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... for a brighter future

Laser pulse shaping for photoinjector applications

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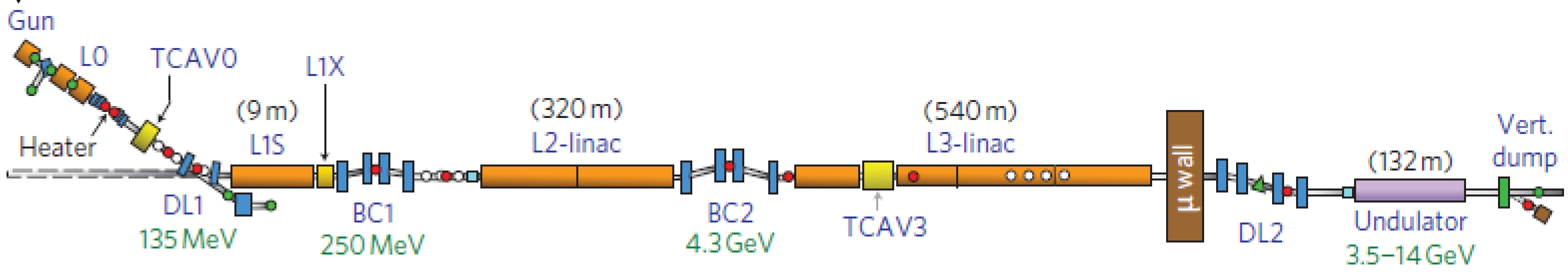
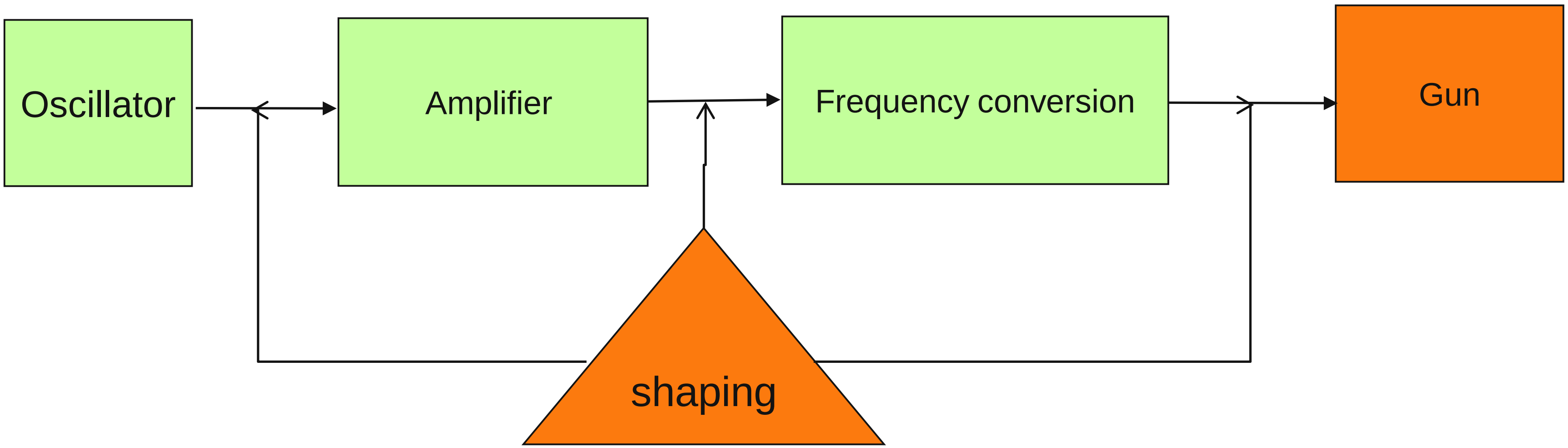
An XFEL starts with a laser, well, normally …

Drive laser, LCLS



An XFEL start with a laser, well, normally …

A typical drive laser



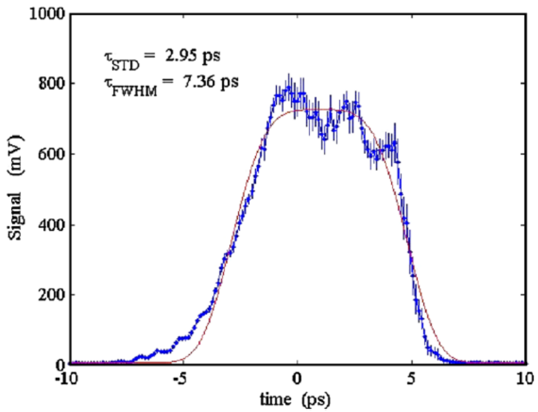
Content

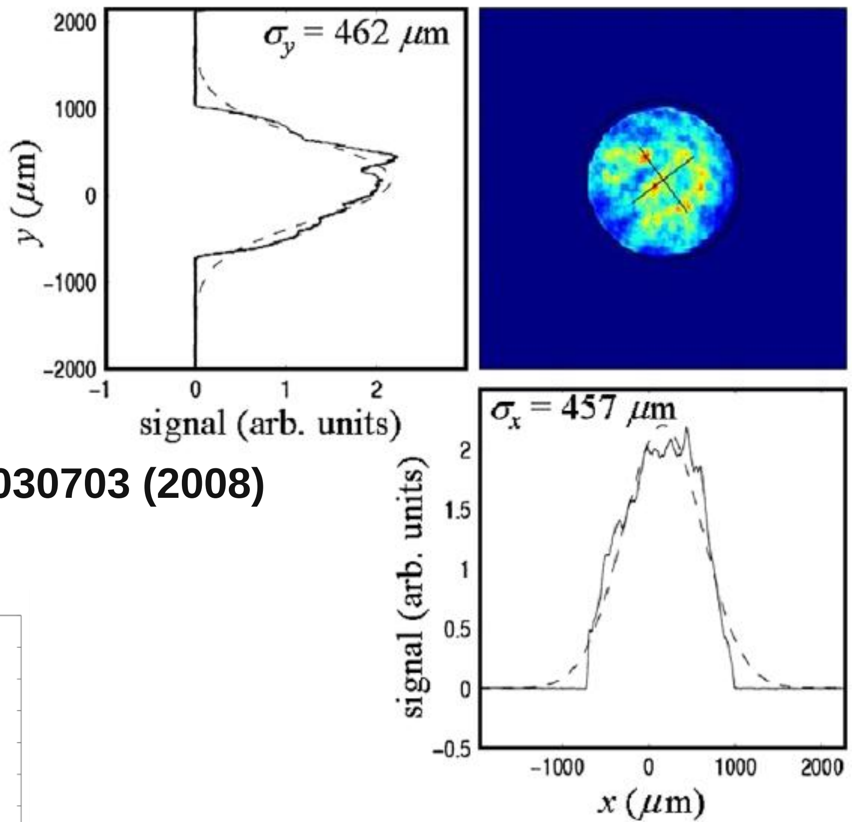
- Implications of the LCLS success
- The case of pulse shaping
  - Minimize emittance growth due to space charge force
  - Uniform ellipsoidal beam is the holy grail
- Review of pulse shaping techniques and examples

  If your work is not cited, it is my ignorance, not bias.
  - Cylindrical shaping
  - Ellipsoidal shaping
- Ellipsoidal shaping at APS
  - Scheme and beam simulation
  - A proof of principle experiment
- Adaptive control
- Conclusion

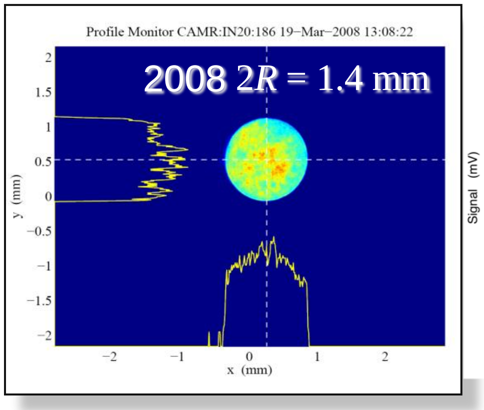
Implication of the LCLS success

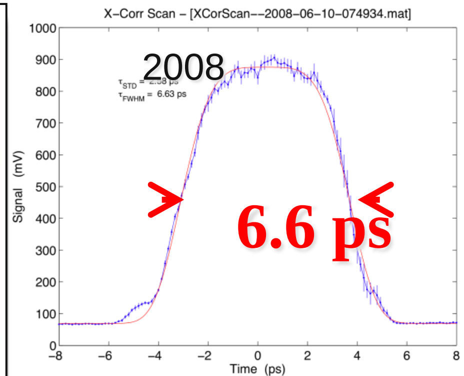
- LCLS drive laser pulse shape





Phys. Rev. ST Accel. Beams **11, 030703 (2008)**





White, Bifringence crystal, ICFA FLS 2010, Stanford

Implication of the LCLS success

- Performance comparison

Table 1 | Design and typical measured parameters for both hard (8.3 keV) and soft (0.8–2.0 keV) X-rays. The 'design' and 'hard' values are shown only at 8.3 keV. Stability levels are measured over a few minutes.

Parameter	Design	Hard	Soft	Unit
Electrons				
Charge per bunch	1	0.25	0.25	nC
Single bunch repetition rate	120	30	30	Hz
Final linac e^- energy	13.6	13.6	3.5–6.7	GeV
Slice† emittance (injected)	1.2	0.4	0.4	μm
Final projected† emittance	1.5	0.5–1.2	0.5–1.6	μm
Final peak current	3.4	2.5–3.5	0.5–3.5	kA
Timing stability (r.m.s.)	120	50	50	fs
Peak current stability (r.m.s.)	12	8–12	5–10	%
X-rays				
FEL gain length	4.4	3.5	~1.5	m
Radiation wavelength	1.5	1.5	6–22	Å
Photons per pulse	2.0	1.0–2.3	10–20	10^{12}
Energy in X-ray pulse	1.5	1.5–3.0	1–2.5	mJ
Peak X-ray power	10	15–40	3–35	GW
Pulse length (FWHM)	200	70–100	70–500	fs
Bandwidth (FWHM)	0.1	0.2–0.5	0.2–1.0	%
Peak brightness (estimated)	8	20	0.3	10^{32} *
Wavelength stability (r.m.s.)	0.2	0.1	0.2	%
Power stability (r.m.s.)	20	5–12	3–10	%

*Brightness is photons per phase space volume, or photons s^{-1} mm^{-2} $mrad^{-2}$ per 0.1% spectral bandwidth.
†'Slice' refers to femtosecond-scale time slices and 'projected' to the full time-projected (that is, integrated) emittance of the bunch.

P. Emma et al, NATURE PHOTONICS, 2010; Y. Ding, PRL, 2009

Implication of the LCLS success

- Observation
  - LCLS proved the robustness of the FEL theory
  - LCLS benefited from low charge, high acceleration gradient operation
- Will a better beam (I nC, <<1 mm mrad) help?
  - More photons per pulse: some users just want more photons!
  - Shorter undulator lines/lower beam energy
- Critical for low-gradient injectors in both cost and performance
  - DC and perhaps SC gun
  - For Hi-rep rate XFEL, XFELO, and ERL

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  - Uniform ellipsoidal beam is the most desirable
- Review of pulse shaping techniques and examples
  - Cylindrical pulse
  - Ellipsoidal pulse
- Ellipsoidal pulse at APS
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- Adaptive control and candidates
- Conclusion

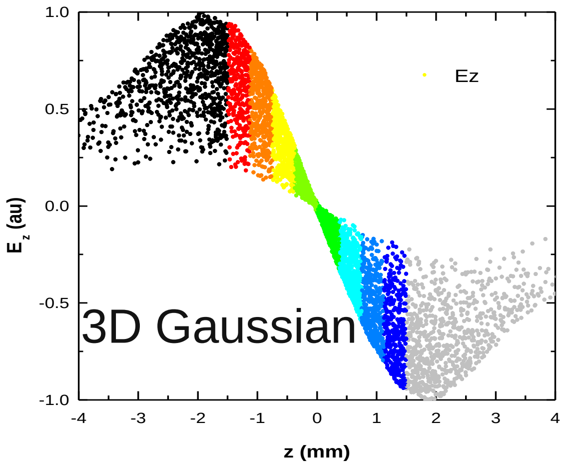
The case of pulse shaping

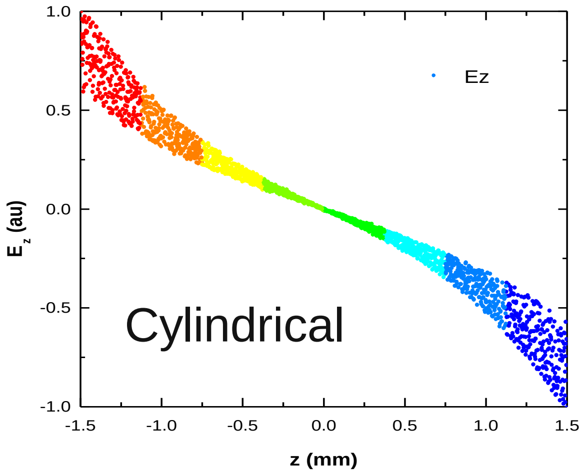
- Most of emittance growth is due the space charge, when beam energy is low in the inject however
  - Emittance growth due to **linear** space charge force can be compensated
    - *Carlsten, NIMA 285, 313, (1989)*
    - *Serafini and Rosenzweig, PRE 55, 7565 (1997)*
  - Homogeneous ellipsoidal beam is the holy grail
    - *Uniform electron density distribution in a ellipsoid*
    - *Has linear space charge force (M. Reiser, Theory and Design of Charged Particle Beams, Wiley, New York. 1994)*

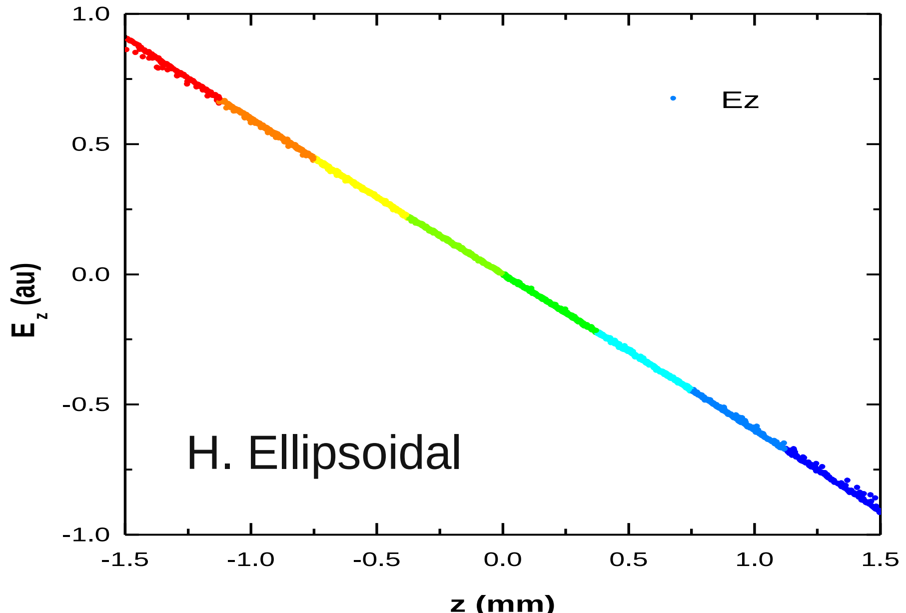
$$\left(\frac{x}{A}\right)^2 + \left(\frac{y}{B}\right)^2 + \left(\frac{z}{C}\right)^2 = 1.$$

$$\vec{E} = (E_x, E_y, E_z) = \frac{\rho_0}{\varepsilon_0}(M_x x, M_y y, M_z z), \quad \begin{cases} M_z = \dfrac{1+\Gamma}{\Gamma^3}(\Gamma - \arctan\Gamma), \qquad M_x = M_y = \frac{1}{2}(1 - M_z) \\ \Gamma \equiv \sqrt{A^2/C^2 - 1} \end{cases}$$

Space charge force distribution: three geometries







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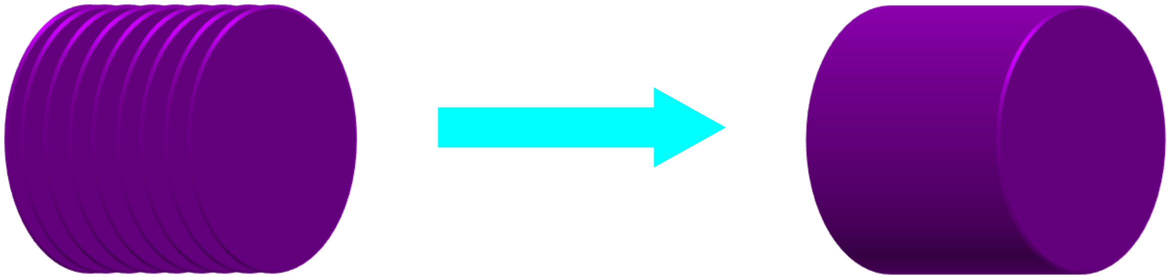
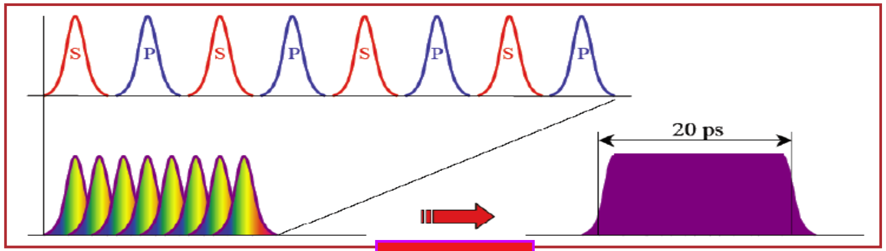
Cylindrical: pulse stacking

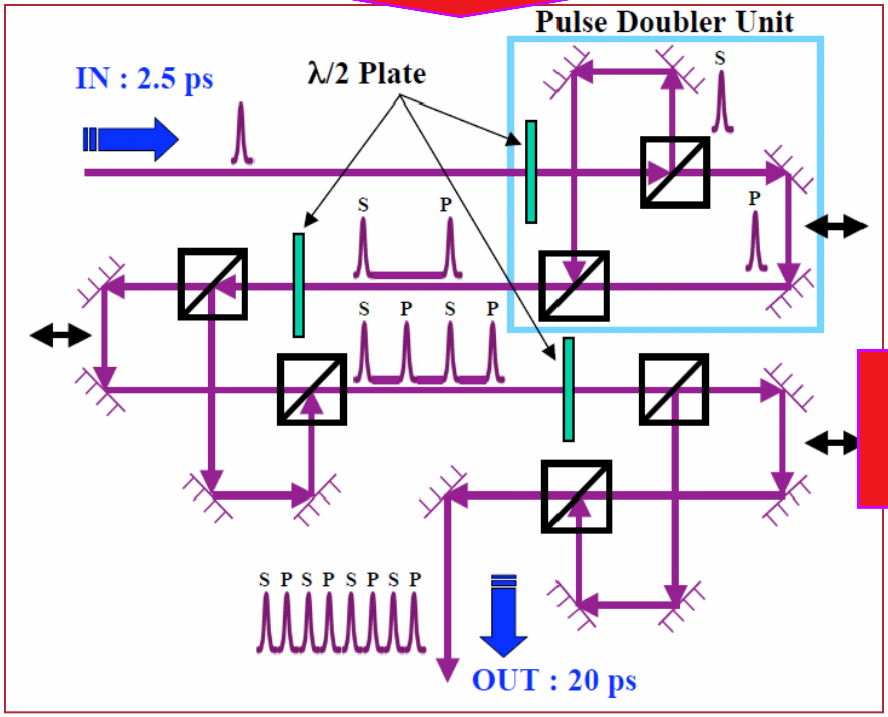


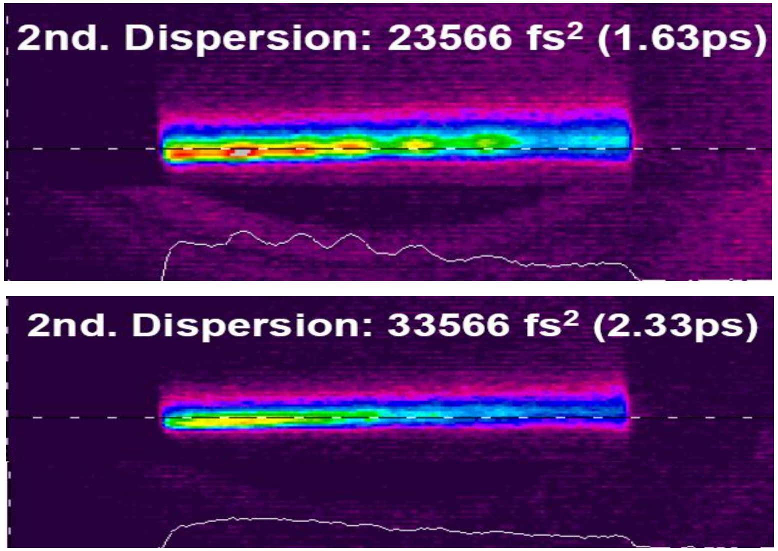
- Separate control of longitudinal and transverse profiles
- Transverse: mostly by clipping a Gaussian
- Excellent for longitudinally flat topped pulse
  - Interferometer setup
    - *C. Sider, Appl. Opt.* ***37****, 5302 (1998).*
    - *Tomizawa, Quantum Electronics 37, 697 (2007)*
  - Bi-fringence crystals (BFC)
    - *I.V. Bazarov, D.G. Ouzounov, B.M. Dunham, Phys. Rev. ST AB 11, 040702 (2008).*
    - *A. K. Sharma, et al., Phys. Rev. ST Accel. Beams 12, 033501 (2009).*
    - *Zhang, WEPB03; Rimjaem, WEPB09; Sannibale, WEPB36;*
    - *LCLS, FLASH, SPARC, ANL, PSI, et c*
    - *Beam emittance results varies……*

Cylindrical: pulse stacking with interferometer, SPRING 8

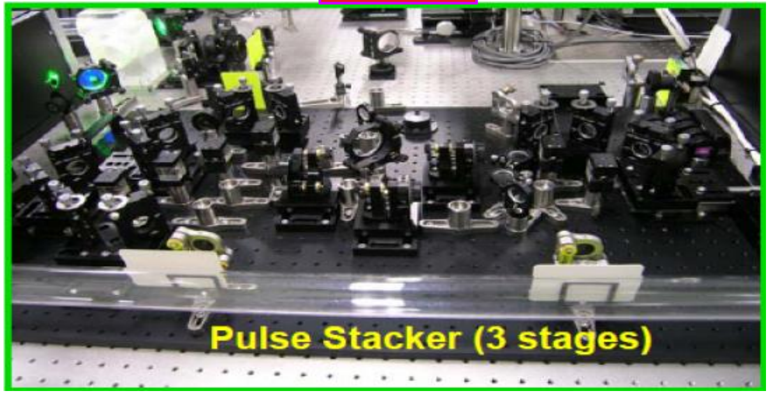


Scheme





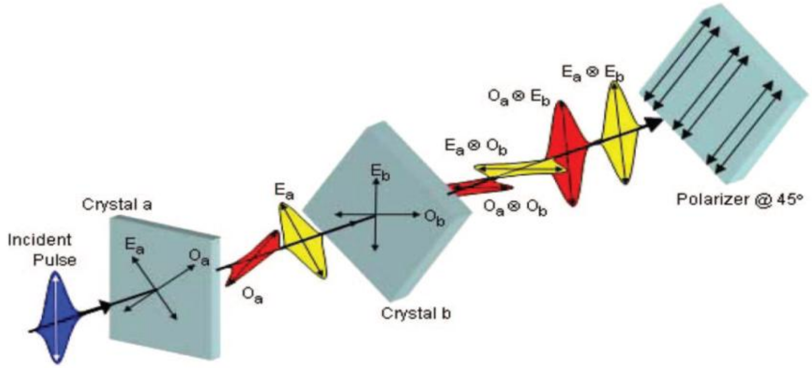
Setup



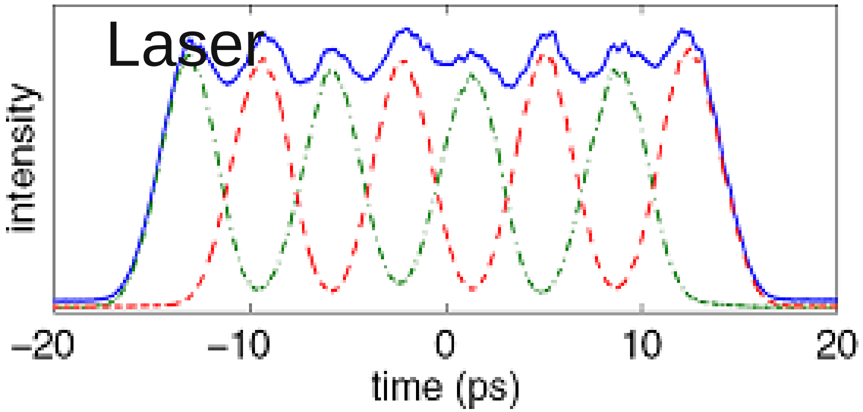
Tomizawa, Quantum Electronics 37, 697 (2007)

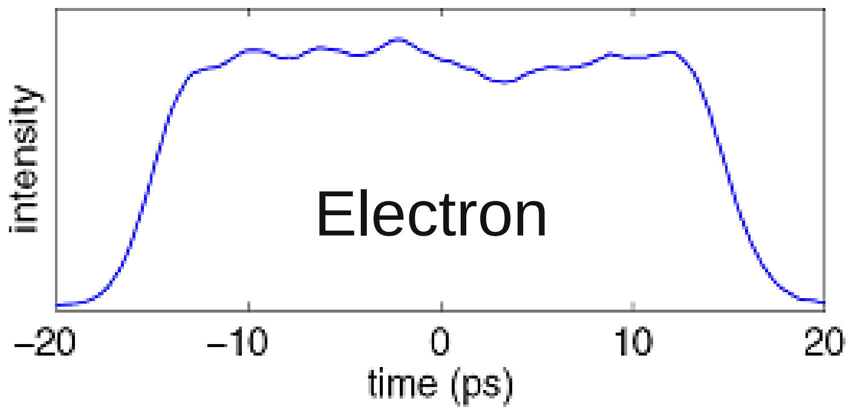
Cylindrical: pulse stacking with an BFC, Cornell

- Excellent longitudinal flat topped pulse and beam
  - *Old idea: H. E. Bates et al., Appl. Opt. 18, 947 (1979)*
  - *C. S. Zhou, et al., Applied Optics 46, 1 - 5 (2007).*
  - *I.V. Bazarov et al, Phys. Rev. ST AB 11, 040702 (2008).*

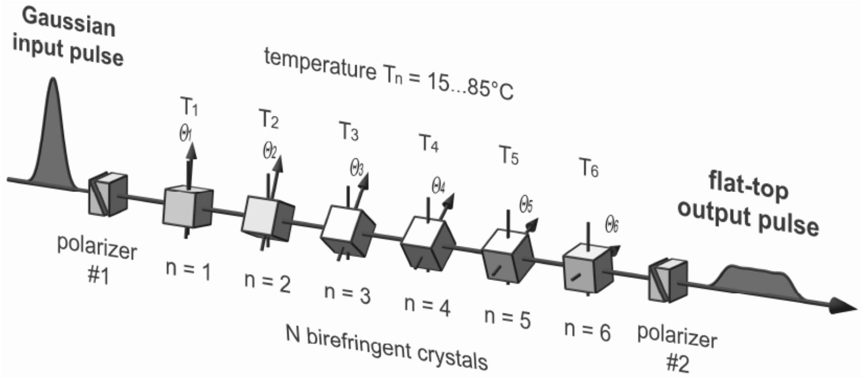


$$\Delta t = x\left(\frac{1}{V_o} - \frac{1}{V_e}\right),$$

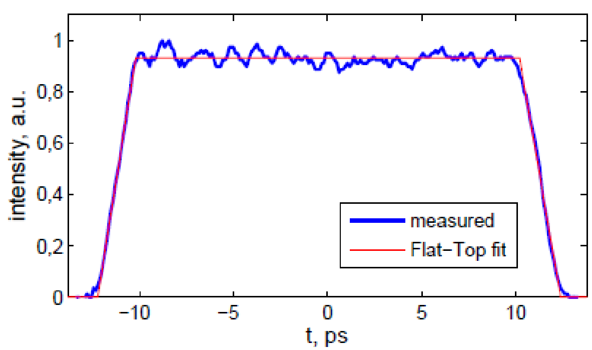


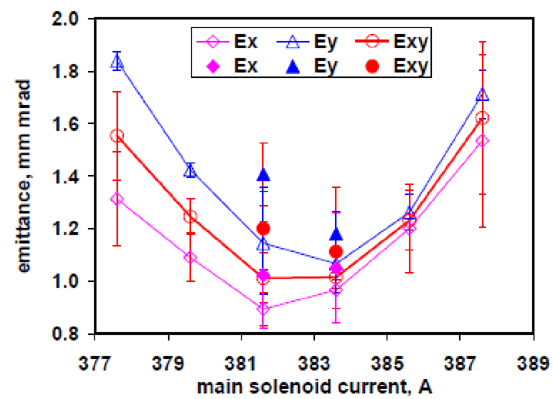


Cylindrical: pulse stacking with an Solc fan filter, PITZ



- Continuous crystal angle, temperature stabilized, polarized, before amplification
- Excellent longitudinal flat topped pulse with 10-13 crystals; Transverse: clipped Gaussian, described as “round and flat”
  - *I. Solc, "Birefringent chain filters," J. Opt. Soc. Am.* ***55, 621-625 (1965).***
  - *I. Will, Opt Express, 16, 14922 (2008).*
  - *S. Rimjaem et al, FEL 2009*





Cylindrical: phase engineering

- Separate control of longitudinal and transverse
- A temporally square pulse (phase tailoring) + transverse top hat shaping (mostly clipping)
- Tried and being tried by many (LCLS, SPARC, PSI(WEPB14), FERMI), etc

Bi Gaussian → Temporal square Transverse Gaussian → Beer can

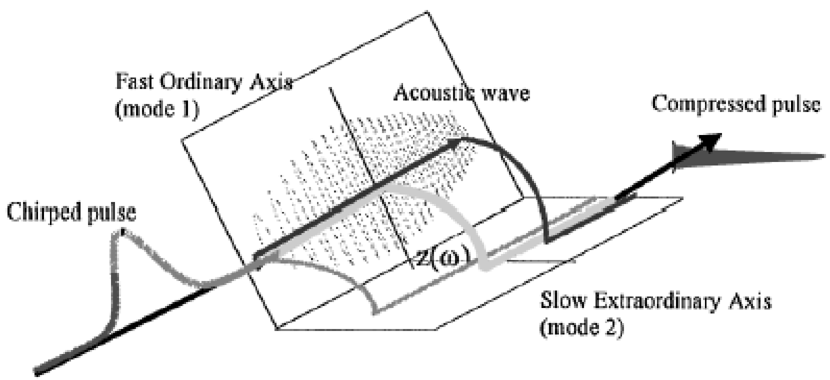
Phase engineering via SLM, DAZZLER, spectrum mask, etc

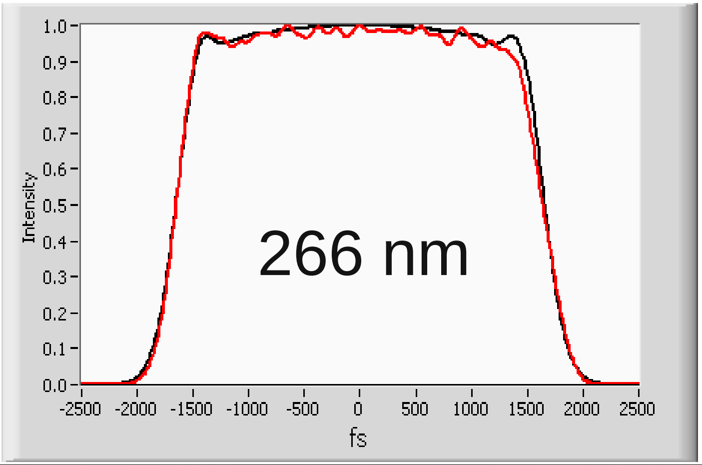
Transverse via aspherical lens, clipping, deformable mirrors, etc

Zhang et al., Opt Express 11, 1942 (2003).
Hoffnagle et al, Apll. Opt. 39, 6488 (2000).

Cylindrical: a phase engineering device

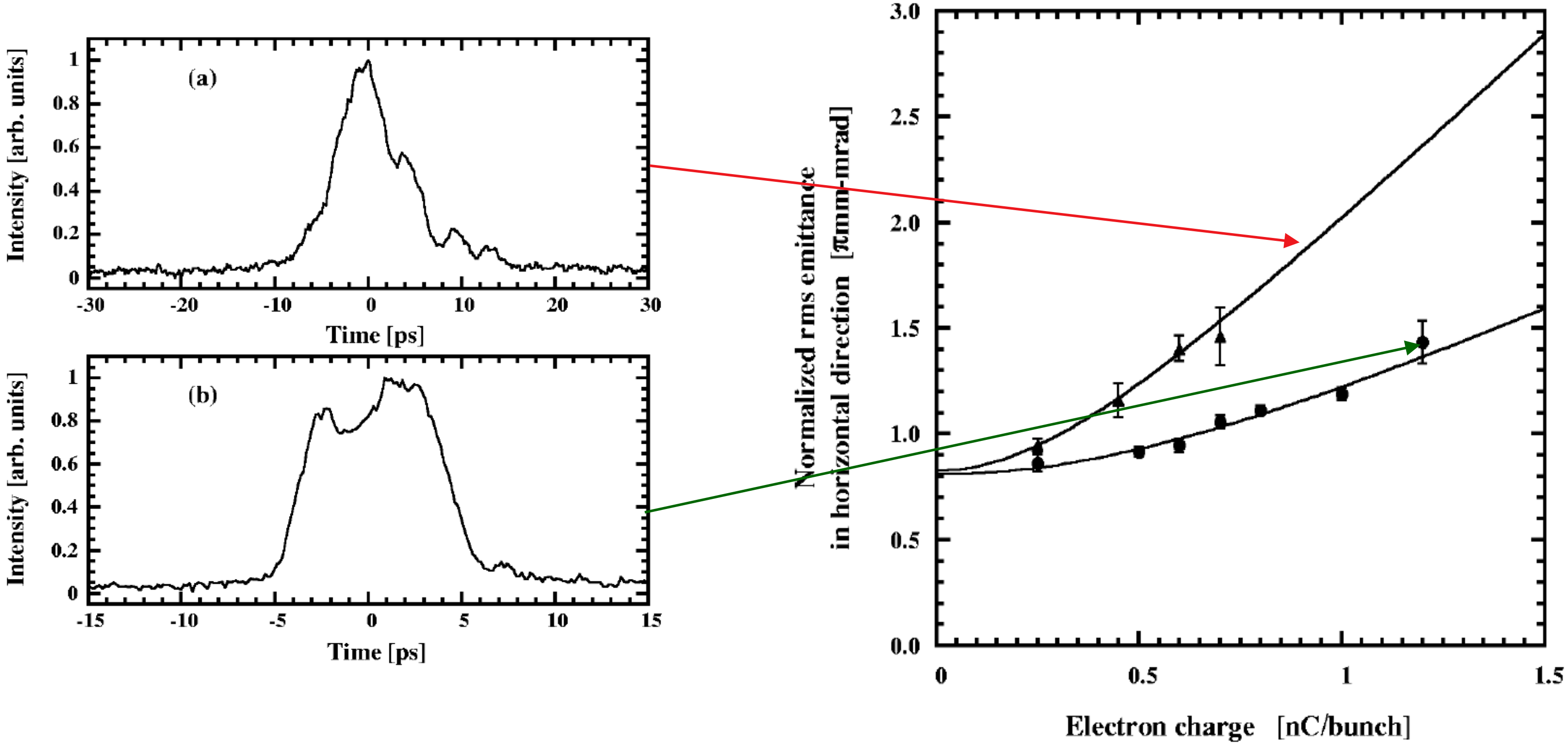
- A device widely used in laser and optical research
  - F. Verluise, V. Laude, Z. Cheng, Ch. Spielmann, and P. Tournois, Opt. Lett. 25, 575 (2000).
- DAZZLER and similar phase modulation device have been applied to photoinjector related laser pulse shaping for cylindrical pulse
  - H. Tomizawa et. al., Nucl. Instrum. Methods A **557**, 117 (2006).
  - J. Yang, et al., J. Appl. Phys. **92**, 1608 (2002).
  - S. Cialdi, et al., Appl. Opt. **46**, 4959 (2007). UV version available
- UV version available
  - http://fastlite2.siteo.com/en/page15.xml
  - T. Oksenhendler, CLEO 07





Cylindrical: Phase engineering, Sumitomo Heavy Ind

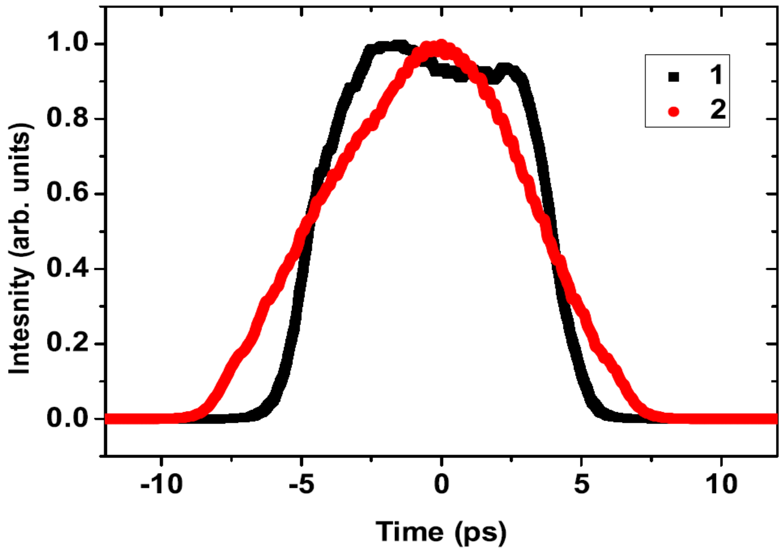
- SLM for pulse shaping
- Significantly improved emittance
- 14 MeV, 1 nC, 9 ps pulse



Yang et al., J. Appl. Phys 92, 1608 (2002)

Cylindrical: phase engineering, SPARC

A. CIANCHI *et al.*, Phys. Rev. ST Accel. Beams **11, 032801 (2008)**



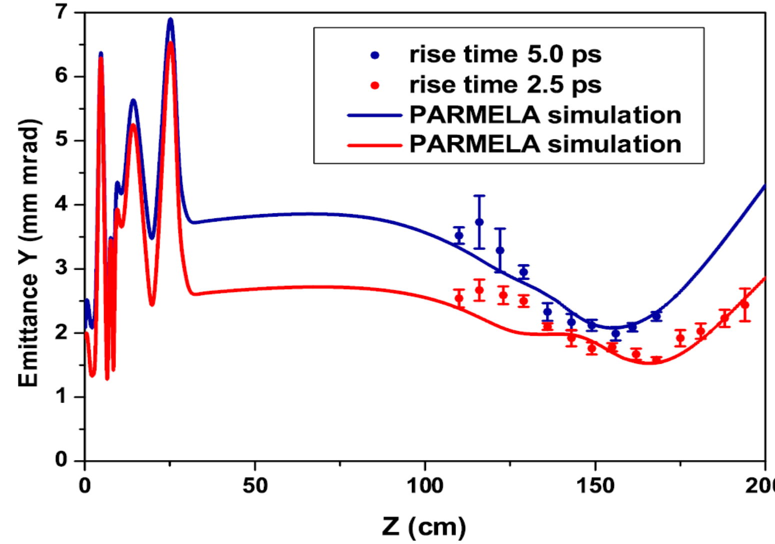


TABLE IV. Parameters of the beam corresponding to the best brightness result.

Parameter	Value
Energy	5.65 MeV
Charge	0.83 nC
Laser spot size	360 μm
Laser pulse length	8.9 ps FWHM
Phase ($\varphi - \varphi_{\max}$)	8^0

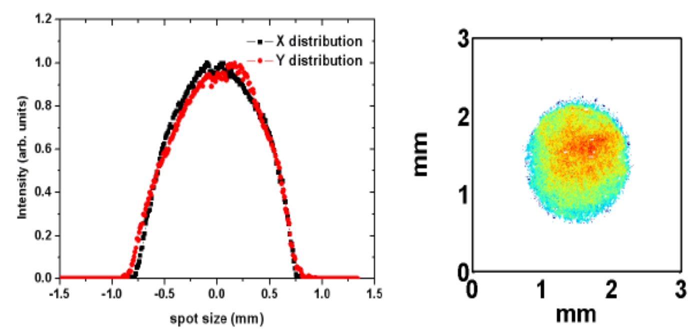
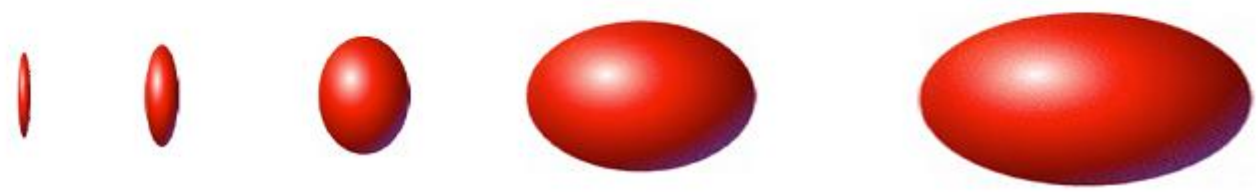


FIG. 10. (Color) Left: Typical projected transverse profile of the laser spot on the virtual cathode. Right: 2D laser spot profile.

Cylindrical: summary

- Separate longitudinal and transverse control
- Effectiveness demonstrated world wide
- Maturing and in production mode, especially using bifringence crystal stacker, which can be implemented right before delivery to the gun.

Ellipsoidal: blow-out



- L. Serafini, AIP Conf. Proc. **413**, 321 (1997).
- O. J. Luiten et al, Phys. Rev. Lett. **93**, 094802 (2004).
- B. J. Claessens, Phys. Rev. Lett. **95**, 164801 (2005).
- J. B. Rosenzweig et al., Nucl. Instrum. Methods A **557**, 87 (2006).
- P. Musumeci, et al., Phys. Rev. Lett. **100**, 244801 (2008).
- Measurement at PITZ, O'Shea et al, 2009 ICFA

- Pro
  - Easy to implement: Need a short pulse (100 fs) with initial parabolic transverse distribution, no longitudinal shaping needed
- Con
  - Highly non-linear and only work at low charge <20 pC

Ellipsoidal: blow-out

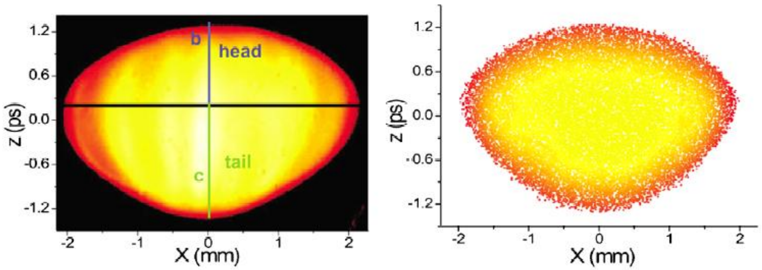
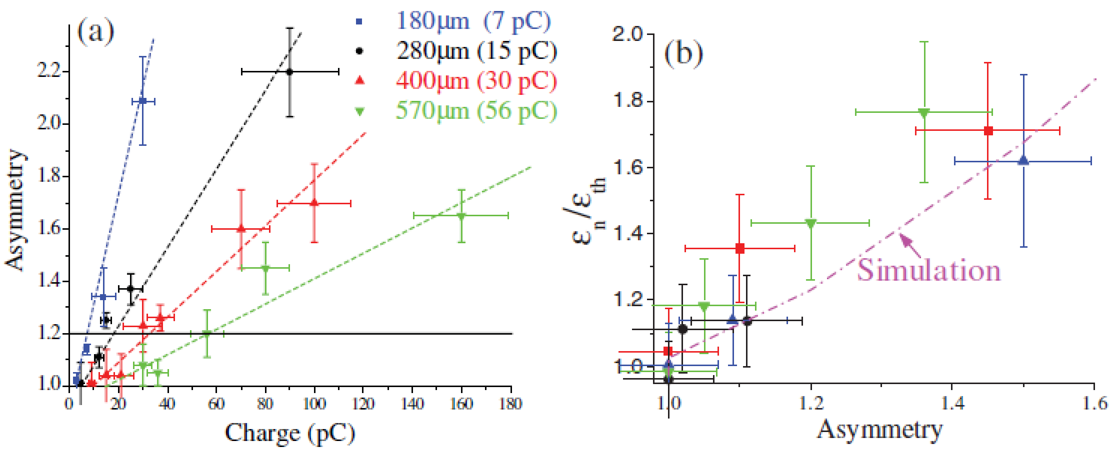
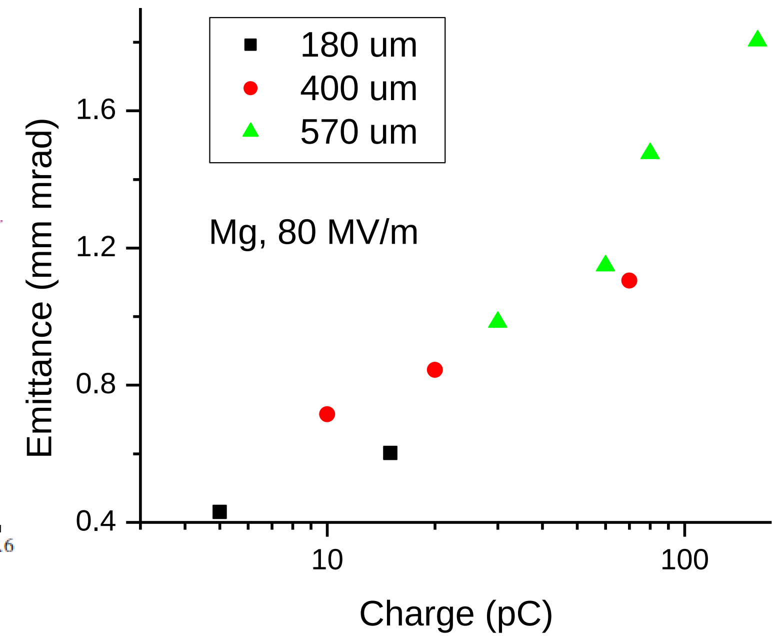


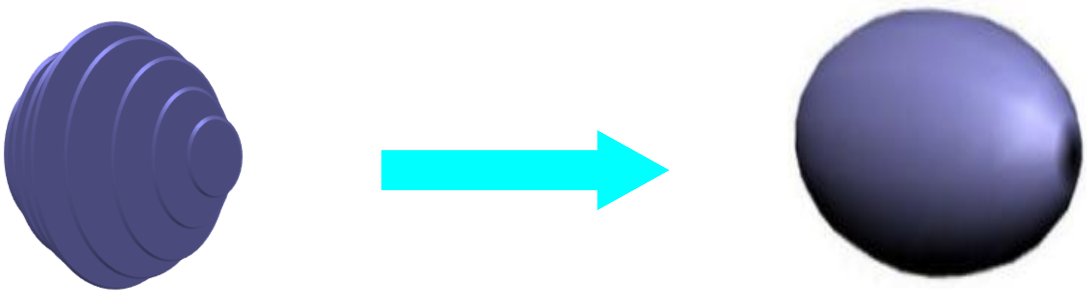
FIG. 5 (color online). Measured (left) and simulated (right) asymmetric beam distribution for $Q = 50$ pC.





- Charge < 20 pC for emittance ~ thermal emittance, at 80 MV/m.
- P. Musumeci, et al., Phys. Rev. Lett. **100**, 244801 (2008).

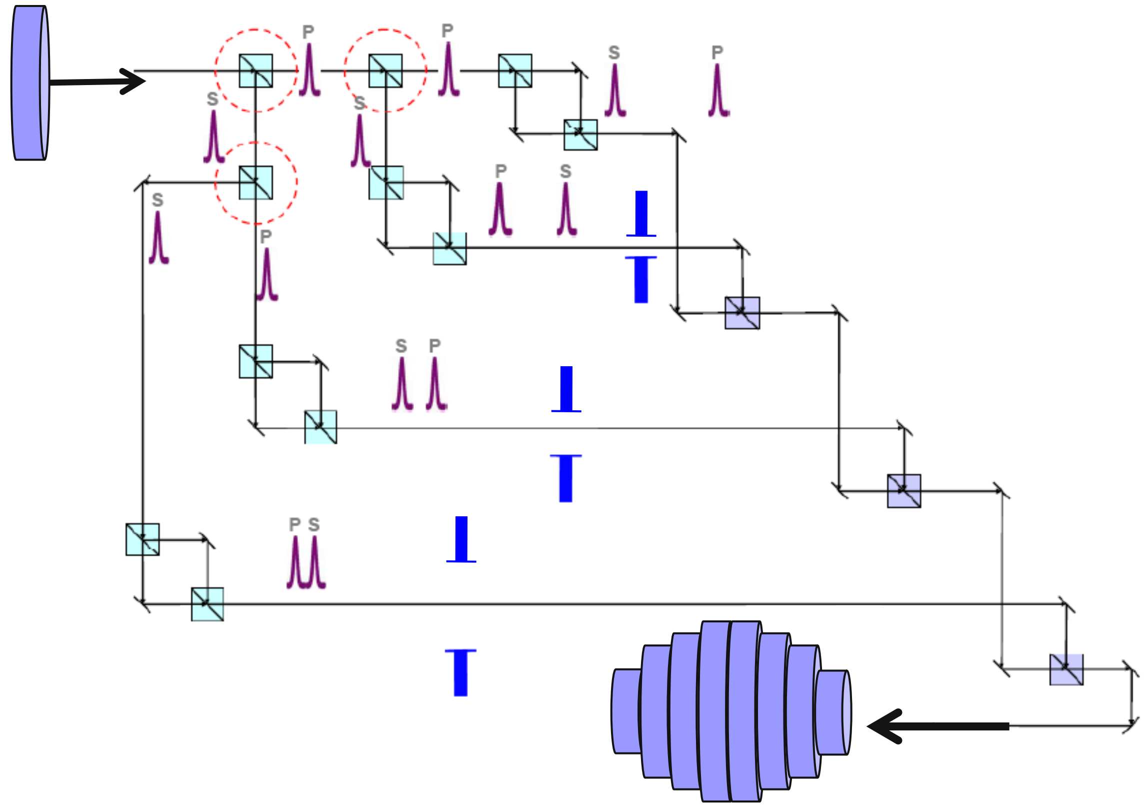
Ellipsoidal: pulse stacking



- Longitudinal and transverse profiles are not independent
- First beam simulation by Limborg
  - *C. Limborg-Deprey and P. Bolton, Nucl. Instrum. Methods A **557**, 106 (2006).*
- Design exists, but with low efficiency
  - *Vicario, ICFA FLS2010, Stanford; H. Tomizawa, private communication.*

Ellipsoidal: pulse stacking, an interferometer design

Complex implementation, energy losses 75%



Vicario, ICFA FLS2010, Stanford; Tomizawa, private communication, 2006

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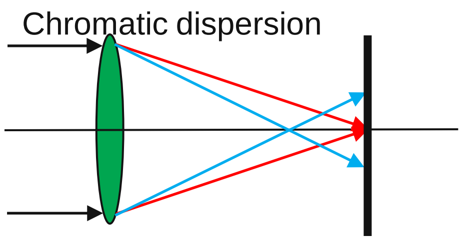
Ellipsoidal pulse at APS: scheme

- Difficulties
  - Simultaneous evolving longitudinal and transverse profiles
  - Homogeneous in 3-D
  - Actually a 2-D problem due to rotation symmetry
- Hope: coupling between time and space via chromatic dispersion

Frequency domain		Time domain	Chromatic dispersion	Spatiotemporal
Phase: $\phi(\omega)$ Amplitude: $A(\omega)$	=	Phase: $\omega(t)$ Amplitude: $A(t)$	→	Size: $r(t)$ Amplitude: $A(t)$



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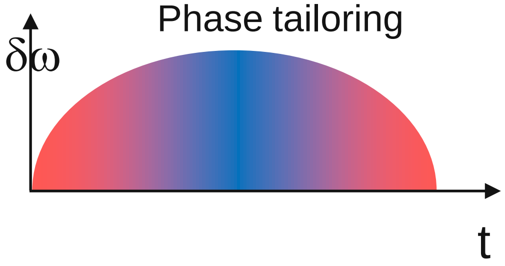

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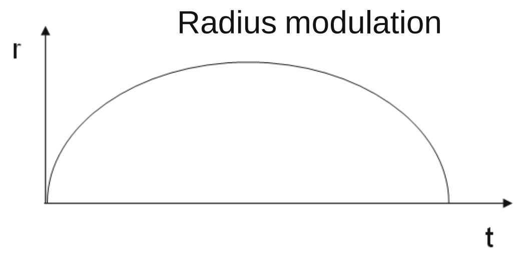


Ellipsoidal pulse at APS: math

- A EM pulse can be written as

$$E(r,t) = A(r,t)\exp(-i\phi(t))$$
$$\phi(t) = \int \omega(t)dt$$

- An ellipsoidal pulse

$$r_b(t) = r_{\max}\sqrt{1-(t/T)^2}$$
$$A(r,t) = const$$

- Chromatic Dispersion

$$\frac{1}{f(\omega)} = [n(\omega)-1]\left(\frac{1}{R_1}-\frac{1}{R_2}\right) \Rightarrow \delta f = -\frac{f_0}{n_0-1}\frac{dn}{d\omega}\delta\omega$$

- Gaussian beam

$$w(\delta\omega) = w_0\left[1+\left(\frac{\delta f(\delta\omega)}{z_R}\right)^2\right]^{1/2} \xrightarrow{\delta f >> z_R} w \propto \delta f \propto \delta\omega$$

- Therefore

$$\delta\omega(t) \sim \sqrt{1-(t/T)^2} \rightarrow w(t) \sim \sqrt{1-(t/T)^2}$$

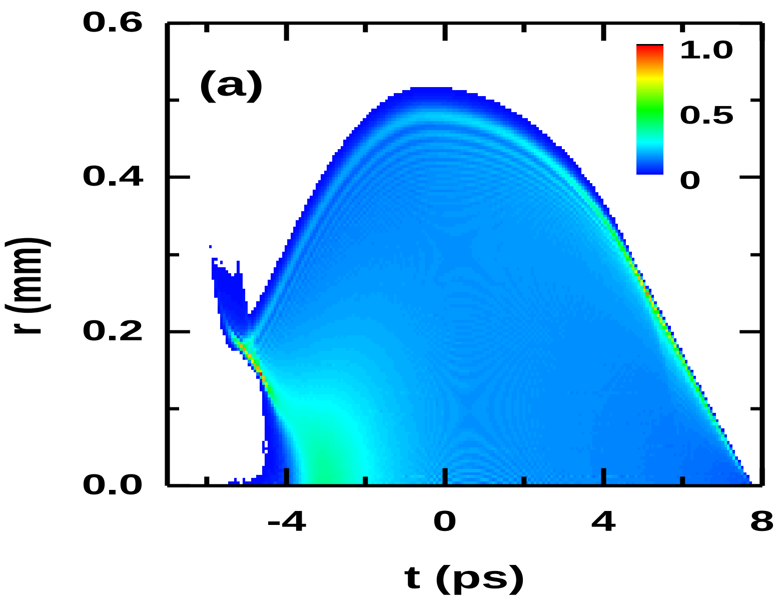
$$\Rightarrow \phi(t) = \int \omega(t)dt = \int(\omega_0 + \delta\omega(t))dt = \omega_0 t \pm \frac{\Delta\omega}{2}\left[t\left(1-\left(\frac{t}{T}\right)^2\right)^{1/2} + T\sin^{-1}\frac{t}{T}\right]$$

$$\Rightarrow A(t) = A_0\left[1-(t/T)^2\right]^{1/2}$$

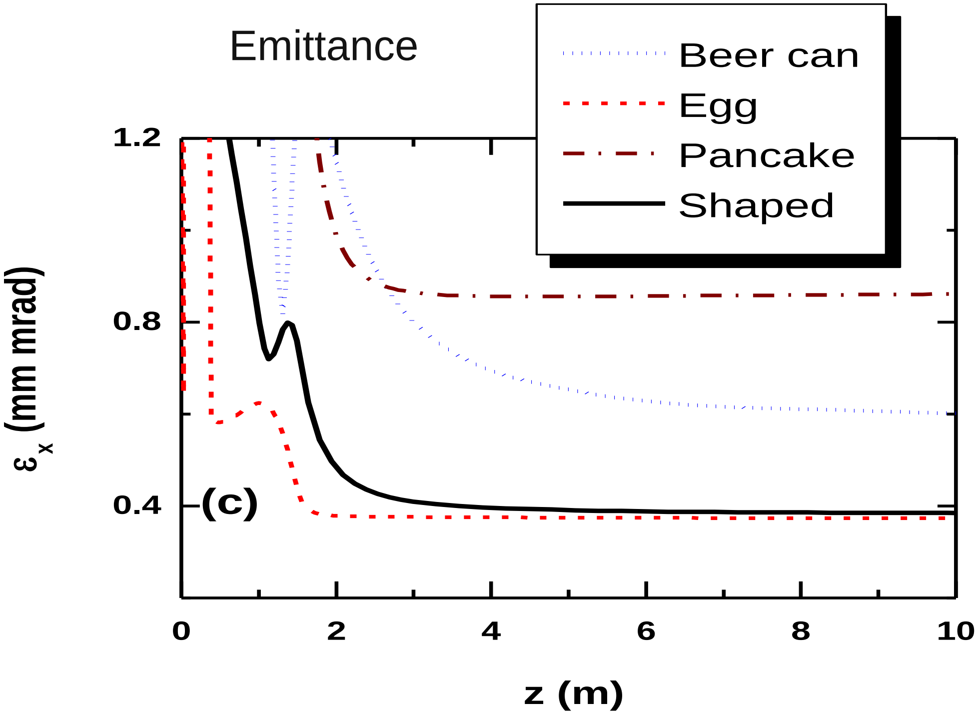
Y. Li and J. Lewellen, PRL 100, 078401(2008)

Ellipsoidal pulse at APS: beam simulation

Spatiotemporal profile



Emittance



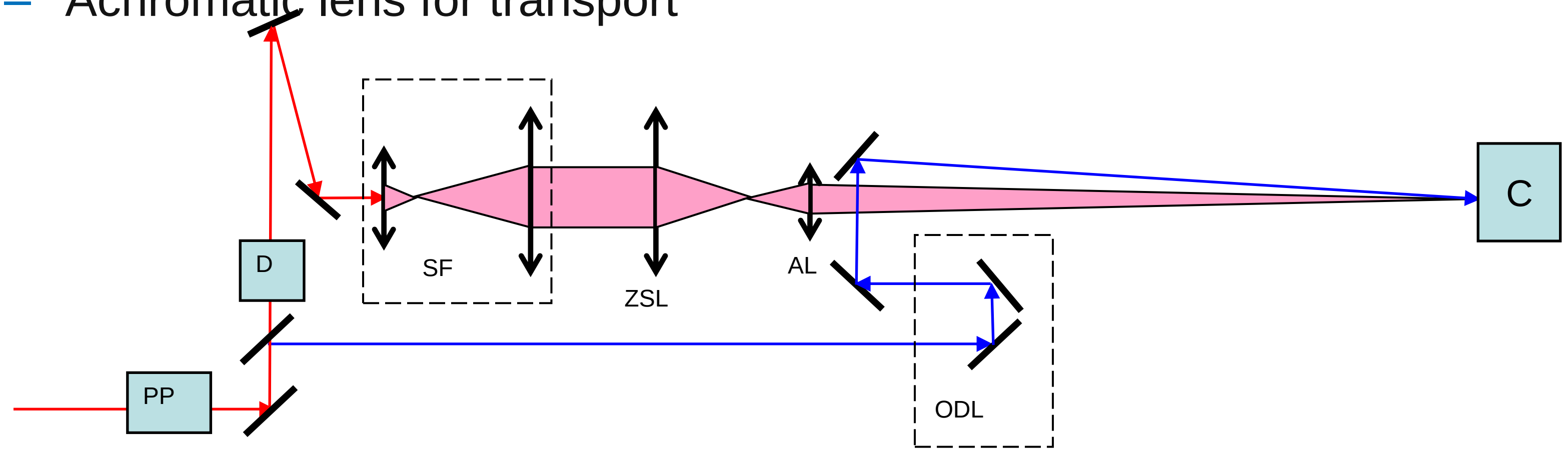
Geometry	Shaped	UE	UC	PC
Max radius (mm)	1	1	1	1
Full length (ps)	12	12	10	0.1 rms
ε_x (mm mrad)	0.38 (0.57, 0.65*)	0.36 (0.57)	0.61 (0.79, 0.95*)	0.86 (0.95)

Y. Li and J. Lewellen, PRL 100, 078401(2008)

Simulation condition for LCLS from: M. Ferrario et. al., Proc. EPAC 2000, p. 1642.

Ellipsoidal pulse at APS: a proof of principle experiment

- Experimental setup
  - 800 nm laser, 1 kHz, 10 nJ per pulse, 40 nm bandwidth
  - ZnSe lens as the focal lens for high dispersion
    - *25-mm diameter, 88.9-mm radius of curvature, and 2.9-mm center thickness, Janos Technology, A1204-105,*
    - *Dispersion 250 fs2/mm at 800 nm)*
  - DAZZLER as the phase modulator
  - Achromatic lens for transport

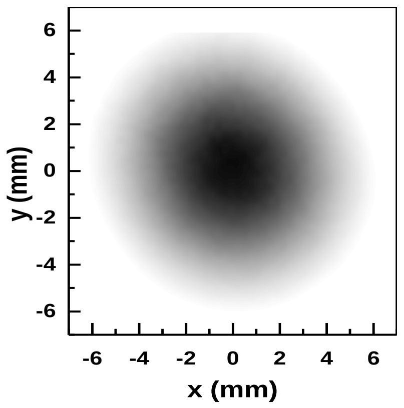


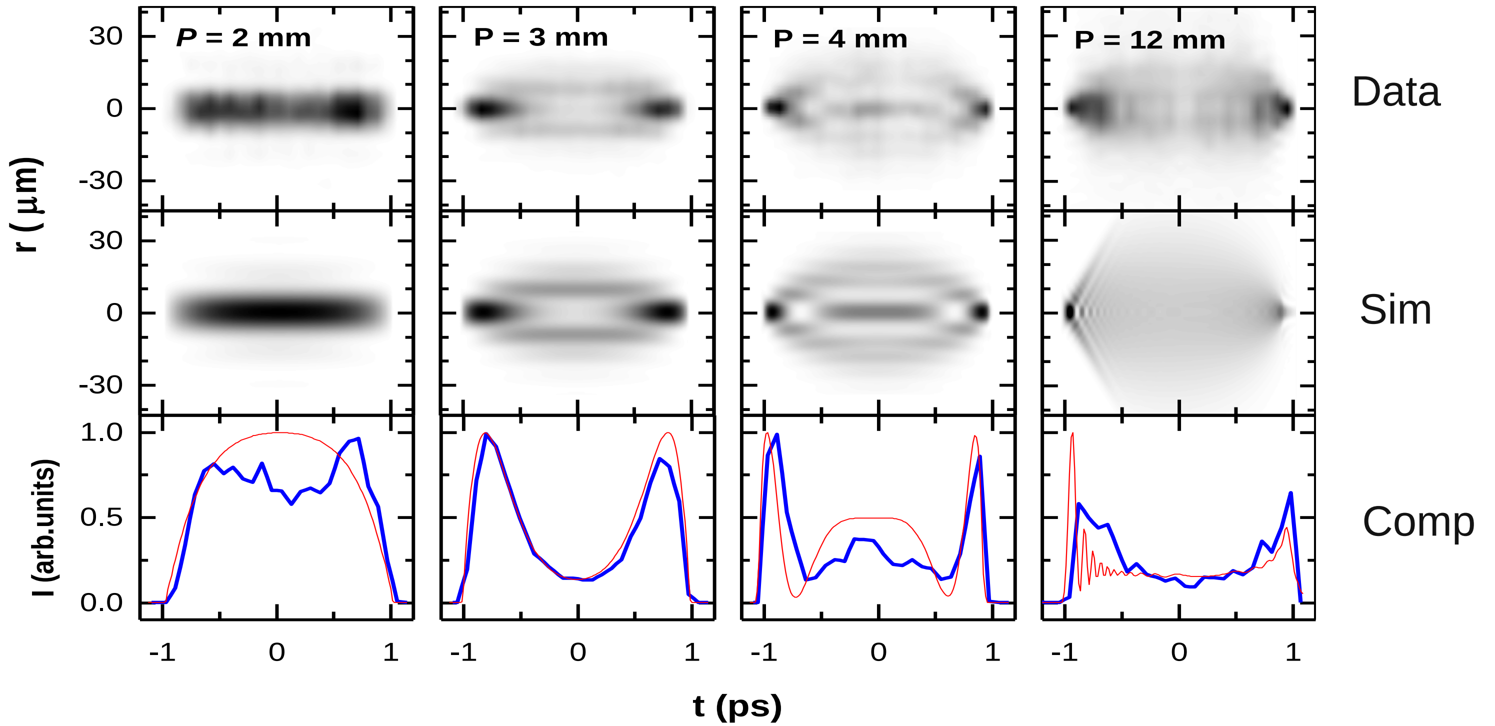
PP: pulse picker; D: AOPDF; SF: achromatic spatial filter; ZSL: ZnSe lens; AL: achromatic image relay lens; ODL: optical delay line; C: camera.

Y. Li and S. Chemerisov, Opt. Lett. 33, 1996 (2008); Li, Lewellen and Chemerisov, PRSTAB 12, 020702 (2009).

Ellipsoidal pulse at APS: a proof of principle experiment

Input beam





- Excellent agreement between data and simulation
- Further work needed for
  - Demonstration in UV with larger beam
  - Beam experiment

Y. Li and S. Chemerisov, Opt. Lett. 33, 1996 (2008).
Li, Lewellen and Chemerisov, PRSTAB 12, 020702 (2009).

Ellipsoidal: summary

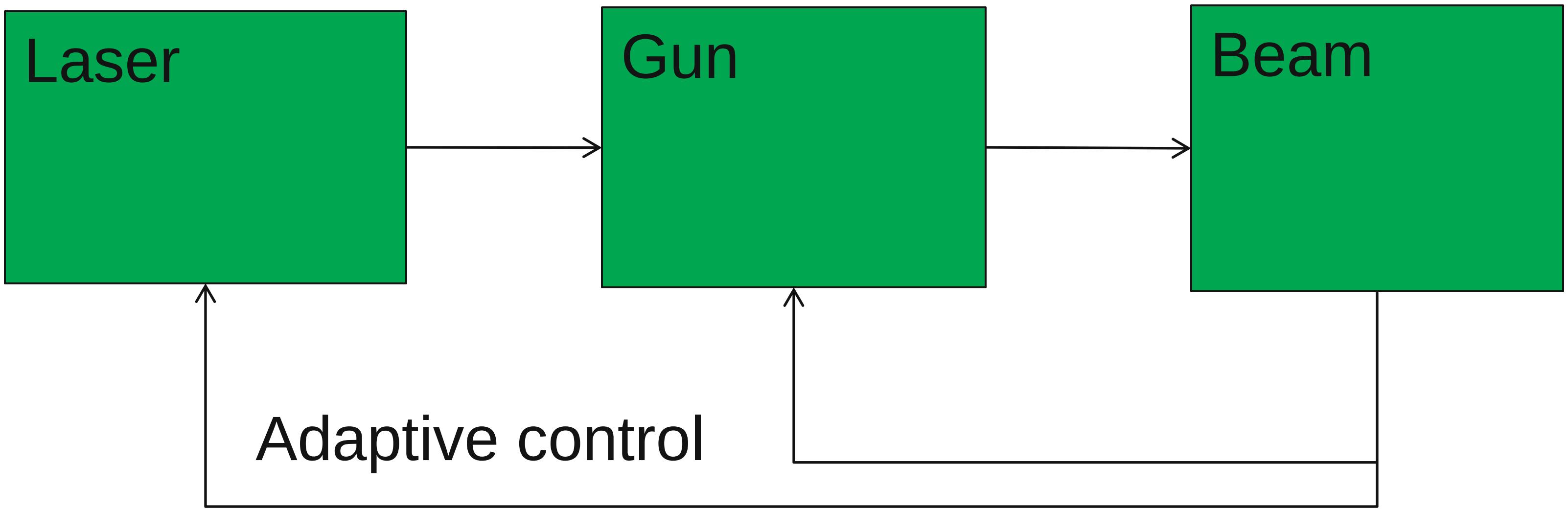
- Blow-out scheme works but not applicable for light source applications
- Longitudinal and transverse profile are not separable thus intrinsically more complex.
- Designs exist, though very limited RD
- The need is overshadowed by the success of LCLS and the maturing cylindrical pulse shaping via BFC

Content

- Implications of the LCLS success
- The case of pulse shaping
  - Minimize emittance growth due to space charge force
  - Uniform ellipsoidal beam is the holy grail
- Review of pulse shaping techniques and examples
  - Cylindrical pulse
  - Ellipsoidal pulse
- Ellipsoidal pulse at APS
  - Scheme and beam simulation
  - A proof of principle experiment
- Adaptive control
- Conclusion

Adaptive control: the concept

- Emittance growth due to space charge force is nonlinear and complex, one solution may not fit all.
- Need adjustable pulse shapers



Adaptive control: already demonstrated in simulation

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 034202 (2005

Multivariate optimization of a high brightness dc gun photoinjector

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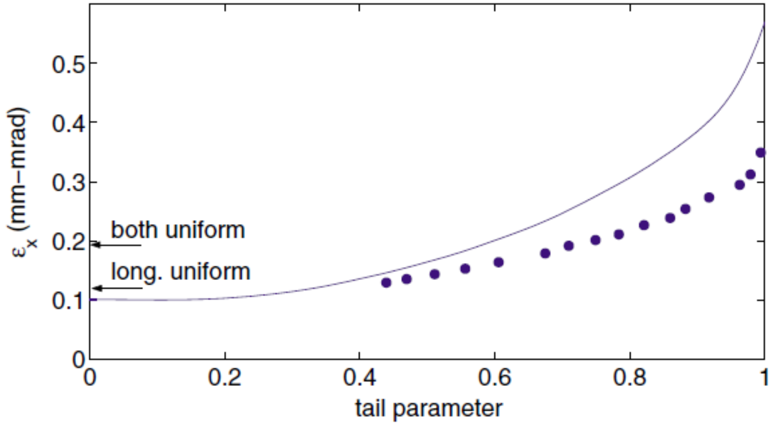
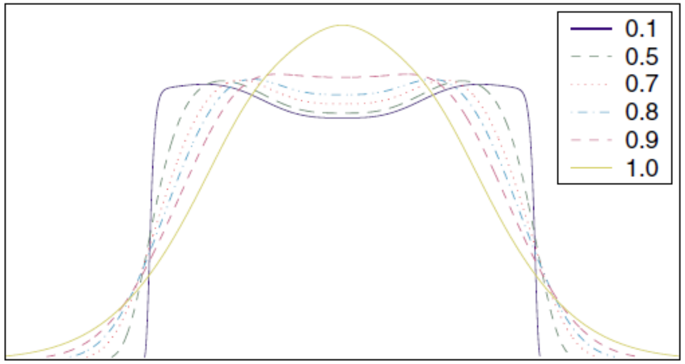
(Received 1 February 2005; published 24 March 2005)

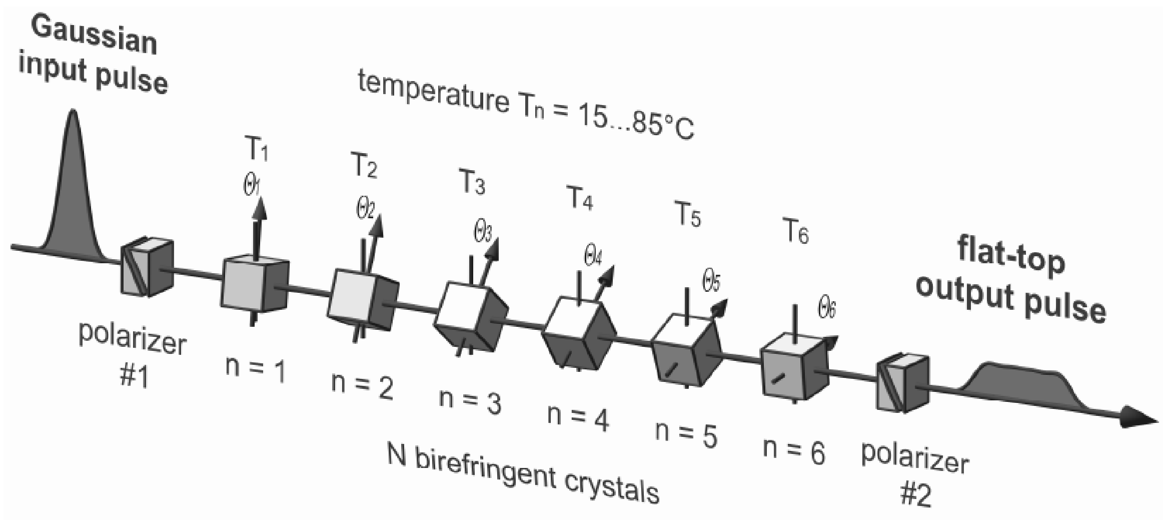
We have conducted a multiobjective computational optimization of a high brightness, high average current photoinjector under development at Cornell University. This injector employs a dc photoemission electron gun. Using evolutionary algorithms combined with parallel computing resources, the multivariate parameter space of the photoinjector was explored for optimal values. This powerful computational tool allows an extensive study of complex and nonlinear systems such as the space-charge dominated regions of an accelerator, and has broad areas of potential application to accelerator physics and engineering problems. In the present case, the optimized injector is simulated to deliver beam of very high quality (e.g., a rms normalized emittance of 0.1 mm mrad for 0.1 nC, and 0.7 mm mrad for 1 nC bunches). The field strengths of the active elements of the injector are moderate and technically practical. The relevance of these results to various novel linac-based accelerator proposals is pointed out.

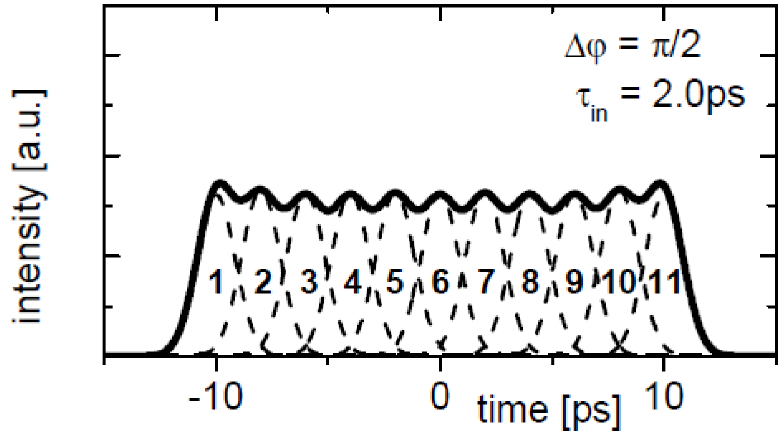
Papadopoulos, WEPB37

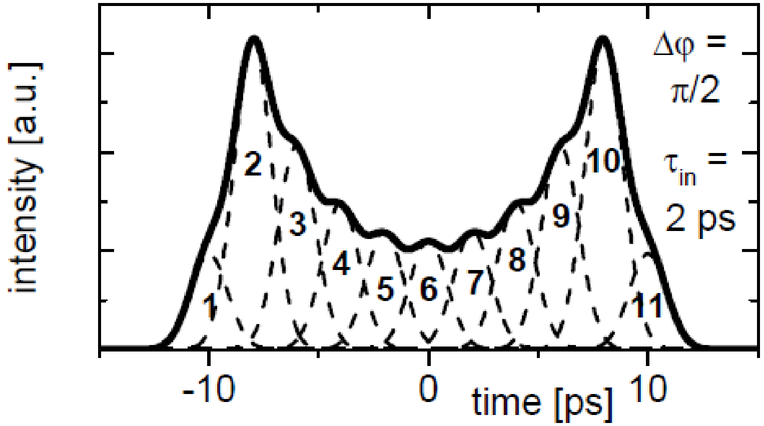




Adaptive control: candidate 1

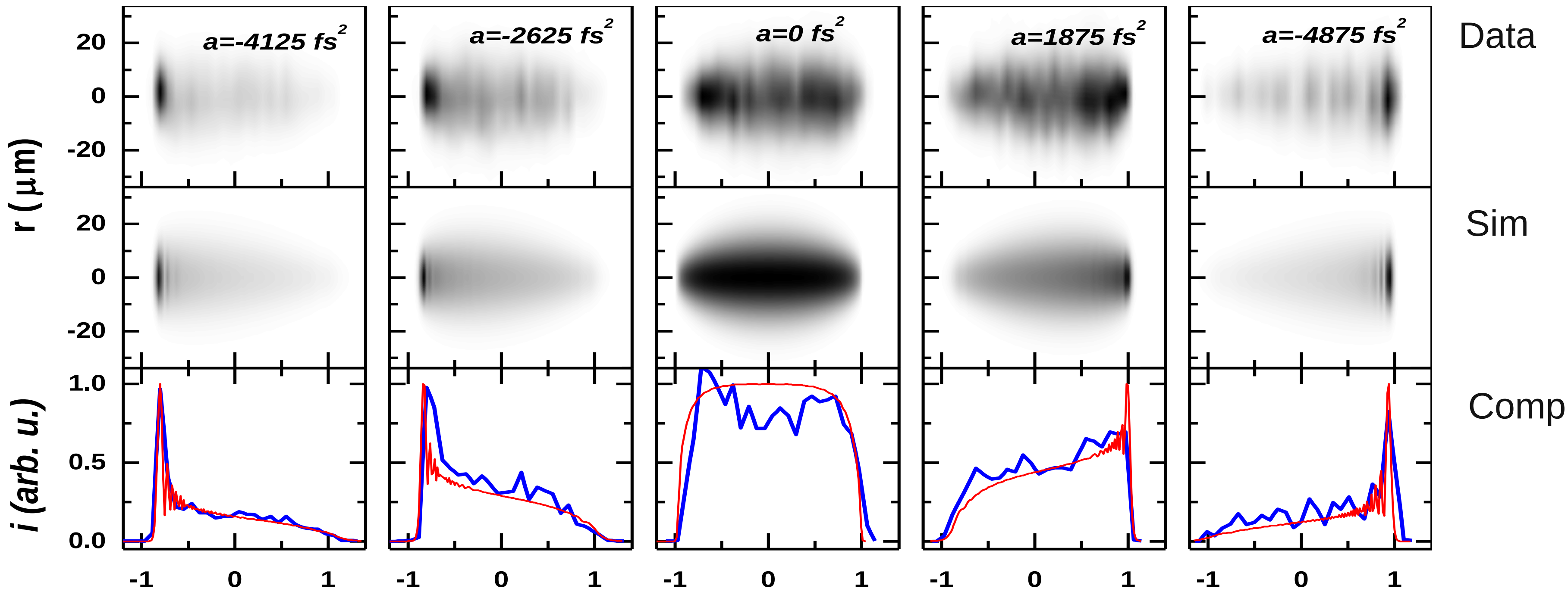






I. Will, Opt Express, 16, 14922 (2008).

Adaptive control: potential candidate 2



- Beam radius: $1/e^2$ width of 3 mm

Li, Lewellen and Chemerisov, PRSTAB 12, 020702 (2009).

Content

- Implications of the LCLS success
- The case of pulse shaping
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  - Uniform ellipsoidal beam is the holy grail
- Review of pulse shaping techniques and example

  If your work is not cited, it is my ignorance not bias.
  - Self evolving (blow out)
  - Pulse stacking
  - Phase engineering
- 3D, Ellipsoidal pulse at ANL
  - Scheme and effect on emittance growth
  - A proof of principle experiment
- Adaptive control
- Conclusion

Conclusions

- We reached a plateau in pulse shaping
  - Pulse stacking for cylindrical pulse via bifringence crystals is maturing and in production mode
  - These are “good enough” for low charge operation of high gradient guns such as the LCLS injector
  - Schemes for ellipsoidal beam are being developed
  - Adaptive control: theoretically feasible and practically no show stop
  - To go forward: dedicated test facility
- 1 nC, 0.5 mm mrad beams may lead to better and more cost effective XFELs
  - More photons, higher photon energies
  - Shorter linac or undulator lines