Ultra-short, Ultra-High Brightness Electron Beams for Single-Spike FEL Operation

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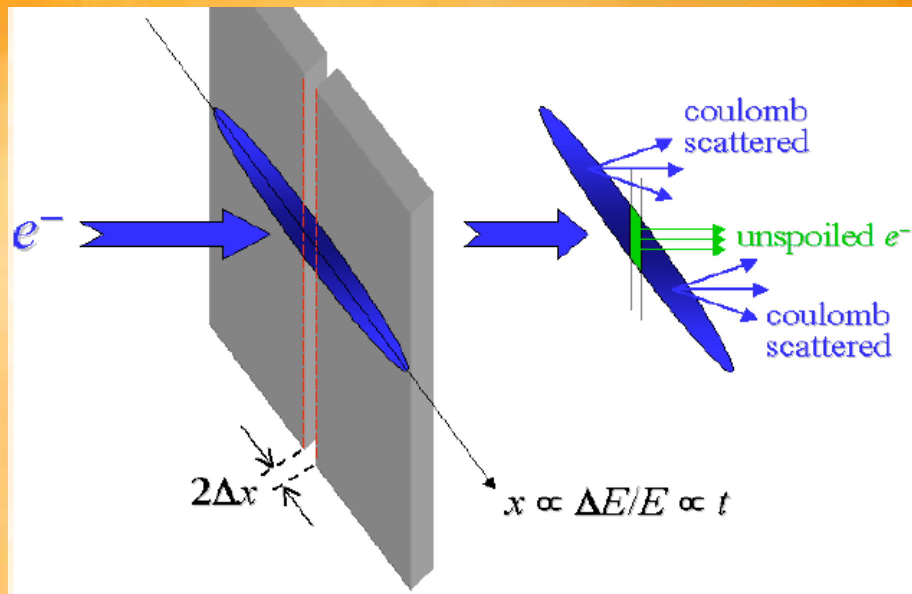
Ultra-short FEL pulses

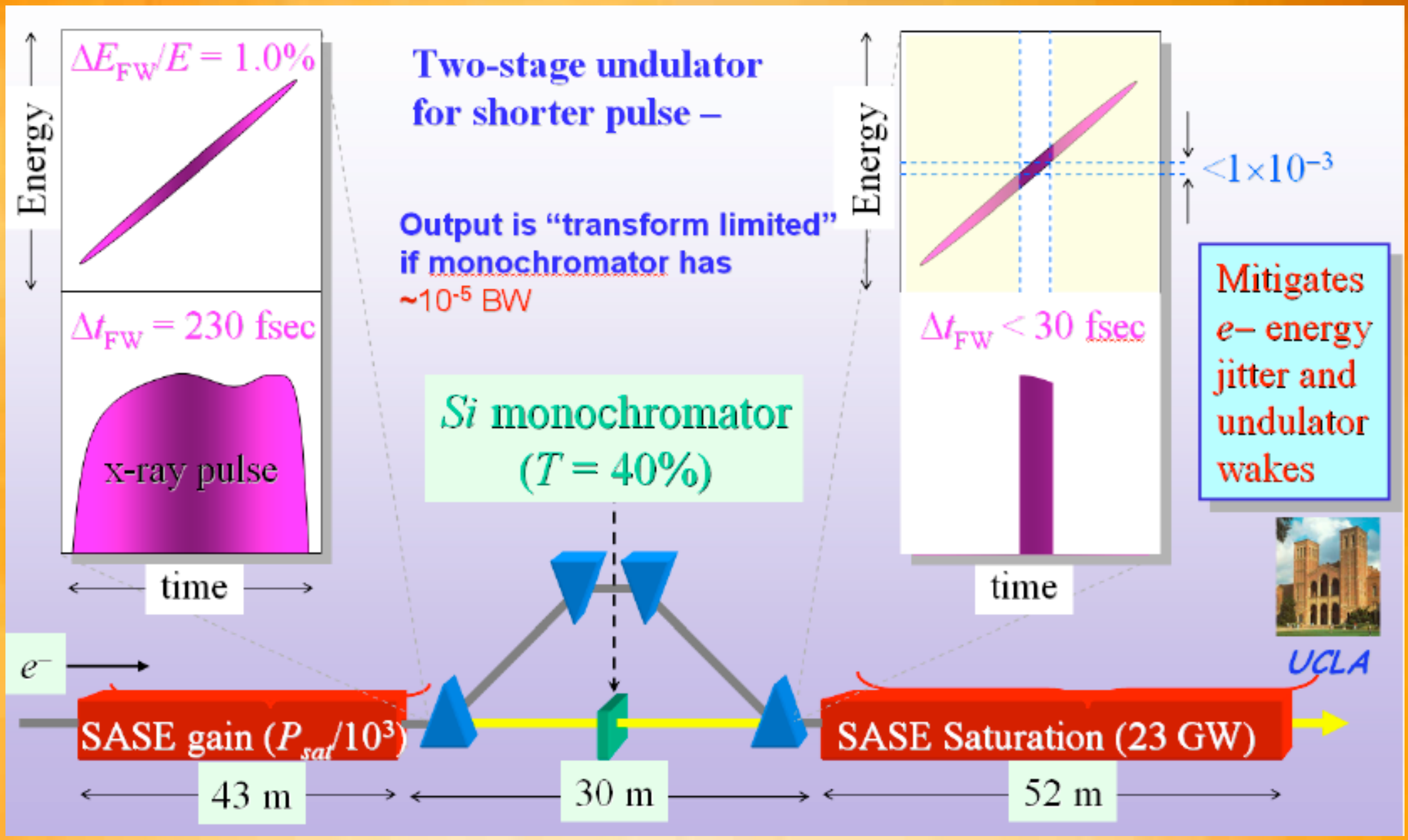
- Investigations at atomic *electron* spatio-temporal scales
  - Angstroms-nanometers (~Bohr radius)
  - Femtoseconds (electronic motion, Bohr period)
- 100 femtoseconds using standard techniques
- Many methods proposed for the fsec frontier
  - Slotted spoiler; ESASE; two stage chirped pulse
  - Unsatisfactory (noise pedestal, low flux, etc.)
  - Unproven
- Use clean ultra-short electron beam
  - Myriad of advantages in FEL and beam physics

Slotted spoiler method



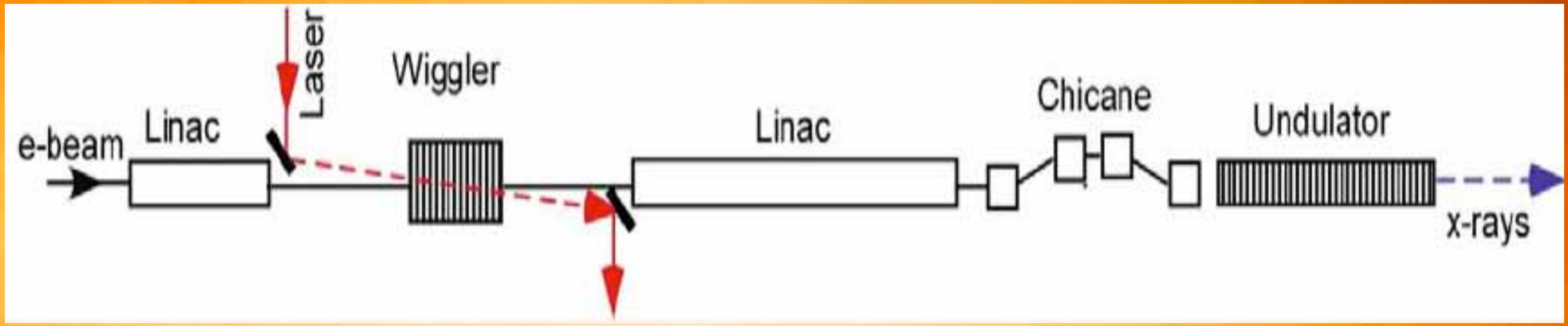
- Slot in chicane center (high dispersion)
- Problems:
  - Wakes (spoiler and “standard”),
  - spontaneous background
- Beam not higher brightness…

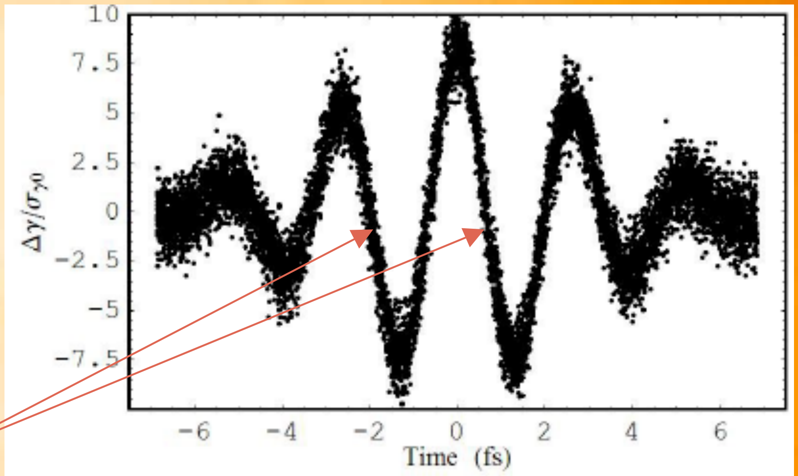
Two-Stage Chirped-Pulse Seeding



- Still backgrounds, large pedestal
- Collective effects from entire beam

Enhanced SASE





- Modulation at ~μm λ
- Pulse train of spikes
- FEL ρ enhanced by ~2
- Still full beam, backgrounds…

A new path: ultra-low charge electron beam

- Excellent phase space (⊥ and ||)
  - Very low emittance
  - Highly compressible
- Ultra-short beam
  - Very high brightness
  - Bunch ~ cooperation length; <u>super-radiant</u> *single spike*
  - Short cooperation length; *femtosecond pulse*
  - *Clean*, ultra-short pulse
- Mitigate collective effects dramatically
  - CSR instability
  - Undulator beam-pipe wakes

Working backwards: FEL requirements

- 1D dimensionless gain parameter

$$\rho_{1D} = \left[\frac{JJ\left(K_{rms}\right)K_{rms}k_p}{4k_u} \right]^{2/3}$$

- 1D gain length $L_{g,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}}$
- Cooperation length $L_{c,1D} = \frac{\lambda_r}{4\pi\sqrt{3}\rho_{1D}}$
- Single spike operation

$$\sigma_{b,SS} < 2\pi L_{c,1D} = \frac{\lambda_r}{2\sqrt{3}\rho_{1D}}$$

Numerical example: SPARX

- Take 2 GeV operation, “standard undulator”, λ=3 nm
- Peak current *I*=2 kA, $\rho_{1D} = 1.8 \times 10^{-3}$
- Estimate single spike condition:

$$\sigma_{b,SS} = 0.48\ \mu\text{m (1.6 fsec)}$$

- Note: with ultra-small *Q*, ρ is enhanced
  - Spike is a bit shorter…
  - FEL gain better

Compression scaling

- Beam momentum distribution in ζ, ignoring slice spread

$$p_z(\zeta) \cong p_{\max}\sin\left(k_{RF}\zeta\right) \cong p_0\left[1-\cot\left(\phi_0\right)k_{RF}\delta\zeta - \tfrac{1}{2}\left(k_{RF}\delta\zeta\right)^2\right]$$

- Quadratic term no longer dominant
- Include uncorrelated term $\sigma_{\delta p,\,th} = \sqrt{\delta p_{th}^2}\,/\,p_0$
- Moments: $\left\langle \delta\zeta^2 \right\rangle = \sigma_\zeta^2$

$$\frac{\left\langle \delta p^2 \right\rangle}{p_0^2} = \frac{\left(k_{RF}\sigma_\zeta\right)^4}{2} + \cot^2\left(\phi_0\right)\left(k_{RF}\sigma_\zeta\right)^2 + \sigma_{\delta p,\,th}^2$$

$$\frac{\left\langle \delta\zeta \cdot \delta p \right\rangle}{p_0} = -\sigma_\zeta \cot\left(\phi_0\right)\left(k_z\sigma_\zeta\right)$$

Compression with chicane

- Needed chicane essentially unchanged

$$R_{56} = \frac{k_{RF}\sigma_\zeta^2 \cot(\phi_0)}{\frac{1}{2}(k_{RF}\sigma_\zeta)^4 + (k_{RF}\sigma_\zeta)^2 \cot^2(\phi_0) + \sigma_{\delta p,th}^2} \underset{\delta p_{th}/p_0 << k_{RF}\sigma_\zeta \cot\phi_0}{\overset{k_{RF}\sigma_\zeta << 1}{\Rightarrow}} \frac{1}{k_{RF}\cot(\phi_0)} = \frac{\lambda_{RF}\tan(\phi_0)}{2\pi}$$

- Final bunch length/initial

$$\frac{\sigma_\zeta^*}{\sigma_\zeta} = \sqrt{\frac{\frac{1}{2}(k_{RF}\sigma_\zeta)^4 + \sigma_{\delta p,th}^2}{\frac{1}{2}(k_{RF}\sigma_\zeta)^4 + \sigma_{\delta p,th}^2 + (k_{RF}\sigma_\zeta)^2 \cot^2(\phi_0)}} \cong \frac{\sigma_{\delta p,th}}{\sqrt{\sigma_{\delta p,th}^2 + (k_{RF}\sigma_\zeta)^2 \cot^2(\phi_0)}} \cong \frac{\sigma_{\delta p,th}}{(k_{RF}\sigma_\zeta)\cot(\phi_0)}.$$

- "Thermal" spread from velocity bunching

$$\sigma_{\delta p,th} \cdot p_0 = 30\left[Q(pC)^{1/3}\right] \text{ keV/c (from simulation)}$$

- Simple in low *Q* limit

$$\sigma_\zeta^* \cong \frac{\sigma_{\delta p,th}}{k_{RF}\cot(\phi_0)} \cong 4.8\times 10^{-3}\,\frac{\lambda_{RF}(\text{m})Q(\text{pC})^{1/3}}{p_0(\text{MeV})\cot(\phi_0)}$$

Main example: SPARX

- Compression at 2 GeV before undulator
- Need $\sigma_\zeta^* \cong 480$ nm
- Choose to accelerate 23° forward of crest
- Deduce upstream beam of $\sigma_\zeta = 9\ \mu\mathrm{m}$
  - Must produce from *velocity buncher*
- Check consistency with energy spread

$$\sigma_{\delta p} \cong \cot(\phi_0)(k_z\sigma_\zeta) << \rho_{1D}$$

  - We have $\sigma_{\delta p} \cong 2.1\times10^{-4} << \rho_{1D}\ \left(>1.8\times10^{-3}\right)$
  - Final energy comp. OK (not in LCLS case)

Photoinjector scaling

- Change beam *Q* while keeping plasma frequency (*n* and aspect ratio) same
- Dimensions scale $\sigma_i \propto Q^{1/3}$
  - Shorter beam…
- Emittances:

$$\text{Space charge, } \varepsilon_{x,sc} \propto k_p^2 \sigma_x^2 \propto Q^{2/3},$$
$$\text{RF/chromatic aberration, } \varepsilon_{x,RF} \propto \sigma_z^2 \sigma_x^2 \propto Q^{4/3},$$
$$\text{Thermal emittance, } \varepsilon_{x,th} \propto T_c^{1/2} \sigma_x \propto Q^{1/3}.$$

- At low *Q*, $\varepsilon_{x,th}$ dominant in Ferrario WP

$$\varepsilon_n(\text{mm-mrad}) = \sqrt{a_1 Q(\text{nC})^{2/3} + a_2 Q(\text{nC})^{4/3} + a_3 Q(\text{nC})^{8/3}} \propto 0.33 \cdot Q(\text{nC})^{1/3} (\text{mm-mrad})$$

$a_1 = 0.11$, $a_2 = 0.18$, $a_3 = 0.23$

- With optimized low *Q* vel. bunching

$$\varepsilon_n(\text{mm-mrad}) = \sqrt{a_1 Q(\text{pC})^{2/3} + a_2 Q(\text{pC})^{4/3}}$$

$a_1 = 1.1 \times 10^{-3}$, $a_2 = 2.7 \times 10^{-3}$

Low charge working point

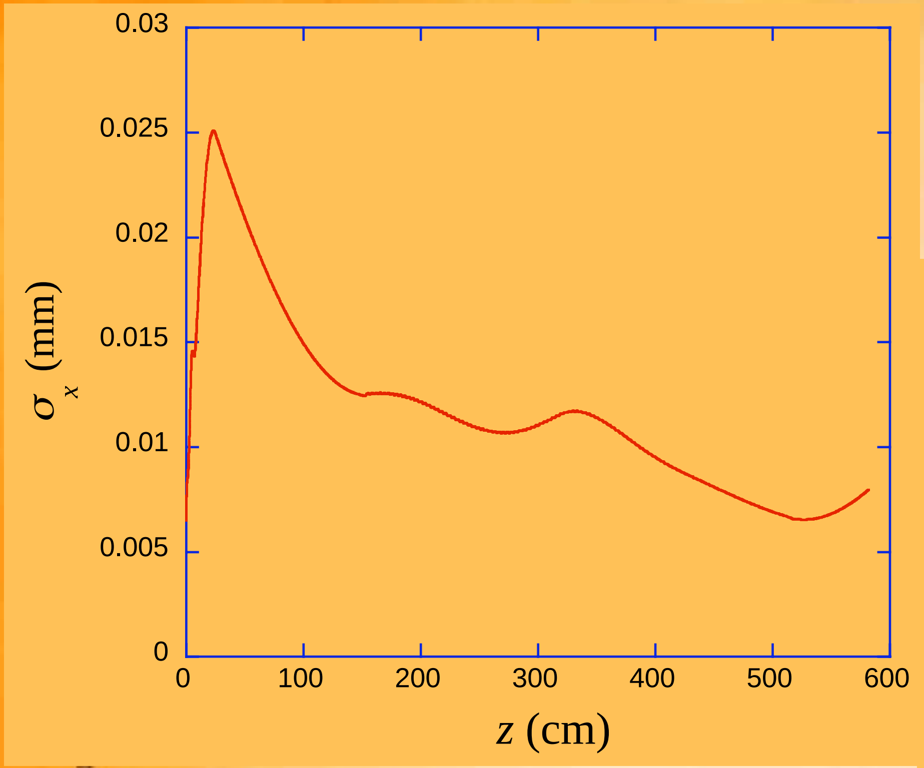
- Velocity bunching gives $\sigma_\zeta \cong \sigma_0 Q(\mathrm{nC})^{1/3}$
  - Space charge limit on long. dynamics
- Need $\sigma_0 \cong 10\sigma_\zeta \cong 90\ \mu\mathrm{m}\ (0.3\ \mathrm{psec})$
  - Not that short… factor of 10 below present
- Work at *Q*=1 *pC* (factor of 10^3)
- Emittance > compensated value
  - Thermal plus ~2 growth in vel. Buncher
- Higher brightness beam in the end!

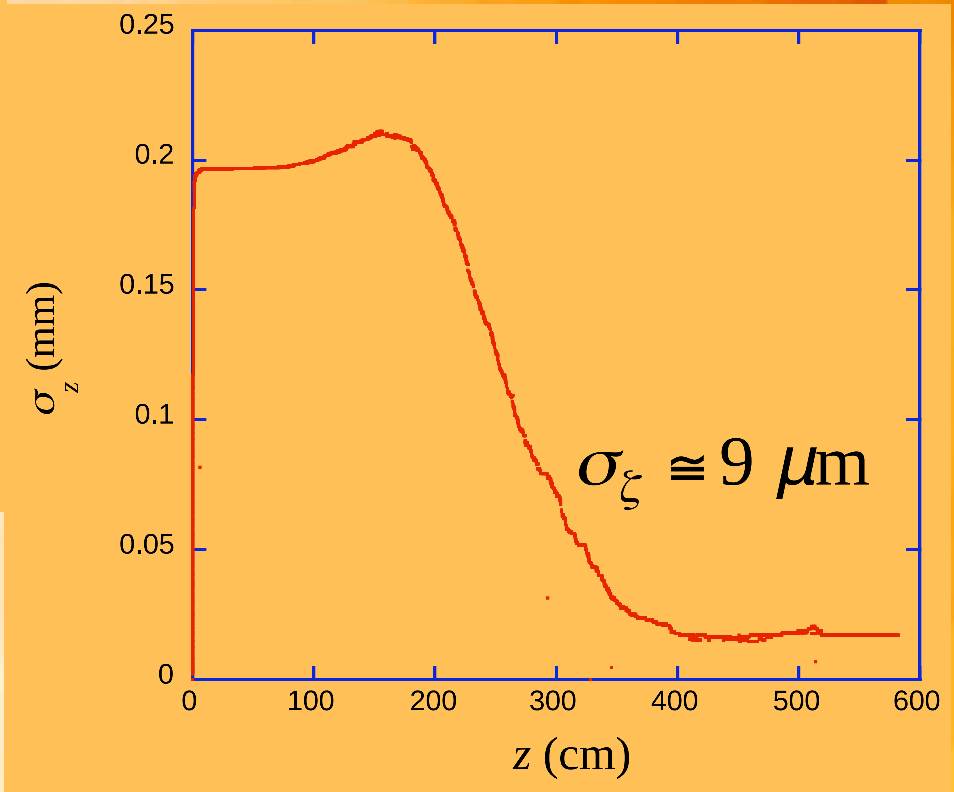
Beam simulations for 1 pC case (UCLA PARMELA)

Summary

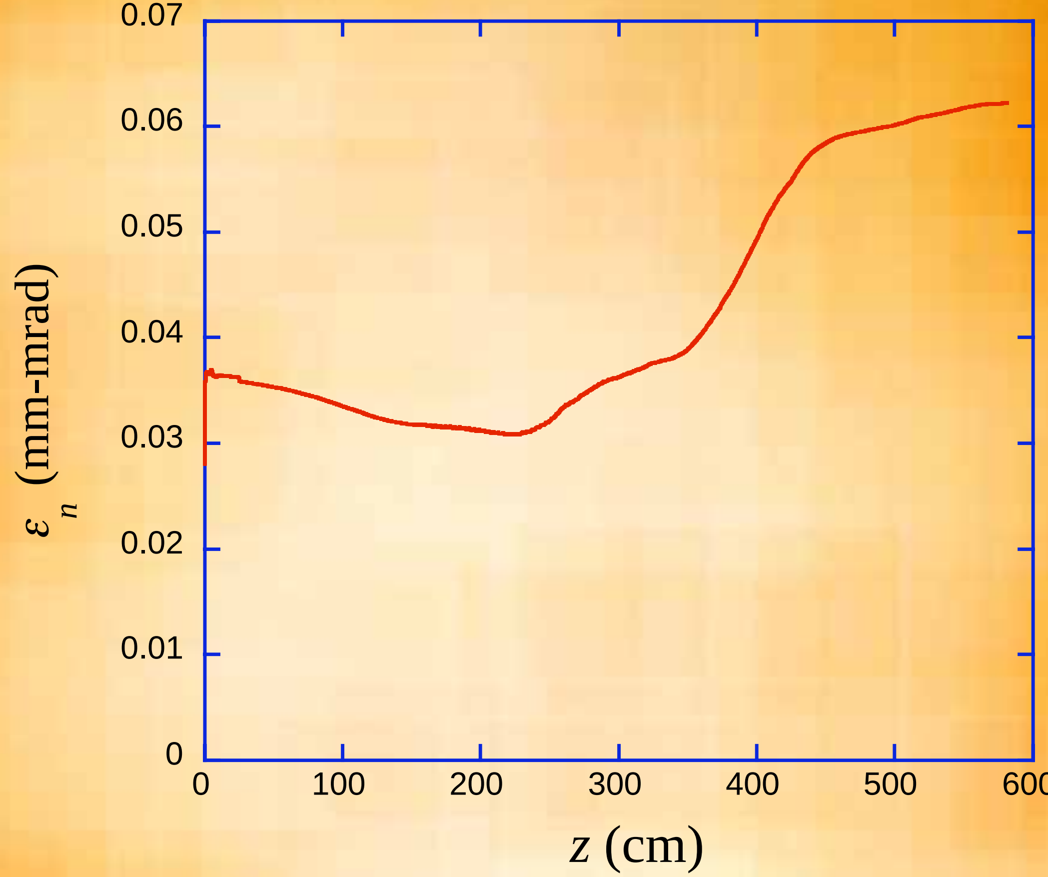
Charge	1 pC (6.2E6 electrons)
Laser pulse length (full)	1 psec (280 fsec rms)
Gun maximum on-axis electric field	110 MV/m
Average traveling wave section field	13.5 MV/m
Initial laser beam radius (full)	100 microns
Thermal emittance	0.033 mm-mrad
Emittance after velocity bunching	0.062 mm-mrad
Final bunch length (rms)	9 μm (28 fsec)
Energy after velocity bunching section	17.9 MeV
Final relative momentum spread	0.31%

Beam envelope evolution



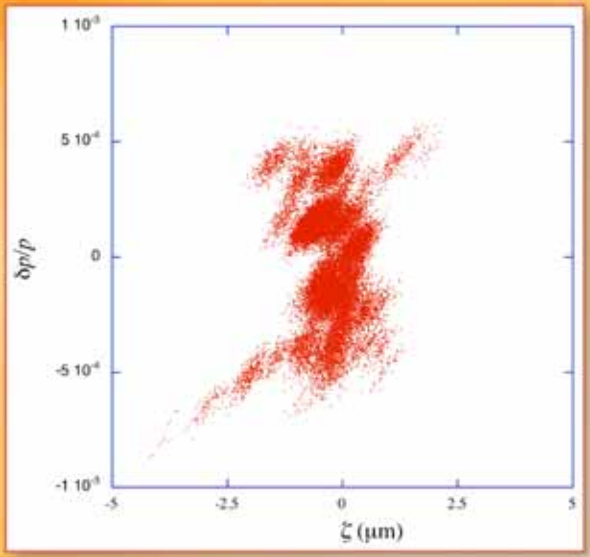


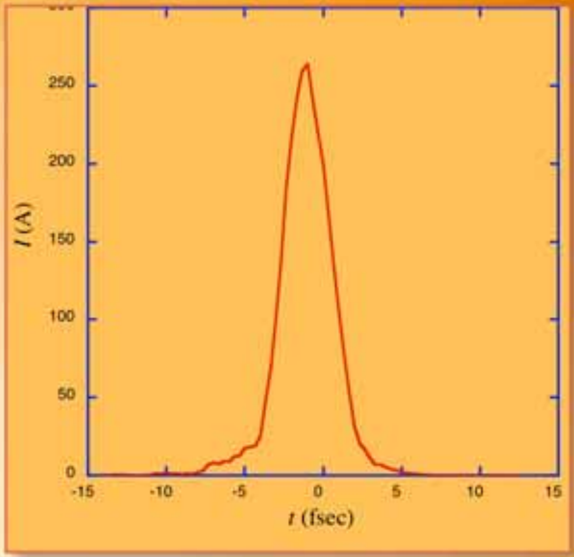
Emittance evolution



Still very small, optimization not guaranteed

Compression at SPARX





- SPARX example, compress at 2 GeV, $\sigma_{\delta p} = 2.4 \times 10^{-4}$
- Compressor: $R_{56} \cong 1.7$ cm $\quad \theta_b = 25$ mrad
- Analytical est. of growth in ε, $\sigma_{\delta p}$: $\Delta\sigma_{\delta p} \cong 10^{-5}$ $\quad \Delta\varepsilon_n \cong 6 \times 10^{-9}$ m-rad
- With I=260 A, and $\varepsilon_n = 6.2 \times 10^{-8}$ m-rad

$B = 1.35 \times 10^{17}$ A/m^2 *Two orders of magnitude* enhanced

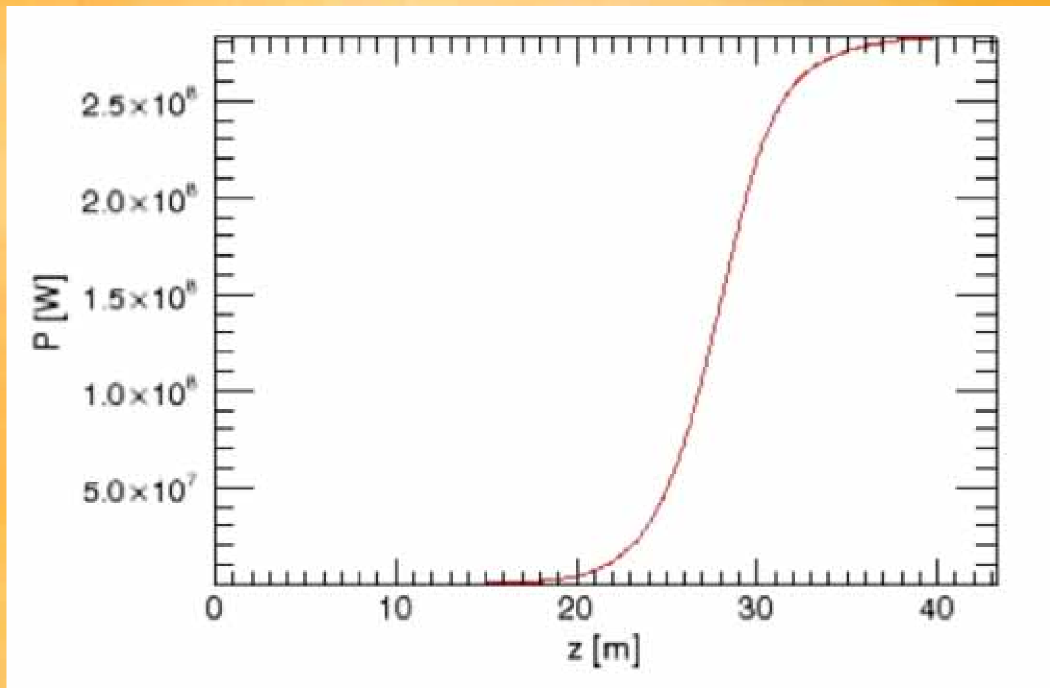
Genesis simulation of SPARX

- Standard case

Undulator wavelength λ_u	2.8 cm
Undulator strength K_{rms}	1.516
Resonant wavelength λ_r	3 nm
Focusing β-function	12.5 m
Dimensionless gain parameter ρ_{1D}	2.3×10^{-3}

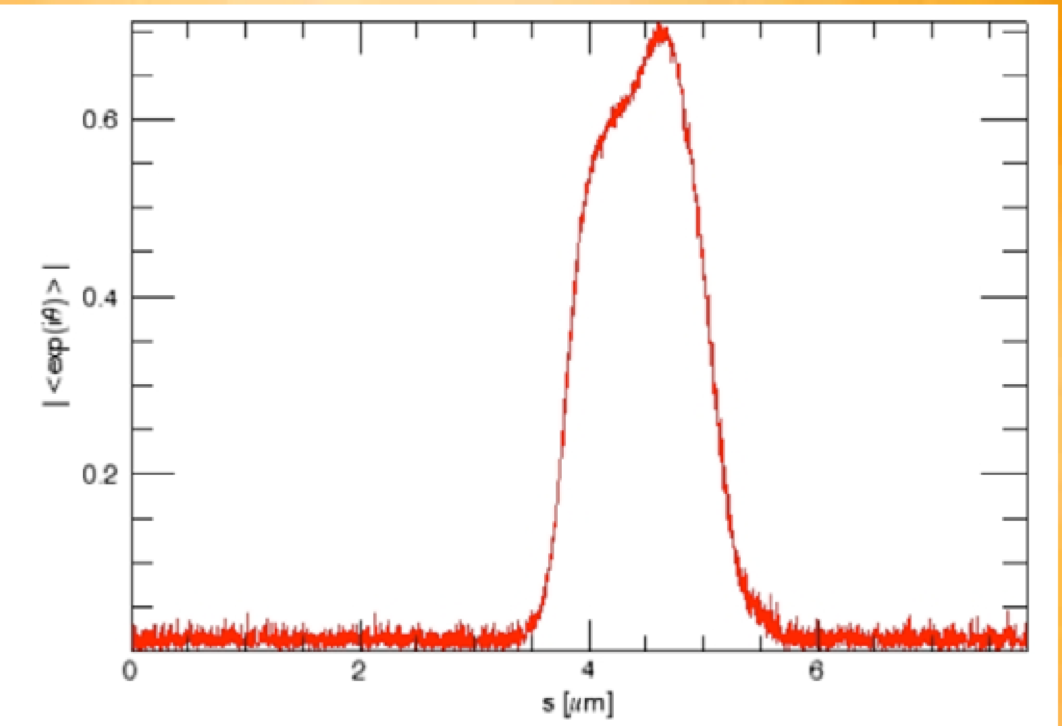
- Start-to-end from PARMELA/Elegant
- Do *not* take advantage of lower ε by changing β to evade diffraction $"Z_R" = 4\pi\sigma_x^2/\lambda_r = 83$ cm
- Single spike operation!

FEL peak power



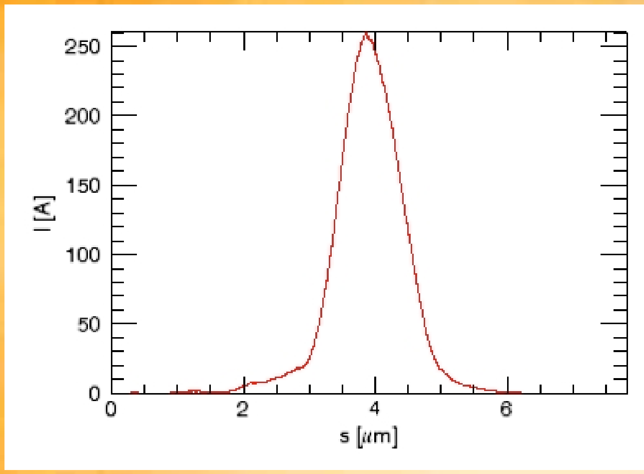
Saturation in <30 m

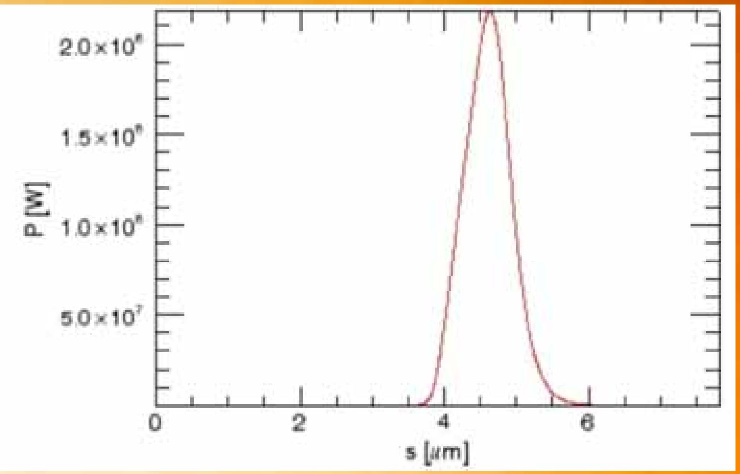
Bunching at fundamental



Well saturated, ~uniform

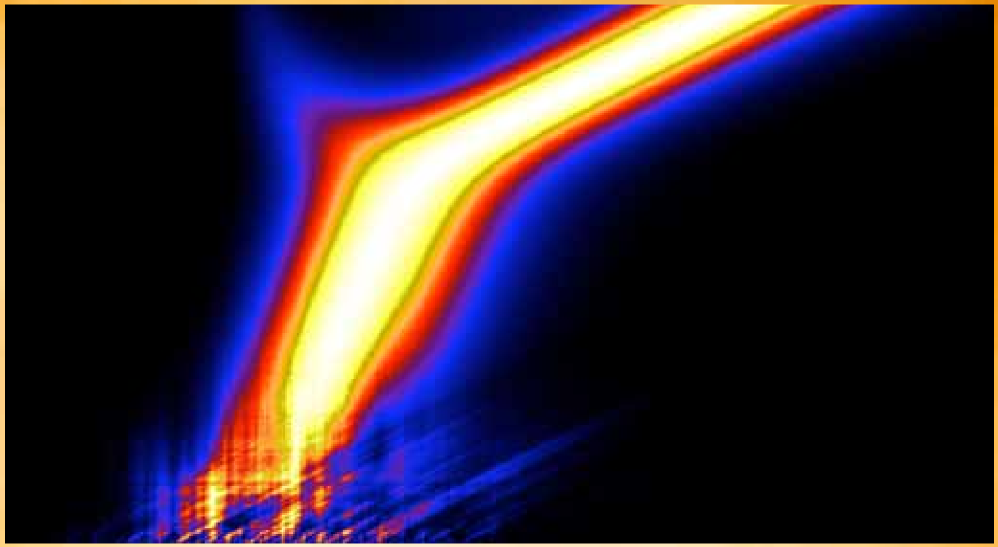
Power profile





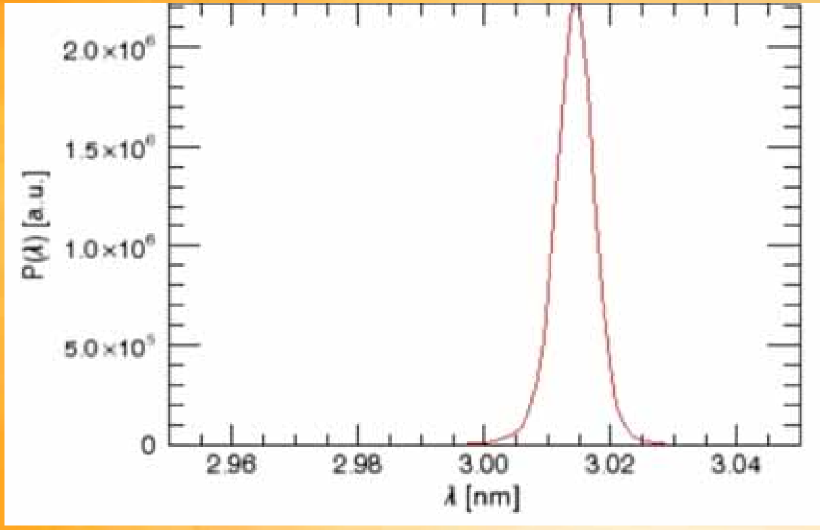
- 220 MW peak power (/10 from standard)
- <1.5 femtosecond rms pulse!!!
  - LCLS simulations show *300 attoseconds*…
- Narrower than e-beam

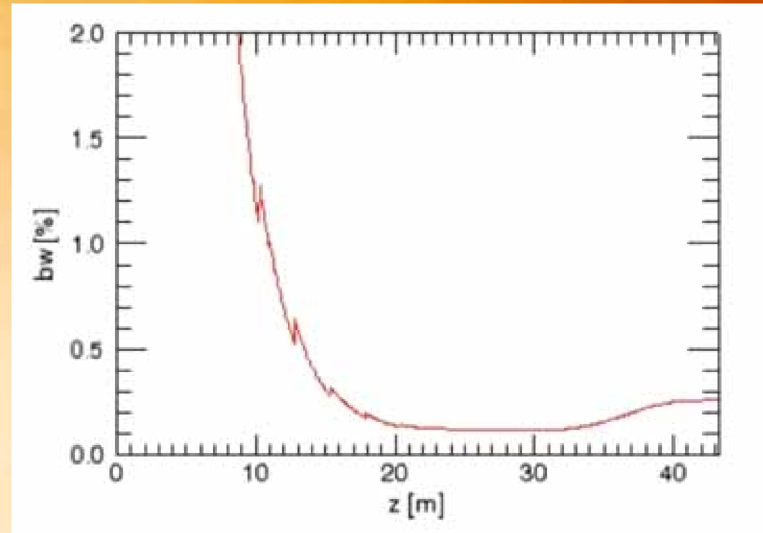
Power evolution



- Vertical z
- Horizontal ζ
- Extremely clean pulse

Spectral properties

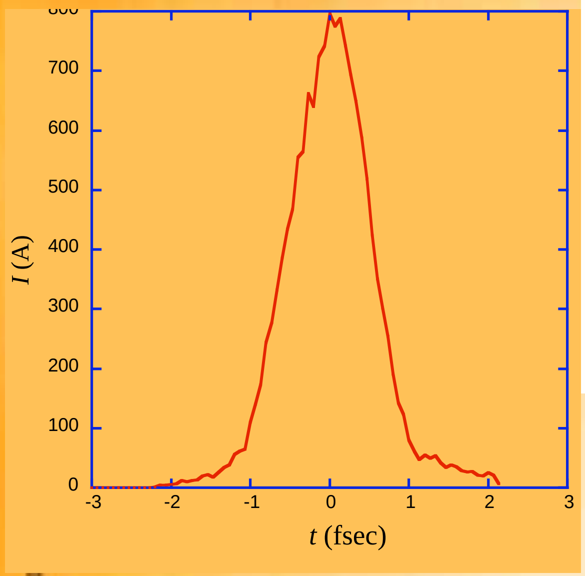




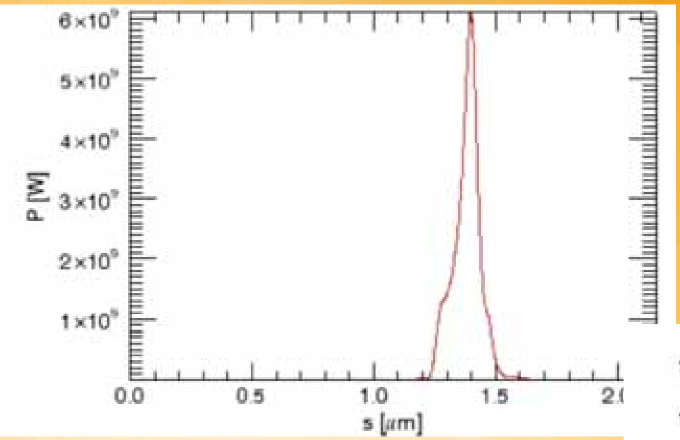
- Nearly bandwidth limited at onset of saturation

$$\sigma_{\omega}\sigma_{t} = 1.2$$

Extension to LCLS (non-optimized)

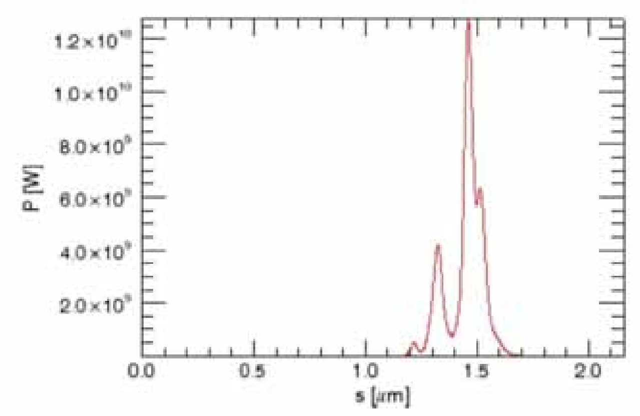


800 A, 160 nm rms



Onset of saturation

Deep saturation



- Interesting things happen at saturation
  - Function of shorter λ and L_c
- S. Reiche will discuss in detail

Conclusions; future work

- Very promising option
  - Extended for LCLS at 1.5 Å (Reiche talk); XFEL
  - Excellent emittance and gain; can allow shorter λ
- Marry to "blowout regime" injector; shorter beams
- Excellent beam scenario, *but…*
- All measurements change
  - Low energy similar to electron diffraction scenario
  - *Coherent optical* signals at high energy
- Clean up noise
  - Dark current has much more charge
  - Natural focusing; may use dual deflector/collimator
- 1st test possible at SPARC (vel. bunching only)
  - Beam dynamics of 1st stage compression (1 pC)
  - Scaled FEL operation

See SPARX note (below); PRL (v. soon)

Generation of Ultra-Short, High Brightness Electron Beams for Single Spike SASE FEL Operation

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