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Physics Requirements for LINAC Stabilization and Technical Solutions

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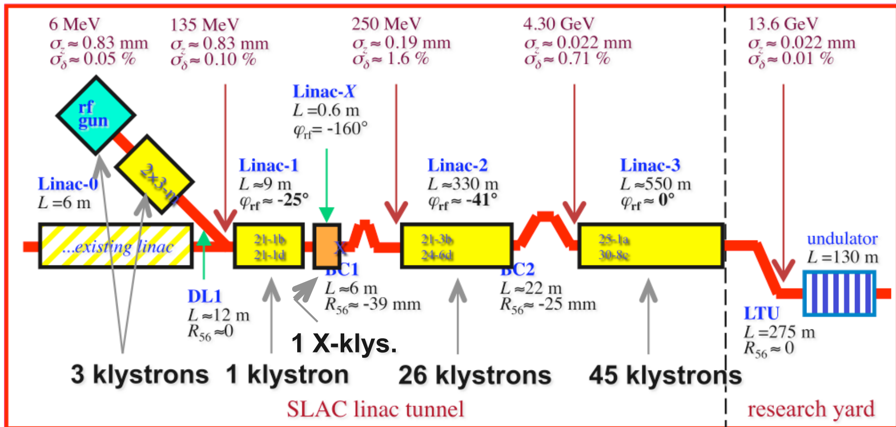
Customary disclaimer....

- Examples come only from pulsed lepton linacs (two FELs, two colliders)
  - *One is being commissioned, one is being constructed, two aren’t (yet)*

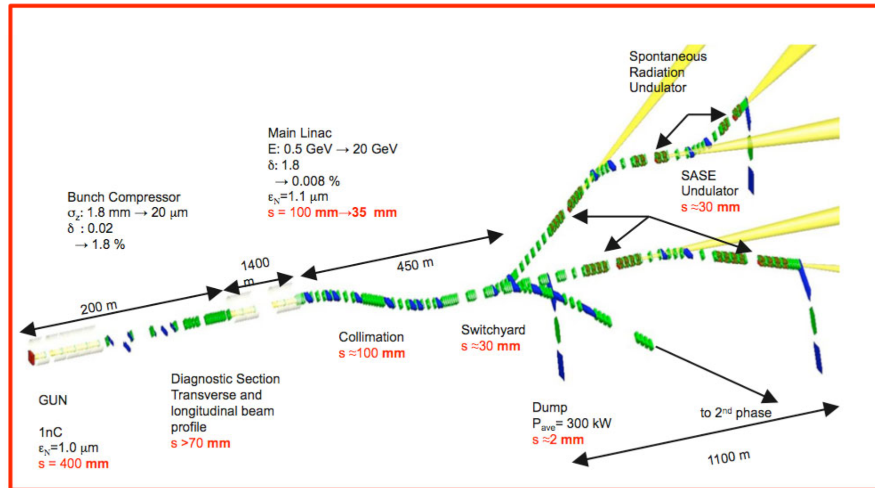
Outline

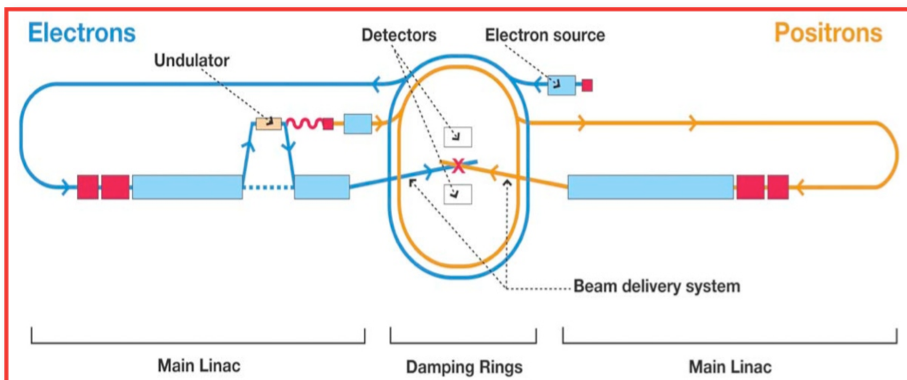
- Preliminaries
- Linac end-user expectations
- Recent stability requirements
- Example solutions
  - Magnet stabilization
  - Beam-based feedback
  - Fast trajectory control
- Wrap-up

LCLS XFEL: 13.6GeV NC linac (~1km)

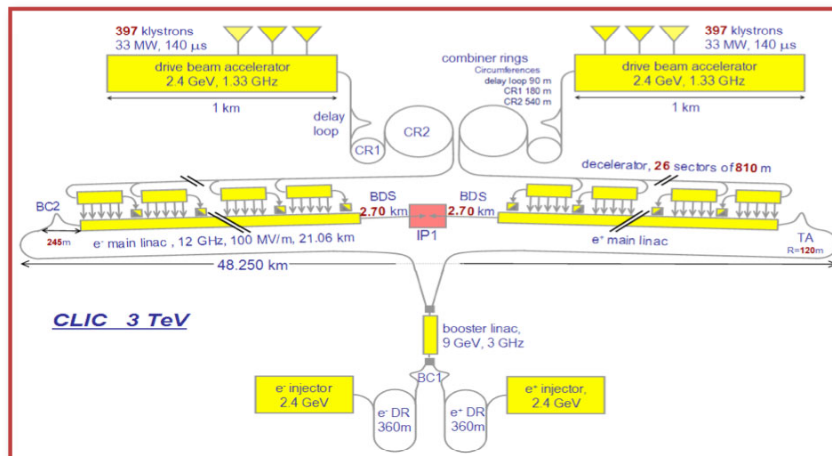


EU-XFEL: 20GeV SC linac (~1.6km)





ILC: 2x 250GeV SC linacs (2x ~11km)



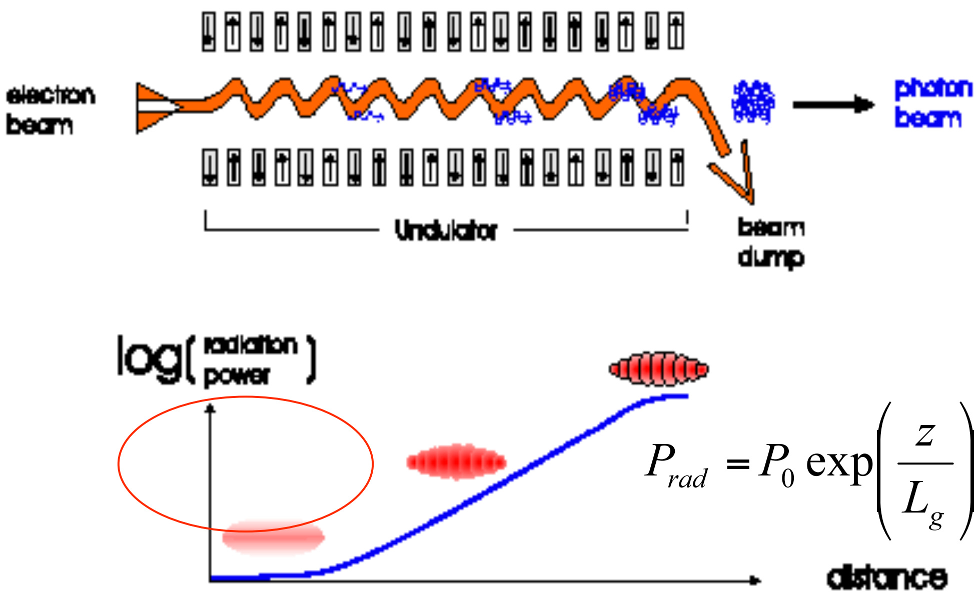
CLIC: 2x 1.5TeV NC linacs (2x ~21km)
(+ drive beam linacs)

A few design parameters

	ILC	CLIC	EU-XFEL	LCLS	units
Energy	500 CM	3000 CM	20	13.6	GeV
RF frequency	1.3	12	1.3	12	GHz
Linac rep rate	5	50	10	120	Hz
Beam pulse length	970	0.15	650	--	us
Bunches/pulse	2670	312	3250	1	
Charge/bunch	3.2	0.6	1.0	1.0	nC
Bunch length	300	44	25	20	um
Luminosity	2	5.9			10^{34} $cm^{-2}s^{-1}$
Horiz. beam size at IP	640	45			nm
Vert. beam size at IP	5.7	0.9			nm
Peak current			5	3.4	kA
Slice emittance			0.9	1.2	mm-mrad

XFEL Principle

Linac based Self Amplification of Spontaneous Emission (SASE) Free Electron Lasers (FELs) in the X-Ray regime (~0.85 - 60 Å)



$$P_{rad} = P_0 \exp\left(\frac{z}{L_g}\right)$$

Gain Length $L_G = \frac{1}{\sqrt{3}}\left(\frac{I_A \gamma^3 \sigma_r^2 \lambda_u}{4\pi \hat{I} K^2}\right)^{\frac{1}{3}}$

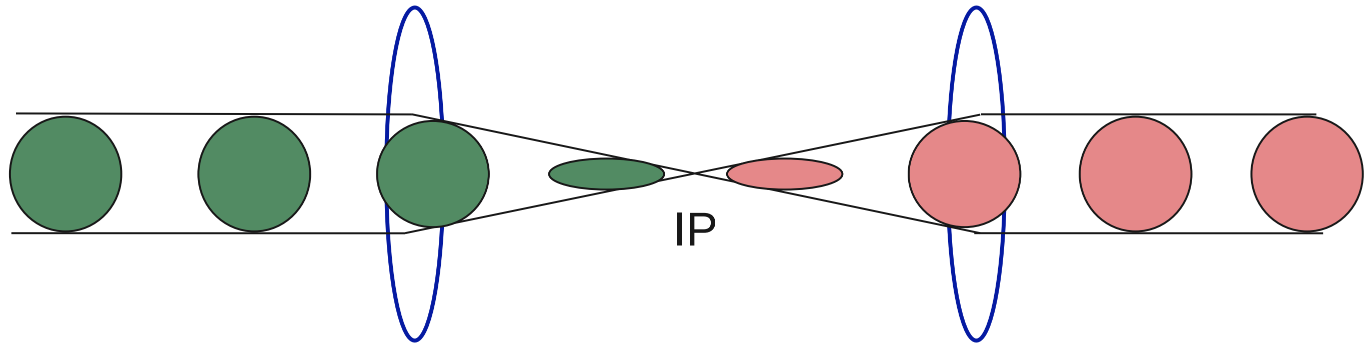
Electron bunch modulated with its own synchrotron radiation field
⇒ micro-bunching
⇒ more and more electrons radiate in phase until saturation is reached

Requires excellent electron beam quality:
- low (slice) emittance
- low energy spread
- extremely high charge density

Winni Decking

Colliders

Squeeze as much as possible to get the highest luminosity



Luminosity ($cm^{-2}\,s^{-1}$)

$$L \approx \frac{n_b N^2 f_{rep}}{A} H_D$$

n_b = bunches / train
N = particles per bunch
f_{rep} = repetition frequency
A = beam cross-section at IP
H_D = e+/e- enhancement factor

Requires excellent beam quality:

- Extremely high particle densities
- Bunches colliding at the focal point

Linac stability expectations

- **FEL Photon Source**
  - Photon beam pointing accuracy and stability
  - Photon wavelength, intensity (brilliance)
  - Photon bunch arrive time relative to a fiducial (pump probe experiments)

- **Linear Collider**
  - Energy precision and stability
  - Luminosity
  - Integrated luminosity

→

Particle density

Relative pointing accuracy at the IP

Relative arrival time at the IP

Small beams (nm)
Low emittance (nm-rad)

→

Very tight tolerances
High-resolution diagnostics

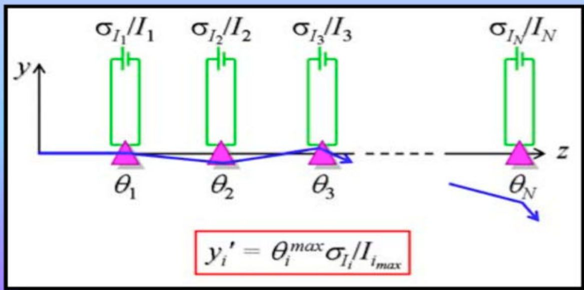
Critical LCLS Accelerator Parameters

Critical LCLS accelerator parameters

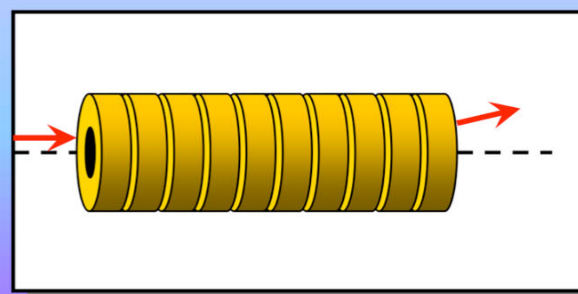
- Final energy 13.6 GeV (stable to 0.1%)
- Final peak current 3.4 kA (stable to 12%)
- Transverse emittance 1.2 mm-mrad (stable to 5%)
- Final energy spread 1e-4 (stable to 10%)
- Bunch arrival time (stable to 150 fs)

P. Emma

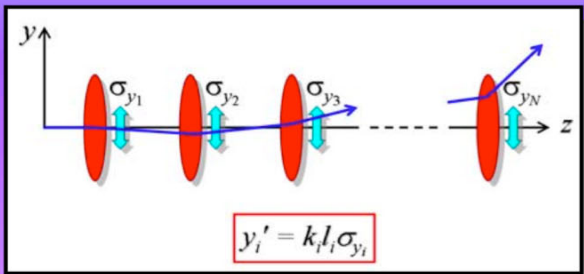
Sources of Transverse Beam Jitter



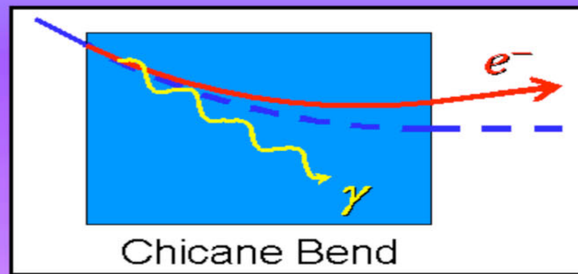
Steering coil current regulation



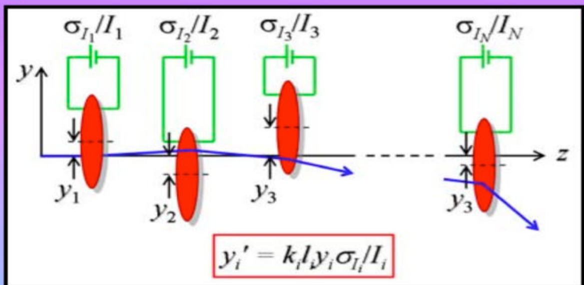
Wakefield kicks with charge jitter



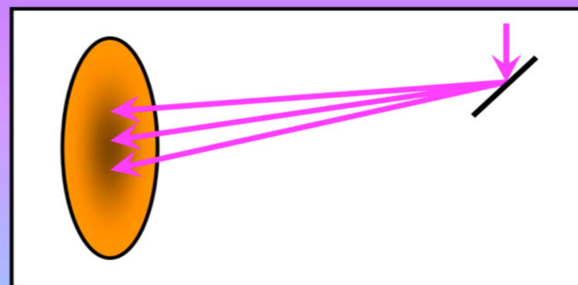
Quadrupole magnet transverse vibration



CSR kicks with charge or bunch length jitter



Quadrupole current regulation with misalignments



Drive laser pointing jitter

P. Emma, J. Wu, *EPAC'06*, p. 151.

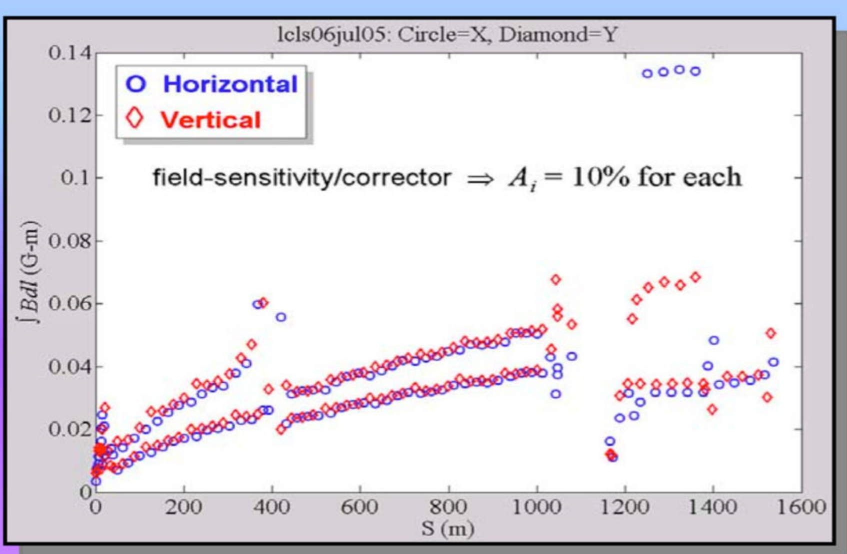
$$A_i = y_i'\sqrt{\frac{\beta_i}{\epsilon_i}}$$ Normalized invariant amplitude per item (n-sigma)

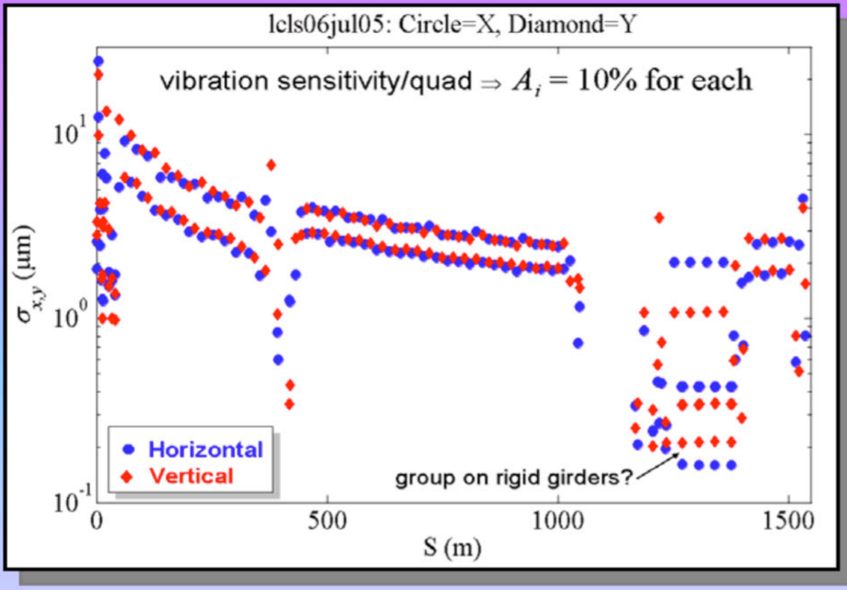
$$A_T^2 = \sum y_i'^2 \frac{\beta_i}{\epsilon_i}$$ Total amplitude² for N uncorrelated kicks

→ **GOAL**: $A_{x,y} < 10\%$ rms

Smaller ε means tighter tolerances

Calculate Jitter Sensitivities for Each Component





Steering coil sensitivities through entire accelerator

Quadrupole vibration sensitivities through entire accelerator

LCLS Regulation Example:

241 *staged* coils:

$\Delta I/I < 0.01 - 0.003\%$

Form a tolerance budget for all components…

LCLS Quadrupole Vibration Example:

12 quads < 500 nm

100 quads < 100 nm

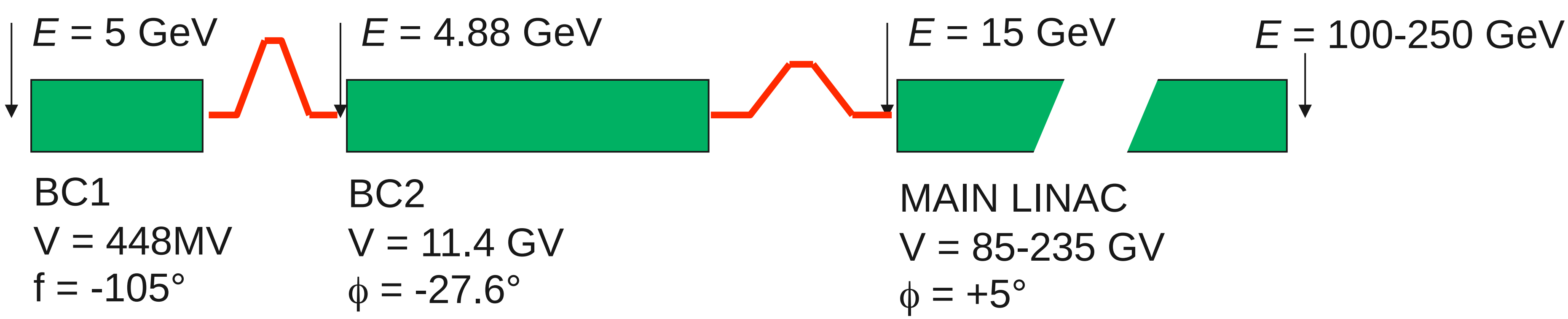
35 quads < 50 nm

P. Emma, J. Wu, *EPAC'06*, p. 151.

Example: sensitivities to RF phase & amplitude

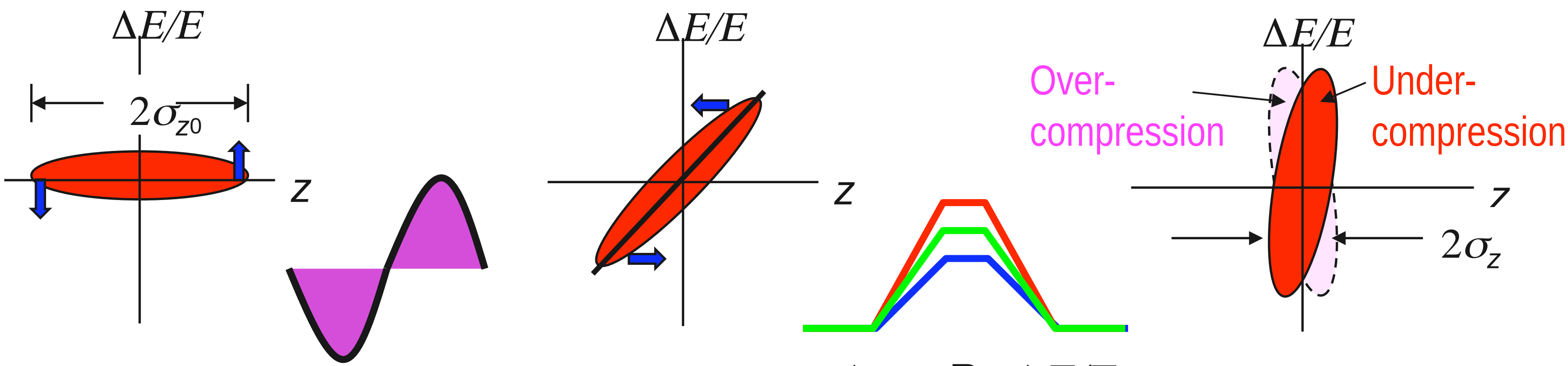
- **ILC energy stability requirement: 0.1% ΔE/E for 200-500GeV**
  - RF phase & amplitude stability (vector sum over all cavities)

- **RF amplitude and phase also talk to *luminosity***
  - Emittance growth accelerator (energy spread)
  - Transverse jitter from cavities (cavity tilt, RF coupler kicks,…)
  - Timing jitter at IP (from bunch compressors):
    - ***Tolerance: 235fs (~70 μm) for ΔL/L loss of 2%***



N. Walker

Bunch compressors

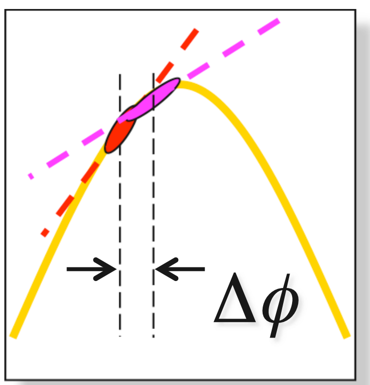


$V = V_0 \sin(\omega\tau)$

RF chirp

$\Delta z = R_{56} \Delta E/E$

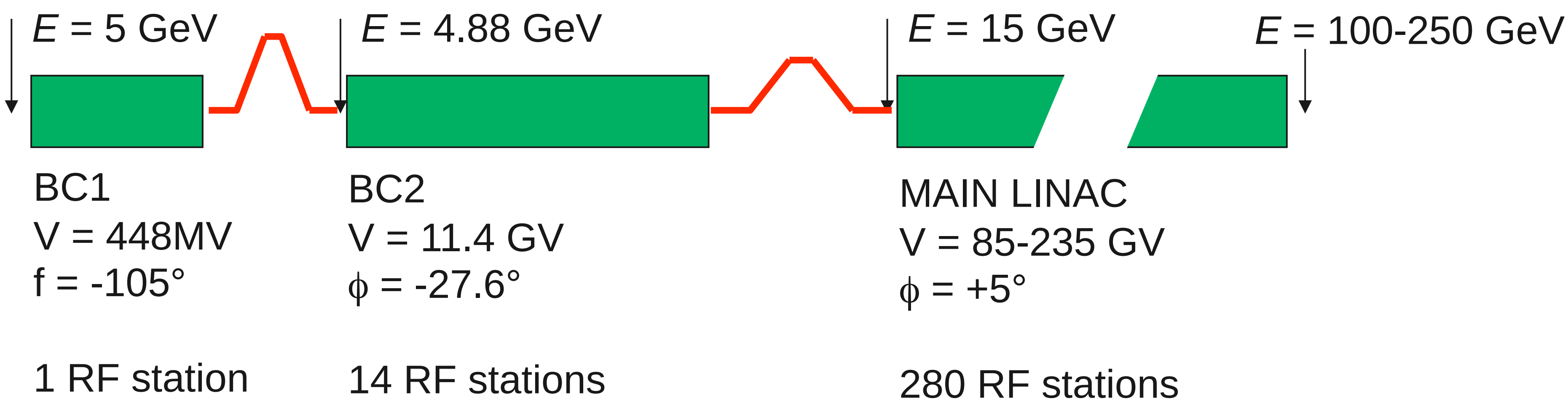
Energy-dependent path length



RF amplitude or phase jitter becomes:

- Bunch length jitter
- Jitter in arrival time at IP

Sensitivity to a 1 degree error in BC1 Phase (1 klystron)

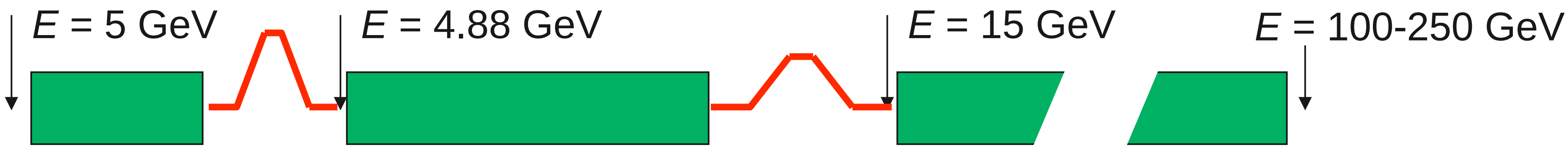


1° error ⇨	**7.5MeV** ⇨	**76MeV** ⇨	**76MeV**
	581μm	**274μm**	**274μm**

For bunch to arrive within 70μm of IP:
BC1 phase error must be less than 0.25 deg

N. Walker

Sensitivity to a 1% error in BC1 Amplitude (1 klystron)



BC1	BC2	MAIN LINAC
V = 448MV	V = 11.4 GV	V = 85-235 GV
f = -105°	ϕ = -27.6°	ϕ = +5°
1 RF station	14 RF stations	280 RF stations

1% error →	**2.6MeV** →	**26MeV** →	**26MeV**
	199μm	**94μm**	**94μm**

For bunch to arrive within 70μm of IP:
BC1 amplitude error must be less than 0.74%

N. Walker

ILC RF phase & amplitude tolerances from RDR

	Phase (degree)		Amplitude (%)		Limitation
	Correlated	Uncorr.	Corr.	Uncorr	
Bunch compressors	0.24	0.48	0.5	1.6	Timing stability at IP (luminosity)
Main Linac	0.35	5.6	0.07	1.05	Energy stability

- **Tolerances must apportioned over all subsystems in the chain, eg**
  - RF master oscillator, reference distribution, signal paths, LLRF,...
  - (Also implicitly assumes something about disturbance envirnment)

- **Correlated or uncorrelated errors...?**
  - Correlated: eg RF master oscillator, AC power line, environment, ...
  - Uncorrelated: eg cavity field probes, measurement noise, ...
  - Partially correlated: eg common klystron modulator, relay racks,...

Conservative approach: assume all errors are correlated

LCLS Longitudinal Fast-Jitter Tolerance Budget

tolerances are rms values

$|\langle \Delta E/E_0 \rangle| < 0.1\%$ **and** $|\Delta I/I_0| < 12\%$

	Parameter	Symbol	LCLS	Unit
laser timing (w.r.t. RF) →	Gun timing jitter	Δt_0	0.50	psec
laser energy →	Initial bunch charge	$\Delta Q/Q_0$	2.0	%
mean phase of 2 klys. →	mean L0 rf phase	φ_0	0.10	deg
1 klys. →	mean L1 rf phase	φ_1	0.10	deg
1 X-klys. →	mean Lh rf phase X-band	φ_h	0.50	X- deg
mean phase of 26 klys. →	mean L2 rf phase	φ_2	0.07	deg
mean phase of 45 klys. →	mean L3 rf phase	φ_3	0.15	deg
mean amp. of 2 klys. →	mean L0 rf voltage	$\Delta V_0/V_0$	0.10	%
1 klys. →	mean L1 rf voltage	$\Delta V_1/V_1$	0.10	%
1 X-klys. →	mean Lh rf voltage	$\Delta V_h/V_h$	0.25	%
mean amp. of 26 klys. →	mean L2 rf voltage	$\Delta V_2/V_2$	0.10	%
mean amp. of 45 klys. →	mean L3 rf voltage	$\Delta V_3/V_3$	0.08	%

P .McIntosh

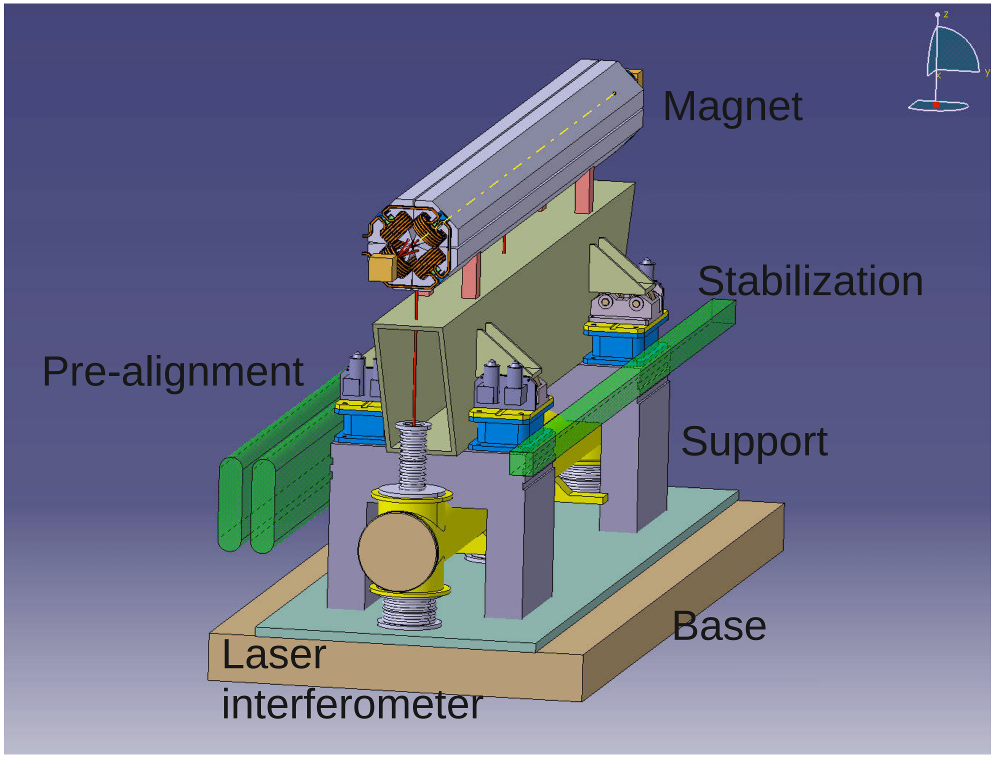
Examples of luminosity loss sources (CLIC)

Source	budget	raw tolerance
Damping ring extraction jitter	1%	
Magnetic field variations	?%	
Bunch compressor jitter	1%	
Quadrupole jitter in main linac	1%	$\Delta\epsilon_y = 0.4\,\mathrm{nm}$ $\sigma_{jitter} \approx 1.5\,\mathrm{nm}$
Structure pos. jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04\,\mathrm{nm}$ $\sigma_{jitter} \approx 200\,\mathrm{nm}$
Structure angle jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04\,\mathrm{nm}$ $\sigma_{jitter} \approx 170\,\mathrm{nradian}$
RF jitter in main linac	1%	
Crab cavity phase jitter	1%	$\sigma_\phi \approx 0.01^\circ$
Final doublet quadrupole support jitter	1%	$\sigma_{jitter} \approx 0.18\,\mathrm{nm}$
Other quadrupole jitter in BDS	1%	
...	?%	

D. Schulte

CLIC beam line mockup nano-stabilization demonstration

- Demonstrate 0.1nm vertical stability and 5nm horizontal stability above 4Hz for the final focus doublets
- Demonstrate 1nm vertical stability and 5nm horizontal stability above 1Hz for the main beam quadrupoles



- Should be demonstrated with realistic equipment in an accelerator environment
- Verified by at least two independent systems

Claude Hauviller

Beam experiment at CESRTA

- 1st phase: Demonstration of nm-sensitivity for beam motion observation
- 2nd and 3rd phase: demonstration of quad stabilization on a nm-level

- Installation of high sensitivity electronics onto an existing BPM at CESR: BBQ electronics. (M.Gasior et al. (CERN); successfully used for tune diagnostics at CERN, FNAL, BNL
- Using CESR with low emittance beams (order of micrometers)
- Optimization of this electronics for very low frequencies: 10 Hz – 100Hz; observation of beam spectra; selection of narrow frequency window with lowest beam eigen-motion
- Controlled low amplitude beam excitation through current modulation of a corrector dipole.
- Trying to obtain a reasonable signal to noise ratio for beam oscillations of nm-size (expected measurement time: 15 minutes)

HS, 15.5.2009

H. Schmickler

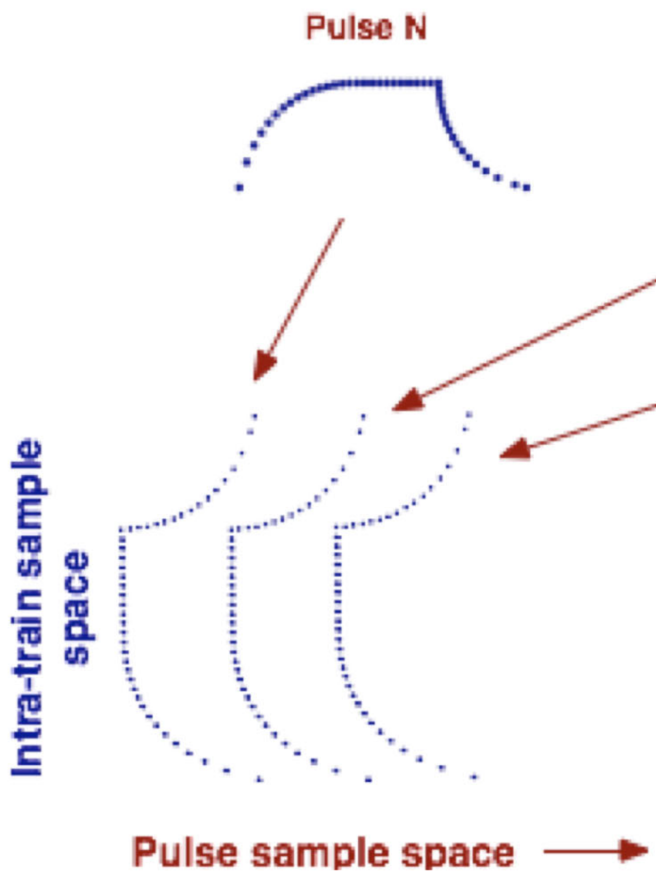
Beam stability timescales

- Slow
  - Ground motion, settling
  - Thermal, diurnal
- Medium
  - Vibration: magnets, cooling
  - AC line frequency
  - RF phase reference drift
  - Acoustic noise
- Fast
  - Power supply ripple
  - AC line voltage
  - Gun laser trigger
  - RF phase jitter, timing jitter

- Correlated (common-mode) or uncorrelated
  - In time
  - Over multiple systems
- Deterministic (correctable) or random
  - Depends on frequency content relative to the pulse- or bunch- rep rate

Bandwidths are rarely defined when stability is specified

Feedback preamble: two sample spaces



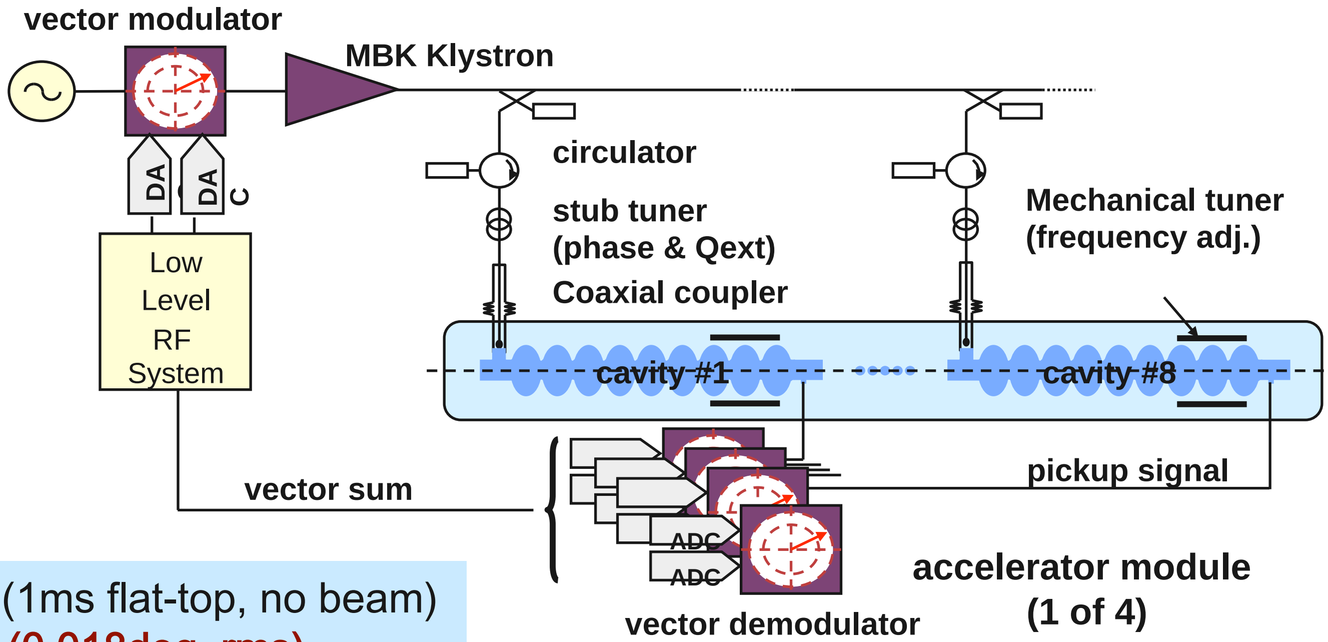
'Intra-train sample space:

- 'Windowed' sampled data system
- Sampling rate = bunch rate
- Window length = number of bunches

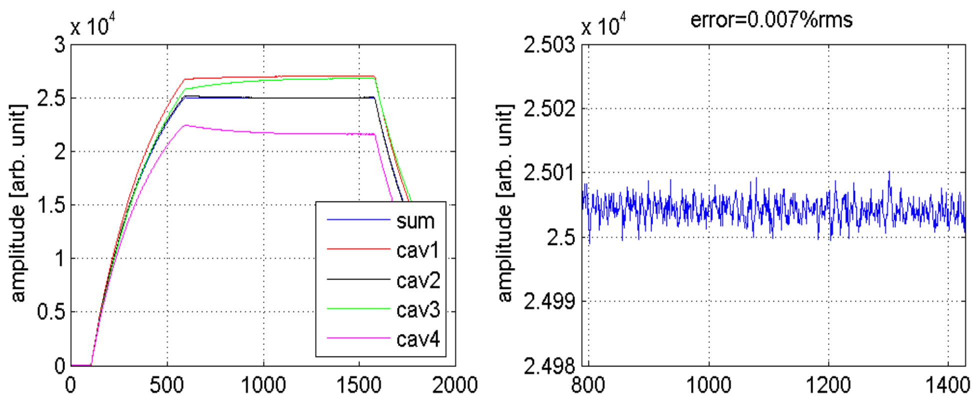
'Pulse-to-pulse' sample space:

- 'Steady state' sampled data system
- Sampling rate = pulse repetition rate

LLRF regulation of SC cavities with heavy beam loading



4-cavity VS control (1ms flat-top, no beam)
0.007% rms (0.018deg. rms)



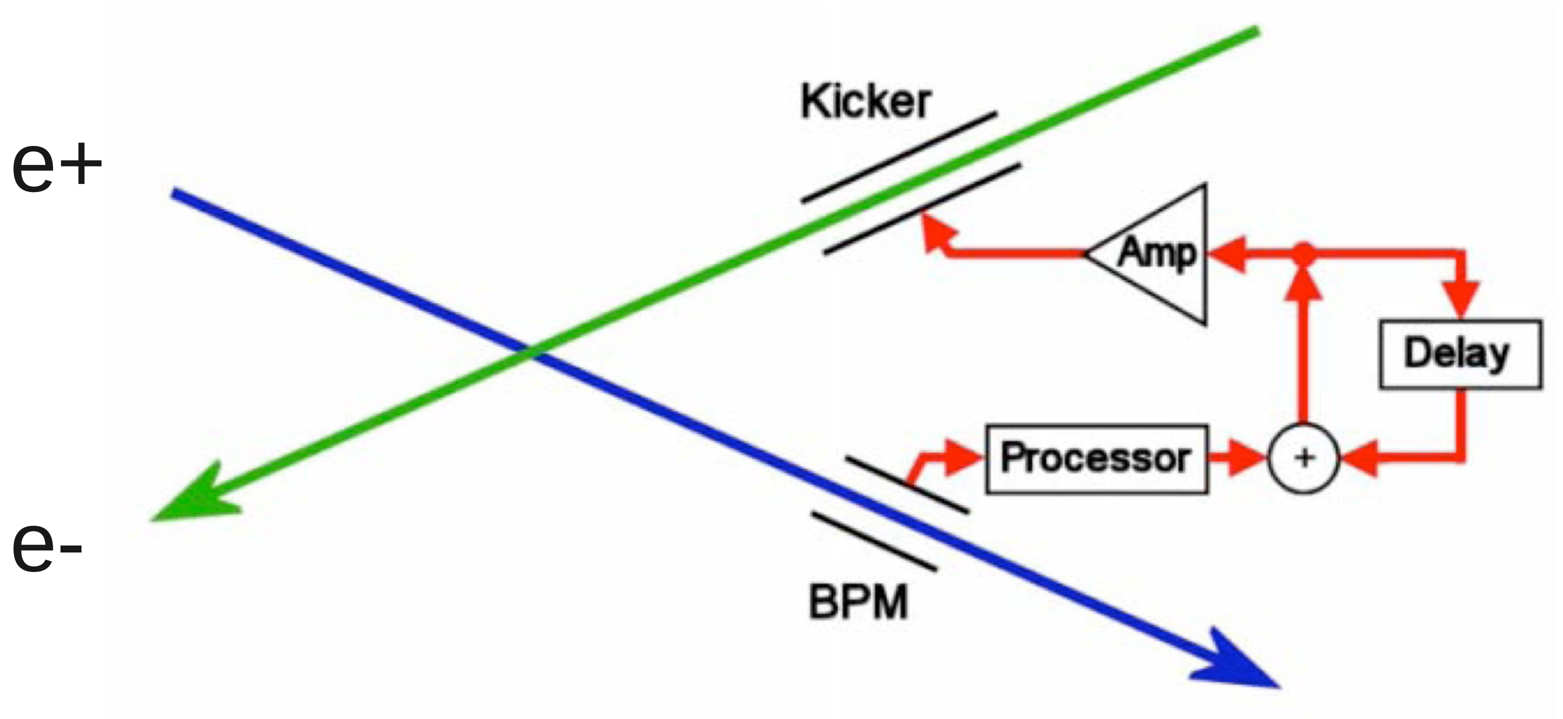
S.Michizono

Stability specs are difficult
(<0.1% dE/E for all bunches)

- Heavy beam loading
- Beam loading transients
- Narrow cavity bandwidth
- Lorentz-force detuning
- Operation close to quench

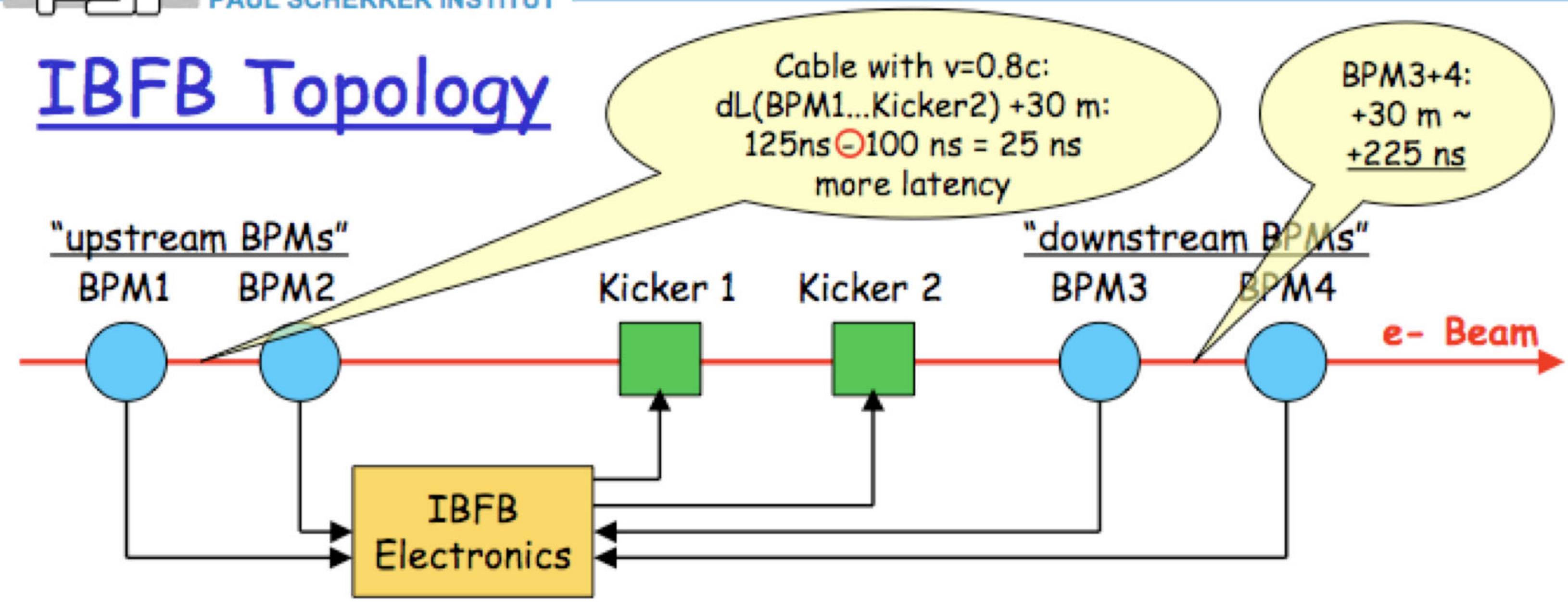
IP beam-based feedback for LC

- Maximize luminosity by correcting trajectory within bunch train
- Kicker and bpm must be close together for fast correction rate
- Need very high precision single-pass bpms



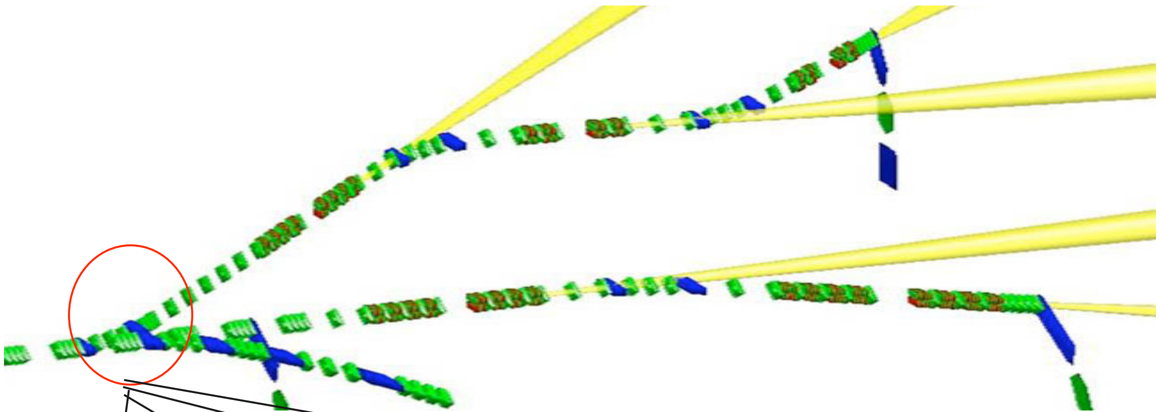
P. Burrows

IBFB Topology



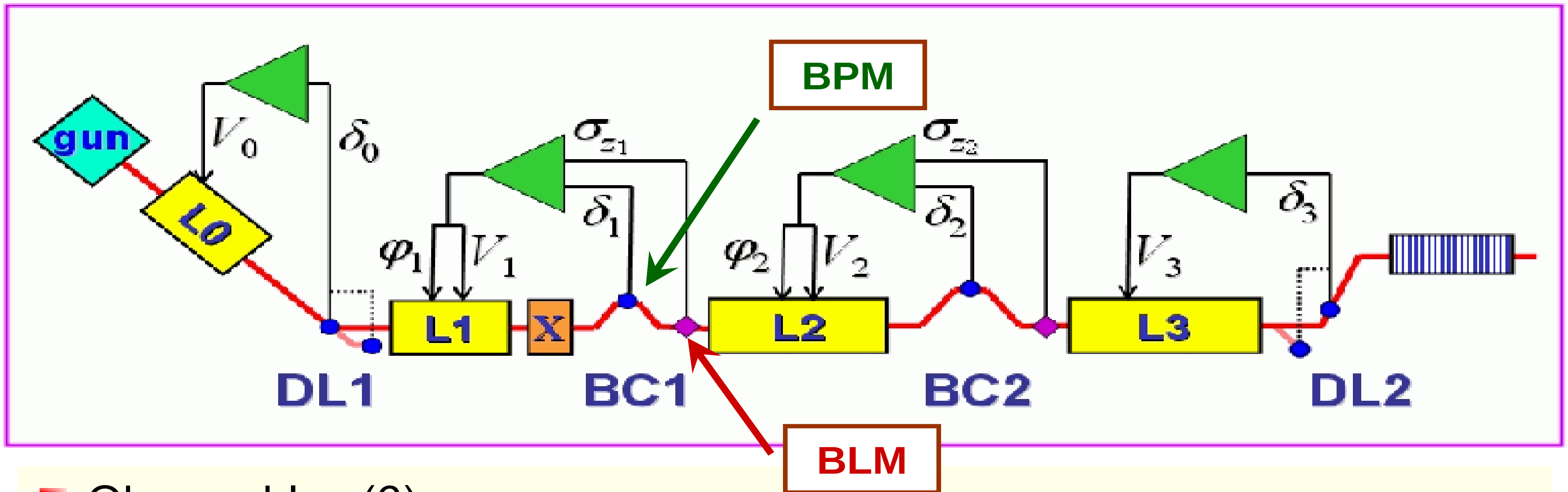
- Use beam positions at upstream BPMs of bunch no. N, N-1, N-2, N-3,... to calculate kicks for bunch no. N+1 using a model (200 ns bunch spacing)
- Use downstream BPMs to check & correct model (less fast)
- Why upstream (not downstream) BPMs for fast feedback loop ?
  - Less latency (beam and cable signals travel in parallel)
  - -> Larger distance between BPMs -> better angle resol.
  - BPM1+2 see unkicked beam: IBFB puts less noise onto the beam

EU-XFEL Active element switch-yard



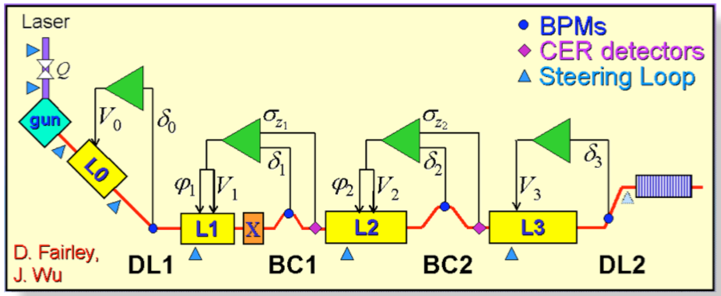
DC Magnet	Slow switch pulse to pulse	High Q Resonator	Programmable fast kicker for individual bunches
One beamline only Commissioning option	Duty cycle reduced by # beamlines TDR option	Fixed bunch pattern, full duty cycle	Flexible $\frac{\Delta\Theta}{\Theta} < 2\times10^{-4}$

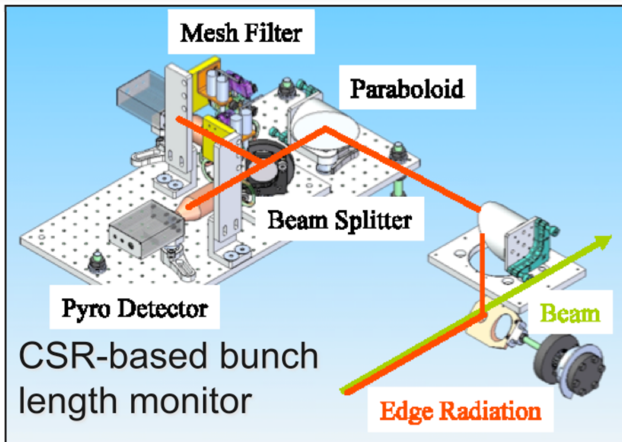
LCLS longitudinal feedback system schematic



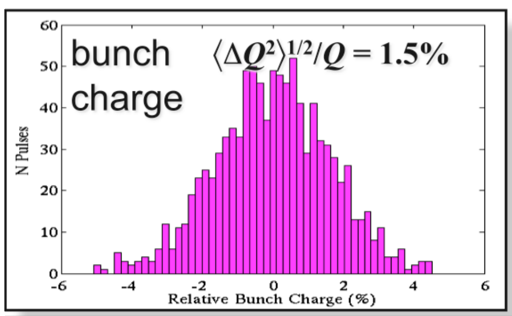
- Observables (6):
  - Energy: E_0 (at DL1), E_1 (at BC1), E_2 (at BC2), E_3 (at DL2)
  - Coherent Radiation power → bunch length: $\sigma_{z,1}$ (at BC1), $\sigma_{z,2}$ (at BC2)
- Controllables (6):
  - Voltage: V_0 (in L0), V_1 (in L1), V_2 (effectively, in L2)
  - Phase: φ_1 (in L1), φ_2 (in L2),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

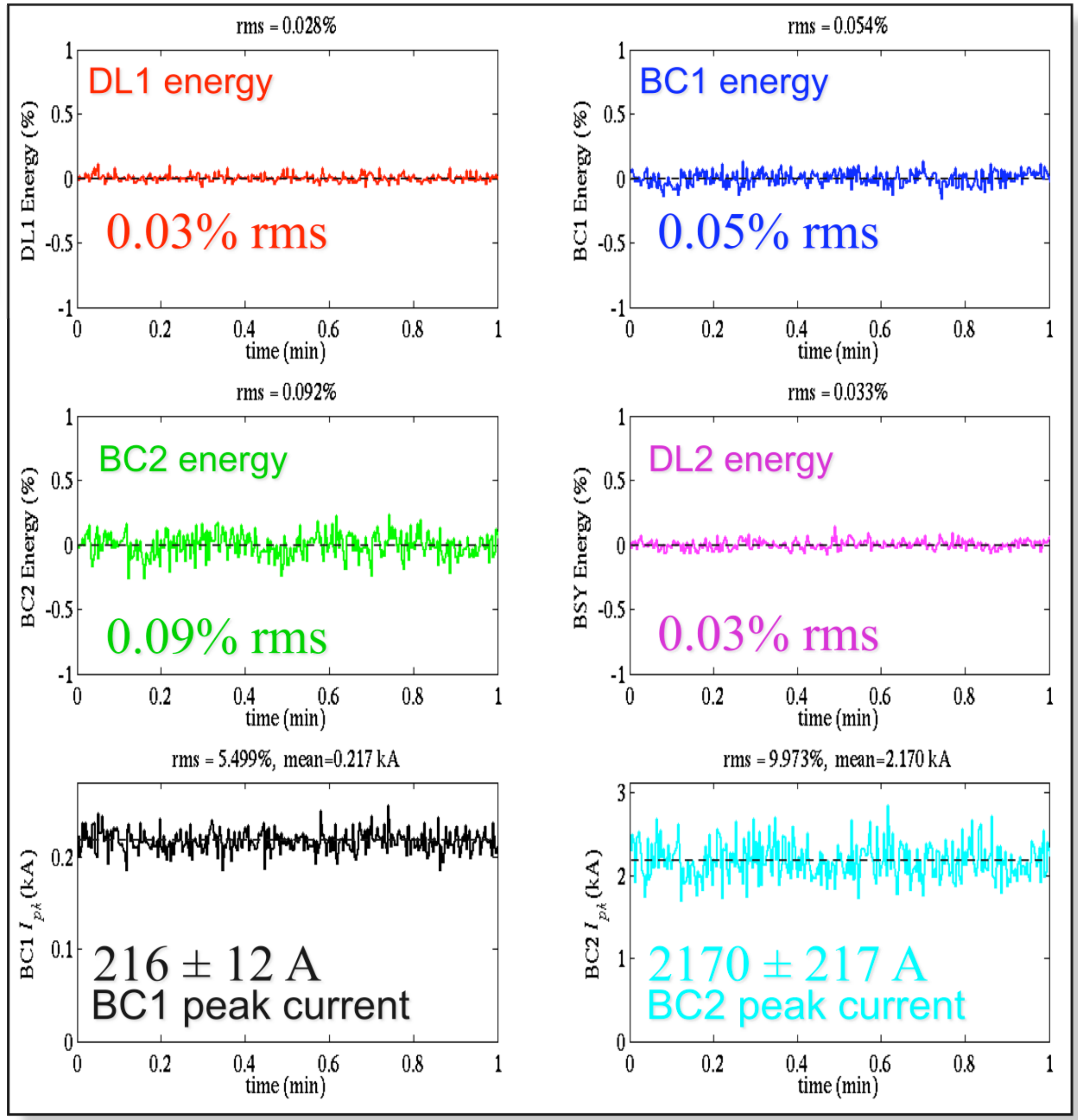
Bunch Length & Energy Feedback Systems



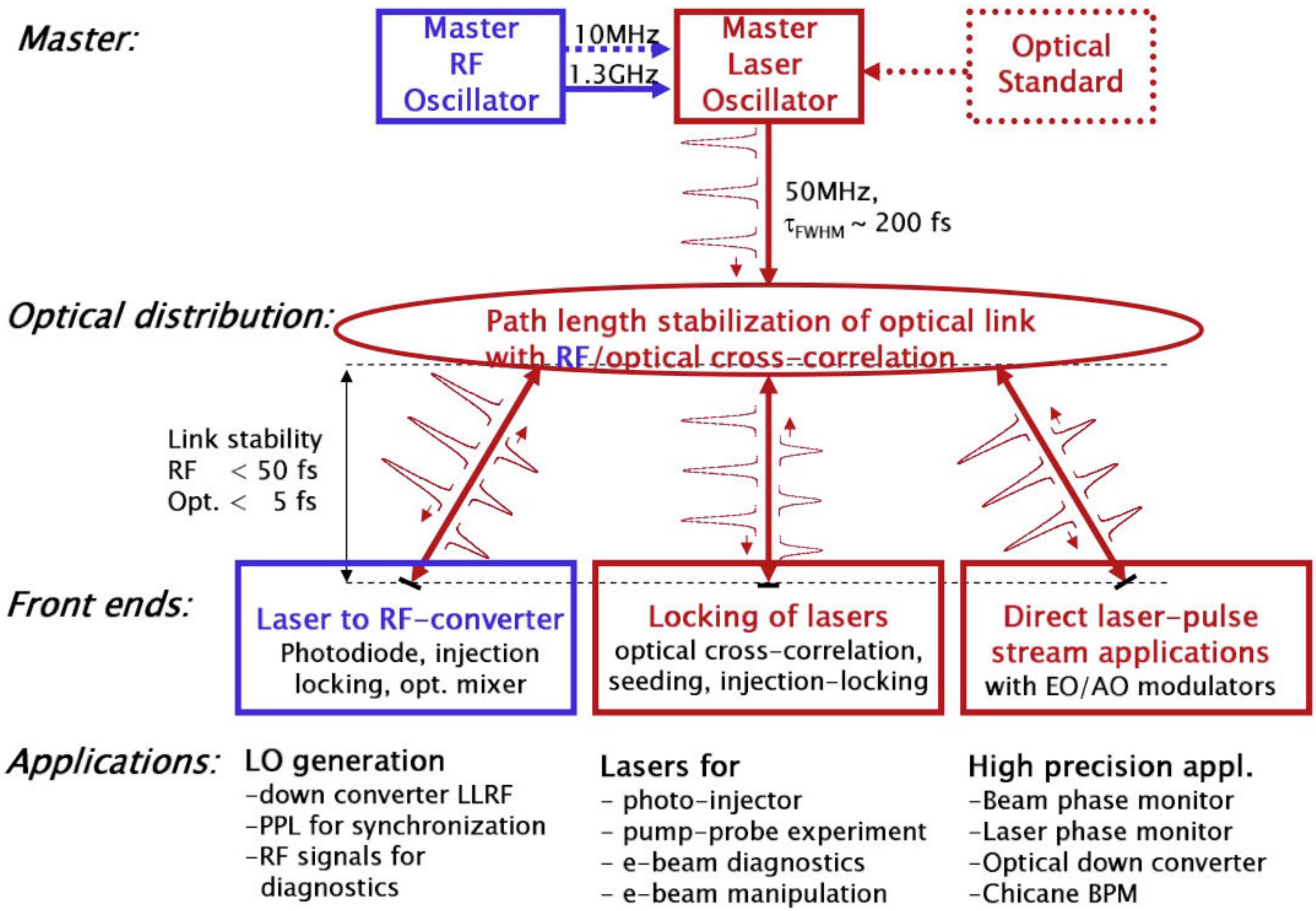


Charge feedback: $Q = 0.25$ nC





Layout of laser based synchronisation



Holger Schlarb

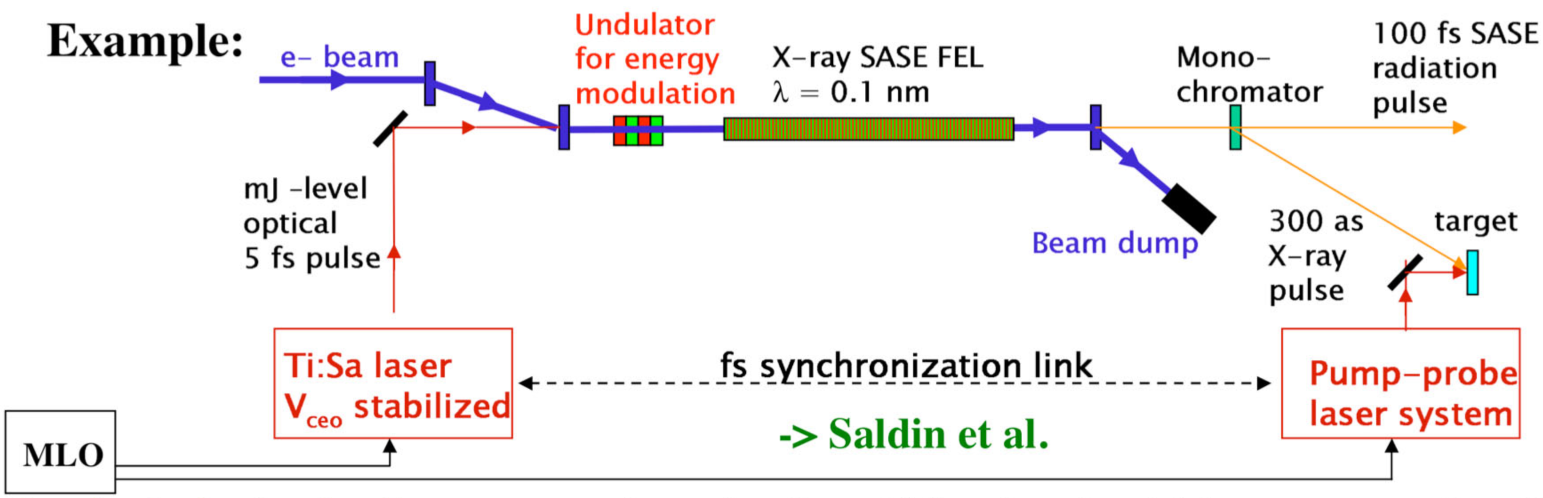
Attosecond synchronization! - outlook & upgrade -

- always based on electron beam manipulation by lasers

Requirements:

1. Electron beam is synchronized to laser < $\sigma_t \sim$ 30-60 fs
2. Manipulation laser to exp. laser on femtosecond level

Example:



Optical clocks for lasers: synchronized to 100as level within macro pulse (1ms)

Avoids problems with vibration and diffuse ground motion (< 1kHz, 30ns=100as)

Fiber link operates at small unity gain frequency (10Hz) for resynchronization

Holger Schlarb

Wrap-up

- Linac stability requirements have never been more stringent
- Future machines are already promising to demand even better stability

We can't control what we can't measure...

Thank you for your attention