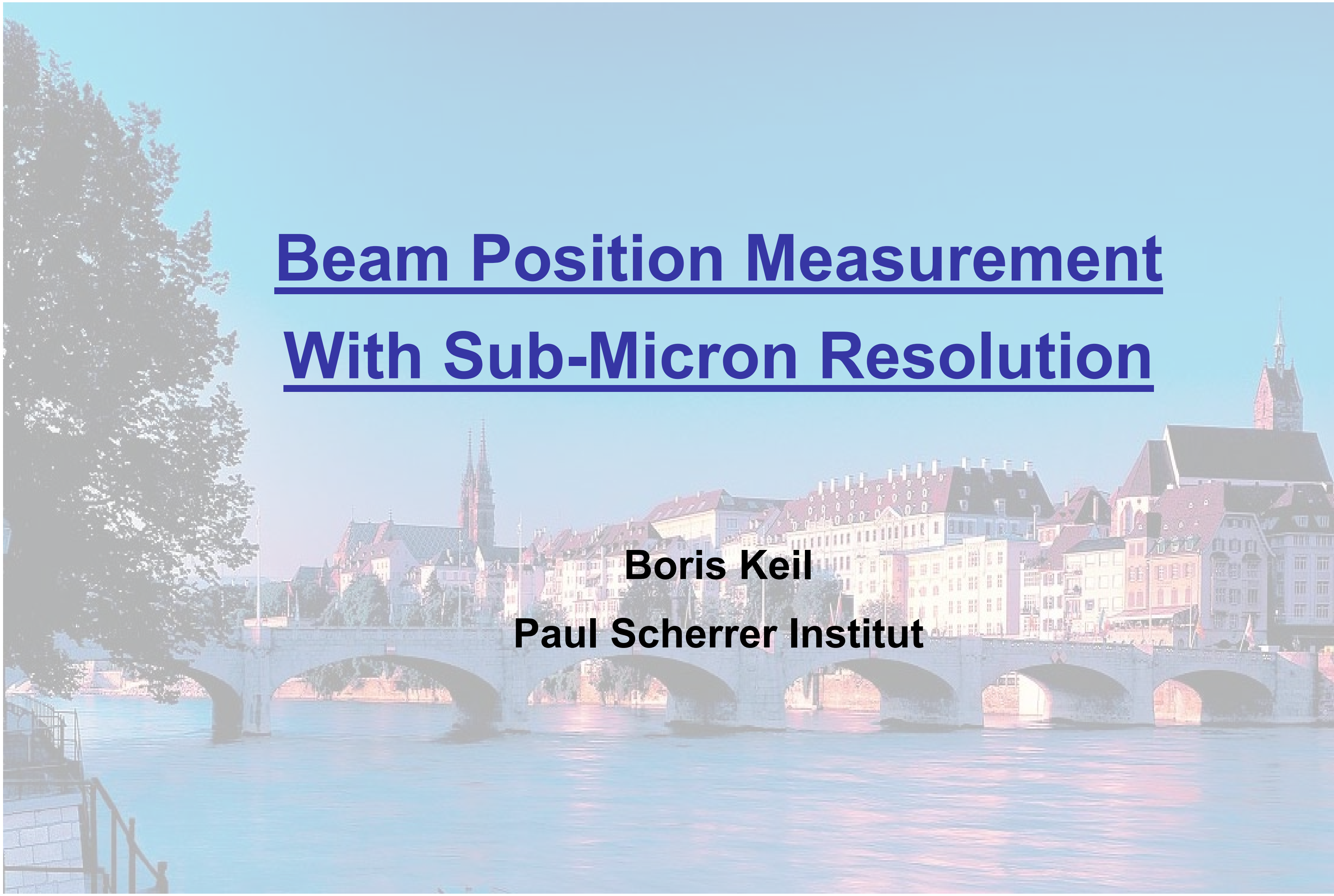

Beam Position Measurement With Sub-Micron Resolution

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Outline

- Introduction
- Requirements & Applications
- Pickup Types & Electronics
- Summary

Introduction

- Topic:
  Techniques & aspects of beam position measurement at 3rd & 4th generation light sources & colliders

- Focus on:
  - RF BPMs (no X-Ray, laser wire, …)
  - Few selected aspects, designs & methods
  - Linac-based FELs
  - Differences to 3G ring machines

- Many topics equally relevant for light sources & colliders

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BPM Requirements

Ring Light Sources

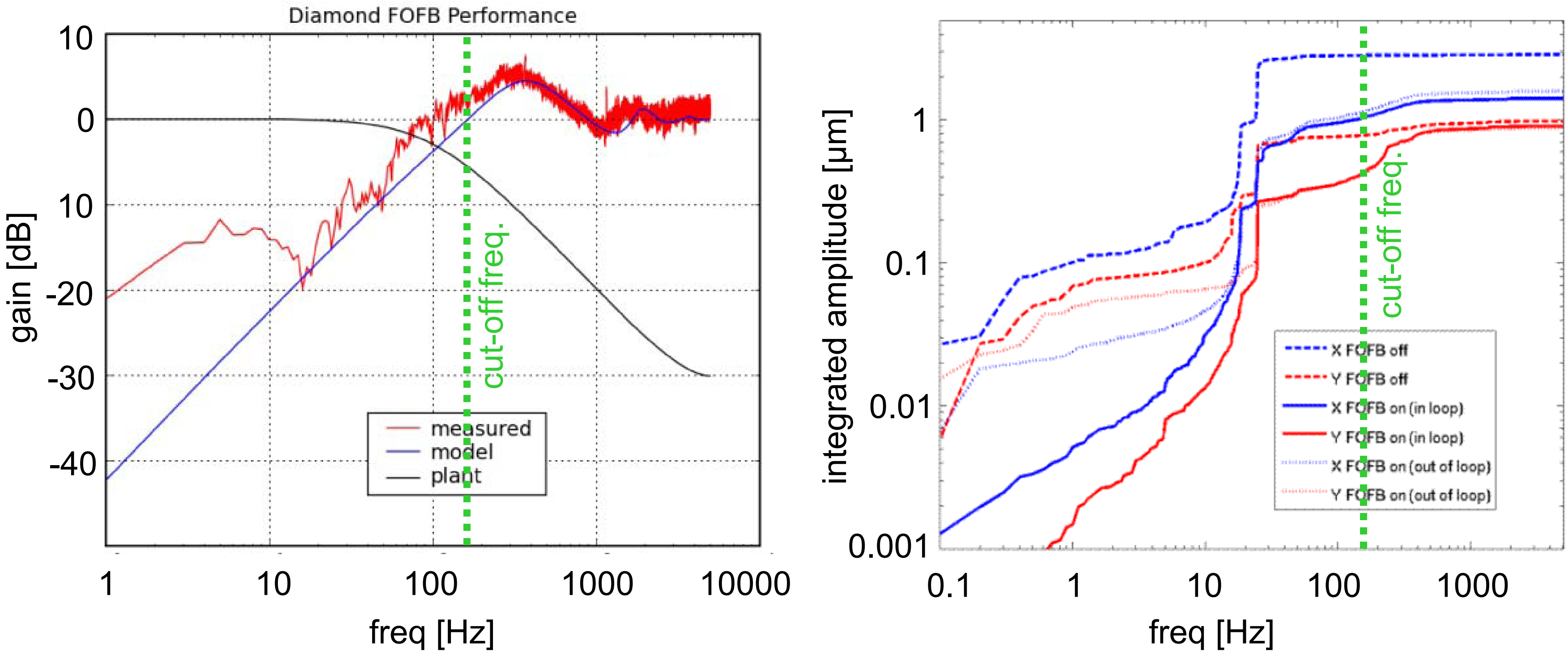
- BPM requirements driven by fast orbit feedbacks: want ~σ/10 photon beam stability at end of beamline
- Vertical e-beam size σ~2-5μm
- Want few 100nm BPM noise (<1kHz) / drift (seconds …days) for orbit feedback

Linac FELs

- BPM requirements (also) driven by beam-based alignment of quadrupole magnets in undulator area
- Single-bunch FELs: typ. ~10-100Hz rep rate
  → Feedback only for random perturbations <1-10Hz
  → Machine should be inherently stable >1-10Hz
- Bunch-train FELs (E-XFEL) & ILC: few 100ns bunch spacing. Additional BPM requirements by intra-train feedbacks.

Storage Rings: Fast Orbit Feedback (FOFB)

Typical performance of modern FOFB system:



- Motivation for lowest BPM noise & drift: are modulated back onto the beam (even amplified when frequency > cut-off)

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

FOFB Algorithm: Impact on BPM Requirements

„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

FOFB Algorithm & BPM Requirements (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:
  - ✓ 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
- Needs sufficiently powerful real-time feedback computation engine (µPs, DSPs, FPGAs, or combination)

Impact of Machine Design on BPM Requirements

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

→ At a well-designed machine, many BPM system specifications are not relevant for beam stability → difficult to get funding for upgrades of older BPM systems ...

BPMs For Beam-Based Magnet Alignment

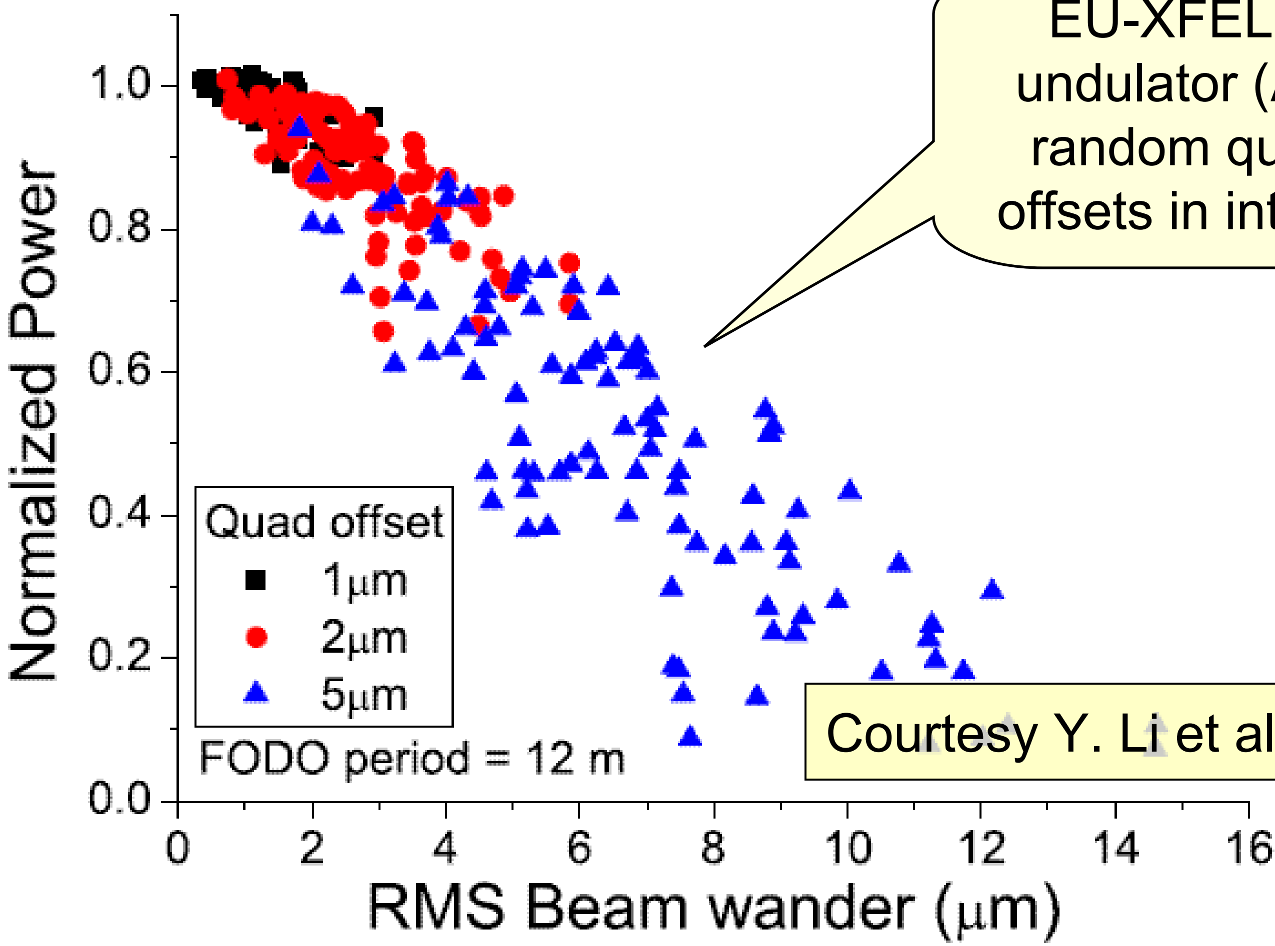
Ring Light Sources

- Local bump in quadrupole magnet: Find bump amplitude where quad strength change causes minimal orbit distortion
- Goal: Calibrate BPM offset, reduce coupling
- Moderate requirements on BPM resolution & drift (>>1µm)

Linac FELs

- Undulator length up to ~200m, segmented: 1 quadrupole & BPM every few meters
- SASE process: Needs <σ/10 (~3µm @ λ~0.1nm) deviation from straight e-beam trajectory over >2-3 gain lengths (~10-20m) for sufficient (~90%) electron-photon overlap
- Raubenheimer 1990: Quadrupole alignment via dispersion-free steering (e.g.: LCLS, EU-XFEL)

Quadrupole Alignment Error vs. FEL Power



EU-XFEL: SASE1 undulator (λ=0.1nm), random quadrupole offsets in interval [-x,x]

Courtesy Y. Li et al. (DESY), 2009

Dispersion-Free Steering (DFS)

Method

- Beam trajectory is straight (only) if beam-energy-independent
- Measure trajectory for different energies, iterative correction of quadrupole center (e.g. via 2D mover)
- Advantage (over ballistic method, …): accounts for all dipole fields (quad, undulator errors, earth & stray fields, …)
- BPMs must only measure relative beam movement: initial unknown BPM & magnet offsets ~100µm (!) O.K.

Resulting BPM Requirements

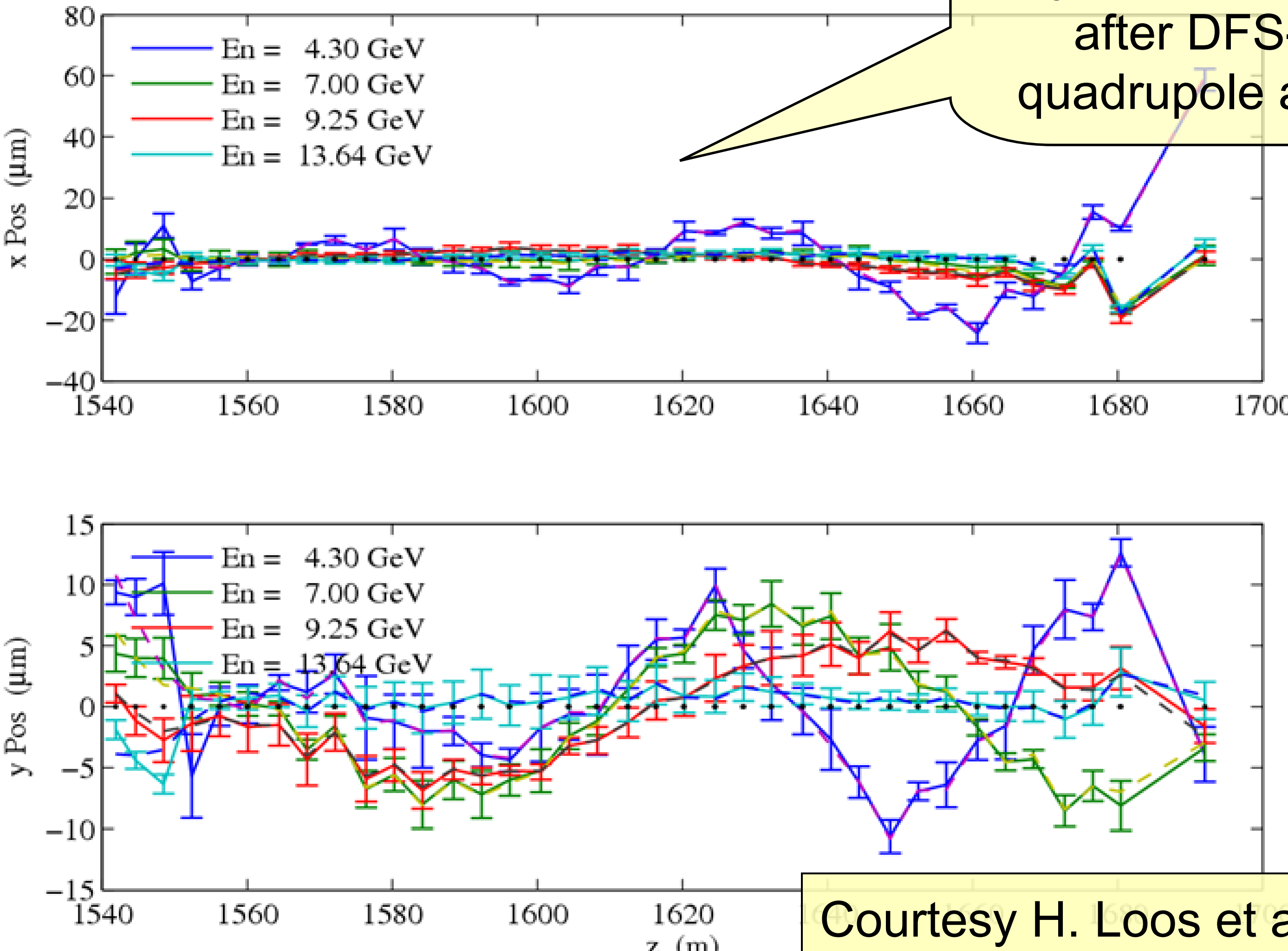
Not necessarily single-bunch

- Resolution for σ~30µm beam size (LCLS, EU-XFEL)
  - typ. ~1µm if ΔE/E ~ some 10%
  - typ. ~100nm if ΔE/E ~ few %

σ/300, not σ/10: → BPM specs driven by magnet alignment strategy (or vice versa)

DFS @ LCLS

Measured LCLS beam trajectories in undulator after DFS-based quadrupole alignment



Courtesy H. Loos et al., 4/3/2009

Transverse Beam Profile

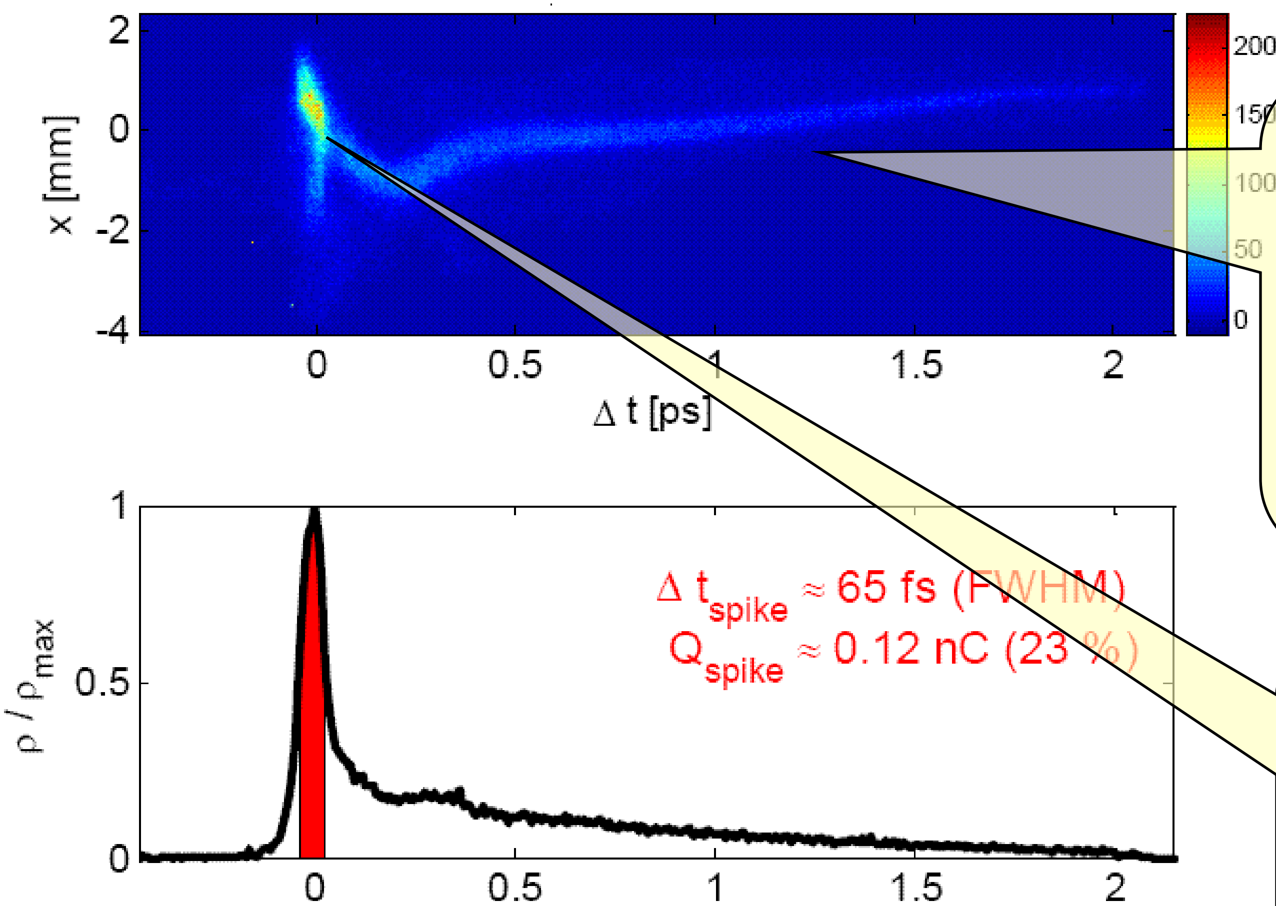
Ring Light Sources

- 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

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

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Common Pickups

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

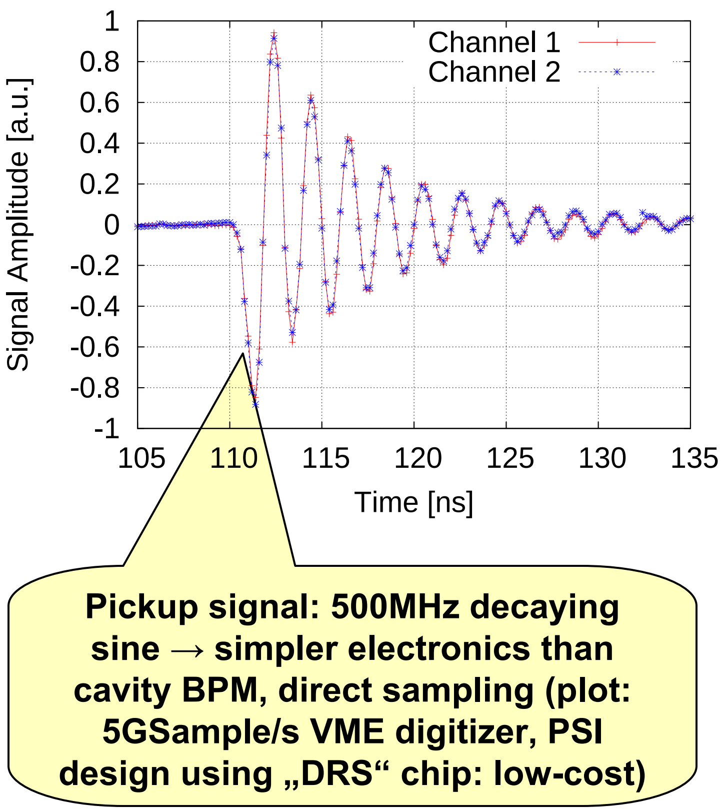
	Button	Matched Stripline	Resonant Stripline, Normal Coupling	Single Cavity Normal Coupling	Two Cavities, Hybrid Coupling
Signal/Noise	–	– / +	+	+	+
Monopole Mode Suppression	–	–	–	– / +	+
Single-Bunch Resolution (@ low charge)	–	– / +	+	+	++
Electronics Drift	– / +	– / +	– / +	– / +	+
Weight 10mm pipe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

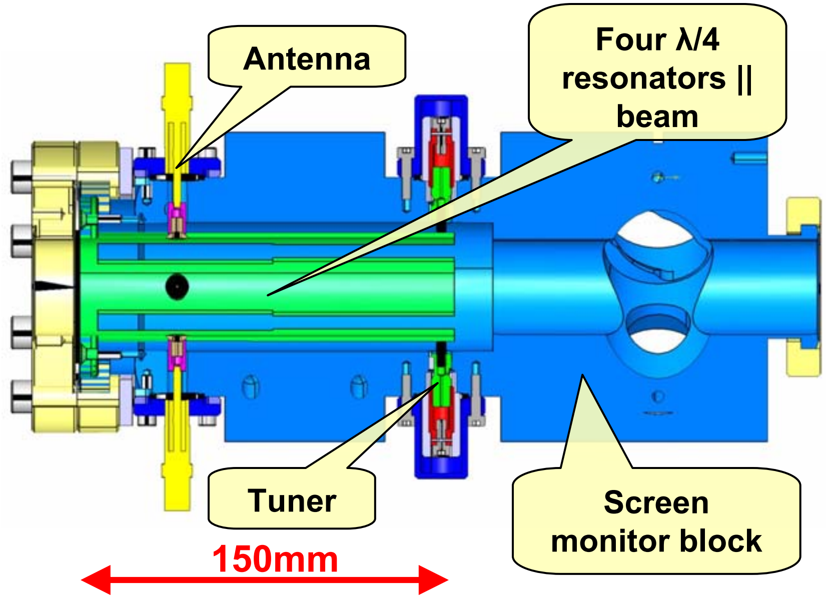
performance

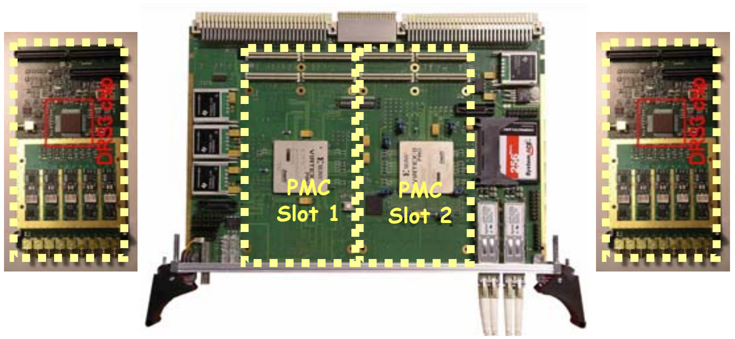
budget

Resonant Stripline Pickup

- Standard pickup for PSI XFEL test injector: needs ~10µm resolution at 10...200pC (poster: A. Citterio et al.)
- Signal/noise superior to button at 10pC. Potential for sub-µm resolution at higher bunch charge with suitable electronics (hybrid, ...)



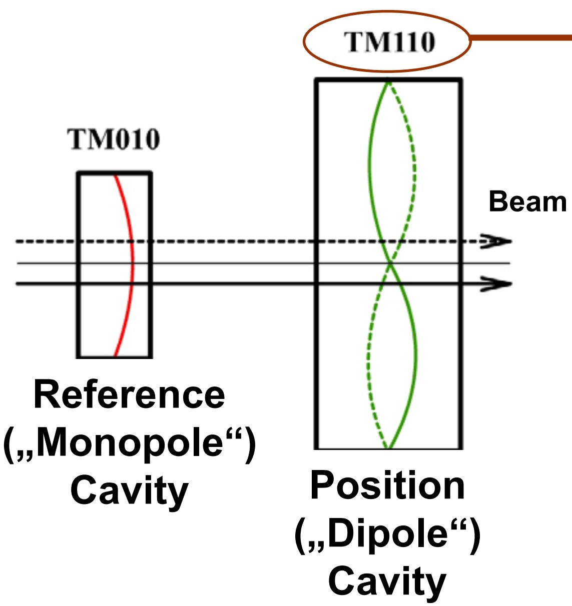


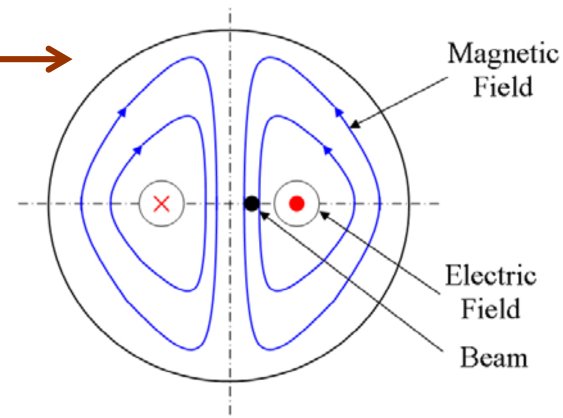


Cavity BPM Pickups

Many types & designs (→ overview talk D. Lipka). Examples:

- LCLS: 11.4 GHz. Waveguide to electronics (→ talk Stephen Smith)
- SCSS (H. Maesaka et al.): Weight- and cost-optimized design for lower frequencies. Cables to electronics. Well suited for larger beam pipe diameters (SCSS: 4.8GHz, E-XFEL: 3.3GHz).



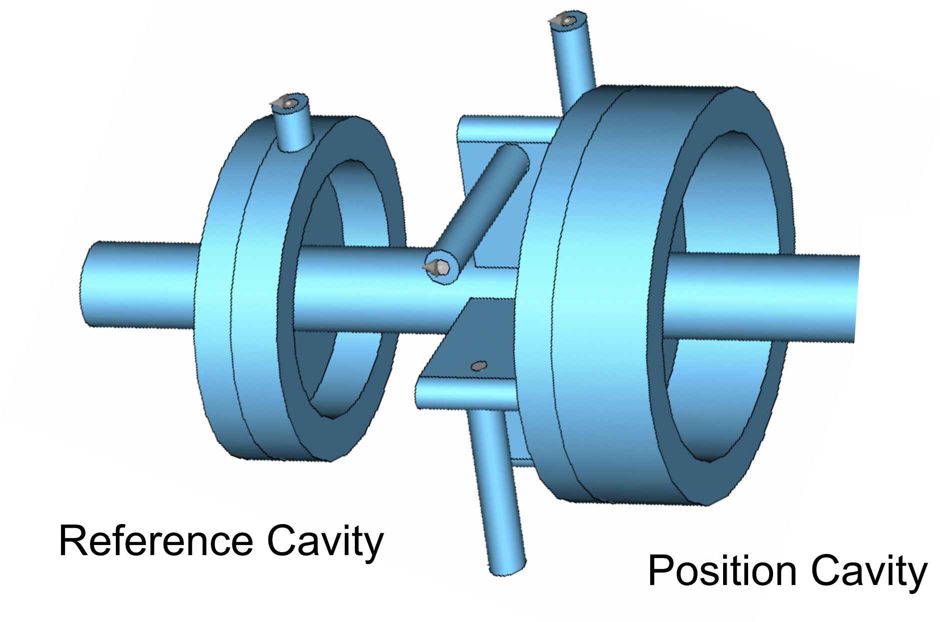


- **Reference Cavity: Signal ~ Bunch Charge.**
- **Position Cavity: Signal ~ Charge * Position**

Pictures: Courtesy A. Liapine, D. Lipka

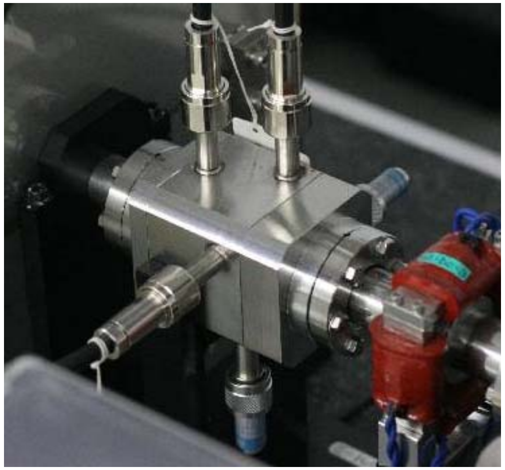
Cavity BPM Pickups (Cont'd)

- Allow mode-selective coupling (LCLS, SCSS, ...): Position cavity waveguides / antennas couple to dipole mode, suppress large monopole mode signal
- Result: easier monopole suppression in electronics than pickups with normal couplers → highest resolution (<< 1 μm) & low drift



(Visible: vacuum, couplers)

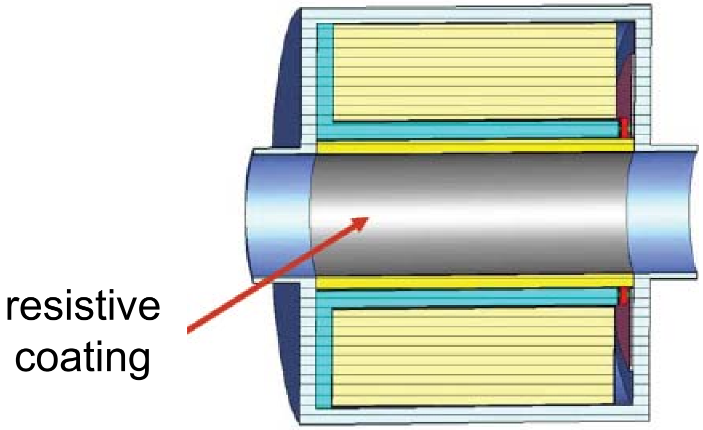
SCSS type (4.8 GHz).
L = 100 mm overall.

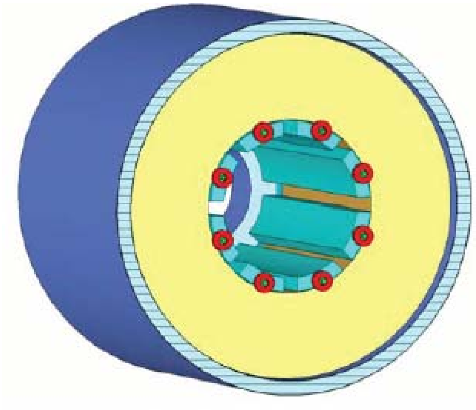


Pictures: Courtesy D. Lipka

Colliders: Current Transformer BPM

- Ceramic gap in beam pipe: wall (mirror) current flows over transformers („segmented wall current monitor“). Current ratio used for position calculation.
- ILC version: 2.6µm (x) / 5.2µm (y) resolution (3.2nC, 300ns bunch spacing, 0.3–80MHz BW).
- CLIC version (0.67ns bunch spacing, 760pC) 180nm (x) / 350nm (y) resolution (not single bunch).

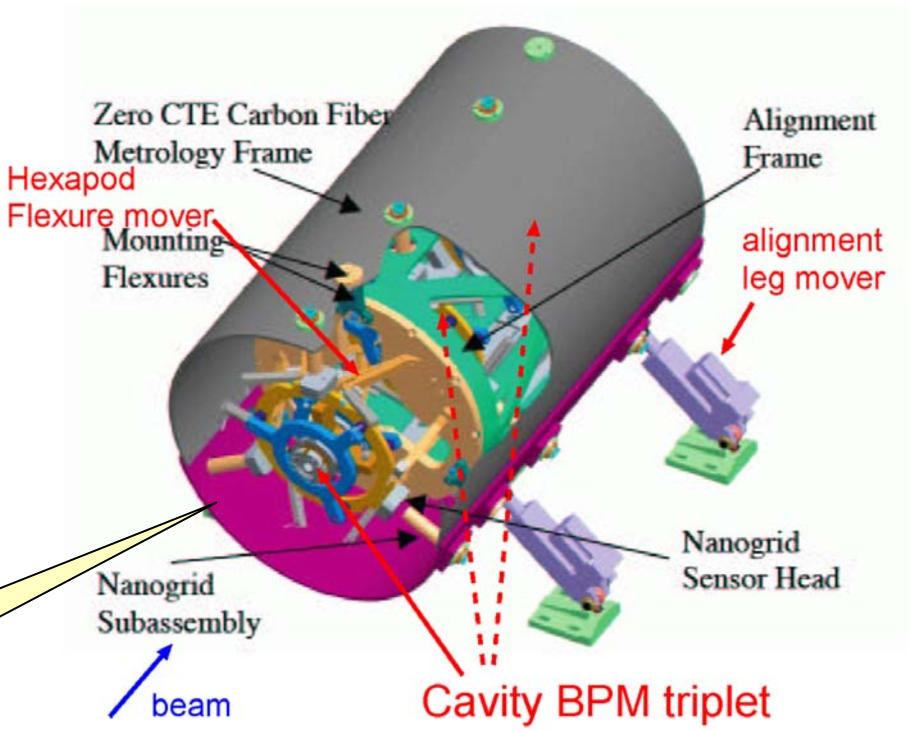




Courtesy L. Søby, DIPAC'07

Pickup Supports

- Sub-µm position resolution: want also low drift of electronics <u>and mechanics</u>
- Mechanical drift: ~100nm with suitable support material & temperature stability („passive support")
- ILC IP: want ~2nm resolution → use „active" support



SLAC/LLNL "nm-BPM": 15.6nm resolution (cavity triplet, somewhere hidden in the support ...)

Courtesy M. Ross
APAC 2007

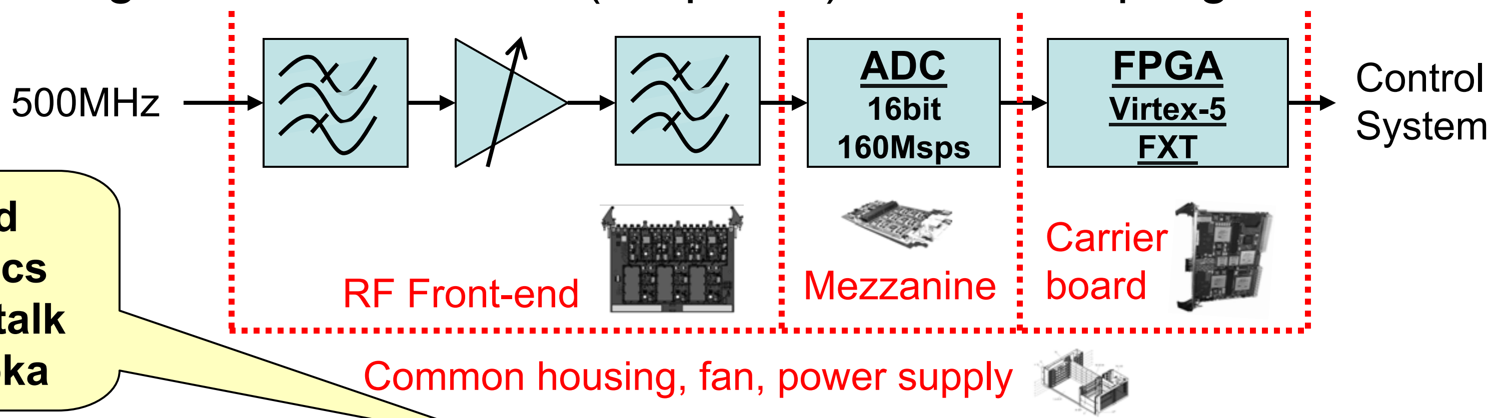
BPM Electronics

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

	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%

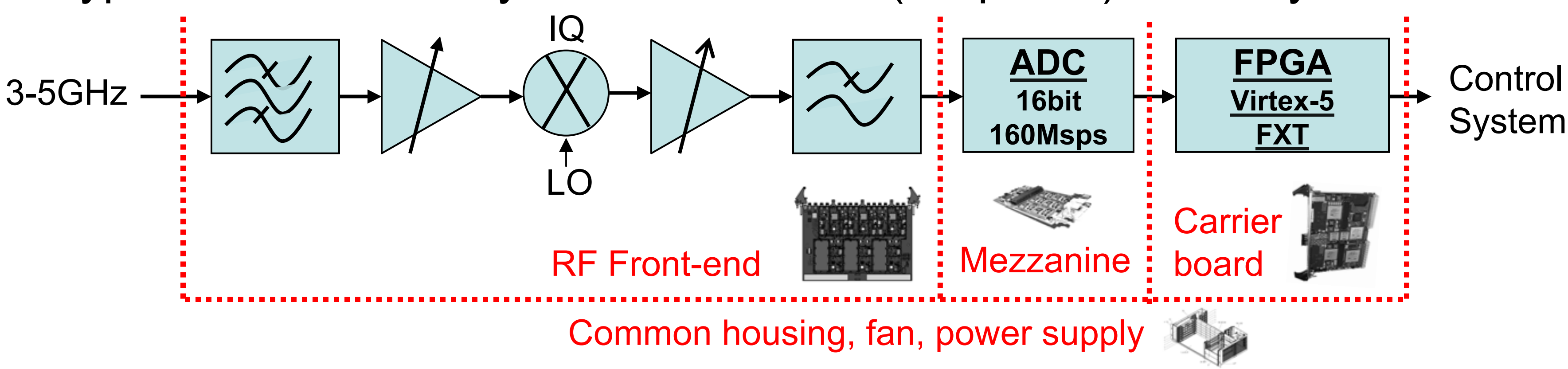
BPM Electronics (Cont'd)

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



Detailed electronics designs: talk by D. Lipka

- 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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Summary

- Beam position measurement is not just pickup & electronics technology, but an overall concept involving machine design & operation.
- The design of magnet lattice & optics, RF & air conditioning systems, choice of beam-based alignment techniques & orbit correction algorithms as well as the bunch charge and its temporal variation strongly affect the required BPM performance.
- Kennedy (slightly misquoted): Don't (just) ask what the BPM system can do for your machine, but (also) what your machine can do for the BPM system.

Thank you
for your attention!