Towards ultrastable linac-driven free electron lasers

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NGLS RF and Beam-based Feedback Team

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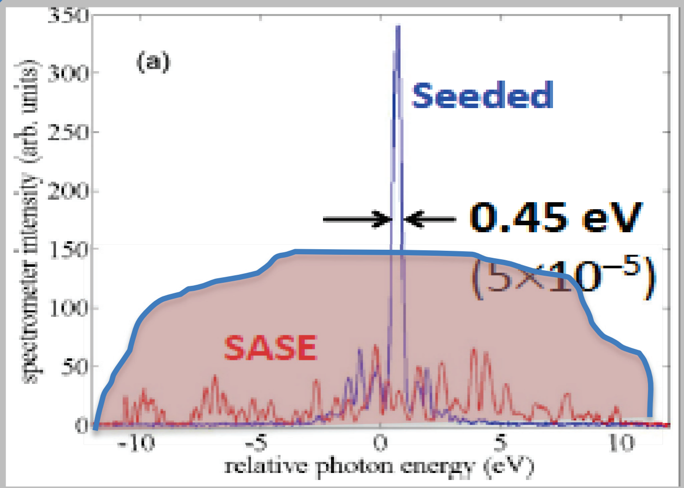
Why do we need ultrastable linacs for FELs?

Energy Stability for seeding: e.g. self-seeding

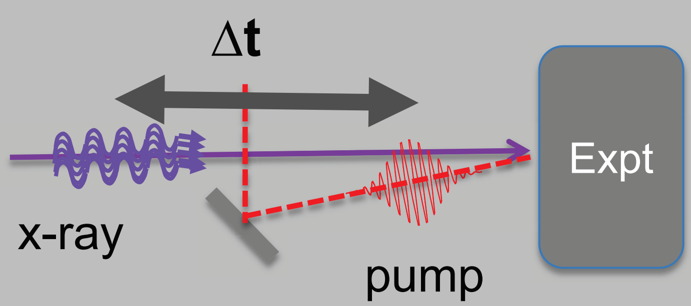
- Seeding increases FEL amplitude stability.
- Electron beam energy jitter moves the FEL bandwidth in and out of the selected seeding frequency resulting in large amplitude jitter of seeded FEL pulse.
- Many seeding schemes require stability of energy, linear and quadratic chirp, etc. for stable FEL output.



HXRSS@SLAC

Pump-probe synchronization: e.g. X-ray arrival time

- Critical for FEL science case
- Electron beam energy jitter creates arrival time jitter in the bunch compressors.
- Current schemes with >10 fsec jitter require shot-by-shot measurement on post-process binning.
- **If we can reduce x-ray jitter AND synchronize with pump laser, data can be averaged for a fixed delay.**



Why do we need ultrastable linacs for FELs?

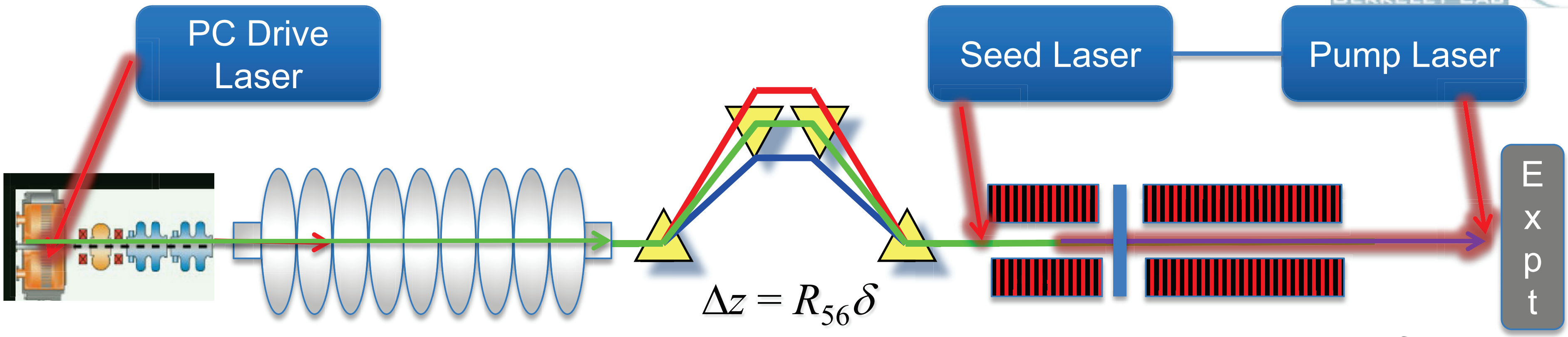
Energy Stability for seeding: e.g. self seeding

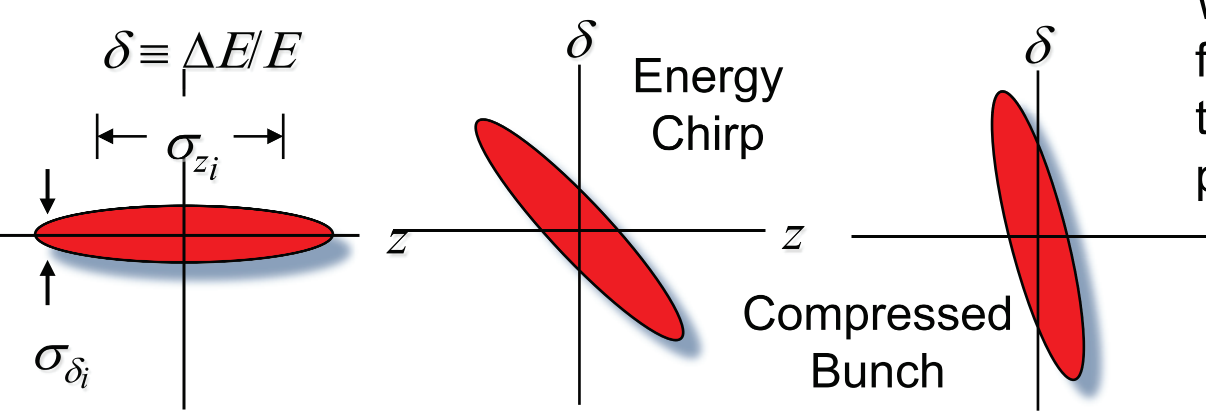
- For high rep-rate linacs (>several kHz) it is extremely challenging to do post-process binning because data from each pulse must be recorded.
- Therefore, it is critical (necessary?) to stabilize the arrival time **AND** synchronize the pump laser to less than a fraction of the x-ray pulse length to allow averaging for fixed pump-probe delays.
- Good news! This can be achieved and is already being done at FLASH with room to improve.
- This talk describes our efforts at modeling the stability performance and understanding the "ultimate" stability.

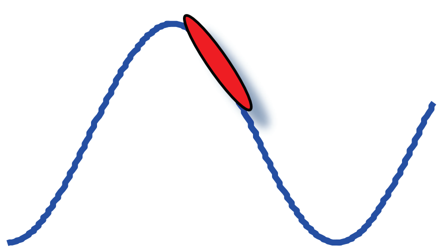
Pur

- If ... synchronize with pump laser, data can be averaged for a fixed delay.

Simplified Longitudinal Beam Dynamics







We can write equations for the first and second moments of the longitudinal beam parameters.

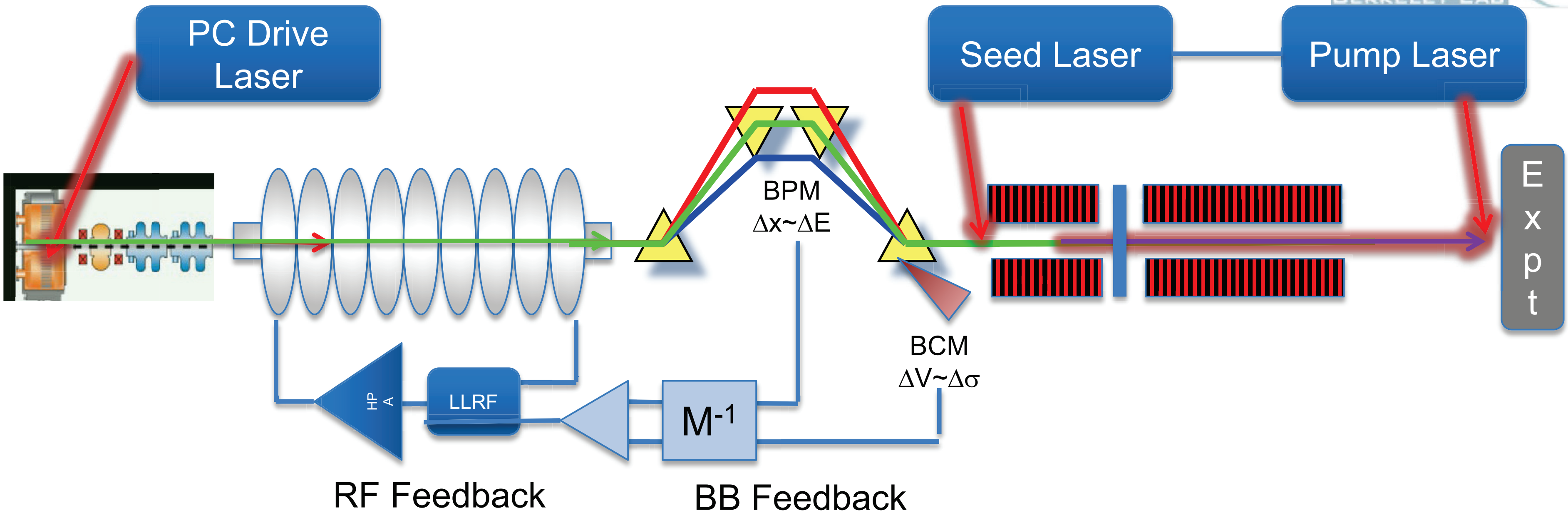
$$\sigma_{z_i}^2 = \left(1 + k_i R'_{56_i}\right)^2 \sigma_{z_{i-1}}^2 + \left(R'_{56_i} \sigma_{\delta_{i-1}} \frac{E_{i-1}}{E_i}\right)^2 + 2\left(1 + k_i R'_{56_i}\right) R'_{56_i} \frac{E_{i-1}}{E_i} \langle z_{i-1}\delta_{i-1}\rangle$$

$$\sigma_{\delta_i}^2 = k_i{}^2 \sigma_{z_{i-1}}^2 + \left(\sigma_{\delta_{i-1}} \frac{E_{i-1}}{E_i}\right)^2 + 2k_i \frac{E_{i-1}}{E_i} \langle z_{i-1}\delta_{i-1}\rangle$$

$$\langle z_i\delta_i\rangle = \left(1 + k_i R'_{56_i}\right) k_i \sigma_{z_{i-1}}^2 + R'_{56_i} \left(\sigma_{\delta_{i-1}} \frac{E_{i-1}}{E_i}\right)^2 + \left(1 + 2k_i R'_{56_i}\right) \frac{E_{i-1}}{E_i} \langle z_{i-1}\delta_{i-1}\rangle$$

$$\Delta t_i = \Delta t_{i-1} + \frac{1}{c}\left(\frac{\Delta E}{E}\right)_i R'_{56_i}$$

Simplified RF Cavity and Feedback Dynamics



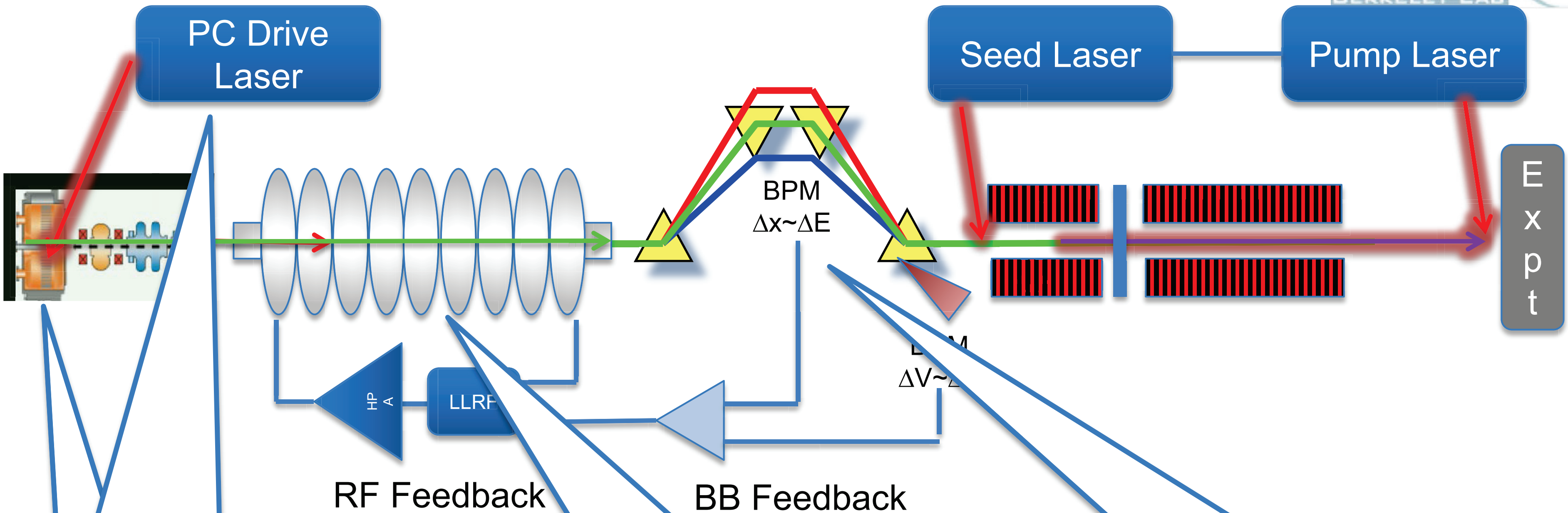
RF Model:
- Includes cavity response of fundamental and HOMs
- RF feedback model includes
  - Delays
  - Klystron response
  - PU and ADC noise
  - I and Q processing
  - PI controller

BBFB Model:
- Transform of $\Delta E/E$ and $\Delta\sigma$ to ΔV and $\Delta\phi$
- Pickup noise for BPM and BCM (or BAM)
- PI controller

Mode-locked laser oscillator dynamics

Under Development

Jitter Sources



PC Drive Laser:
- Pulse energy
- Time jitter
- Pulse length

Gun+Injector:
- RF Amp+Phase
- Bunch Charge

Linac:
- RF Amplitude+Phase
- ADC noise
- Klystron noise
- Beam loading modulation

Beam-based Feedback:
- Energy measurement (BPM)
- Arrival time (BAM)
- Bunch shape (BCM)

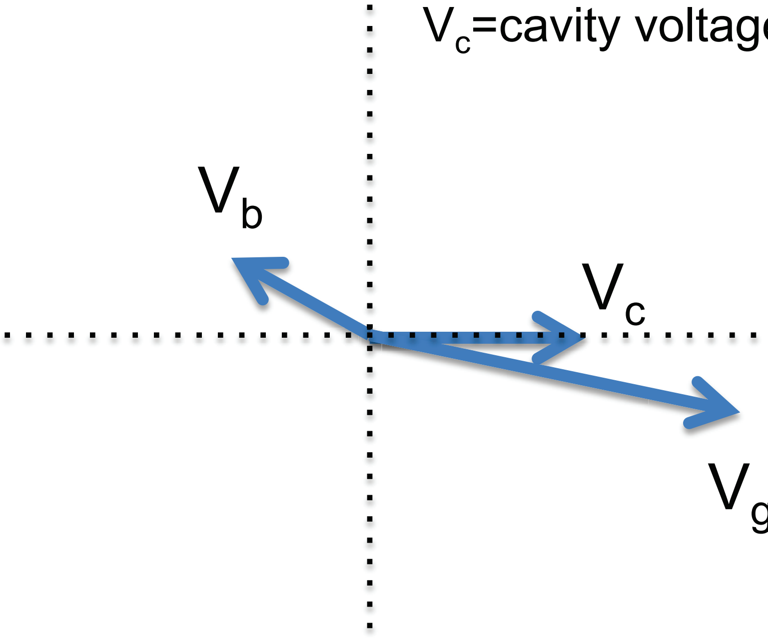
Beam Loading Modulation

- **Variation of the beam charge and arrival time modulate the beam-induced cavity voltage and present a sizeable perturbation to the cavity voltage.**
- **RF feedback will respond to perturbations in field. BB feedback will respond to resulting energy and bunch length errors within bandwidth of cavity response!**

V_b=beam voltage

V_g=generator voltage

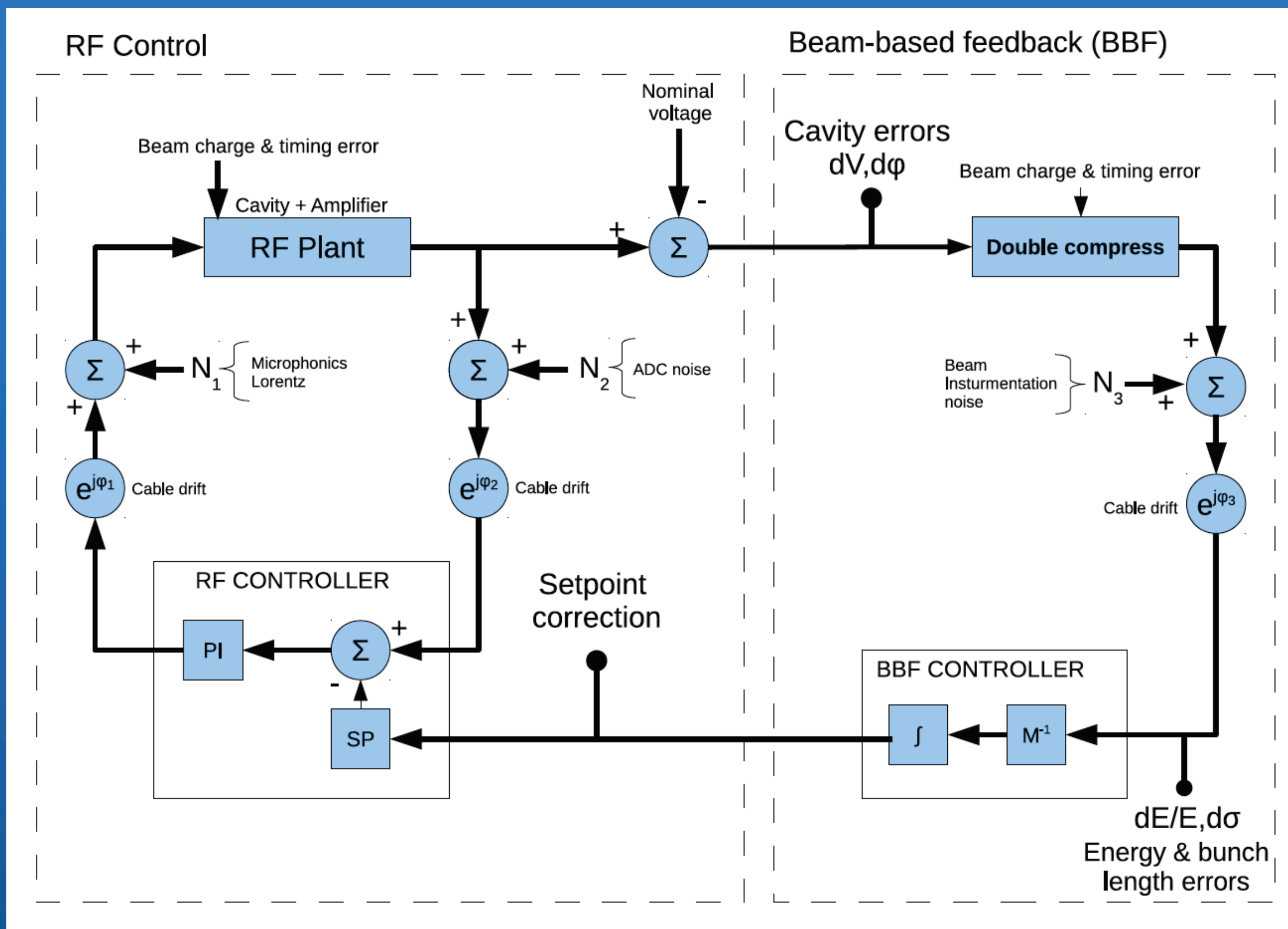
V_c=cavity voltage



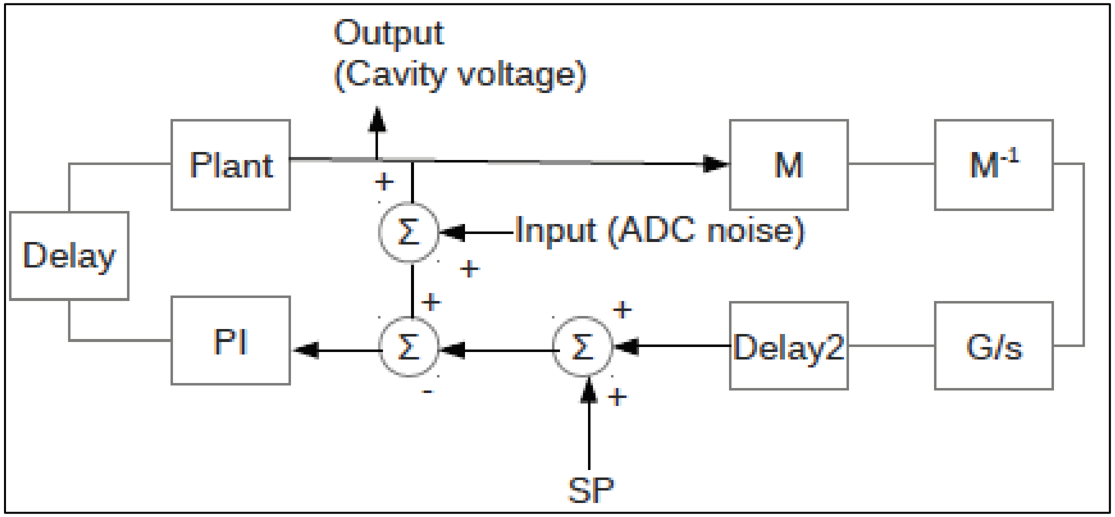
Beam-induced cavity voltage is roughly ½ the cavity voltage. Beam current and phase modulations cause major perturbations to cavity voltage and phase

Numerical model

Complete knowledge of the longitudinal beam dynamics, and the RF cavity, RF feedback and BBFB, allows us to express each linac section as a control system with signal and noise inputs.



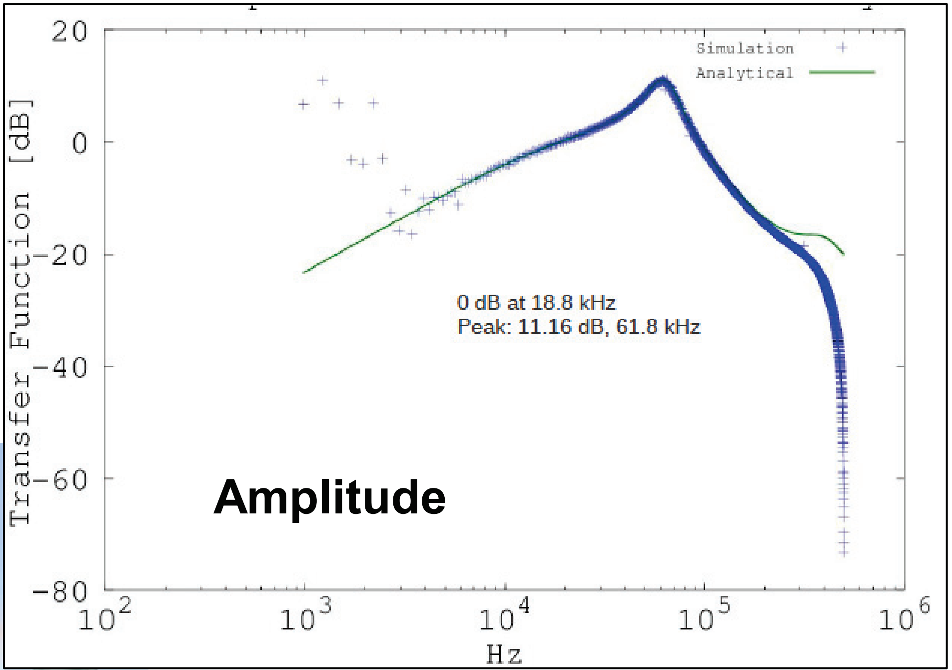
Simplified Linac Transfer Function

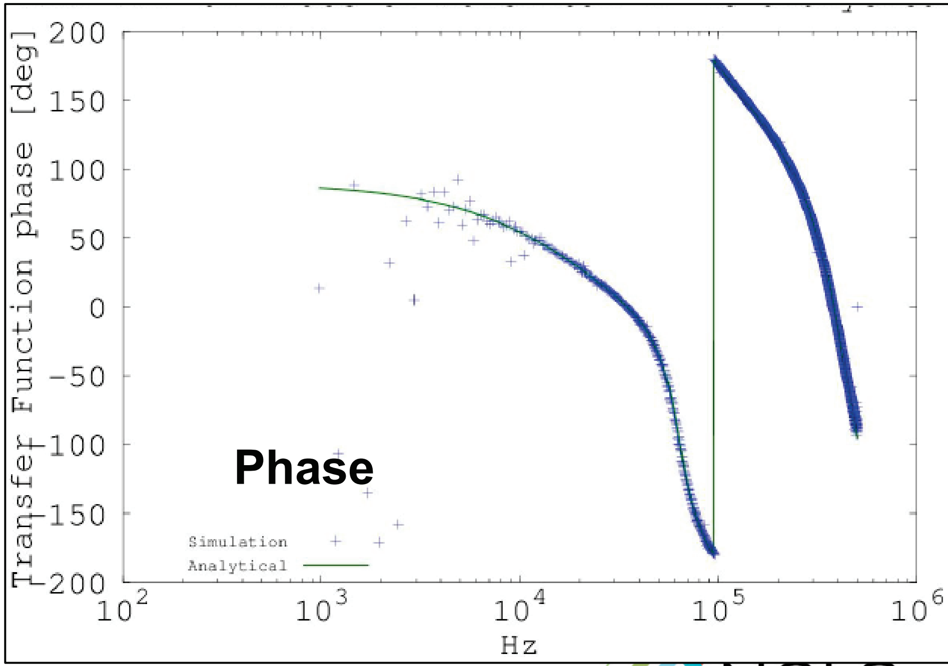


$$Delay_2 = e^{-s(T_2+T_{Sim})}$$

$$TF_{LLRFBBF_{CL}} = -\frac{TF_{LLRF}}{1+TF_{LLRF}Delay_2\frac{g}{s}}$$

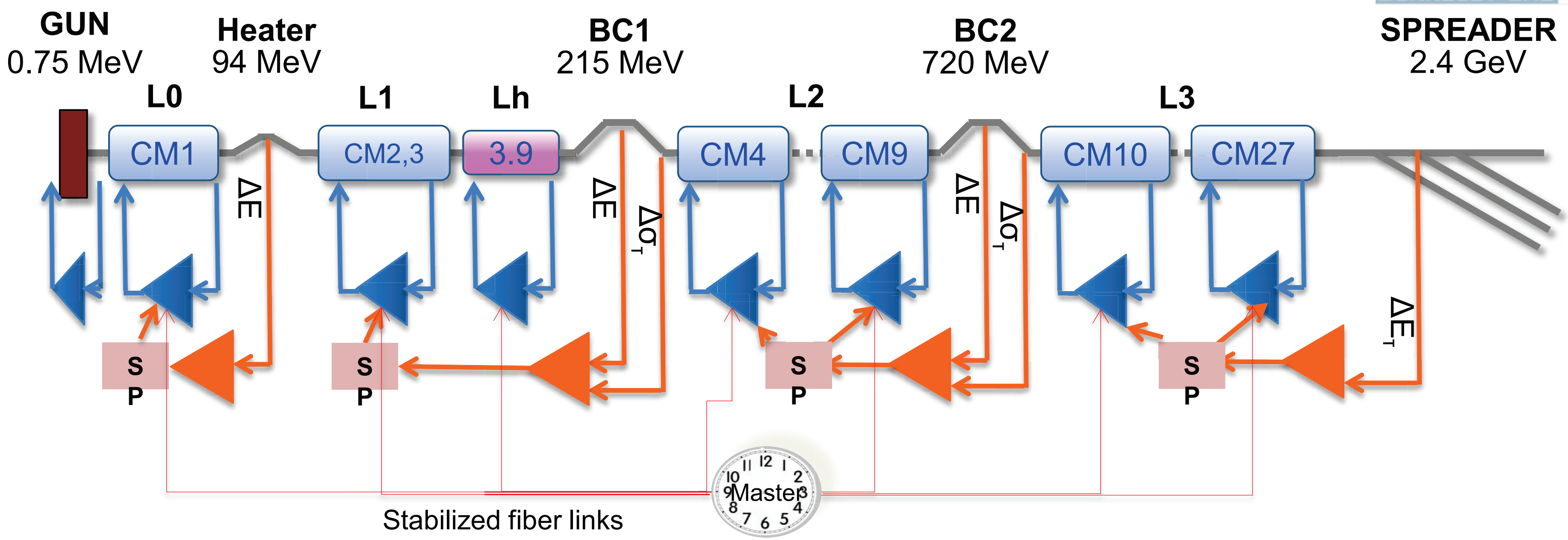
Analytic model and simulation agree for simple linac. Now let's try a full machine…





NGLS next generation light source

Global Approach: RF and BB Feedback



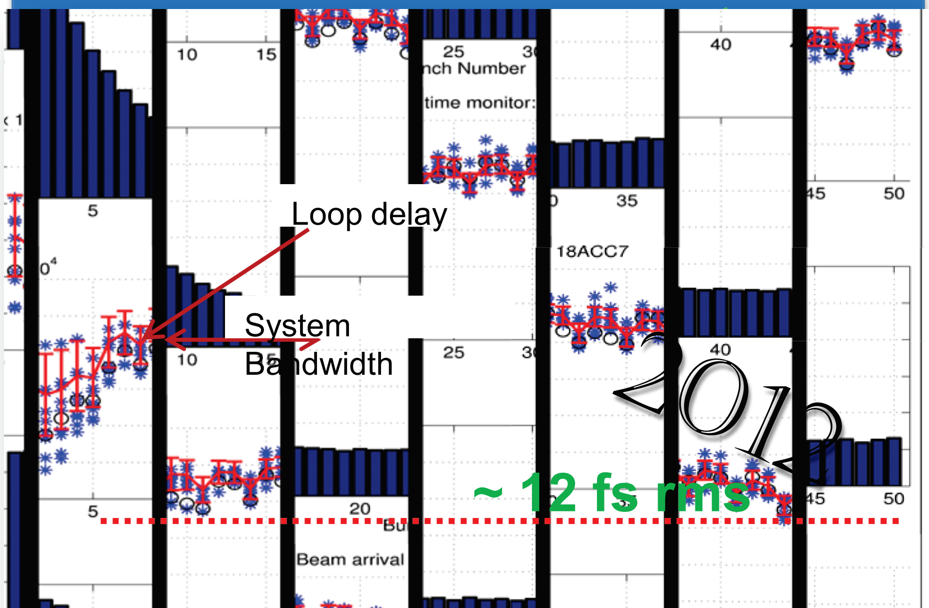
Use the model to study the performance of an entire machine

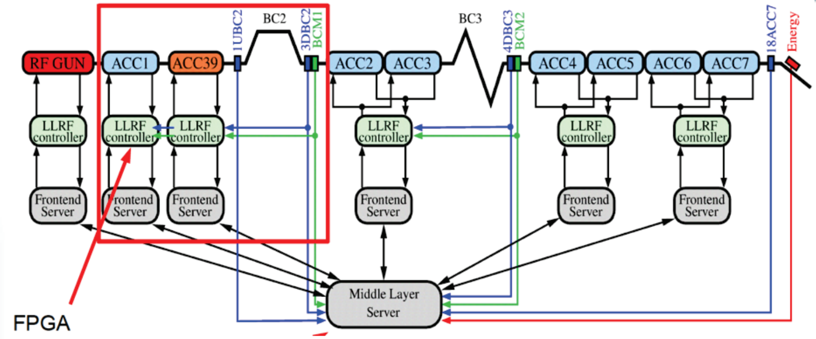
- Measure e^- energy (4 locations), bunch length (2 locations), arrival time (end of machine)
- Feedback to RF phase & amplitude, external lasers
- Entire machine referenced with stabilized fiber links
- Stabilize beam energy (~10^{-5}), peak current (few %?), arrival time (<10 fs)

Gold standard: FLASH

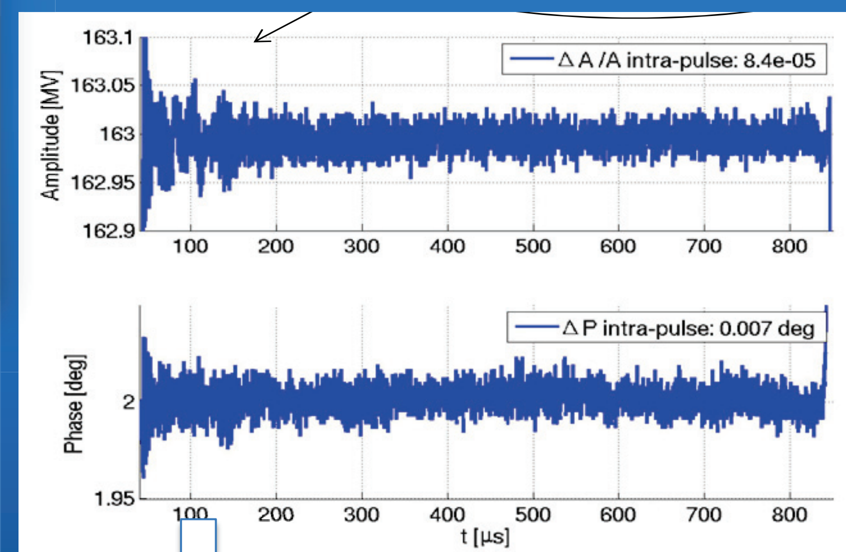
- **FLASH: RFFB and BBFB**

Arrival time jitter ~20 fsec (after initial RF transient)





Combination of fast and slow RF and BB FBs

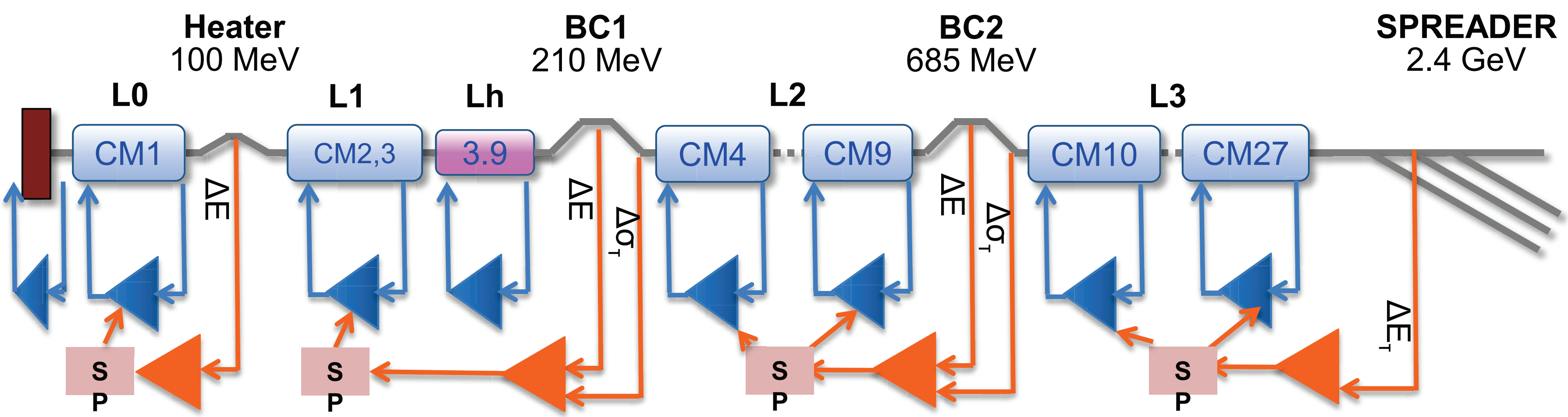


ΔE/E~5e-5.

Wonderful performance has already been achieved at FLASH with possible improvements in the future!

S. Pfeiffer, C. Schmidt, DESY

Full Machine Model



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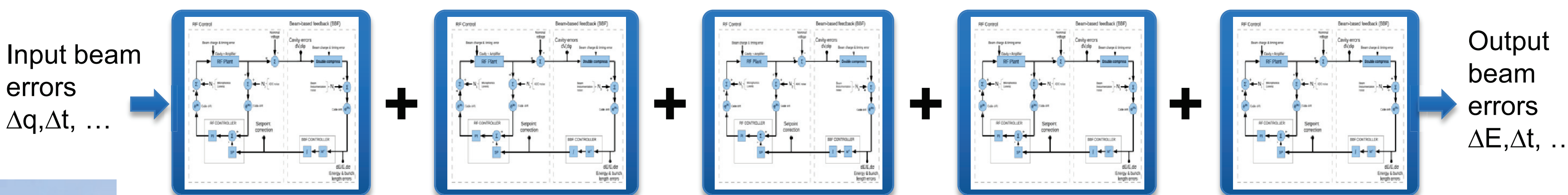
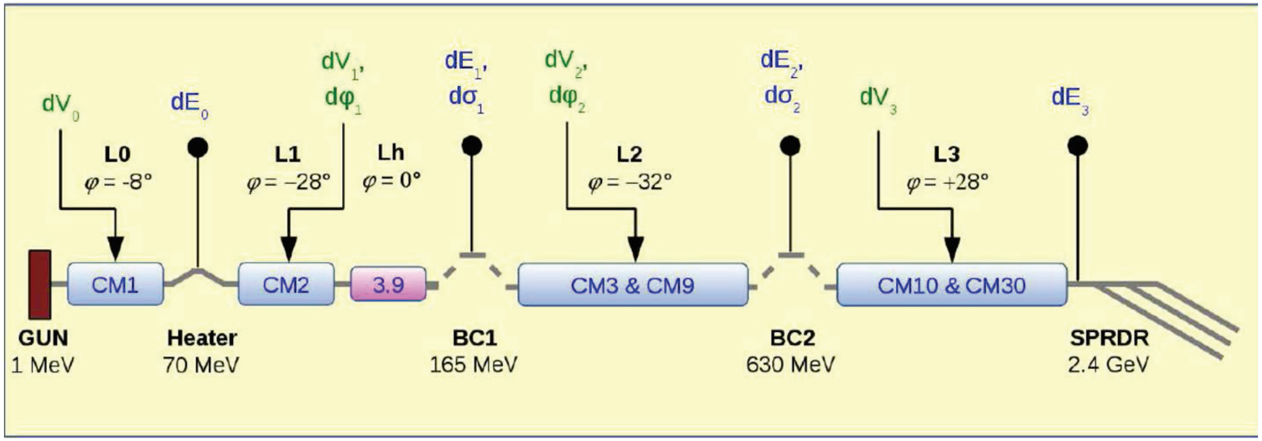


We model the full machine as 5 individual linac/bunch compressors. R_{56} can be zero. The model allows expansion to include each cavity and control of how the RF and BB feedback is distributed.

Beam-based Feedback

- Use measurements of energy and bunch length error at dispersive sections (i.e. laser heaters and bunch compressors) to further stabilize RF.



Use empirically measured linearized response matrix to transform beam measurements back to RF set points.

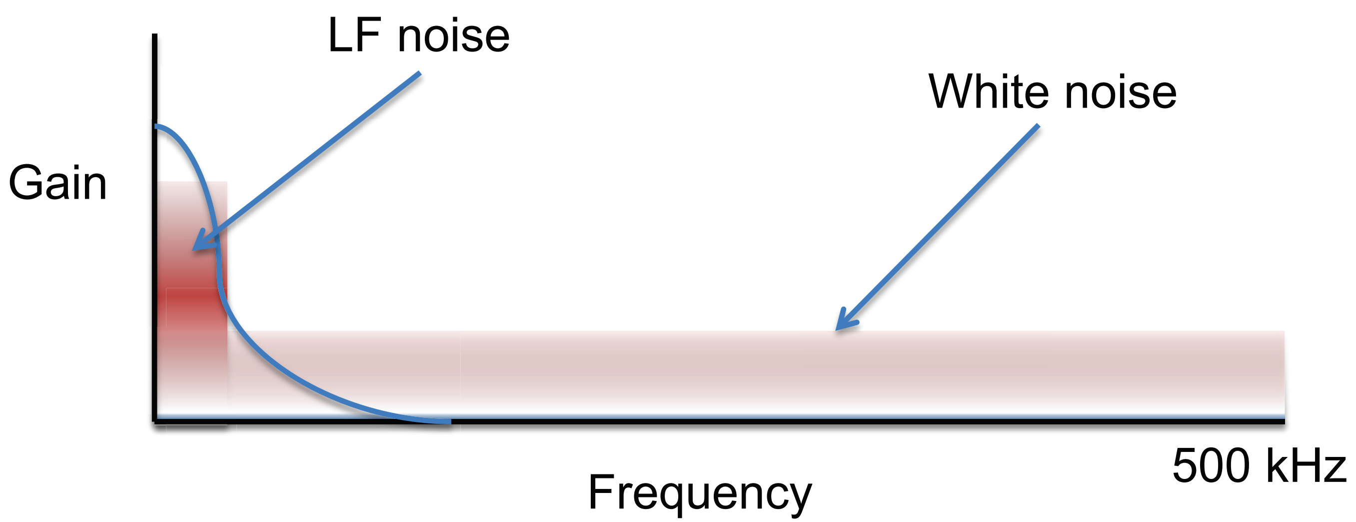
$$\begin{pmatrix} dE_0 \\ dE_1 \\ d\sigma_1 \\ dE_2 \\ d\sigma_2 \\ dE_3 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & \cdots & M_{16} \\ M_{21} & M_{22} & \cdots & M_{26} \\ \vdots & \vdots & \vdots & \vdots \\ M_{61} & M_{62} & \cdots & M_{66} \end{pmatrix} \times \begin{pmatrix} dV_0 \\ dV_1 \\ d\varphi_1 \\ dV_2 \\ d\varphi_2 \\ dV_3 \end{pmatrix}$$

Response is created over 0.1% amplitude and 0.1 deg phase deviations (~10x expected stability level.)

NGLS next generation light source

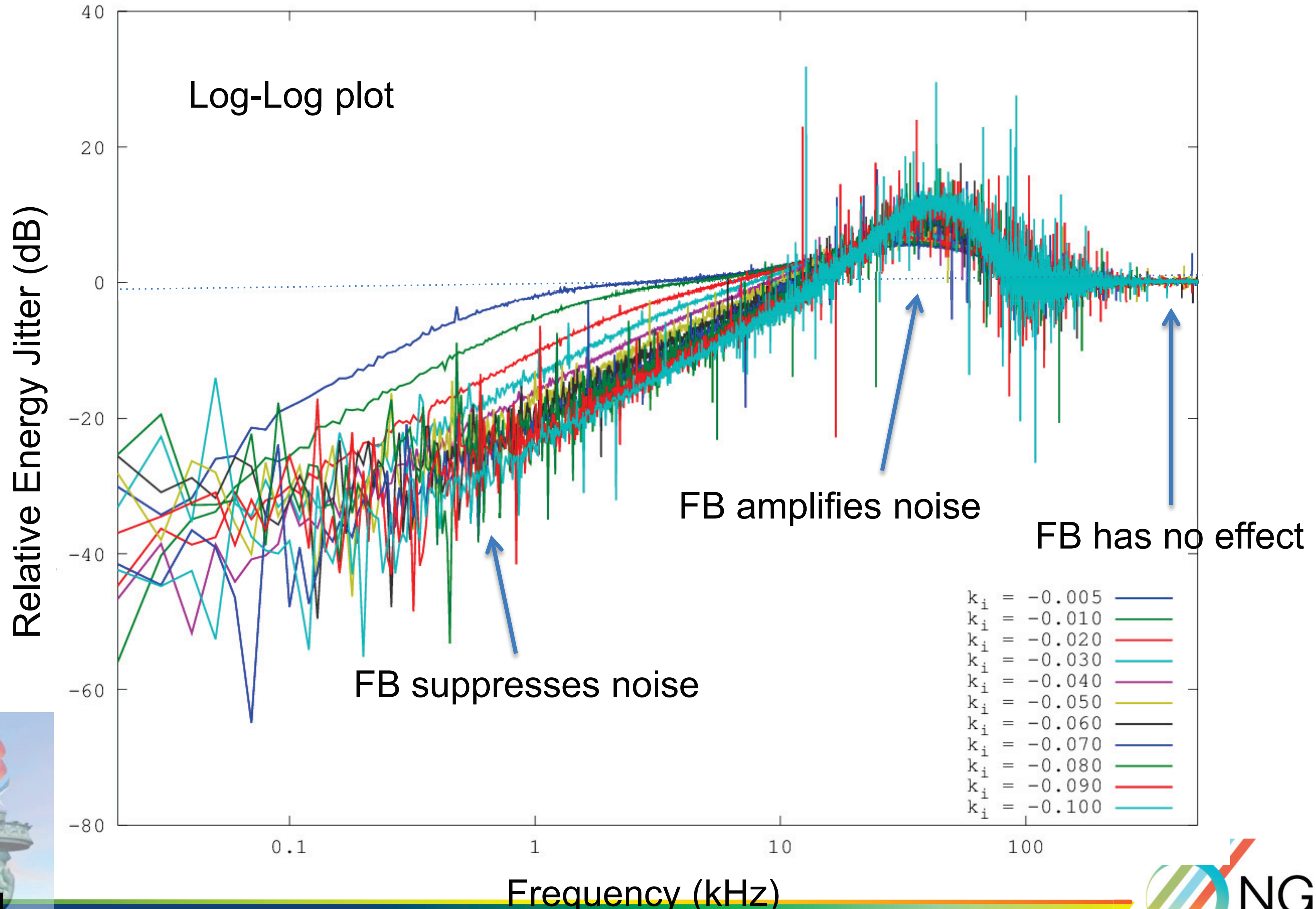
RF and BB Feedback Frequency Response

- The actuators for both the RF and BB FB are the SC RF cavities. Therefore the frequency response of both feedback will be limited by the response of the cavities.
- The FB performance will be strongly correlated to the frequency spectrum of the RF and beam perturbations.
- Feedback is ineffective for perturbations outside bandwidth.



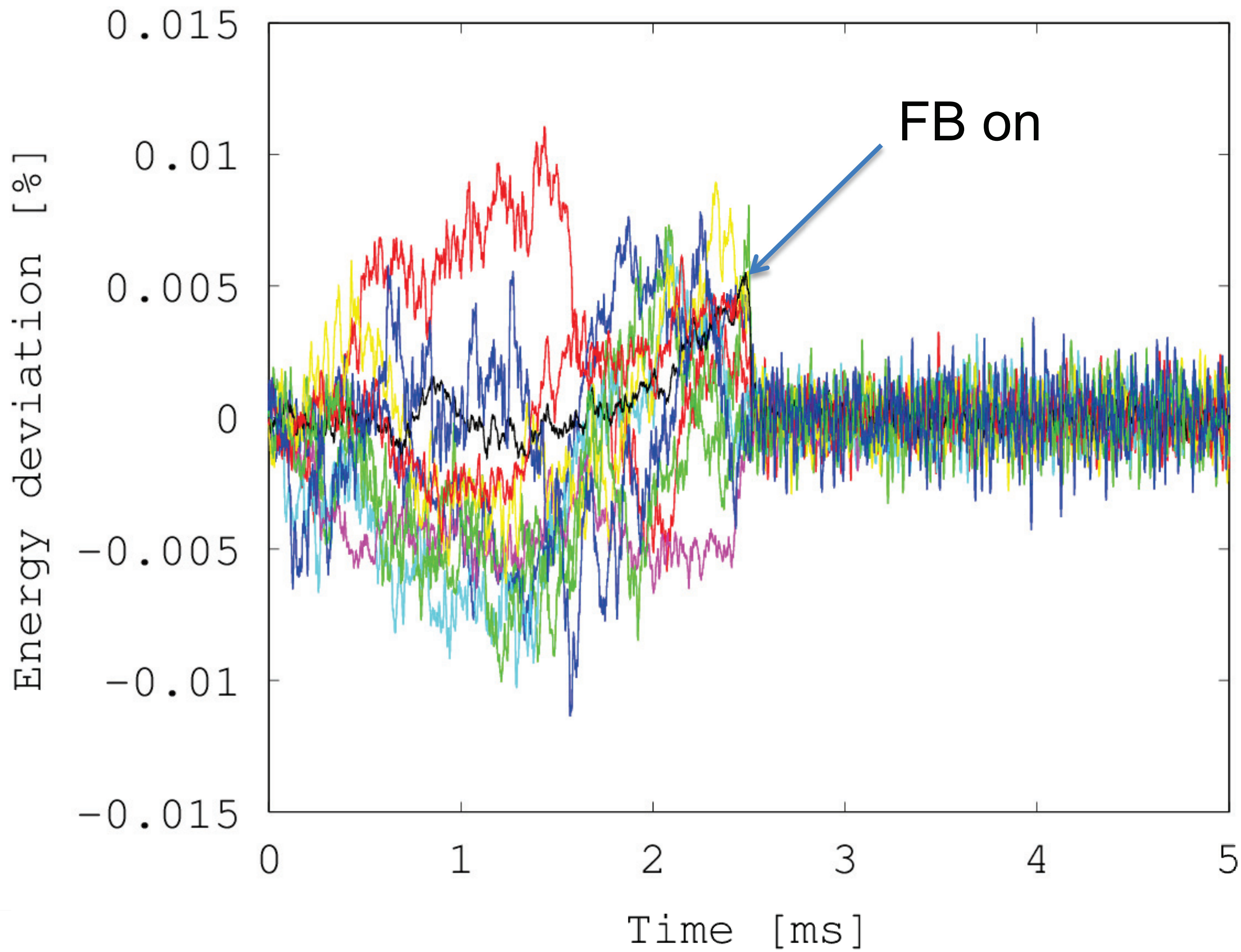
Example: System response to white noise

- **Measure E_3 response with white noise charge perturbations of 1%.**

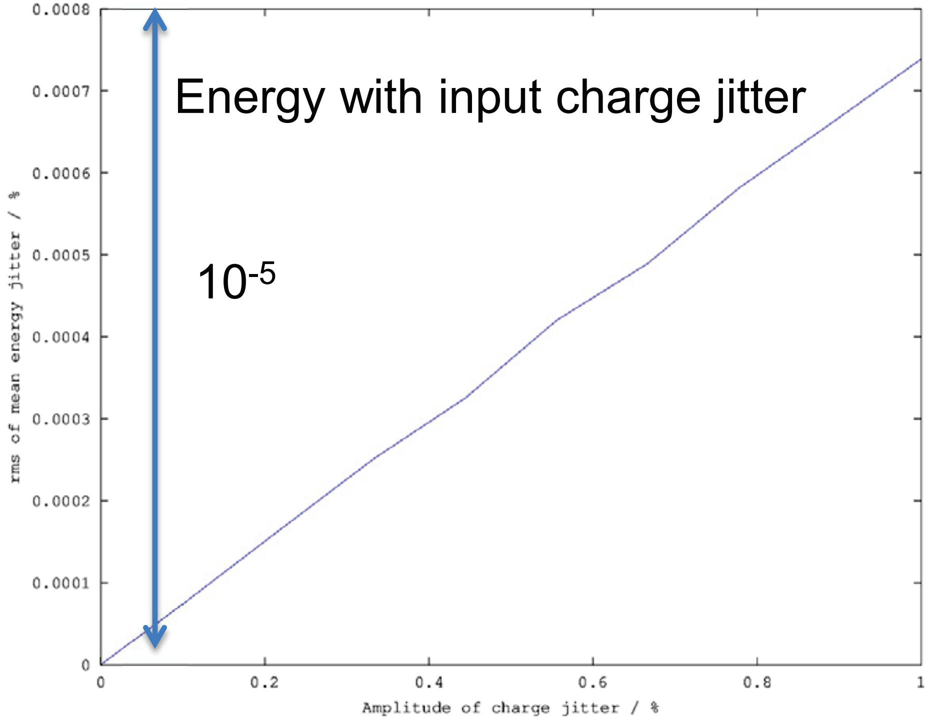


Energy with time jitter

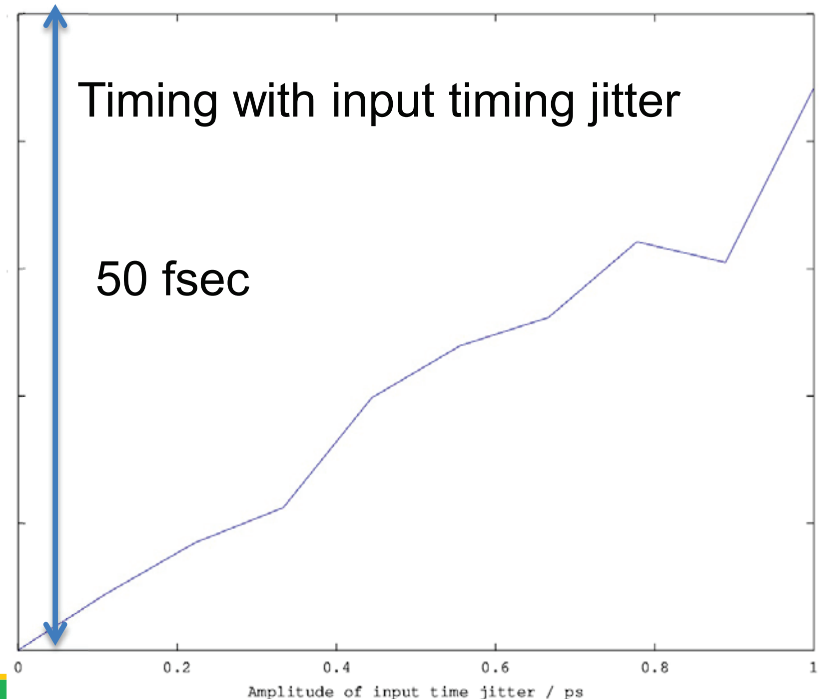
- **Multiple runs with 1 kHz band-filtered input jitter (charge)**



Example model output: energy and timing jitter



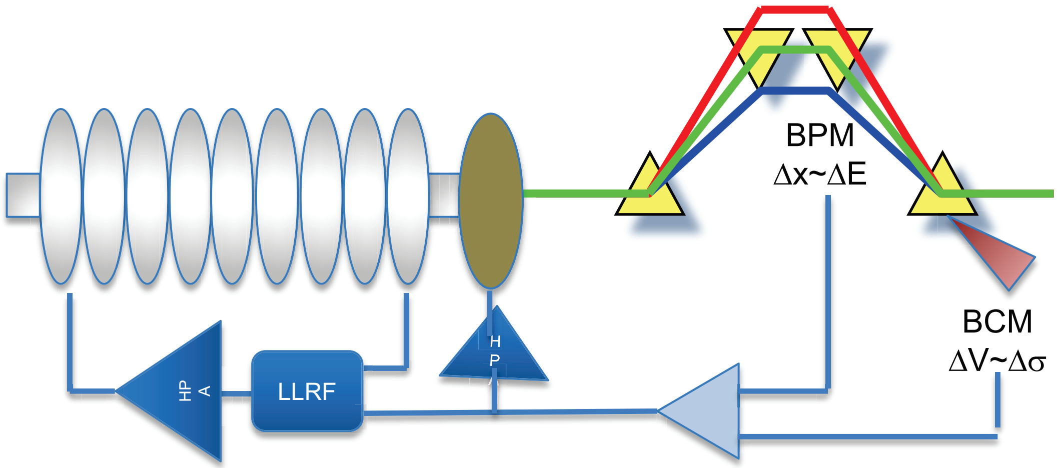
- Nominal NGLS parameters
- 100 Hz band-filtered input jitter spectrum
- Beam PU jitter not included
- Only one input jitter considered.



- **N.B. Results strongly dependent on spectrum of jitter from injector. We need "real" injector jitter to make "real" NGLS predictions.**

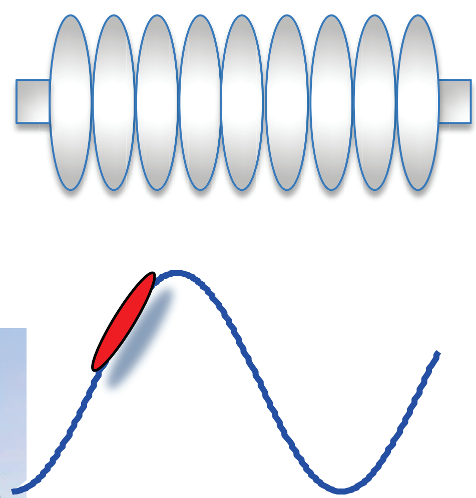
Future Directions: two examples

- **Low-latency "tweeter" system**



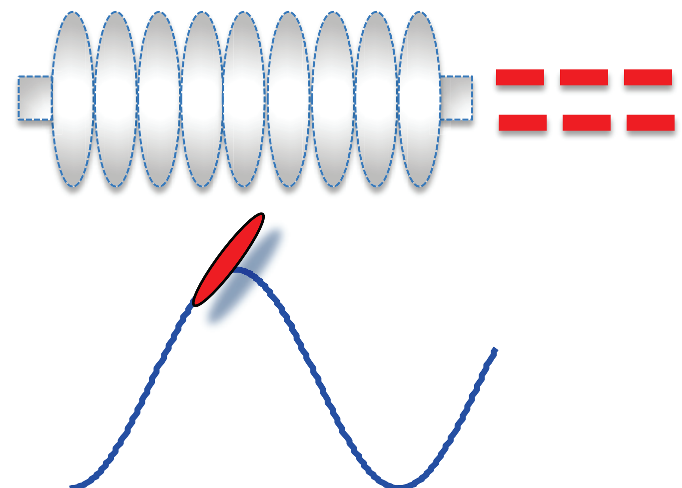
Use a copper cavity as actuator at each BC. Low delay of <0.5 microsec by keeping electronics in the tunnel. Estimate bandwidth >150kHz.

- **Use passive bunch wakefield manipulation (i.e. wakefield dechirper)**



Main linac must be operated off crest to remove chirp from final BC. More sensitive to phase noise.

Accelerate on crest and remove chirp using beam wakefields. Reduce energy jitter. Self-synchronizing.



Summary

- We have developed a model of the beam dynamics, RF system, and beam-based feedback that can be used to predict the jitter performance of the linac.
  - Beam dynamics approximates centroid and first beam moments
  - Full RF system model includes: RF processing, amplifier, ADC noise, delays, cavity model
  - Beam-based feedback model includes energy and bunch length PU noise
  - Band-limited noise of injected beam parameters

- Primary results:
  - Output jitter from linac depends on injected beam jitter and jitter bandwidth
  - Ability of feedback to control jitter depends on feedback bandwidth, determined mainly by loop delay
  - Bandwidth can be extended with a “tweeter” system using copper cavity actuator with low delay.

- Stable electron beams from linacs can be achieved with RF and beam-based feedback
  - Using “achieveable” parameters for the injected beam, RF feedback, and beam PU noise
  - Energy stability <4e-5, Timing jitter<10 fsec
  - Stable longitudinal phase space distribution:
    - pulse shape, peak current, energy chirp

- Further work planned
  - Characterize ultimate resolution of energy, bunch length, and arrival time diagnostics
  - Characterize noise sources in APEX photoinjector