The *LCLS* X-Ray FEL and Related R&D at the *SPPS*

TJNAF

January 30, 2004

P. Emma, *SLAC*

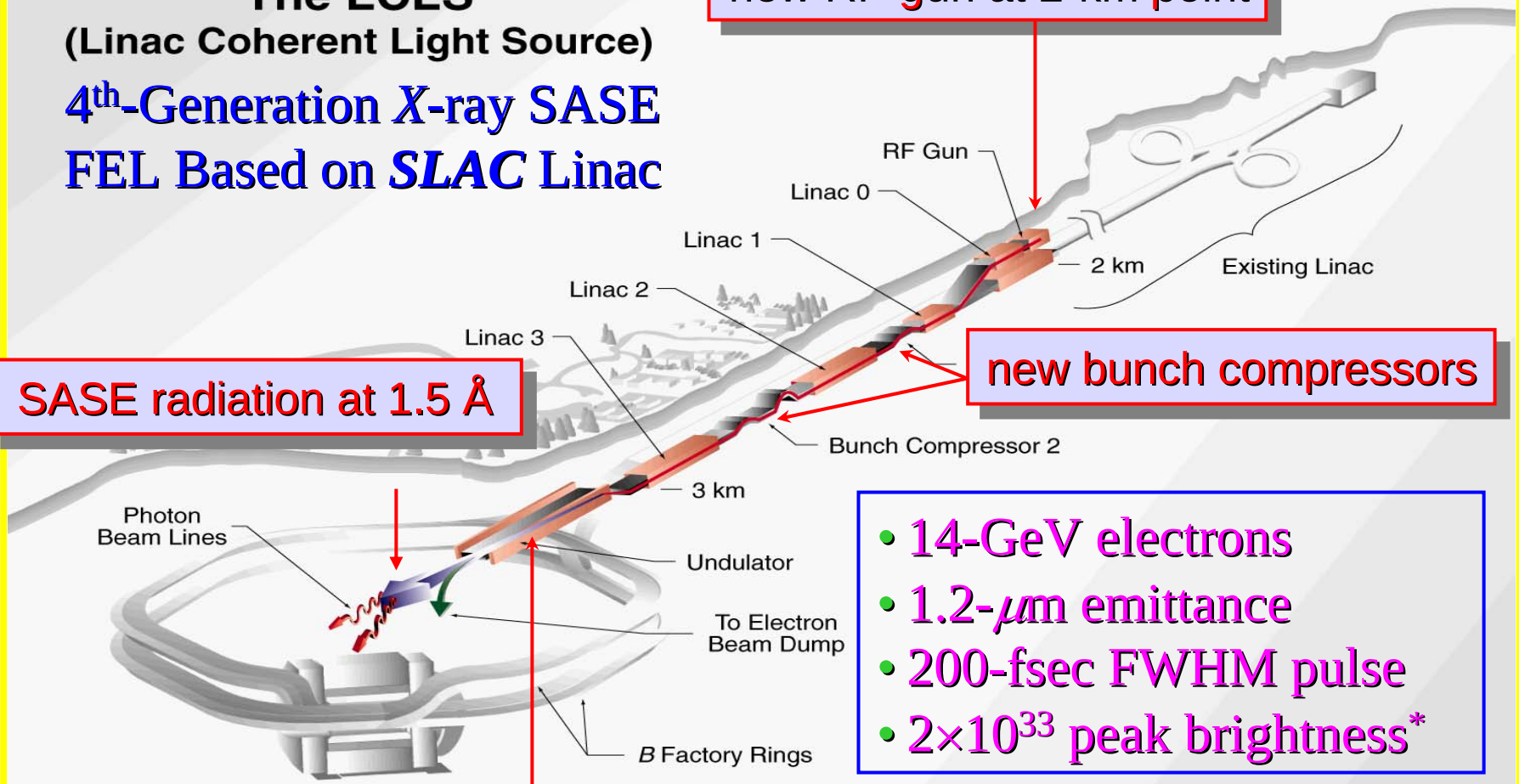
Jefferson Lab's
CENTER for ADVANCED STUDIES of ACCELERATORS

Linac Coherent Light Source (*LCLS*)

The LCLS
(Linac Coherent Light Source)

4th-Generation *X*-ray SASE FEL Based on *SLAC* Linac

new RF-gun at 2-km point



new bunch compressors

SASE radiation at 1.5 Å

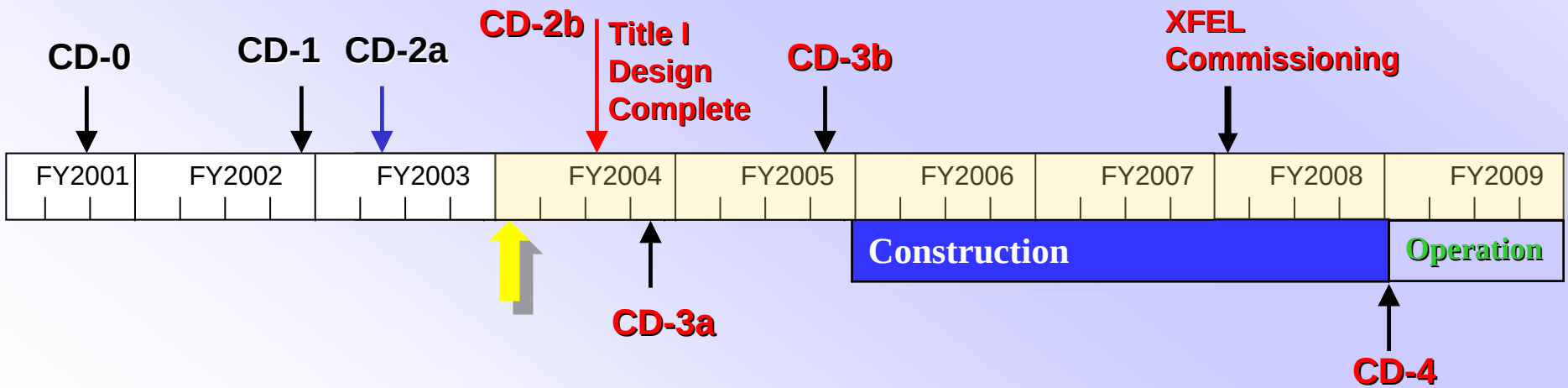
- 14-GeV electrons
- 1.2-μm emittance
- 200-fsec FWHM pulse
- 2×10^{33} peak brightness*

120-m undulator in research yard

* photons/sec/mm^2/mrad^2/0.1%-BW

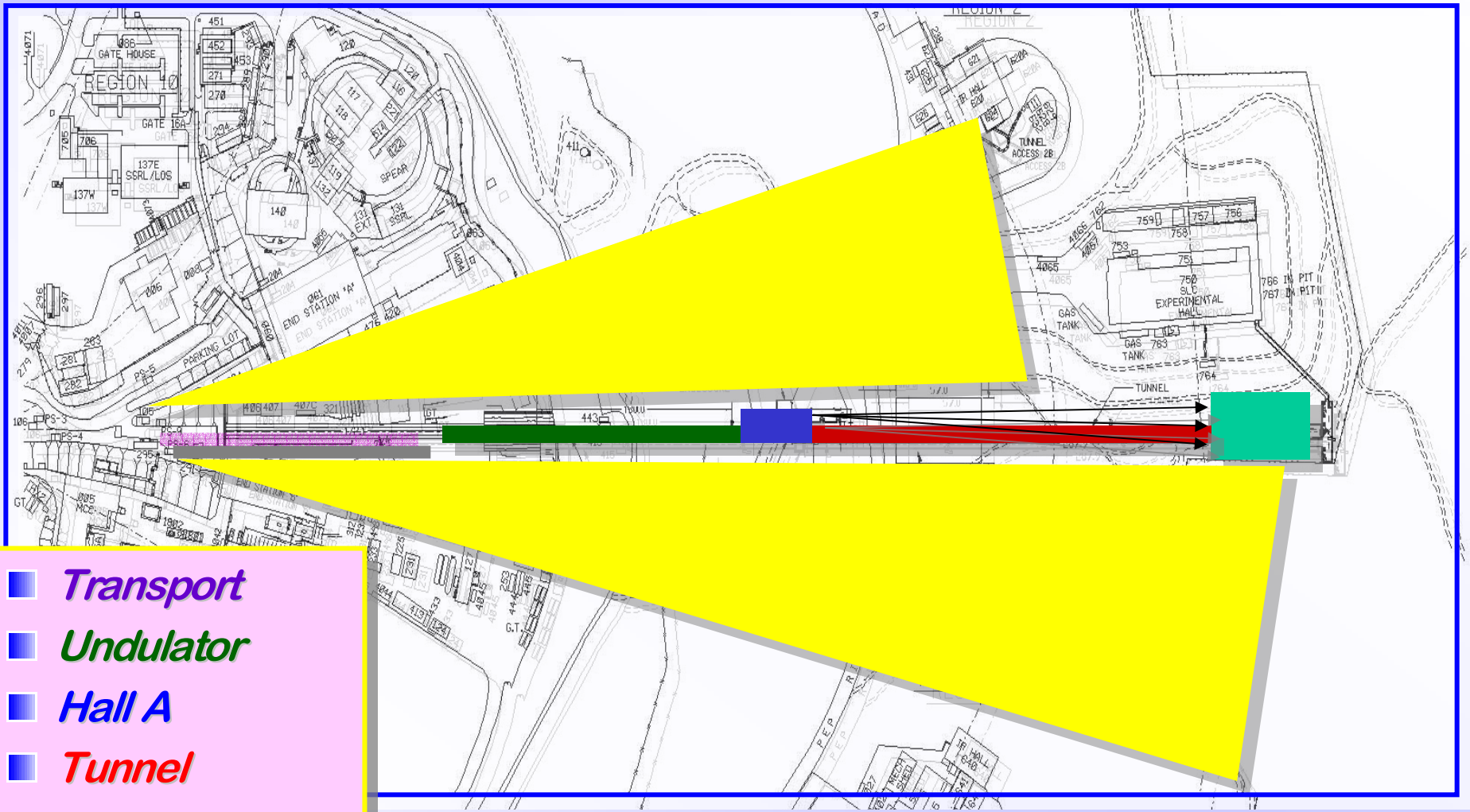
LCLS - Estimated Cost, Schedule

- $220M-$260M Total Estimated Cost range
- $265M-$315M Total Project Cost range
  - *FY2005 Long-lead purchases for injector, undulator*
  - *FY2006 Construction begins*
  - *FY2007 FEL Commissioning begins*
  - September 2008 *Construction complete – operations begins*



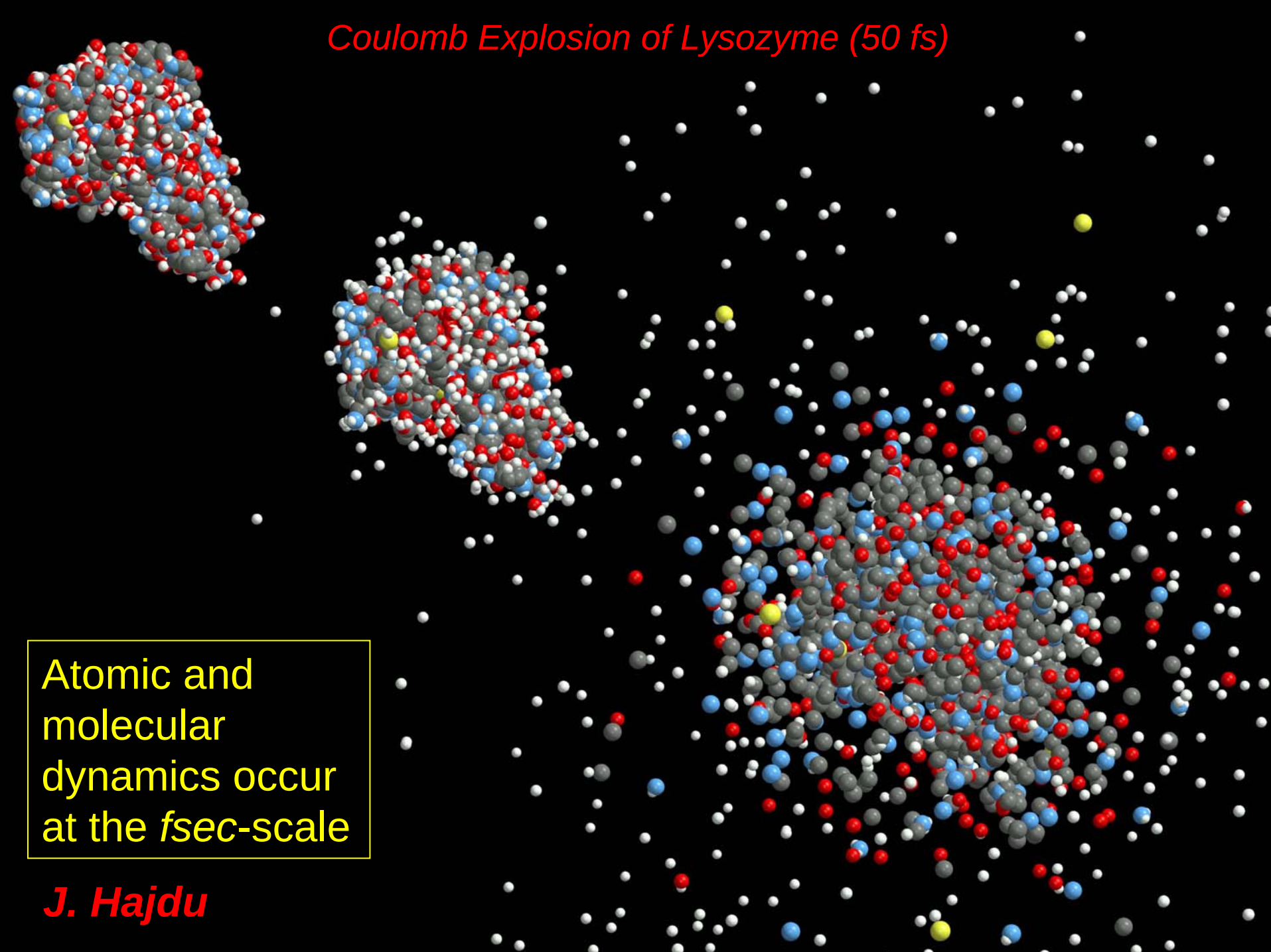
J. Galayda

LCLS – Current Layout and Future Expansion Capacity

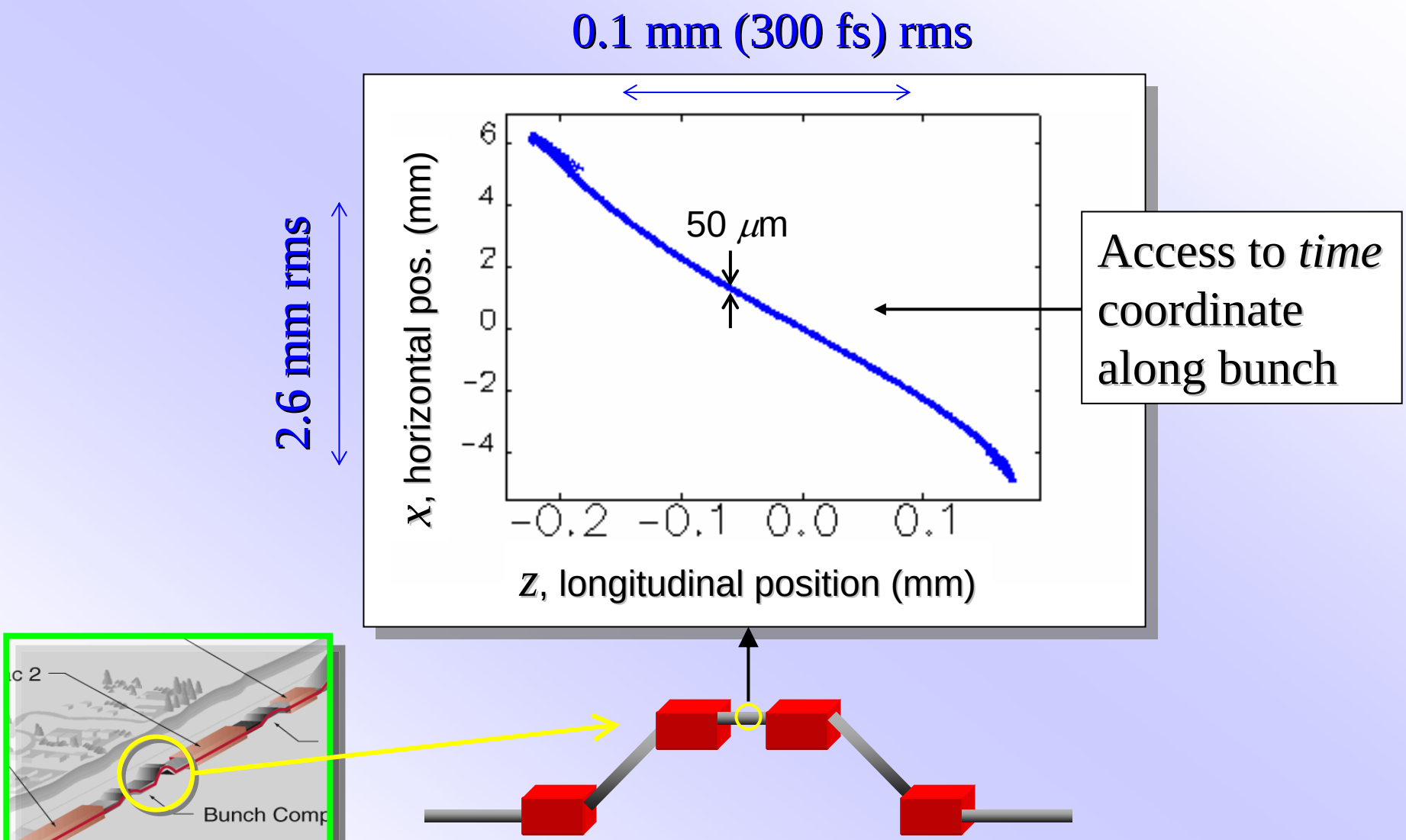


- Transport
- Undulator
- Hall A
- Tunnel
- Hall B
- 3 Beams/mirror
- Expansion

J. Galayda

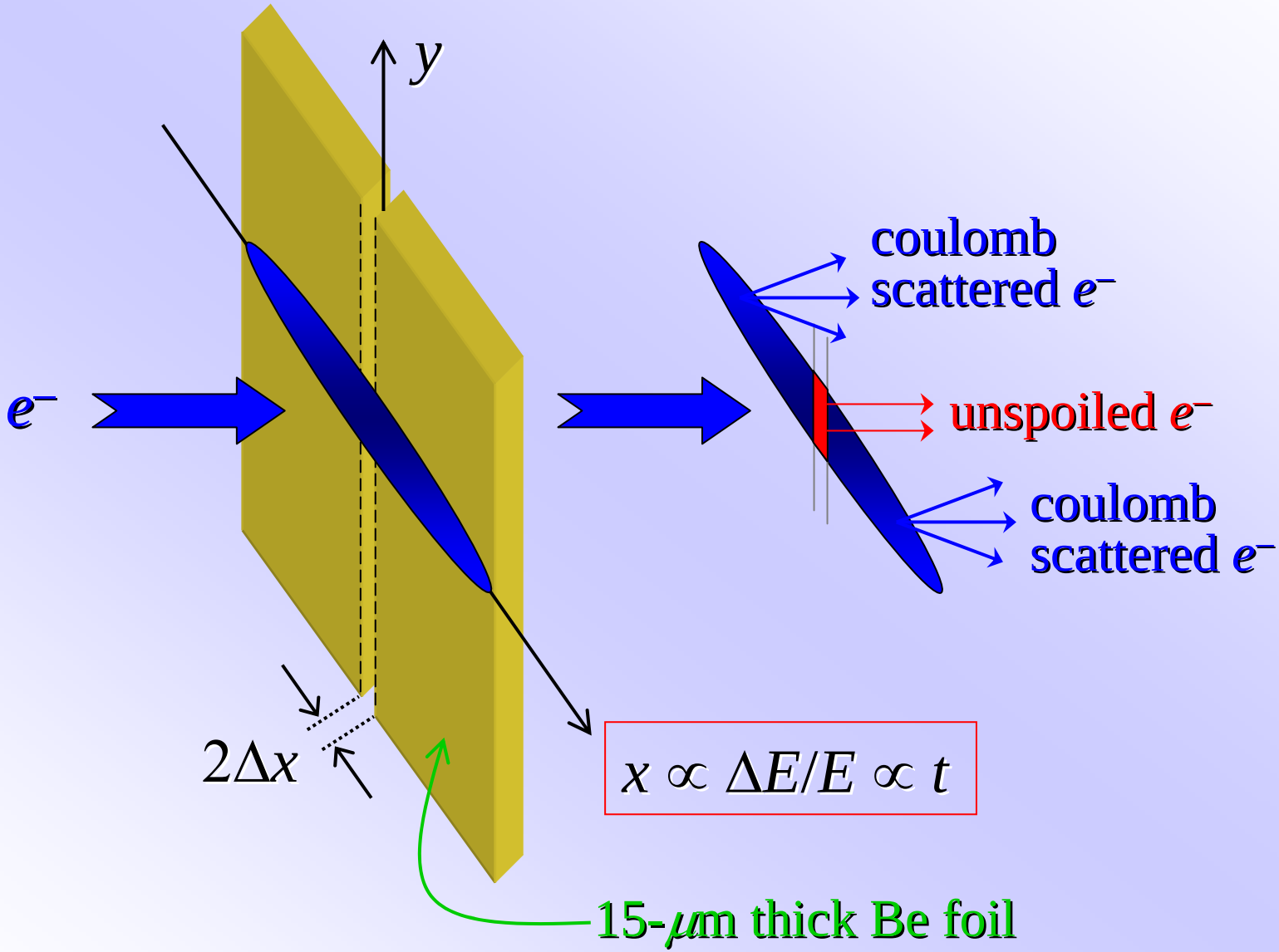

Coulomb Explosion of Lysozyme (50 fs)
Atomic and molecular dynamics occur at the *fsec*-scale
J. Hajdu

Exploit *Position-Time* Correlation on e^- bunch at Chicane Center



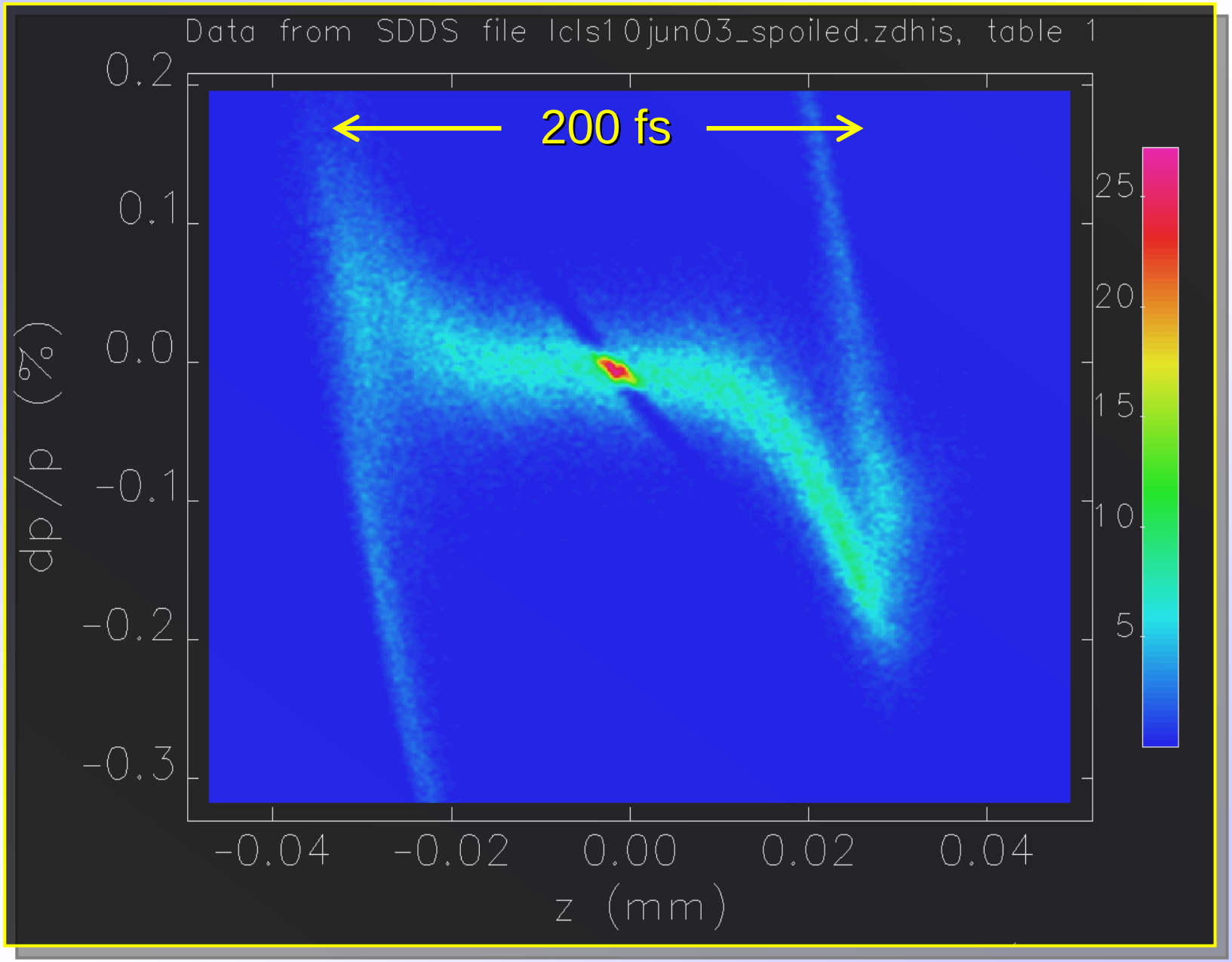
LCLS BC2 bunch compressor chicane
(similar in other machines)

Add thin slotted foil in center of chicane

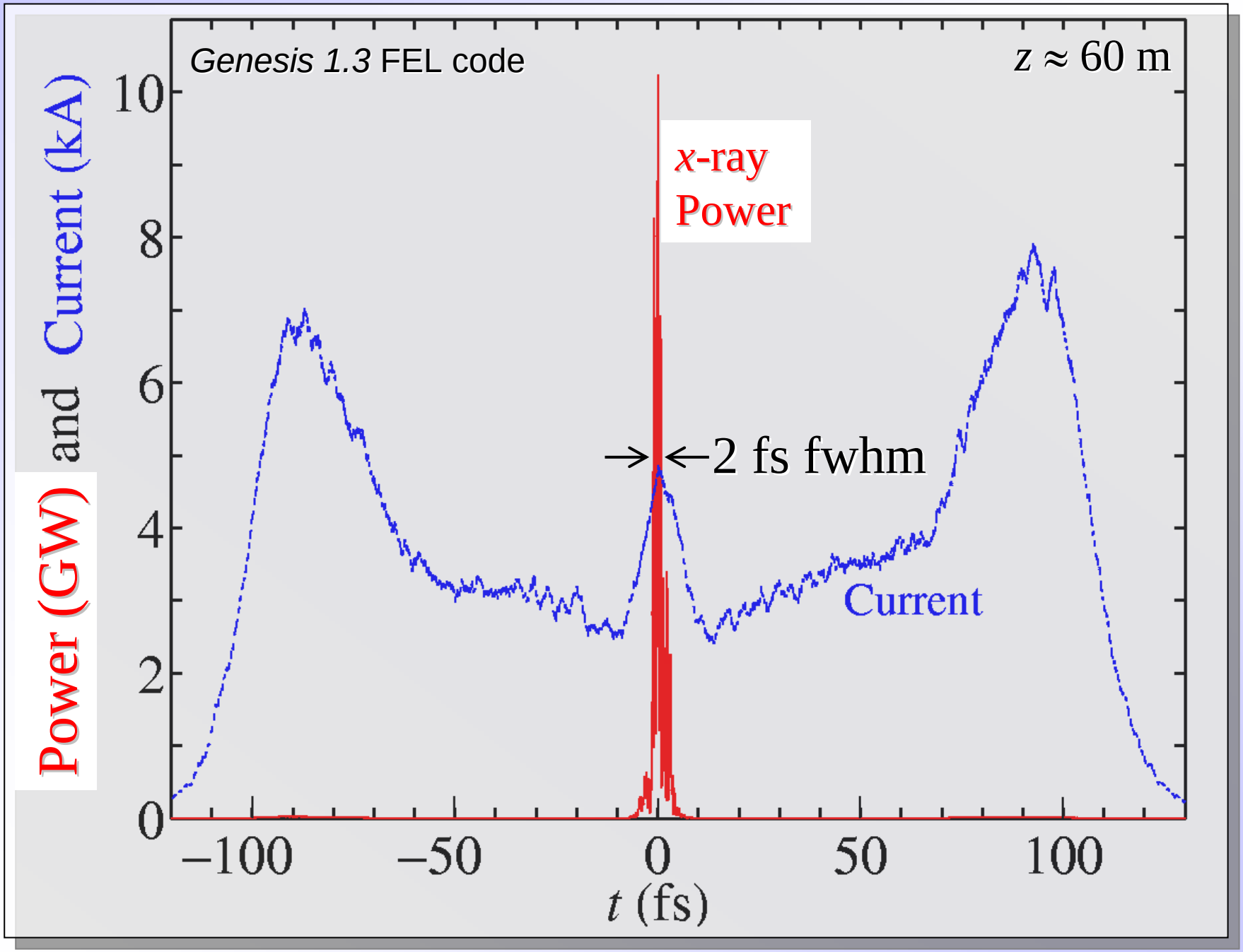


P. Emma, M. Cornacchia, K. Bane, Z. Huang, H. Schlarb (DESY), G. Stupakov, D. Walz, ***PRL***

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

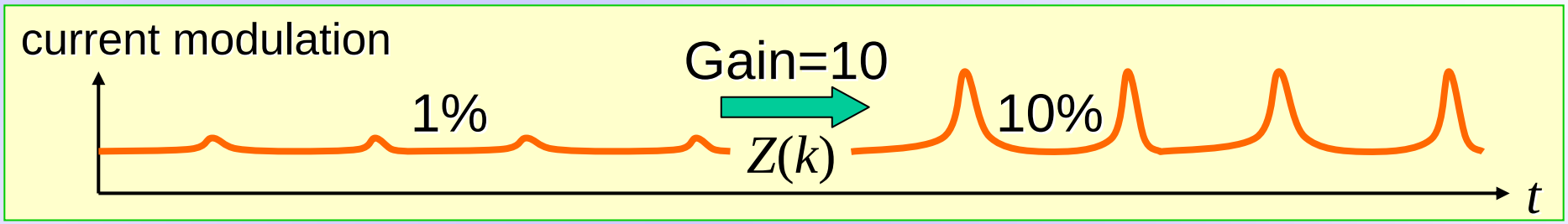


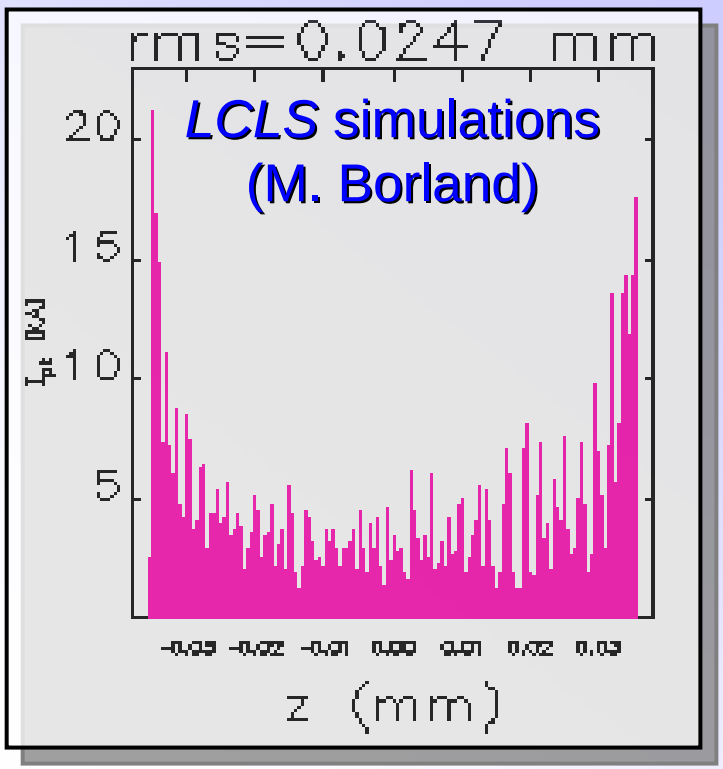
$\Delta E/E$

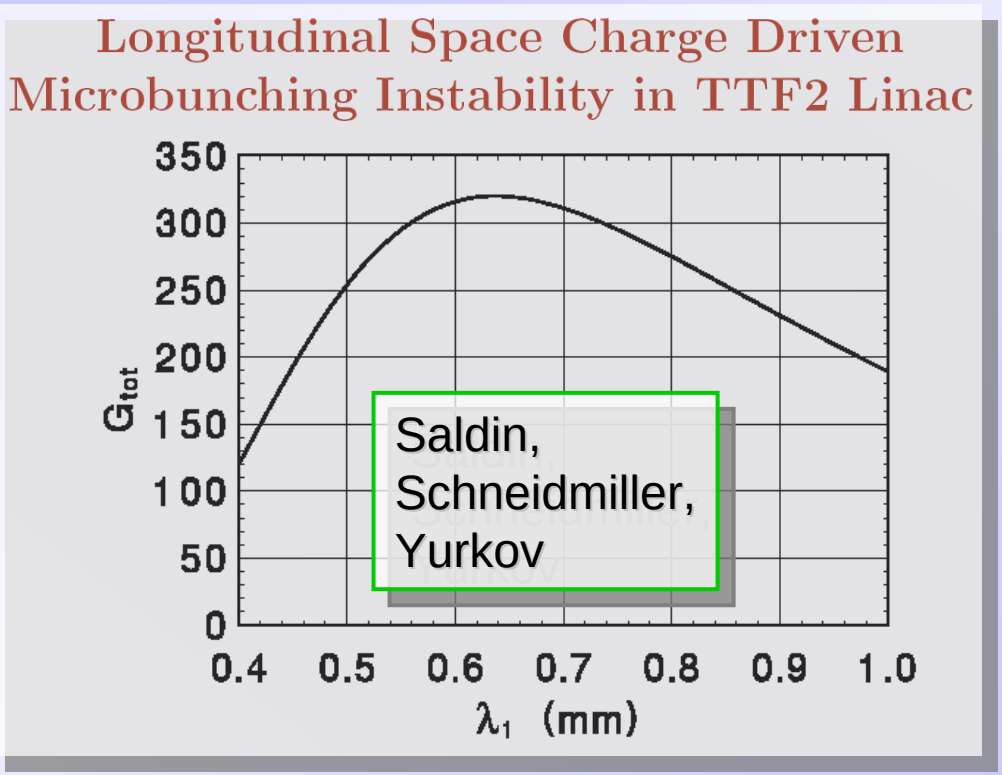

Genesis 1.3 FEL code
z ≈ 60 m
x-ray
Power
→←2 fs fwhm
Current
Power (GW) and Current (kA)
10
8
6
4
2
0
−100
−50
0
50
100
t (fs)

Micro-Bunching Instabilities

- FEL instability needs very "cold" e^- beams (small ε and E-spread)
- Such a cold beam is subject to other "undesirable" instabilities in the accelerator (CSR, Longitudinal Space-Charge=LSC, wakefields)

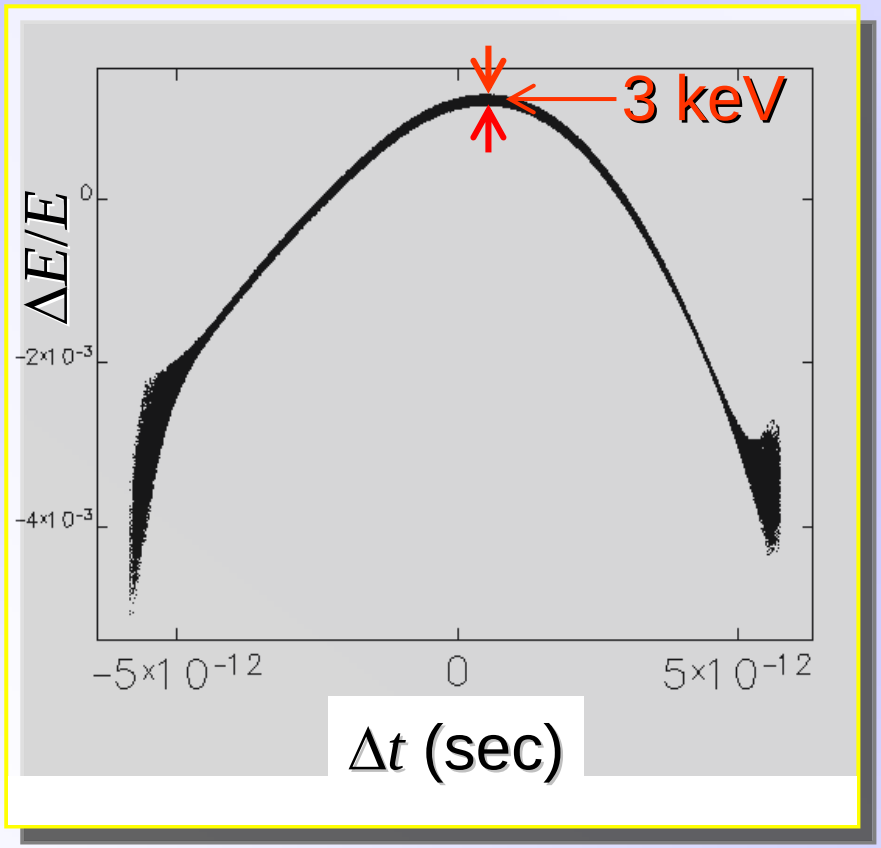




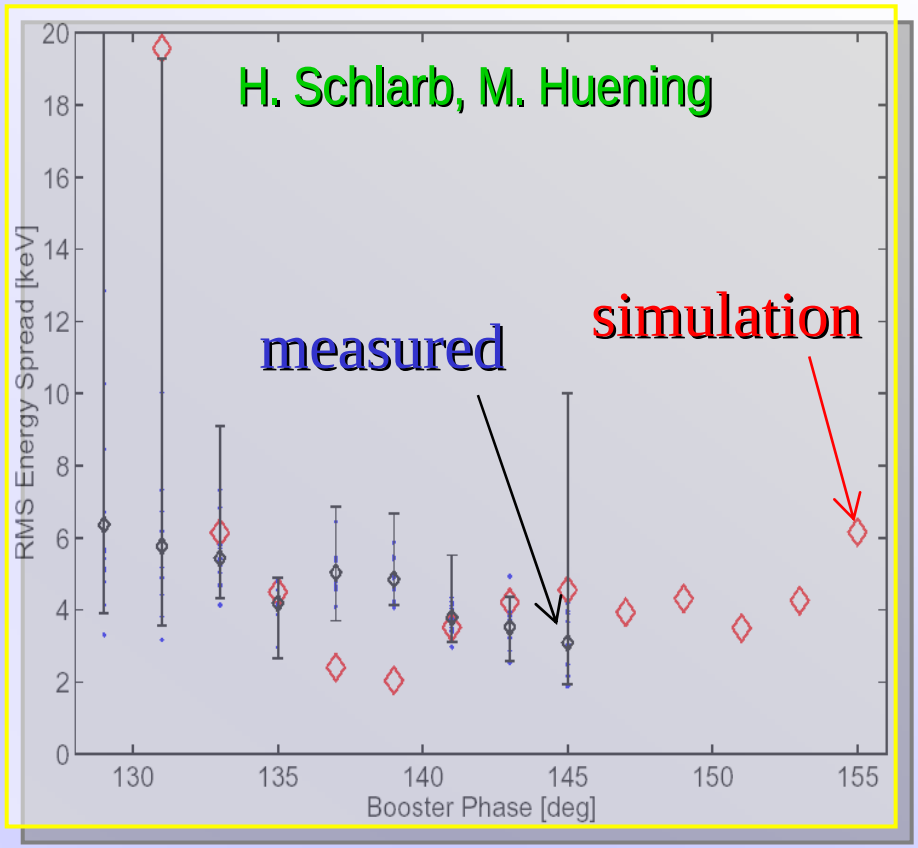


How cold is the photo-injector beam?

Parmela Simulation



TTF measurement

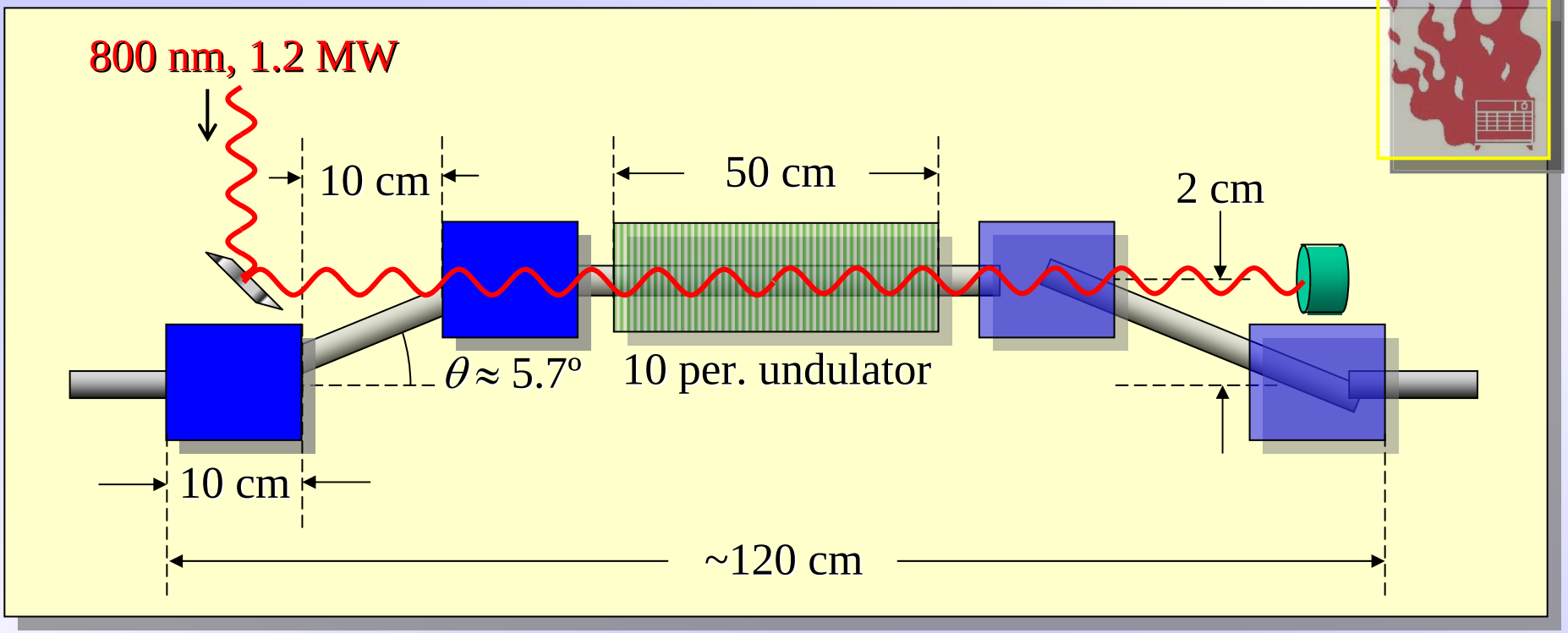


3 keV, accelerated to 14 GeV, and compressed ×36 ⇒

$3/14\times10^{6}\times36 < 1\times10^{-5}$

Too small to be useful in FEL (no effect on FEL gain when $<1\times10^{-4}$)

Laser Heater for Landau Damping

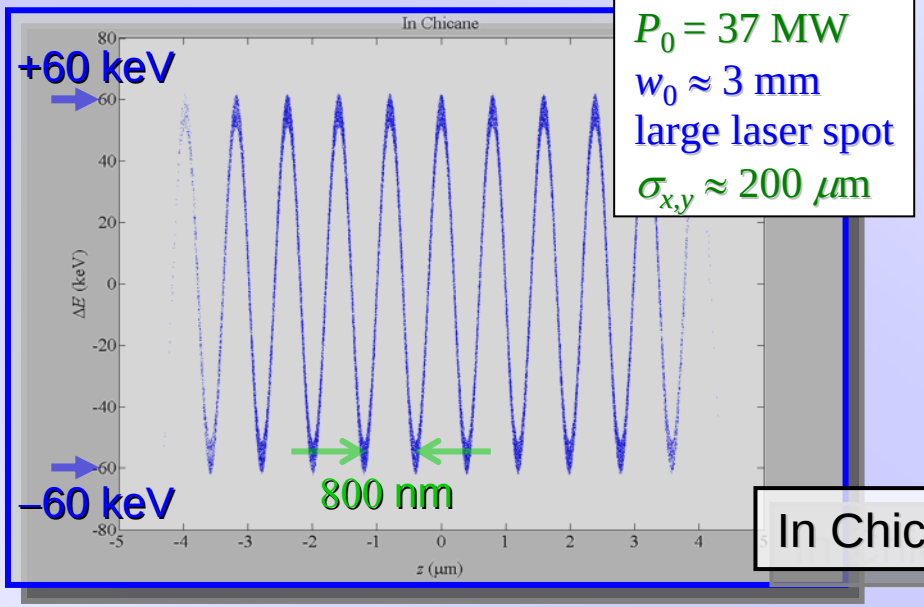


- Laser-electron interaction in undulator induces energy modulation (at 800 nm) $\Rightarrow$ 40 keV rms
- Inside weak chicane for laser access and time-coordinate smearing (Emittance growth negligible)

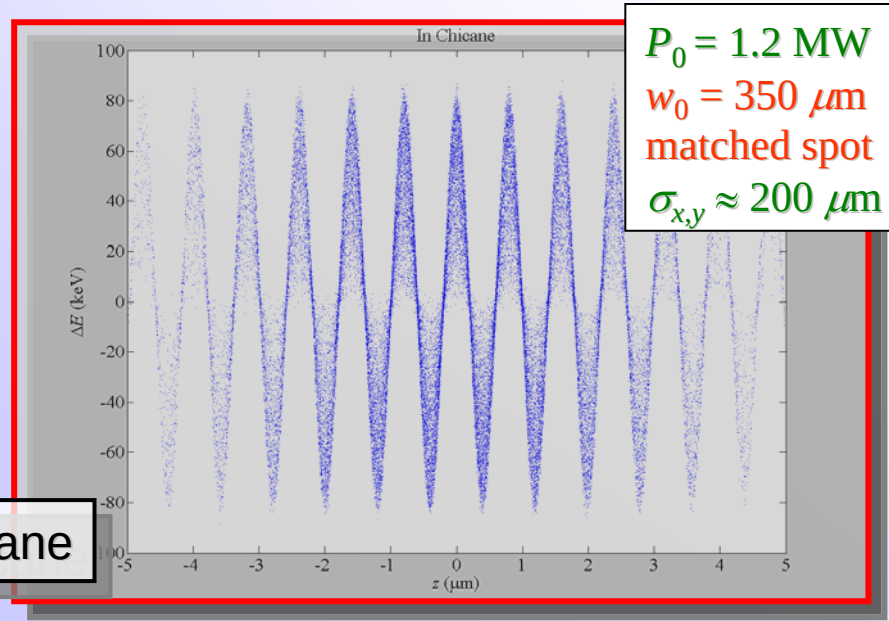
Z. Huang, M. Borland (ANL), P. Emma, J. Wu, R. Carr, C. Limborg, G. Stupakov, J. Welch

laser spot much bigger than e^- spot

laser spot similar to e^- spot



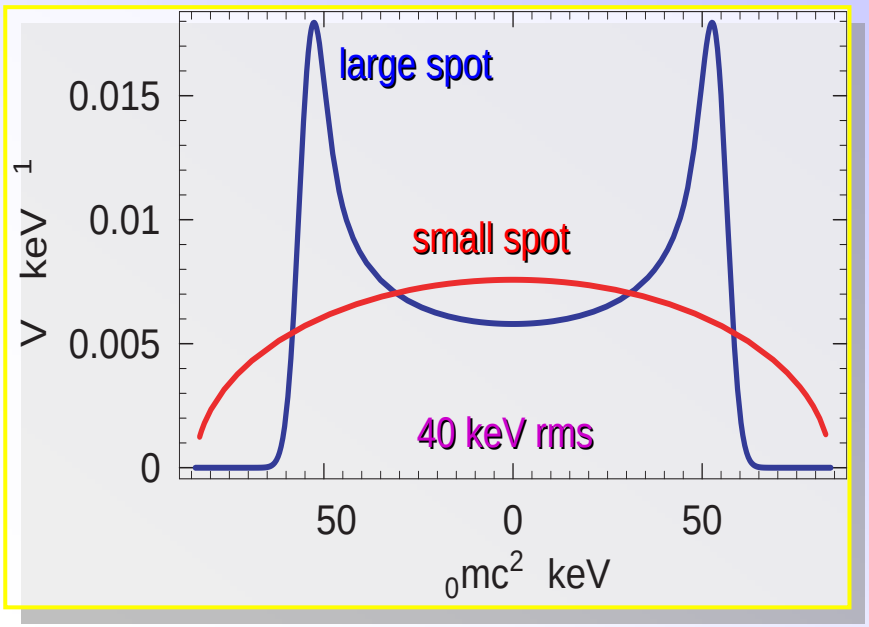
$P_0 = 37$ MW
$w_0 \approx 3$ mm
large laser spot
$\sigma_{x,y} \approx 200$ μm

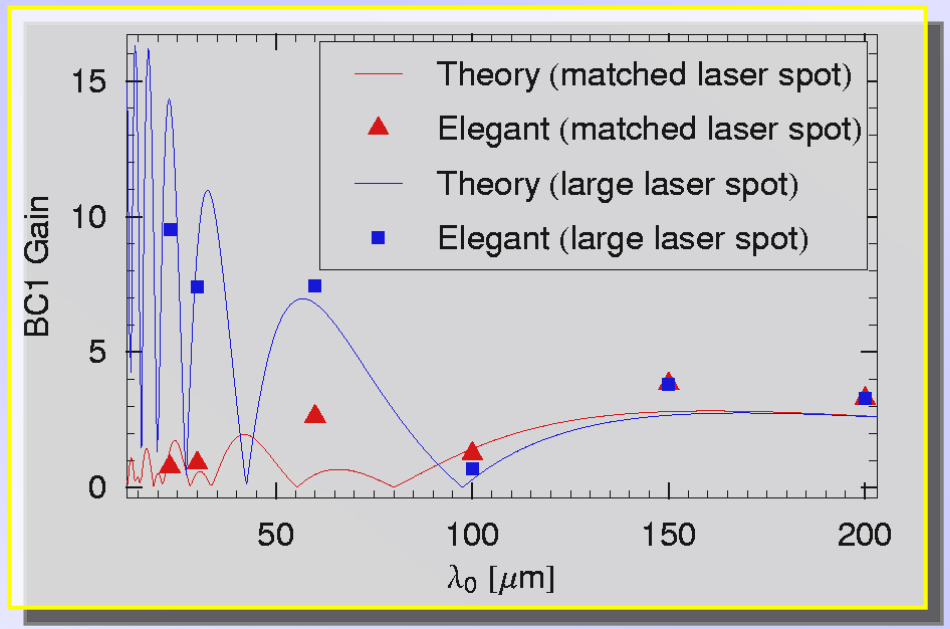


$P_0 = 1.2$ MW
$w_0 = 350$ μm
matched spot
$\sigma_{x,y} \approx 200$ μm

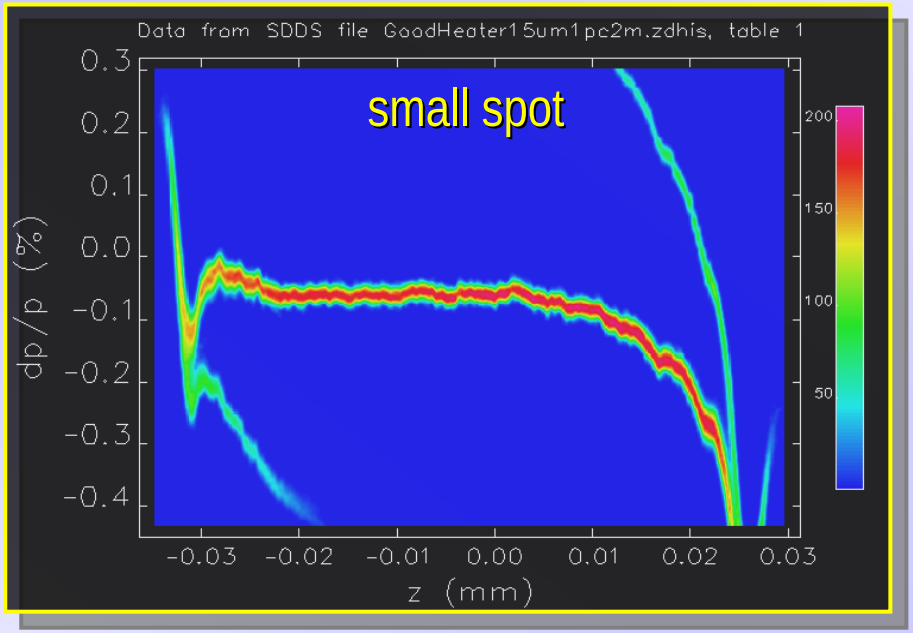
In Chicane

800-nm structure then gets smeared by chicane: $\Delta\sigma_z \approx \langle x'^2 \rangle^{1/2} |\eta_x| >> \lambda$

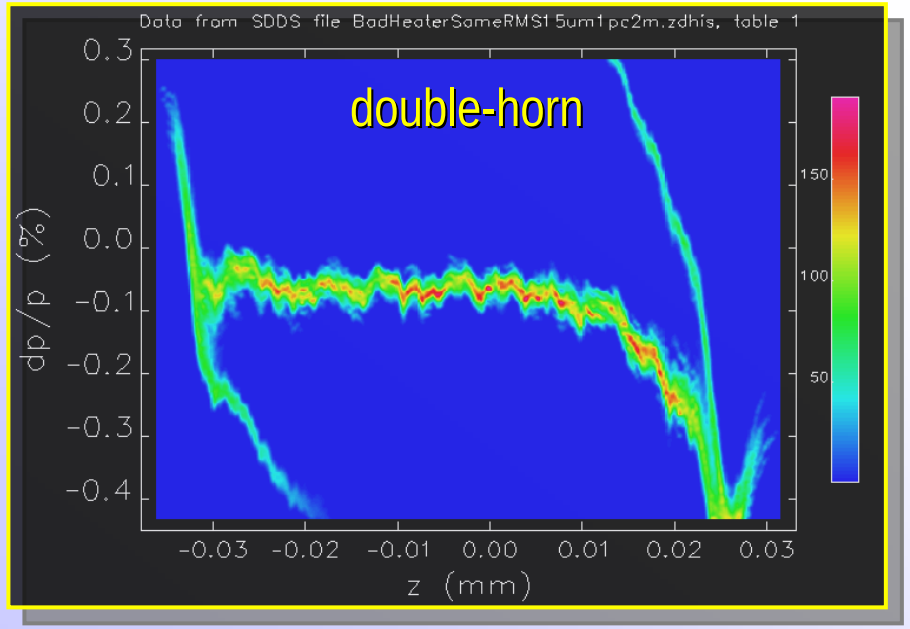




The GOOD (w_0 = 350 μm, P_0 = 1.2 MW),

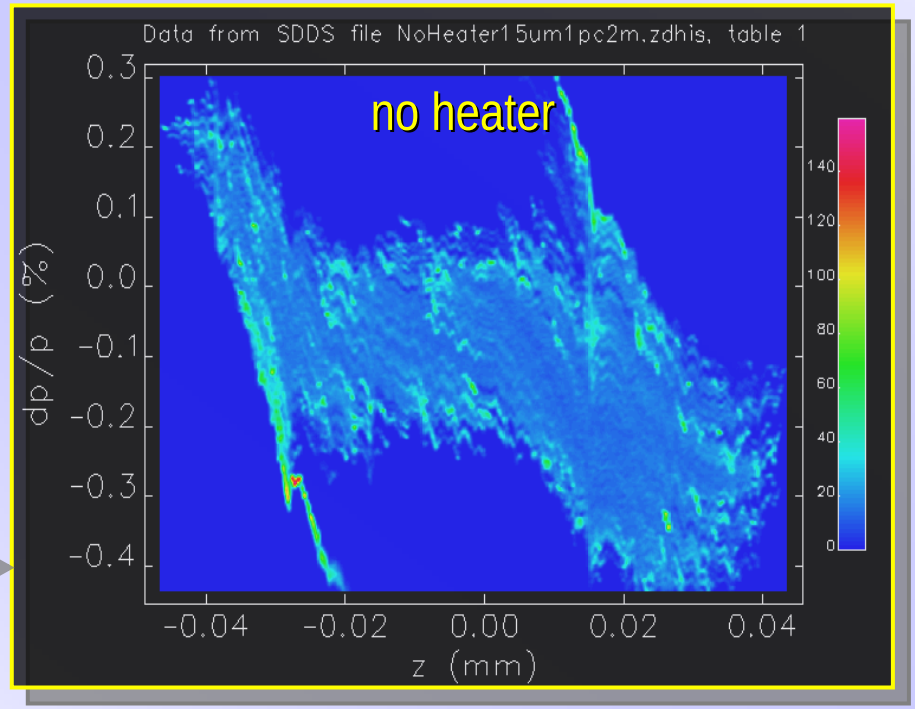


the BAD (w_0 = 3 mm, P_0 = 37 MW),



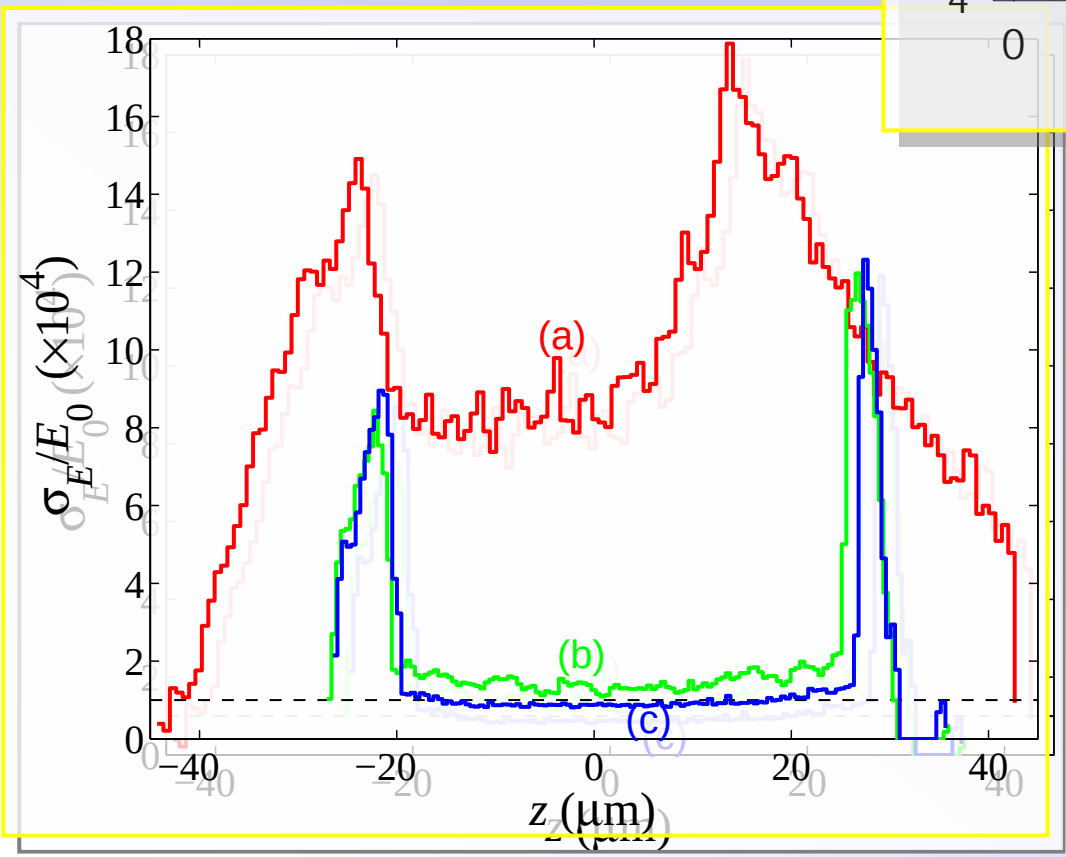
Final long. phase space at 14 GeV for initial 15-μm, 1% seed

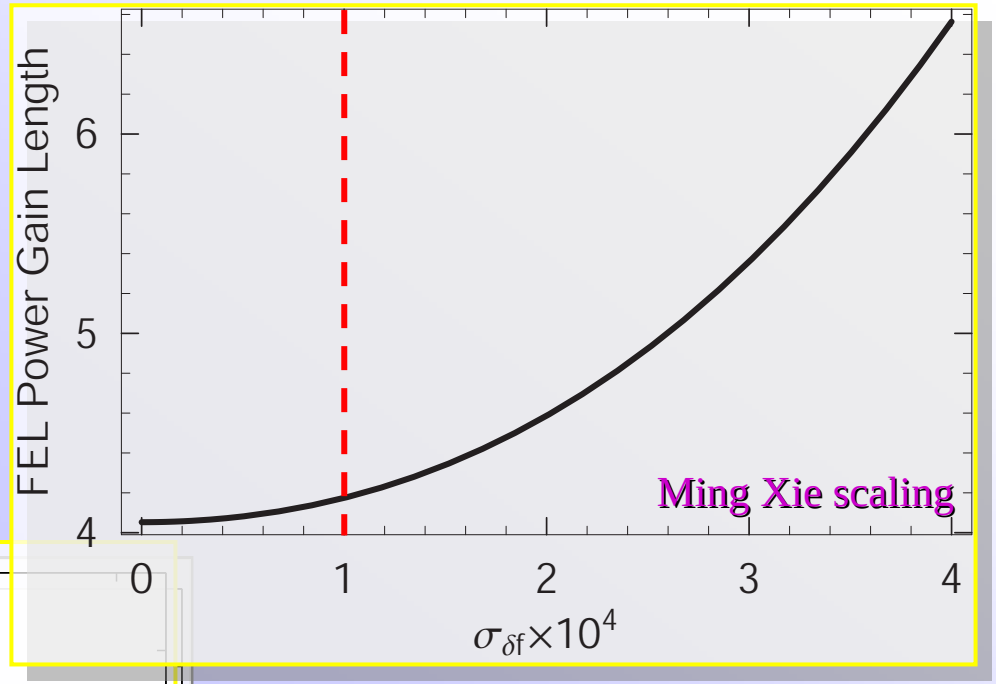
and the UGLY (no heater)



Sliced final energy spread in FEL at 14 GeV

$\lambda_0 = 15\ \mu\text{m}$, $\Delta I/I_0 = 1\%$





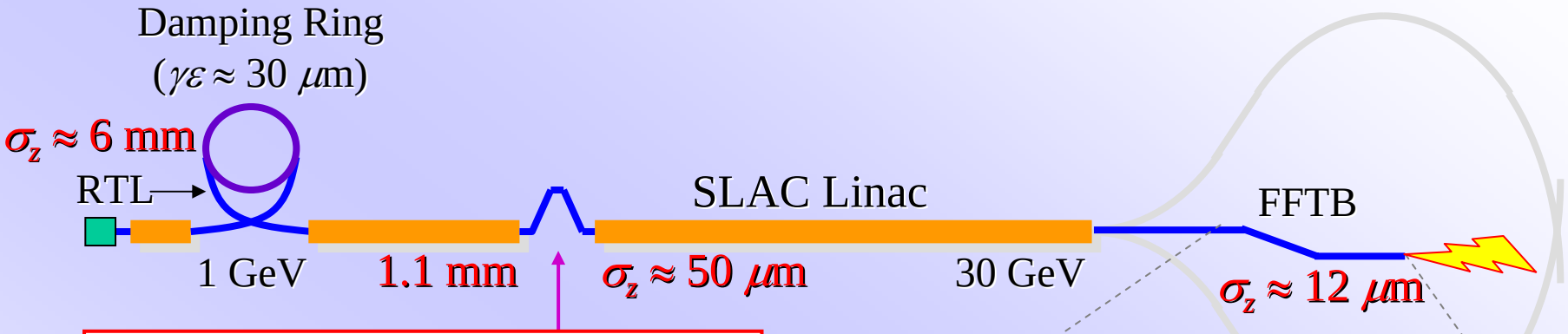
(a) No heater

(b) $w_0 = 3$ mm, $P_0 = 37$ MW

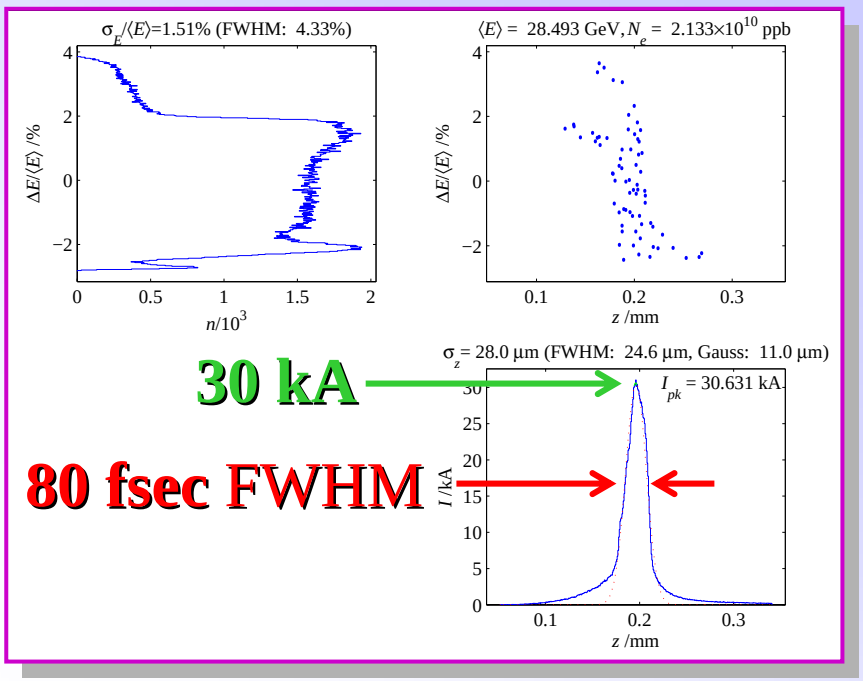
(c) $w_0 = 350\ \mu$m, $P_0 = 1.2$ MW

to be published in PRSTAB

Short Bunch Generation in the SLAC Linac



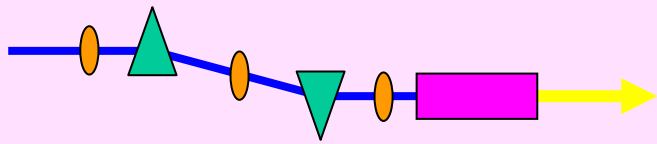
add 14-meter chicane compressor in linac at 1/3-point (9 GeV)



30 kA

80 fsec FWHM

Existing bends compress to **40 fsec**

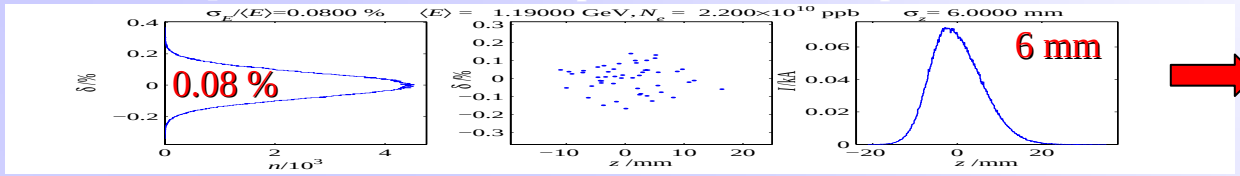


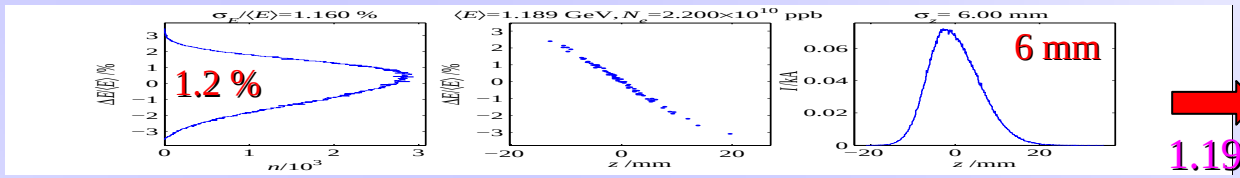
compression by factor of 500

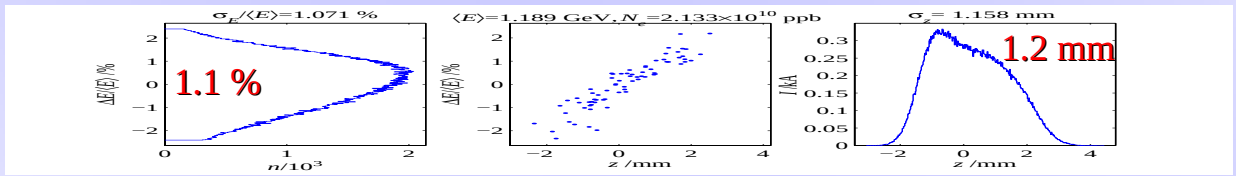
P. Emma *et al.*, PAC'01

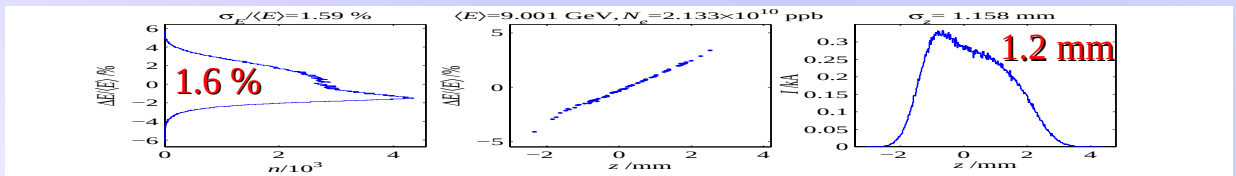
Particle tracking in 2D…

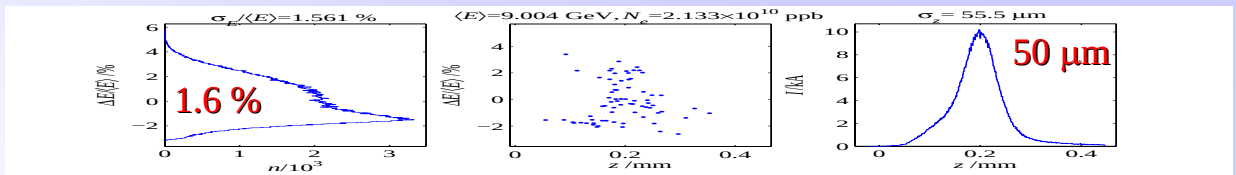
energy profile ⇩ phase space ⇩ temporal profile ⇩

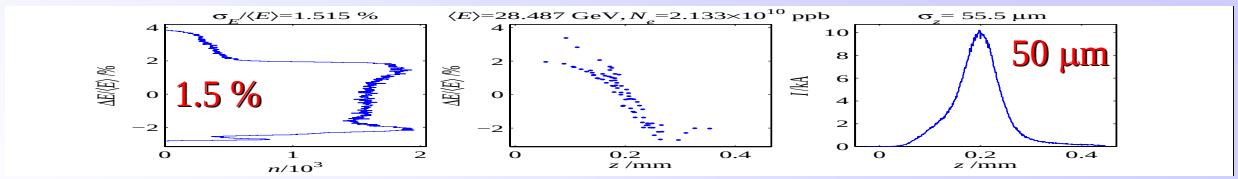


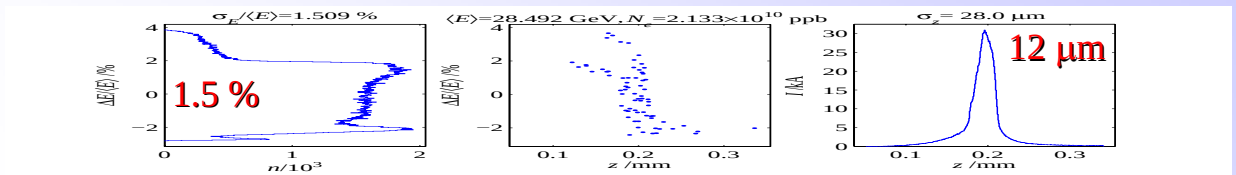


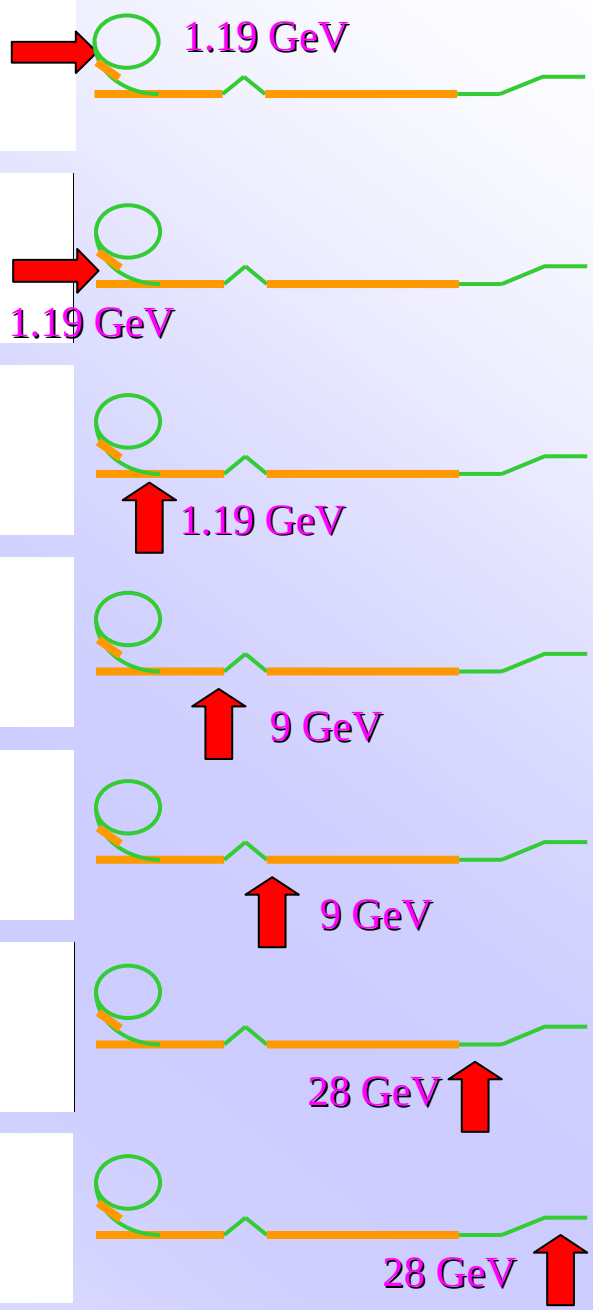




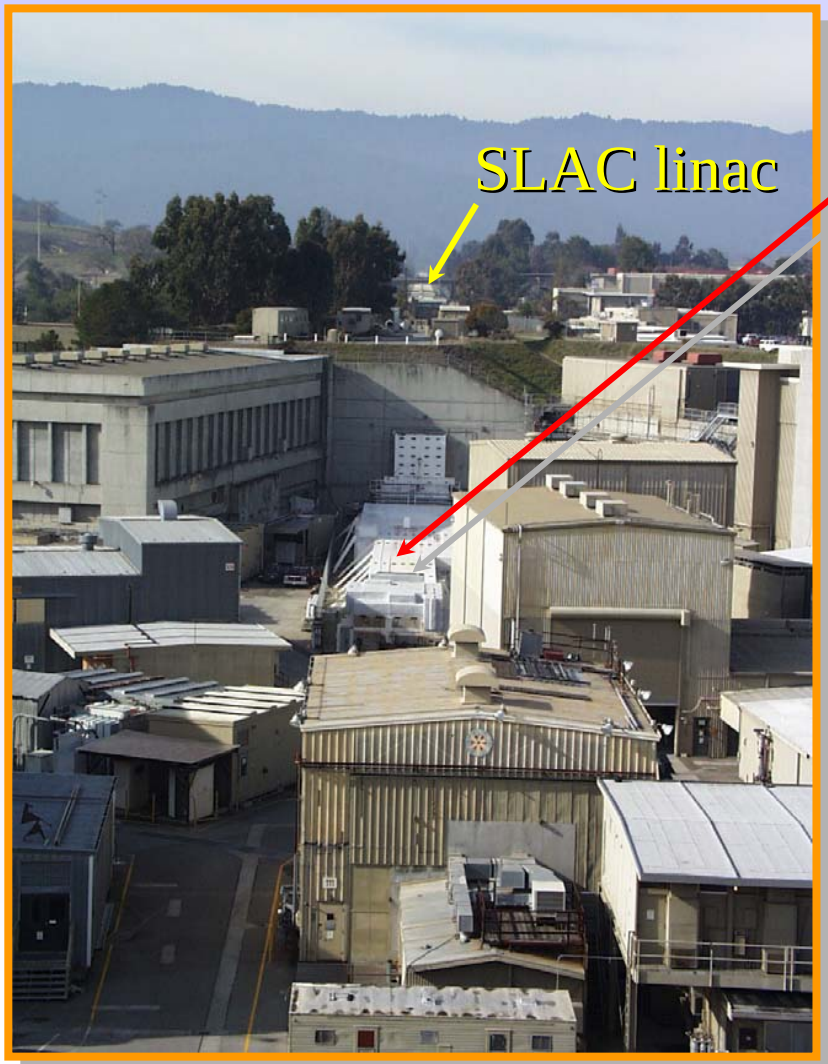




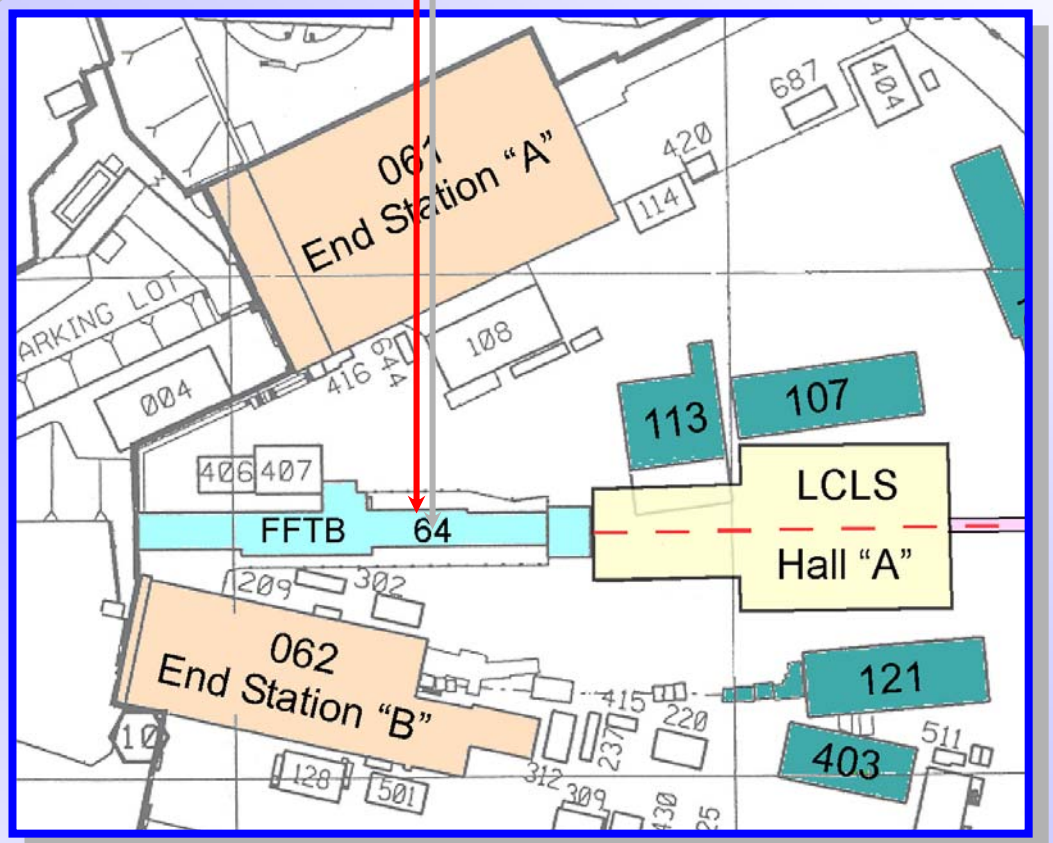




Linac and FFTB Hall



add undulator to FFTB hall at end of linac



Undulator parameters: $L_u \approx 2.5$ m, $\lambda_u = 8.5$ cm, $K \approx 4.3$, $B \approx 0.55$ T, $N_p \approx 30$

Source comparisons

	Peak brightness**	Pulse length (fsec)	Average flux (photons/sec)	Photons per pulse per 0.1% BW	Rep. Rate (Hz)
Table top laser plasma	1×10^{9}	500	1×10^{6}	100	1×10^{4}
ALS* (streak camera)	5×10^{17}	4×10^{4}	2×10^{8}	2×10^{4}	1×10^{4}
ALS slicing (undulator)	1×10^{17} (6×10^{19})	100	1×10^{5} (3×10^{4})	10 (300)	1×10^{4}
ESRF	1×10^{24}	8×10^{4}	3×10^{10}	3×10^{7}	900
SPPS	1×10^{25}	80	2×10^{7}	2×10^{6}	10

** photons/sec/mm^2/mrad^2/0.1%-bw

* streak camera resolution 1 psec, dqe 0.01

J. Hastings

ESRF
F. Sette

SPPS Collaboration

UC Berkeley

Roger W. Falcone
Aaron Lindenberg
Donnacha Lowney
Andrew MacPhee

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MSD Argonne National Lab

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Henry Chapman
Carl Calleman
Magnus Bergh
Gosta Huldt

DESY

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Thomas Tschentscher
Horst Schulte-Schrepping

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Reinhard Pahl

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Sean Brennan
Roman Tatchyn
Jerome Hastings
Kelly Gafney

Copenhagen University

Jens Als-Nielsen

Lund University

Jörgen Larsson
Ola Synnergren
Tue Hansen

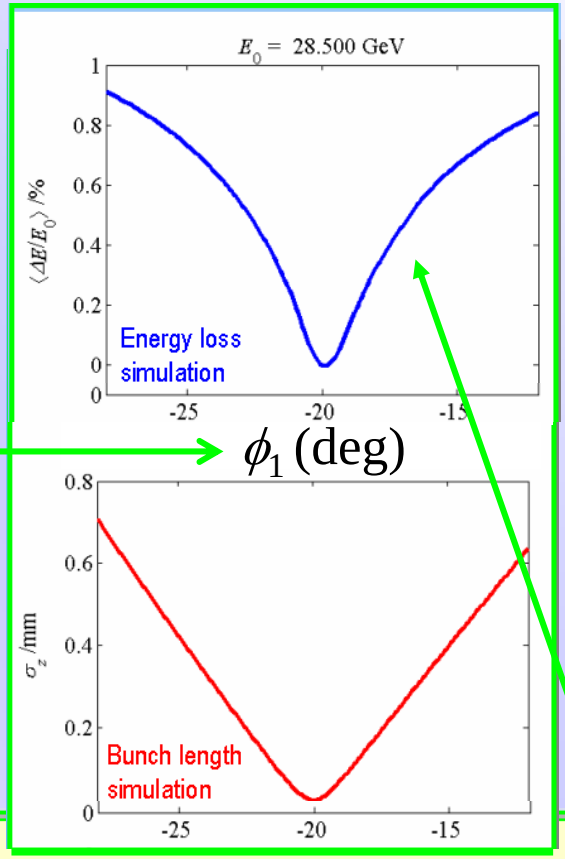
Chalmers University of Technology

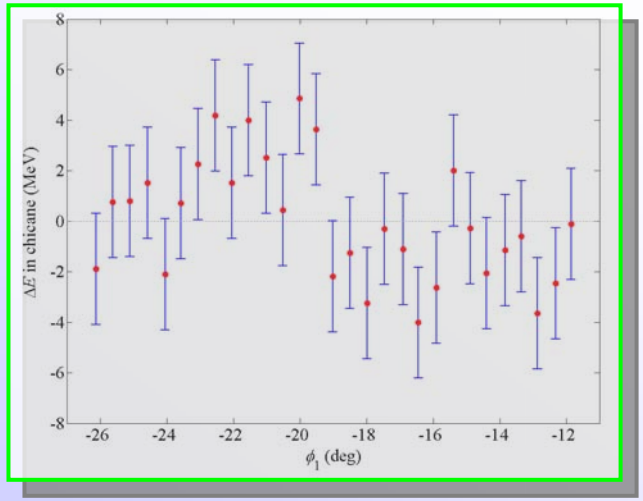
Richard Neutze

R&D at SPPS Towards LCLS

- Wakefields of micro-bunch in RF structures
- Develop bunch length diagnostics
- RF phase and voltage stability of linac
- Emittance growth in compressor chicane (CSR)

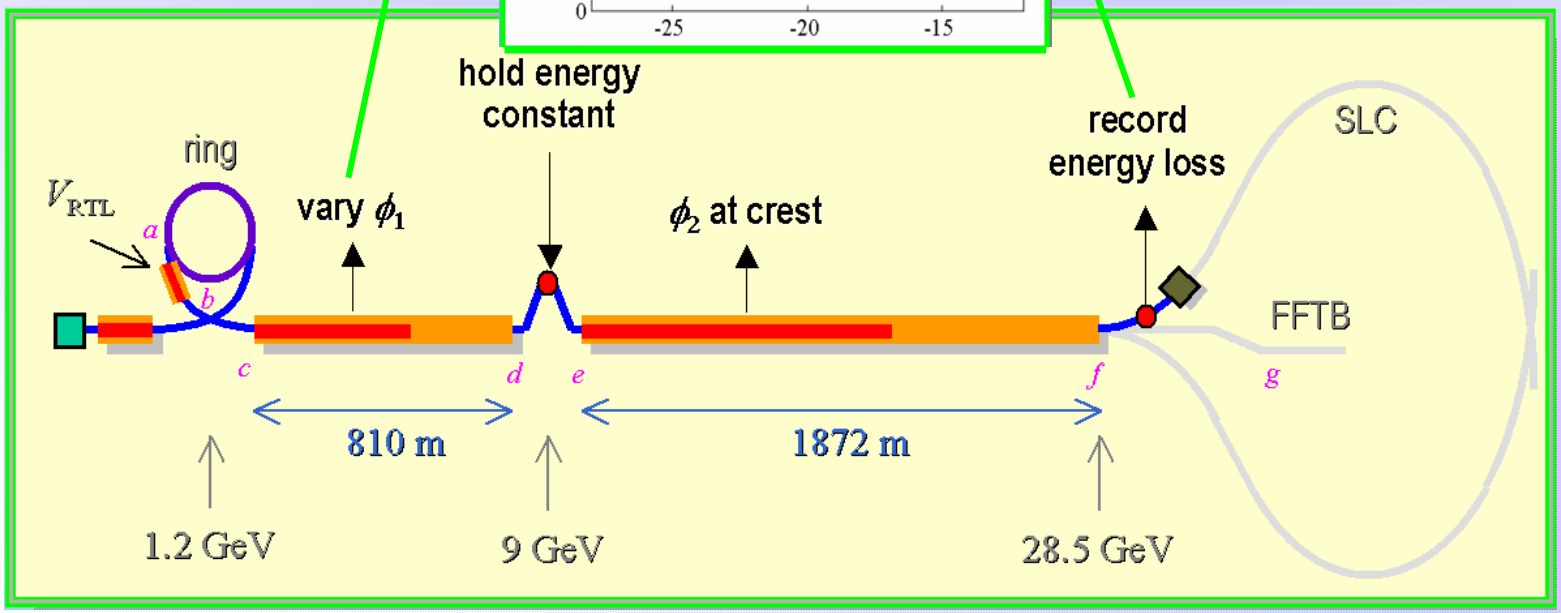
Wakefield energy-loss used to confirm bunch length…



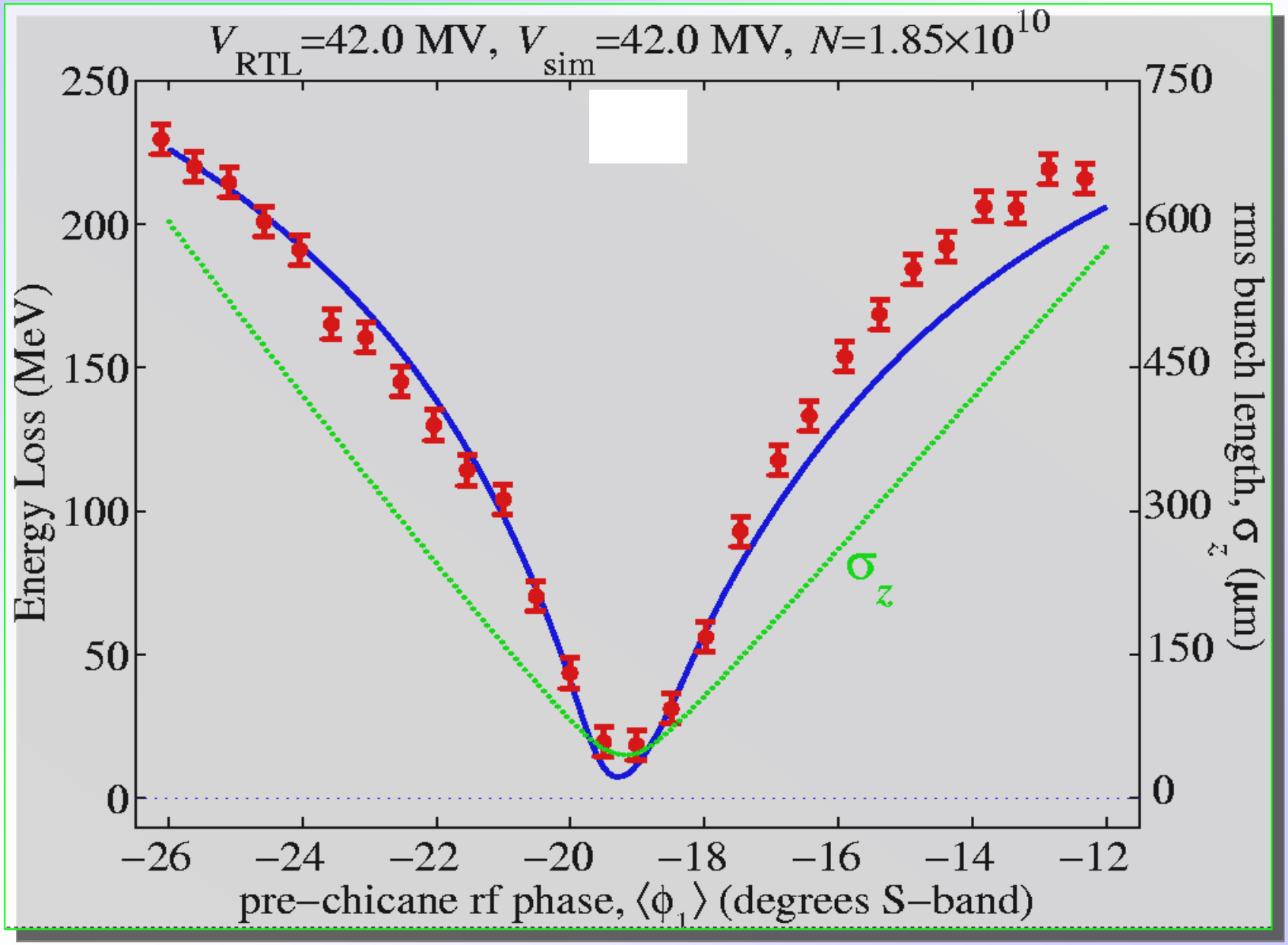


Chicane energy constant to <5 MeV (0.06%) rms

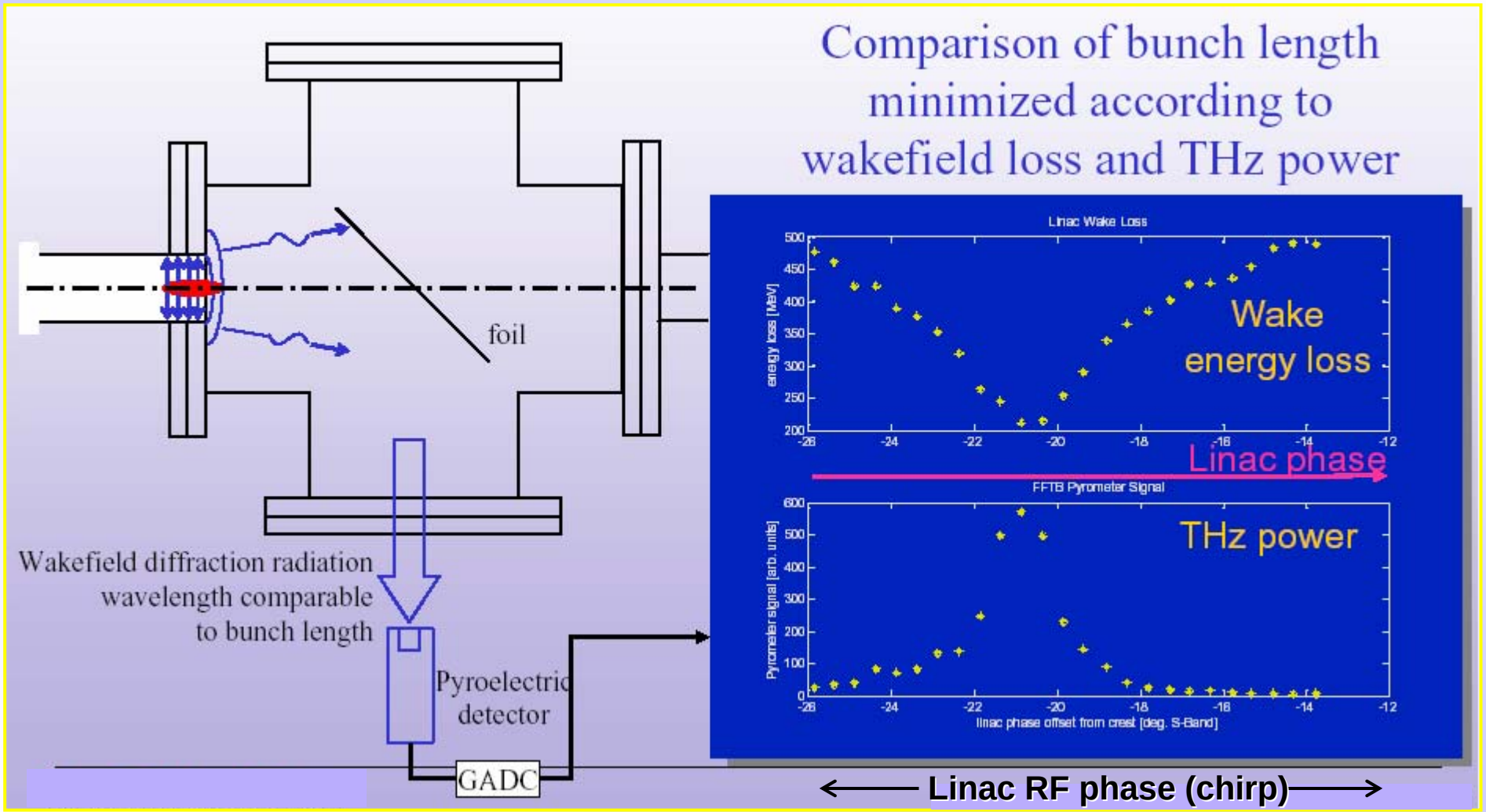
K. Bane *et al.*, PAC'03



Bunch length confirmed with strong *wakefield*-induced energy loss of 1870-m of SLAC linac: $\sigma_{z_{min}} \approx 50\ \mu$m.

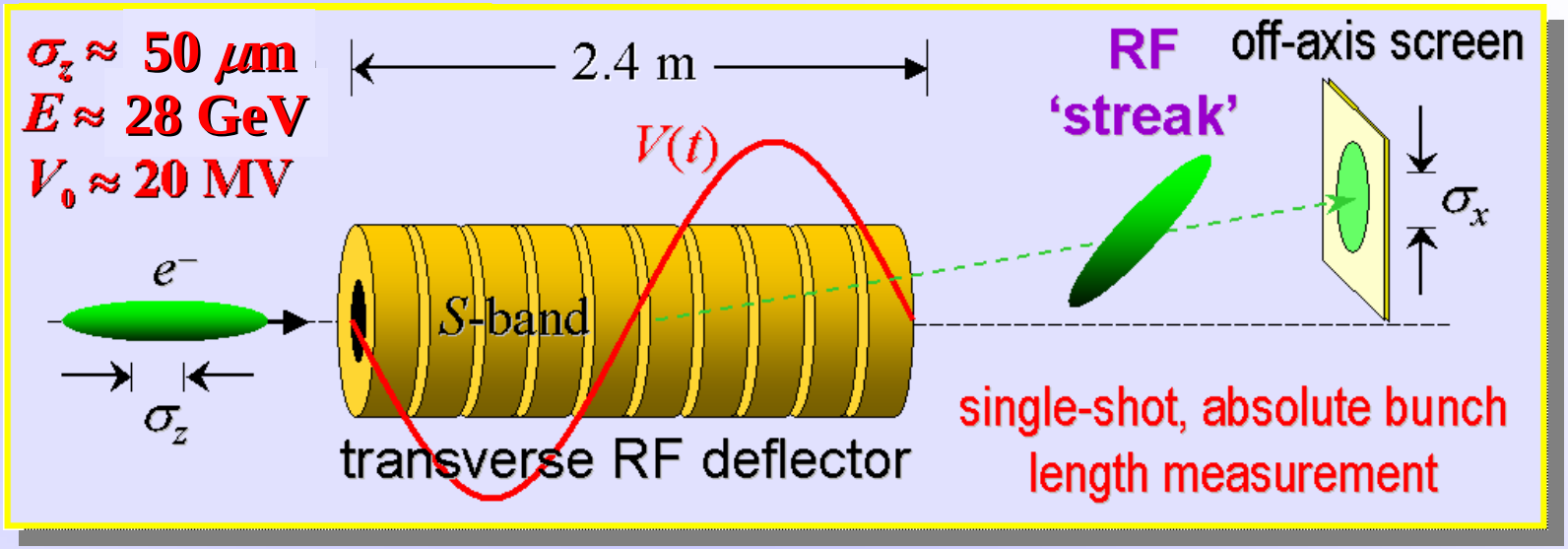


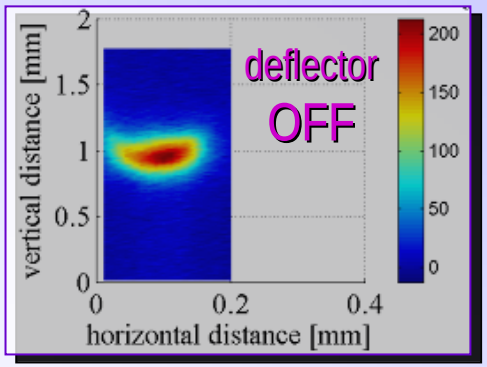
Far-Infrared Detection of Wakefields from Ultra-Short Bunches

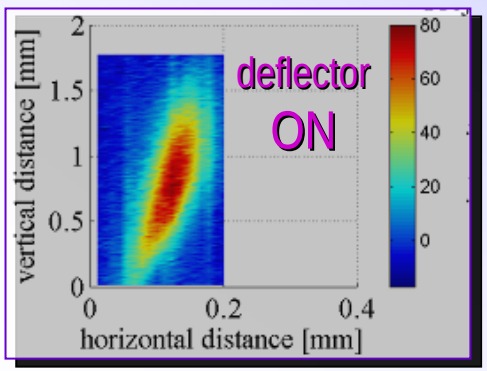


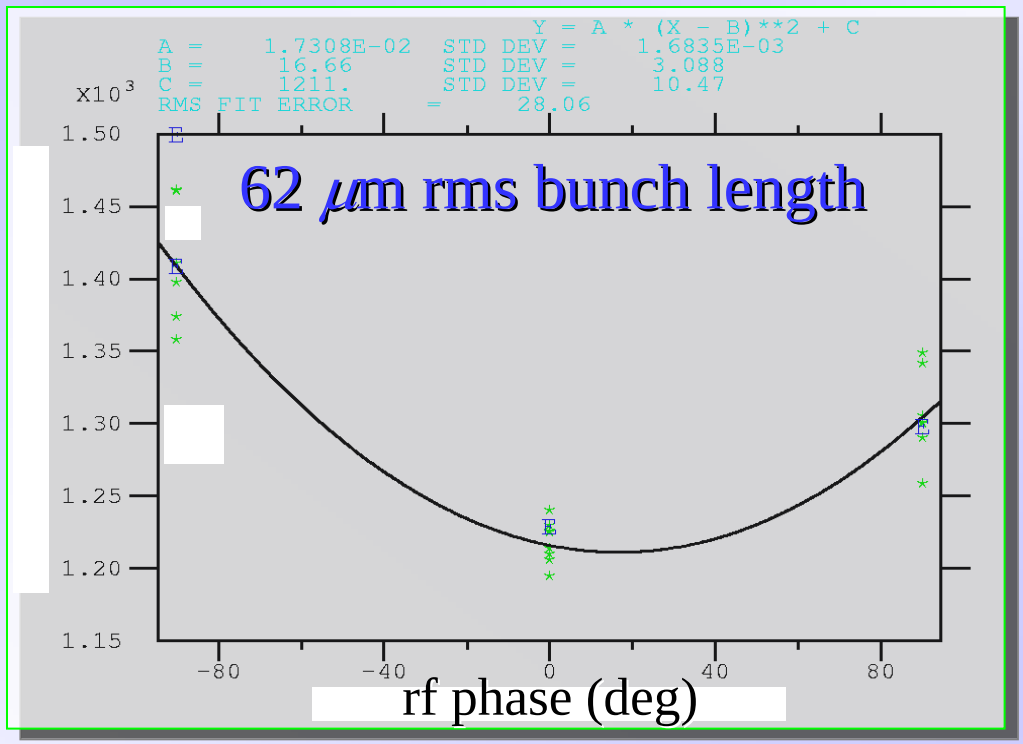
H. Schlarb (DESY), *et al.*

Bunch length is also measured with transverse *deflecting rf* : $\sigma_z \approx 50$ to 70 μm



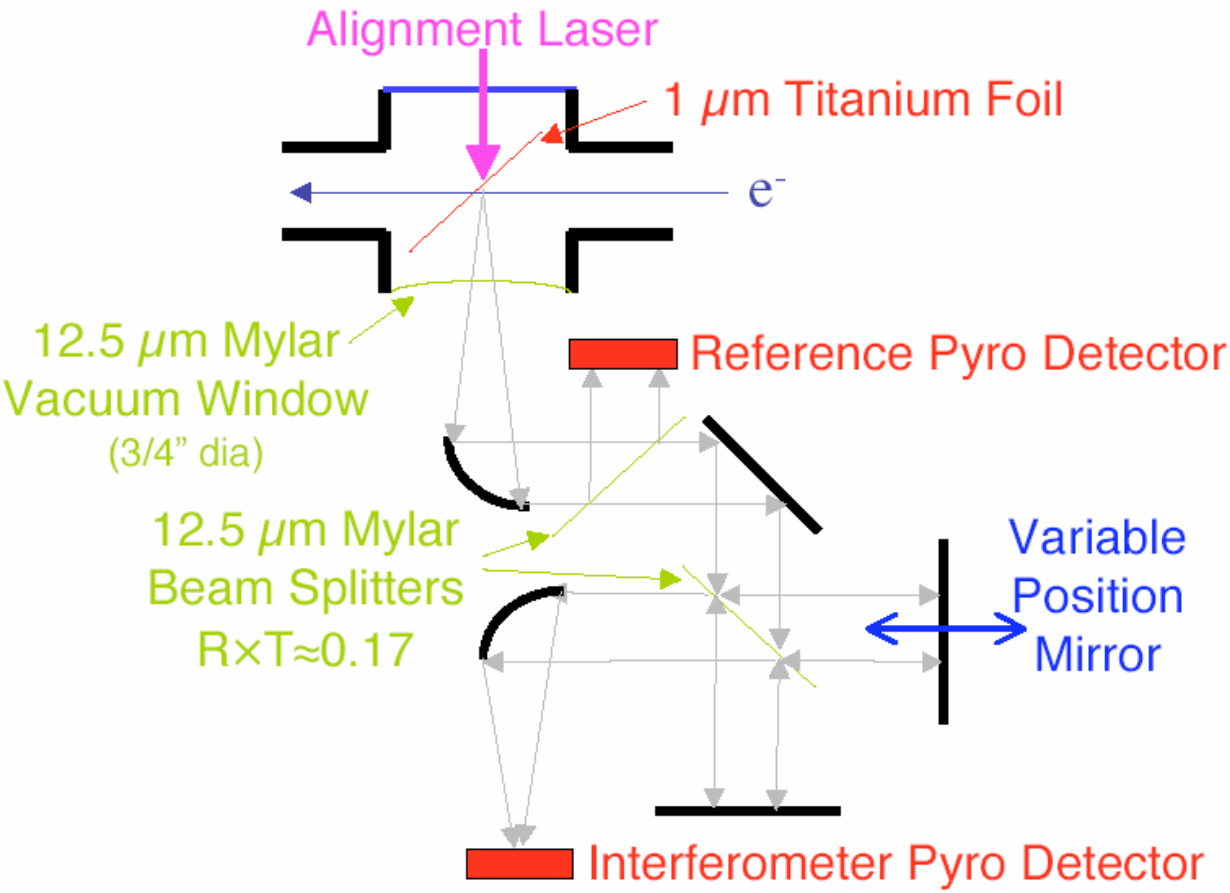






R. Akre *et al.*, EPAC'02

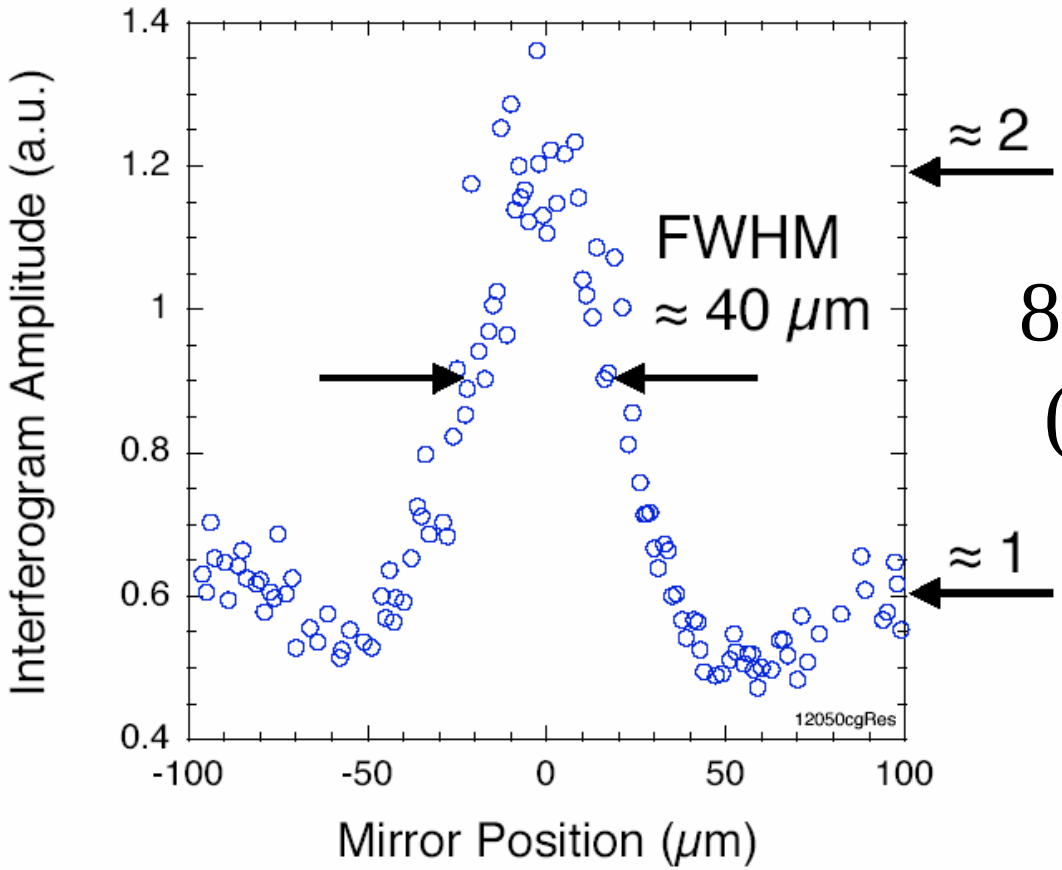
Michelson Interferometer for CTR Bunch Length Measurement



- Transition Radiation coherent for $\lambda > (2\pi)^{1/2}\sigma_{z,\ Gaussian}$ (CTR)

P. Muggli, M. Hogan

First Measurement of SLAC Ultra-short Bunch Length!

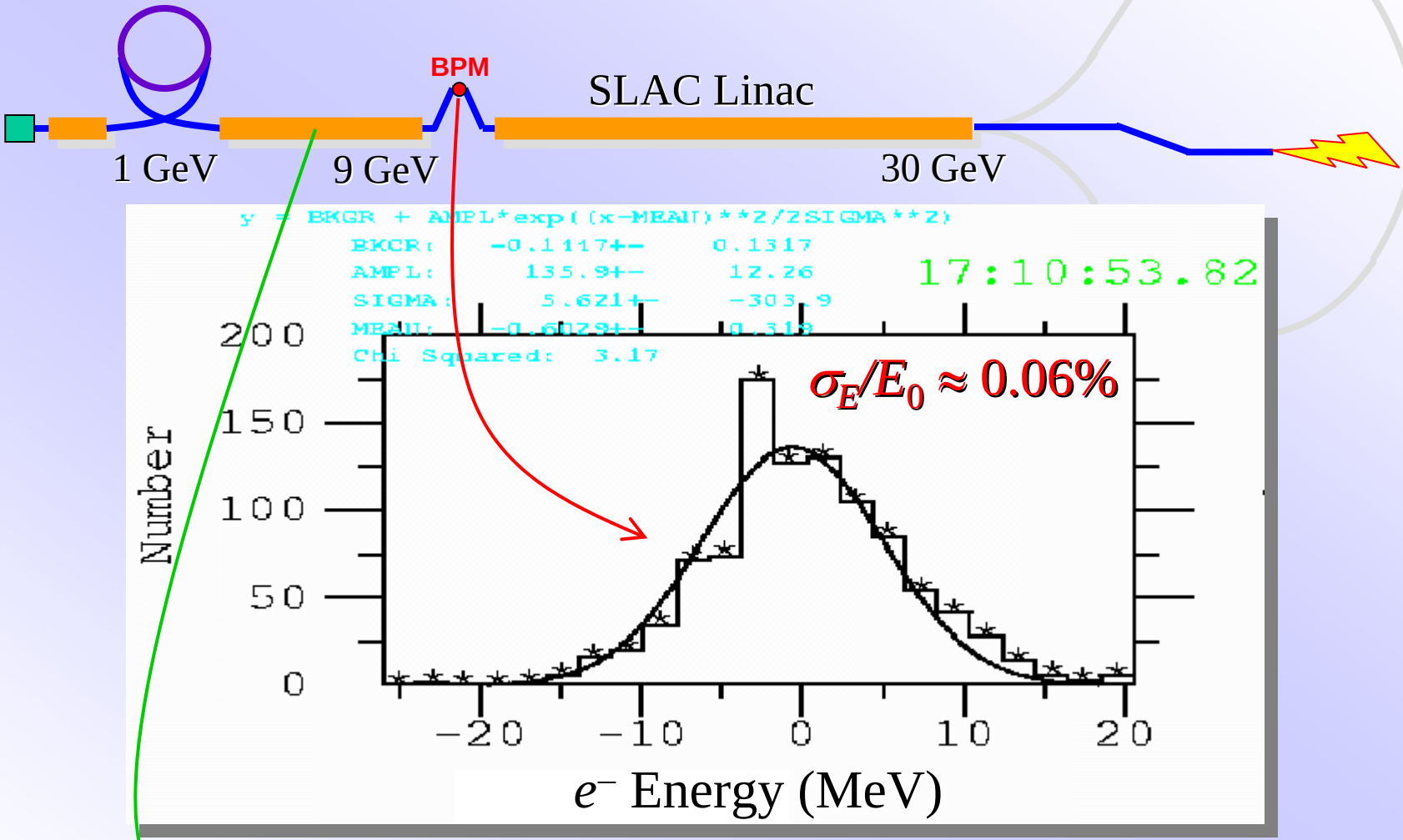


80 fs rms
(15 kA)

- $\sigma_{bunch,\ Gaussian}$=2×FWHM/2.35/√2≈24 μm (Preliminary value! Not optimized)
- Limited by long wavelength cut-off
- NDR compressor voltage: 42 MV/m, 2-6BNS phase -21°

P. Muggli, M. Hogan, 12/05/03

Linac Phase Stability Estimate Based on Energy Jitter in Chicane



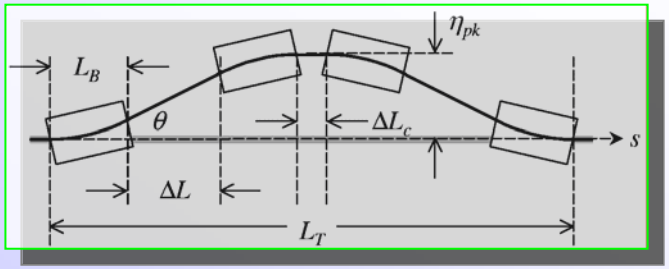
$\langle \Delta\phi^2 \rangle^{1/2} < 0.1$ deg (100 fs)

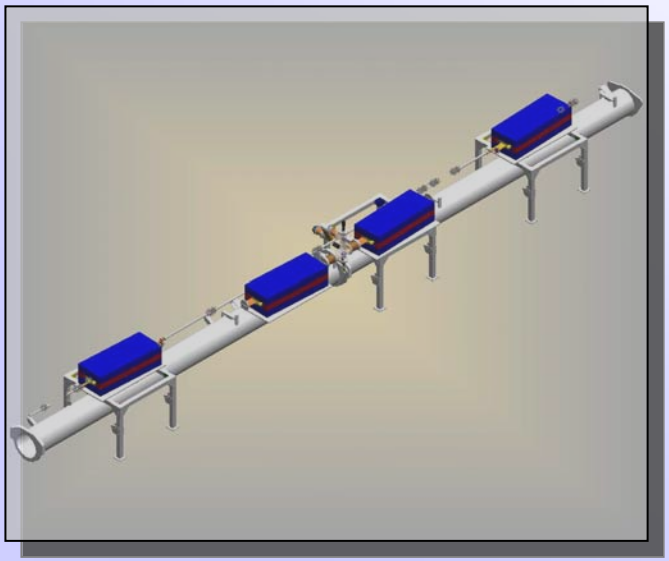
Chicane Parameters

14.3 m

Table 1: Chicane and beam parameters [2].

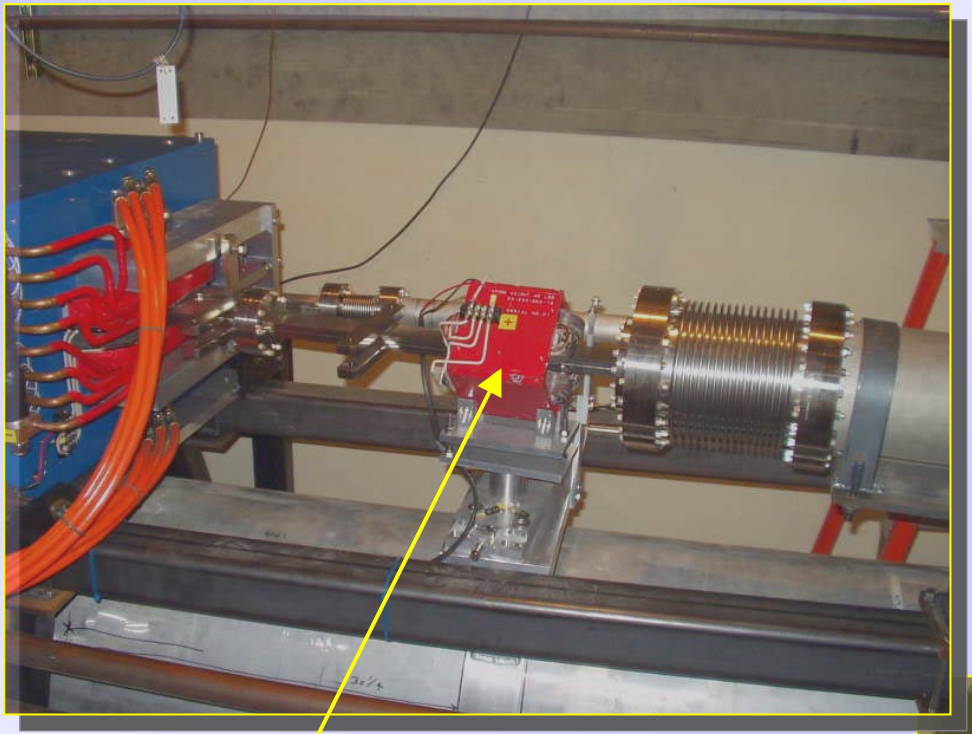
parameter	symbol	value	unit
Bunch charge	Ne	3.0-3.4	nC
e^- energy	E_0	9.00	GeV
rms corr. energy spread	σ_E/E_0	1.55	%
init. rms bunch length	σ_{s_0}	1.15	mm
final rms bunch length	σ_{s_f}	50	μm
x norm. emittance	$\gamma\epsilon_x$	27-45	μm
momentum compaction	R_{56}	-76	mm
bend angle per dipole	$\lvert\theta\rvert$	97	mrad
bend magnet length	L_B	1.80	m
drift from bend-1 to 2	ΔL	2.80	m
drift from bend-2 to 3	ΔL_c	1.50	m
peak dispersion	η_{pk}	449	mm
initial x beta-func.	β_x	56.3	m
initial x alpha-func.	α_x	3.29	





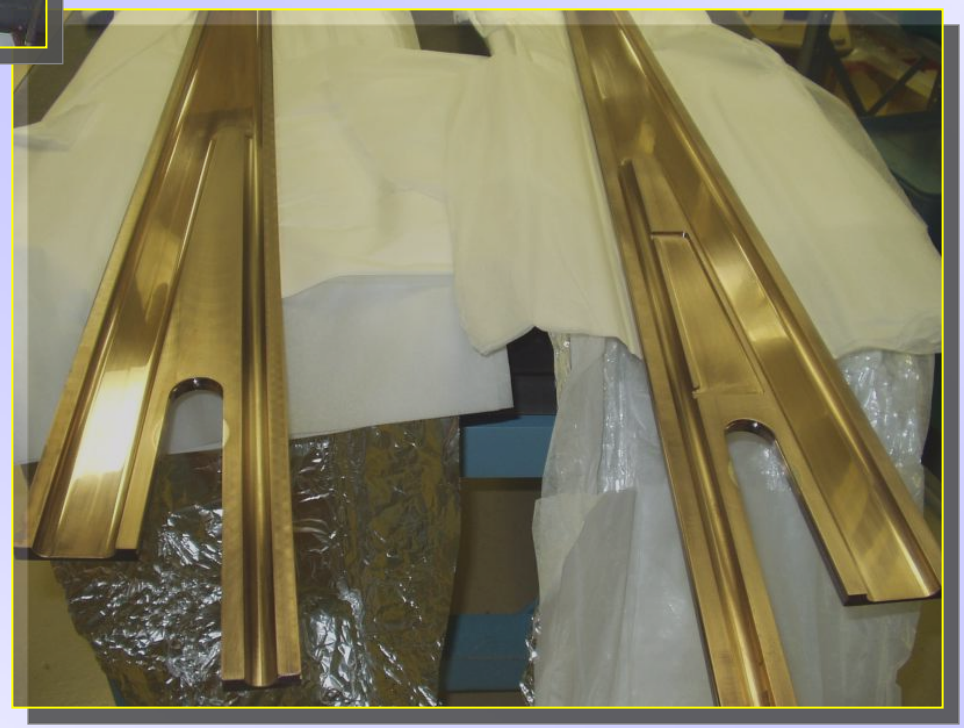
L. Bentson *et al.*, PAC'01


e^-
14-m chicane in
sector-10 of
SLAC linac



Small ‘tweaker’ quads included to control residual *x*-dispersion.

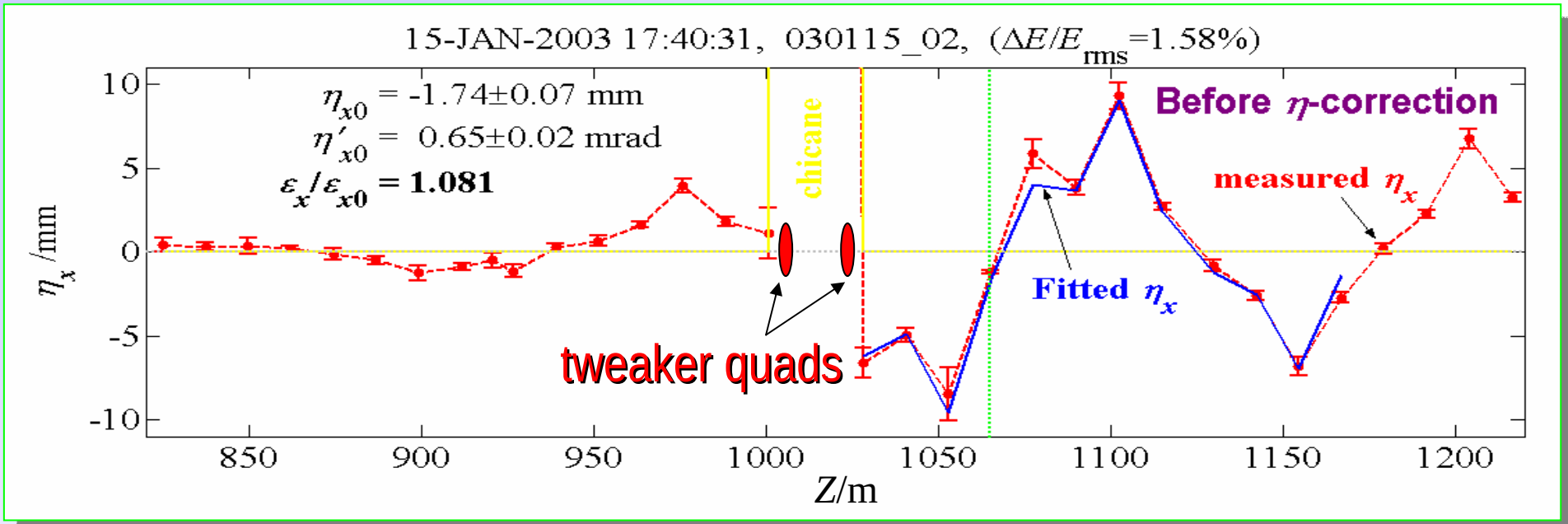
Last Y-chamber was copper coated to limit resistive-wake.

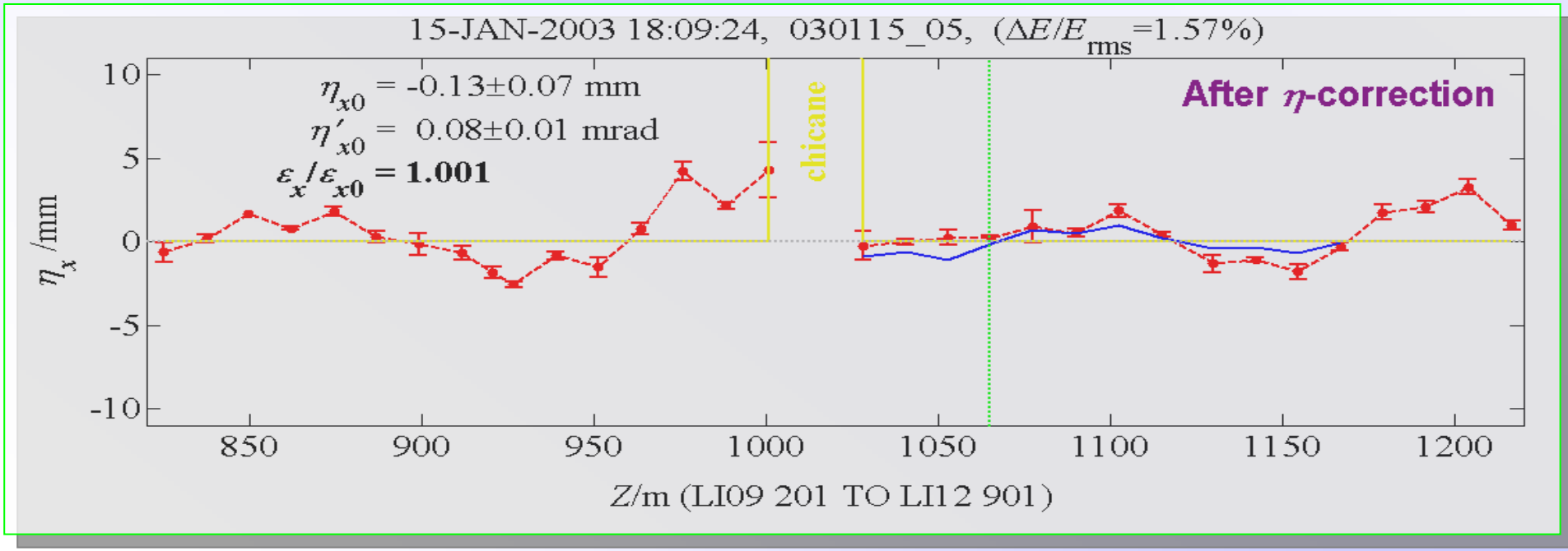


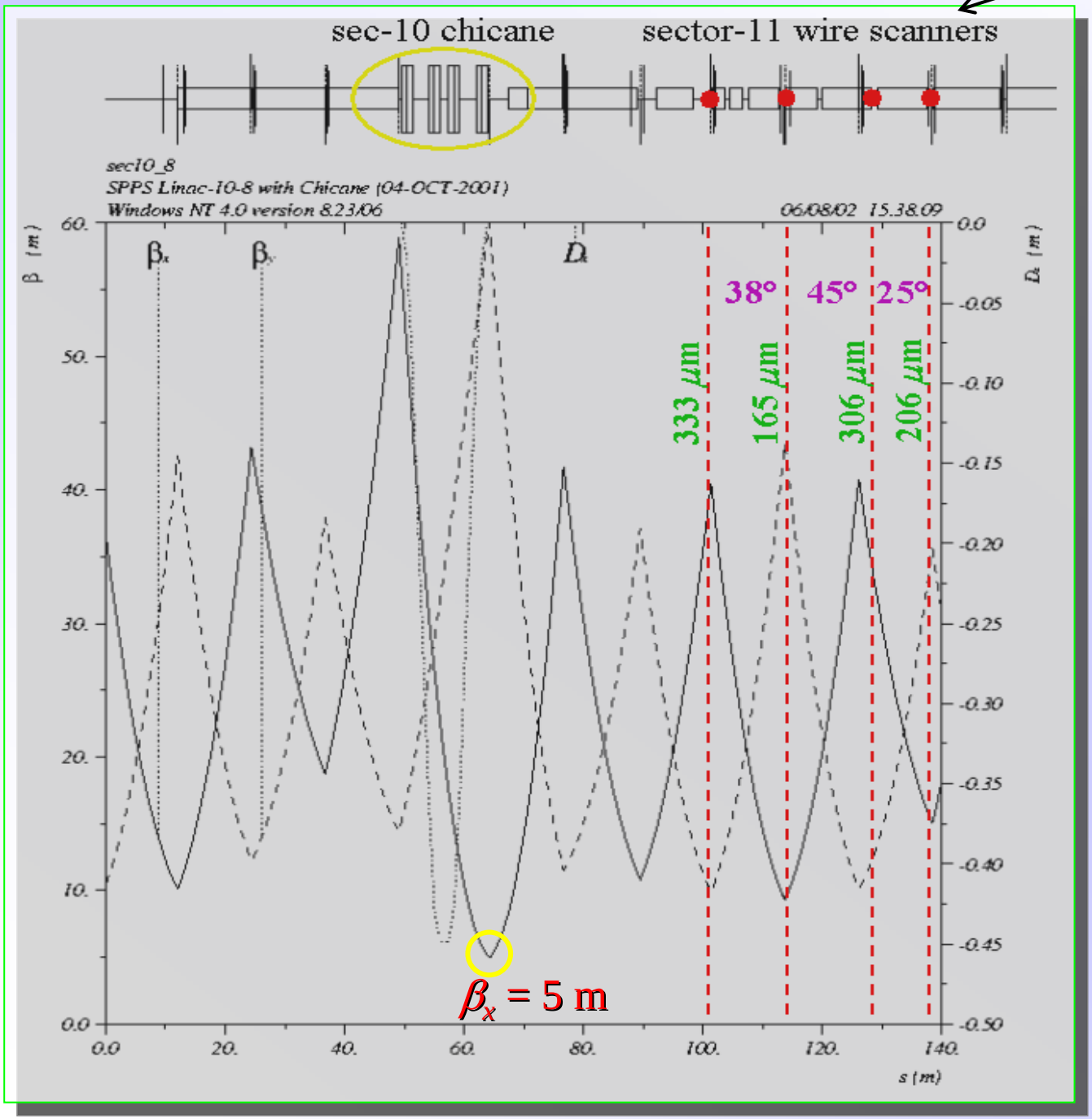
Vacuum chamber too large for CSR shielding…

$(\pi\sigma_z R^{1/2})^{2/3} \approx 8\ \text{mm} << r$

Dispersion is measured by energy variations correlated with BPM readings







Four wire-scanners within 60 m of end of chicane — used to measure *x*-emittance.

Emittance measured with precision of 2-4%, over <1 hour.

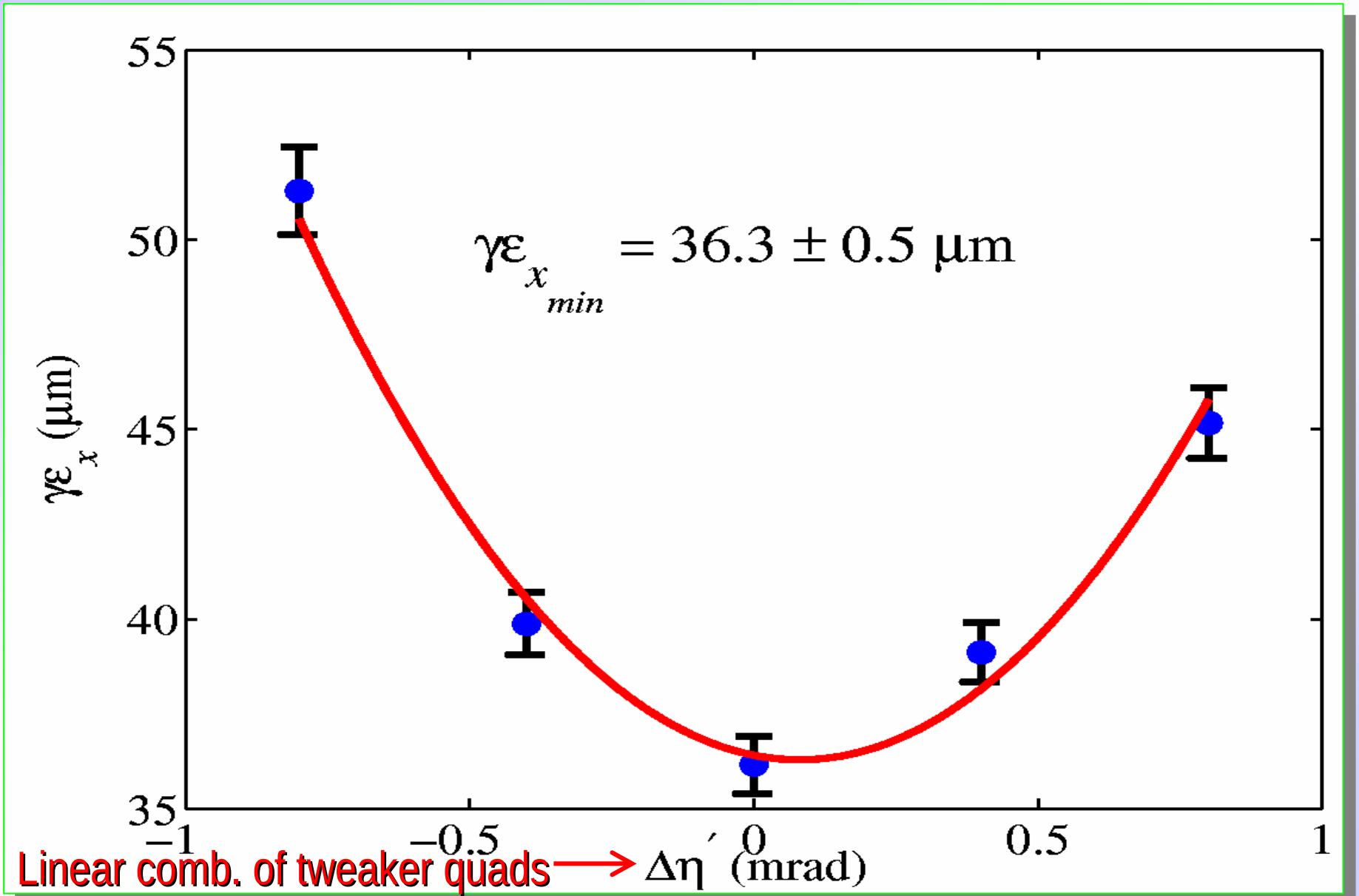
Horizontal beta function through chicane effects emittance growth… has been matched and verified:

	β_x (m)	α_x	ζ_x
Design:	47.2	–2.03	1.000
Measured:	50.6 ± 1.7	–2.17 ± 0.08	1.002 ± 0.003

$$\zeta_x \equiv \frac{1}{2}(\beta_0\gamma - 2\alpha_0\alpha + \gamma_0\beta) \geq 1,$$

$$\gamma = \frac{1+\alpha^2}{\beta}$$

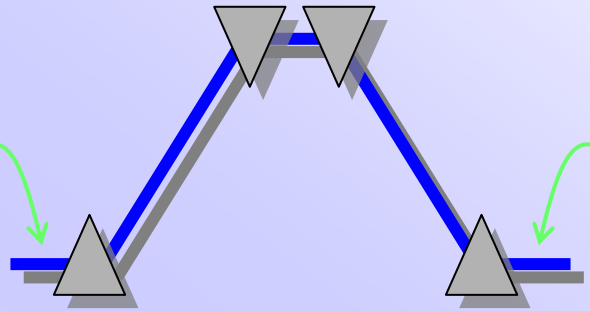
Residual x-dispersion (and its angle) is precision minimized using 'tweaker' quads in the chicane

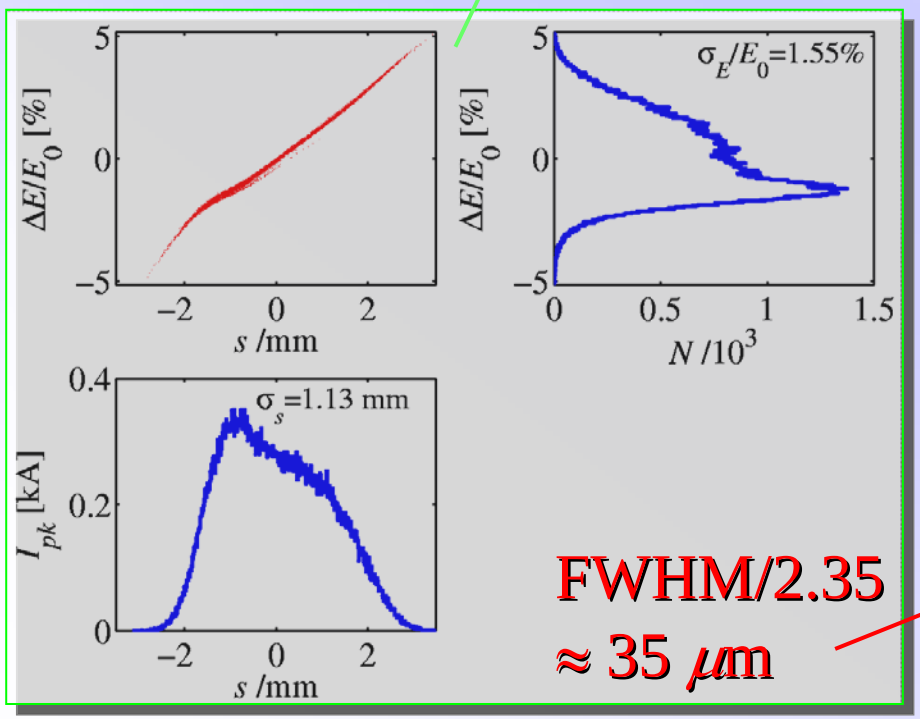


CSR simulations with 1D model (unshielded)

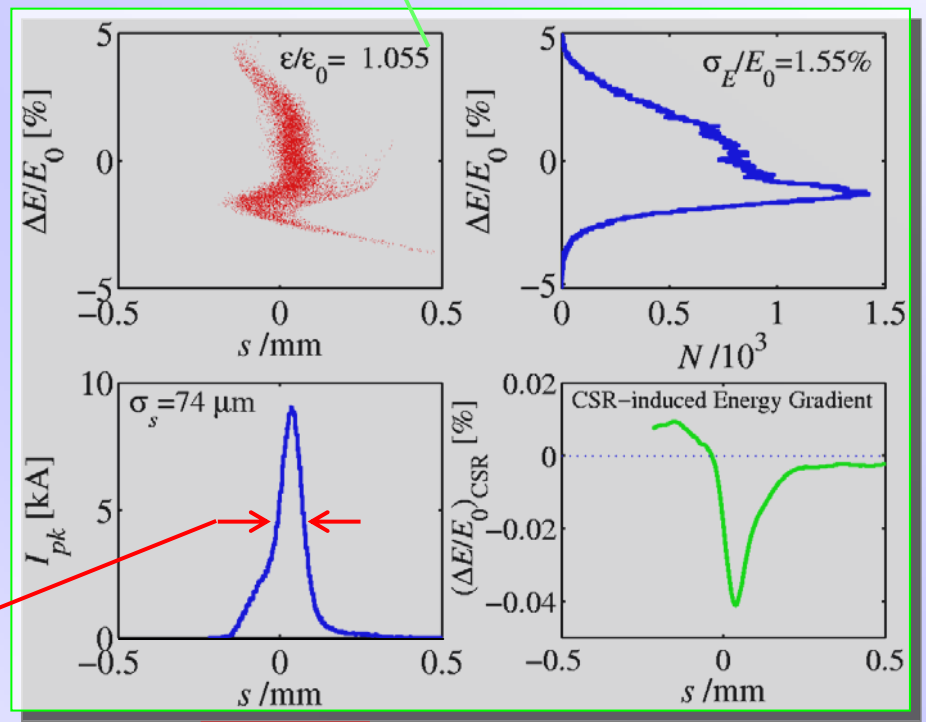
(good agreement with 3D-model studied by F. Stulle - DESY)

3.4 nC





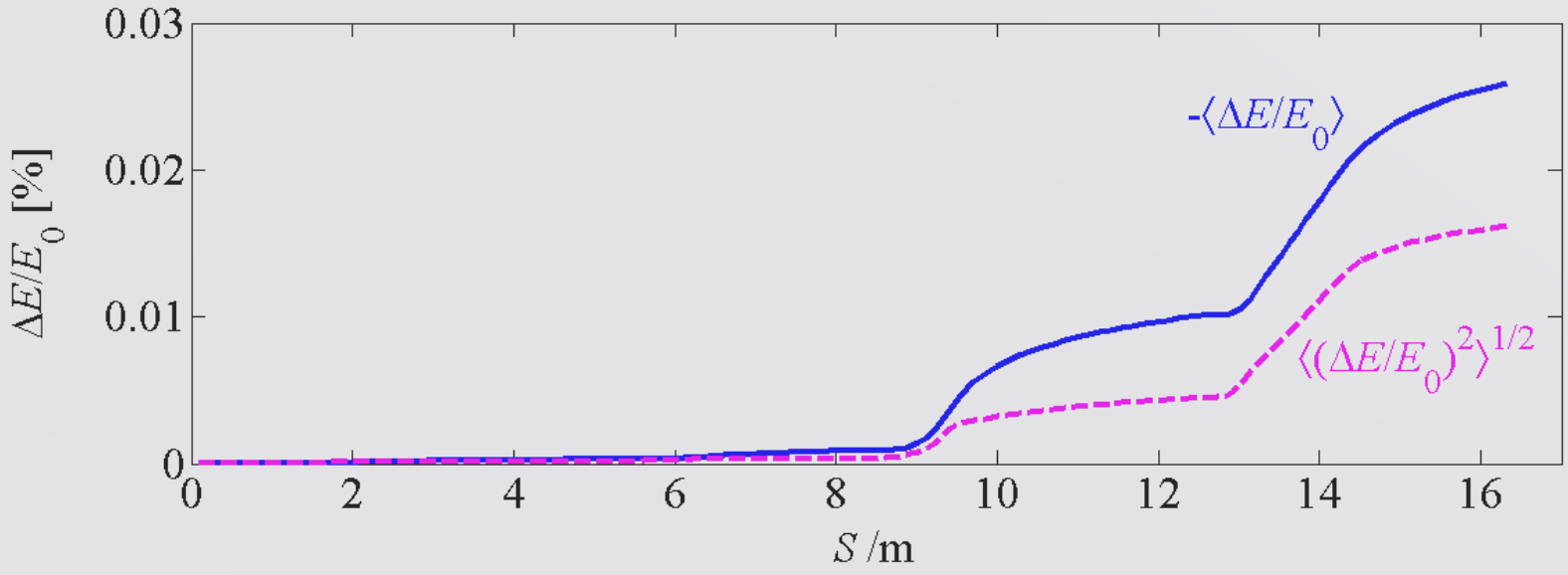
FWHM/2.35
≈ 35 μm

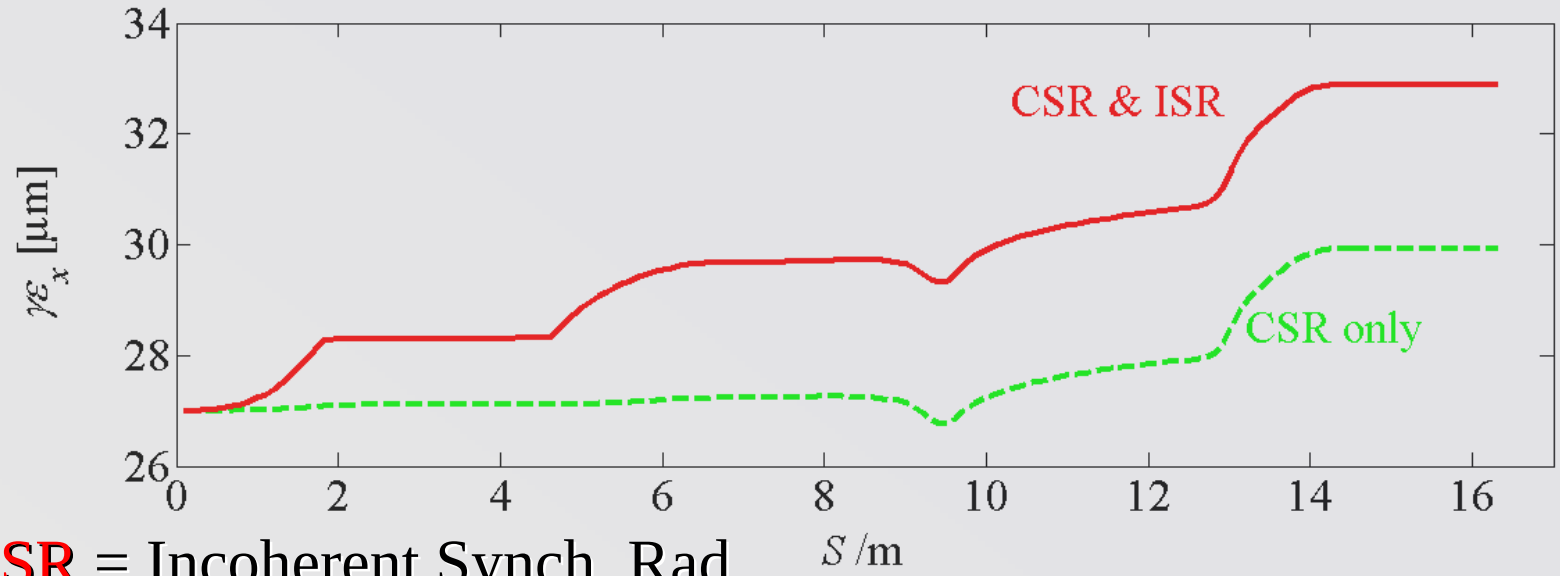


0.3 kA

9 kA

CSR simulations (1D) along chicane



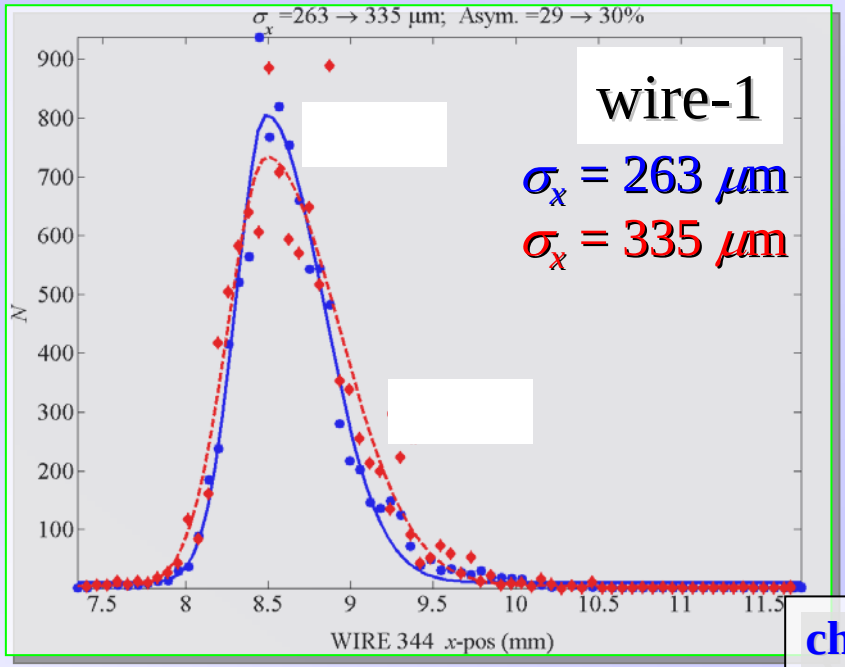


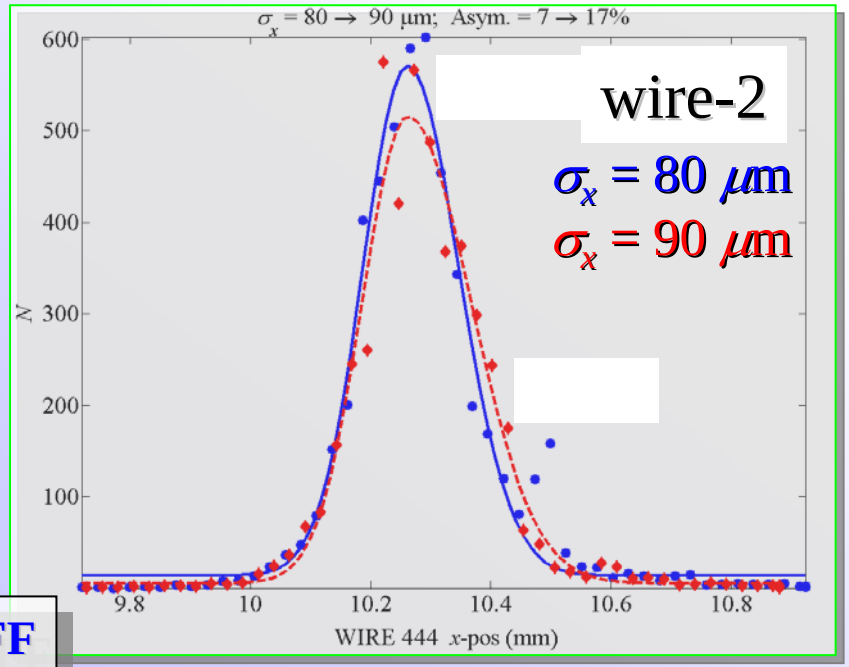
~20%

~10%

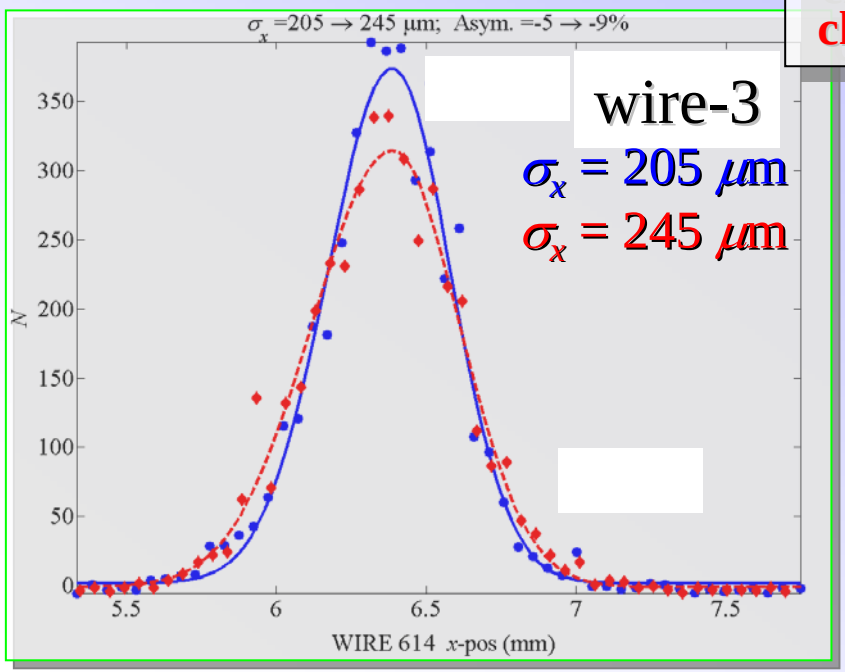
ISR = Incoherent Synch. Rad.

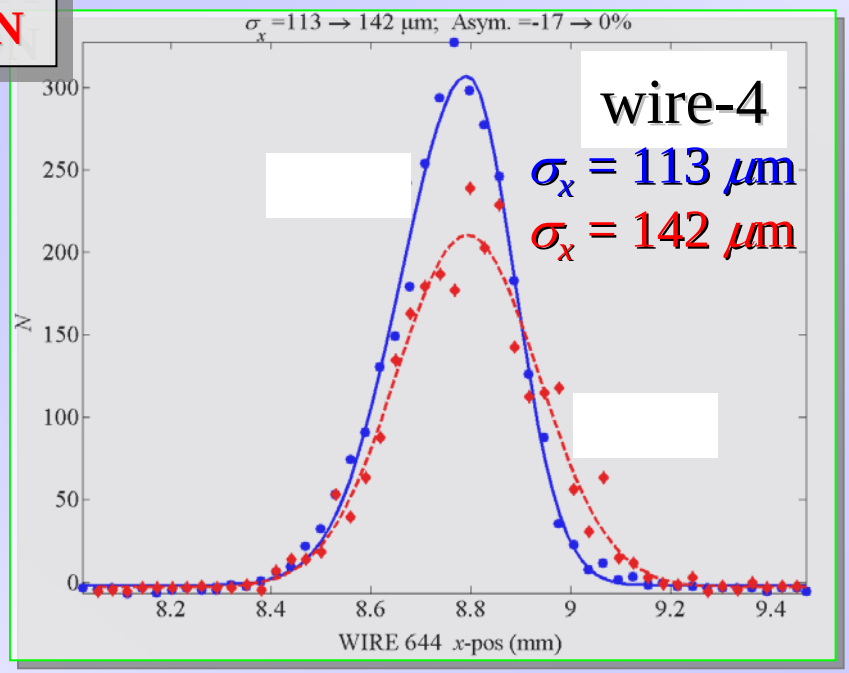
All 4 individual beam sizes with asymmetric-gaussian fits





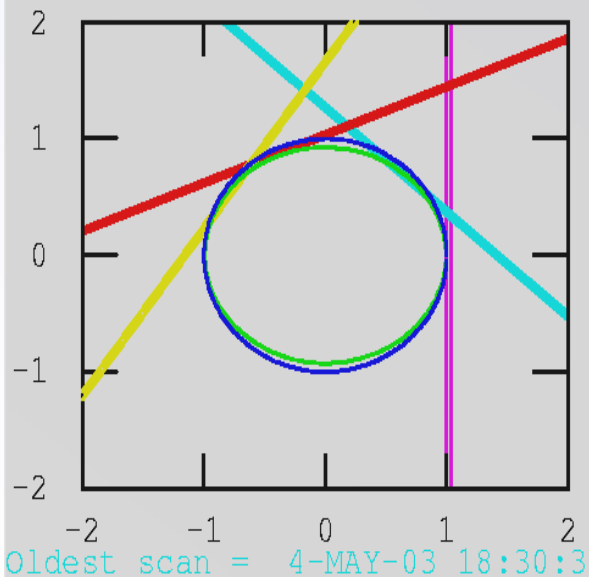
chicane-OFF
chicane-ON





LI11 X-PLANE ELEC

2.759+- 0.058	(3.000)	EMITTANCE(mE-5)
2.765+- 0.056	(3.000)	BMAG*EMIT(mE-5)
1.002+- 0.003	(1.000)	BMAG
0.067+- 0.033	(0.000)	BMAG_COS
0.003+- 0.026	(0.000)	BMAG_SIN
50.562+- 1.687	(47.260)	BETA (m)
-2.169+- 0.076	(-2.031)	ALPHA
282.342+- 5.647	(278.586)	SIG(344)(um)
89.211+- 1.784	(94.425)	SIG(444)(um)
214.340+- 4.287	(224.732)	SIG(614)(um)
117.517+- 2.350	(123.646)	SIG(644)(um)
2.079+- 0.022		INTENSITY
3.472821		CHISQ/DOF
0.323+- 0.040		ASYM(344)
0.145+- 0.059		ASYM(444)
-0.111+- 0.045		ASYM(614)
-0.198+- 0.028		ASYM(644)

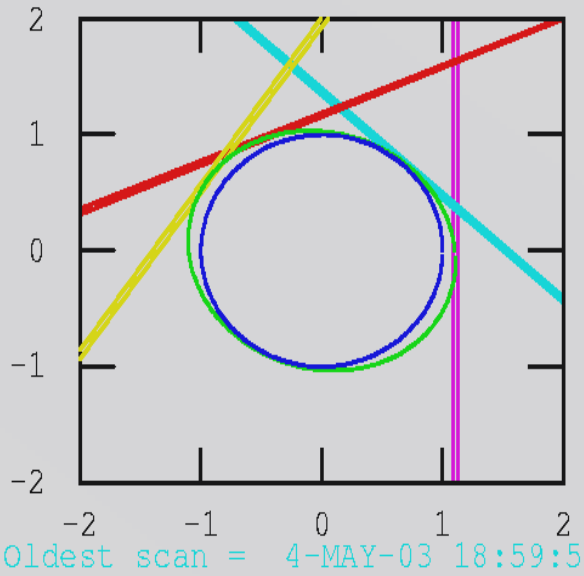


Chicane OFF

$\gamma\varepsilon_x = 27.6 \pm 0.6\ \mu m$

LI11 X-PLANE ELEC

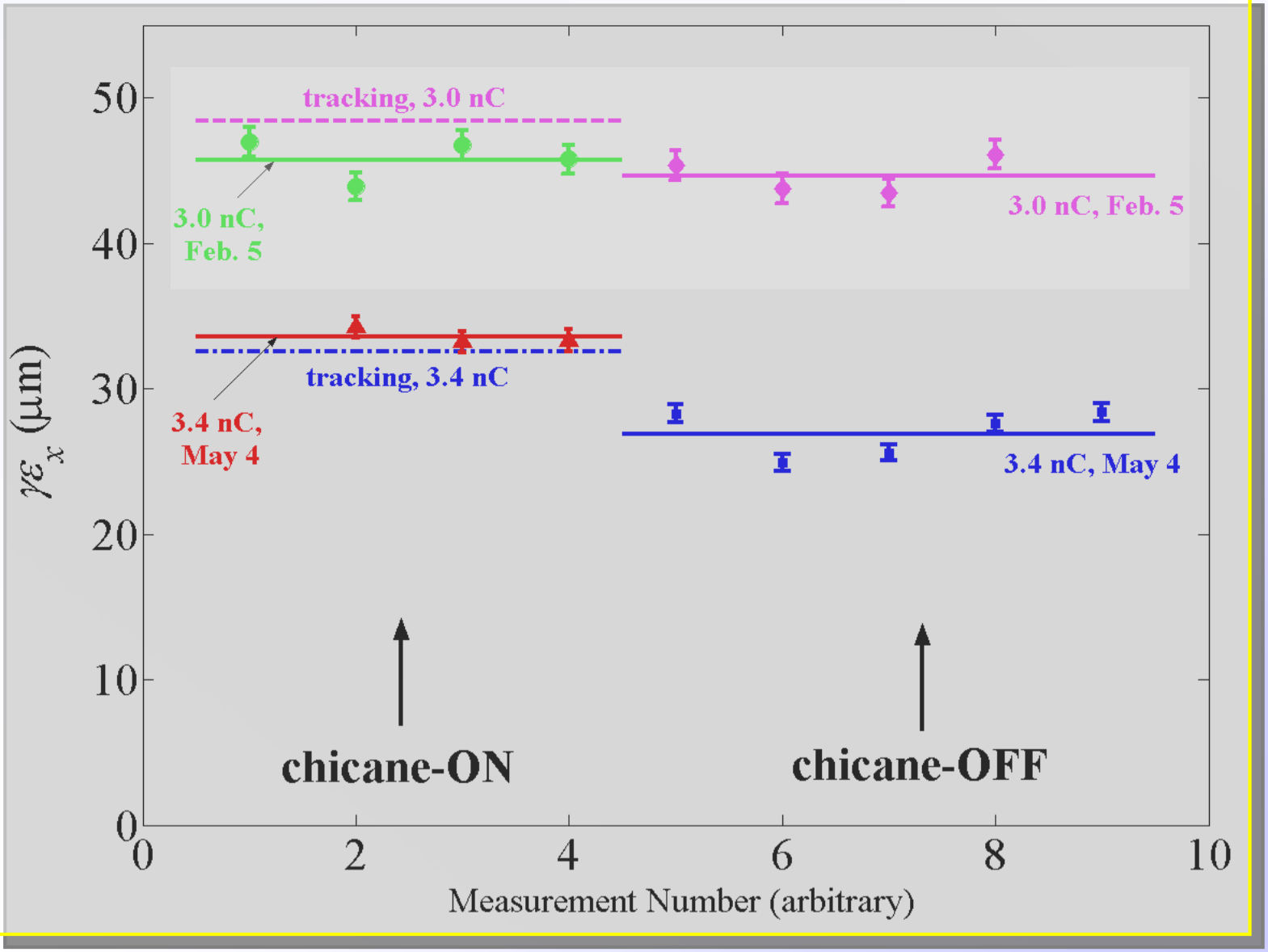
3.424+- 0.073	(3.000)	EMITTANCE(mE-5)
3.445+- 0.070	(3.000)	BMAG*EMIT(mE-5)
1.006+- 0.004	(1.000)	BMAG
0.067+- 0.033	(0.000)	BMAG_COS
0.087+- 0.027	(0.000)	BMAG_SIN
50.754+- 1.721	(47.260)	BETA (m)
-2.093+- 0.076	(-2.031)	ALPHA
307.978+- 6.160	(278.586)	SIG(344)(um)
96.366+- 1.927	(94.425)	SIG(444)(um)
242.204+- 4.844	(224.732)	SIG(614)(um)
139.556+- 2.791	(123.646)	SIG(644)(um)
2.183+- 0.141		INTENSITY
.0184539		CHISQ/DOF
0.376+- 0.034		ASYM(344)
0.170+- 0.036		ASYM(444)
-0.059+- 0.039		ASYM(614)
-0.291+- 0.046		ASYM(644)



Chicane ON

$\gamma\varepsilon_x = 34.2 \pm 0.7\ \mu m$

Bend-Plane Emittance: Chicane ON and OFF



Bend-plane emittance data is consistent with calculations and sets upper limit on CSR effect

P. Emma *et al.*, PAC'03

Concluding Remarks

- Emittance growth consistent with calculations, but no rad. measurements
- ***SPPS*** will run until ***LCLS*** displaces the beamline in ~2007
- ***LCLS*** will begin operation at end of 2008
- Spontaneous device can be added to ***LCLS*** to allow ***Super-SPPS*** in long-term
- Thanks Alex and Lia for invitation