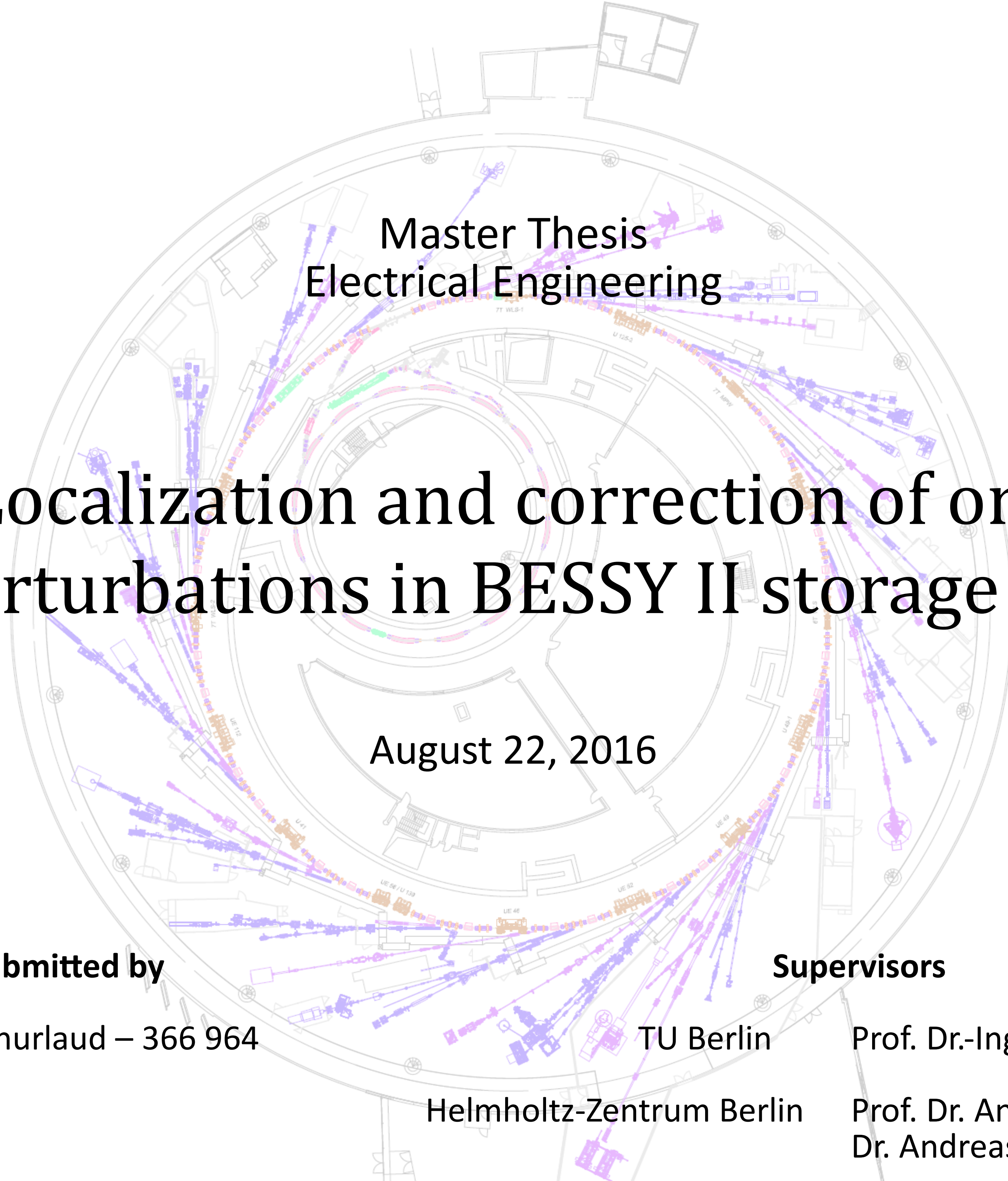


Master Thesis
Electrical Engineering

Localization and correction of orbit perturbations in BESSY II storage ring

August 22, 2016

Submitted by

Olivier Churlaud – 366 964

Supervisors

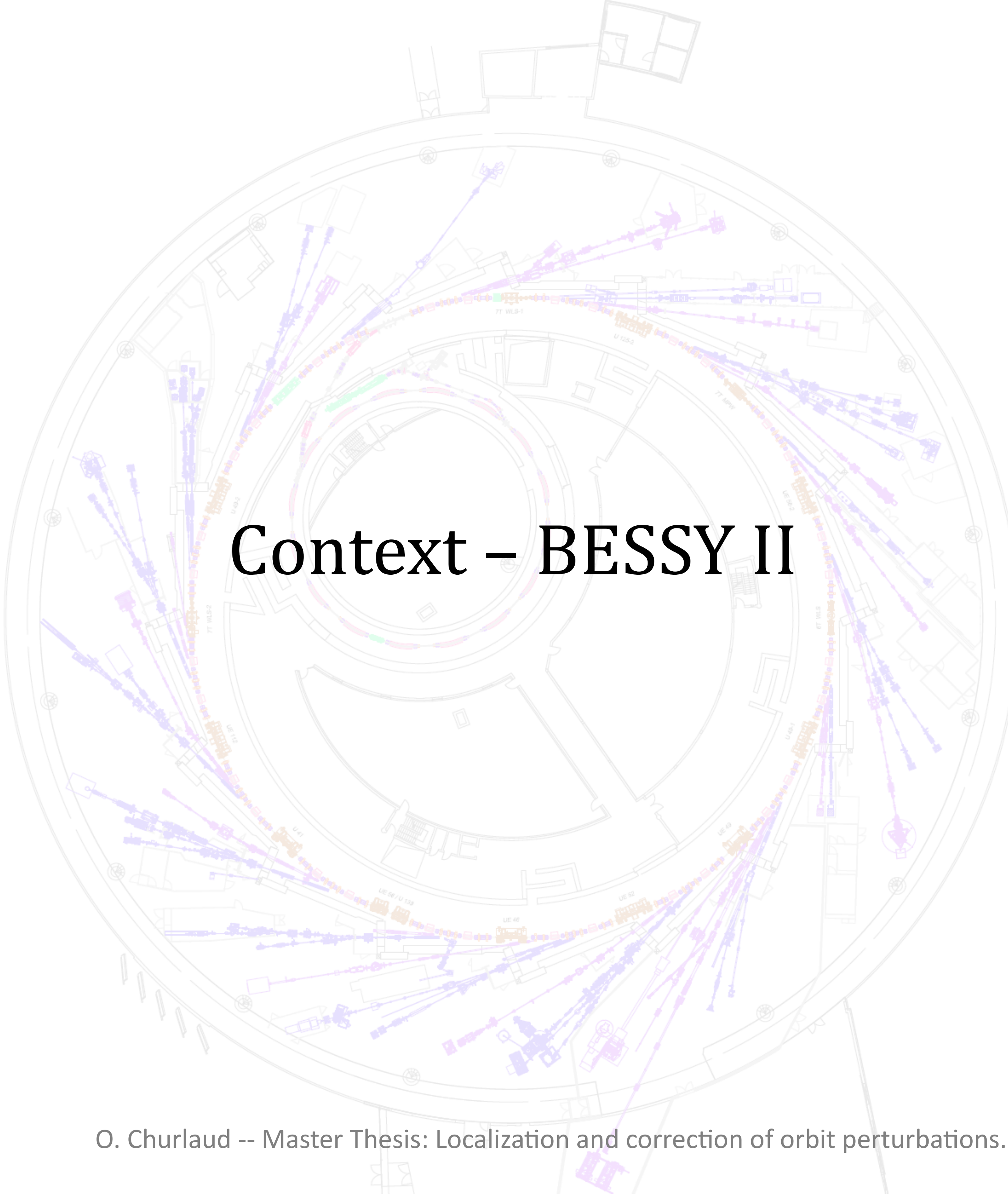
TU Berlin — Prof. Dr.-Ing. Jörg Raisch

Helmholtz-Zentrum Berlin — Prof. Dr. Andreas Jankowiak
Dr. Andreas Schälicke

Localization and correction of orbit perturbations in BESSY II storage ring

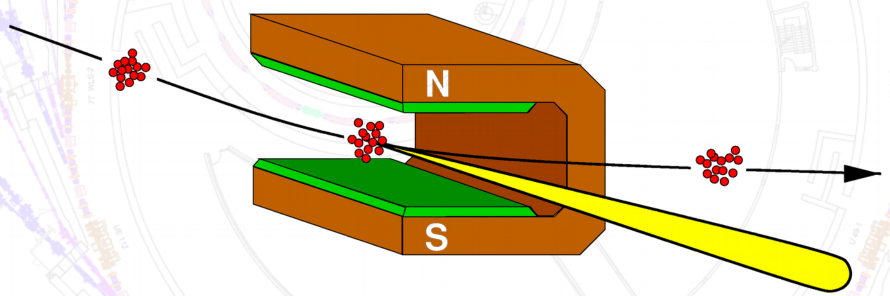
- Context – BESSY II
- Common objective
- Particle accelerator physics
- Example: Perturbation source localization
- **Correction: State of the art at BESSY II**
- **Correction improvement: harmonic correction**
- **Simulations and control propositions**
- Conclusion

Context – BESSY II



Context – BESSY II

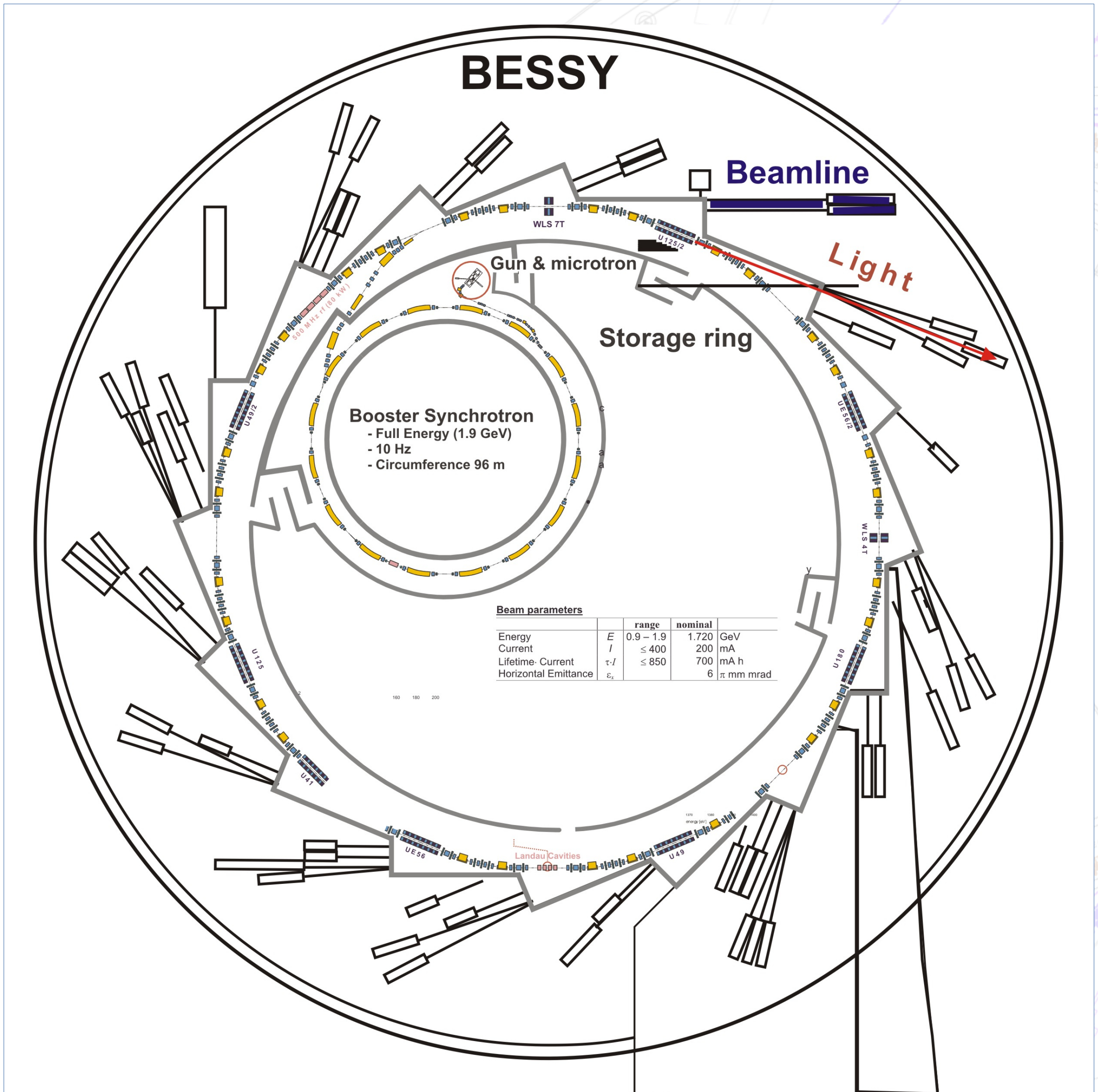
- Facility of Helmholtz-Zentrum Berlin since 2009, inaugurated in 1998.
- It is a light source : **No collision!**
  - Electrons are used to produce wide spectrum lights (synchrotron radiation)



  - Light rays are used by **guest** scientists to study e.g. material properties
  - BESSY scientists are responsible for the good functioning and constantly work on improving light ray quality

Image source: photon-science.desy.de

Context – BESSY II



Numbers

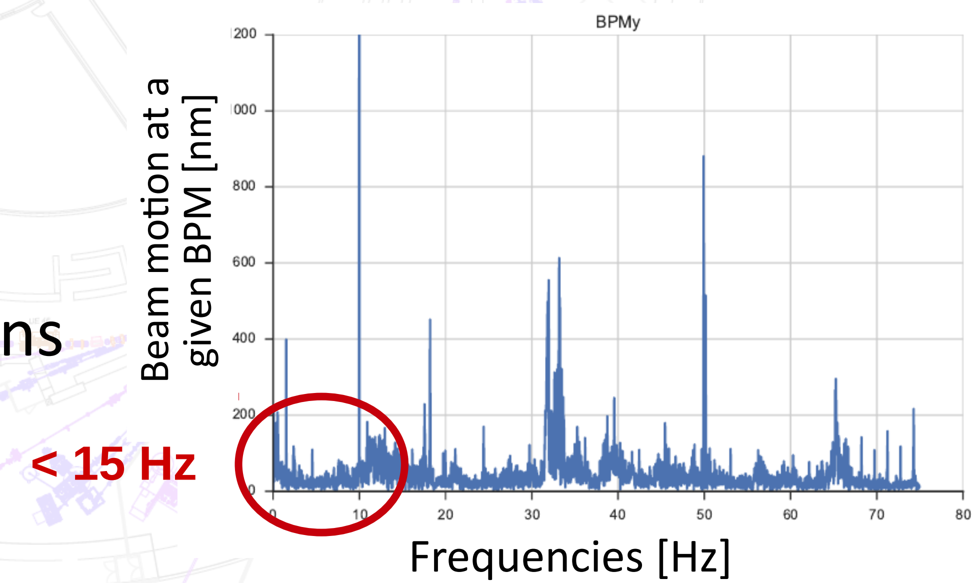
Energy of stored e-	**1.7 GeV**
Current in ring	**300 mA**
Ring circumference	**240 m**
Beamline number	**≈ 50**
Guest scientists	**> 2000 / y**

Take away message

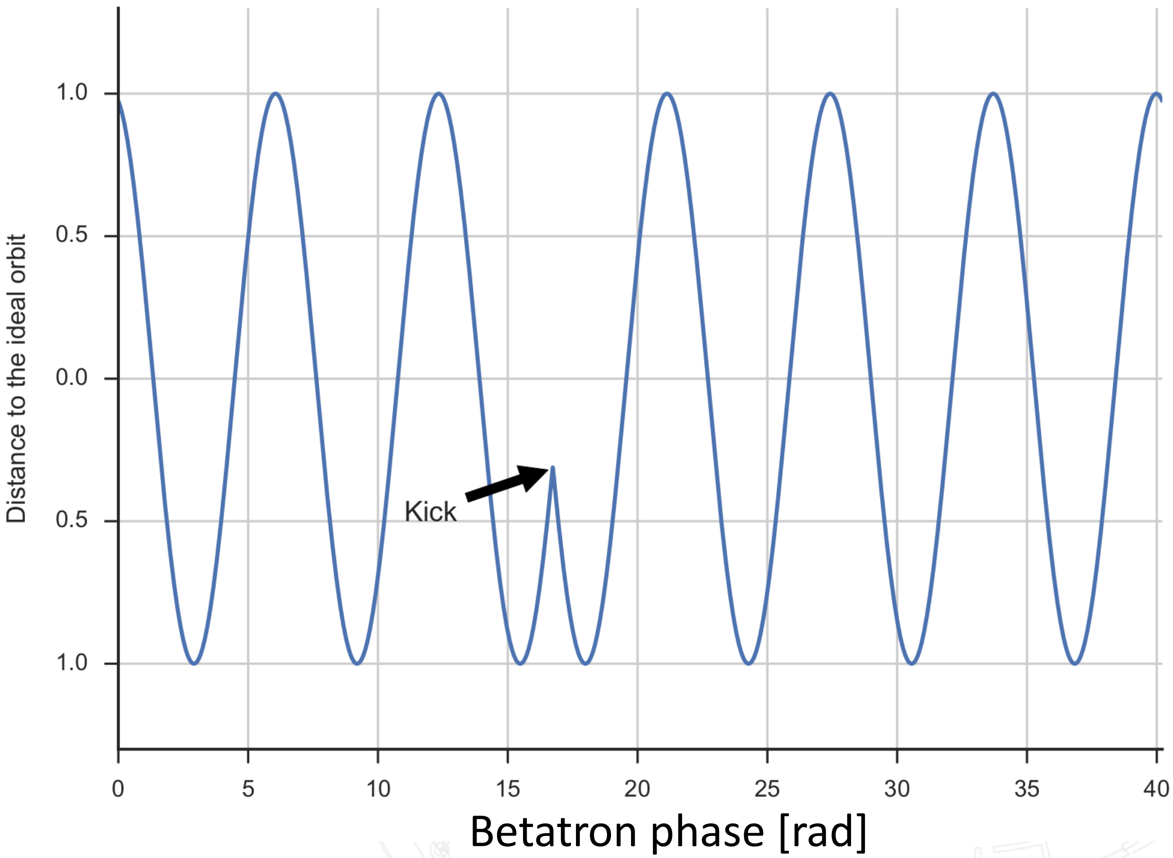
- We want a stable and reliable light.
- For this the electron beam must be as focused as possible.
- Beam dimensions: **100x20 µm**

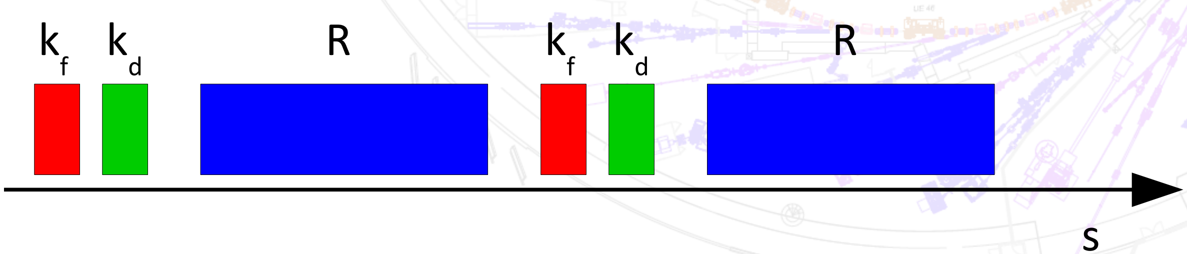
→ **We want to keep the electrons close to the nominal orbit. 10% error authorized.**

- The accelerator is designed for that but we have a lot of **time dependant** perturbations to cope with.



Particle accelerator physics – Definitions





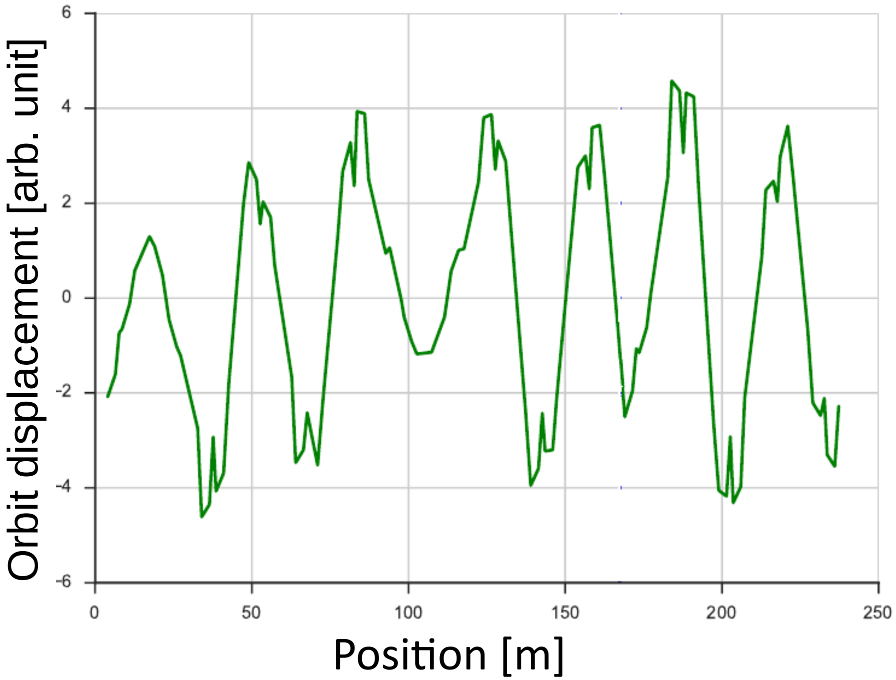
Displacement or betatron oscillation

$$x(s)=\sqrt{\varepsilon\,\beta(s)}\cos\left(\Psi(s)+\phi\right)$$

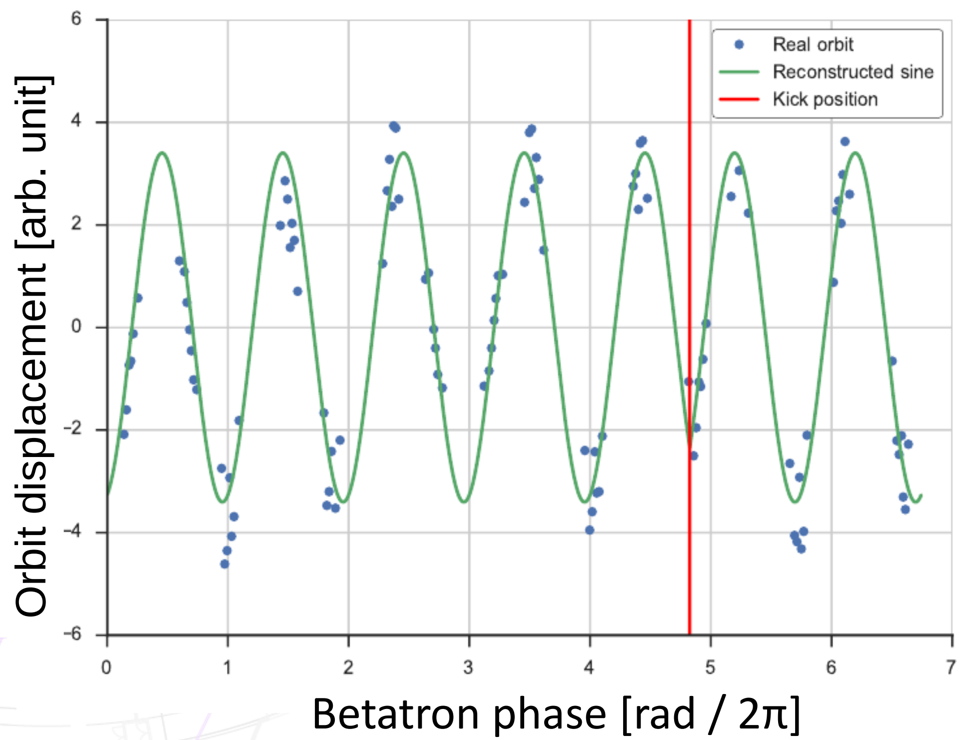
beta function

betatron phase

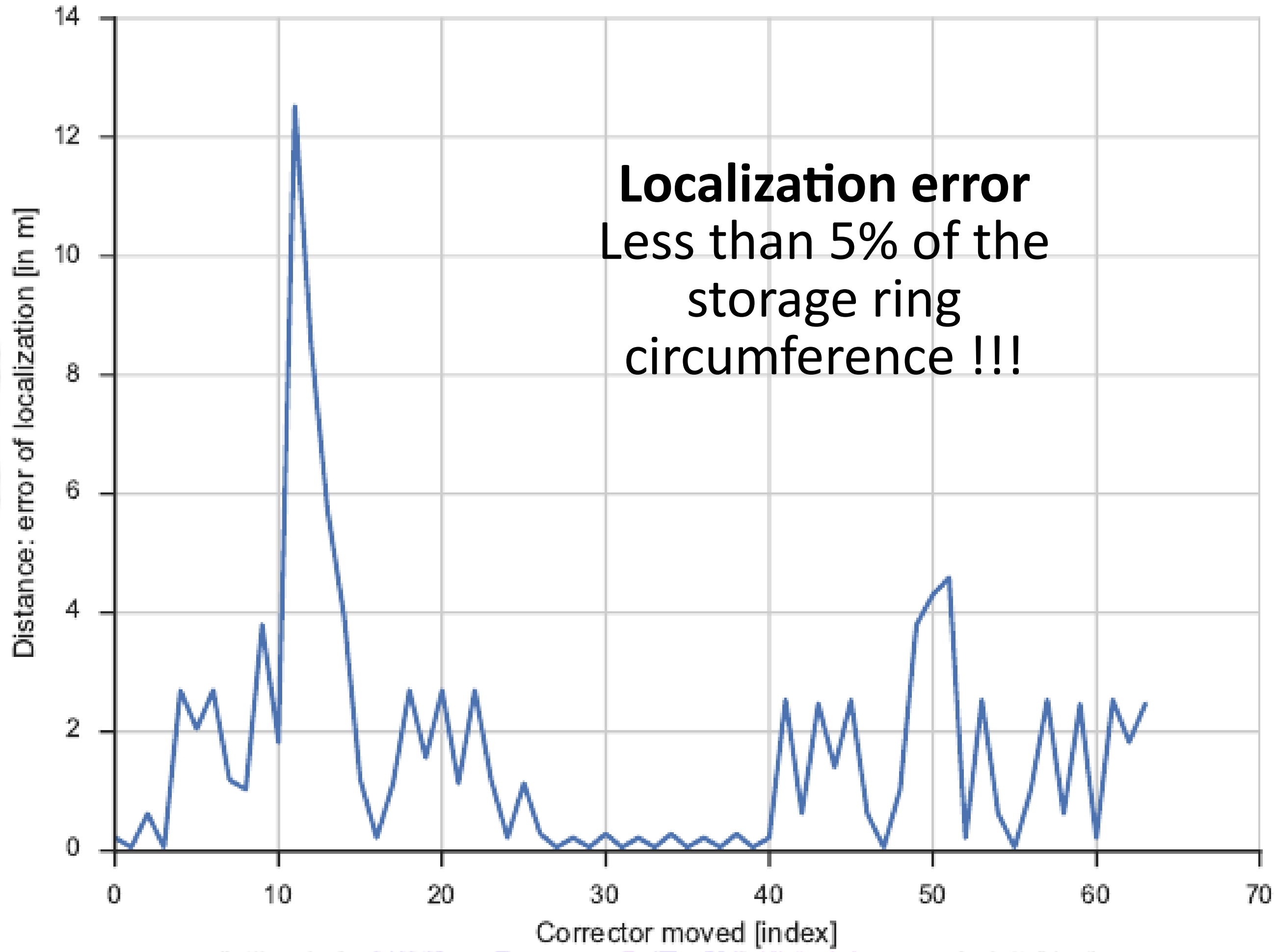
Localization of orbit perturbations

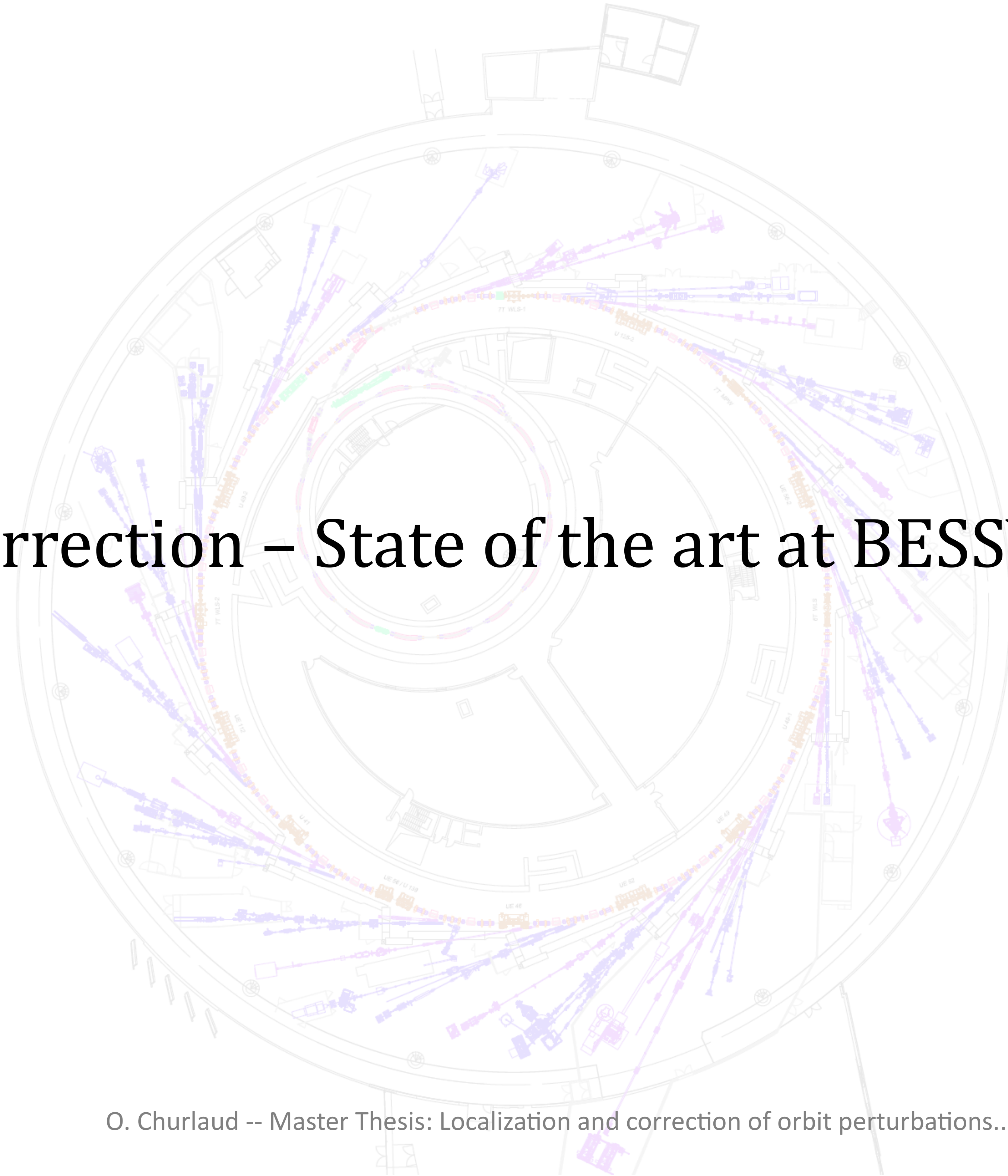


Algorithm implemented to do this.



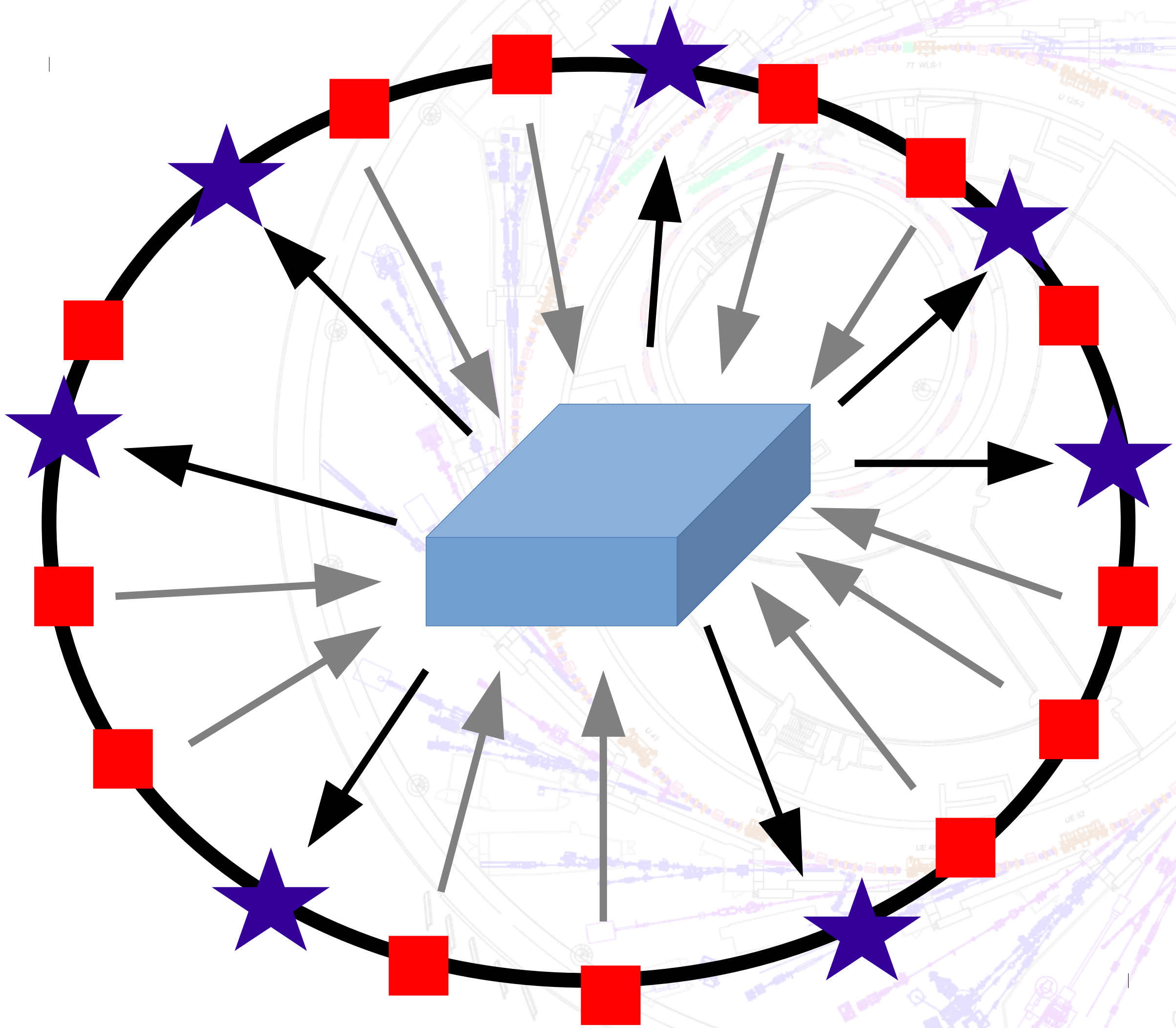
Localization of orbit perturbations





Correction – State of the art at BESSY II

BESSY II – State of the art
Architecture



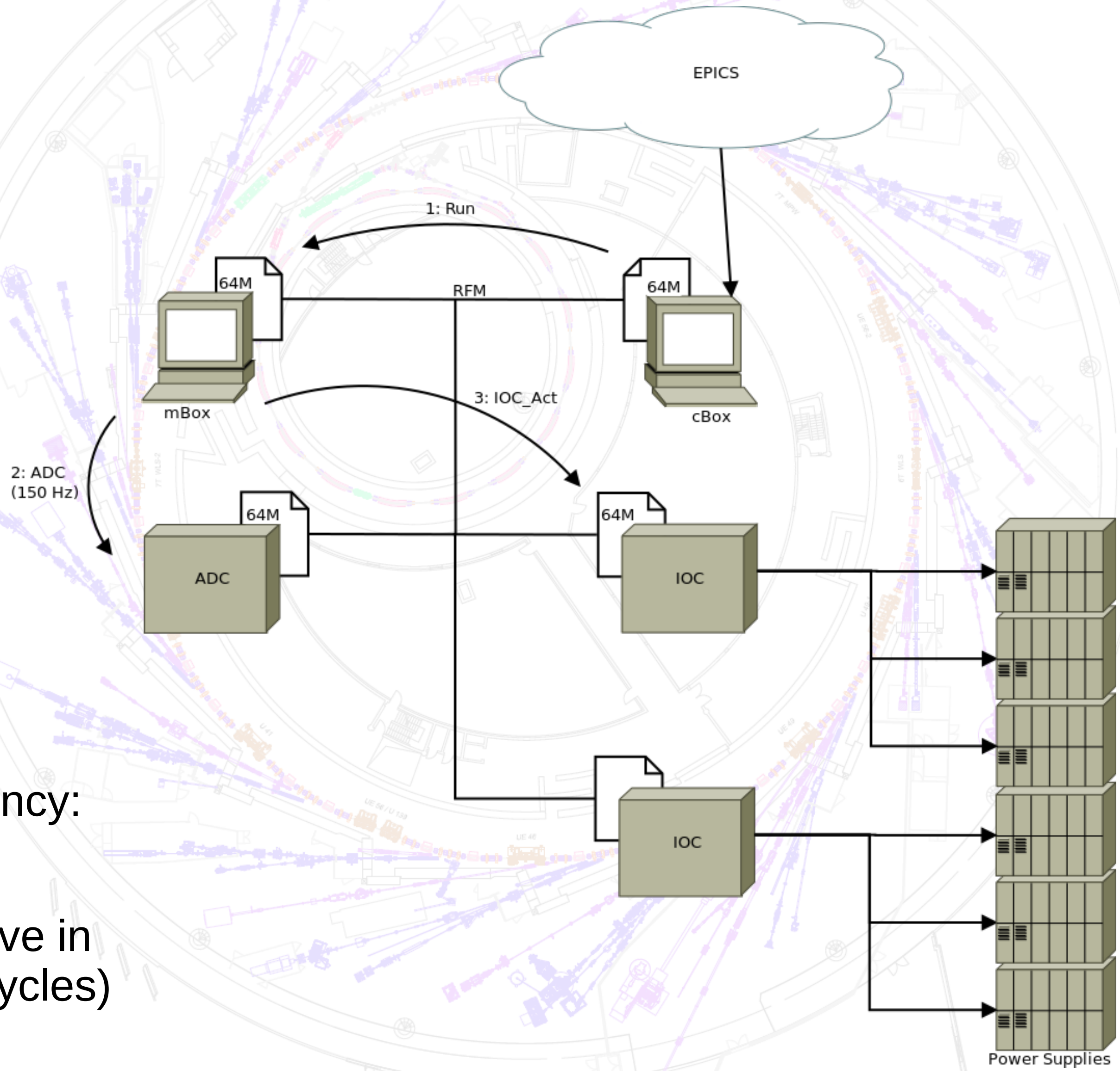
Beam Position Monitors – Read orbit position

Servers – Handle and calculate correction

Corrector magnets – Apply correction

108/108 BPMs
64/48 Corrector Magnets

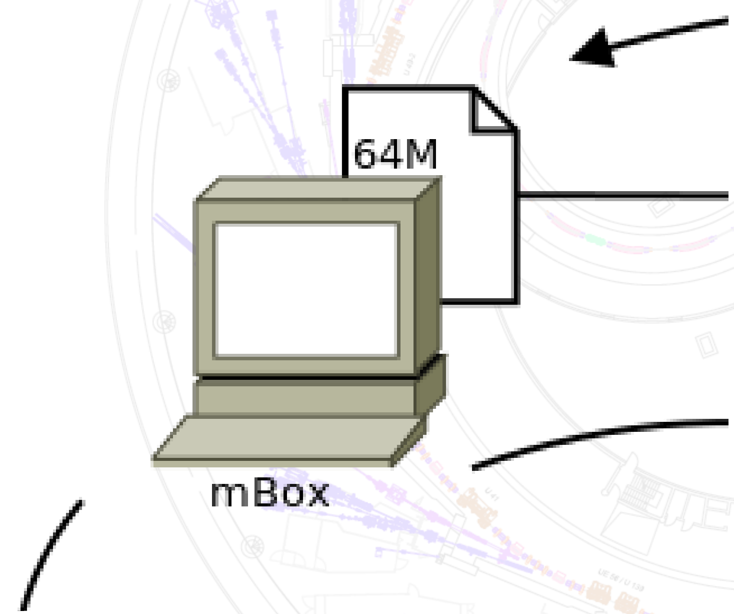
BESSY II – State of the art
Architecture



Sampling frequency:
150 Hz

Correction effective in
< 1s (approx. 5 cycles)

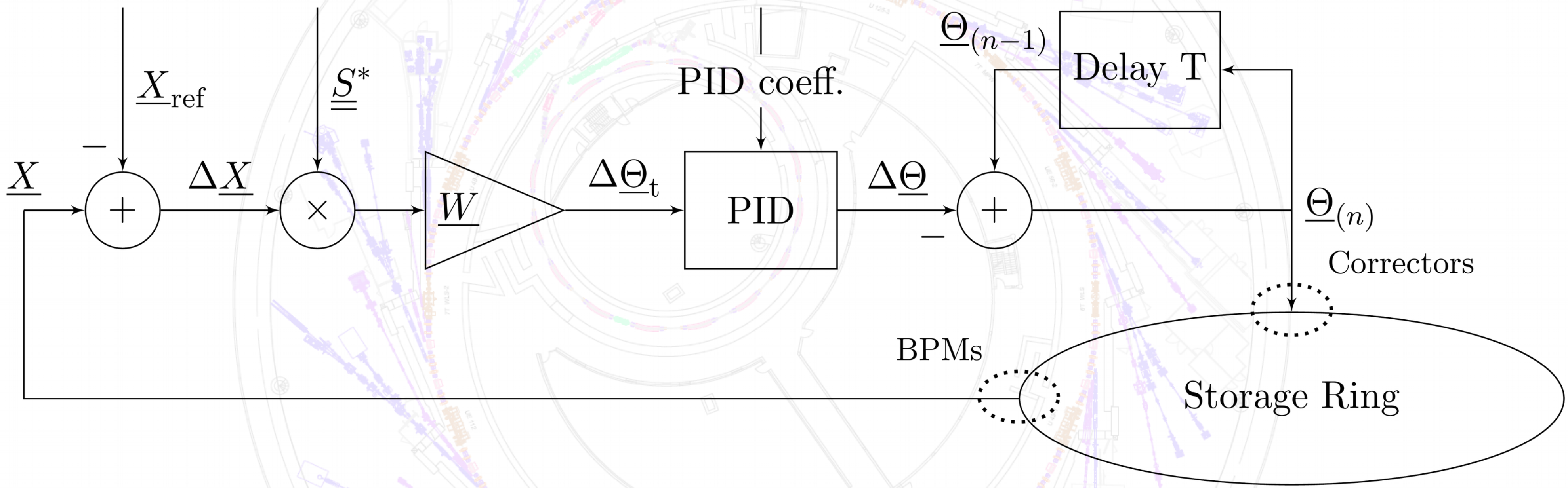
BESSY II – State of the art
Actor of interest



The control process happens here.

- Rewritten in C++ during the thesis
- Added correction and communication modules

BESSY II – State of the art
Correction process



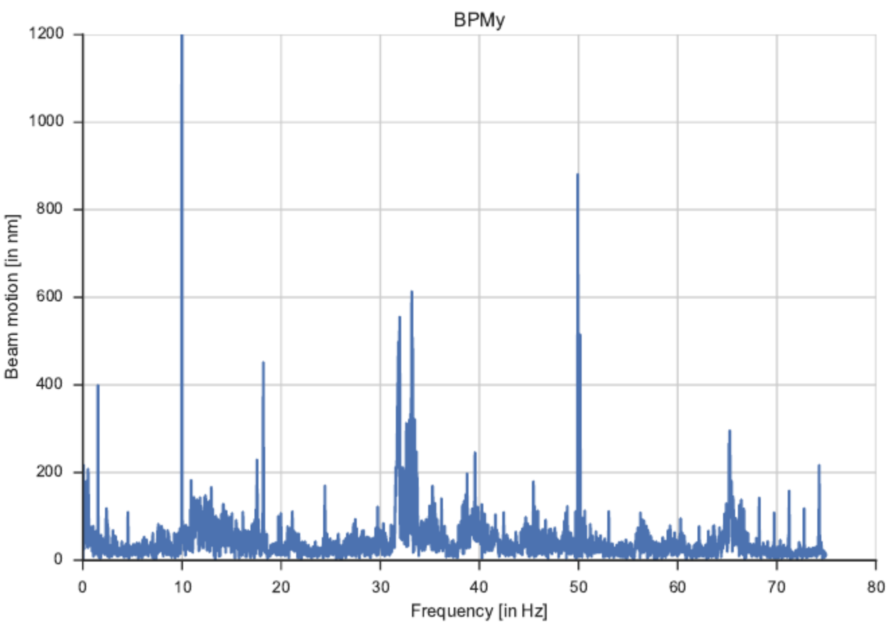
PID
P = 0.8
I, D = 0

Delay T
represents the cycle duration (1/150 s)

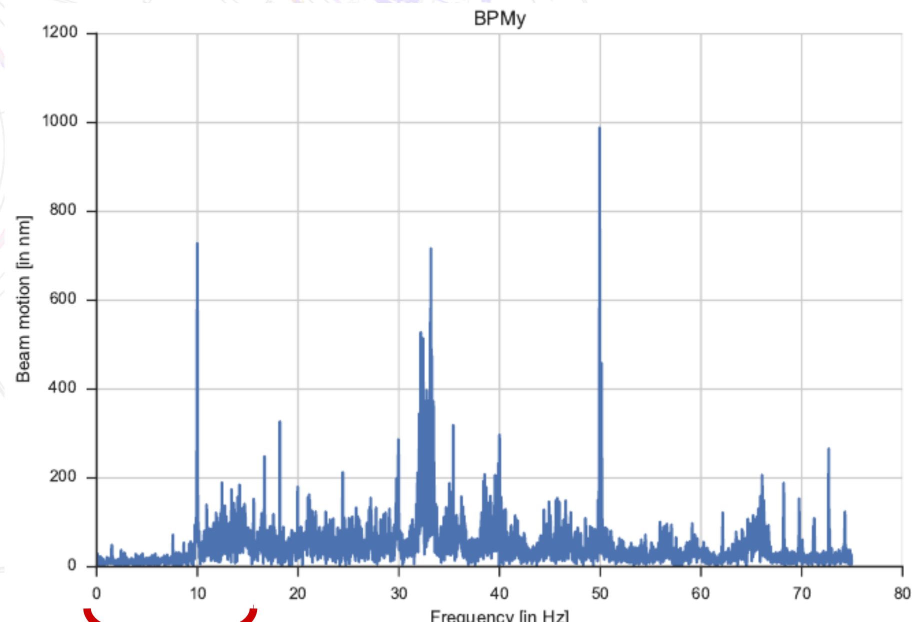
Correctors & BPMs x/y
M = 108/108 BPMs (Beam Position Monitor)
N = 64/48 Corrector Magnets

I rewrote this from MATLAB to C++.

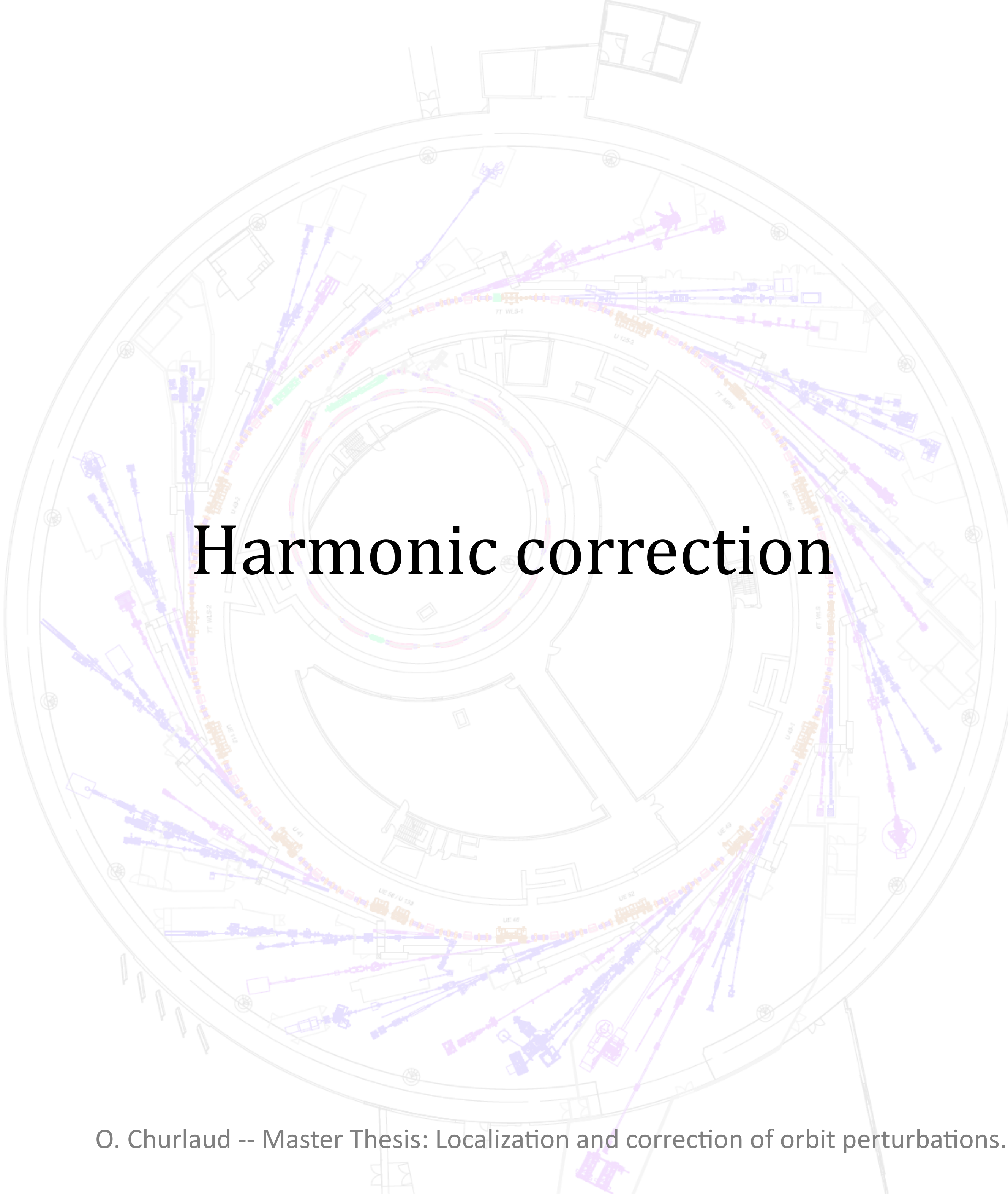
Correction status at BESSY II



Without Correction

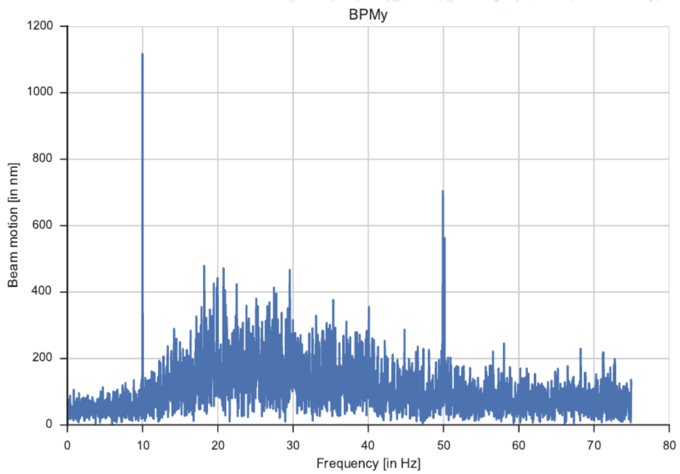


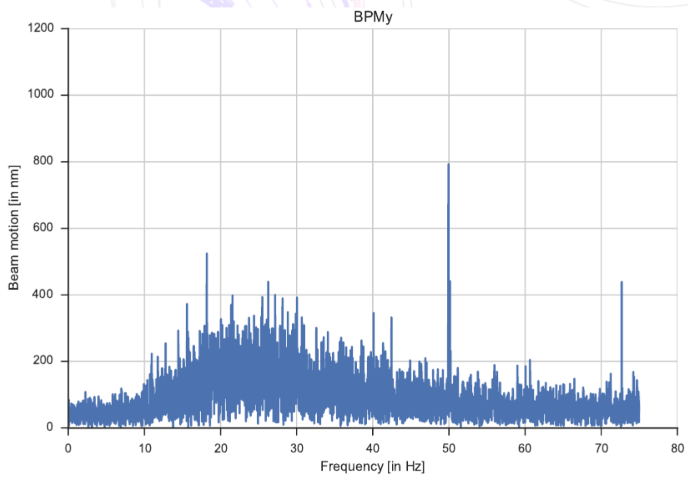
With Correction



Harmonic correction

Correction improvement – harmonic correction





- Problem: presence of harmonic perturbations.
- Solution idea: generate the opposite wave.
- Correction:

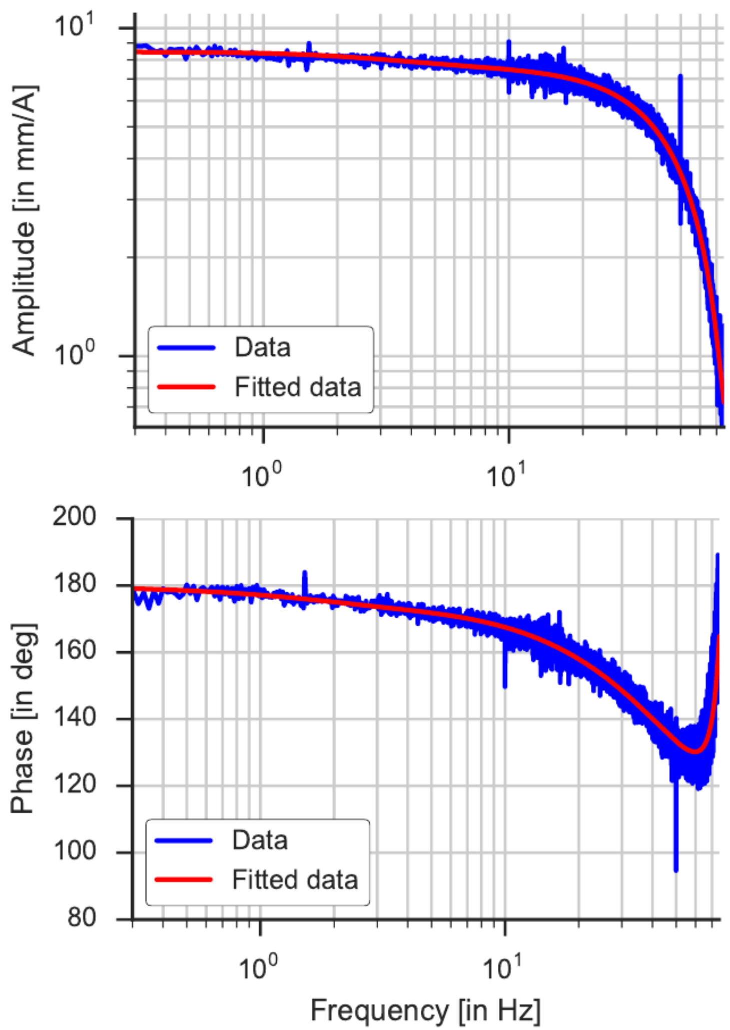
$$x[n] - h * u[n]$$

u: sinusoidal signal with the frequency to remove.

h: FIR to change the amplitude and phase.

Simulation – Control

Simulation and control
1 – System identification



We need a model.

1) Generate a sine sweep as input of the storage ring
2) Transfer function identification

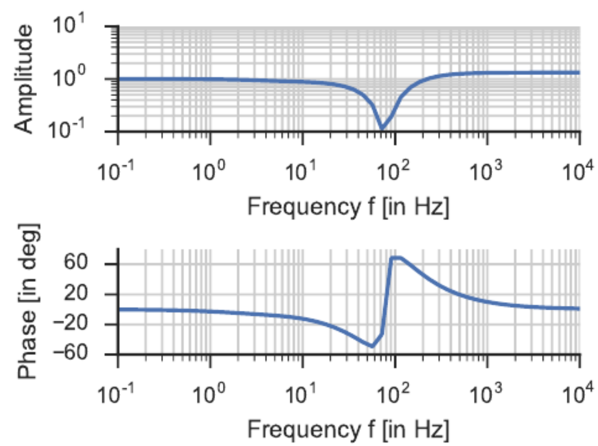
$$G(j\omega) = \frac{S_{\theta x}(j\omega)}{S_{\theta\theta}(j\omega)} \qquad (**)$$

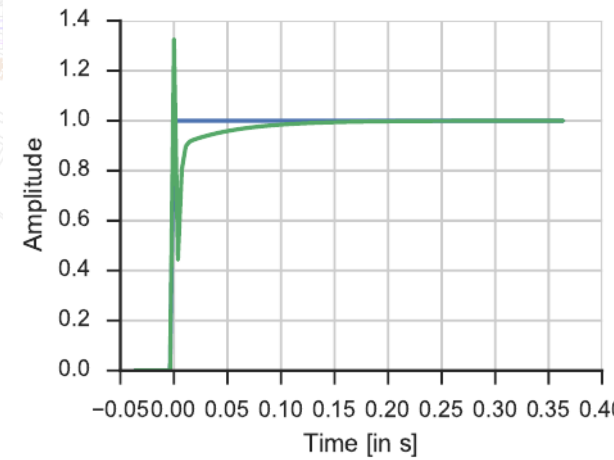
3) Vector fitting (with vfit3, Gustavsen)
4) Zero reduction (see next slide)

** S_{ux} = fft(R_{ux}) [cross-] spectral density

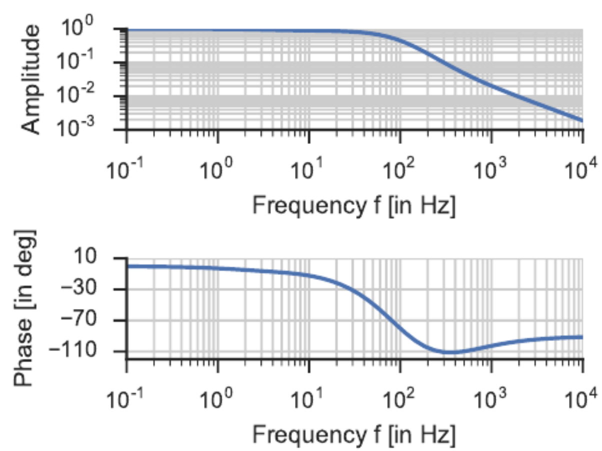
Simulation and control
1 – System identification

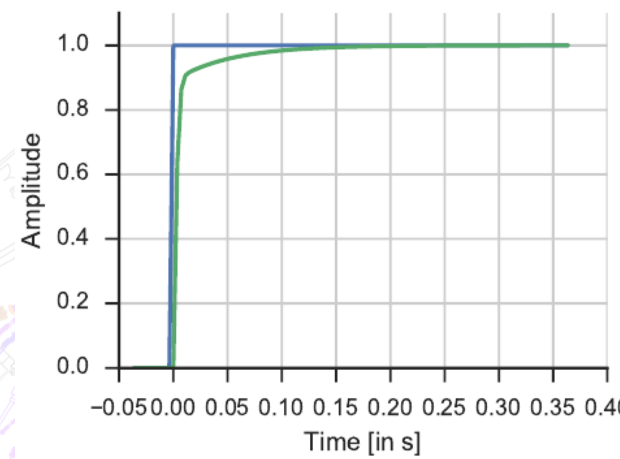
Before reduction



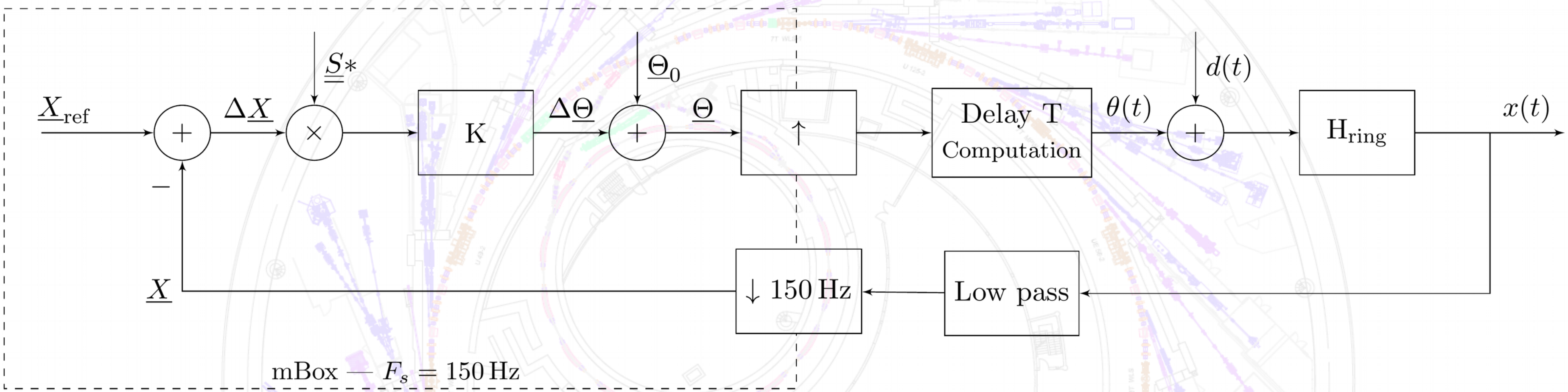


After reduction

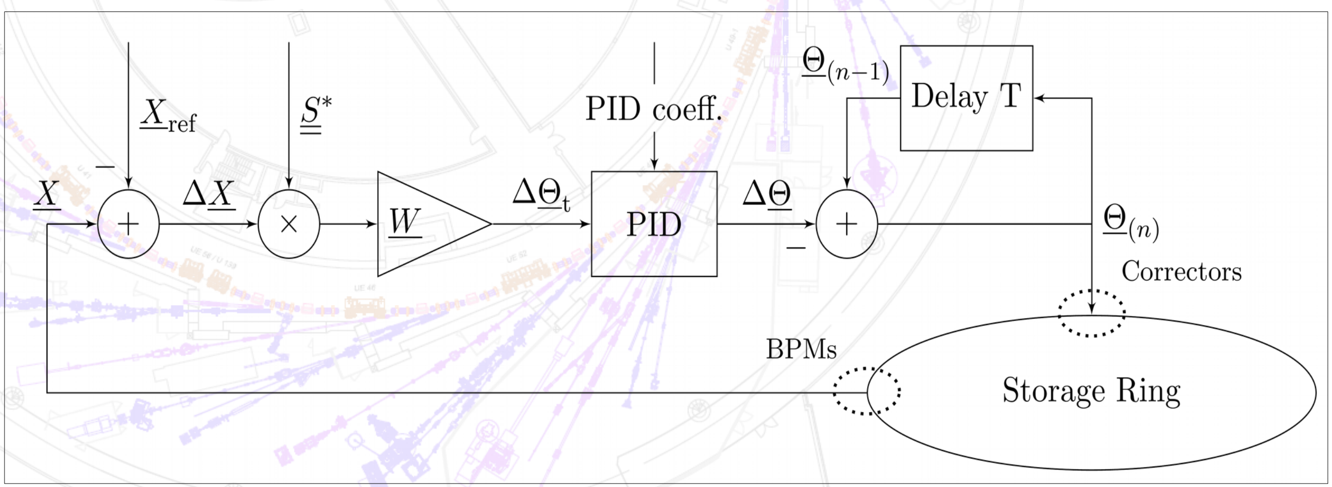




Simulation and control
2 – *Model*

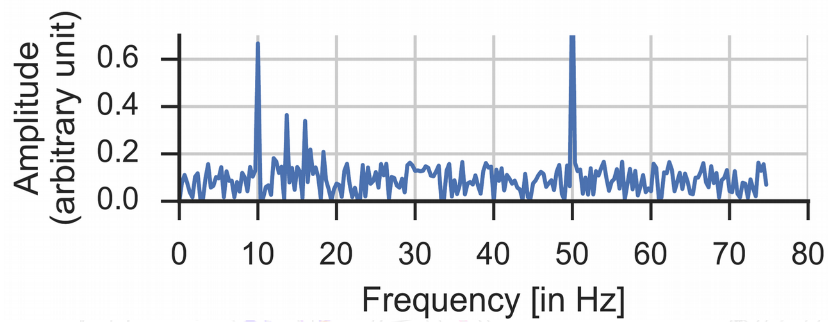


The original architecture

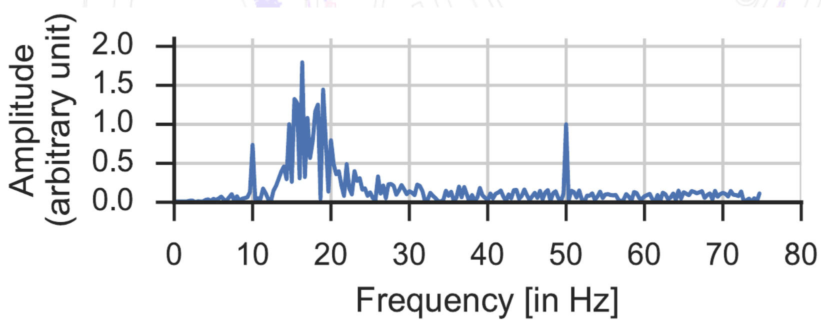


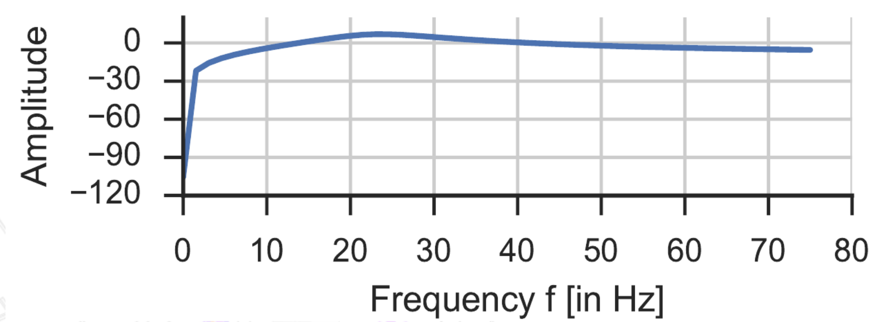
Simulation and control
3 – Results: better PID

Perturbation

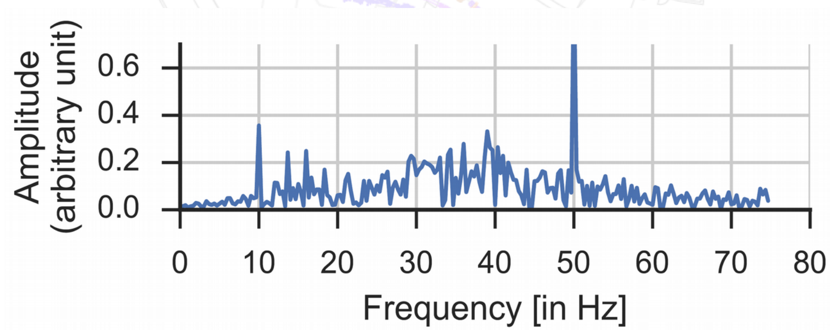


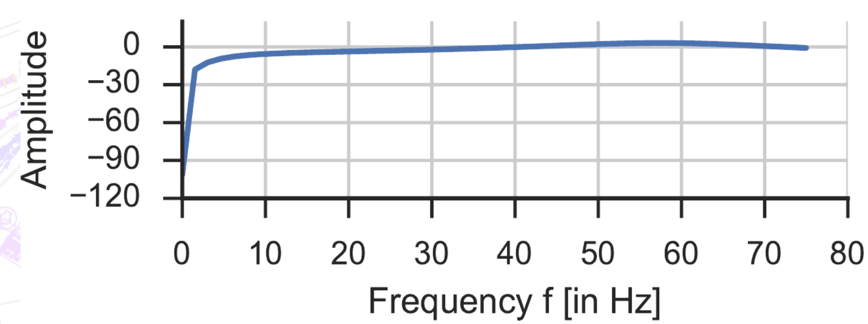
Previous PID
Scale x3



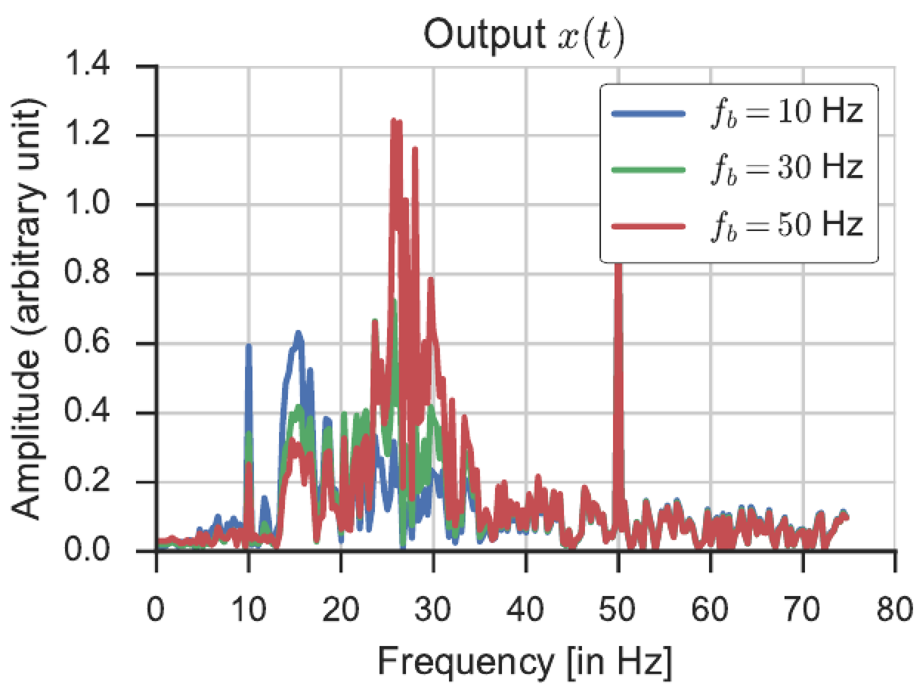


Better PID





Simulation and control
… *optimal correction direction* …



- Design of a H_∞-Controller (based on Skogestad)
- Results deceiving: the weight function was obviously not good enough
- This is the direction to go!

Conclusion

- Good results obtained during the thesis
  - Produced a synthesis of current situation
  - Harmonic perturbations removed in quasi-systematic way
  - Localization of single perturbations now possible

- Opening to future improvement
  - First steps in modelling the whole environment + simulating it.
  - First step in the direction of optimal correction
  - Future work should deal with MIMO controllers

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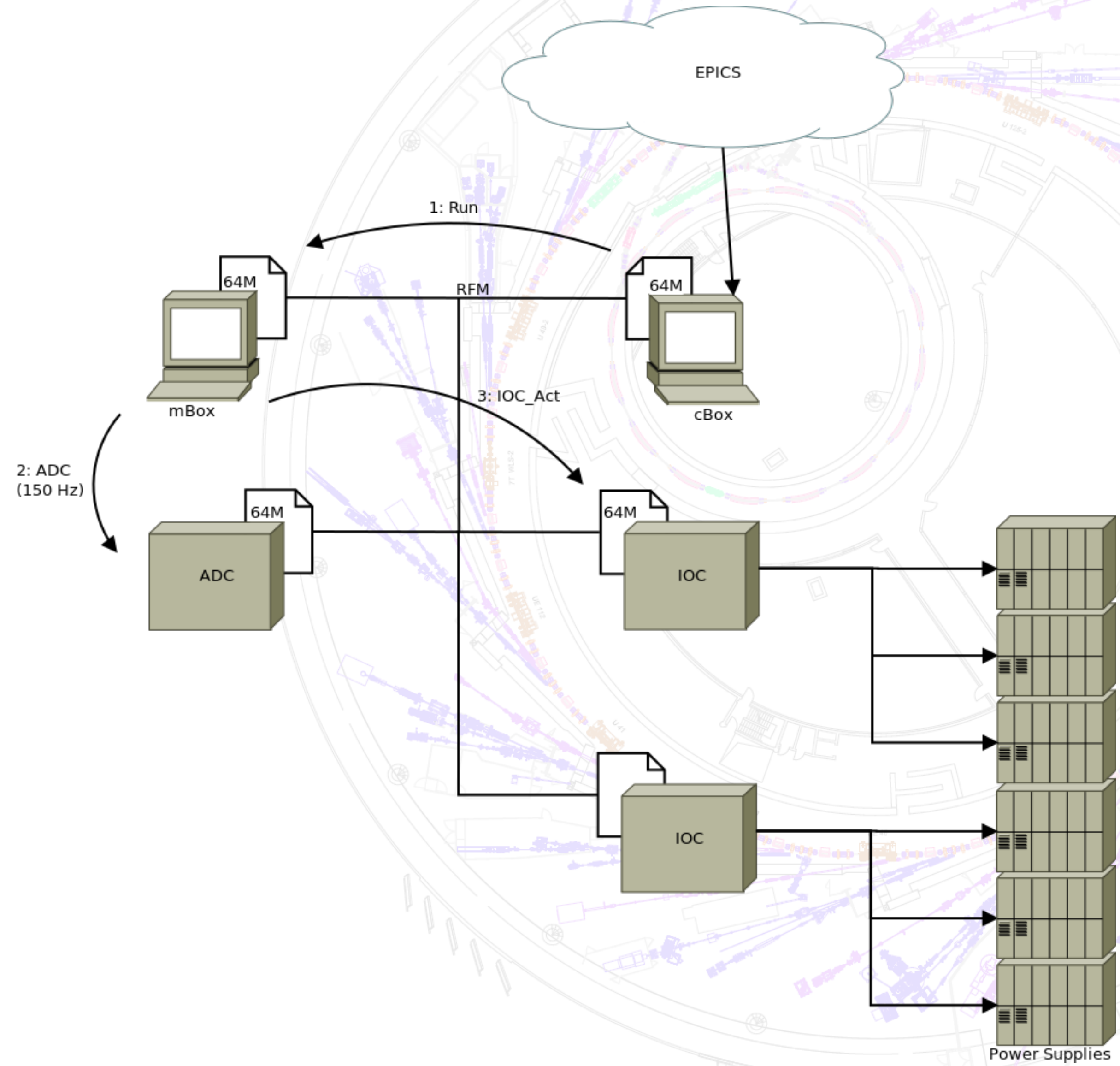
- R. Wang, *Introduction to orthogonal transforms: with applications in data processing and analysis*. Cambridge University Press, 2012, ch. 8.

Backup slides

BESSY II – How does the correction work?



Start

1) *Start* triggered by op.
2) cBox reads values in EPICS, write them to RFM
3) cBox tells mBox to start
4) mBox reads RFM and initializes

Process

1) mBox waits for ADC interr.
2) mBox reads ADC
3) mBox computes correction
4) mBox writes correction on RFM and emits interr.
5) back to 1)

Meanwhile..

When the PS receive the interr. they change their values.

Correction – Response matrix S

- Idea: solve the *inverse problem.*

- If we apply a correction $\underline{\Theta}$, it results an orbit modification of $\underline{X}$. ($\underline{\Theta}$ represents N magnets correctors, $\underline{X}$ represents M BPMs).

$$\underline{X} = \underline{\underline{S}}\,\underline{\Theta}$$

- In our case we know $\underline{X}$ and we deduce $\underline{\Theta}$ from

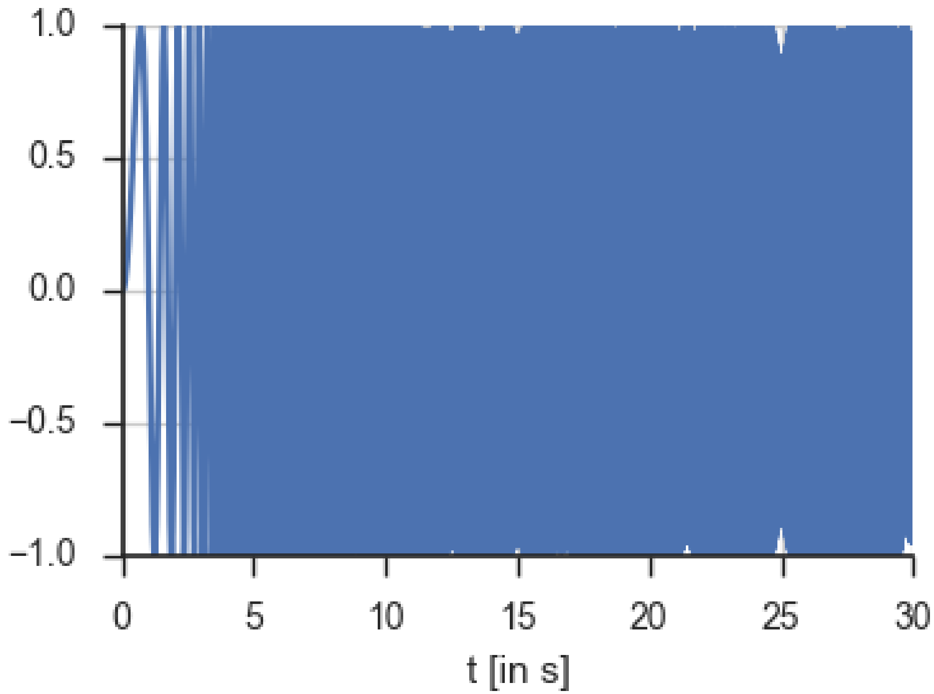
$$\underline{\Theta} = \underline{\underline{S}}^{*}\,\underline{X}$$

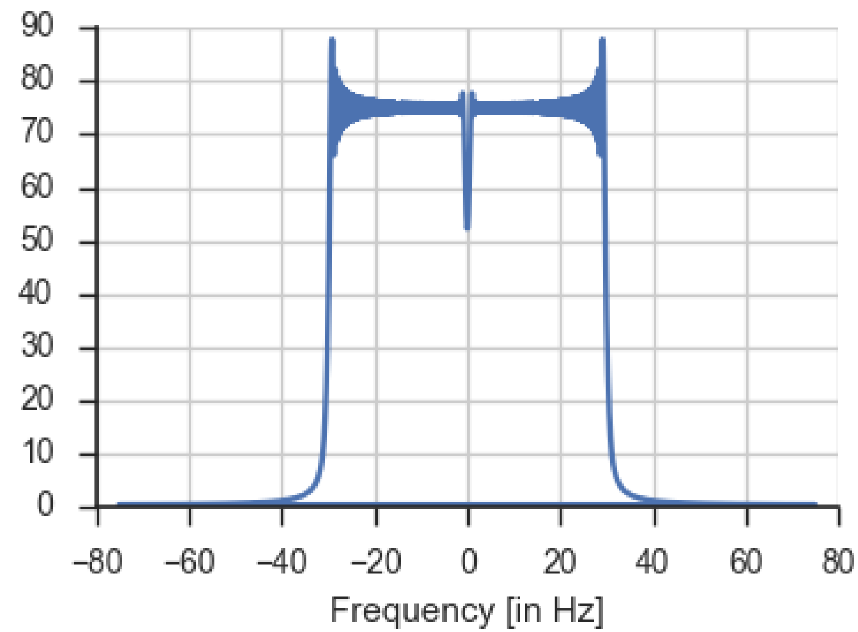
- $\underline{\underline{S}}^{*}$ is the pseudo inverse of S (calculated with the SVD decomposition)

Control – Sine sweep

$$f(t) = 2f_{\text{min}} \cdot t + \frac{f_{\text{max}} - f_{\text{min}}}{2 \cdot t_{\text{max}}} t^2.$$

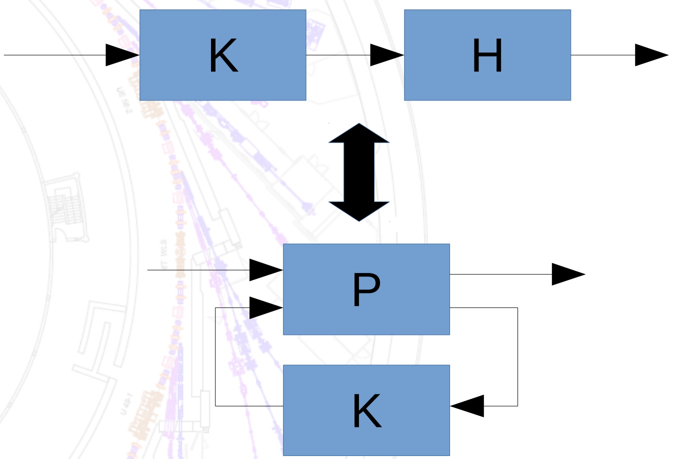
$$u(t) = A \sin(2\pi f(t)).$$





Control – Optimal corrector

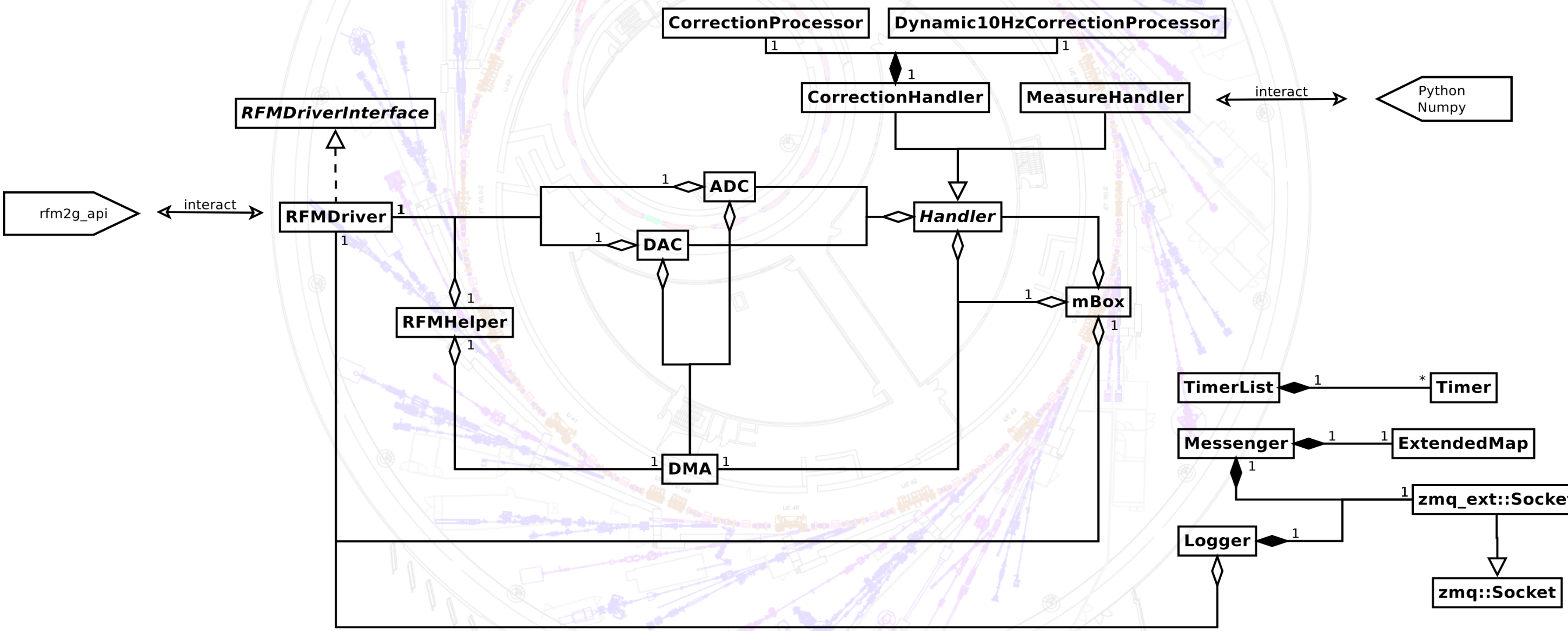
- System = Ring + delay
- Weight inputs $$W_p = \frac{s/M + \omega_b}{s + A\,\omega_b}$$
  - $M \approx 1$
  - $A << 1$
  - $\omega_b = 30 \times 2\pi$
- Transform it to a plant
- Use hinfsyn() function



- Problem: What exact values of A, M and ω_b ?

mBox++

Modular, very modular…
Expandable
Hopefully more maintainable



mBox++

– cBox orders
– BPM values

mBox++

Publishes logs and errors
– port 3333, zeroMQ

Publishes BPMs, CMs, raw DAC data
– port 3333, zeroMQ

Exchange data (S-Matrix, BPM number,….)
– port 3334, zeroMQ

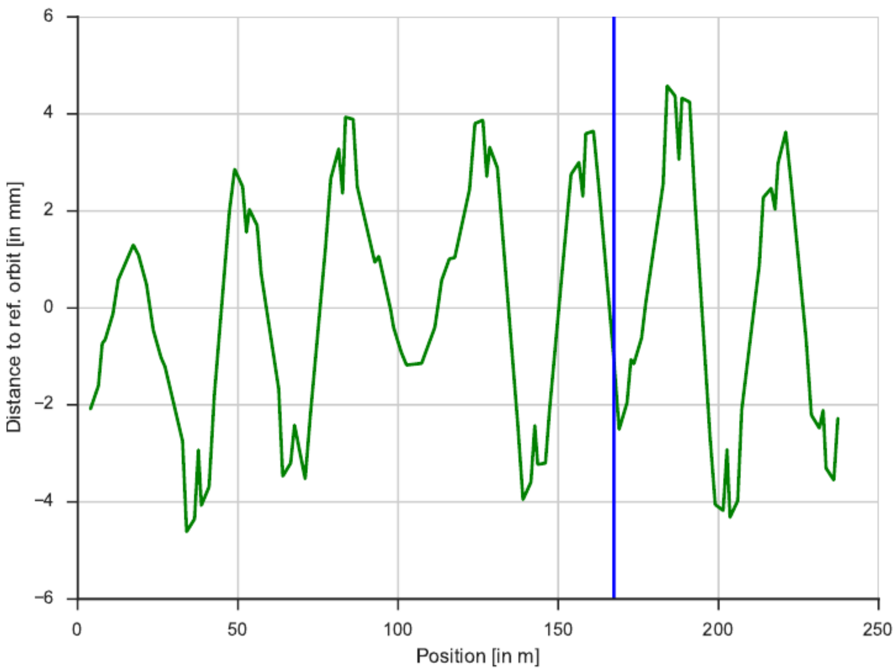
Data used by external scripts (Python, MATLAB, C++, PHP...)

– raw DAC data (CMs)

mBox++

- In experimentation mode:
  - Call the mBox with --experiment <python_script.py>
  - The python script should read the BPMs, and return the correction (see for Doxygen doc and `experimentScripts` folder for examples

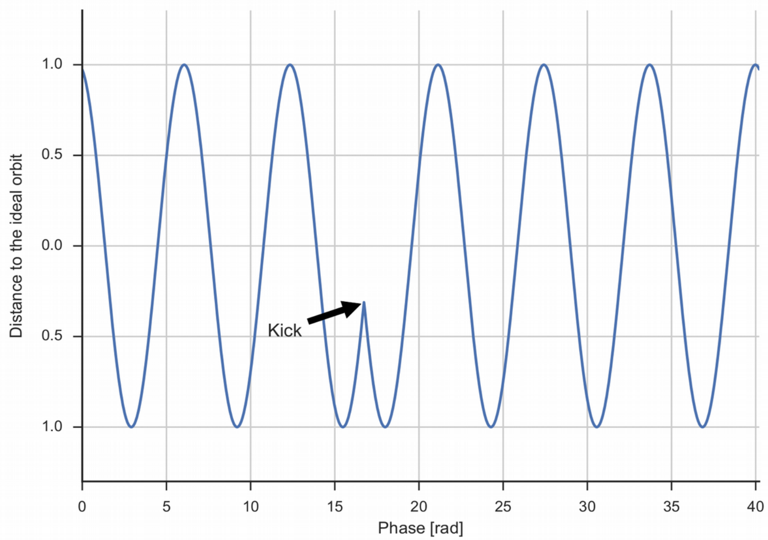
Localization or orbit perturbations
1 – Problem



Problem setting:

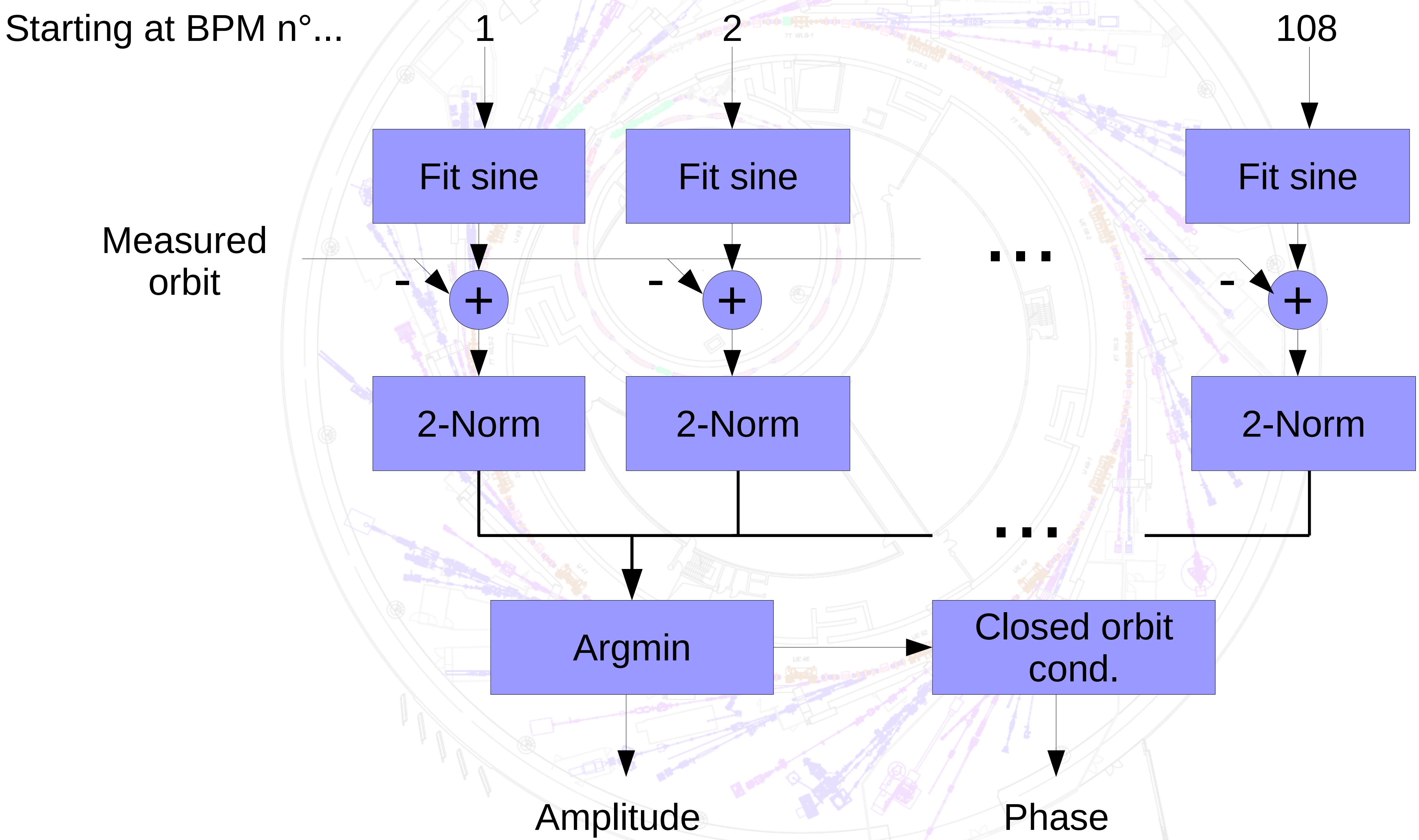
- we have an orbit
- we have ONE perturbation

To find the kick, see the orbit as below.

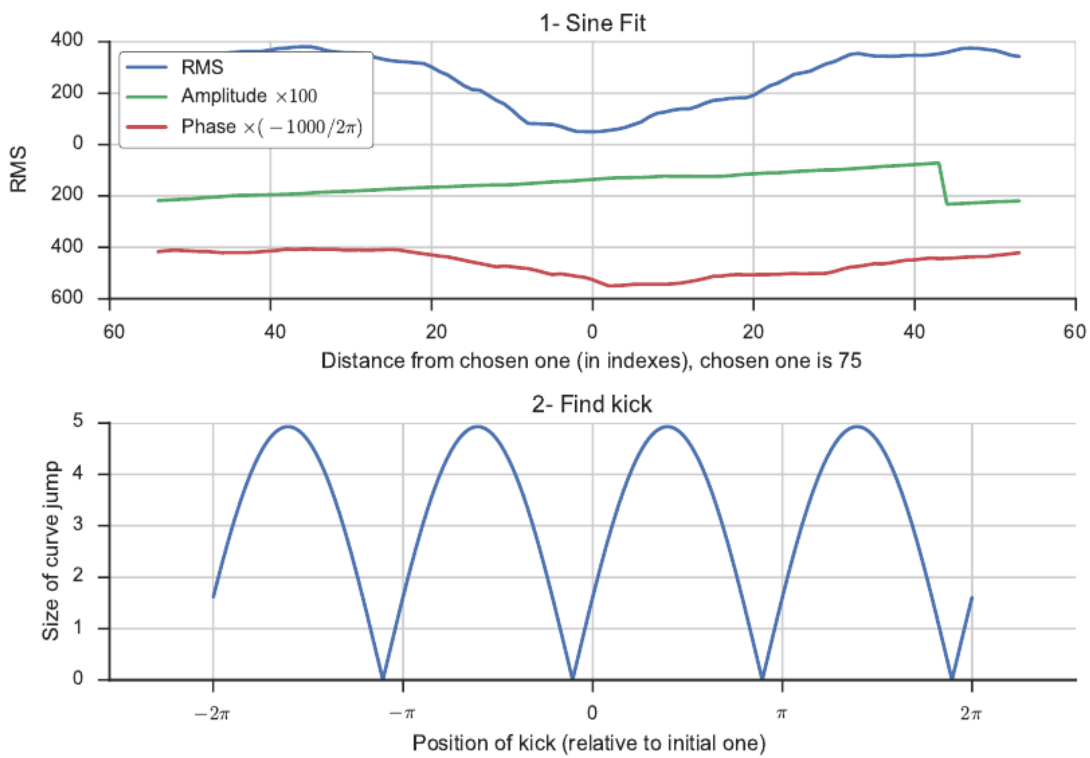


Localization or orbit perturbations

2 – Algorithm



Localization of orbit perturbations
2 – Algorithm



Algorithm

1) Find a best fitting sine left and right of each BPM
2) Pick the best result
3) Refine the kick position: change the phase to verify the closed orbit condition

Localization of orbit perturbations
3 – Results