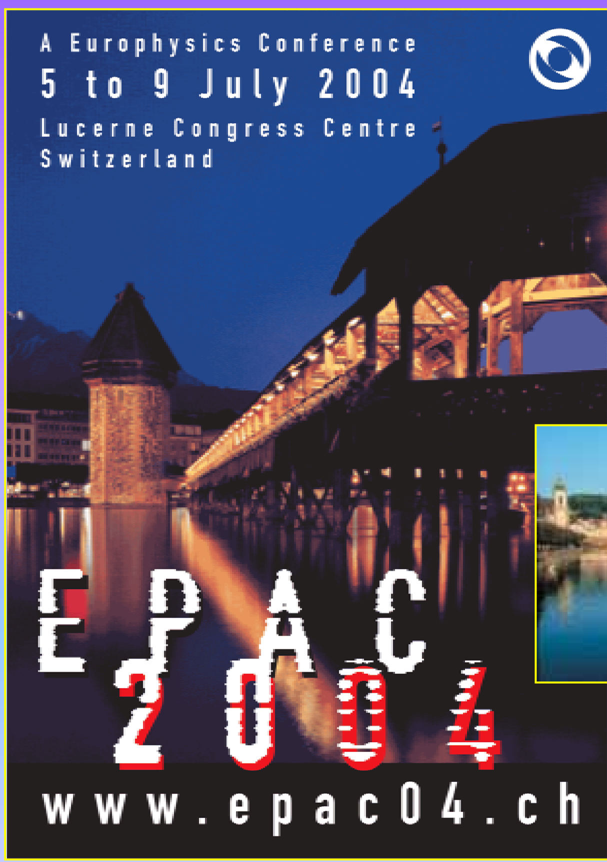
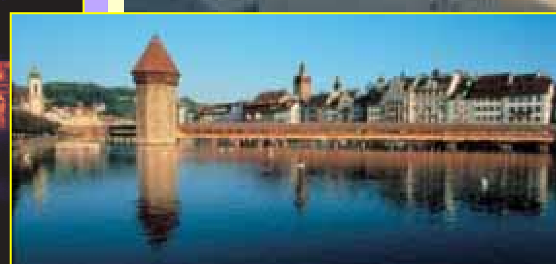
Issues and Challenges for Short Pulse Radiation Production

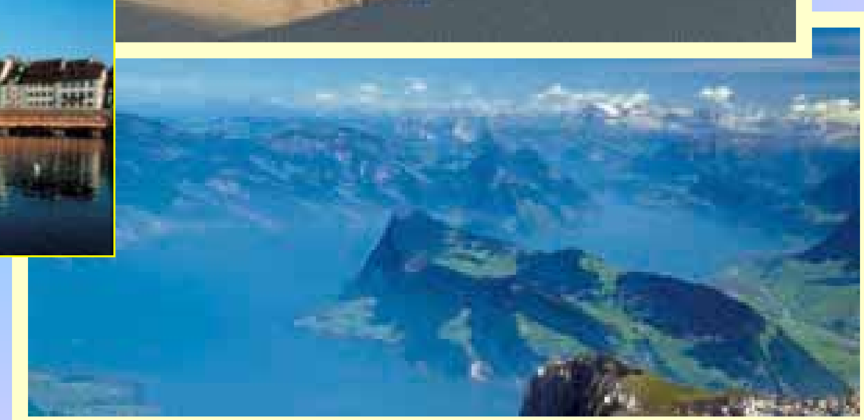
Paul Emma

Stanford Linear Accelerator Center

July 8, 2004







How Short?

…defined by New York Traffic Commissioner T.T. Wiley in 1950 as:

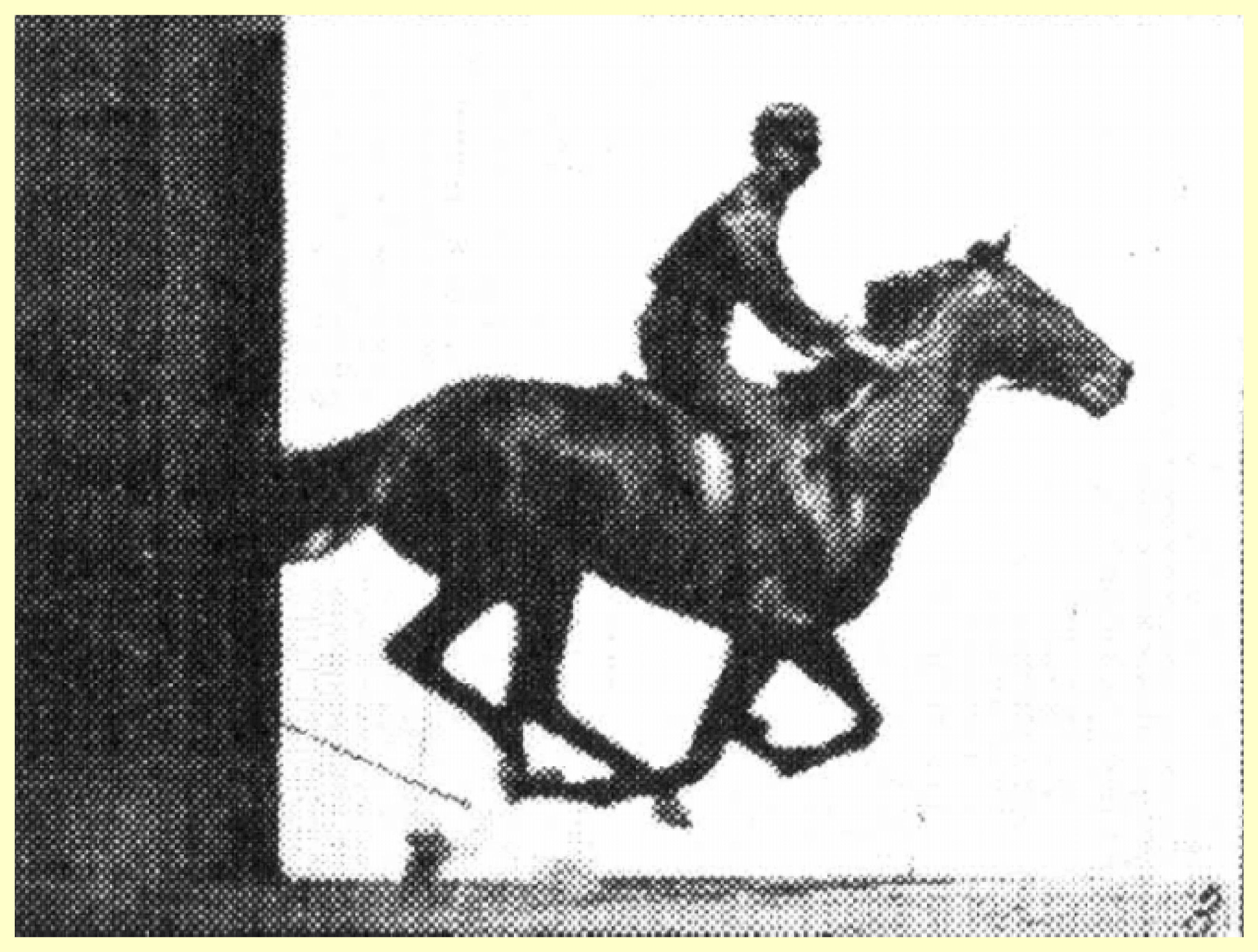
"…the time between the light turning green and the guy behind you honking."

-W. Safire, *NY Times*, March 7, 2004

Several FEL proposals go beyond even this:

- **sub-femtosecond pulses**
- **1-Å radiation**
- **GW power levels**
- **unprecedented brightness**

why so short…



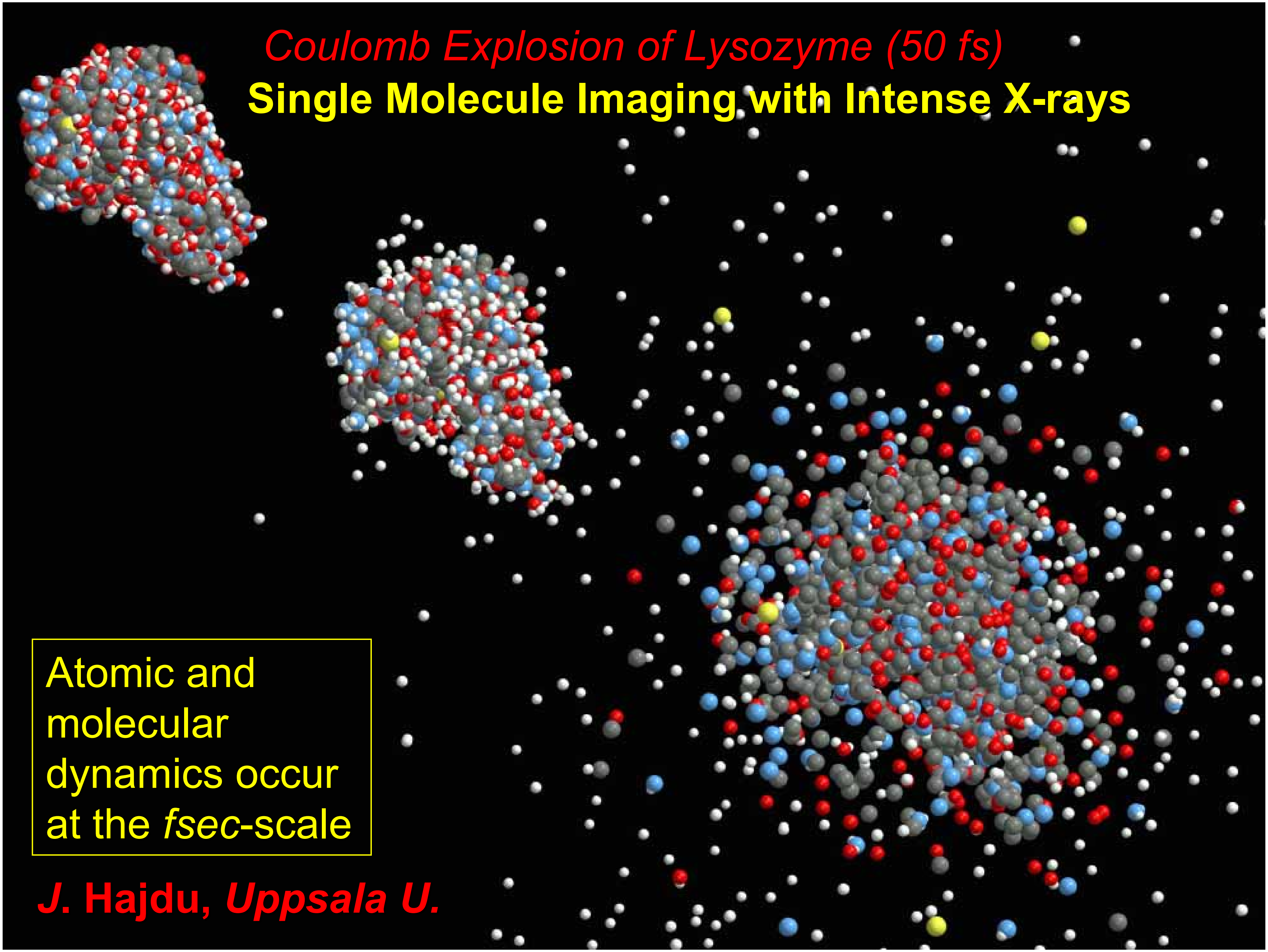
E. Muybridge at L. Stanford in **1878**

disagree whether all feet leave the ground during gallop…

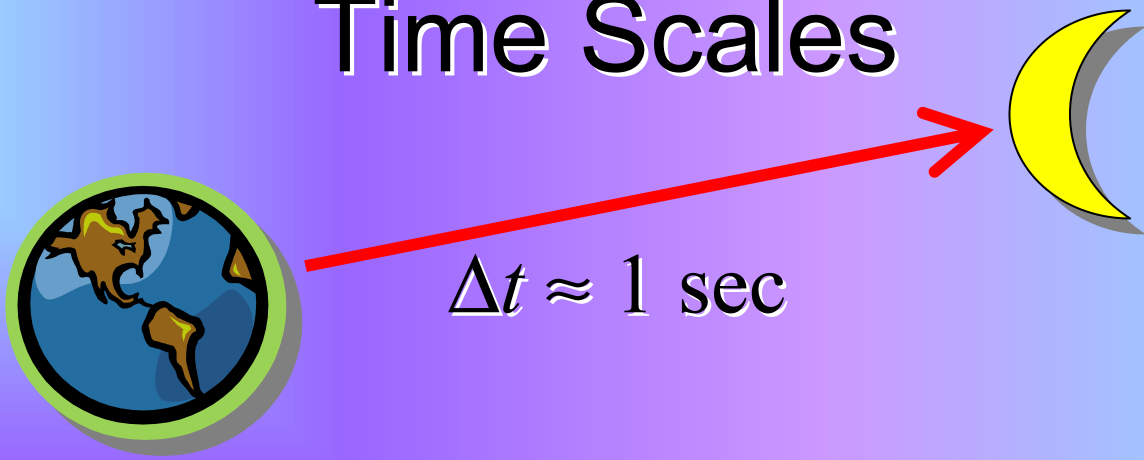
E. Muybridge

used spark photography to freeze this 'ultra-fast' process

E. Muybridge, *Animals in Motion*, ed. L. S. Brown (Dover Pub. Co., New York 1957).


Coulomb Explosion of Lysozyme (50 fs)
Single Molecule Imaging with Intense X-rays
Atomic and molecular dynamics occur at the fsec-scale
J. Hajdu, Uppsala U.

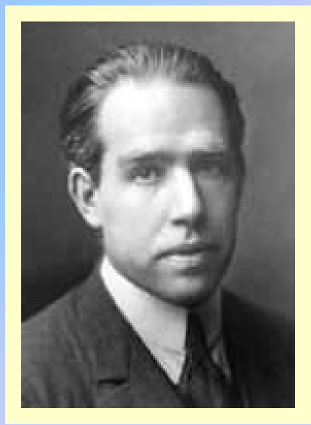
Time Scales



1 **femto**-second (fs) = 10^{-15} sec $\Rightarrow$ 0.3 μm

1 **atto**-second (as) = 10^{-18} sec $\Rightarrow$ 0.3 nm

In Neils Bohr’s 1913 model of the Hydrogen atom it takes about **150 as** for an electron to orbit the proton.
– *Nature*, 2004



Outline

- *Electron bunch limitations*
- *Photon pulse limitations*
- *Schemes for short pulse generation*
- **SPPS** *results* (Sub-psec Pulse Source)

Just a tick: Scientists are using ever-shorter time scales to investigate chemical reactions.
Nature, *February 26, 2004*

Electron bunch length is limited by…

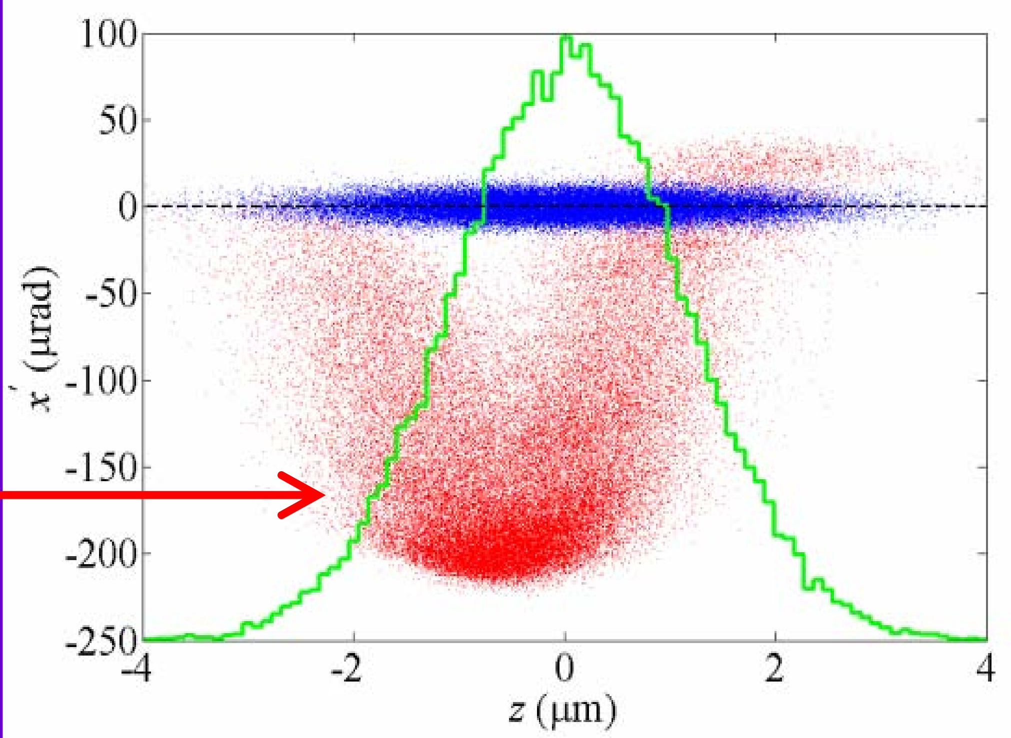
- Coherent synch. rad. (CSR) in compressors
- Longitudinal wakefields in linac & undulator
- Space-charge forces in accelerator
- System jitter (RF, charge, etc)

Try to compress σ_z in LCLS to 1 μm…

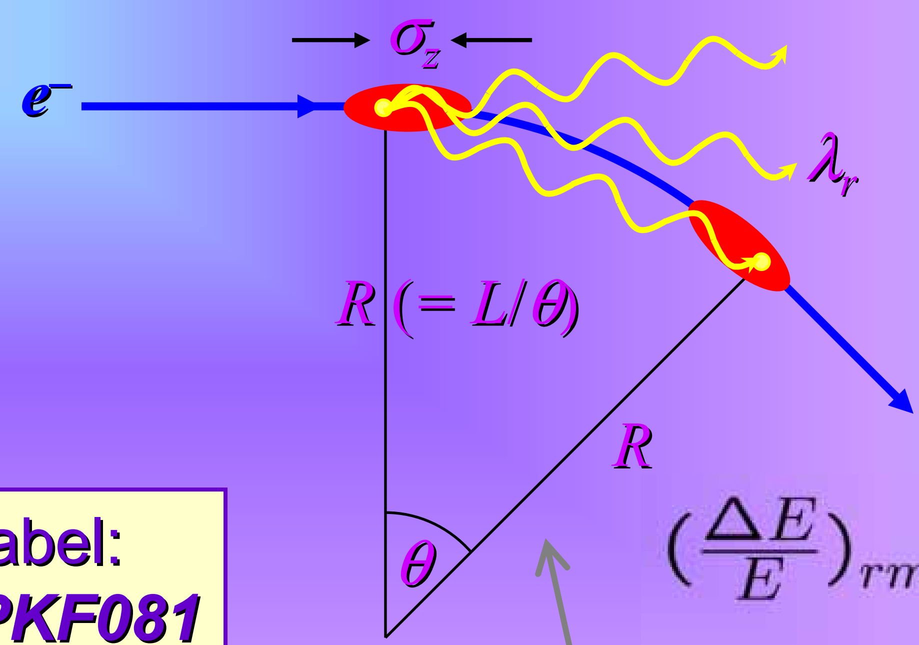
~~CSR~~: $\varepsilon/\varepsilon_0 = 1$

CSR: $\varepsilon/\varepsilon_0 \approx 14$

brightness destroyed



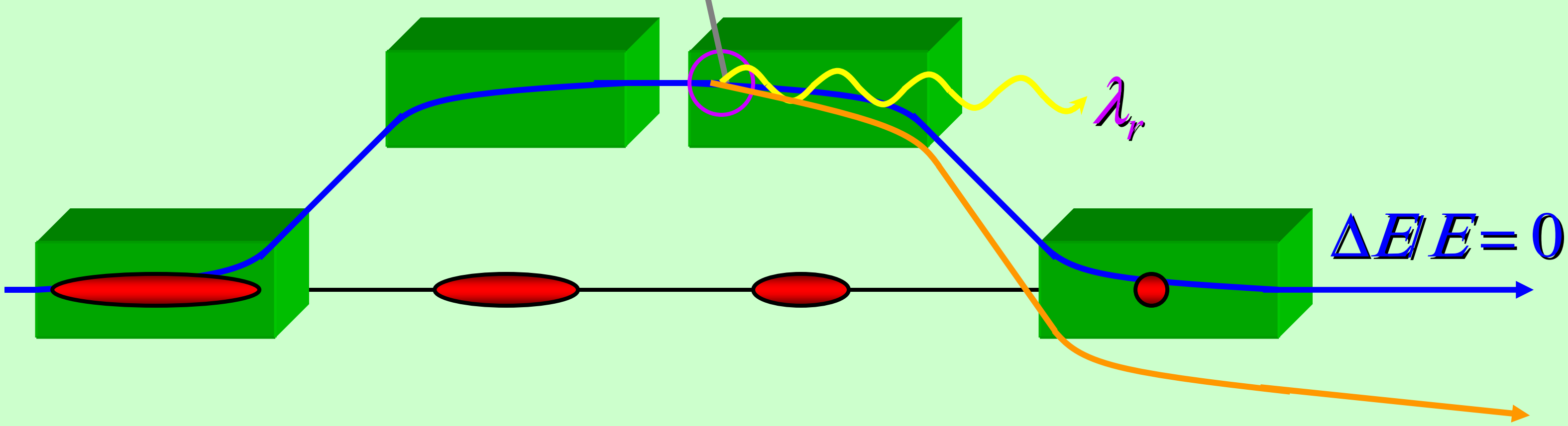
Coherent Synchrotron Radiation in Bends



Coherent radiation for $\lambda_r > \sigma_z$

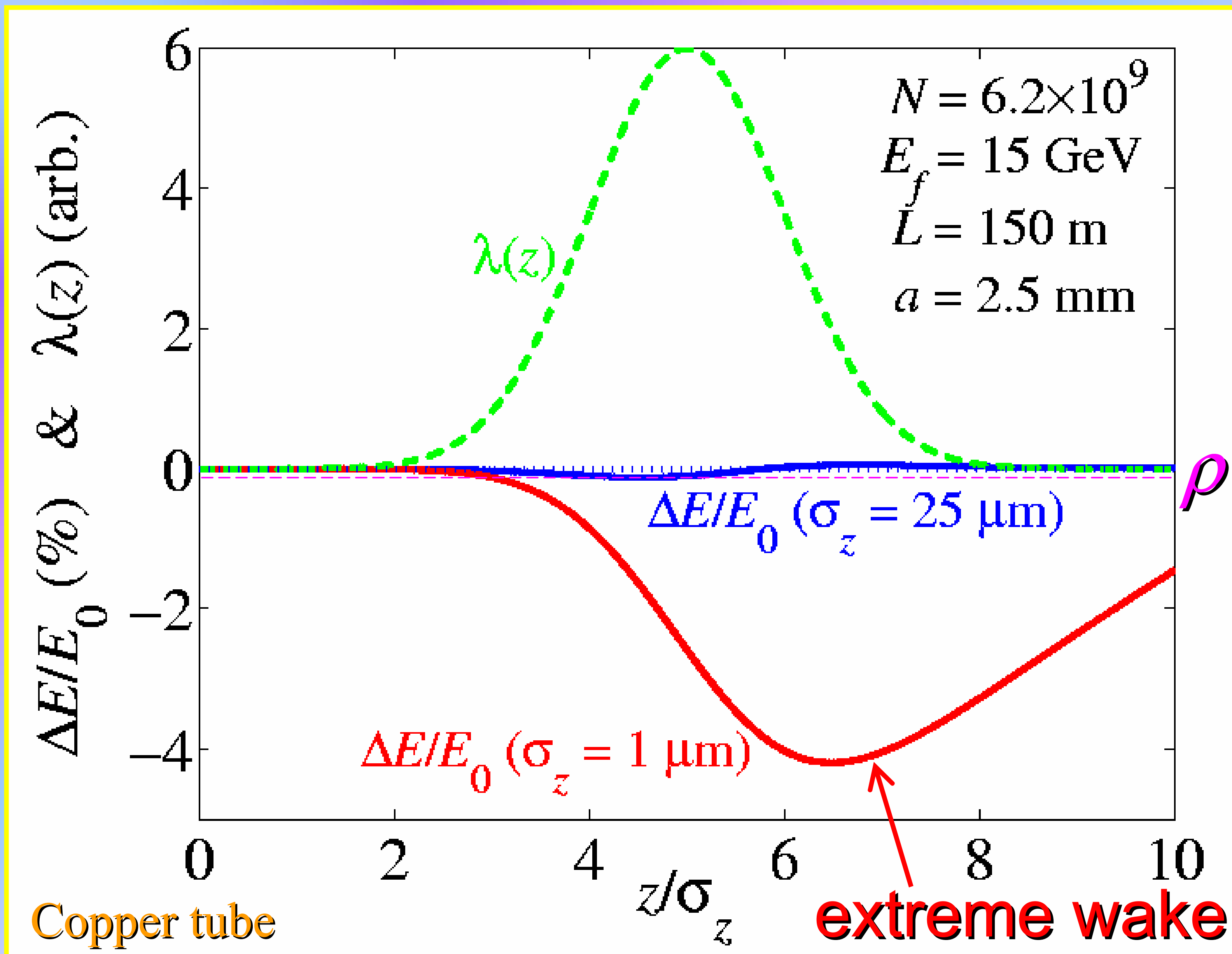
A. Kabel:
MOPKF081

$$\left(\frac{\Delta E}{E}\right)_{rms} \approx 0.22\frac{r_e N L}{\gamma R^{2/3}\sigma_z^{4/3}}$$



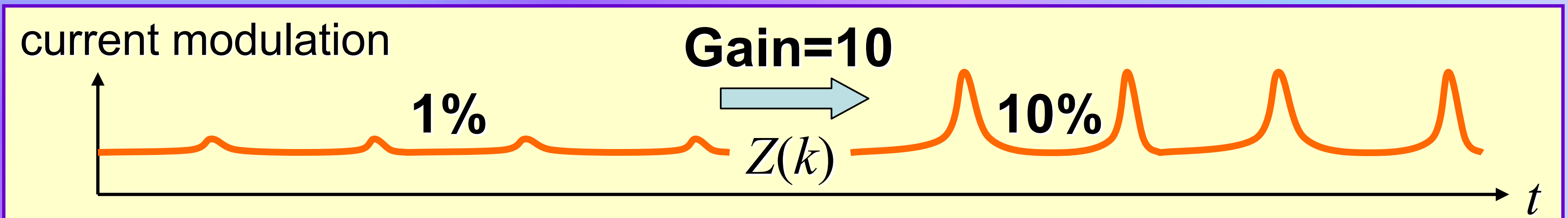
bend-plane emittance is ruined → $\Delta E/E < 0$

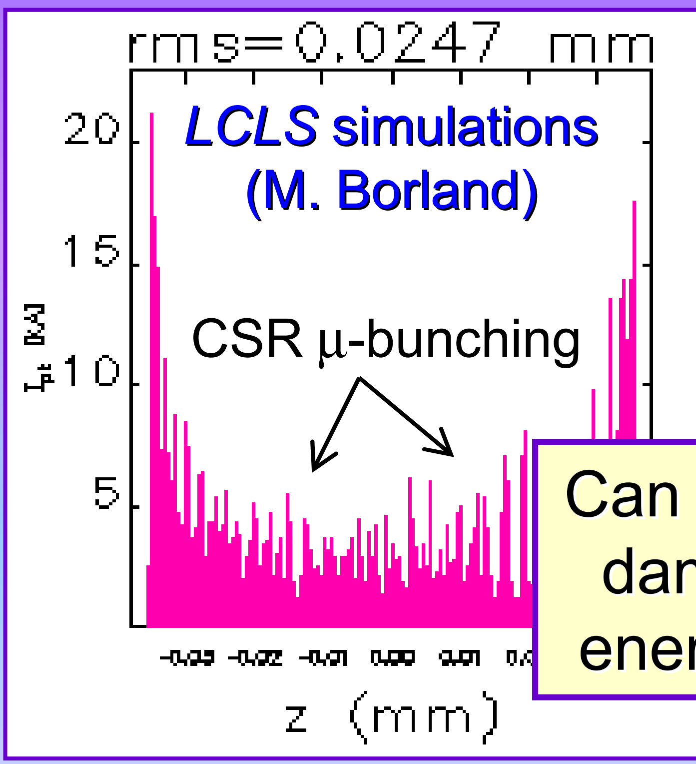
Resistive-Wall Wakefields in Undulator



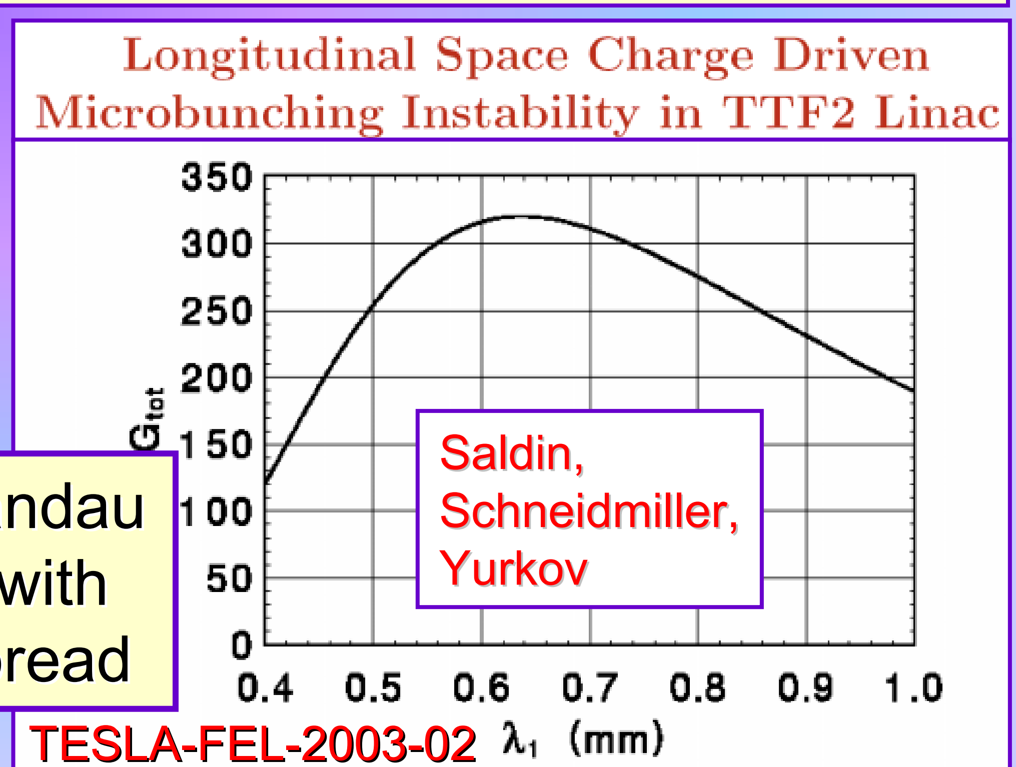
Micro-Bunching Instabilities

- FEL ‘instability’ needs very “**cold**” e^- beam (small $\varepsilon_{x,y}$ & **E-spread**)
- **Cold** beam is subject to “undesirable” instabilities in accelerator (**CSR**, Longitudinal Space-Charge, wakefields)



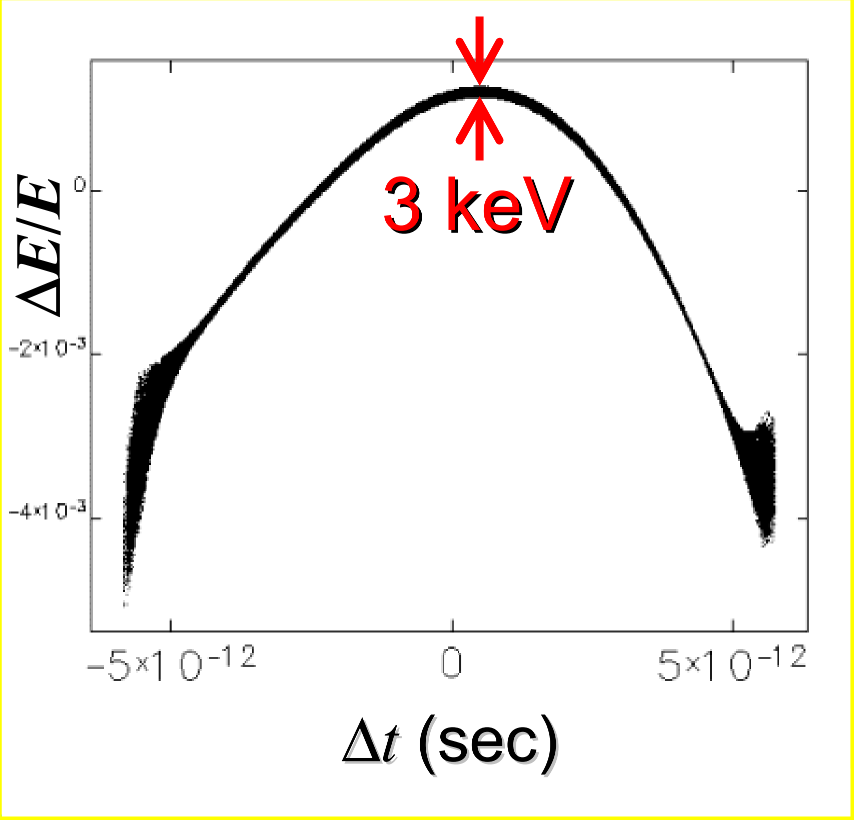


Can be Landau damped with energy spread

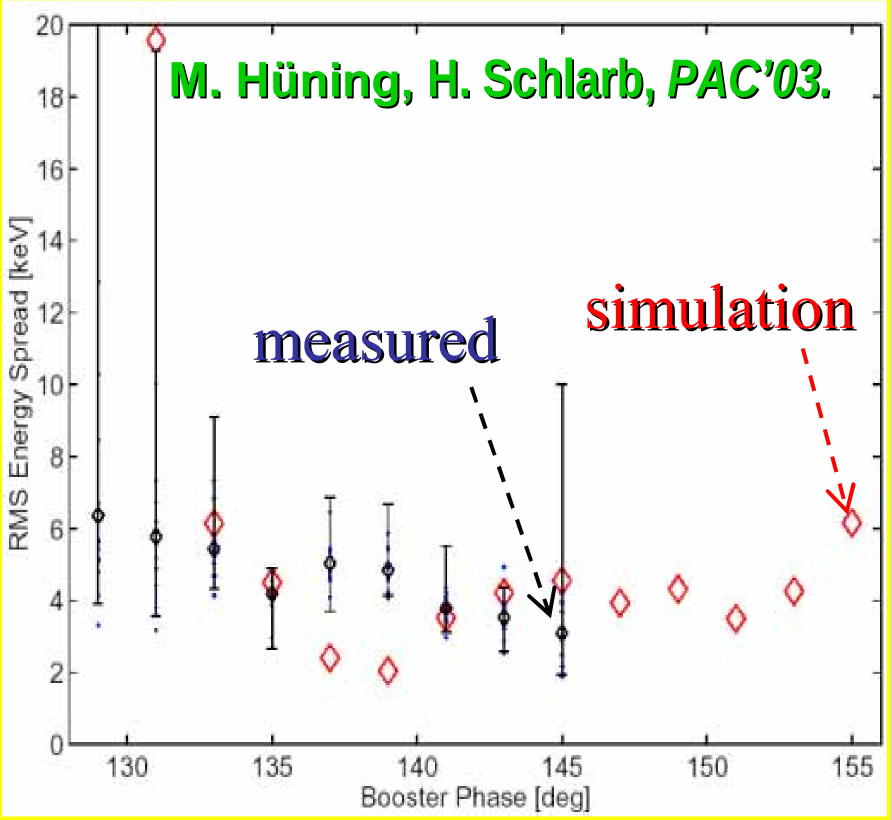


How cold is the photo-injector beam?

Parmela Simulation



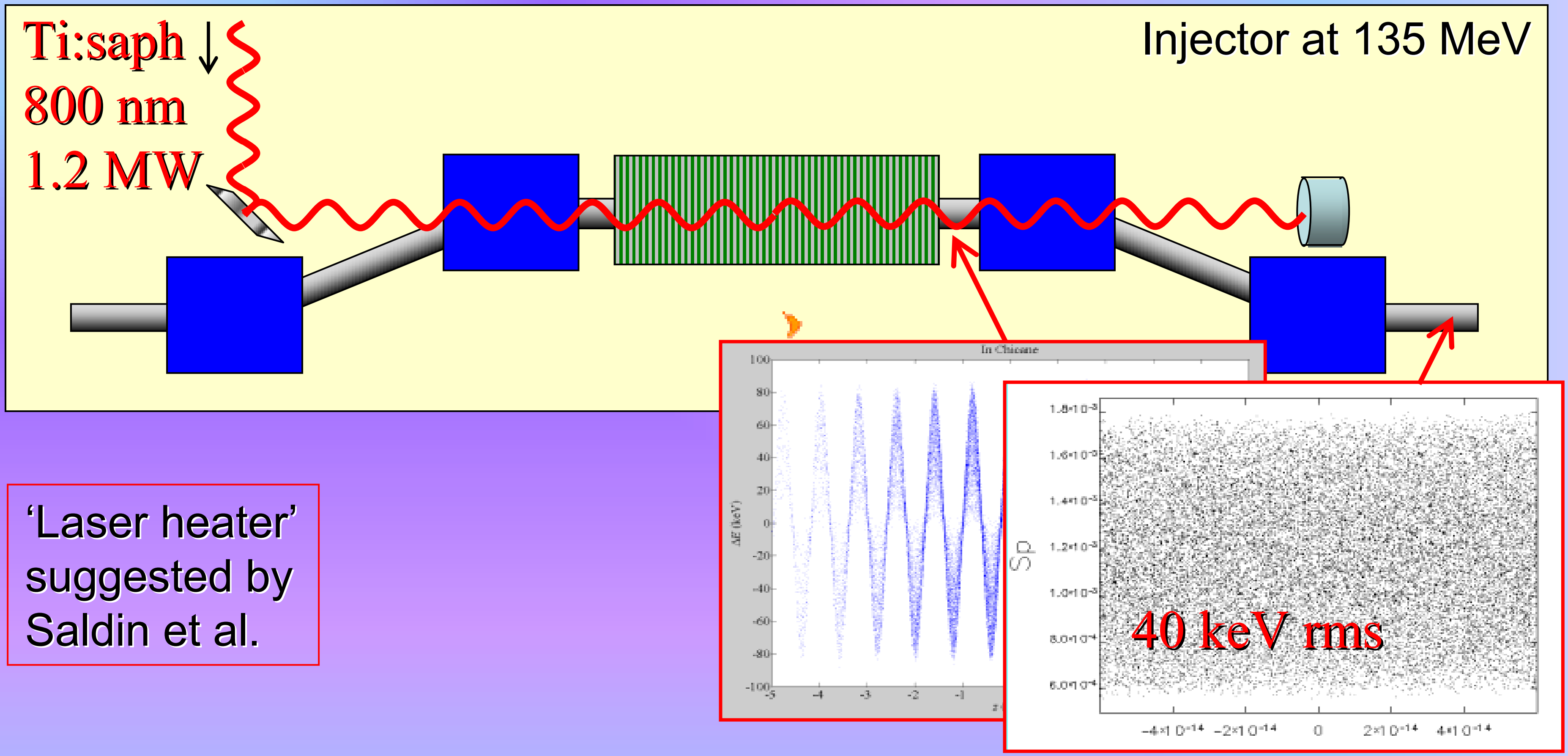
TTF measurement



3 keV, accelerated to 14 GeV, & compressed ×36 ⇒ $\underline{1\times10^{-5}}$

Too small to be useful in FEL (no effect on FEL gain when $<10^{-4}$)

'Laser Heater' in LCLS for Landau Damping

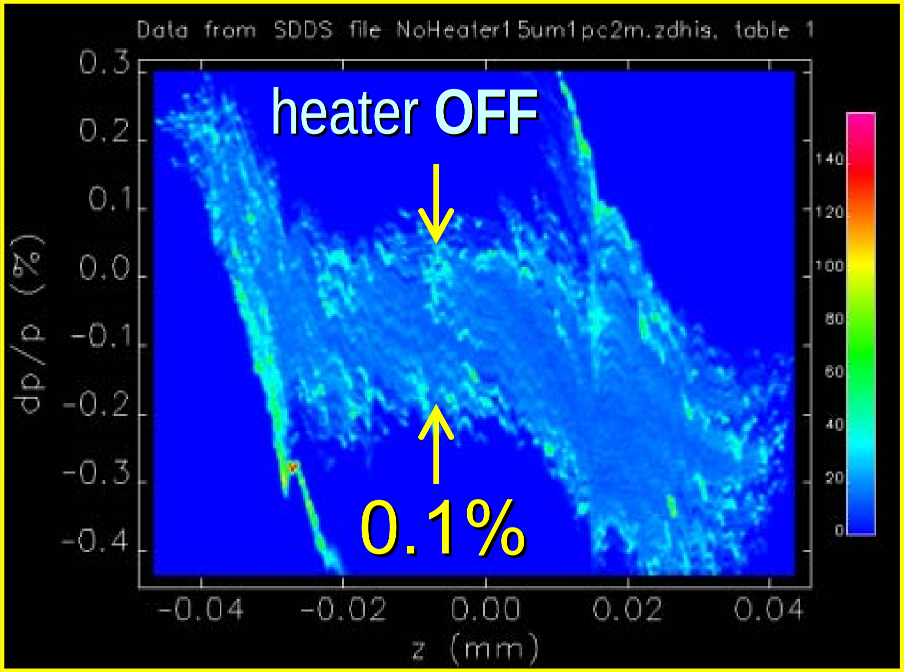


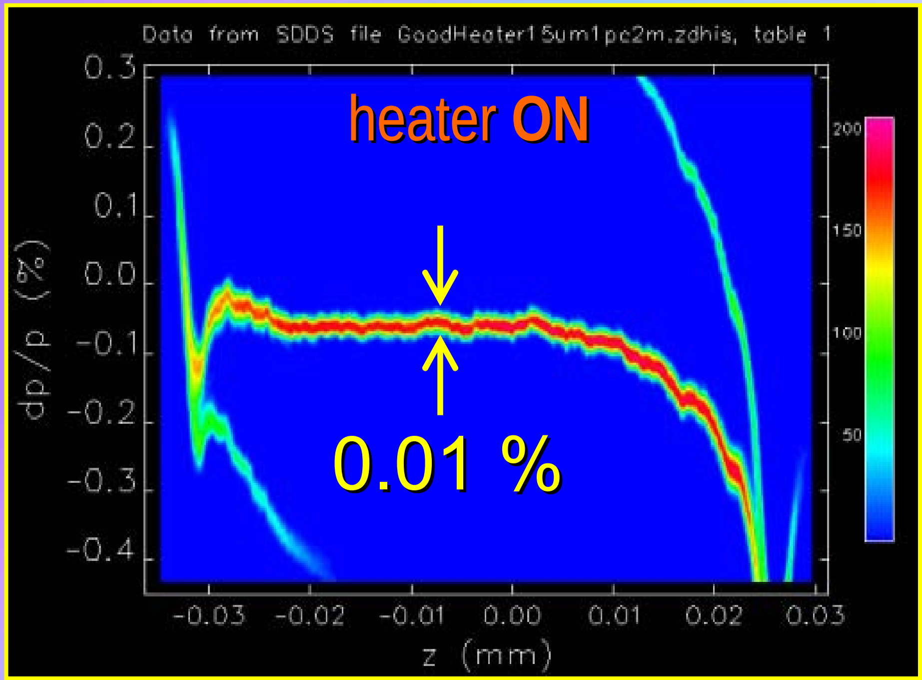
'Laser heater' suggested by Saldin et al.

- Laser-e^- interaction $\Longrightarrow$ 800-nm *E*-modulation (40 keV rms)
- Heater in weak chicane for time-coordinate smearing
- Energy spread in next compressors smears μ-bunching

Huang: ***WEPLT156***, Limborg: ***TUPLT162***, Carr: ***MOPKF083***

In *LCLS* tracking, final energy spread blows up without 'Laser-Heater'





Final longitudinal phase space at 14 GeV
for initial 15-μm, 1% modulation at 135 MeV

Z. Huang et al., SLAC-PUB-10334, 2004 ...accepted in ***PR ST AB***, June 2004

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Just a tick: Scientists are using ever-shorter time scales to investigate chemical reactions.
Nature, *February 26, 2004*

FEL pulse duration limited by intrinsic bandwidth

$$\sigma_t \sigma_\omega \geq 1/2$$

For X-ray FEL:

$\lambda_r \approx 1$ Å,

$\sigma_\omega / \omega_0 \approx 0.04\%$,

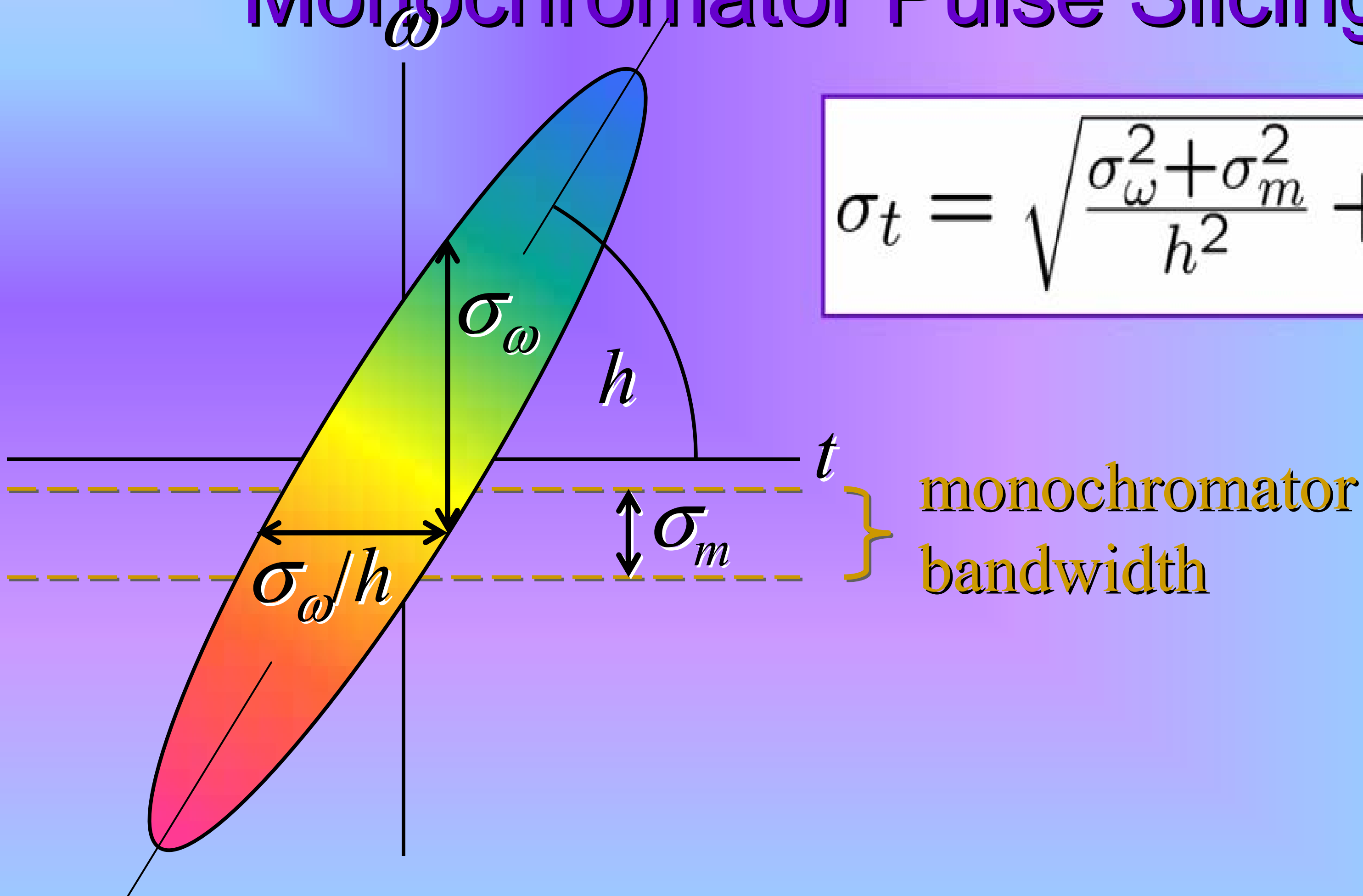
$\sigma_t \geq 100$ as

For shorter pulses:

- shorter wavelength, λ_r
- larger ρ (smaller $\varepsilon_{x,y}$)
- low-gain (large $\Delta\omega$)
- seeded start-up

FEL-type:	N_u	L_u	$\Delta\omega/\omega$
Saturated SASE	$\sim 1/\rho$	$\sim 20L_g$	$\sim\rho$
Seeded High-Gain	$<1/\rho$	$<20L_g$	$>\rho$
Seeded Low-Gain	$\sim 1/(4\pi\rho)$	$\sim 2L_g$	$\sim 4\pi\rho$

Monochromator Pulse Slicing



$$\sigma_t = \sqrt{\frac{\sigma_\omega^2+\sigma_m^2}{h^2} + \frac{1}{4\sigma_m^2}}$$

$$\sigma_m/\omega_0 = 10^{-4},\ \sigma_\omega/\omega_0 = 5\times10^{-4},\ h \to 2\% \Rightarrow \sigma_t \approx 5\text{ fs}$$

S. Krinsky, Z. Huang, PR ST AB, **6**, 050702 (2003).

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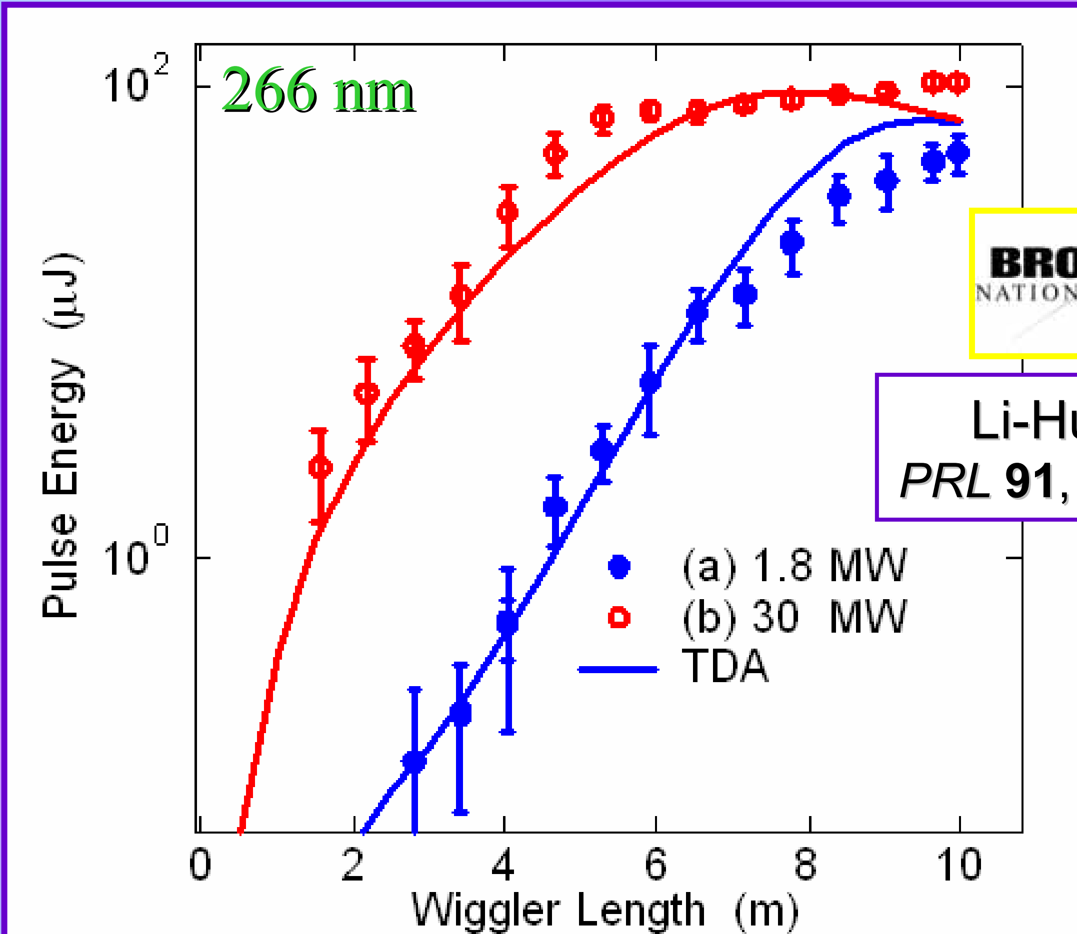
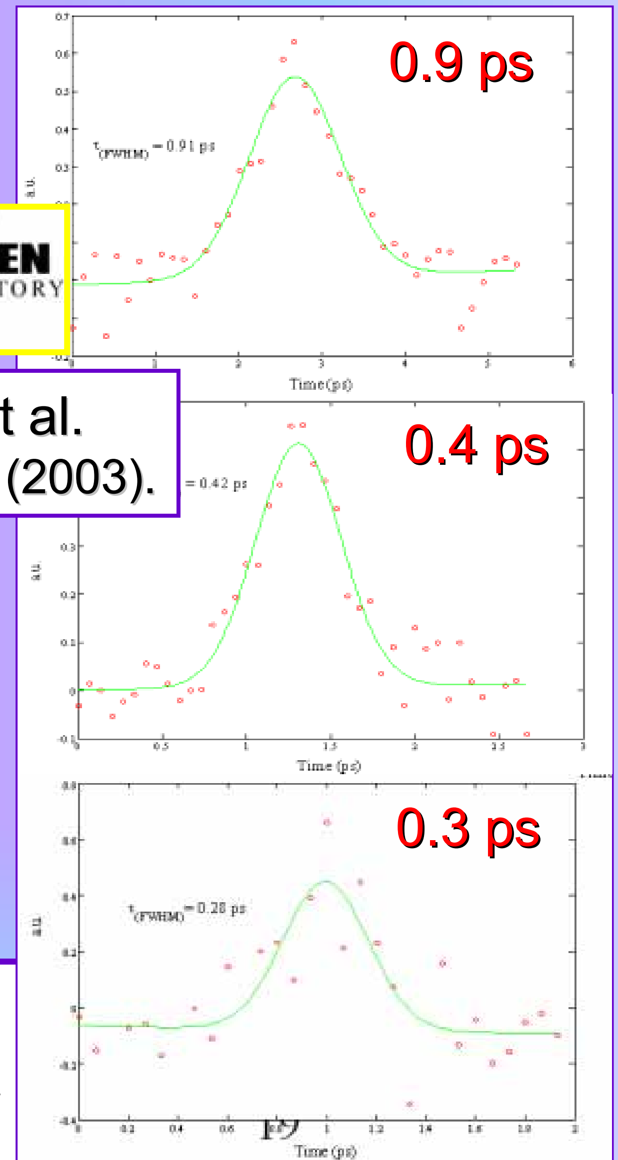
HGHG Saturation at *DUVFEL*

pulse length control
with seed laser





Li-Hua Yu et al.
PRL **91**, 074801 (2003).

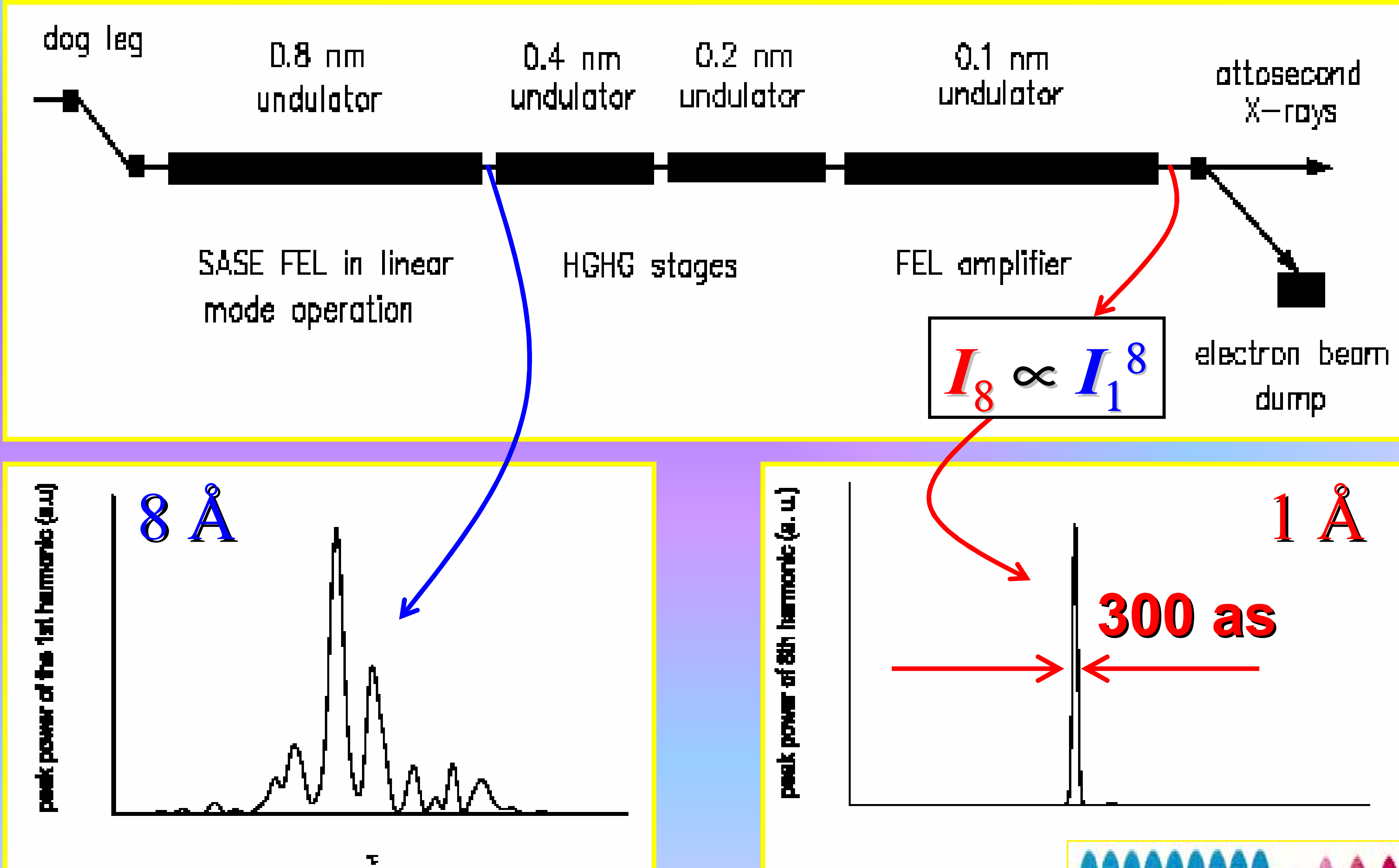
$I_{pk} = 300$ A, $\sigma_E/E_0 = 0.01\%$

$P_{in} = 1.8$ MW: $\sigma_z = 0.6$ ps, $\gamma\varepsilon = 2.7$ μm, $d\psi/d\gamma = 8.7$

$P_{in} = 30$ MW: $\sigma_z = 1.0$ ps, $\gamma\varepsilon = 4.7$ μm, $d\psi/d\gamma = 3.0$

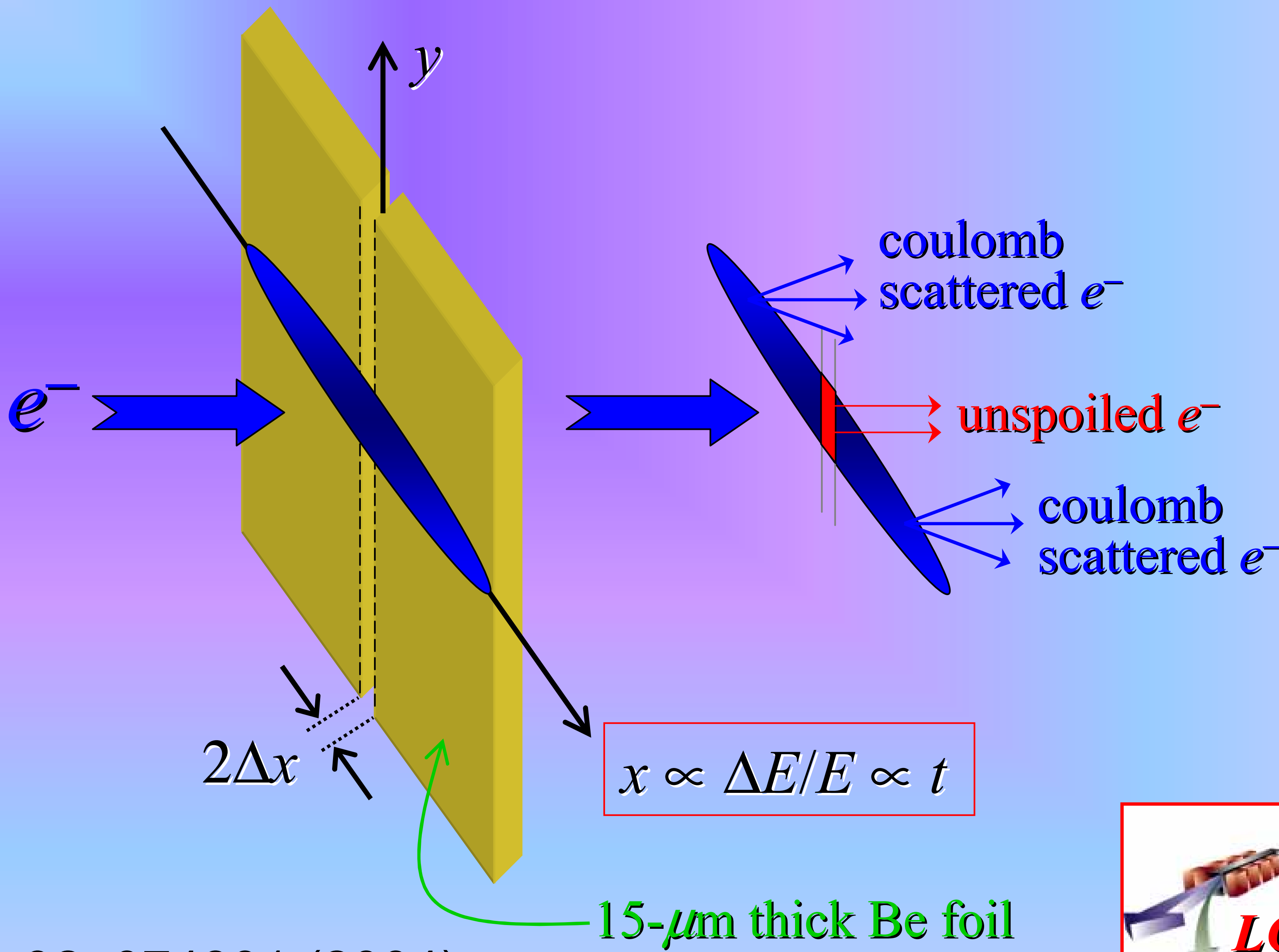
Statistical Single-Spike Selection

Un-seeded single-bunch HGHG (8 → 4 → 2 → 1 Å)



Saldin et al., *Opt. Comm.*, **212**, 377 (2002).

Add thin slotted foil in center of chicane

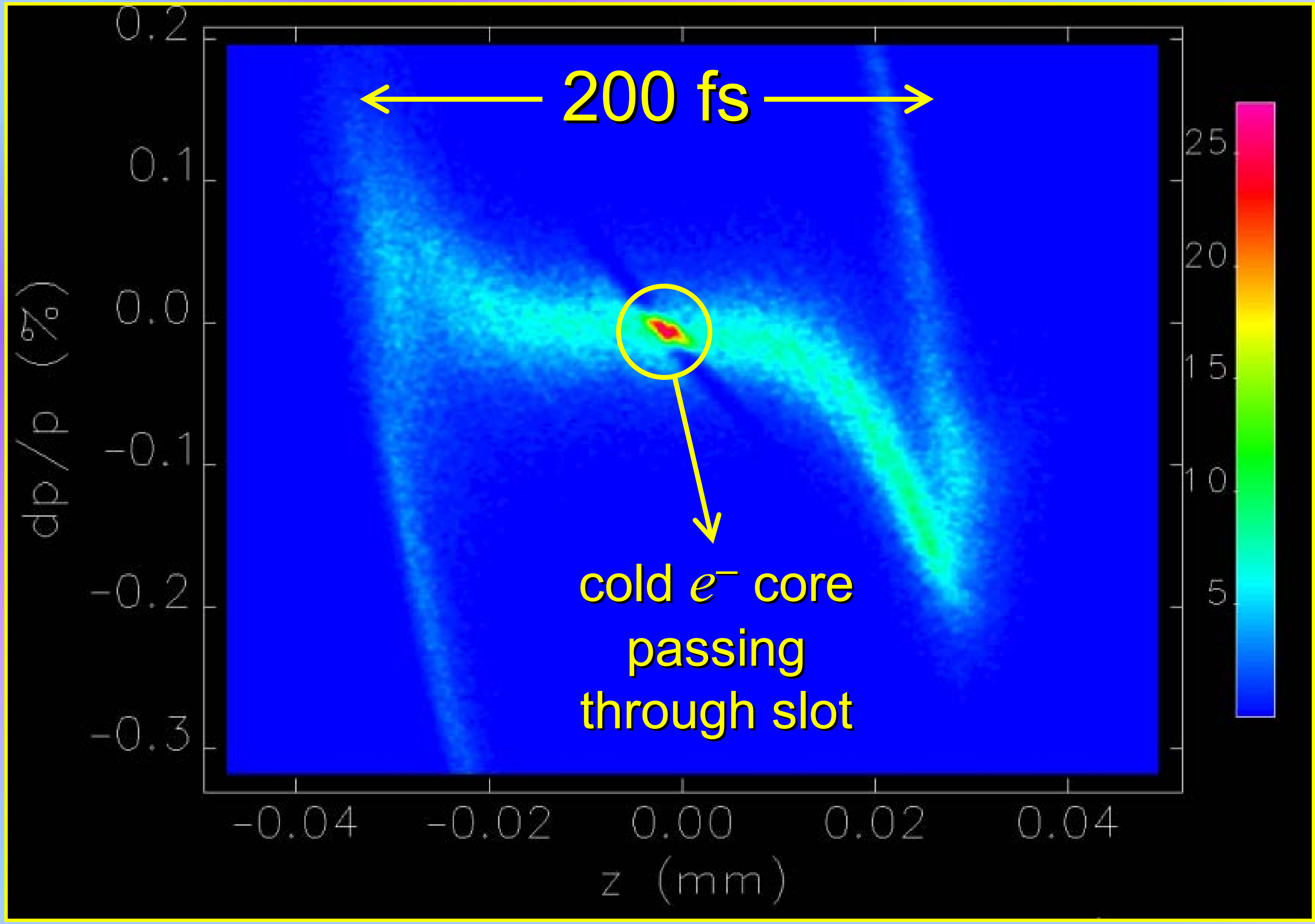


PRL **92**, 074801 (2004).

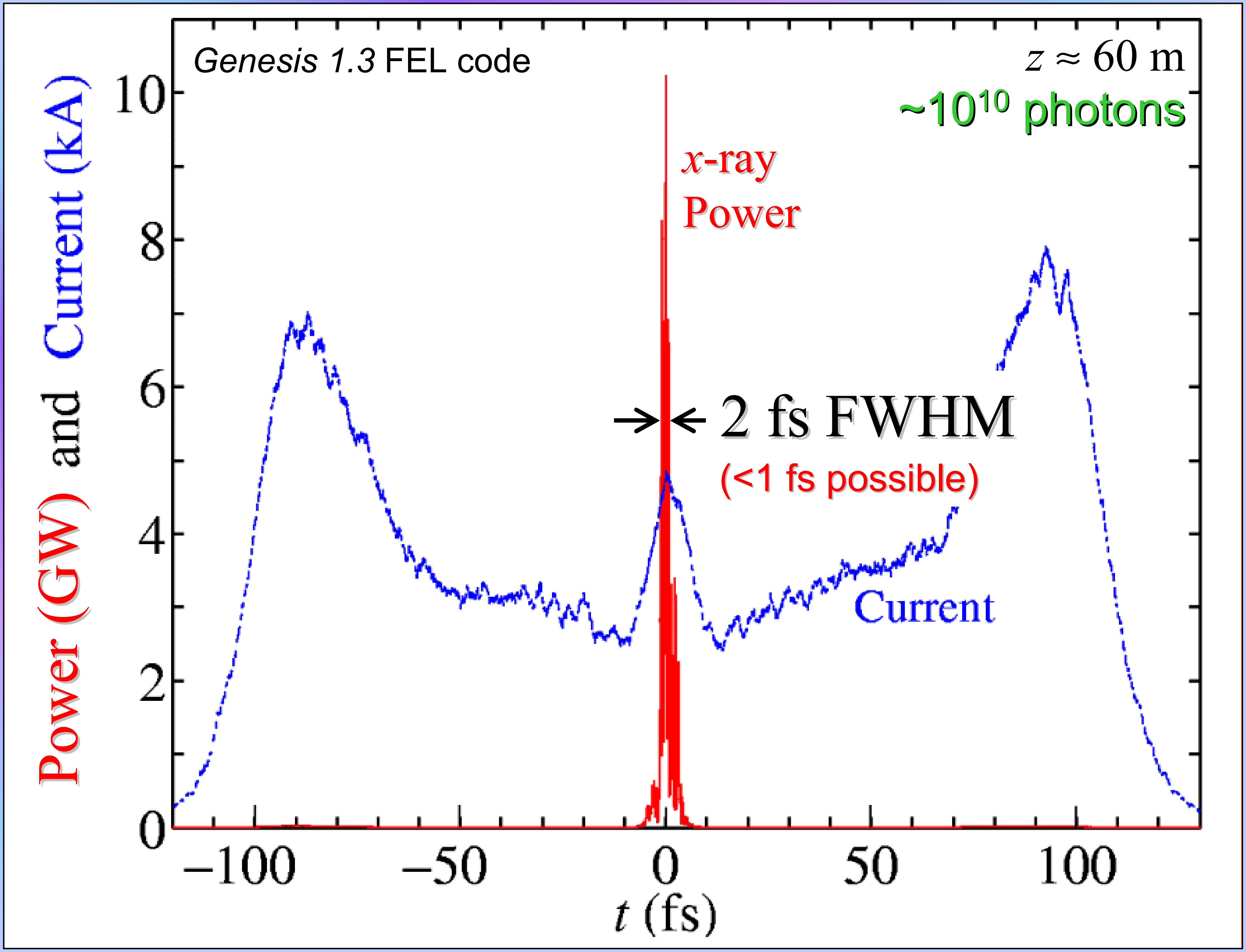
P. Emma, M. Cornacchia, K. Bane, Z. Huang, H. Schlarb, G. Stupakov, D. Walz (SLAC)

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

ΔE/E



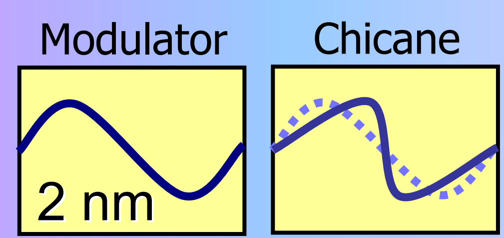
No design changes to FEL – only foil added in chicane



Genesis 1.3 FEL code
z ≈ 60 m
~10^10 photons
x-ray
Power
2 fs FWHM
(<1 fs possible)
Current
Power (GW) and Current (kA)
t (fs)
10
8
6
4
2
0
−100
−50
0
50
100

2 nm, 100 MW, 100 fs

Mod. tuned so only high energy e^- interact with 2-nm HC FEL radiation



LUX electron beam parameters:

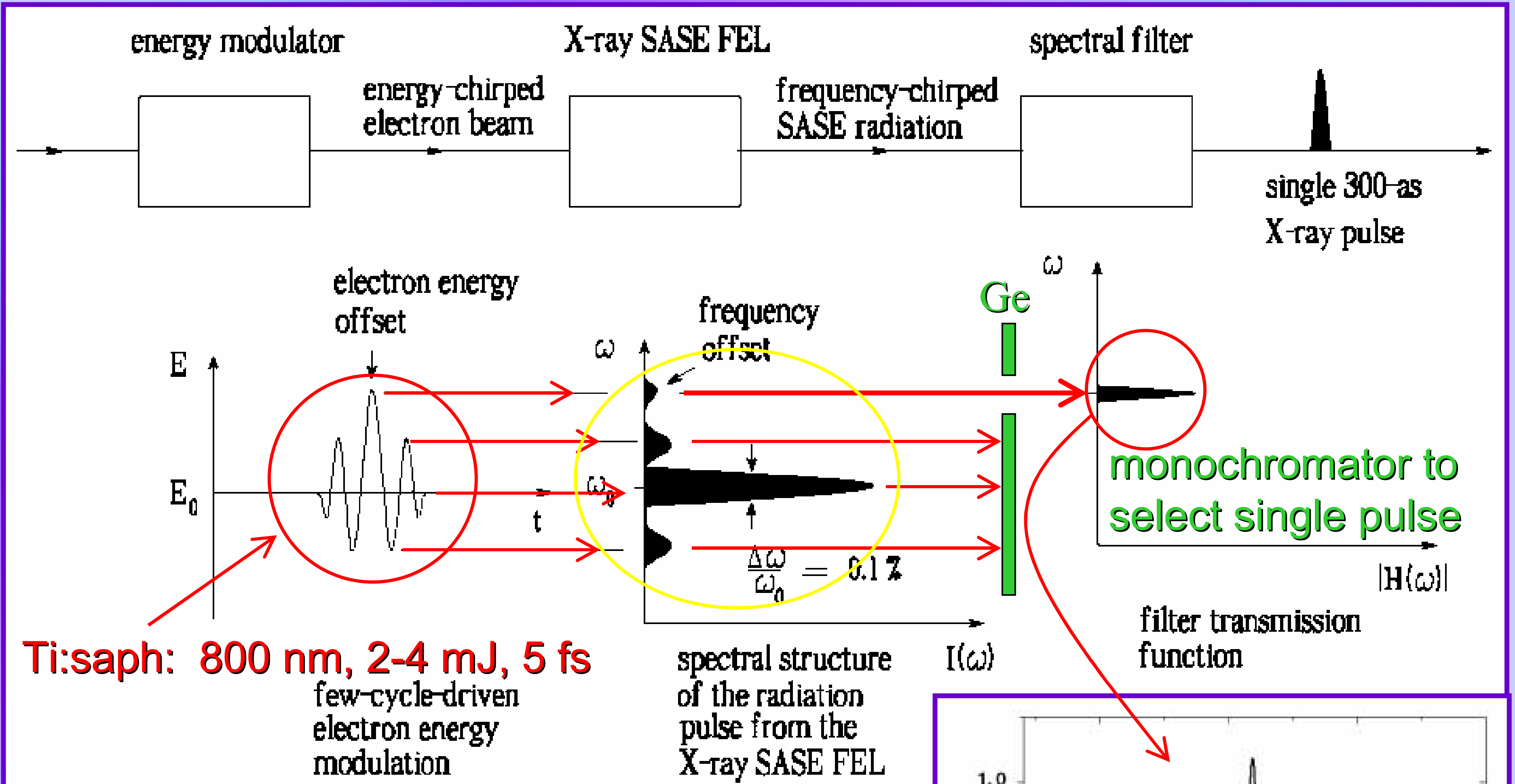
e^- energy	= 3 GeV
emittance	= 2 mm-mrad
energy spread	= 0.3 MeV
peak current	= 500 A

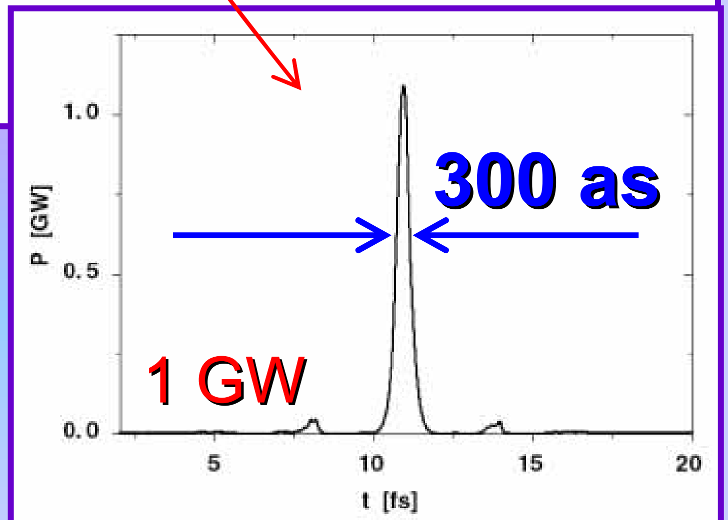
Generation of Attosecond Pulses…

A. Zholents, W. Fawley

PRL **92**, 224801 (2004).

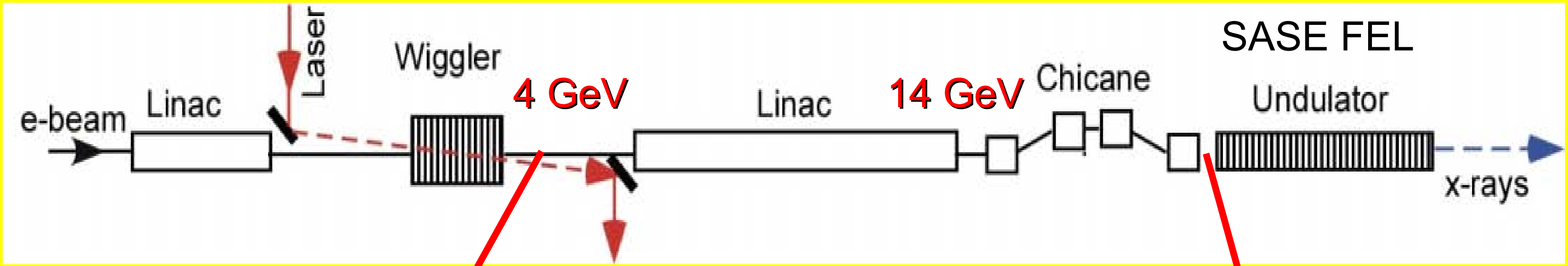
MOPKF072

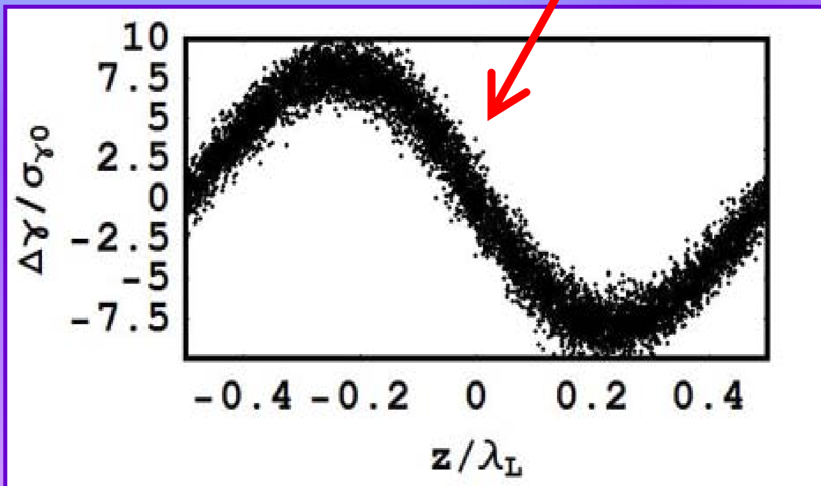


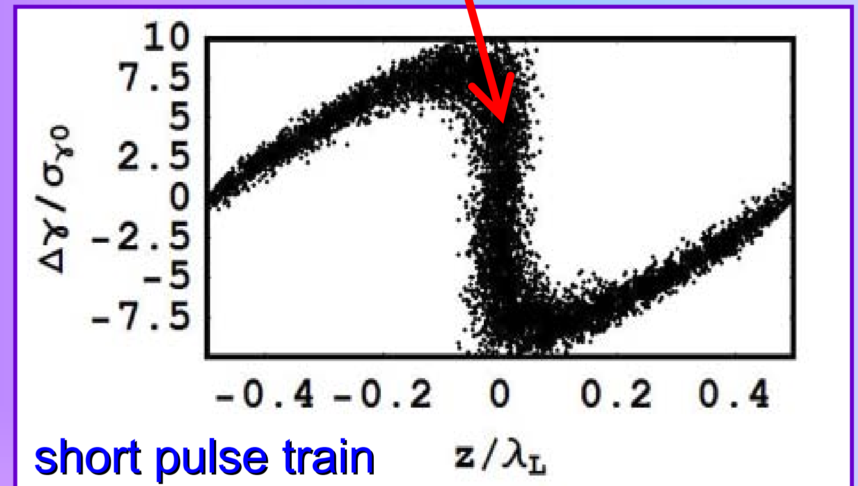


monochromator is broadband Ge crystal diffracting from the (1 1 1) lattice planes (pre-monochromator to reduce power)

Saldin et al., *Opt. Comm.*, **237**, 153 (2004).

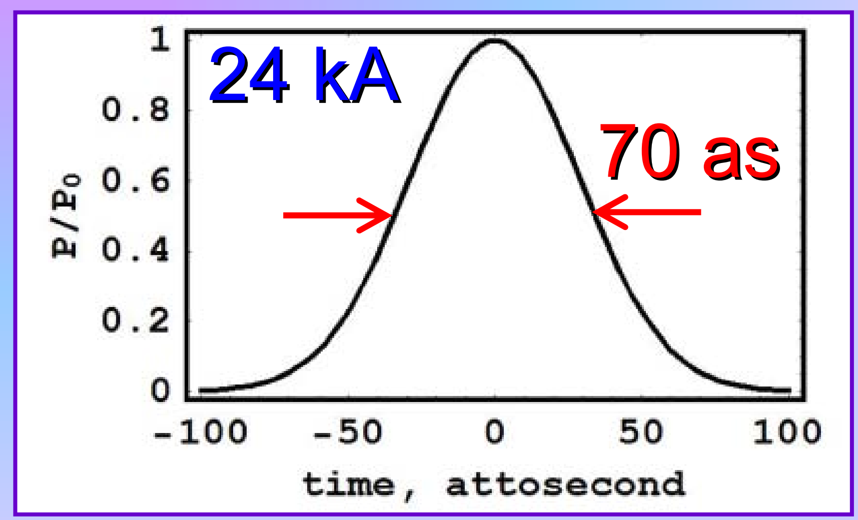






800-nm modulation (few GW)

Allows synchronization between laser pulse and x-ray pulse



***E*-SASE** (applied to *LCLS*)

A. Zholents

(submitted to *PRL*)

BERKELEY LAB

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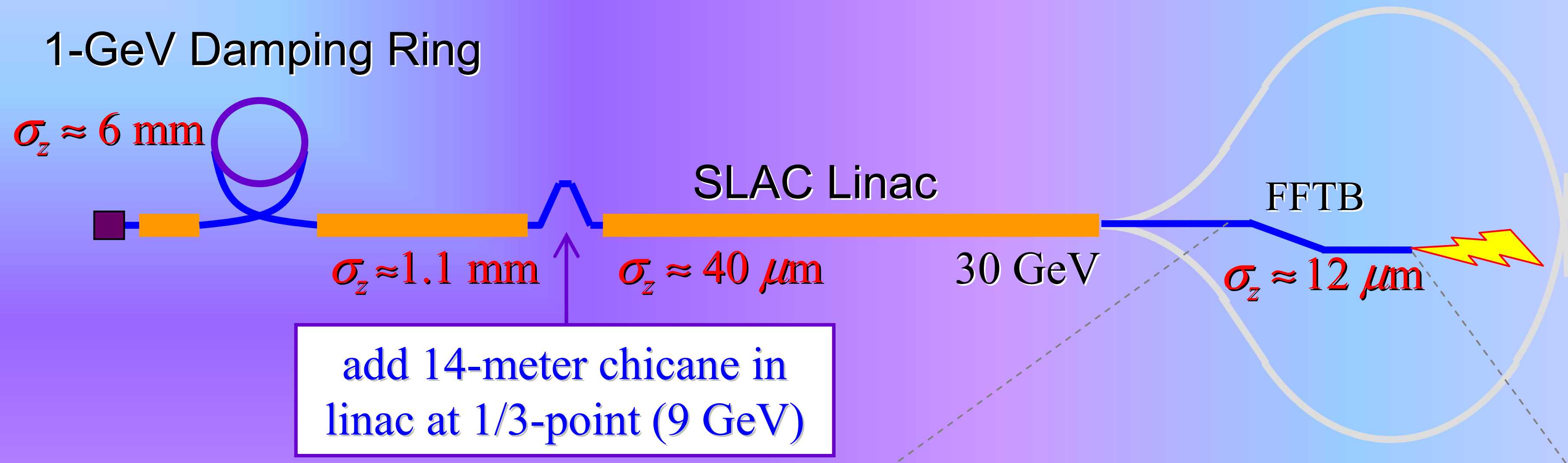
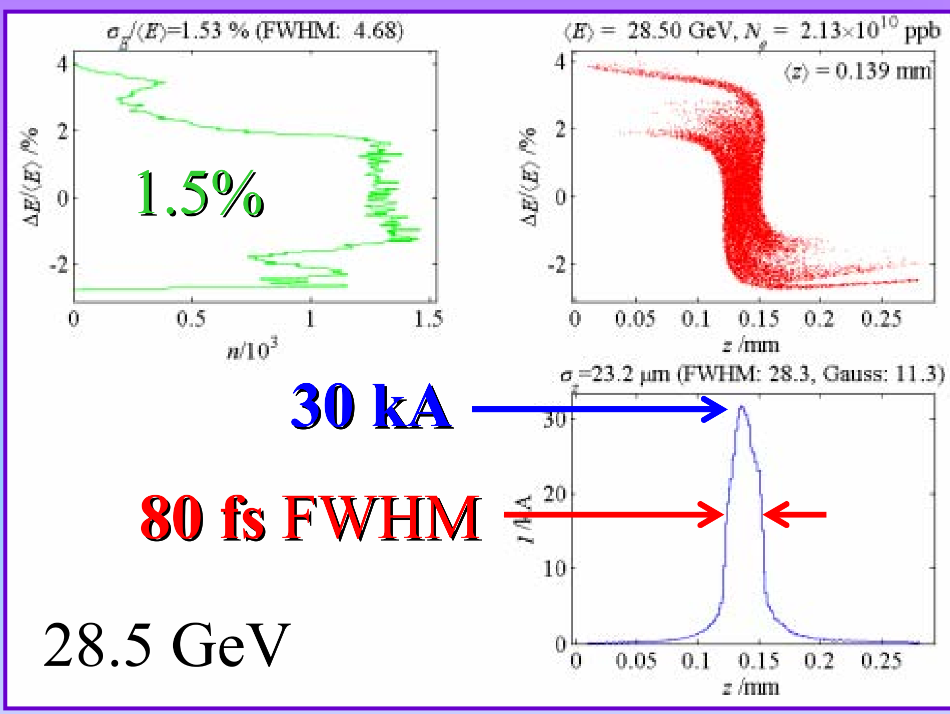
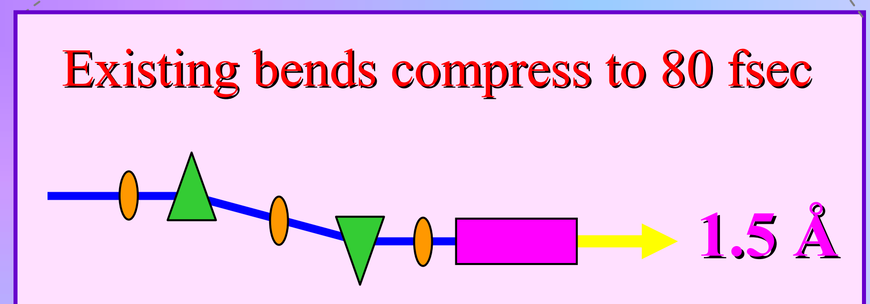
Nature*, February 26, 2004*

Short Bunch Generation in the *SLAC* Linac







compression by factor of 500

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

Source comparisons

	Peak brightness**	Pulse length (fsec)	Average flux (photon/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**

* streak camera resolution 1 psec, ΔQ_e 0.01
** photons/sec/mm^2/mrad^2/0.1%-BW

J. Hastings, ***SLAC***

Sub-Picosecond Pulse Source

Undulator,
view upstream

Dave Fritz, Soo Lee, David Reis

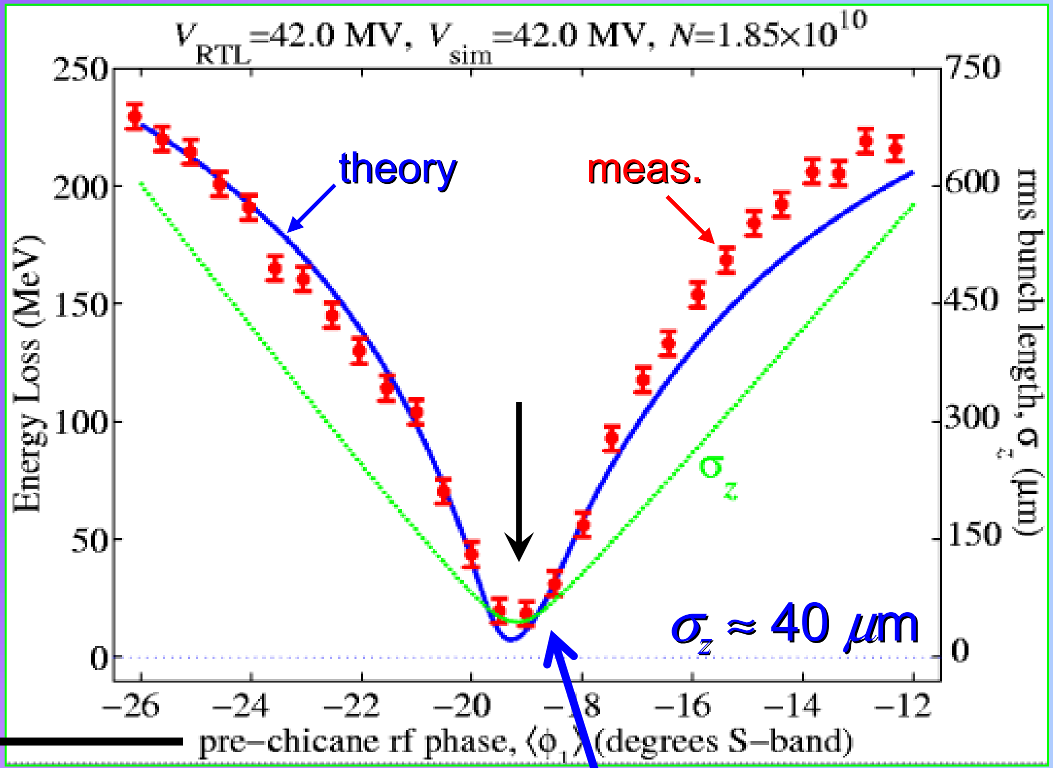
Undulator parameters: $L_u \approx 2.5$ m, $\lambda_u = 8.5$ cm, $K \approx 4.3$, $B \approx 0.55$ T, $N_p \approx 30$

R&D at SPPS Towards X-Ray FELs

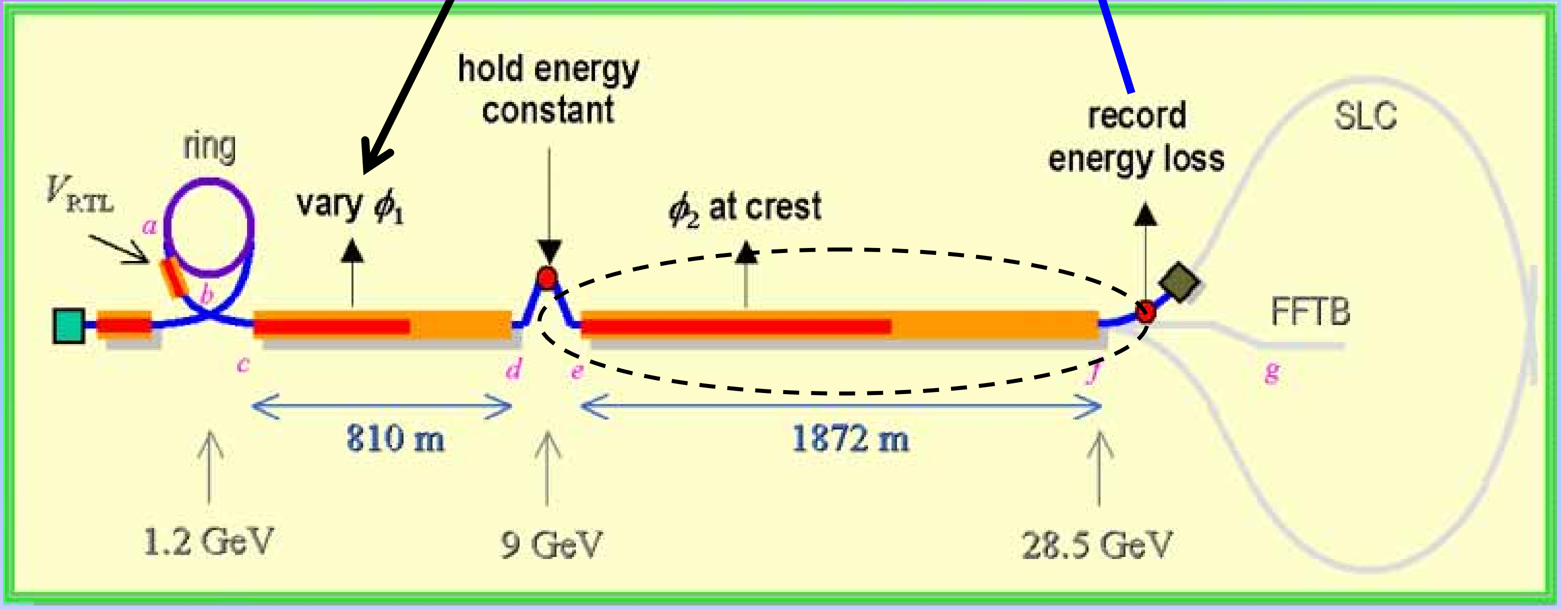
- Measure wakefields of micro-bunch
- Develop bunch length diagnostics
- Study RF phase stability of linac
- Measure emittance growth in chicane (CSR)
- X-ray optics and transport

PPS
Sub-Picosecond Pulse Source

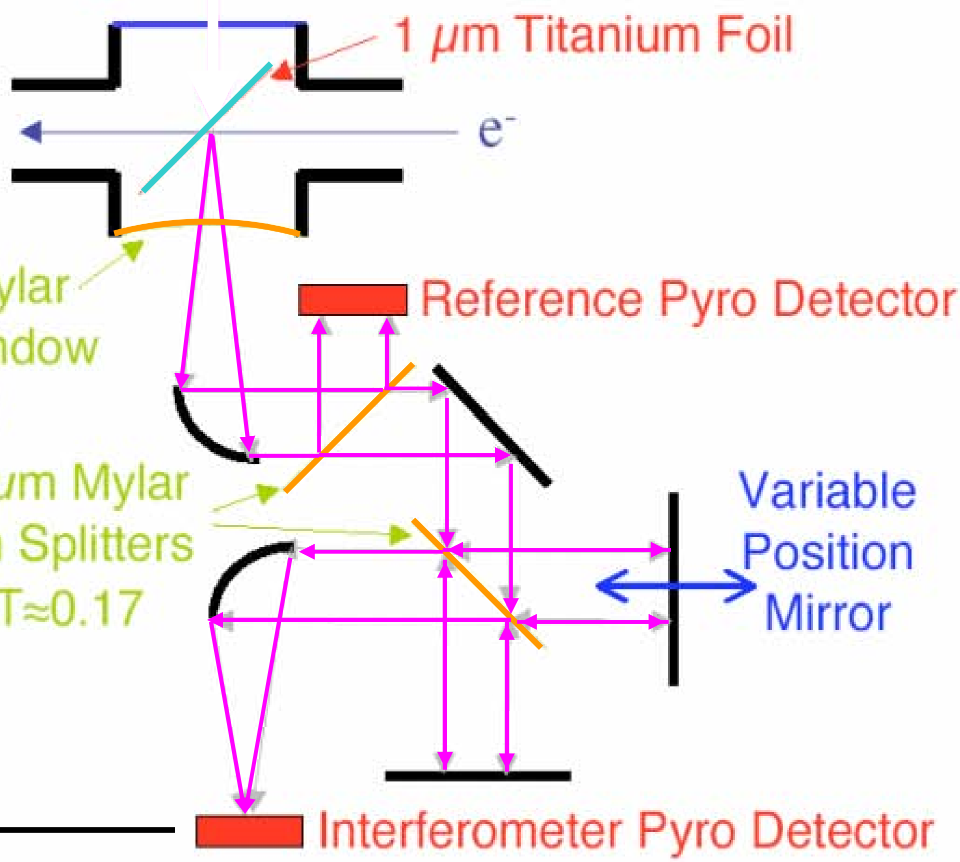
Wakefield energy-loss used to **set** and confirm **minimum** bunch length

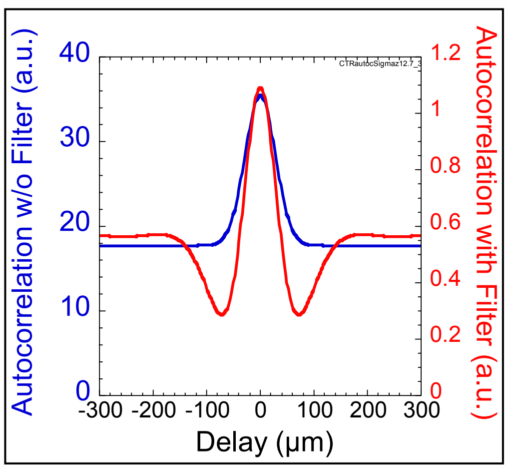


K. Bane *et al.*, PAC'03



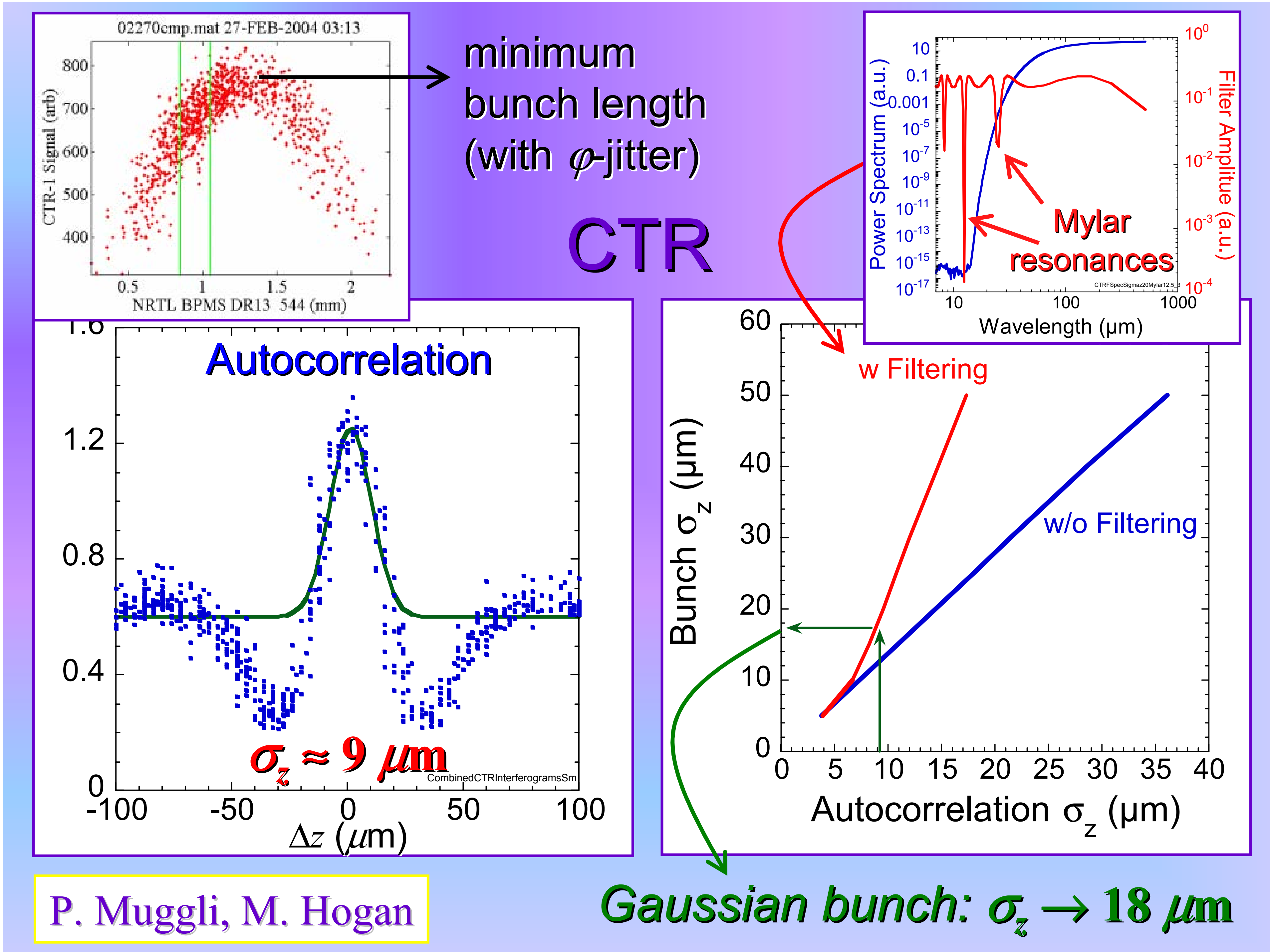
Michelson Interferometer for CTR Bunch Length Measurement





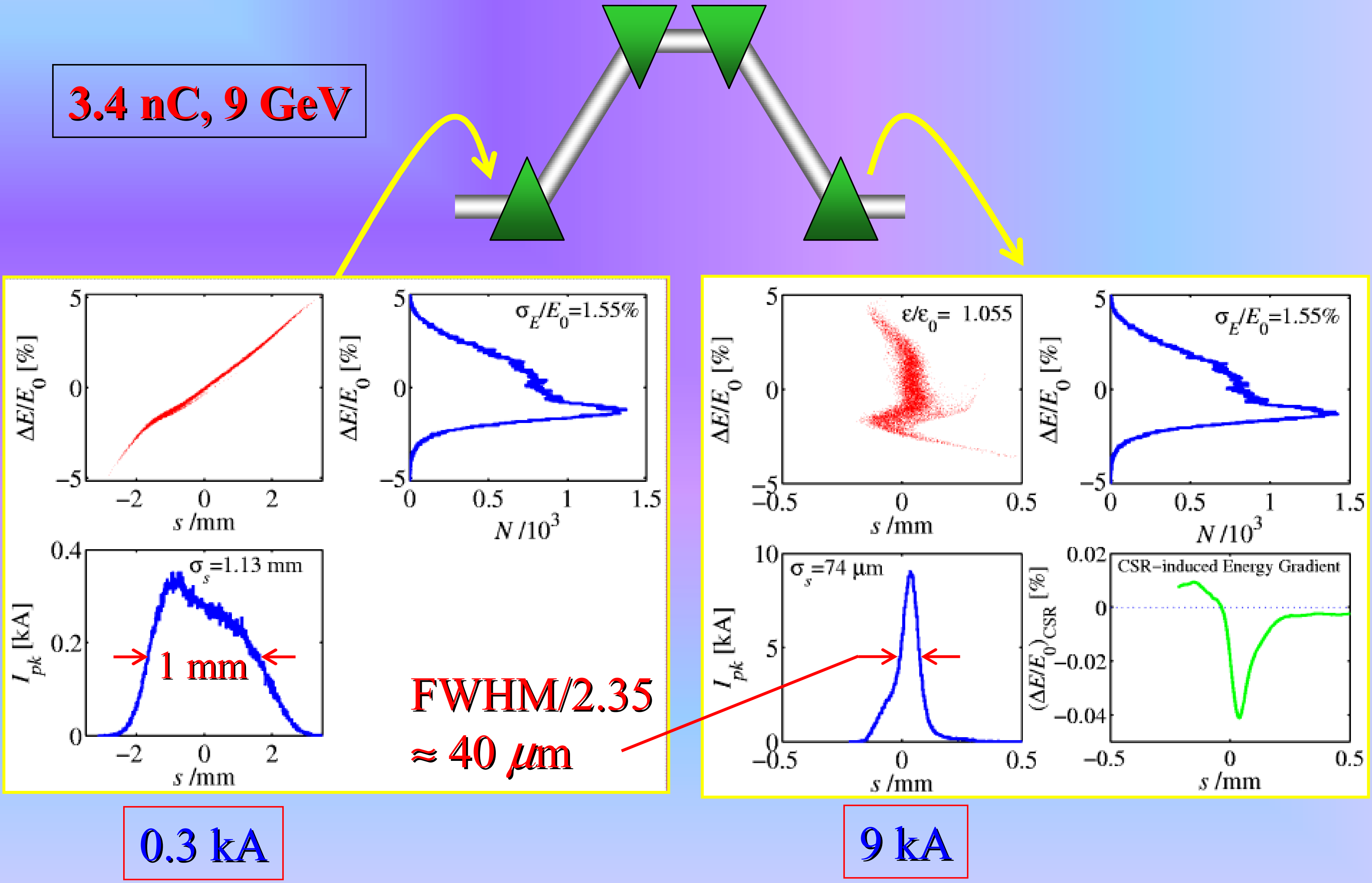
- Transition radiation is coherent for $\lambda/2\pi > \sigma_z$ (CTR)

P. Muggli, M. Hogan

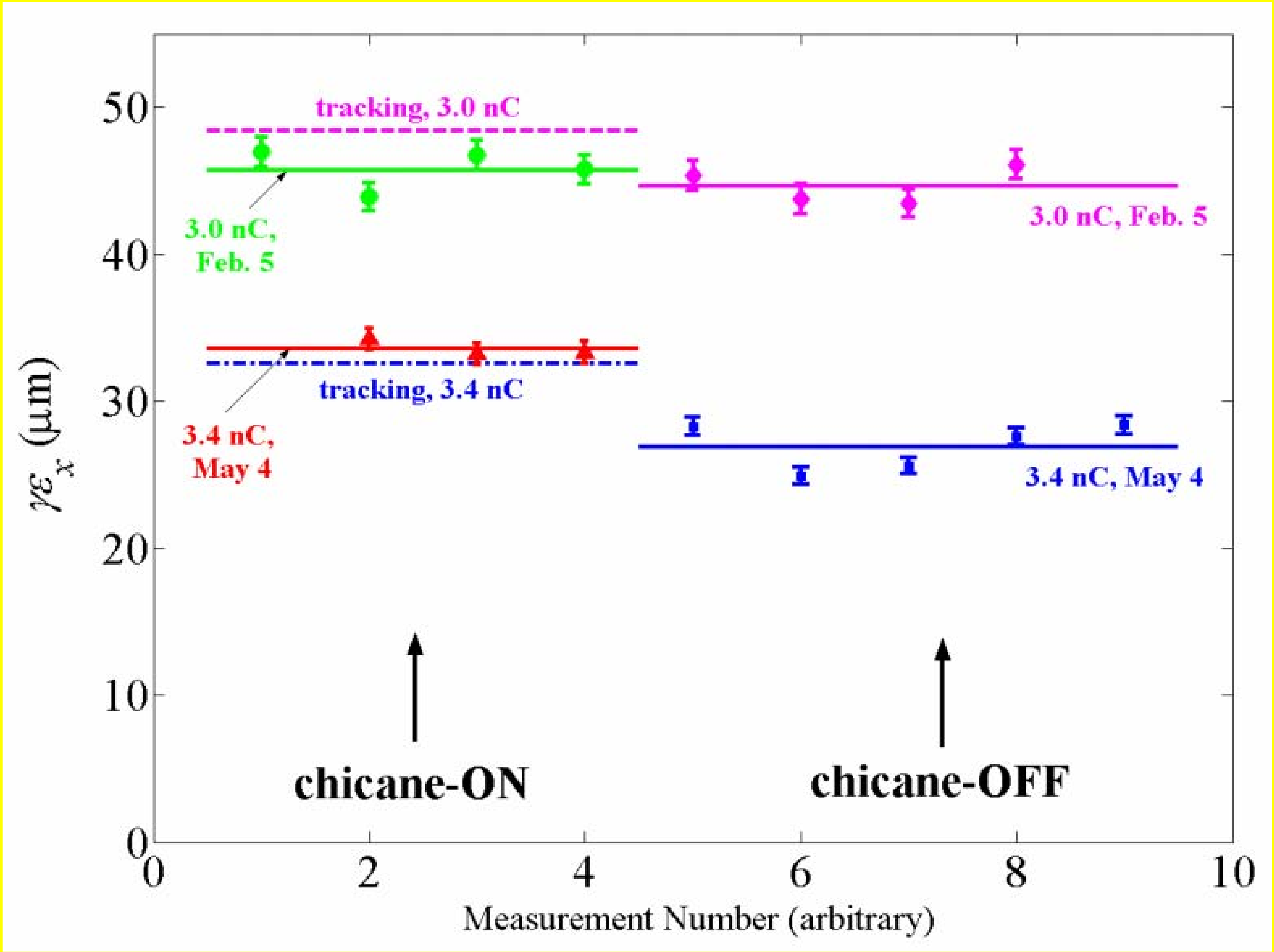

02270cmp.mat 27-FEB-2004 03:13
CTR-1 Signal (arb)
NRTL BPMS DR13 544 (mm)
minimum bunch length (with φ-jitter)
CTR
Power Spectrum (a.u.)
Filter Amplitude (a.u.)
Wavelength (µm)
Mylar resonances
Autocorrelation
$\sigma_z \approx 9\ \mu m$
CombinedCTRInterferogramsSm
Δz (μm)
w Filtering
w/o Filtering
Bunch σ_z (µm)
Autocorrelation σ_z (µm)
P. Muggli, M. Hogan
Gaussian bunch: $\sigma_z \rightarrow 18\ \mu m$

SPPS chicane CSR simulations with 1D model (unshielded)

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



Bend-Plane Emittance: Chicane ON and OFF



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

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

Concluding Remarks

- Very short x-ray pulses are key to exploring ultra-fast science at future light sources
- Linac-based FEL's offer high power, very high brightness, and possibly sub-femtosecond pulses at ~1-Å wavelengths
- Advances in ultra-short, high-power table-top lasers will greatly influence future LS designs, as will e^- gun development ($\gamma\varepsilon_{x,y} < 1\ \mu$m)
- **Thanks to the many who contributed to this presentation…**

Z. Huang, W. Fawley, and A. Zholents