Accelerator Physics Challenges of X-Ray FEL SASE Sources

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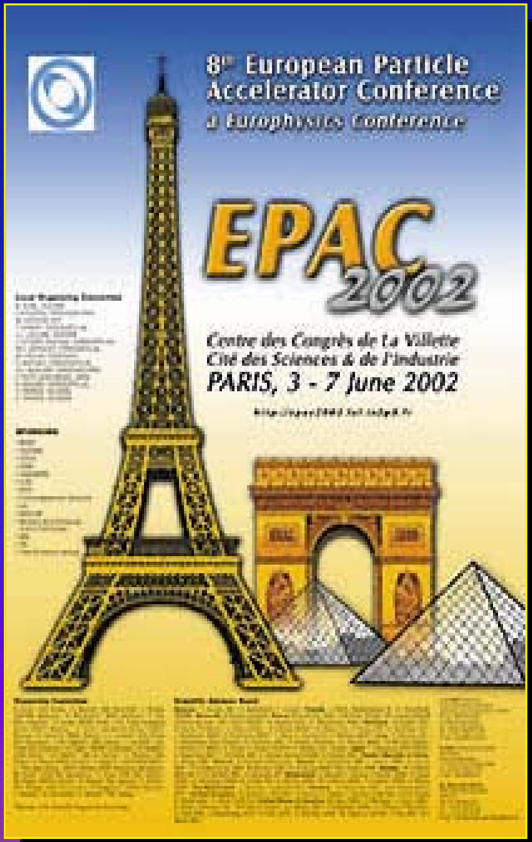


Why a Linac-Based Free-Electron Laser (FEL*) ?

- Longitudinal emittance from linac is much smaller than ring
- Bunch length can approach 100 fsec with small energy spread
- Potential for 10^{10} brightness increase and 10^2 pulse length reduction
- Much experience gained from linear collider operation and study (SLC, JLC, NLC, TESLA, CLIC)
- At *SLAC*, the linac is available
- at *DESY*, XFEL fits well into TESLA collider plans

Use SASE** (Self-Amplified Spontaneous Emission)
$\Rightarrow$ no mirrors at 1 Å

* Motz 1950; Phillips 1960; Madey 1970
** Kondratenko, Saldin 1980; Bonifacio, Pellegrini 1984

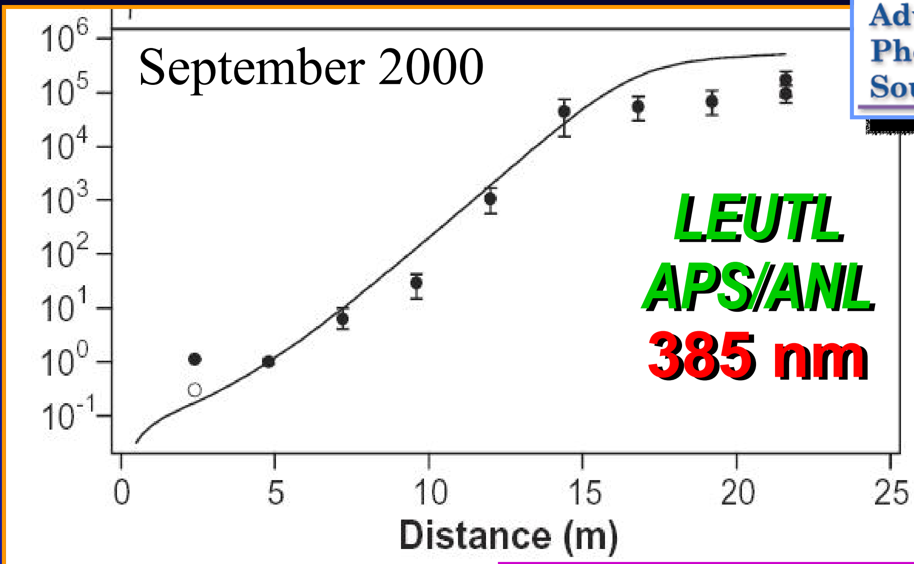
SASE Saturation Results

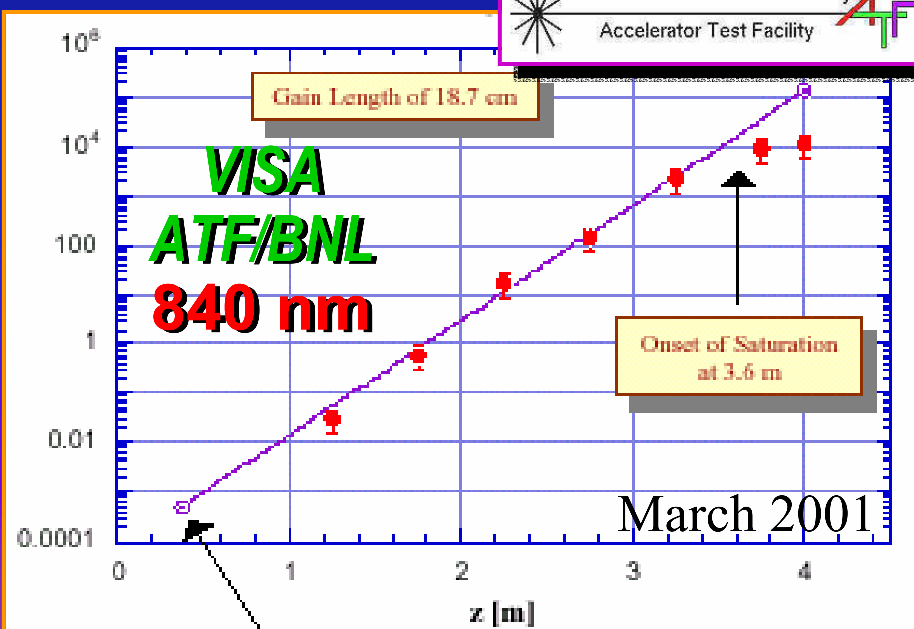
XFEL → 0.1 nm

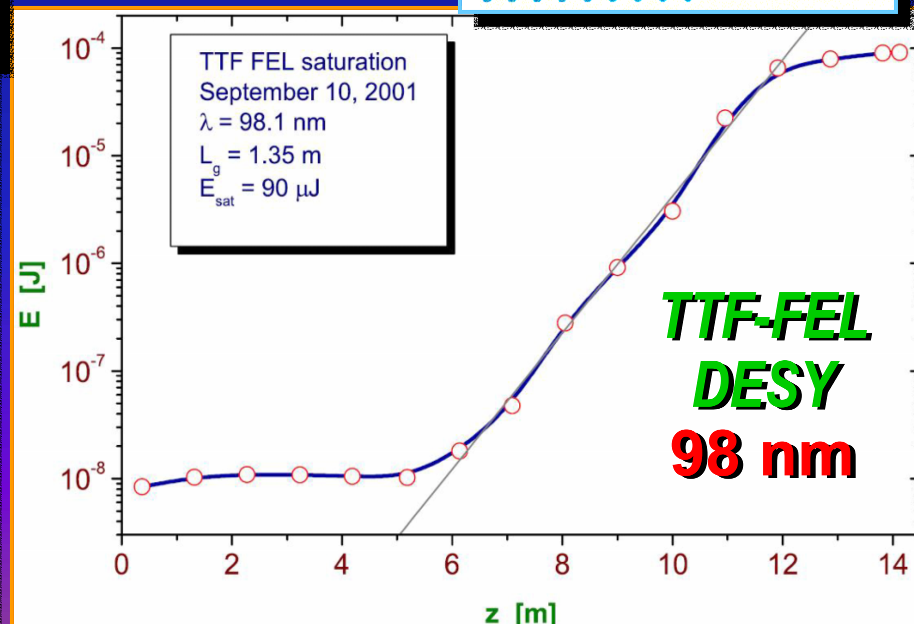
(or 1 Å)

Just 20 months ago:
SASE saturation not yet demonstrated

Since September 2000:
3 SASE FEL's demonstrate saturation





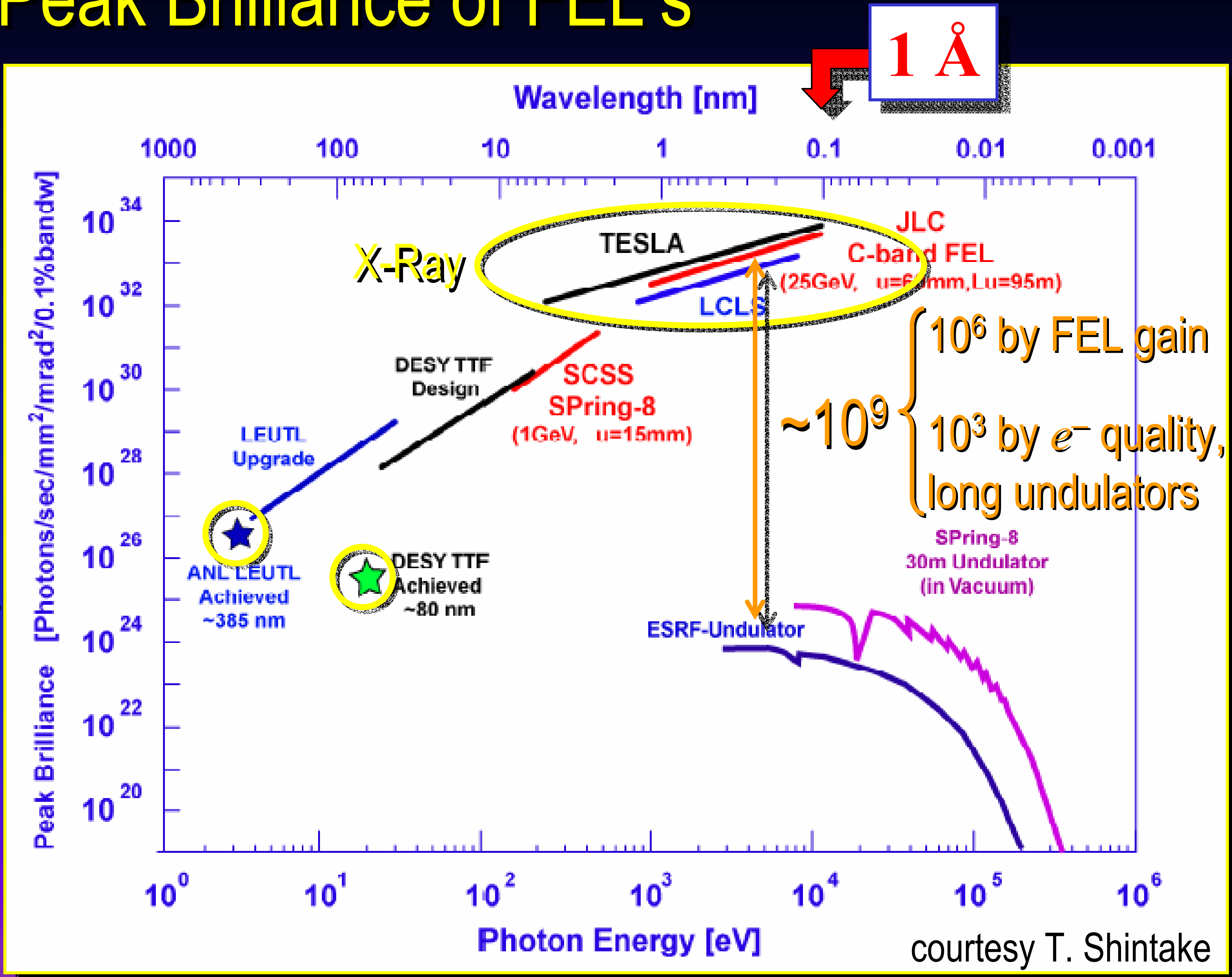


Proposed/Planned SASE X-Ray FEL's

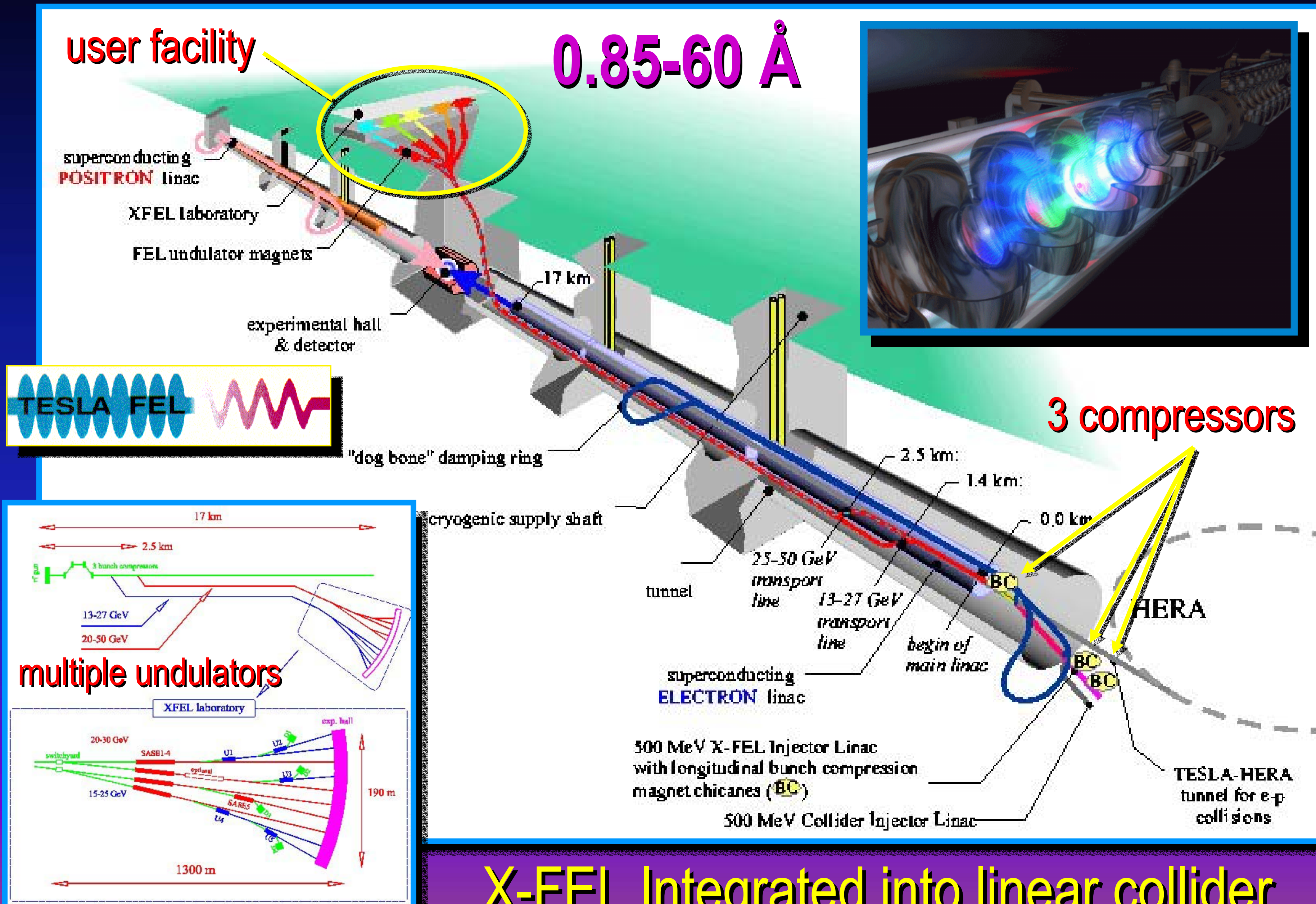
- TESLA-XFEL at *DESY* (0.85-60 Å)
- LCLS at *SLAC* (1.5-15 Å)
- INFN/ENA FEL in Roma (15 Å)
- Fermi FEL at *Trieste* (12 Å)
- SCSS at *Spring-8* (36 Å)
- 4GLS FEL at *Daresbury* (SXR)
- SASE-FEL at *BESSY* (12-600 Å)

Peak Brilliance of FEL's

photons per phase-space volume per band-width

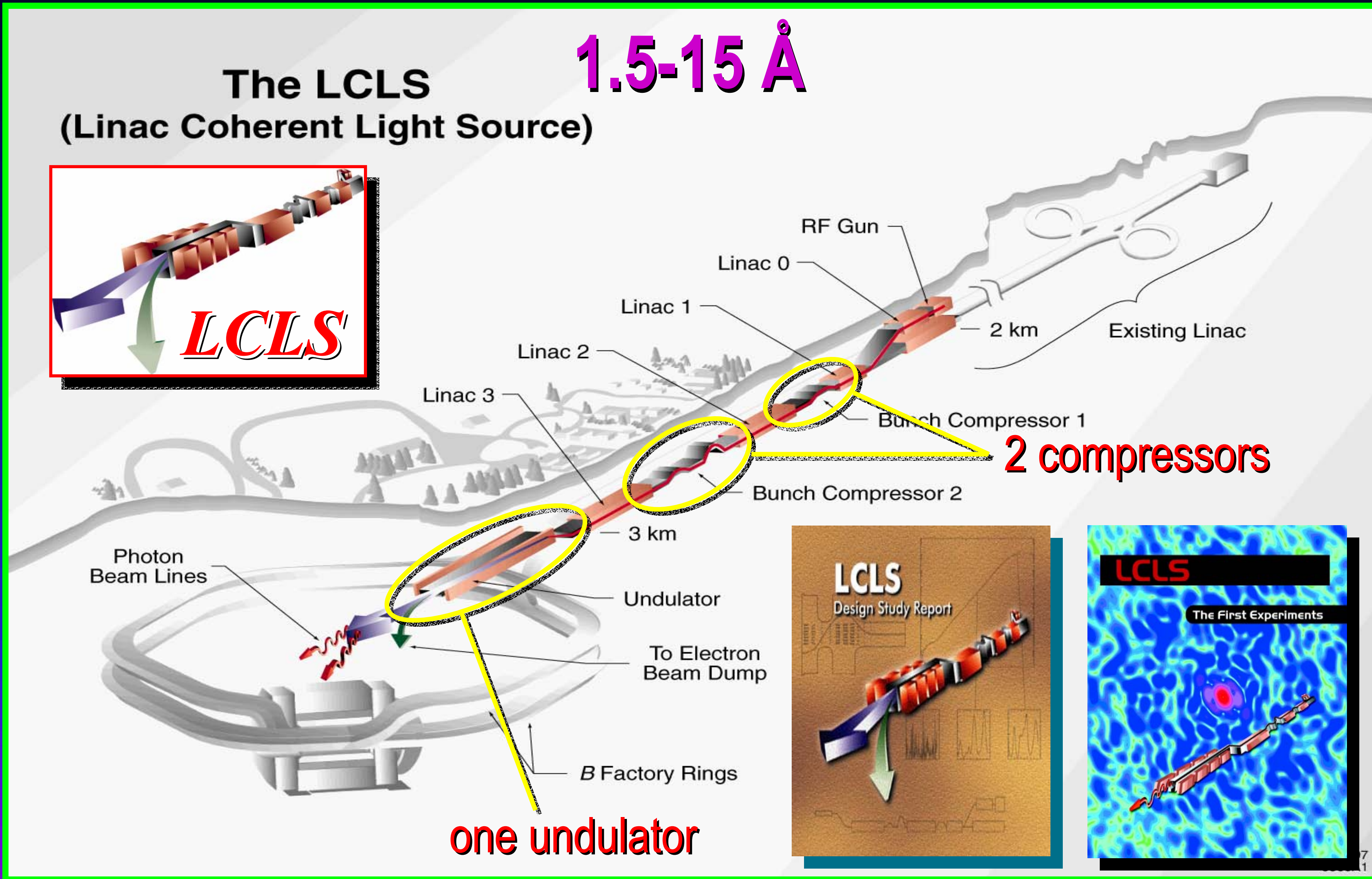


TESLA XFEL at *DESY*



X-FEL Integrated into linear collider

LCLS at *SLAC*



X-FEL based on last 1-km of existing *SLAC* linac

SASE FEL Electron Beam Requirements

$$\varepsilon_N < \gamma \frac{\lambda_r}{4\pi}$$

radiation wavelength (~1.5 μm realistic goal)

transverse emittance: $\varepsilon_N < 1\ \mu$m at 1 A, 15 GeV

peak current

undulator period

$$\sigma_\delta < \rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_N}\left(\frac{K}{\gamma}\right)^2\right)^{1/3}$$

energy spread: <0.08% at I_{pk} = 4 kA, $K \approx 4$, $\lambda_u \approx 3$ cm, …

beta function

undulator ‘field’

$$L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

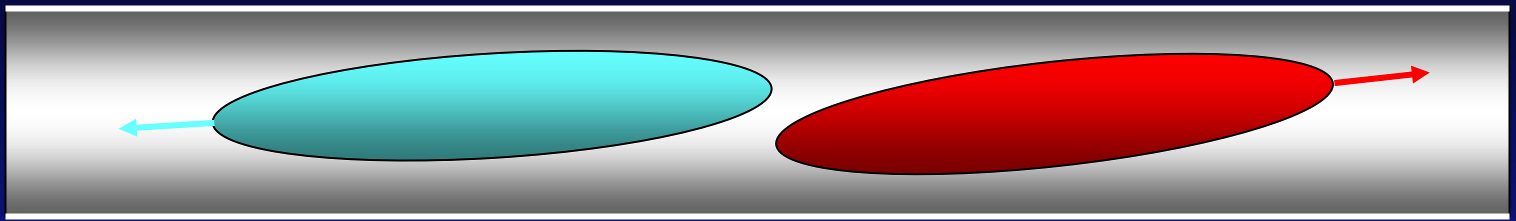
FEL gain length: $20L_g$ > 100 m for $\varepsilon_N \approx 1.5\ \mu$m

Need to increase peak current, preserve emittance, and maintain small energy spread, all simultaneously

AND provide stable operation

‘Slice’ versus ‘Projected’ Emittance

For a collider…



…collision integrates over bunch length — emittance ‘***projected’*** over the bunch length is important

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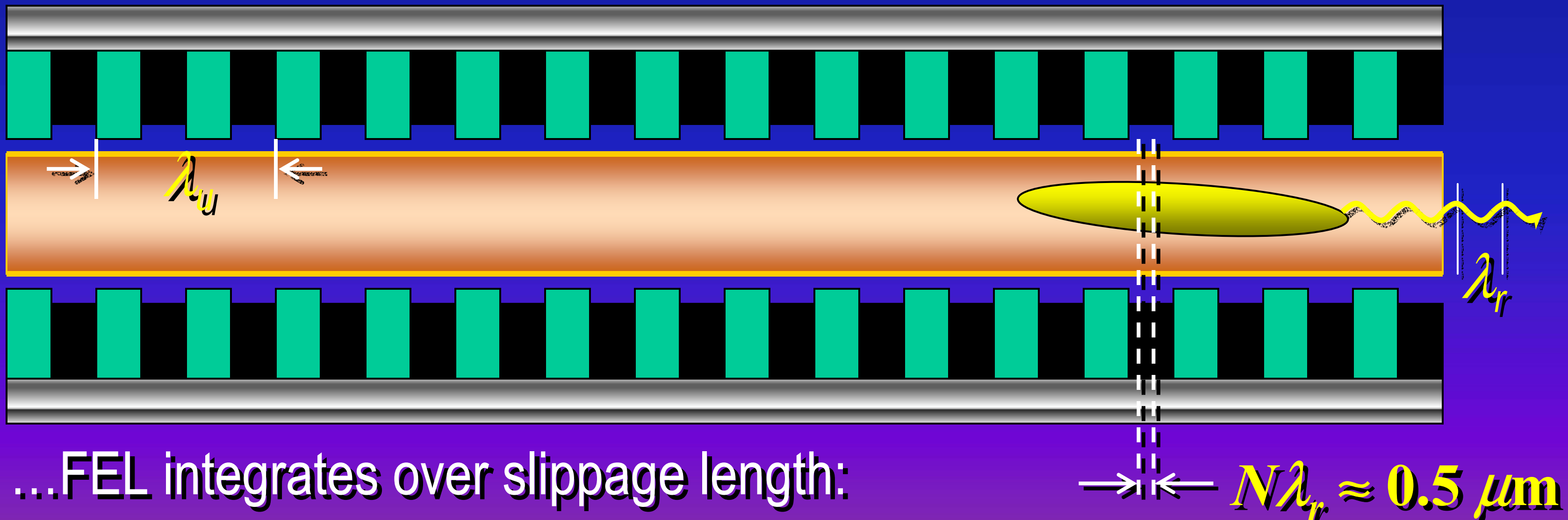
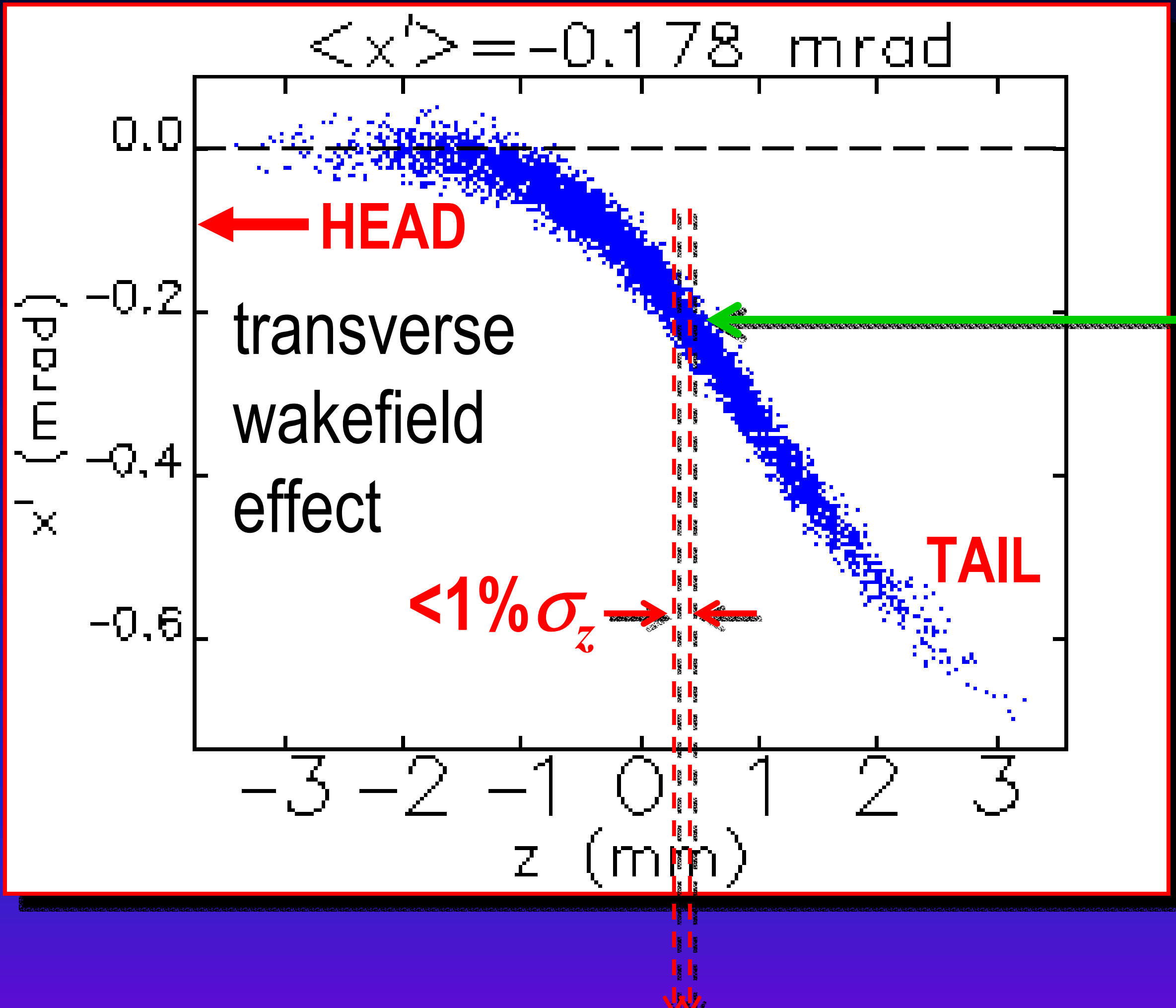
For an FEL… e^- slips back in phase w.r.t. photons by λ_r per period



…FEL integrates over slippage length:
‘***slice’*** emittance (and *E*-spread) is important

Slice Emittance is Less Sensitive



however, centroid shifts of slices can be important

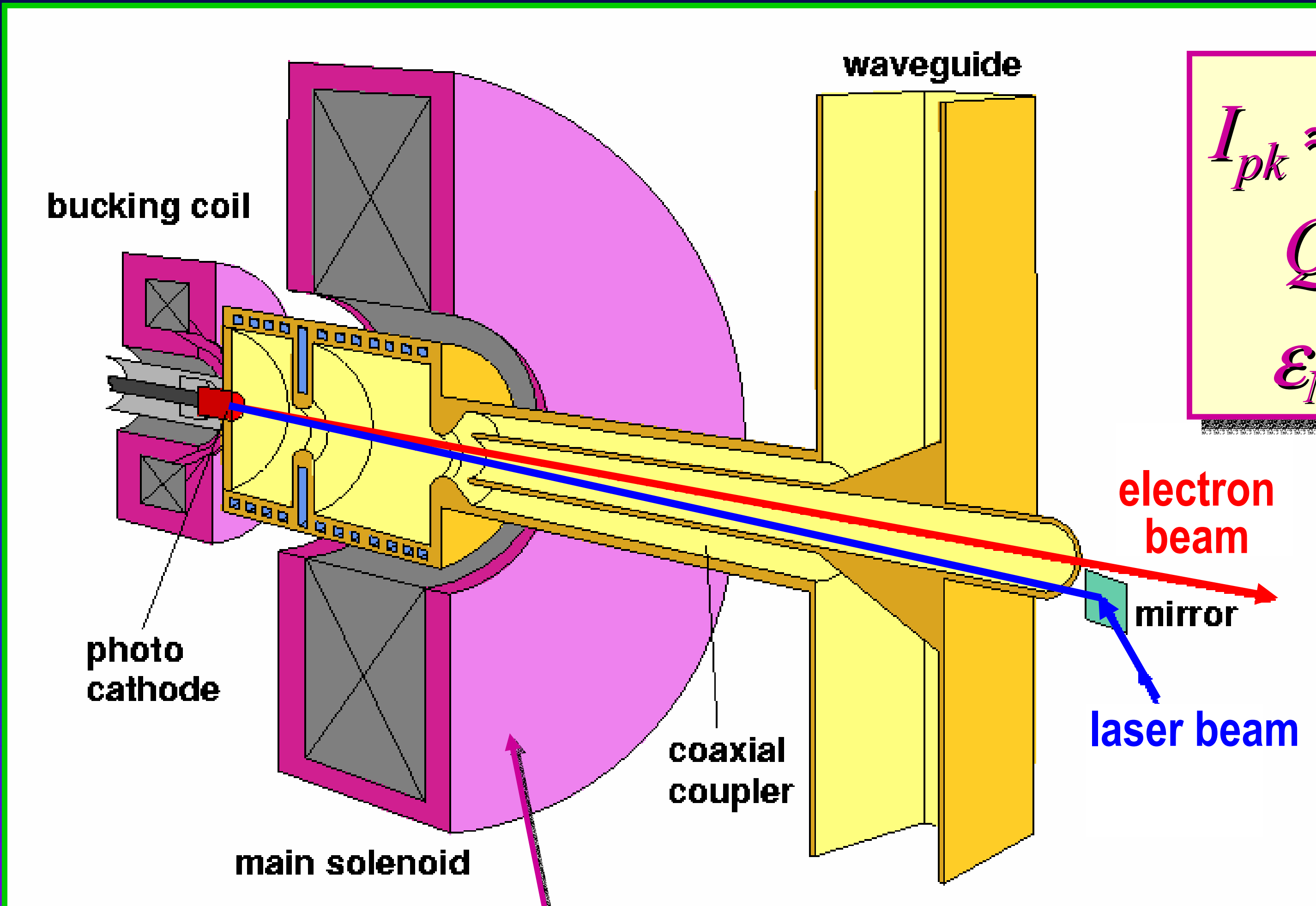
…as can β variations along bunch

emittance of short 'slice' not affected by transverse wakes

…also true for quad-misalignments, CSR, and RF kicks

RF Photo-Cathode Gun

rapid RF-acceleration to avoid space-charge dilution



$I_{pk} \approx$ 50-100 A

$Q \approx$ 1 nC

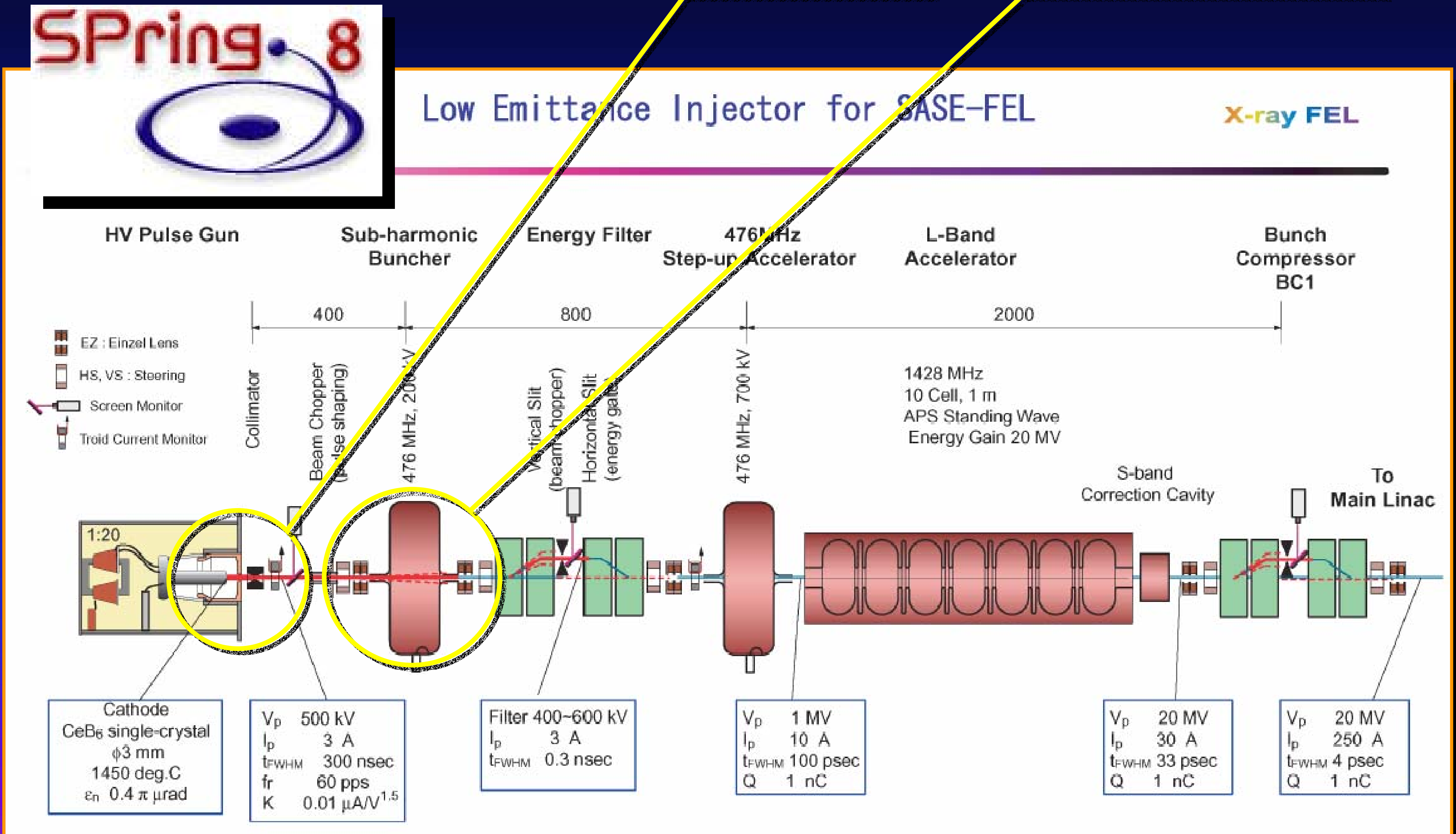
$\varepsilon_N \approx$ 1 µm

emittance compensation solenoid

courtesy J. Rossbach

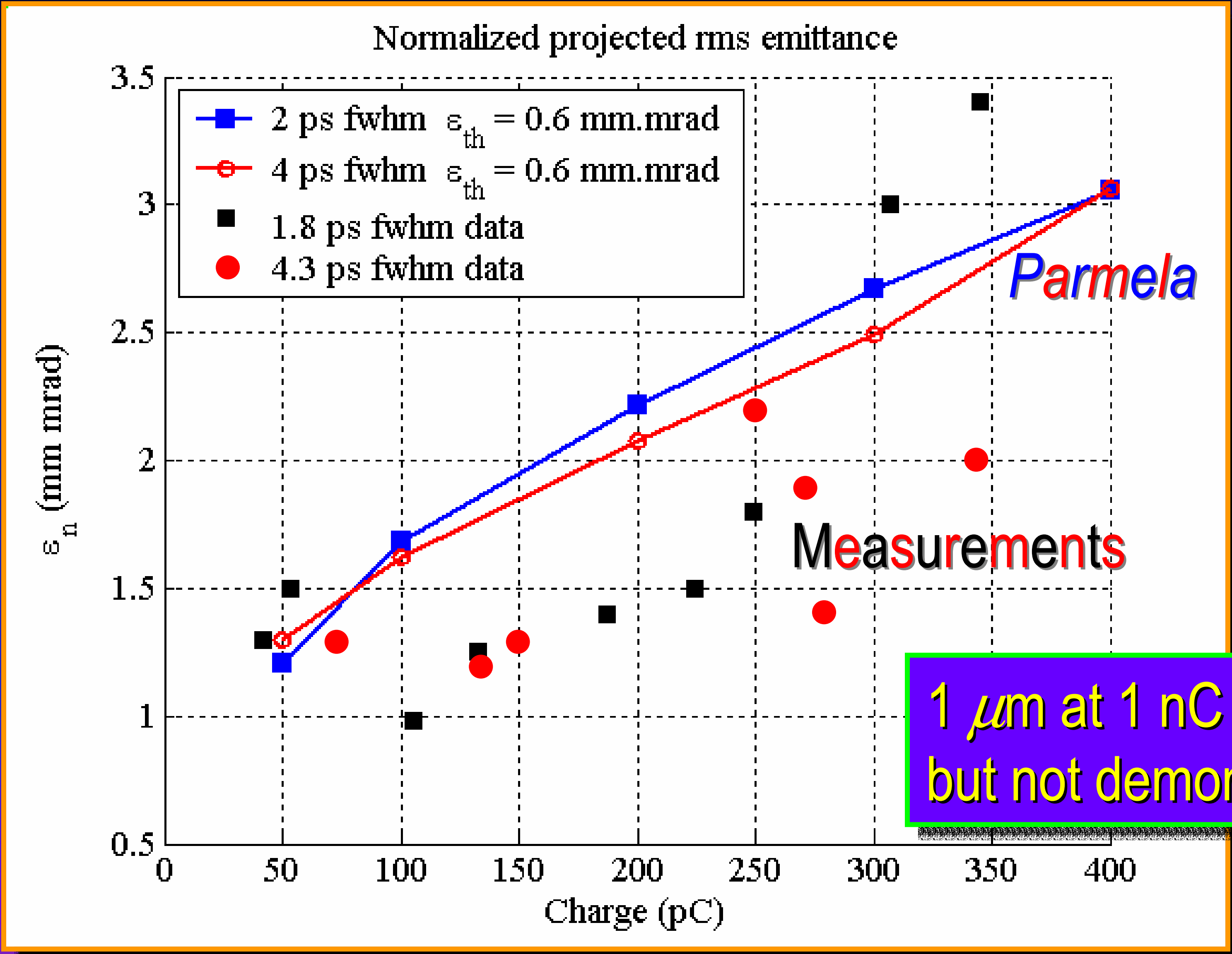
Thermionic pulsed high-voltage gun

…at Spring-8 *SCSS* (0.1-0.5 nC), CeB_6 cathode and sub-harm. bunchers



T. Shintake, TUPRI116

Emittance Results from Gun Test Facility at SLAC



'projected' emittance at reduced charge levels

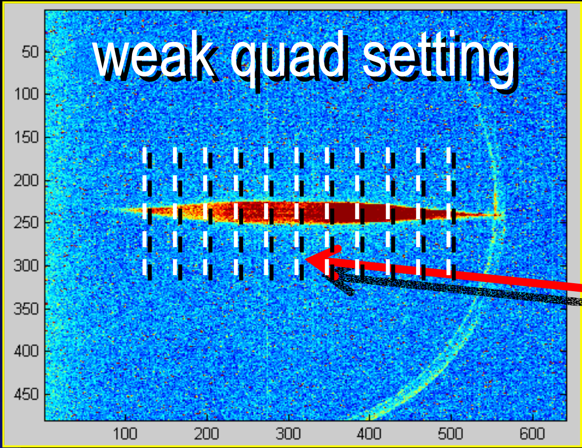
gaussian bunch at GTF limits $\gamma\varepsilon_x$

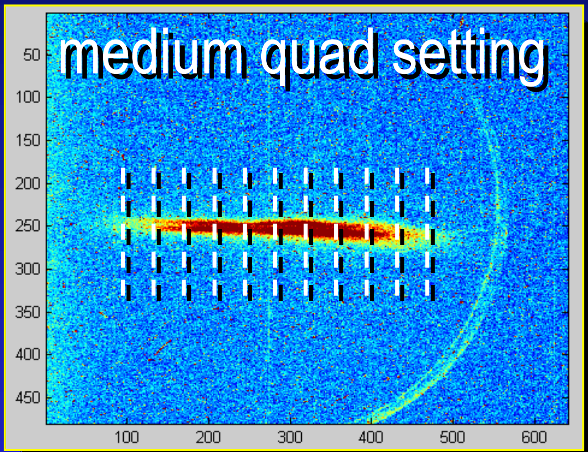
1 μm at 1 nC possible, but not demonstrated yet

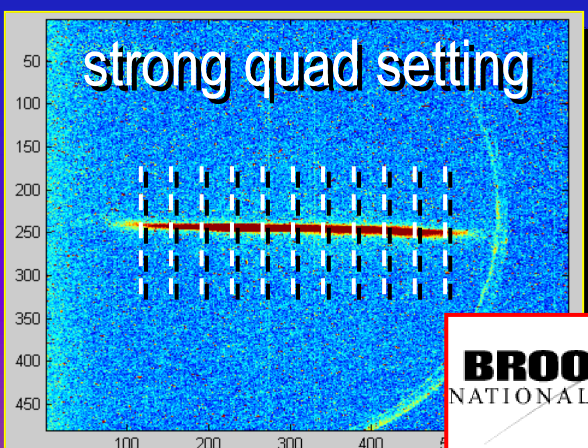
C. Limborg, TUPRI041, TUPRI042, TUPRI043

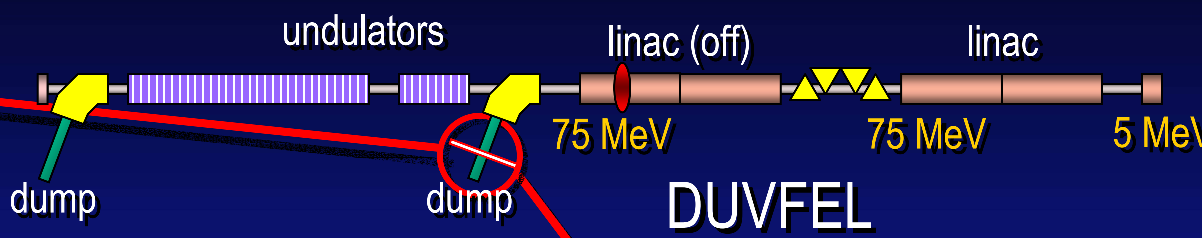
courtesy S. Gierman, J. Schmerge

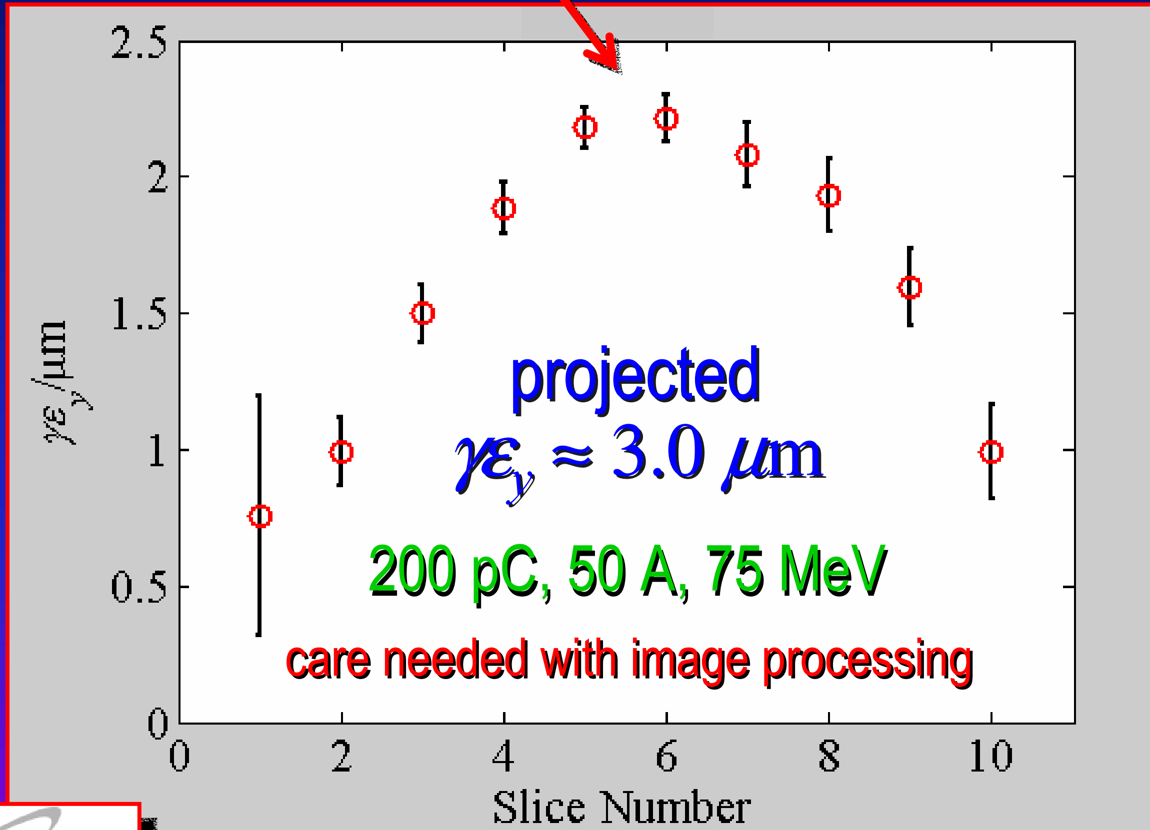
Slice ε_y Measurements at *BNL*





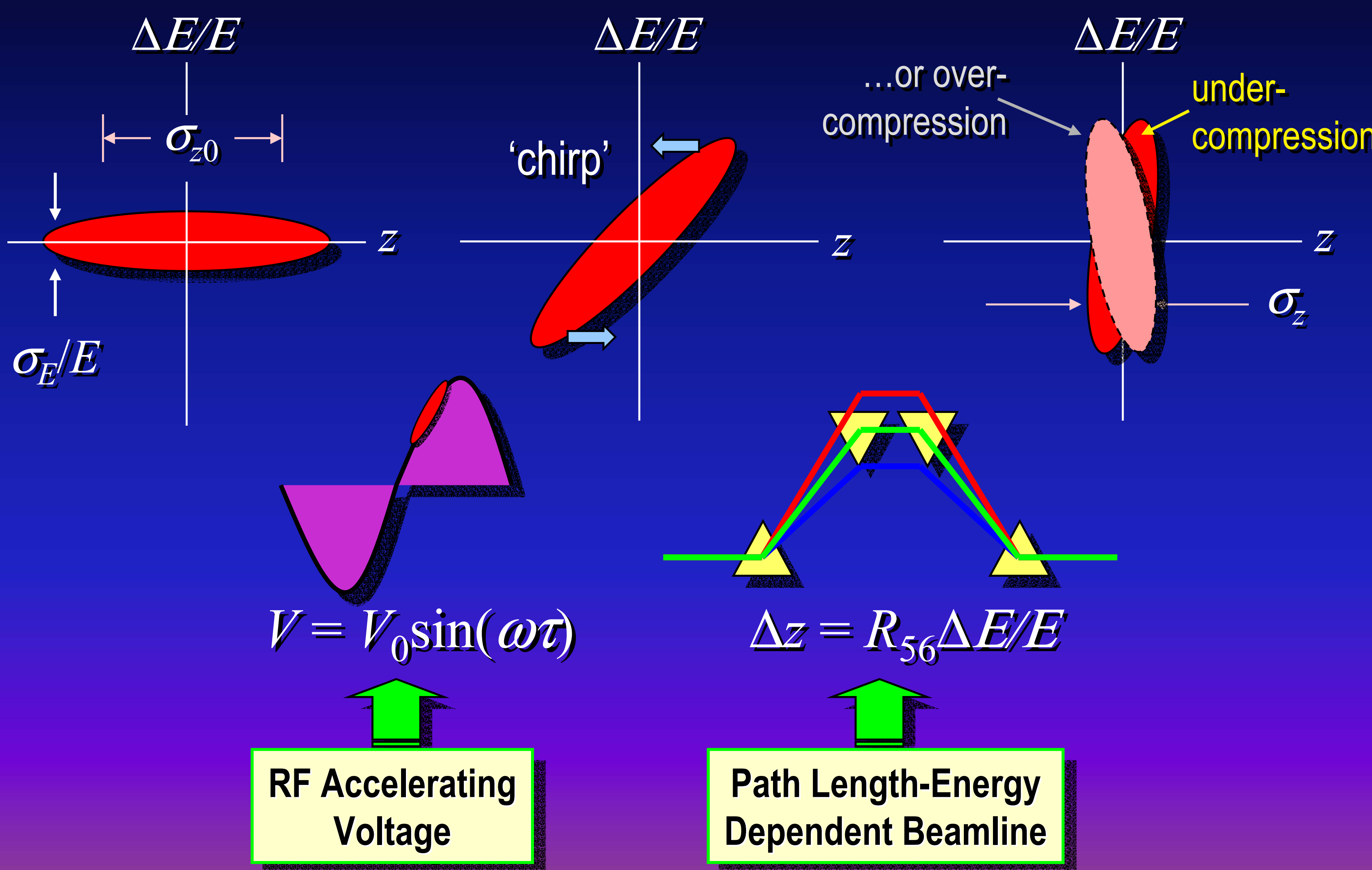






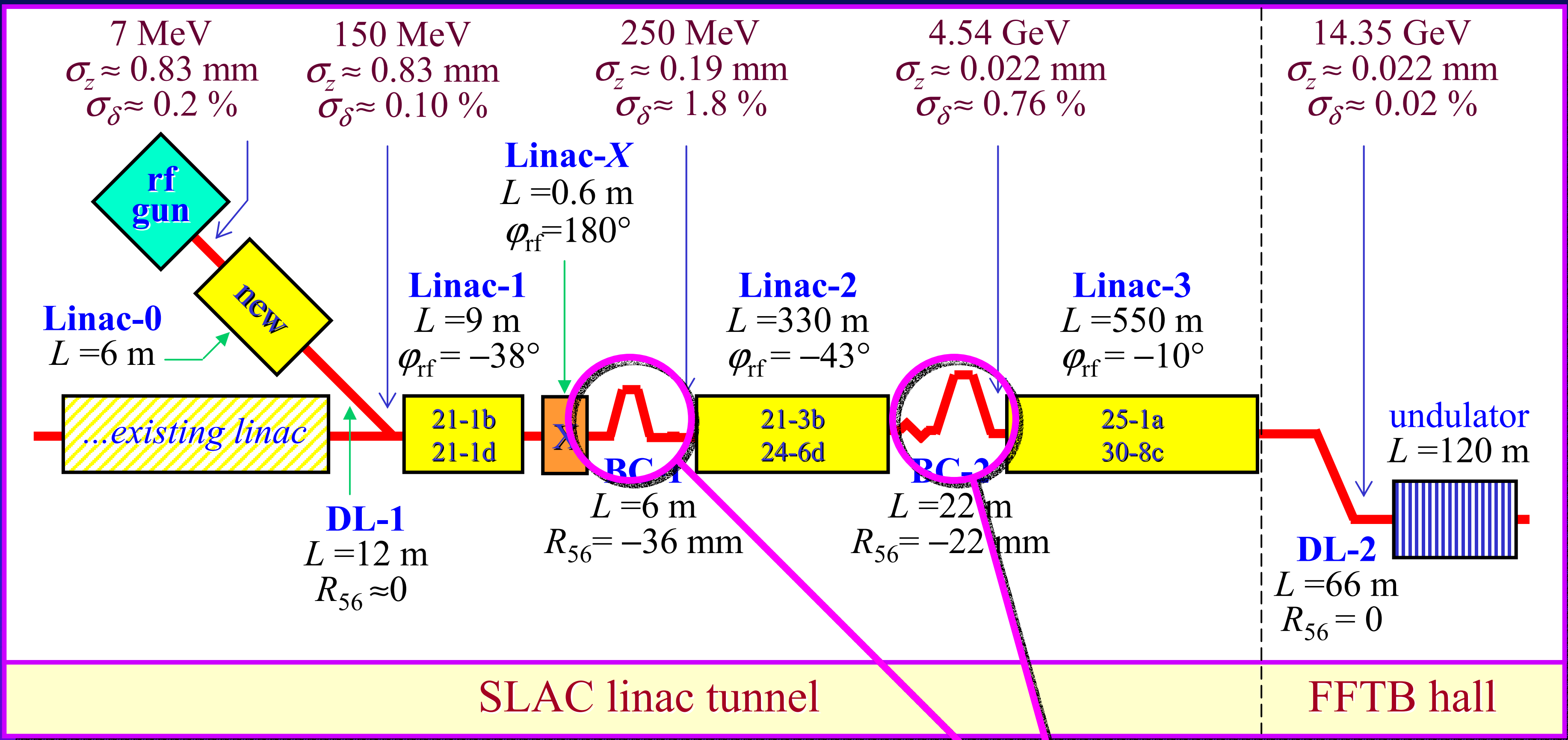
Data from SDL at *BNL*: W. Graves, et al.

Magnetic Bunch Compression



LCLS Linac Parameters for 1.5-Å FEL

single bunch, 1-nC, 120-Hz



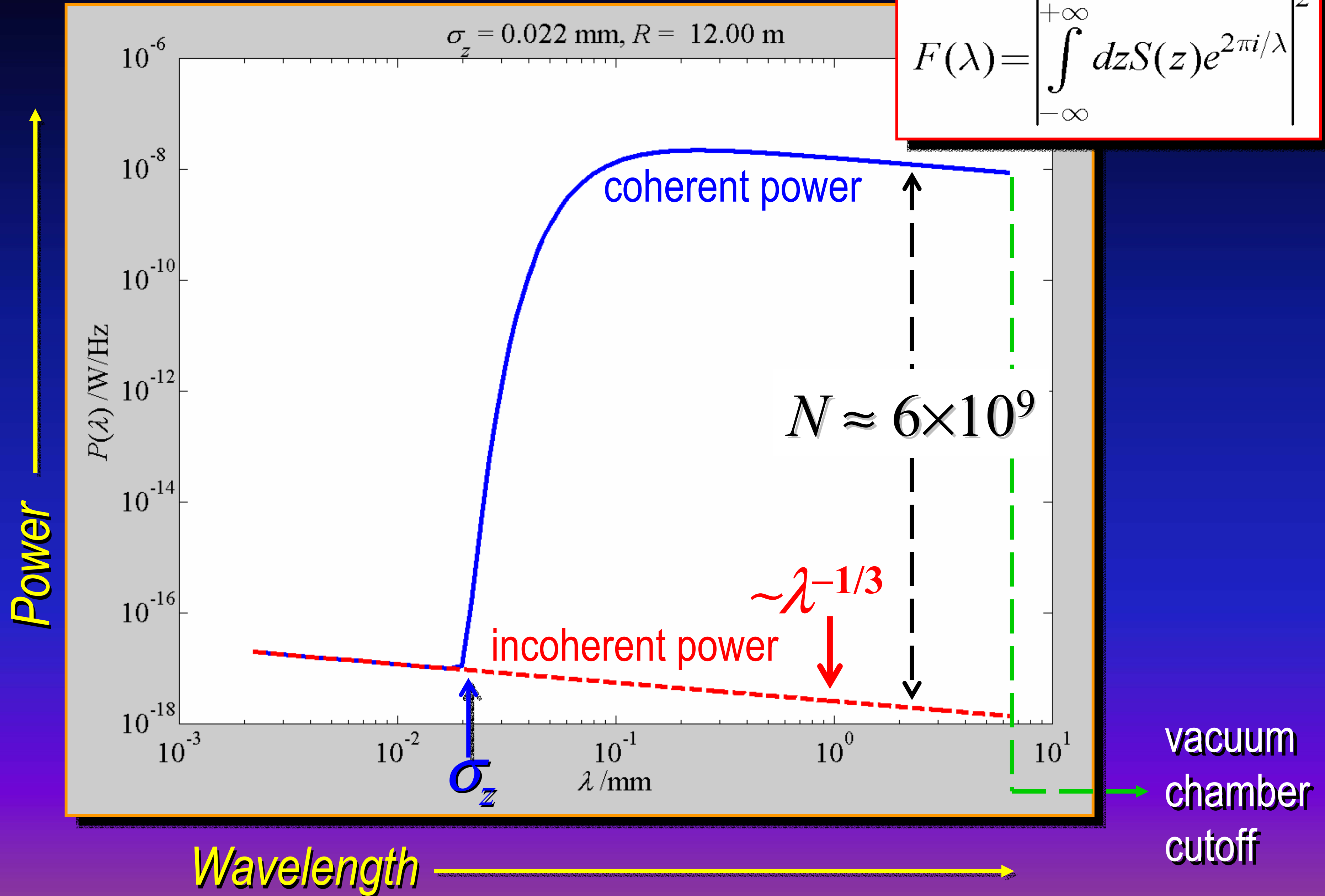
(RF phase: ϕ_{rf} = 0 at accelerating crest)

Two stages of bunch compression

Coherent Synchrotron Radiation

$$P(\lambda) = P_0 N\{1 + NF(\lambda)\}$$

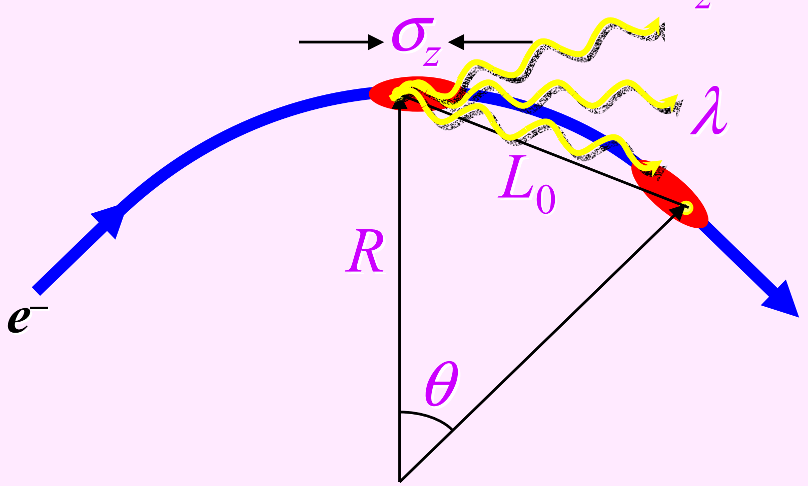
$$F(\lambda) = \left| \int_{-\infty}^{+\infty} dz S(z) e^{2\pi i/\lambda} \right|^2$$



Coherent Synchrotron Radiation (CSR)

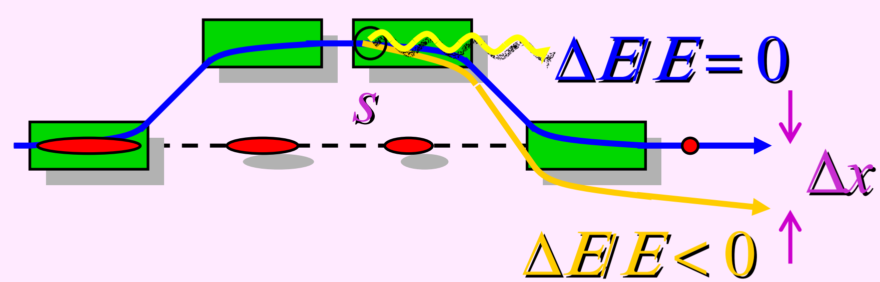
- Powerful radiation generates energy spread in bends
- Energy spread breaks achromatic system
- Causes bend-plane emittance growth (short bunch worse)

coherent radiation for $\lambda > \sigma_z$



overtaking length: $L_0 \approx (24\sigma_z R^2)^{1/3}$

bend-plane emittance growth

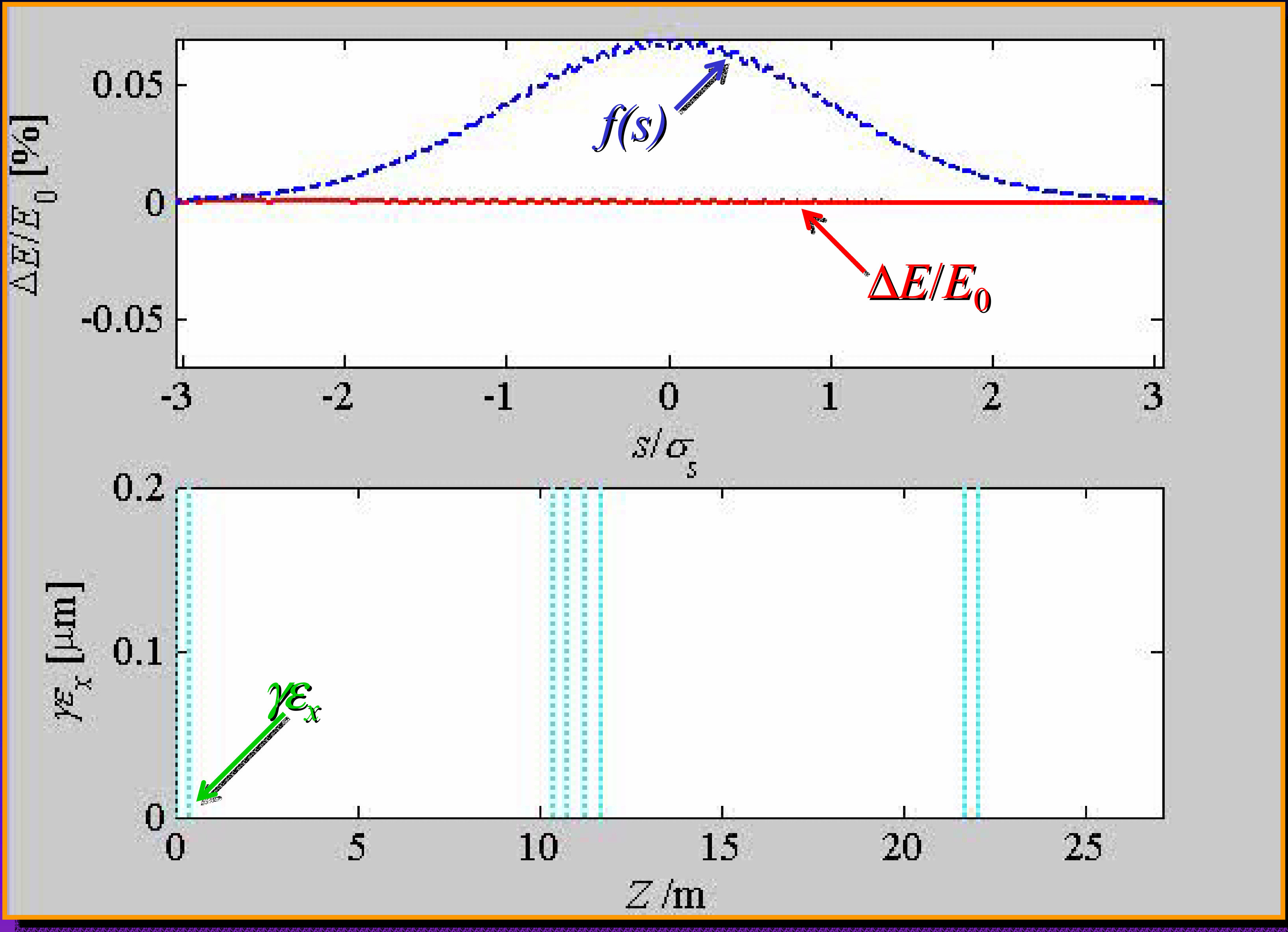


$$\Delta x = R_{16}(s)\Delta E/E$$

$$W(s) \sim \int_{s-R\phi^3/24}^{s} \frac{1}{(s-s')^{1/3}} \frac{\partial\lambda(s')}{\partial s'} ds'$$

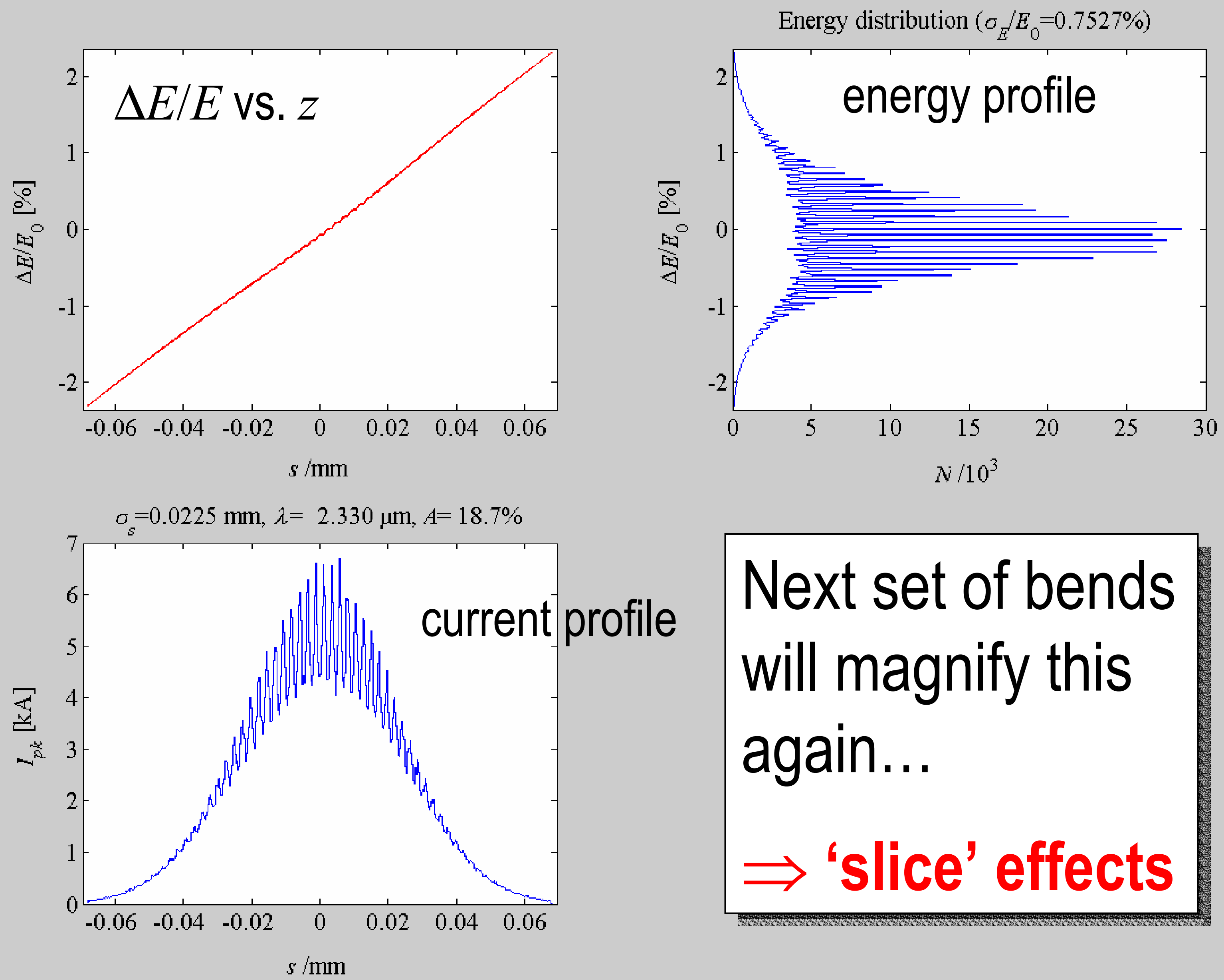
CSR wake is strong at very small scales (~1 μm)

CSR Microbunching* Animation



* First observed by M. Borland (ANL) in LCLS ***Elegant*** tracking

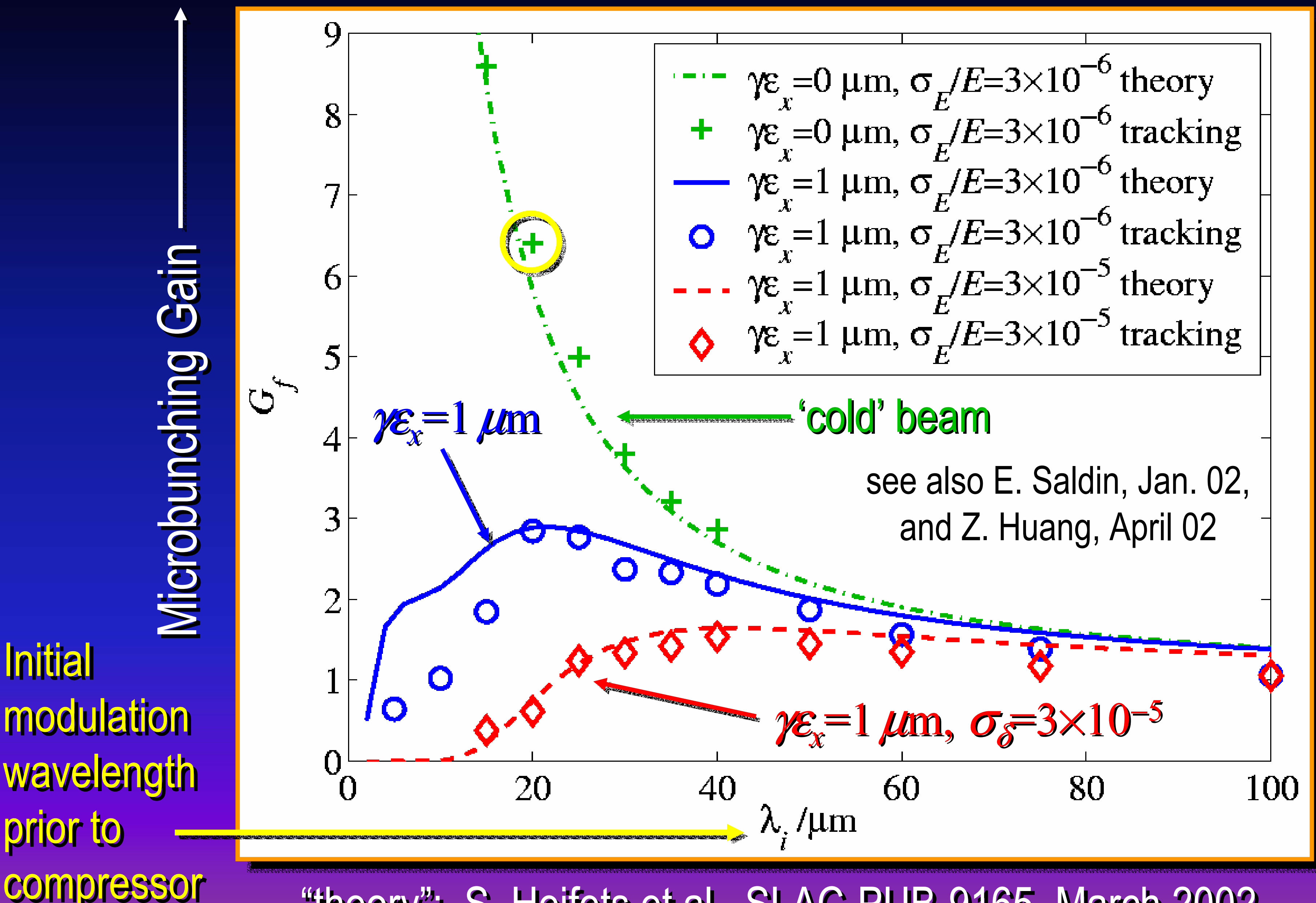
…Energy Profile also modulated



Next set of bends will magnify this again…

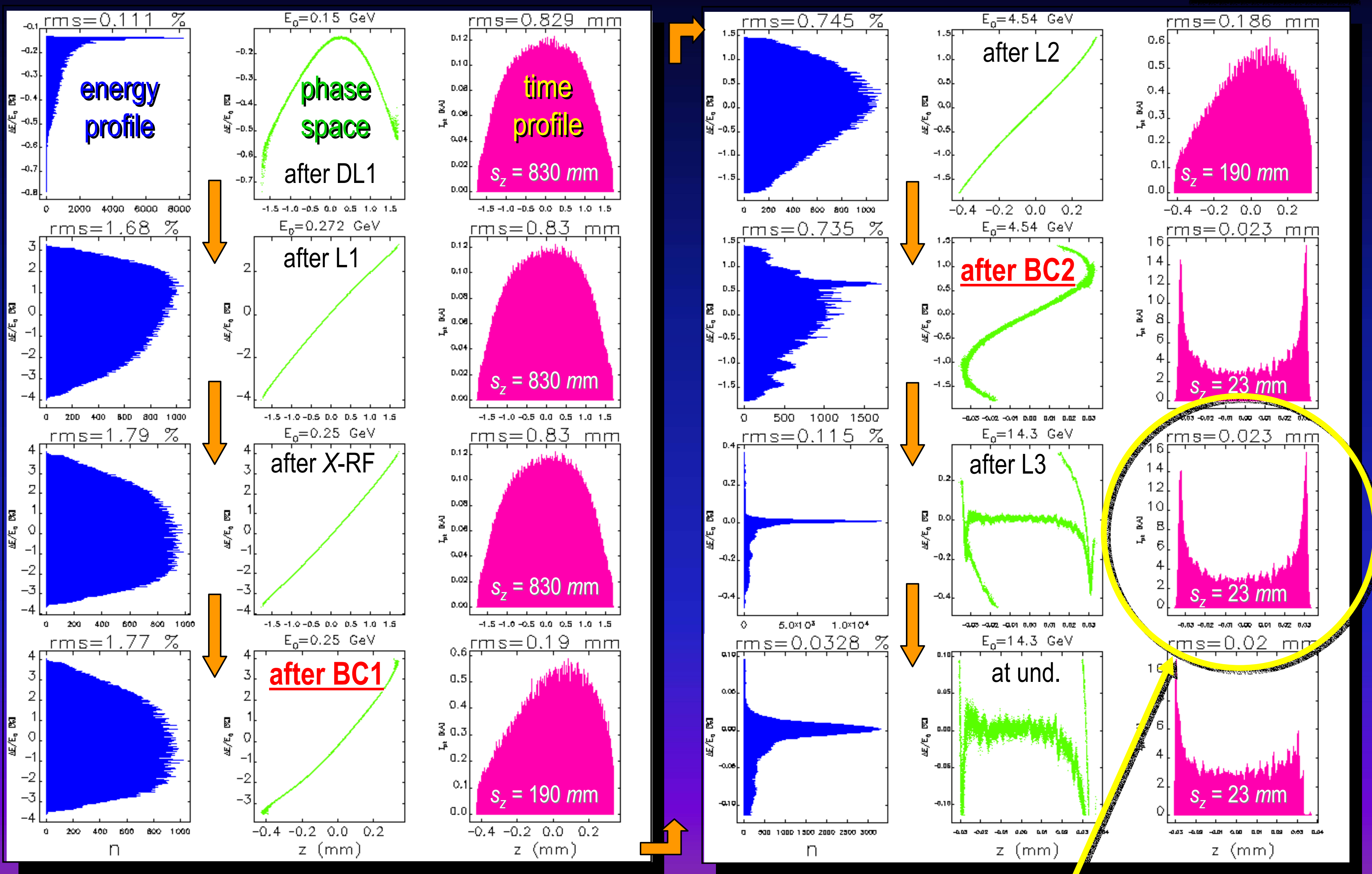
⇒ **'slice' effects**

CSR Microbunching Gain vs. λ



"theory": S. Heifets et al., SLAC-PUB-9165, March 2002

Evolution of *LCLS* Longitudinal Phase Space

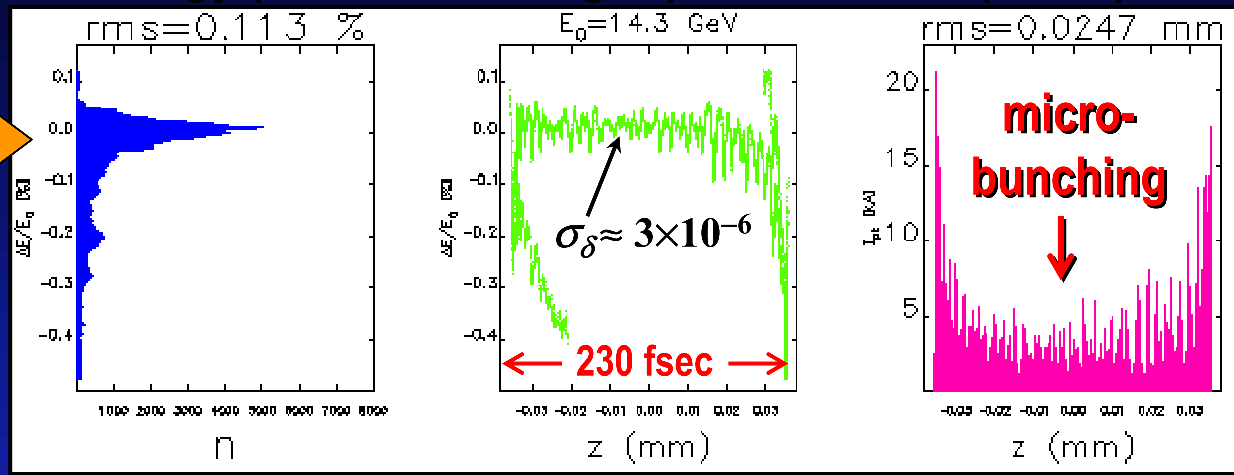


Current spikes further drive CSR

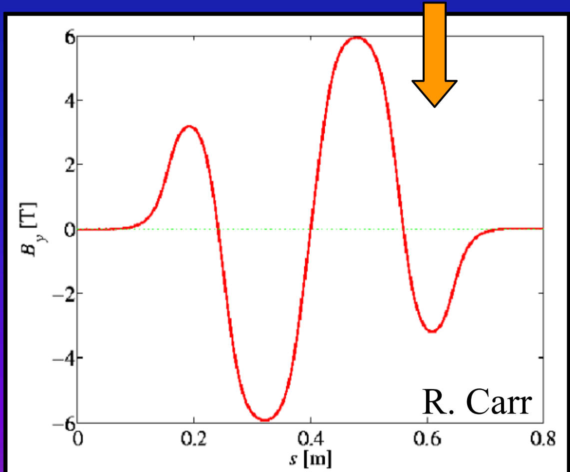
CSR Micro-bunching in *LCLS*

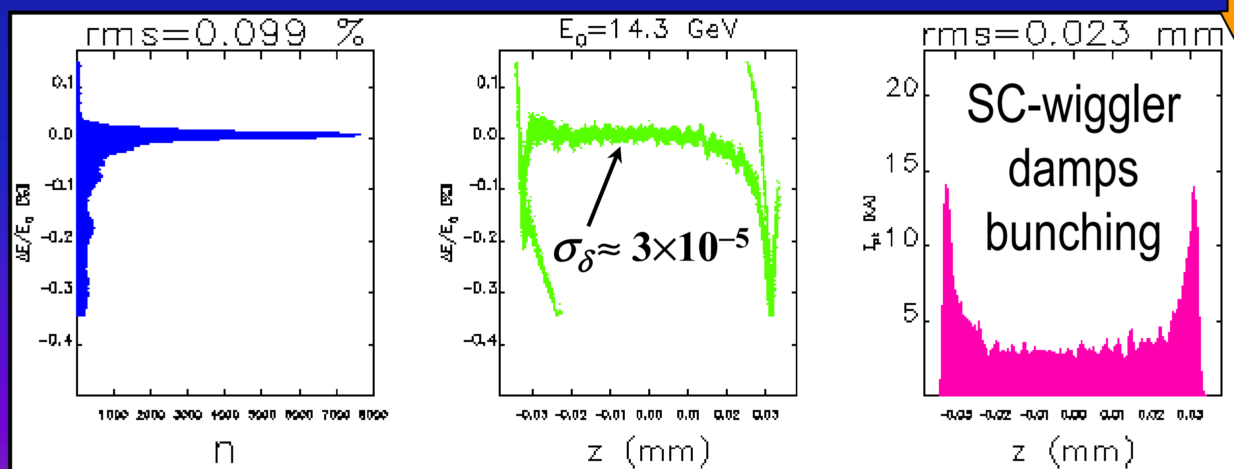
energy profile　　long. space　　temporal profile

CSR can amplify small current modulations:



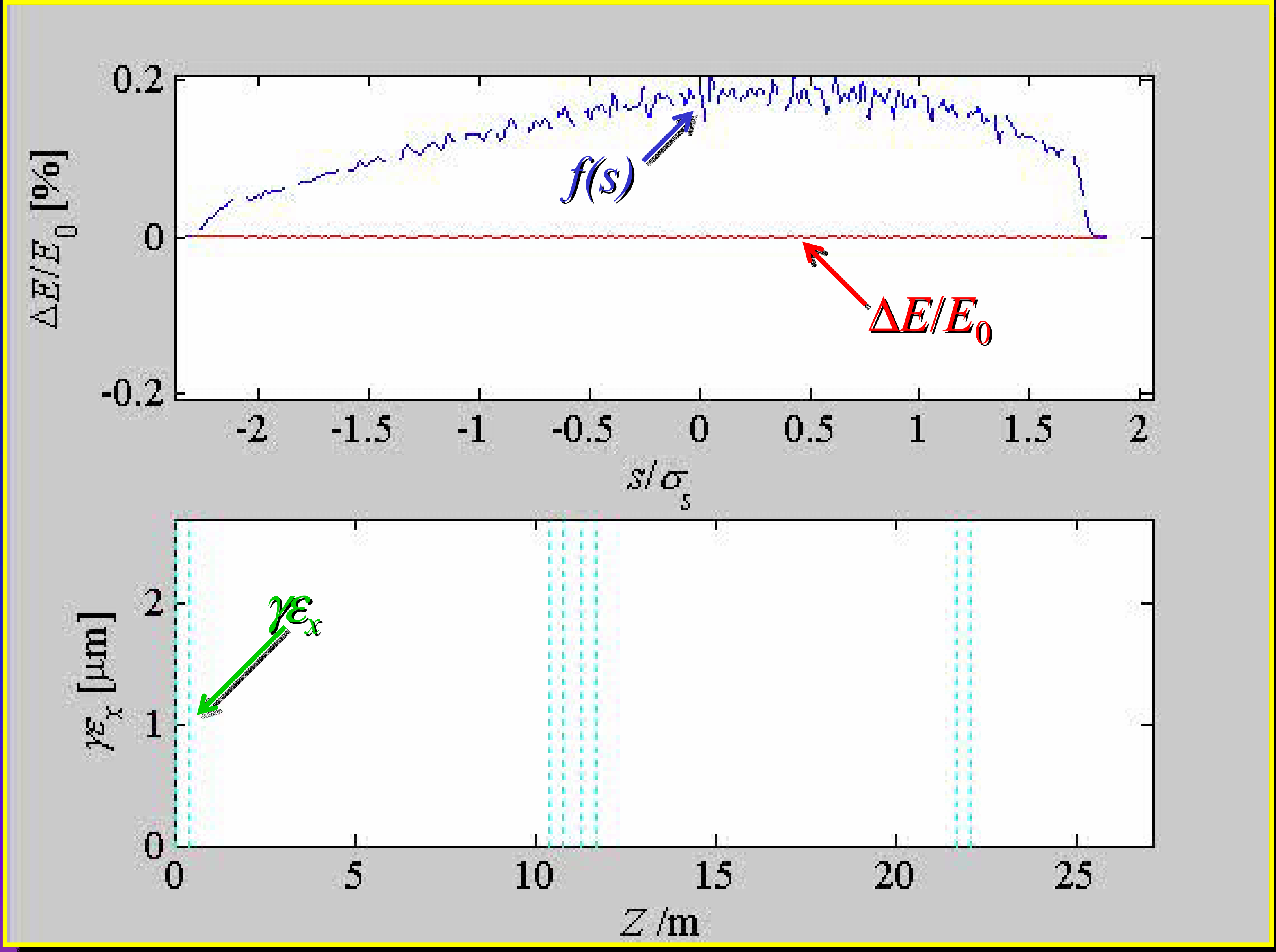
Super-conducting wiggler prior to BC increases uncorrelated *E*-spread ($3\times10^{-6} \rightarrow 3\times10^{-5}$)



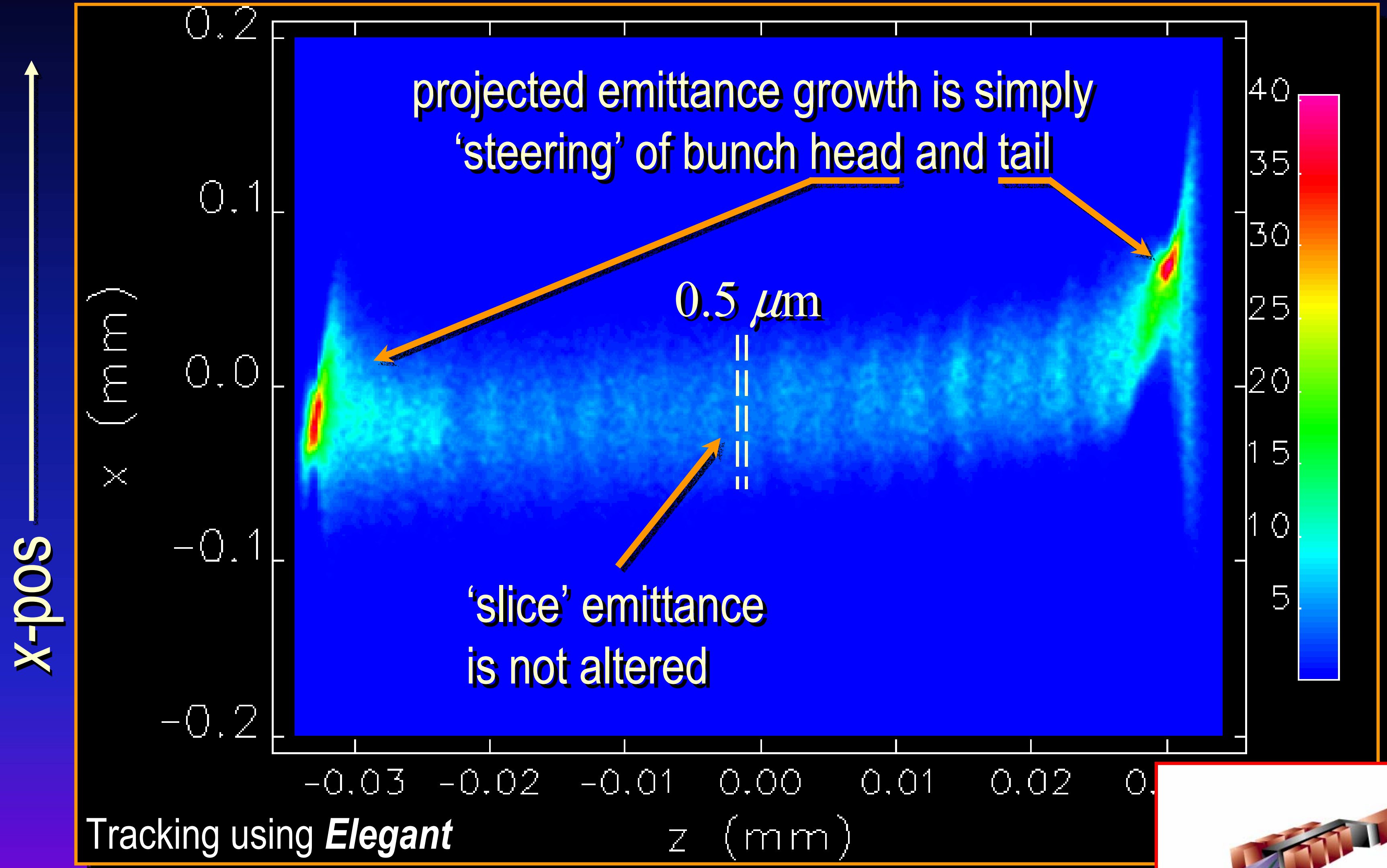


tracking with *Elegant* code, written by M. Borland, ANL

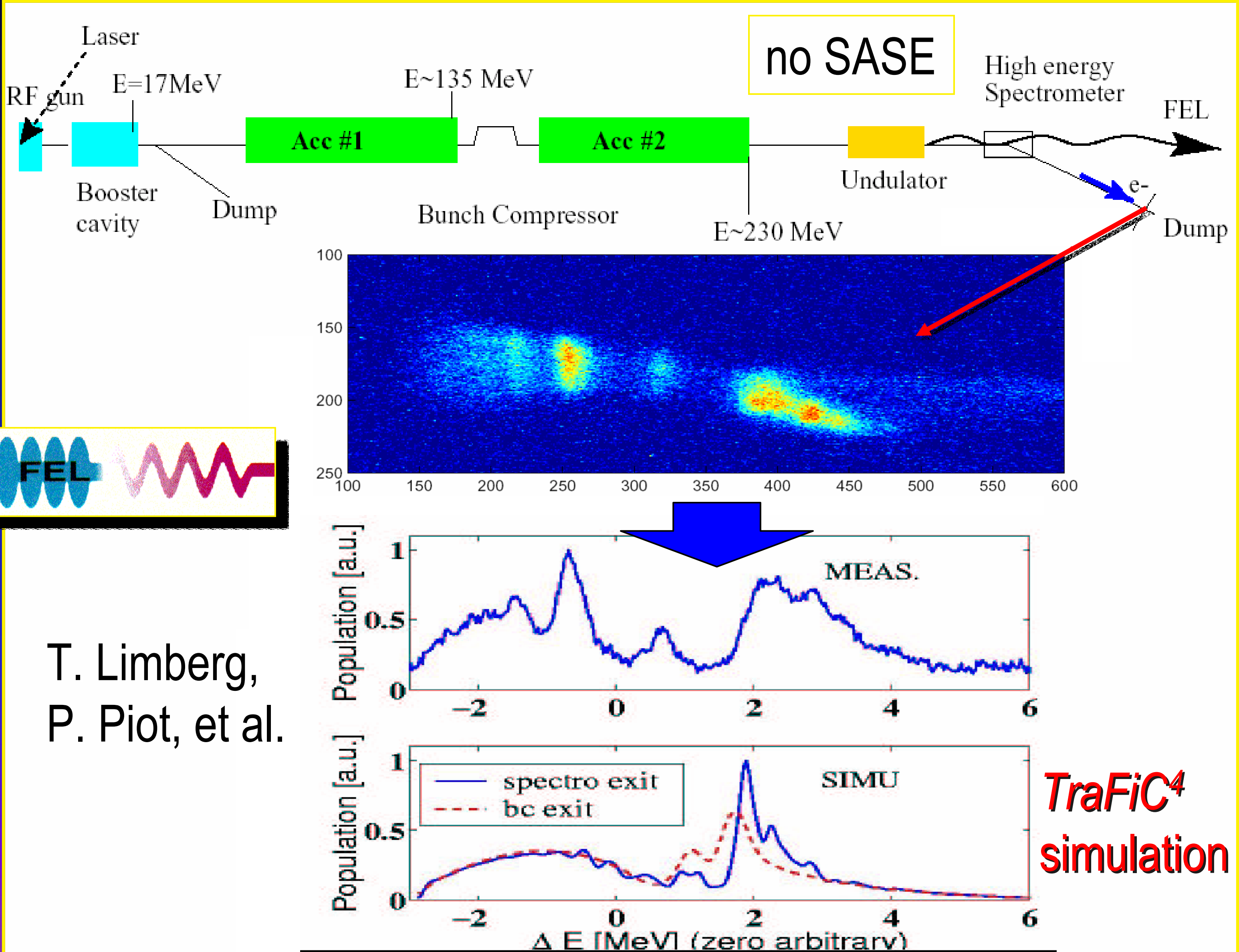
CSR in Chicane (animation through *LCLS* BC2)



CSR Projected Emittance Growth (simulated)



Energy Spectrum at TTF-FEL (DESY)



T. Limberg, P. Piot, et al.

TraFiC⁴ simulation

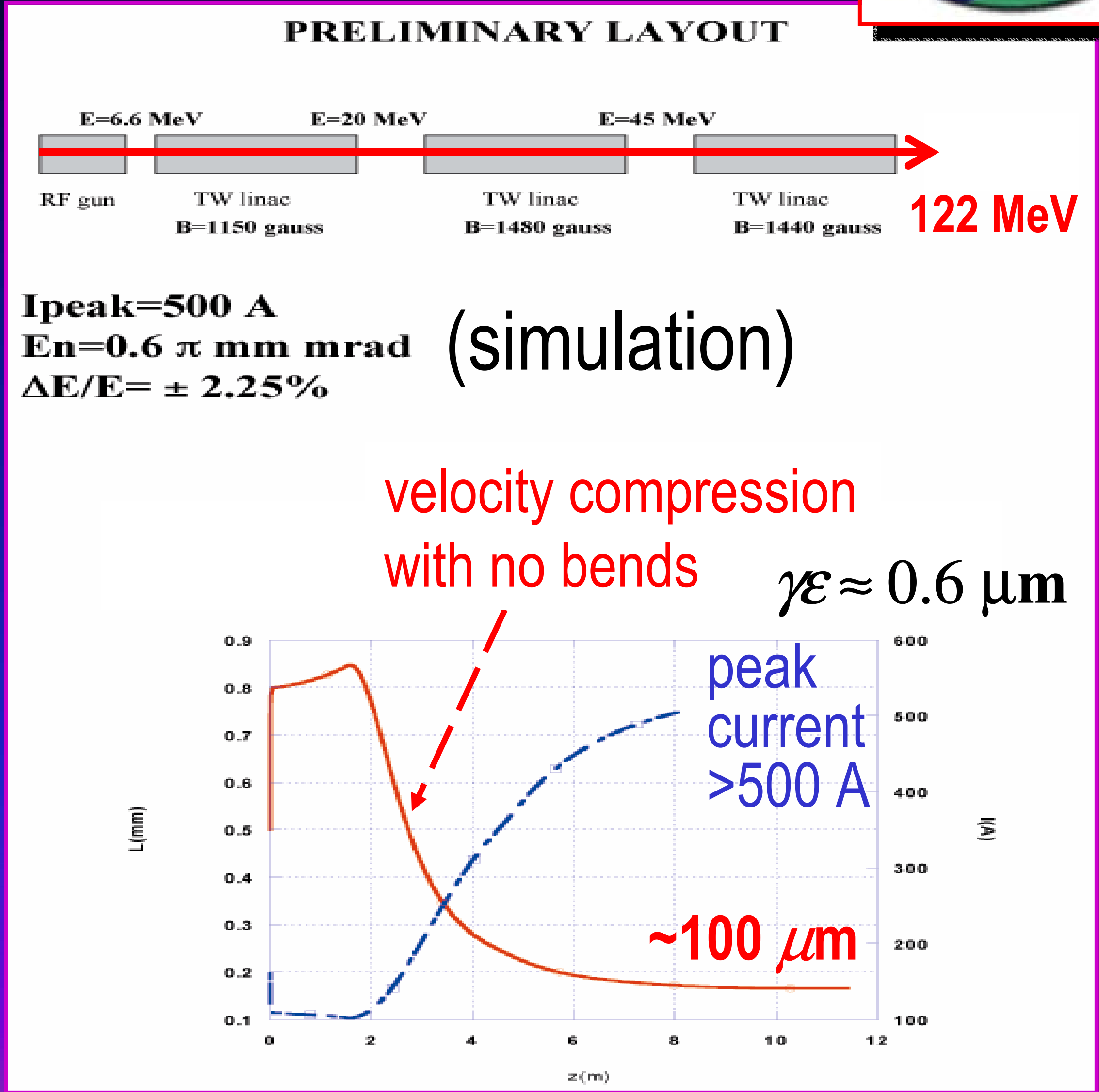
SPARC Project at INFN-LNF

1st stage bunch compression *without* bend magnets

SPARC Project @ INFN-LNF

Collab. Among ENEA-INFN-CNR-Univ. Roma2-ST-INFM

9.4 M€ funding

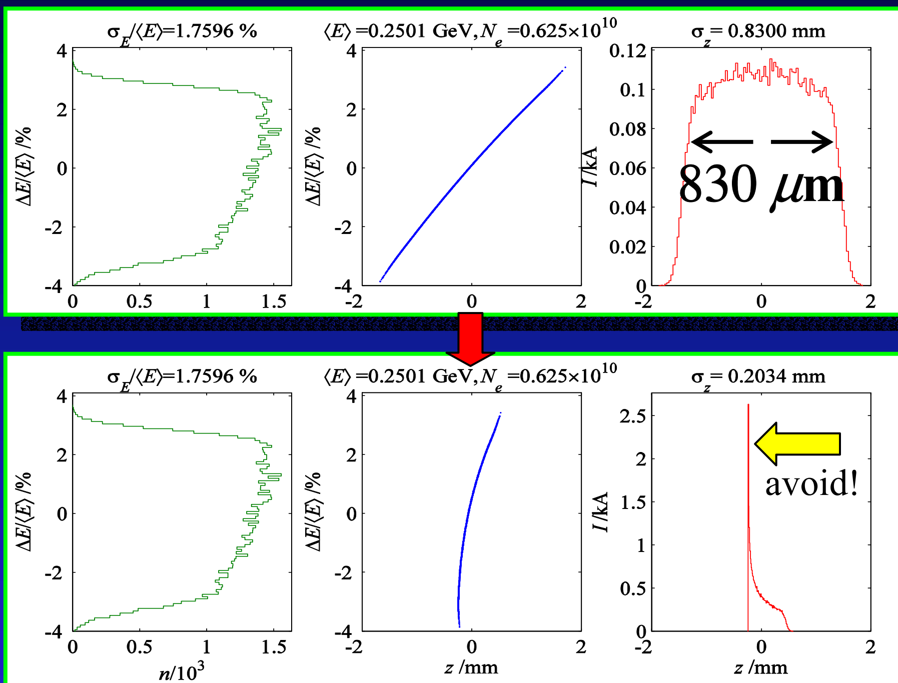


L Serafini, WEYLA001   M. Ferrario, TUPRI056

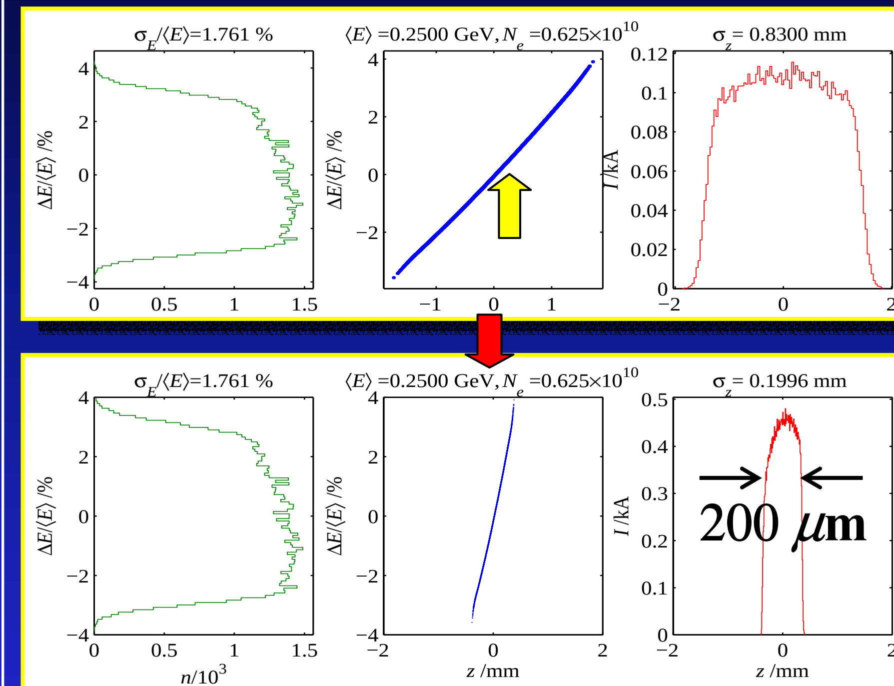
C. Ronsivalle

Harmonic RF used to Linearize Compression

RF curvature and 2nd-order compression cause current spikes



Harmonic RF at decelerating phase corrects 2nd-order and allows unchanged *z*-distribution



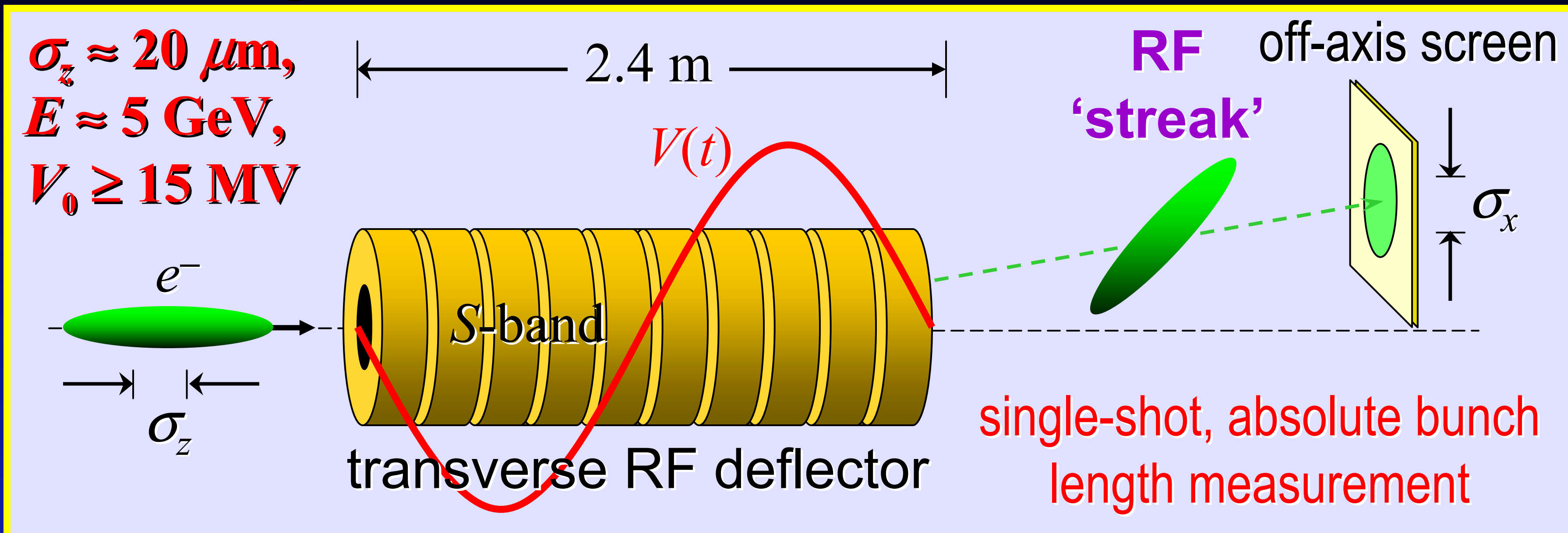
3rd harmonic used at TTF/TESLA

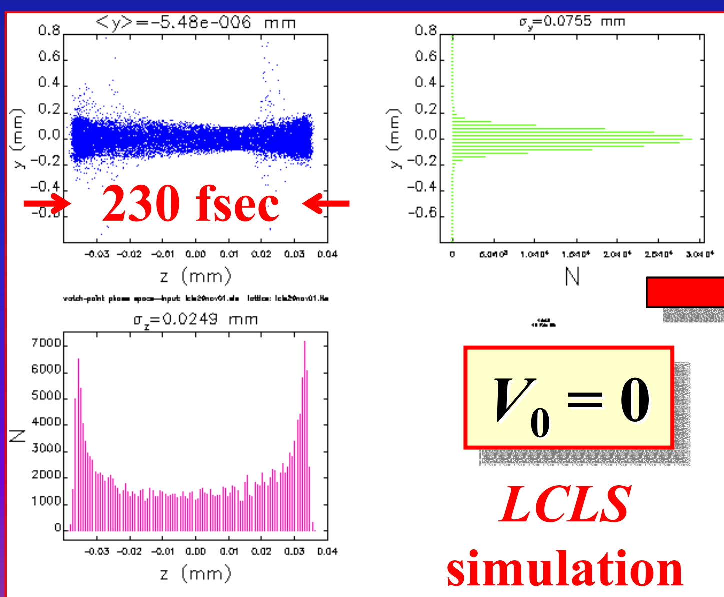
4th harmonic used at LCLS

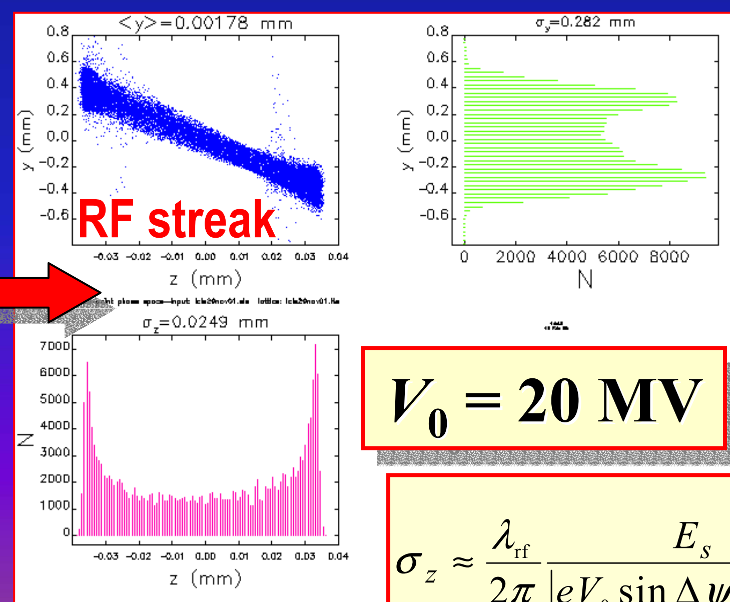
$$eV_x = \frac{E_0\left[1-\frac{1}{2\pi^2}\frac{\lambda_s^2 T_{566}}{R_{56}^3}\left(1-\sigma_z/\sigma_{z_0}\right)^2\right]-E_i}{\left(\lambda_s/\lambda_x\right)^2-1}$$

0.5-m X-band section for *LCLS* (22 MV, 11.4 GHz)

Diagnostics: Transverse RF Deflector





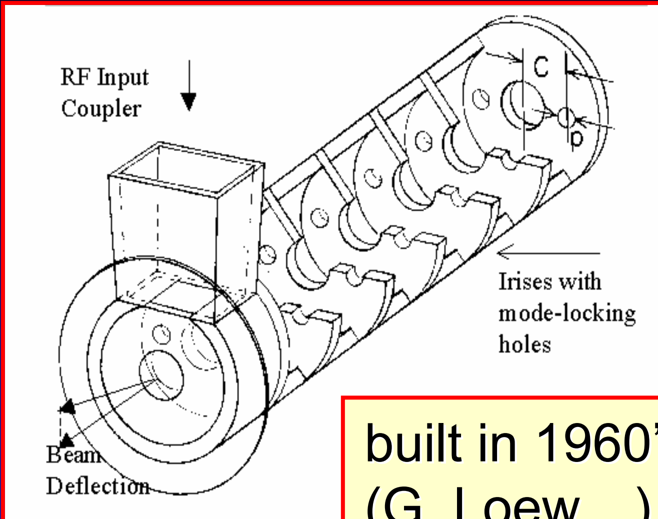


resolves ~20-fsec structure

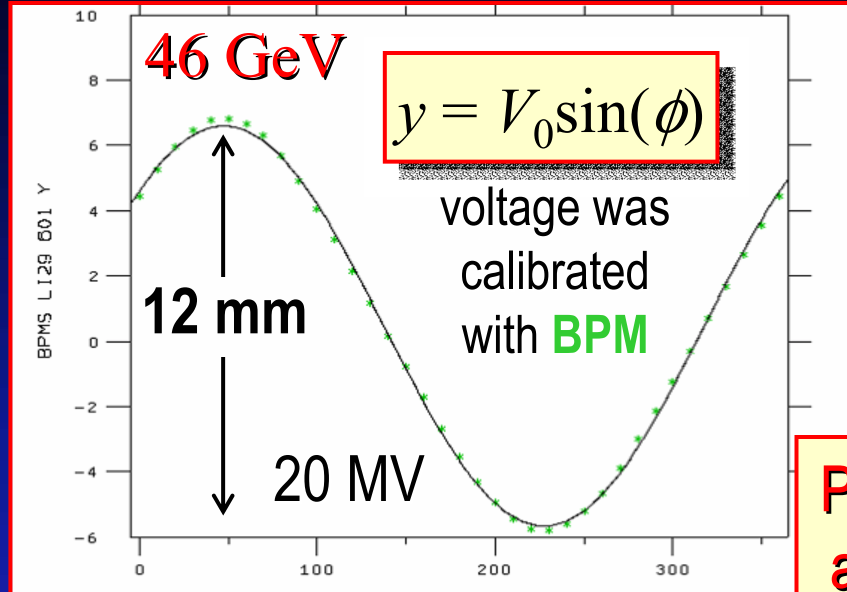
R. Akre, THPRI097

$$\sigma_z \approx \frac{\lambda_{\rm rf}}{2\pi} \frac{E_s}{\left|eV_0 \sin\Delta\psi \cos\varphi\right|} \sqrt{\frac{\left(\sigma_y^2 - \sigma_{y0}^2\right)}{\beta_d \beta_s}}$$

Measurements with Deflector at *SLAC*

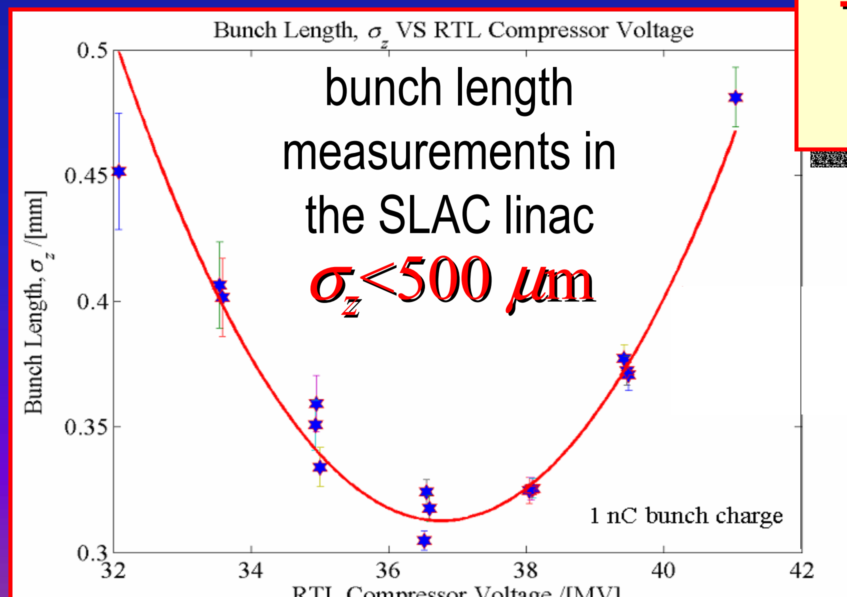


built in 1960's
(G. Loew…)



Planned also for TTF at *DESY*

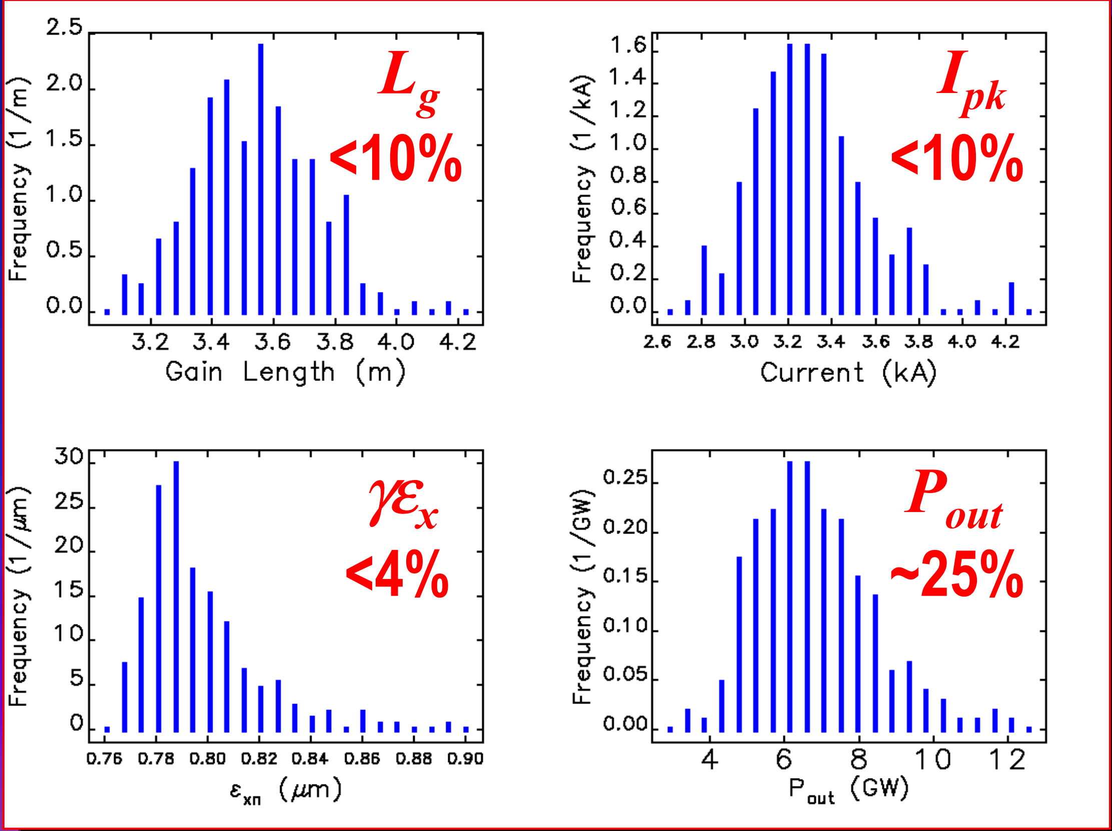
Location of installation at girder 29-4 in the linac



Machine Stability Simulations (M. Borland, ANL)

- Track 10^5 particles with ***Parmela*** → ***Elegant*** → ***Genesis***
- Repeat 230 times with 'jitter' in gun, RF, magnets, etc.
- Include wakefields and CSR

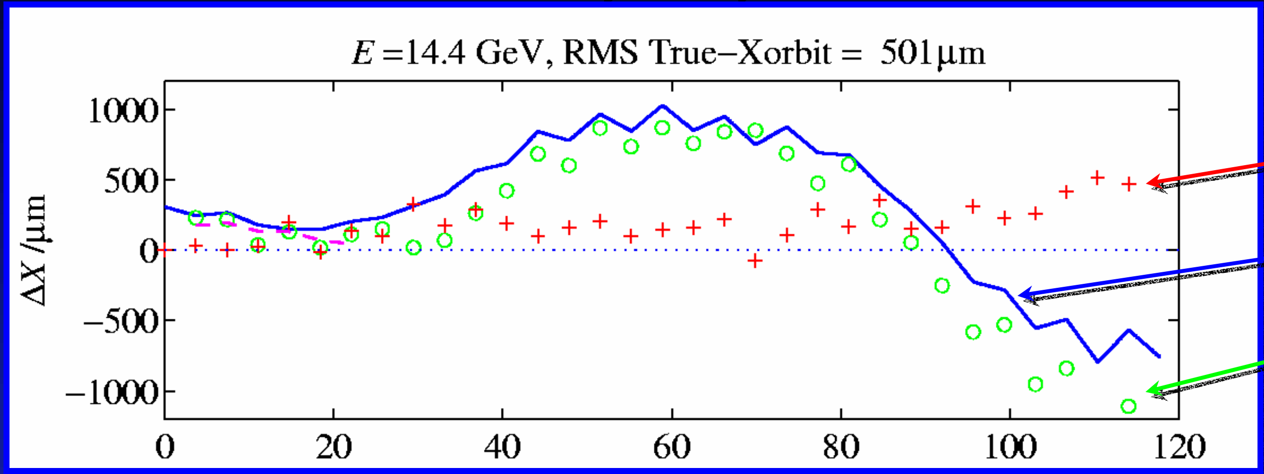
Advanced Photon Source



Provides realistic estimate of operational stability and verifies machine *'jitter budget'*

Undulator Beam-Based Alignment (*LCLS*)

uncorrected undulator trajectory



S/m

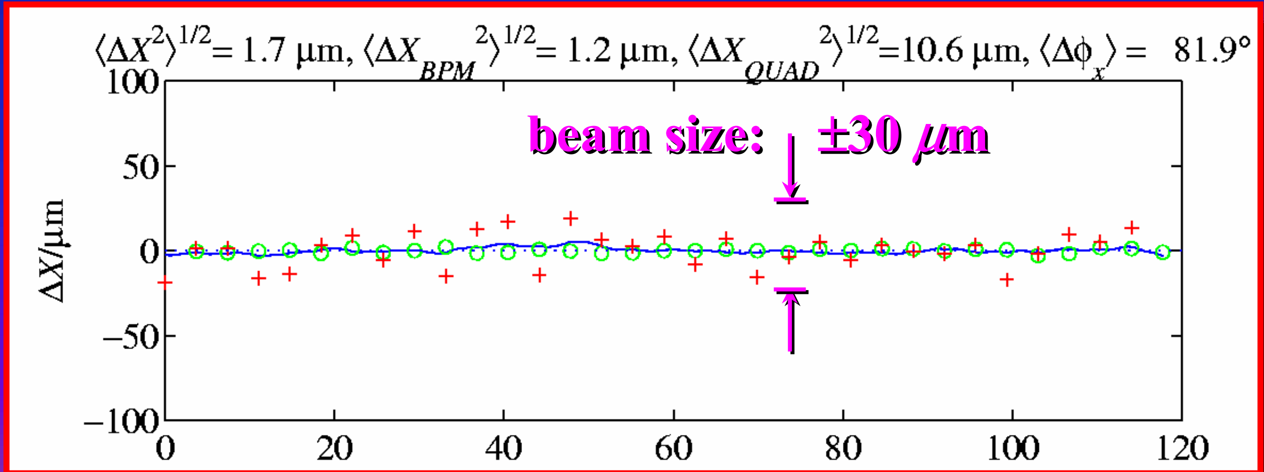
$\sigma_x > 500\ \mu m$

Quadrupole positions

Trajectory

BPM read-back

trajectory after 3rd pass of BBA



S/m

$\sigma_x \approx 1.5\ \mu m$
$\langle \Delta\phi \rangle \approx 82^o$

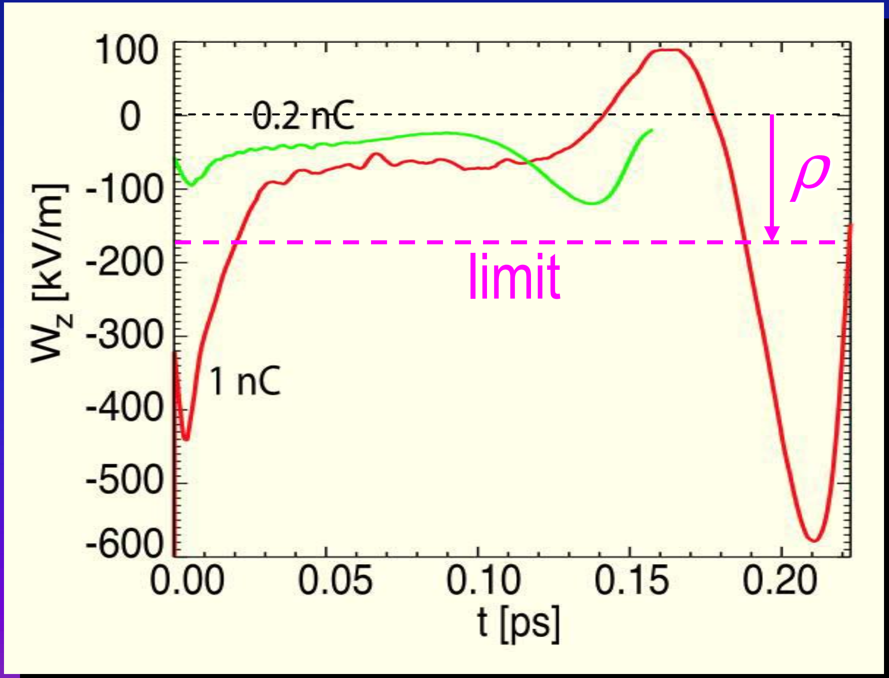
BBA also used for TESLA-FEL: *DESY* (B. Faatz)

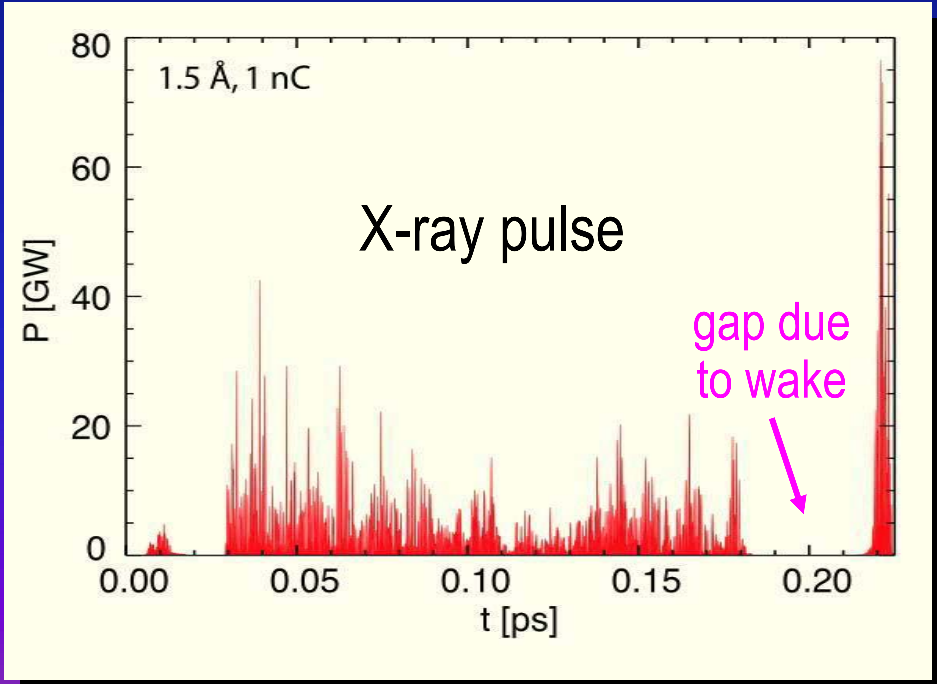
Resistive-Wall Wakefields in the Undulator

- Strong magnetic field in undulator requires small gap…
- Need small radius pipe ($r \approx 2.5$ mm, $L_u \approx 120$ m: *LCLS*)

$$\left(\frac{\sigma_E}{E}\right)_{RW} \approx (0.22)\frac{e^2 cNL_u}{\pi^2 rE\sigma_z^{3/2}}\sqrt{\frac{Z_0}{\sigma}}$$

Wake changes 'slice' energy during exponential gain regime — more damaging than incoming 'chirp'

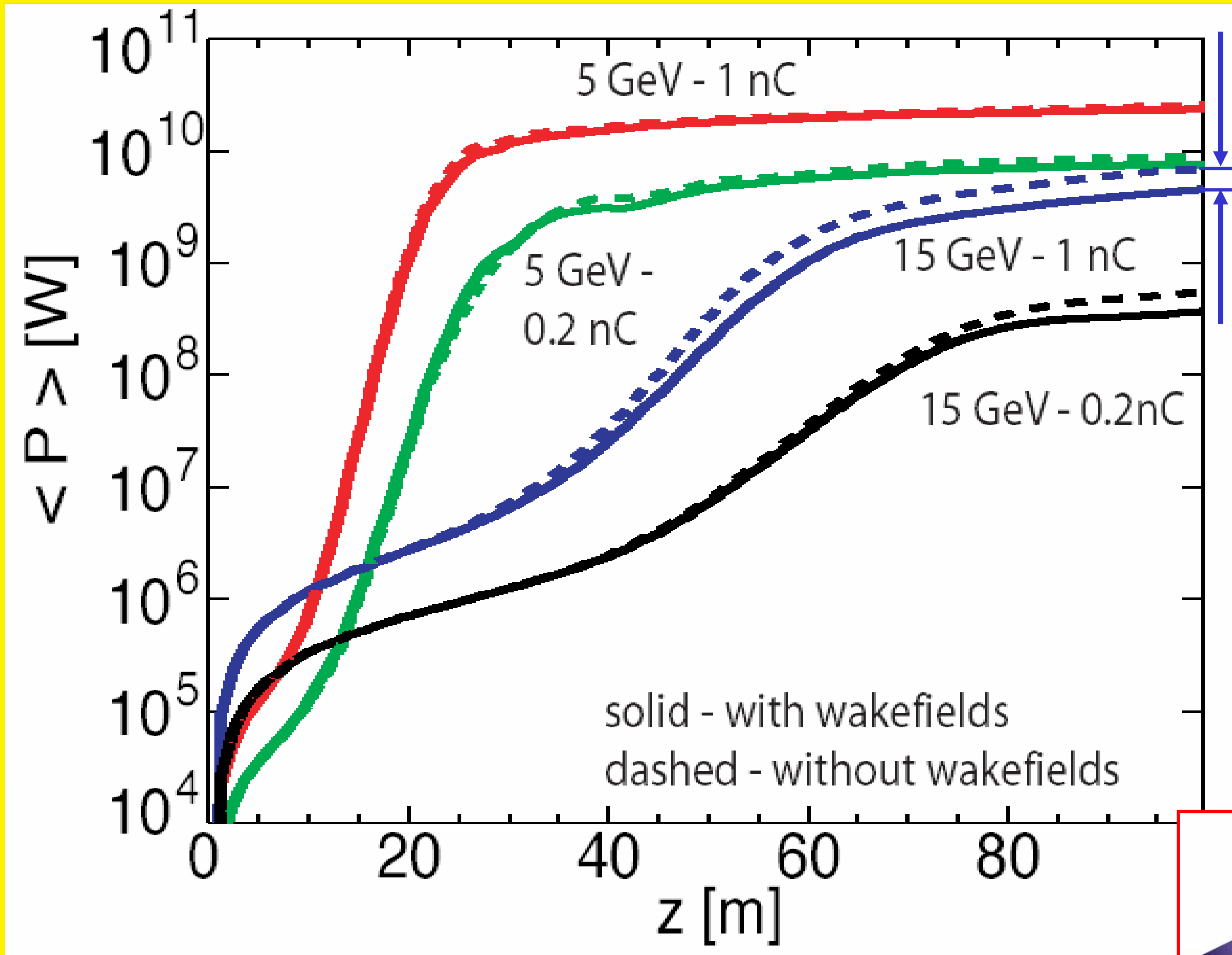




Courtesy S. Reiche

Need smooth copper pipe

FEL Output Power with Undulator Wakefields



~40% power loss due to wakefield

Genesis 1.3, S. Reiche, NIM A 429 (1999) 242.

Emittance Exchange: Transverse to Longitudinal

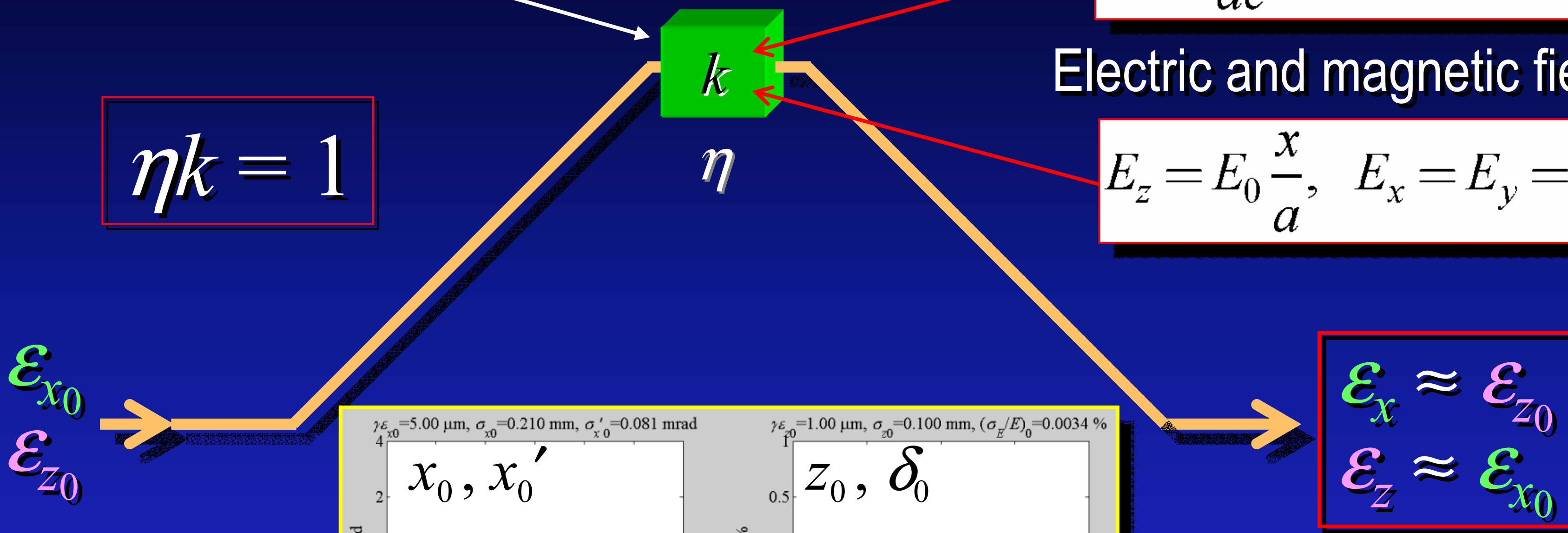
transverse RF in a chicane…

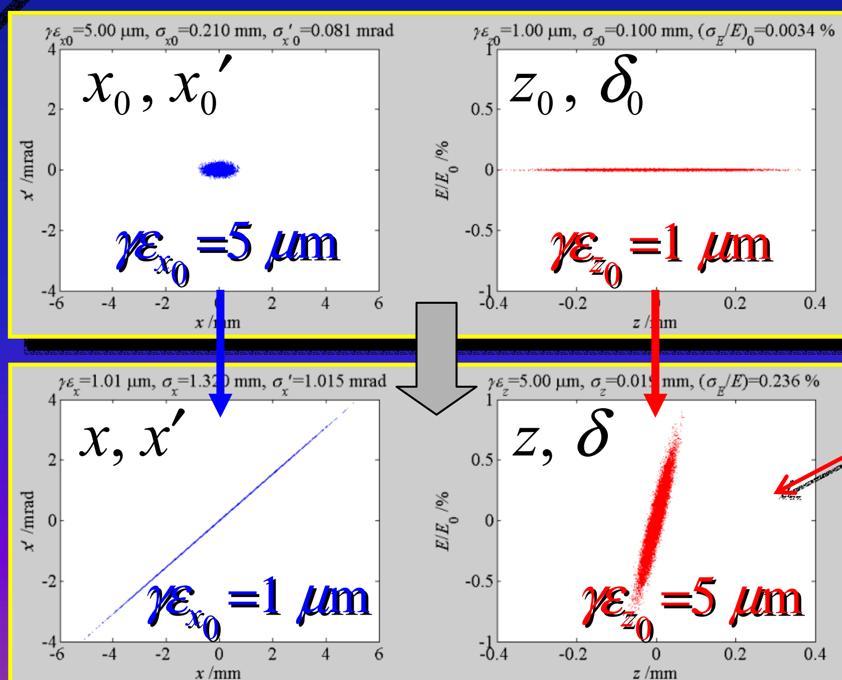
$$B_y = \frac{E_0}{ac} z, \quad B_x = B_z = 0$$

Electric and magnetic fields

$$E_z = E_0 \frac{x}{a}, \quad E_x = E_y = 0$$

$$\eta k = 1$$



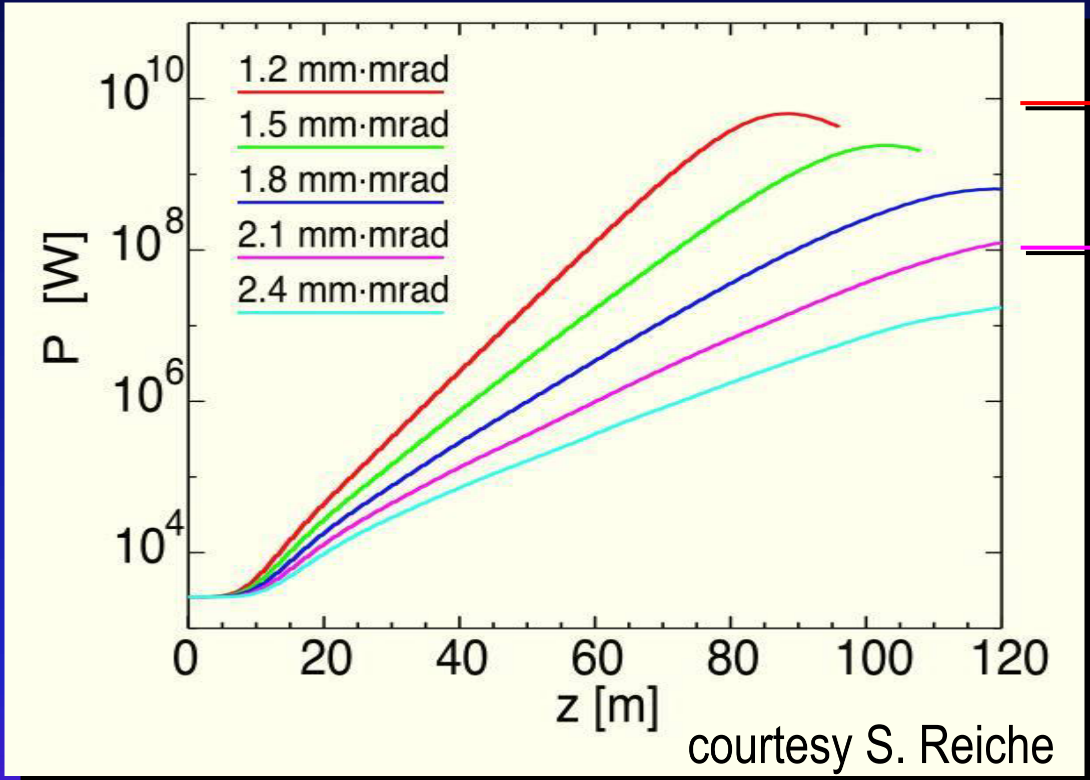


system also compresses bunch length

M. Cornacchia, P. Emma, SLAC-PUB-9225, May 2002

Final Comments

For *LCLS*, slice emittance >1.8 μm will not saturate (*TESLA* ?)



$\varepsilon_N = 1.2\ \mu m$ → $P = P_0$

$\varepsilon_N = 2.0\ \mu m$ → $P = P_0/100$

Merci Beaucoup

SASE FEL is not forgiving — instead of mild luminosity loss, power nearly switches **OFF**

electron beam ***must*** meet brightness requirements