Characterisation of Closed Orbit Feedback Systems

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The Goal of Closed Orbit Feedback

- To keep the orbit of the stored beam in a synchrotron within:
  - **specified deviations**
    - For instance, 10% of RMS beam size is allowed as RMS deviation
    - Must be accompanied by frequency range, for instance 1mHz – 1000Hz
  - from **desired positions**
    - Centre of nearby multipole magnet
    - Potential offsets for user demands: ‘golden orbit’
    - Monitors with low uncertainty (electronic noise, thermal expansion and ground motion)
  - at all **observed locations**
    - Betatron waves in both planes sampled in phase space (~ 4 BPMs per period), similar number of correctors if complete correction is desired.
  - and at all **times.**
    - Over long times (reliability, precision)
    - Correct within short time (accuracy at high bandwidth, low latency)

The Source of Orbit Deviations

- A kick $\Delta x'$ will create an orbit deviation Δx on the closed orbit in a synchrotron:

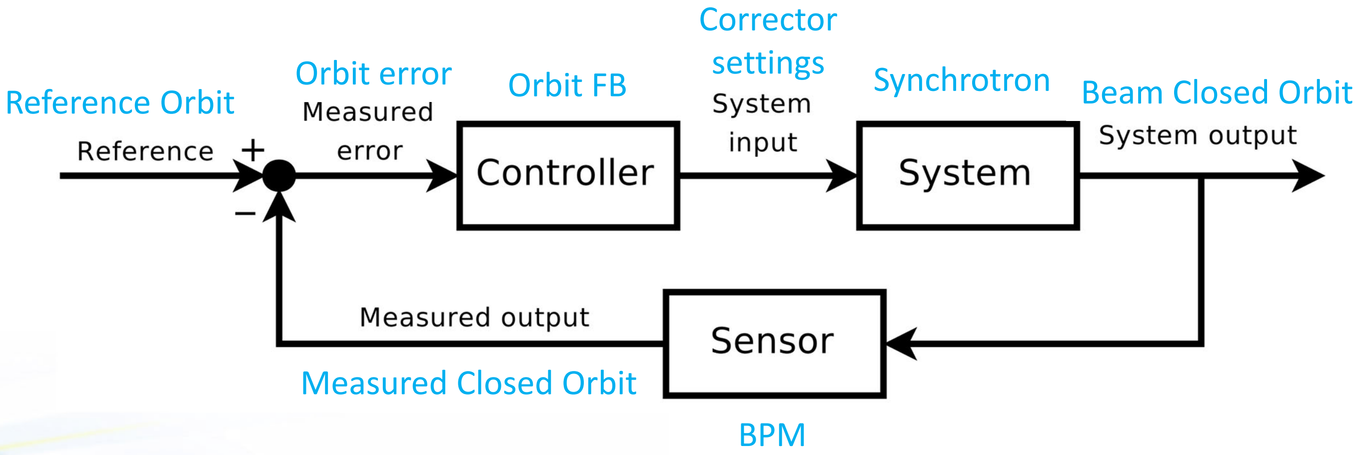
$$\Delta x = \Delta x' R_{ij} = \Delta x' \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi \nu} \cos\left(\left|\Psi_i - \Psi_j\right| - \pi \nu\right)$$

- β_i, β_j are the beta-functions at observation or kick
- Ψ_i, Ψ_j are the phase advances at observation or kick
- ν is the betatron tune in this plane
- The $\sin \pi \nu$ term in the denominator acts as a scaler to ALL orbit deviations
- The **Orbit Response Matrix** is built from all R_{ij}
- There is an extra term for synchrotrons that cross transition energy

Control Theory

- ***Control theory** in control systems engineering is a subfield of mathematics that deals with the control of continuously operating dynamical systems in engineered processes and machines.*

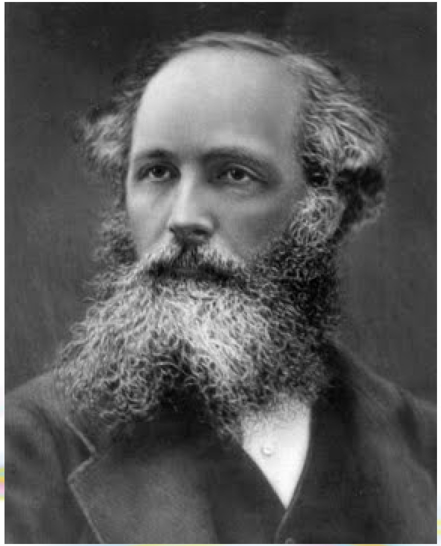
Wikipedia

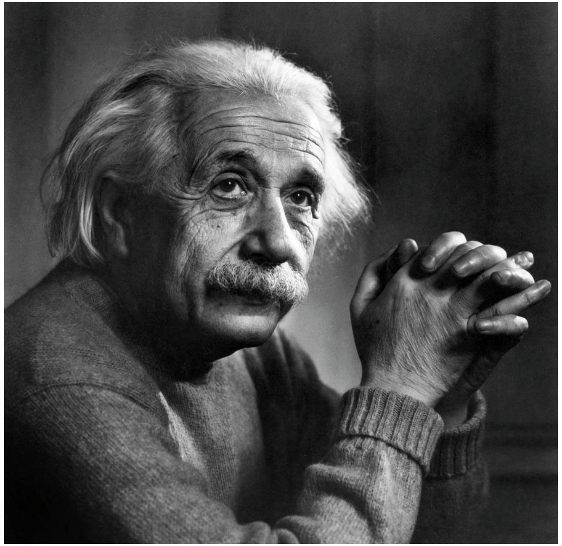


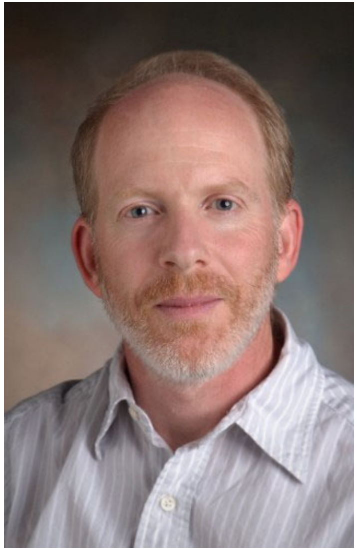
- Closed Orbit Feedback Systems require **Control Theory!**

Feedback for Physicists

"Feedback and its big brother, control theory, are such important concepts that it is odd that they usually find no formal place in the education of physicists."

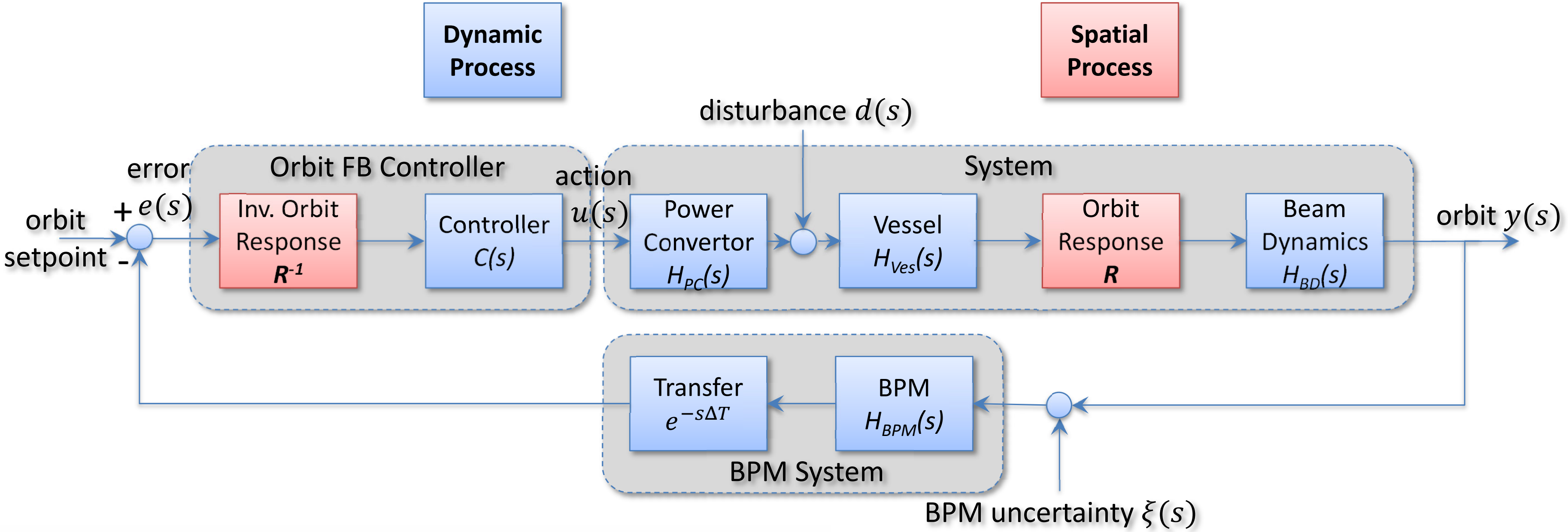






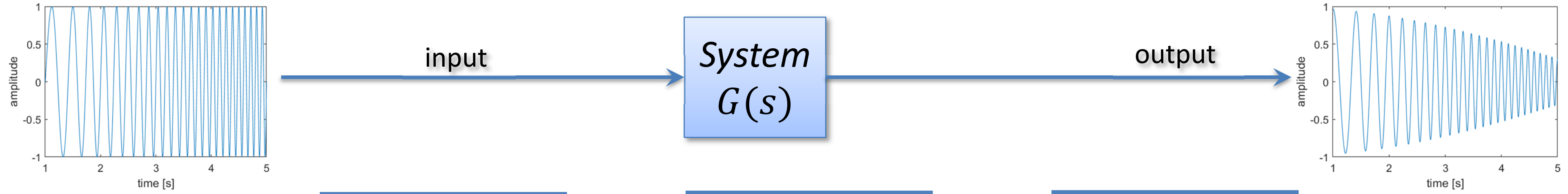
J. Bechhoefer, Feedback for physicists: A tutorial essay on control, DOI:10.1103/RevModPhys.77.783

Dynamic and Spatial Processes in a Control Loop



- Knowledge all the dynamics required, either from calculations or from measurements
- Starting model for each component is low pass filter together with latency
- Simple inverse ORM only works for 'square' problem
- Sensitivities like disturbance to orbit $\frac{y(s)}{d(s)}$ can be investigated analytically or measured

System Identification



Known signal

- Beam position
- Input data
- Current
- Kick

Device under test

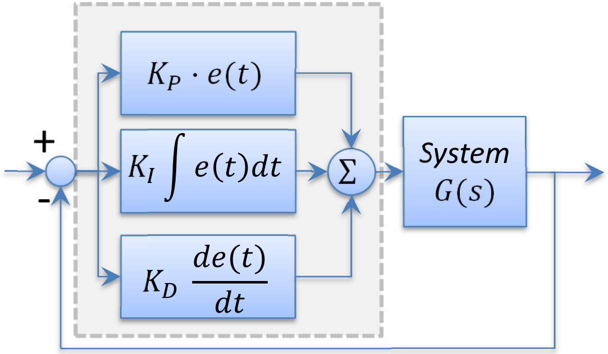
- BPM system
- Control process
- Magnet
- Beam

Acquired signal

- Orbit reading
- Output data
- B-field
- Orbit response

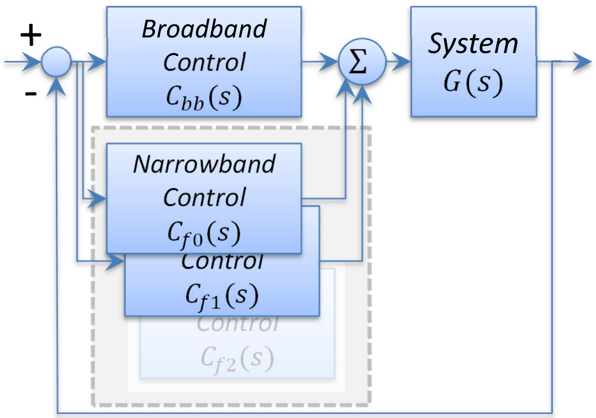
Some Control Algorithm Choices

Proportional, Integral, Derivative Control



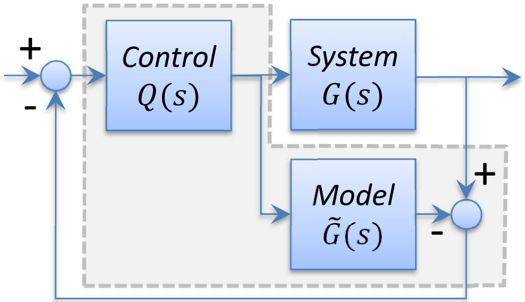
- Trivial choice, most controllers are PID
- Intuitive to understand
- Not a good fit if system has latency
- Empirical tuning, but not trivial
- Often ends up using mostly K_I
- OK, but sub-optimal performance

Added Harmonic Suppressors



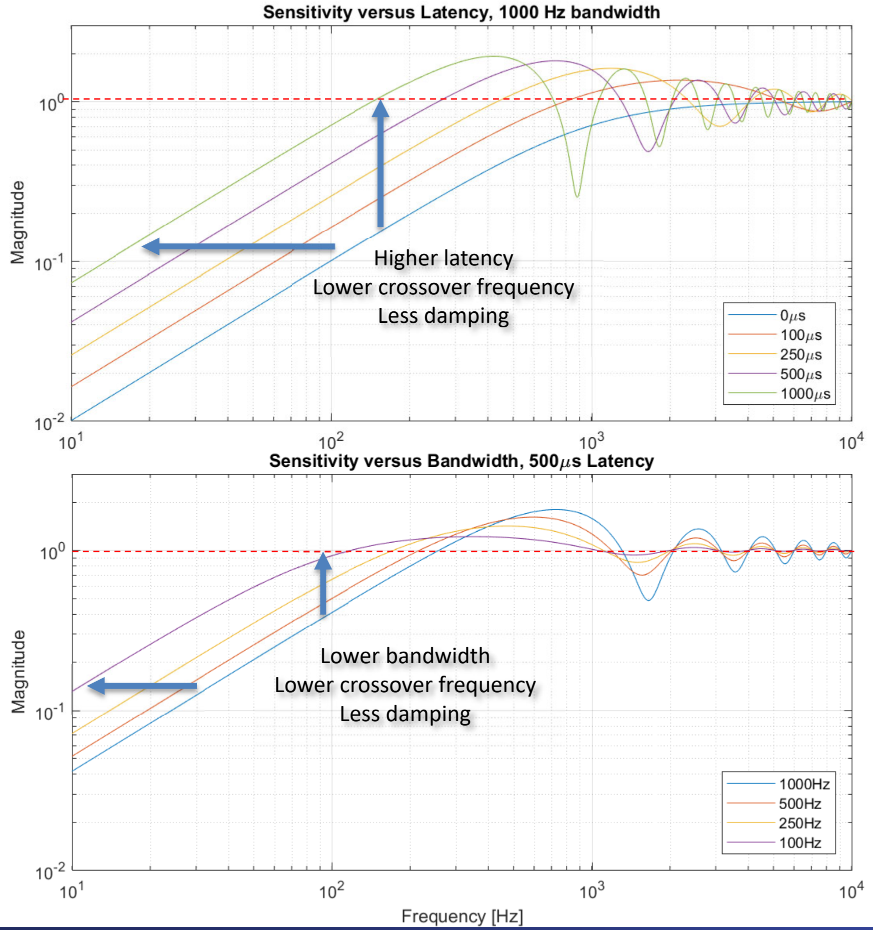
- Frequently used as extension to PID
- Add suppressors for mains harmonics
- Narrowband filter and phase shifter allow individual feedback phase
- Better overall performance

Internal Model Control



- Design based on knowledge of model
- Model/system difference used for feedback
- Model must be pre-determined
- Remains well controlled with latency

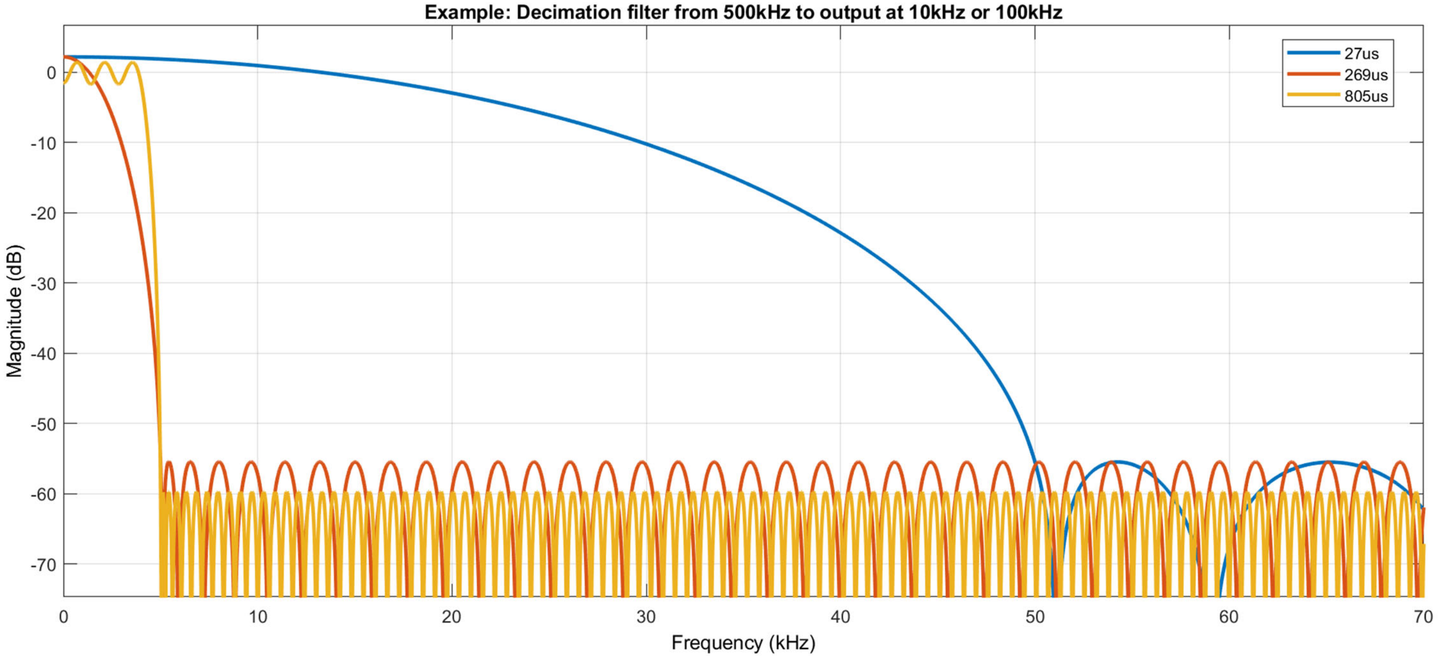
Disturbance to Orbit vs Latency and Bandwidth



- Simplified model: low pass + latency
- Using Internal Model Control
- Performance measure: **sensitivity crossover frequency** from damping to enhancing
- Damping below crossover is predictable
- How fast is fast enough?
  - Depends on disturbance spectrum
  - Depends on users experiments (typically speeding up)

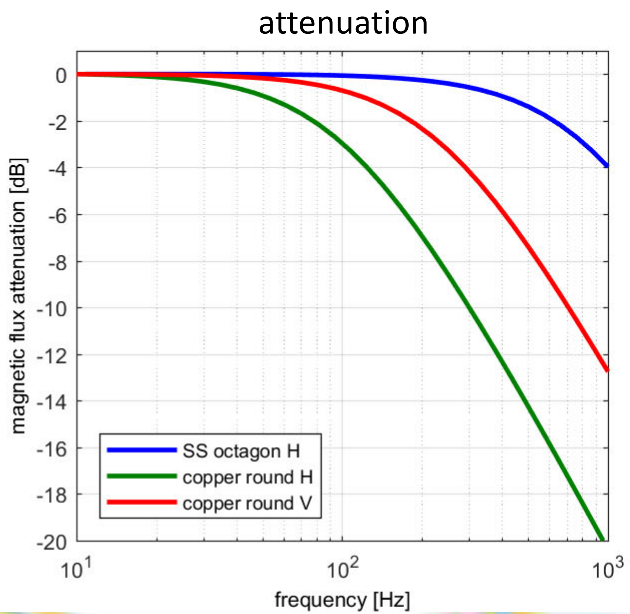
BPM Dynamics

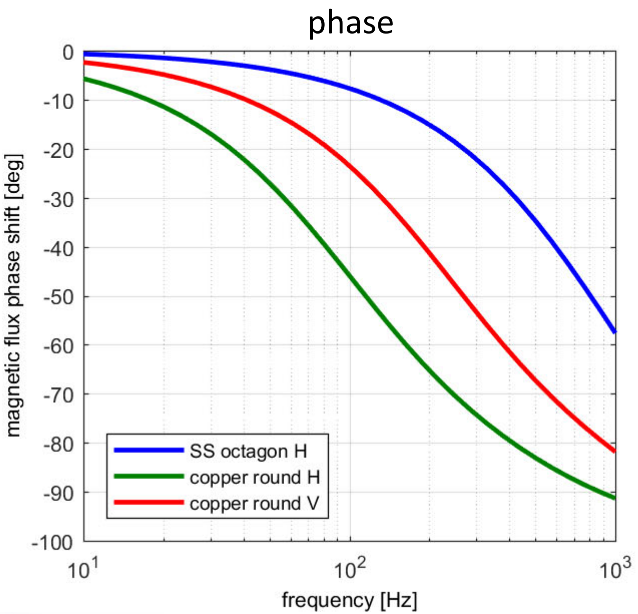
- BPMs have to use low pass filters before decimation, typically finite impulse response (FIR) low pass filters
- This will cause systematic latency of typically half the length in samples
- **Sharper** drops will inevitably cause **longer** latency
- **Shallow** drops require **higher** output sample frequency to meet Nyquist criterion
- Latency is visible as linear phase slope or group delay $-\frac{d\phi}{d\omega}$

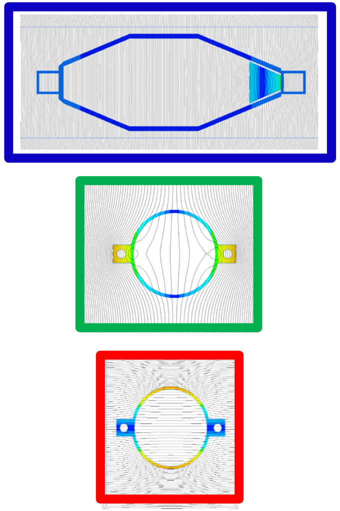


Magnet and Vessel Dynamics

- Magnets and vessels are both low pass filters and latency due to eddy currents
- Simulations and measurements are required to estimate effects of complex geometries
- Complete geometry must be included: magnet laminations, joke, vessel, cooling channels
- Various control approaches for mixed dynamics of slow and fast corrector magnets exist







Orbit Response Matrix Inversion Strategies

Singular Value Decomposition (SVD) of orbit response matrix

$$R = U\Sigma V^*$$

allows various approaches to inversion of non-square ORM

SVD Pseudoinverse

- $R^+ = V\Sigma^{-1}U^*$
- Over-emphasises 'high' modes, frequently noisy or unstable

Truncated SVD

- $\tilde{R} = V\tilde{\Sigma}U^*$
- $\tilde{\Sigma} = \Sigma^{-1}$ and $\tilde{\sigma}_{nn} = 0$ for $n > k$
- Deliberately ignores 'higher' modes entirely

Tikhonov Regularisation

- $\hat{R} = VDU^*$
- $D_{nn} = \frac{\sigma_{nn}}{\sigma_{nn}^2+\alpha^2}$
- α used to 'tame' high modes
- Essentially varies gain per mode

Mode Space Controller

- $M = \Sigma^{-1}U^*$
- Apply controller(s) in mode space M
- Transform to action VM

Implementation Themes

Components:
in-house or
commercial?

Controller:
FPGA, DSP or CPU?

For upgrades:
What works,
What to upgrade?

Interface Technology:
What speed?
Which standard?

ARIES Workshop

- 2nd day on Orbit Feedback
- Reports of achievements and talks about the future
- (ALS-U), ASTRID-2, AS, ESRF-U, FAIR, LHC, (NSLS-II), PETRA-III, SIRIUS, (SLS-2), (RHIC)
- Instrumentation Technologies
- Whole workshop here:

https://indico.cern.ch/event/743699

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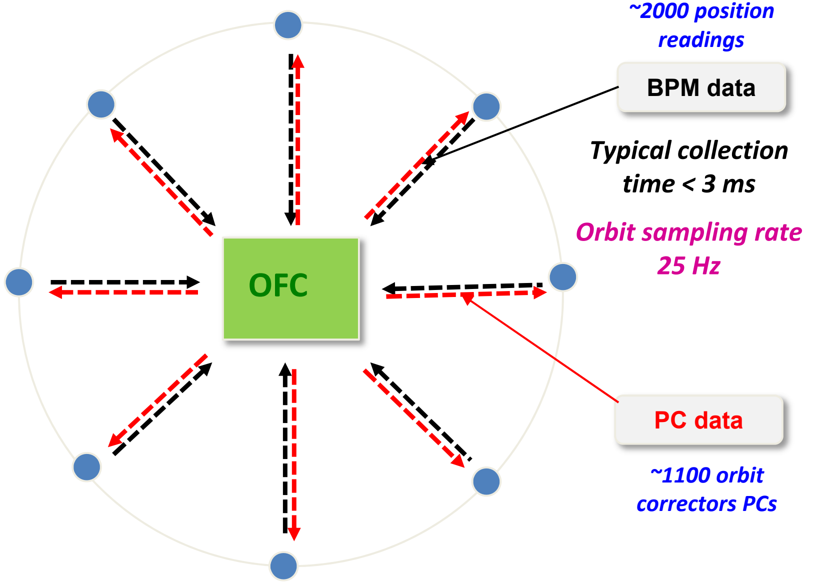
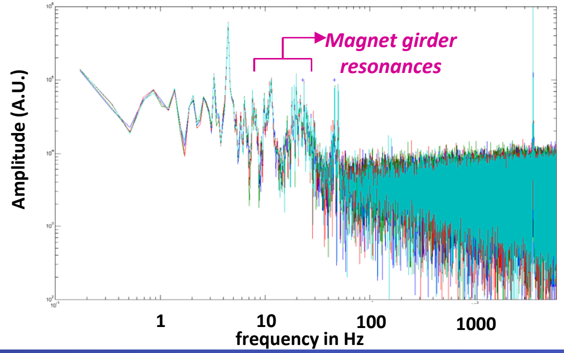
LHC: Scaling laws of COFB

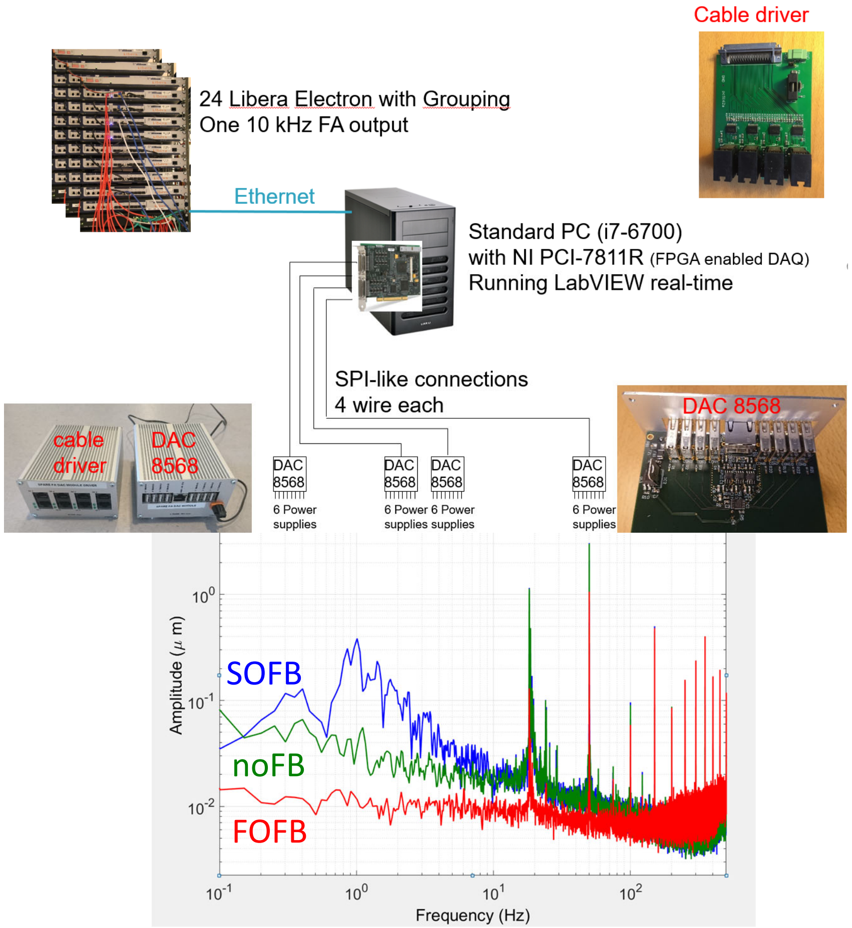
- Everything designed in-house
- ~2000 BPMs and ~1100 correctors
- Large size, slow communications, 25 Hz update rate
- Correction in central Orbit Feedback Controller (OFC)
- 2nd level of topological hierarchy
- In use during ramp and stored beam
- Stored beam with reduced eigenvalues and gain to reject BPM errors
- Latency: several 10 ms
- Corrector BW: a few Hz ?
- Sensitivity crossover: ~0.5 Hz





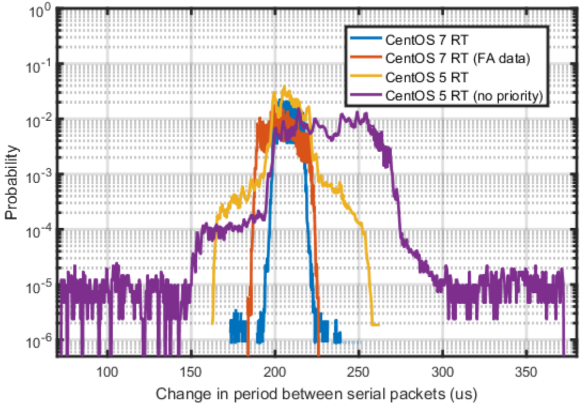
ASTRID-2: Cost optimised solution

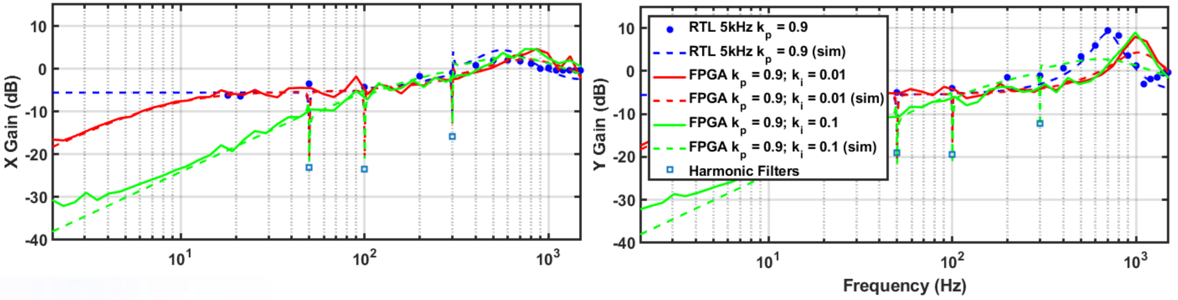
- Commercial BPMs feeding data into PC with LabView RT driven FPGA
- 24 BPMs, 12 correctors, 10 kHz
- In-house DACs feed in-house PCUs on analogue input
- Fast DAC adds 1% to slow DAC
- Want to add harmonic suppressors
- Latency 600-800 µs
- Corrector BW ~1 kHz
- Sensitivity crossover ~150 Hz



Australian Synchrotron: From RT Linux to FPGA

- Prototyping using low cost PC hardware
- Fighting jitter in ‘real time’ OS
  - 5 kHz update rate only
- After prototyping, change to FPGA implementation
  - no jitter
  - 10 kHz update rate
- PI and harmonic suppressors
- Fast and slow correctors merged using Soleil approach
- Latency: 120 µs (!)
- Corrector BW: 500-1000 Hz
- Sensitivity crossover: ~300 Hz



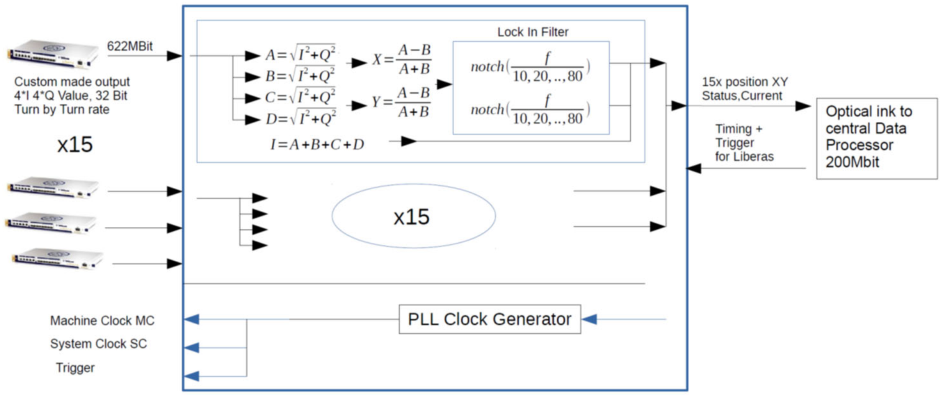


Australian Government

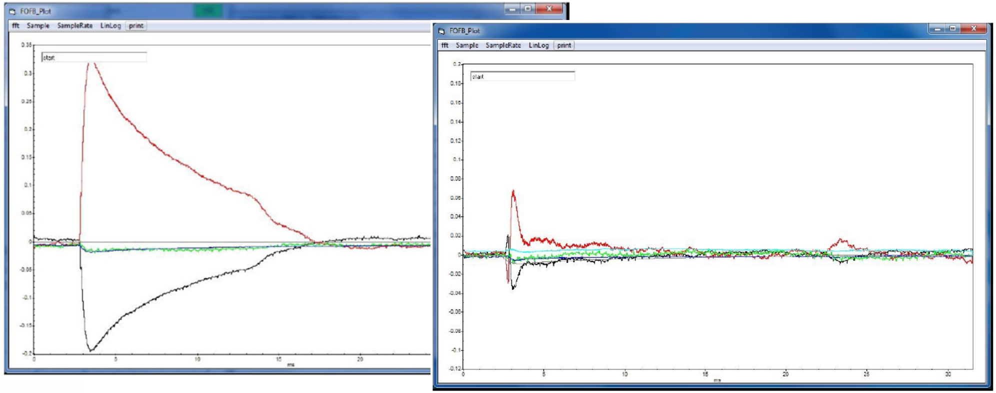
ANSTO

PETRA III: Large and fast data rate

- Commercial BPMs, in-house data combiner, FPGA controller and PSU
- Large: 250 BPMs, 100 fast correctors
- Running at TbT rate: 130.1 kHz!
- Features: PID, 50 Hz suppressor, feedforward during injection
- Latency: 338 µs
- Corrector BW: 1 kHz
- Sensitivity crossover: ~150-200 Hz (deliberately limited)



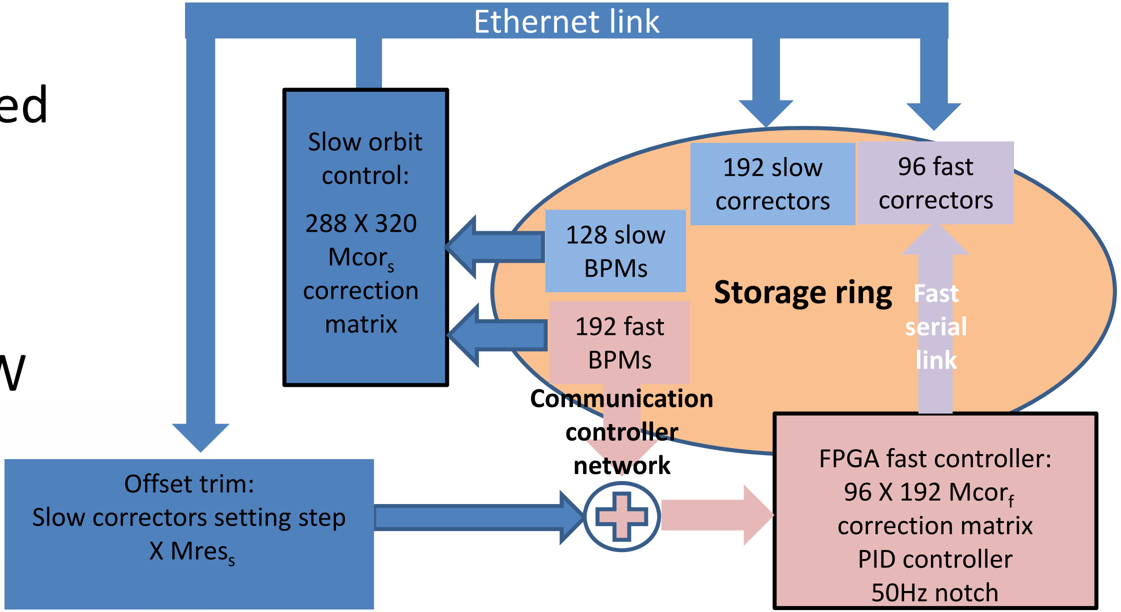
Injection feedforward off / on



ESRF-U: Keep recently upgraded COFB

- Commercial BPMs and corrector PSU
- In-house designed FPGA controller
- Mix of slow/fast BPMs and slow/fast correctors!
- PID and 50Hz suppressor, Added feedforward correction during injection
- Latency: 630 µs
- Corrector BW (fast): 500 Hz BW
- Sensitivity crossover: 150 Hz

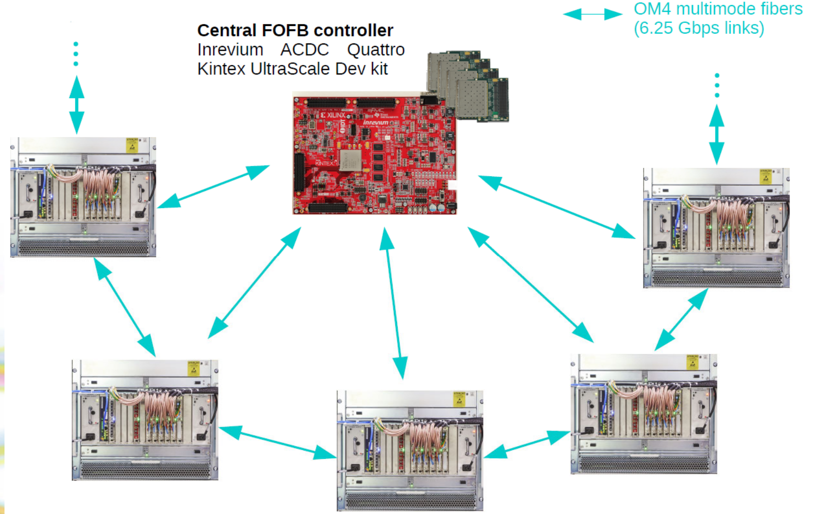
- Hybrid slow/fast orbit control



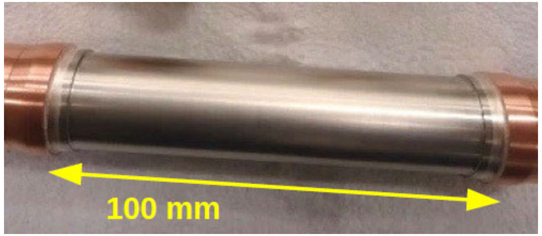
ESRF | The European Synchrotron

SIRIUS: Whole system in-house and open hardware

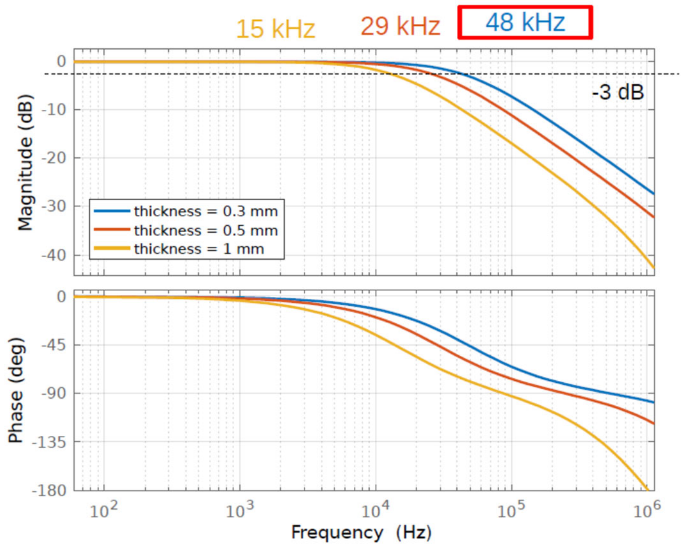
- BPMs are built in MTCA
- Controller in FPGA, update rate 96.5 kHz
- Plan Tikhonov regularisation and advanced control
- Slow and fast correctors used together
- Latency: 20 µs (target)
- Corrector BW: 10 kHz
- Sensitivity crossover: >1kHz (target)



300um thick stainless steel chamber in corrector

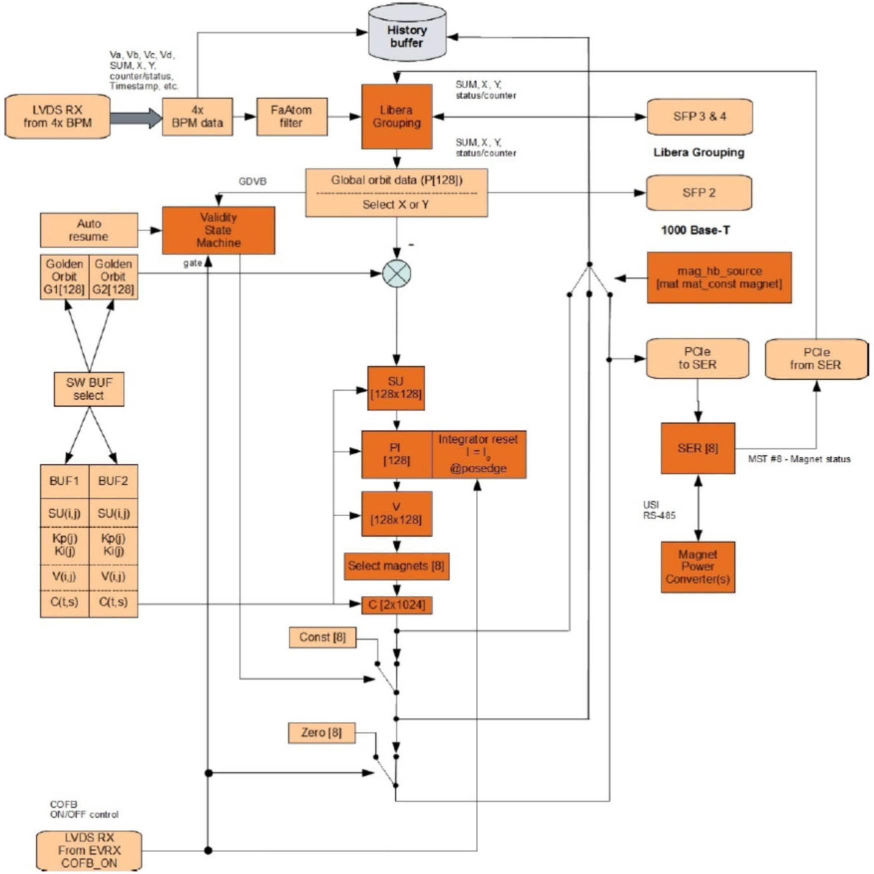


Magnetic Field Frequency Response for different chamber thicknesses



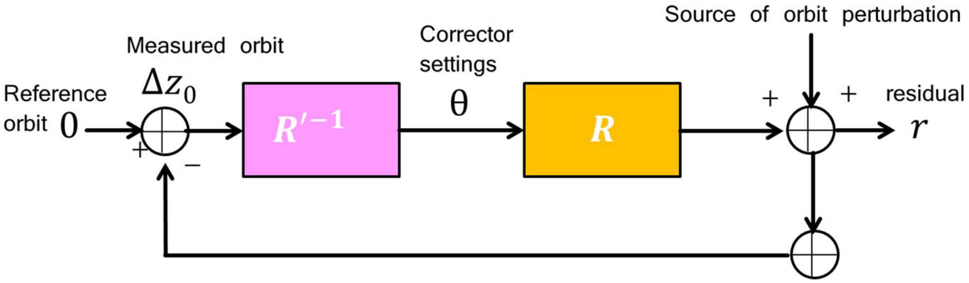
Instrumentation Technologies: Commercial Solution

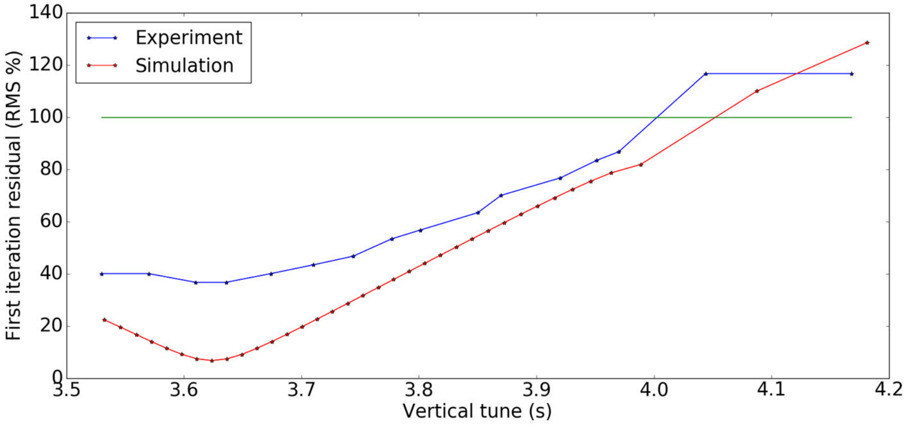
- BPMs with integrated COFB on FPGA and event receiver
- Customisation on interface to corrector power supplies
- 6.5 Gb/s links for orbit data
- Nice: PI control in mode space!
- Double buffered configuration
- COFB running on some installations
- Sensitivity cross over 300 Hz @ TPS



FAIR: Fast COFB in ramping synchrotron

- Commercial BPMs and Controller in FPGA
- Operating in fast ramping (0.3-2.7 Hz) hadron ring
- No details about correctors
- Algorithm development in-house
  - Investigation of spatial model and system/model mismatch
  - Re-visiting harmonic analysis as an alternative to SVD
  - Exploiting symmetry in the ring to optimise process of inversion





Summary

- COFB as integral part of synchrotron design from the start
- Control Theory and System Identification are good starting points
- Latency and bandwidth of all components must be closely watched
- Workshop has shown many technology choices, all proven to work
- Trends for the future:
  - BPM fast data rate 10 kHz -> 100 kHz
  - BPM bandwidth 2 kHz -> 20 kHz
  - Corrector BW 500 Hz -> 5 kHz
  - Latency 600 µs -> 60 µs
  - Sensitivity crossover frequency 200Hz -> 2kHz

Thank you!

And thanks to all the authors!