Digital BPMs and Orbit Feedback Systems

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Outline

- stability requirements at SLS storage ring
- digital beam position monitors (DBPM)
- SLS global fast orbit feedback system
- SLS multi bunch feedback system
- beam stabilization plans at European XFEL

Stability Requirements at SLS

- **Angular stability:** **$\Delta\Theta_{beam} < 1\ \mu rad$ ***
  *** typical $< 10\ \mu m$ at the experiment**
- **Position stability:**
  $\sigma/10$ at Insertion Devices (ID)
  → low beta ID: vertical beam size ~10 μm (1% coupling)
  → **1 μm RMS in vertical plane**
- **suppression** of orbit distortion up to 100 Hz by factor of >5
- fast compensation of orbit distortions due to **ID gap changes**

Beam Stability Strategy at the SLS

- **reduce drifts and vibrations as much as possible**
  (air and water temperature regulation, proper girder design, top-up operation,...)
- **reduce well-known noise sources by feed forward** (ID gap changes,...)
- **suppress remaining noise on e^- beam by fast orbit feedback**
- **use all available correctors for fast orbit feedback**
  (no distinction between slow and fast orbit feedback)

➡ lock beam to center of BPMs

➡ monitor mechanical movement of BPMs with respect to adjacent quads by encoder system

➡ good feedback systems:

beam stability ≈ BPM stability & resolution

Why digital BPMs ?

- **digitize beam position as early as possible to**
  - simplify RF front end
  - minimize non-linearities of analog components (mixers, etc.)
  - minimize temperature dependencies & drifts in electronics

  ➡ minimize beam current dependence, guarantee high stability and reproducibility of beam position

- **reduce number of analog components in processing chain**

  ➡ potential to reduce noise sources

- **high flexibility in output bandwidth of digital BPM due to programmable filters (+decimation)**

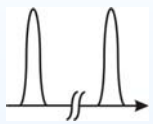
  ➡ single pulse, turn-by-turn capability (broadband BPM)
  closed orbit capability (narrow band BPM)

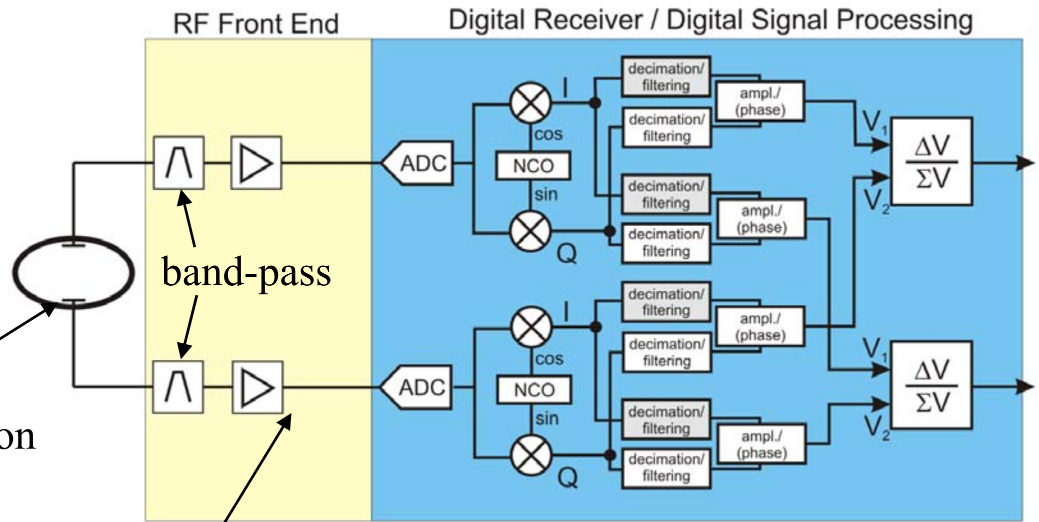
  ➡ choose operating mode for required application (machine studies, orbit feedbacks,...)

Digital Beam Position Monitor (DBPM)

principle:

e⁻ bunches





band-pass

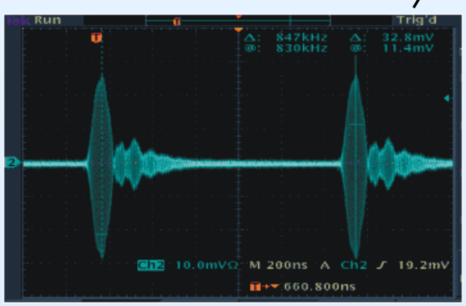
transfer function of pick-up

BW 1

y position

BW 2

direct sampling of RF



(f_{rep} « $f_{band\text{-}pass}$)

- provide enough oscillations to be sampled
- bunch-by-bunch resolution: distinction between pulses
- omitting RF mixer → reduce non-linearities
- multi bandwidth BPM (simultaneously)

SLS DBPM Specifications and Performance

Parameter	Specification for SLS	SLS DBPM Performance
RF carrier freq.	500 MHz	
IF carrier freq	36 MHz	
Dynamic Range	1-400 mA	1-400 mA
Beam Current Dependence 1-400 mA relative 1 to 5 range	< 100 µm < 5 µm	< 100 µm < 30 µm
position measuring radius	5 mm	5 mm
resolution*) / BW	< 1 µm @ 2 kHz < 20 µm @ 0.5 MHz	0.8 µm @ 2 kHz 17 µm @ 0.5 MHz

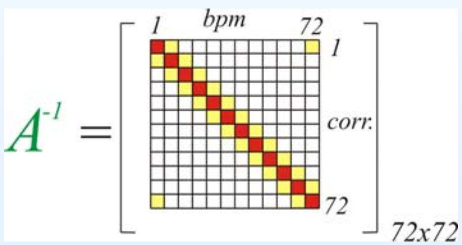
*) with SLS ring vacuum chamber geometry

recent developments: DBPM
(Instrumentation Technology)
(scaled to SLS ring vacuum chamber geometry)

resolution: < 1 µm @ 0.5 MHz BW
beam current dep.: < 2 µm (1:5 range)

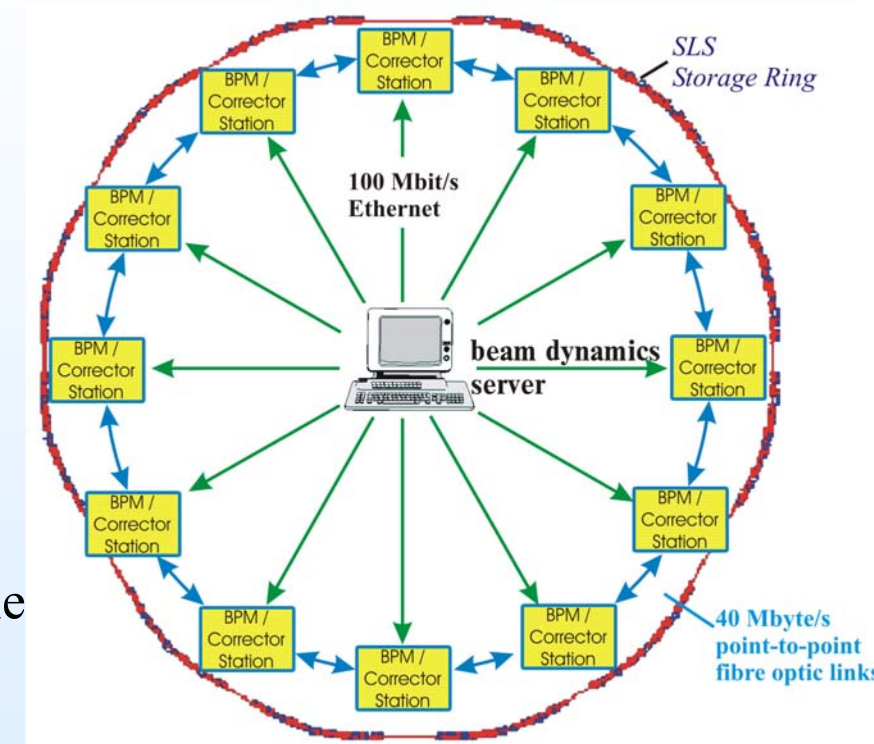
SLS Fast Orbit Feedback Layout

- only one feedback (no separation between slow and fast feedback)
- 72 BPMs / 72 corrector magnets in each plane, 12 sectors
- sampling and correction rate: 4 kHz
- inverted response matrix: sparse matrix

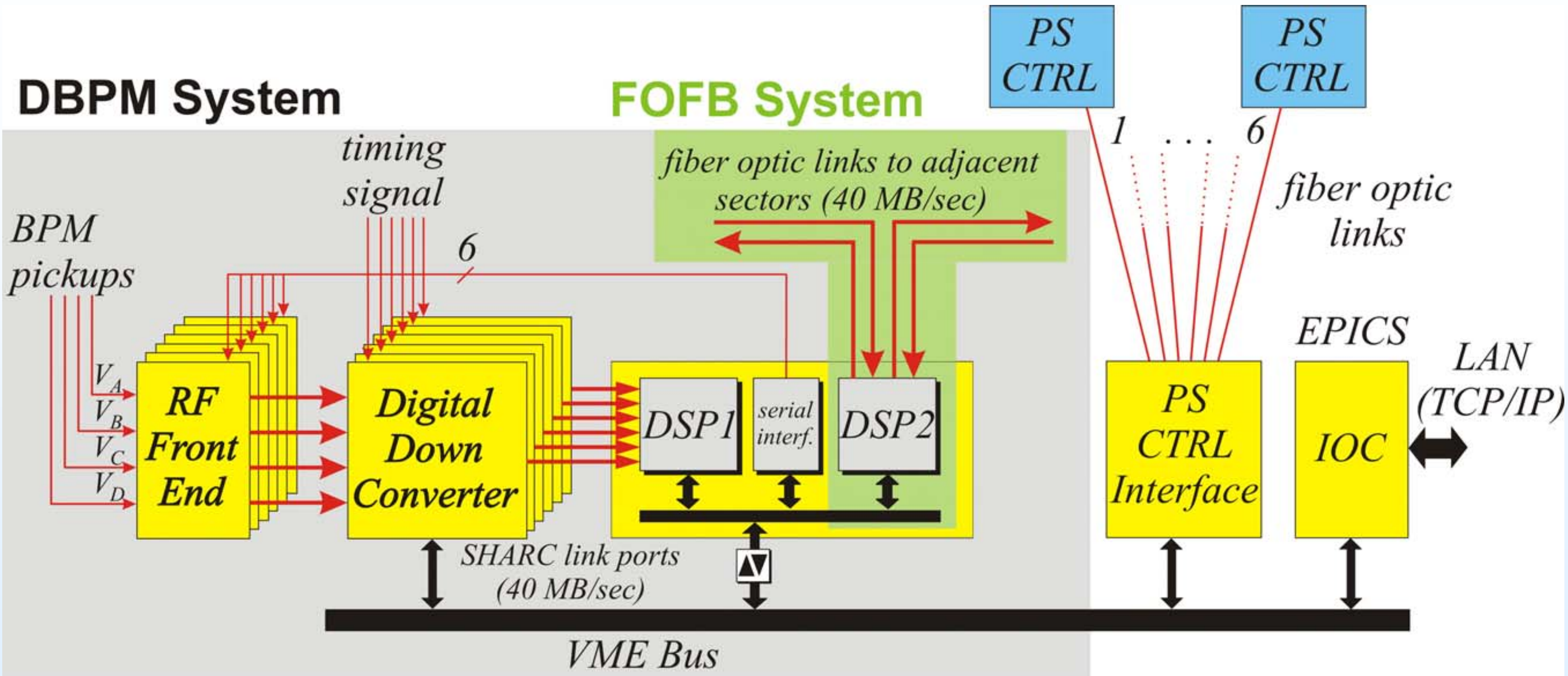


➡ decentralized data processing possible

- point-to-point fiber optic ring structure for global data exchange



SLS DBPM / Fast Orbit Feedback Hardware Layout (sector view)



technology choice: 1998

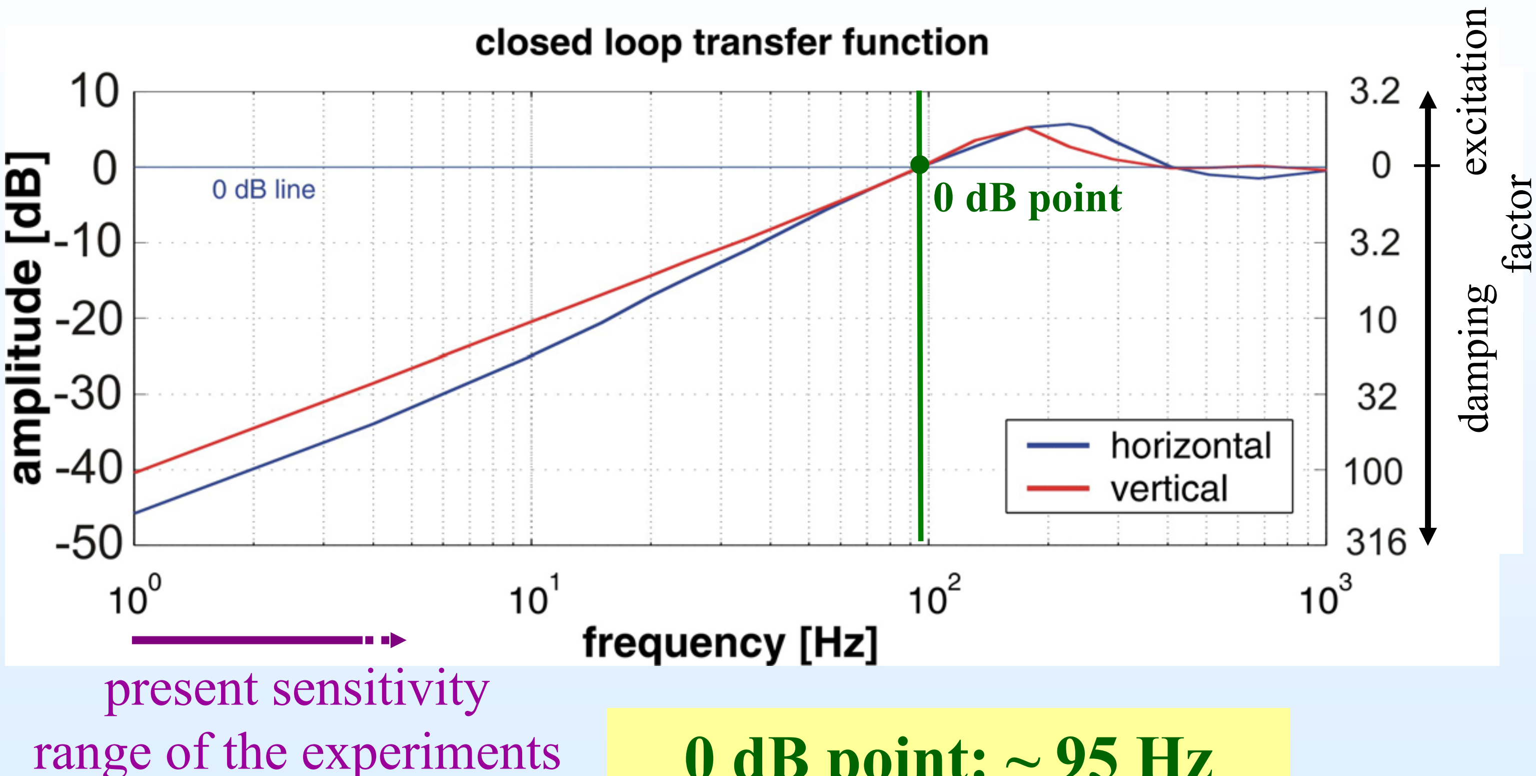
Performance: Stability Frequency Ranges

- **short term stability**: ~ 6 ms – 1 s (1 Hz – 150 Hz)
  mainly limited by
  - BPM resolution
  - corrector magnet resolution
  - system latency
  - eddy currents in vacuum chambers

- **long term stability**: 1 s – days (run period)
  mainly limited by
  - reliability of hardware components
  - systematic errors of BPMs
  - thermal equilibrium of the machine (→ top-up)

Performance: Short Term Stability

SLS transfer function measurement

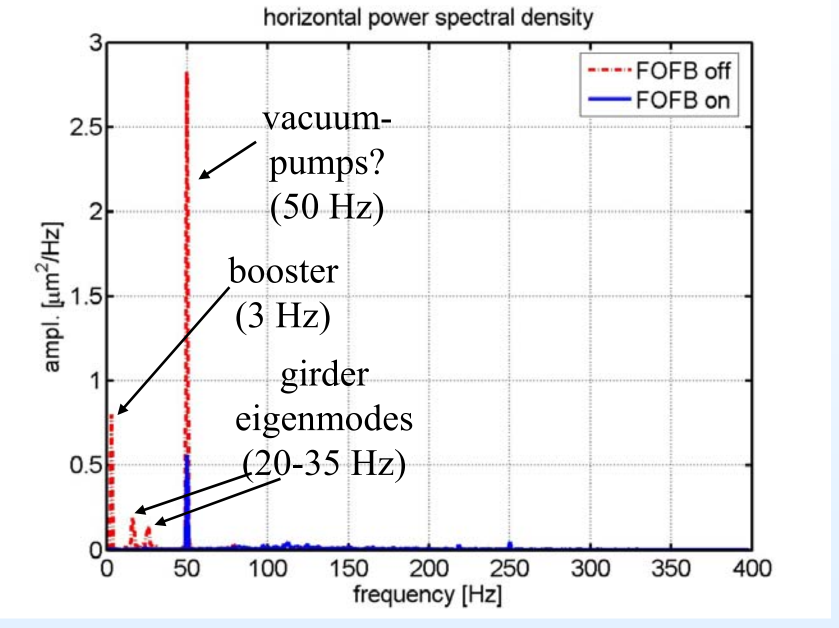


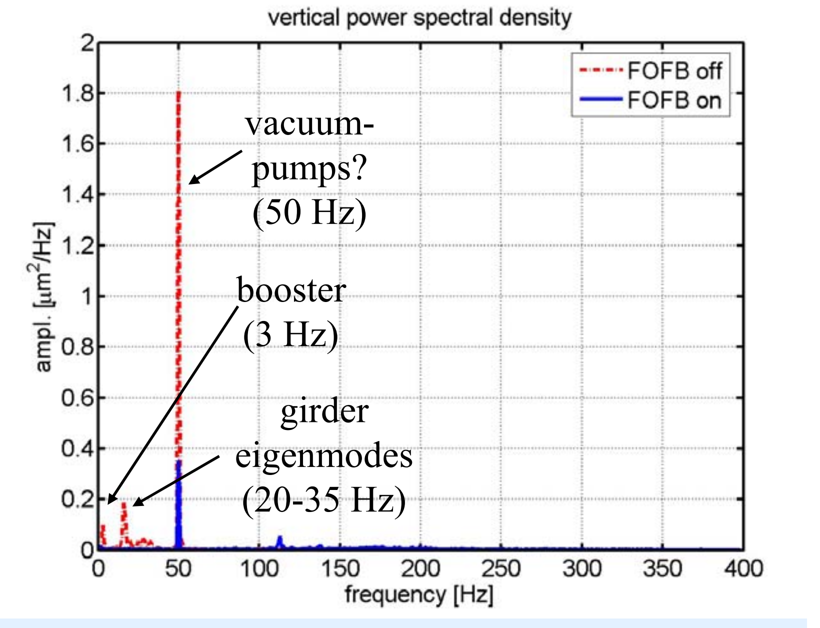
0 dB point: ~ 95 Hz (in both planes)

SLS FOFB: spectral power density (1–400 Hz)

Fast Orbit Feedback off/on

(without any ID gap change)





horizontal

vertical

(measured at tune BPM, outside of the feedback loop, β_x=11 m, β_y=18 m)

SLS FOFB: Cumulated Power Spectral Density

	horizontal		vertical	
FOFB	off	on	off	on
1- 100 Hz	**0.73 µm · $\sqrt{\beta_x}$**	**0.46 µm · $\sqrt{\beta_x}$**	**0.43 µm · $\sqrt{\beta_y}$**	**0.30 µm · $\sqrt{\beta_y}$**
100-150 Hz	0.07 µm · $\sqrt{\beta_x}$	0.18 µm · $\sqrt{\beta_x}$	0.06 µm · $\sqrt{\beta_y}$	0.10 µm · $\sqrt{\beta_y}$
1-150 Hz	0.73 µm · $\sqrt{\beta_x}$	0.49 µm · $\sqrt{\beta_x}$	0.44 µm · $\sqrt{\beta_y}$	0.32 µm · $\sqrt{\beta_y}$

(incl. sensor noise)

RMS values to be scaled with $\sqrt{\beta}$ at desired location

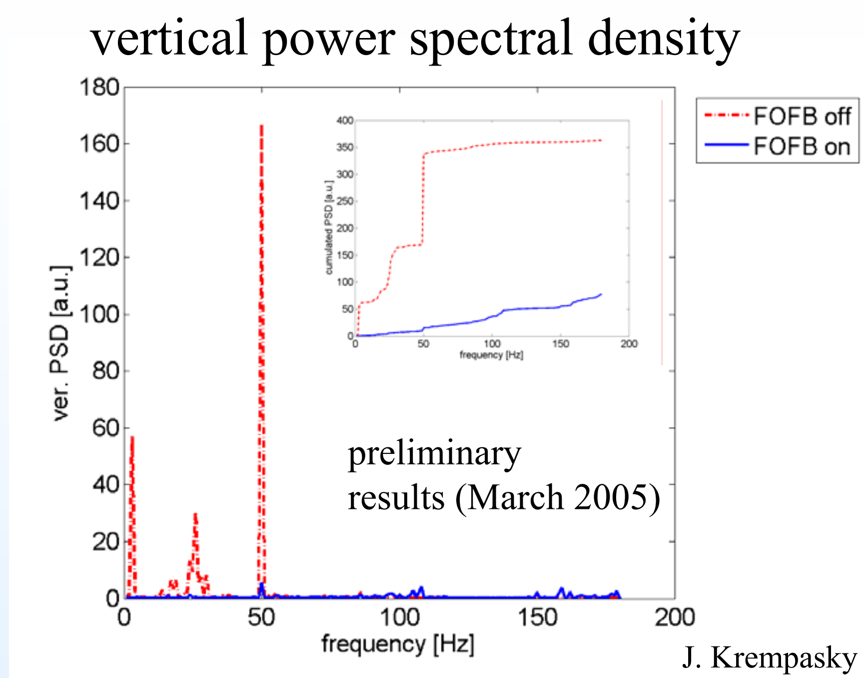
Examples (with FOFB):

Tune BPM (β_y=18 m): $\sigma_y = \sqrt{18} \cdot 0.30\ \mu m$ **= 1.3 µm** (1 – 100 Hz)

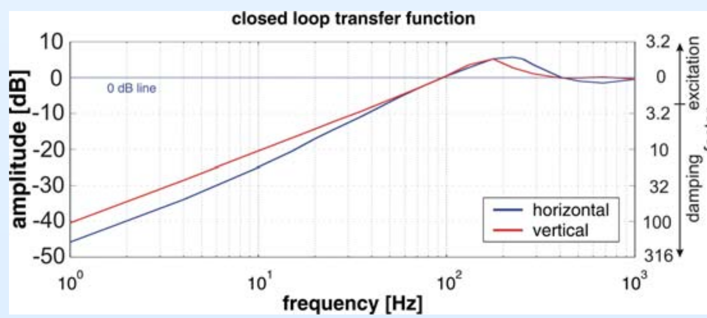
Source point at ID 6S (β_y=0.9 m): $\sigma_y = \sqrt{0.9} \cdot 0.30\ \mu m$ **= 0.28 µm** (1 – 100 Hz)

Performance: Short Term Stability at Photon BPM

external reference:
Photon BPM at beam line 6S
(protein crystallography)



⇒ **successful suppression of noise sources originating from the electron beam**

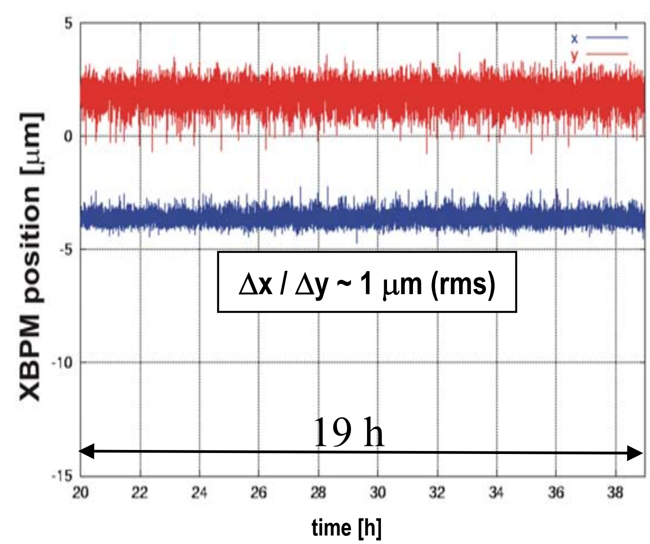


Performance: Long Term Stability

Strategy @ SLS:

- if photon BPMs are reliable enough
  - ⇒ used to minimize systematic effects of RF BPMs, girder drifts, temperature drifts, etc.
  - ⇒ slow PBPM feedback which changes reference orbit of FOFB (cascaded feedback scheme)
  - ⇒ keep photon beam position constant at first PBPM

photon BPM signals (at 06S) at ~ 10 m from source point
data points are integrated over period of 1 s

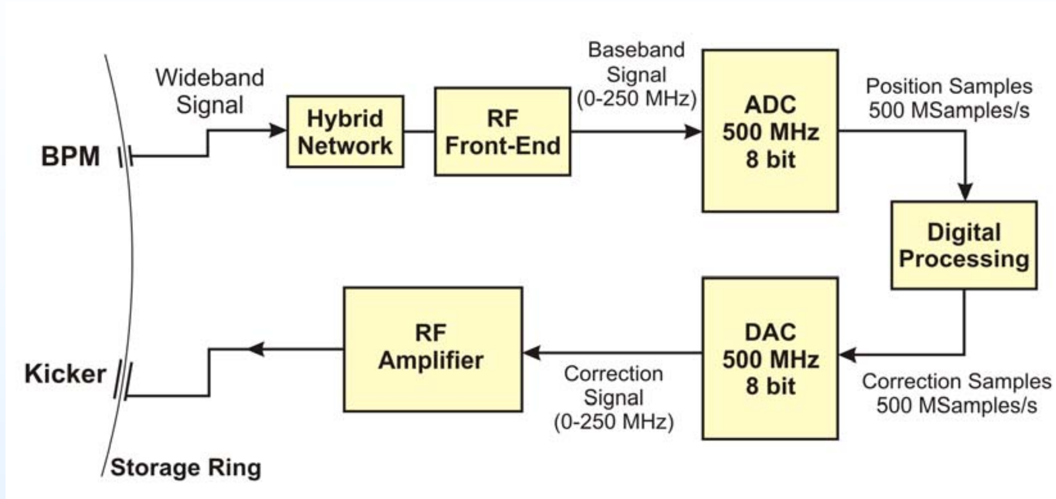


- so far: only one PBPM at ID beam-line 4S and 6S is reliable enough and understood to be integrated in PBPM feedback

SLS Multi Bunch Feedback System

Parameters & Layout

- bunch spacing: 2 ns
- 1 µrad maximum kick angle @ 2.4 GeV (15 kHz – 250 MHz)
- overall latency time ~ 3 µs (3 turns of SLS storage ring)

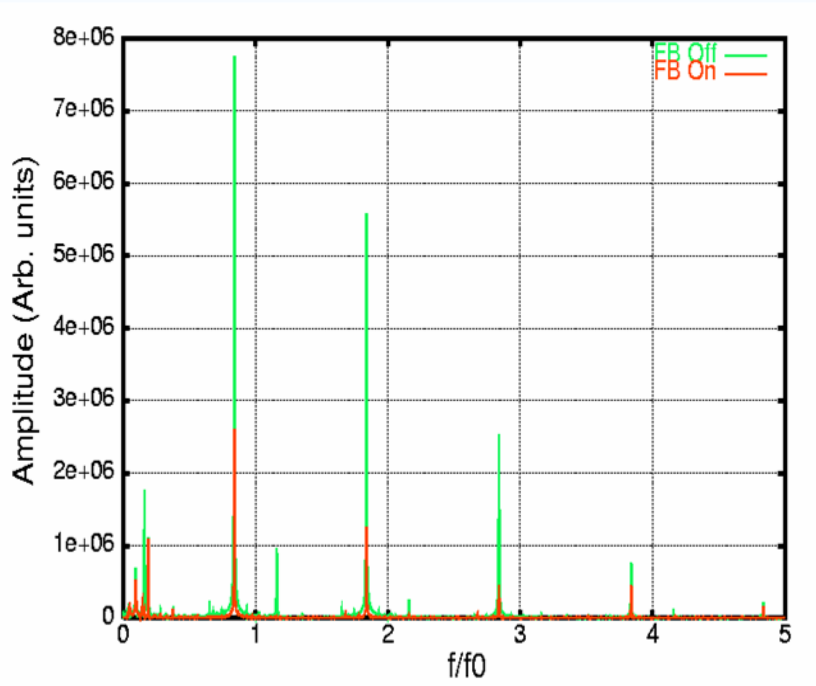


- fast real time ADC and DAC mezzanine boards with 8 bit, up to 1 GS/s and 750 MHz analog band width for low latency data processing
- clock generator for synchronization on picosecond time scale
- MBF has been developed in close collaboration with ELETTRA

SLS Multi Bunch Feedback System

First Results

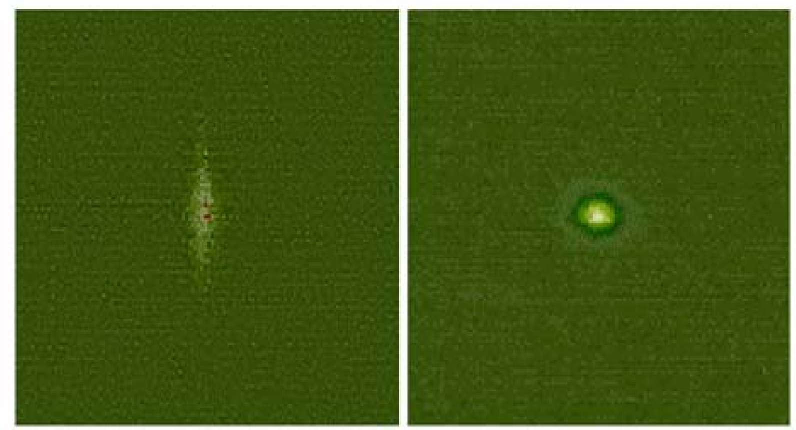
vertical mode pattern in SLS storage ring (revolution frequency f_0 = 1.04 MHz)



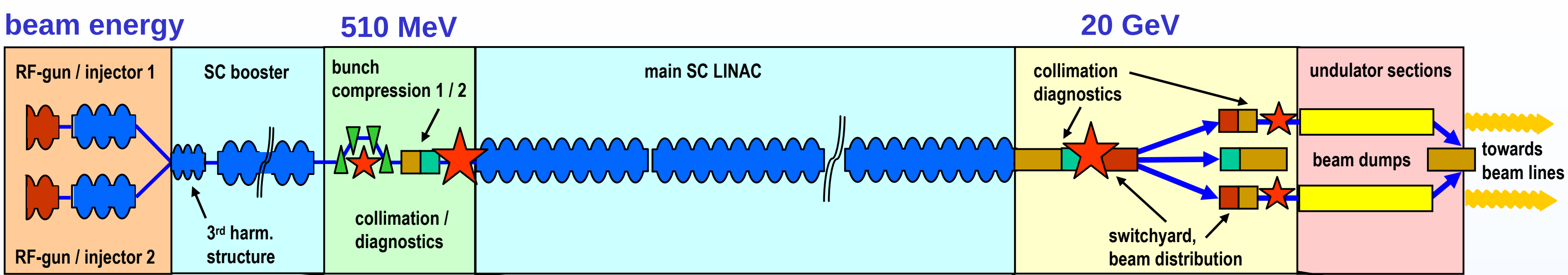
corresponding pinhole camera images

MBF off

MBF on



Requirements for Beam Stabilization along the European XFEL



Injector / Bunch Compressor

- transverse and longitudinal phase space can be deteriorated through beam fluctuations caused by:
  - ⇨ current variations and timing jitter at RF photo gun
  - ⇨ RF transients and wake fields

⇩

beam size $\sigma_{x,y}$: ~ 70 µm
bunch length σ_z : 1.8 – 0.02 mm

stability requirement*:

transverse: $\sigma/10$ → $\Delta x/y$ < 7 µm (rms)
longitudinal: 0.015° @ 1.3 GHz → Δz < 10 µm / 30 fs (rms)

Beam Distribution / Undulator Sections

- transverse beam stabilization behind main LINAC needed for:
  - stable SASE operation
  - stable user operation

⇩

transv. beam size $\sigma_{x,y}$: ~ 30 µm
bunch length σ_z : 20 µm

stability requirement*:

transverse: $\sigma/10$ < 3 µm (rms)

* stability requirements for stable SASE operation at bunch-by-bunch distances of 200 ns

Noise Sources (TTF1)

Fast motions

- switching magnets, power supply jitter
- RF transient, RF jitter
- photocathode laser jitter
- beam current variations
- long range wake fields

Slow and medium term motions

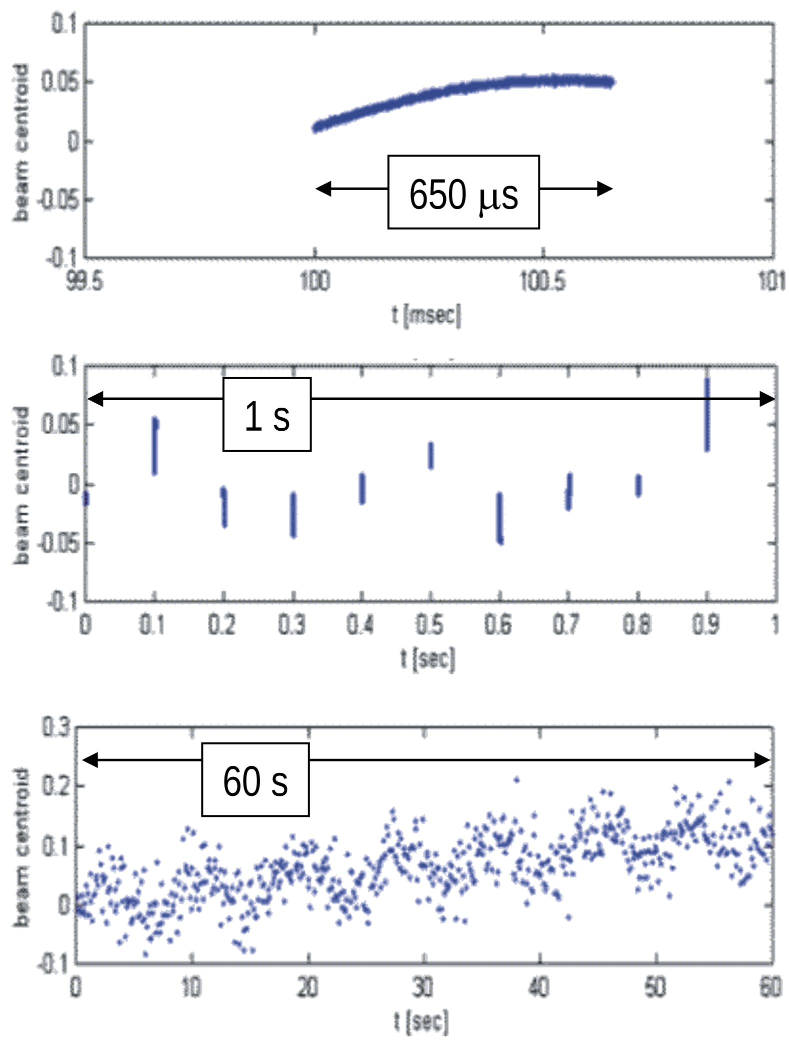
- ground settlement, temperature drifts
- girder / magnet excitation by ground motion, cooling water, He flow…

Leads to:

- beam centroid motions
- beam arrival time jitter

→ **requires intra bunch feedback**
→ **bunch train to bunch train feedback**

example of beam centroid motion (a.u.)



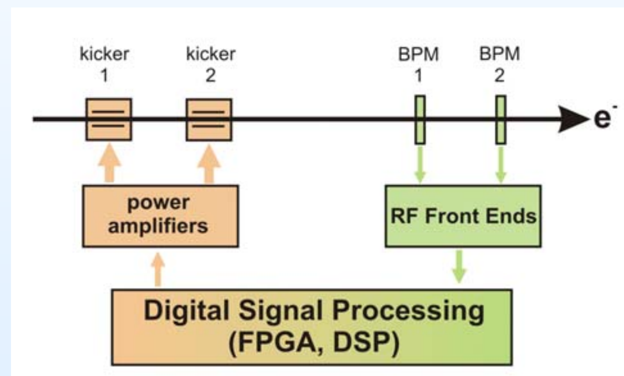
Parameters for Intra Bunch Train FB Systems (IBFB) for the European XFEL:

Stability Requirements behind SC Booster

beam energy:	510	MeV
bunch spacing τ_b:	200	ns
transv. stability:	σ/10	
⇨	< 7	µm (rms)
long. stability:	0.015°	@ 1.3 GHz
⇨	< 10	µm (rms)
⇨	30	fs (rms)

Stability Requirements behind main LINAC

beam energy:	20	GeV
bunch spacing τ_b:	200	ns
transv. stability:	σ/10	
⇨	< 3	µm (rms)



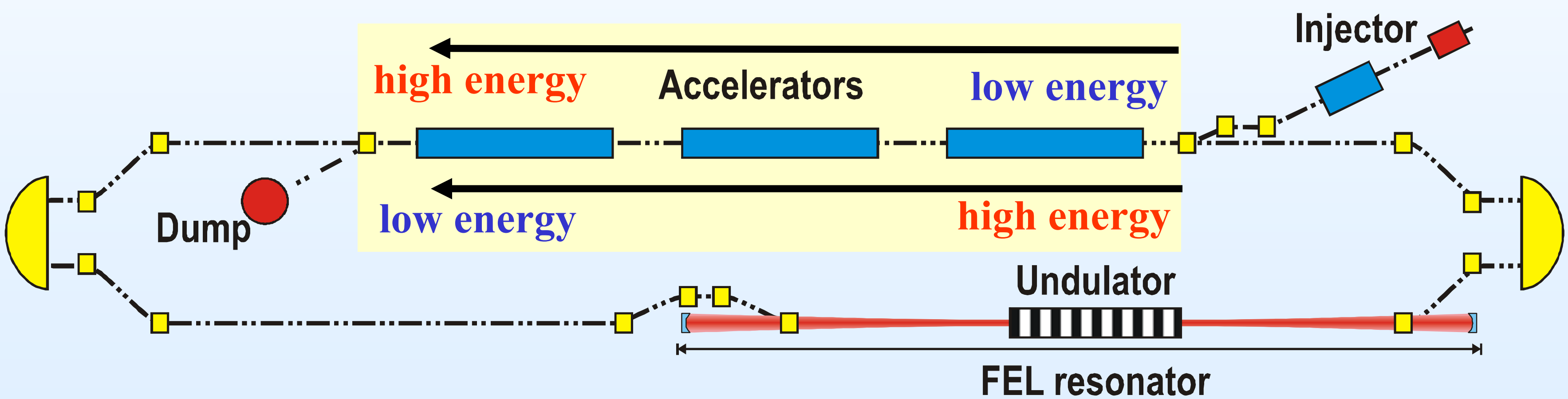
IBFB Parameters

system resolution:	~ 1	µm
system latency:	< 200	ns
ADC / DAC resolution:	~ 12-14	bit @ 1 GS/s
FPGA / DSP data rate:	~ 1	Gbyte/s
FPGA clock rate:	> 200	MHz

RF amplifier (x,y,z)	behind SC Booster		/ behind main LINAC	
power	≤ 4	kW	≤ 10	kW
BW:	≤ 100	MHz	≤ 100	MHz
transv. kick strength:	≤ 5	µrad	≤ 0.5	µrad

Orbit “Feedback” at ERLs

- orbit correction is more feed forward than feedback
- where is orbit stability required? To which level?
- orbit correction necessary along the accelerator? (different energy)
- frequency range of noise sources?



JLAB recirculating FEL

Summary

- digital BPMs already provide few µm resolution
  in the ~MHz bandwidth
  → potential to go to µm resolution with several MHz BW
  in the near future

- sub-µm orbit stability achievable in 3rd generation light sources
  up to several 100 Hz BW
  (good mechanical design of girders, fast orbit feedback system(s))

- photon BPMs → sub-µm resolution of e^- beam due to long lever arm
  → valuable devices to be integrated in orbit feedback systems

- multi bunch feedback system (SLS) under commissioning,
  design of orbit stabilization system for European XFEL has just started

- orbit feedback: certainly some common grounds of storage rings and ERLs...