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Overview of alternative bunch and current-shaping techniques for low-energy electron beams*

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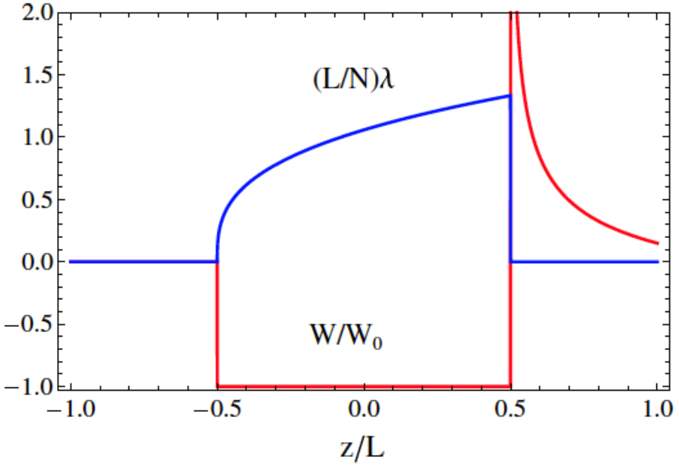
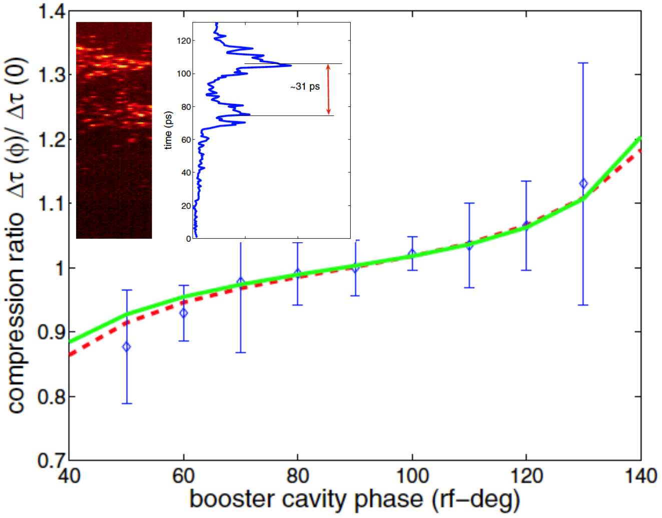
Motivations within the FEL context

*Mitchell, PRSTAB **16** 060703 (2013)*



- **Compression:**
  - compact light sources
  - external injection into short-λ accelerating structures

- **Shaping:**
  - narrowband radiation generation
  - two-color FELs
  - seeding techniques
  - advanced acceleration concepts
  - mitigation of collective effects
  - diagnostics



*Piot, PRSTAB **9** 053501(2006)*

Low-energy-beam bunching methods

- Energy-modulation
  - introduces time-energy correlation along the bunch

fractional momentum spread

field wavevector, phase

$$\delta = \sum_i A_i \cos(k\zeta + \phi_i)$$

normalized field amplitude

electron coordinate

  - exploit the correlation,

$$d\zeta_f = R_{56} d\delta_0 + \mathcal{O}(d\delta_0^2)$$

longitudinal dispersion

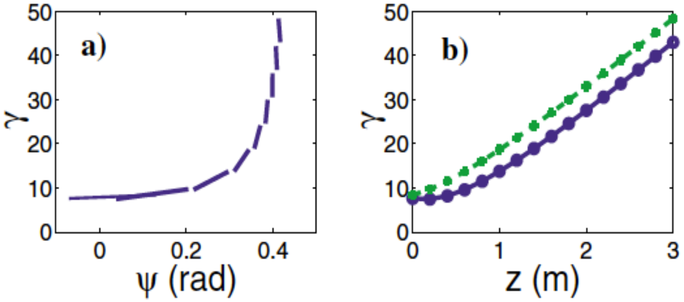
$$R_{56} = \frac{1}{\beta^2\gamma^2}$$ for a drift

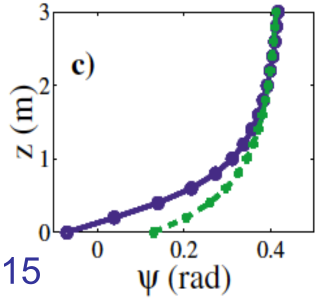
- Velocity bunching
  - phase slippage w.r.t external field

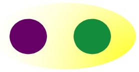
$$\frac{d\Psi}{d\zeta} = k\left(\frac{\gamma}{\sqrt{\gamma^2-1}} - 1\right)$$

$$\frac{d\gamma}{d\zeta} = Ak\sin(\Psi)$$

Kim, NIM A ***275*** *201 (1989)*

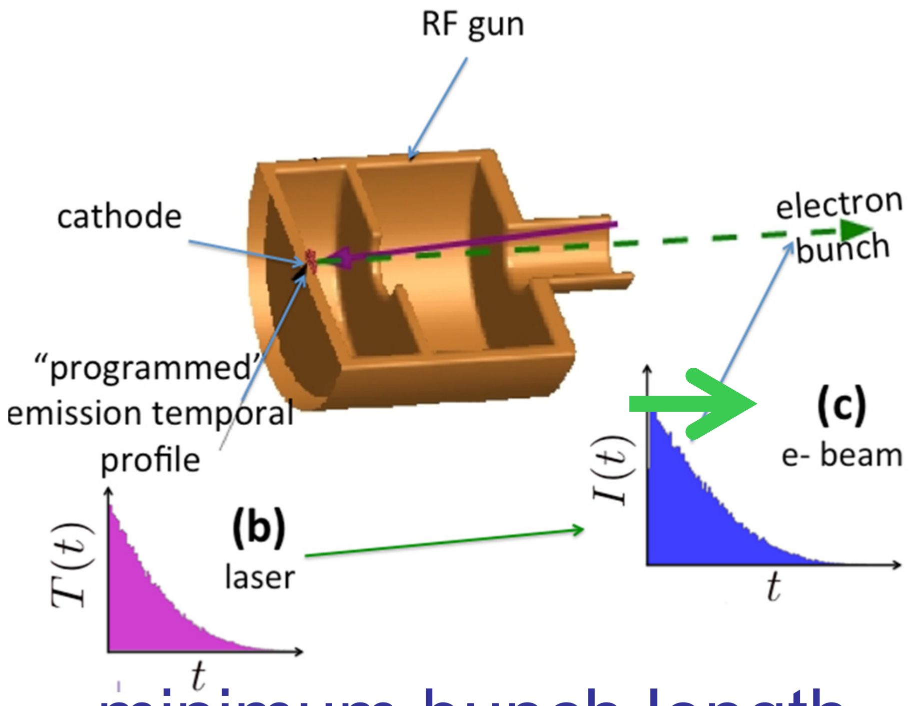


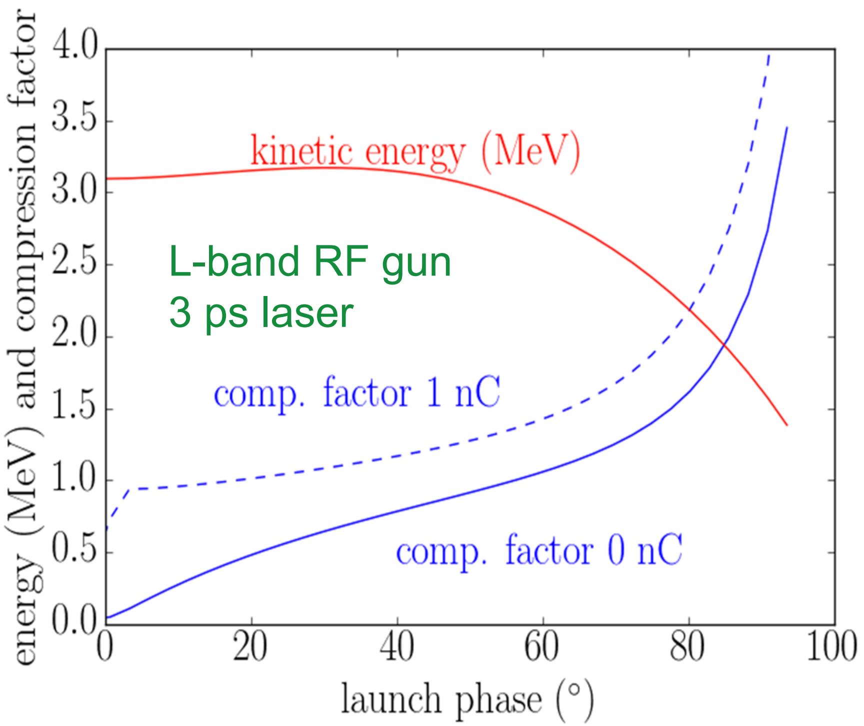




Ab-initio electron-beam shaping

- temporally tailor the emission process to obtain the desired final electron density



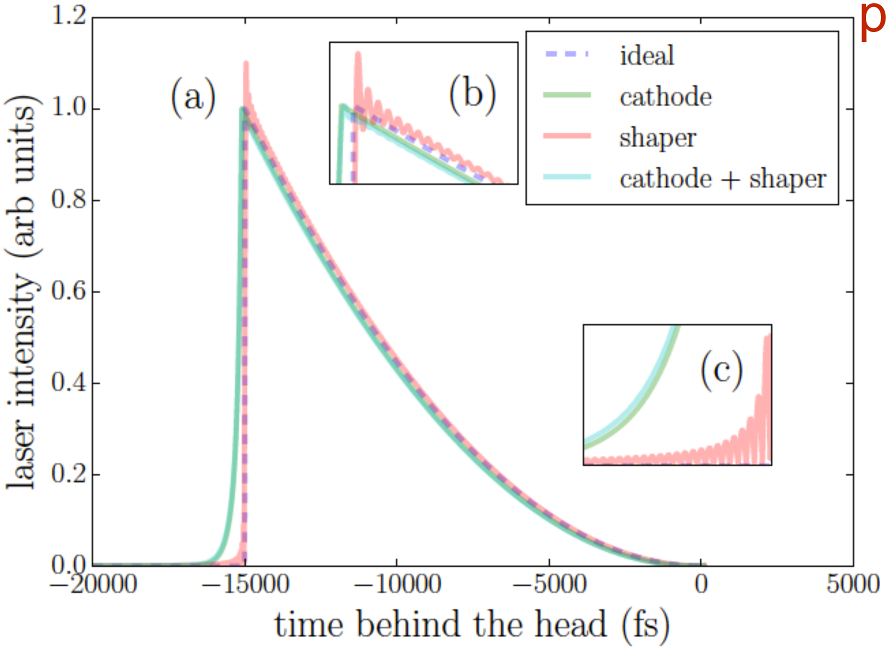


- minimum bunch length downstream of a conventional e- source (e.g. RF gun) is limited by RF and space-charge effects

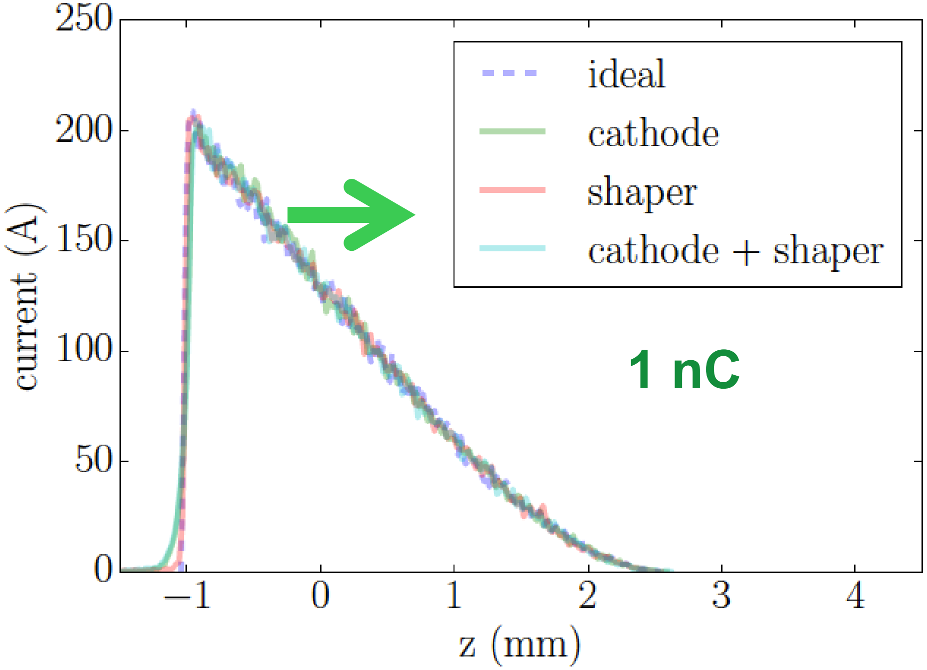
Ab-initio electron-beam shaping via photoemission

- photoemission is a technique of choice
  ➔ shaping accomplished via temporal tailoring of the drive laser.

Simulation of laser shaping (left) and produced e- beam (right) including shaper and phoemission response (CsTe)

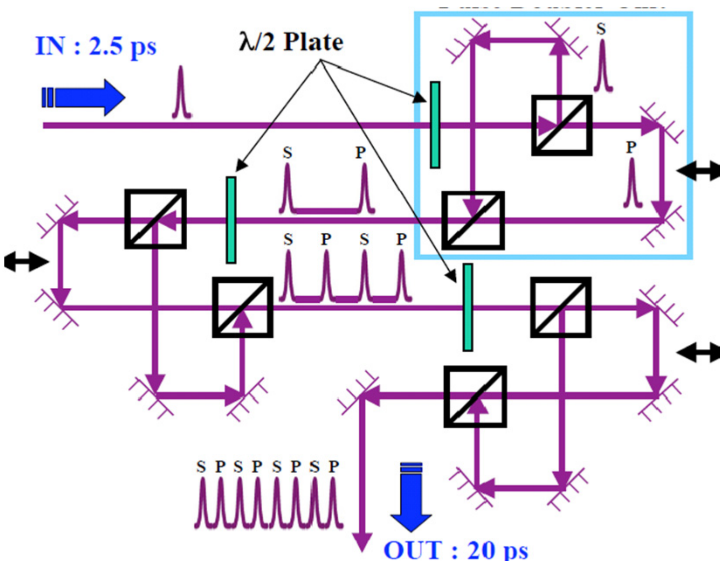


Lemery, PRSTAB 18, 081301 (2015)



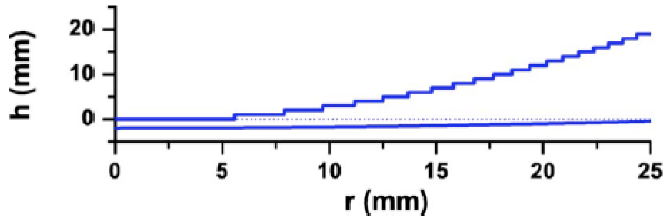
Laser-pulse tailoring

- Line-delay technique



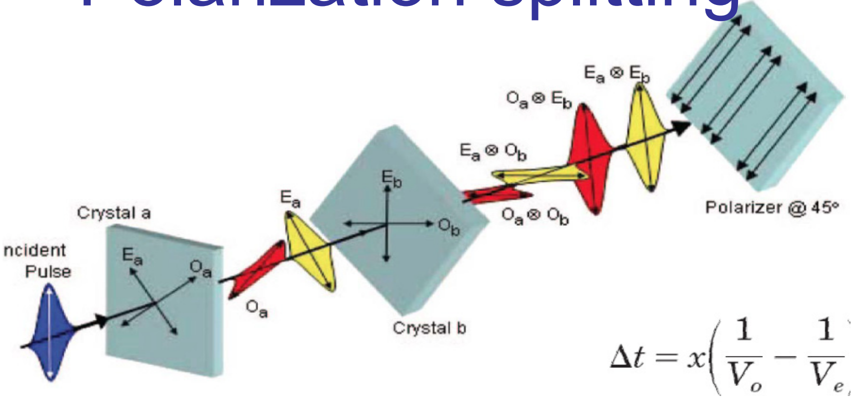
*Tomizawa, QE **37**, 697 (2007)*

- Echelon lenses



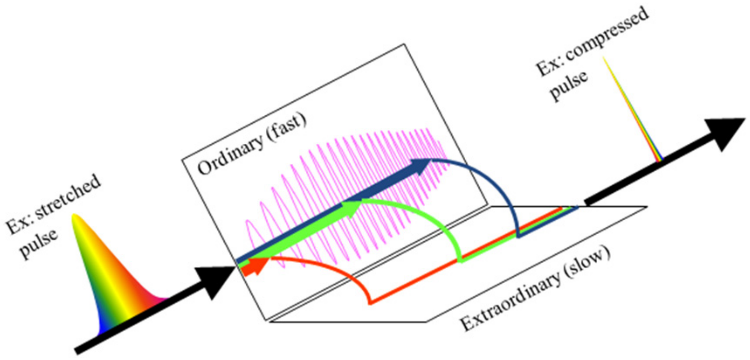
*Li, APL **92**, 01101 (2008)*

- Polarization splitting



*Dromey, App. Opt **46**, 5142 (2007)*

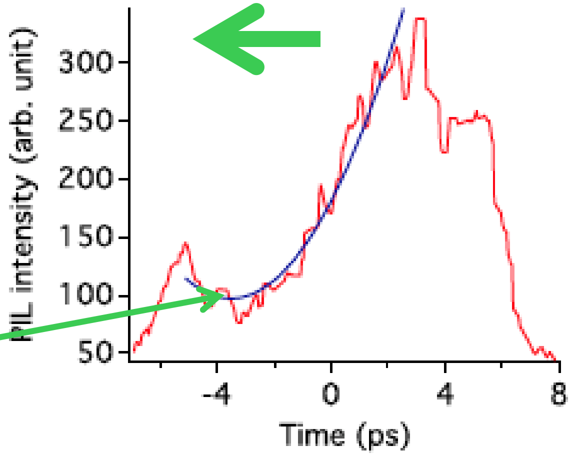
Acousto-optic programmable dispersive filter (DAZZLER®)



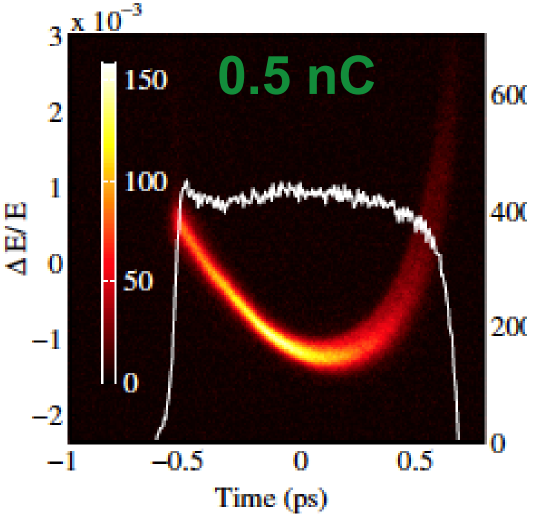
Mitigation of collective effects

- optimum laser shape tuned to pre-compensate wakefield-distortions
- shape has to have an inverted parabolic region

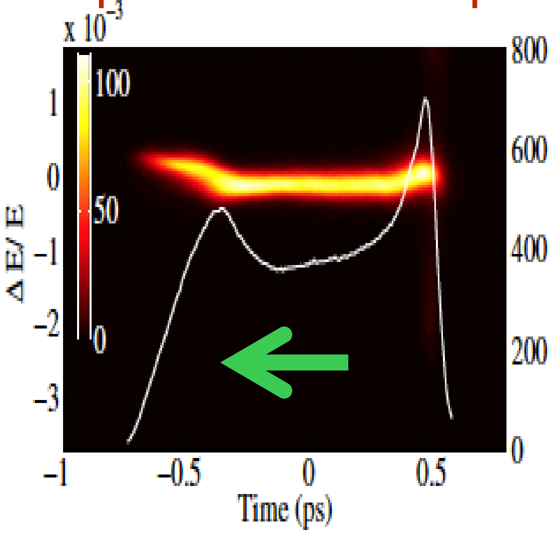
measured UV laser shape



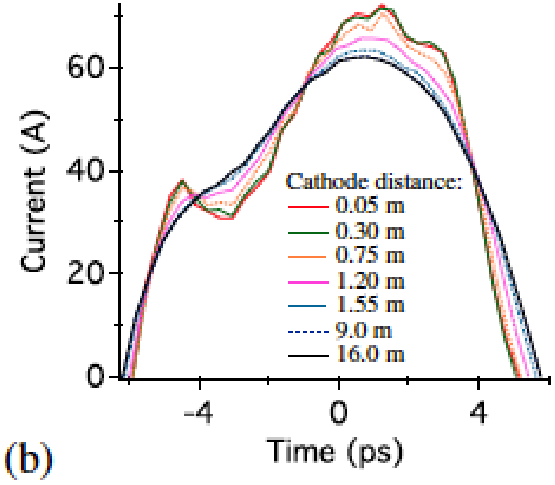
measured nominal



measured w. optimal laser shape



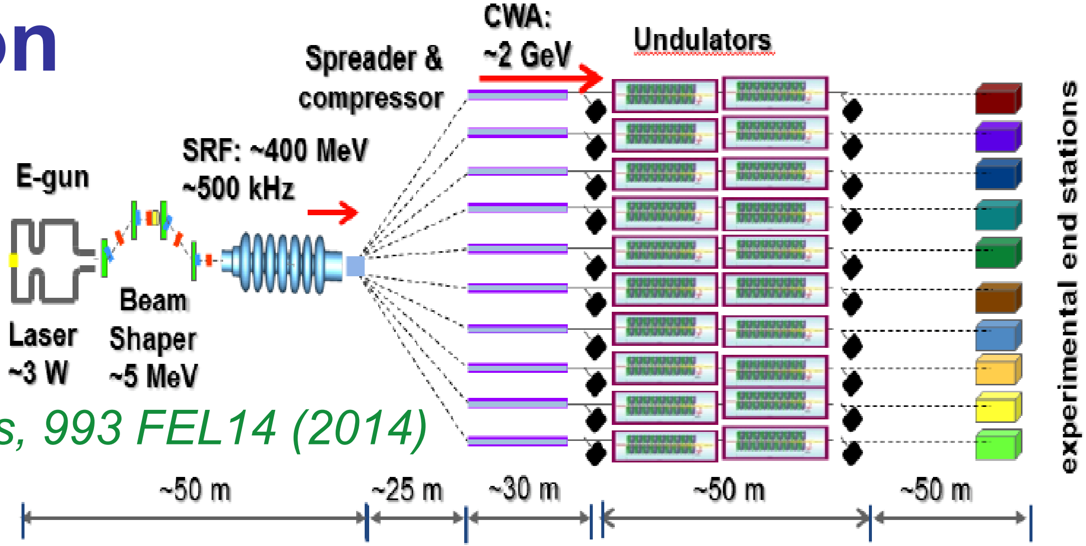
simulated evolution of bunch's current profile



*Penco, PRL **112** 044801 (2014)*

Production of tailored bunch for beam-driven acceleration

- Possible multiple-user FEL facility based on wakefield acceleration

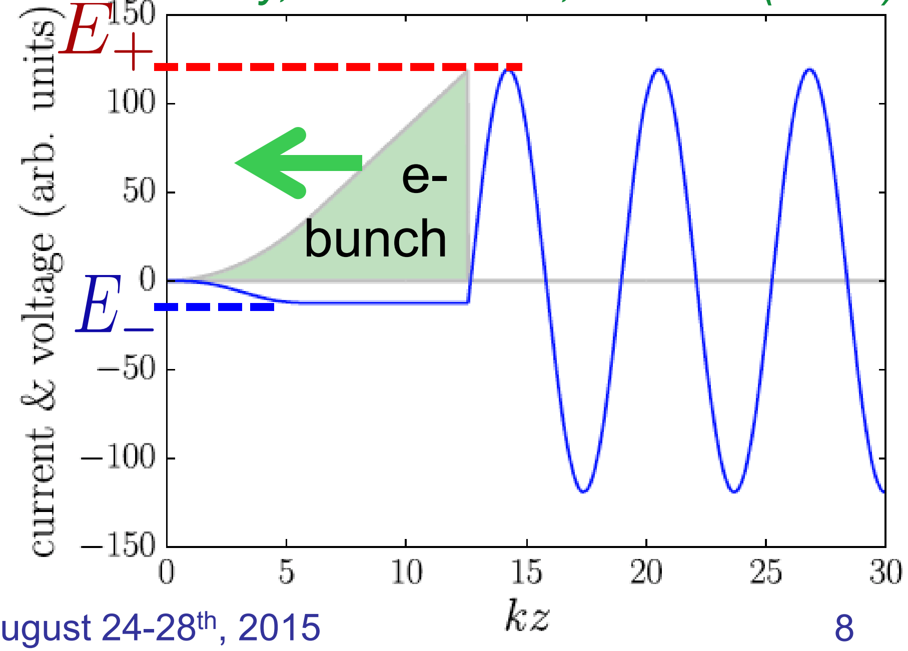


Zholents, 993 FEL14 (2014)

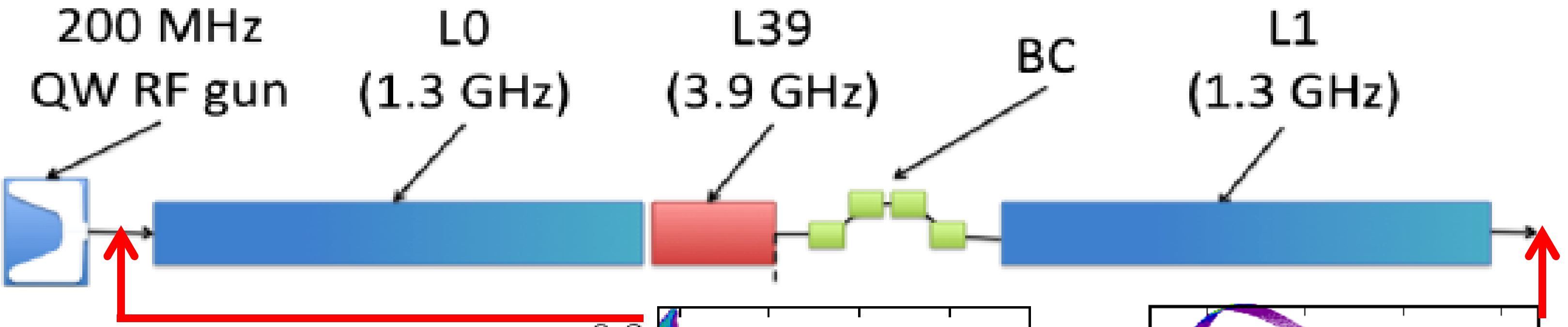
- Important parameters for this type of beam-driven acceleration is the **transformer ratio**

$$\mathcal{R} \equiv \left|\frac{E_+}{E_-}\right|$$

Lemery, PRSTAB 18, 081301 (2015)



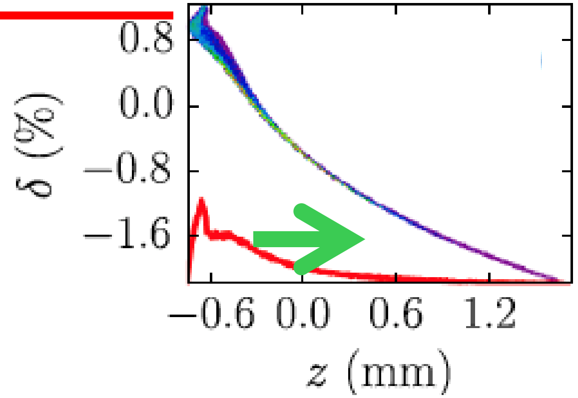
Production of tailored bunch for beam-driven acceleration (II)

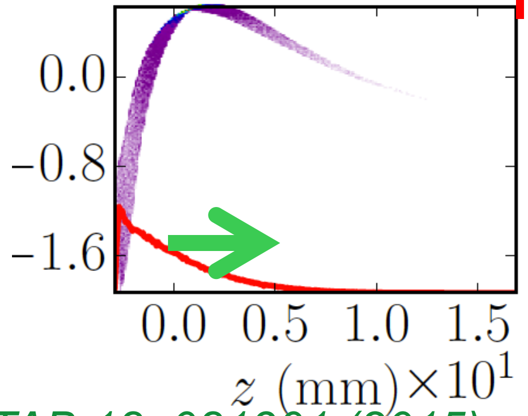


- laser shape combined with acceleration & compression
- close-to-optimal current distribution

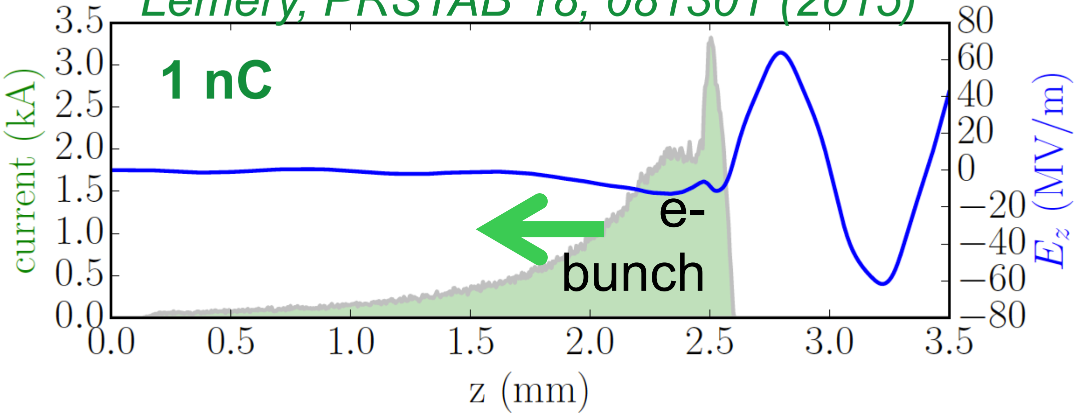
$$E_+ \simeq 65 \text{ MV.m}^{-1}$$

$$\mathcal{R} \simeq 5.5$$



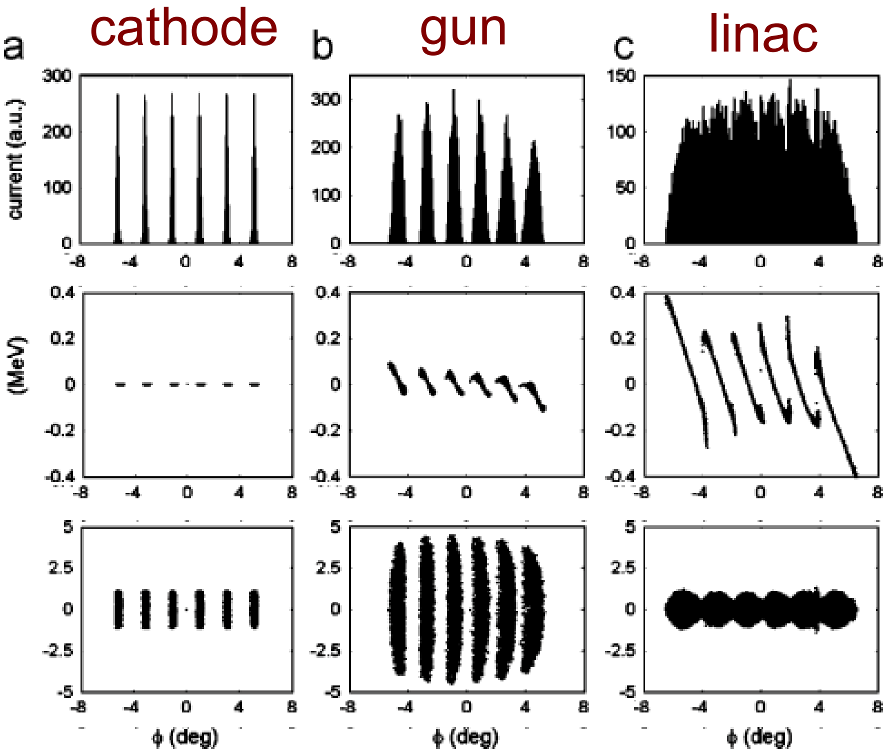


Lemery, PRSTAB 18, 081301 (2015)



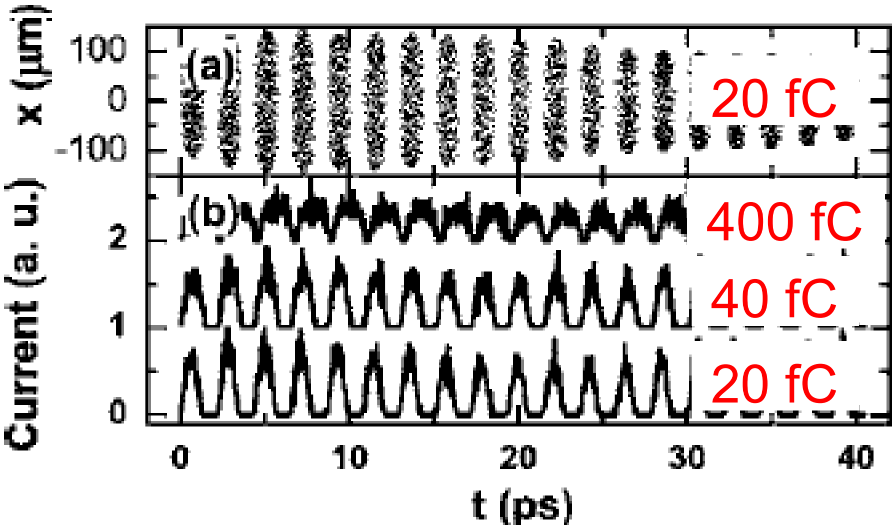
Generation of a bunch train with a laser pulses train

- challenging: initial density modulation is smeared
- *but* local correlations are imparted in the longit. phase space
  ➔ can be recovered w. proper beam line (R_{56})



~1 nC

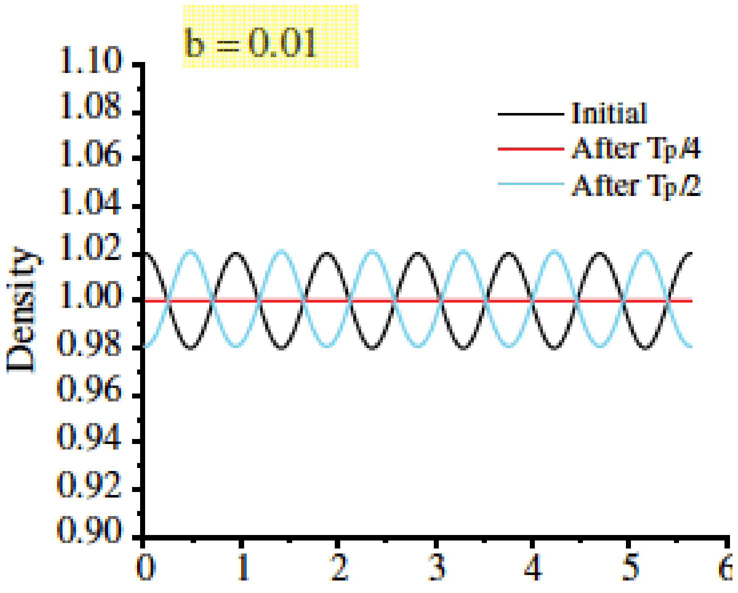
*Boscolo NIM A **577** 409 (2007)*

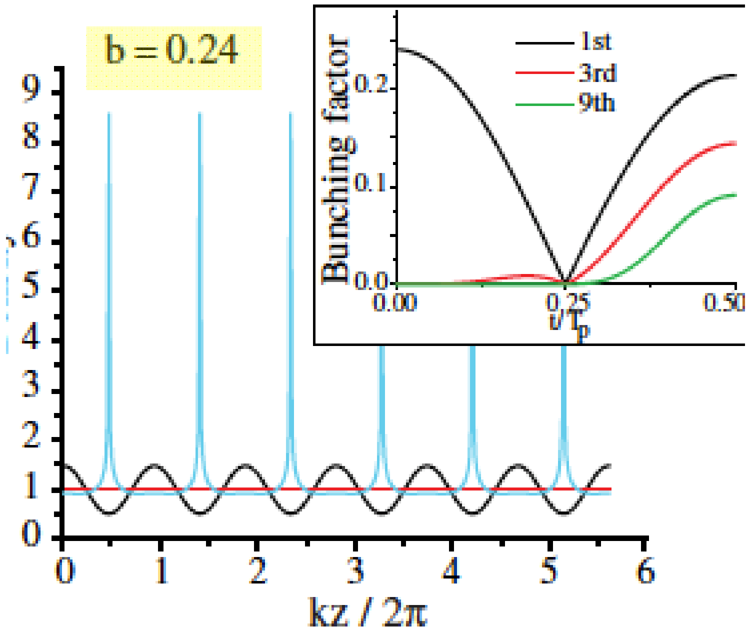


*Li, APL **92**, 01101 (2008)*

Use of velocity fields

- During the formation process, space charge plays an important role on the final shape, e.g. plasma oscillation
- space charge can also be exploited to produce bunch trains via wave-breaking

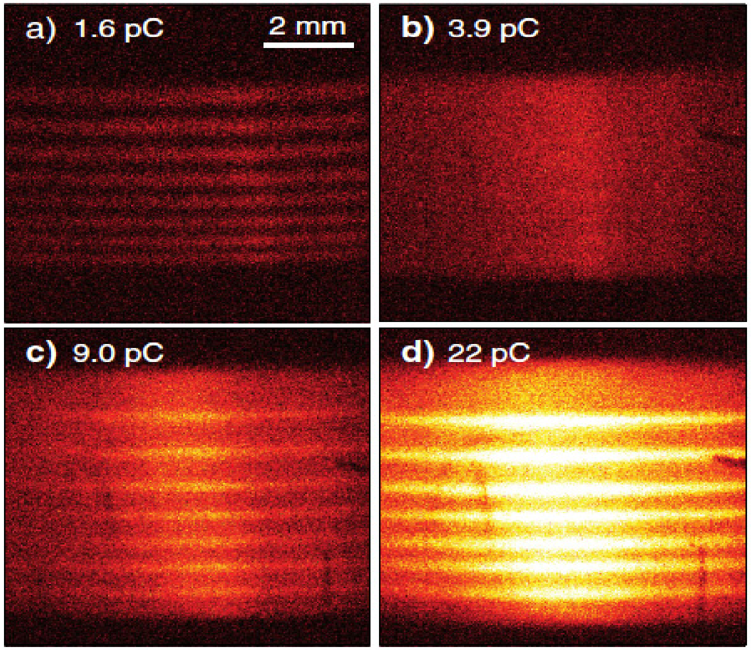


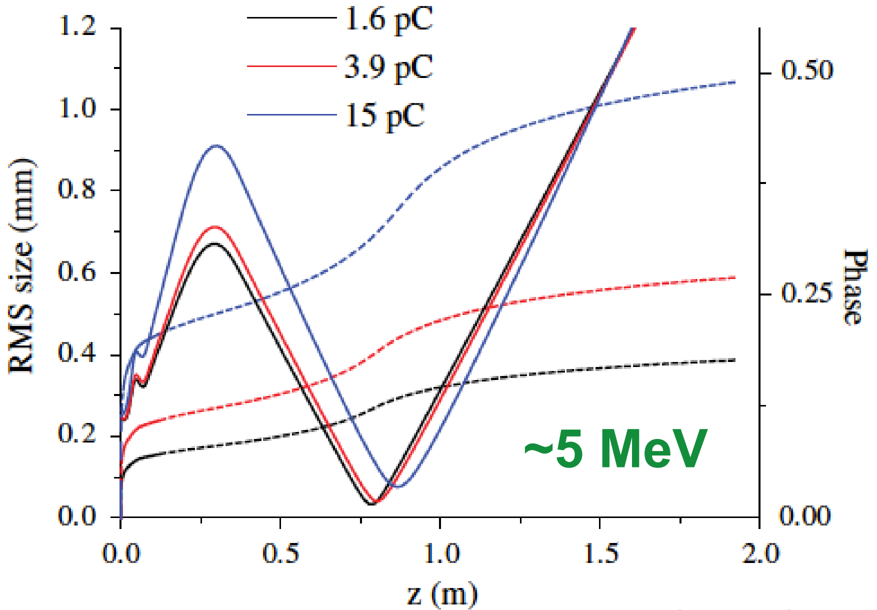


Musumeci PRL ***106*** *184801 (2011)*

Pulse train generation revisited: control of longitudinal space-charge

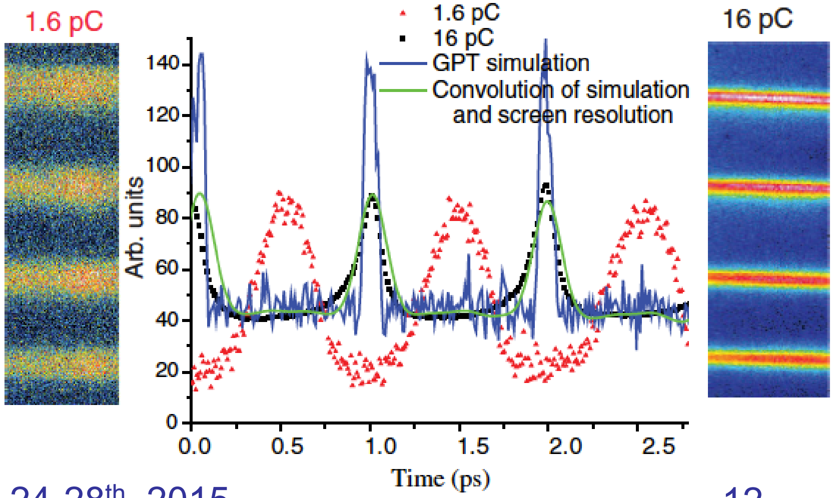
- formation of “spikes” downstream of an RF gun
- charge + spot size to control plasma-phase advance





~5 MeV

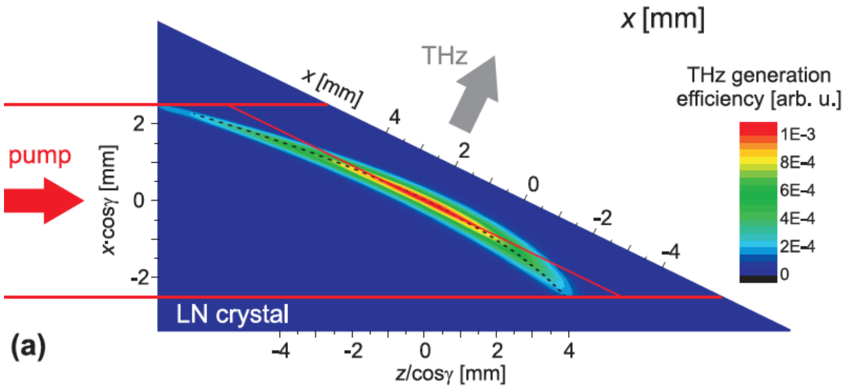
*Musumeci PRL **106** 184801 (2011)*
*Musumeci PRSTAB **16** 100701 (2013)*

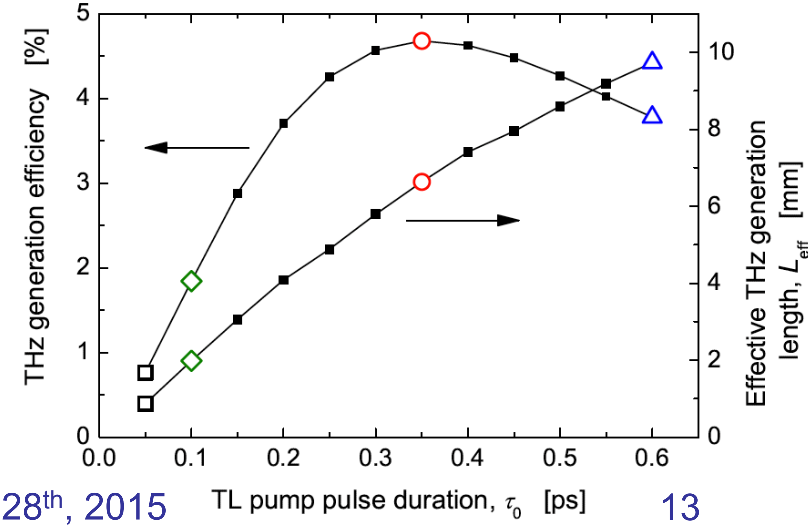


Use of external fields

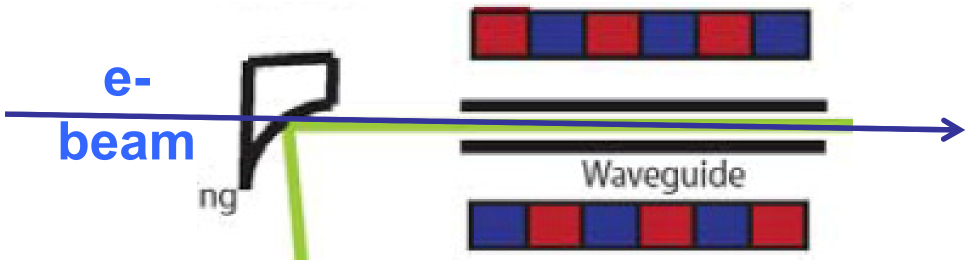
- External field for velocity bunching or energy modulation has so far been limited to RF or optical wavelength
- Emergence of efficient THz-production mechanisms has opened new opportunities ➔ better matching to the beam produced in RF injectors
- capability to manipulate this THz pulse e.g. from TEM_{00} to TEM_{01}* (to get E_z)

Fulop, OE ***18*** *12311 (2010)*





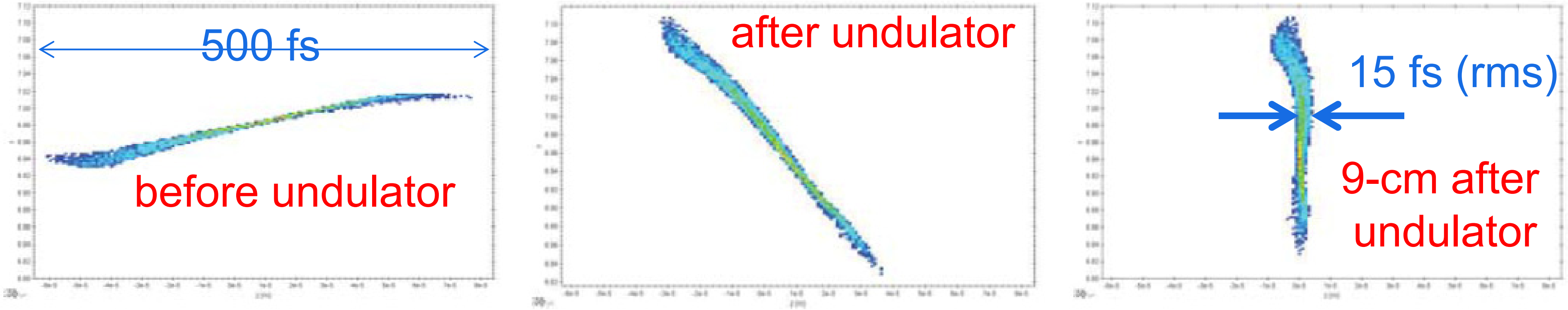
THz IFEL



- THz pulse from optical rectification of IR pulse
- Pulse co-propagated with electron bunch in a undulator + waveguide system
  ➔ natural synchronization

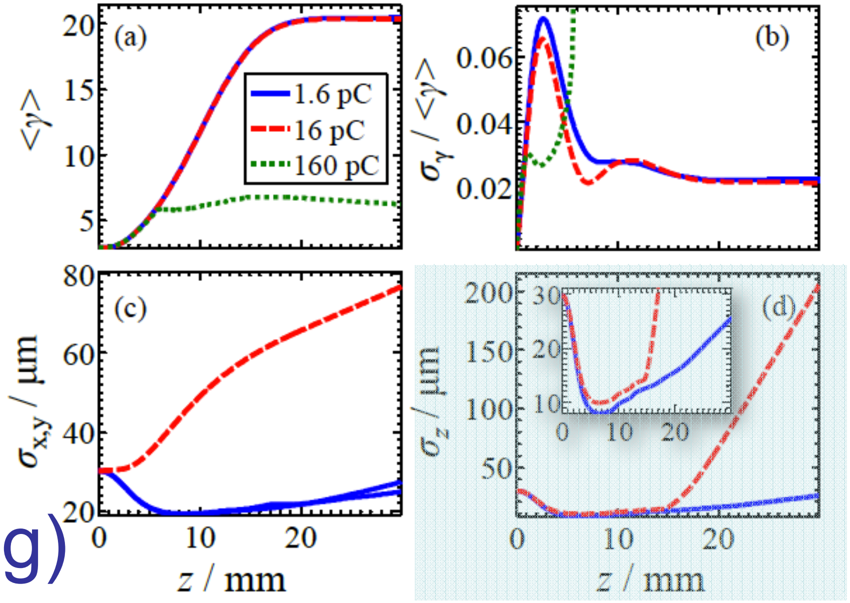
Beam Parameters	
Average γ	7
Normalized Emittance	.1 mm-mrad
Charge	1 pC
Undulator Parameters	
K	1.656
K_L	$2.2 \cdot 10^{-3}$
λ_w	1.77 cm
λ	430 μm
L_u	14.2 cm

*Moody AIP **1507 (AAC10)** 722 (2012)*

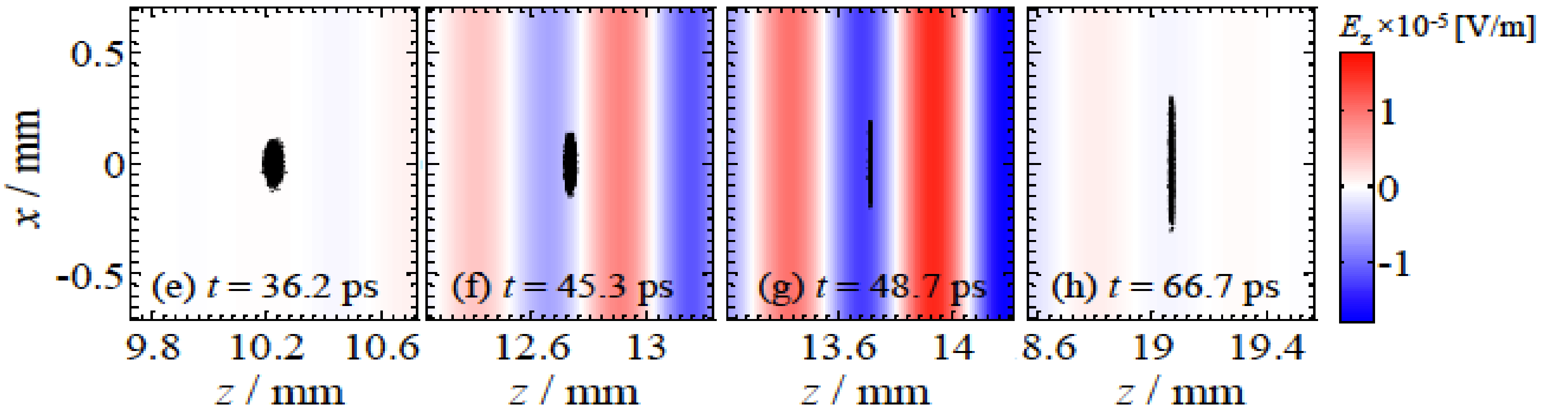


Interaction with a THz traveling pulse

- Radially-polarized THz pulse combined with dielectric-line waveguide
- net energy exchange ➔ accelerate and compress via velocity bunching)



*Wong, OE **21** 9792 (2013)*



Use of self (radiative) fields

- wakefields introduce energy change along the bunch

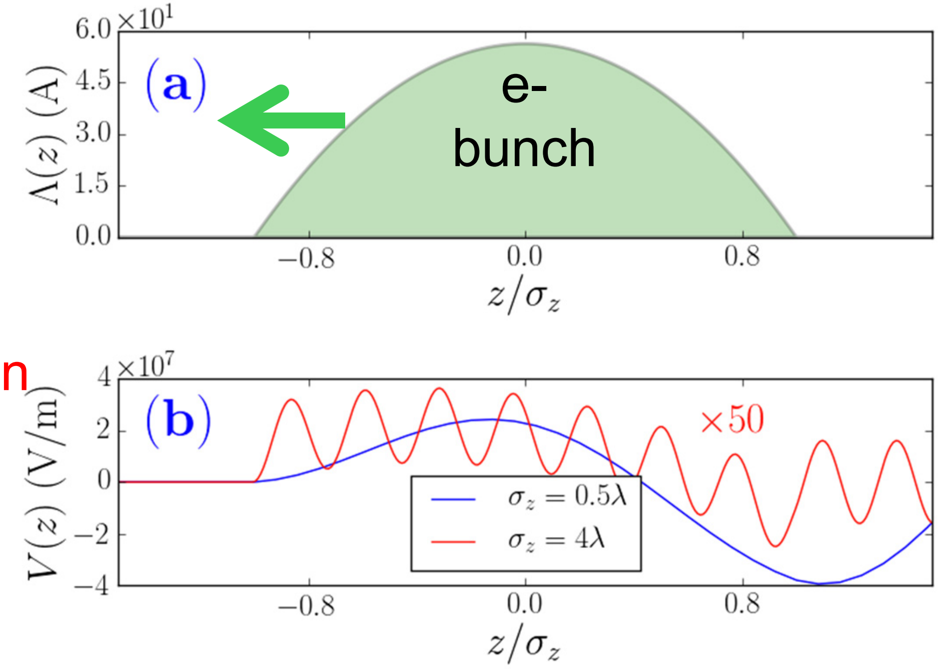
charge

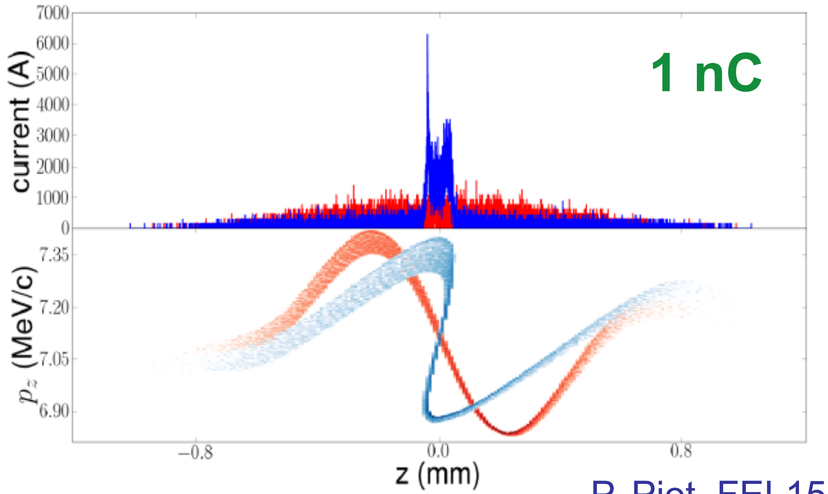
bunch distribution

$$\Delta\mathcal{E}(\zeta) = LQ\int_{-\infty}^{\zeta} G(\zeta-\zeta')\Lambda(\zeta')d\zeta',$$

interaction length

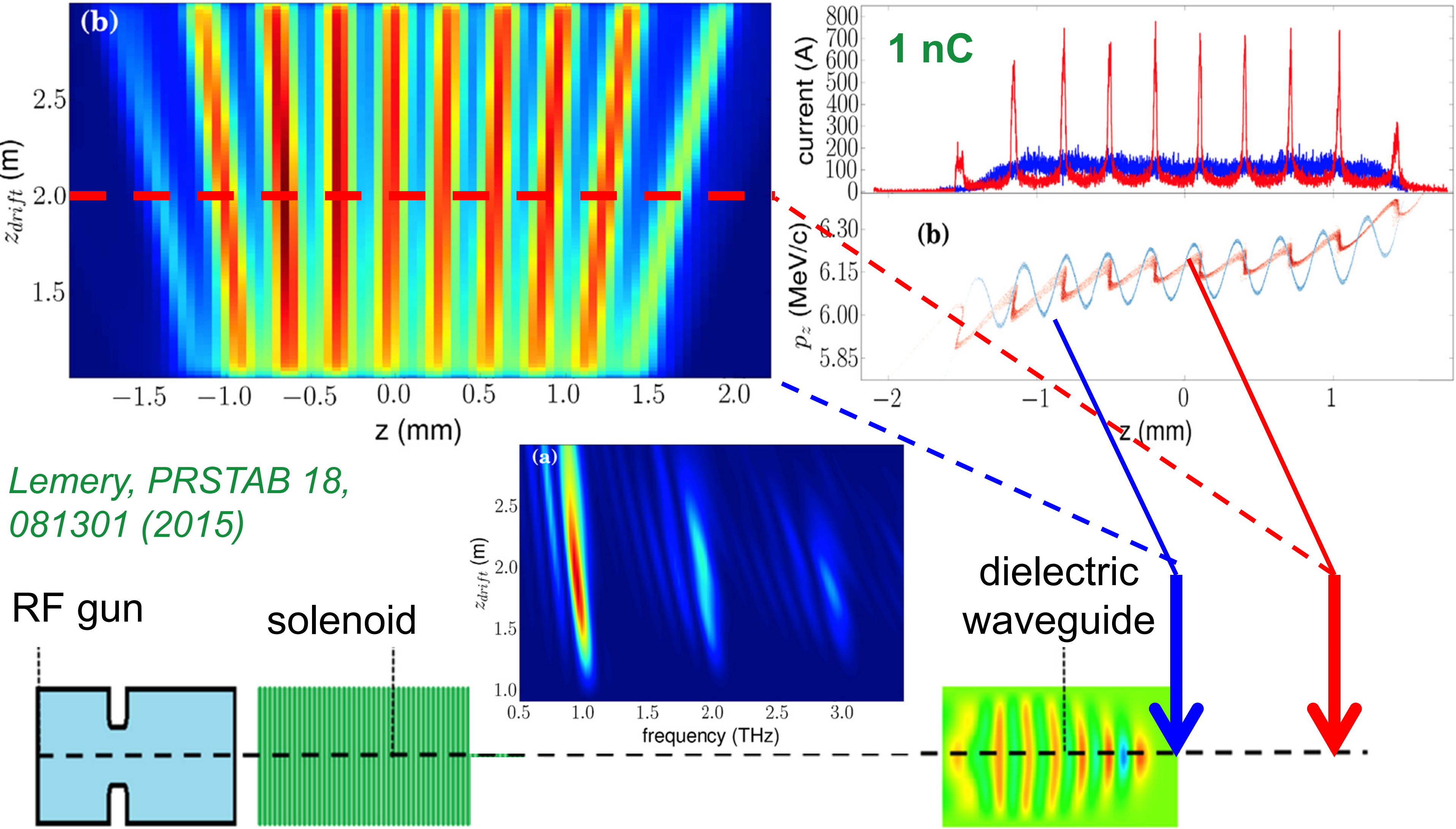
Green's function





- depending on the wakefield wavelength
  ➔ fast modulations
  ➔ chirp for compression
- conversion to density modulations

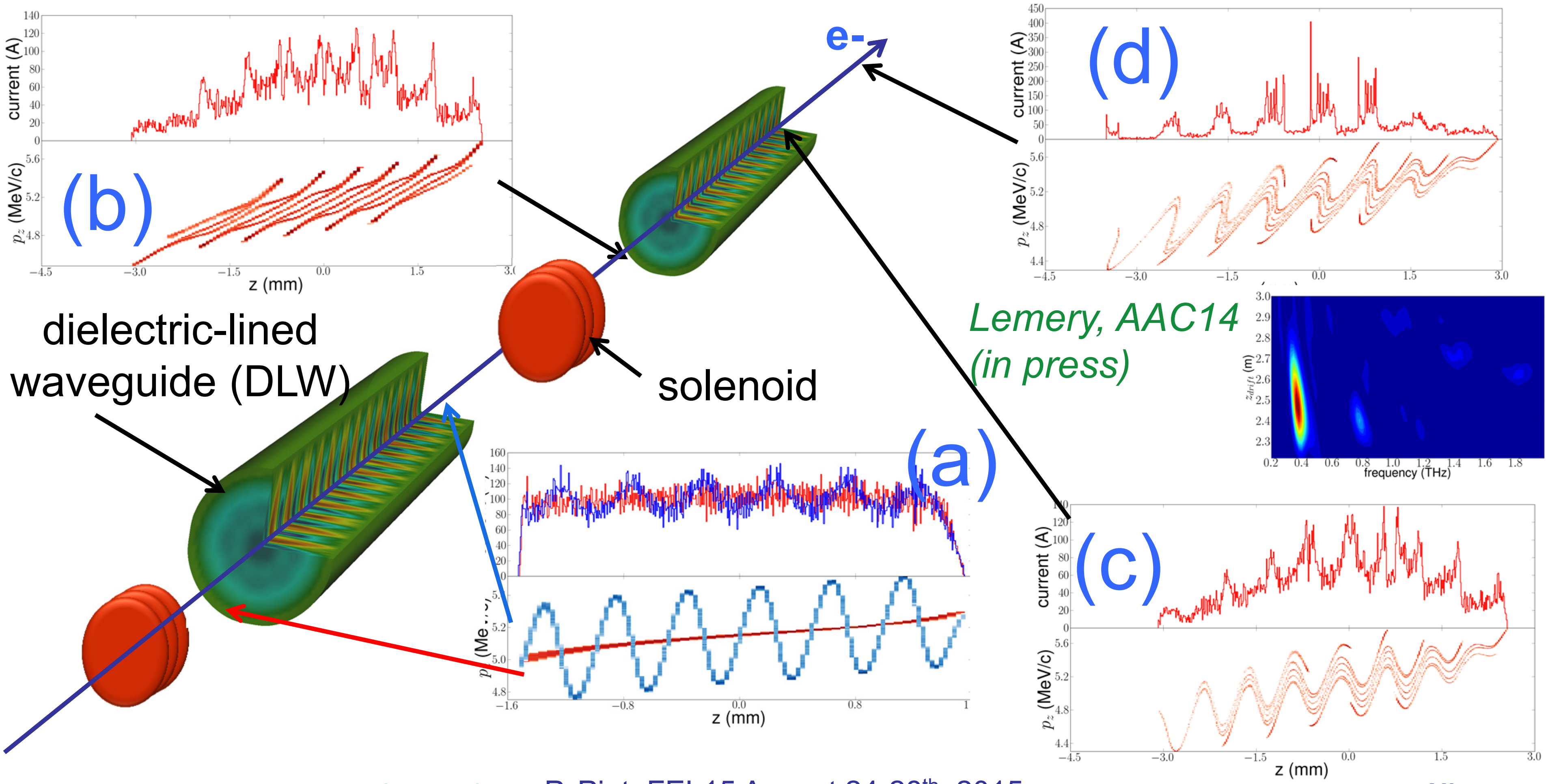
Self interaction with wakefield in a dielectric tube: train formation



Lemery, PRSTAB 18, 081301 (2015)

Self interaction with wakefield in a dielectric tube: forming short structures

- combining several DLW yield to “wakefield-assisted high-harmonic generation” WAHHG



Lemery, AAC14 (in press)

Piot, to be published (2015)

Phase space exchangers

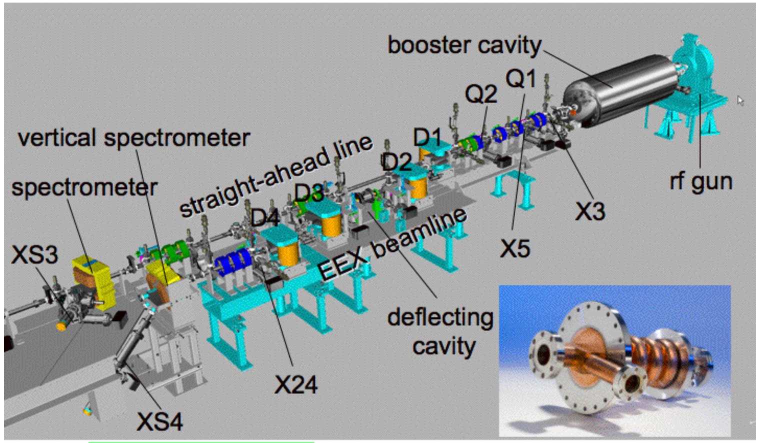
- Beam line exchanging coordinates between two degrees of freedom
  ➔ flexibility to temporal shaping
- In transverse (x_0, x_0') to longitudinal (ζ, δ) phase space exchangers we have

$$\zeta = ex_0 + fx_0'$$
$$\delta = gx_0 + hx_0'$$

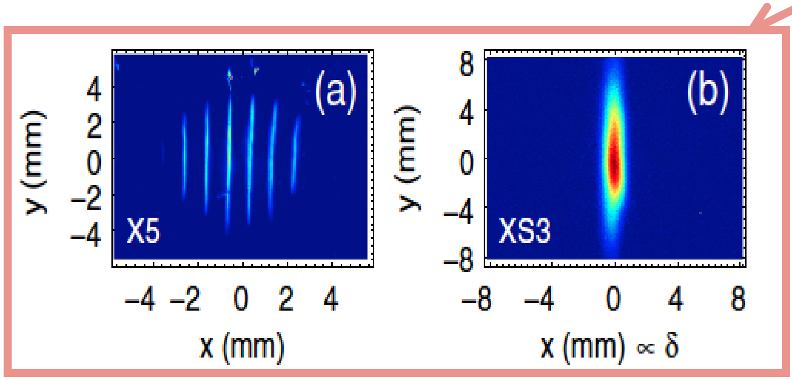
- shaping the **transverse** distribution upstream the exchanger can enable **temporal** tailoring downstream

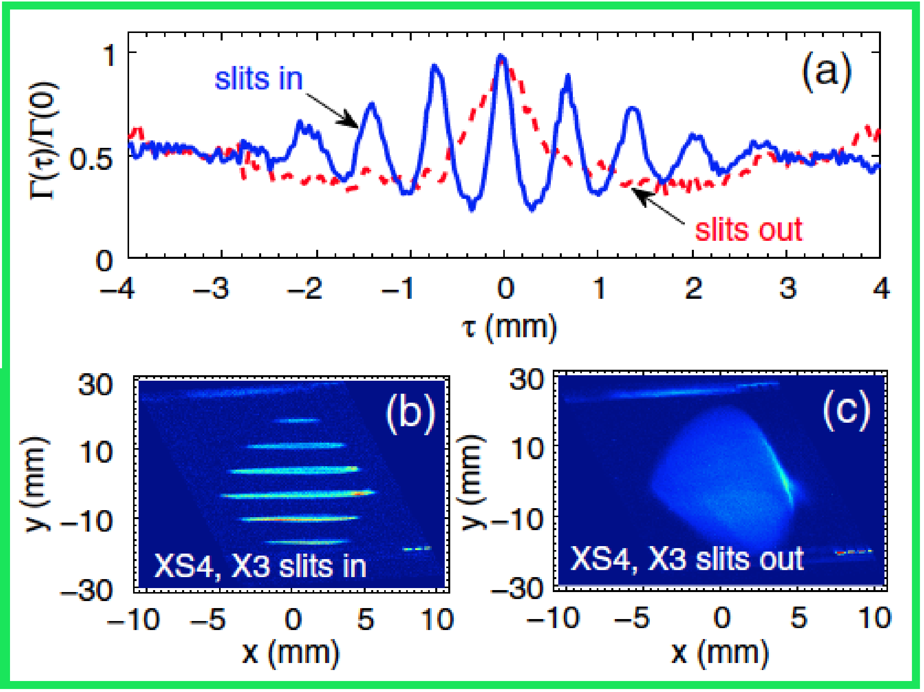
Phase-space exchanger: Bunch-train generation

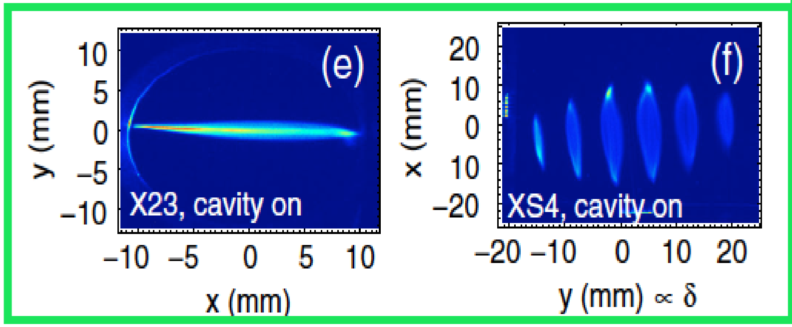
- Tailored transverse distribution via interceptive mask (slits)



Transversely-shaped beam → EEX beamline → Longitudinally-shaped beam





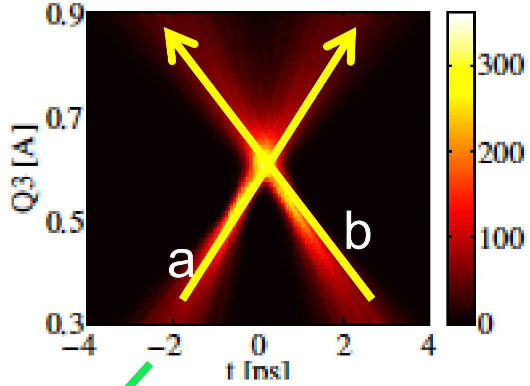


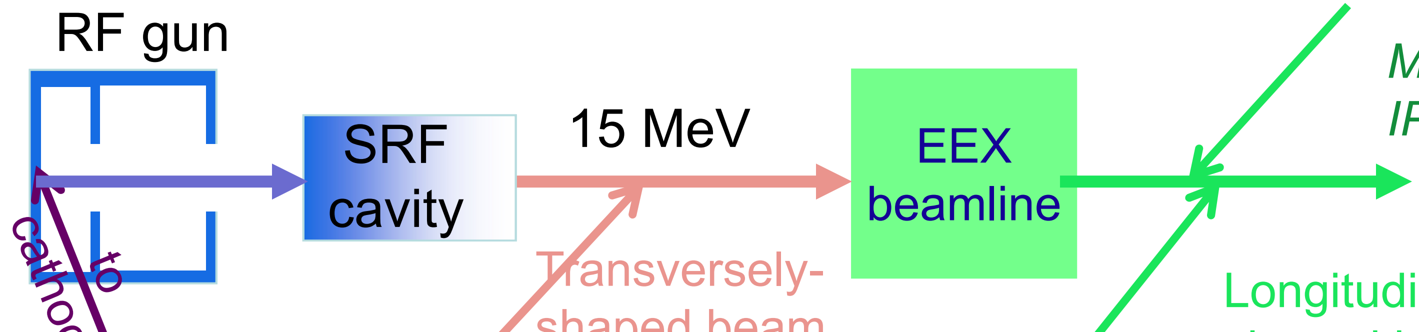
Sun, PRL ***105*** *234801 (2010)*

Phase-space exchanger: twin-pulse formations

- direct imaging of cathode surface into the longitudinal phase space
- a transversely segmented laser pulse yield a "twin" electron bunch

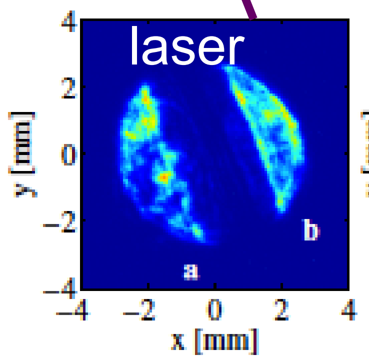
simulated electron bunch distribution

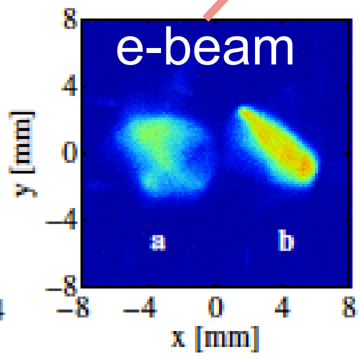


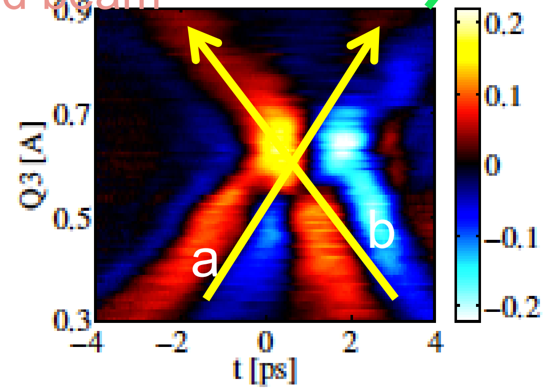


Maxwell, Proc. IPAC12 (2012)

Longitudinally-shaped beam





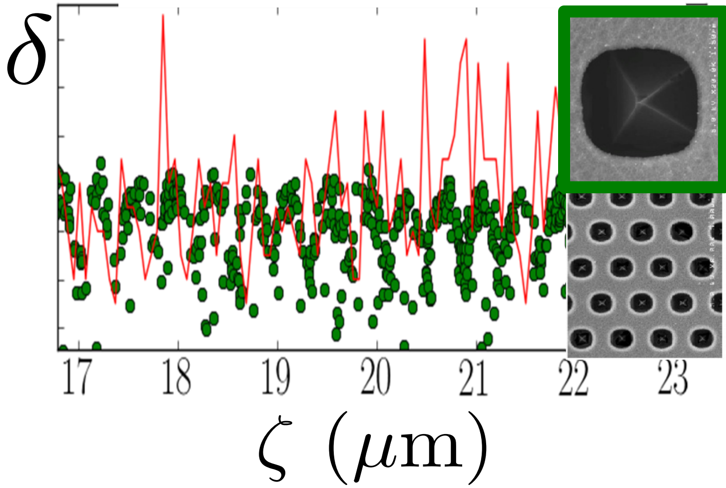


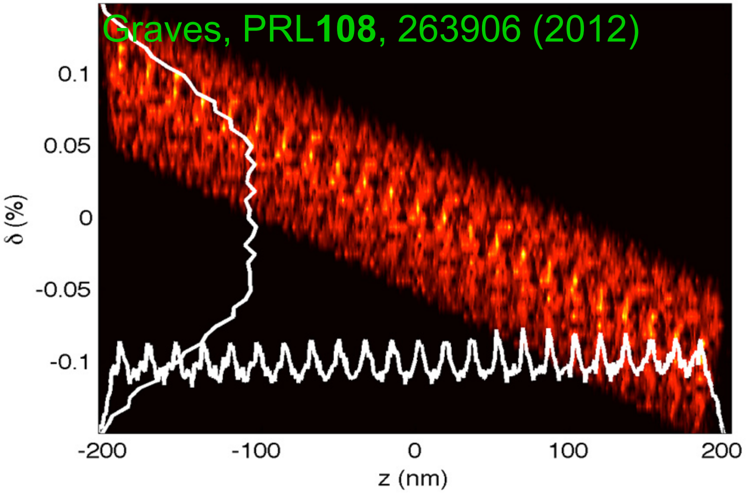
Measured Single shot electro optical imaging of coherent transition radiation

Final comment: beyond photoemission

- Most of the technique describe based on photoemission
- Field emission, e.g., optically-assisted could also be used
  - direct emission with periodicity of field-enhancing laser,
  - use of patterned field-emission cathodes combined with phase-space exchanger (an extension of previous slide to shorter λ)

WARP simulation by A. Lueangaramwong (NIU) 100 nm from cathode




Graves, PRL**108**, 263906 (2012)

Summary

- Over the recent years new applications of low-energy relativistic electron beams (UED, external injection for LWFA,…)
  ➔ development of alternative bunching and current shaping techniques
- Vast range of available techniques are providing new opportunities for light-source designers:
  - mitigation/control of collective effects,
  - new FEL-driver accelerators,
  - compact coherent light sources,
  - …

Acknowledgements

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- **Thank you for your attention**