Optimizing the BPM processor filter for the fast orbit correction

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Issue: A lot of the digital signal processors used to treat the beam signals to generate beam position data, including the Libera, are using the same signal processing scheme as the one used for the so called SDR or Software Defined Receivers designed for radio communication application. Thought it does the job, taking into account the specificity of a storage ring beam signal and orbit correction requirements would allow a better use of the processor resource.
Issues: Why a Fast Orbit Correction

Fast sources of orbit distortion:

- *IDs gap changes*
- *Ground motion*
- *Water circulation*
- *AC mains induced fields*
- *Booster induced fields*

ESRF FOC parameters taken as an example. It is not any longer a state of the art system, but the issues are the same for more advanced designs
EBS FOC: 6 fast BPMs and 3 fast correctors per cell
10 KHz correction update rate
Fast orbit correction principle

- 10 KHz position sampling and correction setting (ESRF)
- Fast BPM number $M=192$  fast corrector number $N=96$

Offsets defining the ideal orbit

$[Y_{\text{ref}}]_{M \times 1}$  

$[\delta Y]_{M \times 1}$

$[Y]_{M \times 1} + [N]_{M \times 1}$

$[R^{-1}]_{N \times M}$

$[\Delta \theta]_{N \times 1}$

N correctors

M BPM

Storage ring

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Orbit correction limitation

10 KHz sampling and correction rate does not mean 5KHz bandwidth!
We are limited to about 150Hz:
By the latency due:
- to the eddy current in the correctors
- to the signal processing in the Libera and the FPGA

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Dynamic issues/ frequency range

**Old ring:**
IDs gap changes: below 1Hz
7 Hz, 30Hz, 60 Hz girders and magnet resonances
10Hz, 50Hz and 150 Hz lines (injector and AC main)

Fast H motion: 4μm  fast V motion: 1.5 μm

**EBS ring:**
IDs gap changes: below 1Hz
girders and magnet resonances shifted above 40Hz
10Hz, 50Hz and 150 Hz lines (injector and AC main)

Fast H motion: ?μm  fast V motion  ?μm (less than 1 μm ?)
NEW FAST ORBIT CORRECTION PERFORMANCE

• Stiffer girders: smaller magnets displacement, but at a higher frequency
• Stronger quadrupoles fields gradient => Larger kicks for a given magnet motion

Eventually, we expect a smaller orbit distortion at high frequency, but maybe a reduced effect of the FOC system due to higher frequencies of the orbit distortions
DQ2-001 Magnet
(between Girders 2 and 3 - Front-end disconnected in 2018)

- Braodband amplification (TF $DQ2/floor$) $1.4 (10/2017) \rightarrow 1.2 (01/2018)$
- Modes at 32Hz and 37Hz
Dynamic issues/ frequency range

**ESRF corrector concept:**

We use a so called PI corrector, with the addition of a dedicated narrow bandwidth 50Hz suppressor.

**Effect:**

$D_r$, residual relative distortion at $f$, for a loop bandwidth $f_c$: $D = f / f_c$

The limiting factor for $f_c$ is the loop delay ...

The bandwidth sets the relative residual orbit distortion at low frequency.
Spectral Vertical Damping [dB], red=normal-latency-no50Hz Notch, black=3extraCycles, purple=6extraCycles

zero-crossings reduced from 140Hz to 110 & 100Hz

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**Fast Orbit Feedback delay contributors (old ring)**

*ESRF Fast Orbit Feedback timing*

- Group delay of the FIR (linear phase, 79 samples): 148 µs
- Distribution of data around the ring (C.C.): 70 µs
- Matrix multiplication 2*7*168 (based on Power PC): 4 µs*
- PID controller: 1 µs
- Write into PS controller: 20 µs
- Power supply: 50 µs
- Eddy currents in the sextupoles (correctors): 75 µs
- Eddy currents in vacuum chamber: 265 µs

* Total: <683 µs

*Must be scaled according to the number of data and depends on the DSP engine (Power PC, FPGA, ...)*

**Will results in a phase shift of 45 degrees at 180Hz ...**
Libera Brillance signal processing

From ADCs @ ADC Sampling Frequency

- DDC @Revolution Frequency
- History Buffer @Revolution Frequency
- ADC Rate Buffer @ADC Sampling Frequency

- Additional Filtering & Decimation
- Additional Filtering & Decimation @Fast Feedback Frequency
- Additional Filtering & Decimation @Slow Acquisition Frequency

- Data on Demand
- Continuous Data Flow

- ADC Rate Data
- First Turns Turn-by-Turn Post Mortem
- Decimated Turn-by-Turn
- Fast Acquisition Interlock Fast Application
- Slow Acquisition
FIR (finite impulse response) filter

\[ x[n] \rightarrow \sum b_0 \rightarrow Z^{-1} \rightarrow \sum b_1 \rightarrow Z^{-1} \rightarrow \sum b_2 \rightarrow Z^{-1} \rightarrow \sum b_N \rightarrow y \]

\(x[n]\): turn by turn BPM data
Effect of the FIR of the FA output

Very good selectivity => low aliasing due to the decimation: required for telecom application, but do we really need it?
Lowest delay limit: moving average filter

26 coefficients filter, all equals to one

Group delay of the FIR: 50 µs (three time lower!)
Undersampling effect

Transfer function of a pure averaging filter

5KHz useful span

10KHz frequency span prone to aliasing

10KHz +/-300Hz => -30dB

Spurious signals falling above the feedback cut off frequency

Extra filtering due to:
- Loop filter
- Limited bandwidth of the correctors
TEST on the old ESRF ring

Horizontal plane, 5 KHz span, FOC off

- Standard Libera filter
- Moving average filter
- Aliasing products
TEST on the old ESRF ring

Horizontal plane, 500 Hz span

Standard Libera filter

Moving average filter:
No extra spurious lines in the useful frequency span
Achievable loop delay on the EBS FOC ...

<table>
<thead>
<tr>
<th>Component</th>
<th>Delay (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group delay of the FIR</td>
<td>50</td>
</tr>
<tr>
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</tr>
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<td>Power supply</td>
<td>50</td>
</tr>
<tr>
<td>Eddy currents in the new correctors</td>
<td>25</td>
</tr>
<tr>
<td>Eddy currents in a 1.5 mm thick vacuum chamber</td>
<td>80*</td>
</tr>
</tbody>
</table>

Total: <300 µs

* For the V correction only, H correction: 400 µs

Will results in a phase shift of 45 degrees at 400Hz ...
Implementation in the FPGA

\[ x[n] \rightarrow Z^{-1} \rightarrow Z^{-1} \rightarrow Z^{-1} \rightarrow y \]

\( b_i = +or-1 \) so no multiplication needed, very low use of FPGA resources
Thank you for your attention
Extra slides (if questions...)}
Old ring situation
Quality of the correction up to 1KHz

Submicron vertical rms residual motion => vertical motion < 10% of the vertical beam size.

\[ \varepsilon_{x_{\text{OFF}}} = 1.3 \times 10^{-12} \]
\[ \varepsilon_{x_{\text{ON}}} = 1.3 \times 10^{-13} \]
\[ \varepsilon_{x_{\text{beam}}} = 4 \times 10^{-9} \]

\[ \varepsilon_{z_{\text{OFF}}} = 3.5 \times 10^{-13} \]
\[ \varepsilon_{z_{\text{ON}}} = 4.8 \times 10^{-14} \]
\[ \varepsilon_{z_{\text{beam}}} = 4 \times 10^{-12} \]

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Shall we need to apply really fast orbit corrections?

If we need a significant damping above 30Hz, the bandwidth of the present FOC may not be enough, but we may not need it ...

*By the way, modern rings with an optimized design of the girders and magnets (SOLEIL, ALBA, Diamond) are in this situation ...*

*Sirius is aiming at a much larger bandwidth*
EBS correctors chamber

Eddy current effect:
- Severe for the H correction: 400\(\mu\)s delay
- 6 time smaller for the V correction

Low delay FIR could make a difference for the vertical orbit correction