Paul Scherrer Institut

Diagnostics and Synchronization Requirements For Linac-Based FELs

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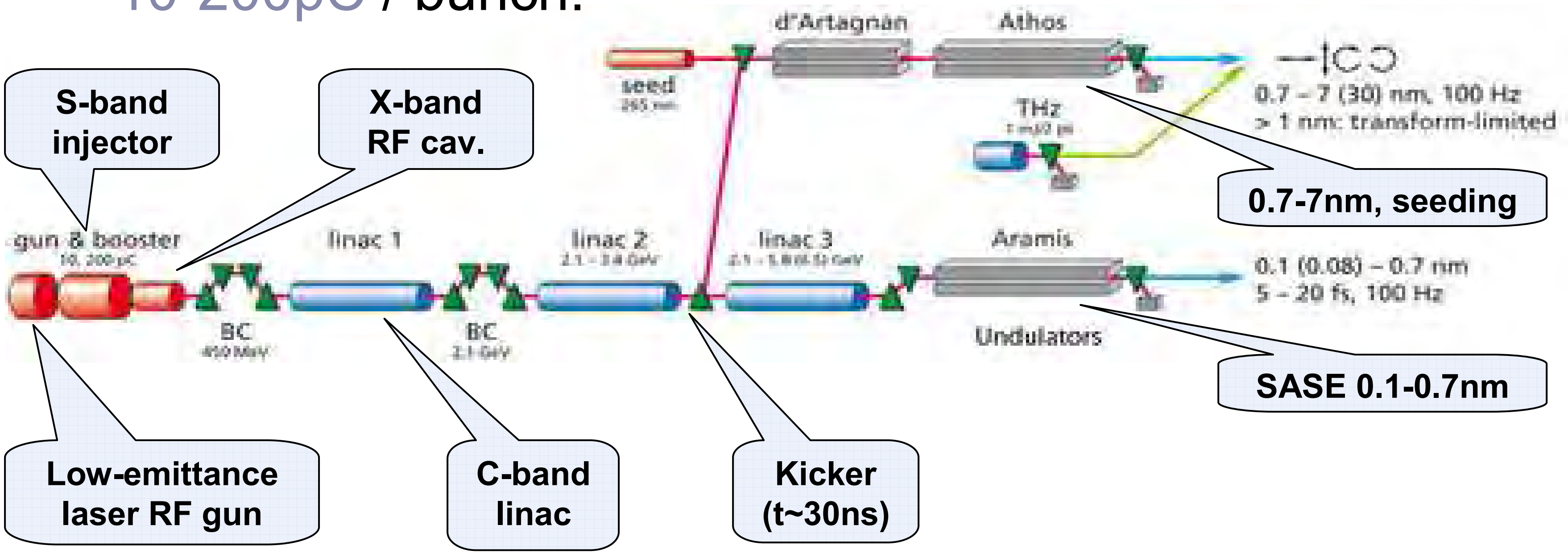
Contents

Disclaimer:
Arbitrary selection of systems needed for & used at linac based FELs. RF-BPM-biased.

Introduction

4G FEL Example: SwissFEL

- L ~ 700m. 5.8GeV.
- Trains of 2-bunches (1 per undulator).
- ~28ns bunch spacing, 100Hz.
- 10-200pC / bunch.



Introduction

4G Linac FEL Light Sources vs. 3G Rings

- 4G: e^- & photon bunch length ~fs (3G: ~ps): ~1000x better timing/synchronization. Longitudinal diagnostics vital.
- 4G diagnostics is single-bunch, for non-Gaussian bunch profiles (3G rings: “Averaged/CW” diagnostics for Gaussian beams).
- 4G Users do pump-probe on fs-scale with “naturally not-so-stable” SASE beam: Single-bunch photon beam diagnostics & data archiving vital (“tag & sort”).

Introduction

4G FEL Trend: Short Bunches, Low Charge

- Initially: FELs wanted Q~1nC bunch charge.

- Drawback: Longer electron/photon bunches (~100fs). SASE: several longitudinal slices lase independently of each other: Longitudinal photon pulse structure has multiple fluctuating spikes.

- Lower charge: Shorter bunches, less spiky photon pulse structure (ideally: single-spike) → better time resolution for users. And: Lower emittance → still many photons (# not ~Q).

Short-Bunch Low-Charge Operation (Cont'd)

- Lower charge (SwissFEL 10pC, E-XFEL/LCLS 20pC): SNR for diagnostics gets worse.
- And: Beam gets smaller (~10µm) & shorter (<10fs). Need even better resolution than at high charge.
- FEL projects chose 5x-20x lower charge during/after diagnostics (BPM, …) development.

AND went from 1-bunch to 2-/multi-bunch operation, 8-30ns bunch spacing …

Introduction

Electron Diagnostics

Photon Diagnostics

Synchronization

Summary

RF BPMs: Typical Requirements

Depend on location:

Injector/linac	~10µm noise/drift (or more) often O.K. (bad trajectory: emittance growth, …).
Undulators	<1µm noise/drift for trajectory alignment (SASE/seeding) & feedback.
Spectrometer & Bunch Compr.	Depends on optics & location. ~10µm noise/drift (~0.01% dE/E) often O.K.

But: Less BPM noise/drift in injector/linac useful:

- Locate & eliminate beam perturbation sources.
- Measure beam size: BPM = wire scanner reference.

Electron Diagnostics

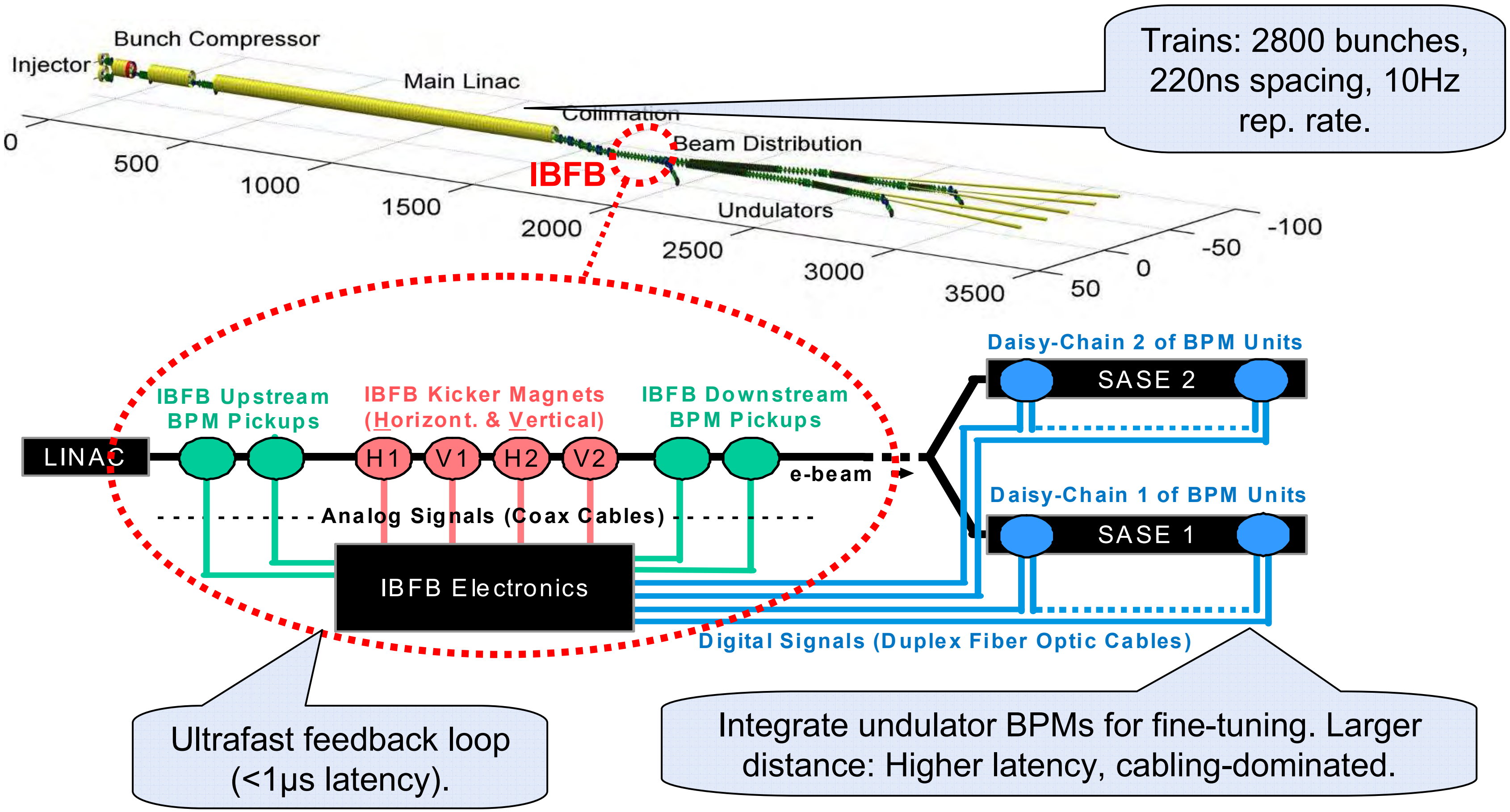
RF BPMs: Trajectory Perturbations & Feedback

- Source suppression vital for ~100Hz single-bunch machines: Trajectory feedback only corrects random perturbations < ~10Hz.

- Feed-forward for non-random perturbations.

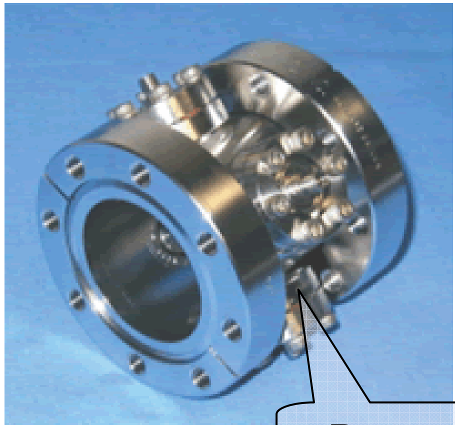
- Long bunch trains allow intra bunch train feedback (IBFB).

Example: E-XFEL Intra Bunch Train Feedback



Electron Diagnostics

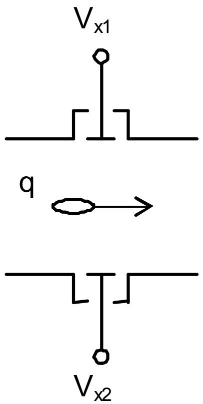
RF BPMs: Common Types

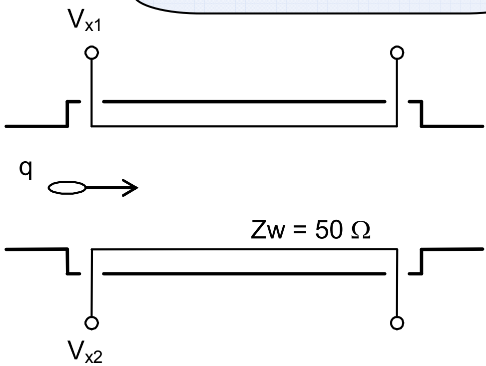


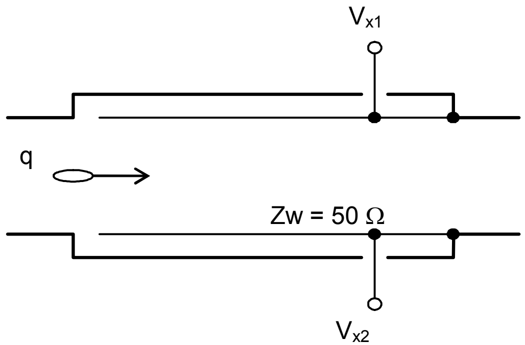
Button

Matched stripline (FLASH)

Resonant stripline (SwissFEL test injector)







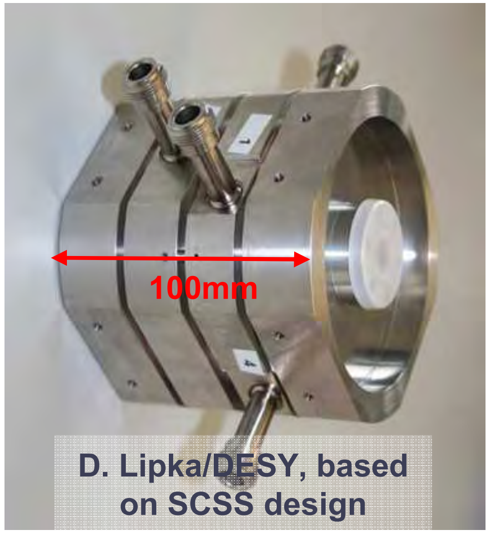
Beam Position = k * $(V_{x1}-V_{x2})/(V_{x1}+V_{x2})$. Factor k (~10mm) determined by geometry.

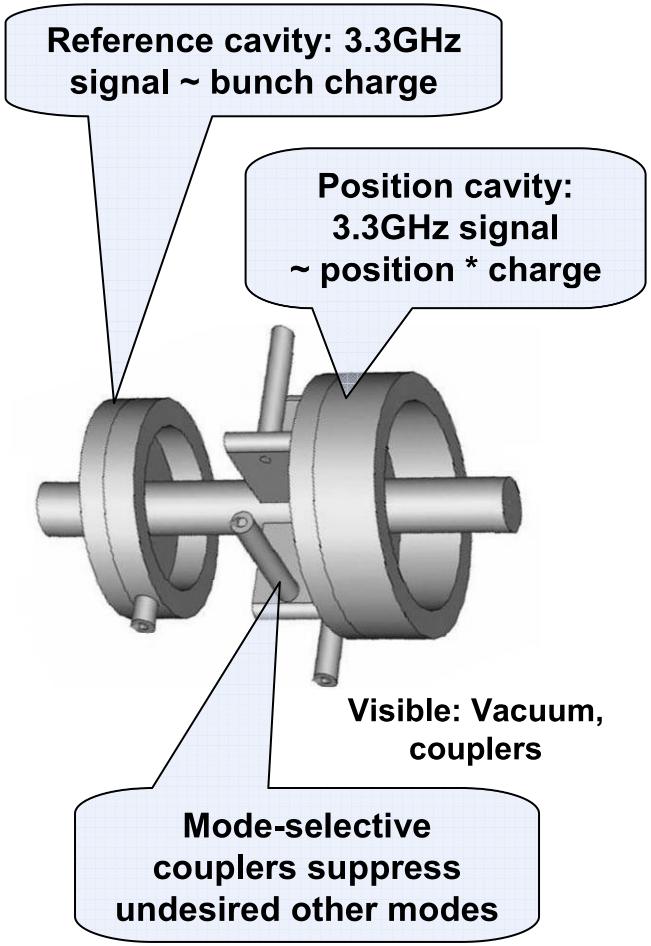
Electron Diagnostics

RF BPMs: Common Types (Cont'd)

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: Zoom!

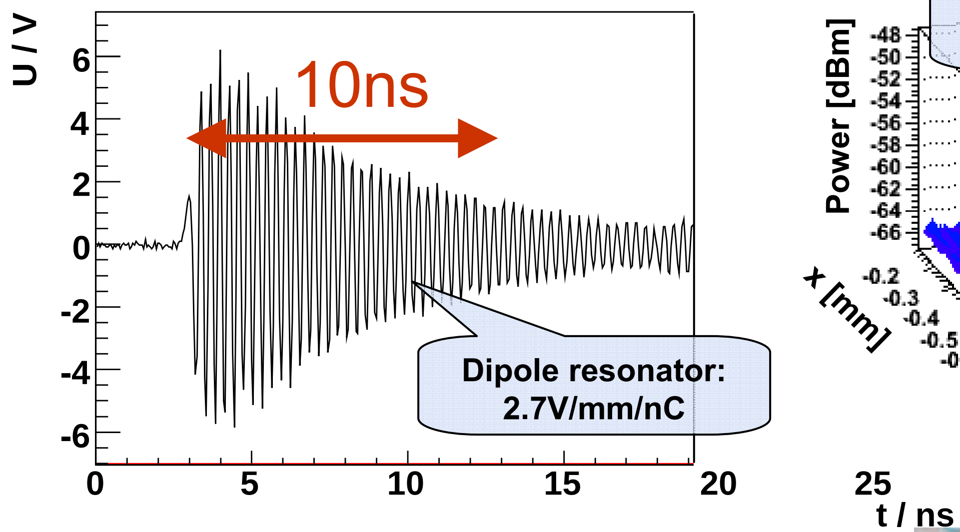
RF BPMs: Common Types (Cont'd)

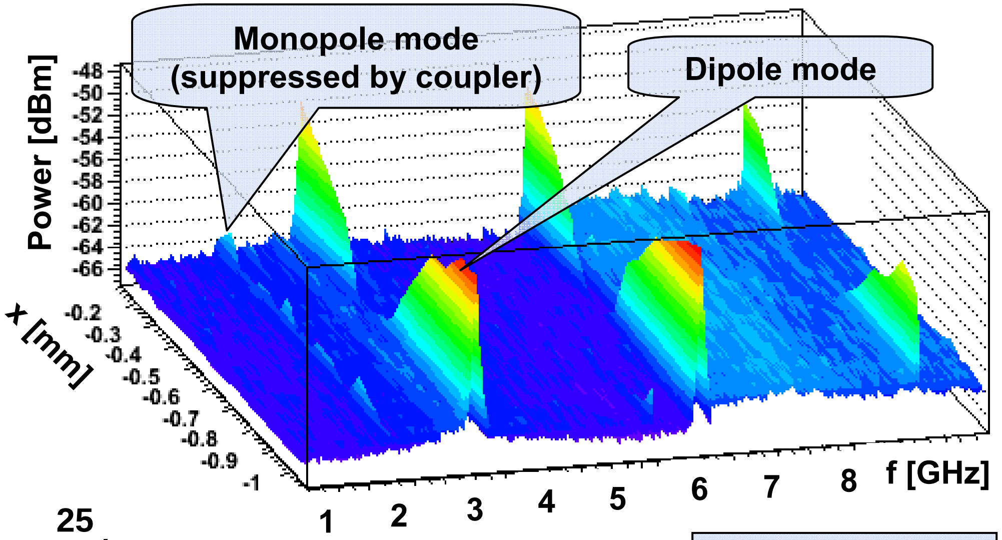
- Buttons: Moderate resolution @ low charge. O.K. with long bunch trains (E-XFEL): Averaging.
- Striplines (matched + resonant): Better low-charge SNR that buttons (resonant: >10x). O.K. for low-charge single-bunch injector/linac/transfer lines.
- Single-resonator cavity + normal couplers: Common-mode suppression limits performance.
- Dual-resonator cavity + mode-suppressing couplers: Optimal performance (common mode suppression, drift, …), highest SNR.

Undulator BPM for LCLS, SCSS, E-XFEL, …

Electron Diagnostics

Example: E-XFEL Cavity BPM



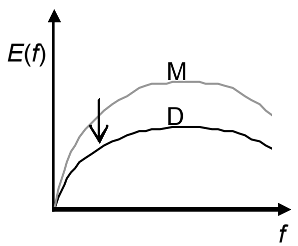
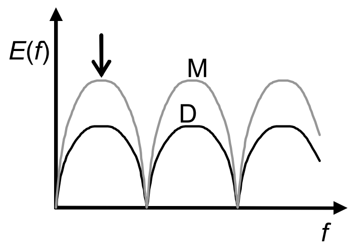
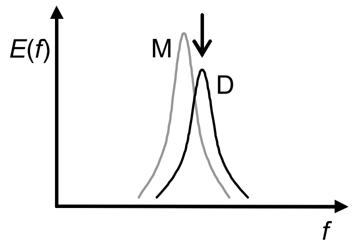
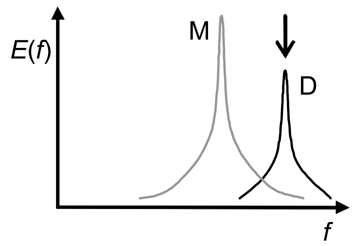


D. Lipka et al.

10mm aperture
(undulators)

40.5mm aperture
(beam transfer
lines, …)

RF BPMs: Common Types (Cont'd)

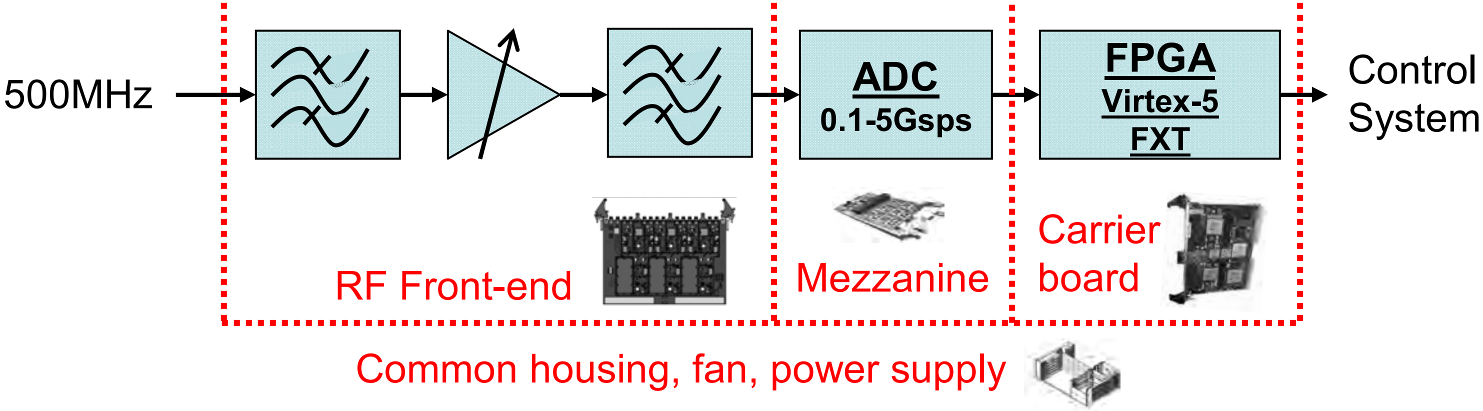
Pickup	Button	Matched Stripline	Resonant Stripline	Cavity
Spectrum				
Monopole Mode Suppression	Modal (hybrid) / electronics	Modal (hybrid) / electronics	Modal (hybrid) / electronics	Modal (coupler), frequency, phase (sync. det.)
Typical RMS Noise, 10pC, *20mm pipe*	~100µm	<60µm (scaled to 20mm pipe)	<4µm (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 …

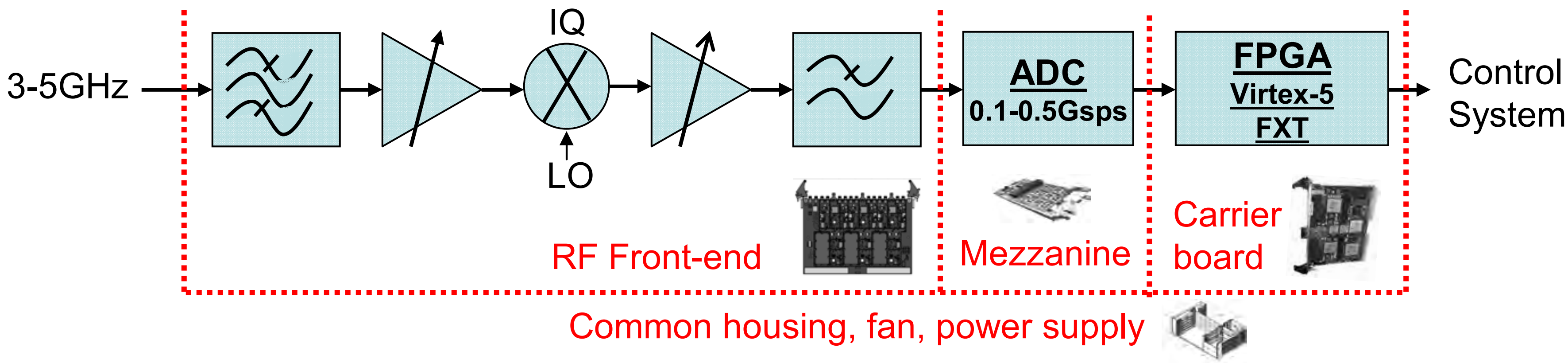
Electron Diagnostics

Typical RF BPM Electronics (Simplified)

- Direct sampling (striplines, buttons)

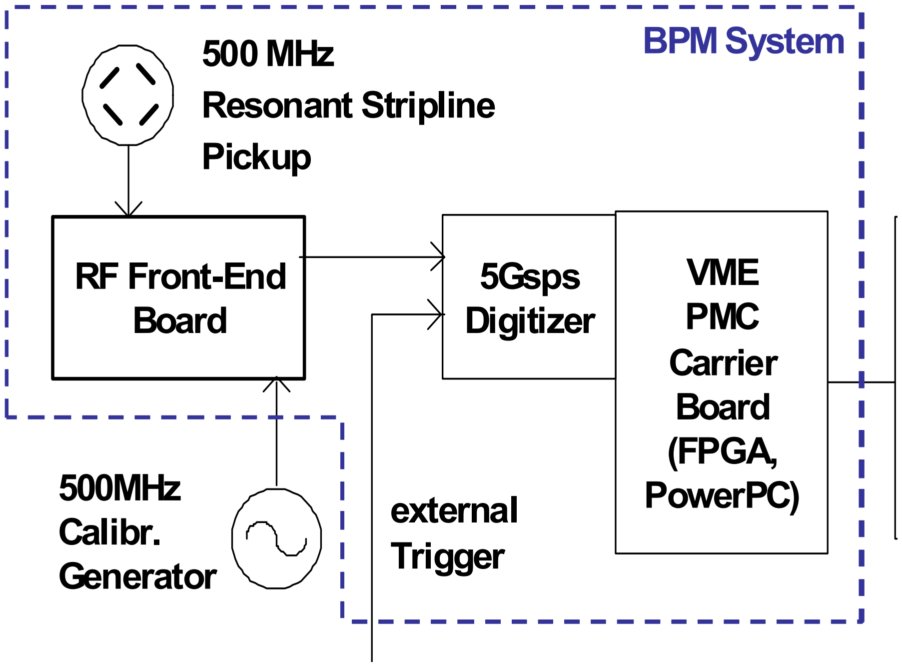


- IQ mixing to baseband (cavity)



Electron Diagnostics

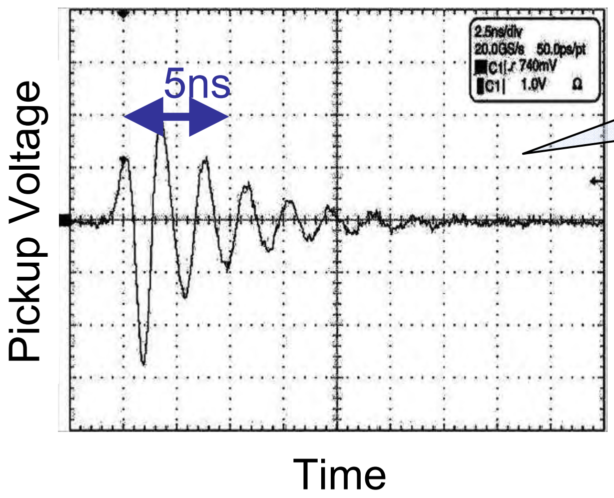
Example 1: Resonant Stripline BPM System



Direct sampling, no mixer (PSI design). Used for SwissFEL test injector (FEL2010, WEPB15).

- Position noise: 7µm @ 5-500pC, 15µm @ 2pC (16mm geom. factor, 45°).
- Range >20mm peak-peak (38mm pipe). Charge noise: <5fC @ 0.5pC.

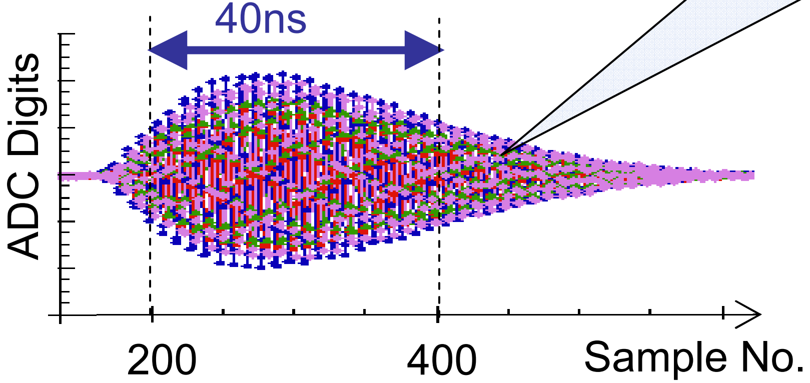
Resonant Stripline BPM System (Cont'd)

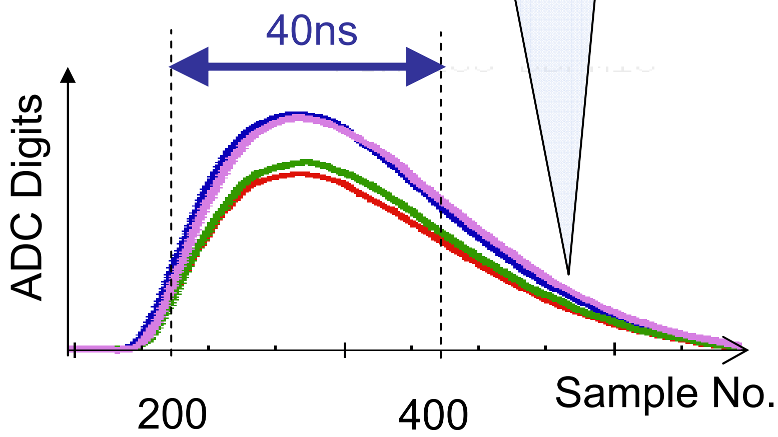


Low-passed pickup signal
(scope measurement)

RFFE output, digitized by BPM electronics (5Gsps), after gain/offset/jitter correction & FIR filtering in FPGA

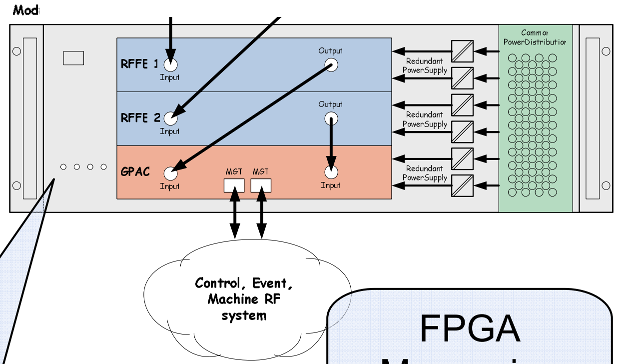
FPGA calculates envelopes of RFFE signals. Beam position calculated from integrals.





Example 2: E-XFEL Cavity BPM Electronics

- PSI in-kind contribution to E-XFEL.
- Comment: Good resolution with tiny range is easy but of little use: Specify range.
- Low drift & good linearity for large charge range are often the bigger challenge.

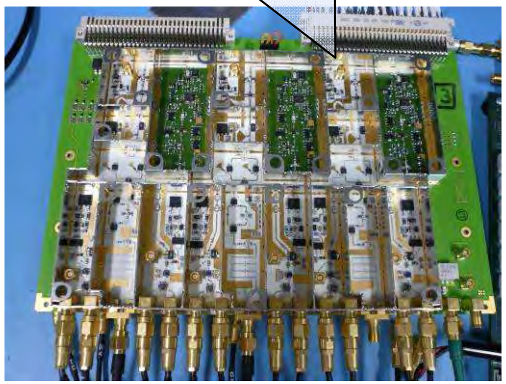


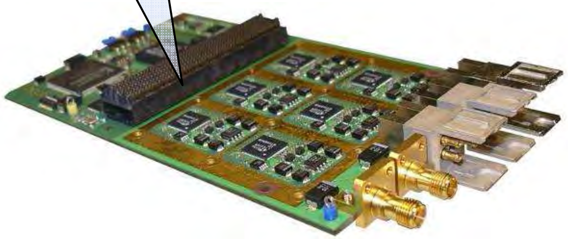
Modular BPM Unit: 2-4 RFFEs, 1 FPGA Board.

FPGA Mezzanine Carrier Board

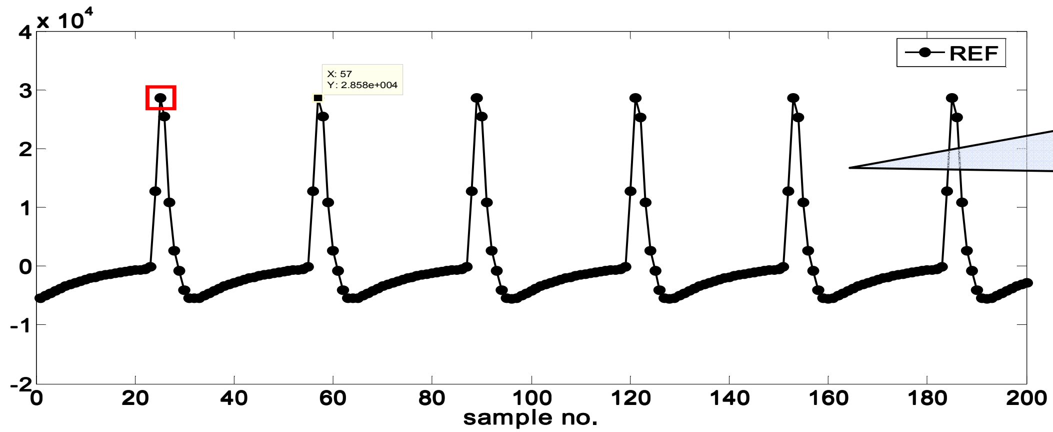
3.3GHz RFFE (IQ mixing to baseband)

6x16bit 160Msps ADC Mezzanine

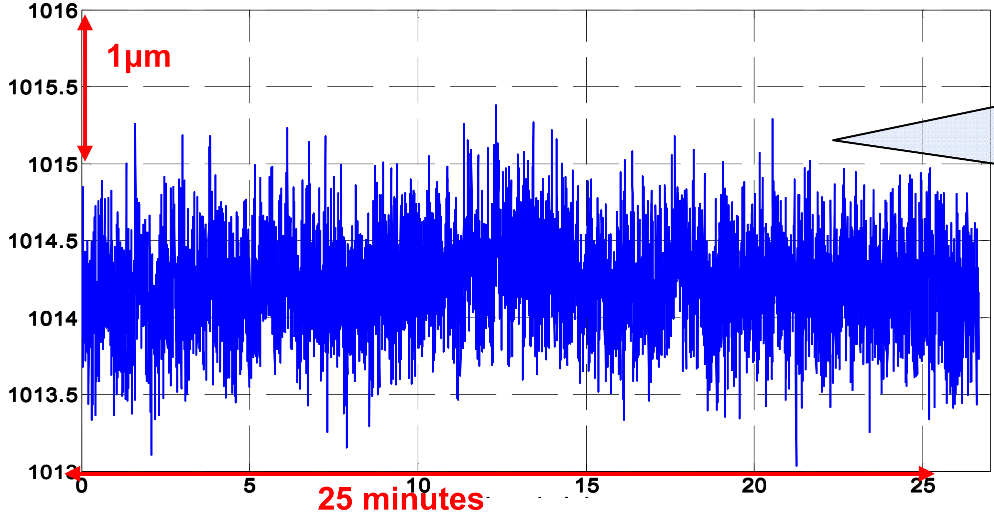




E-XFEL Cavity BPM Electronics (Cont'd)



RFFE output signal (input: 3.3GHz test pulser), sampled by ADC mezzanine.

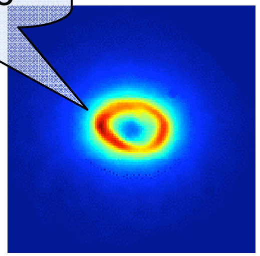


1st prototype test: ~350nm/750nm RMS electronics noise @ 0.3/0.1nC (±1mm range). (beam signal of one pickup split to two electronics – tests with 3 pickups end 2010).

Transverse e-Beam Profile Monitors

Ce:YAG ($Y_3Al_5O_{12}$ + 0.2% Cerium):
- Scintillator, decay ~70ns.
- Saturates at higher charge densities & energies (100MeV: ~0.01pC/μm^2)

COTR (non-) beam profile



OTR:
- Foil (metal or metal-coated, e.g. Al).
- Linear, immediate response:
  - Good for short bunch spacings.
  - Problem: Emitting coherently (COTR: $I \sim N_e^2$) when (tiny) partial micro-bunching. Messes up profile image. Problem for most (all?) linac FELs.

Electron Diagnostics

Transverse e-Beam Profile Monitors (Cont'd)

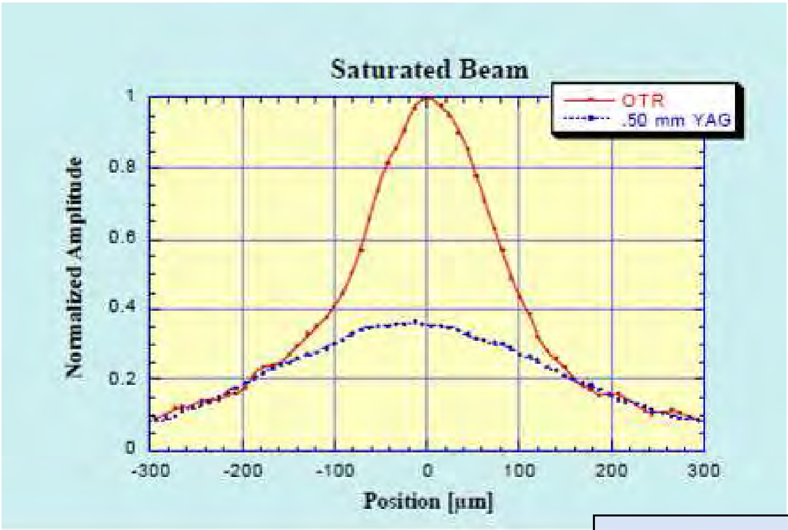
Wire Scanner:

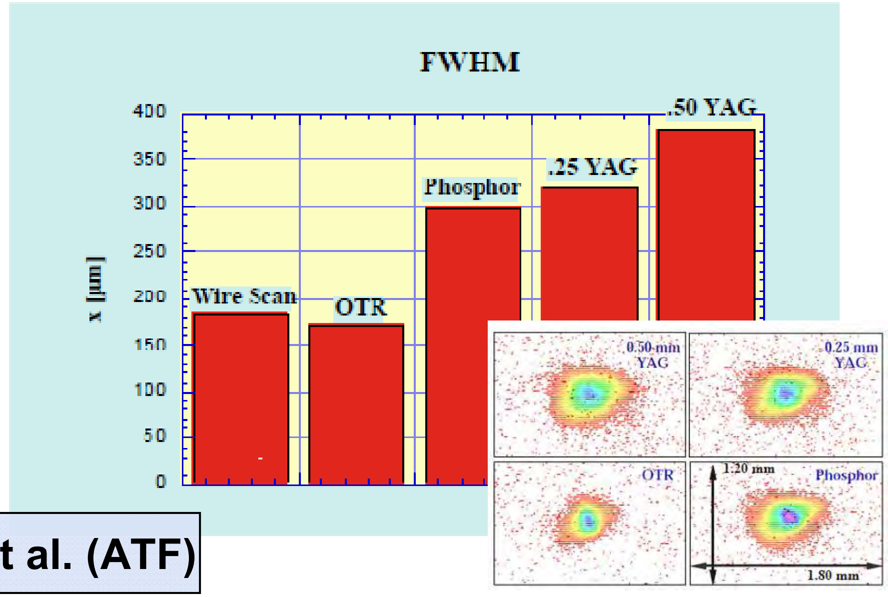
- Working horse for COTR-plagued FELs
- Not single bunch:
  - Use RF BPMs to determine (jittering) bunch center-of-charge position relative to wire
  - Use camera etc. to monitor absolute wire position (vibrations, …)

FELs are in need of a good single-shot/-bunch profile monitor: Linear, response <<10ns, no COTR, ….

Transverse e-Beam Profile Monitors (Cont’d)

Saturated Ce:YAG: Wrong profile, overestimated beam size





A. Murokh et al. (ATF)

Electronics: Screens + COTS cameras. Challenges: 10-30ns bunch spacing, >100Hz image processing (fit) & archiving, …

Beam Loss Monitors: Common Types

Scintillator / Cherenkov fibers + photomultiplier/-diode:

- Frequently used.
- Flexible geometry (wind around beam pipe, …).
- Cherenkov: Fast, locate beam loss by photon-TOF.

Semiconductor diodes / gas ionization chambers / …:

- Proportional mode (large losses) or avalanche / threshold mode (count single particles).

Applications:

- e-beam profile measurement with wire scanners
- Machine protection, …

Electron Diagnostics

Beam Charge Monitors

Absolute: Q vs. ε, …

Wall current monitor (WCM), toroid:
- Simple, robust. Often noise issues @ very low charge.

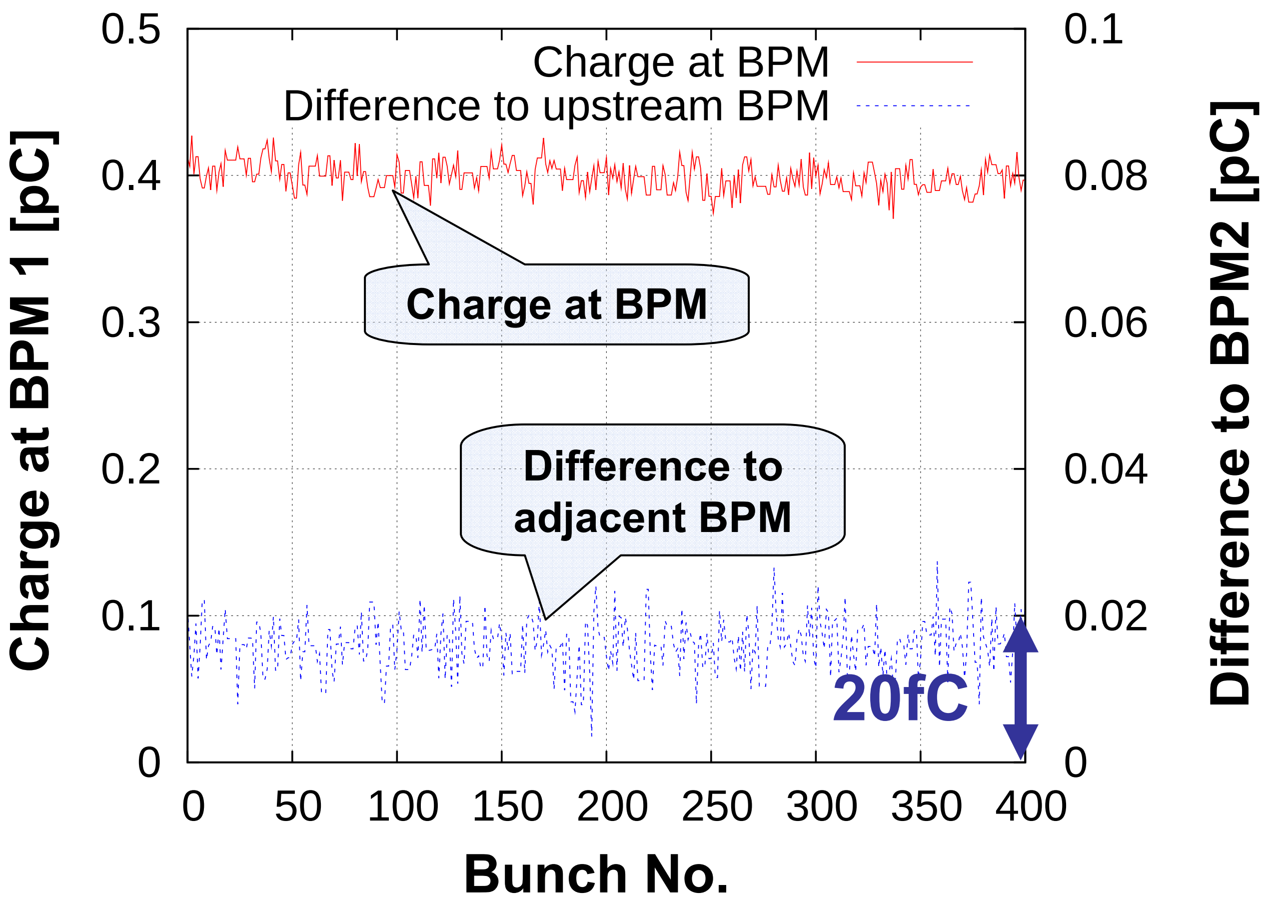
Faraday cup:
- Simple, destructive.

Relative: Beam loss, …

Cavity:
- Can be made sensitive or insensitive to dark current.

RF BPMs:
- Resonant striplines, cavities, …: Good resolution at low charge (typ. few fC or ~0.1%)
- Issues: Abs. calibration, drift, position dependence.

Example: Charge Meas. with Reson. Stripline



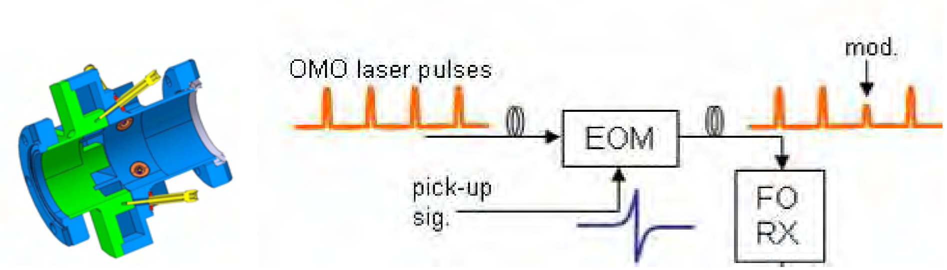
Data from SwissFEL test injector. BPM charge resolution better than WCM, Faraday cup & ICT …

Electron Diagnostics

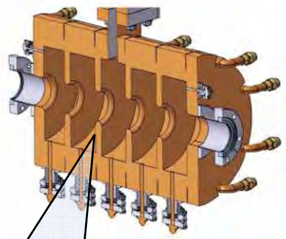
Longitudinal Diagnostics: Few Examples …

Beam arrival time (BAM):

- SwissFEL: 20-40GHz RF button/waveguide pickup in beam pipe. Cable to electro-optical modulator (EOM). Arrival time ~ pickup voltage (near zero crossing) ~ laser pulse polarization/intensity. Resolution <10fs.



LCLS proposal: New X-band TCAV, 2fs



SwissFEL t.i. TCAV

Transverse deflecting cavity (TCAV) + screen:

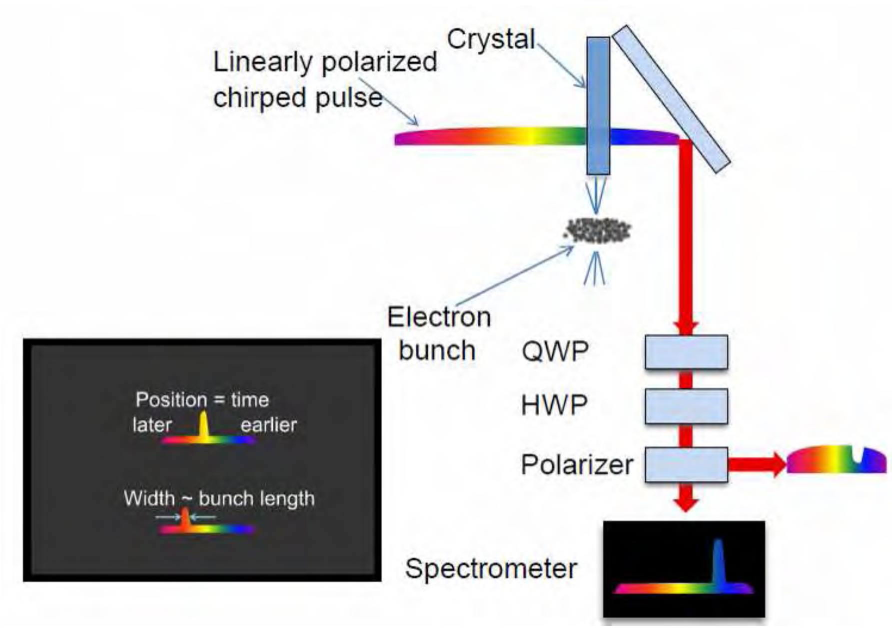
- Translates longitudinal to transverse dimension. Measures sliced emittance & bunch length, E-profile.

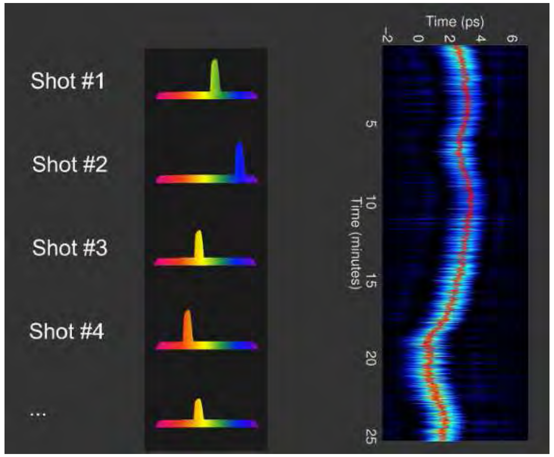
Electron Diagnostics

Longitudinal Diagnostics (Cont'd)

Spectral decoding:

- e-beam modulates polarization of chirped laser pulse in EO crystal. Spectrometer: Bunch length, arrival time.





Images: N. Cutic, FEL2010

Introduction

Electron Diagnostics

Photon Diagnostics

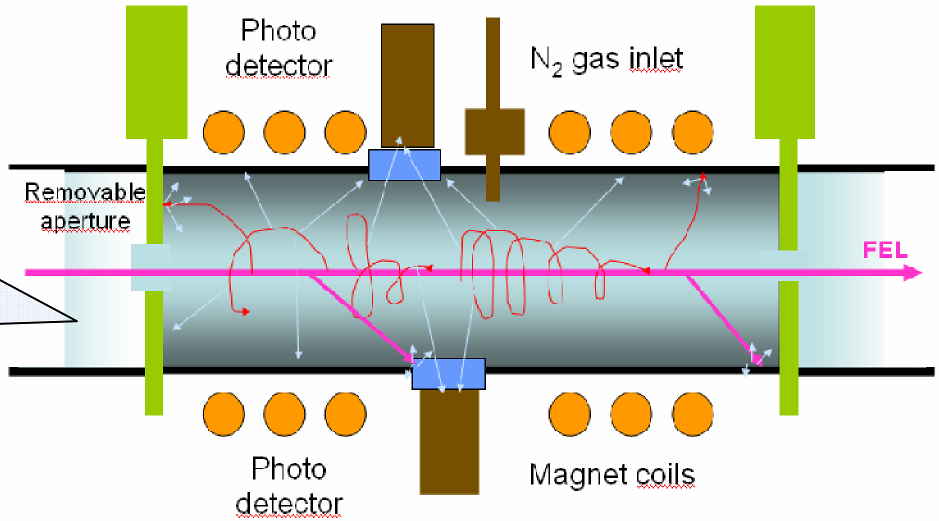
Synchronization

Summary

Existing X-ray Diagnostics: LCLS, …

- Profile (destructive): Ce:YAG screen + attenuators.
- Energy spectrum: Monochromator.
- Pulse energy: From electron energy loss & gas (N_2) fluorescence.
- …

LCLS X-ray pulse energy detector, non-invasive (image: Joe Frisch)



Primary photoelectrons cause N_2 molecules to fluoresce in the near UV

Photon Diagnostics

To-Be-Developed FEL X-ray Diagnostics

Non-invasive single-bunch measurement of X-ray

- Energy spectrum,
- Pulse length / longitudinal profile (sub-fs),
- Arrival time relative to pump laser,
- …

over full X-ray energy & intensity range (~0.1…15keV).

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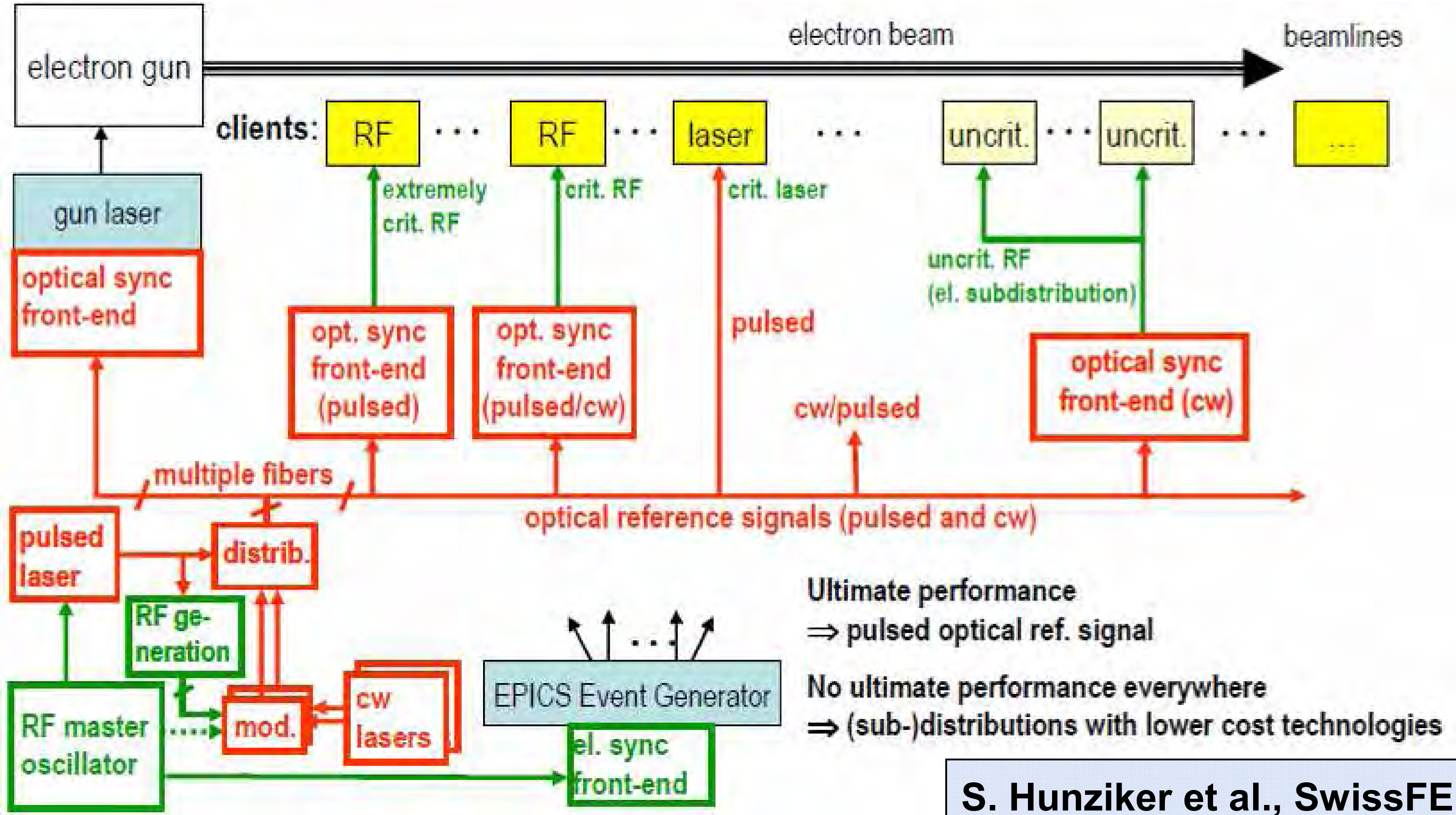
Synchronization

Synchronization of Machine Subsystems

- Synchronize accelerator systems (LLRF, gun/seed laser, …) well enough to achieve reasonably (cost, man power) small FEL photon beam fluctuations.
- "If you can't control it, at least measure it.": Deal with remaining fluctuations by providing single-bunch photon beam arrival time (relative to pump laser) & other data (pulse energy, …) to users.
- If lack of photon diagnostics: Estimate photon from electron beam properties (e-BAM, …).
- Feedback/feed-forward (BAM, …) reduces jitter/drift.

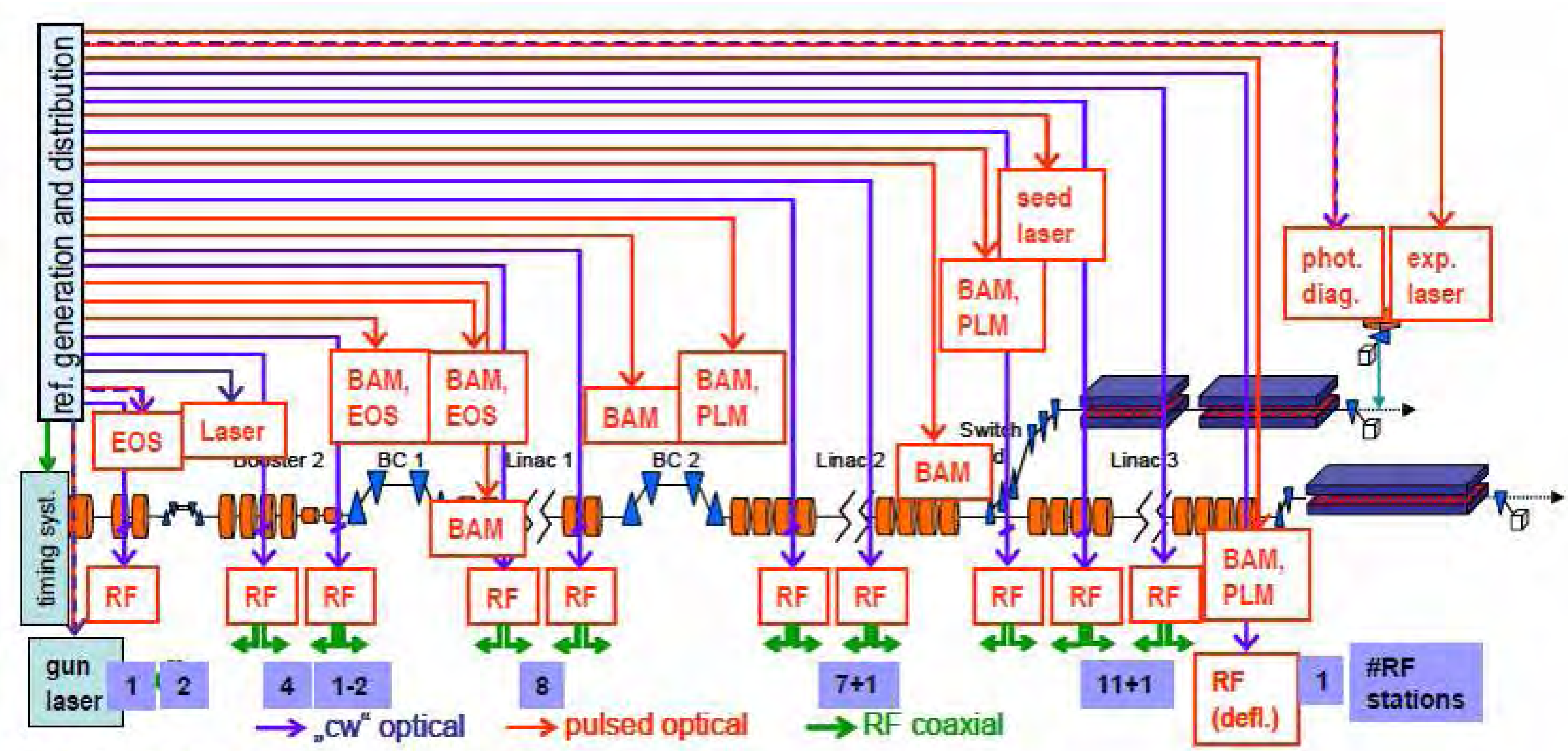
Example: SwissFEL Synchronization System



S. Hunziker et al., SwissFEL CDR

Synchronization

SwissFEL Synchronization System (Cont'd)



An RF station gets its reference signal over a dedicated optical link.
An "RF" block in the drawing represent the number of RF stations indicated below.

S. Hunziker et al., SwissFEL CDR

Synchronization

SwissFEL Synchronization System (Cont'd)

Beam Jitter / Expected Parameter Jitter	arrival time [fs]	peak current [%]	energy [%]
For 0.015 deg S-Band Phase jitter:	4.8	3.4	0.002
For 0.012 % S-Band Voltage jitter:	5.9	0.3	$2 \cdot 10^{-4}$
For 0.06 deg X-Band Phase jitter:	0.3	9.1	0.004
For 0.012 % X-Band Voltage jitter:	1.1	0.02	$6 \cdot 10^{-5}$
For 0.03 deg Linac 1 Phase jitter:	1.7	0.5	0.0015
For 0.012 %Linac 1 Voltage jitter:	2.3	0.07	$2 \cdot 10^{-3}$
For 0.03 deg Linac 2 Phase jitter:	0.007	0.001	$5 \cdot 10^{-4}$
For 0.012 % Linac 2 Voltage jitter:	0.015	$4 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
For 0.03 deg Linac 3 Phase jitter:	$9 \cdot 10^{-3}$	$9 \cdot 10^{-4}$	$6 \cdot 10^{-4}$
For 0.012 % Linac 3 Voltage jitter:	0.02	$3 \cdot 10^{-4}$	$1 \cdot 10^{-3}$
For 2 pC Charge jitter:	2.4	5.9	$6 \cdot 10^{-4}$
For 30 fs initial arrival time jitter:	1.1	3.6	$9 \cdot 10^{-5}$
For 0.01 % Initial Energy jitter:	4.2	0.1	$3 \cdot 10^{-4}$
For 0.001 % BC1 angle jitter:	0.034	0.7	$3 \cdot 10^{-4}$
For 0.001 % BC2 angle jitter:	$4 \cdot 10^{-4}$	0.09	$4 \cdot 10^{-5}$
total	9.701	11.9	$6 \cdot 10^{-3}$

Injector

Linac 1-3

Gun

S. Hunziker et al., SwissFELCDR

Synchronization

Fs-Scale Pump-Probe User Experiments:

- Measurement of pump-probe laser to FEL pulse delay: Resolution/drift ideally < photon pulse length.
- Infrequent absolute calibration of delay measurement (low BAM drift …) desired.
- E-XFEL: 1-2fs photon FWHM for @ 20pC (FLASH: 2fs). BAM with sub-fs jitter/drift desired …
- BAM performance limit depends on signal frequency: Optical (PHz) has more potential than RF (GHz).

Measure FEL Pulse To Pump-Probe Laser Delay

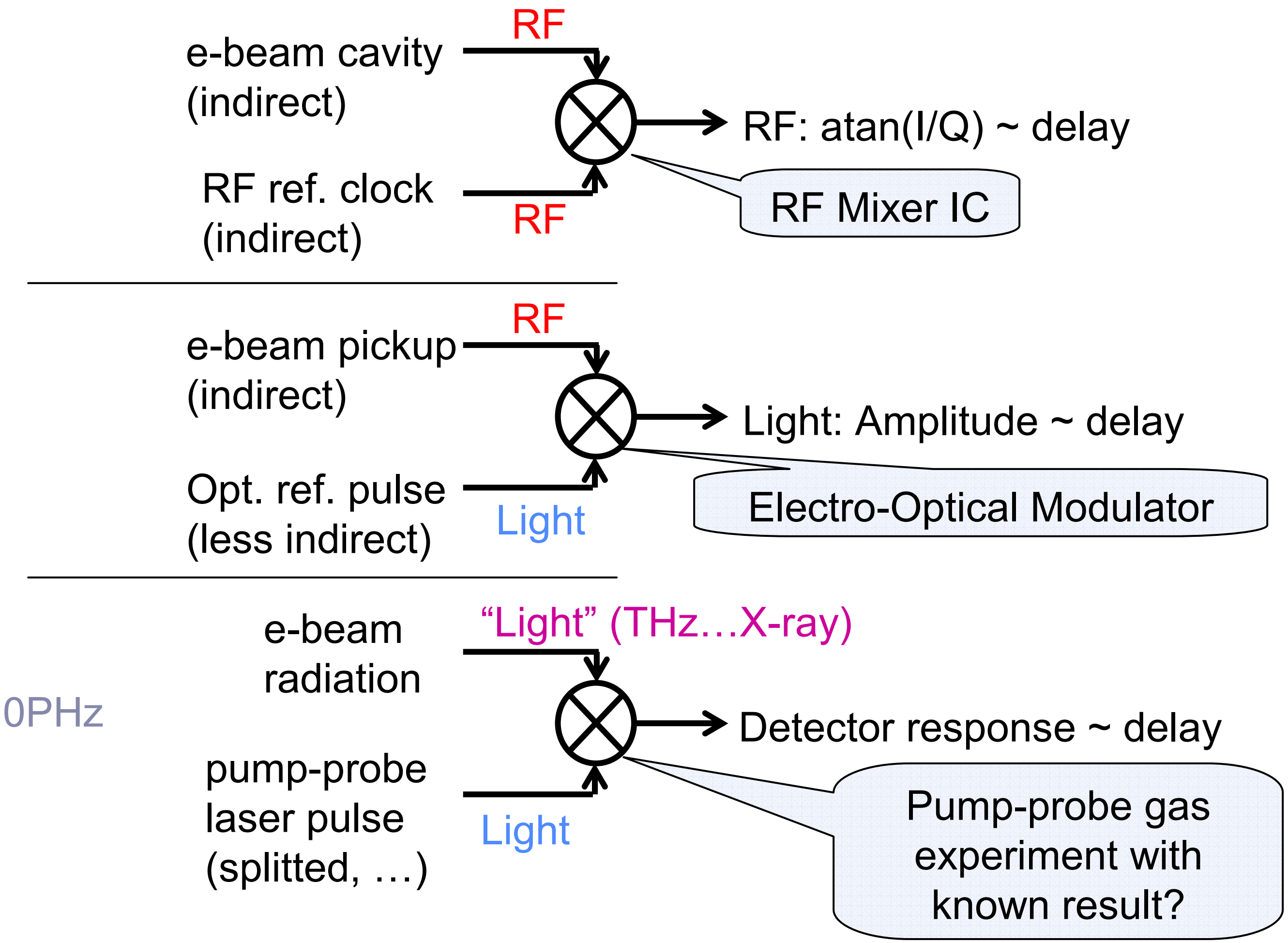
Method 1
"10GHz * 10GHz"

better

Method 2
50GHz * 0.1-1PHz

better

Method 3 (???)
0.1-1000PHz * 0.1-10PHz
<0.1-1fs jitter/drift?



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Summary

- Electron diagnostics for linac-based FELs more mature than photon diagnostics. Single-bunch photon diagnostics & data archiving vital for users.

- 4G (vs. 3G) light sources: Larger system variety, often very small quantities. €xception$: BPMs, LLRF, Sync., … Less common standards, still lot of R&D. Challenge (opportunity?) for companies …

And beam loss monitors. Idea for product name: “Libera Lost & Found” ☺

- FEL machine designs & requirements still evolving (even for already operational machines …).

- 4G FEL diagnostics design is (still) “shooting at moving & shrinking targets”. Waiting for sub-pC 100-as beams …

Thank you for your attention!

Supplementary Slides …

RF BPMs: Pros & Cons of Different Types

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

performance

budget

Resonant Stripline BPM Electronics (Cont'd)

Low-cost 5 GSample/s domino ring sampler (DRS) chip