NSLS-II Fast Orbit Feedback with Individual Eigenmode Compensation

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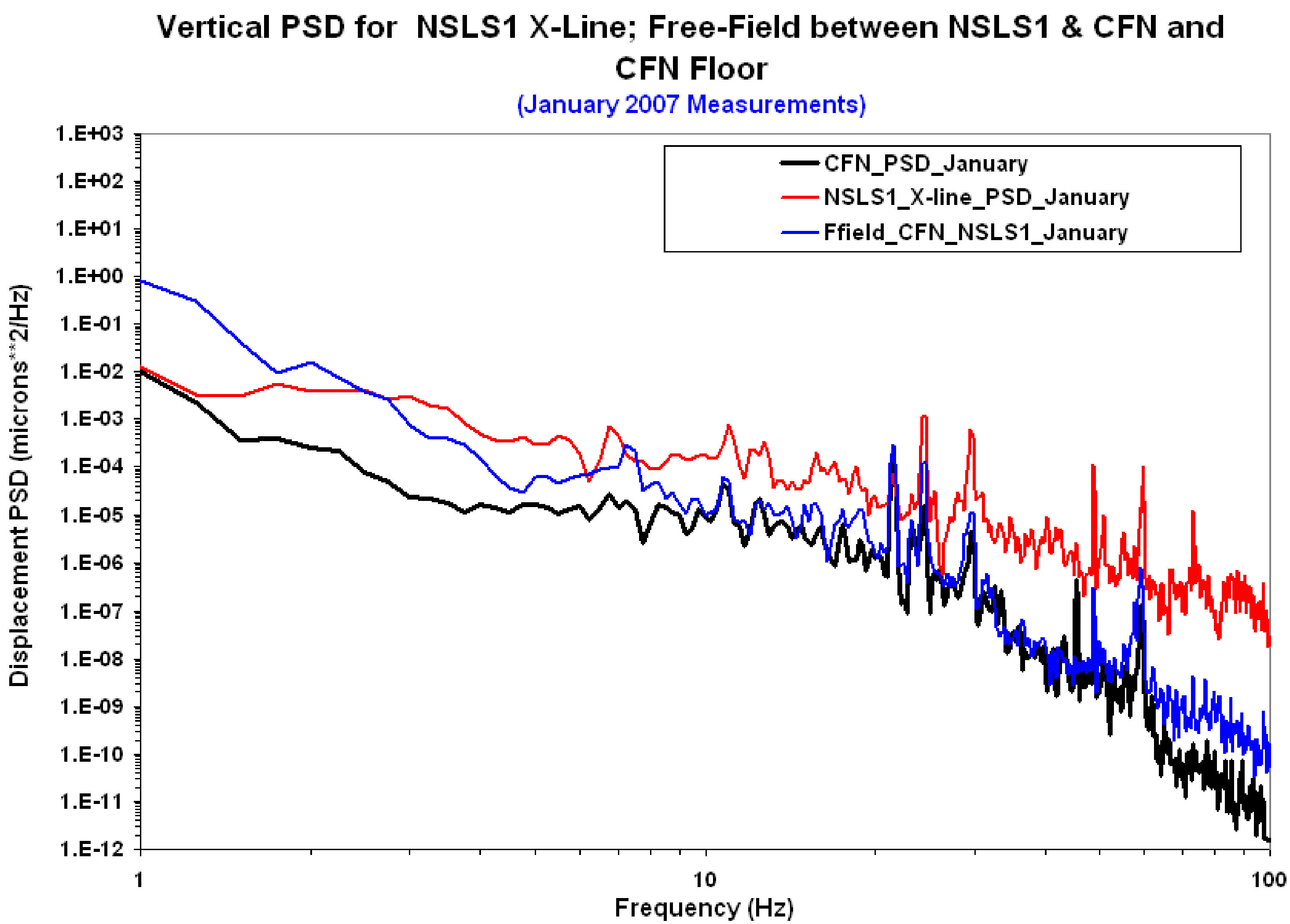
Outline

- NSLS-II orbit feedback system
  - Technical requirements and specifications
  - NSLS-II site field vibration measurement
  - Slow and fast corrector locations
- Fast orbit feedback with individual eigenmode compensation
  - Typical fast orbit feedback algorithm
  - NSLS-II FOFB algorithm with individual eigenmode compensation
  - Comparison of the two algorithms
  - Solving the calculation problems from two directions
- NSLS-II fast orbit feedback implementation
- Summary

NSLS-II technical requirements & specifications

Energy	3.0 GeV	Energy Spread	0.094%
Circumference	792 m	RF Frequency	500 MHz
Number of Periods	30 DBA	Harmonic Number	1320
Length Long Straights	6.6 & 9.3m	RF Bucket Height	>2.5%
Emittance (h,v)	<1nm, 0.008nm	RMS Bunch Length	15ps-30ps
Momentum Compaction	.00037	Average Current	300ma (500ma)
Dipole Bend Radius	25m	Current per Bunch	0.5ma
Energy Loss per Turn	<2MeV	Charge per Bunch	1.2nC
		Touschek Lifetime	>3hrs

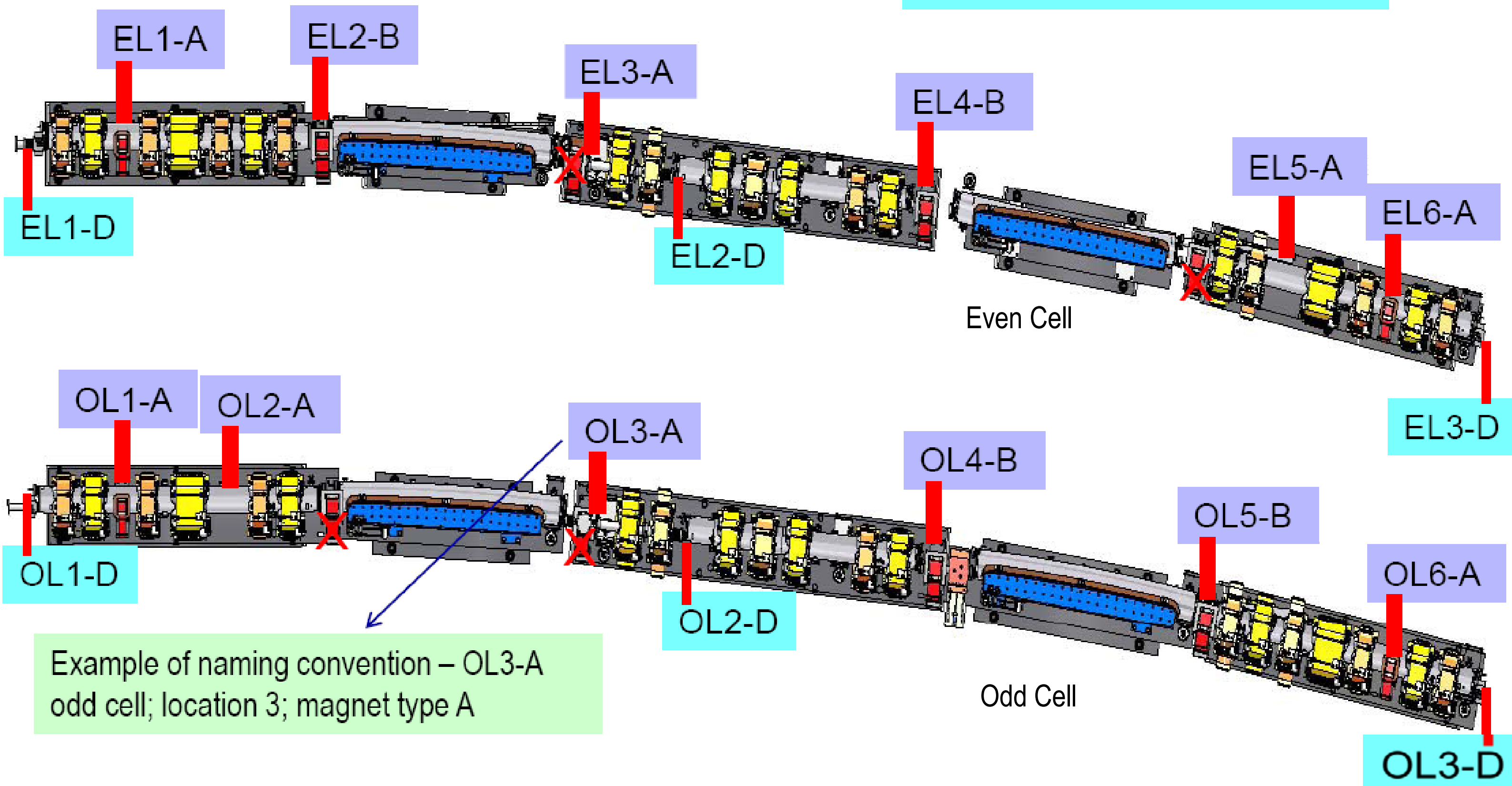
NSLS-II site field vibration measurement



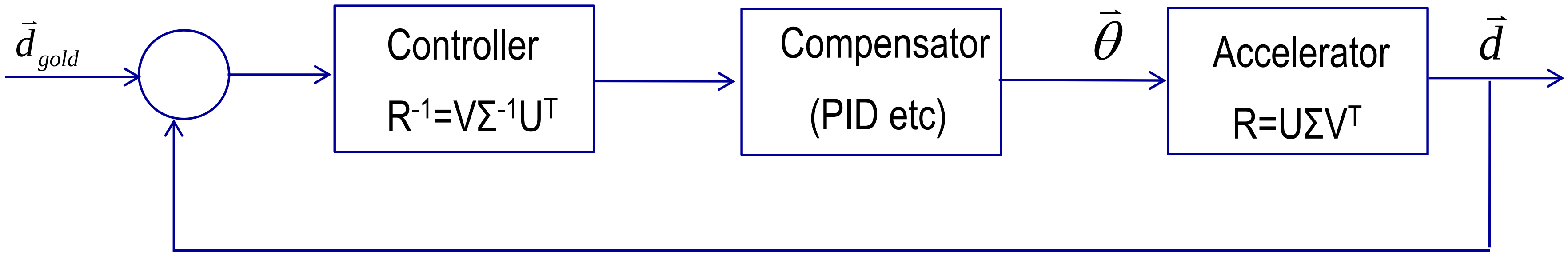
Slow and fast corrector locations

- A & B – Slow corrector; FS DC strength = 800 microrad
- A -100 mm Aperture (qty=8);
- B – 156 mm Aperture (qty=4); mounted over bellows

- D – Air core fast correctors; qty=6
- Mounted Over SS chamber
- FS DC Strength = 10-15 microrad
- Combined DC/AC function



Typical fast orbit feedback algorithm



$$R_{MxN} \bullet \theta_{Nx1} = d_{Mx1}$$

R: response matrix

$$\theta_{Nx1} = R^{-1}{}_{NxM} \bullet d_{Mx1}$$

R^{-1}: reverse response matrix

The ill-conditioned response matrix will cause numerical instability.

Solution: 1) Truncated SVD (TSVD) regularization
2) Tikhonov regularization

Typical fast orbit feedback algorithm

$$R^{-1} = VD\Sigma^{-1}U^{T} = [\tau_1, \tau_2, \ldots \tau_N] \begin{bmatrix} \frac{1}{\sigma_1}\cdot\frac{\sigma_1^{\,2}}{\sigma_1^{\,2}+\alpha} & & & \\ & \frac{1}{\sigma_2}\cdot\frac{\sigma_2^{\,2}}{\sigma_2^{\,2}+\alpha} & & \\ . & . & . & . \\ & & & \frac{1}{\sigma_N}\cdot\frac{\sigma_N^{\,2}}{\sigma_N^{\,2}+\alpha} \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \\ . \\ \delta_N \end{bmatrix}$$

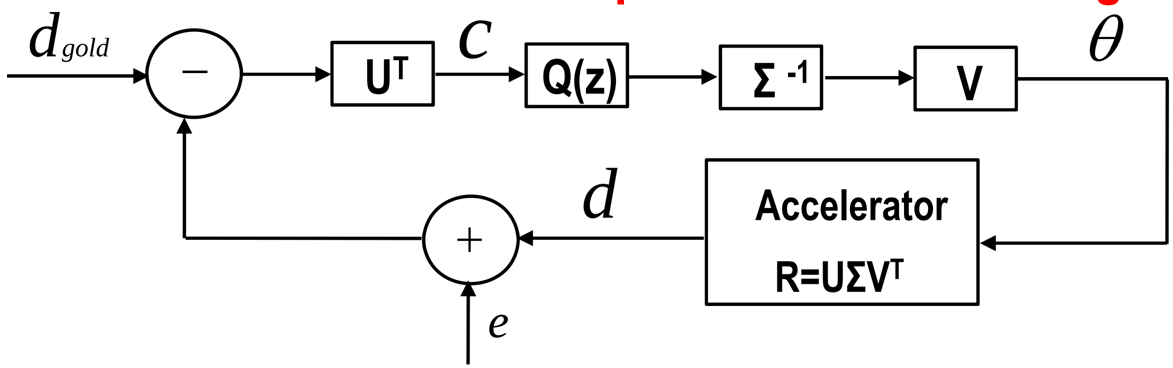
$$\theta_{Nx1} = R^{-1}{}_{NxM} \bullet d_{Mx1} \xrightarrow{\text{For each corrector plane}} \theta_i = R^{-1}{}_{i^{th}row} \bullet d_{Mx1}$$

Each of the corrector setpoint is calculated from a 1xM vector and Mx1 vector multiplication. If 8 BPM/cell in NSLS-II, M=240. Total: ~240 MAC.

NSLS-II FOFB algorithm – compensation for each eigenmode

- Fast orbit feedback system is a typical multiple-input and multiple-output (MIMO) system. For NSLS-II, there are 240 BPMs and 90 fast correctors. The BPMs and correctors are coupled together. One BPM reading is the results of many correctors. One corrector kick can also affect many BPM readings. It is difficult to design a compensator for all noises with different frequencies.
- It is desirable if we can decouple the BPM and corrector relationship so that the MIMO problem can be converted into many single input single output (SISO) problems, for which control theory has many standard treatments.
- Fortunately, SVD already provides a solution: it projects the BPMs input into the eigenspace, where each component is independent. We can design many SISO type compensators (one for each eigenmode) and apply the standard SISO control theory to treat each eigenmode problem in frequency domain without affecting other eigenmodes.

NSLS-II FOFB calculation – compensation for each eigenmode



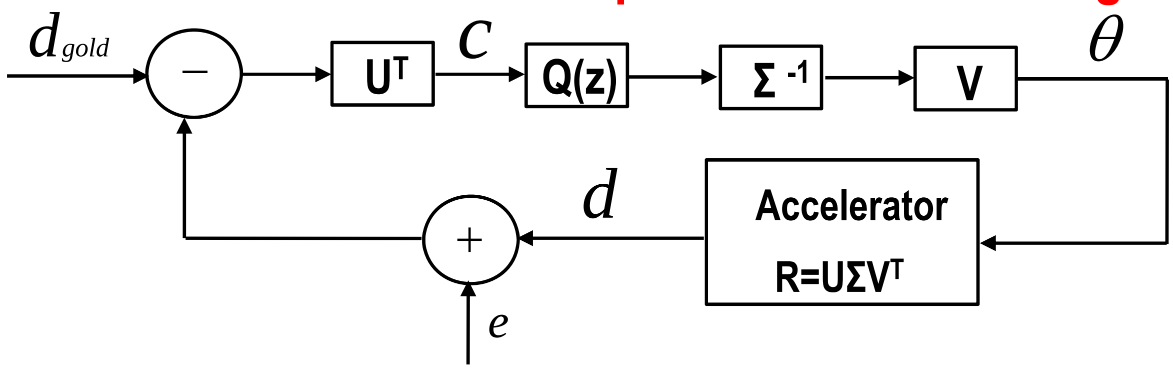
$$Q(z) = \begin{bmatrix} Q_1(z) & 0 & 0 & 0 \\ 0 & Q_2(z) & 0 & 0 \\ . & . & . & . \\ 0 & 0 & 0 & Q_N(z) \end{bmatrix}$$

c_1, c_2, …, c_N is the input projections in the eigenspace.

$Q_1(z)$, $Q_2(z)$, …, $Q_N(z)$ is the compensator for each eigenmode.

We want to prove that $Q_1(z)$, $Q_2(z)$, …, $Q_N(z)$ only corrects the corresponding eigenmode in eigenspace without affecting other eigenmodes.

NSLS-II FOFB calculation – compensation for each eigenmode



In cycle n,

$$c(n) = U^T(d(n) + e(n)) \qquad \theta(n) = V\Sigma^{-1}Q(z)c(n)$$

$$d(n+1) = U\Sigma V^T(V\Sigma^{-1}Q(z)c(n)) + e(n+1)$$

Since, $VV^T = V^TV = I \qquad U^TU = I$

$$d(n+1) = UQ(z)c(n) + e(n+1) \qquad c(n+1) = U^T d(n+1) = Q(z)c(n) + U^T e(n+1)$$

$$\begin{bmatrix} c_1(n+1) \\ c_2(n+1) \\ \cdots\cdot \\ c_N(n+1) \end{bmatrix} = \begin{bmatrix} Q_1(z) & 0 & 0 & 0 \\ 0 & Q_2(z) & 0 & 0 \\ . & . & . & . \\ 0 & 0 & 0 & Q_N(z) \end{bmatrix} \begin{bmatrix} c_1(n) \\ c_2(n) \\ \cdots\cdot \\ c_N(n) \end{bmatrix} + U^T e(n+1)$$

The pure effect of Qi(z) is on the ith eigencomponent.

The noise signals are also decoupled into the eigenspace.

This gives us freedom to suppress the noises in eigenspace using SISO control theory.

Decpoupling or not ? Calculation compare

Without decoupling:

$$\theta_{Nx1} = Q(z)R^{-1}{}_{NxM} \bullet d_{Mx1}$$

For each corrector plane, M multiplication and accumulation(MAC), followed by k MAC for corrections.

Calculation (one plane): One corrector : M+k N correctors: N*(M+k)

With decoupling:

$$c(n) = U^T(d(n) + e(n))$$

It takes NxM MAC to decouple the inputs into eigenspace.

$$\theta(n) = V\Sigma^{-1}Q(z)c(n)$$

It takes N*k MAC for N compensators in each eigenmode. It takes N*N to get one corrector strength.
Calculation (one plane): One corrector: N*(M+N+k) N correctors: N*N*(M+N+k)

Assume N=90, M=240, k=3:

Calculation Amount	Without Decouping	With Decouping
One corrector strength (one plane)	M+k =243	N(M+N+k)= 29970
90 corrector strength (one plane)	N(M+k) = 21870	N*N*(M+N+k) = 2697300

Assume 50us of 10Khz FOFB time is used for the caluclations: N*N*(M+N+k)/50us=5.400 GMAC/s.

For doing two plane FOFB in 10us: 5.4*5*2= 54 GMAC/s

The high end DSP chip gives about 200-300 Millions floating point operations (MFLOP).

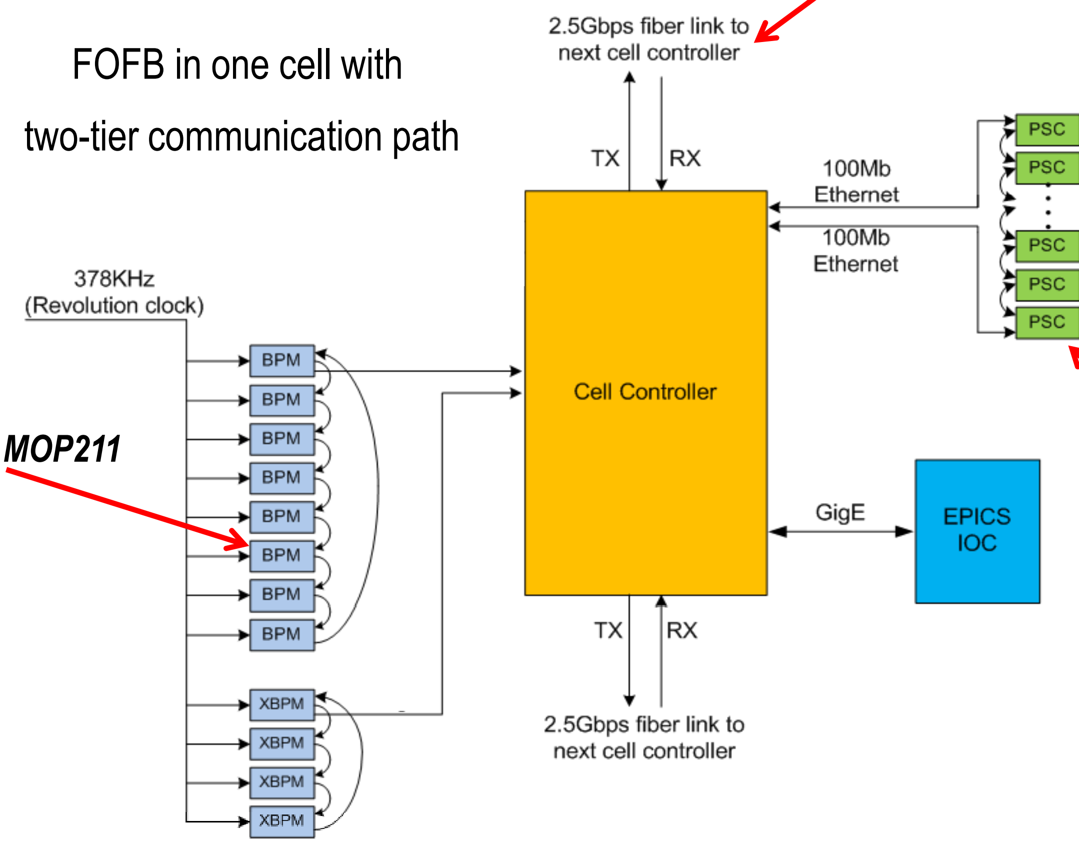
Solving the calculation problems from two directions

Distributed FOFB system:

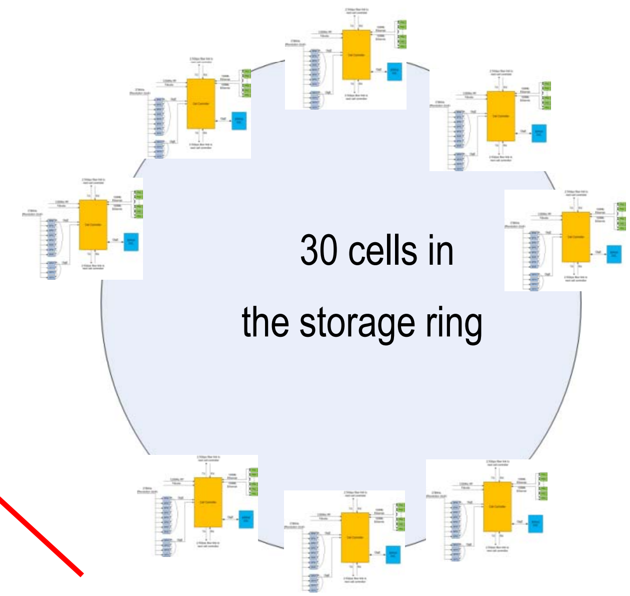
PAC11 MOP196

FOFB in one cell with

two-tier communication path



PAC11 MOP211

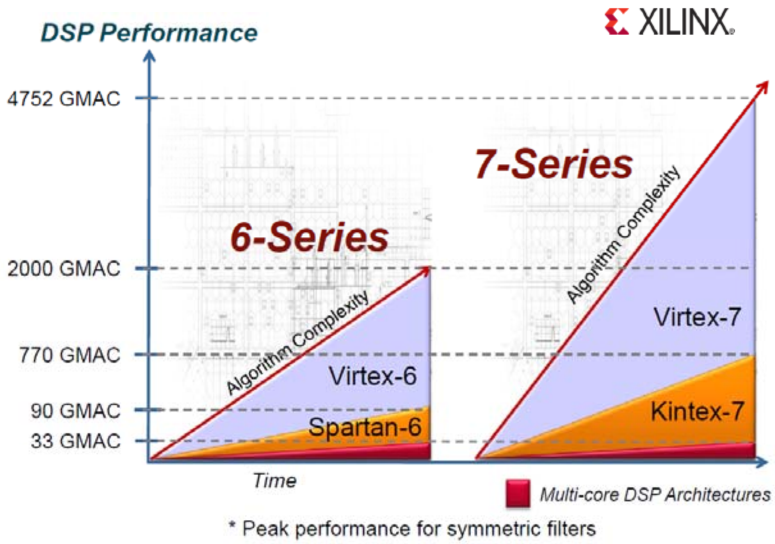


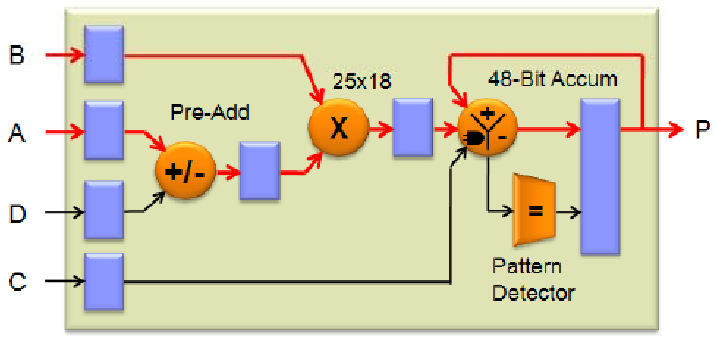
PAC11 TUP193

All the BPM data is delivered to all the 30 cell controller within 12us, cell controller only needs to calculate the local corrector strength. This distributed architecture reduces the calculation by factor of 30.

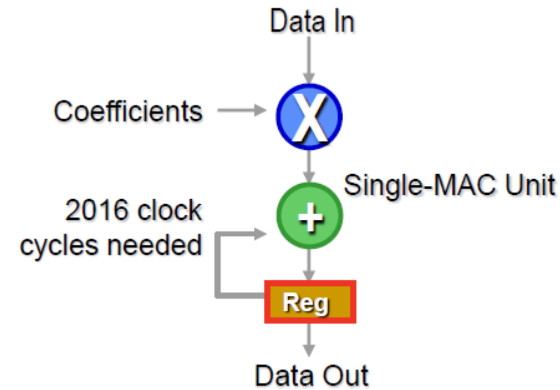
Solving the calculation problems from two directions

FPGA's powerful DSP performance

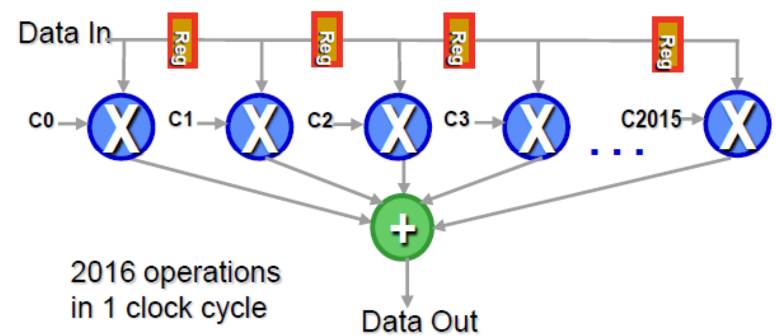




One of the DSP48 block in FPGA



Standard DSP/CPU process: sequential

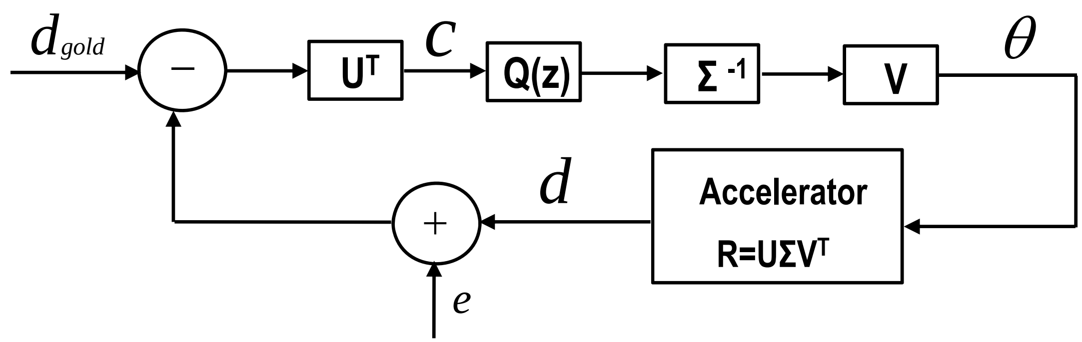


FPGA's fully implementation

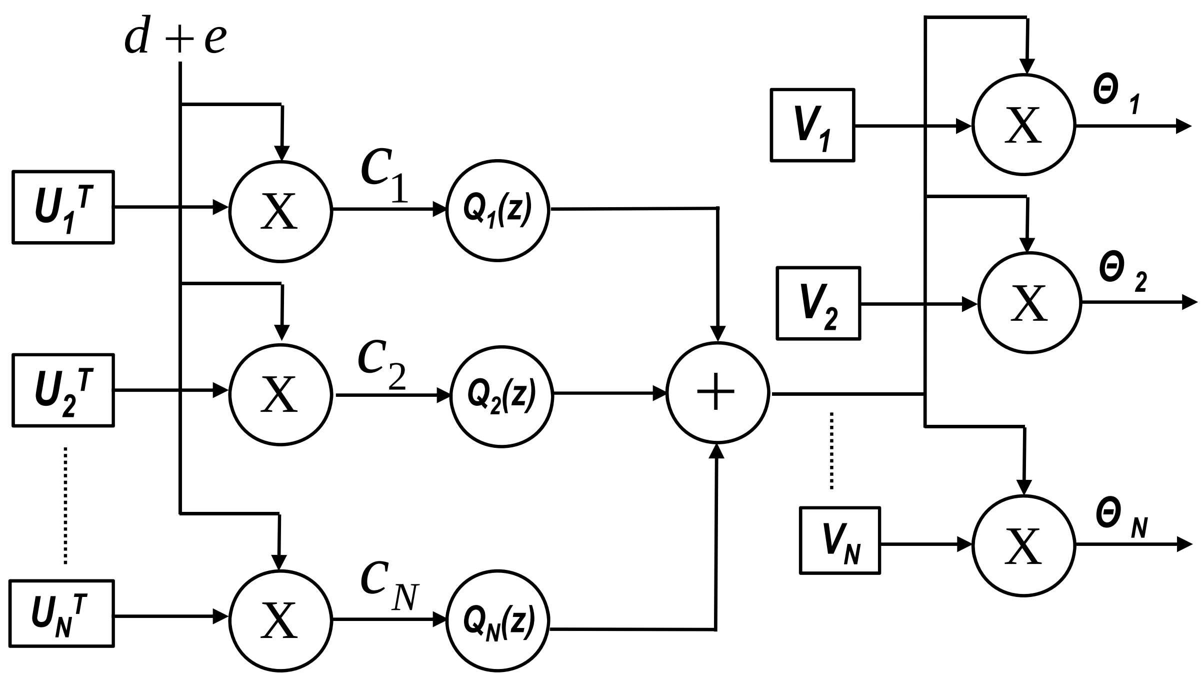
FPGA 's DSP power is mainly gained through the parallel computation capability. The parallelism increases FPGA DSP power (vs genetic DSP or CPU) by a factor of more than 2000 (Virtex 6).

Solving the calculation problems from two directions

FOFB calculate in FPGA:



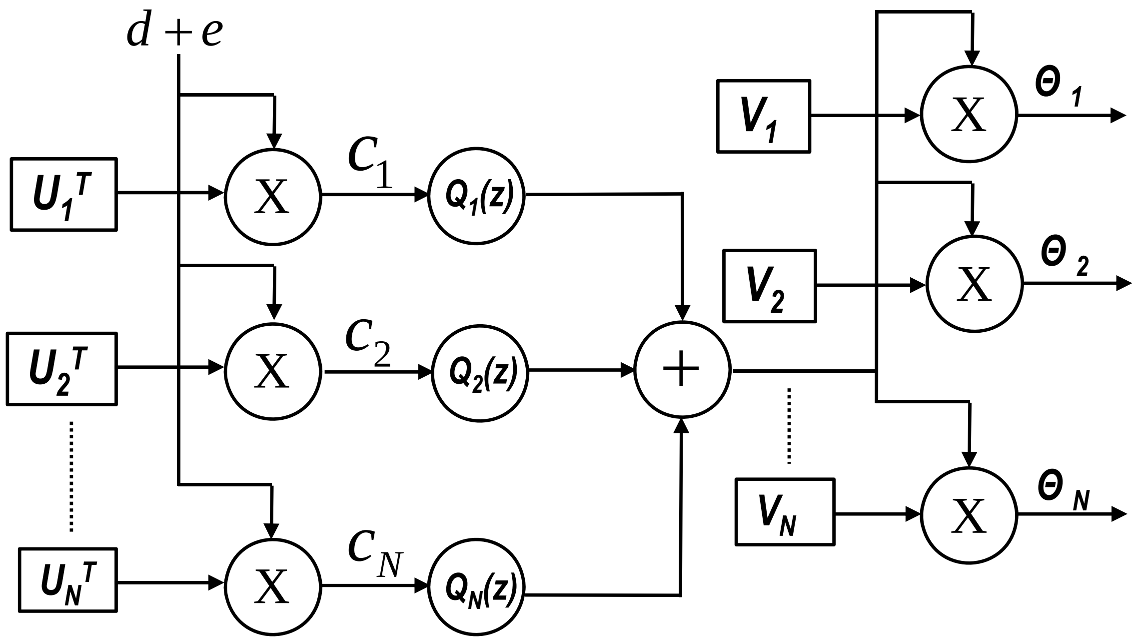
NSLS-II FOFB Model



Implementation of NSLS-II FOFB (diagonal matrix Σ^{-1} is included in Q(z) as gain factors)

Solving the calculation problems from two directions

FOFB calculate amount in FPGA:



Decoupling into eigenspace: $\mathrm{c(n) = U^T (d(n) + e(n))}$

All components $c_1(n)$, $c_2(n)$, …, $c_N(n)$ is calculated in parallel (M MAC)

Compensation for each eigenmode: $\mathrm{Q(z)c(n)}$

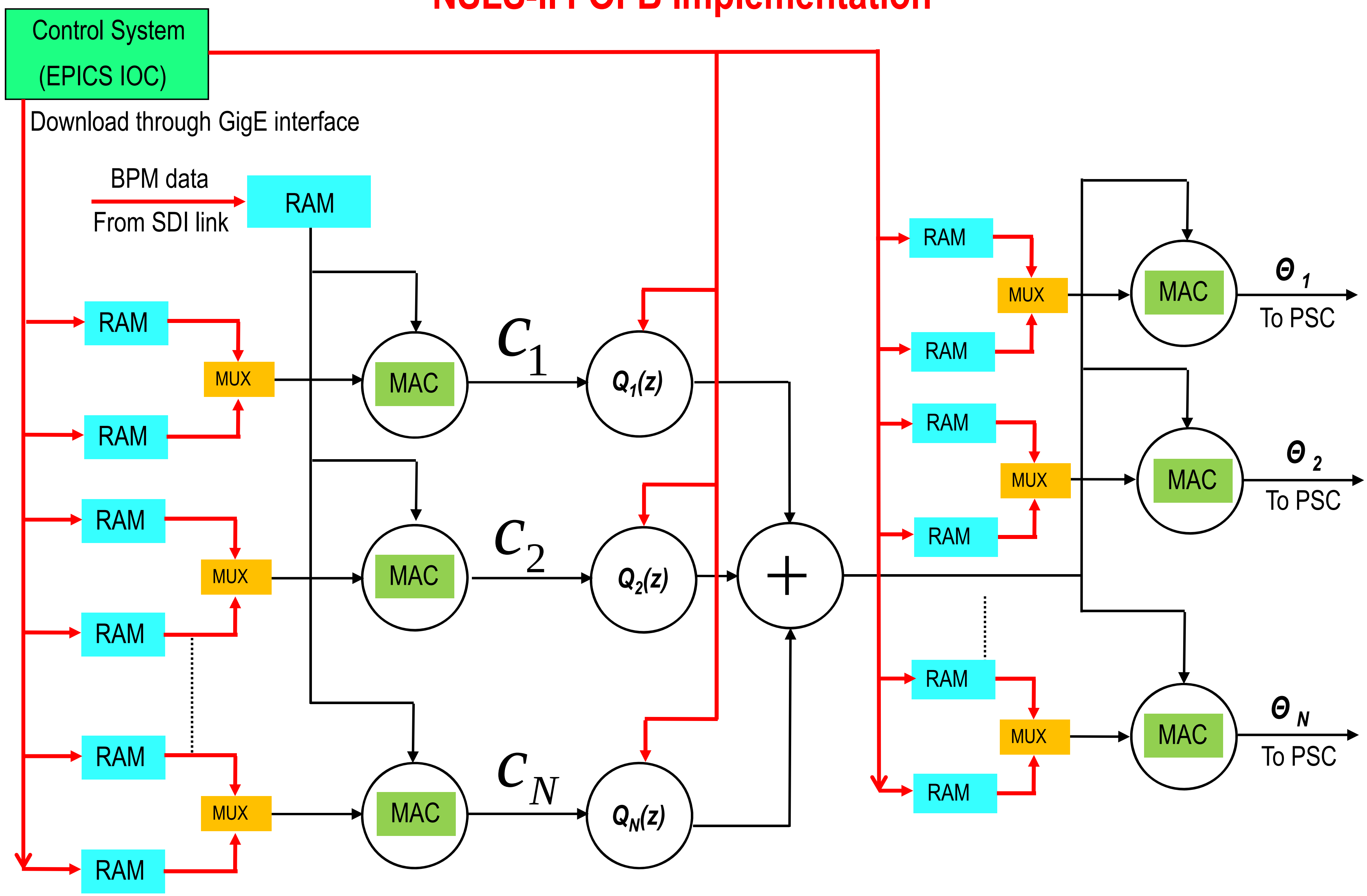
The k step compensations are done in parallel. (k MAC)

Corrector strength calculation: $\theta(n) = \mathrm{V\Sigma^{-1}Q(z)c(n)}$

All corrector strength is calculated in parallel: N MAC

The total calculation is reduced to: M+N+k = 240 + 90 + 3 = 333 MAC. FPGA will finish it within a few us.

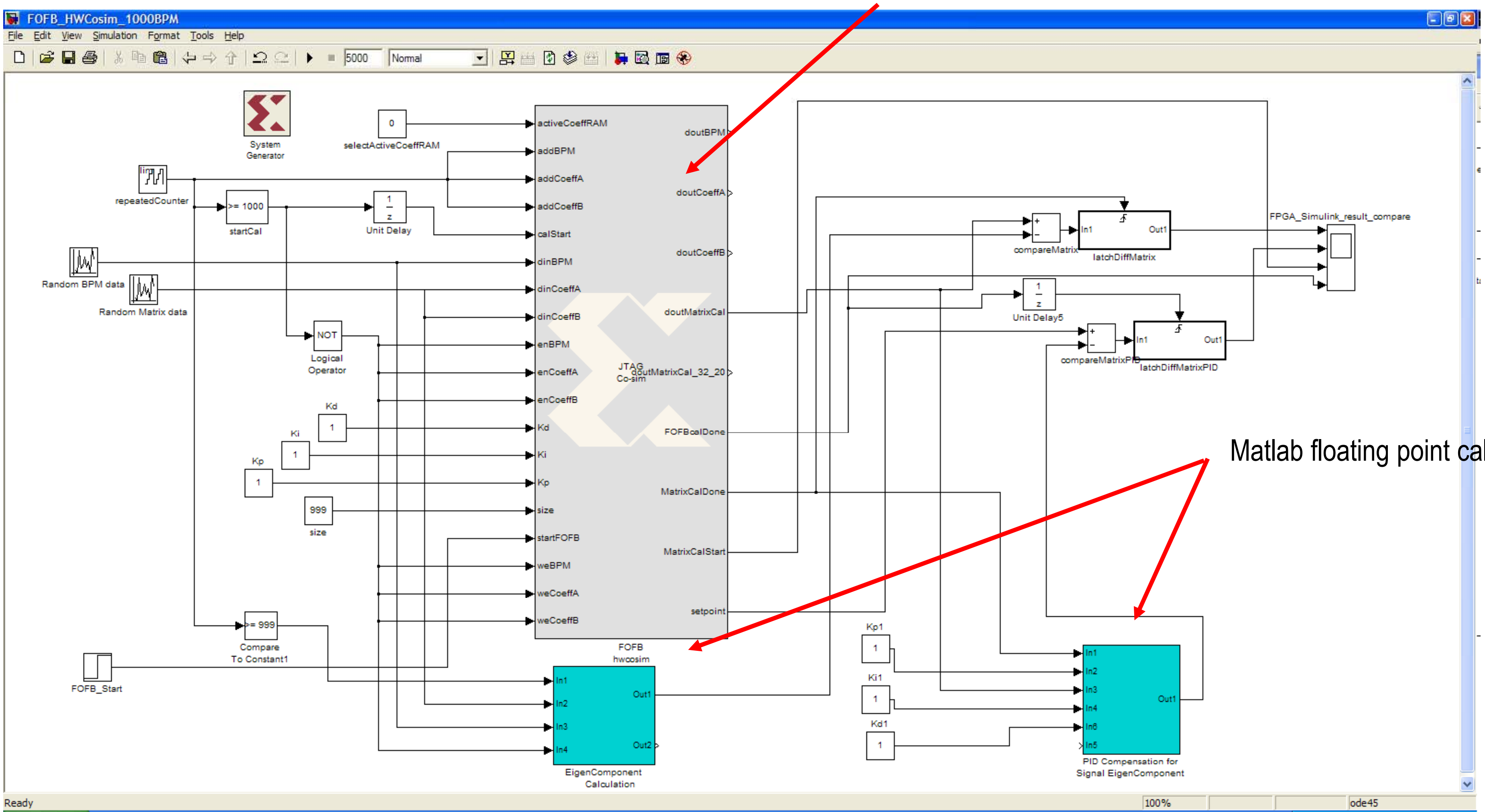
NSLS-II FOFB Implementation



NSLS-II FOFB Implementation

Floating point calculation vs fixed point calculation: FPGA computation is usually fixed point calculation, the quantization errors should be carefully controlled so that the calculation is accurate.

FPGA fixed calculation block

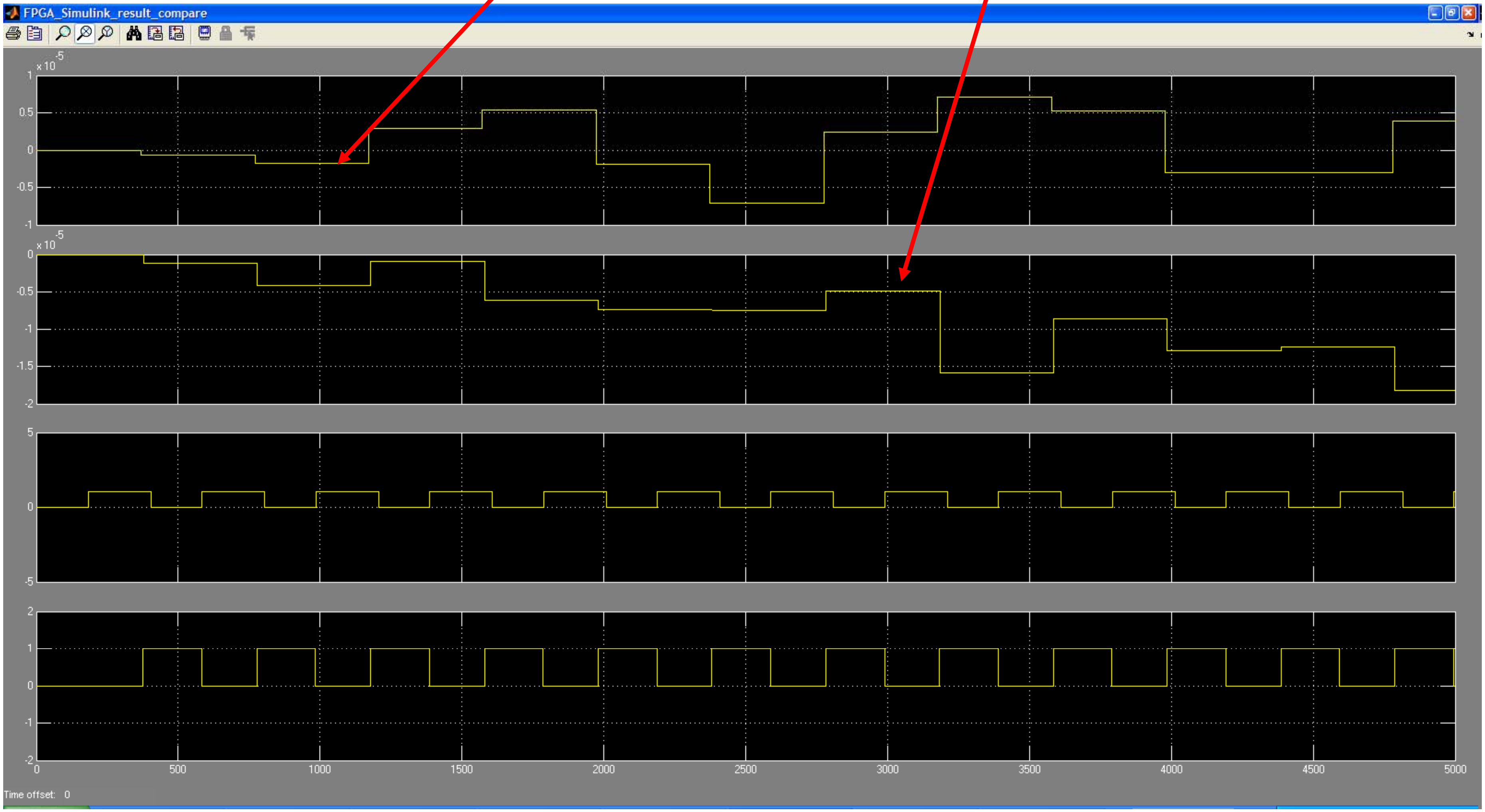


Matlab floating point calcu

NSLS-II FOFB Implementation

Error with PID calculation for one eigenmode

Decoupling calculation error



Summary

- Fast orbit feedback algorithm with individual eigenmode compensation is proposed. The typical MIMO feedback problem is converted into many SISO problems. This algorithm enables accelerator physicists to correct the beam orbit in eigenspace.
- We compared the calculations for FOFB with and without individual eigenmode compensation. We found that the proposed NSLS-II FOFB algorithm needs a large amount of calculations. This challenge is solved from two directions: a distributed, two-tier FOFB architecture, and the use of FPGA's powerful parallel DSP computation resources.
- We implemented the NSLS-II FOFB calculation in Xilinx Virtex FPGA chip. The fixed point quantization errors are studied to make sure the FOFB calculation is not only fast enough, but also accurate enough.
- We expect a successful application of the NSLS-II FOFB algorithm during the NSLS-II commissioning and daily operation.

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