Sub-fs electron beam generation at UCLA Pegasus Laboratory

P. Denham, P. Musumeci
UCLA Department of Physics and Astronomy

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- UCLA Pegasus Laboratory group

  E. Cropp, P. Denham, M. Lenz, S. Crisp, A. Fisher, D. Garcia. Graduate students.

  A. Ody. Development engineer

- Collaborators: A. Kogar, R. K. Li, J. Maxson, G. Andonian, F. Carbone, D. Filippetto, A. Minor, J. Luiten, S. Karkare, A. Murokh

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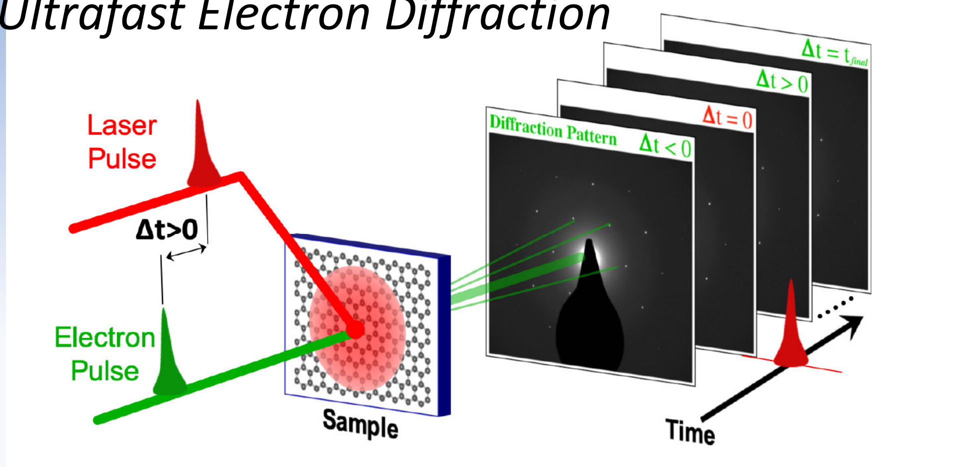
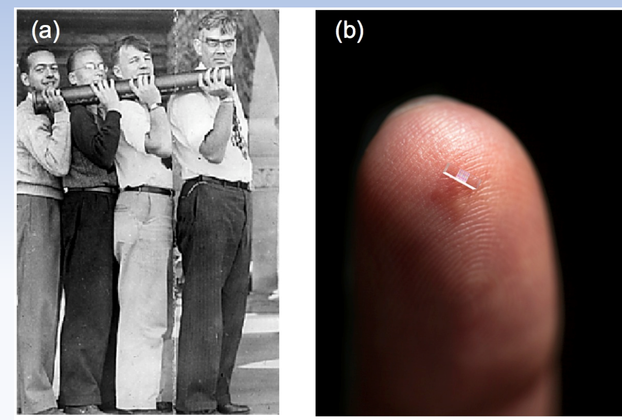
  - DOE Accelerator Stewardship DE-SC0009914.
  - NSF Accel Science PHY-1734215
  - GBMF4744 Accelerator-on-a-Chip

Application of sub-fs electron bunches

Ultrafast Electron Diffraction

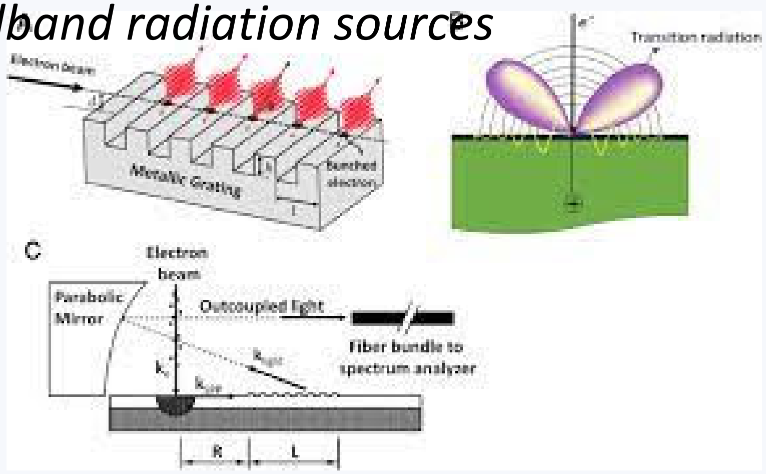


Injection into optical-scale accelerators

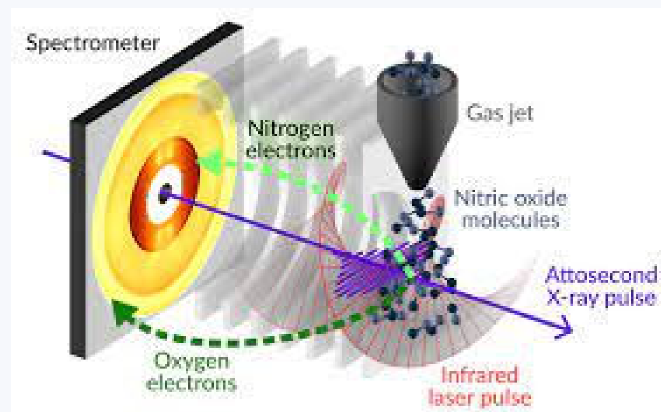


Microwave linac invented 1948 | Microchip accelerator invented 2013

Broadband radiation sources



Electron-based attoscience



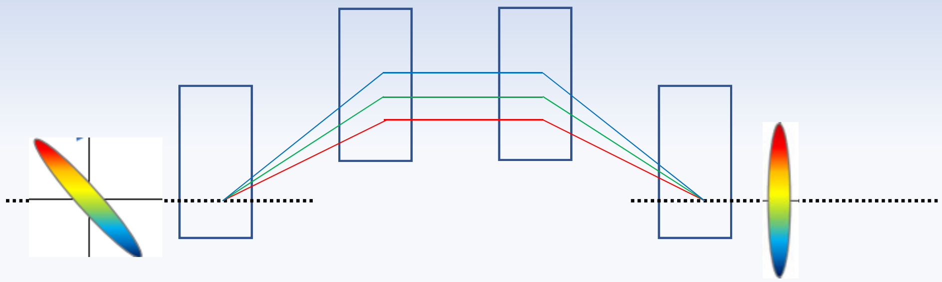
Outline

- Velocity bunching compression for low energy beamlines
- Non linear effects in ultrashort bunch generation
  - RF and space charge. (P. Denham et al. https://arxiv.org/abs/2106.02102)
- Compensation of non-linearities
  - Laser shaping.
  - Higher harmonic RF compensation.
- Start-to-end simulations of PEGASUS beamline.
- Sub-fs bunch length measurement techniques.

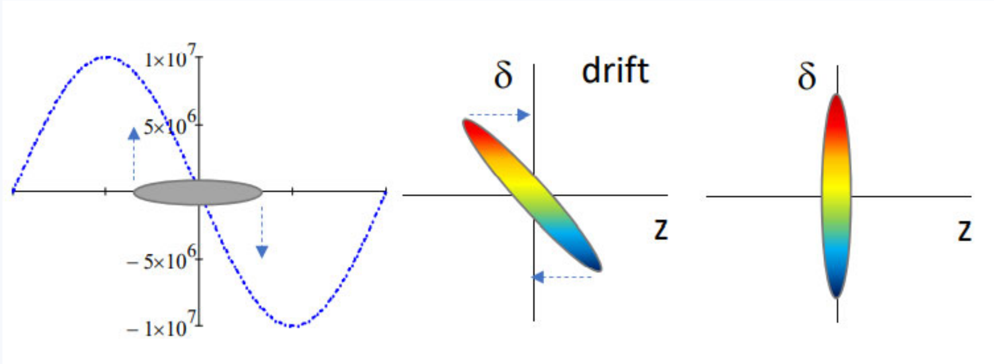
How to obtain ultrashort electron bunches

- Need a strongly chirped longitudinal phase space.
- **Magnetic compression:** higher energy electrons take a longer path through the bends, while lower energy take a shorter path. Longitudinal focus is achieved in a shorter distance. Needed for ultra-relativistic beams.
- **Ballistic compression**: RF cavity imparts negative chirp on beam then beam drifts to longitudinal focus. Favored at lower energy.

- Magnetic compression

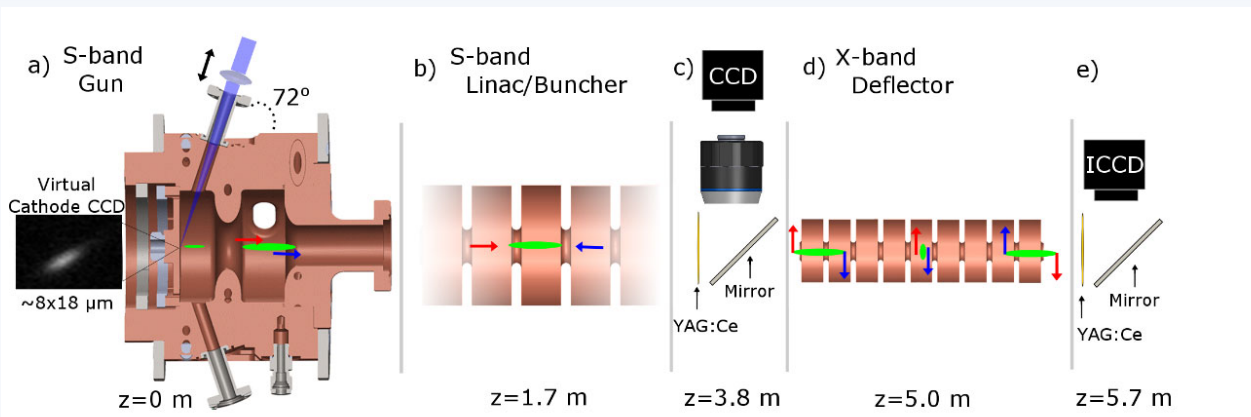


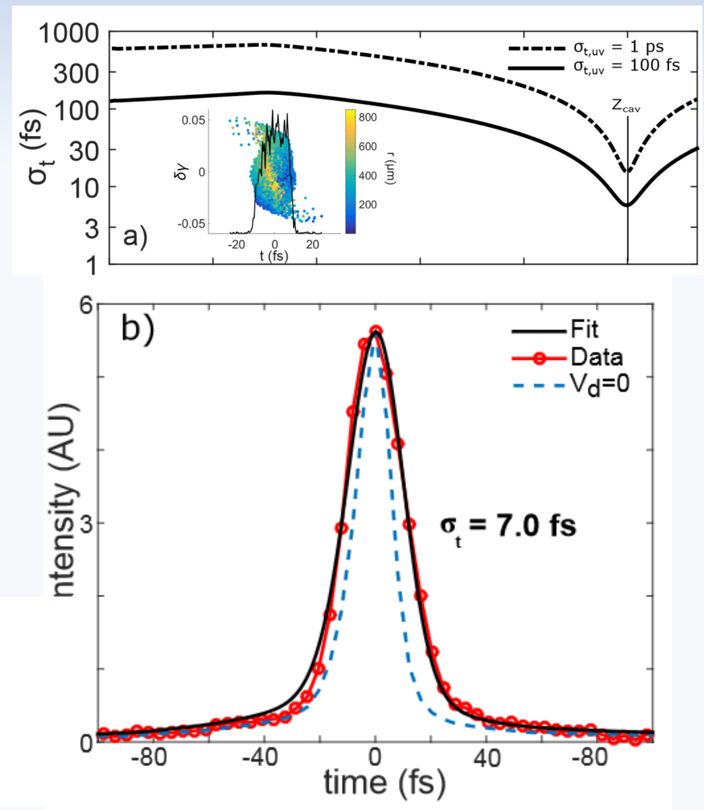
- Ballistic compression

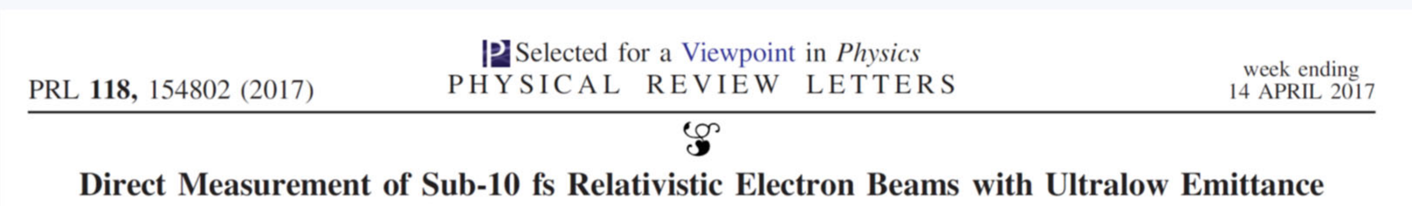


Sub 10fs RF compression at few MeV energies

- Demonstrated sub 10fs RF compression at Pegasus.
- Shorter initial pulse achieved shortest focus.
- What are the limitations?
  - How do optimal bunch lengths scale with beam and RF parameters?







Selected for a Viewpoint in *Physics*

PRL **118,** 154802 (2017) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2017

Direct Measurement of Sub-10 fs Relativistic Electron Beams with Ultralow Emittance

Non linear effects in RF compression

$$f = \frac{1}{\eta_1 \alpha k} = \frac{m_0 c^2 \gamma^3 \beta^2}{e V_0 k}$$

Ballistic bunching is inherently non-linear.

RF curvature

$$\boxed{\Delta\gamma = -\alpha \sin(k z_0)}$$

Vacuum dispersion

$$\boxed{z = z_0 + s\frac{\Delta\beta}{\beta} = z_0 + s\sum_{n=1}^{\infty} \eta_n \Delta\gamma^n}$$

$$\eta_1 = \frac{1}{\beta^2\gamma^3}$$

$$\eta_2 = \frac{2-3\gamma^2}{2\gamma^6\beta^4}$$

$$\eta_3 = \frac{2-5\gamma^2+4\gamma^4}{2\gamma^9\beta^6}$$

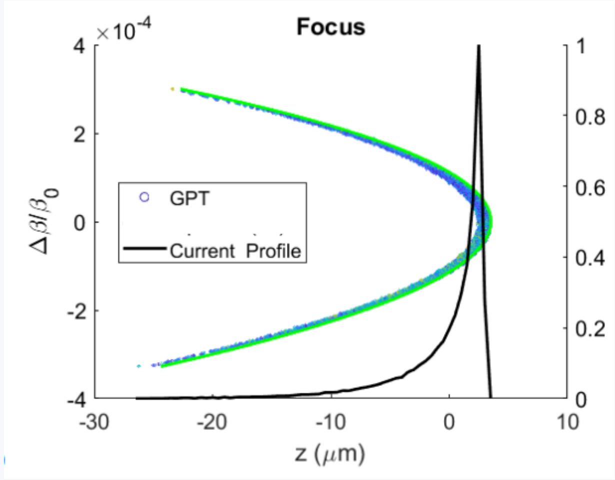
- These cause emittance growth

$$\epsilon_{RF}^2 \approx \sigma_{z0}^2 \left[2\eta_2^2\alpha^4 k^4 \sigma_{z0}^4 + \frac{1}{6}\left(\eta_1\alpha - 6\eta_3\alpha^3\right)^2 k^6 \sigma_{z0}^6\right]$$

- Distortions manifest as a ramped current profile.
- To compute final bunch length we can include emittance growth in envelope analysis

$$\epsilon_{zz'}^2 = \epsilon_{z_0 z_0'}^2 + \epsilon_{RF}^2$$

$$\sigma_{zf} = \frac{1}{\sqrt{\frac{1}{\sigma_{z0}^2} + \frac{\sigma_{z0}^2}{\epsilon_{zz'}^2 f^2}}} \approx \frac{f\epsilon_{z,z'}}{\sigma_{z0}}$$

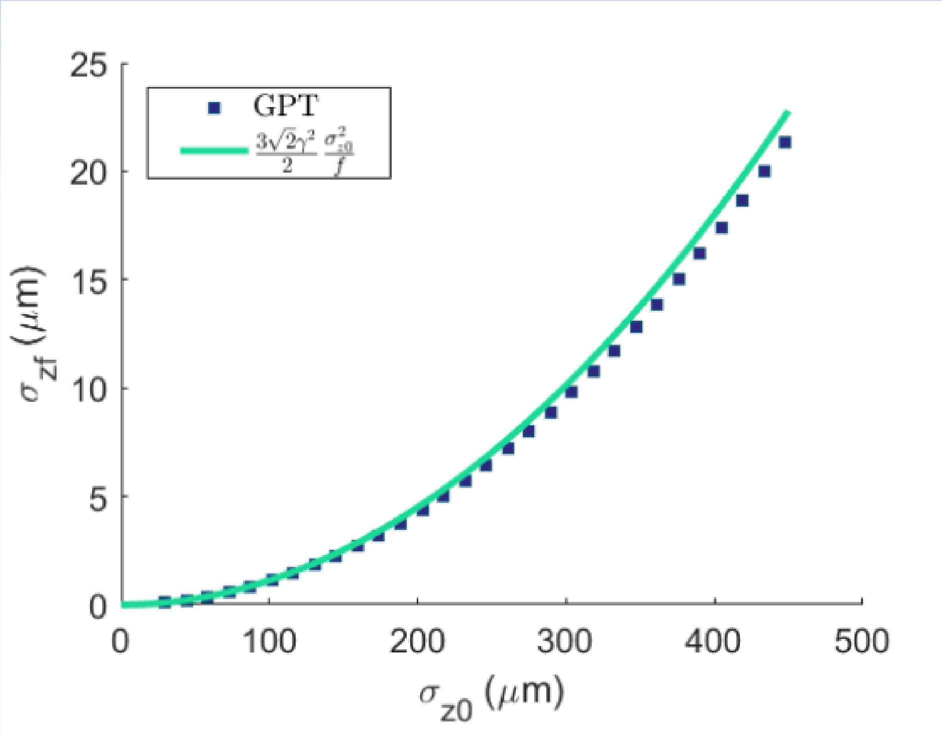


Analytical estimate of bunch length from RF non-linearities (Ignoring space charge).

At few MeV energies, bunch length dominanted by quadratic distortions at the ballistic focus

$$\sigma_{zf} \propto \frac{\gamma^2 \sigma_{z0}^2}{f}$$

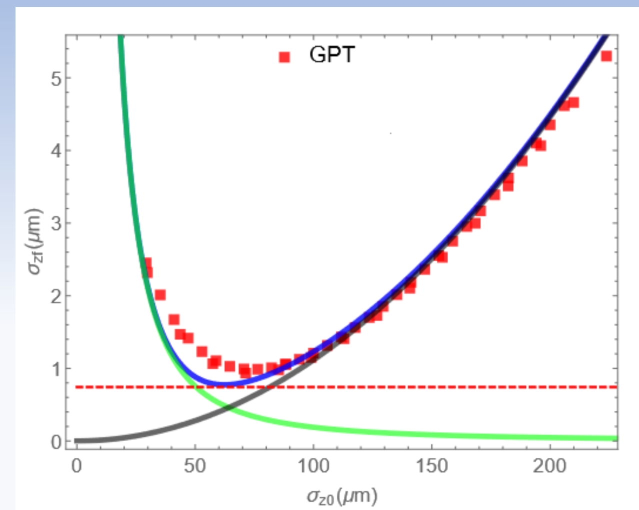
- Smaller longitudinal emittance enables better compression.
- Few electron pulses (stroboscopic) can achieve attosecond durations.
- What about single shot? Space charge limits?



Limitations set by space charge (linear and nonlinear)

1. Space charge at first order is included using longitudinal perveance

$$\sigma_z'' = \frac{K_L}{\sigma_z^2} + \frac{\epsilon_{z,z'}^2}{\sigma_z^3}$$

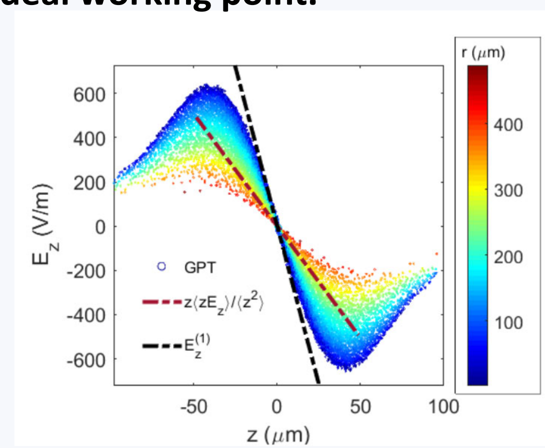


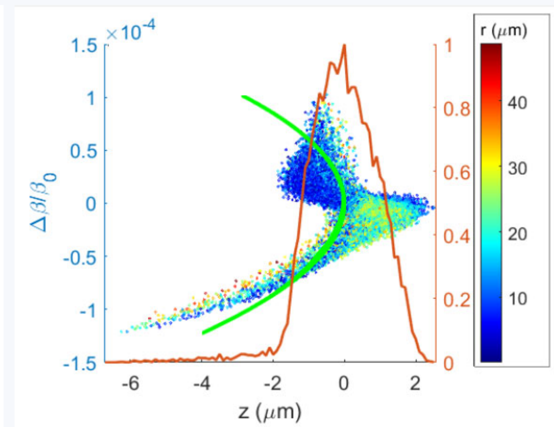
2. Non-linear space charge forces: e.g., Gaussian induces emittance grows up to ballistic focus. Effect amplified for shorter initial bunches.

Fine tune initial bunch length for optimum compression—Optimal trade off between space charge and RF effects-- Ideal working point.

$$fixed\ focal\ length\ optimum\ \sigma_{zf} \propto Q^{1/2}\gamma^{-3/2}$$

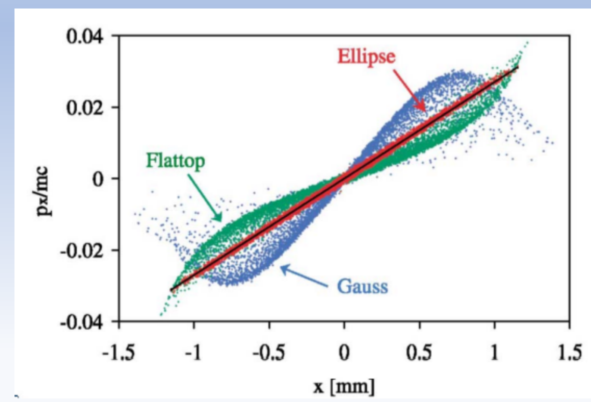
Emittance growth sensitive to electron 3D distribution and its evolution.





Electron beam shaping

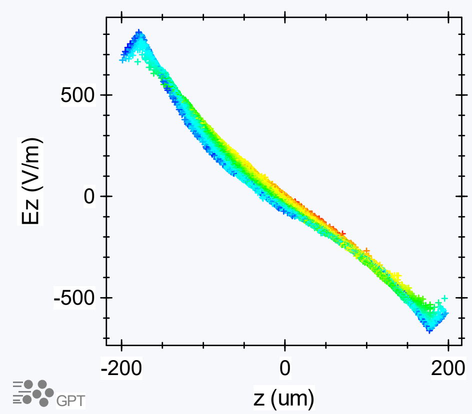
- Shaping cathode drive laser allows control on initial configuration space (i.e. x,y,z distribution).

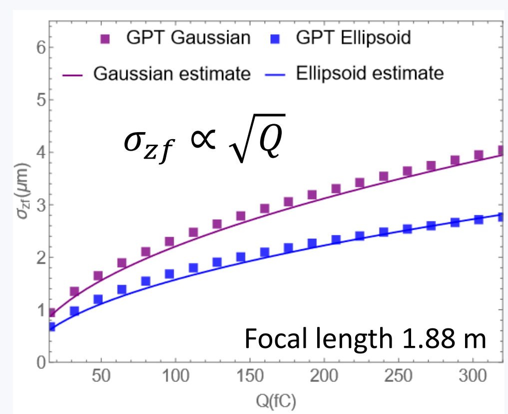


- Best case scenario, uniformly filled ellipsoid.
  Stretch laser pulse and use long parabolic temporal profile.

- Linear space charge forces → linearly correlated phase space →shorter final bunch lengths.

Ellipsoid dist.





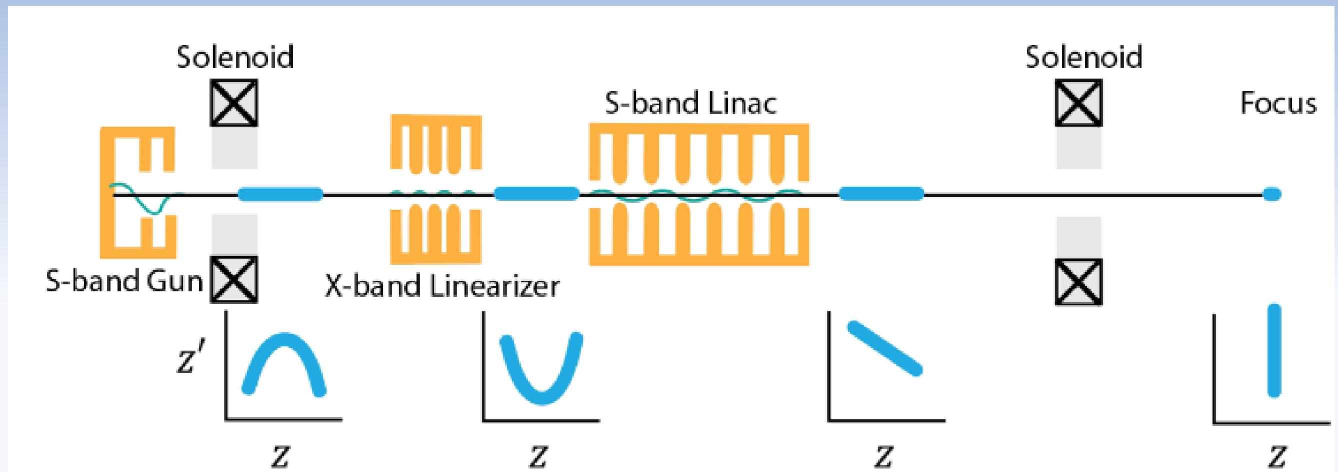
Higher harmonic compensation of emittance growth

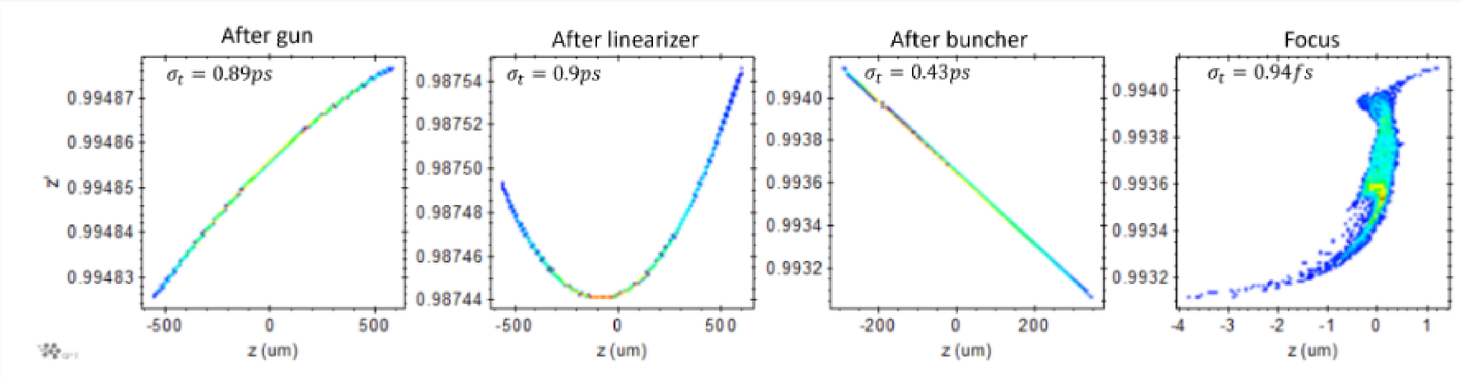
- Deceleration in 3rd harmonic cavity removes second order curvature.

$$\alpha_x = 2\frac{|\eta_2|}{\eta_1}\left(\frac{k}{k_x}\right)^2 \alpha^2$$

- Third order removal possible as well properly tuning Linac gradient and phase

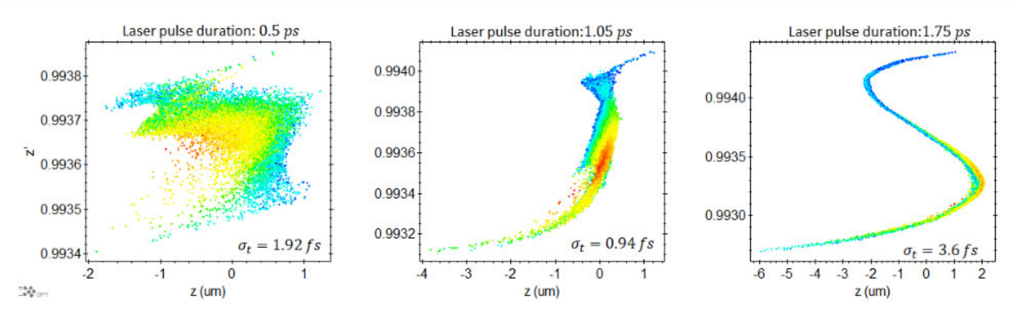
- Compensation allows longer bunch lengths to be used to relax space charge effects.

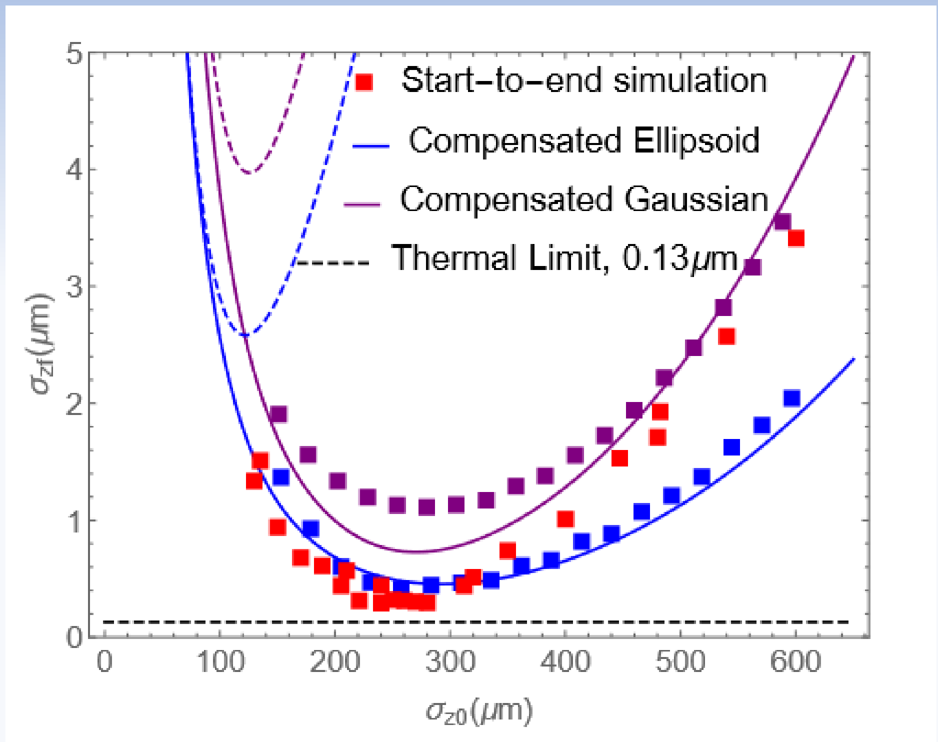




Start-to-end simulations for UCLA PEGASUS

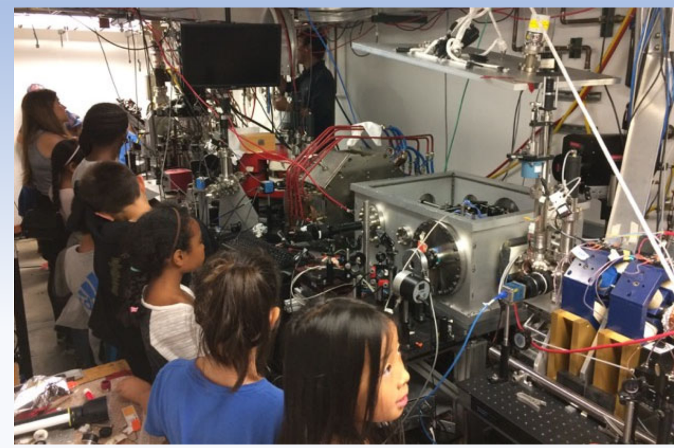
- 10^6 electrons – 160 fC bunches
- Shortest bunches achieved when 2nd and 3rd order RF non-linearities are compensated, and electronic distribution is optimally shaped into uniform ellipsoid.
- Approaching final limit -- set by initial beam thermal emittance.

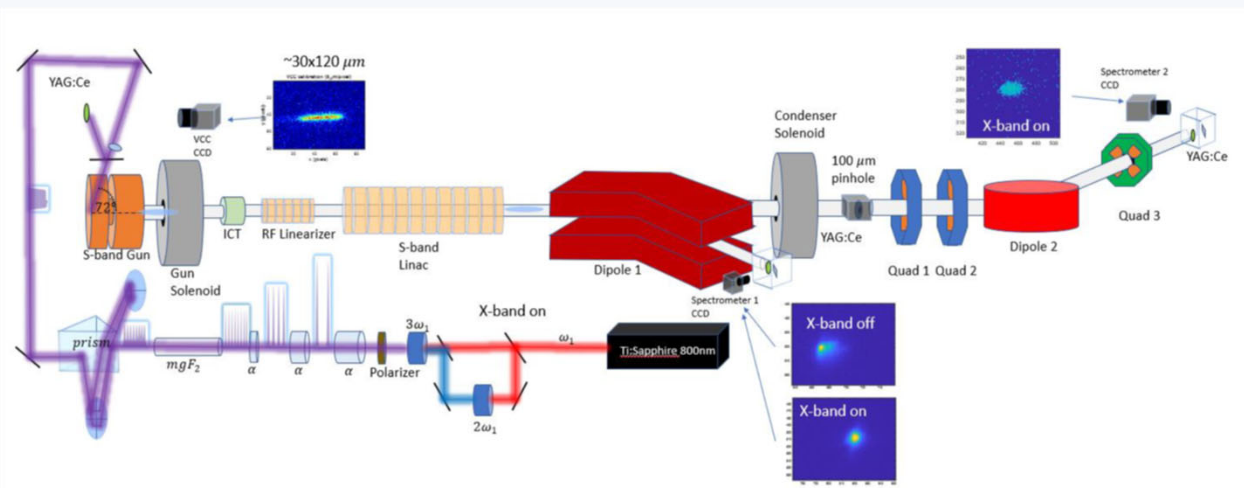




High peak brightness beam research at UCLA Pegasus Laboratory

- **3-14 MeV student-run university-size accelerator beamline optimized for sub-pC beams**
- High brightness electron beams:
  - High resolution ultrafast electron diffraction
  - Single shot imaging / UEM
  - *THz acceleration*
  - *High efficiency THz FEL*





J Maxson, et al., Direct measurement of sub-10 fs relativistic electron beams with ultralow emittance. **Phys. Rev. Lett., 118 154802 (2017)**

D. Cesar, et al., Demonstration of single-shot picosecond time-resolved MeV electron imaging. **Phys. Rev. Lett., 117, 024801 (2016)**

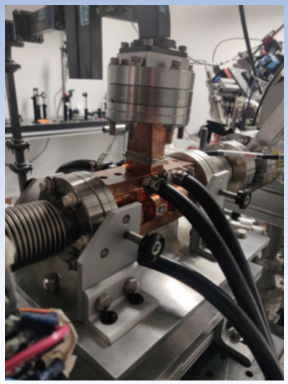
E. Curry et al. Meter-scale THz-driven acceleration of a relativistic electron beam. **Phys. Rev. Lett. 120, 094801 (2018)**

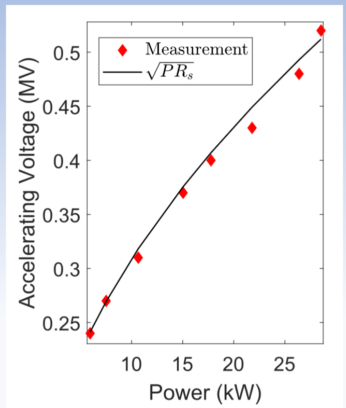
A. Fisher, Y. Park et al. High efficiency single pass THz FEL. **Nature Photonics, 16, 441 (2022)**

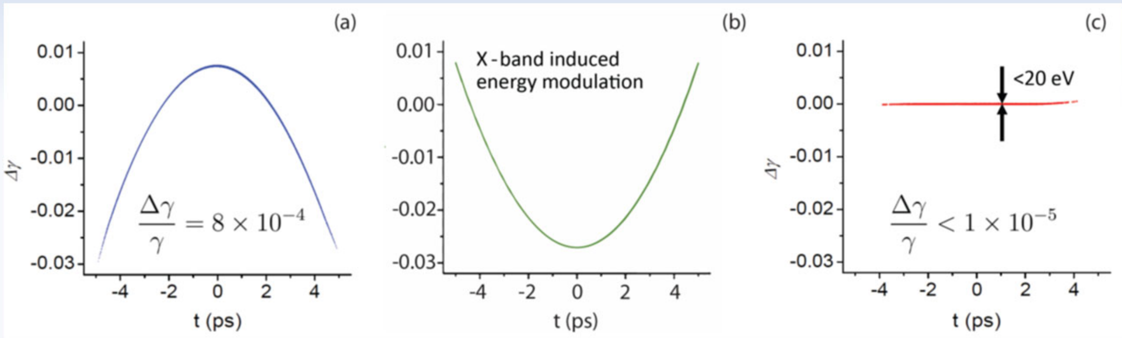
Demonstration of X-band LPS linearization

- Install and commission X-band cavity
- Removal of non-linearities in LPS for energy spread minimization as well.
- Application to minimize chromatic aberrations in ps-time resolved MeV TEM

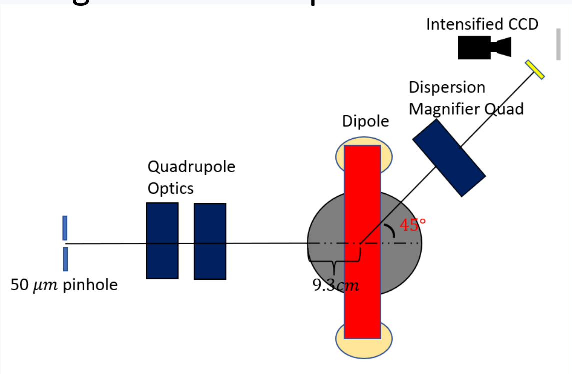
P. *Denham, et al.*, "X-Band Harmonic Longitudinal Phase Space ... presented at the *NAPAC*'22

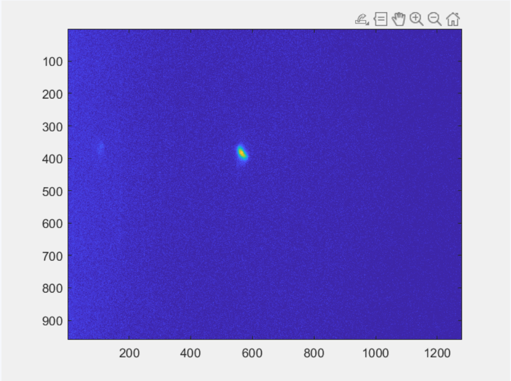




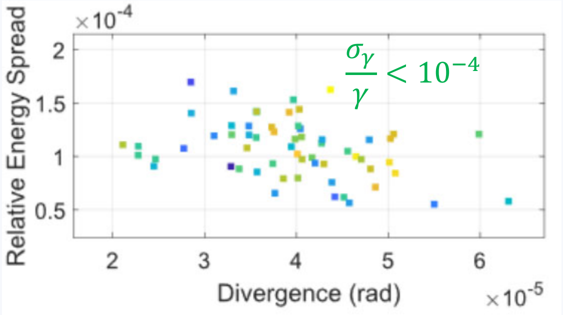


high resolution spectrometer



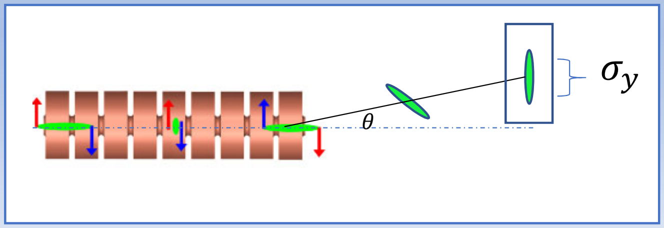


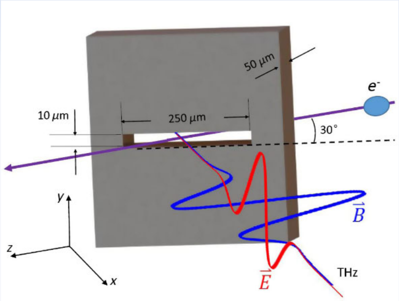
$\beta - tron$ contribution subtraction



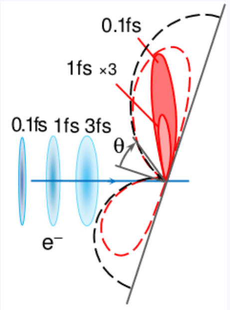
Options for sub-fs electron bunch measurements

- RF techniques.
  - RF deflecting cavity--Resolution limited by cavity frequency and screen resolution.
- THz streaking
  - Sensitive to timing jitter
  - Limited availability of THz power
- Laser techniques.
  - Laser Induced energy modulations in DLA or bend magnets?
- Radiative techniques.
  - Optical transition radiation—coherence factor suppressed by transverse extent of the bunch.
  - Different geometries enhance optical coherence.





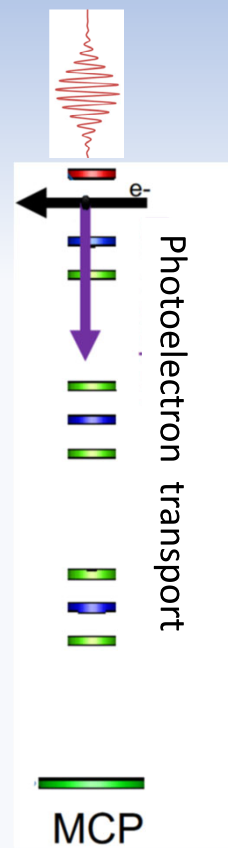
L. Zhao, et al. Phys. Rev. X 8, 021061



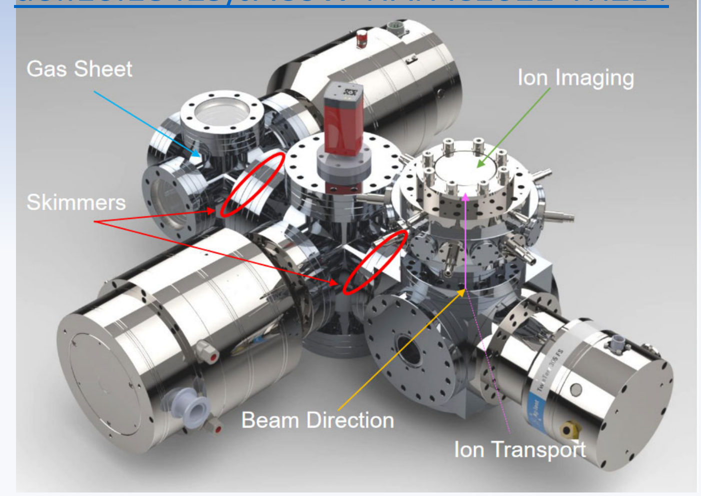
M.V. Tsarev and P. Baum 2018
New J. Phys. **20** 033002

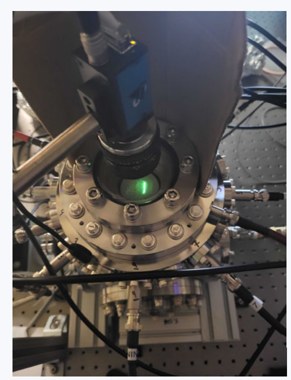
Ionized electron Velocity Map Imaging

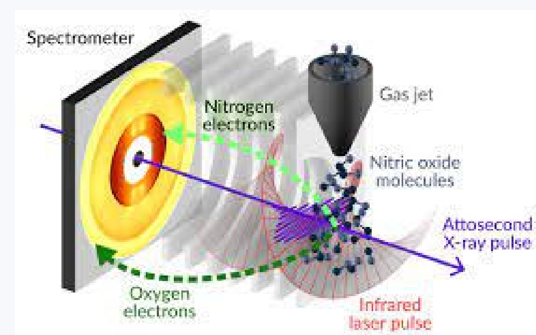
- Learn a lesson from attosecond X-ray sources
- Set e-beam ballistic focus at gas sheet plane.
- Impact ionization of gas sheet.
- Laser streaking of “knocked” electrons.
- Ion microscope tuned to image velocity space at interaction point.
- Image time dependent streak profile—signature of e- beam duration.
- What is the signature exactly? What dilutes the signal dependence on bunch duration?



doi:10.18429/JACoW-NAPAC2022-THZE4

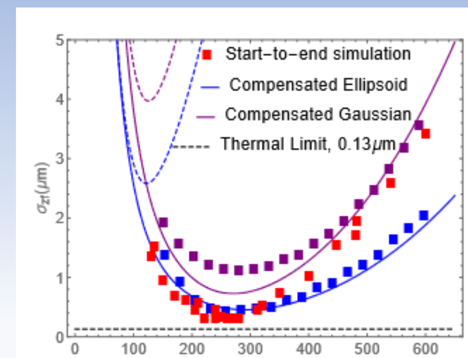


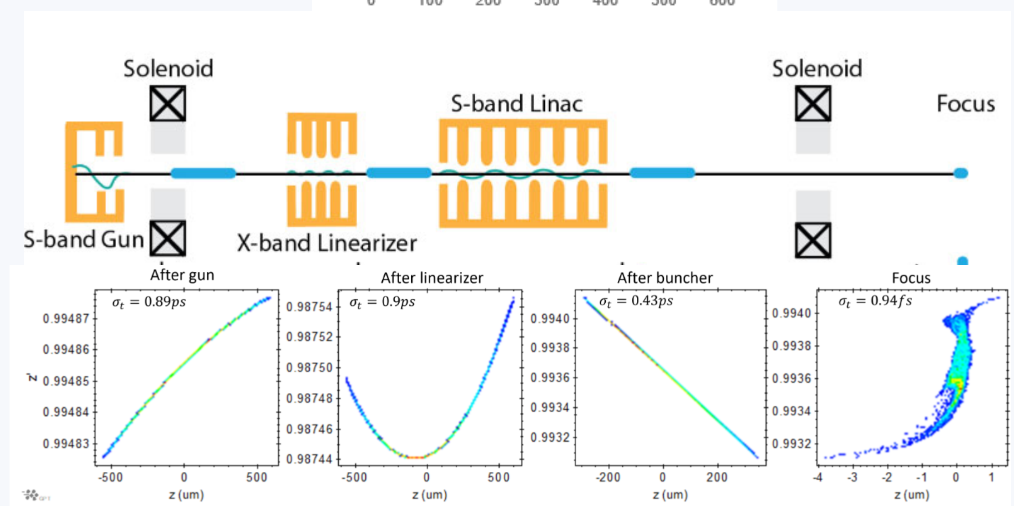




Summary: Ultrashort Beam generation at PEGASUS.

- Single shot UED temporal resolution determined by the bunch length at ballistic focus.
- Competing non-linear effects limiting the shortest achievable bunch length.
- Overcome non-linearities with laser shaping of electron beam and higher harmonic compensation.
- Bunch lengths in attosecond to sub-fs regime (for 10-100 fC charge) achievable.
- Implemented X-band and took measurements of LPS linearization—reduced energy spread.
- Seeking novel bunch length diagnostic to measure sub-fs bunches. Developments underway.





Laser Induced Energy Modulations in a Dipole

Plane wave Interaction

$$\vec{r}(t) = R(\cos(\omega_c t)\hat{x} + \sin(\omega_c t)\hat{z})$$
$$\vec{v}(t) = R\omega_c(-\sin(\omega_c t)\hat{x} + \cos(\omega_c t)\hat{z})$$
$$\vec{E} = \hat{x}E_0 \cos(k(z - ct) + \psi)$$
$$\phi = \omega_c t$$

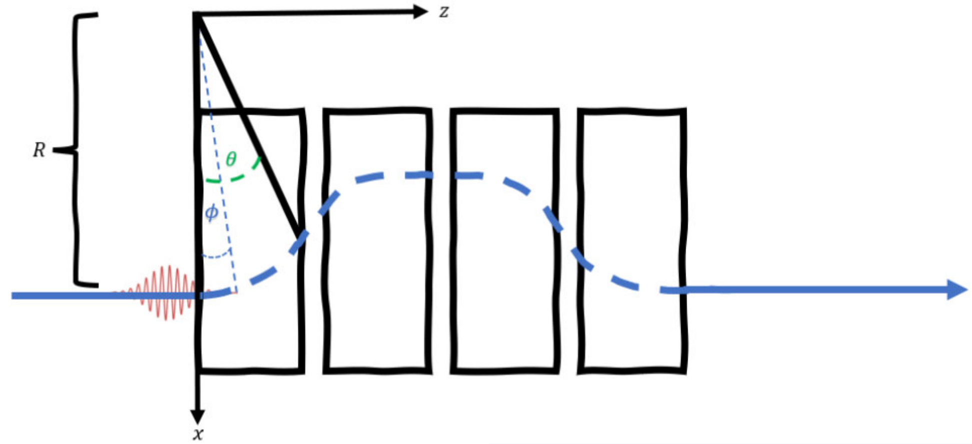
Neglecting interaction between laser and beam prior to chicane entrance

$$\frac{dE}{dt} = \vec{F} \cdot \vec{v} \rightarrow \frac{d\gamma}{dt} = \frac{qE_0}{mc^2} v_x \cos(k(z - ct) + \psi)$$

$$\frac{d\gamma}{dt} = -\frac{qE_0 R\omega_c}{mc^2} \sin(\phi) \cos\left(kR\left(\sin(\phi) - \frac{\phi}{\beta}\right) + \psi\right)$$

$$\therefore \frac{d\gamma}{d\phi} = -\frac{qE_0 R}{mc^2} \sin(\phi) \cos\left(kR\left(\sin(\phi) - \frac{\phi}{\beta}\right) + \psi\right)$$

$$\therefore \Delta\gamma = \frac{qE_0 R}{mc^2} \int_0^{\phi_{max}} \sin(\phi) \cos\left(kR\left(\sin(\phi) - \frac{\phi}{\beta}\right) + \psi\right) d\phi$$



How do we preserve temporal structure in transport?