OVERVIEW OF FAST BEAM POSITION FEEDBACK SYSTEMS

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INTRODUCTION

- Precise control and stability of beam trajectory are essential to the successful operation of different types of particle accelerators.

1. Careful accelerator design
2. Continuous identification and minimization/removal of noise sources
3. **Active feedback systems**

- **Fast beam position feedbacks**, in particular, are crucial in those cases where requirements for short (ms-s) and medium (minutes-days) term stability are strictest.

- **Storage Ring Synchrotron Radiation Sources**
- **Large Hadron Collider**
- **Electron linacs (e+/e- colliders and single-pass FELs)**
- **Interaction Points in colliders**

OUTLINE

- Stability Requirements

- Fast Beam Position Feedback Systems for:
    - Storage Ring Synchrotron Radiation Sources
    - Large Hadron Collider
    - Electron Linacs (e+/e- colliders & FEL)
    - Interaction Point in Colliders

- Concluding Remarks

STABILITY REQUIREMENTS

S.R. Synch. Rad. Sources

- Emittance of a few nm·rad
- Optimized optical functions (low β straights)
- Ability to control and minimize emittance coupling <1%
- $\sigma_y < 10\mu m$ and $\sigma_{y'} < 10\mu rad$ at Insertion Devices source points
- Stability goal of 5 -10% of σ_y and $\sigma_{y'}$

→ **Sub-micron stability**

Large Hadron Collider

- Hadron machine that requires continuous orbit control for safe and reliable machine operation
- Global orbit controlled within 0.5mm rms
- Collimators efficiency depends on beam orbit

→ **Stability better than $\sigma/6 < \sim 25\mu m$ at collimator jaws**

Electron Linacs (e+/e- colliders & FEL)

- Preserve small emittance provided by damping rings / gun
- Keep ‘golden’ trajectory that reduces or compensates for wake field effects in accelerating structures and minimizes quadrupole induced dispersion

→ **Stability from tens down to some microns**

- ***FEL undulators***: keep overlap between electron beam and emitted radiation
- σ ~ few tens of micron
- Stability goal of 10 % of σ

→ **Few micron stability**

Interaction Point in Colliders

- Maintain Luminosity

→ **Stability to a fraction of spot size**

Fast Beam Position Feedback Systems for

STORAGE RING SYNCHROTRON RADIATION SOURCES

- Evolution
- Correction Algorithms
- Feedback Control Algorithms
- System Architecture
- ID Feed forward Systems

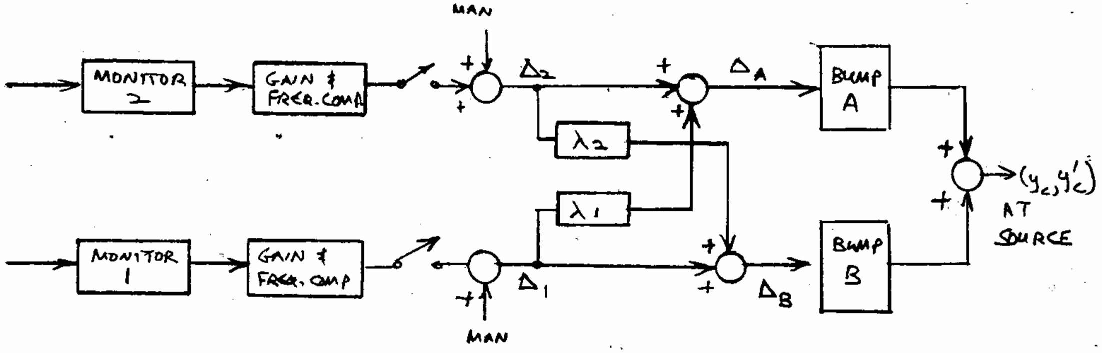
FROM ANALOG TO DIGITAL, FROM LOCAL TO GLOBAL

- Local Orbit Feedback:

R. O. Hettel
SSRL, 1982-86

- Servo/controller: analog linear electronics

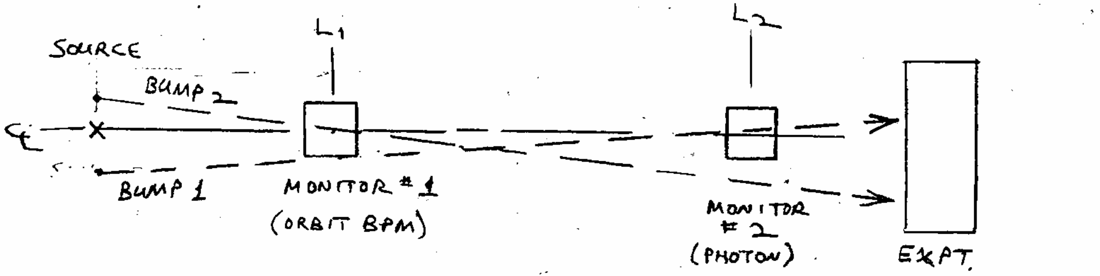
2-MONITOR, 4-MAGNET STEERING SERVO SYSTEM



BUMP A & BUMP B ARE LINEARLY INDEPENDENT, COMPENSATED

Δ_1 DRIVES BUMP 1. THAT CAUSES NO DISPLACEMENT AT MONITOR 2.

Δ_2 DRIVES BUMP 2 THAT CAUSES NO DISPLACEMENT AT MONITOR 1.

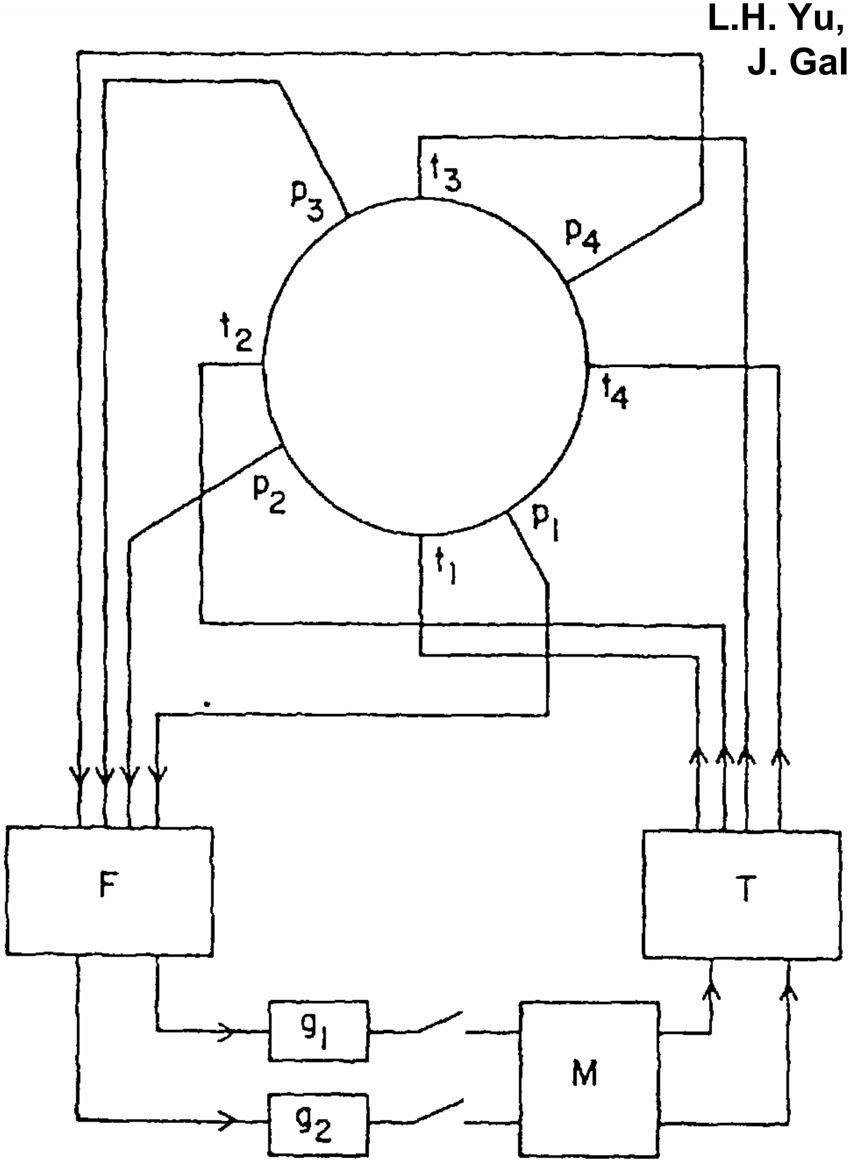


FROM ANALOG TO DIGITAL, FROM LOCAL TO GLOBAL

- Global Harmonic Feedback:

L.H. Yu, R. Biscardi, J. Bittner, E. Bozoki,
J. Galayda, S. Krinsky, R. Nawrocky,
O. Singh, G. Vignola
NSLS, 1988

- Servo/controller: analog linear electronics

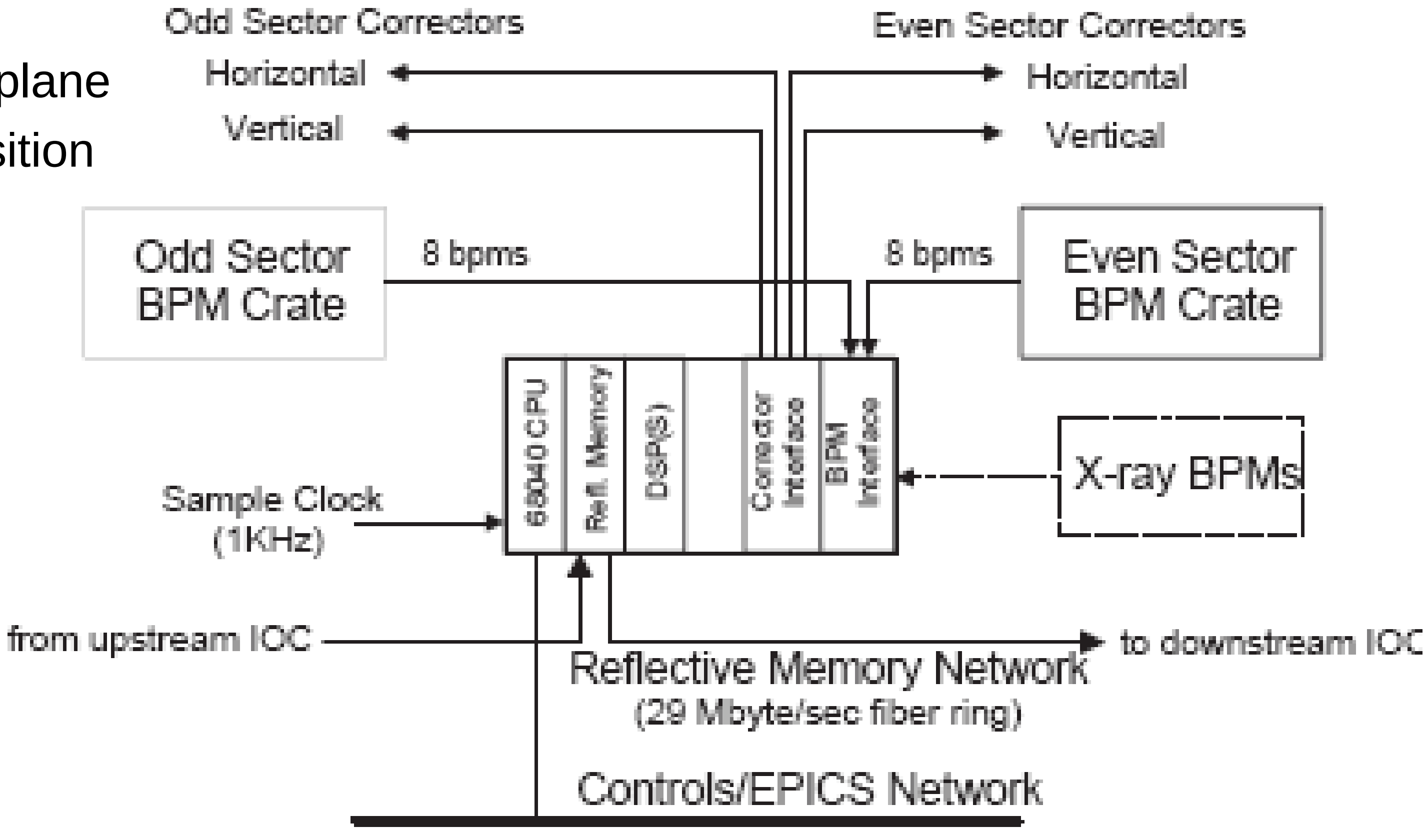


FROM ANALOG TO DIGITAL, FROM LOCAL TO GLOBAL

- Digital Global Feedback:

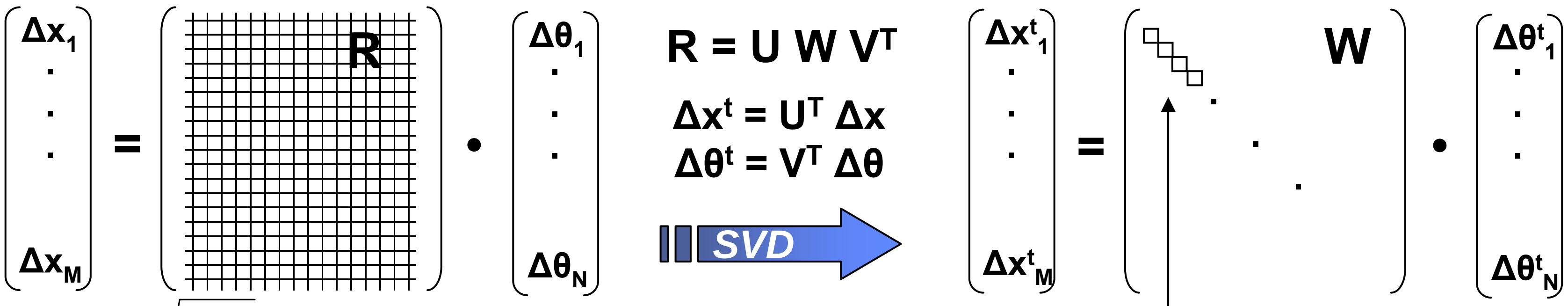
J. Carwardine, Y. Chung, F. Lenkszus, et al.
APS, 1996-97

- Digital controller (DSPs)
- Reflective memory
- 160 BPMs, 38 correctors/plane
- Singular Value Decomposition



CORRECTION ALGORITHM

- Inversion of Response Matrix based on Singular Value Decomposition (SVD):



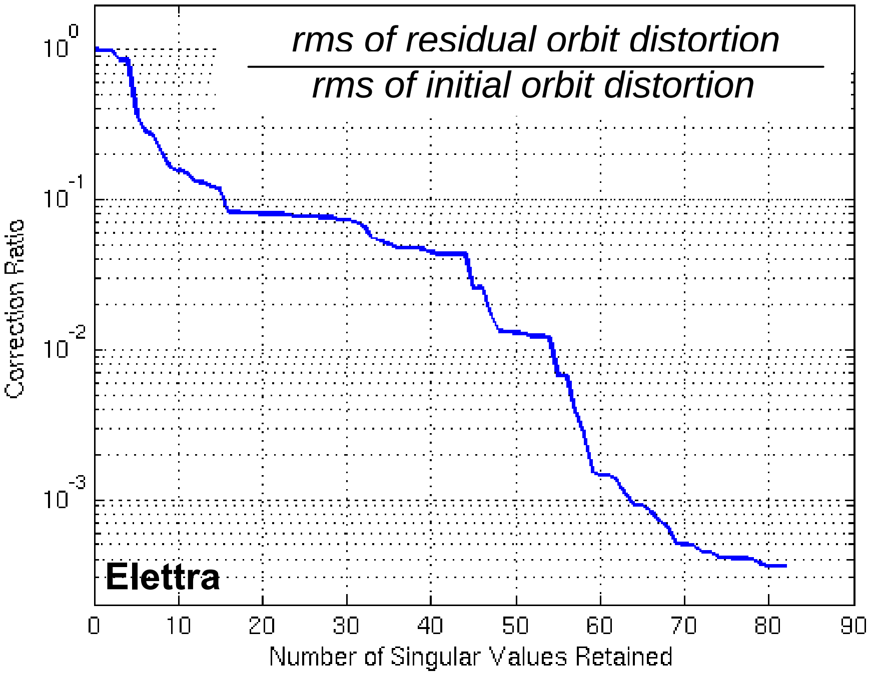
$$R = U\,W\,V^T$$

$$\Delta x^t = U^T\,\Delta x$$

$$\Delta\theta^t = V^T\,\Delta\theta$$

Singular values

$$R_{ij} = \frac{\sqrt{\beta_i \beta_{cj}}}{2\sin \pi Q}\cos\left(\left|\varphi_i - \varphi_{cj}\right| - \pi Q\right)$$



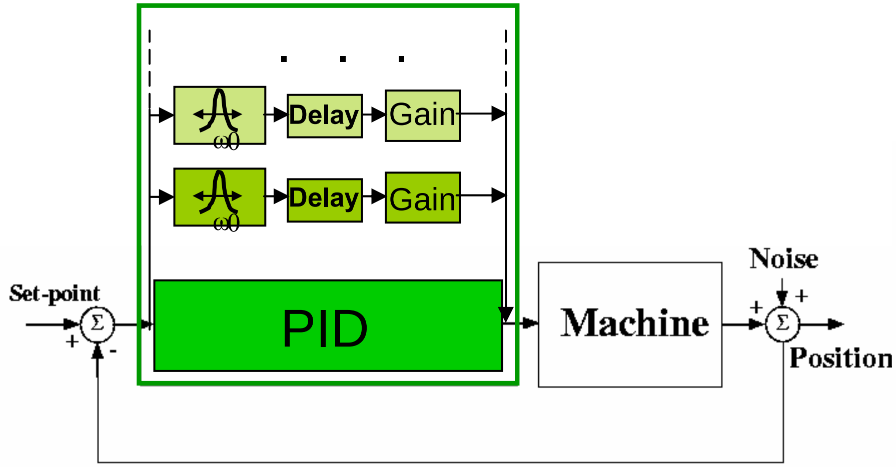
- Number of retained singular values: compromise between orbit correction needs, control strength limits, sensitivity to noise (BPM, etc…)

- Add weighting coefficients

- Transform original Multi-Input-Multi-Output (MIMO) system into a number of Single-Input-Single-Output (SISO) ones

FEEDBACK CONTROL ALGORITHMS

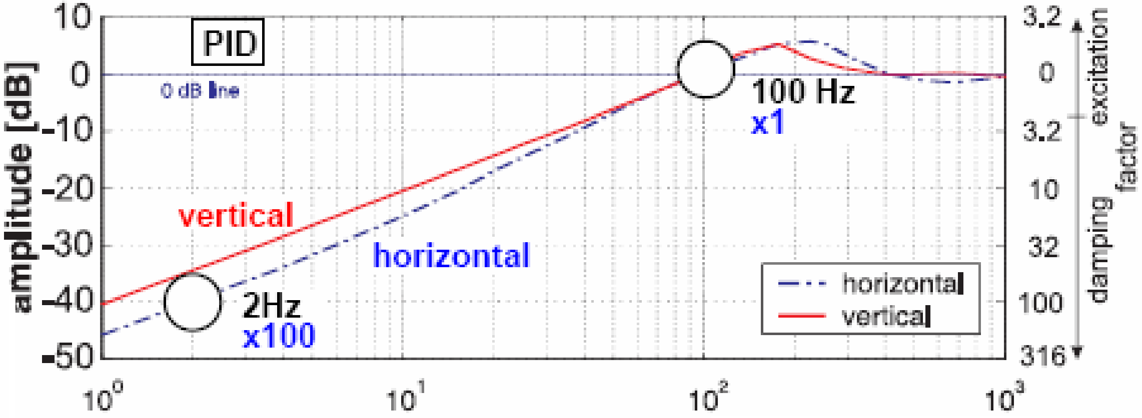
- Proportional Integral Derivative (PID) + 'Harmonic Suppressors'



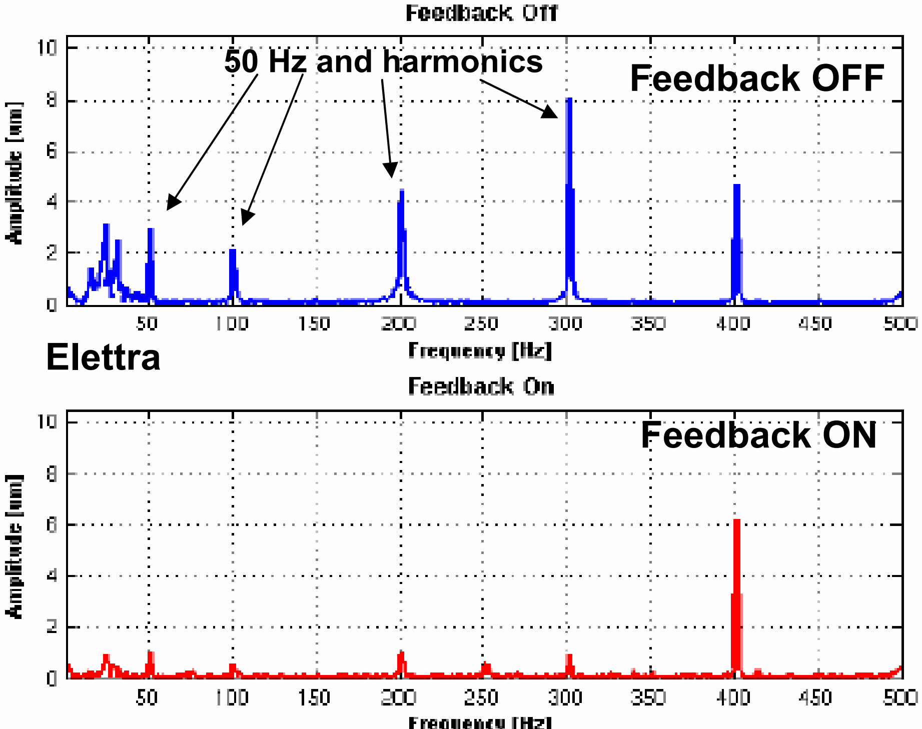
- Feedback repetition rate 5 – 10kHz

<u>- Noise attenuation up to 100 - 150Hz</u>

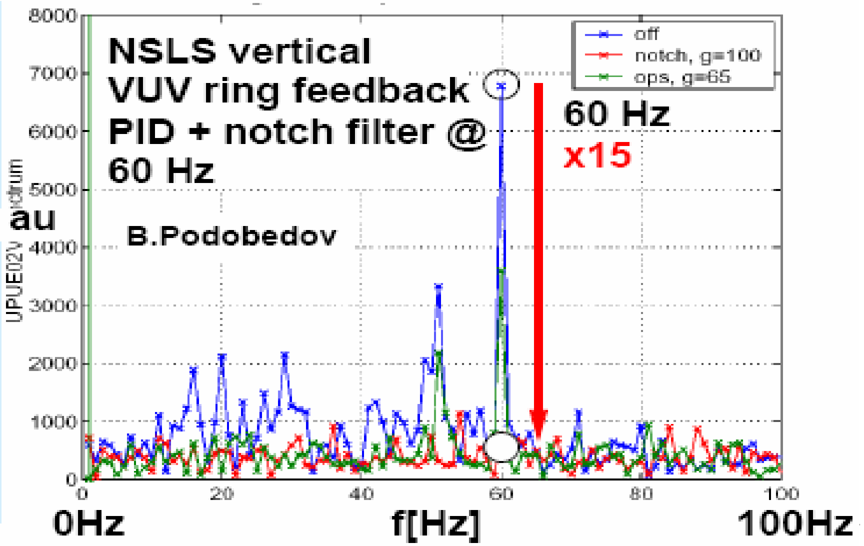
Closed loop transfer functions at the SLS (damping up to ~100 Hz)



M. Boege, T. Schilcher



Elettra

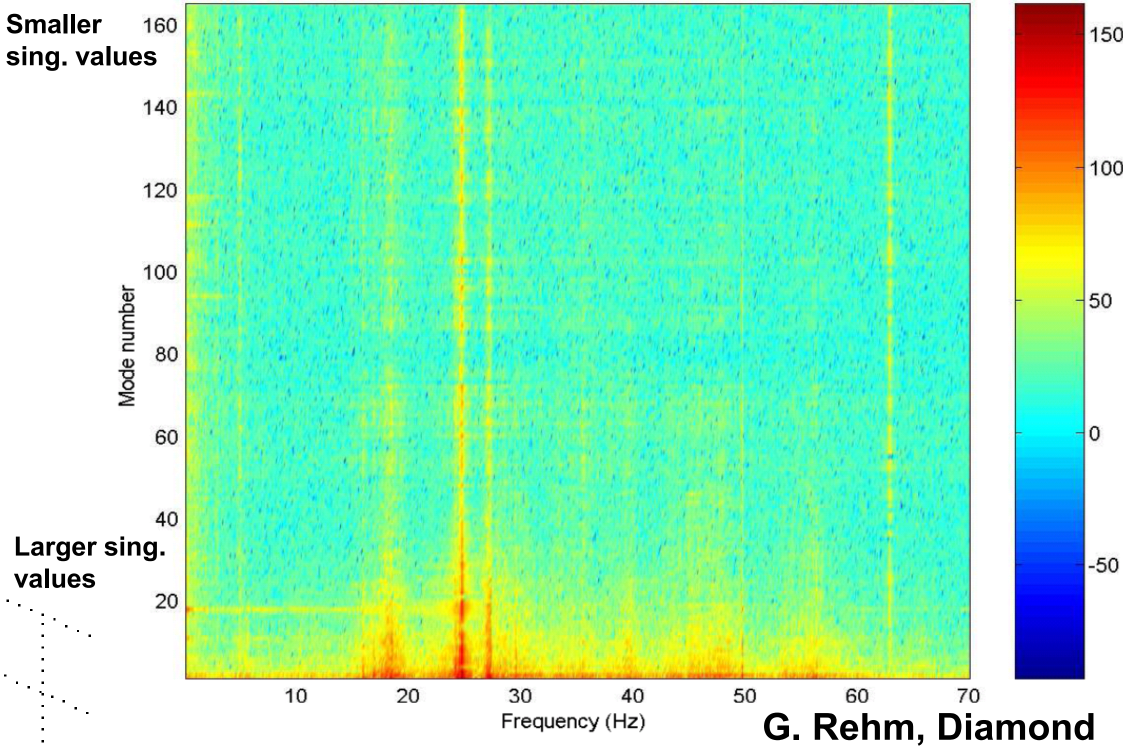


NSLS vertical VUV ring feedback PID + notch filter @ 60 Hz

B.Podobedov

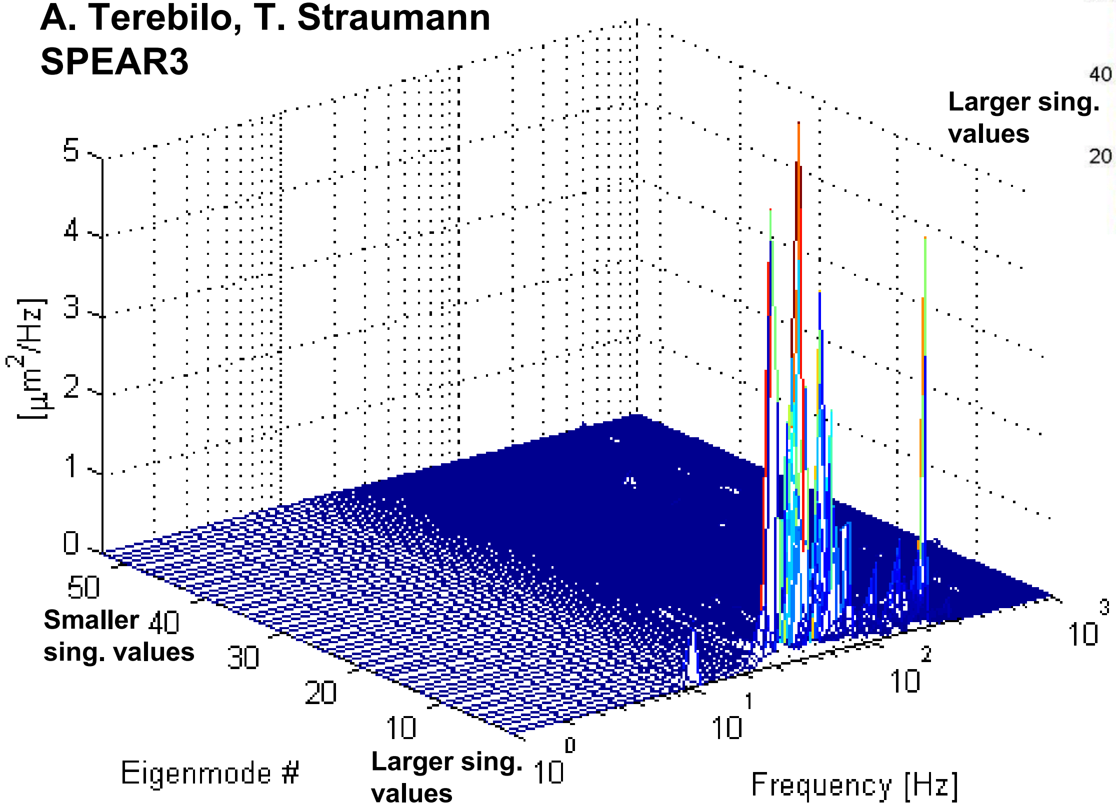
ORBIT ERROR FREQUENCY SPECTRUM IN THE SVD TRANSFORMED SPACE

- ‘Legitimate’ perturbations are aligned more with modes associated to larger singular values, while random noise (BPMs, etc…) is uniformly distributed



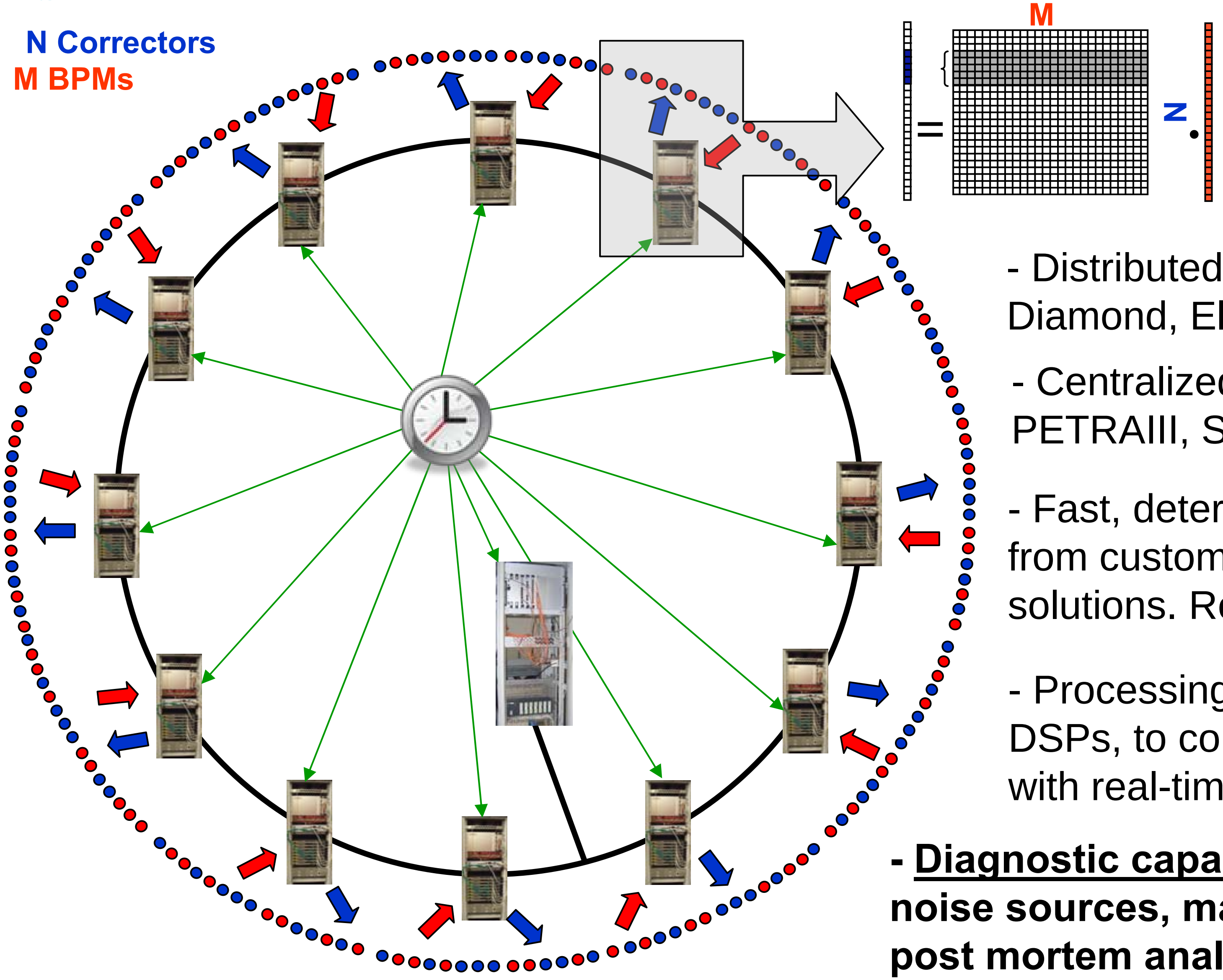
G. Rehm, Diamond

A. Terebilo, T. Straumann
SPEAR3



→ Correction channels with small associated singular value are assigned reduced bandwidth and gain (individual assignment of PID parameters)

SYSTEM ARCHITECTURE



- Distributed processing [ALS, APS, Diamond, Elettra, SLS, Soleil, etc…]

- Centralized processing [ALBA, ESRF, PETRAIII, SPEAR3, etc…]

- Fast, deterministic, reliable network: from custom designs to Ethernet based solutions. Redundancy.

- Processing platform: from FPGAs, DSPs, to control system computers with real-time operating system

- __Diagnostic capabilities__: localize beam noise sources, machine physics studies, post mortem analysis, direct measure of system transfer function, etc…

ID FEEDFORWARD SYSTEMS

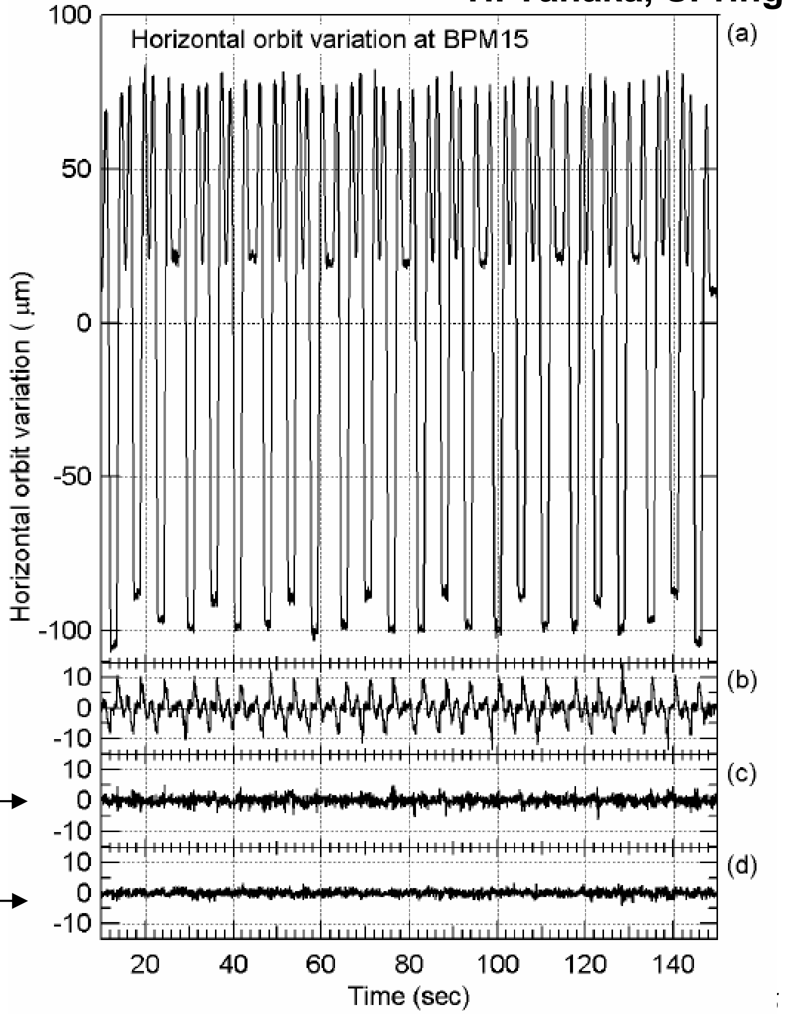
- In addition to feedbacks, feed forward systems are implemented to compensate for the residual orbit distortion associated with the operation of the IDs.

- In case of ID with a relatively fast switching rate of the radiation polarization (up to some tens of Hz), specific strategies to evaluate the feed forward look up tables:

- dynamic effects
- disentangle real distortion from background noise

APPLE-2 mechanical switching undulator, 0.1Hz

H. Tanaka, SPring-8



No feed forward

- Horizontal orbit variation

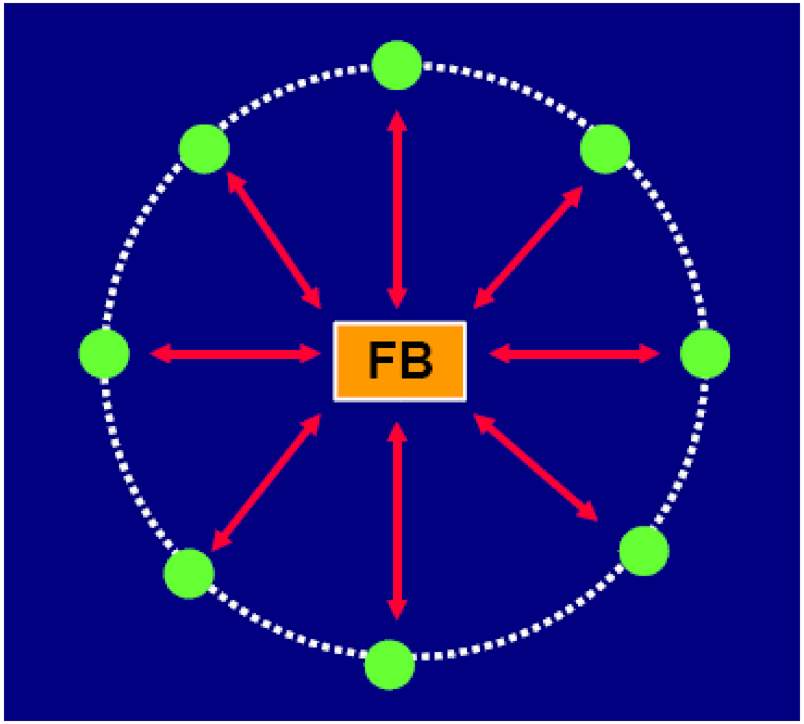
Active Feed forward

No undulator

Fast Beam Position Feedback System for the

LARGE HADRON COLLIDER

LHC ORBIT FEEDBACK

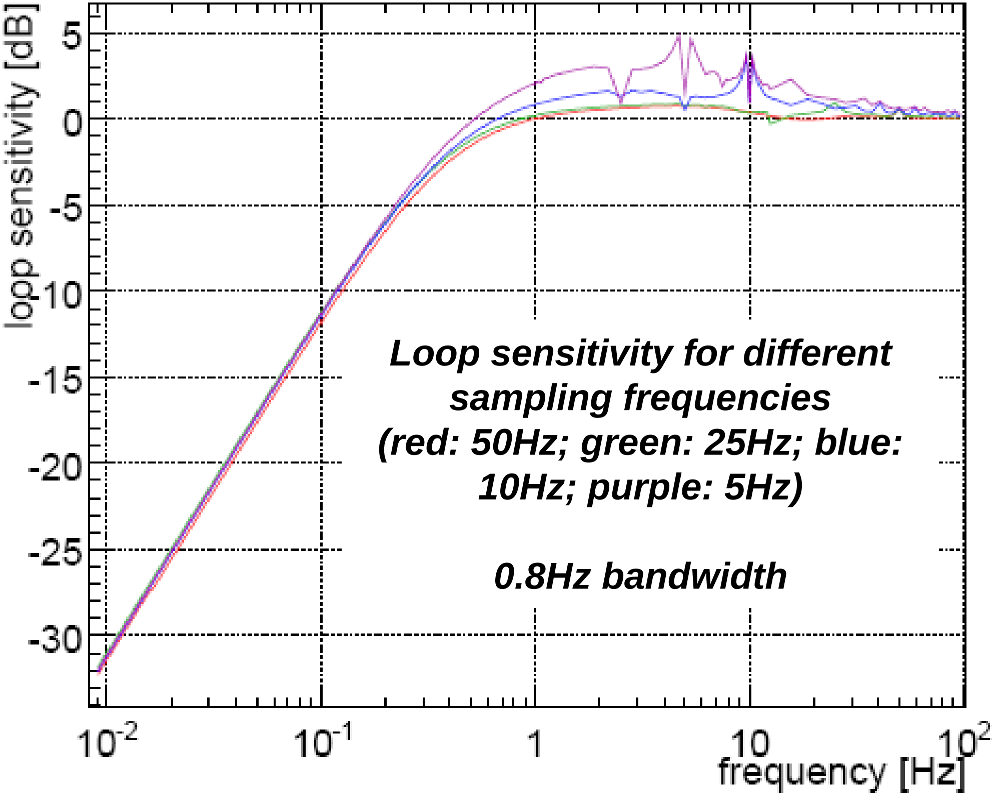


- SVD correction algorithm
- PID controller (with Smith-Predictor extension to compensate for transmission delays)
- Centralized processing architecture, adopts the LHC redundant Technical Network (Gb-Ethernet and QoS)
- Feedback rate: 25 - 50Hz

- >1056 BPMs, ~ 1060 superconducting corrector magnets

- Design of strategies for on-line compensation of component failures is essential.

R. Steinhagen, CERN



Loop sensitivity for different sampling frequencies (red: 50Hz; green: 25Hz; blue: 10Hz; purple: 5Hz)

0.8Hz bandwidth

Fast Beam Position Feedback Systems for

ELECTRON LINACS

(e+/e- Colliders & FEL)

- Pulse-to-pulse Feedbacks
- Intra-bunch Train Feedbacks

LINAC FEEDBACK TYPES

- Pulse-to-pulse Feedbacks:

- Typical beam pulse repetition rates: from few to about one hundred Hz
- Can successfully counteract the effect of drifts and noise up to a few Hz

- Intra-bunch Train Feedbacks:

- Take advantage of the relatively long bunch trains that are available, in particular, from superconducting machines
- Act on a bunch-by-bunch basis within the same train

	Repetition Rate [Hz]	N. bunches/pulse	Bunch interval [ns]	Beam pulse length [ms]
FLASH	**10**	**800**	**1000**	**800**
X-FEL	**10**	**3250**	**200**	**650**
ILC	**5**	**2625**	**369 (180 min.)**	**1000**

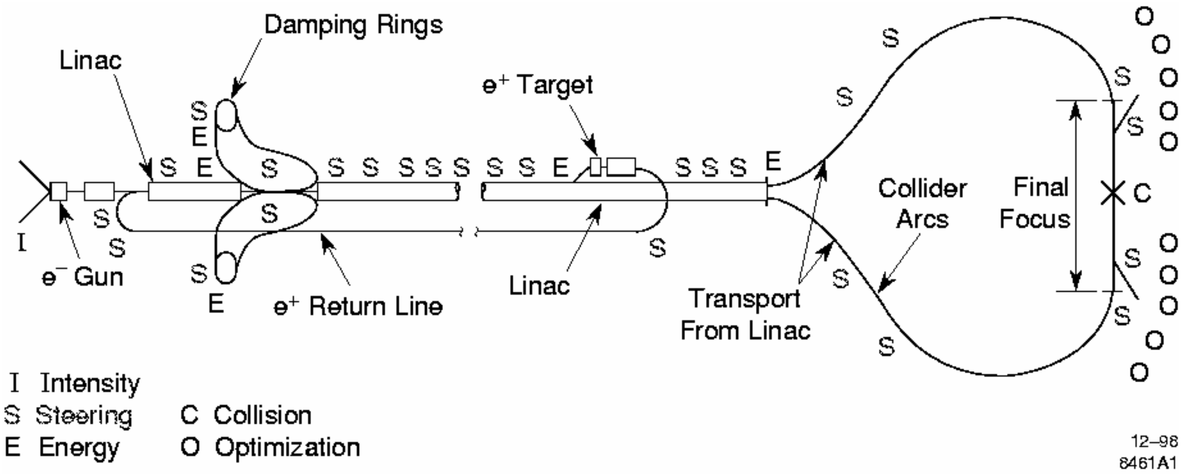
PULSE TO PULSE FEEDBACKS

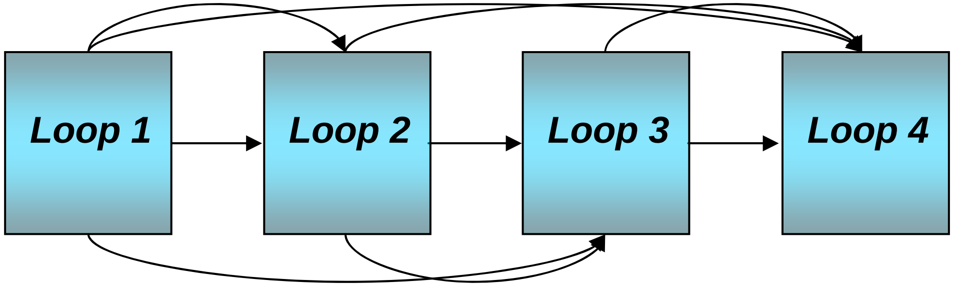
- SLC Trajectory Feedback:

T. Himel, L. Hendrickson et al., SLAC

- State-space formalism for feedback design
- Loops executed by the standard microprocessors that controlled the SLC equipment

- ‘Cascaded’ feedbacks
- Transport matrices between loops adaptively upgraded





- Operated at a subset of the 120 Hz beam rate, due to bandwidth limitations
- In the presence of strong wake fields, the beam transport is different depending on the origin of the perturbation → need more complete interconnection where each feedback got information from all upstream loops.

PULSE TO PULSE FEEDBACKS

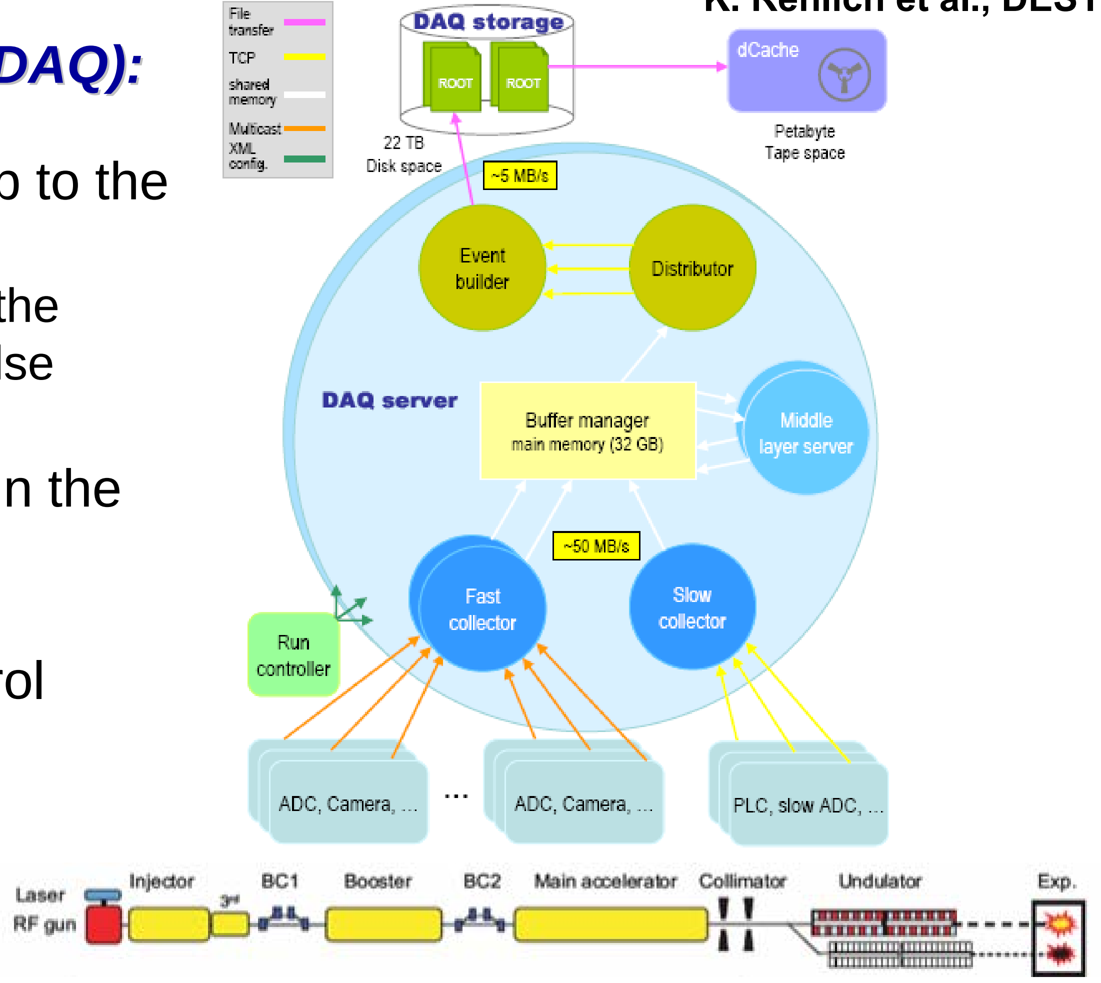
- FLASH Data Acquisition System (DAQ):

K. Rehlich et al., DESY

- Supports pulse-to-pulse feedbacks up to the maximum 10Hz rate
- Provides synchronized data recording of the individual 800 1us-spaced bunches per pulse

- The system is completely integrated in the DOOCS control system of FLASH

- Feedbacks are implemented as control system middle layer processes.

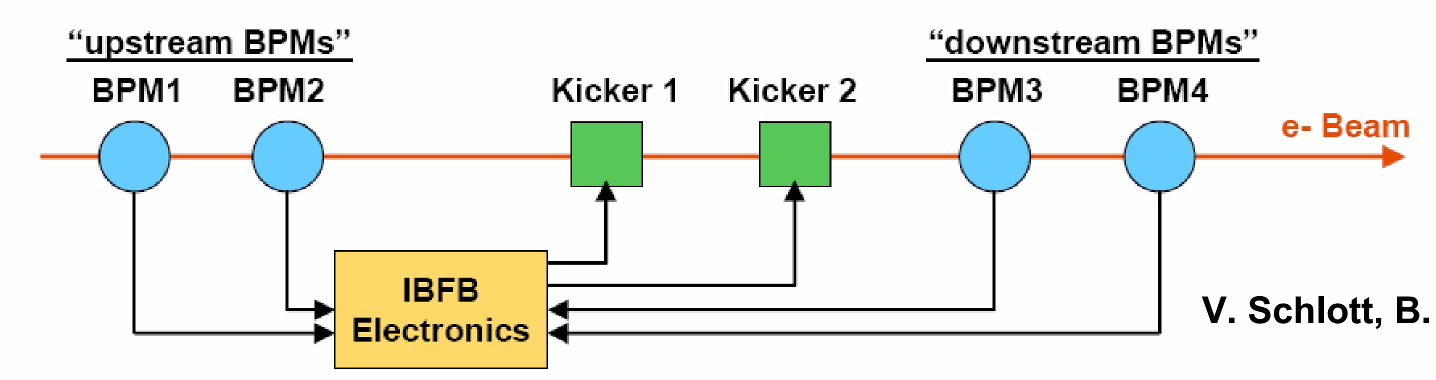


- A similar approach to the implementation of pulse-to-pulse beam feedbacks is being pursued at the LCLS, SCSS, ILC and FERMI@Elettra.

INTRA-BUNCH TRAIN FEEDBACKS

- Intra-bunch train feedback system is under development for the European X-FEL

- Will individually act on the 3250 200ns-spaced bunches that constitute each 10Hz electron macropulse, with a target bunch-to-bunch BPM position resolution <1μm.



V. Schlott, B. Keil et al., PSI

- FPGAs as feedback processing elements. In parallel, DSPs identify and correct repetitive beam perturbations that are the same from bunch train to bunch train using adaptive feed forward.

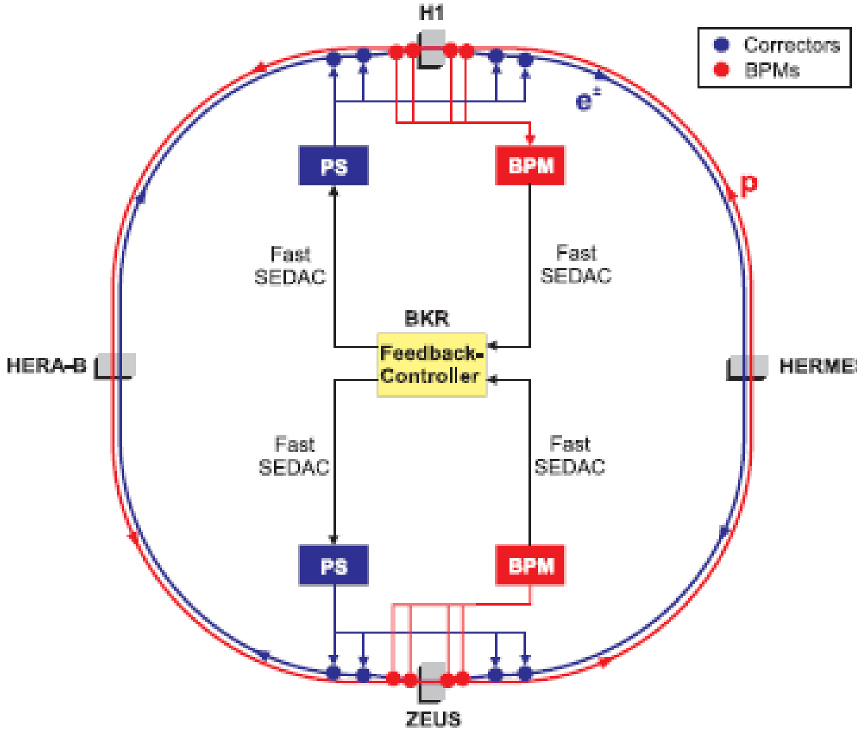
- Downstream BPMs check and adaptively optimize the model used for the calculation of the kicks.

Fast Beam Position Feedback Systems for

INTERACTION POINT IN COLLIDERS

INTERACTION POINT FEEDBACKS

- In circular colliders, trajectory feedbacks implement closed local orbit bumps to adjust the beam position and/or angle at the IP (e.g. RHIC [C. Montag et al.] and HERA-E [J. Keil et al.]).



- Beam-beam deflection mechanism successfully exploited to determine IP beam offsets for feedbacks at electron positron colliders [SLC, KEKB].

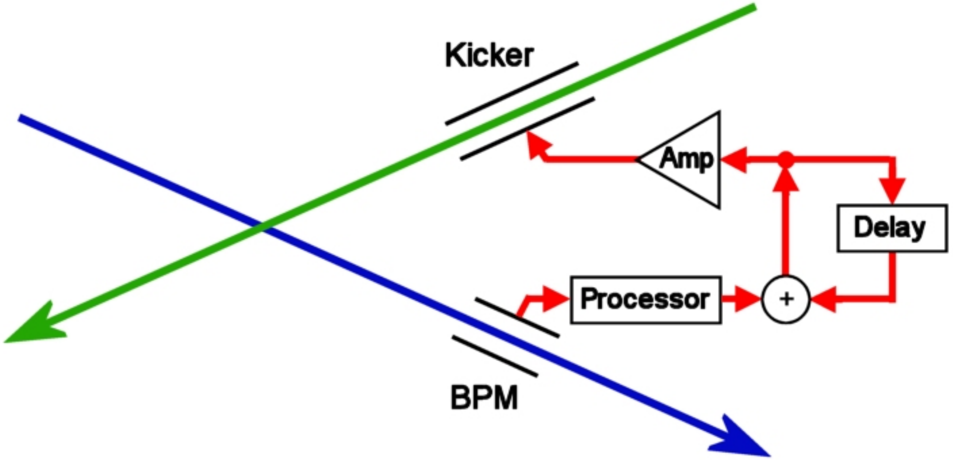
- Luminosity based systems use ‘dithering’ techniques:
  - Operate sub-tolerance variations of the beam position or angle around a given value to allow measurements of the luminosity slope and subsequent change of the trajectory settings.

- Recent system upgrade at PEP-II [A.S. Fisher et al.].

INTERACTION POINT FEEDBACKS

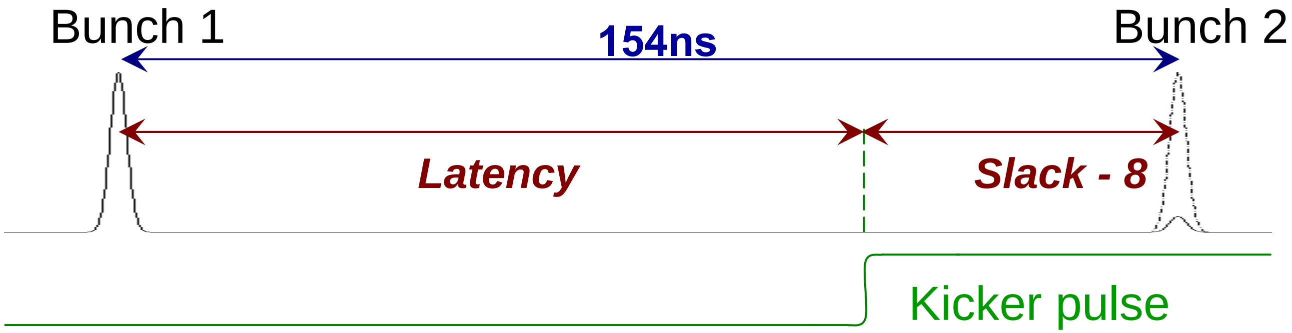
- Intra-Bunch Train Feedback for the ILC Interaction Point:

- Concept: One BPM to measure the position of early bunches in the outgoing beam + one kicker to act on the subsequent bunches of the incoming other beam.



- Based on beam-beam interaction
- Target BPM resolution < 1μm
- FPGA as feedback processing element

- FONT (Feedback On Nano-second Timescales) collaboration



- Tests at KEK-ATF: 140ns latency

P. Burrows (John Adams Institute, Oxford University) et al.

CONCLUDING REMARKS

- Fast beam position feedback systems are evolving ‘fast’: driven by the increasing requirements of accelerator applications and enabled by the progress in digital processing and networking technologies.

- Needed processing computing power seems (is likely) to be adequate.

- Fast beam position feedbacks are key components to achieve and maintain the target machine parameters.

→ Higher levels of reliability and availability

→ Higher levels of system integration (from modelling tool to flexible automation tool, from system to beam diagnostics, etc…)

- Significant (software) effort:

  - Space for collaboration and transfer of expertise (systems) among different accelerator areas (intra-bunch train feedbacks have many analogies with coupled-bunch feedback developed in particle factories and synch. radiation sources; specifications of damping rings are very similar to those of synchrotron radiation sources)
  - COTS components/subsystems exist and can help.

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- M. Boege, B. Keil and V. Schlott (PSI)
- S. Di Mitri, M. Lonza and C. Scafuri (Sincrotrone Trieste)
- A. S. Fisher, N. Phinney, T. Straumann, A. Terebilo (SLAC)
- H. Tanaka and R. Tanaka (SPring-8)

SOURCES OF INSTABILITY

- Mechanical displacement of magnets (quadrupoles). These, in turn, are driven by natural and human induced ground motion, thermally induced effects, cooling liquid flow, etc…

- Current power supplies noise, mains induced noise

- External stray electrical and magnetic fields

S.R. Synch. Rad. Sources

- Gap and phase changes of Insertion Devices
- Fast polarization switching devices (<100Hz)

Large Hadron Collider

- Dynamic effects of superconducting magnets (snapback and decay due to persistent current, ramp induced effects)
- Beta-squeeze of the final focus optics in the experimental insertions

Electron Linacs (e+/e- colliders & FEL)

- Dynamic displacement of quadrupoles and accelerating structures (wake fields)
- Variations of the injected beam

- *Jitters can be transformed from one type to another, which make it difficult to identify the primary noise source.*

Interaction Point in Colliders

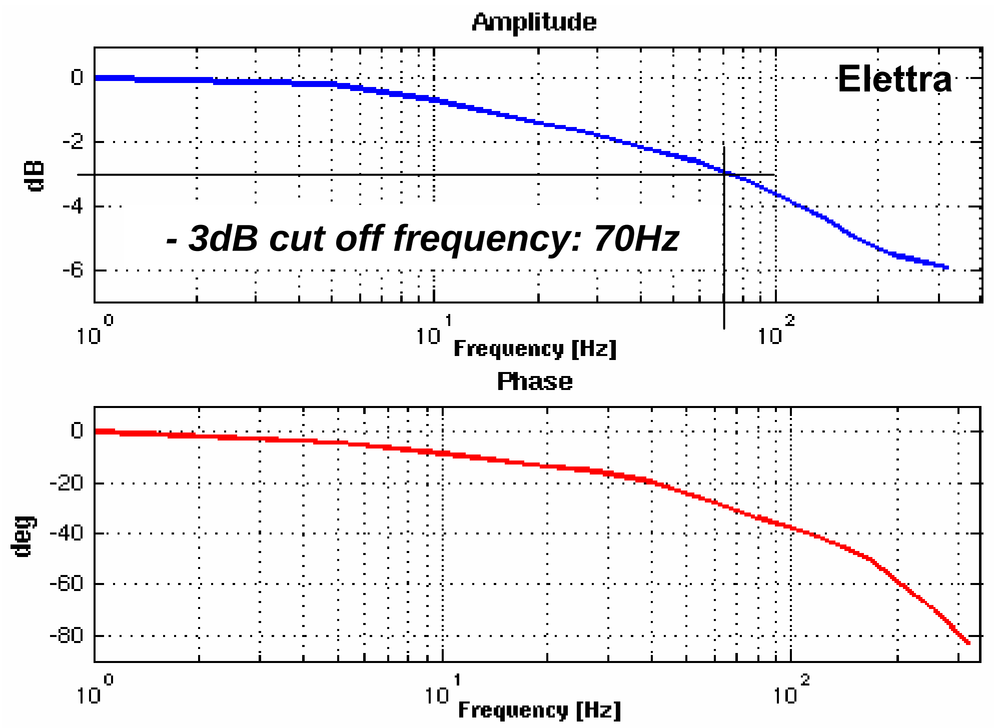
- Vibrations of final focusing magnets

SYSTEM DYNAMICS

- Limits:

1. low-pass behavior of power supply + corrector magnet (eddy currents)

2. latency in data acquisition, transmission and processing (400 – 500 μs)



Elettra

- 3dB cut off frequency: 70Hz

- Solutions:

→ 1. Use reduced number of faster correctors (e.g. air core) dedicated to fast orbit feedback [APS, ESRF, ALS, Soleil], with slow feedback running in parallel

→ 2. Acquire turn-by-turn beam position data from BPMs electronics [PETRA III]