37th ICFA Advanced Beam Dynamics Workshop on Future Light Sources

Feedback Concepts: Experience at SPPS, LCLS Plans

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Feedback Systems in Linac Based Light Sources

- Motivated by beam stability requirement
  - Transverse stability in the undulator
  - Peak current stability
    - Bunch charge
    - Bunch length
      - RF amplitude and phase ***
  - Bunch energy
- Benefits automated tuning algorithms
  - Keeps downstream parameters constant, while tuning upstream

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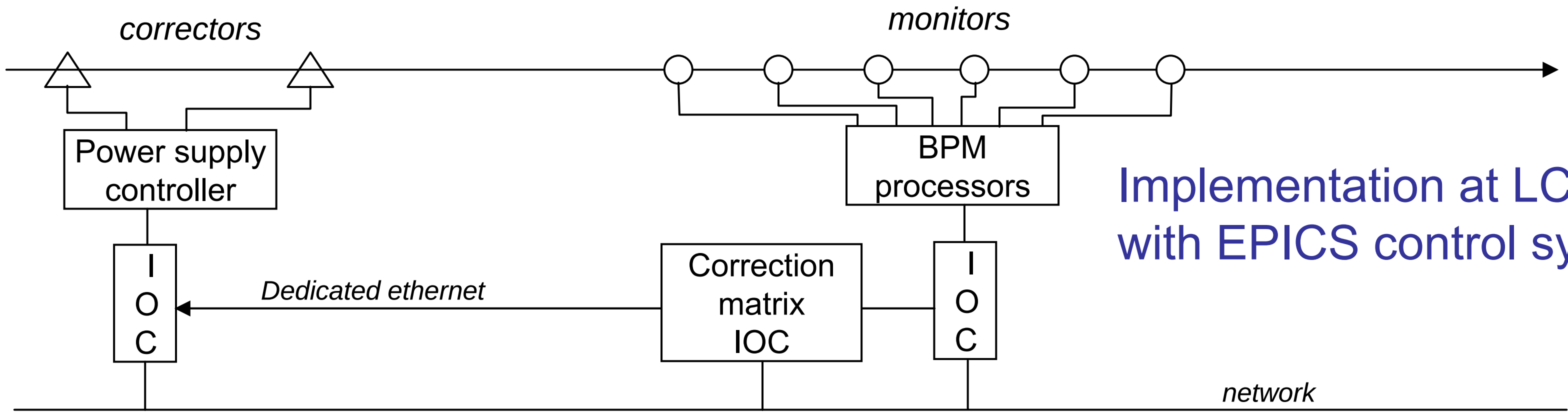
Trajectory feedback

- Well understood at SLAC and elsewhere
- Limitations:
  - Single shot resolution of BPMs (1-5 μm)
  - Response time of steering correctors (eddy currents)
- LCLS requires ~1 μm at 120 Hz



Implementation at LCLS with EPICS control system

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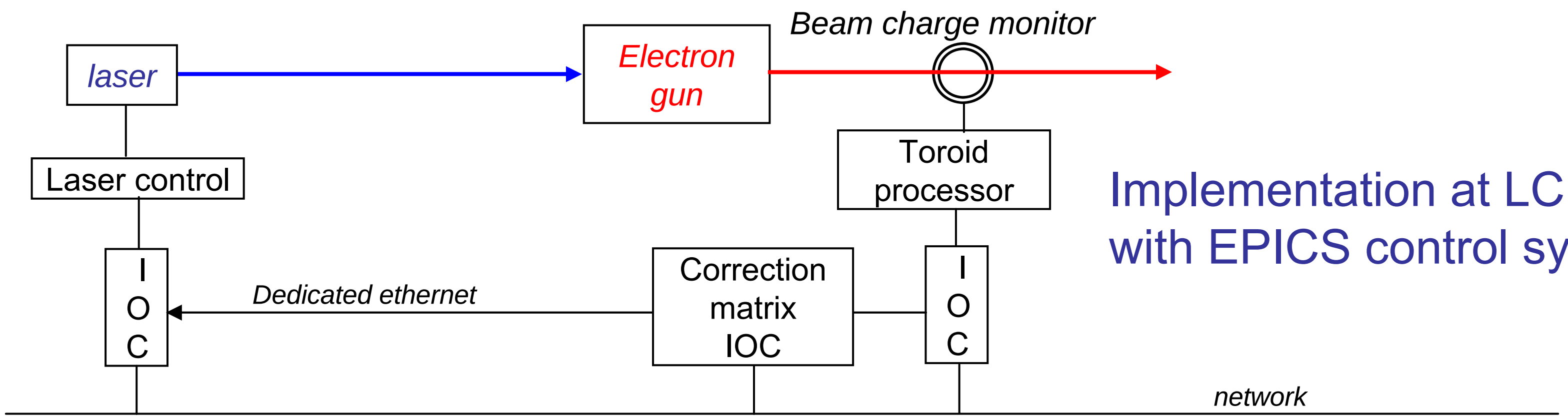
Bunch charge feedback

- RF photoinjector requires stabilization of laser energy per shot
- LCLS requires $\Delta Q/Q_0 < 2\%$



Implementation at LCLS with EPICS control system

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Longitudinal Stability Requirements Set by longitudinal compression dynamics

Parameter	Symbol	LCLS	Unit
Gun timing jitter	Δt_0	0.50	psec
Initial bunch charge	$\Delta Q/Q_0$	2.0	%
mean L0 rf phase	φ_0	0.10	deg
mean L1 rf phase	φ_1	0.10	deg
mean L*h* rf phase X-band	φ_h	0.50	X-deg
mean L2 rf phase	φ_2	0.07	deg
mean L3 rf phase	φ_3	0.15	deg
mean L0 rf voltage	$\Delta V_0/V_0$	0.10	%
mean L1 rf voltage	$\Delta V_1/V_1$	0.10	%
mean L*h* rf voltage	$\Delta V_h/V_h$	0.25	%
mean L2 rf voltage	$\Delta V_2/V_2$	0.10	%
mean L3 rf voltage	$\Delta V_3/V_3$	0.08	%

Criterion based on maintaining peak current

$\Delta I_i/I_0 < 12\%$

$\Delta E/E_0 < 0.1\%$

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Jitter versus Drift

- Feedback can correct long term drift
  - Thermal, power supplies, ground motion
- But not pulse-to-pulse jitter
  - Feedback bandwidth is limited to some fraction of the beam sample rate
  - Hardware must be stable enough to meet LCLS jitter requirements
  - See EO talk by Cavalieri for characterization of SPPS longitudinal jitter

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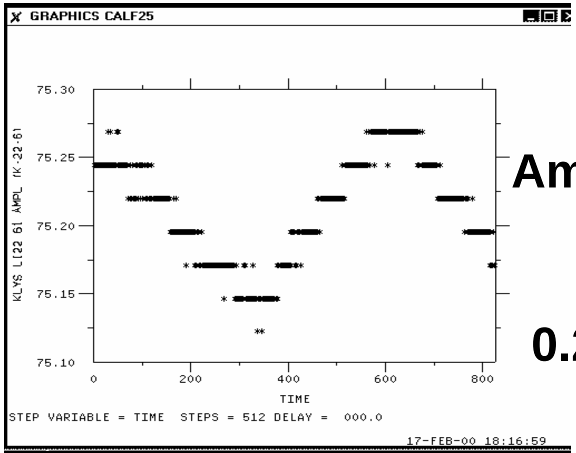
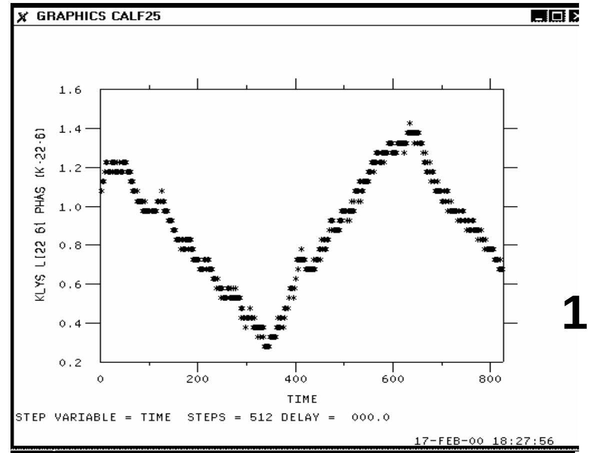
Drift in typical SLAC klystrons



Amplitude

22-6

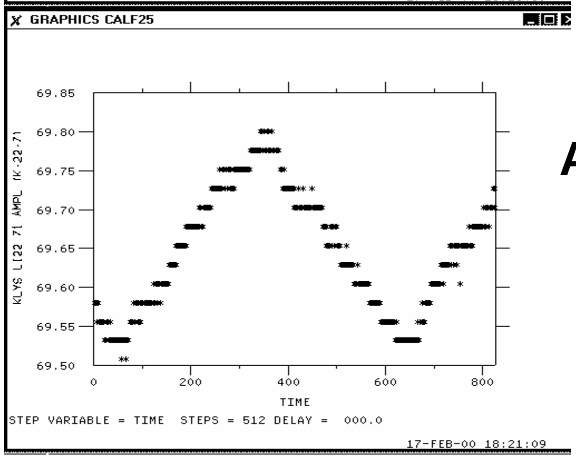
0.20%pp



Phase

22-6

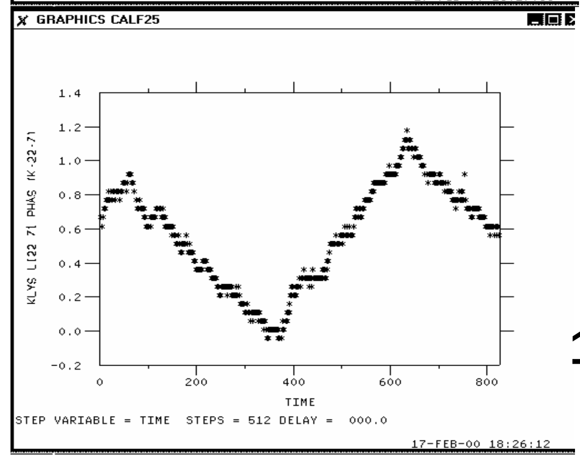
1.2 Deg pp



Amplitude

22-7

0.43%pp



Phase

22-7

1.2 Deg pp

14 minutes data clearly shows need for RF feedback

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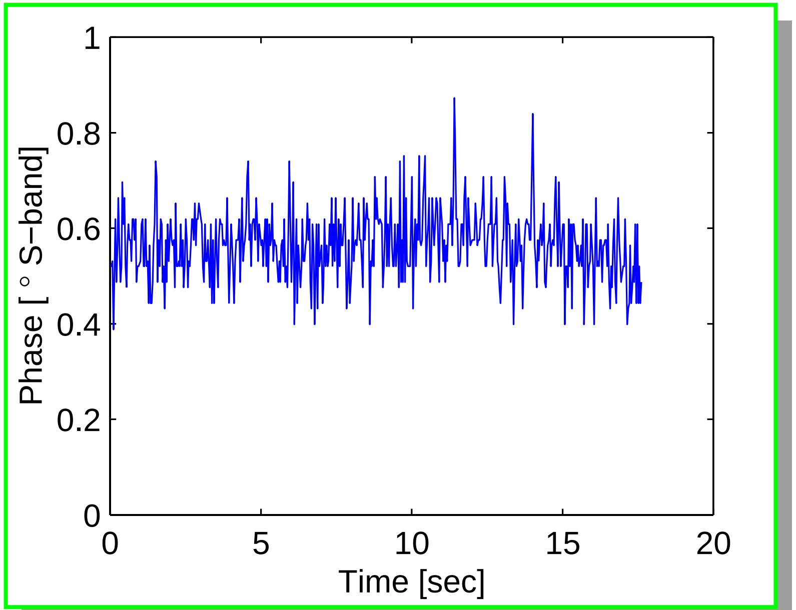
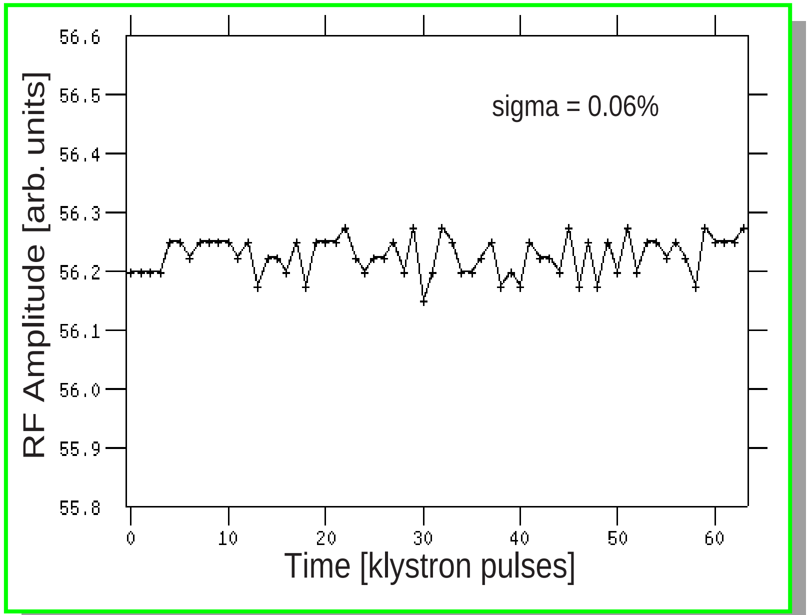
Short term jitter meets LCLS requirements

measured RF performance





klystron phase rms ≈ 0.07°
(20 sec)

klystron ampl. rms ≈ 0.06%
(60 sec)

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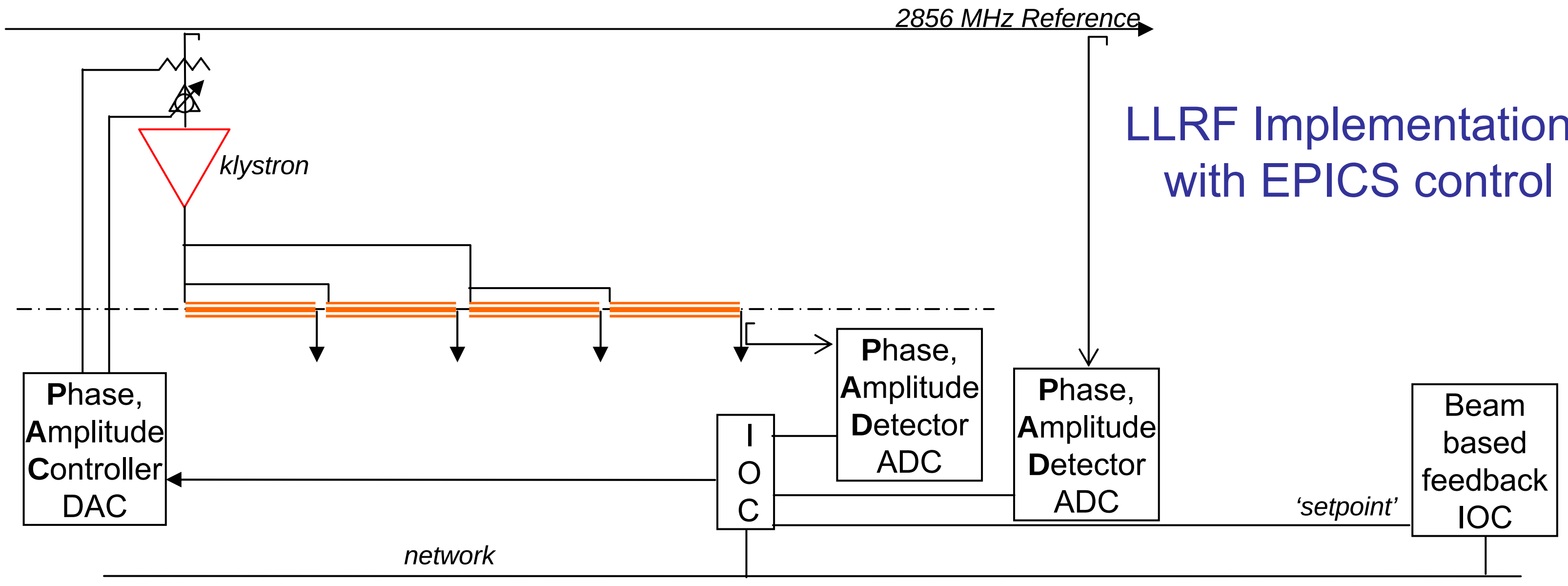
RF hardware loops versus beam-based

- Individual klystrons have phase and amplitude loops
- Reference phase along the linac can't be trusted as an absolute reference at the 0.1° S-band level
- Beam-based feedback ensures correct absolute phase.



LLRF Implementation at LCLS with EPICS control system

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Longitudinal Beam-Based Feedback

- SPPS
  - Separate energy feedback loop for RF ampl.
  - And bunch length feedback loop for RF phase
- LCLS
  - Single, global computation of amplitude and phase based on multiple inputs of energy and bunch length.

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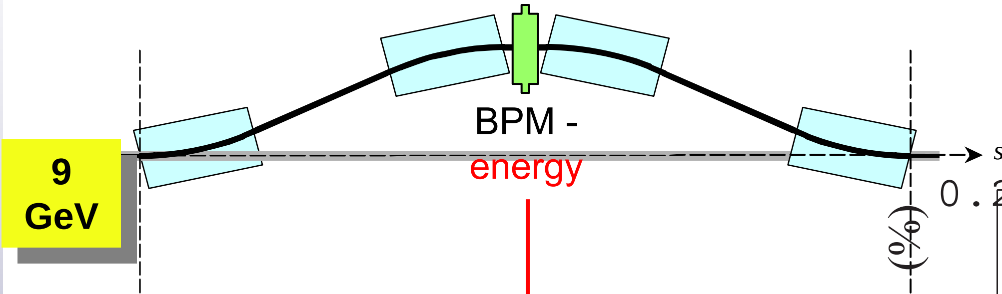
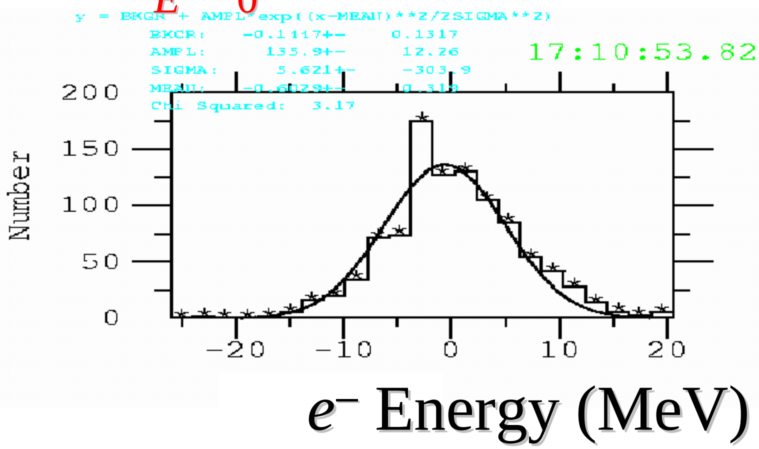
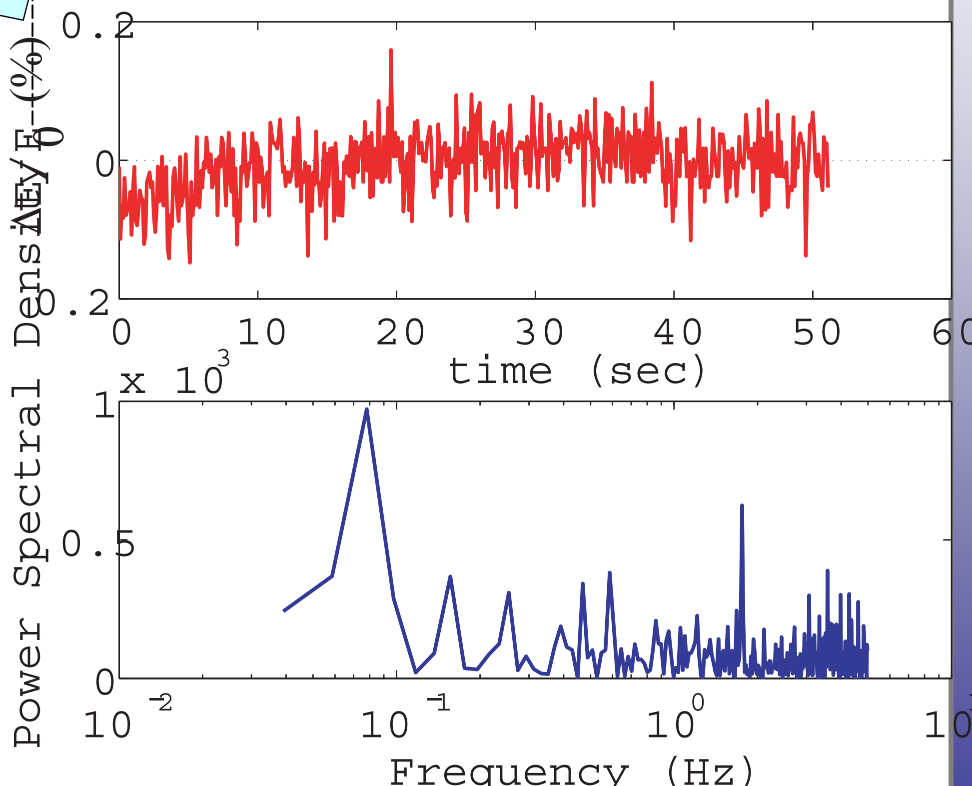
SPPS Bunch Compressor Chicane Energy Jitter Measurements



$\sigma_E/E_0 \approx 0.06\%$



Feedback open loop response



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

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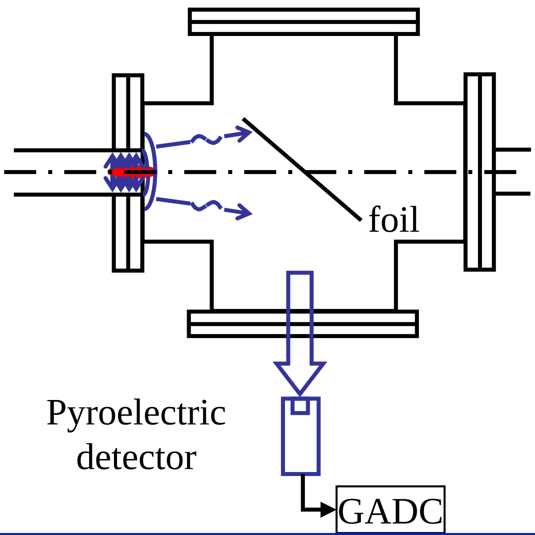
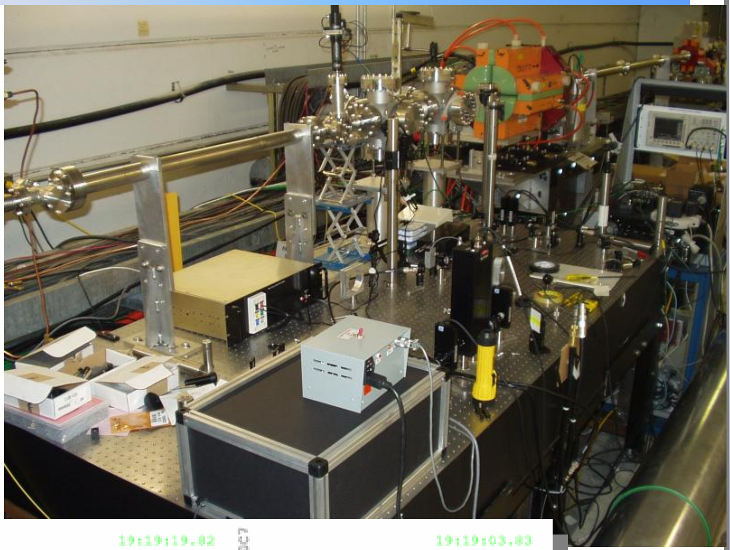
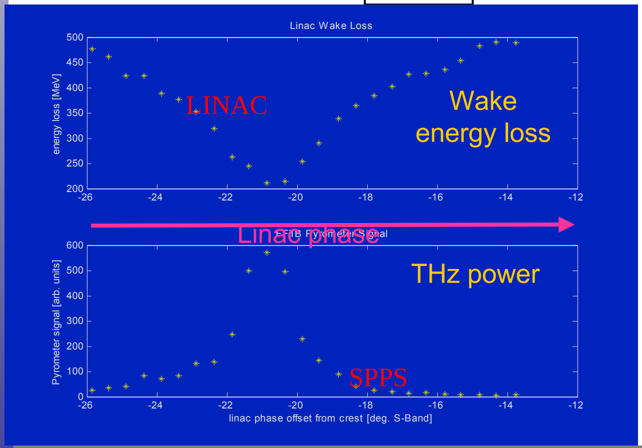
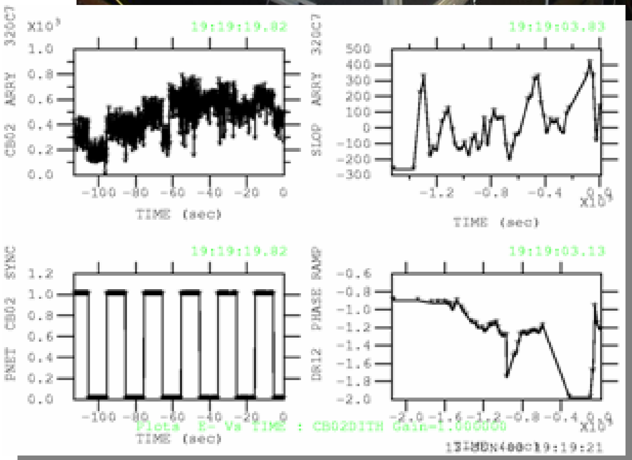
SPPS Coherent radiation Bunch Length Monitor







feedback



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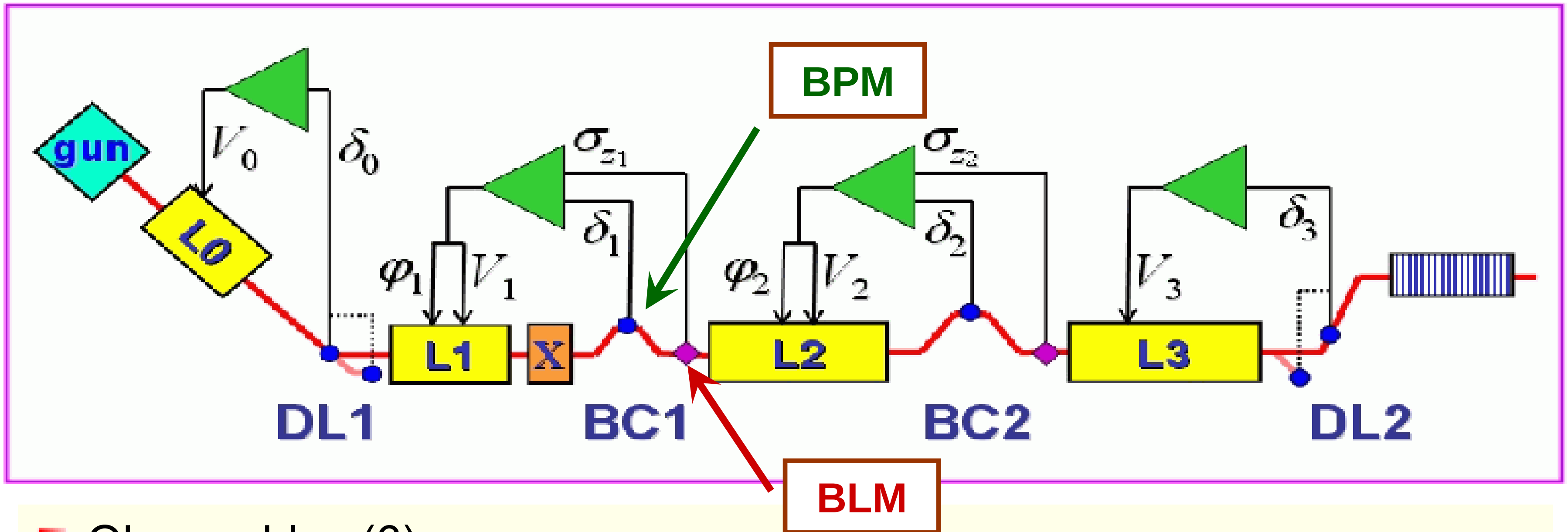
LCLS longitudinal feedback system schematic



- Observables (6):
  - Energy: E_0 (at DL1), E_1 (at BC1), E_2 (at BC2), E_3 (at DL2)
  - Coherent Radiation power → bunch length: $\sigma_{z,1}$ (at BC1), $\sigma_{z,2}$ (at BC2)
- Controllables (6):
  - Voltage: V_0 (in L0), V_1 (in L1), V_2 (effectively, in L2)
  - Phase: φ_1 (in L1), φ_2 (in L2), φ_3 (in L3)

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LCLS feedback algorithm

$$
\begin{pmatrix}
\left(\frac{dE}{E}\right)_0 \\
\left(\frac{dE}{E}\right)_1 \\
\left(\frac{dP}{P}\right)_1 \\
\left(\frac{dE}{E}\right)_2 \\
\left(\frac{dP}{P}\right)_2 \\
\left(\frac{dE}{E}\right)_3
\end{pmatrix}
=
\begin{pmatrix}
\frac{\partial\left(\frac{dE}{E}\right)_0}{\partial\left(\frac{dV}{V}\right)_0} & 0 & 0 & 0 & 0 & 0 \\
\frac{\partial\left(\frac{dE}{E}\right)_1}{\partial\left(\frac{dV}{V}\right)_0} & \frac{\partial\left(\frac{dE}{E}\right)_1}{\partial\left(\frac{dV}{V}\right)_1} & \frac{\partial\left(\frac{dE}{E}\right)_1}{\partial(d\varphi)_1} & 0 & 0 & 0 \\
\frac{\partial\left(\frac{dP}{P}\right)_1}{\partial\left(\frac{dV}{V}\right)_0} & \frac{\partial\left(\frac{dP}{P}\right)_1}{\partial\left(\frac{dV}{V}\right)_1} & \frac{\partial\left(\frac{dP}{P}\right)_1}{\partial(d\varphi)_1} & 0 & 0 & 0 \\
\frac{\partial\left(\frac{dE}{E}\right)_2}{\partial\left(\frac{dV}{V}\right)_0} & \frac{\partial\left(\frac{dE}{E}\right)_2}{\partial\left(\frac{dV}{V}\right)_1} & \frac{\partial\left(\frac{dE}{E}\right)_2}{\partial(d\varphi)_1} & \frac{\partial\left(\frac{dE}{E}\right)_2}{\partial\left(\frac{dV}{V}\right)_2} & \frac{\partial\left(\frac{dE}{E}\right)_2}{\partial(d\varphi)_2} & 0 \\
\frac{\partial\left(\frac{dP}{P}\right)_2}{\partial\left(\frac{dV}{V}\right)_0} & \frac{\partial\left(\frac{dP}{P}\right)_2}{\partial\left(\frac{dV}{V}\right)_1} & \frac{\partial\left(\frac{dP}{P}\right)_2}{\partial(d\varphi)_1} & \frac{\partial\left(\frac{dP}{P}\right)_2}{\partial\left(\frac{dV}{V}\right)_2} & \frac{\partial\left(\frac{dP}{P}\right)_2}{\partial(d\varphi)_2} & 0 \\
\frac{\partial\left(\frac{dE}{E}\right)_3}{\partial\left(\frac{dV}{V}\right)_0} & \frac{\partial\left(\frac{dE}{E}\right)_3}{\partial\left(\frac{dV}{V}\right)_1} & \frac{\partial\left(\frac{dE}{E}\right)_3}{\partial(d\varphi)_1} & \frac{\partial\left(\frac{dE}{E}\right)_3}{\partial\left(\frac{dV}{V}\right)_2} & \frac{\partial\left(\frac{dE}{E}\right)_3}{\partial(d\varphi)_2} & \frac{\partial\left(\frac{dE}{E}\right)_3}{\partial(d\varphi)_3}
\end{pmatrix}
\begin{pmatrix}
\left(\frac{dV}{V}\right)_0 \\
\left(\frac{dV}{V}\right)_1 \\
(d\varphi)_1 \\
\left(\frac{dV}{V}\right)_2 \\
(d\varphi)_2 \\
(d\varphi)_3
\end{pmatrix}
\equiv M
\begin{pmatrix}
\left(\frac{dV}{V}\right)_0 \\
\left(\frac{dV}{V}\right)_1 \\
(d\varphi)_1 \\
\left(\frac{dV}{V}\right)_2 \\
(d\varphi)_2 \\
(d\varphi)_3
\end{pmatrix}
\equiv MC
$$

M^{-1}- **feedback matrix**

$$O \equiv MC$$

$$C_{\text{after}} \equiv C_{\text{before}} + GM^{-1}O$$

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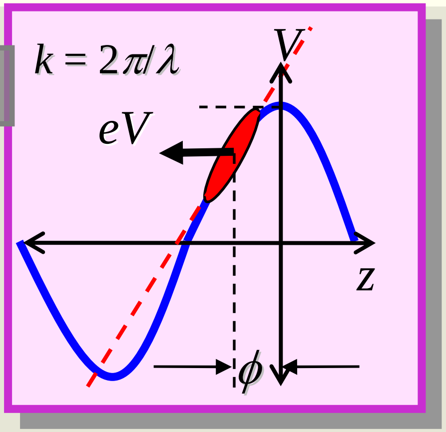
LCLS accelerator system model – J. Wu

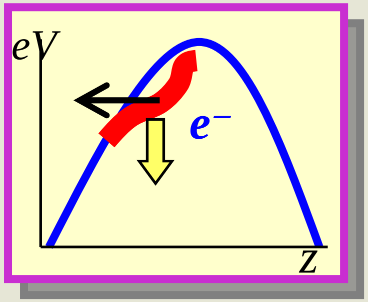
- Linac
  - RF $E \rightarrow E + eV\cos[\varphi + kz]$

ϕ = 0 at accelerating crest



  - Wakefield (structure wake) (K. Bane)

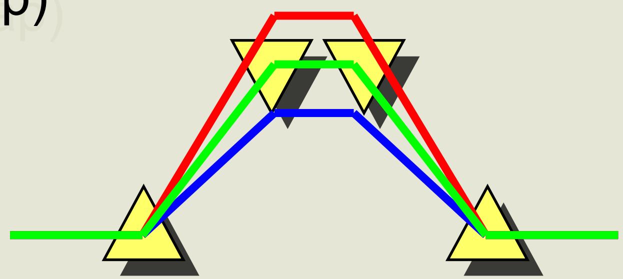
$$w(z) = \frac{Z_0 c}{\pi a^2} e^{-\sqrt{z/s_0}}$$



***SLAC* S(X)-Band:**
$s_0 \approx$ 1.32 (0.77)mm
$a \approx$ 11.6(4.72) mm
z < ~6 mm

- Chicane and Dog-leg (2rd order map)

$$z \rightarrow z + \delta\left(R_{56} + T_{566}\delta\right)$$



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Features of the LCLS feedback model

- PID controller: Proportional, Integral, and Derivative gain
  - Integral gain helps in the low frequency regime
- Cascade scheme:
  - need to keep the off-diagonal elements in the M^{-1} feedback matrix
  - Equivalent to the so-called Multi-stage Cascade
- Sample every beam pulse with no control system latency

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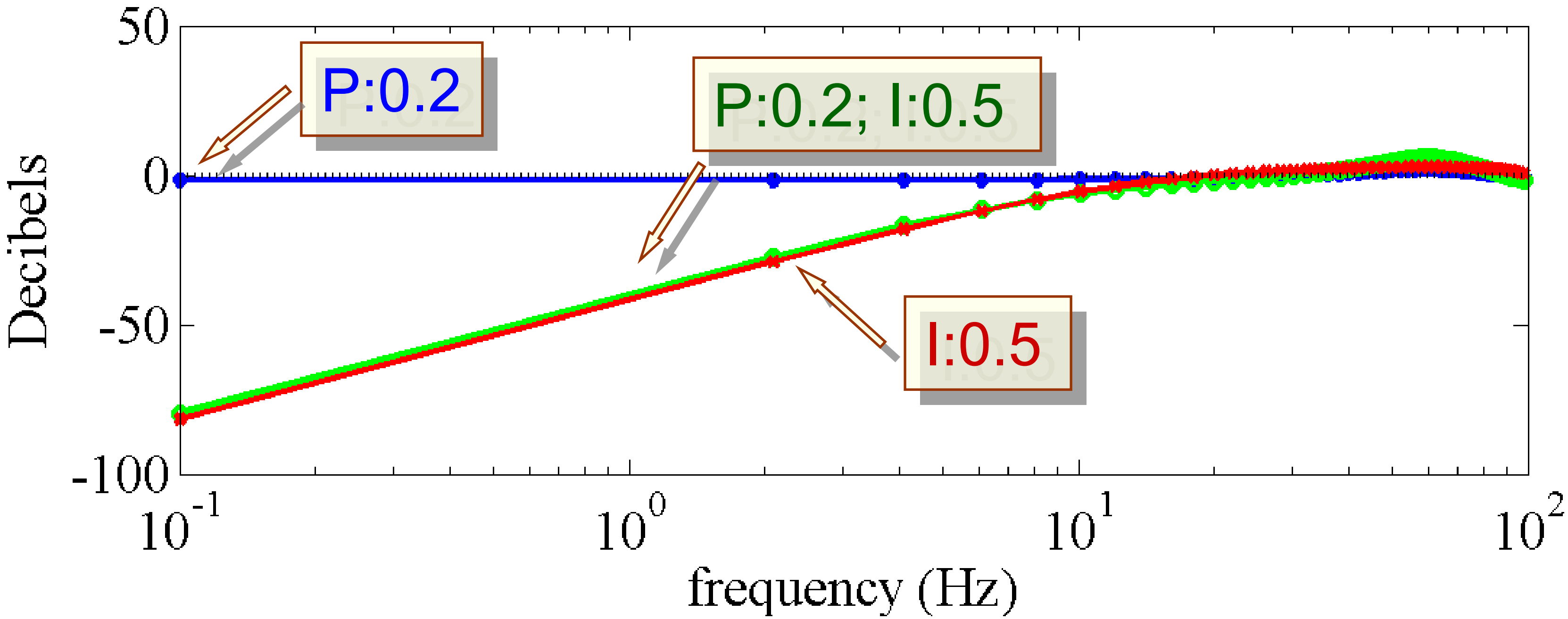
Bode plot (ΔE/E)

$$20\log_{10}\left(\left|\frac{(\Delta E / E)_{on}}{(\Delta E / E)_{off}}\right|\right)$$

Integral Gain helps



$$\arg\left(\frac{(\Delta E / E)_{on}}{(\Delta E / E)_{off}}\right) = 0.0$$

- Adequate damping below 10 Hz
- Similar **Bode plot** for (**ΔI / I**)

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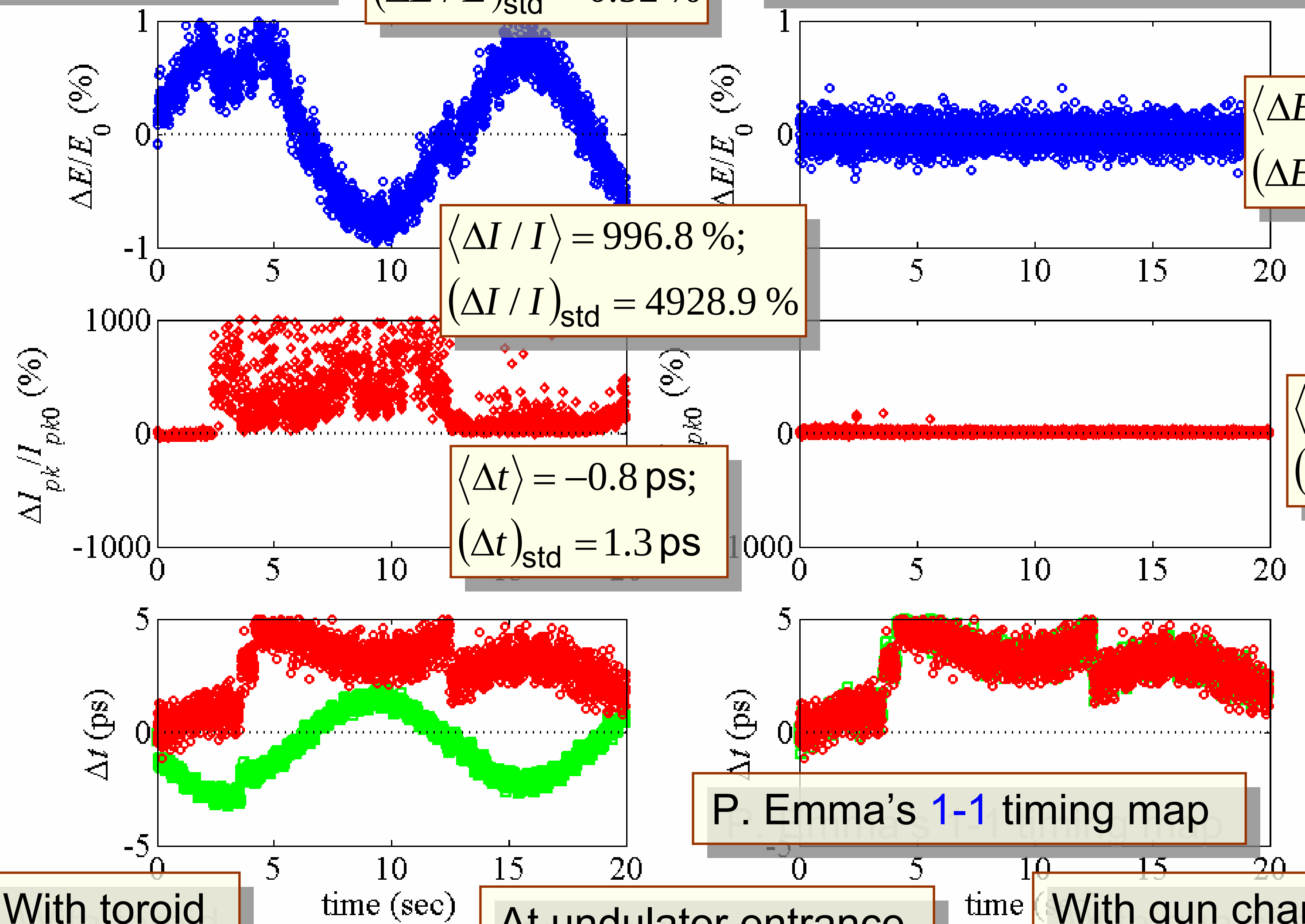
LCLS Feedback Performance (Use CSR ΔP / P)



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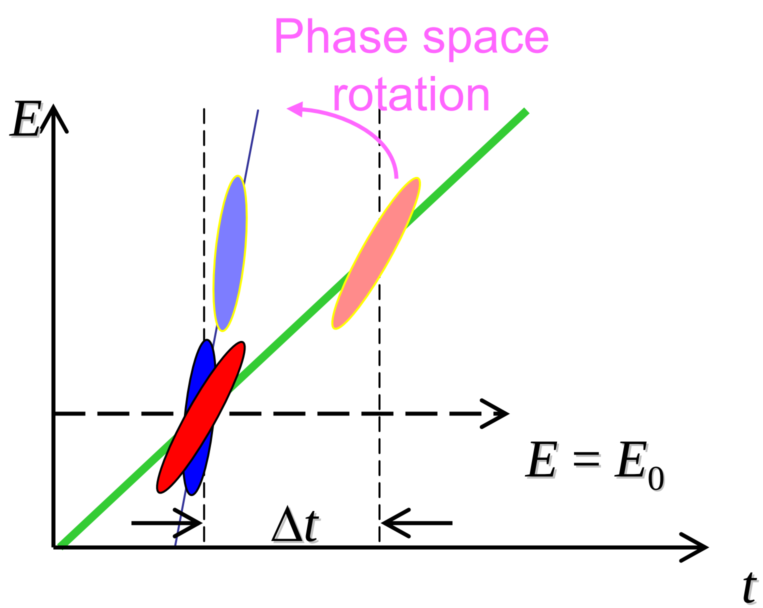
- In the absence of any feedback gun timing jitter is compressed in the chicane
- But energy feedback puts timing errors back to full value



without energy feedback

with energy feedback – P. Emma

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Compensation of errors introduced through the higher harmonic cavity

- The longitudinal feedback cannot distinguish between errors in
  - the fundamental, S-band system
  - And the linearizing, X-band cavity
- Find that fundamental system can easily compensate for errors up to 5% in the higher harmonic system

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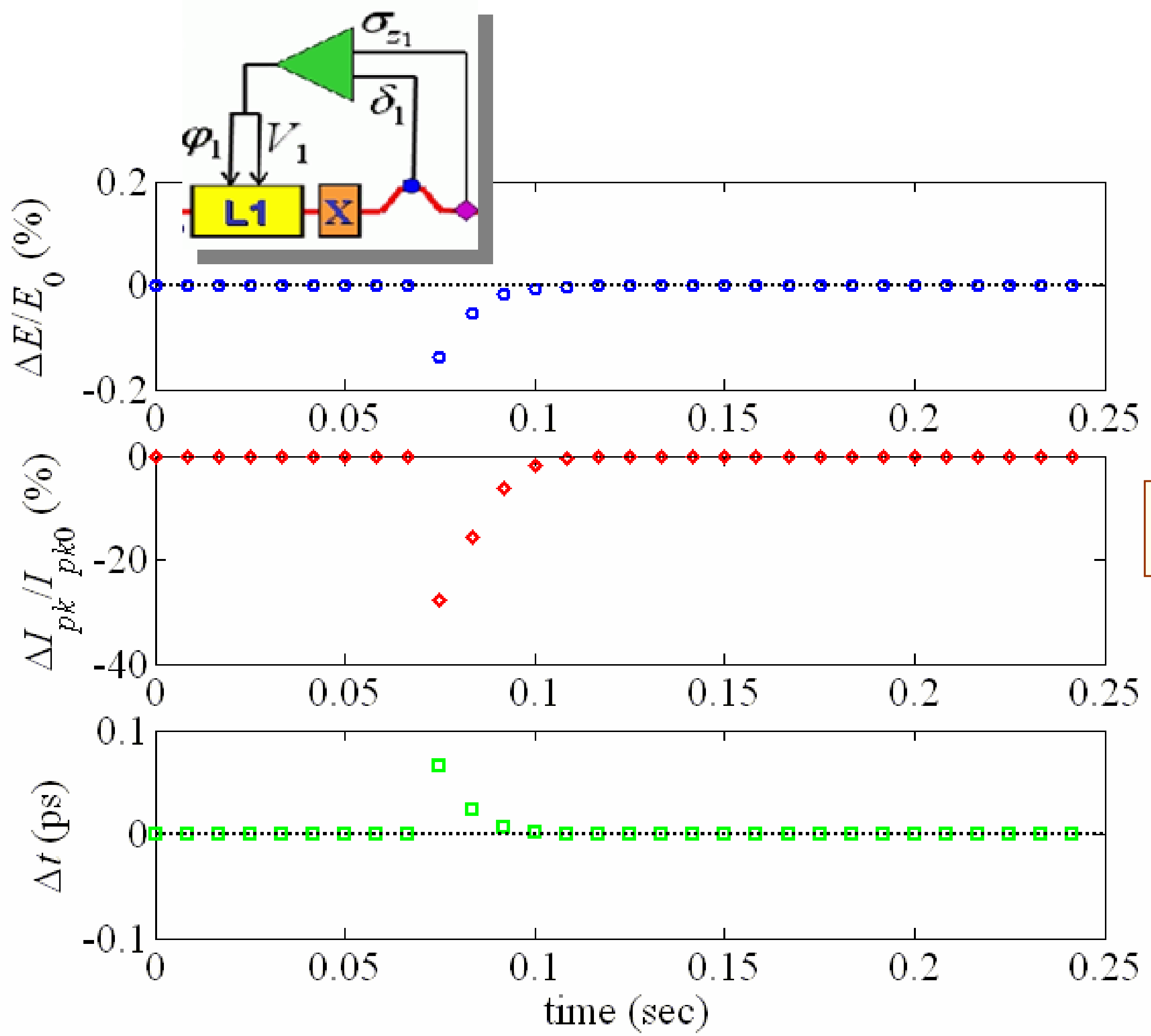
L1 adjustment to compensate Lx jitter



Lx phase jitter + 5°, voltage fixed

L1 adjustment: phase +2.1°, voltage - 2.1 %

- Similarly

Lx voltage jitter + 5 %, phase fixed

L1 adjustment: phase +0.61°, voltage 0.18 %

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Diagnostic monitors for longitudinal feedback

- Energy determined from high resolution BPMs
- Also need single shot bunch length monitors with 5% resolution.
- Based on coherent radiation detection
- Wavelength range and detector type differs for each bunch compressor
  - LCLS BC1 diode detector 1.76 mm < λ < 2.72 mm (110 to 170 GHz)
  - LCLS BC2 pyroelectric detector <2 THz

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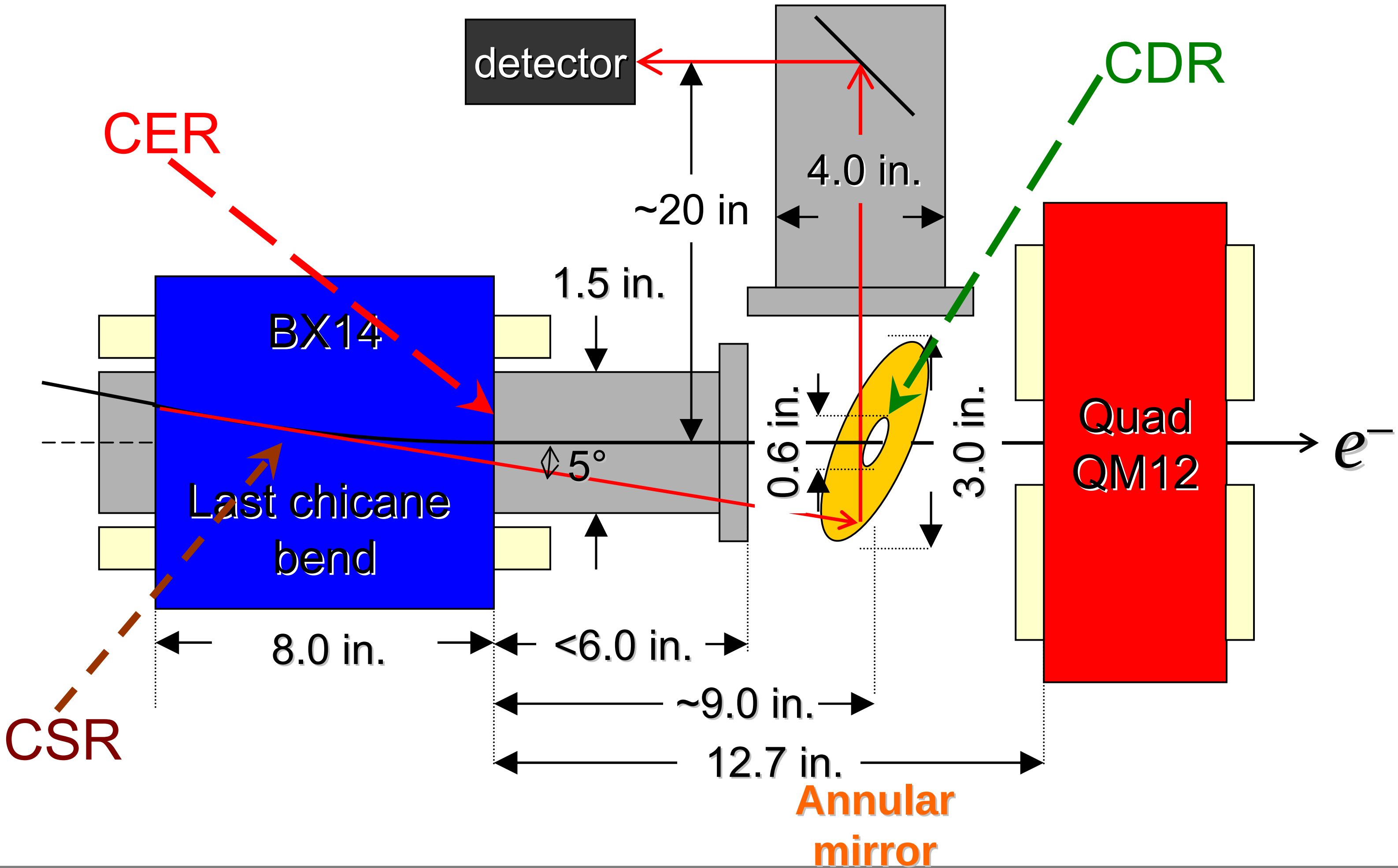
Schematic detection scheme in BC1



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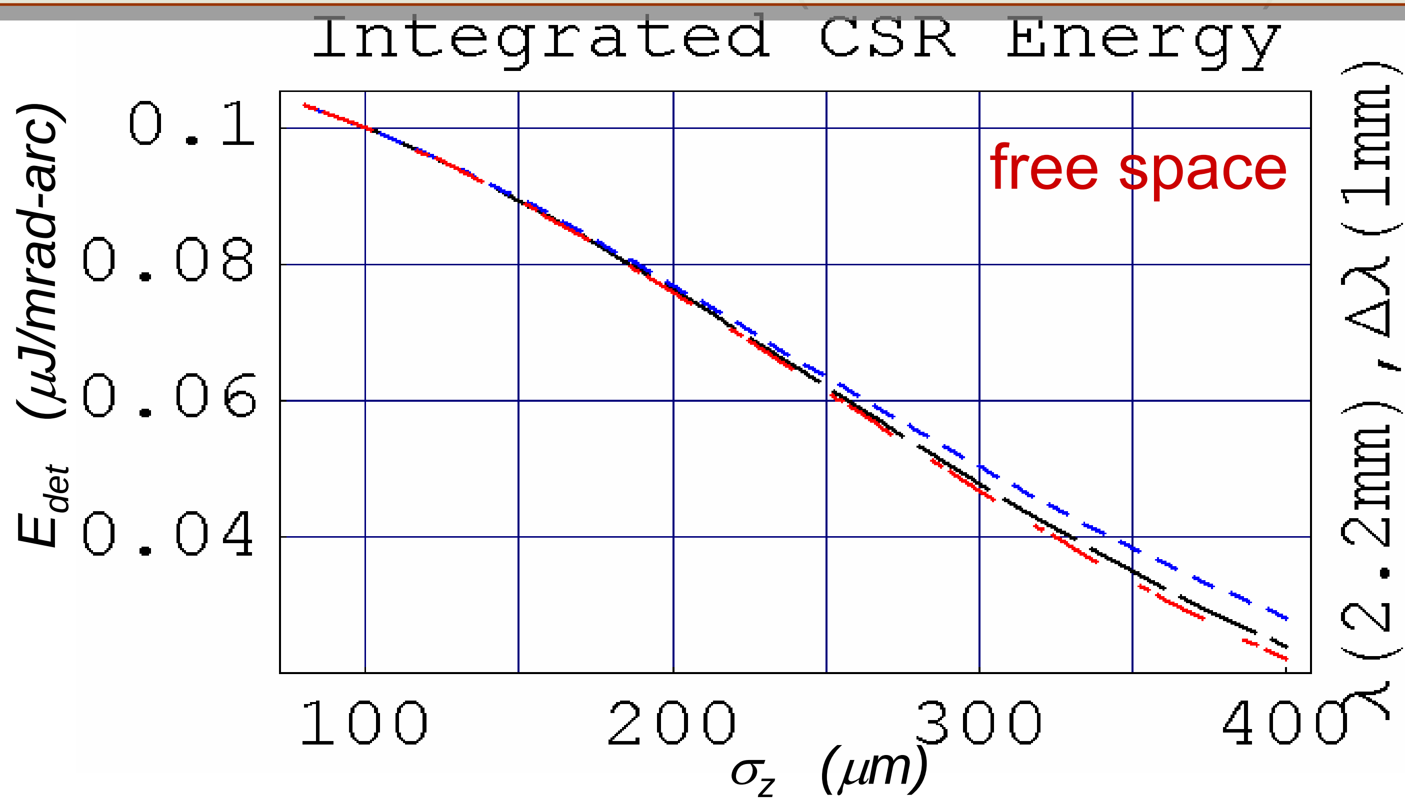
Detector signal versus bunch length at BC1

- Diode detector (WD-06) → spectral response
  1.76 mm < λ < 2.72 mm (110 to 170 GHz)



- Beam pipe cutoff (2 cm radius pipe →1/2 signal, but similar slope)

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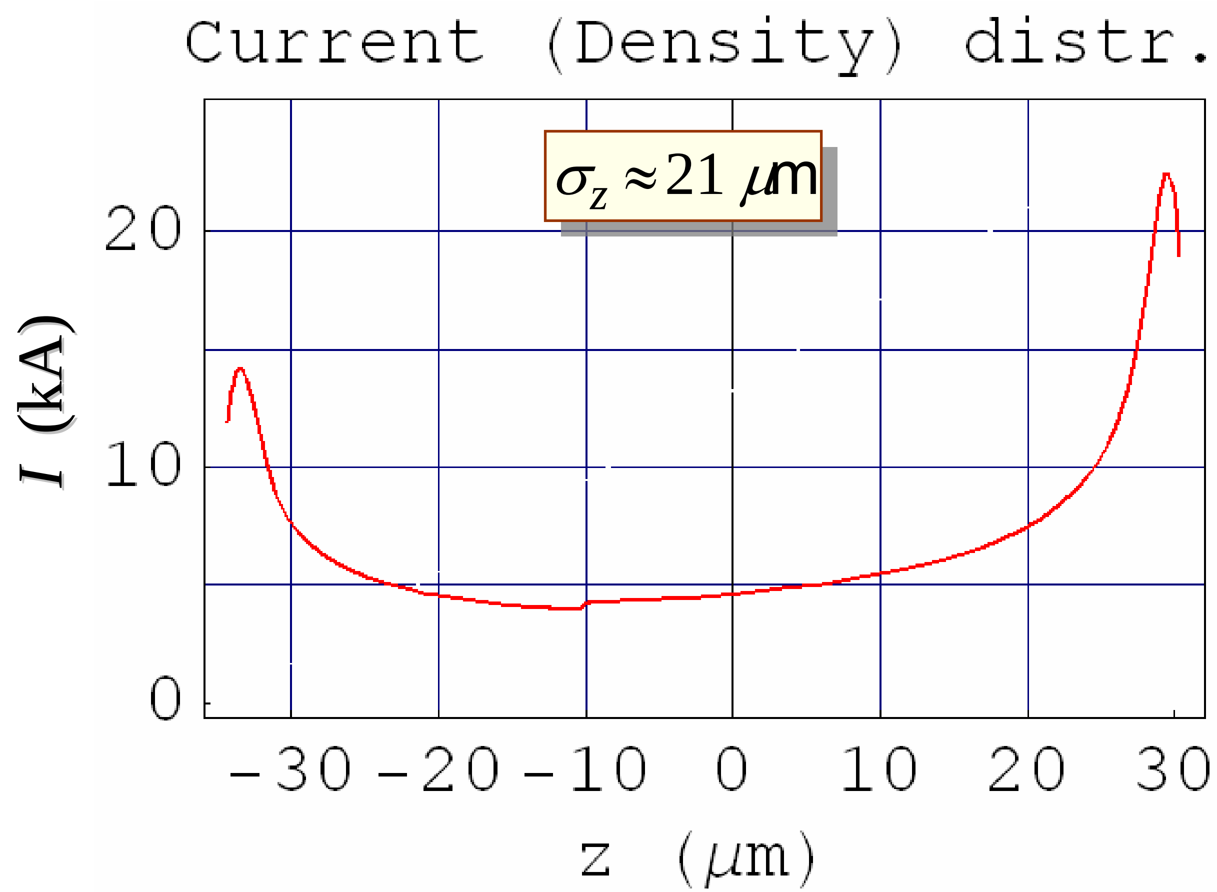
Current profile after BC2

- Wake-induced double-horn structure



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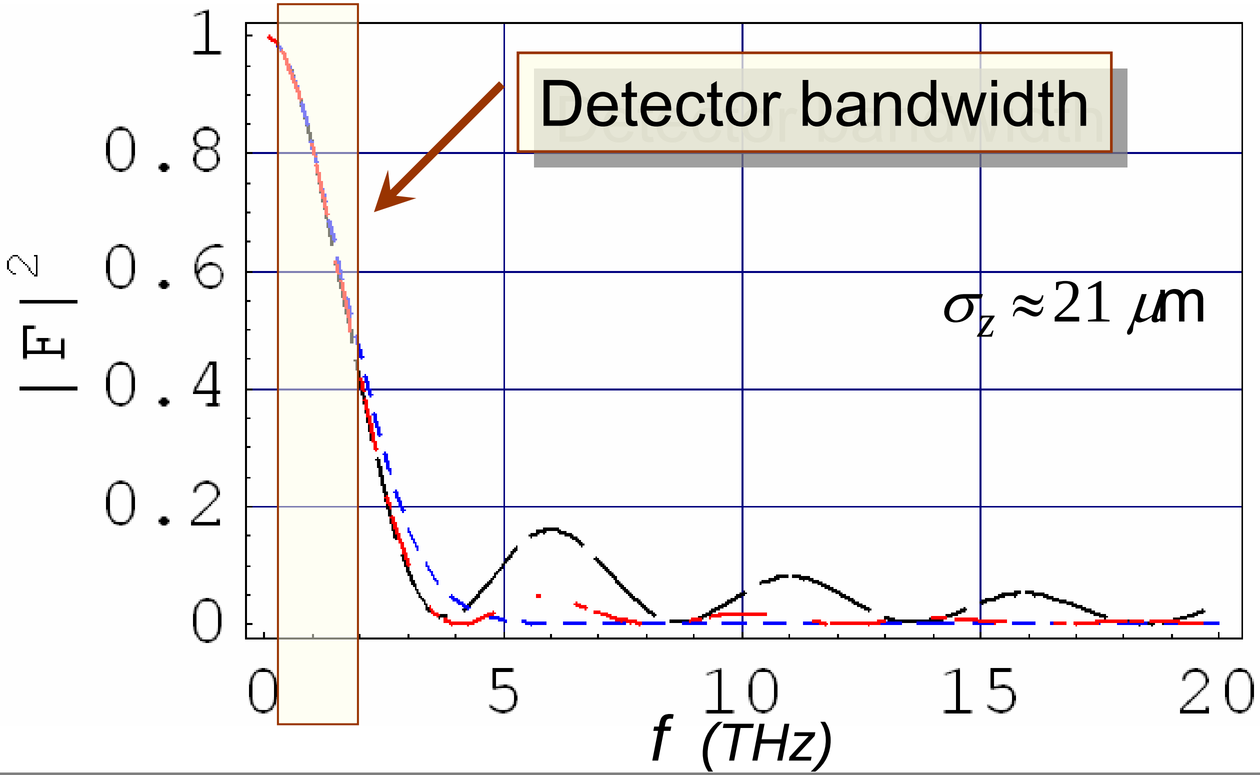
Bunch spectrum after BC2

- Sharp-edge induces high freq. component.
  - However, low freq. region (< 2 THz) independent of shape
- Similarly, for BC1→ parabolic distribution → low freq. region (< 400 GHz)



Black: double-horn

Blue: Gaussian with same σ_z

Red: Step with same σ_z

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Conclusions

- Shot-by-shot feedback essential for stability and tuning
- Adequate experience with trajectory and energy feedback at SPPS
- Coherent radiation monitors demonstrated at SPPS to resolve bunch length errors
- Complete longitudinal feedback system for LCLS is our next challenge

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Coherent radiation as bunch length monitor

- Coherent Radiation (CR) as nondestructive diagnostic tool
  - Synchrotron, Edge, and Diffraction Radiation
- For a group of N_e electrons
  - CR spectrum

$$\frac{d^2I}{d\omega d\Omega} = \left| \sum_{j=1}^{N_e} e^{i\omega t_j} e^{-i\omega \frac{\hat{\vec{n}} \bullet \vec{R}_j}{c}} \right|^2 \frac{d^2 I_0}{d\omega d\Omega}$$

$$\equiv N_e^2 |F|^2 \frac{d^2 I_0}{d\omega d\Omega}$$

Single e^-

  - Form factor → bunch length information

$$|F|^2 = \left| \int n(x,y,z) e^{-ikz} e^{-ik\hat{\vec{n}} \bullet \vec{R}} dxdydz \right|^2$$

$$\approx \left| \int n(x,y,z) e^{-ikz} dxdydz \right|^2$$

with

$$\int n(x,y,z) dxdydz = 1$$

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CSR at BC1 and BC2

- Parameters at BC1 and BC2

	ρ (m)	σ_z (mm)	λ (mm)	f (THz)	I_{peak} (A)
BC1	2.4	0.19	1.2	0.25	400
BC2	14.5	0.021	0.13	2.3	3400

Hence, $P_{csr}(\lambda) = N_e |F|^2 P_{isr}(\lambda)$.

Coherent enhancement and bunch length information

- CSR pulse energy can be as much as μJ

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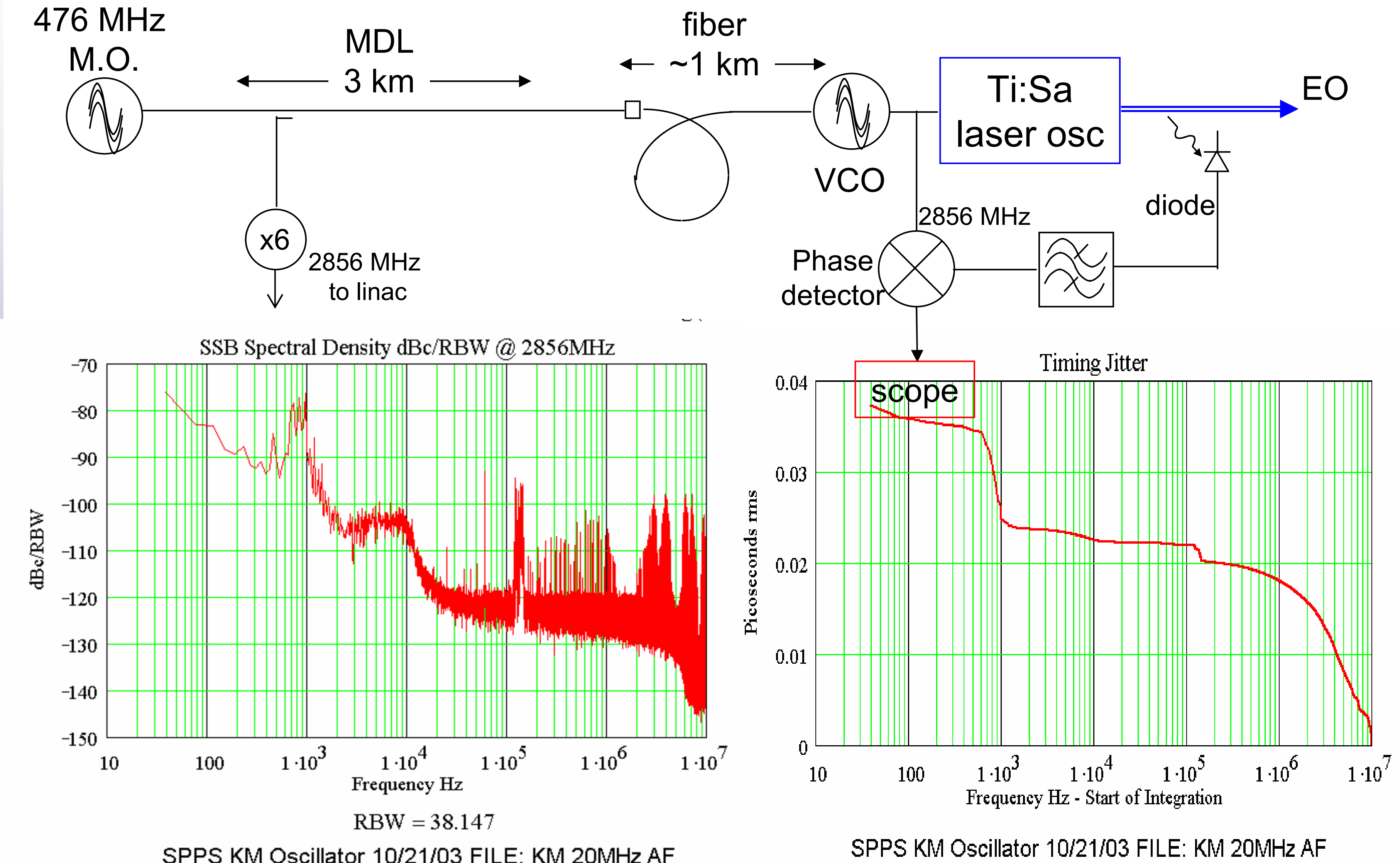
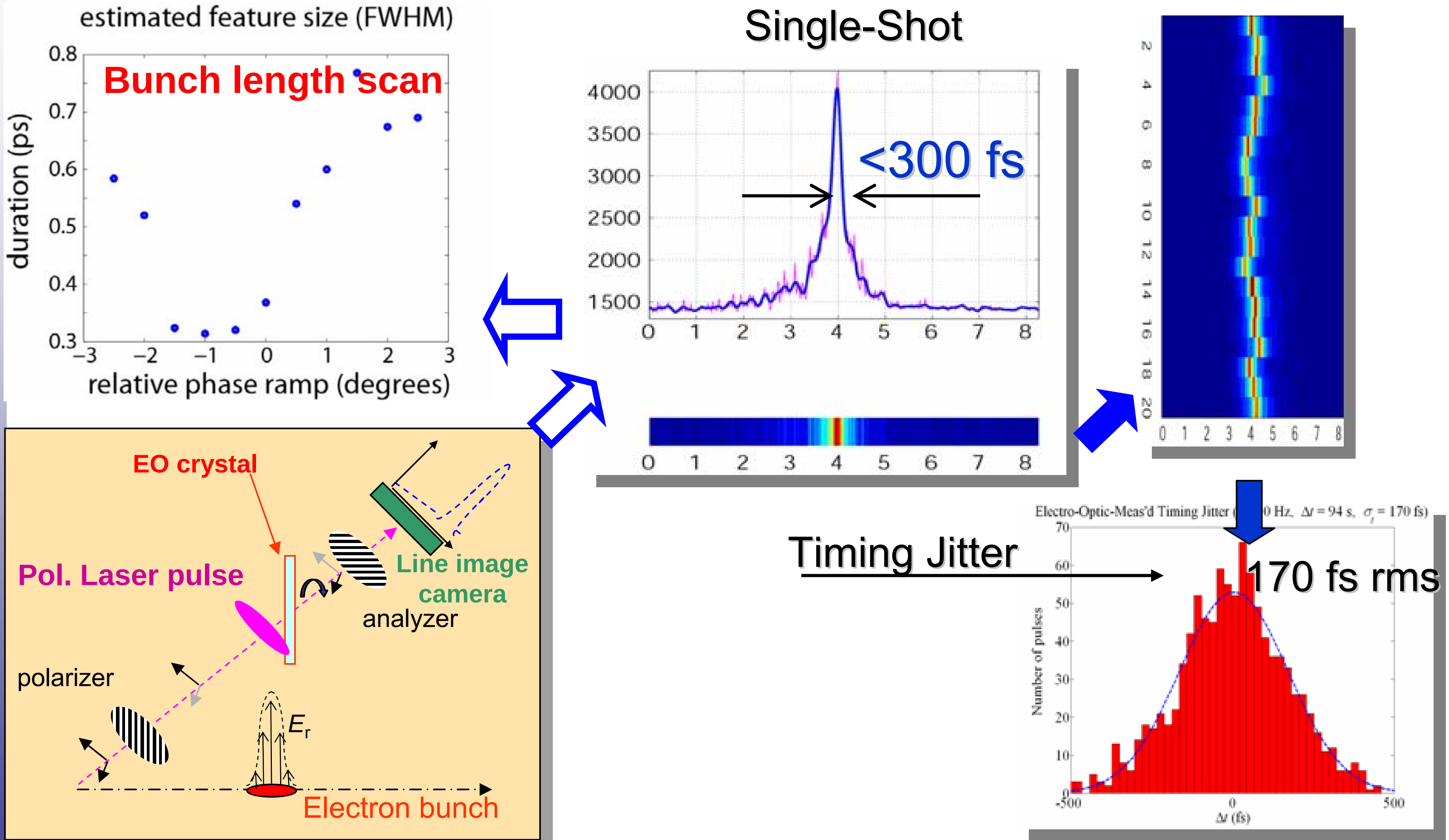
SPPS Laser Phase Noise Measurements – R. Akre



Electro-Optical Sampling at SPPS – A. Cavalieri et al.



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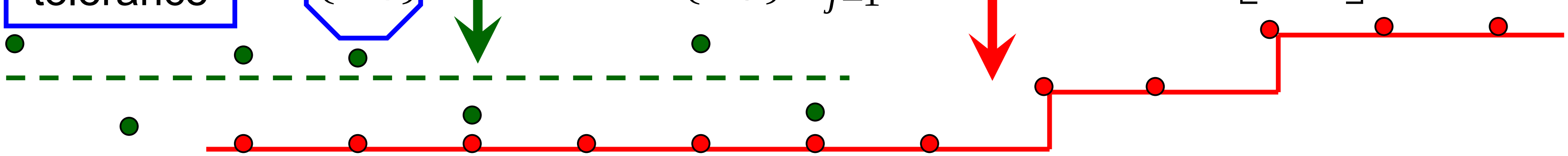
LCLS accelerator system jitter model

- We model the LINAC voltage / phase jitter as the follows
  - Two characteristic frequencies, linear drift, white noise (sets the tolerance), and step-function jitter

$$\begin{Bmatrix} \frac{dV}{V} \\ d\varphi \end{Bmatrix} = \begin{Bmatrix} A_1 \\ B_1 \end{Bmatrix} \sin(2\pi f_1 t) + \begin{Bmatrix} A_2 \\ B_2 \end{Bmatrix} \sin(2\pi f_2 t) + \begin{Bmatrix} A_3 \\ B_3 \end{Bmatrix} t$$

$$+ \begin{Bmatrix} A_4 \\ B_4 \end{Bmatrix} \mathrm{randn}\,(1) + \begin{Bmatrix} A_5 \\ B_5 \end{Bmatrix} \sum_{j=1}^{N_{\text{step}}} \mathrm{H}(t - t_{\text{step},j}) \quad \begin{bmatrix} \% \\ \text{deg} \end{bmatrix}$$

tolerance



with $f_1 = 0.08$ Hz ; $f_2 = 1.7$ Hz ; $A_1 = B_1 = A_5 = B_5 = 1$; $A_2 = B_2 = A_4 = B_4 = 0.1$; $A_3 = B_3 = 1/60$

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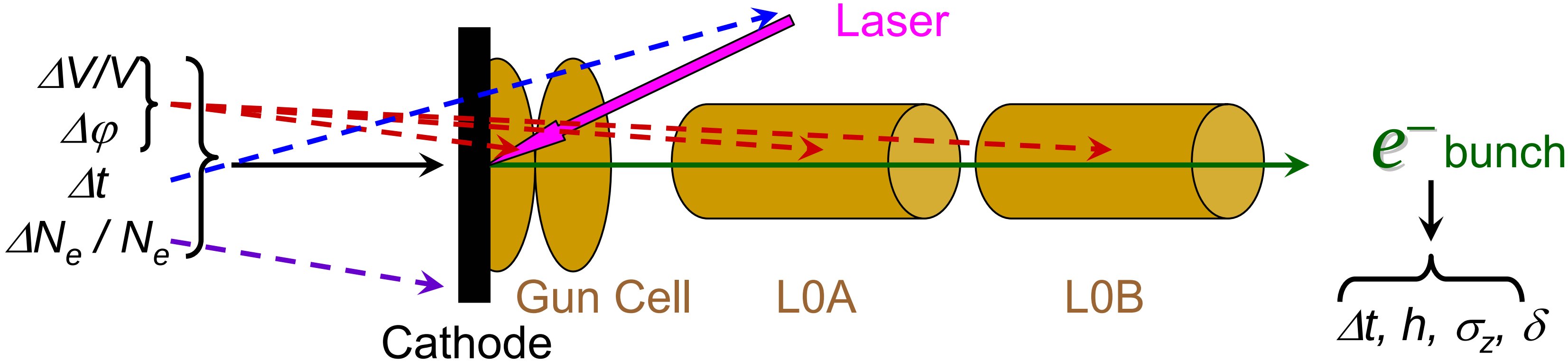
Injector jitter mapping into LINAC

- Use C. Limborg's PARMELA results (with Schottky effect) for injector



- At injector exit, the jitter is then modeled as:

$$y_i = a_{0i} + \sum_{j=1}^{8} \left(a_{1ij} x_j + a_{2ij} x_j^2 + a_{3ij} x_j^3 \right)$$

where $y_i \in (\Delta t, h, \sigma_z, \delta)$, and $h = \langle \delta\, z \rangle / \sigma_z^2$ is the chirp

and $x_j \in \begin{pmatrix} \Delta N_e / N_e, \Delta t_{\text{Laser}}, \Delta\varphi_{\text{Gun}}, \Delta V / V_{\text{Gun}}, \\ \Delta\varphi_{\text{L0A}}, \Delta V / V_{\text{L0A}}, \Delta\varphi_{\text{L0B}}, \Delta V / V_{\text{L0B}} \end{pmatrix}$

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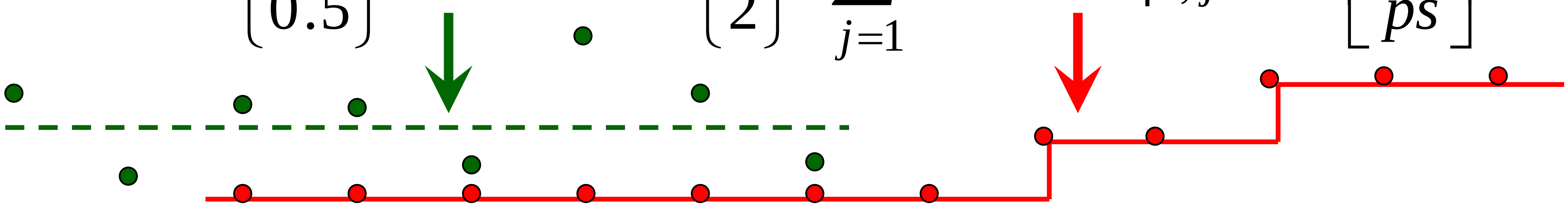
LCLS gun jitter model

- Similarly, the charge / Laser timing jitter at cathode:

$$\begin{Bmatrix} \dfrac{\Delta N}{N} \\ \Delta t \end{Bmatrix} = \begin{Bmatrix} 10 \\ 1 \end{Bmatrix} \sin(2\pi f_1 t) + \begin{Bmatrix} 1 \\ 0.1 \end{Bmatrix} \sin(2\pi f_2 t) + \begin{Bmatrix} 1/6 \\ 1/60 \end{Bmatrix} t$$

$$+ \begin{Bmatrix} 2 \\ 0.5 \end{Bmatrix} \text{randn}(1) + \begin{Bmatrix} 0 \\ 2 \end{Bmatrix} \sum_{j=1}^{N_{\text{step}}} \text{H}(t - t_{\text{step},j}) \quad \begin{bmatrix} \% \\ ps \end{bmatrix}$$



with $f_1 = 0.08$ Hz; $f_2 = 1.7$ Hz;

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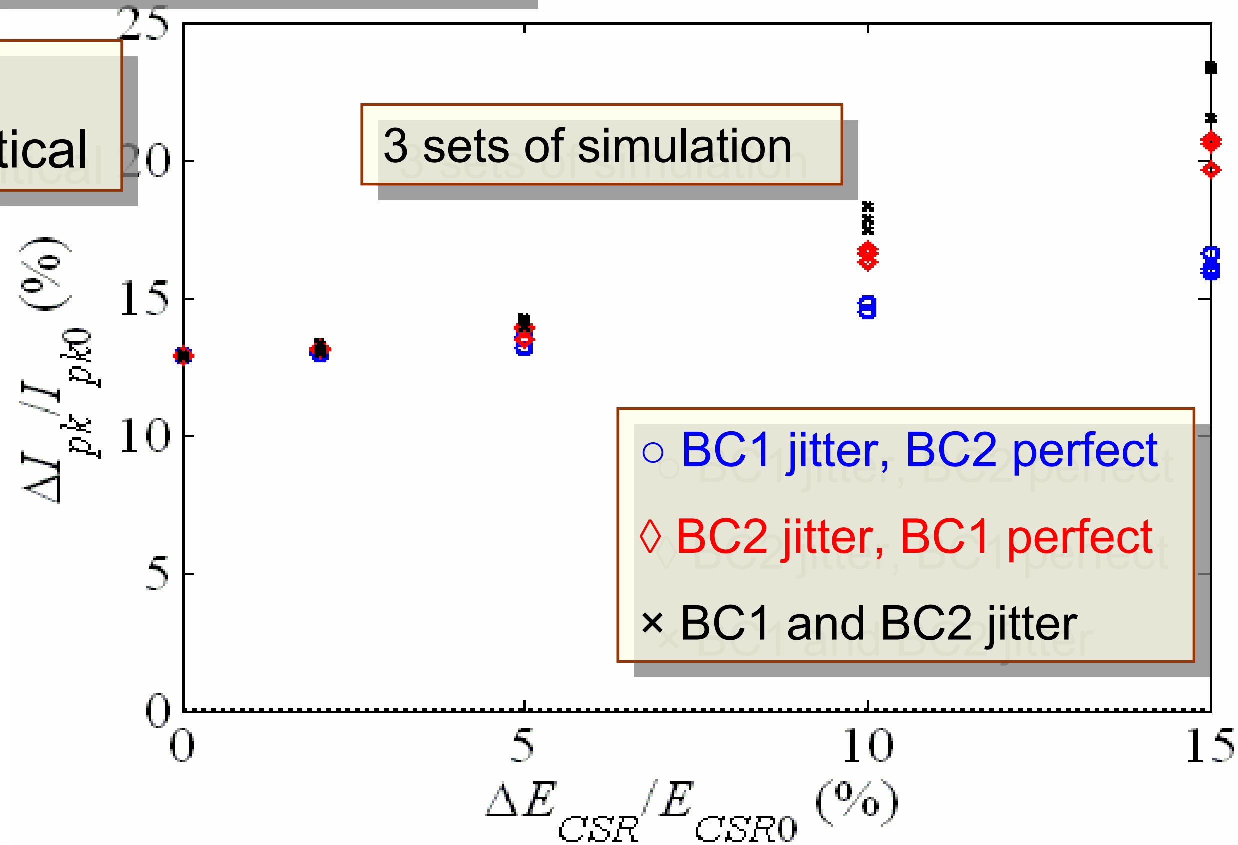
Monitor resolution

- BPM resolution ∈ [25, 40] μm
  ⇒ energy resolution ∈ [1.0, 1.7] × 10^{-4}
  → much better than required

- BLM resolution
  - BC2 → more critical



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