

# Attosecond x-ray pulses in the *LCLS* using the slotted foil method

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& 11TH FEL USERS WORKSHOP

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*Fel* 2004  
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# Proposals for Femtosecond and Sub-Femtosecond X-ray Pulses

- |  |                |
|--|----------------|
| ■ E. Saldin et al., <i>Opt. Comm.</i> , <b>212</b> , 377 (2002). | <b>300 as</b>  |
| ■ D. Moncton, W. Graves, SRI Conf., (2003).                      | <b>400 as</b>  |
| ■ P. Emma et al., <i>PRL</i> <b>92</b> , 074801 (2004).          | <b>2000 as</b> |
| ■ W. Fawley, A. Zholents, <i>PRL</i> <b>92</b> , 224801 (2004).  | <b>110 as</b>  |
| ■ E. Saldin et al., <i>Opt. Comm.</i> , <b>237</b> , 153 (2004). | <b>300 as</b>  |
| ■ E. Saldin et al., submitted to <i>Opt. Comm.</i> (2004).       | <b>300 as</b>  |
| ■ W. Fawley et al., <i>FEL'04</i> (Wednesday morning)            |                |

# ***OUTLINE***

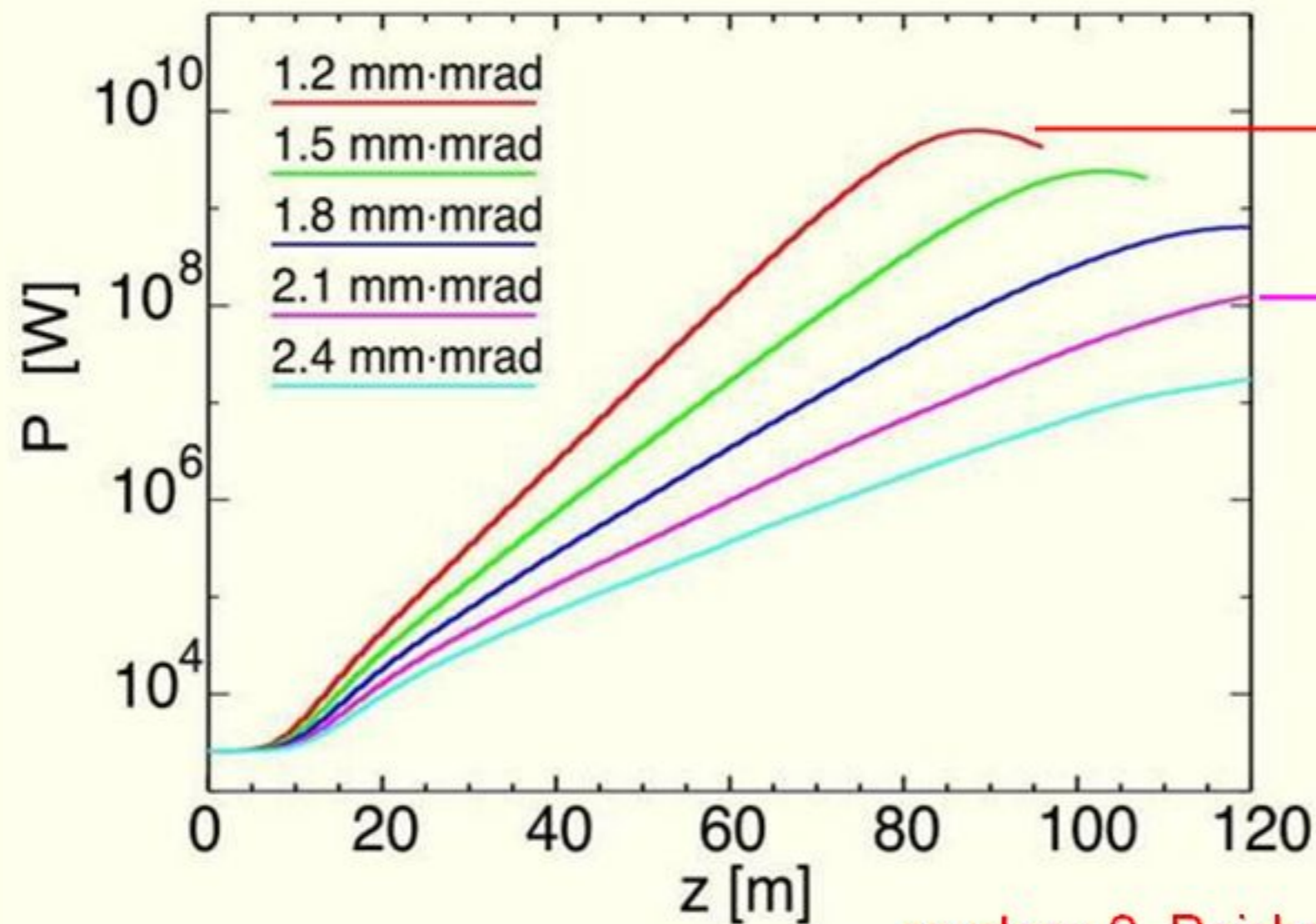
- Review of previous work (2-fs FWHM)
- Exploring limits of the technique
- Altered parameters for 400-as pulses



# Transverse Emittance is Critical for X-ray FEL

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

$\sim 1 \mu\text{m}$  at  $1.5 \text{ \AA}$ ,  $15 \text{ GeV}$



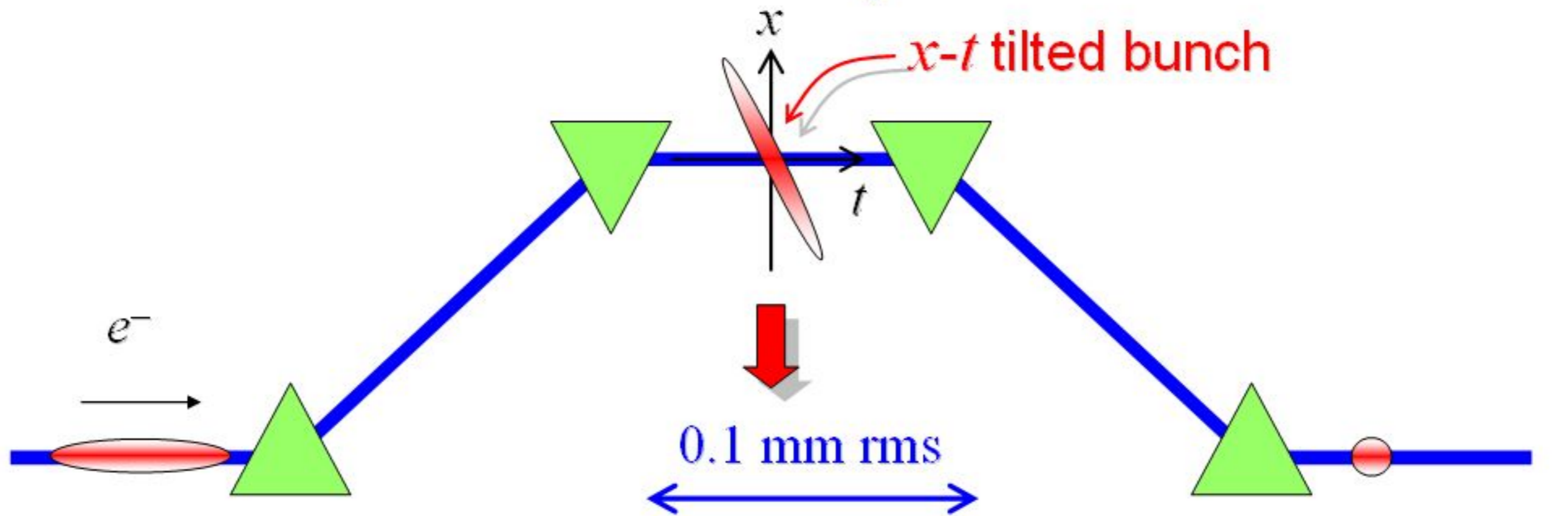
$\varepsilon_N = 1.2 \mu\text{m} \rightarrow P = P_0$

$\varepsilon_N = 2.0 \mu\text{m} \rightarrow P = P_0/100$

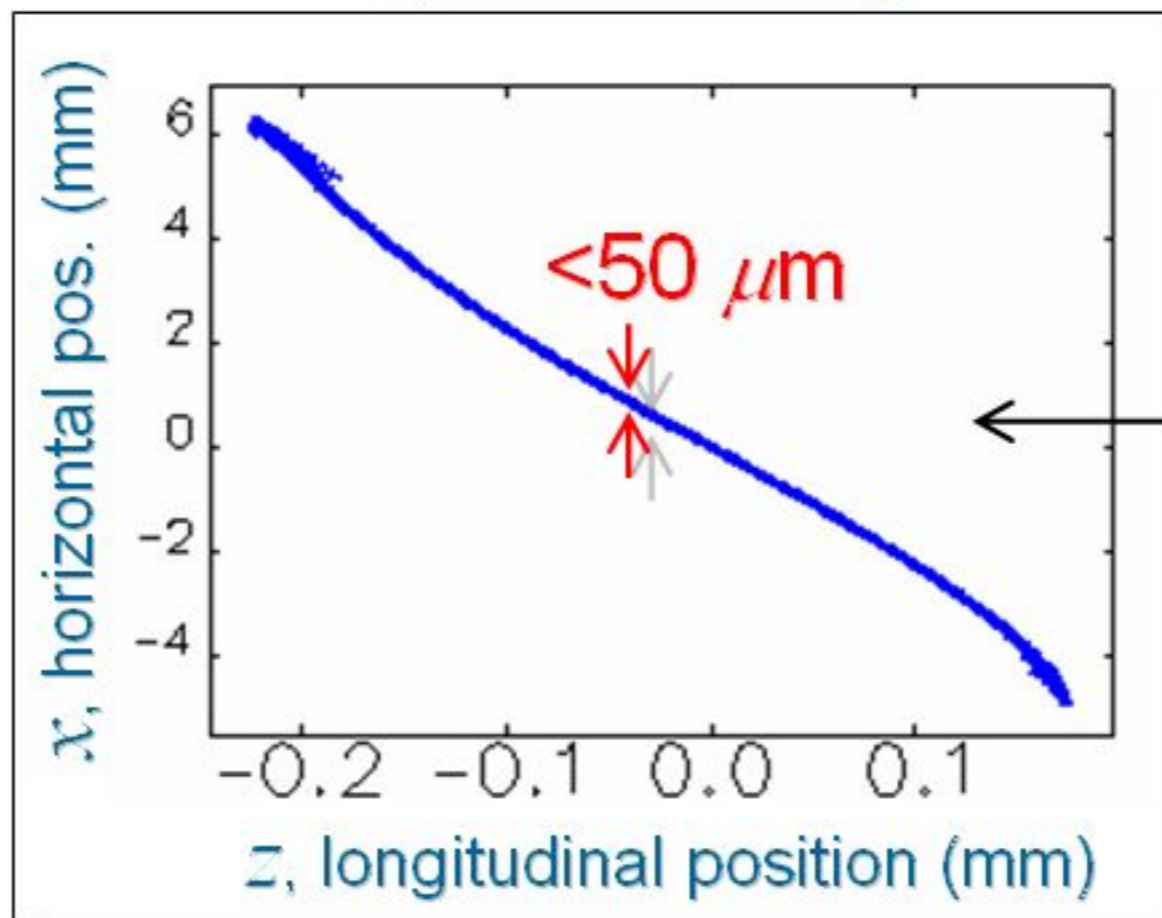
Can we spoil most of the  $e^-$  bunch and leave  $\sim 1 \text{ fs}$  to lase?

courtesy S. Reiche

# Concept



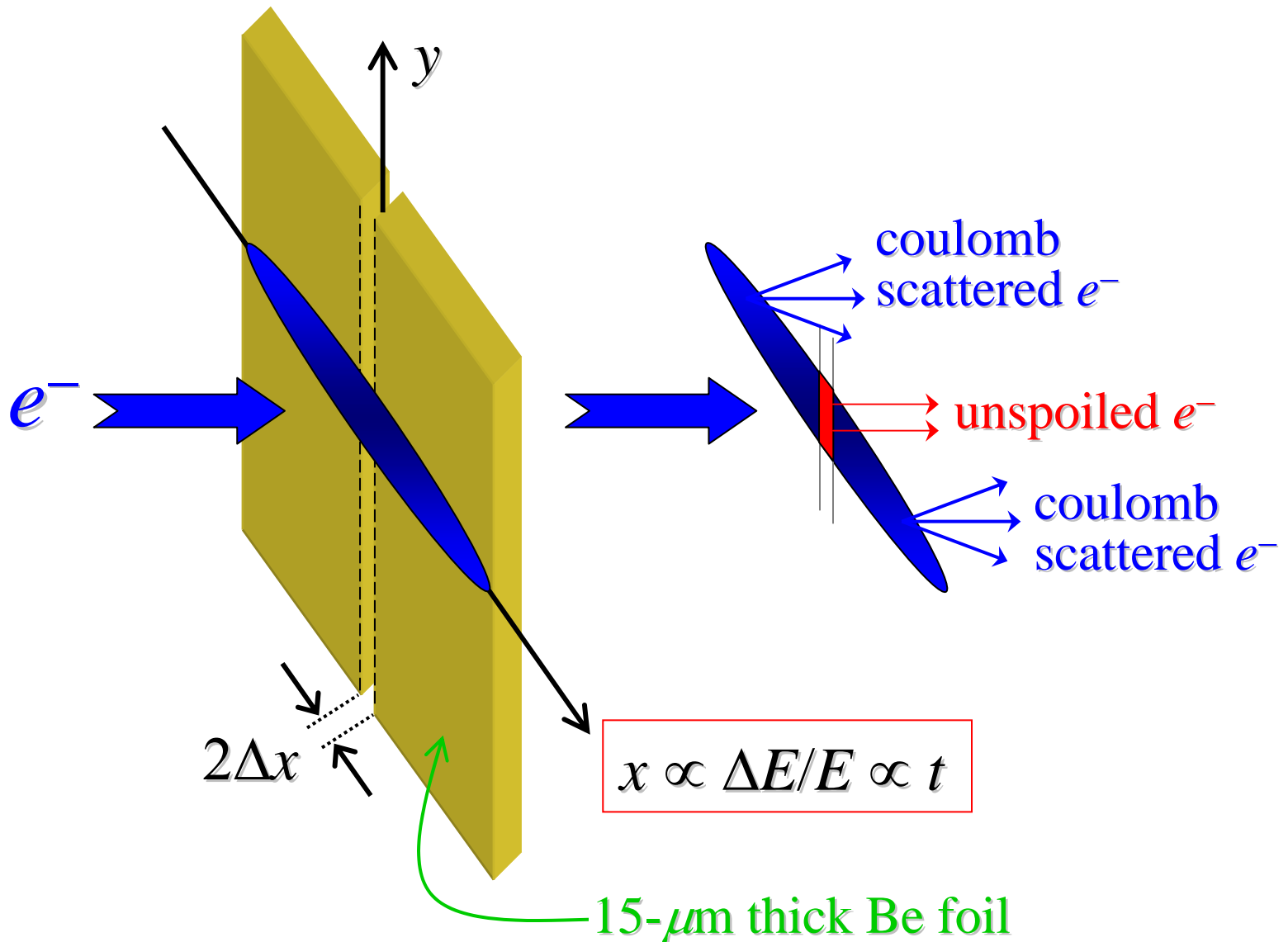
2.6 mm rms



Easy access to  
*time* coordinate  
along bunch

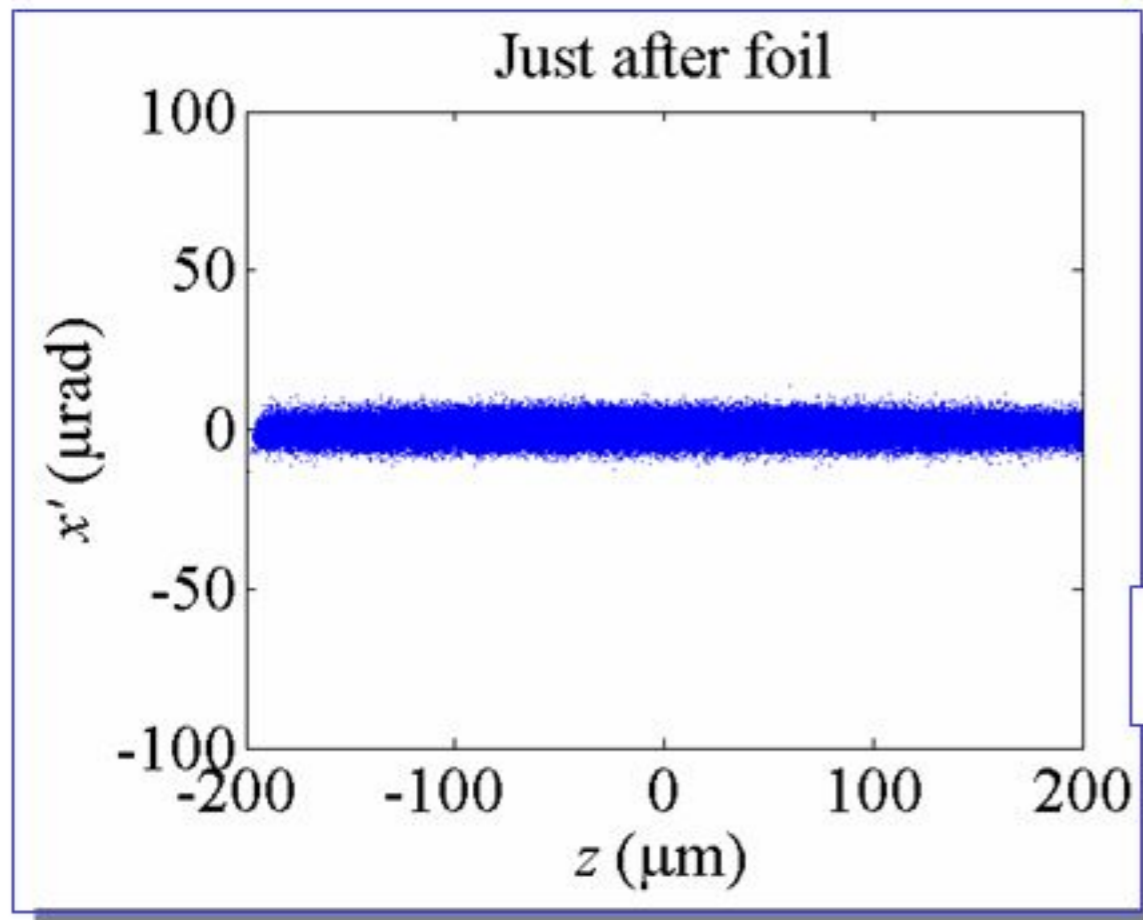
1-nC case

# add thin slotted foil in center of chicane



*PRL* **92**, 074801 (2004).

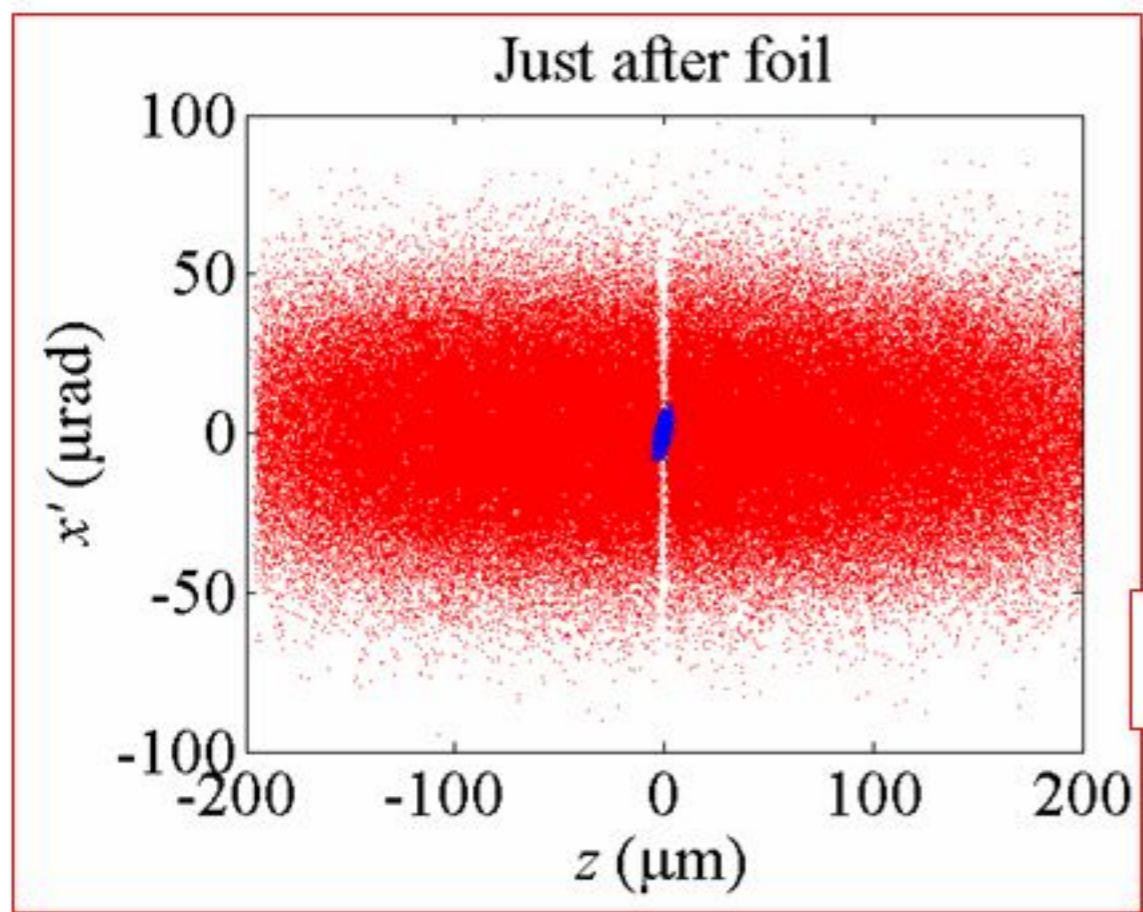
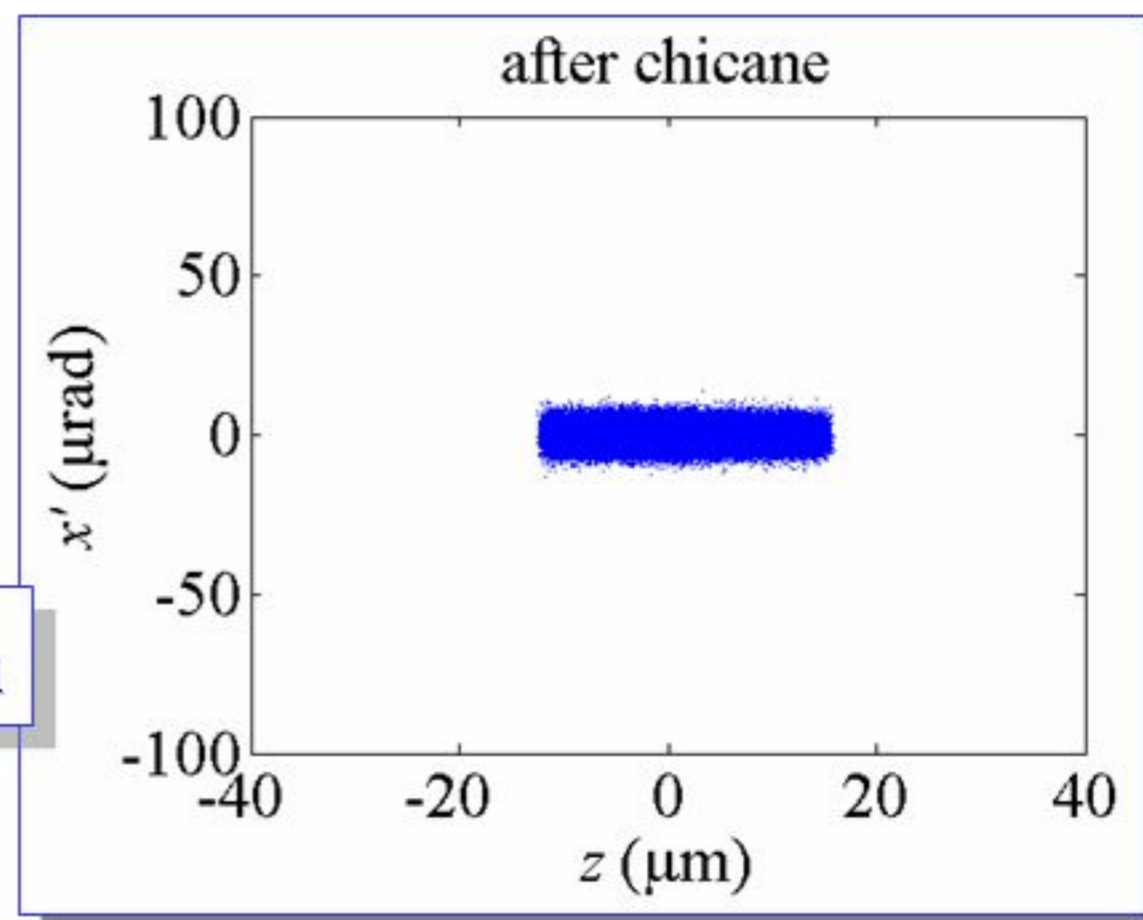
P. Emma, M. Cornacchia, K. Bane, Z. Huang, H. Schlarb, G. Stupakov, D. Walz (SLAC)



no  
foil



$\epsilon_x \approx 1 \mu\text{m}$

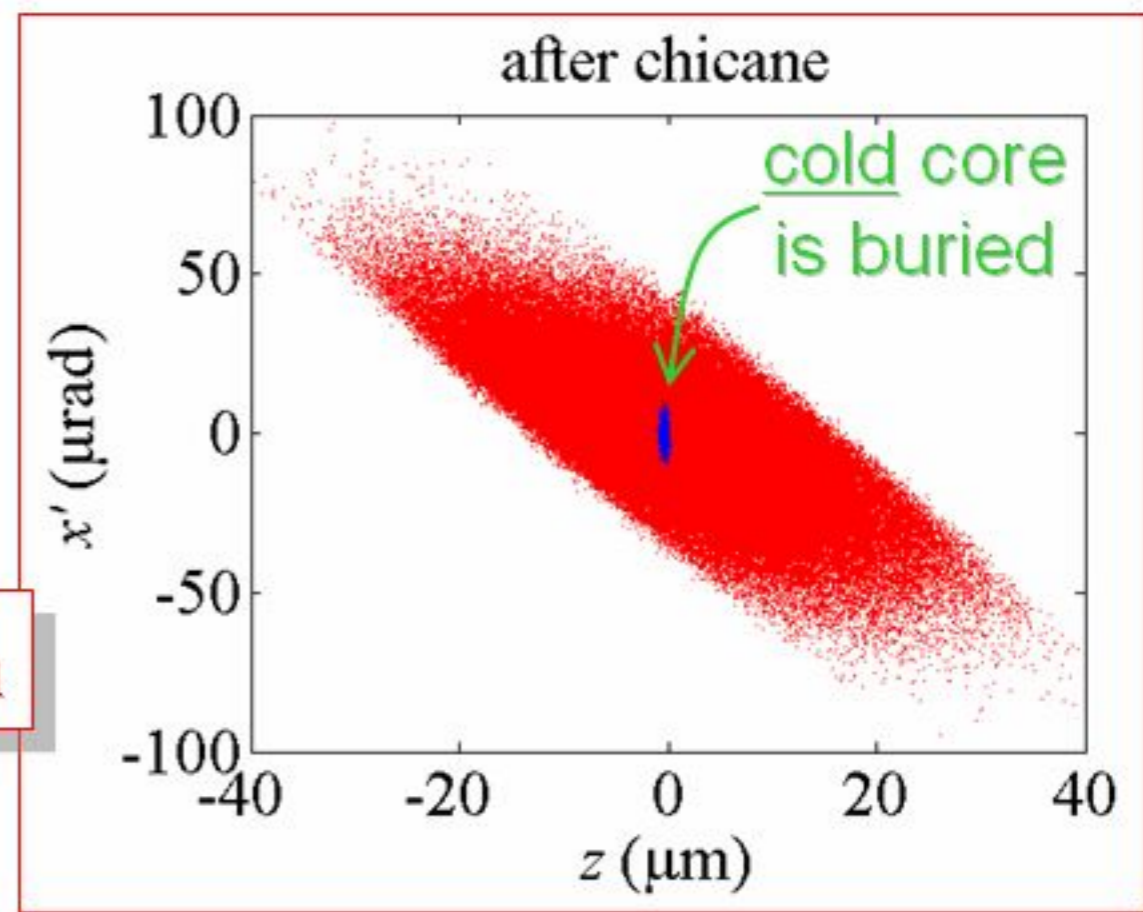


foil

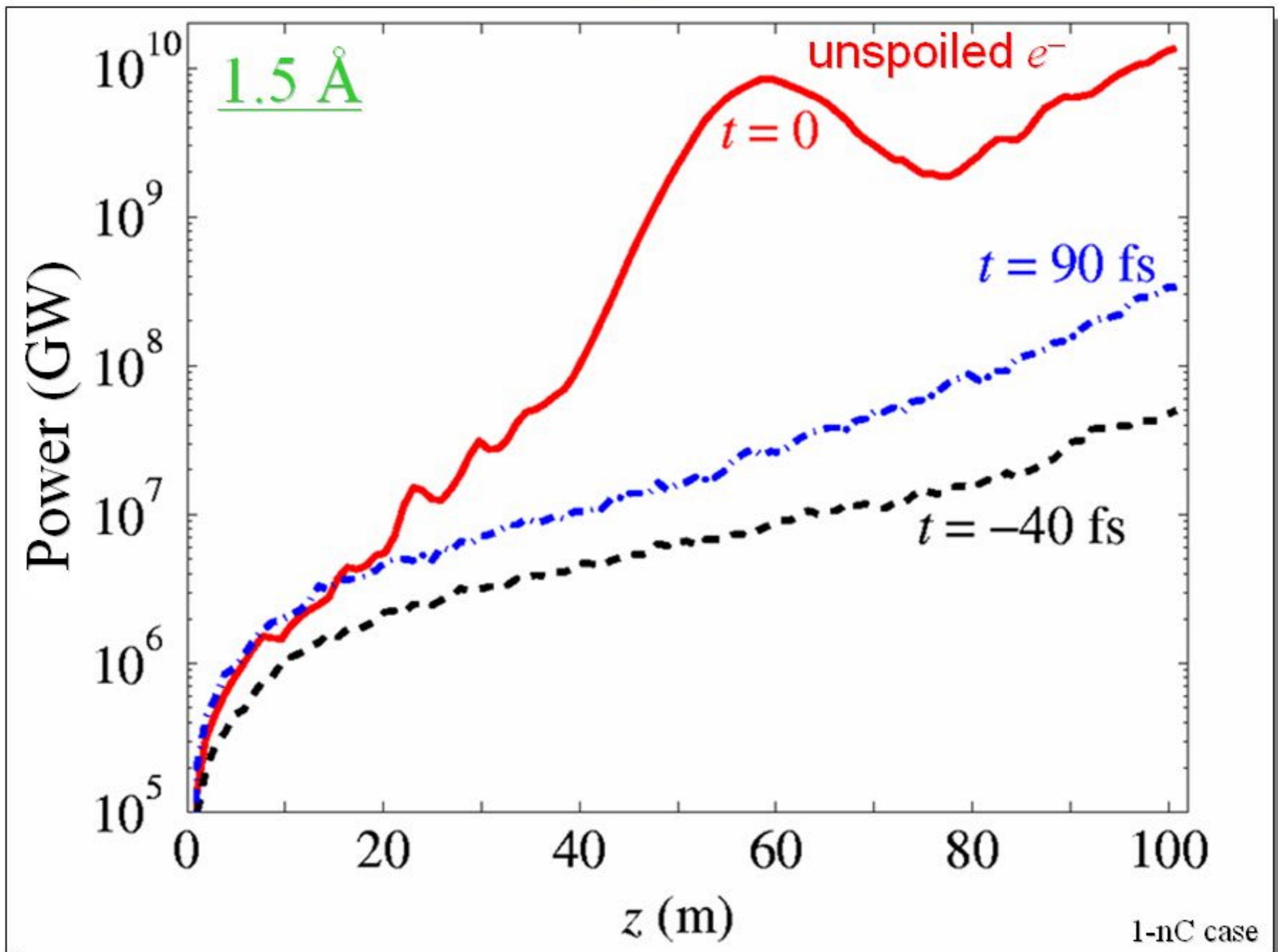


$\epsilon_x \approx 6 \mu\text{m}$

100-pC case



# FEL amplifies only 'cold' beam core



# Start-to-End Simulations

- *Parmela* for injector [1] ( $E \leq 135$  MeV)
- *Elegant* [2] for linac/compressors (wake, CSR, etc)
- *Elegant* [2] for Coulomb scattering of very thin foil
- K. Bane code for foil wakefield (1-nC case only)
- *Genesis 1.3* [3] for time-dependent FEL run

[1] C. Limborg (SLAC)

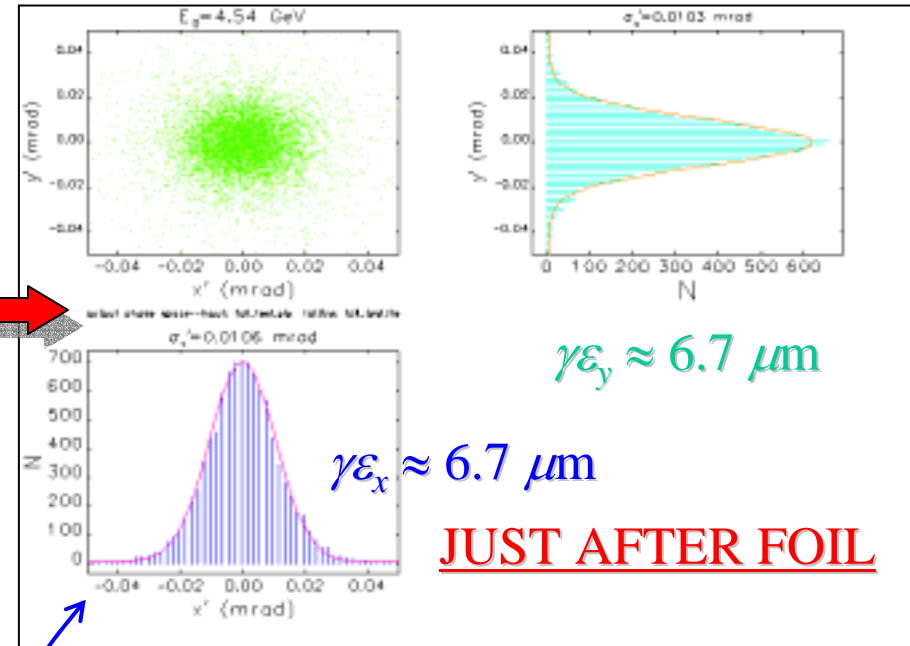
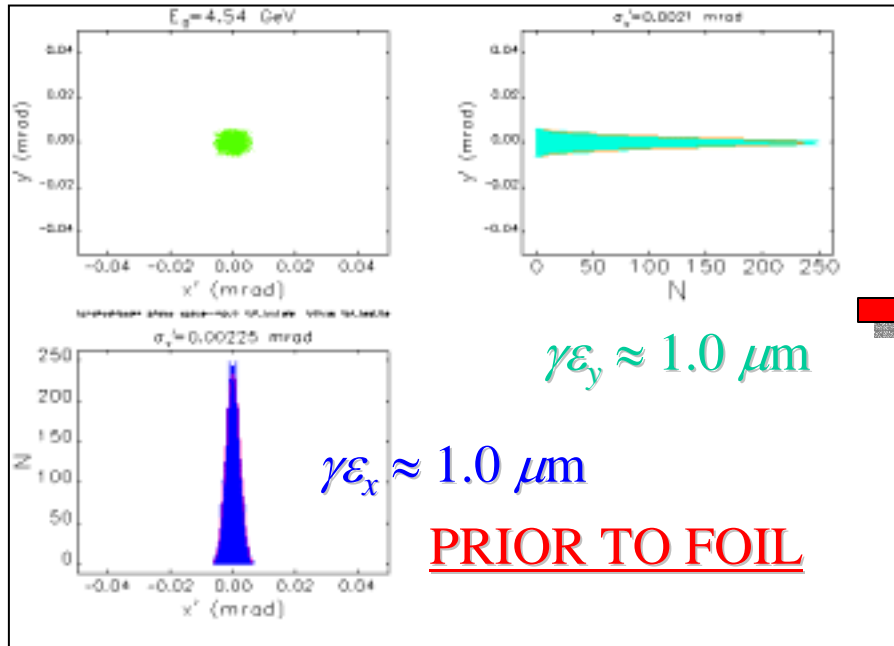
[2] M. Borland (ANL)

[3] S. Reiche (UCLA)

# Coulomb Scattering

## FOIL:

- Beryllium
- rad. length:  $X_0 = 35 \text{ cm}$
- thickness:  $x = 50 \mu\text{m}$

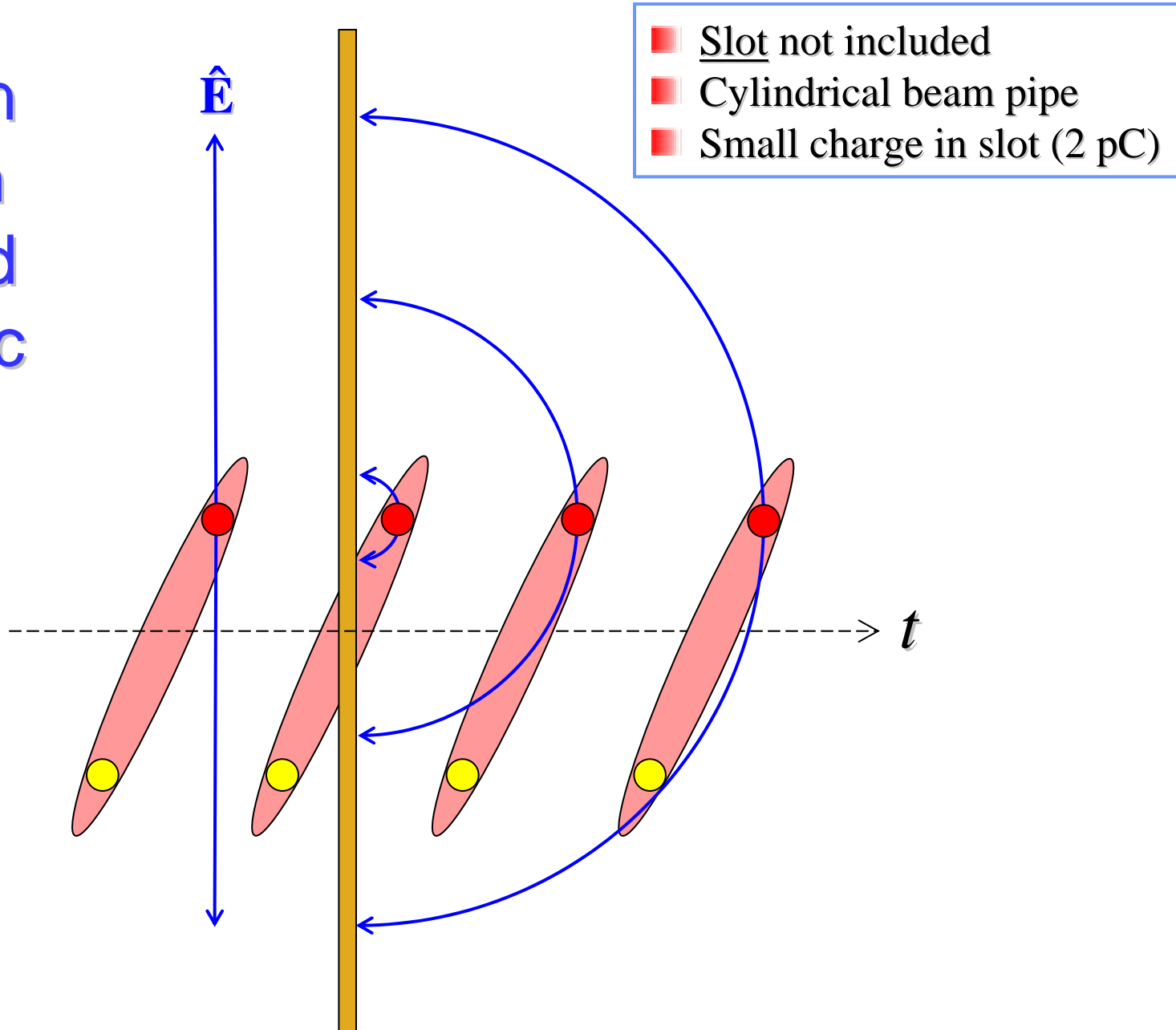


$$\theta_{rms} \approx \frac{14 \text{ MeV}}{pc} \sqrt{x/X_0} [1 + 0.038 \ln(x/X_0)]$$

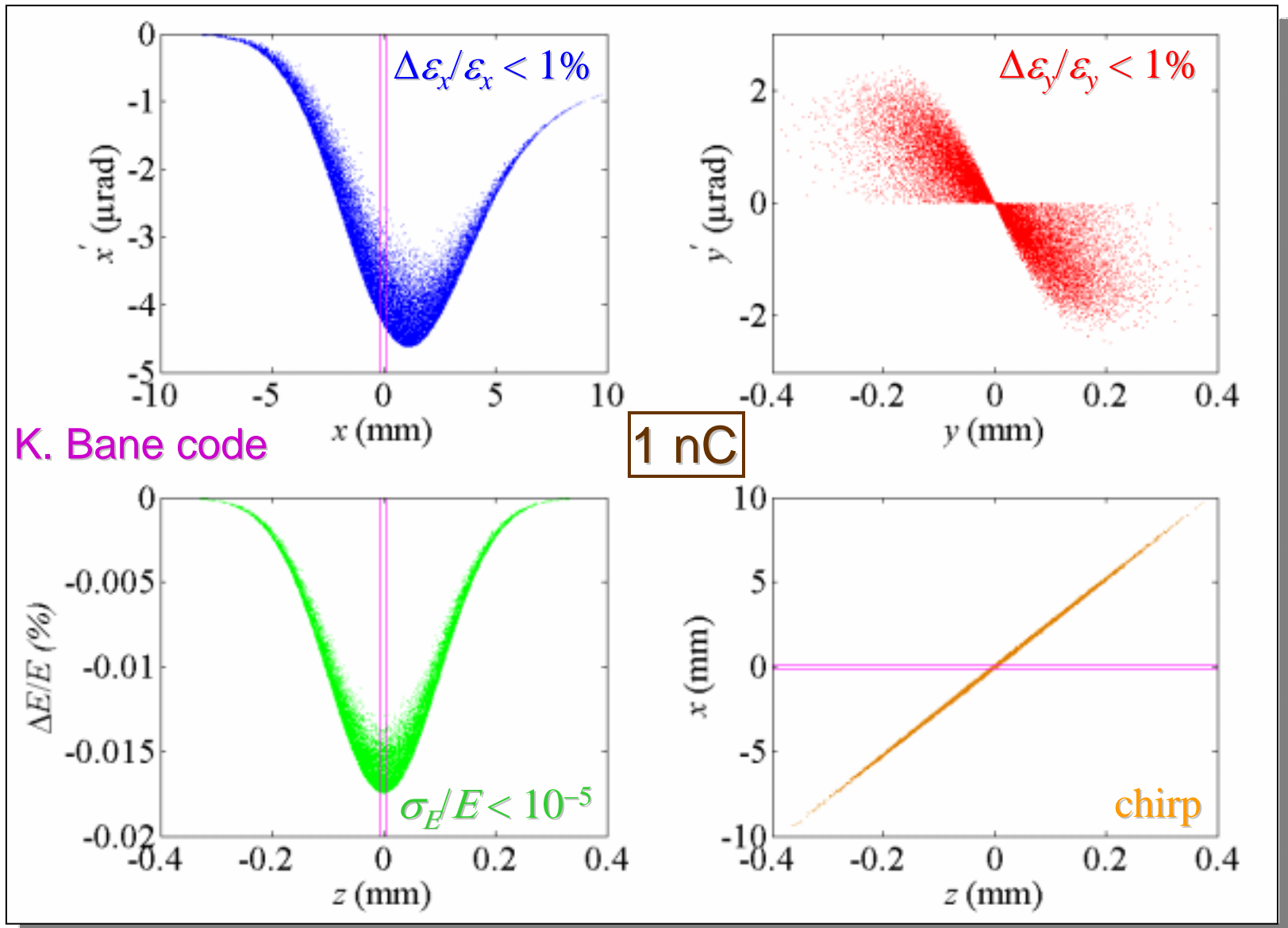
15% over-estimate for  $x/X_0 \approx 10^{-4}$

Coulomb scattering in thin-foil: *Elegant* (M. Borland)

Transition  
Radiation  
Wakefield  
of Metallic  
Foil  
( $\gamma \gg 1$ )

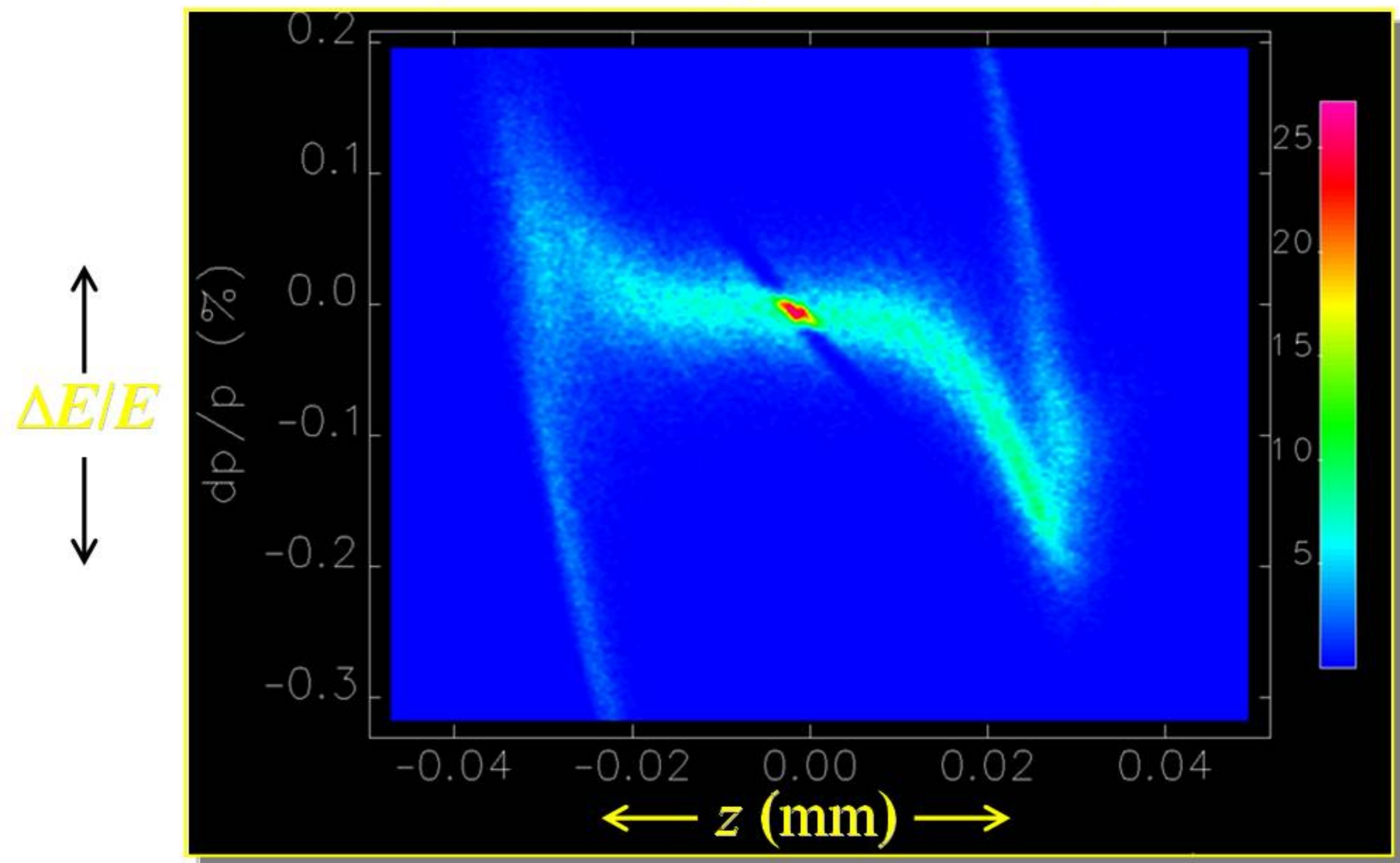


# Foil-wakefield (without slot) at 4.54 GeV



insignificant effect (without slot), even at 1 nC

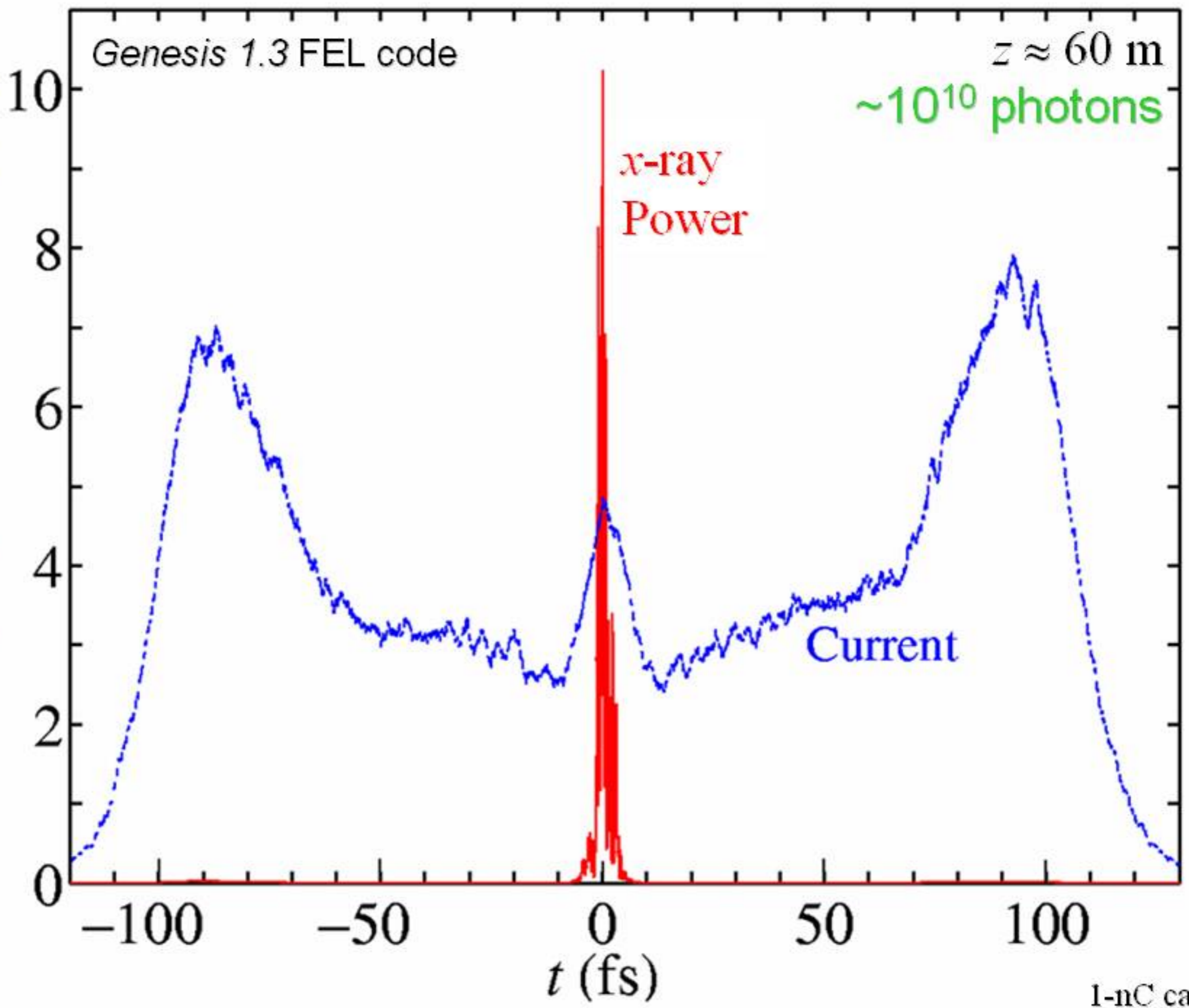
Track 200k macro-particles through entire *LCLS* up to 14.3 GeV



No design changes to FEL – only foil added in chicane

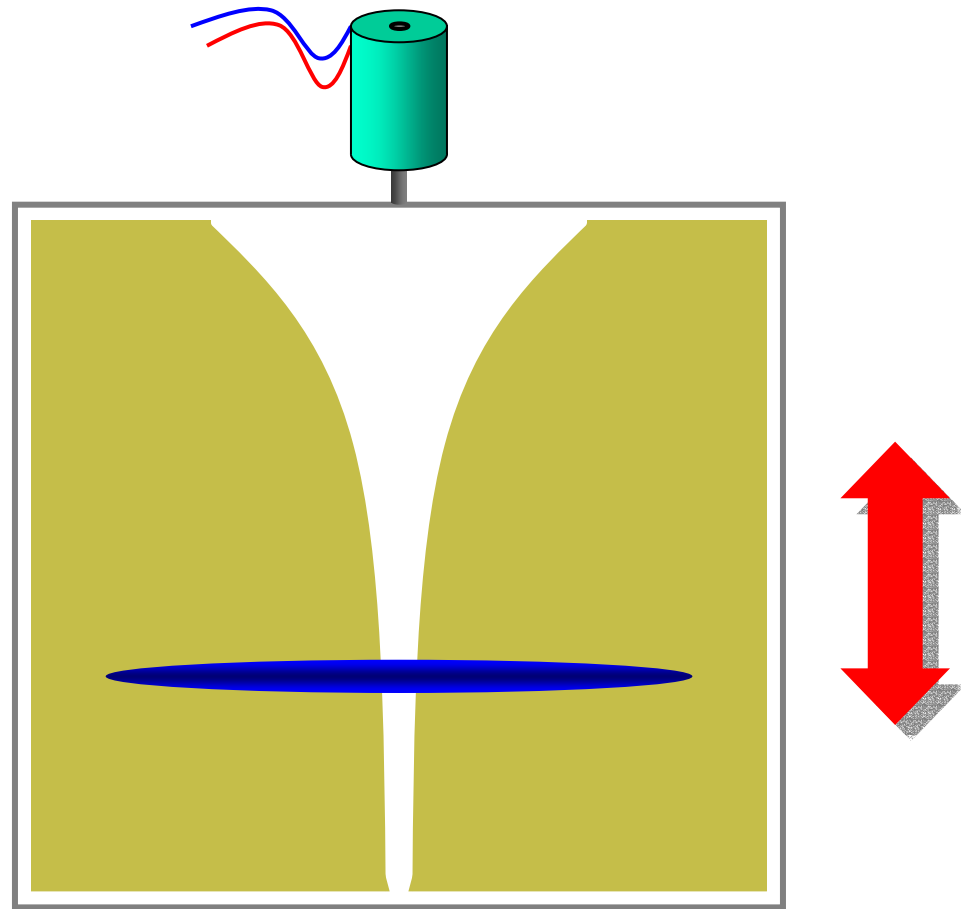
1-nC case

Power (GW) and Current (kA)



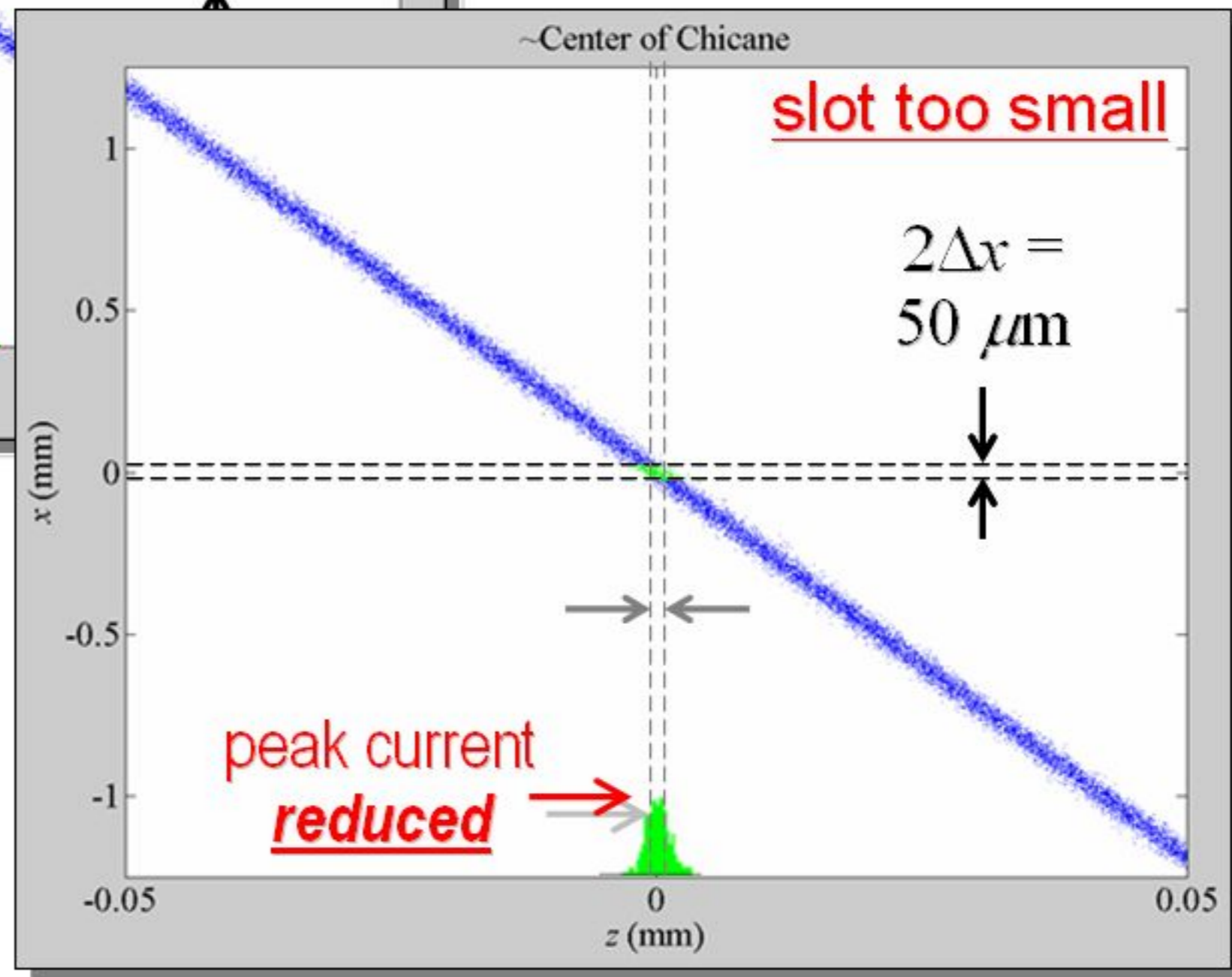
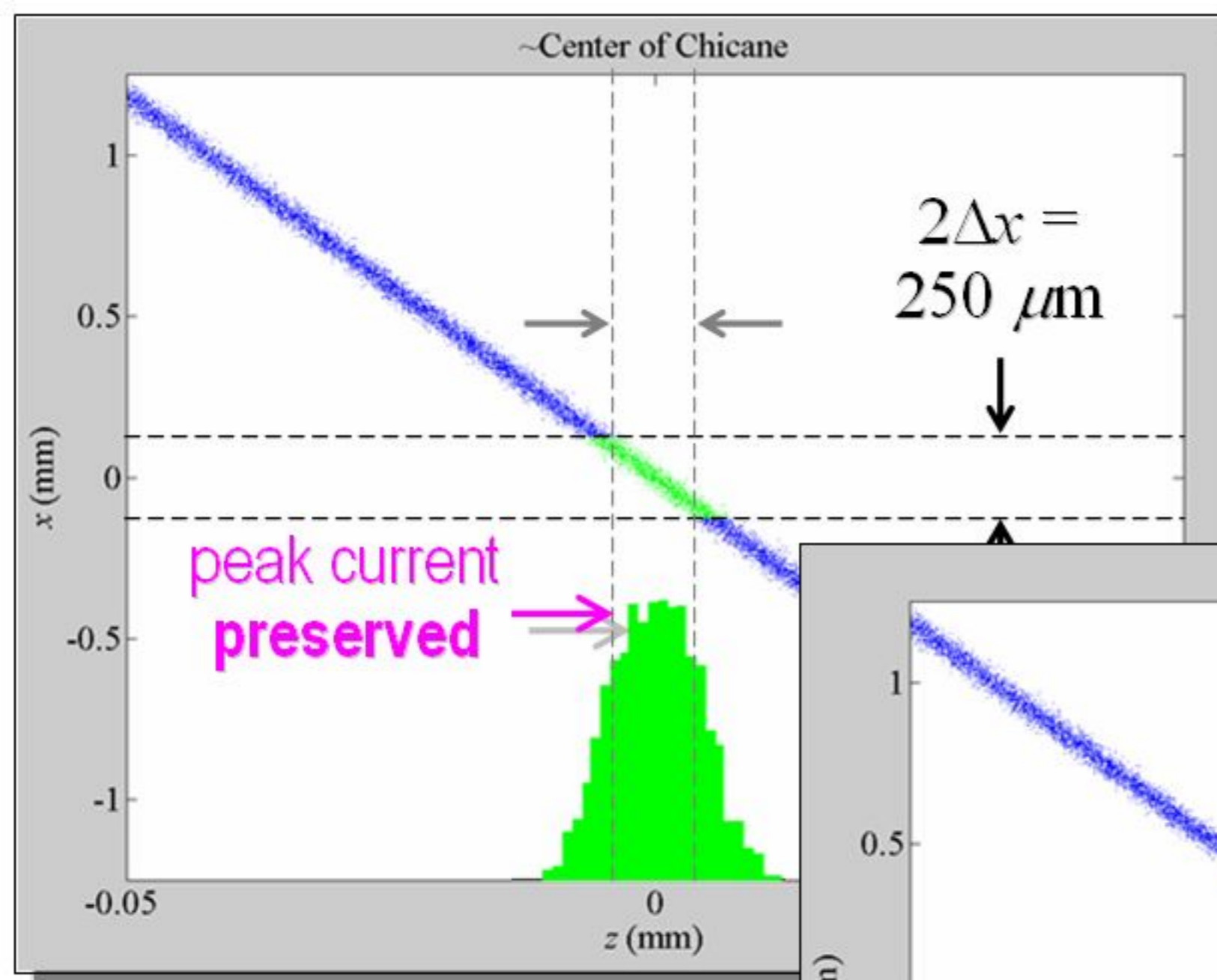
I-nC case

# Pulse Length Control With Stepping Motor



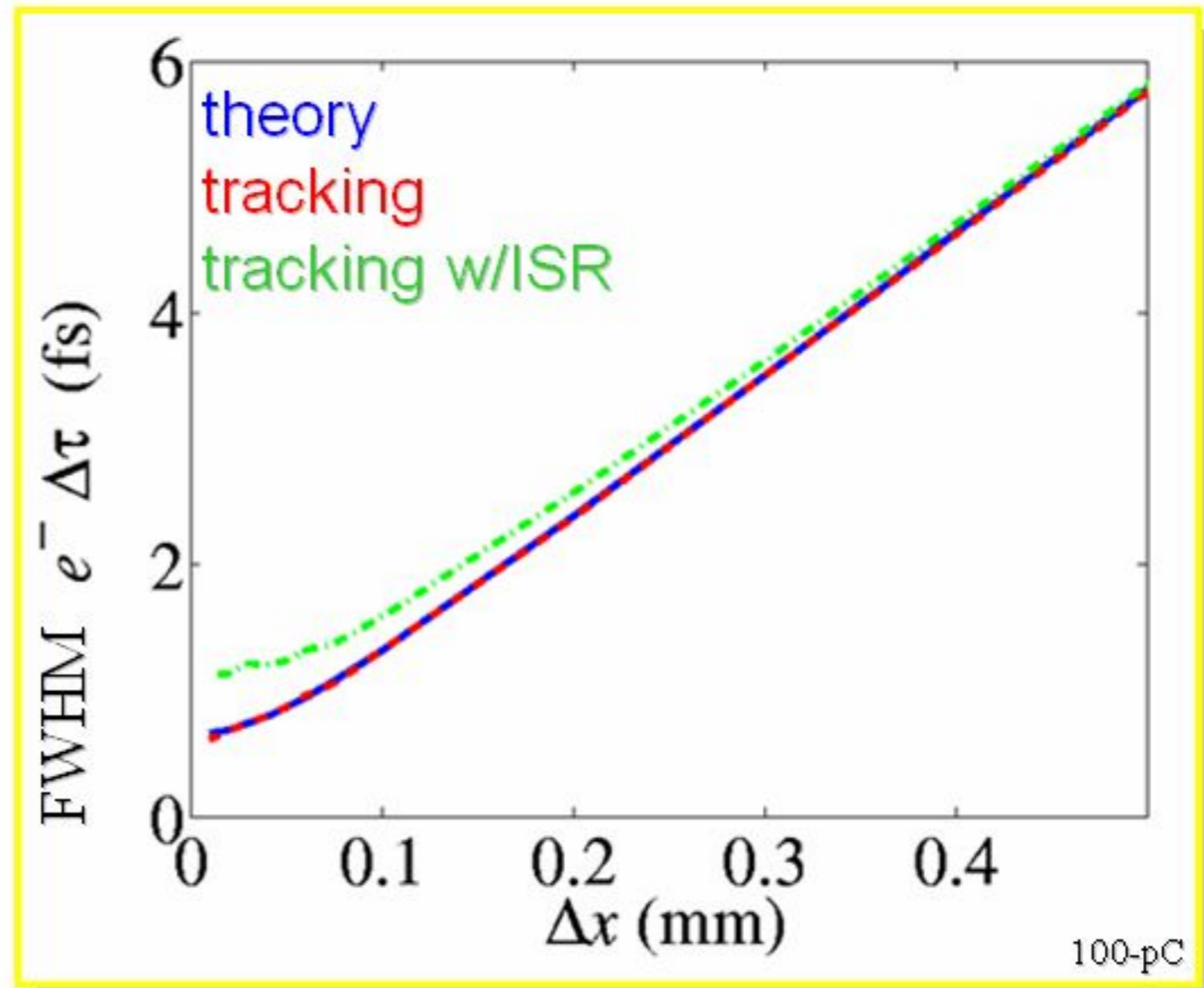
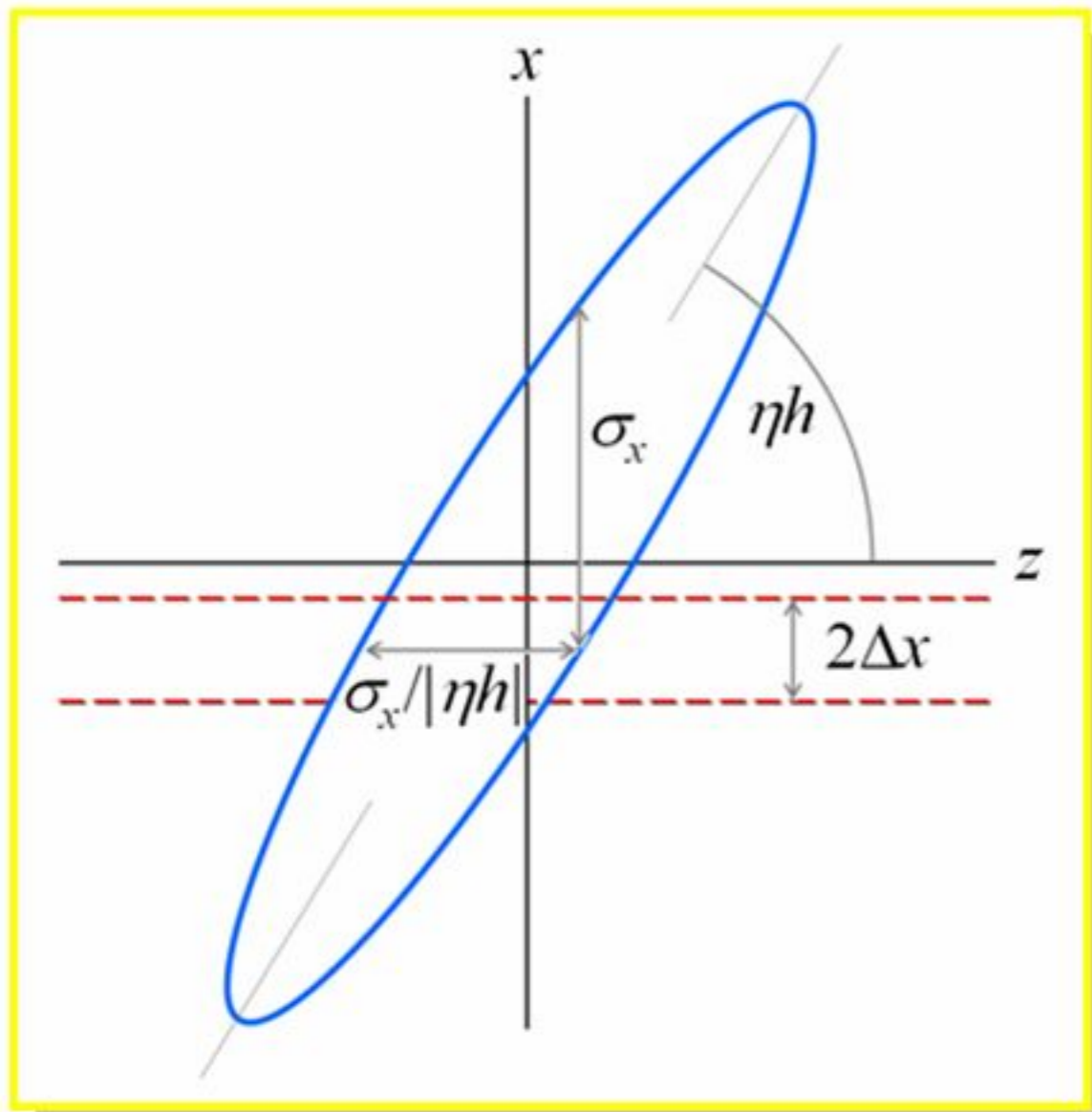
Tapered slot width allows pulse length control with simple stepping motor

Choose slot for  
shortest  $e^-$  pulse,  
while retaining full  
peak current:  
 $\Delta x \gtrsim 3(\epsilon\beta)^{1/2}$



# Unspoiled $e^-$ FWHM Pulse Length after Chicane

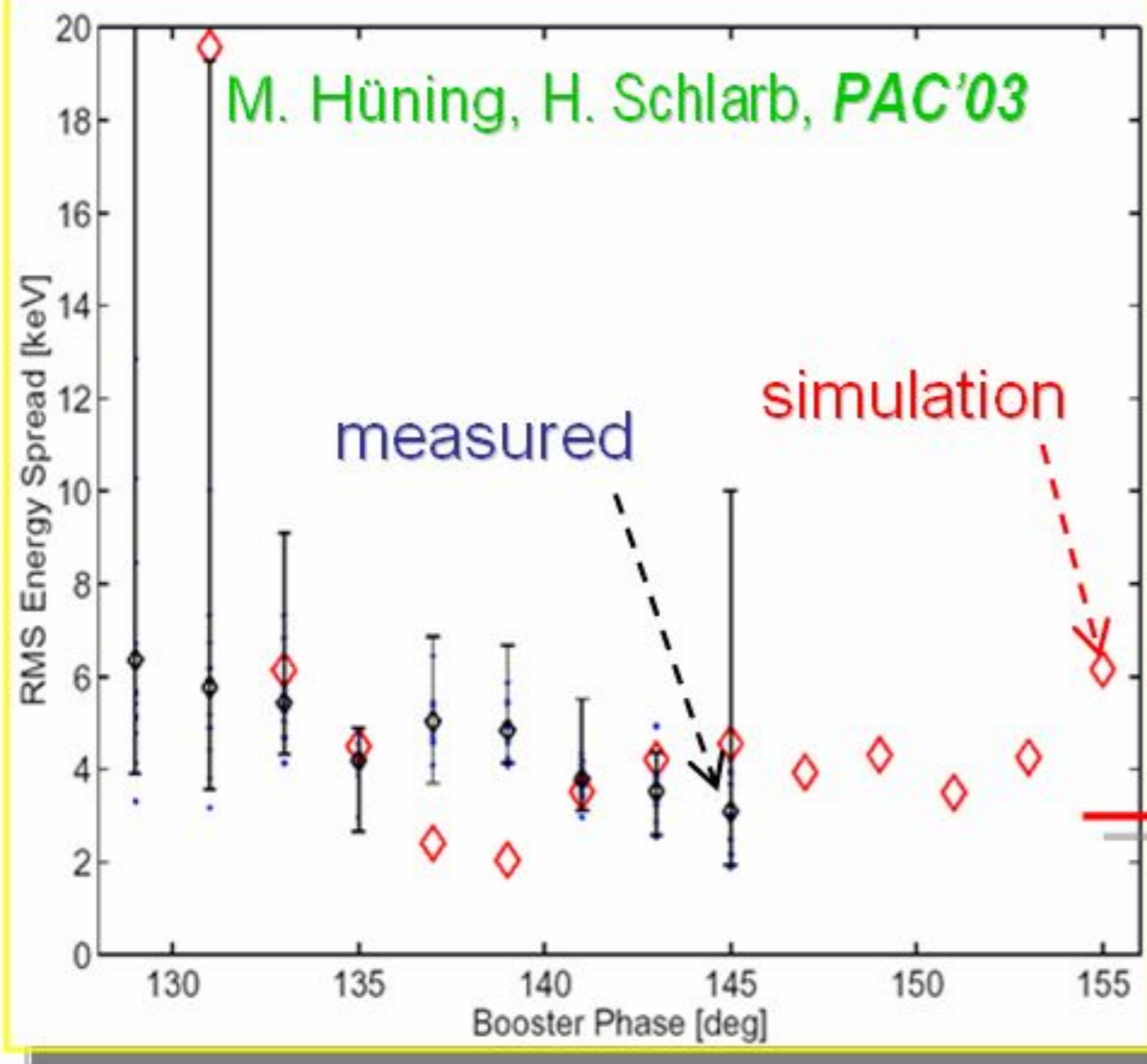
$$\Delta\tau \approx \frac{2.35}{|\eta h|c} \sqrt{\underbrace{\eta^2 \sigma_{\delta_0}^2}_{\sim \text{limit}} + \underbrace{(1 + hR_{56})^2}_{\ll 1} \left[ \Delta x^2 / 3 + \epsilon\beta \right]}$$



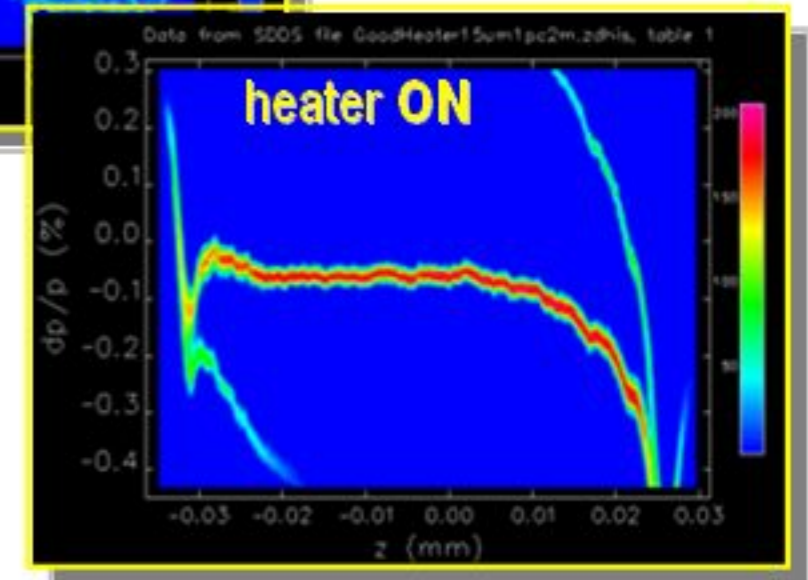
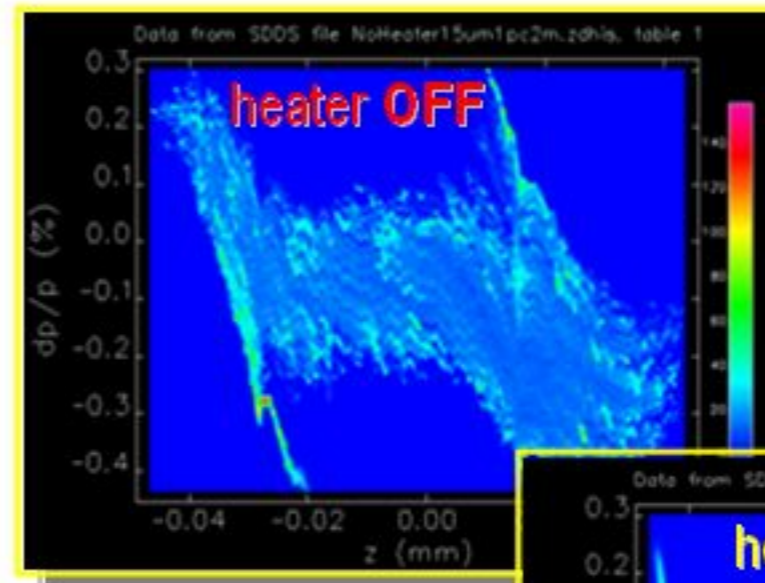
# Need small uncorrelated energy spread

## TTF measurement

M. Hüning, H. Schlarb, *PAC'03*



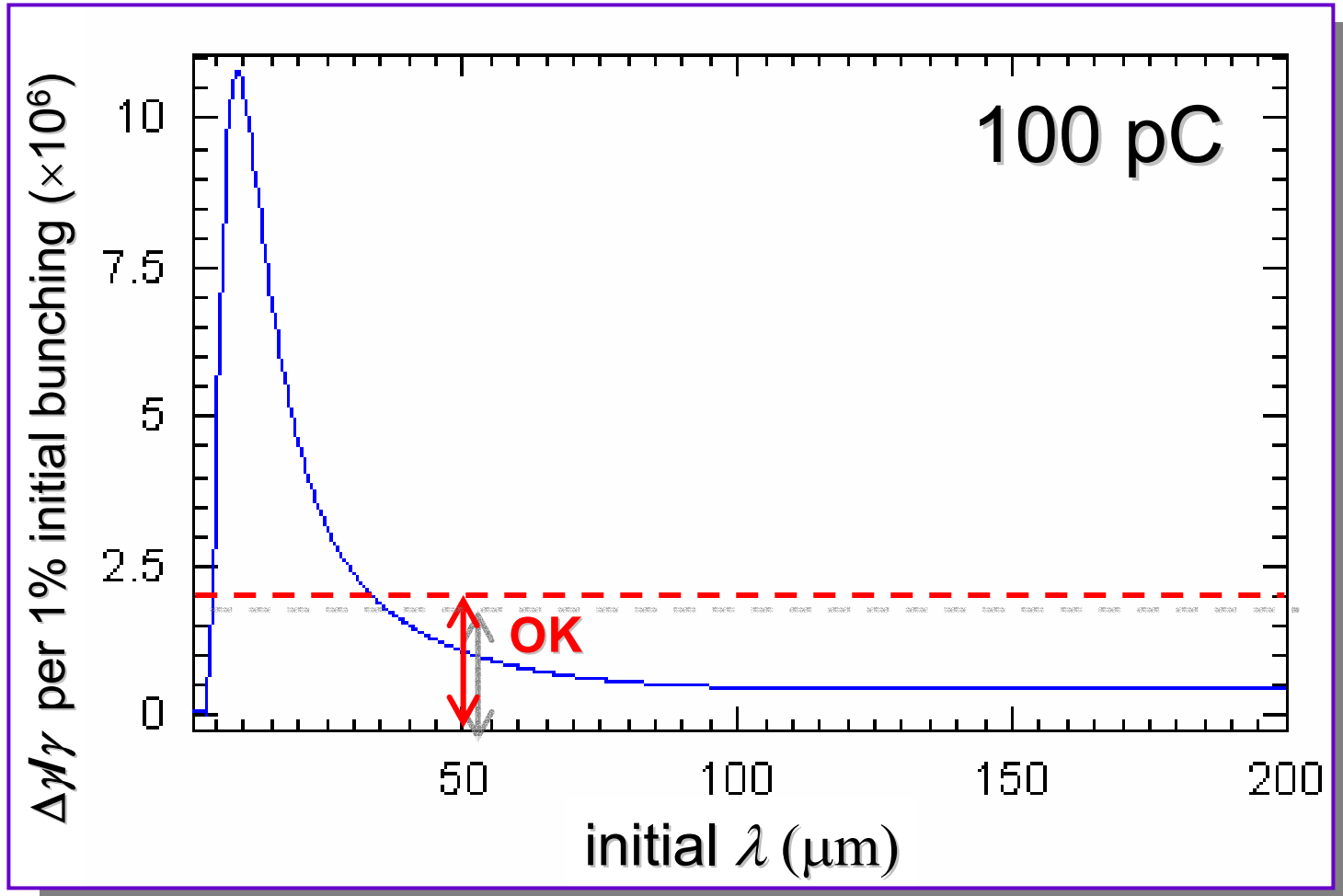
Micro-bunching instability needs 'beam-heater' to Landau damp **LSC & CSR** (Z. Huang, *FEL'04*, Monday)



For sub-fs pulse, use **100-pC bunch charge** to preserve 3-keV energy spread and assume  $\gamma\epsilon_{x,y} \approx 0.5 \mu\text{m}$  at 100 pC...

# LSC/CSR Micro-bunching Instability Limits

Induced  $\Delta\gamma/\gamma$  up to BC2



Initial current modulations must be  $<2\%$   
at wavelengths longer than  $50 \mu\text{m}$ .

# BC2 chicane and beam parameters for sub-fs case

**100 pC**

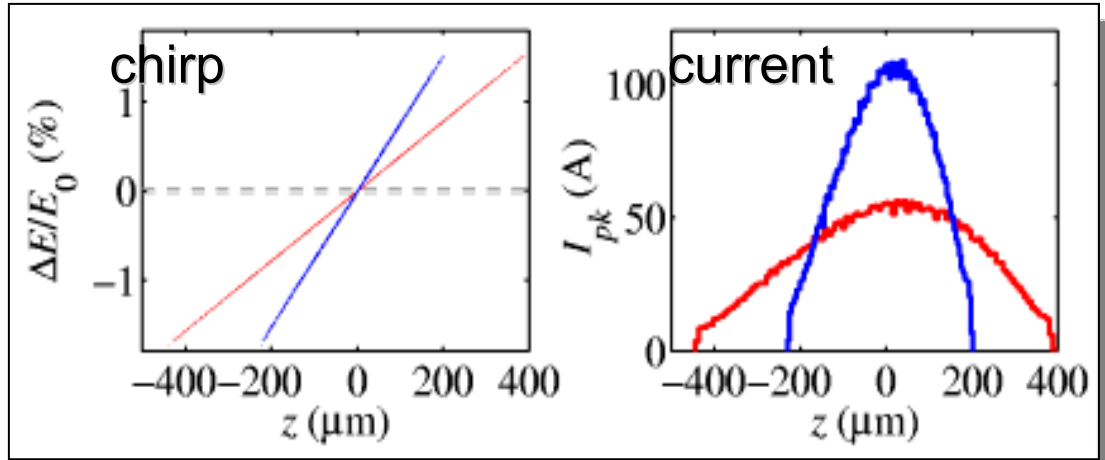
BC2 start →  
BC2 center →

## FOIL:

Beryllium:  $X_0 \approx 35$  cm

Thickness:  $x = 50$   $\mu\text{m}$

Slot-width:  $\Delta x = 140$   $\mu\text{m}$



## Use same:

- $\sigma_{z0}$
- BC1  $R_{56}$
- BC2  $R_{56}$

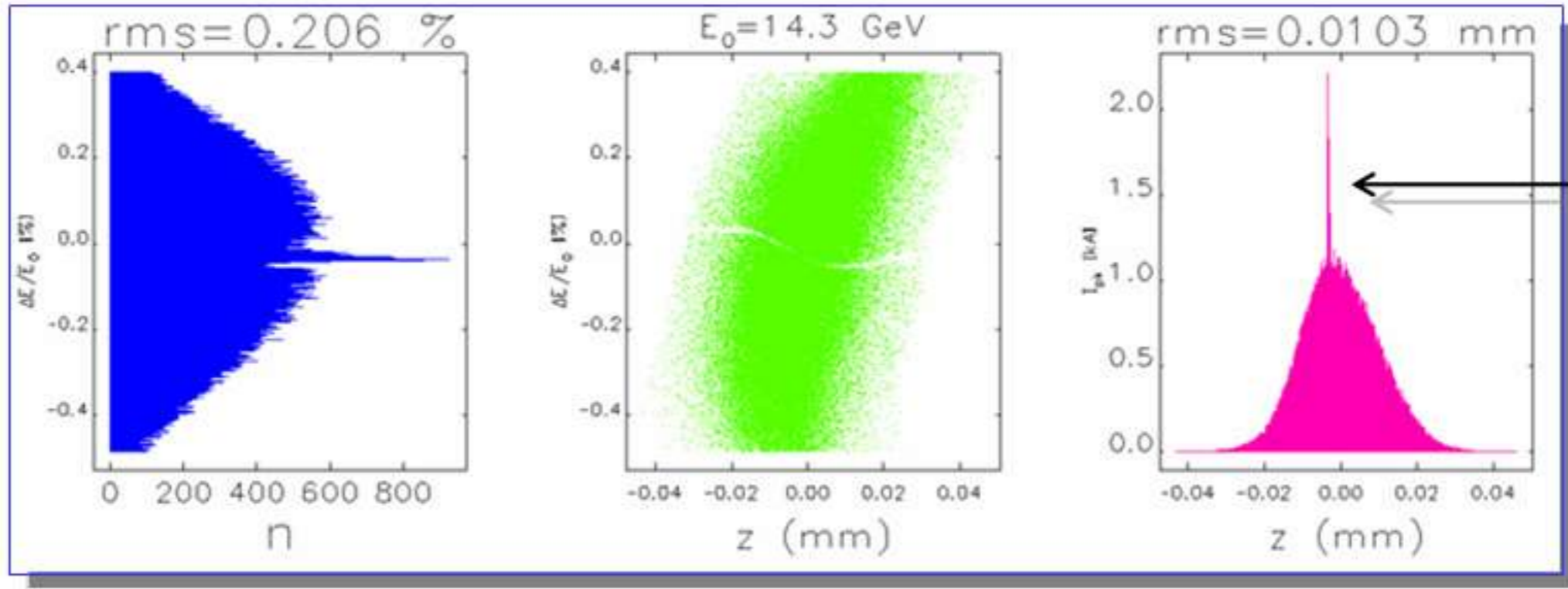
## Adjust:

- charge ↓
- RF phases
- chirp ↑,  $h$
- $\beta_{x,y}$  in foil ↓

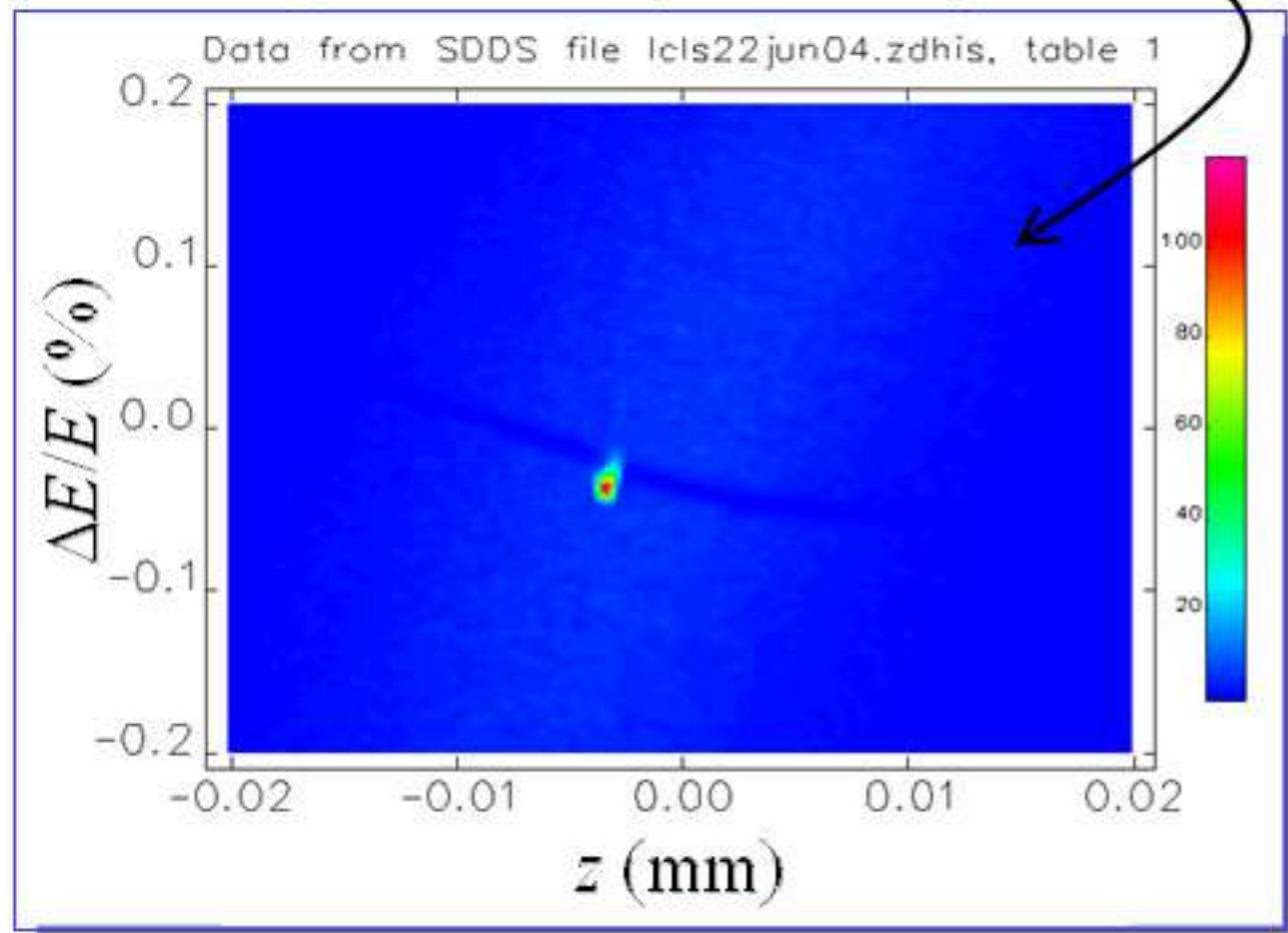
Table 1: LCLS BC2 chicane and beam parameters.

Parameter	symbol	value	unit
bunch charge	$Q$	100	pC
chicane energy	$E_0$	4.54	GeV
chicane dispersion	$\eta$	363	mm
momentum compaction	$R_{56}$	-24.7	mm
energy chirp	$h$	39.0	1/m
rms initial $E$ -spread	$\sigma_{\delta_0}$	3.1	$10^{-6}$
beta at foil	$\beta$	8.0	m
normalized emittance	$\gamma\epsilon$	0.5	$\mu\text{m}$
length of each bend	$L_B$	0.50	m
angle of each bend	$ \theta_B $	1.98	deg
B1-B2 & B3-B4 drift	$\Delta L$	10.0	m

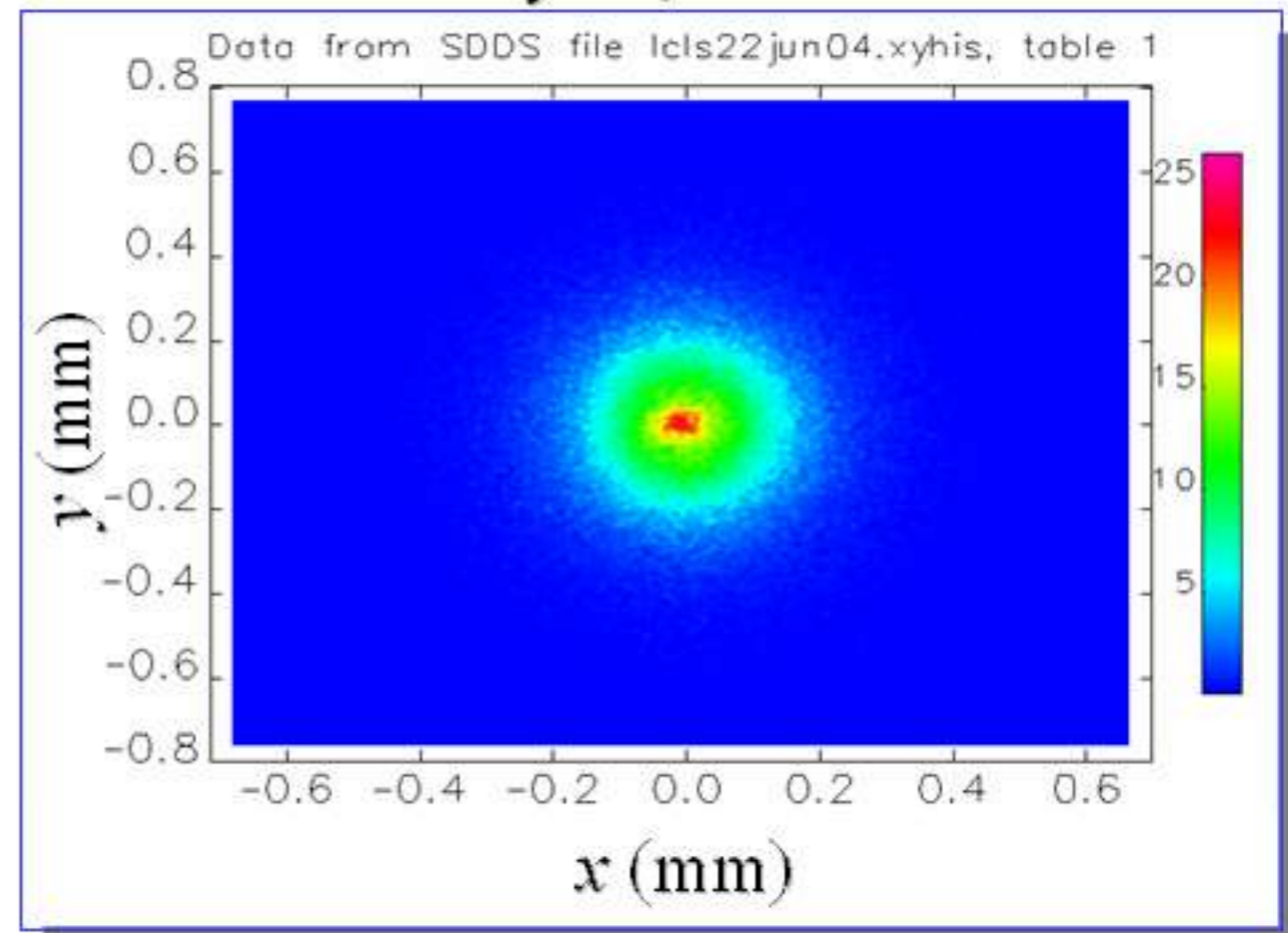
# Particle Tracking up to Undulator (14 GeV)



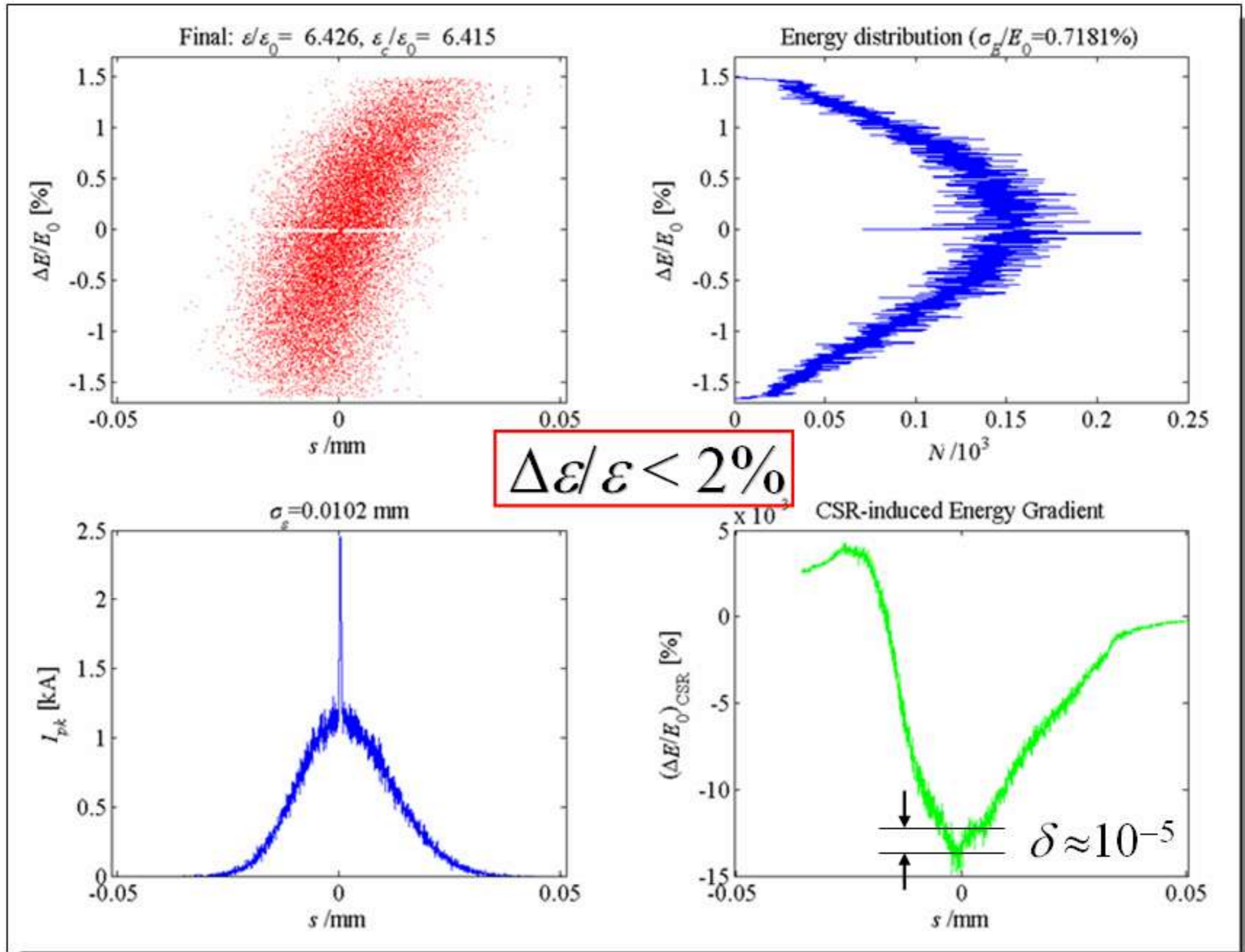
longitudinal phase space



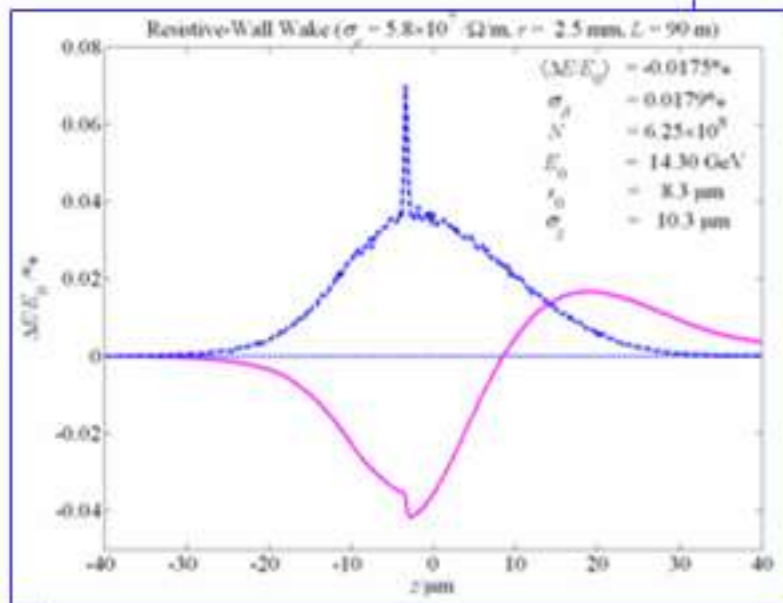
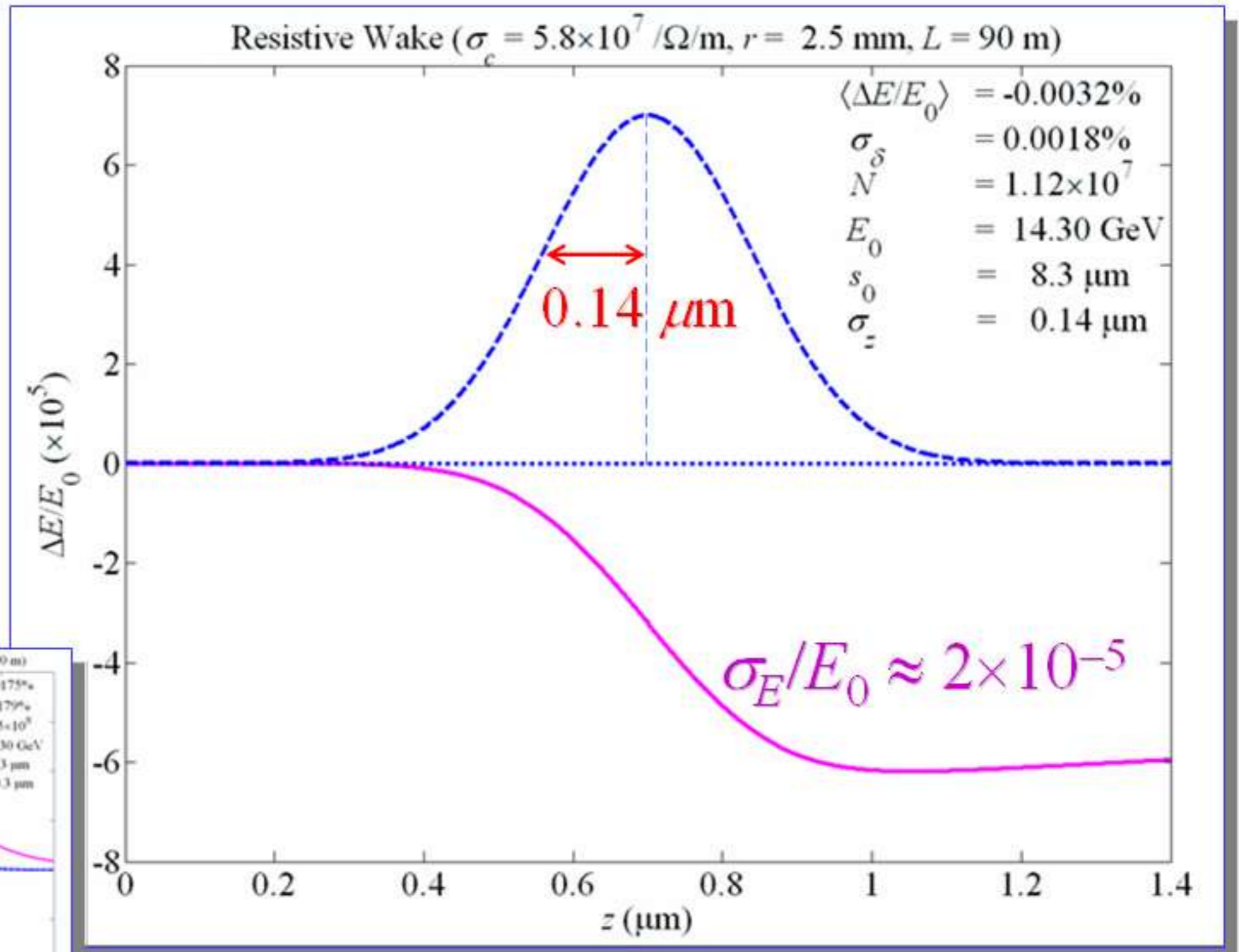
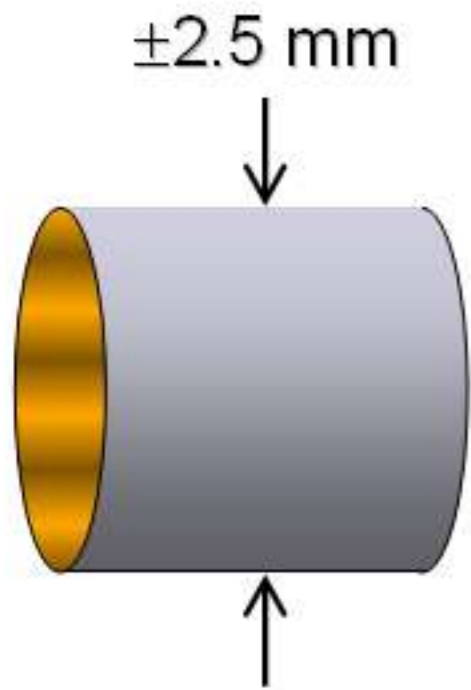
$x$ - $y$  space



# CSR (1D) in BC2 with foil-induced spike

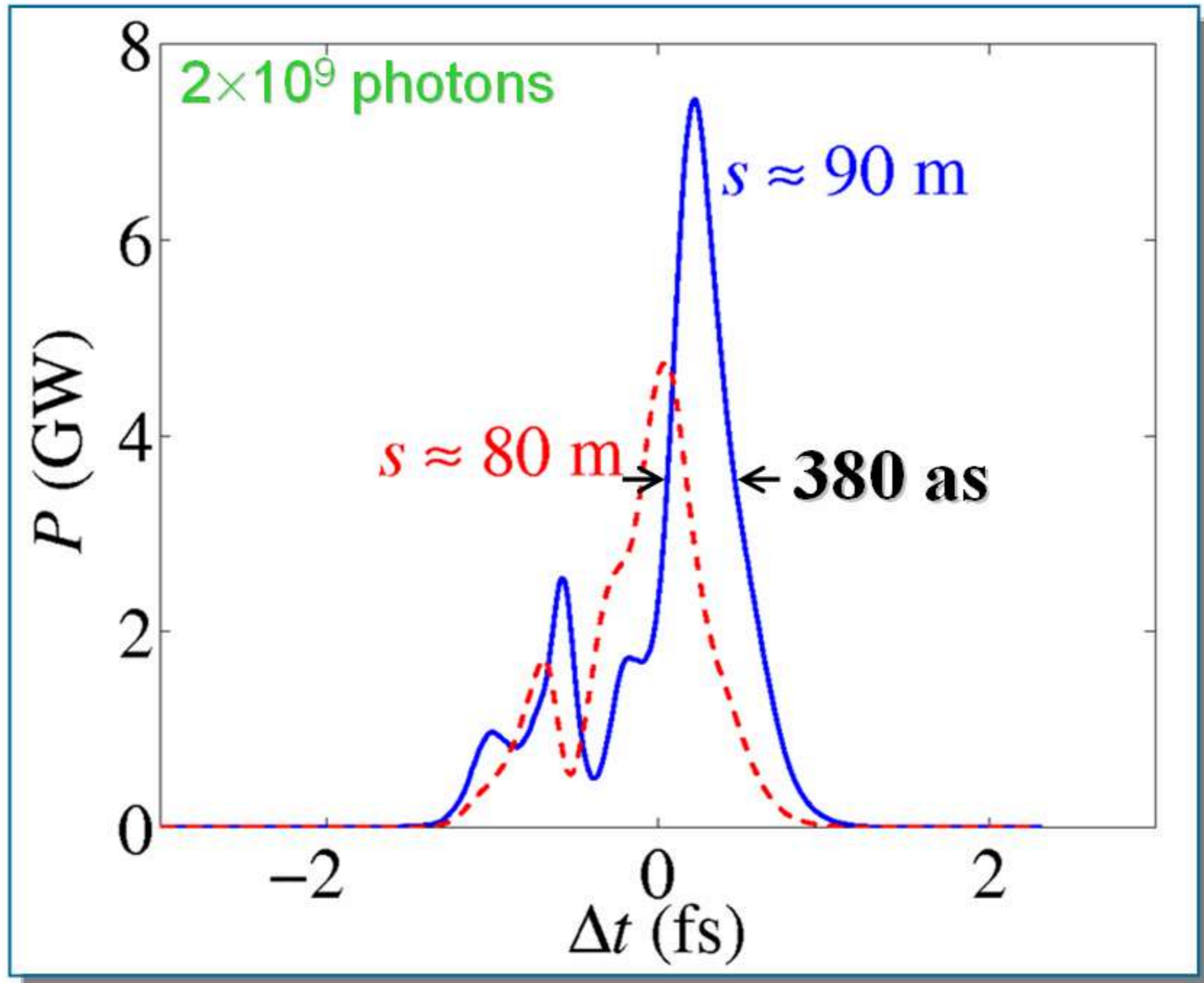


# Resistive-Wall Wakefield in Undulator is Small



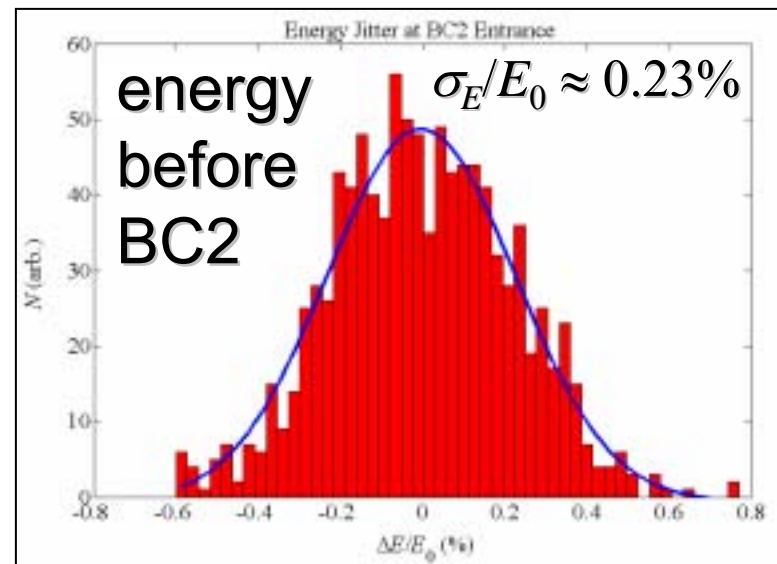
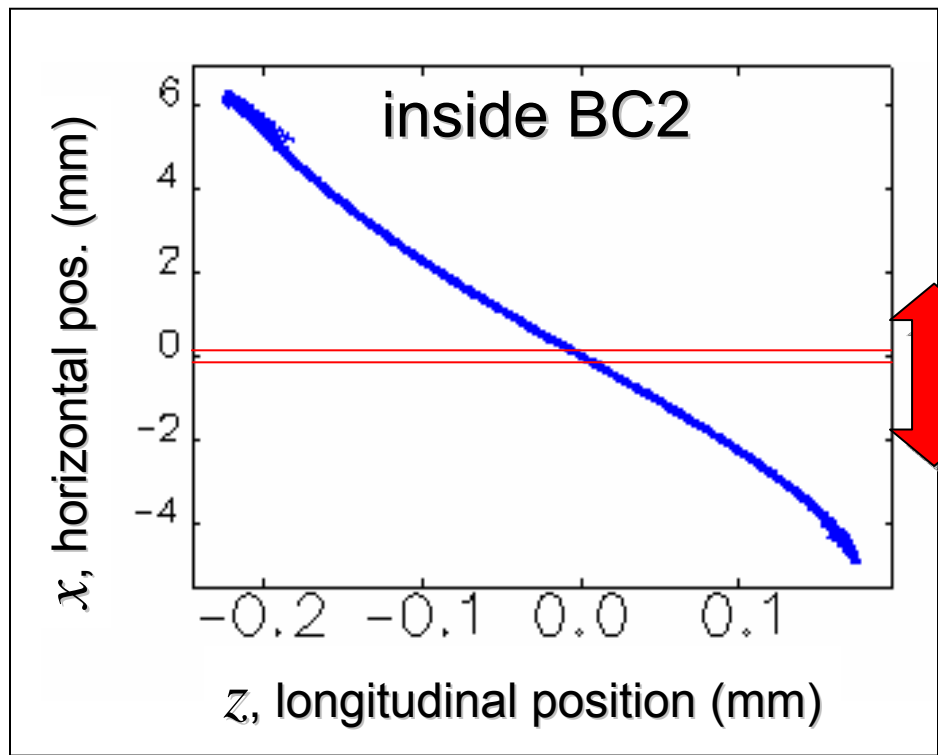
Copper,  $L = 90 \text{ m}$ ,  $r = 2.5 \text{ mm}$ ,  $E = 14 \text{ GeV}$  (unchanged by AC-conductivity)

# 380-attosecond FWHM X-ray pulse at $s = 90$ m (7.5 GW)



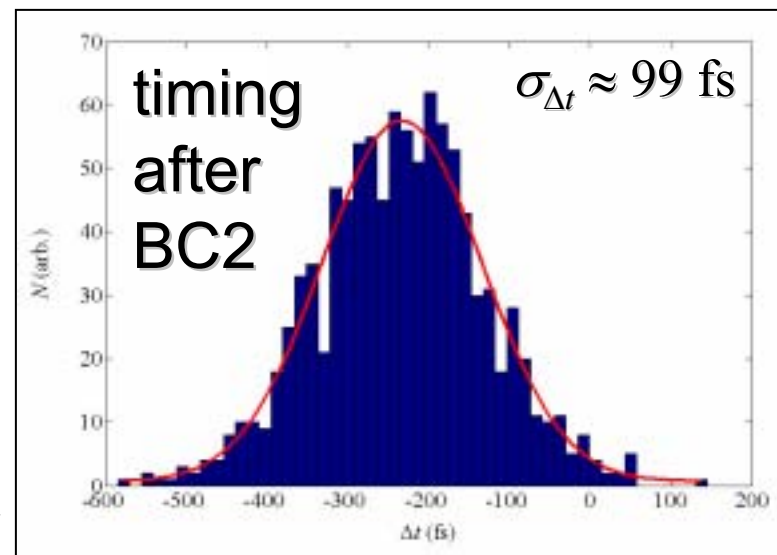
# Energy and Timing Jitter

**rms jitter:**  $\Delta Q/Q = 2\%$ ,  $\Delta t_{gun} = 0.5$  ps,  
 $\Delta\phi_{RF} = 0.1^\circ$ ,  $\Delta V/V = 0.1\%$



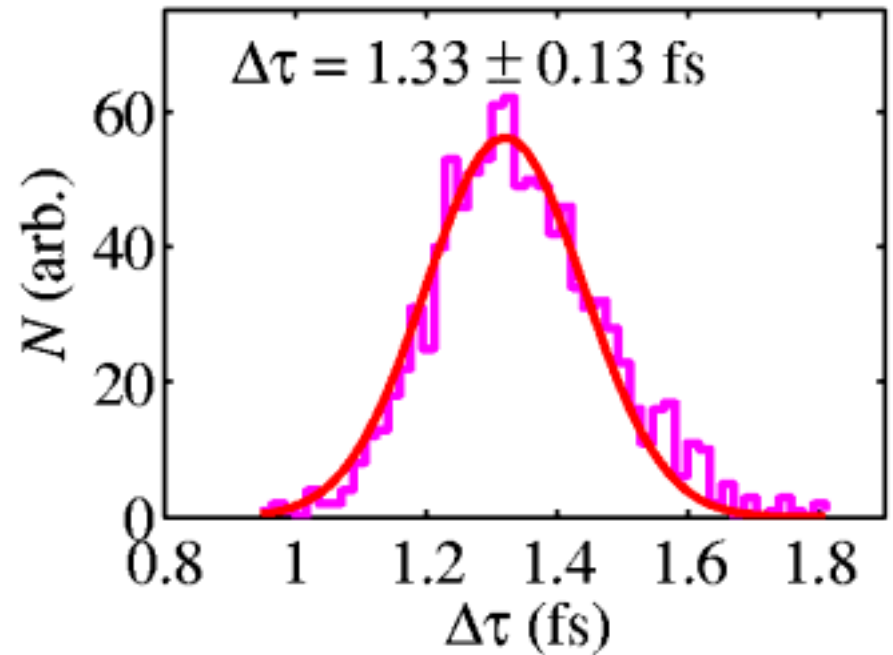
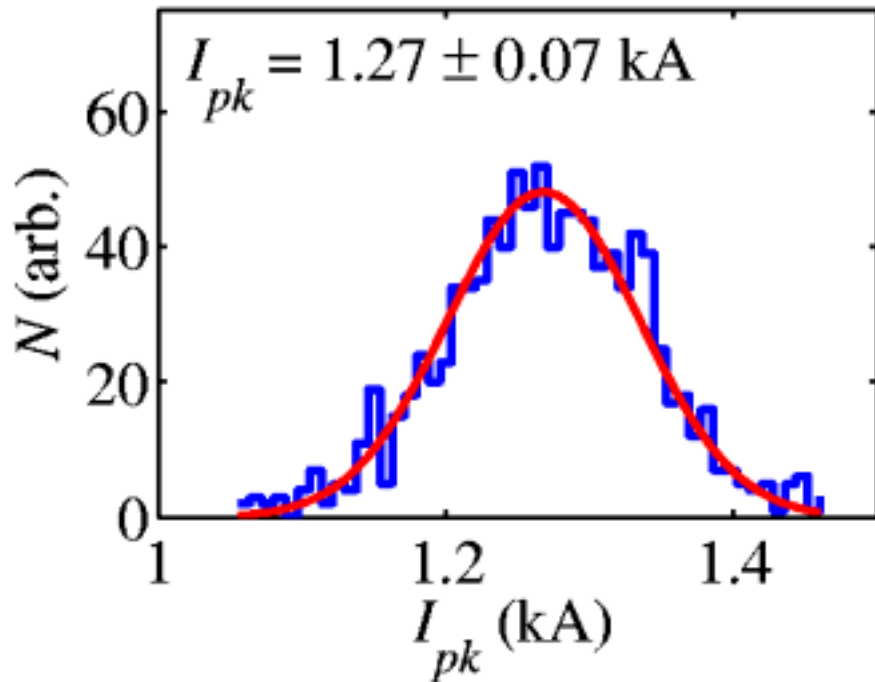
0.23% energy jitter  $\rightarrow$   
800  $\mu\text{m}$   $x$ -jitter (30%  
of rms beam size)

Energy jitter after BC2 is suppressed by fixed slot, but timing jitter is still 100 fs rms  $\rightarrow$



# Peak Current and Pulse Duration Jitter

**rms jitter:**  $\Delta Q/Q = 2\%$ ,  $\Delta t_{gun} = 0.5$  ps,  
 $\Delta\phi_{RF} = 0.1^\circ$ ,  $\Delta V/V = 0.1\%$



<10% peak current & pulse width jitter, but **100-fs timing jitter**

# *Concluding Remarks*

- 2 fs FWHM x-ray pulse possible in *LCLS* with baseline design + simple foil
- Photons per pulse reduced ( $10^{12} \rightarrow 10^{10}$  or  $10^9$ )
- Pulse length is easily adjustable
- Precisely spaced double pulses available
- 400-as pulse looks possible with reduced charge and modified compression parameters
- This extreme case is non-trivial, requiring low emittance and low intrinsic energy spread, but also at low charge.

Thanks: K. Bane, M. Cornacchia, H. Schlarb, G. Stupakov,...