# High Precision Orbit Stabilization In Future Light Sources

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# Contents / Disclaimer

No comprehensive overview, but few selected aspects, topics & examples from author‘s field of work / experience (3G rings, 4G linac FELs):

- Introduction / New Machines
- Orbit Stability Aspects
- BPMs
- Orbit Feedbacks, Algorithms
- Summary

# Some Future Light Sources

Some values coarse estimates or preliminary, just for qualitative comparison ...

| | $E_{max}$ [GeV] | $\varepsilon_x/\varepsilon_z$ [pm rad] | $\sigma_x$ [μm] | $\sigma_z$ [μm] | bunch spacing | $N_{train}$ *** | $f_{train}$ [Hz] | $Q_{bunch}$ [nC] |
|---|---|---|---|---|---|---|---|---|
| SCSS | 8 | 50 | ~30 | ~30 | 4.2ns | 1-50 | 60 | 0.3 |
| SwissFEL* | 5.8 | 10-30 | 10-30 | 10-30 | 50ns | 1-2 | 100/400 | 0.01-0.2 |
| E-XFEL | 17.5 | 30 | ~30 | ~30 | 200ns | 3250 | 10 | 0.1-1 |
| NLS* | 2.3 | 110 | ~50 | ~50 | 1ms/1μs | CW | CW | 0.001-1 |
| Cornell ERL* | 5 | 8-500 | ~10-100 | ~10-100 | 0.77ns | CW | CW | 0.0008-0.08 |
| NSLS-II | 3 | 510/8** | 30-180 | 3-12 | 2ns | 1056 | 0.4M | 1.25 |
| MAX-IV | 3(1.5) | 240/9 | 44 | 2.6 | 10ns | 141 | 0.6M | 6.25 |

* Proposed    ** With damping wigglers    *** # Bunches per train or revolution (rings: 80% filling)

- New linac FELs: Trend to low charge / short bunch (single spike mode)
- New rings: Low coupling/emittance, damping wigglers, medium energy

# Future Light Sources (Cont'd)

- **New storage rings**: "Sub-micron" beam stability no longer sufficient, need "sub-fraction-of-micron" ($\sigma$/10 ~ 200nm) vertical e-beam stability. Evolution of present technology (NSLS-II: Button RF BPM pickup geometry, ...).

- **New linac-based machines**: 2 classes

  - Single bunch or short bunch trains (<200ns), ~100Hz rep. rate (SwissFEL, SCSS): Need source-suppression of random orbit perturbations > few Hz

  - Long bunch trains or CW, bunch rep. rate up to MHz or more (E-XFEL, NLS, ERLs): Feedback can suppress orbit perturbations >>10Hz (vibrations, ...)

  - All machine types: May use adaptive feed-forward for reproducible perturbations (mains, ...)

# Outline

- Introduction / New Machines
- **Orbit Stability Aspects**
- BPMs
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# Orbit Stability Aspects

## Storage Rings:

Need typ. Sigma/10 ~ 200nm vertical RMS orbit stability (and/or corresponding angle stability) . But: Photon beamlines also need:

- Stable e-beam dimensions (control/feedback of ultra-low coupling, ...). SLS: Fast beam wobbling for polarization switching needs fast skew-quad corrections.
- Stable p-beamline mechanics (monochromator/mirror vibrations, ...) & e-/p-BPM supports (T-drift, vibrations).

Improve not just center-of-charge e-beam stability, but also source suppression (beamline elements, ...). Integrate fast high-BW photon BPMs (blade, residual gas, ...), coupling control etc. into orbit feedback.

# Orbit Stability Aspects (Cont'd)

- **New Linac FELs:**

  - Round beams, not flat like rings. For low-charge modes (e.g. SwissFEL 10pC): $\sigma$<10µm, comes close to vertical beam size in 3G rings.

  - e-Beam stability in main linac less critical (emittance growth, ...)

  - Want ~$\sigma$/10 stability in undulators for lasing (electron-photon overlap & relative phase, pointing/intensity stability)

  - Static Beam trajectory alignment & local straightness in undulators (Earth's field shielding, DFS, ...) much more critical than in rings

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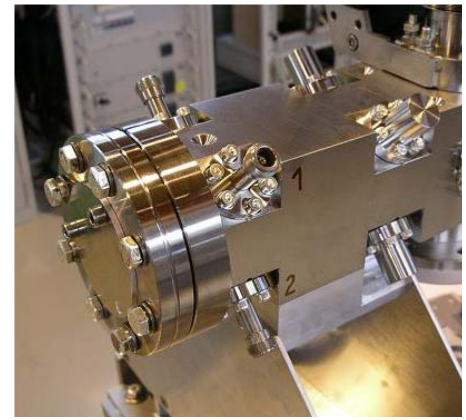
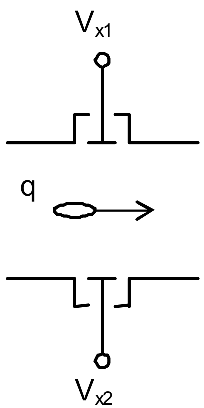
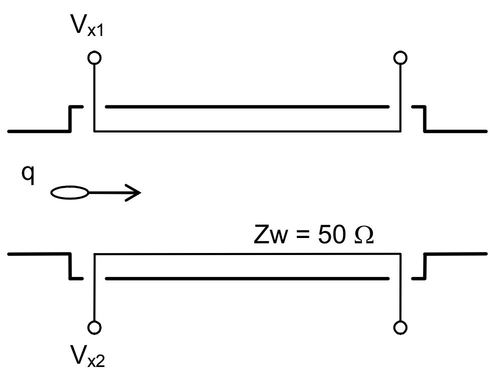
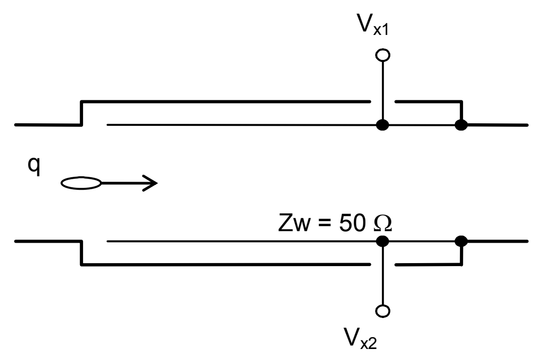
# Common BPM Pickups: Buttons & Striplines

| Button (Bergoz) | Matched Stripline (FLASH) | Resonant Stripline (SLS Linac, …) |
| --- | --- | --- |
|  |  |  |
|  |  |  |





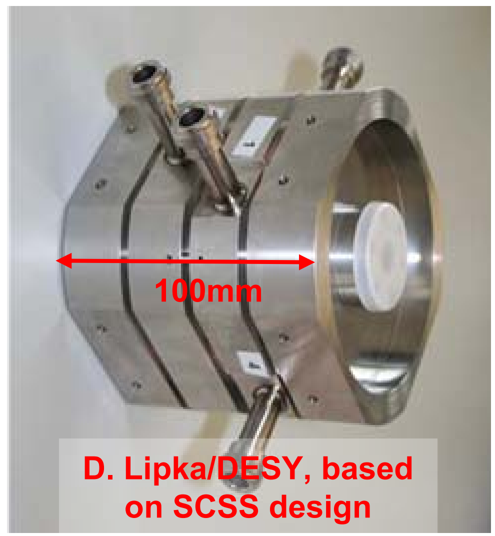


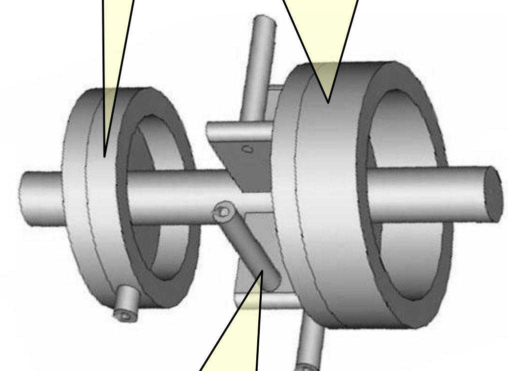
Beam Position = k * $(V_{x1}-V_{x2})/(V_{x1}+V_{x2})$. Factor k (~10mm) determined by geometry.

# Common BPM Pickups: Cavities

Dual-resonator,
waveguide connectors,
mode-selective
(LCLS, 11.4GHz)

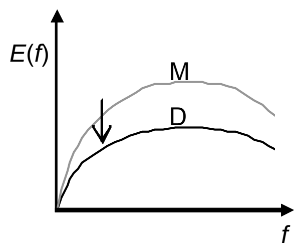
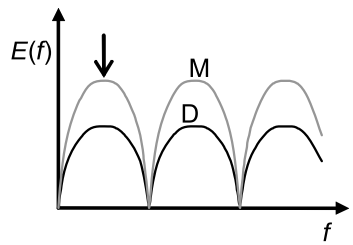
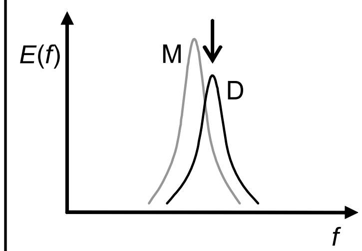
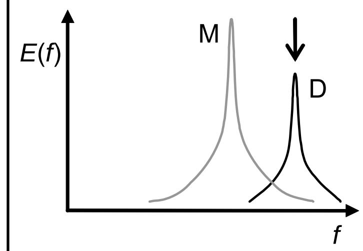
Dual-resonator,
coaxial connectors,
mode-selective
(E-XFEL, 3.3GHz)




Beam Position = k * ($V_{Pos\_Cav}$ / $V_{Ref\_Cav}$). Factor k: Not fixed, variable via attenuator.

# Common Pickups (Cont’d)

| ***Pickup*** | Button | Matched Stripline | Resonant Stripline | Cavity |
|---|---|---|---|---|
| ***Spectrum*** |   |   |   |   |
| ***Monopole Mode Suppression*** | Modal (hybrid) / electronics | Modal (hybrid) / electronics | Modal (hybrid) / electronics | Modal (coupler), frequency, phase (sync. det.) |
| ***Typical RMS Noise, 10pC, <u>*20mm pipe*</u>*** | >100µm | <60µm (scaled to 20mm pipe) | <10µm (estimated for 20mm pipe) | <1µm |
| ***Typical Electronics Frequency*** | 300…800MHz | 300…800MHz | 500-1500MHz | 3-6GHz |

“Typical” noise: Examples from some existing machines & electronics, not theoretical limit …

# Common BPMs

**Qualitative/subjective pros & cons ...**

**"Standard" BPM types for warm linac beam lines (where ~ 5 - 50µm resolution is needed)**

**Typical choice for SASE undulators, intra-train & IP feedbacks: sub-µm single-bunch resolution**

**Standard for ring machines: SNR uncritical (averaging over many bunches), minimal beam impact**

| | Button | Matched Stripline | Resonant Stripline, Normal Coupling | Single Cavity Normal Coupling | Two Cavities, Hybrid Coupling |
|---|---|---|---|---|---|
| Signal/Noise | – | – / + | + | + | + |
| Monopole Mode Suppression | – | – | – | – / + | + |
| Single-Bunch Resolution (@ low charge) | – | – / + | + | + | ++ |
| Electronics Drift | – / + | – / + | – / + | – / + | + |
| Weight 10mm pipe | + + | + | + | + | + |
| Weight 40mm pipe | + + | – / + | – / + | – / + | – / + |
| Design Effort | + + | – / + | – / + | – / + | – |
| Fabrication Costs | + + | – / + | – / + | – / + | – / + |
| Tuning Effort | + + | + + | – / + | + | + |

performance

budget

# BPMs: Impact of Transverse Beam Profile

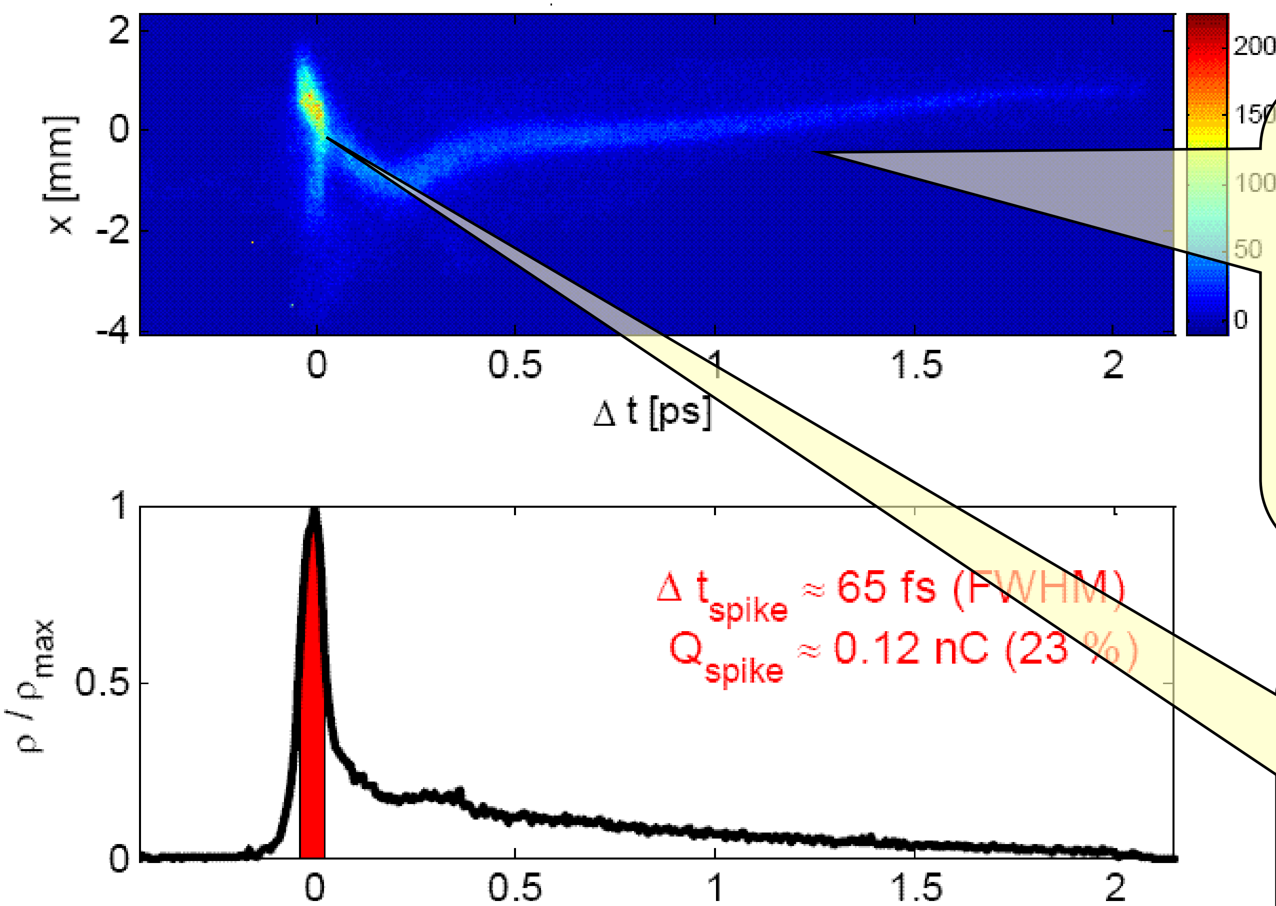
## Ring Light Sources

- Synchrotron radiation damping: Gaussian 3D profile, no bunch tilt

## Linac FELs

- Machines without higher-harmonic RF: nonlinear (sine) accelerating RF fields cause non-Gaussian longitudinal & transverse profile
- Result: fraction of bunch that is lasing is not at center of charge → suboptimal (or no) lasing although BPMs show ideal straight undulator trajectory
- Is problem for trajectory feedback (not for magnet alignment!)
- Cure: Linearize RF accel. field via higher-harmonic structures → ~Gaussian profile → necessary for sub-µm position measurement of the lasing part of the bunch

# BPMs: Transverse Beam Profile (Cont'd)




Example: Correlation between transverse and longitudinal charge distribution @ FLASH (measured by transverse deflecting cavity, H. Schlarb et al.).

Lasing electrons not at transverse center of charge. Cure (FLASH + E-XFEL): 3rd harmonic RF

Courtesy B. Faatz et al., SINAP 2008

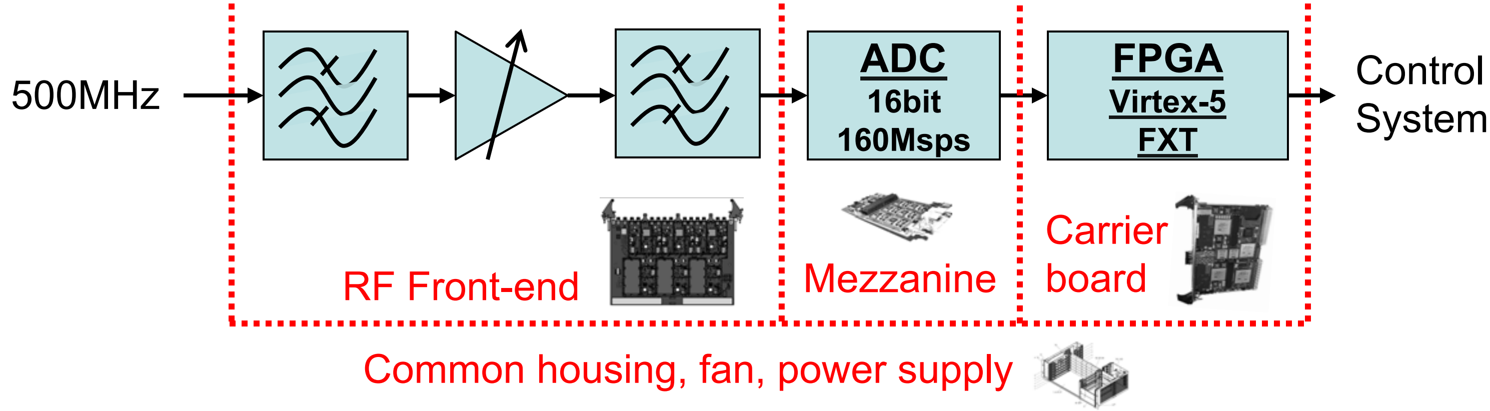
# BPM Electronics

- Main challenge is fulfilling all specifications simultaneously, not just one (e.g. resolution).
- People tend to focus on low resolution, but e.g. low drift & bunch charge/pattern dependence are often more difficult to achieve.

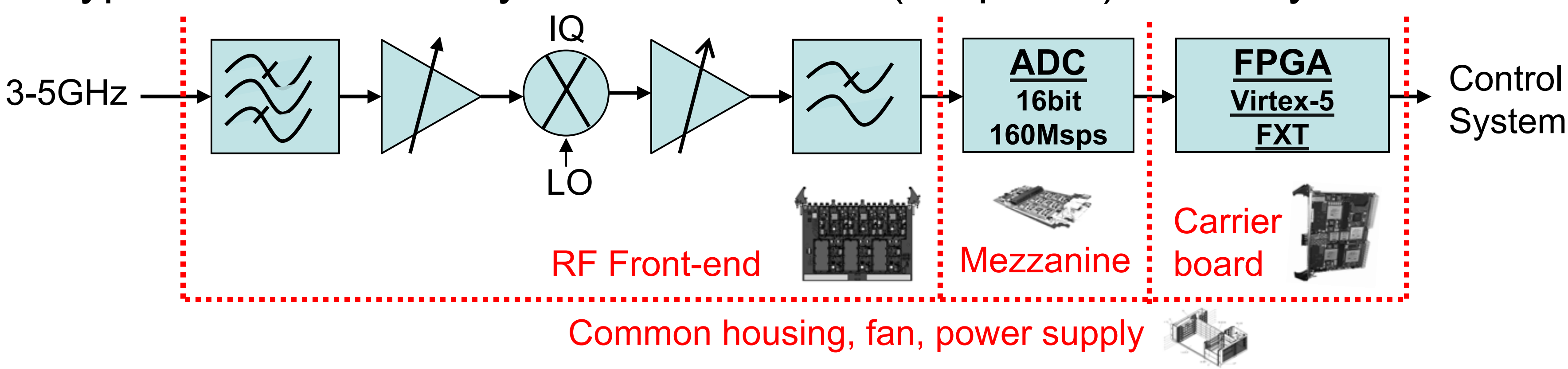
| | Typical (3G Ring, ID BPMs) | Typical (Linac, SASE-Undulator) |
|---|---|---|
| Resolution / BW | 200nm < 1 kHz | 500nm < 50MHz |
| Drift (hour/week) For Specified Environment | 100nm/1µm | 100nm/1µm |
| Beam Charge Dependence | ... | 100nm/1% |
| Bunch Pattern Dependence | ... | n.a. |
| Position Range | +-5mm | +-1mm |
| Bunch Charge/Current Range | 0.1-400mA | 0.01-0.5nC |
| Differential Nonlinearity | ... | 0.03% FS |
| Integral Nonlinearity | ... | 2% FS |
| Bunch-to-Bunch Crosstalk | n.a. | 100nm |
| x-y Coupling | 2% | 1% |
| Initial Offset & Gain Error | 100µm / 3% | 100µm / 3% |

# BPM Electronics (Cont’d)

- Typical 3G ring button electronics (simplified): direct sampling




- Typical 4G linac cavity BPM electronics (simplified): homodyne rec.




→ Modular system: 3G ring & 4G linac BPM systems can use same ADC & FPGA boards & crates/housing, with customized RF front-ends

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# Feedback Algorithms for Rings & Linacs:

## „Standard“ Algorithm: SVD, PID Control, Uniform Gains

- SVD: rotate BPM & corrector vectors into space where beam response matrix has only diagonal elements (eigenvalues)
- Drawback: BPM vectors („perturbation patterns“) with smallest eigenvalues (huge corrector ΔI for tiny orbit Δx) mainly unreal, caused by BPM noise: vector least useful for correction of real perturbations, but main cause of feedback-induced beam noise
- Usual cure: do not correct such BPM patterns (set small eigenvalues to 0: “eigenvalue cut-off”)
- Usual problem: orbit not corrected (exactly) to desired positions

# Feedback Algorithm (Cont'd)

## Improvement Idea (M. Heron et al., EPAC'08, THPC118):

- Feedback will modulate much less noise onto orbit if each BPM pattern („eigenvector") has its own PID loop, with gain weighted by eigenvalue (→ "Tikhonov regularization"):
  - ✓ Real perturbations: corrected fast (high loop gain)
  - ✓ Perturbations mainly pretended by BPM electronics noise: corrected slowly → noise averaged, much less feedback noise on the beam
- Algorithm can reduce BPM noise requirements for new 3G rings & improve beam stability at existing machines

# Machine Design: Impact on Transverse Feedback

## Impact of BPM noise reduced by:

- Minimization of quotient between largest & smallest SVD eigenvalue (conditioning number) – depends on lattice/optics & BPM/corrector locations.
- Large beta functions @ BPMs

## BPM electronics bunch charge & pattern dependence irrelevant by:

- Top-up injection
- Filling pattern feedback

## BPM position drift of mechanics & electronics reduced/eliminated by:

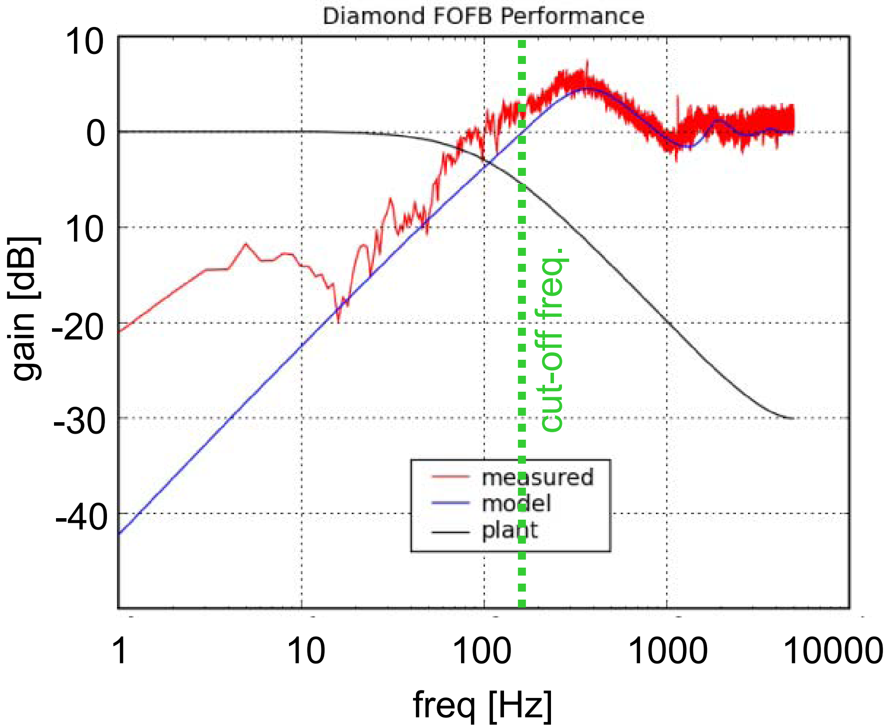
- Air temperature stabilization
- Photon BPMs for orbit feedback

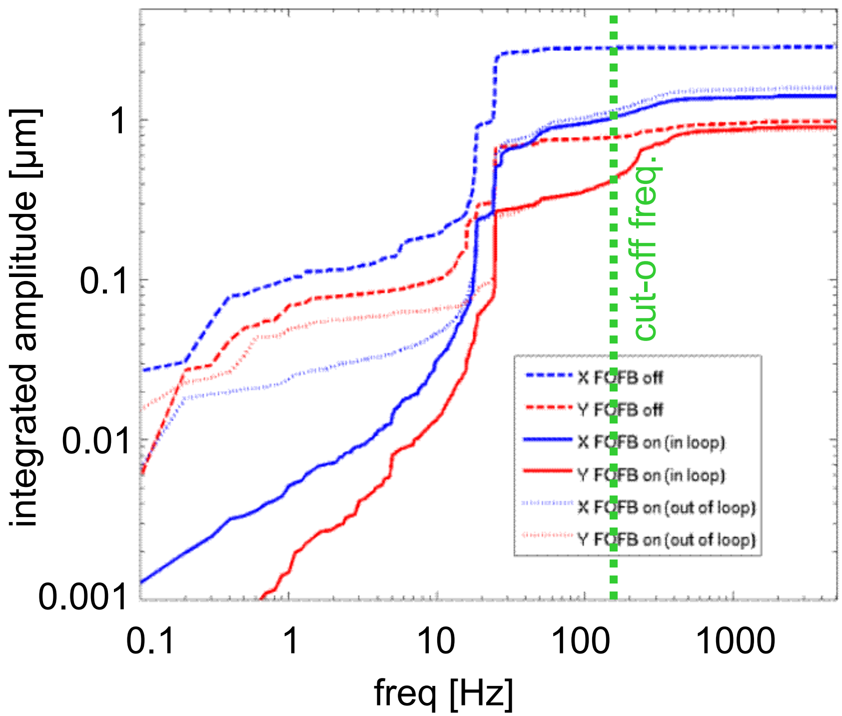
Ideal case: SVD touches just 3 correctors if 1 BPM changes → superposition of localized bumps, robust

## SVD Algorithm For Linacs

- No. of BPMs & correctors can be chosen as desired (2+2, more)
- Robustness (energy variation, …): Depends on BPM/corr. loc.

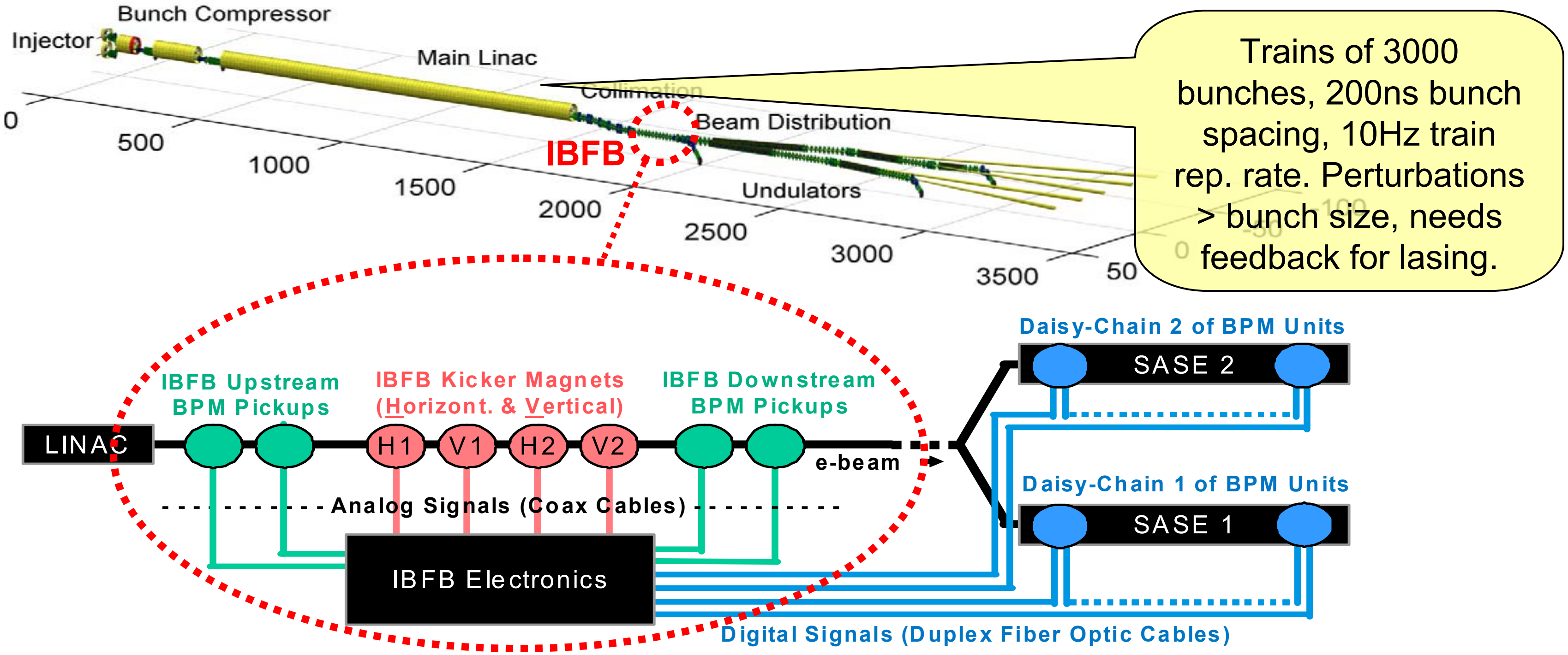
# Example: Diamond FOFB Performance




Plots: Courtesy G. Rehm et al. (EPAC'08)

# E-XFEL: Transverse Intra-Train Feedback (IBFB)




- Downstream BPMs for fast feedback loop, RF stripline kickers, latency ~1µs.
- Additional adaptive feed-forward (train-to-train) for repetitive perturbations.
- Upstream BPMs for calibration (kicker amp gain & phase, …).
- Undulator BPM pickups used to correct perturbations between IBFB & undulators, and for slow (~10Hz) global feedback with normal magnets.

# Transverse Beam Trajectory Perturbations

… in E-XFEL undulators, preliminary/estimated (W. Decking)

| ***Train-To-Train Perturbations*** *(Peak-To-Peak)* | ***Horizontal [μm]*** | ***Vertical [μm]*** | ***Random*** |
|---|---|---|---|
| **Mechanical Vibrations** | **28** | **28** | **yes** |
| **Power Supply Noise** | **12.6** | **12.6** | **yes** |
| **Vibration-Induced Dispersion Variation** | **2.5** | **2.5** | **yes** |
| **Sum Train-To-Train** | **43.1** | **43.1** | |
| | | | |
| ***Additional Intra-Train Perturbations*** *(Peak-To-Peak)* | | | |
| **Beam Distribution Kicker Drift** | **0** | **120** | **no** |
| **Beam Distribution Kicker Noise** | **0** | **1** | **yes** |
| **Wake Fields** | **25** | **25** | **no** |
| **Spurious Dispersion (3% E-Chirp)** | **30** | **30** | **no** |
| **Spurious Dispersion (1E-4 E-Jitter)** | **0.1** | **0.1** | **yes** |
| **Nonlinear Residual Dispersion (3% E-Chirp)** | **136** | **0** | **no** |
| **Nonlinear Residual Dispersion (1E-4 E-Jitter)** | **0.5** | **0** | **yes** |
| **Sum Intra-Train** | **191.6** | **176.1** | |
| | | | |
| **Sum Overall** | **234.7** | **219.2** | |

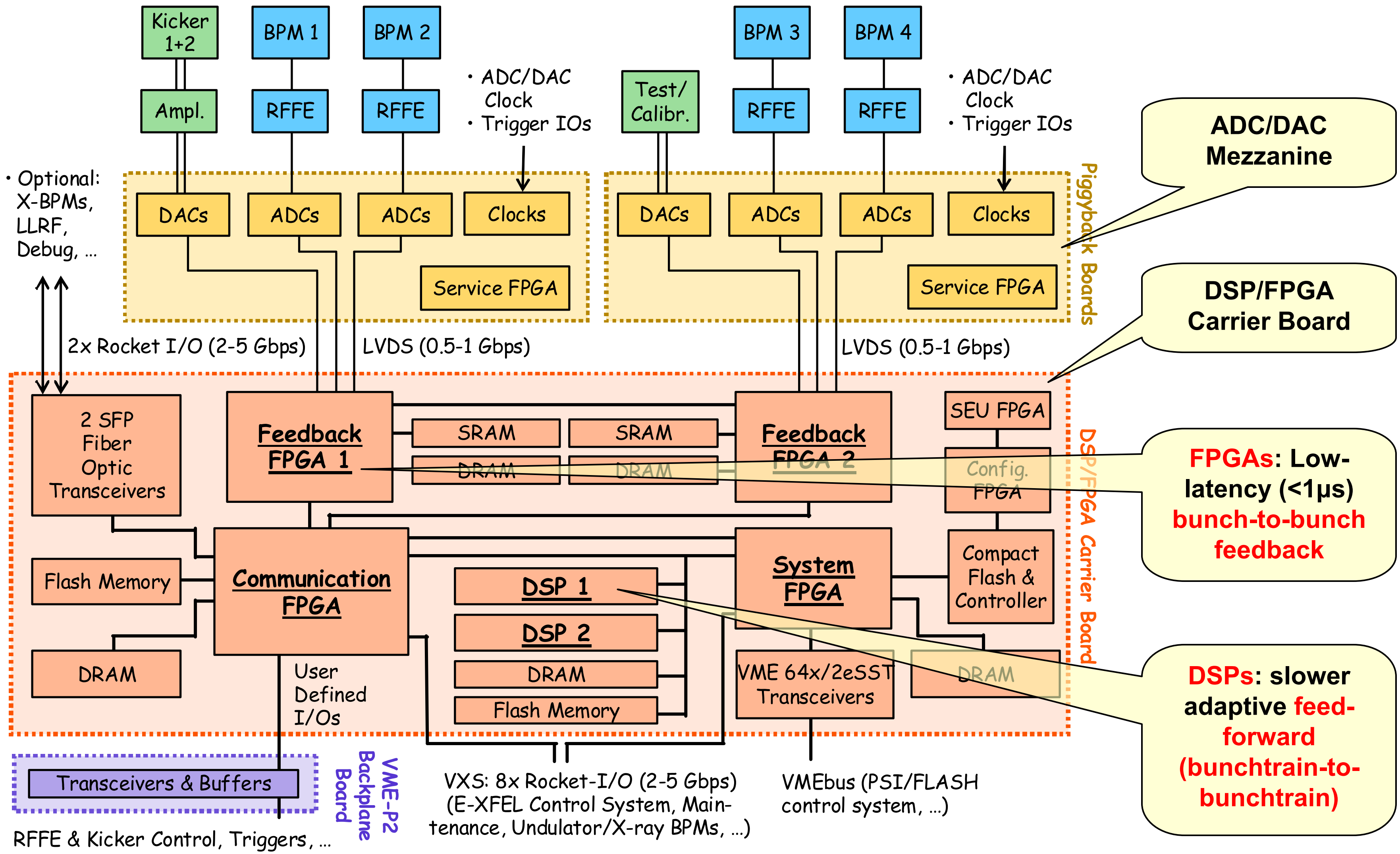
**Low-frequency perturbations (<< 10kHz):**

**Random position offset of each bunch train, should be corrected to ~σ/10 (~3μm) within ~20μs after 1st bunch (dump first ~100 bunches) → needs fast intra-bunchtrain feedback (IBFB), latency ~1μs**

**High-frequency perturbations (>10kHz):**

**Mainly non-random, i.e. reproducible → correct by adaptive feed-forward (train-to-train)**

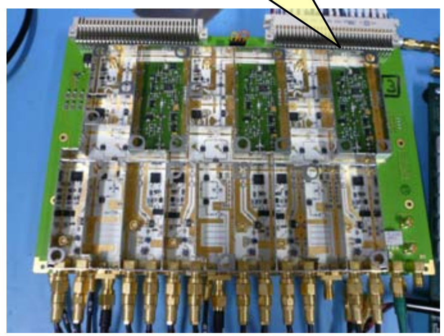
# Fast Intra-Train Feedback: Typical Electronics



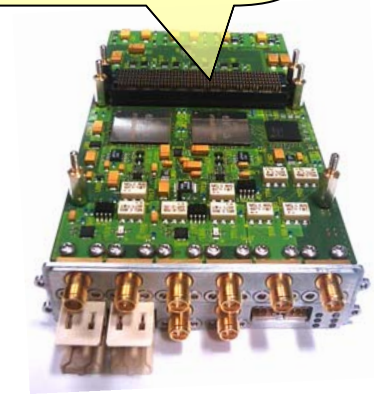
# Fast Intra-Train Feedback: Typical Components

3-6GHz Cavity BPM Pickup

Cavity BPM RFFE



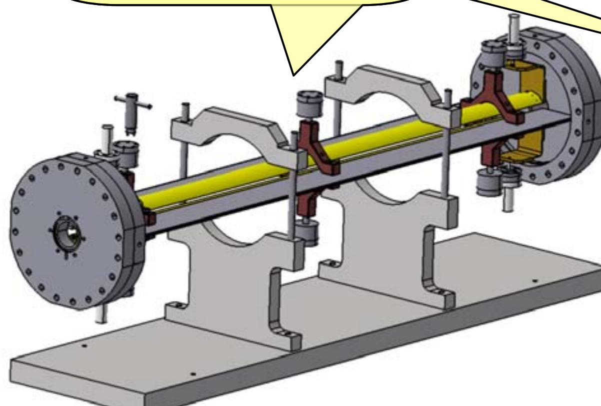
ADC/DAC Mezzanine

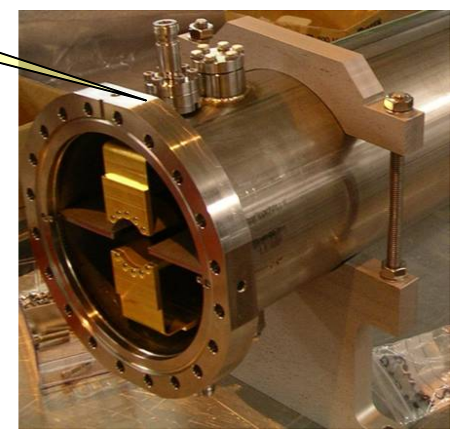


FPGA/DSP Carrier

Low-Latency RF Power Amplifier

In-Vacuum Stripline Kicker





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# Summary

- New storage rings need “sub-fraction-of-micron” orbit stability (~200nm).
- New low-charge linac FELs: Close to vertical orbit stability requirements of 3G rings. Feedback BW limited by bunch rep. rate -> need source suppression of perturbations, or long bunch trains / CW + feedback.
- Cavity BPMs offer good cost-to-performance ratio, interesting as standard BPM for new low-charge linac FELs. Buttons are low-cost option for main linac of medium-high charge FELs.
- Linacs & rings can share BPM electronics components, can use same feedback algorithm & hardware (typ. 0.1-10kHz correction rate). Long-train or CW FELs may need ultrafast Intra-Bunchtrain feedback (E-XFEL) & MHz correction rate.