Issues and R&D Critical to the LCLS

Paul Emma

SLAC

UCLA

Stanford
Linear
Accelerator
Center

Advanced
Photon
Source

SSRL

LLNL

BROOKHAVEN
NATIONAL LABORATORY

Los Alamos

15 GeV
Electrons

LCLS

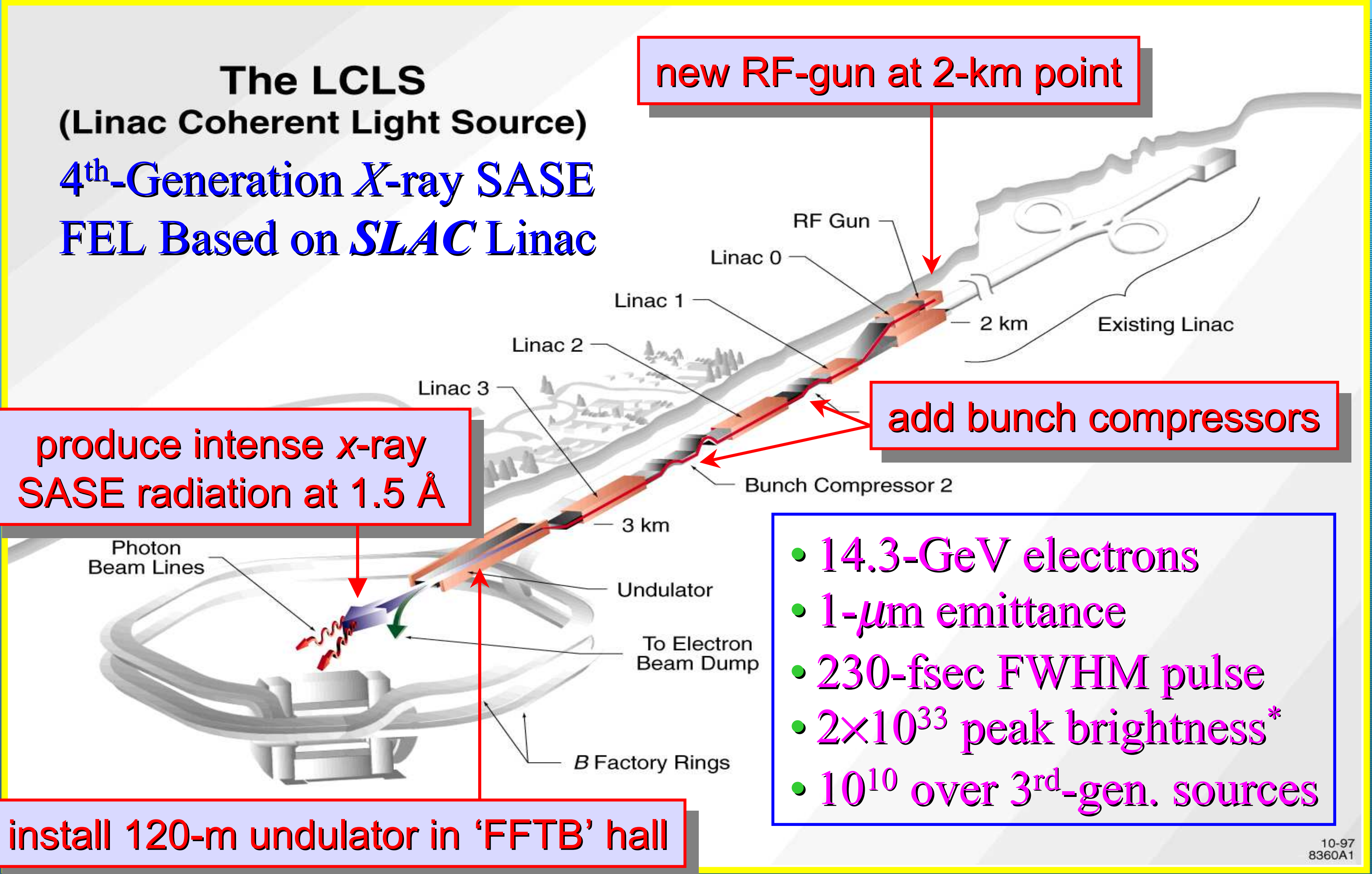
1.5 Å
X-Ray

Linac Coherent Light Source

CUBS

PAC-2001, Chicago, IL

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

add bunch compressors

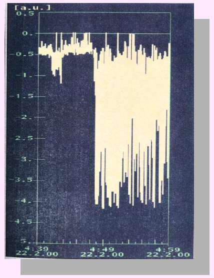
produce intense *x*-ray SASE radiation at 1.5 Å

install 120-m undulator in ‘FFTB’ hall

- 14.3-GeV electrons
- 1-μm emittance
- 230-fsec FWHM pulse
- 2×10^{33} peak brightness*
- 10^{10} over 3rd-gen. sources

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

Other FEL-based sources being tested, built, or planned…



- **TESLA Test Facility (TTF) at *DESY***
  - ¬Lasing with gain ~3000 observed at 80-180 nm
- ***X*-ray TESLA FEL at *DESY* (associated with linear collider)**
  - ¬ TDR written

TESLA FEL

- **Source Development Laboratory (SDL) at *BNL*-NSLS**
  - ¬ Electron beam testing
- **Harmonic Generation (HGHG) successful at *BNL*-ATF**
- **VISA experiment at *BNL*-ATF**
  - ¬ Saturation achieved, March 2001

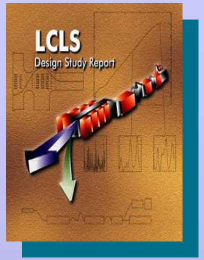
Brookhaven National Laboratory
Accelerator Test Facility

- **FEL's under study in Japan, Italy, England and Germany (BESSY II)**
- ***Low Energy Undulator Test Line (LEUTL) at ANL-APS***
  - ¬ ***High gain and saturation observed at 390 nm***

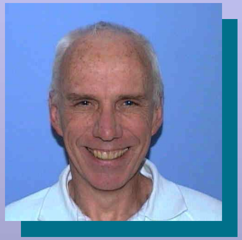
Advanced
Photon
Source

LCLS Project Update

- Design Study Report published 1998 (SLAC-R-521) led by Max Cornacchia



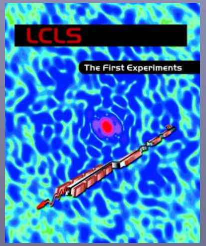
- New *LCLS* project leader at ***SLAC*** is John Galayda (formerly of ***ANL/APS***)



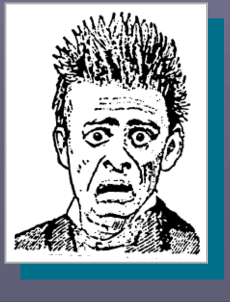
- *Critical Decision-0* (***CD-0***) approval was signed by DOE in June 2001

The U.S. Department of Energy

- Published plan for first 5 experiments (femto-chemistry, atomic physics, warm dense matter, …), Sep. 2000



- Pre-engineering in 2003, construction in 2004, and operation in 2007



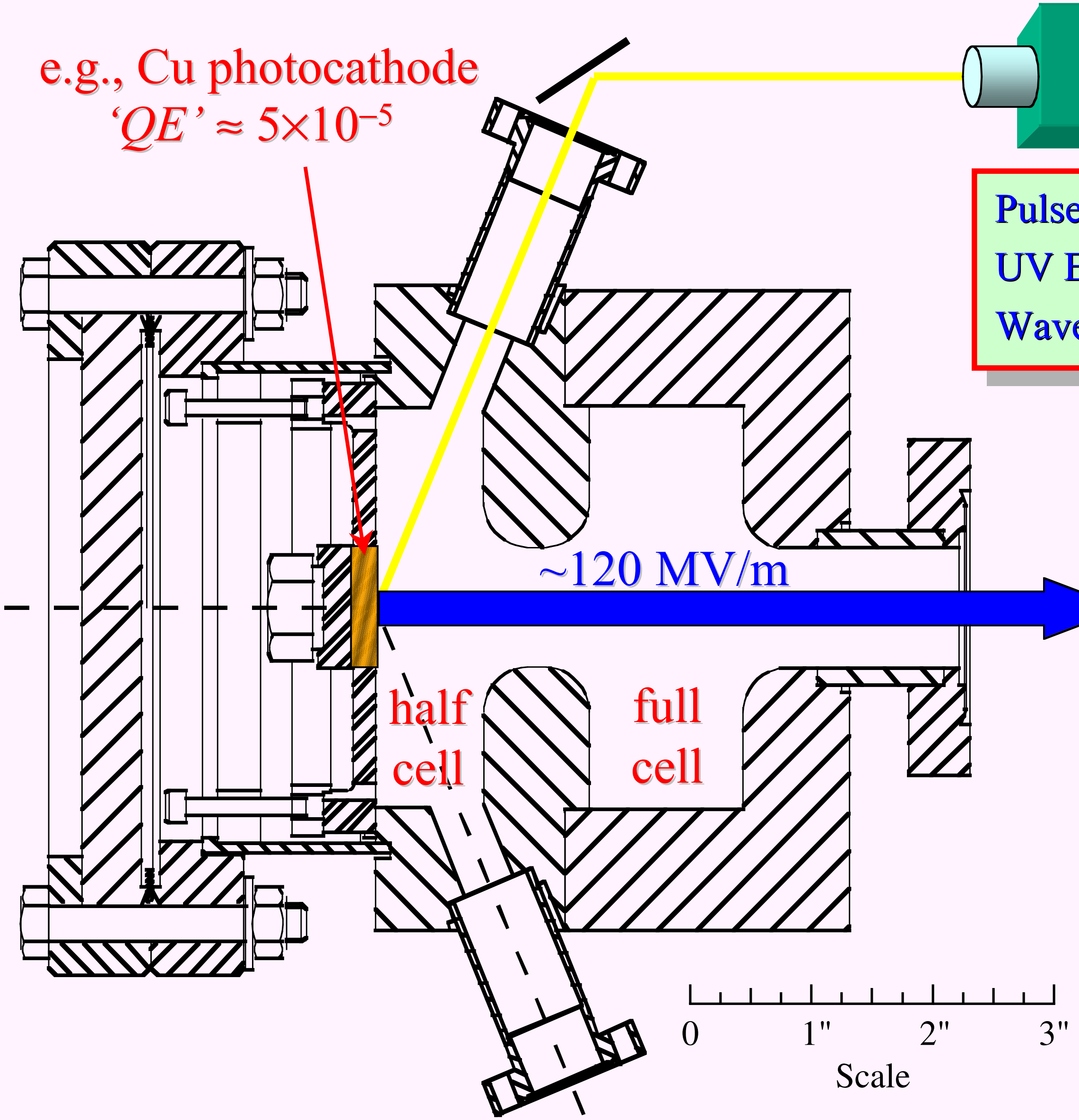
LCLS Issues and R&D

- Injector Requirements
  - $\gamma\varepsilon \le 1\ \mu$m at 1 nC and 100 A
  - Stability <1 psec timing & <2% charge
- Acceleration and Compression
  - ε-preservation → ‘CSR’ and wakefields
  - RF stability of 0.1°, 0.1% rms
- Undulator
  - Design, precise fabrication, and thermal stability
  - Trajectory alignment to <5 μm
  - Undulator wakefields
- X-ray optics

RF Photo-Cathode 1.6-cell S-band Gun

UCLA

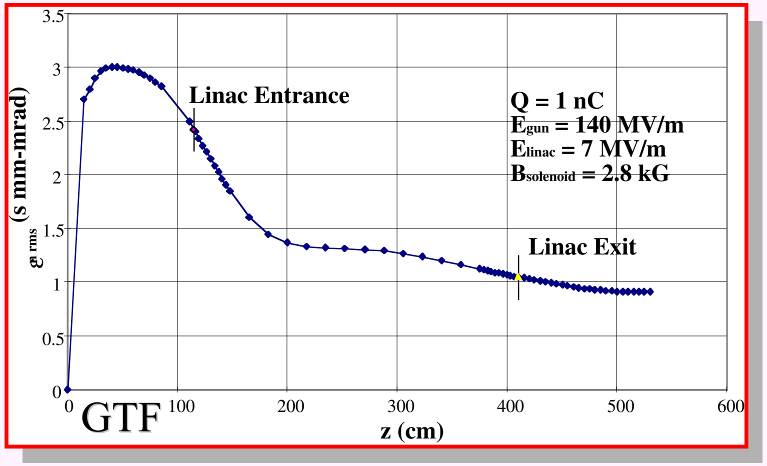
Designed by:
D. Palmer (SLAC)
R. Miller
J.N. Weaver
X.-J. Wang (BNL)
I. Ben-Zvi,
K. Batchelor
C. Pellegrini (UCLA)
J. Rosenzweig
K.-J. Kim (ANL)


e.g., Cu photocathode
'QE' ≈ 5×10^{-5}

Pulse:	10 ps FW
UV Energy:	0.1 mJ
Wavelength:	266 nm

e^-

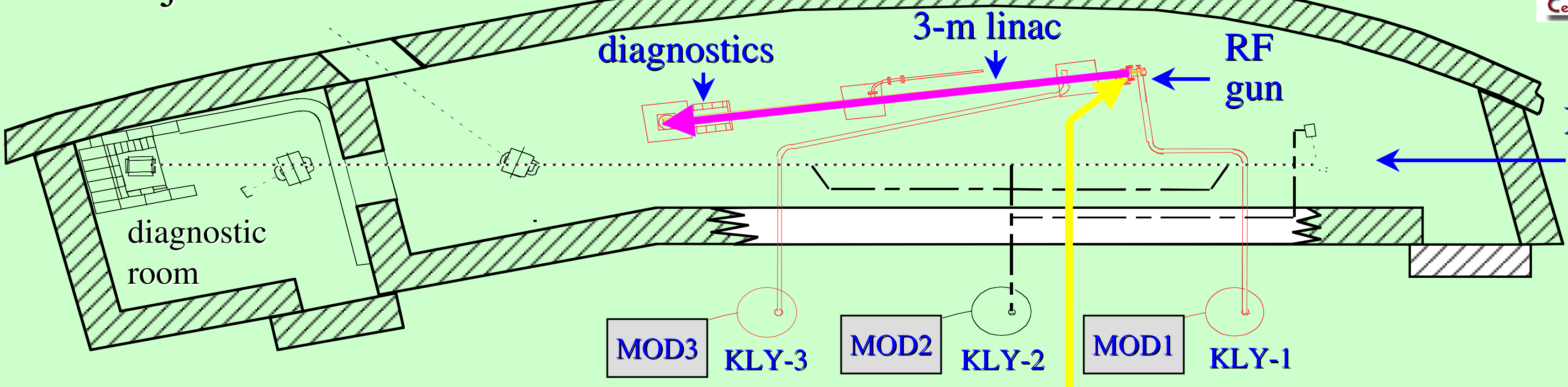
Booster linac:	150 MeV
Emittance:	1 μm
Charge:	1 nC
Current:	100 A



Courtesy of J. Clendenin, M. Hernandez, J. Schmerge, *SLAC*

Gun Test Facility (GTF) in SSRL Injector Vault

LCLS Injector R&D



diagnostics

3-m linac

RF gun

Injector vault

diagnostic room

MOD3

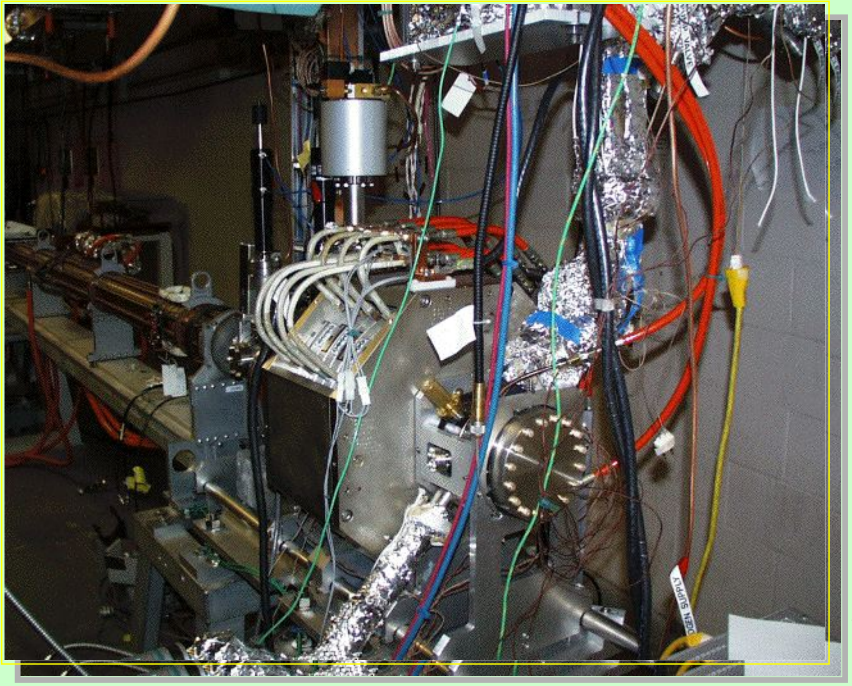
KLY-3

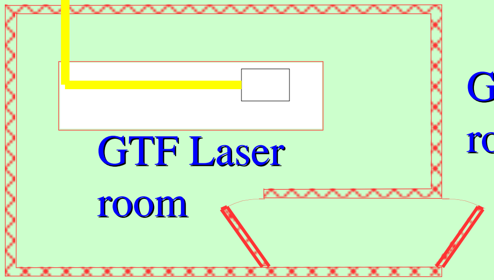
MOD2

KLY-2

MOD1

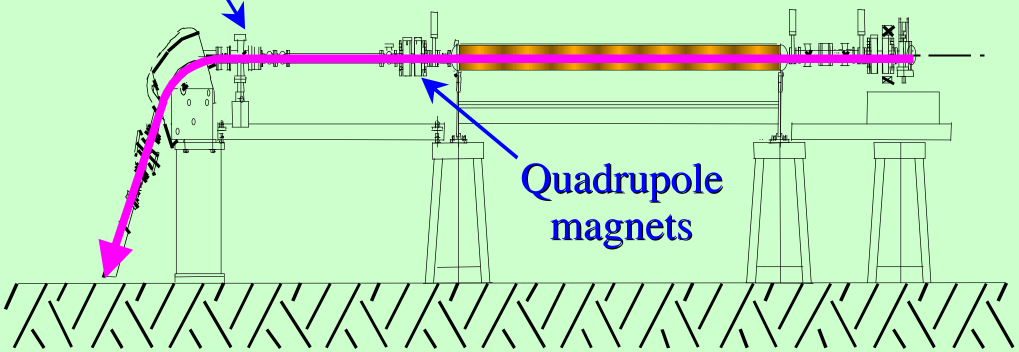
KLY-1





GTF Laser room

GTF control room

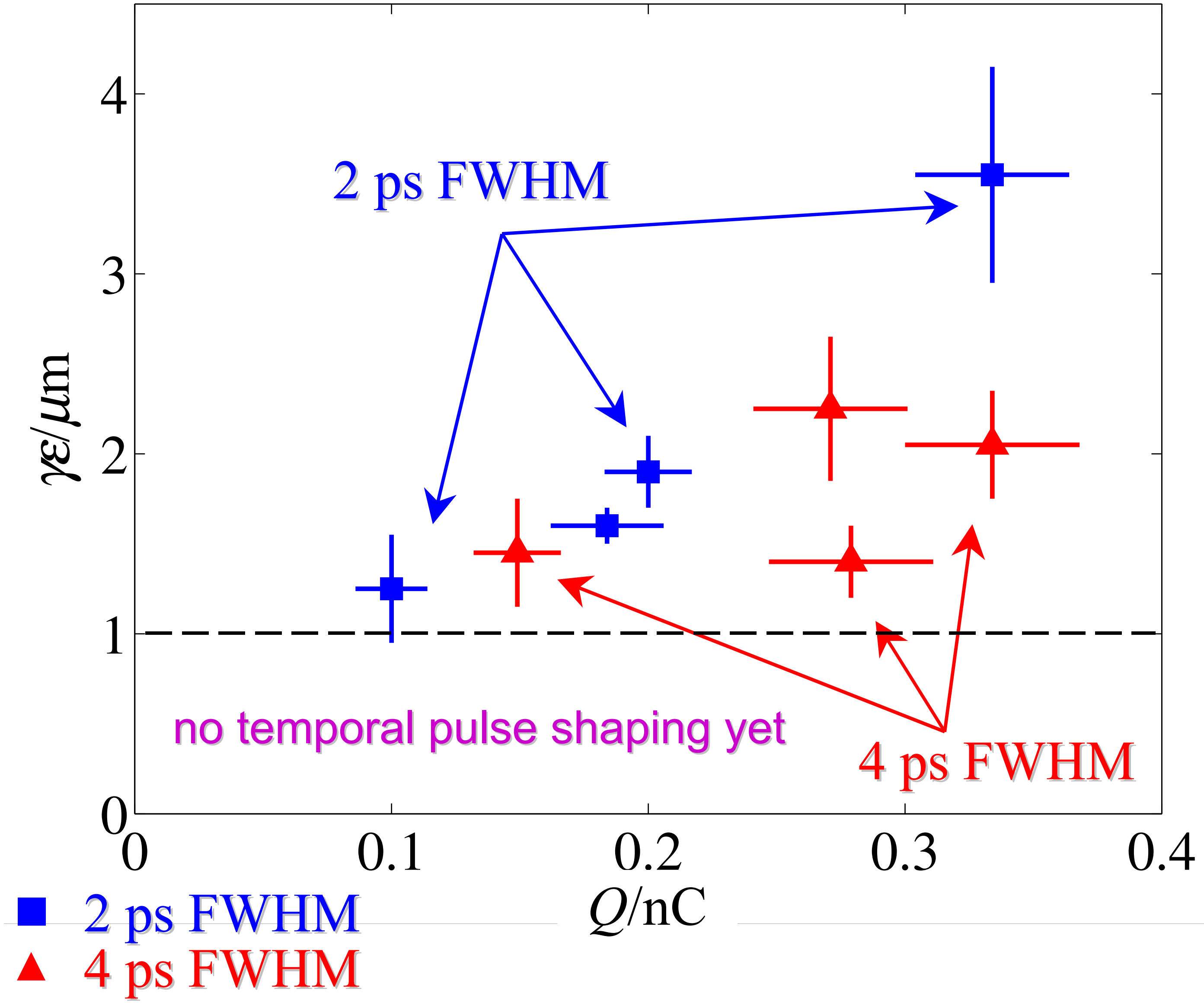


YAG screen

Quadrupole magnets

Courtesy of J. Schmerge, ***SLAC***

GTF Emittance Measurements: Spring 2001



Quad-scans on YAG screen, no space charge correction

LCLS requires:
10 ps FWHM
$Q = 1$ nC
$\gamma\varepsilon = 1\ \mu m$

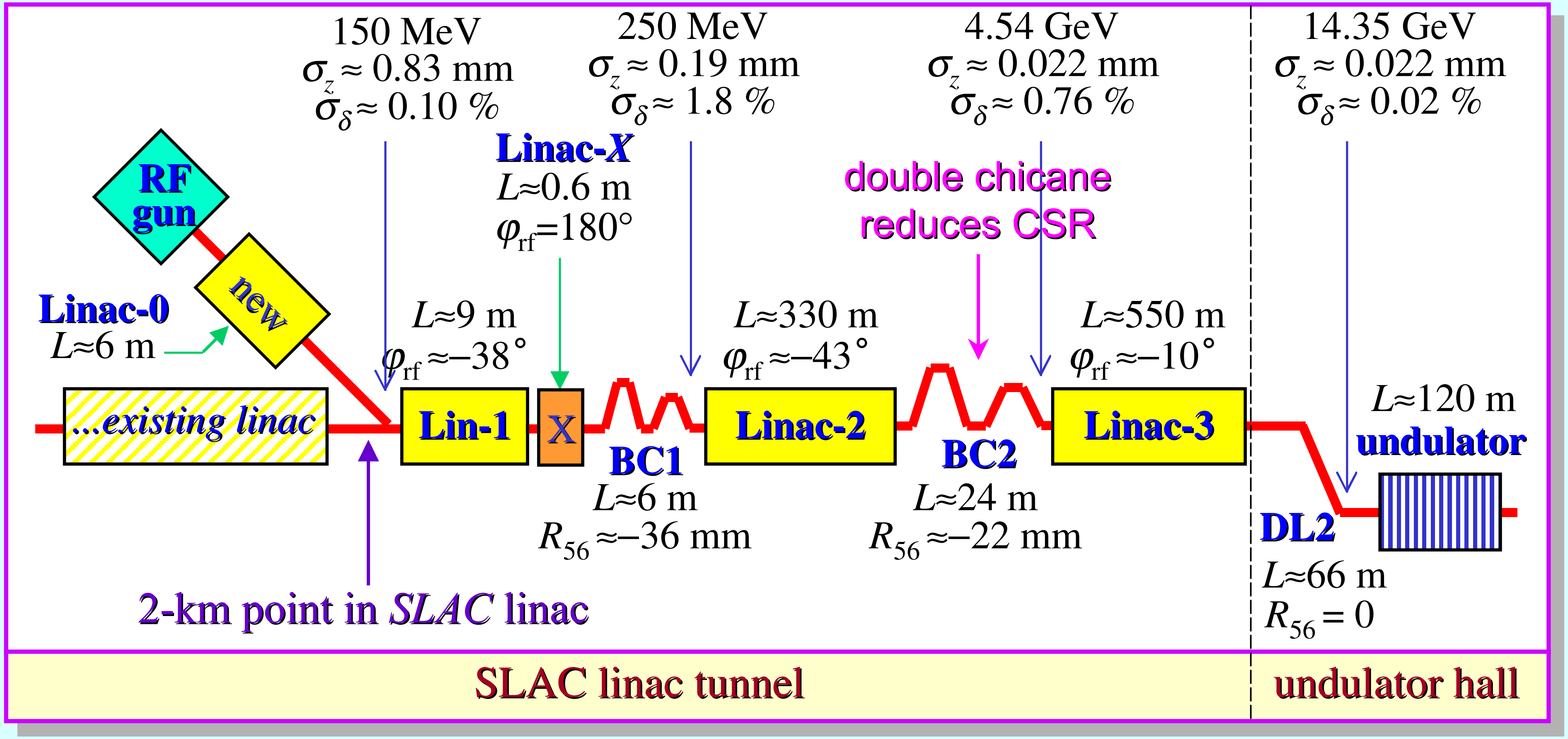
more work ahead…

BNL/ATF result
May 2001:
●
$Q \approx 0.5$ nC
$\gamma\varepsilon \approx$ **0.84** μm

V. Yakimenko
et. al., FEL2001

S. Gierman, J. Schmerge, ***SLAC***

LCLS Acceleration and Compression



RF gun

new

Linac-0
$L \approx 6$ m

...existing linac

2-km point in *SLAC* linac

150 MeV
$\sigma_z \approx 0.83$ mm
$\sigma_\delta \approx 0.10$ %

$L \approx 9$ m
$\varphi_{rf} \approx -38°$

Lin-1

Linac-*X*
$L \approx 0.6$ m
$\varphi_{rf} = 180°$

X

BC1
$L \approx 6$ m
$R_{56} \approx -36$ mm

250 MeV
$\sigma_z \approx 0.19$ mm
$\sigma_\delta \approx 1.8$ %

$L \approx 330$ m
$\varphi_{rf} \approx -43°$

Linac-2

double chicane
reduces CSR

BC2
$L \approx 24$ m
$R_{56} \approx -22$ mm

4.54 GeV
$\sigma_z \approx 0.022$ mm
$\sigma_\delta \approx 0.76$ %

$L \approx 550$ m
$\varphi_{rf} \approx -10°$

Linac-3

14.35 GeV
$\sigma_z \approx 0.022$ mm
$\sigma_\delta \approx 0.02$ %

DL2
$L \approx 66$ m
$R_{56} = 0$

$L \approx 120$ m
undulator

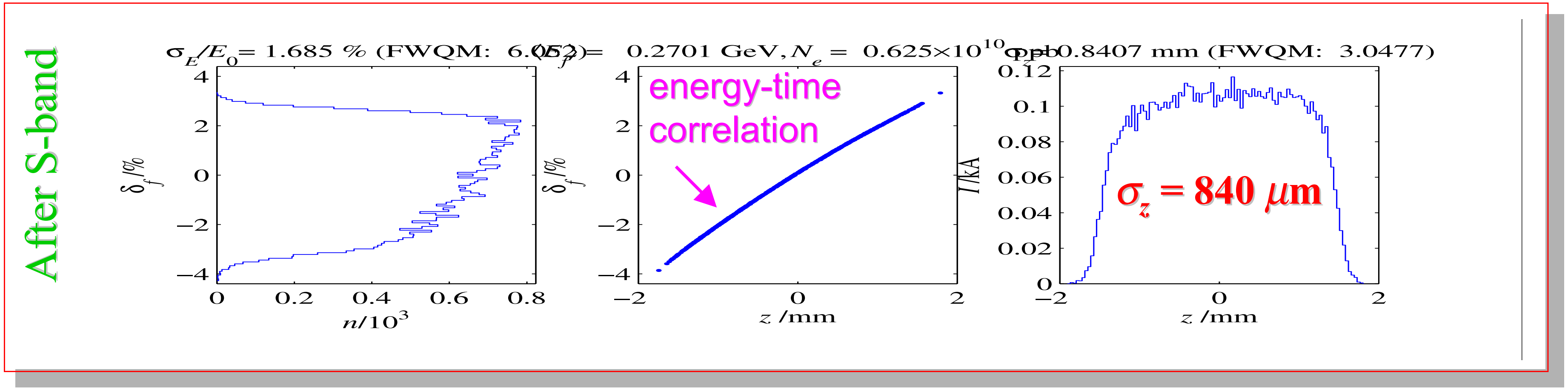
SLAC linac tunnel

undulator hall

- Emittance control given coherent synchrotron radiation in bends
- Adequate machine stability (RF, charge, bunch-timing, …)

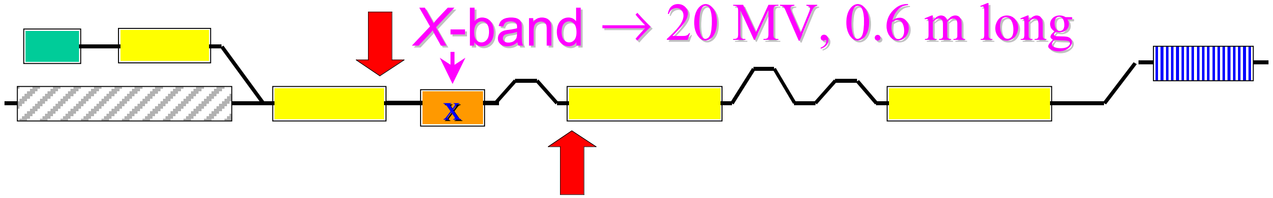
X-band compensation

S-band RF curvature and T_{566} non-linearity

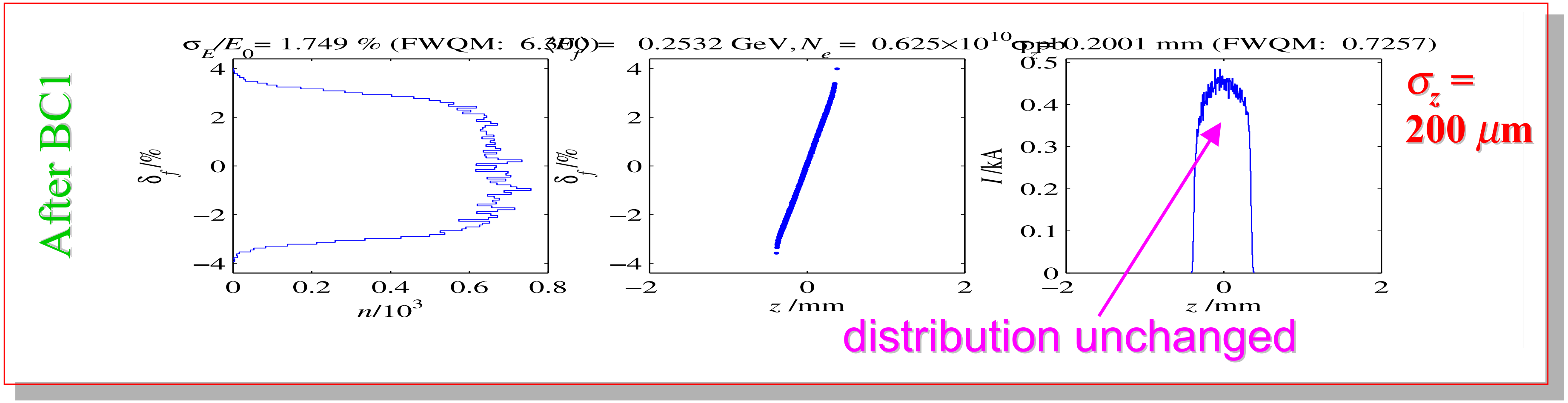


energy-time correlation

$\sigma_z = 840\ \mu m$



X-band → 20 MV, 0.6 m long



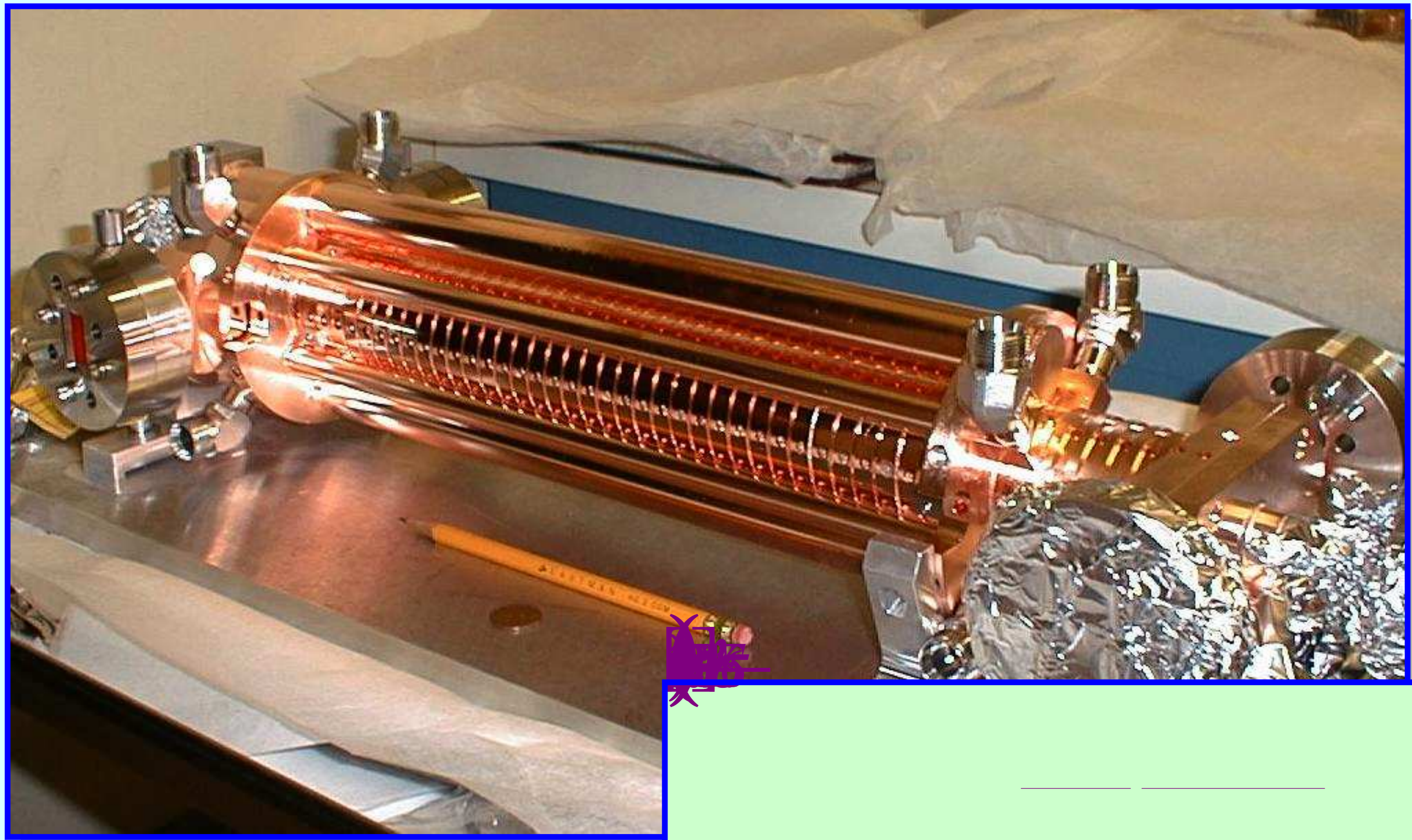
$\sigma_z =$ $200\ \mu m$

distribution unchanged

…linearizer also reduces bunch length sensitivity to timing jitter

Similar scheme used at TESLA: ***DESY*** (P. Piot, et. al.)

0.5-Meter X-Band RF Accelerating Structure

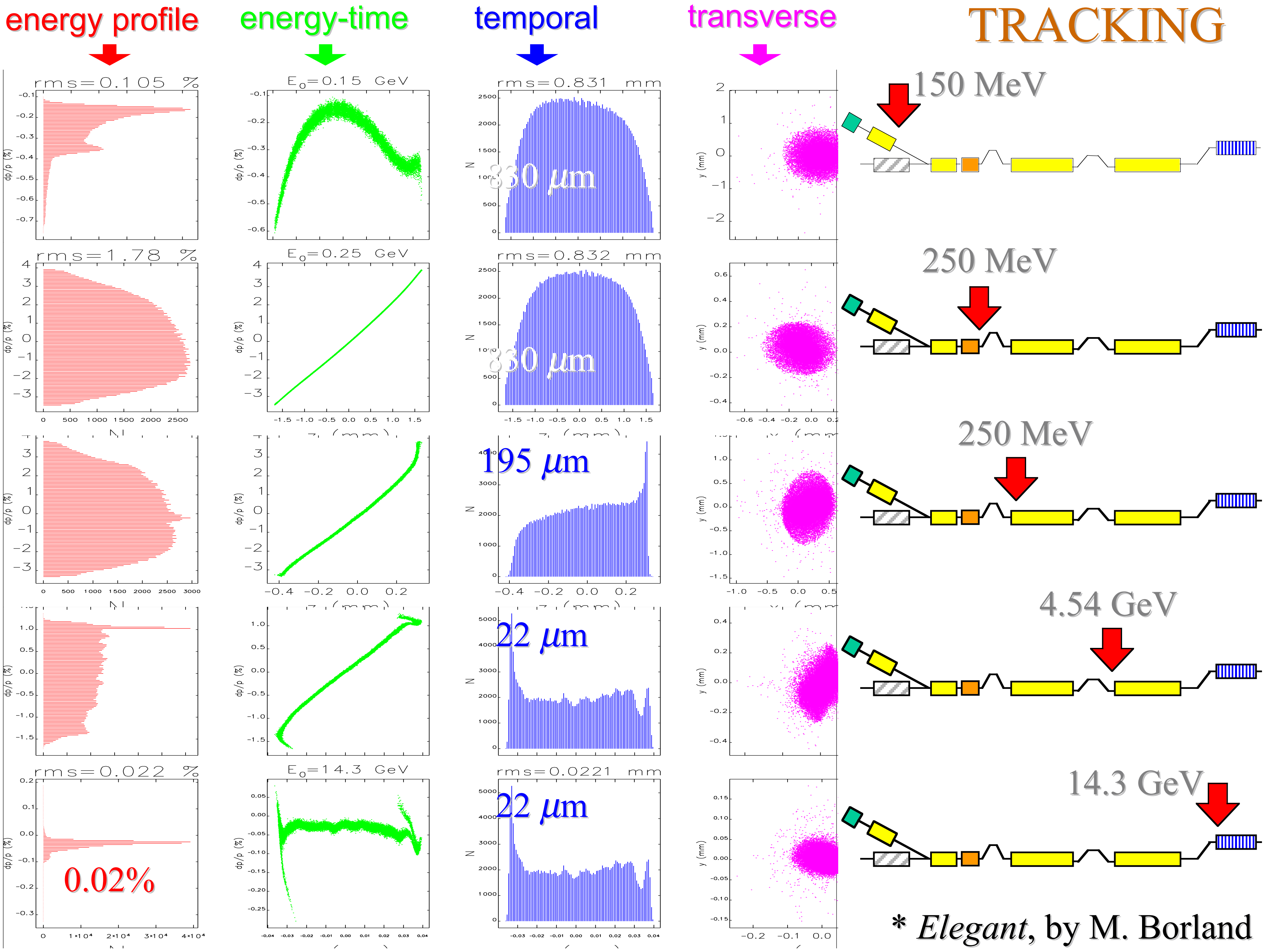


$V = 22$ MV
$f = 11.4$ GHz
$P = 30$ MW
$L = 0.6$ m
$E = 250$ MeV

And…

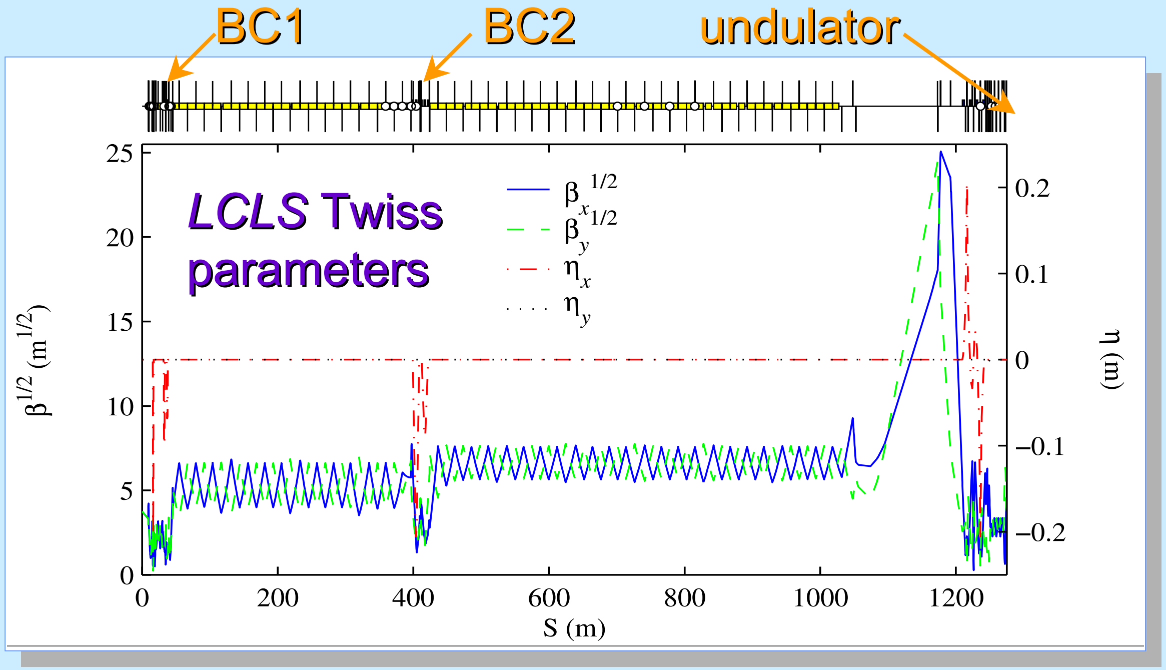
Linearizer allows analytical modeling of wakes (~uniform pulses) and therefore fast, automated *LCLS* parameter optimization

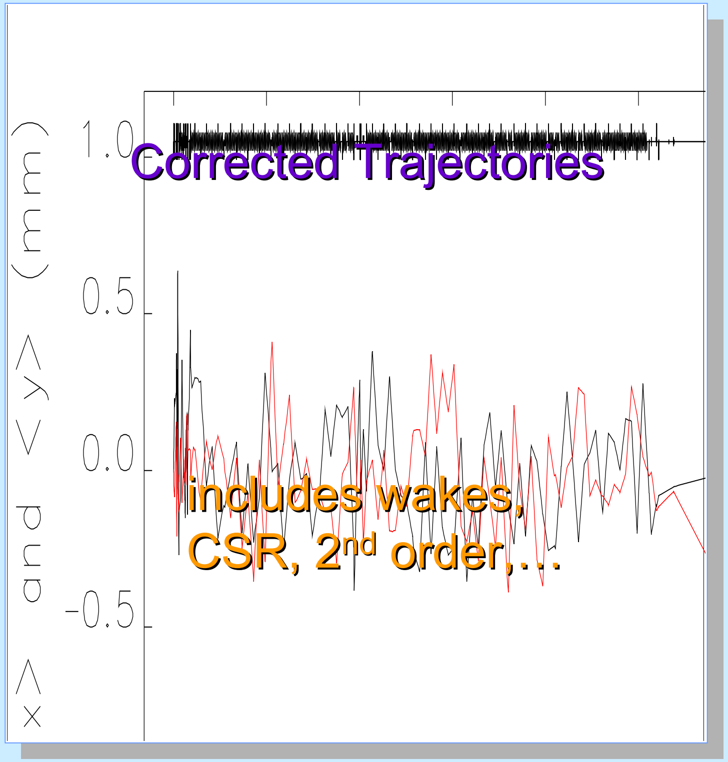
TRACKING



* *Elegant*, by M. Borland

Start-to-End Simulations

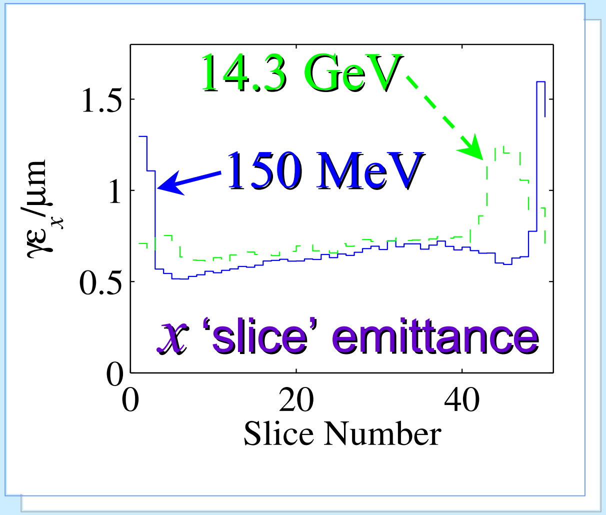




Corrected Trajectories

includes wakes, CSR, 2nd order,…

Ming-Xie method



x 'slice' emittance

gain length
per slice

CSR model
is critical

Time-sliced beam is input to *Genesis-1.3*, including centroid and rms of each slice in 6D

S. Reiche, **WPPH119**

M. Borland, **WPPH103**

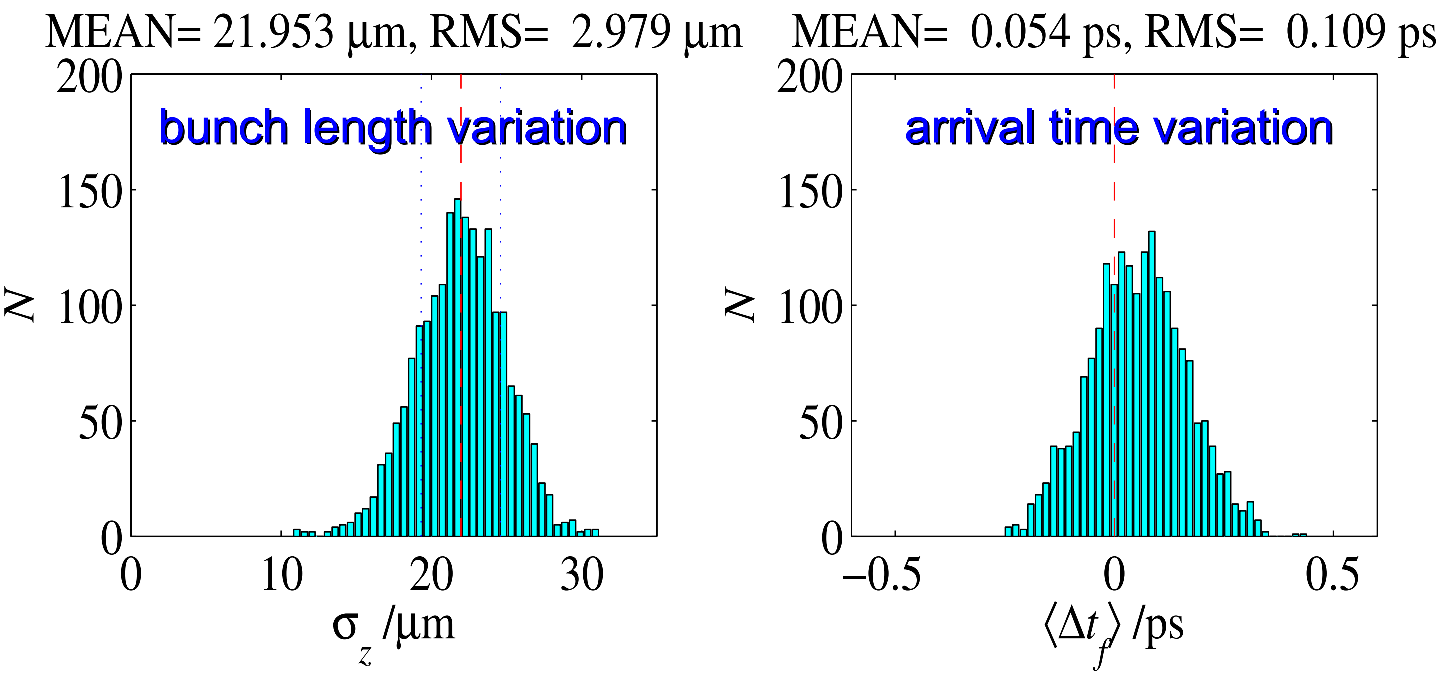
Stability Studies

Pulse-to-pulse ‘jitter’ estimates based on repeated tracking including parameter variations

- linac ⟨phase⟩ 0.1 deg-S rms
- linac ⟨voltage⟩ 0.1% rms
- Gun timing jitter 0.9 psec
- Charge jitter 2% rms

R. Akre, **TPAH105**

Track 100k macro-particles in long.-2D 2000 times with ‘jitter’…



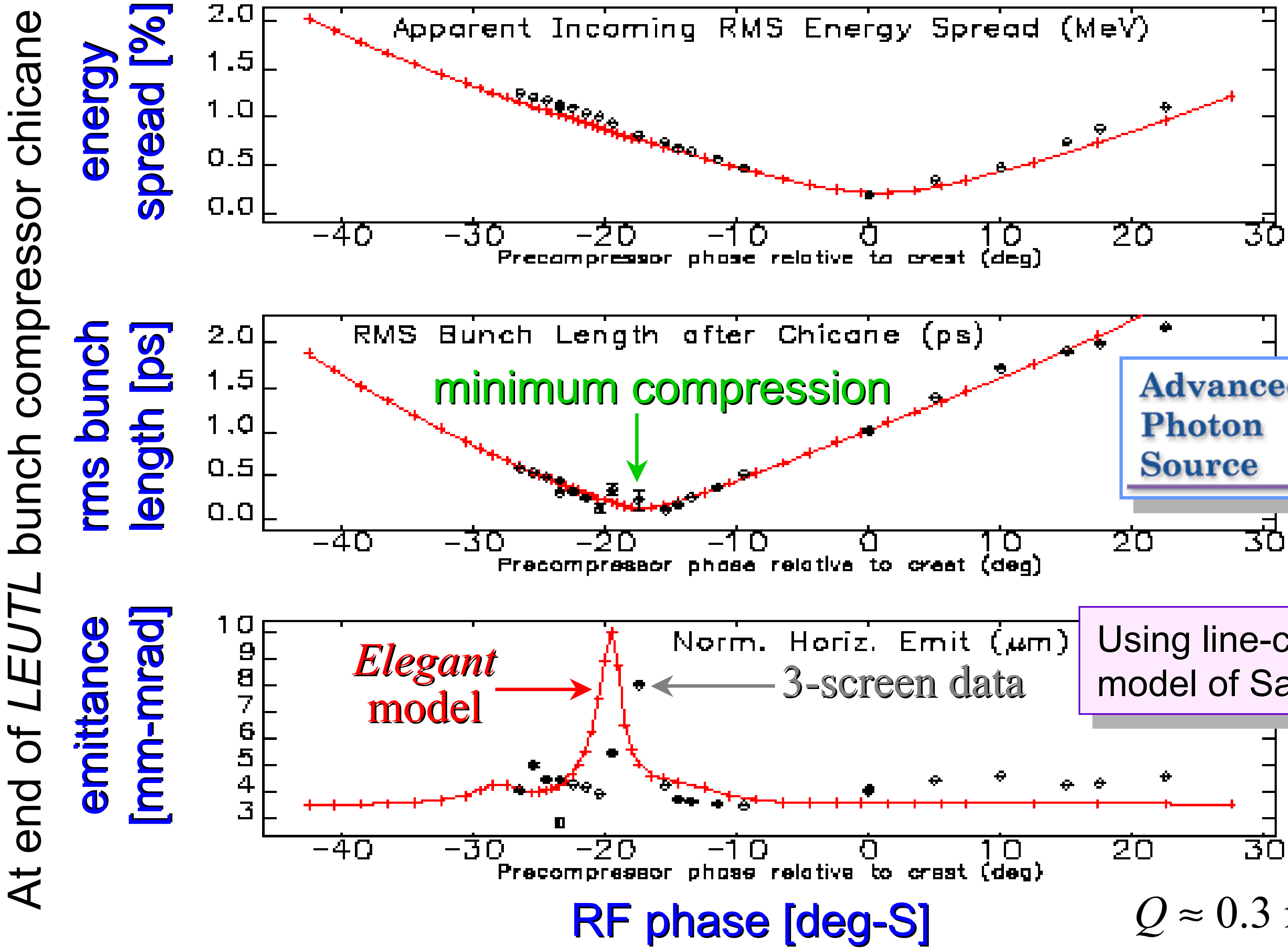
22 ± 3 μm rms

0 ± 109 fsec rms

More studies including CSR and 6D tracking in…

M. Borland, **WPPH103**

LEUTL CSR Measurements (***ANL***)



Using line-charge CSR model of Saldin, et. al.

$Q \approx 0.3$ nC

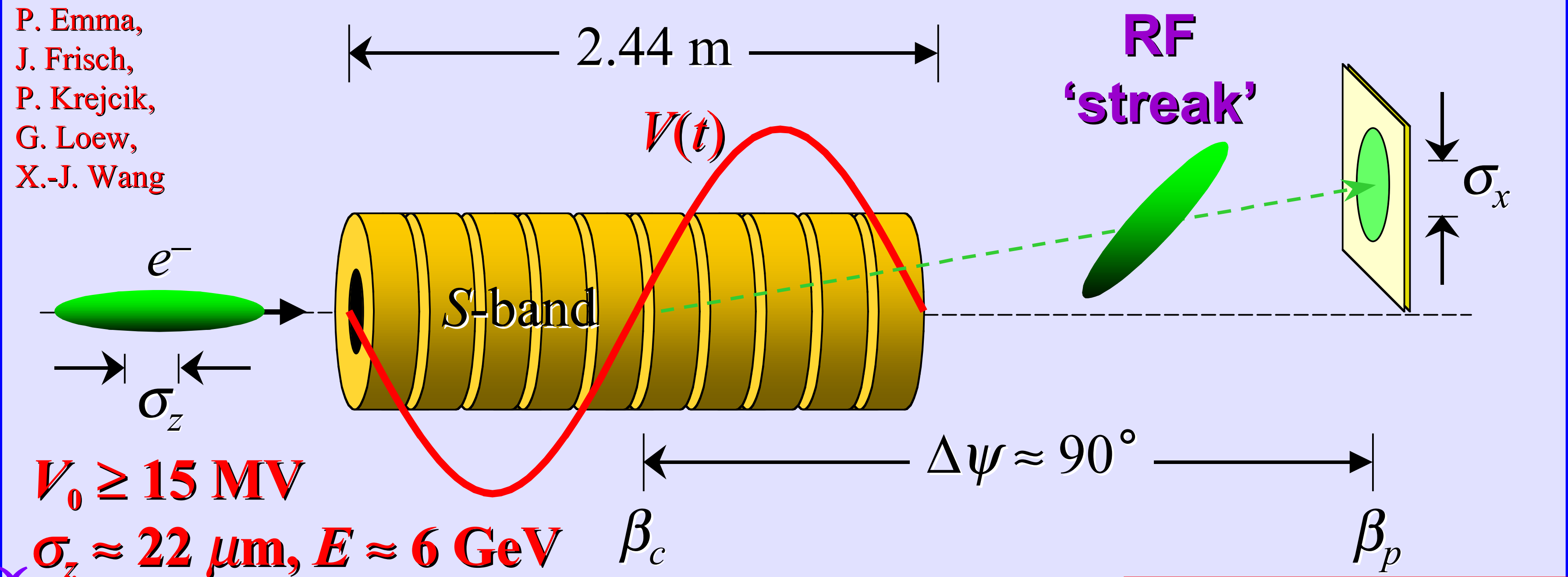
Courtesy M. Borland, J. Lewellen, ***ANL***

← over-compression

M. Borland, **RPAH001**

Transverse RF Deflector for Bunch Length Measurement

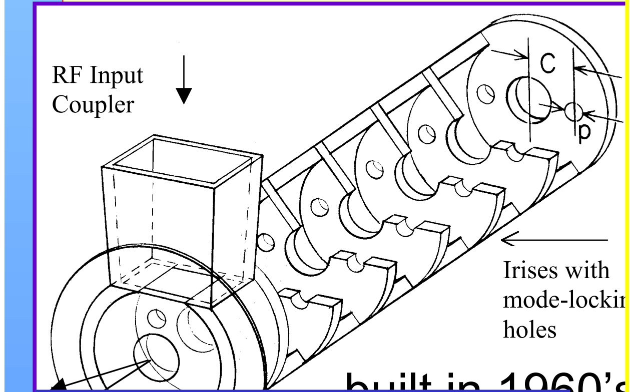
P. Emma,
J. Frisch,
P. Krejcik,
G. Loew,
X.-J. Wang



$V_0 \geq 15$ MV

$\sigma_z \approx 22\ \mu$m, $E \approx 6$ GeV

[illegible]

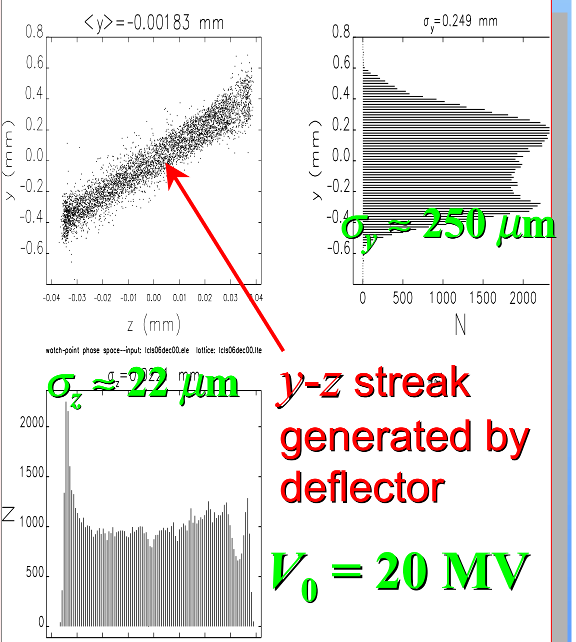


built in 1960's

)

P. Krejcik, **WPAH116**

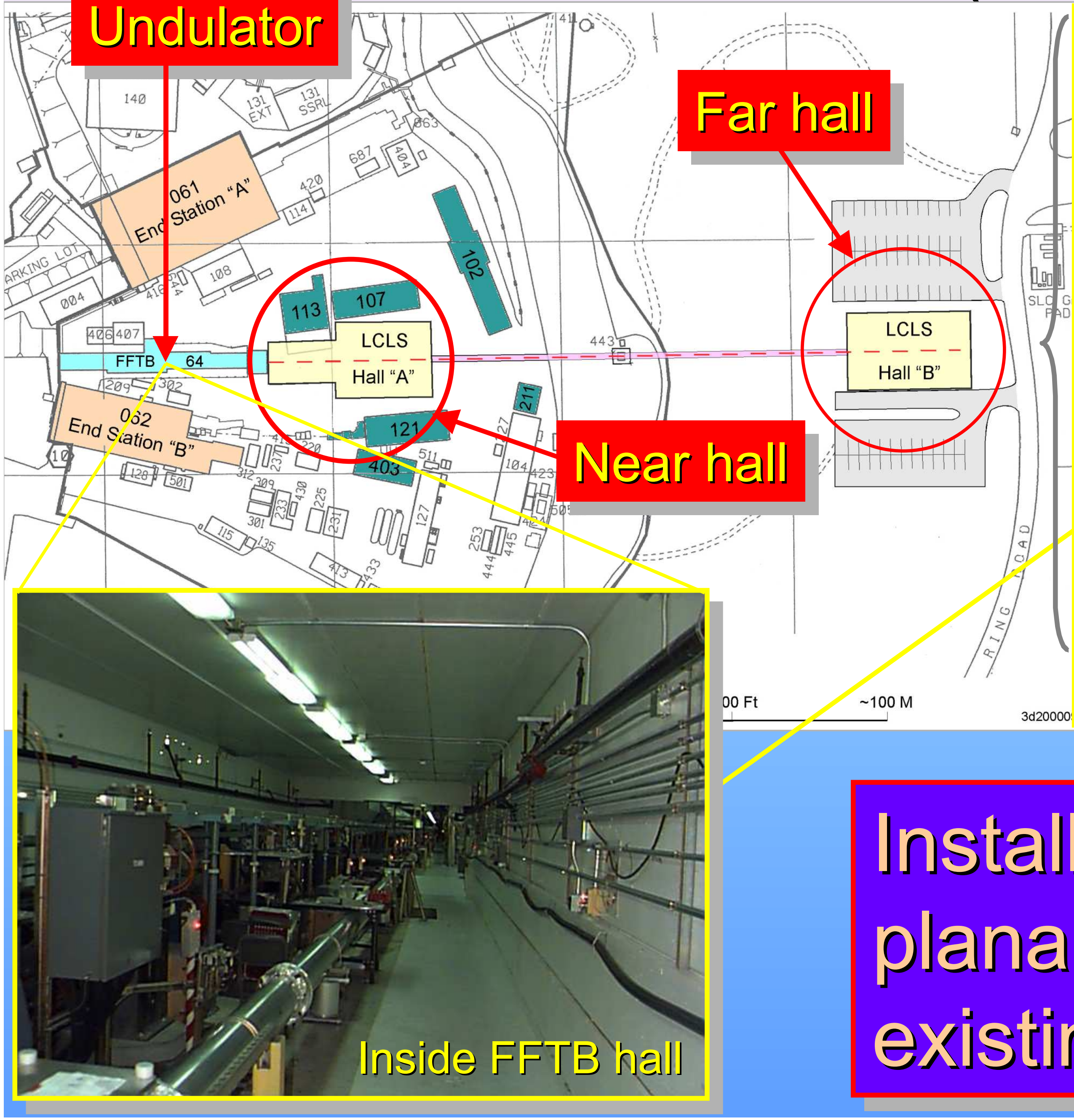
Location of installation at girder 29-4 in the linac

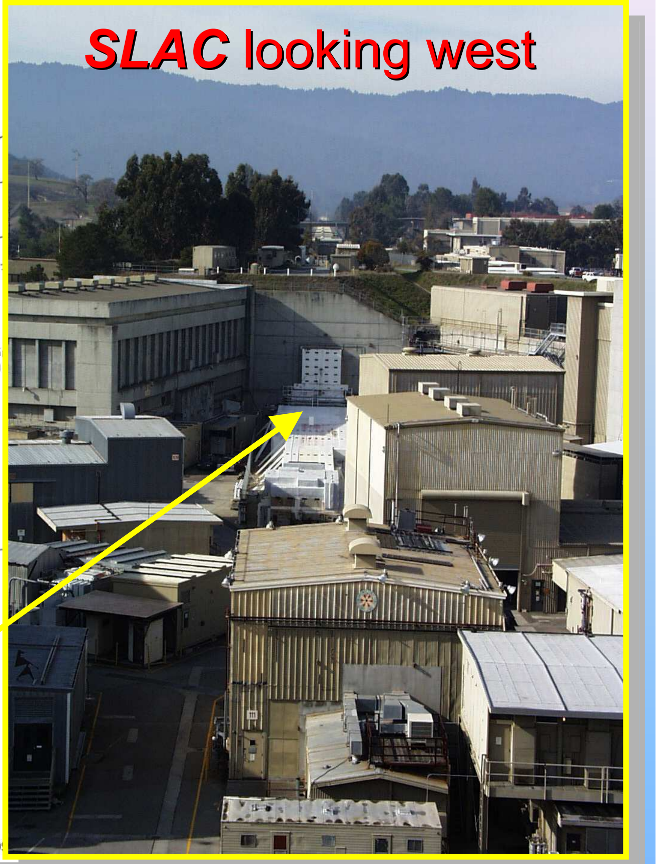


y-z streak generated by deflector

$V_0 = 20$ MV

Undulator Hall (FFTB)

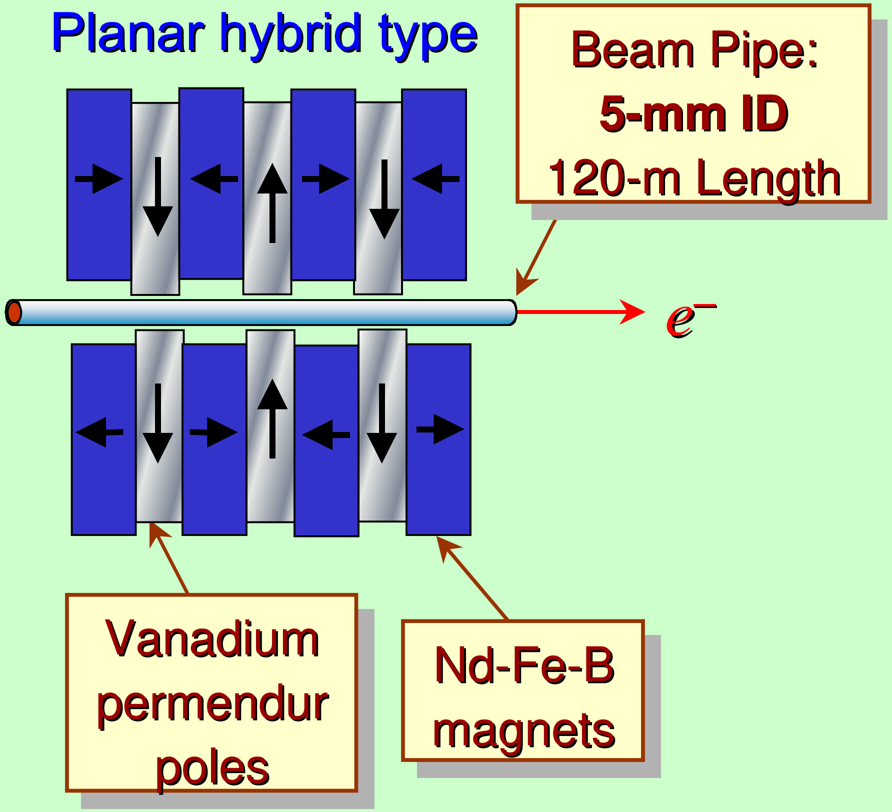



***SLAC** looking west*

Install 122-m long planar undulator in existing FFTB hall

Undulator (ANL/APS)

Advanced Photon Source



Planar hybrid type

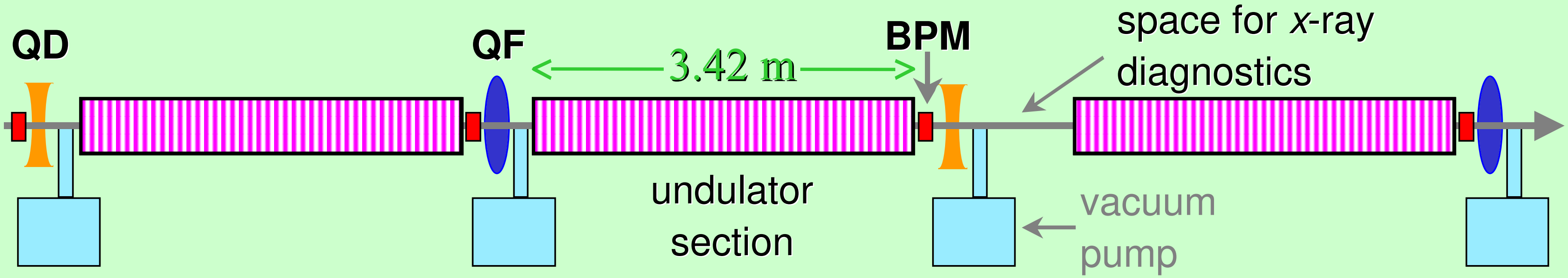
Beam Pipe:
5-mm ID
120-m Length

Vanadium permendur poles

Nd-Fe-B magnets

undulator line length	122	m
undulator period, λ_u	30	mm
undulator parameter, K	3.71	
undulator section length	3.42	m
magnetic gap height	6.0	mm
No. of undulator sections	33	
break length (short)	0.19	m
break length (long)	0.42	m

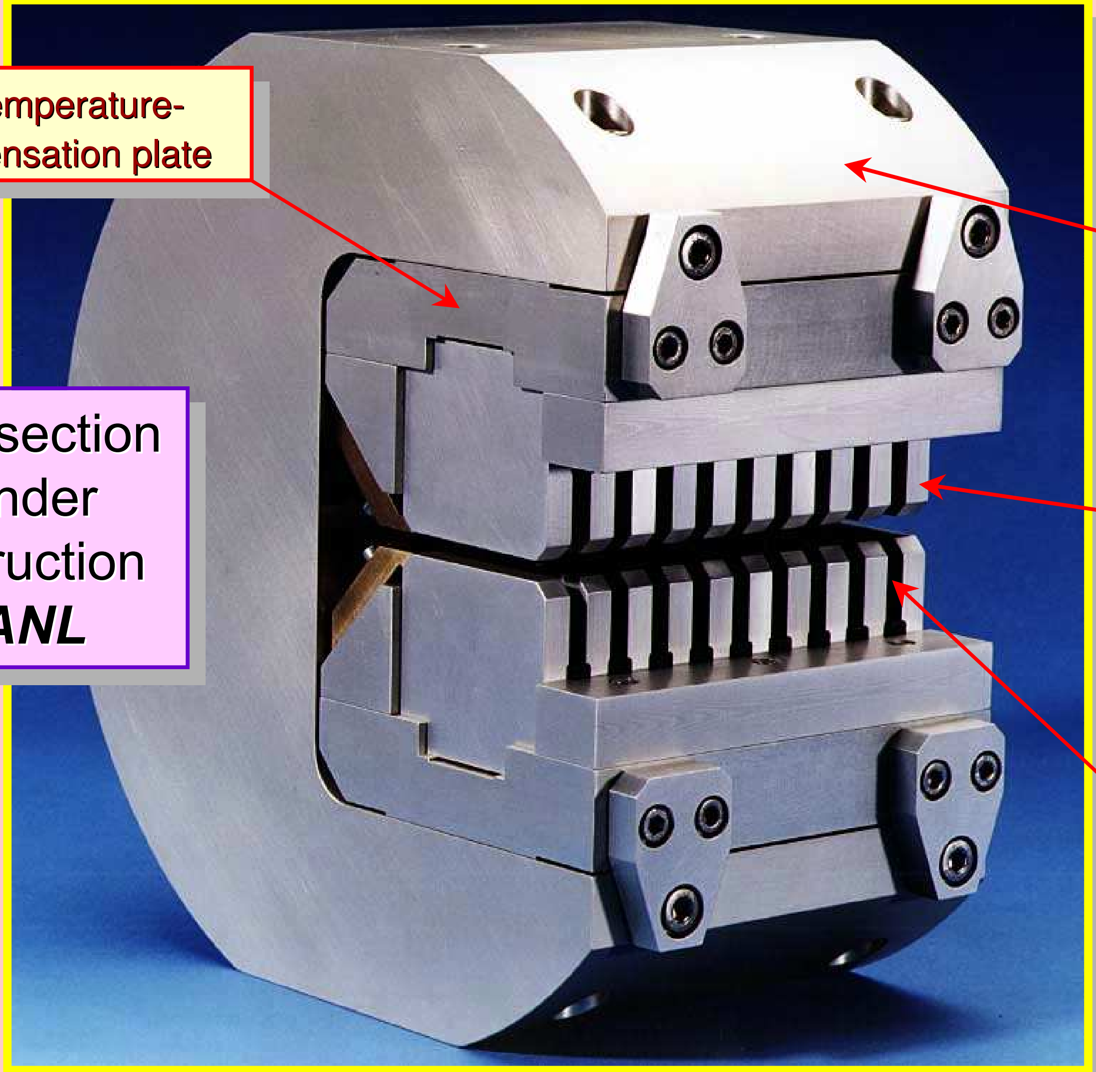
1-μm BPM → cavity and button-type in compact package (G. Decker, ***ANL***)



Quad-magnets and undulator sections on independent movers

E. Moog, **TOPA012**

LCLS 9-Pole Prototype Undulator (ANL)



Al temperature-compensation plate

Titanium strong-back

Va permendur poles

Nd-Fe-B magnets

3.4-m section is under construction at ***ANL***

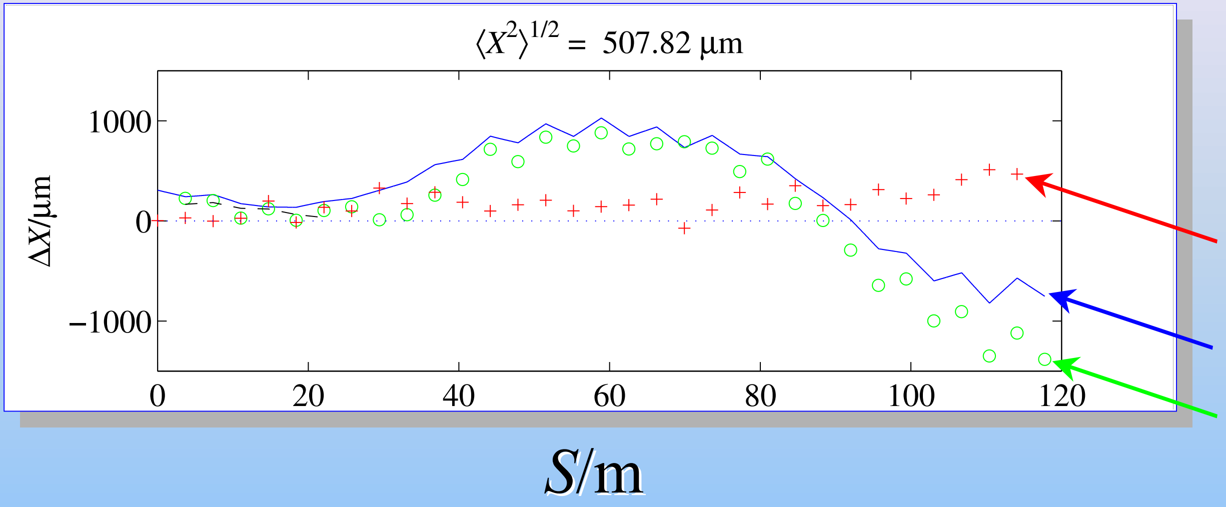
Advanced Photon Source

Courtesy E. Gluskin, *ANL*

E. Moog, **TOPA012**

Undulator Beam-Based Alignment

uncorrected trajectory



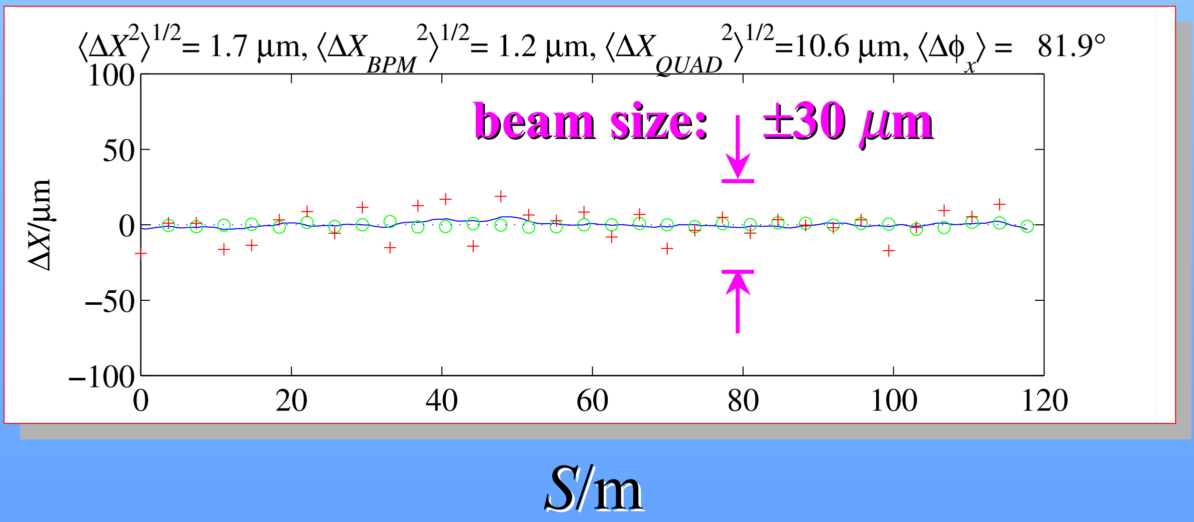
$\sigma_x > 500\ \mu m$

Quadrupole positions

True trajectory

BPM read-back

trajectory after 3rd pass of BBA



$\sigma_x \approx 1.5\ \mu m$

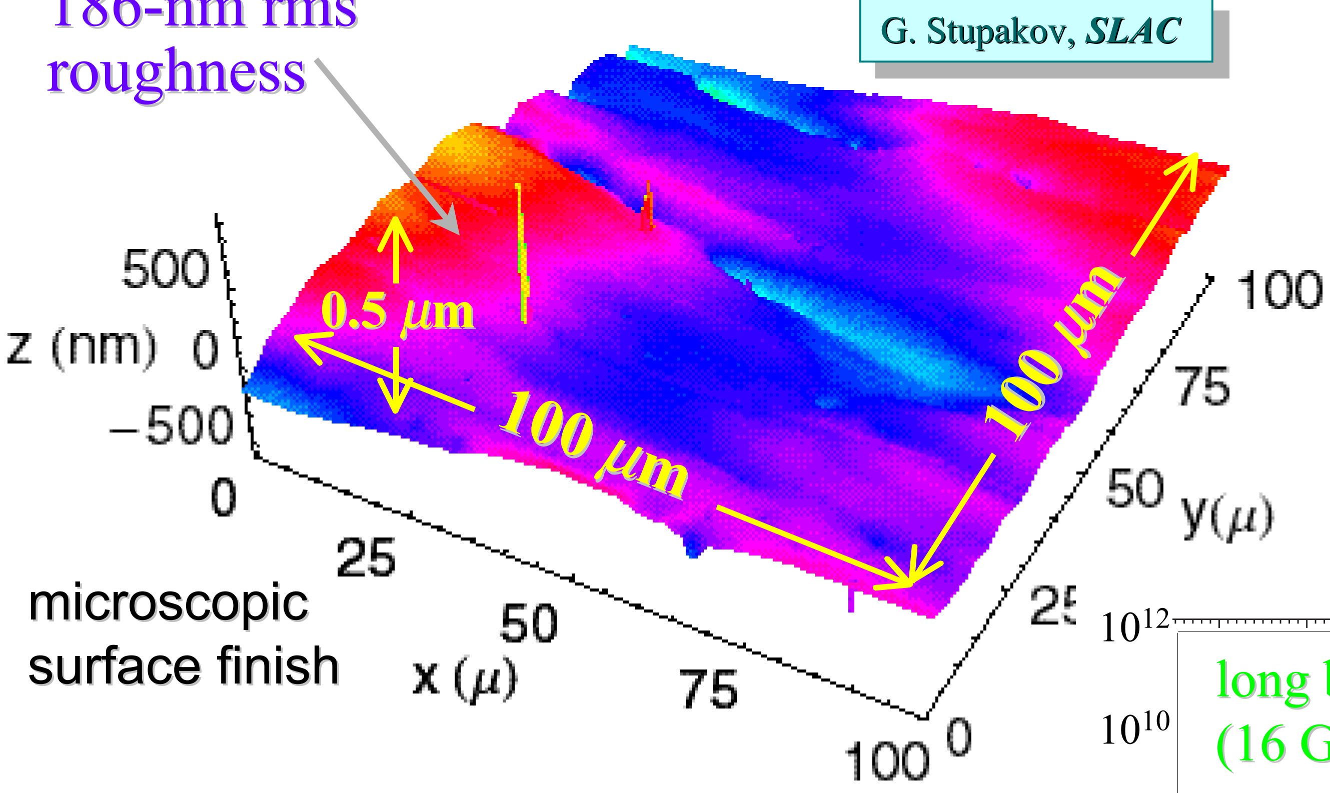
$\Delta\varphi \approx 100^\circ$

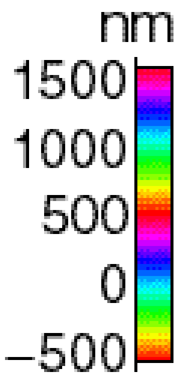
RON simulation shows saturation length increase by <1-gain length (R. Dejus, N. Vinokurov)

PAC-2001, Chicago, IL

BBA used at TTF-FEL: ***DESY*** (P. Castro, et. al.)

Wakefields in Undulator





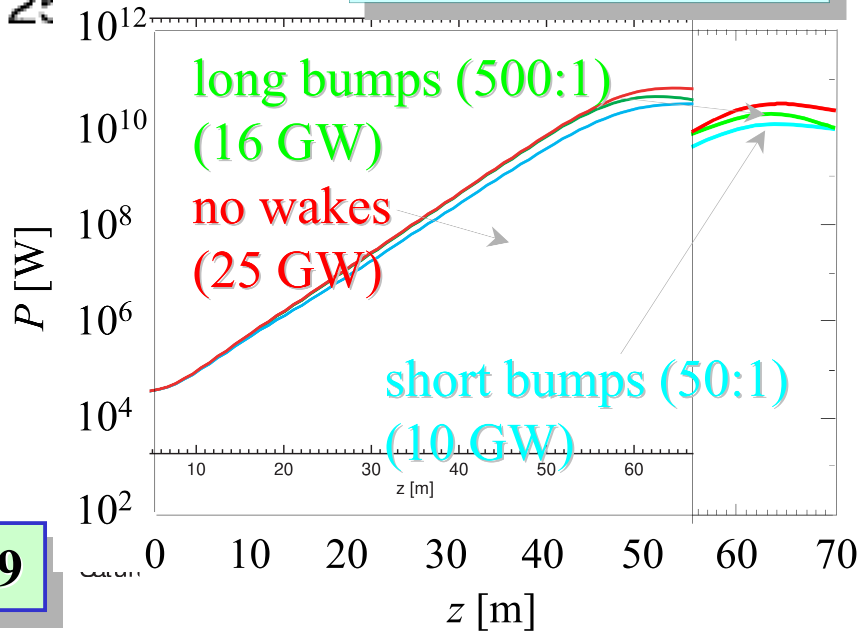
186-nm rms roughness

G. Stupakov, ***SLAC***

microscopic surface finish

‘long’ aspect ratio of surface roughness is important

Courtesy S. Reiche, ***UCLA***

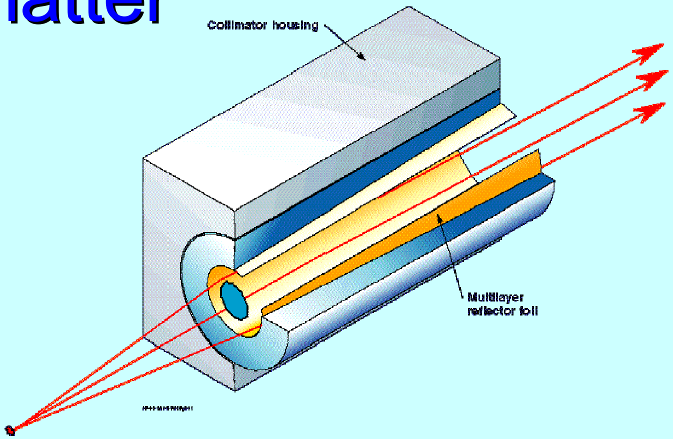


Simulate SASE gain with *Genesis* including ***roughness*** and ***resistive-wall*** wakefields…
$\gamma\varepsilon = 1.1$ mm, $I_{pk} = 3.4$ kA, $Q = 1$ nC

S. Reiche, **WPPH119**

X-ray Optics R&D

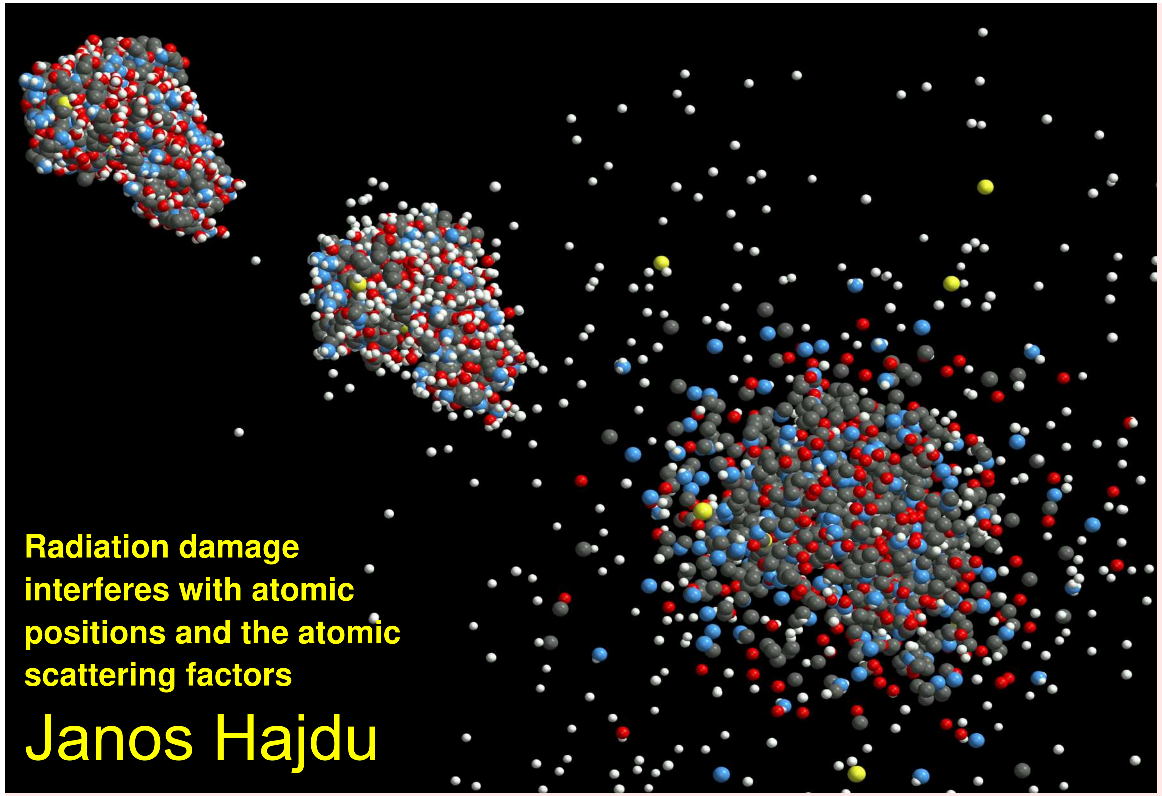
- Intense *x*-ray interaction with matter
  - Theory, modeling
  - component survivability
  - diffraction exp't FY01
- Attenuation cell $(1 \rightarrow 10^{-4})$
  - Gases (N, Ar, Xe, …)
  - Differential pumping
- Experimental station needs
  - Mirror optics
  - Crystal optics
- Temporal compression
- Focusing optics



x-ray collimating and focusing optics from smooth mandrel & sputtered W-Re


LCLS device is even smaller

Motivation for even shorter *x*-ray pulses



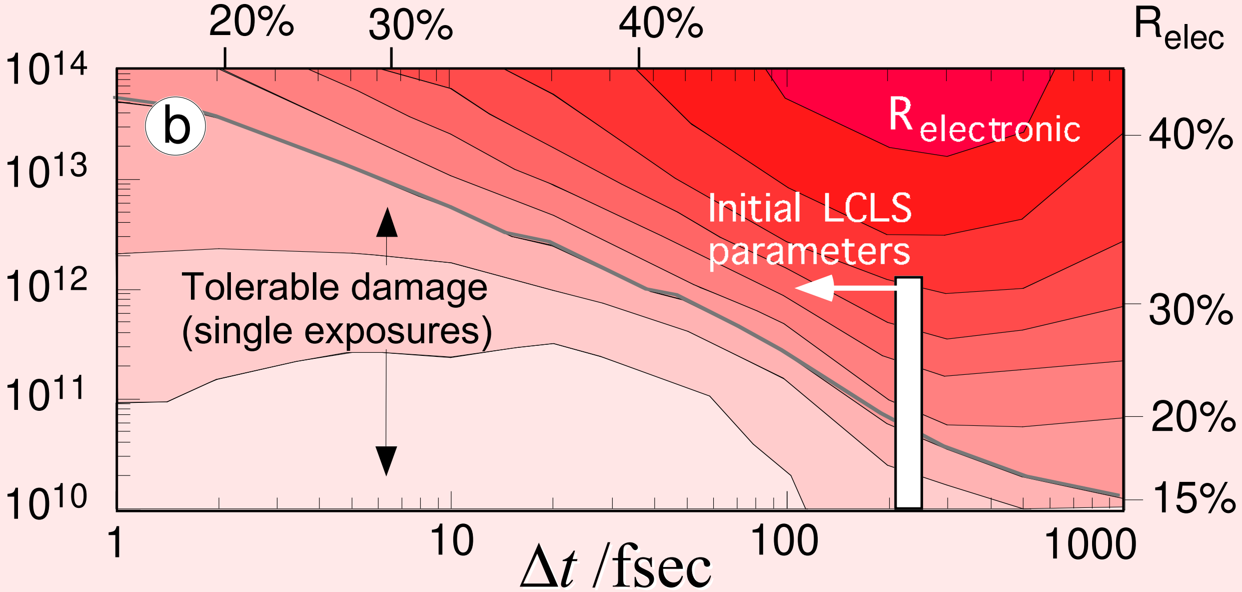
Radiation damage interferes with atomic positions and the atomic scattering factors

Janos Hajdu

Coulomb Explosion of Lysozyme (50 fs)

Further e^- compression difficult:

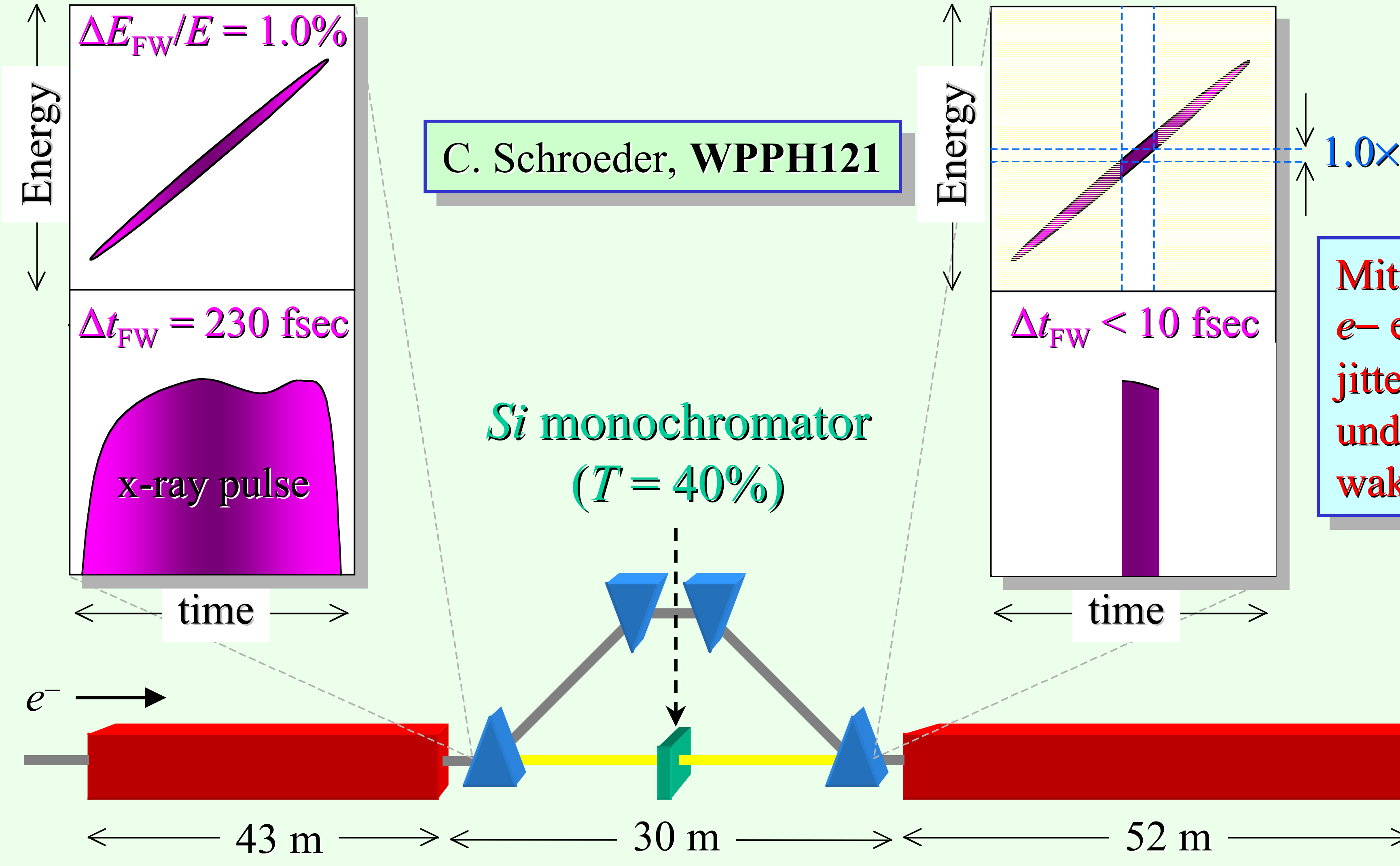
- CSR in bends
- Undulator wakefields



Compress *x*-ray pulse with chirp & slicer (R. Bionta, ***LLNL***)

…or…

Two-stage undulator for shorter pulse



$\Delta E_{FW}/E = 1.0\%$

Energy

$\Delta t_{FW} = 230$ fsec

x-ray pulse

time

C. Schroeder, **WPPH121**

Energy

1.0×10^{-4}

$\Delta t_{FW} < 10$ fsec

time

Si monochromator

($T = 40\%$)

e^-

43 m

30 m

52 m

SASE gain ($P_{sat}/10^3$)

SASE Saturation (23 GW)

Mitigates
e– energy
jitter and
undulator
wakes

UCLA

PAC-2001, Chicago, IL

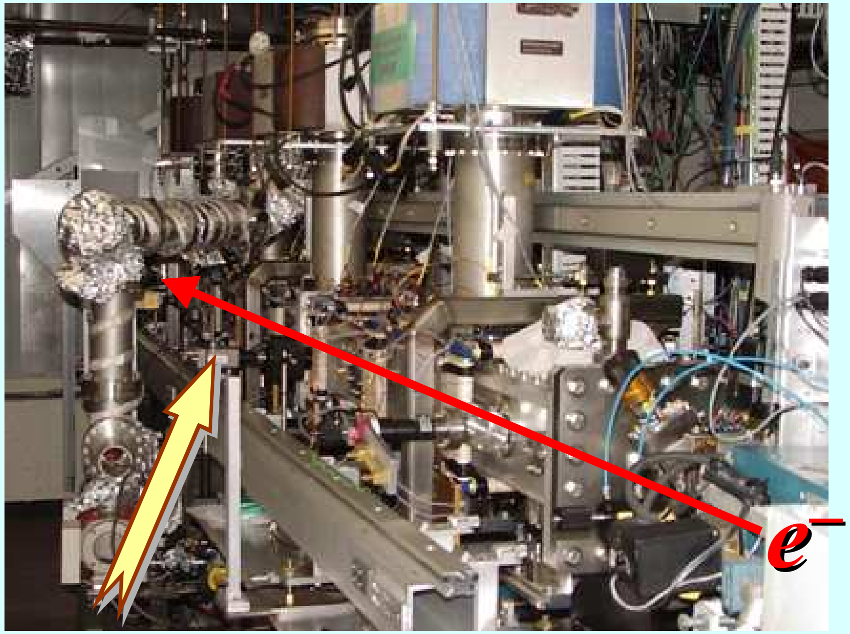
Also a ***DESY*** scheme which emphasizes line-width reduction (B. Faatz)

Visible to Infrared SASE Amplifier

VISA

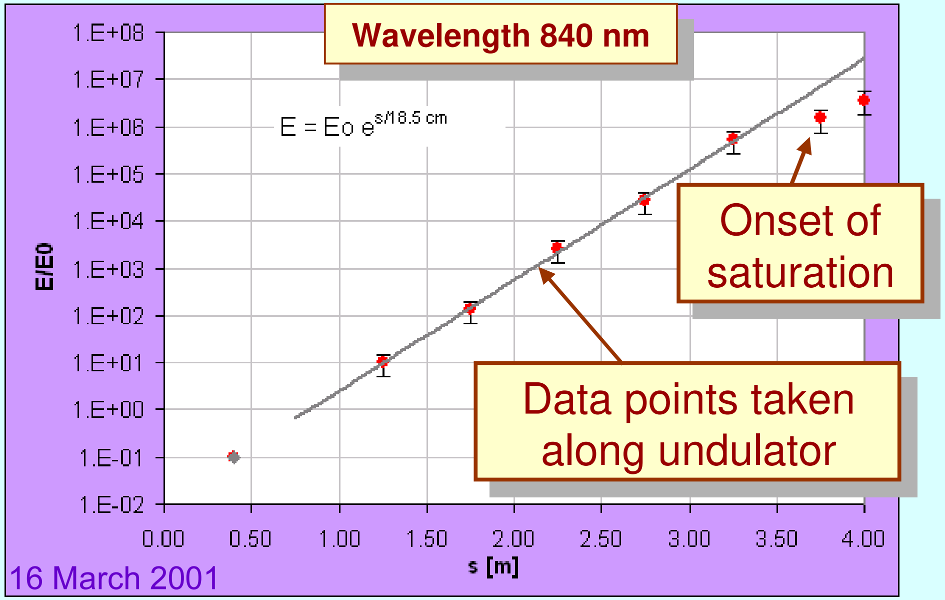
Brookhaven National Laboratory
Accelerator Test Facility

BNL-LLNL-SLAC-UCLA



Pop-In Diagnostics

Pulse Energy vs Position



16 March 2001

Onset of saturation

Data points taken along undulator

Wavelength	**840nm**
Average Charge	**170 pC**
Measured Projected Emittance:	**1.7 μm**
Energy Spread	**0.07 %**
Gain Length	**18.7 cm**
Total Gain	**2×10^7**

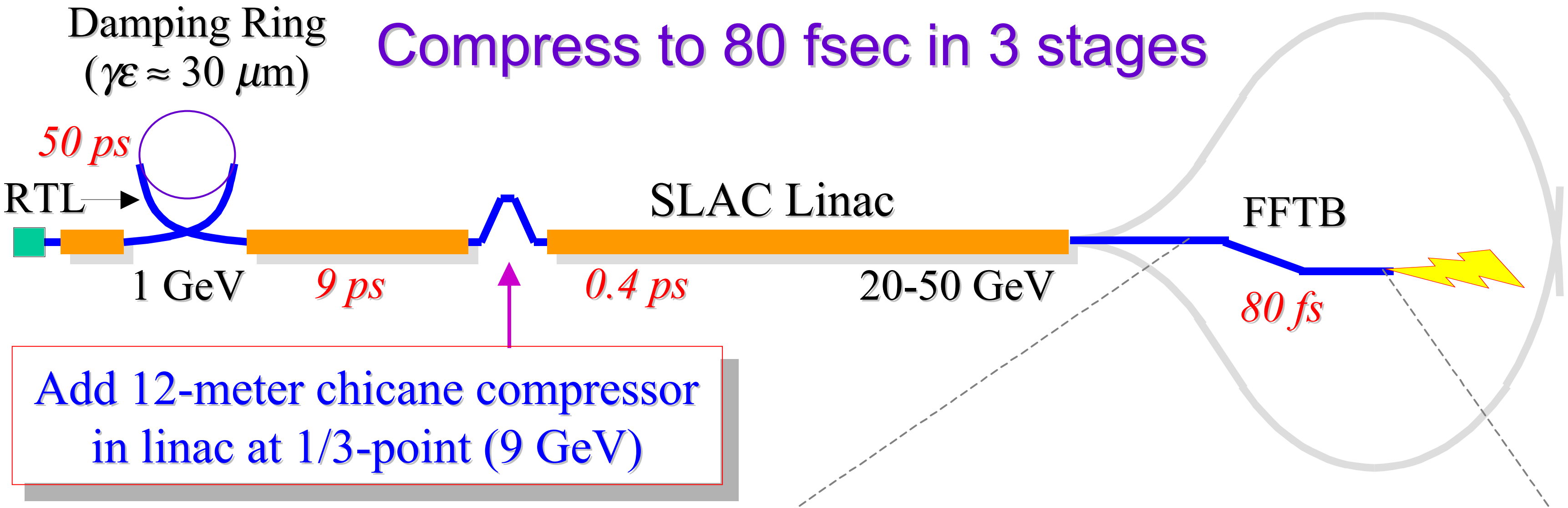
Preliminary results (unpublished) showing large gain (2×10^7) in SASE FEL radiation and evidence of saturation at 840 nm.

A. Tremaine, **WPPH122**

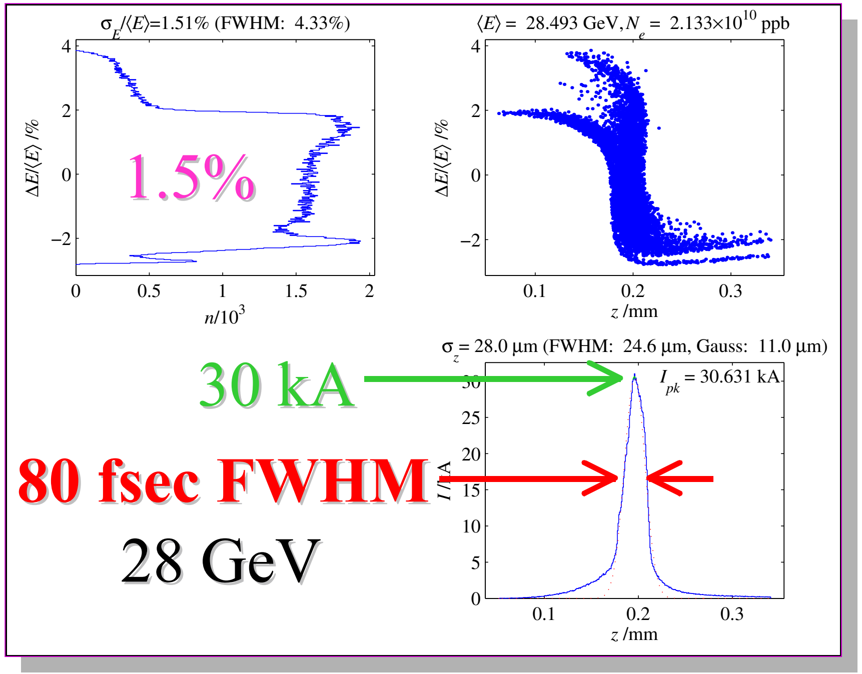
A. Murokh, **WPPH118**

Short Bunch Generation in the SLAC Linac

Compress to 80 fsec in 3 stages



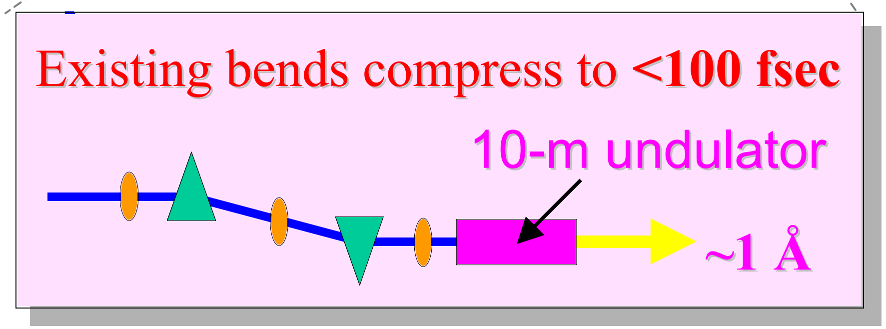
Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)



30 kA

80 fsec FWHM

28 GeV


Existing bends compress to **<100 fsec**

Add to understanding of CSR and *X*-ray optics

P. Emma, **FPAH165**

Summary of Key Issues

- Emittance generation and preservation
  - Gun $\gamma\varepsilon \approx 1\ \mu\mathrm{m}$, repeatable at 120 Hz
  - Need better understanding of CSR
- Stable operation
  - RF, laser, and feedback systems
- Undulator errors and trajectory control
  - Fabrication, alignment, and BPMs
  - Wakefields
- SASE saturation at ~1Å