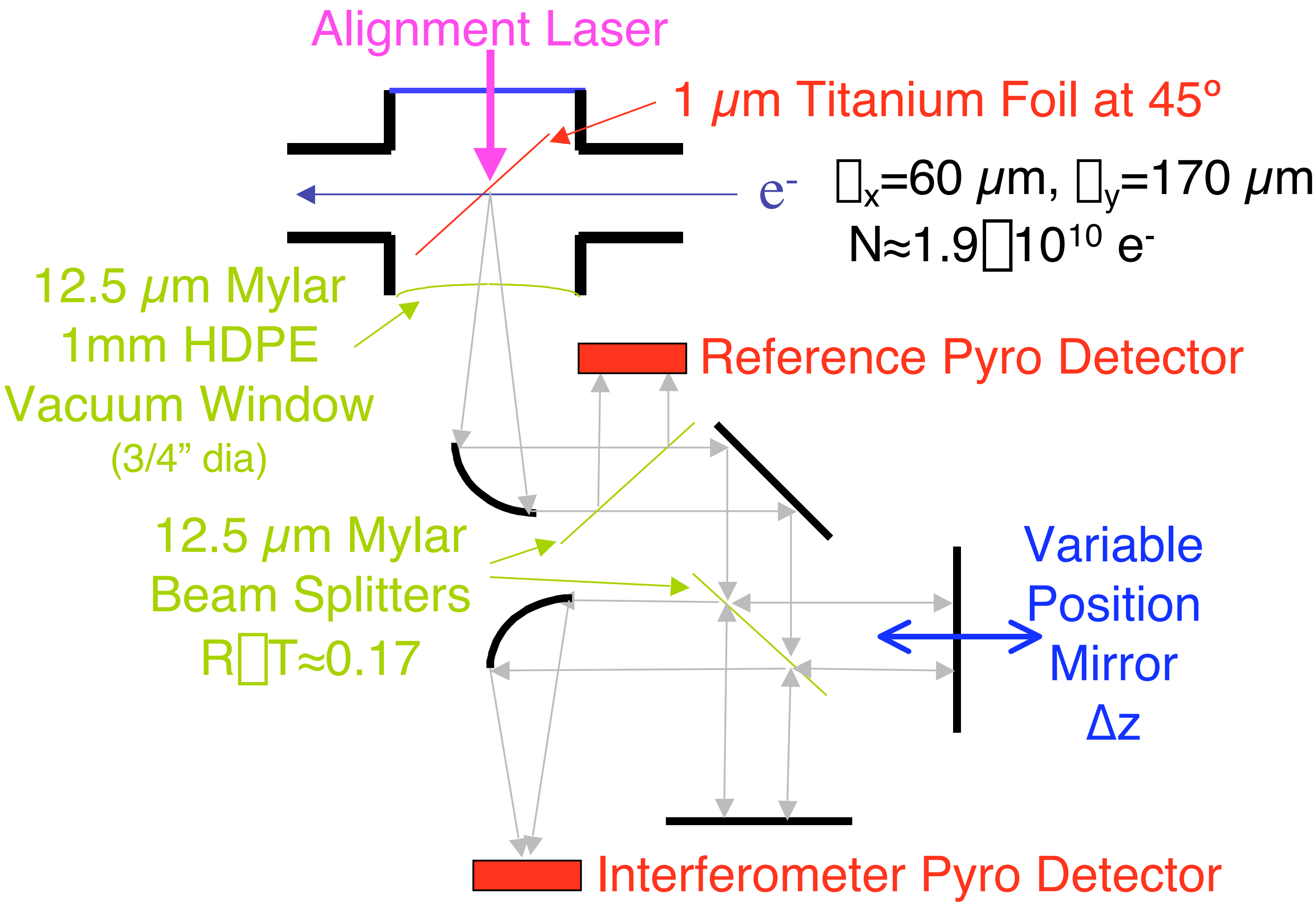
- Intensity $I_D=(E_{ref.}+E_{var.})^2$ on autocorrelator detector:

$$I_D(t;\tau) = 2\underbrace{\int \left|RTE(t)\right|^2 dt}_{\text{Background}} + 2\underbrace{\int \left|RT\right|^2 E(t)E(t+2\tau/c)dt}_{\text{Interferogram/autocorrelation}}$$

INTERFEROMETER/ AUTOCORRELATOR

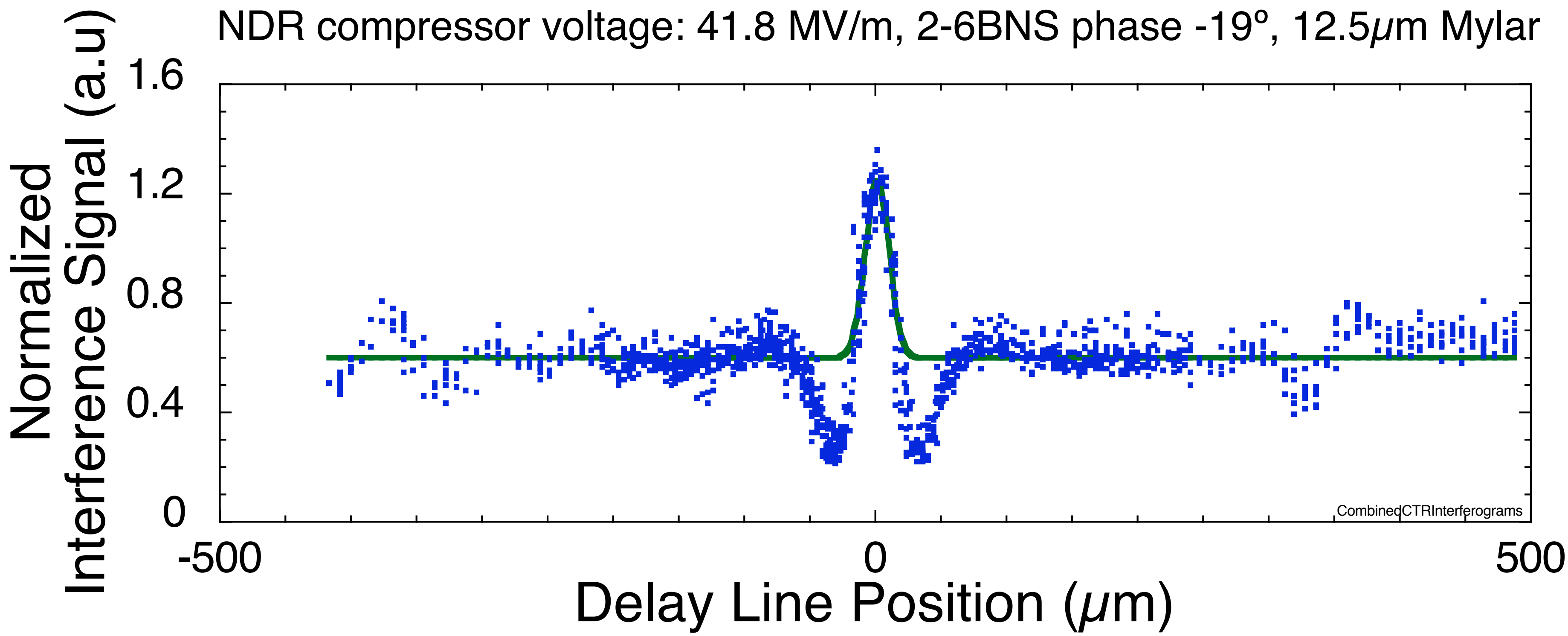
- For each □ or Δz, measure the energy: $S_D(\Delta z)=\iint I_D(t;\Delta z)\, dt\, ds$
- Autocorrelation signal characteristics:
  - Symmetric (even if the bunch shape is not)
  - Background="2", peak="2"+"2", contrast of 2
  - Extends to long wavelengths, i.e., to long delays (CTR)
  - FFT(interferogram) => bunch spectrum
  - requires multiple (similar) bunches
- Pros and cons of CTR Interferometry
  - Simple and inexpensive (<$10k)
  - No sophisticated timing required
  - Symmetric trace
  - Multi-bunch measurement
  - Requires knowledge of broadband response of the entire system

CTR MICHELSON INTERFEROMETER



- Interference signal normalized to the reference signal
- Motion resolution Δz_{min}=1 μm or ≈14 fs (round trip)
- Mylar: R≈22%, T≈78%, RT≈0.17

CTR INTERFEROGRAM



- Trace is symmetric (even if the bunch shape may not be)
- Peak/background ratio =2
- Large “dips” on either sides of the peak
- Modulation far from the peak

NARROWING/BROADENING SOURCES

Interferometer "transmission" can be affected by: *
(amplitude and phase)

- Water absorption in humid air
- Vacuum window size cut-off (long □)
- Interferometer optics aperture (long □)
- Pyro-electric detector resonances
- Beam splitter(s)/window Fabry-Perot resonances

*C. Settakorn, PhD thesis, Stanford (2001).

BEAMSPLITTER R & T, 45°

Thickness *d*

Index of refraction n

Angle of incidence 45°

$$R(\square) = \square r \frac{1 \square e^{i\square}}{1 \sqcap r^2 e^{i\square}}$$

$$T(\square) = (1 \square r^2)\frac{e^{i\square/2}}{1 \sqcap r^2 e^{i\square}}$$

$$r_{\square}(\square) = \frac{1 \square \sqrt{2n^2 \square 1}}{1 + \sqrt{2n^2 \square 1}} \qquad r_{//}(\square) = \frac{n^2 \square \sqrt{2n^2 \square 1}}{n^2 + \sqrt{2n^2 \square 1}}$$

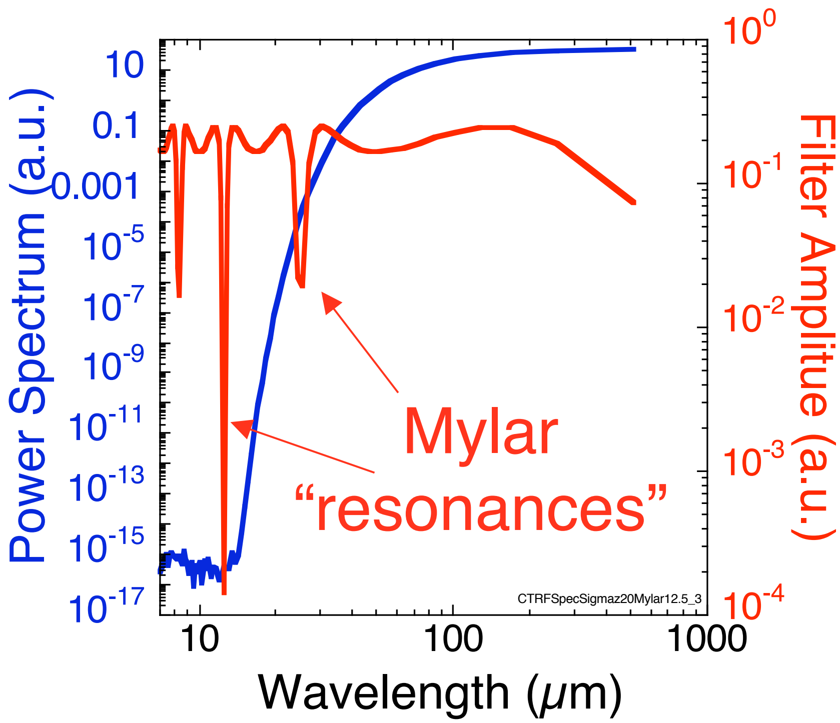
Mylar: n=3, n=n(□)?

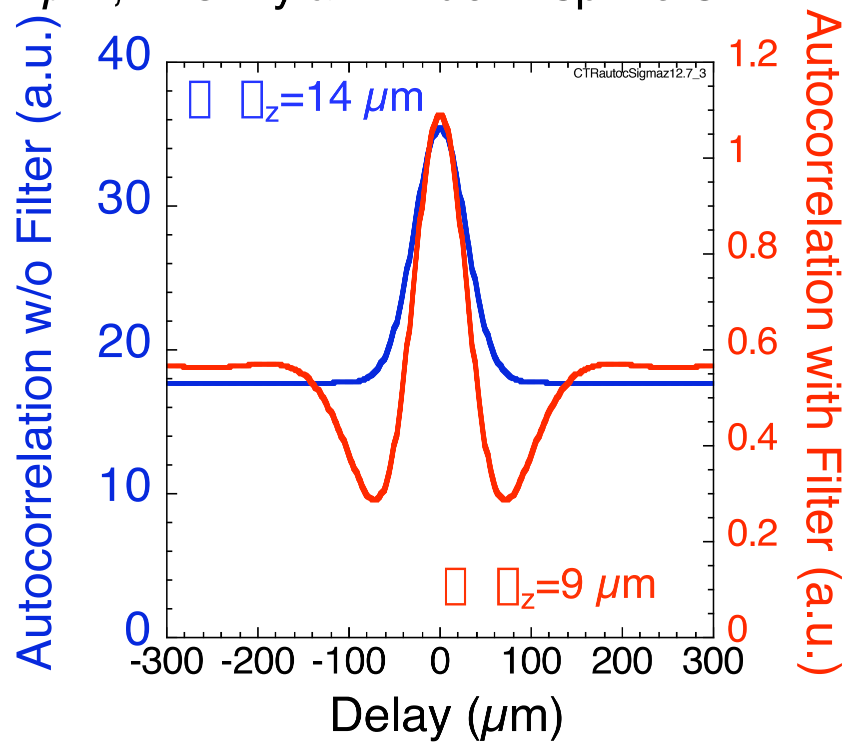
- Include in a simple autocorellation calculation
- Interferometer delay Δz or □ => relative phase shift 2kΔz

MYLAR FABRY-PEROT

Simple model:

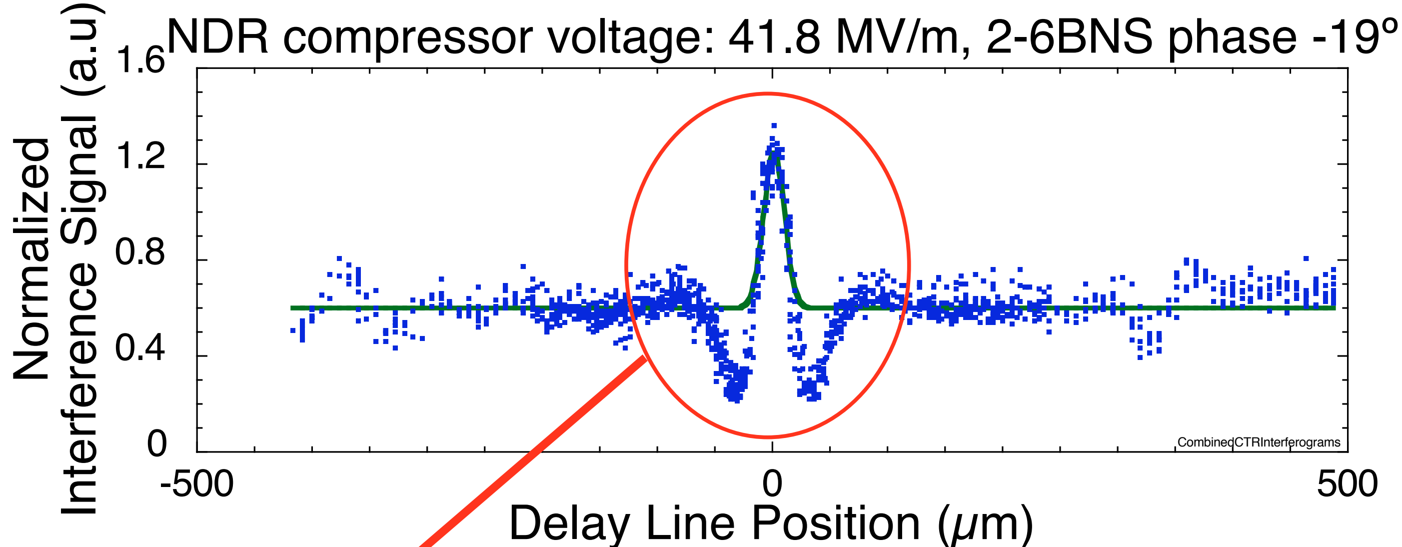
Gaussian, σ_z=20 μm, d=12.7 μm, n=3 Mylar window+splitters

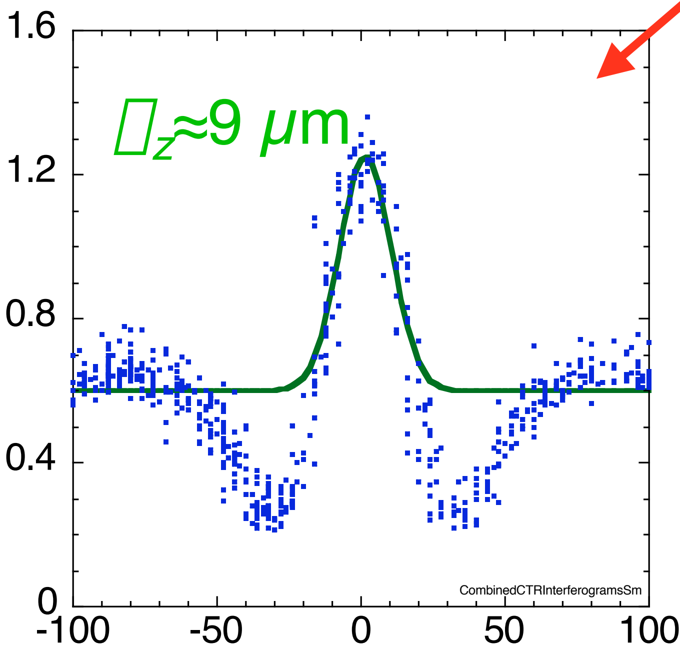


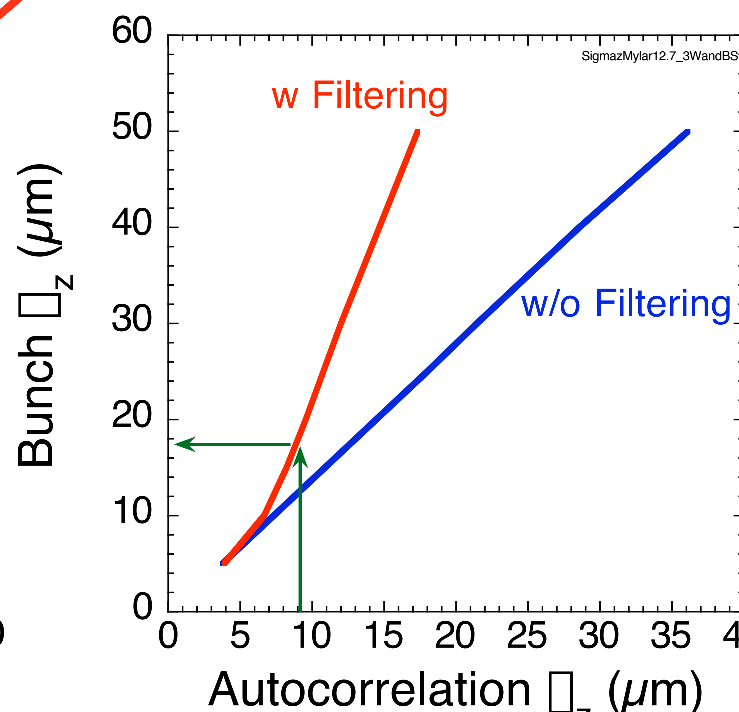


- Fabry-Perot resonance: $\lambda=2d/nm$, m=1,2,…, n=index of refraction
- Signal attenuated by Mylar beam splitter: $(RT)^2$
- Modulation/dips in the interferogram
- Smaller measured width: $\sigma_{Autocorrelation} < \sigma_{bunch}$!

Corrected Gaussian Width







Autocorrelation:

σ_z≈9 μm

Gaussian Bunch

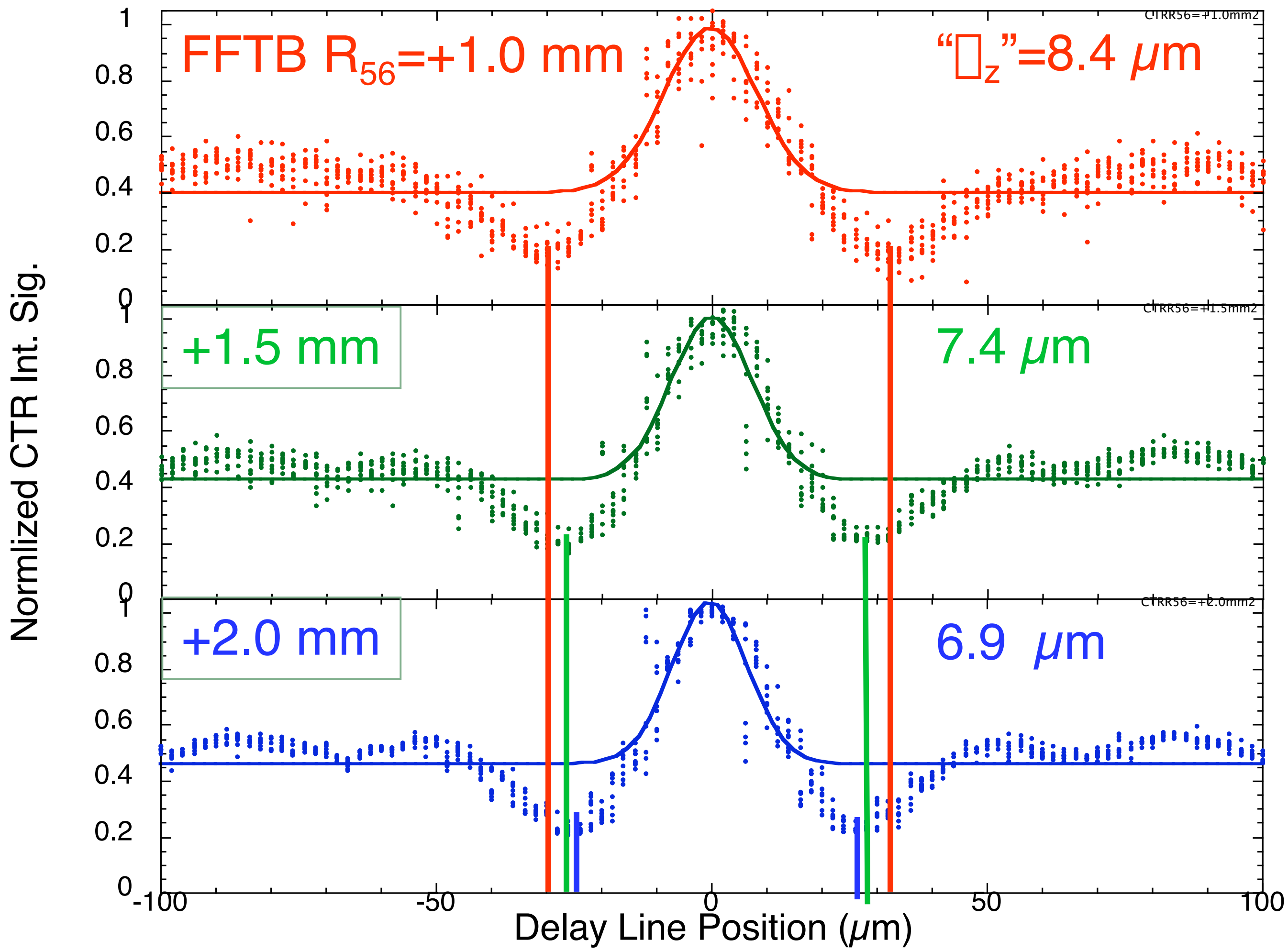
σ_z≈18 μm

or

τ≈120 fs

USC

FFTB R_{56} DEPENDENCY



$\sigma_z \approx 17$ μm or 114 fs (corrected)

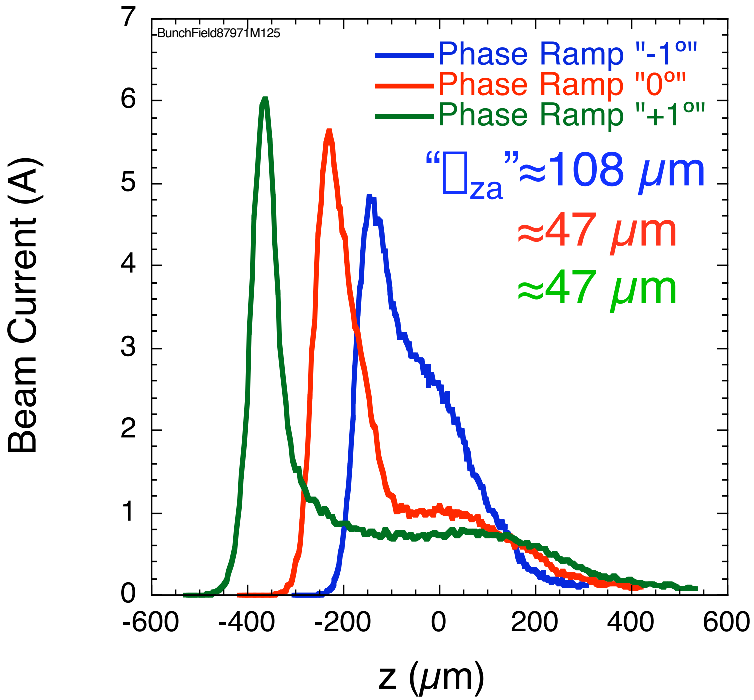
$\sigma_z \approx 13$ μm or 86 fs

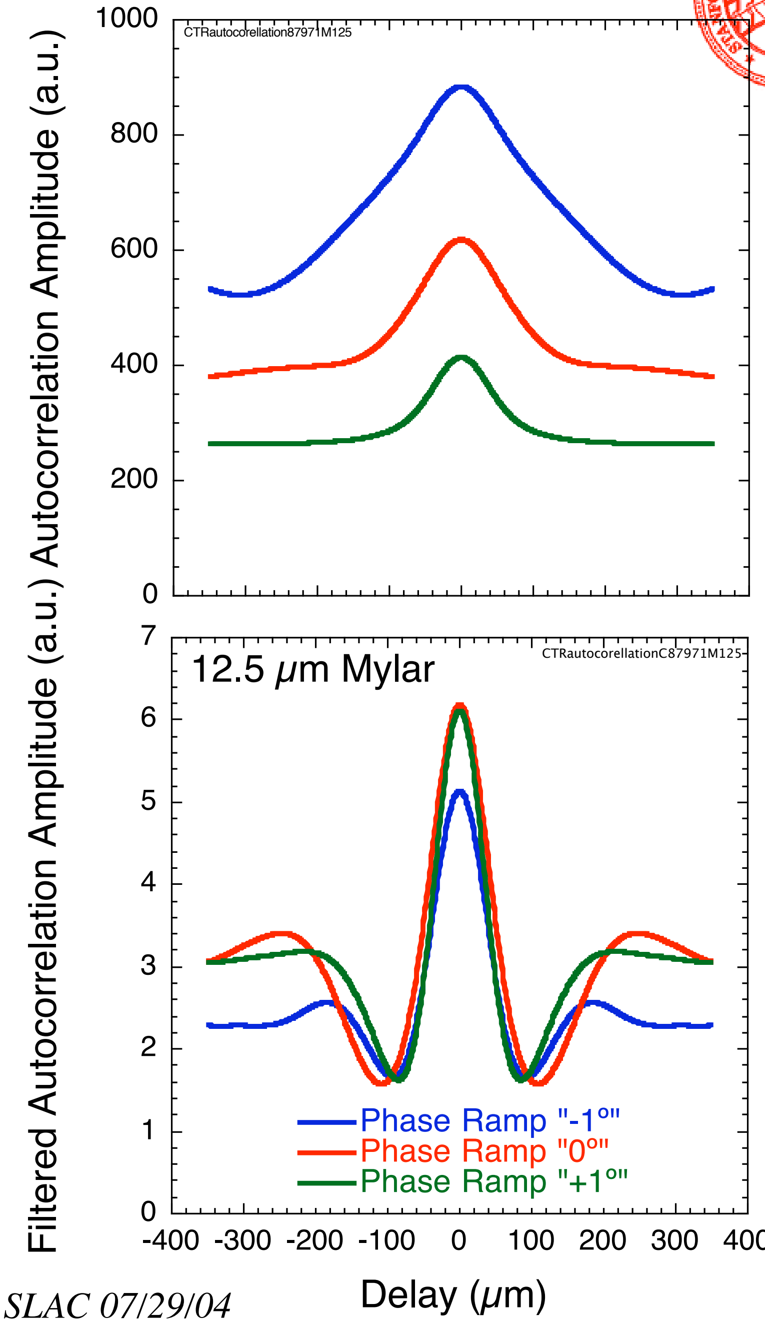
$\sigma_z \approx 11$ μm or 74 fs

- Measurable, but weak dependency
- Variations masked by beamsplitter transmission characteristics

MYLAR EFFECT
(Example)

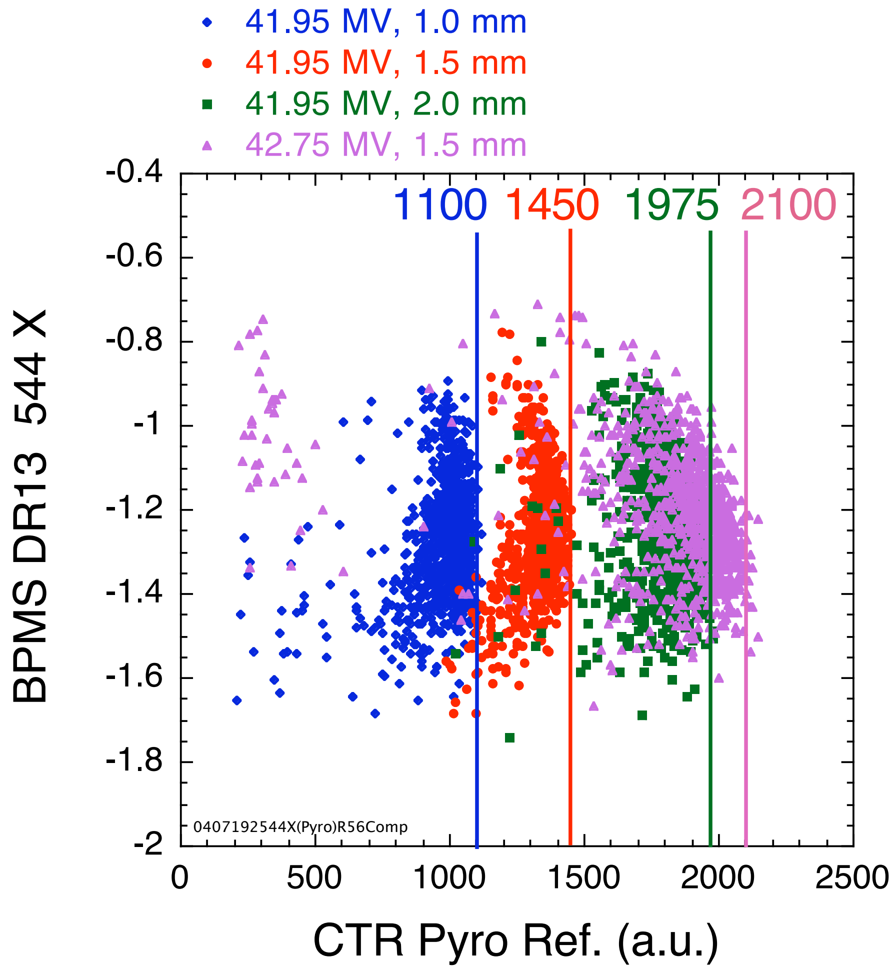
Beam current profiles for PWFA





- Beamsplitter “filtering” masks beam profile features

CTR AMPLITUDE DEPENDENCY @ PEAK COMPRESSION



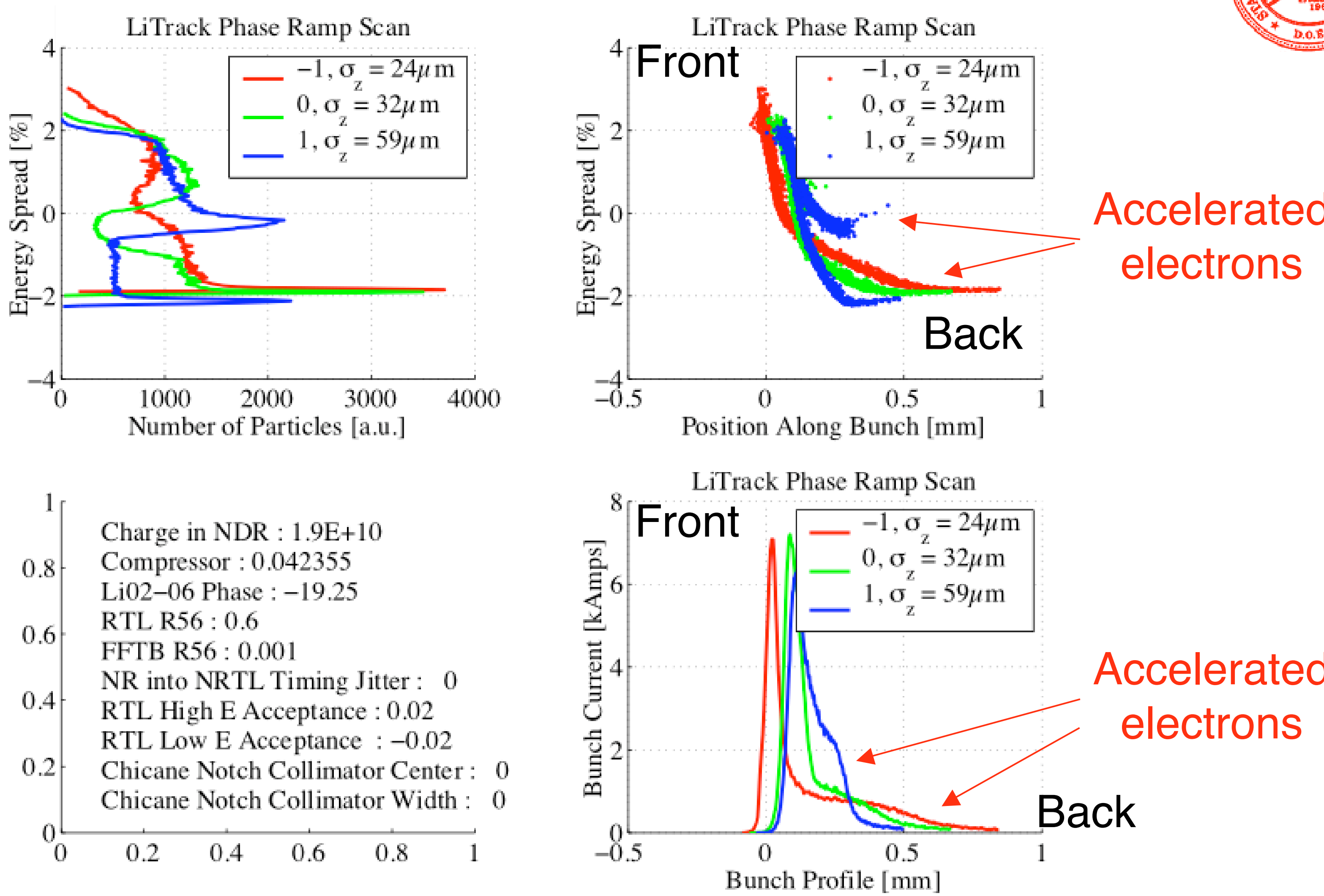
Gaussian Bunch:

$$E_{CTR} \approx N^2/\sigma_z$$

- Amplitude variations are clear(er)
- Amplitude related to bunch current profile

e^- BUNCH MANIPULATION

LITrack
K. Bane,
P. Emma



- Energy spectrum <-> phase space <-> current profile
- “σ_z” does not fully describe the bunch shape

Accelerator Center

Upstream of Plasma

UCLA

SLAC – PUB – 3945
April 1986
(A)

SLC ENERGY SPECTRUM MONITOR USING SYNCHROTRON RADIATION*

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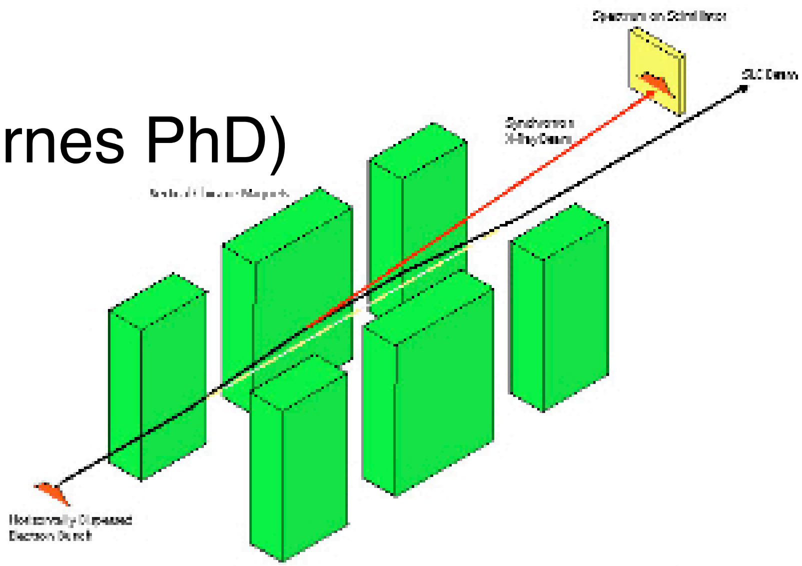
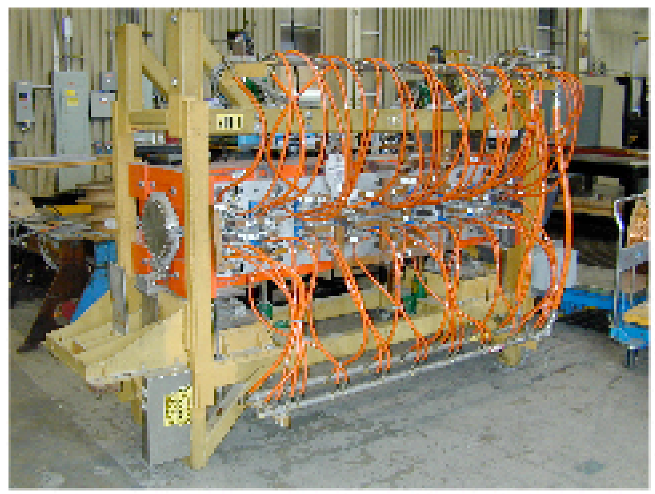
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

C. Barnes PhD)



X-Ray Spectrometer Schematic

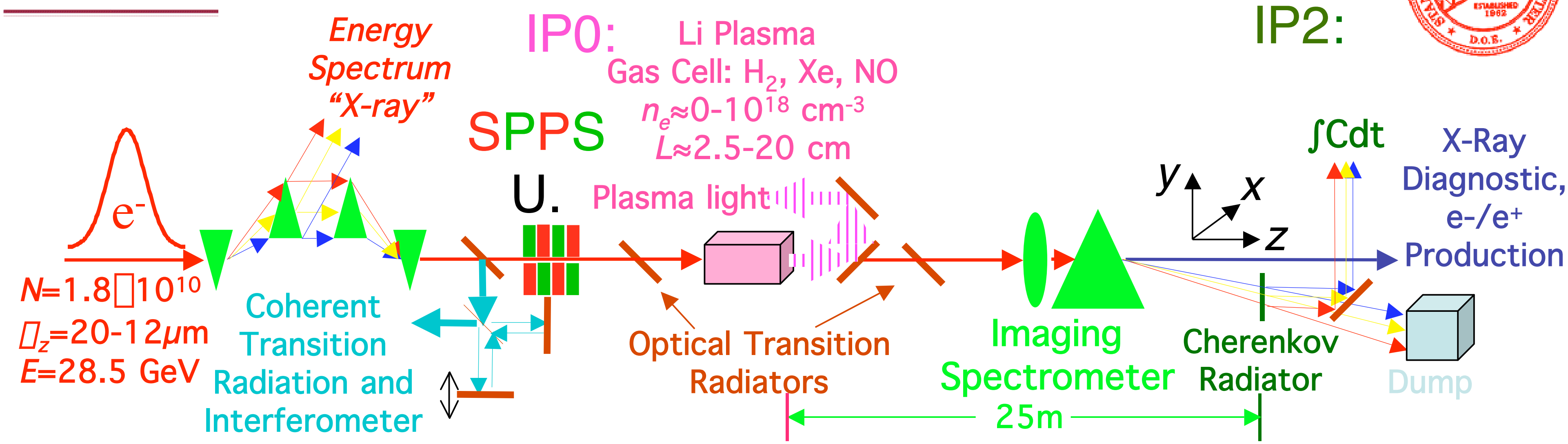


Spectrometer Chicane Magnet

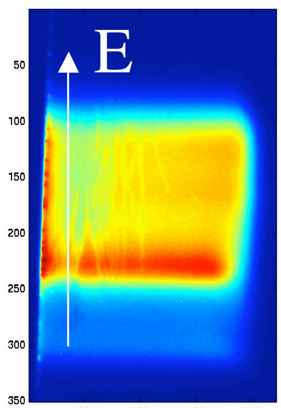
Scintillato[r] Detector

M. J. Hogan SLAC EPAC2003

Experimental Set Up



- X-ray Chicane



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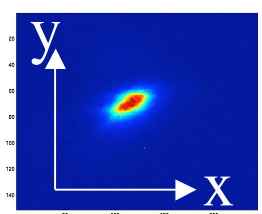
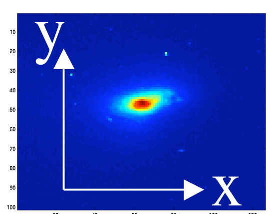


Downstream



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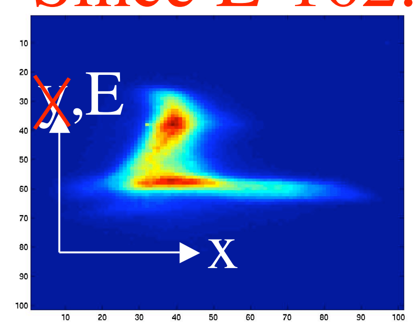
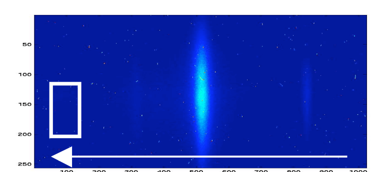
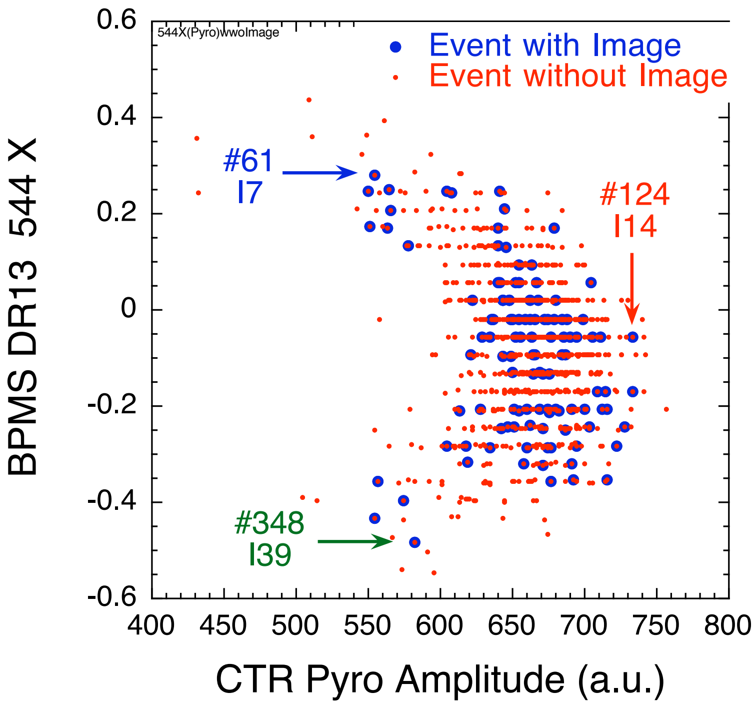


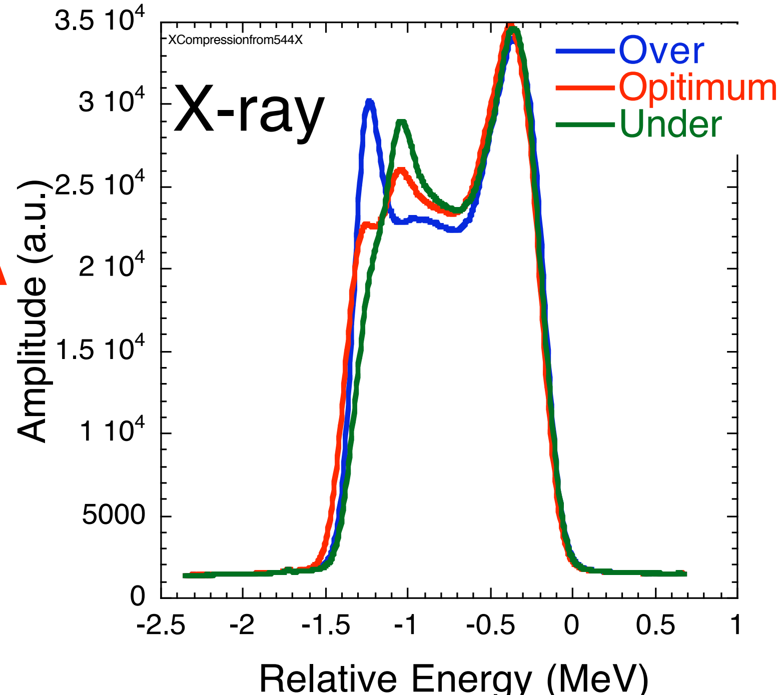
- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV

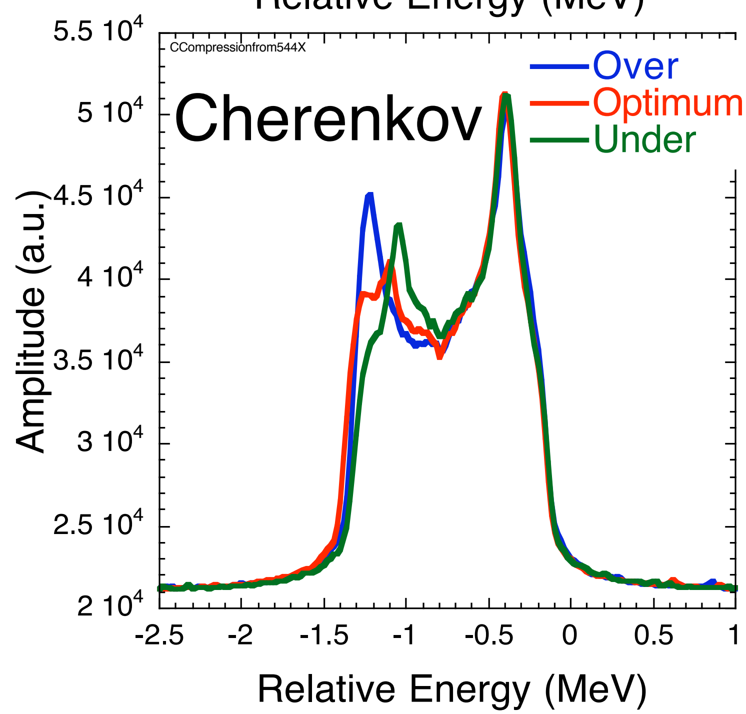
- Plasma Light



BUNCH COMPRESSION & ENERGY SPECTRA







- Pyro amplitude is ambiguous
- Energy spectra are not
- They are complimentary
- Clear correlation between Energy spectrum and E-164X outcome

E164X: A Plasma Wakefield Acceleration Experiment

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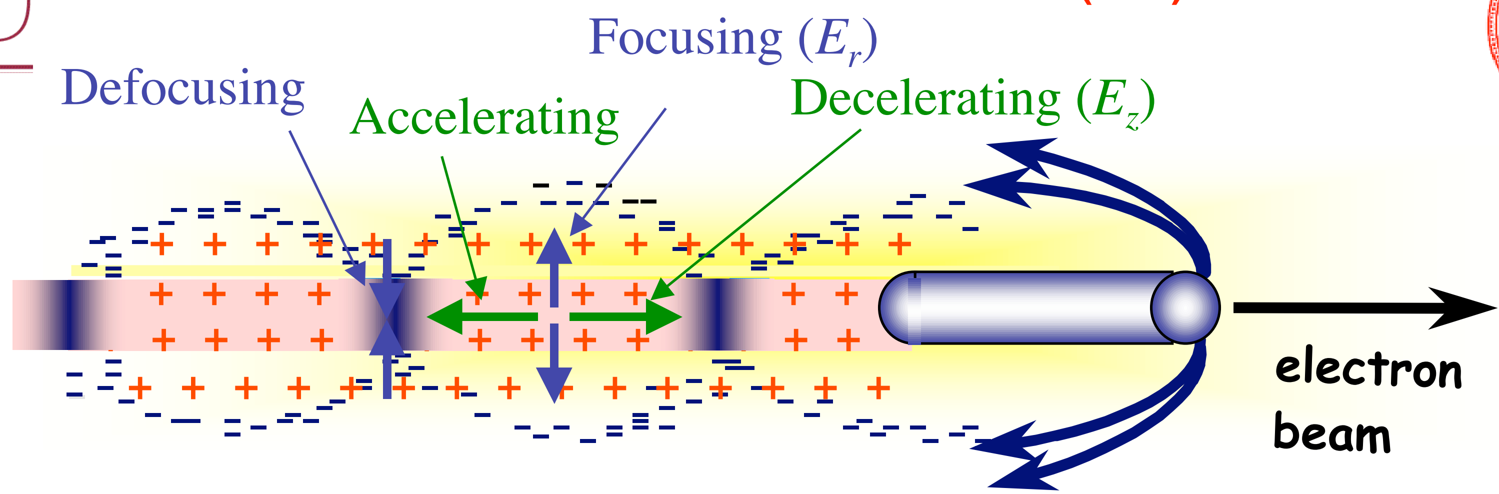
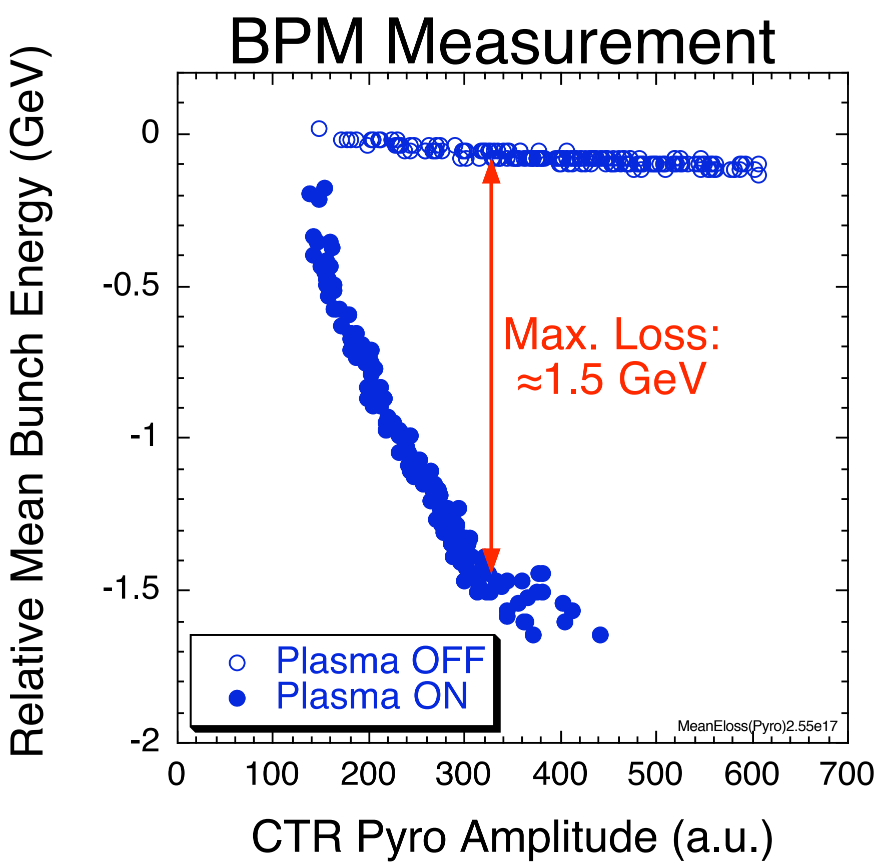
PLASMA WAKEFIELD (e^-)

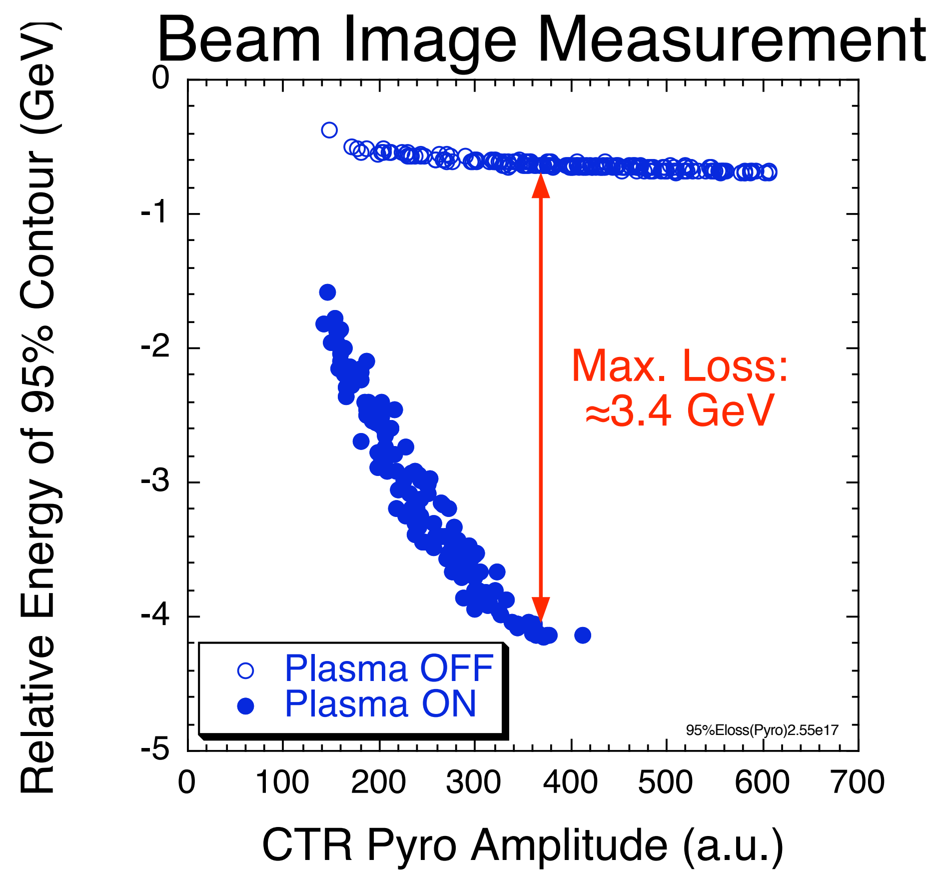


- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge forces => energy loss
  + focusing
- Plasma e^- rush back on axis => energy gain
- Linear scaling: $E_{acc} \approx 110 (MeV/m) \frac{N/2 \times 10^{10}}{(\sigma_z/0.6mm)^2}$ $\approx 1/\sigma_z^2$ @ $k_{pe}\sigma_z \approx \sqrt{2}$
- Plasma Wakefield Accelerator (PWFA) = Transformer
  Booster for high energy accelerator
- At n_e=2.6x10^{17} cm^{-3}: f_{rf}≈4.5 THz accelerator
  (for σ_z≈20 μm) $E_{acc.}$≈40 GV/m, B_θ/r≈ 8MT/m

$n_e \approx 2.55$□10^{17} cm^{-3} ENERGY LOSS

L≈10 cm, N≈1.8□10^{10}

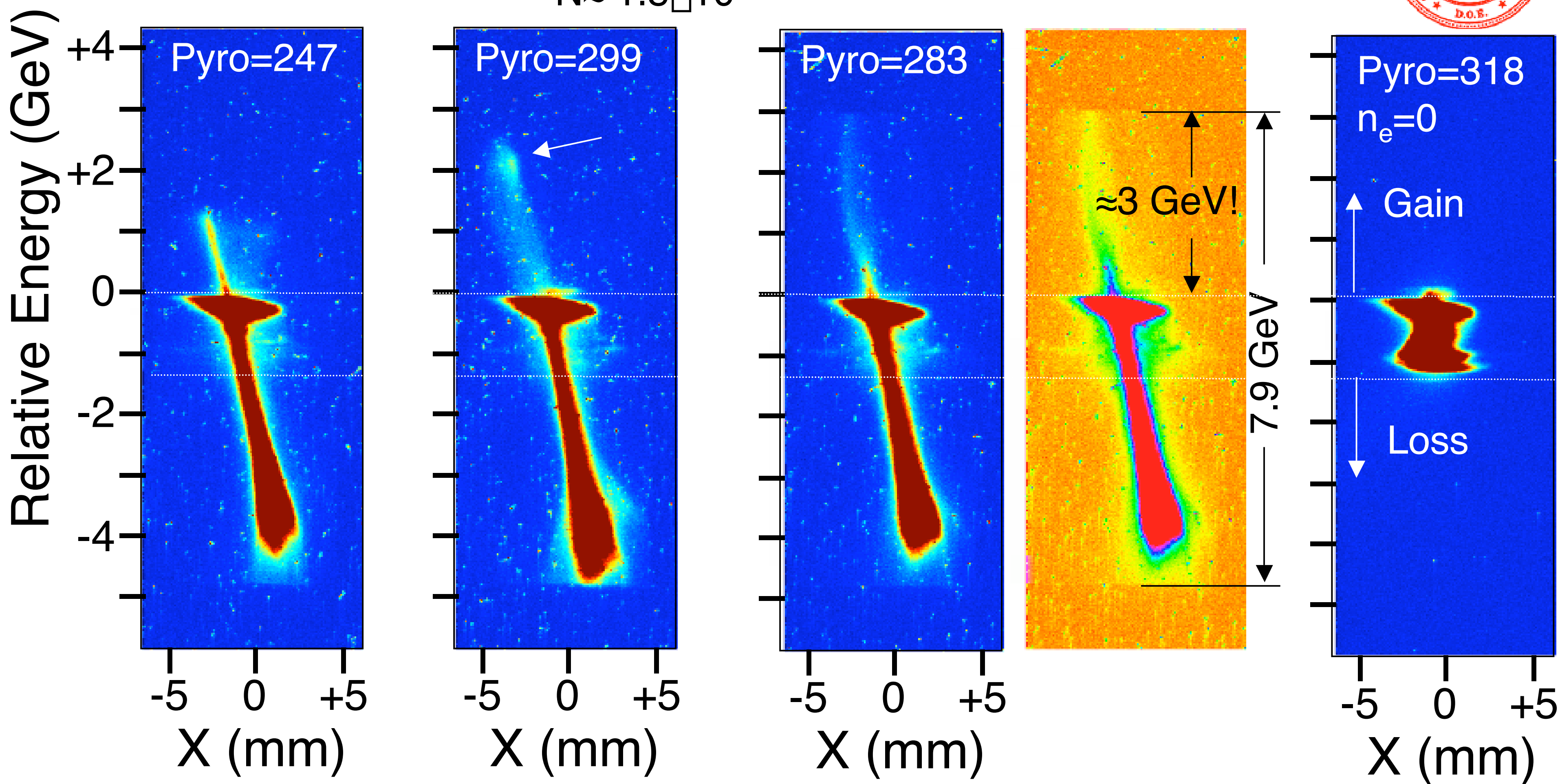




- Energy loss correlates with CTR energy (1/□$_z$?)
- Peak energy gradient 3.4 GeV/10 cm! (or 34 GeV/m!)

$n_e \approx 2.55 \times 10^{17}$ cm^{-3}, L≈10 cm RESULTS

$N \approx 1.8 \times 10^{10}$



- Energy gain reaches ≈3+1 GeV or ≈40 GeV/m
- ≈7% of charge or ≈200 pC with $E > E_0$
- Energy gain depends on the details of the incoming beam (x,y,z)

CONCLUSIONS

- First and only(?) measurement of SLAC short bunches
- CTR interferometry shows bunches as short as 74 fs, but …
- Beam splitter Fabry-Perot alters the measurement and CTR has limitations: multiple bunches , symmetric
- Short bunch confirmed by ionization of Li, NO, Xe, and H_2
- Measure single bunch energy spectrum to retrieve profile/current distribution
- CTR interferogram and amplitude, and bunch spectrum are key for E-164X and future E-…
- CTR interferometer can be improved: thinner Mylar splitter, vacuum box, …
- Retrieve/incorporate bunch current profiles: in CTR and E-164X, work in progress …