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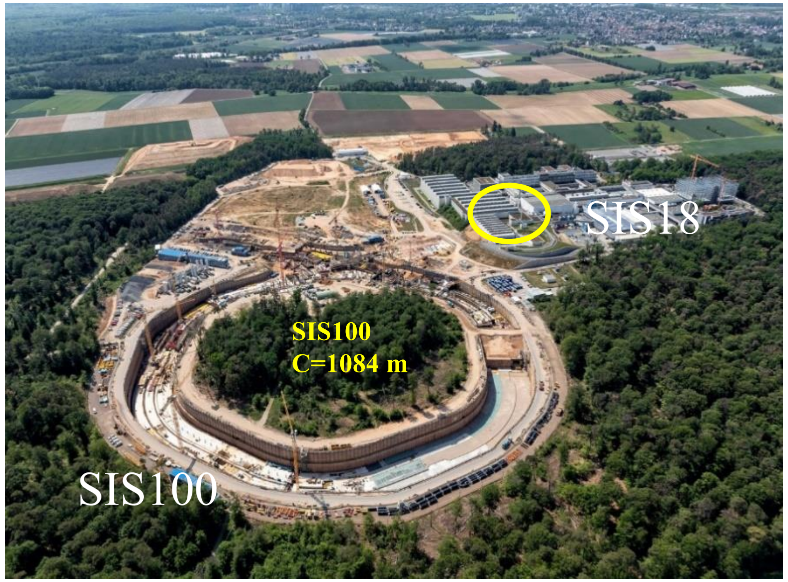
SIS-18 closed orbit feedback (COFB) system: Identification and Stability

Outline

- GSI and FAIR
- Introduction to the COFB system
- System identification and stability
- Technical details of SIS18/SIS100 COFB
- Experimental results:
  - Spatial model mismatch
  - Temporal system identification
  - Orbit correction and manipulation
  - Model mismatch induced COFB instability

GSI & FAIR

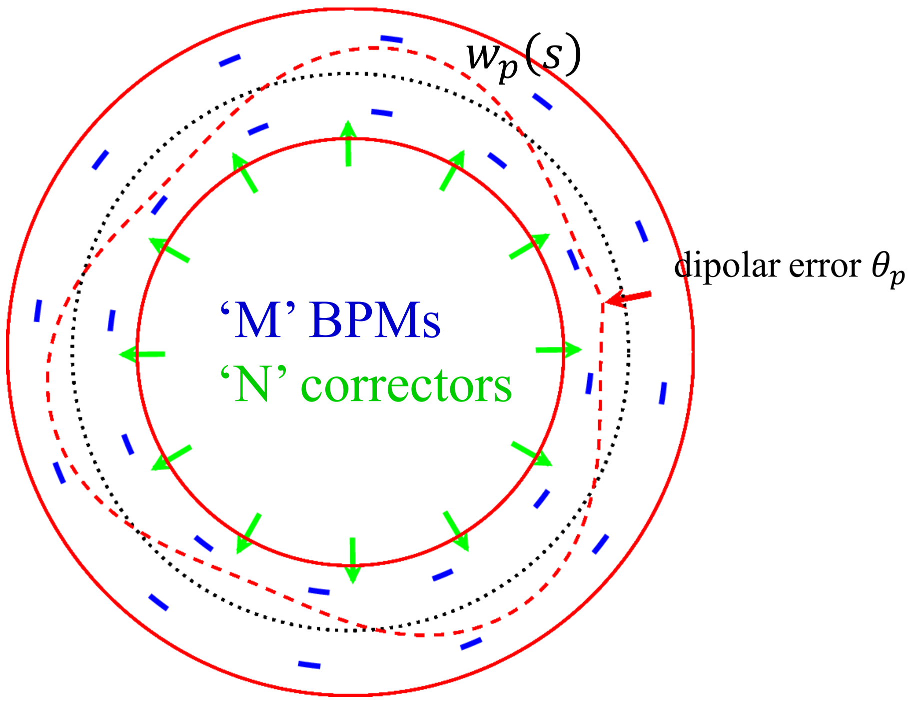


Fast ramping synchrotron → SIS-18 as Injector for FAIR SIS-100

Parameter/Ring	SIS18	SIS100
Circumference (m)	216	1084
Magnetic rigidity (Tm)	18	100
Injection energy	11 MeV/u for U^{28+} 70 MeV/u for protons	200 MeV/u for U^{28+} 4.5 GeV/u for protons
Extraction energy	200 MeV/u for U^{28+} 4.5 GeV/u for protons	2.7 GeV/u for U^{28+} 29 GeV/u for protons
Beam intensity (per pulse)	1.5 10^{11} ions 5. 10^{12} protons	5. 10^{11} ions 4. 10^{13} protons
Magnets	Normal conducting	Super conducting
Ramp rate (max)	10 T/s (variable)	4T/s
Repetition frequency (Hz)	2.7	0.7
Beam size	5-30 mm (MTI) (1σ)	20-30 mm (1σ)

Feedback system project drivers:
- Beam quality → Preparation for better control on the beam quality for users and support the upgrade plan for achieving SIS-100 intensities
- Machine protection → Higher intensity bring higher risks with off centered beams
- Machine set-up time → Dealing with cycle-to-cycle variations and reduction of machine set-up time

Closed orbit perturbation and correction



Schematic of the SIS18 perturbed orbit

12 similar sections each with one BPM and steerer (correction), i.e. M = N = 12

Effect of a dipole perturbation on closed orbit perturbation is given by the following equation

$$w_p(s) = \frac{\sqrt{\beta(s_i)\beta(s)}}{2\sin(\pi Q_z)} \cos(|\mu(s) - \mu_i| - \pi Q)\,\theta_p$$

s:	spatial co-ordinate along the ring
dipolar error θ_p:	Unknown field error or corrector strength
closed orbit w_c:	Averaged beam position over several turns around the ring
β:	beta function
μ:	phase advance with respect to the defined position
Q:	coherent tune in either transverse plane

$$-w_p(s) = \sum_{n=1}^{N} \frac{\sqrt{\beta(s_i)\beta(s)}}{2\sin(\pi Q_z)} \cos(|\mu(s) - \mu_i| - \pi Q)\,\theta_n$$

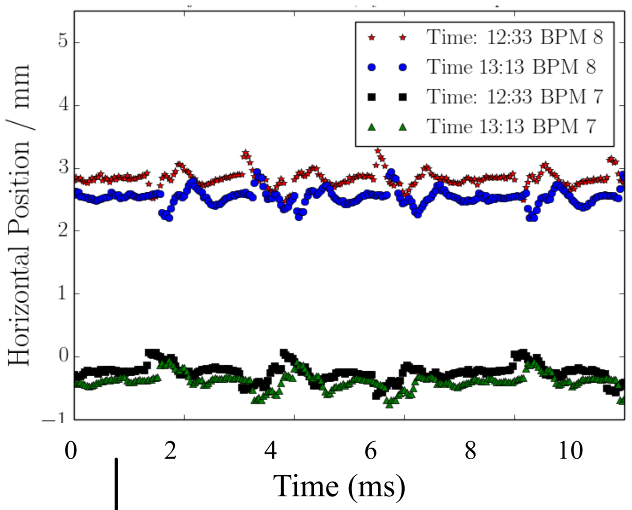
$$[\boldsymbol{W}]_{\boldsymbol{M\times 1}} = [\mathbf{R}]_{\boldsymbol{M\times N}}[\Theta]_{\boldsymbol{N\times 1}} \qquad [\Theta]_{\boldsymbol{N\times 1}} = [\mathbf{R}]^{-\mathbf{1}}_{\boldsymbol{M\times N}}[\boldsymbol{W}]_{\boldsymbol{M\times 1}}$$

SVD based inversion

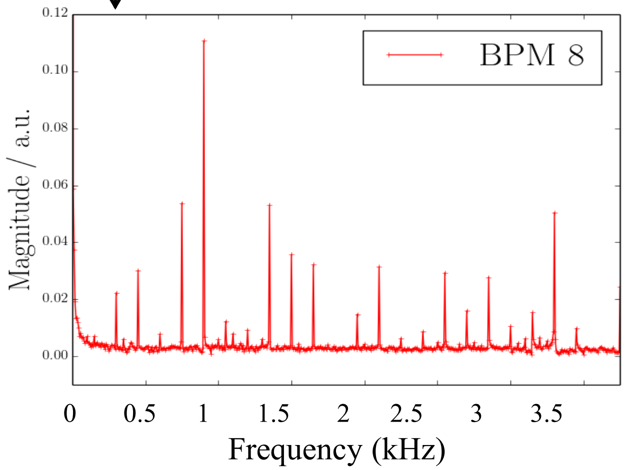
- **R** is completely determined by the location of steerers and BPMs and the quadrupole settings (for a linear lattice)
- ORM referred to as spatial model , and as long as the machine settings remain constant, it is fixed (usually!)

Closed orbit perturbations in SIS18

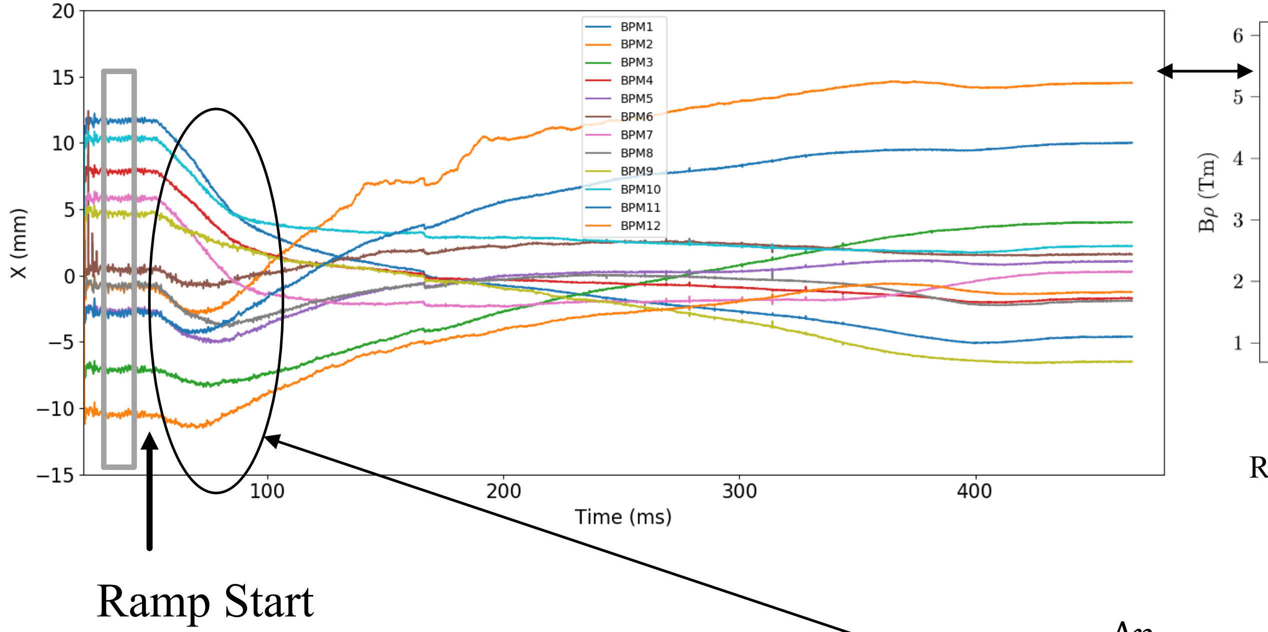
At injection



Fourier Transform

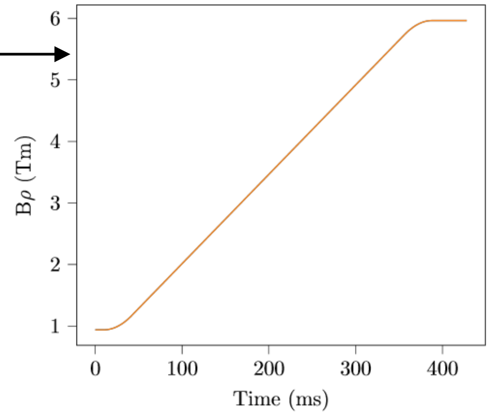


During whole cycle



$$x_D = D_x \frac{\Delta p}{p}$$

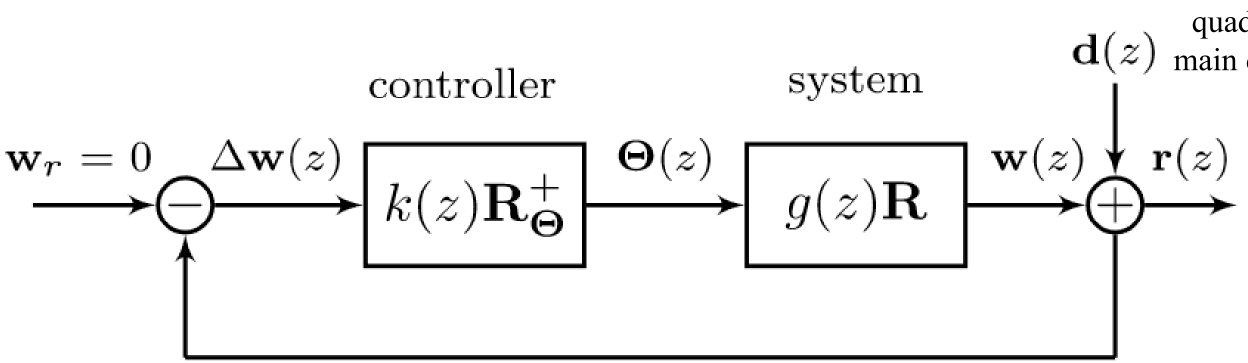
Rigidity



Ramping times from 100-500 ms

- Thin chambers to fast ramping, significant components till 3 kHz in the horizontal plane.
- In some cases, there are shot-to-shot changes/shifts in the orbit due to lack of synchronism between power grid and accelerator triggers or due to hysteresis of magnets
- The mismatch between beam energy and dipole field is not actively corrected in SIS18 so a dispersion induced orbit shift is observed during the ramp

Challenges for SIS-18 closed orbit feedback system



system model $\mathbf{G}(z) = g(z)\,\mathbf{R}$

We can separate the spatial and temporal parts of the system model

$$g(z) = g_1(z)_{\text{ BPM}} \ldots g_m(z)_{\text{power supplies.}}\; g_n(z)_{\text{ correctors}}$$

controller $\mathbf{K}(z) = k(z)\mathbf{R}_{\boldsymbol{\Theta}}^{+}$

Spatial model mismatch ($\mathbf{R}^{-1}$ vs $\mathbf{R}_{\boldsymbol{\Theta}}^{+}$)

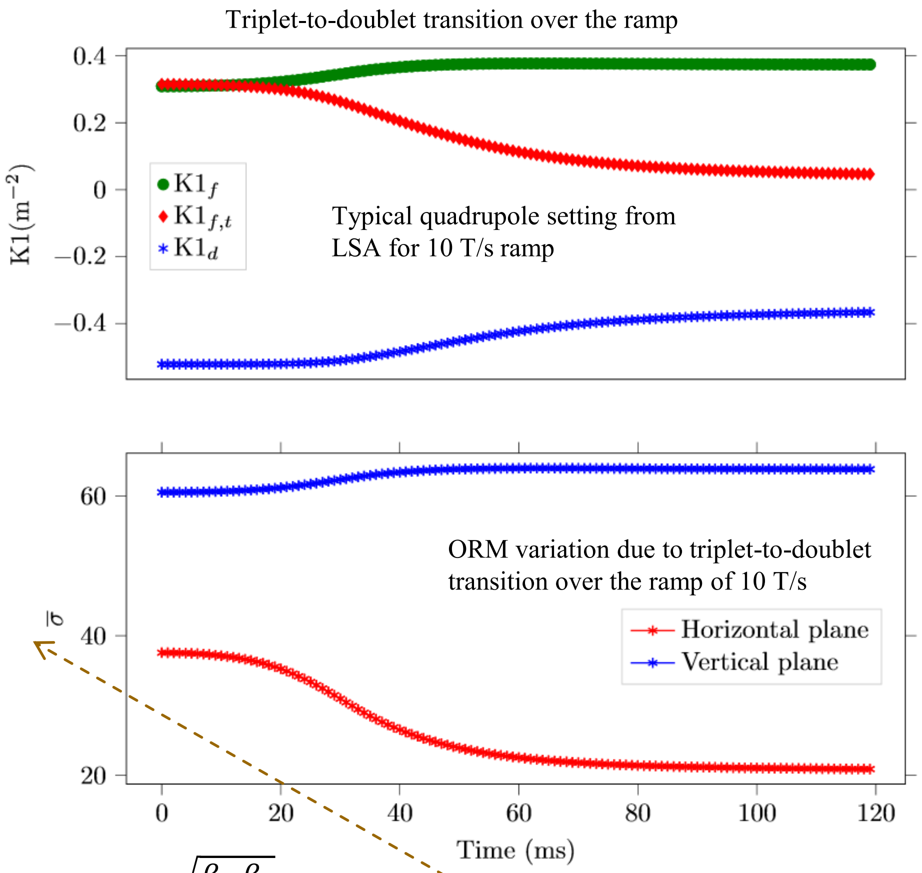
- Changing lattice and rigidity
- Differences between real model and machine model
- Intensity dependent tune shift
- Intentional simplication of inverted ORM ($\mathbf{R}_{\boldsymbol{\Theta}}^{+}$) for computation simplicity or stability (circulant symmetry, normalization etc.)

Transfer function g(z):

- Quite of few components in the loop not measured
- Thin chambers for fast ramping of magnets, frequencies upto 3 kHz visible in the beam motion

S.H. Mirza, R. Singh, P. Forck and H. Klingbeil, Closed orbit correction at synchrotrons for symmetric and near-symmetric lattices, **Phys. Rev. Accel. Beams 22, 072804**, (2019)

Spatial model mismatch: optics variation over ramp

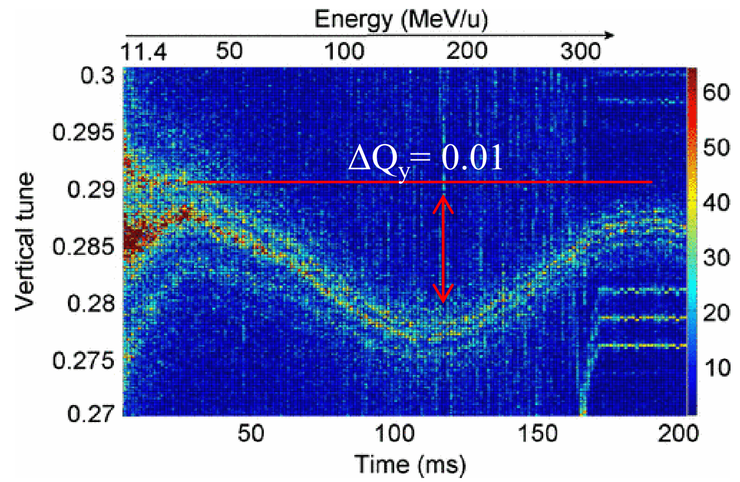


$$R_{mn} = \frac{\sqrt{\beta_m \beta_n}}{2\sin(\pi Q_z)} \cos(|\mu_m - \mu_n| - \pi Qz)$$

SVD

$$\begin{bmatrix} R_{11} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots \\ R_{m1} & \cdots & R_{mn} \end{bmatrix} = \begin{bmatrix} U_{11} & \cdots & U_{1m} \\ \vdots & \ddots & \vdots \\ U_{m1} & \cdots & U_{mm} \end{bmatrix} \begin{bmatrix} \sigma_1 & \cdots & 0 \\ \vdots & \sigma_2 & \vdots \\ 0 & \cdots & \sigma_n \end{bmatrix} \begin{bmatrix} V_{11} & \cdots & V_{1n} \\ \vdots & \ddots & \vdots \\ V_{n1} & \cdots & V_{nn} \end{bmatrix}$$

R. Singh, O. Boine-Frankenheim, O. Chorniy, P. Forck, R. Haseitl, W. Kaufmann, P. Kowina,K. Lang, and T. Weiland, Interpretation of transverse tune spectra in a heavy-ion synchrotronat high intensities, Phys. Rev. ST Accel. Beams, 16, 034201, (2013)

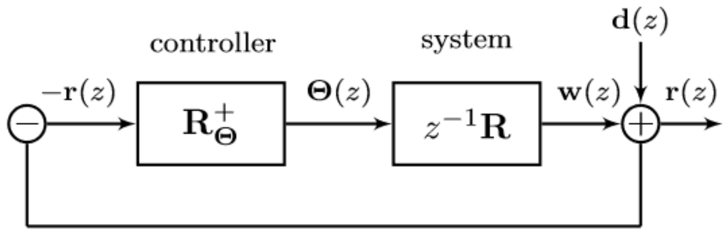


Design considerations for COFB system

- How many ORMs need to be updated during the ramp to have a fast correction and avoid any potential COFB instability?
- Can intensity dependent tune shifts be tolerated by COFB system?

Characterization of spatial model mismatch

For slow regime: When the rate of orbit correction is too slow as compared to the dynamics of the system i.e. the system is in steady state before the application of next correction step



R is the actual system model and $\mathbf{R}_\theta^+$ and inverse of known model

$$r_1 = (\mathbf{I} - \mathbf{R}\mathbf{R}_\Theta^+) r_0$$

correction matrix $\mathbf{M} = (\mathbf{I} - \mathbf{R}\mathbf{R}_\Theta^+)$

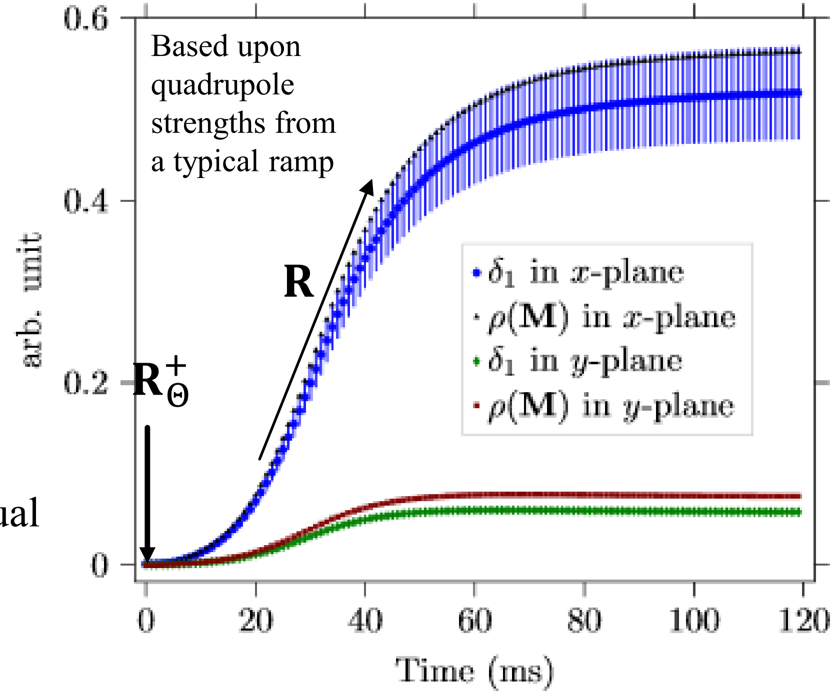
$$\boldsymbol{\rho}(\mathbf{M}) = \mathbf{max}\{|\lambda_i|\}$$

The condition of COFB system stability is:

$$\boldsymbol{\rho}(\mathbf{M}) \leq 1$$

The spectral radius condition of COFB stability

simulations for SIS18



Measurable: first iteration residual

$$\delta_1 = \frac{r_{1,RMS}}{r_{0,RMS}} \qquad \delta_1 \leq 1$$

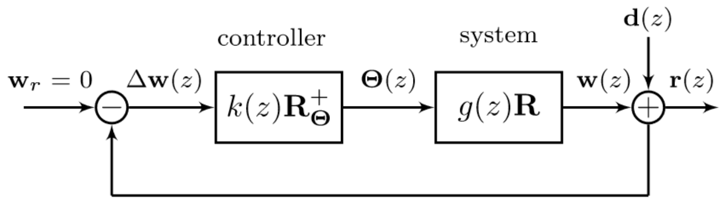
$$\boldsymbol{\rho}(\mathbf{M}) \geq \delta_1$$

Injection ORM usage for the full ramp will not lead to instability in slow regime in known model is the actual model!

S. H. Mirza, R. Singh, P. Forck, B. Lorentz, **Performance of the closed orbit feedback systems with spatial model mismatch, Phys. Rev. Accel. Beams 23, 072801 – Published 6 July 2020**

COFB bandwidth and controller parameters

For fast regime: When the rate of orbit correction is comparable to the dynamics of the system



Delay free first order system model $g(z) = \mathcal{Z}(\frac{a}{s+a})$

Controller for such a system in internal model controller e.g. IMC approach

$$k(z) = [g(z)]^{-1}\frac{Z(z)}{1-Z(z)}$$

Z(z) is a low pass filter

$$Z(z) = \mathcal{Z}(\frac{b}{s+b})$$

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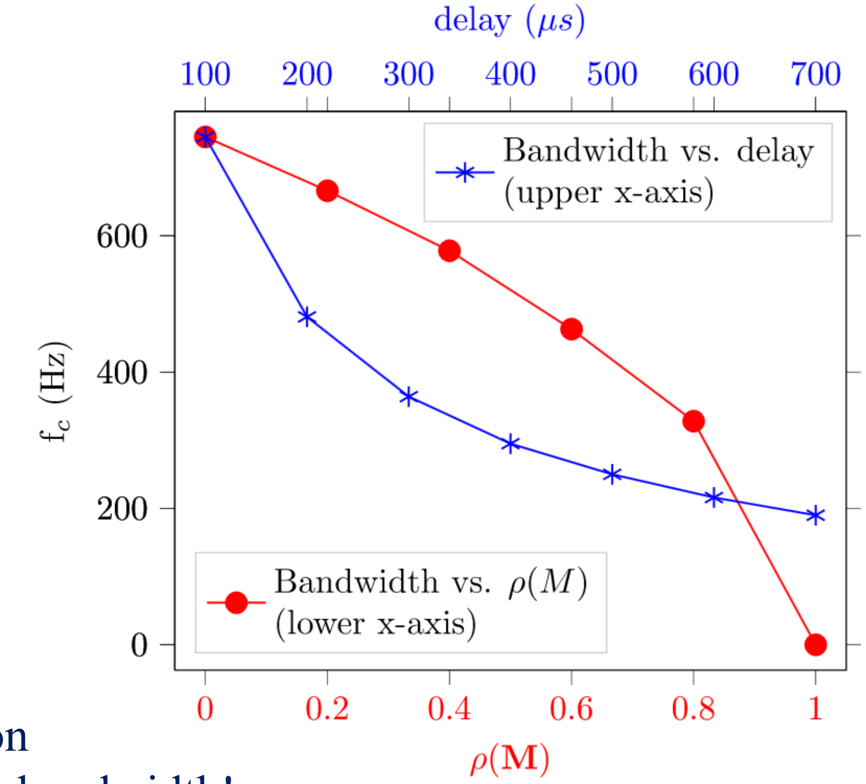
sensitivity function
disturbance to output

$$\mathbf{S}(\mathbf{z}) \triangleq [\mathbf{I} + g(z)\mathbf{R}k(z)\mathbf{R}_{\Theta}^{+}]^{-1}$$

$$S(z) = \frac{1-Z(z)}{1-\rho(\mathrm{M})Z(z)}$$

controller parameter dependence on model mismatch

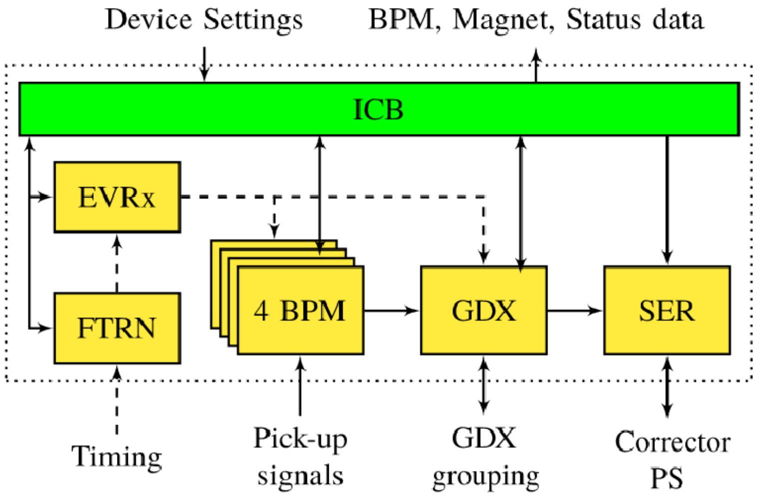
$$\boldsymbol{k_\rho(z) = k_{(\rho(M)=0)}(z)[1-\rho(\mathrm{M})]}$$



Spatial model mismatch plays a direct role in controller parameter determination
A less aggressive controller will keep COFB stable with reduction in correction bandwidth!

M. Abbott, Using an Internal model controller for electron beam position fast feedback ,Diamond Light Source, internal document, (2007)
S. H. Mirza, R. Singh, P. Forck, B. Lorentz, **Performance of the closed orbit feedback systems with spatial model mismatch, Phys. Rev. Accel. Beams 23, 072801 – Published 6 July 2020**

SIS18/100 COFB hardware description



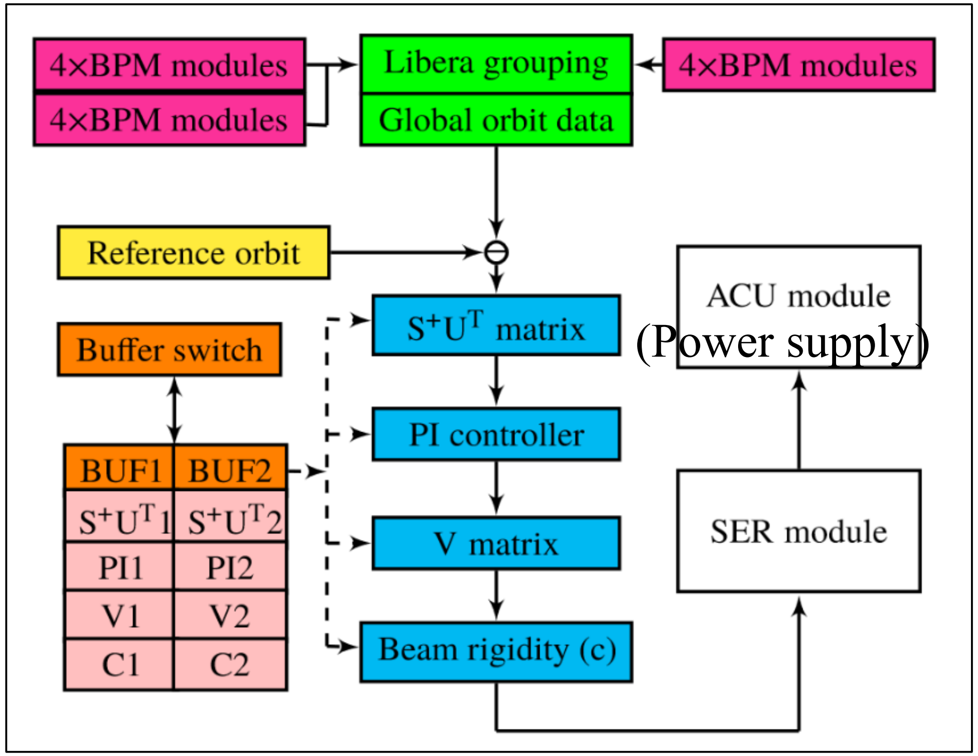
BPM: Beam position module **EVRx**: Event Receiver module

FTRN: Fair Timing Receiver Node

GDX: Gigabit Date eXchange

SER: Serial communication module

GDX design overview



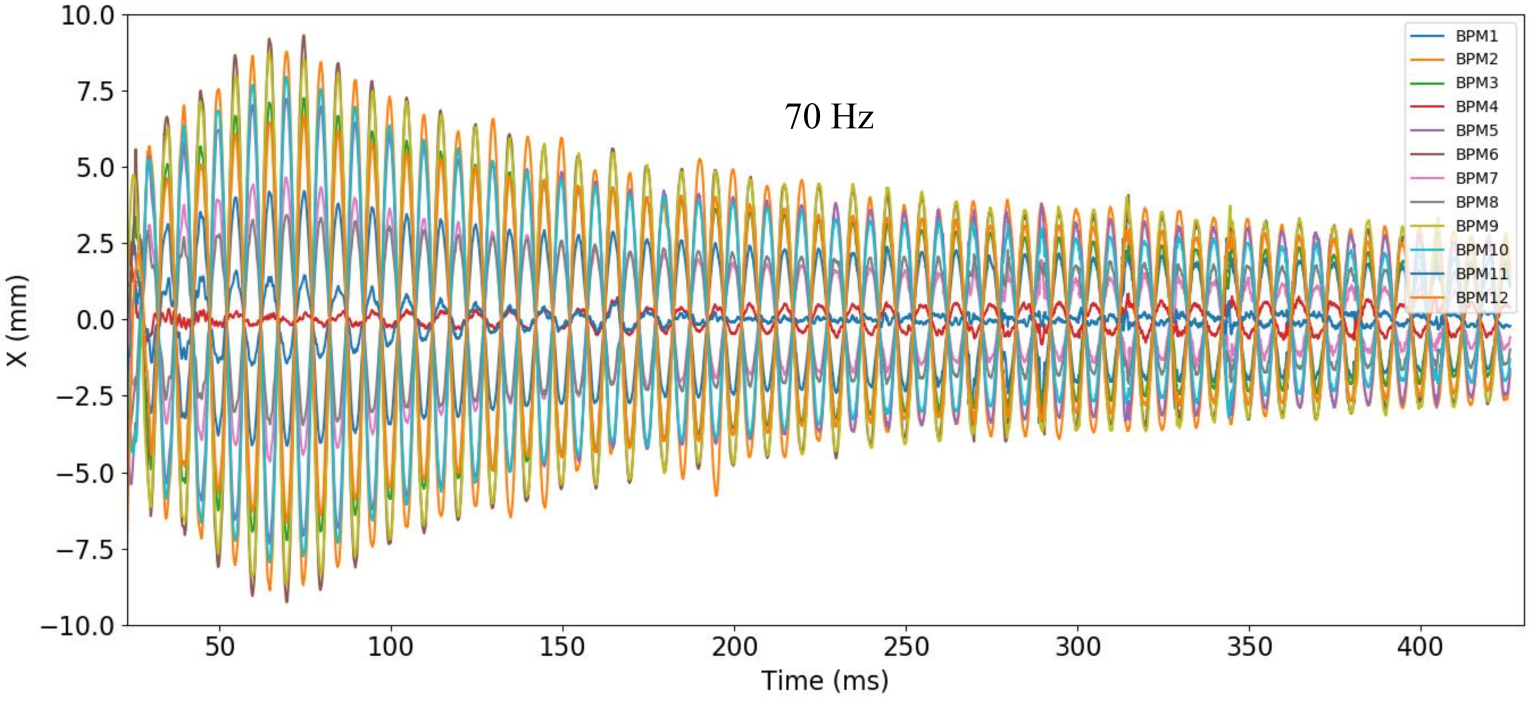
- ❖ The BPM data is averaged over 100 µs (10 kHz) to obtain the orbit
- ❖ Data is shared between all Liberas and is grouped in GDX module to form closed orbit vector of size 12 in SIS-18 (84 in SIS-100)
- ❖ Controller is implemented in FPGA of the GDX module
- ❖ A "waveform generator" mode is also implemented in SER module for ORM measurements

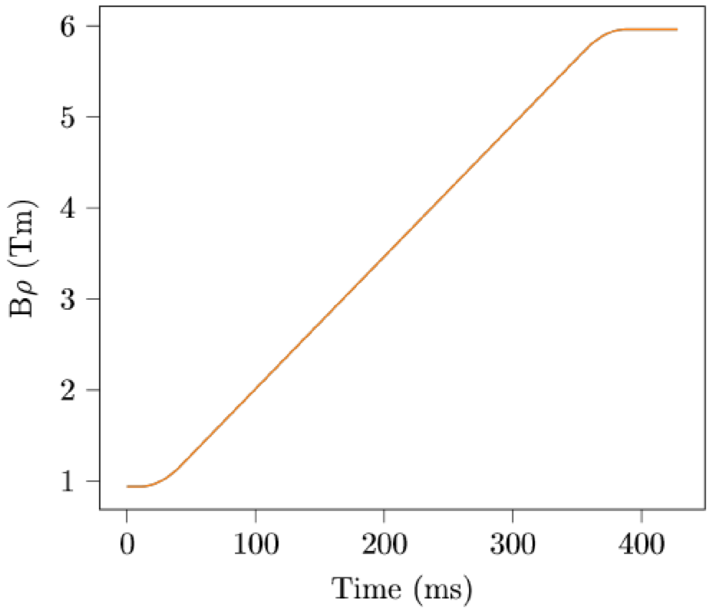
- ❖ Two buffers are implemented for the online ORM and controller parameters update with 20-50 Hz update rate
- ❖ The golden orbit and rigidity can be updated at the 10 kHz calculation rate

R. Singh et al., First beam-based tests of fast closed orbit feedback system at GSI SIS18, in Proceedings of the 6th Beam Instrumentation Conference (IBIC 2019), Malmo, Sweden, 2019

Model mismatch over SIS18 acceleration ramp

Beam: $^{40}Ar^{+18}$ **Number of particles:** 1.0E8 **Injection Energy:** 11 MeV/u **Extraction energy:** 300 MeV/u



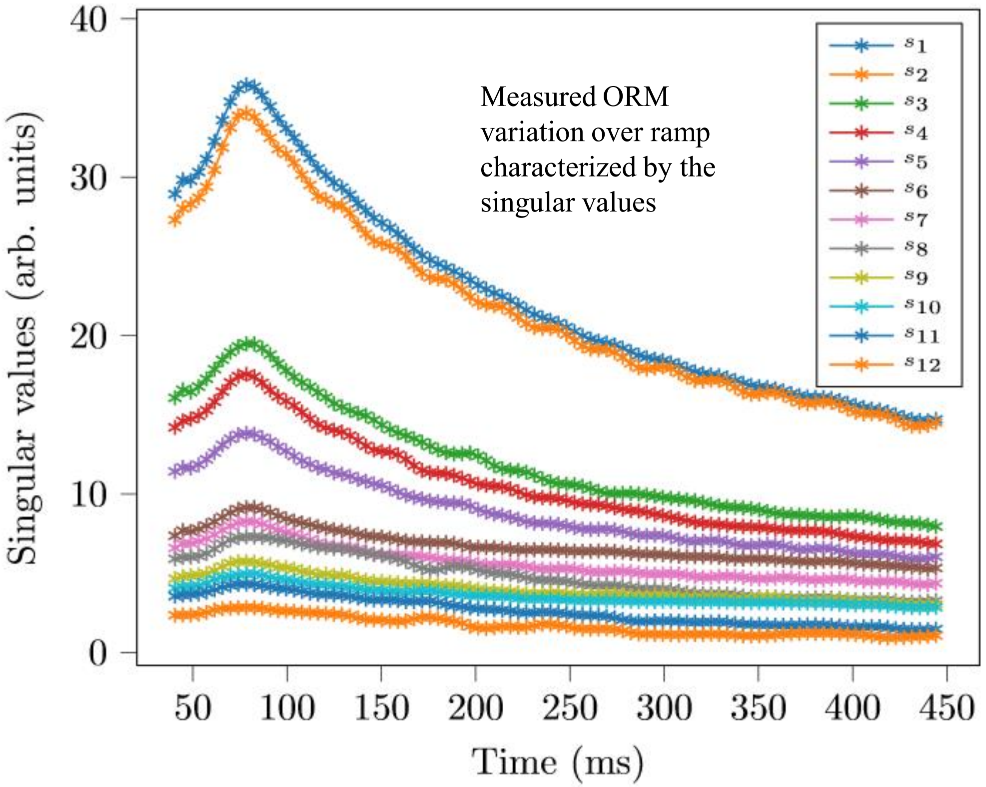


- The waveform generator implemented in SER module of Libera hardware was used for the excitation of the beam through all steerers one by one for ORM measurement
- Excitation of 70 Hz and amplitude corresponding to 1 mrad was applied and the resultant response was normalized with the beam rigidity (right figure)
- This method of ORM measurement is robust to any BPM offsets as well as provides the ORM change during the ramp
- A change in the response of the closed orbit over the ramp can be seen.

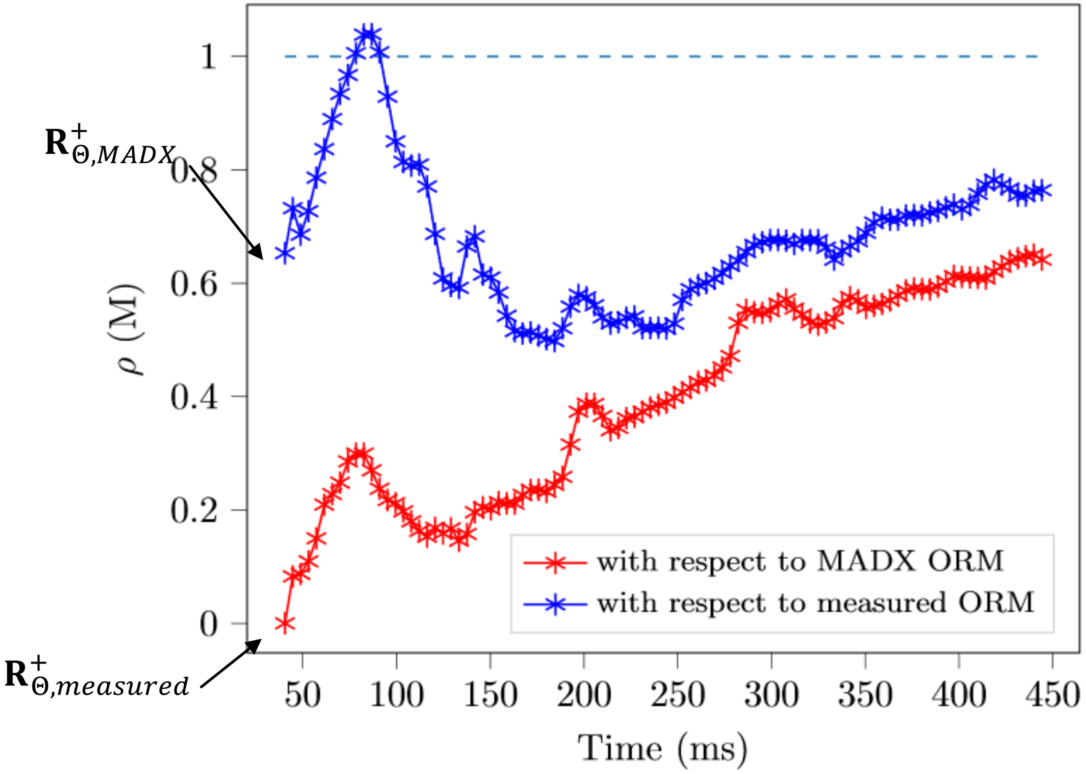
Measurement of model mismatch over ramp for SIS18

Beam: $^{40}Ar^{+18}$ **Number of particles:** 1.0E8 **Injection Energy:** 11 MeV/u **Extraction energy:** 300 MeV/u

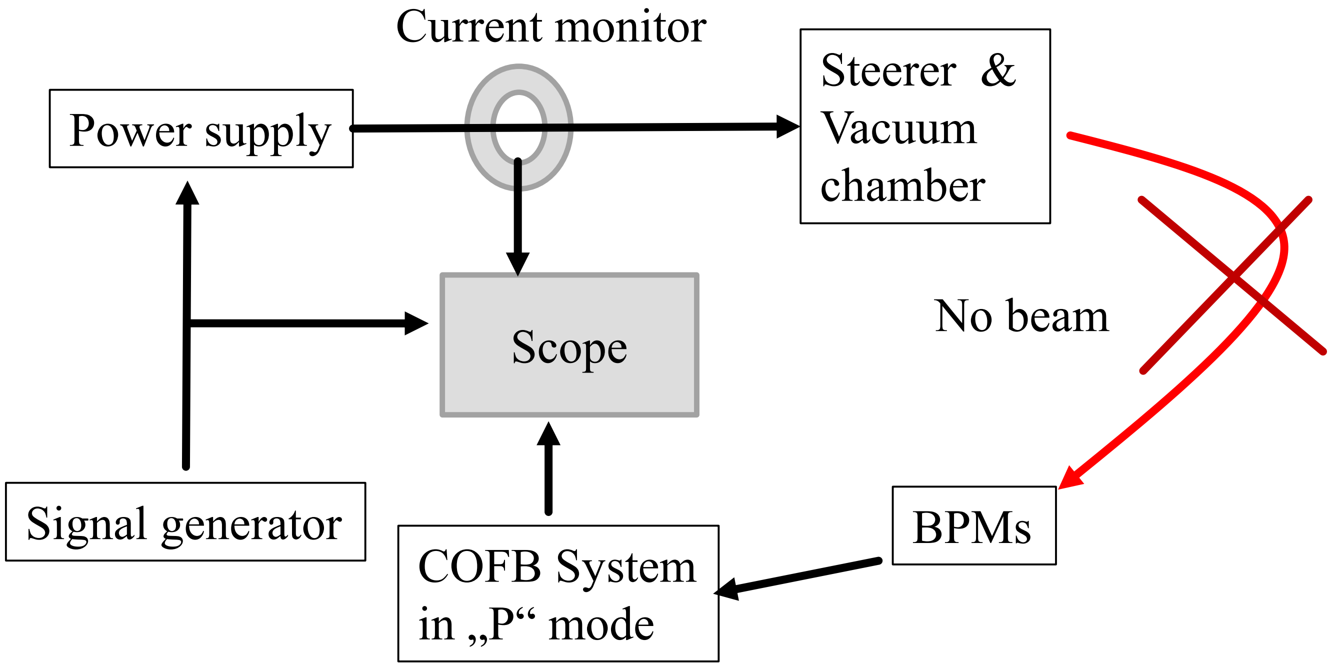
The variation of the highest singular value of the measured ORM over the ramp

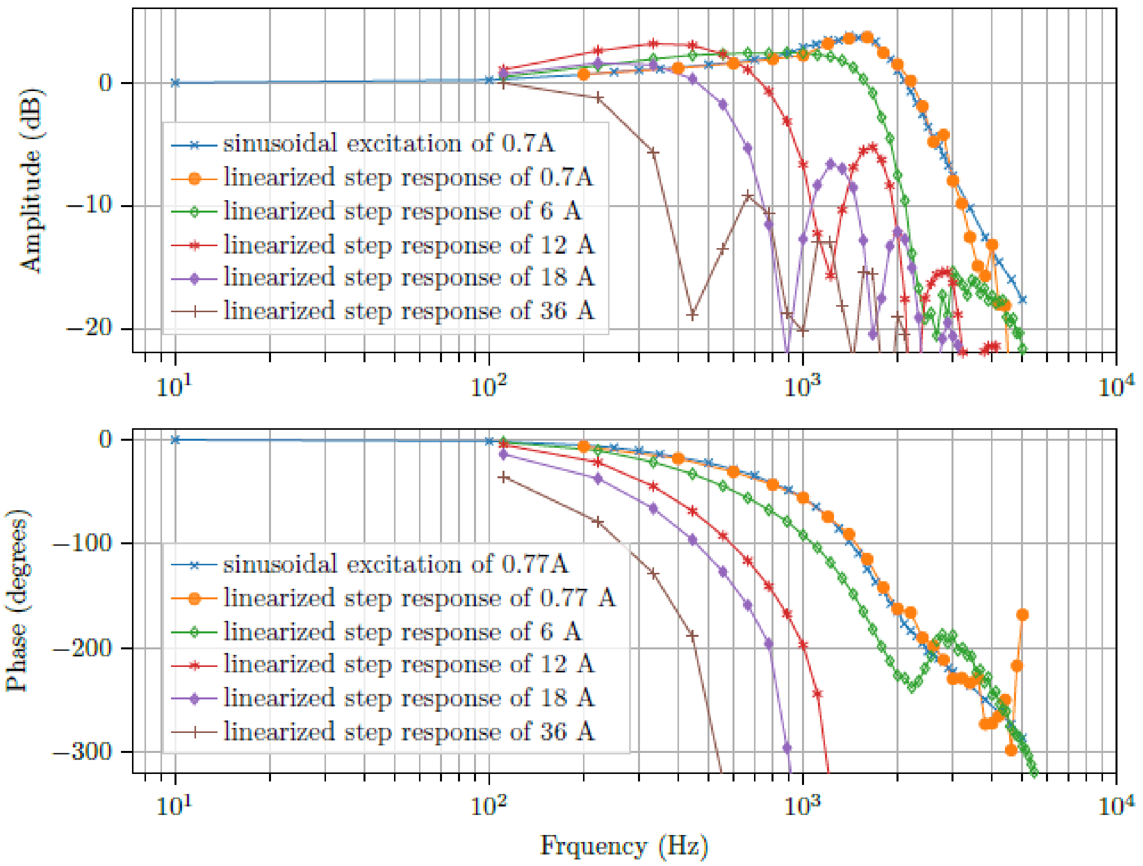


The spectral radius of the correction matrix i.e. $\boldsymbol{\rho}(\mathbf{M}) = \boldsymbol{\rho}(\mathbf{I} - \mathbf{R}(\mathbf{t})\mathbf{R}^{+}_{\Theta,injection})$ with respect to injection ORM for both MADX model ORMs and measured ORMs and → Significant discrepancy



Temporal system identification: transfer function measurement





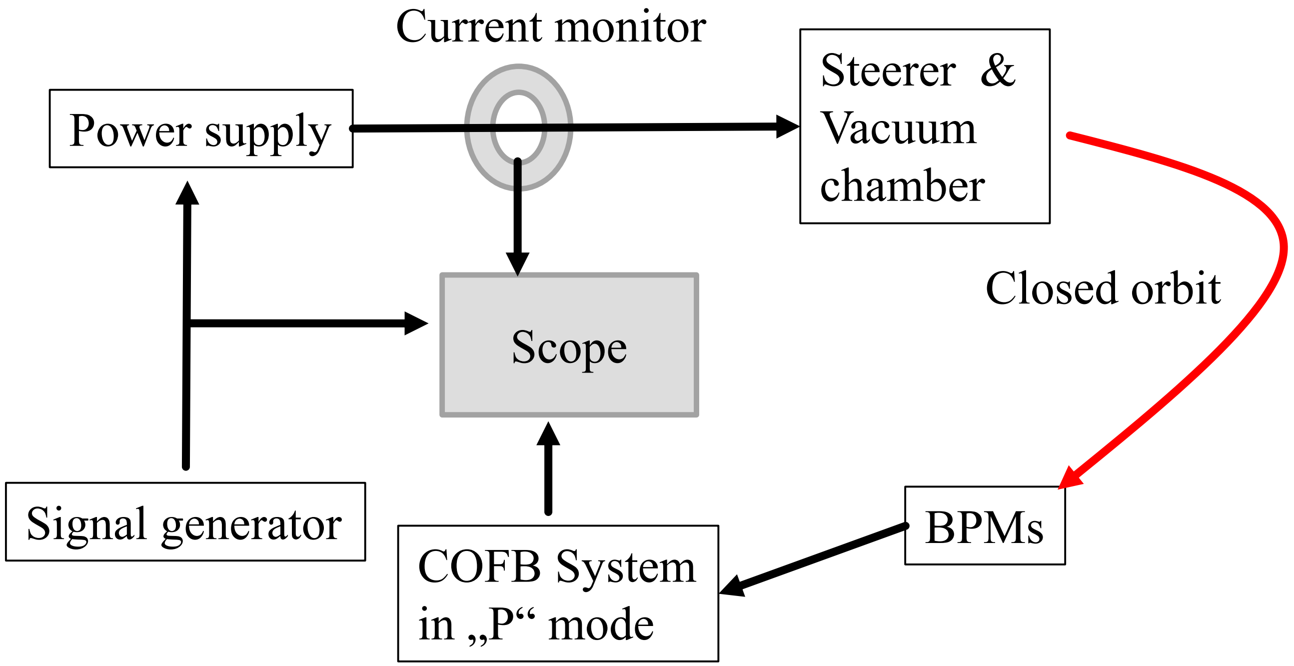
- ➢ Signal Generator, Scope, COFB system are triggered with the same signal
- ➢ Steerer & power supply frequency response measured with sinusoidal input and step input with several amplitudes

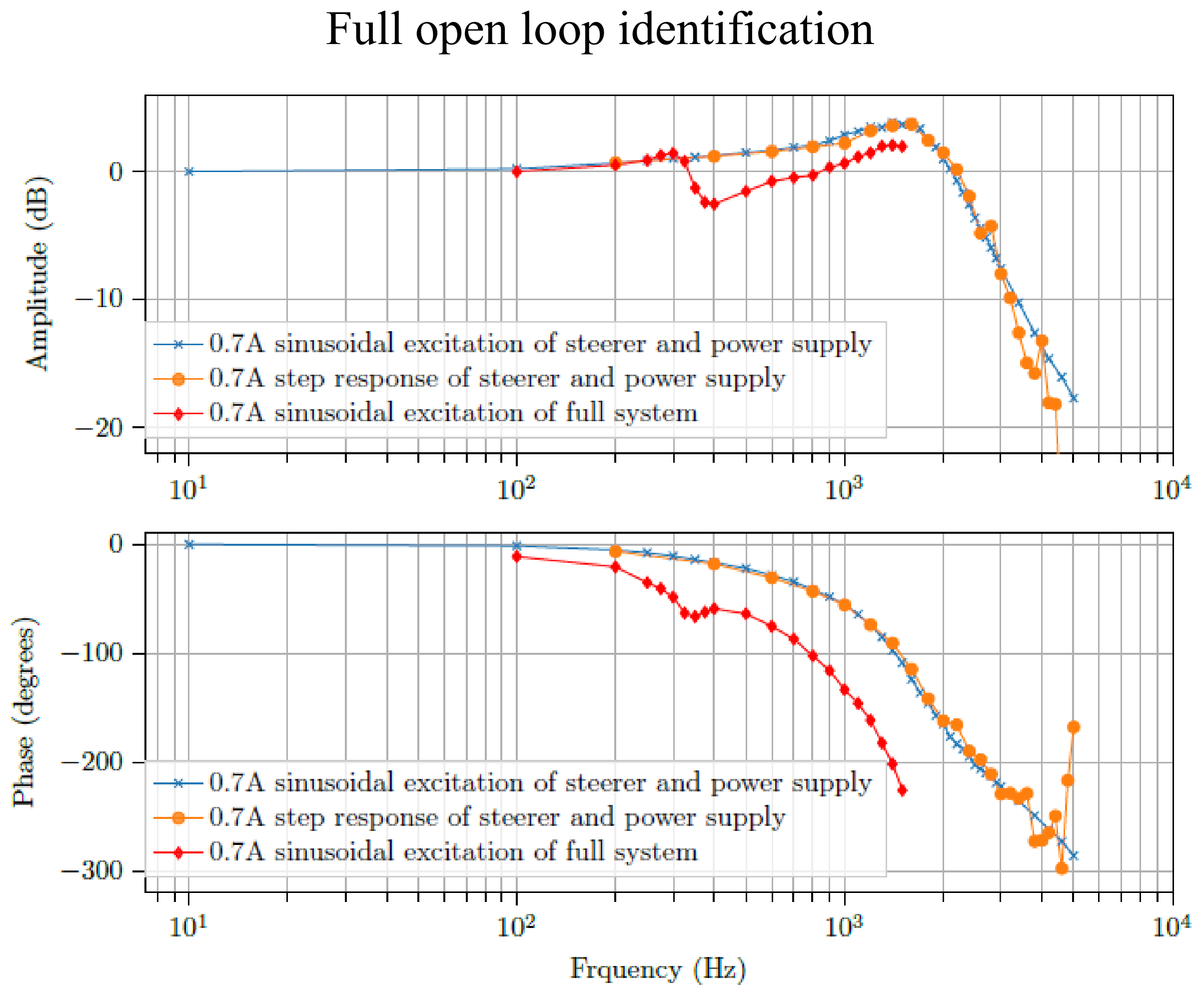
→ Amplitude frequency dependence (Slew rate)

- ➢ BPM response → 3-5 kHz bandwidth for orbit data

A. Reiter and R. Singh, Comparison of beam position calculation methods for application in digital acquisition systems, Nuclear Inst. and Methods in Physics Research, A, Volume 890, p. 18-27.

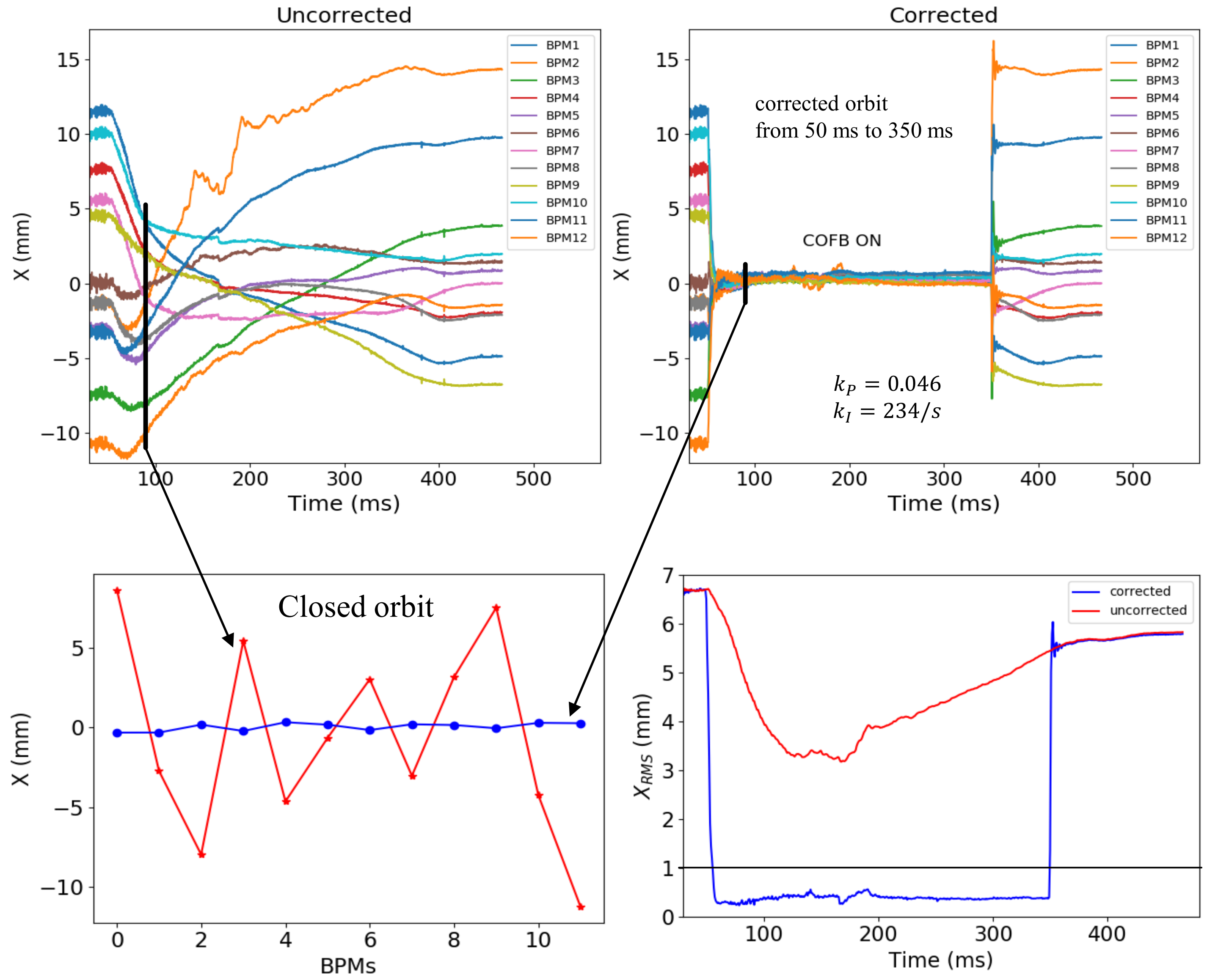
Temporal system identification: transfer function measurement





- The “full system” open loop response included in the loop are steerer power supply, magnet, vacuum chamber, BPMs and Libera hardware modules
- Measurement were done for injection energy and settings corresponding to lower currents
- Direct comparison between input and output signals were in “steerer space”
- Some steerers were found to have different dynamics which pose extra complexity for evaluating the COFB system and achievable bandwidth

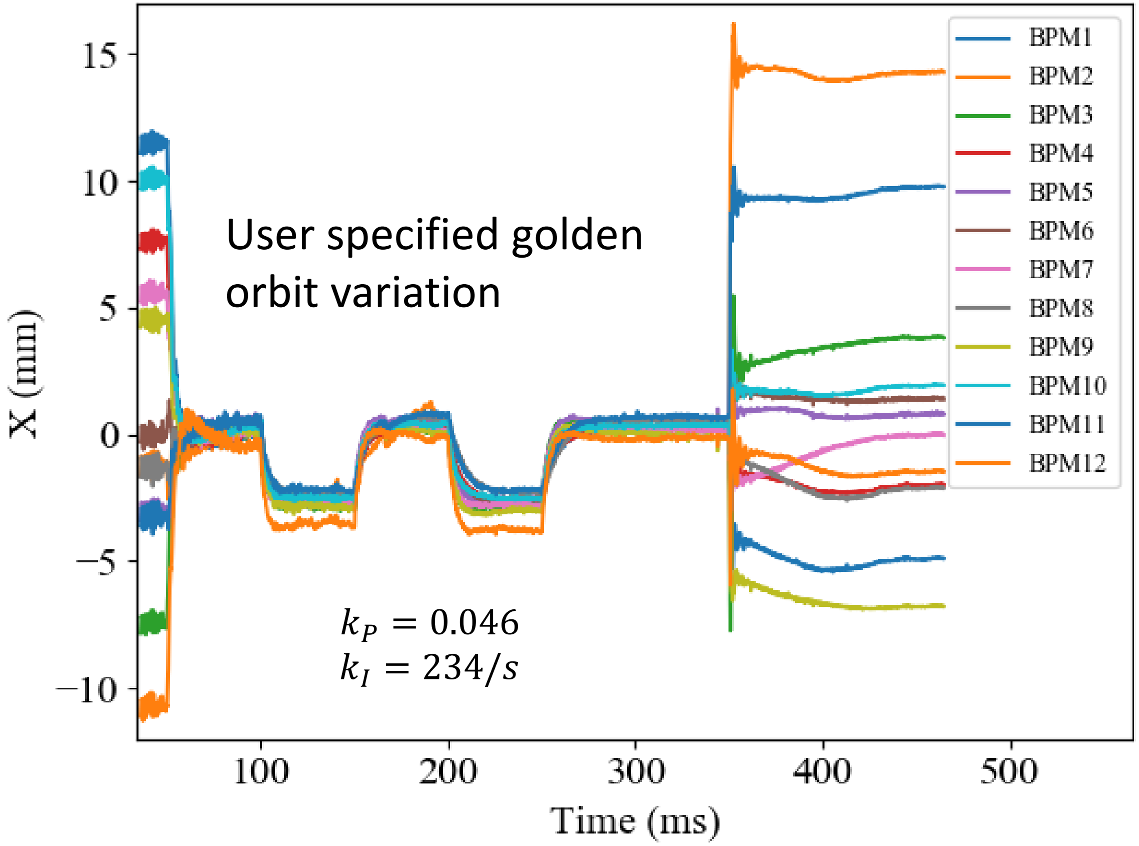
First results: On-ramp orbit correction in SIS18



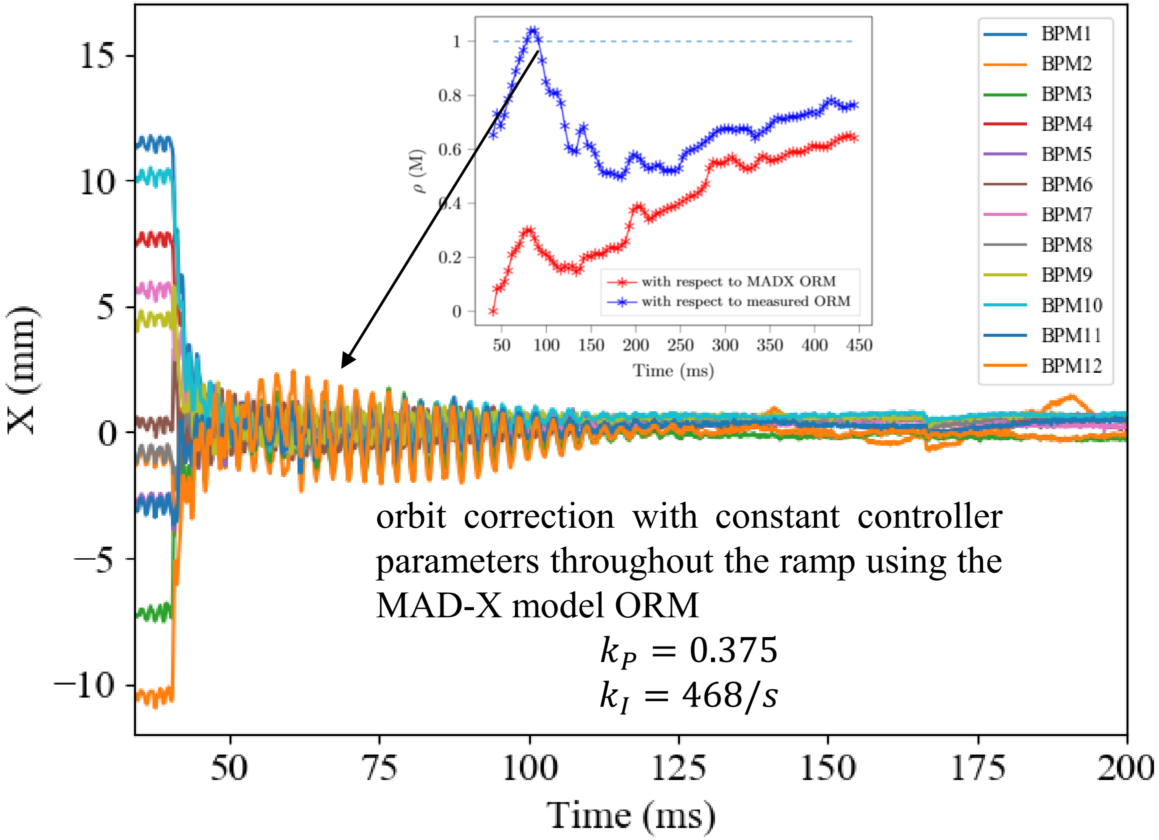
- ❖ First attempt of on-ramp orbit correction for the full ramp with the injection ORM.
- ❖ Controller values were very conservative.
- ❖ The typical criterion of RMS orbit < 10% of the beam size was achieved. The closed orbit RMS in horizontal plane was reduced to below 1 mm. Correction up to 300 Hz was achieved.

First results: Changing reference orbit and stability

A new feature of piecewise variation of Golden orbit over the ramp is implemented in COFB algorithm.
A maximum of 64 different Golden orbits can be adjusted for one ramp.



Model mismatch puts an upper limit on the controller parameters as $k_p(z) = k_{(\rho=0)}(z)[1 - \rho(\mathrm{M})]$ to avoid COFB instability. The model mismatch-induced oscillations are shown below when the controller parameters are not scaled with model mismatch



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Summary

- A closed orbit feedback system with 10 kHz correction rate has been commissioned for SIS18 with focus on robustness. The Libera Hadron PlatformB is used for the controller implementation as well as the beam positon calculation and processing.
- Some theoretical investigations were performed:
  - The spectral radius as a practical condition for COFB instability was introduced; relevant for machines with unavoidable model mismatch
  - The achievable bandwidth of the COFB reduces with increase in spatial model mismatch. Controller parameters need to be tuned according to model mismatch.
- “Single shot” ORM over the full acceleration ramp is measured and the model mismatch was measured with respect to the known injection ORM.
- Orbit correction is performed over the ramp and the closed orbit RMS below 1 mm (@10 KHz) is achieved.
- A deterioration in closed orbit stability and performance in presence of model mismatch is demonstrated with beam experiments in SIS18.
- The nominal controller parameters derived from steerer frequency response can be too aggressive in presence of model mismatch and slew rate dependence.

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Thank you!