Design of the ATF2 FB/FF Systems

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Introduction

ATF2: Final focus test beam line facility at KEK

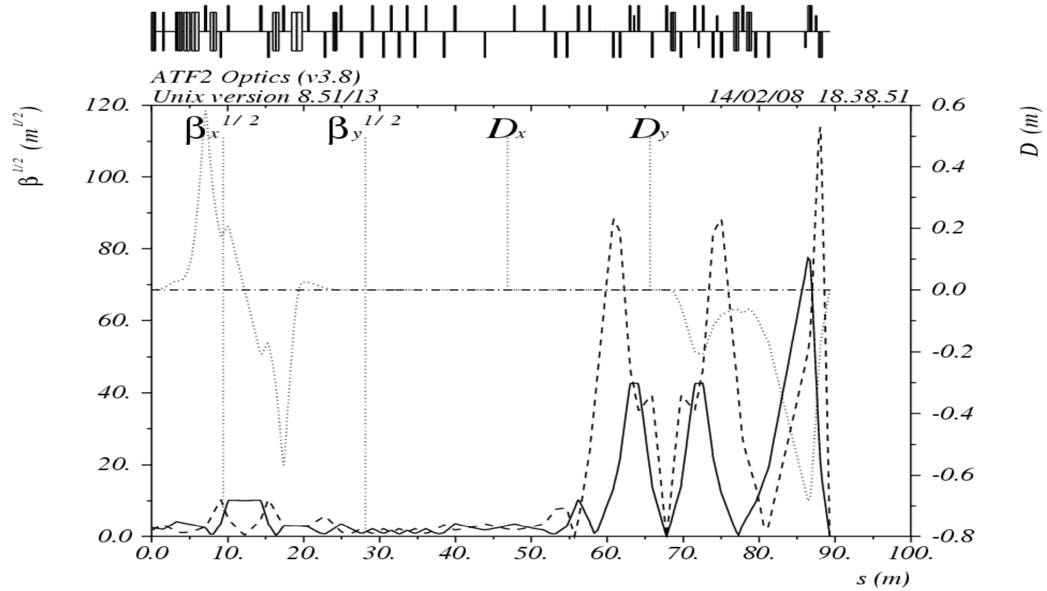
In principle the ATF2 optics design is identical to that for the ILC in spite of the two order of magnitude lower beam energy (Raimondi & Seryi final focus system).

Perfect bed to make experiments on beam dynamics and technologies for beam delivery systems in linear colliders.

The two major goals for the ATF2 facility:

- achivement of a 30-40 beam sizes
- control of beam position down to 5 % of the rms beam size at the IP, which will require a stability control better than 1μm at the ATF2 final focus entrance.

M. Woodley optics v3.8



Parameter	ATF2		ILC (nominal)
Nominal energy [GeV]	1.3		250
Energy spread [%]	~ 0.1		~ 0.1
$\gamma\epsilon_y^*$ [nm·rad]	30		40
$\gamma\epsilon_x^*$ [nm·rad]	3000		10000
β_y^* [mm]	0.1		0.4
β_x^* [mm]	4.0		21
Bunch length σ_z [mm]	8.0		0.3
Single bunch operation:			
	Goal A	Goal B	
N_{bunch} [10^{10}]	0.5	0.5	–
Multibunch operation:			
	Goal A	Goal B	
n_{bunch}	1-20	3-20	2625
N_{bunch} [10^{10}]	0.5	0.5	2

Introduction

Bunch-Bunch FB Systems

Aim:

- Position and angle jitter corrections to achieve goal 2: control of the beam position at level $\approx 5\ \%\ \sigma^{*}_{y}$ (ATF2 goal 2)

Studies on progress:

- Design of a fast intra-train FB to be located in the ATF2 EXT line (FONT project)
- Design of a fast intra-train IP-FB to achieve the desired position control
- Simulations to understand the dynamics of the system, assuring an optimal performance of the FB system
- Realistic simulations: understand and determine the several error sources
- Joint operation of the different FB systems: bunch-bunch, pulse-pulse (FB integration)
- Check the robustness of the model and possible integration in flight simulator (collaboration with other tasks)

EXT intra-train FB
The FONT project

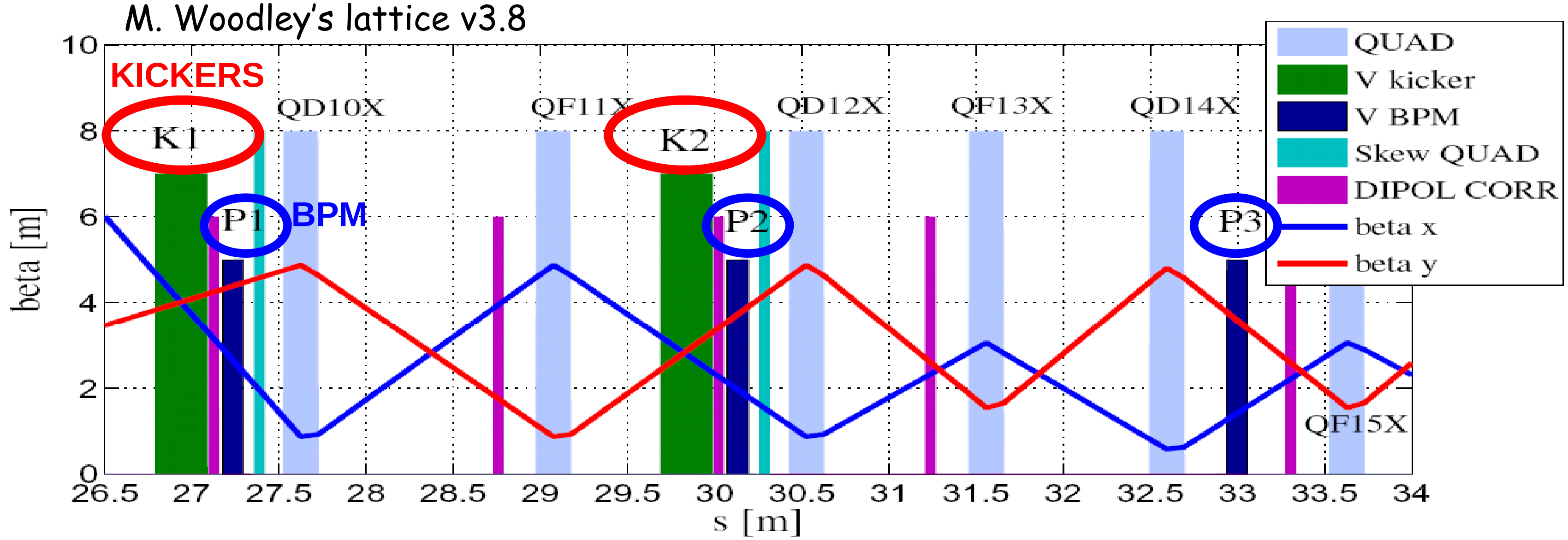
- The ATF2 beam line will allow us to test fast intra-train feed-back (FB) and feedforward (FF) systems for beam stability:
  - FB system in extraction line (to operate in multibunch mode)
  - FF ring to extraction line (which can operate in multibunch or single bunch mode) :
    - to model the ILC Turnaround trajectory FF system [A. Kalinin, P. N. Burrows, "Turnaround feed-forward correction at the ILC", EUROTeV-REPORT-2007-050, June 2007]
    - to stabilise the beam in the ATF2 correcting the jitter originated in the DR
- FONT: Feedback systems on Nanosecond Timescales. [See the talk by Philip Burrows]

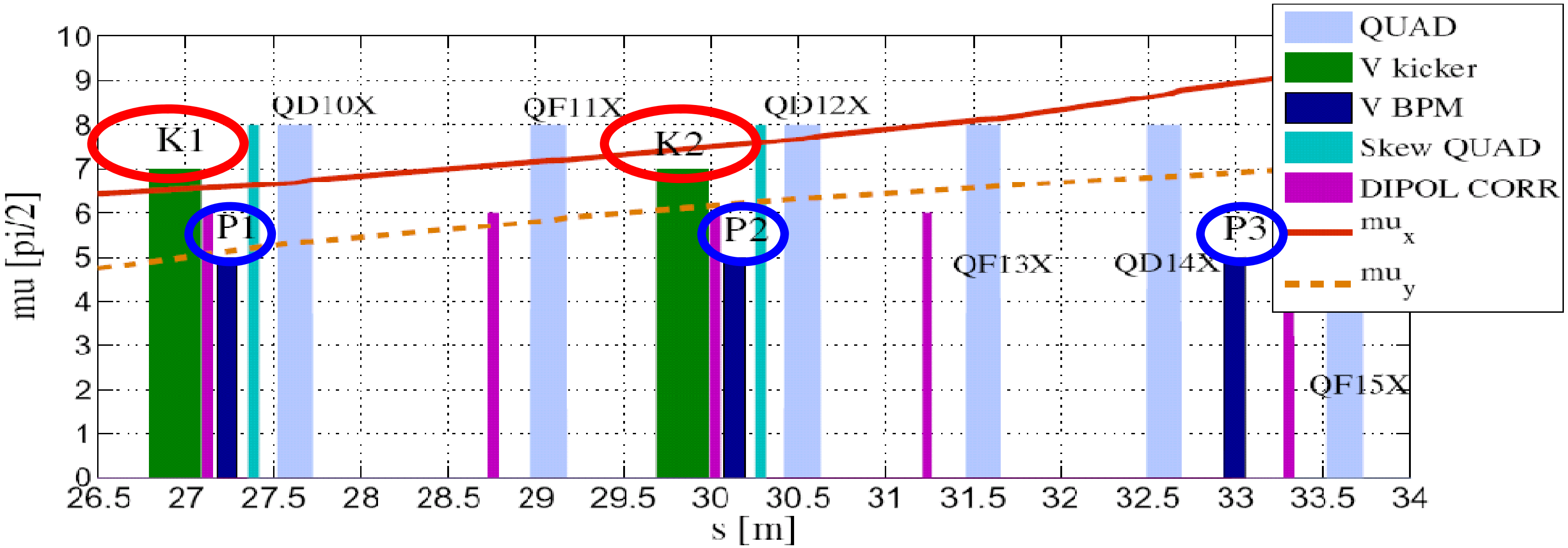
Summary of the results of latency time of the previous FONT tests

Test	Facility	Train length [ns]	Bunch spacing [ns]	**Latency** [ns]
FONT1	NLCTA (SLAC)	170	0.087	67
FONT2	NLCTA (SLAC)	170	0.087	54
FONT3	ATF (KEK)	56	2.8	23
FONT4	ATF (KEK)	420	140	132

FONT5 is being designed to perform both FB and FF tests at ATF2!

Layout of FONT at ATF2





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Tentative kicker parameters
(approximate estimate)

Kick angle of fast stripline kicker:

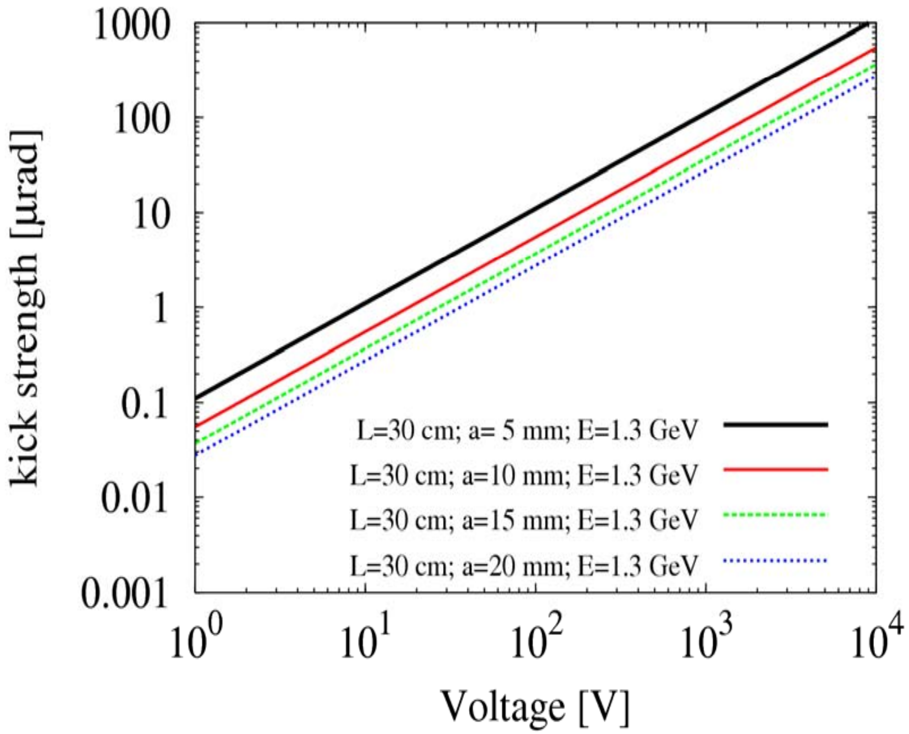
$$\Delta\theta = 2g\frac{eV}{E}\frac{L}{a}$$

"g" is the stripline coverage factor or geometry factor:

$$g = \tanh\left(\frac{\pi\omega}{2d}\right) \leq 1$$

(determined by the shape of the electrode)

V: peak voltage
E: beam energy (1.3 GeV)
R: impedance (50 Ω)
L: kicker length (30 cm without flanges)
$a=2r$: kicker gap width (~15 mm)
r: half gap



Rise and fall times of the pulse : < 150 ns (avoiding crosstalk between subsequent bunches)

For example: a=15 mm; kick of 10 μrad ✹ 🕔 0.4 kV
a=15 mm; kick of 100 μrad ✹ 🕔 3.0 kV

Simulation set up

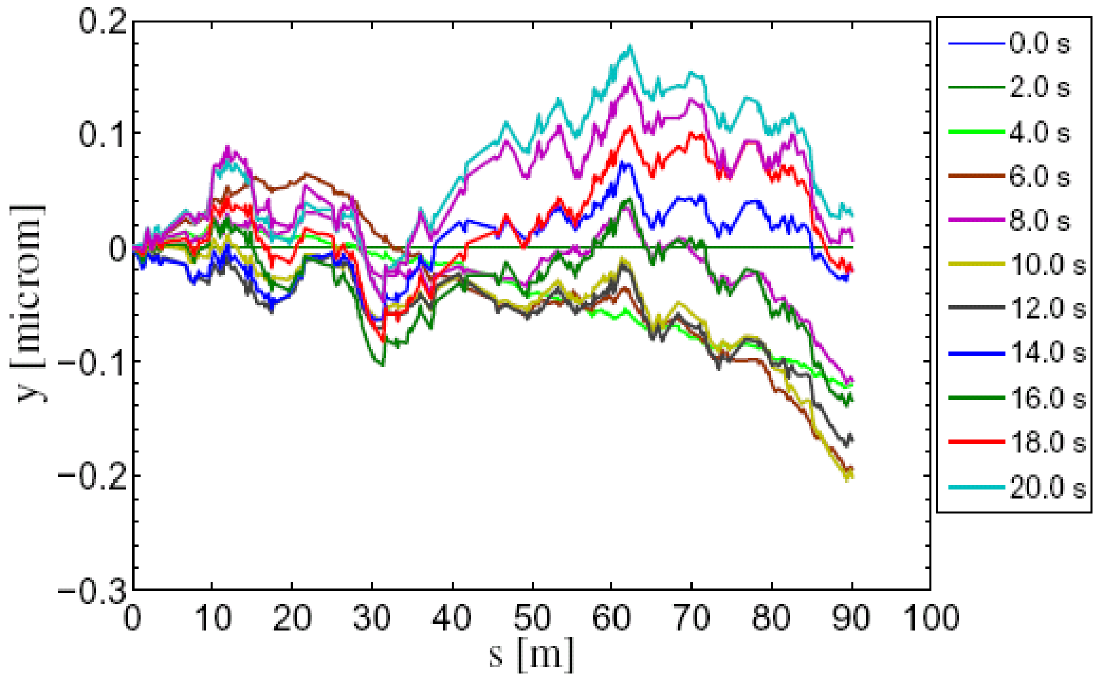
- Using the tracking code PLACET-Octave (developed at CERN)
- First only considering the y, y' correction (most critical). Straight extension to x, x' correction
- Study the jitter propagation
- EXT-bunch-bunch FB system:
  - Two kickers (K1 & K2) for vertical position (Y) and angle (Θ) correction
  - Three pickups (P1, P2, P3) for transfer matrix reconstruction and for FB loop
  - Assuming a BPM rms noise of 1 μm (input BPM resolution)
  - Assuming a kicker strength error (Here we assume < 0.5 %)
- Normal random distribution of initial vertical jitter positions with a width of +/- 40 % σ_y (rms beam size at the entrance of the extraction line)
- Apply static misalignment using "standard errors" + alignment procedure (connection with other tasks: BBA methods and orbit-steering)
- Introducing ground motion (GM) misalignment (model K)
- IP-bunch-bunch FB system:
  - IP-BPM (resolution ~ nm)
  - Kicker near IP
  - More detailed study in progress

Simulation set up

Impact of the GM in the vertical element position

For the simulation we have used a GM package which is implemented in the tracking code Placet and is based on the models provided by A. Seryi
[A. Seryi, http://www.slac.stanford.edu/~seryi/gm/model]

Vertical misalignment of the elements in the ATF2 beam line applying the GM **model K** (KEK site) at different time moments:

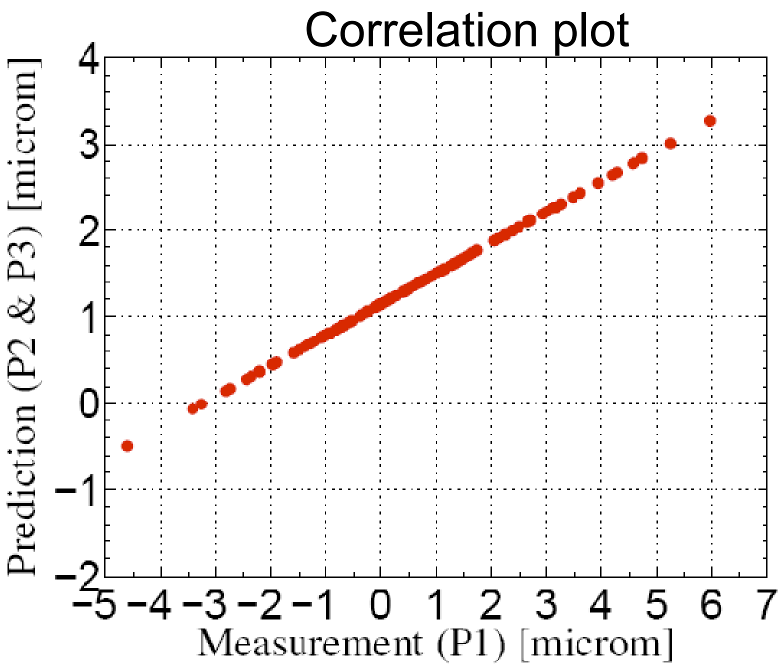


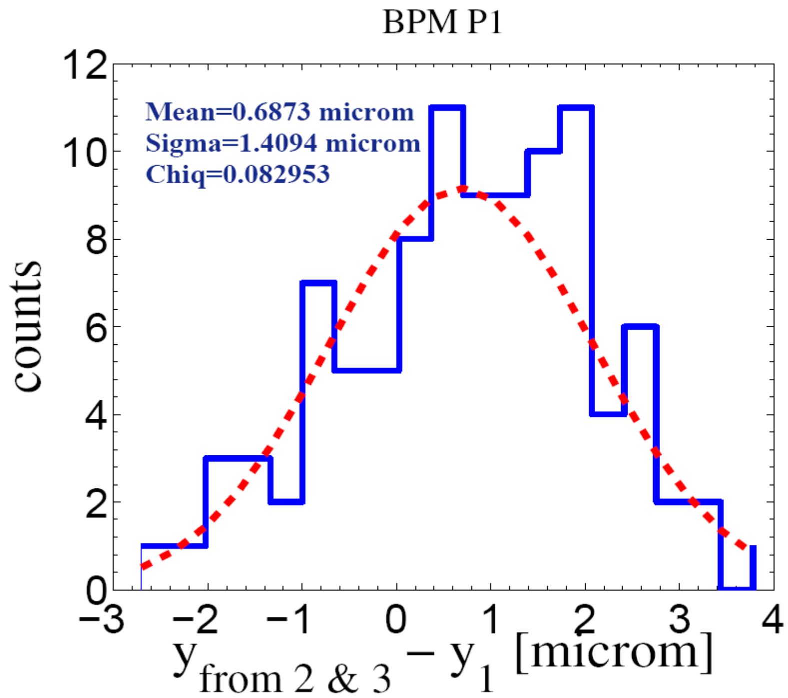
BPM resolution for FONT at ATF2

- From simulation results using the tracking code Placet-octave for 100 shots

It is obtained for BPMs with input noise of 1 μm and shows the method accuracy for the given statistics

$$\sigma_{\text{reso},i} = \sqrt{\langle (y_{i,\text{measured}} - y_{i,\text{predicted}})^2 \rangle}$$





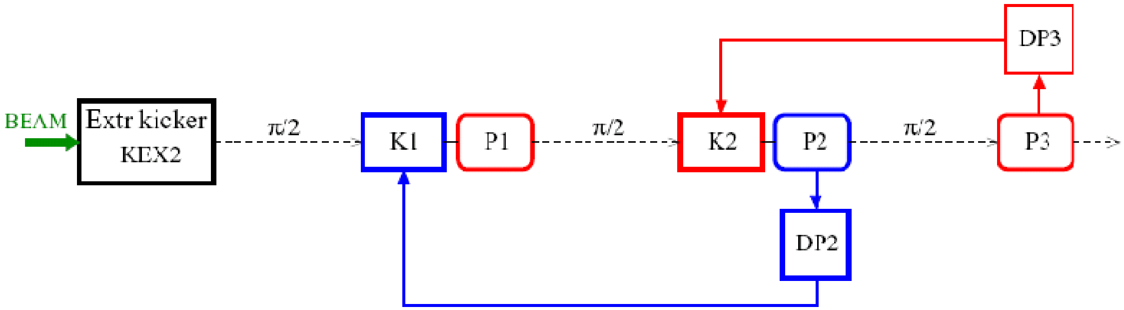
Simulation of the EXT Bunch-Bunch FB

(in the context of FONT)

Using a SVD algorithm:

- The SVD algorithms easy to implement and very robust. Commonly used in orbit steering correction (using several correctors and BPMs), it can also be used for fast FB
- In the case of a fast-FB important to select appropriate BPMs and correctors for the FB (optimisation of the FONT element positions)
- Measure the position and angle jitter of the first bunch in a train (if bunch- bunch correlation)
- Knowing the response matrix, apply the SVD method to correct the rest of the bunches of the train

Alternative: using a classical PID control loop



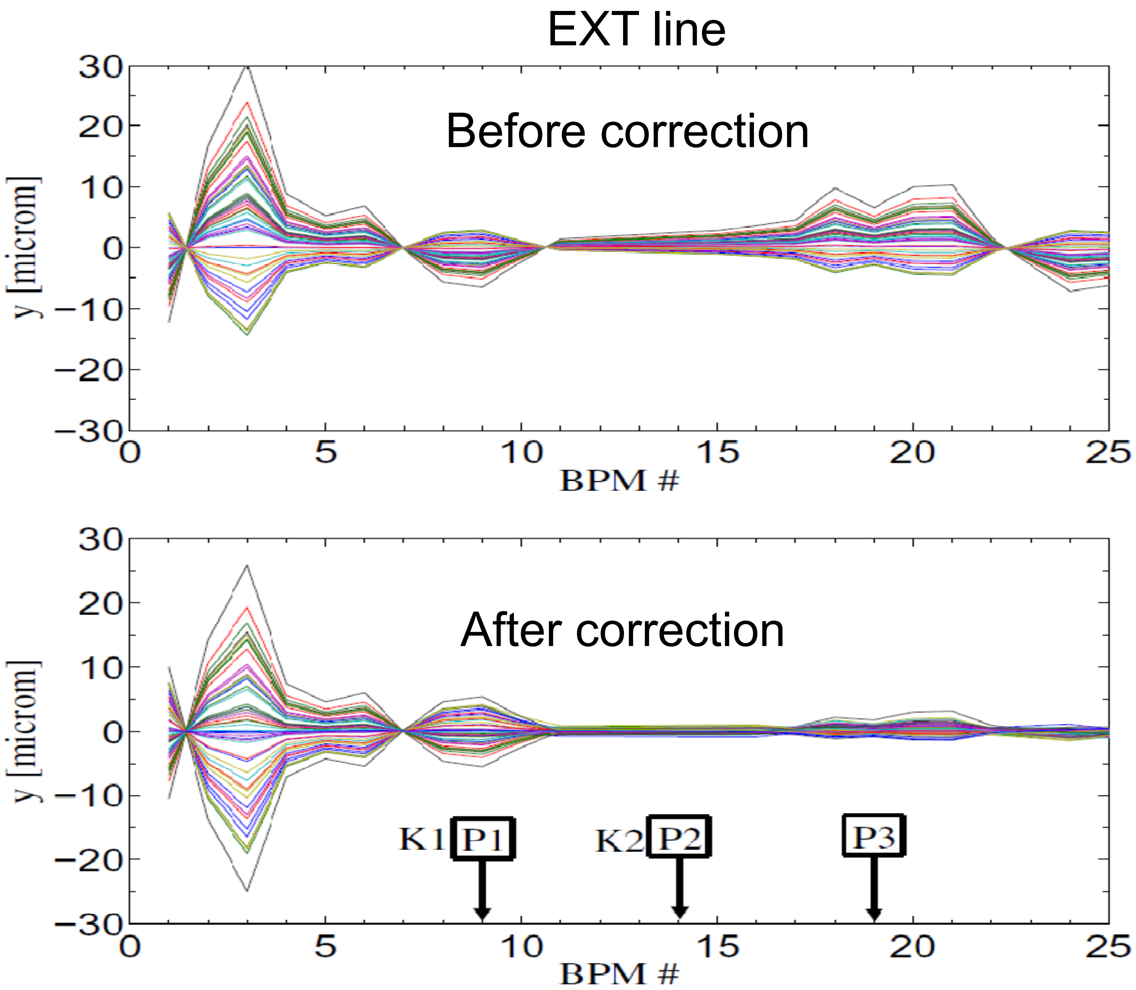
Time of flight P2-K1 = 10.65 ns
Time of flight P3-K2=10.53 ns

Example #1. Vertical position correction.

Residual jitter propagation

Optimistic case:

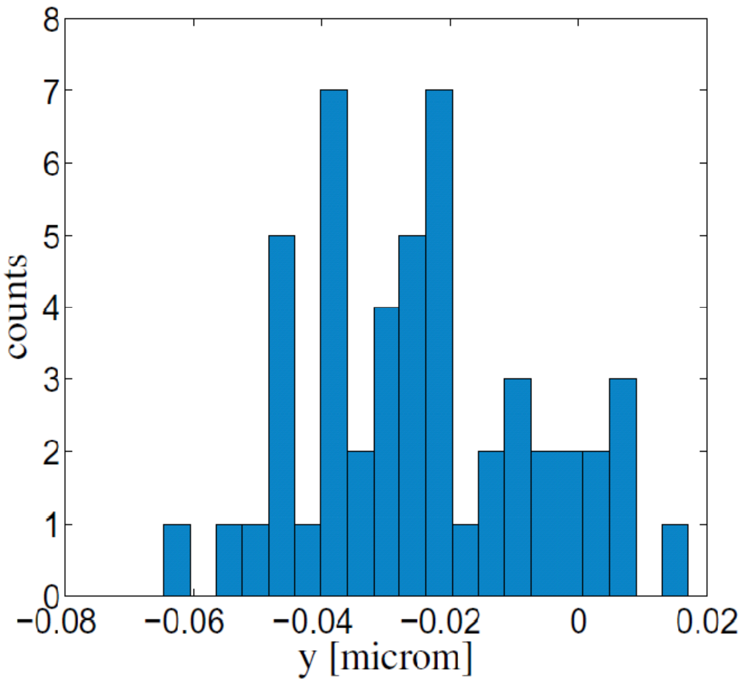
- Example for 100 shots with $40\ \%\ \sigma^*_y$ initial jitter
- Only applying GM model K (10 s)
- No static misalignment
- Input BPM resolution: 1 μm
- Kicker strength error: 0.5 %
- Applying then EXT shot-shot FB correction



Example #1. Jitter distribution at the IP

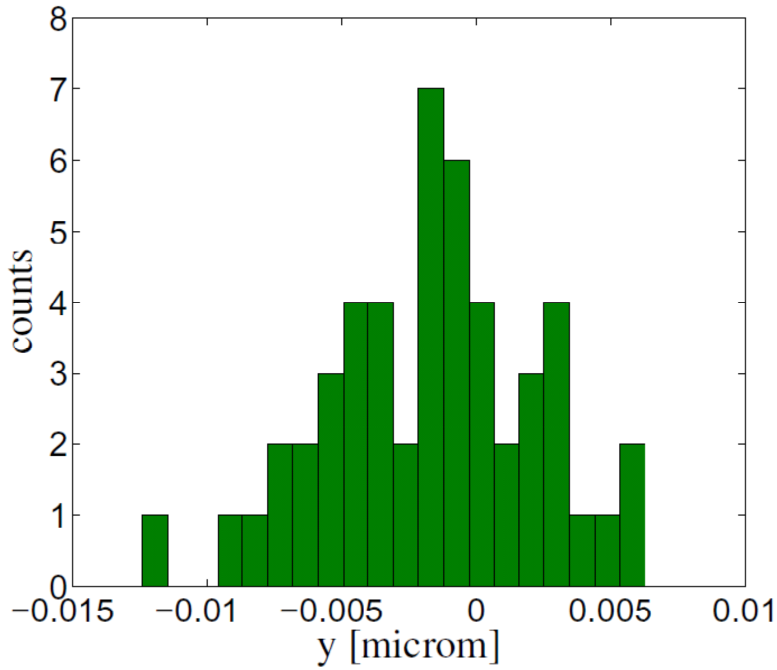
Assuming 1 μm BPM resolution and 0.5 % kicker strength error

Before correction



Mean = -0.0244 μm
Sigma= 0.0183 μm

After correction



Mean = -0.0016 μm
Sigma= 0.0039 μm

≈ a factor 5 reduction

Example #1. Sensitivity to BPM resolution

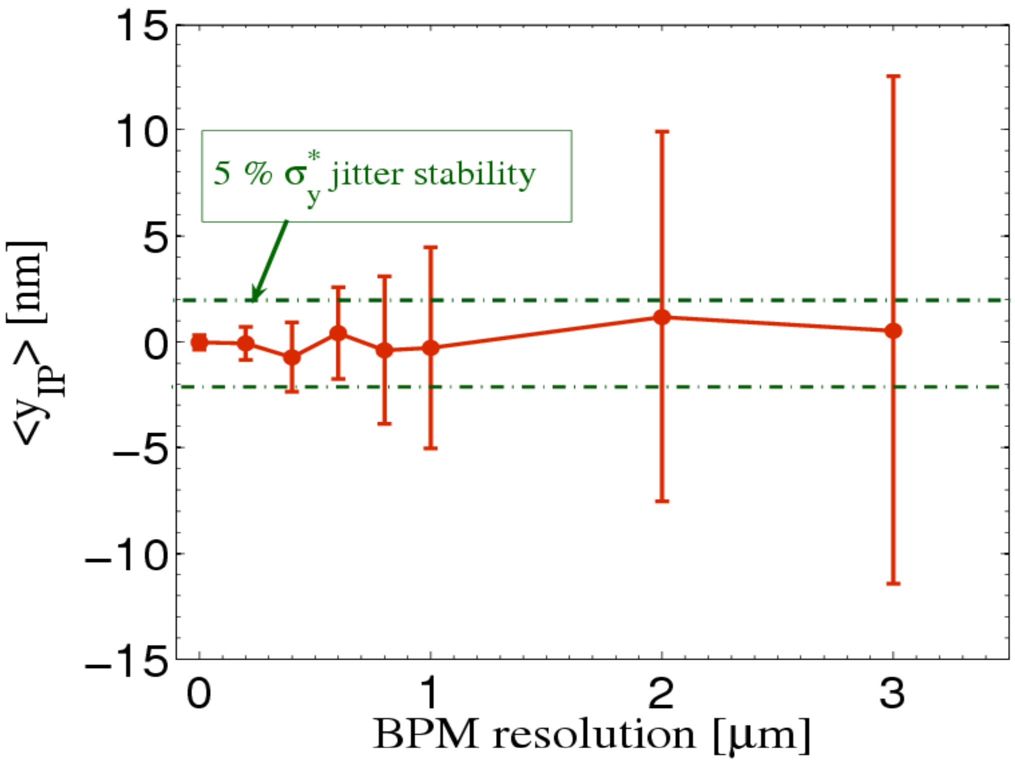
Considering an initial random jitter distribution with a rms error of 40 % of the initial beam size

Each point is the average over 50 seeds

The error bars correspond to the standard deviation

Residual jitter at IP vs BPM resolution:

If we consider that the residual jitter at the IP < 5% σ^*_y then BPM resolution must be better than 1 μm. With 1 μm BPM resolution a control position ~ 10% σ^*_y may be feasible



Example #1. Sensitivity to kicker strength error

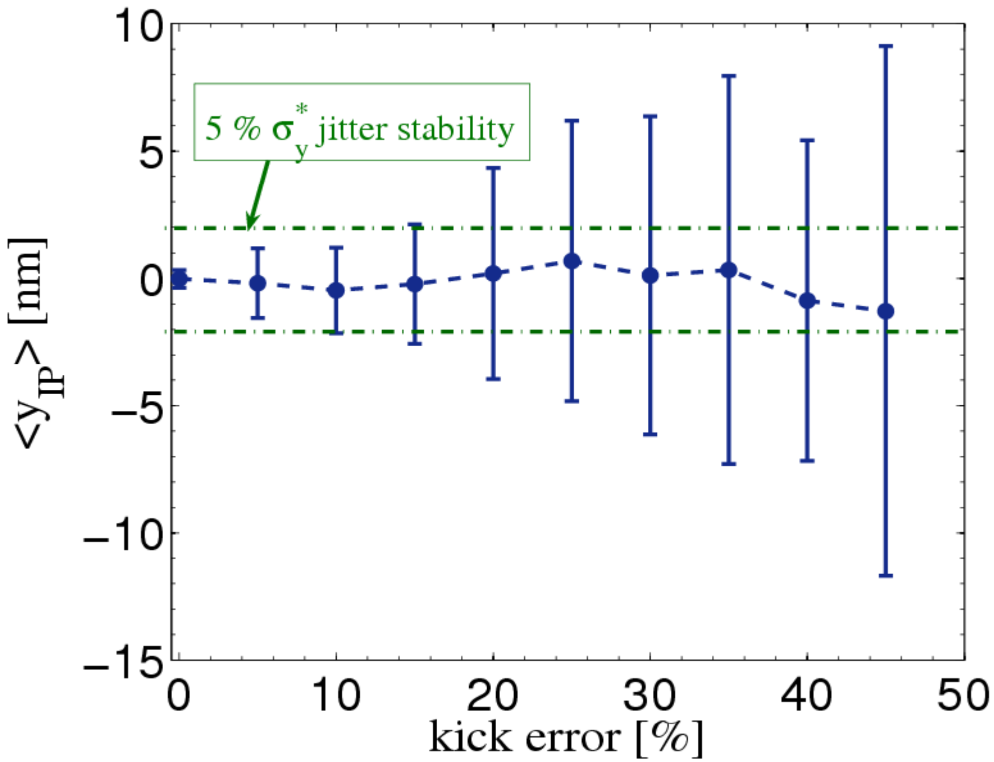
Considering an initial random jitter distribution with a rms error of 40 % of the initial beam size

Each point is the average over 50 seeds

The error bars correspond to the standard deviation

Residual jitter at IP
vs kicker strength error
(FB gain error):

In this case we obtain that the mean value of the residual jitter is practically constant, and the standard deviation increases as the kick strength error.
Tolerable kick error < 10 %
of the kick angle

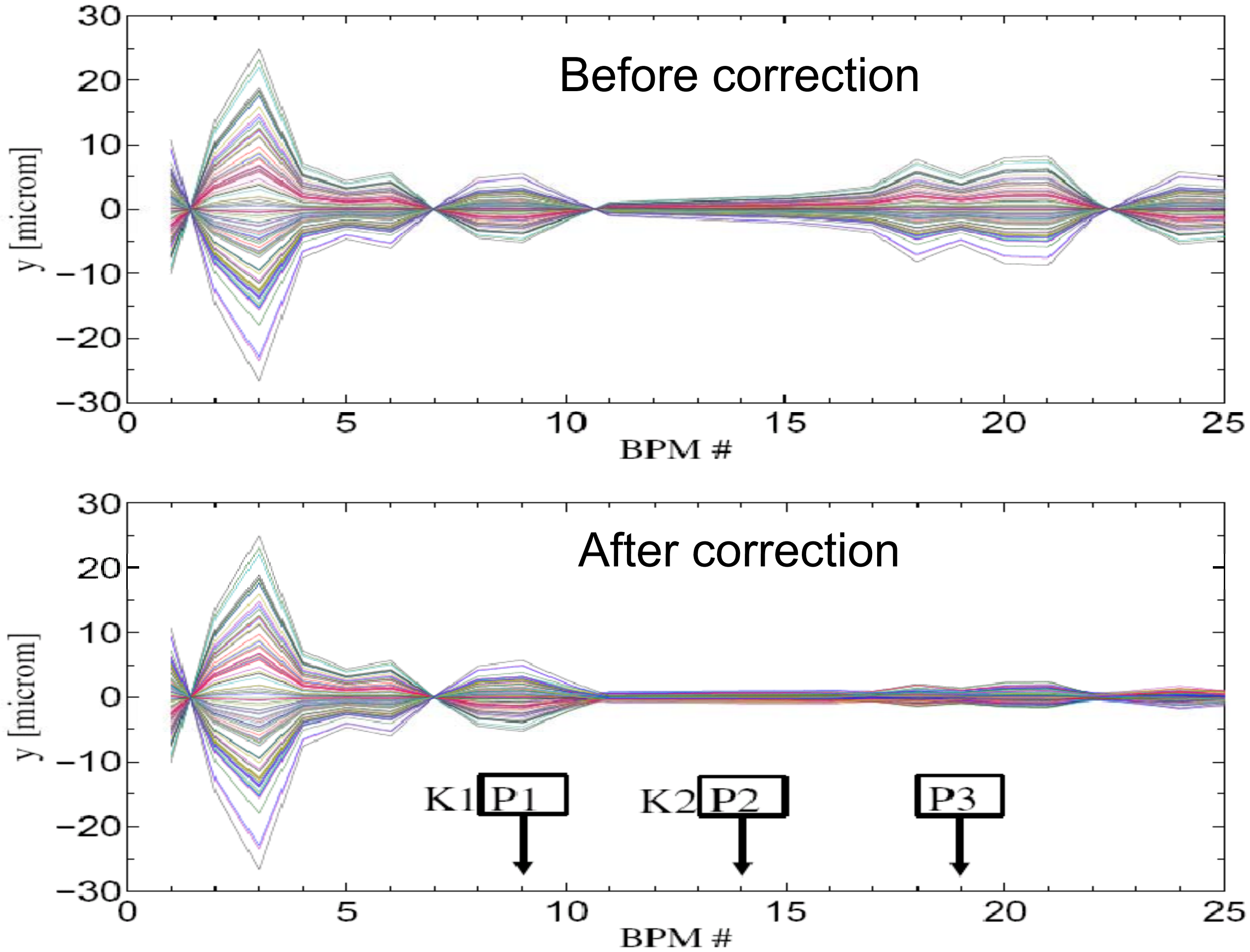


Example #2 of vertical position correction.

Residual jitter propagation

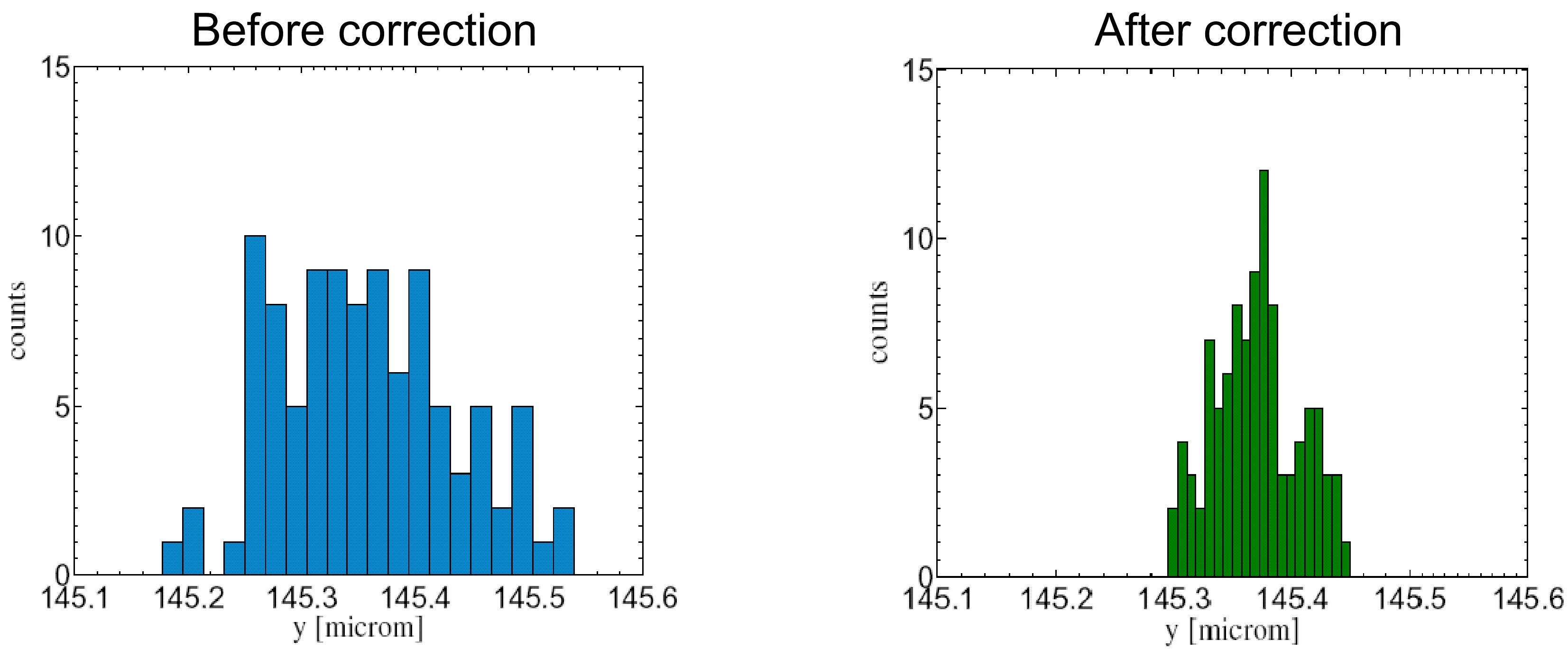
A little more realistic:

- Example for 100 shots with 40 % σ^*_y initial jitter
- Including standard static misalignment errors + BBA technique
- Applying GM model K (10 s)
- Input BPM resolution: 1 μm
- Kicker strength error: 0.5 %
- Applying then EXT shot-shot FB correction



Example #2. Jitter distribution at the IP

The EXT fast intra-train FB help to improve the shot-to-shot deviation at the EXT line. However, downstream … big impact from the misalignment of the quadrupoles and sextupoles in the FFS. The main impact coming from the final doublet alignment errors



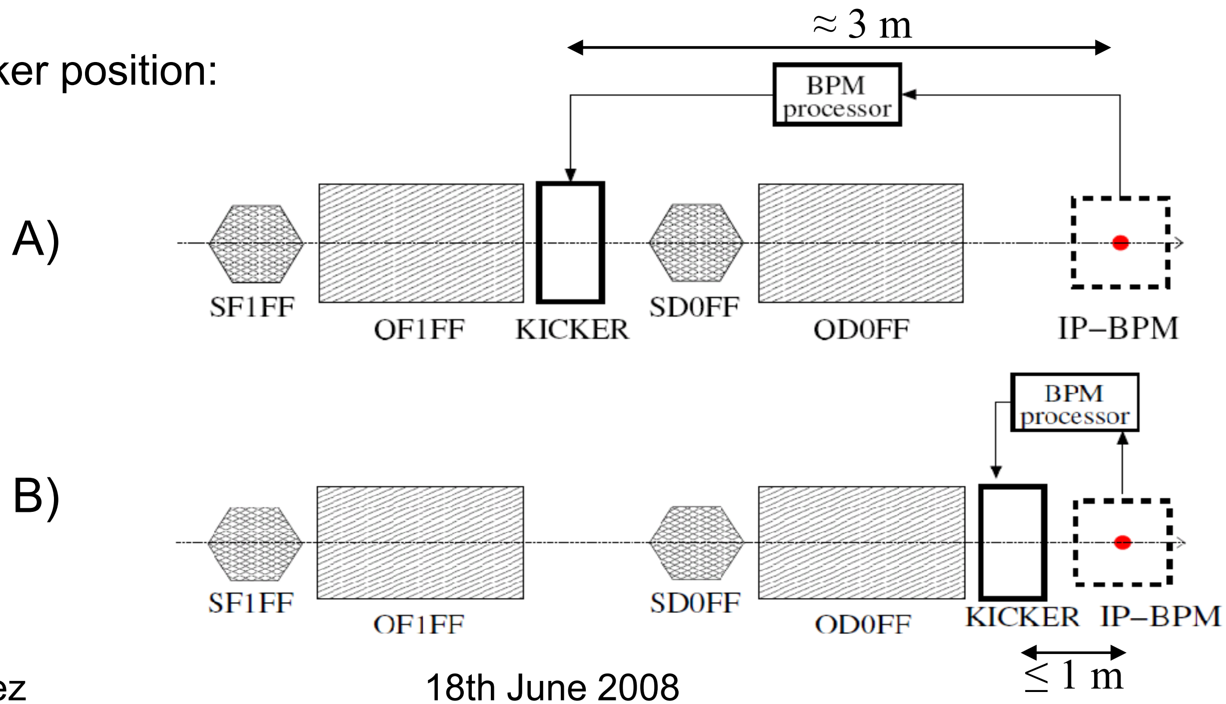
Necessary the combination of BBA methods, orbit steering techniques, feedback systems (at EXT and IP), …

IP Bunch-Bunch FB

Using Honda IP-BPM with nm resolution level
(Y. Honda et al., Phys. Rev. ST-AB 11, 62801 (2008))

Necessary:
Detailed design and optimisation of a robust FB algorithm:
PID control loop, adaptive system …?
Performance simulation and study of the limitations

Specify kicker position:

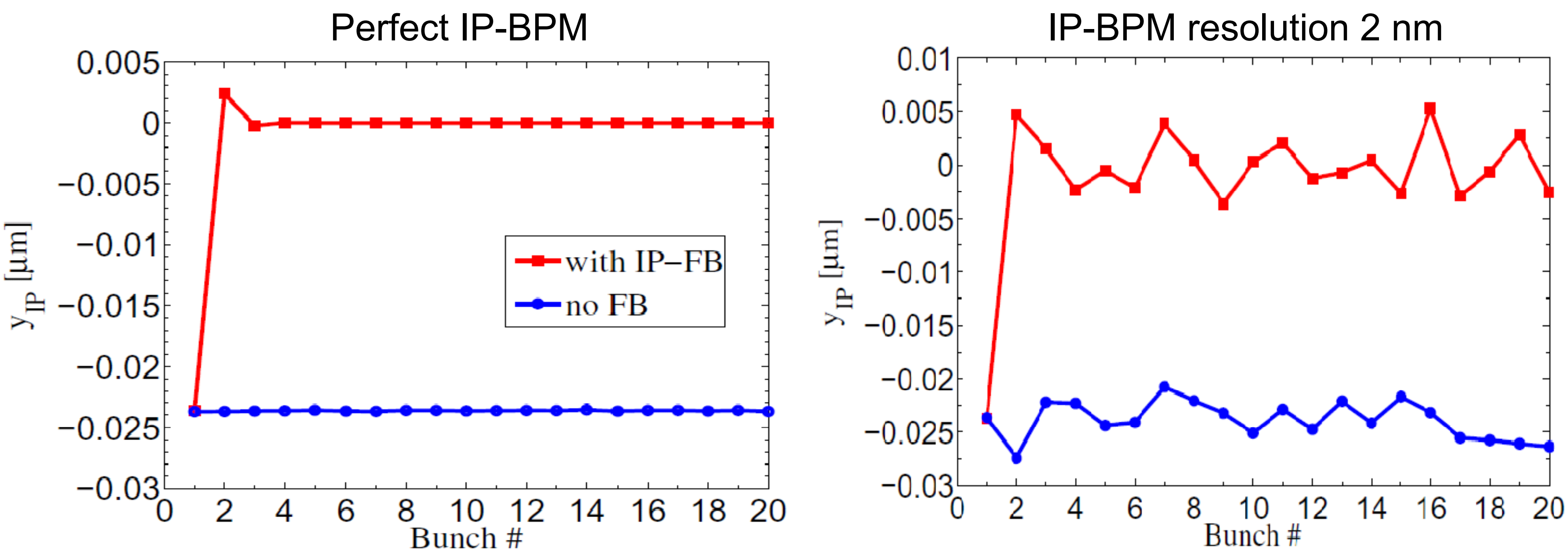


Simulations of the IP Bunch-Bunch FB

Simple model:

10 seconds of GM model K (1 seed), no other vibrations ⇒ mean beam IP offset ≈ -0.024 μm (0.6 σ^*_y)

PI control loop. Gain tuning: K_p=0.8, K_i=0.85

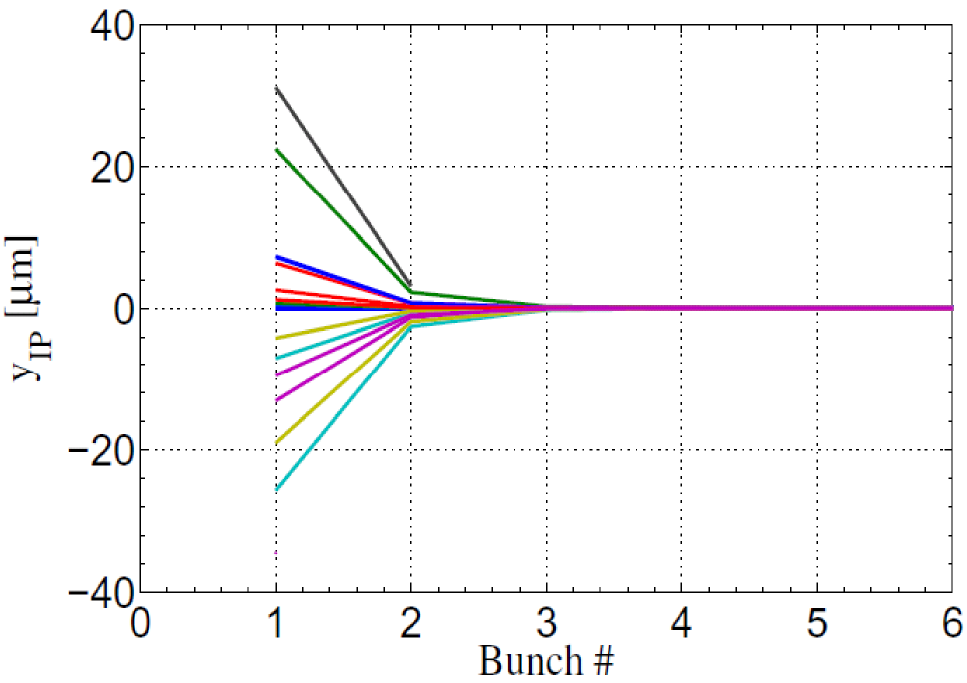


Kick ≈ 0.023 μrad

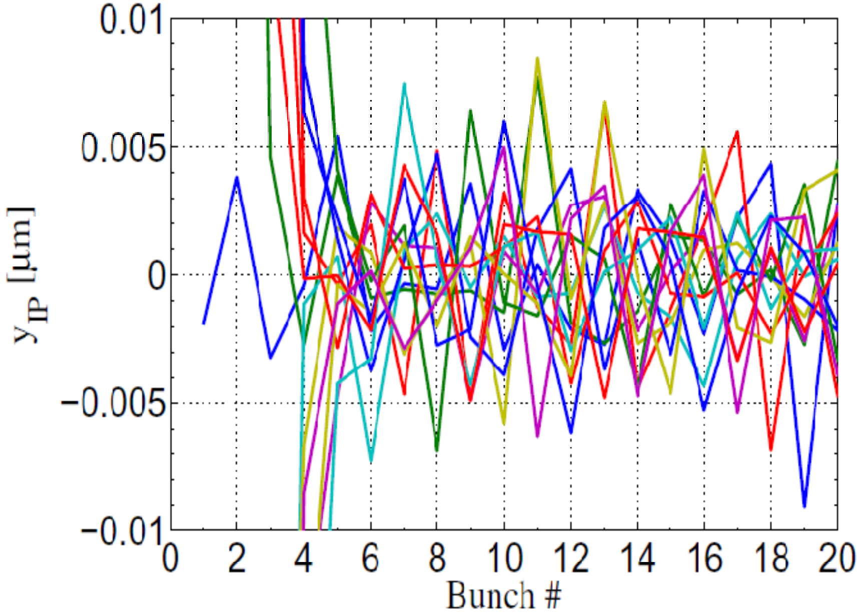
Simulations of the IP Bunch-Bunch FB

Performance of the IP-FB system:

- IP-BPM resolution 2 nm
- For several FD quadrupole position jitters in the interval [0,30] μm (1seed per jitter)



Zoom:

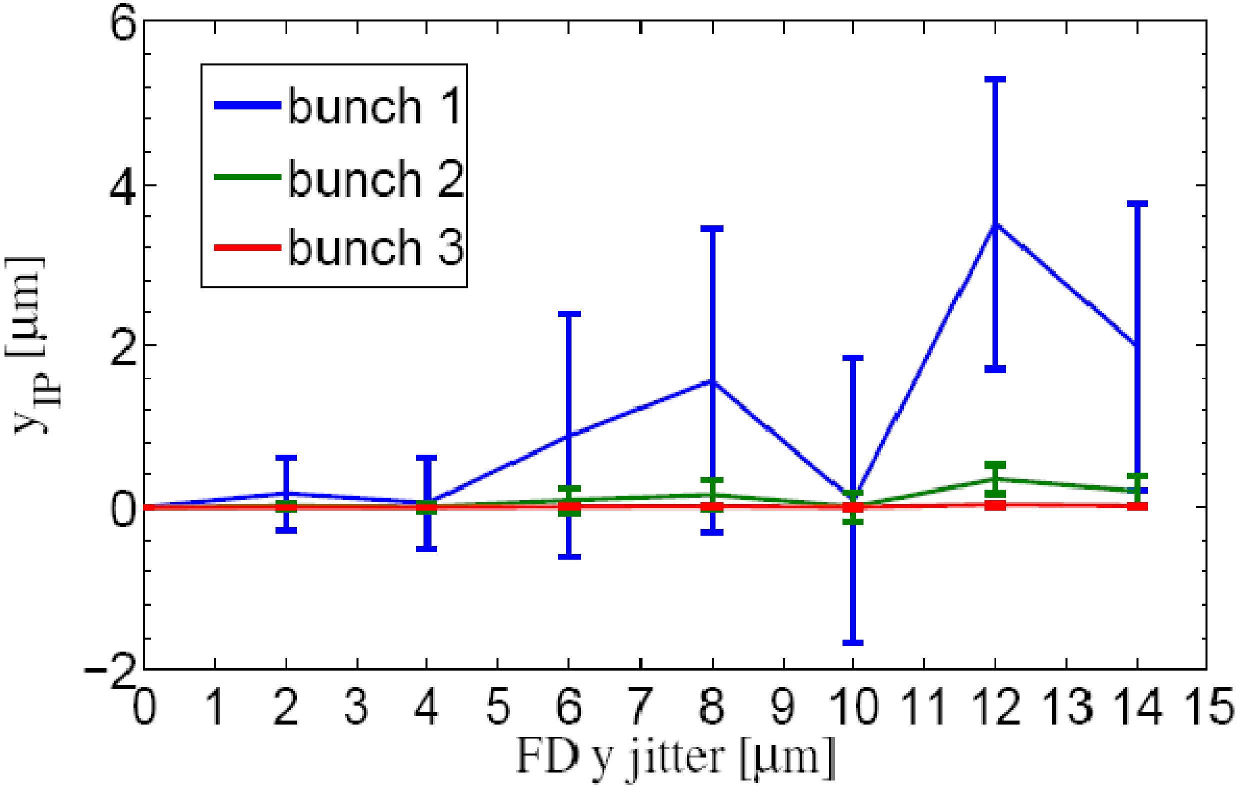


Initial offset 30 μm ✸ Kick 🕔 25 μrad

Simulations of the IP Bunch-Bunch FB

Vertical bunch position at the IP versus the final quadrupole doublet error position jitter

Each point represent the average over 50 machines. The error bars correspond to the standard error $\mathrm{std}/\sqrt{50}$



FB Integration (preliminary)

- Misalignment with survey errors (https://confluence.slac.stanford.edu/display/ATF/Software+Projects)

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- BBA procedure (preliminary): 11 correctors (ZH & ZV) and 50 BPMs along the lattice to minimise $\sqrt{(\sigma^*_x \sigma^*_y)}$. Establish a more realistic model (inter-tasks collaboration)

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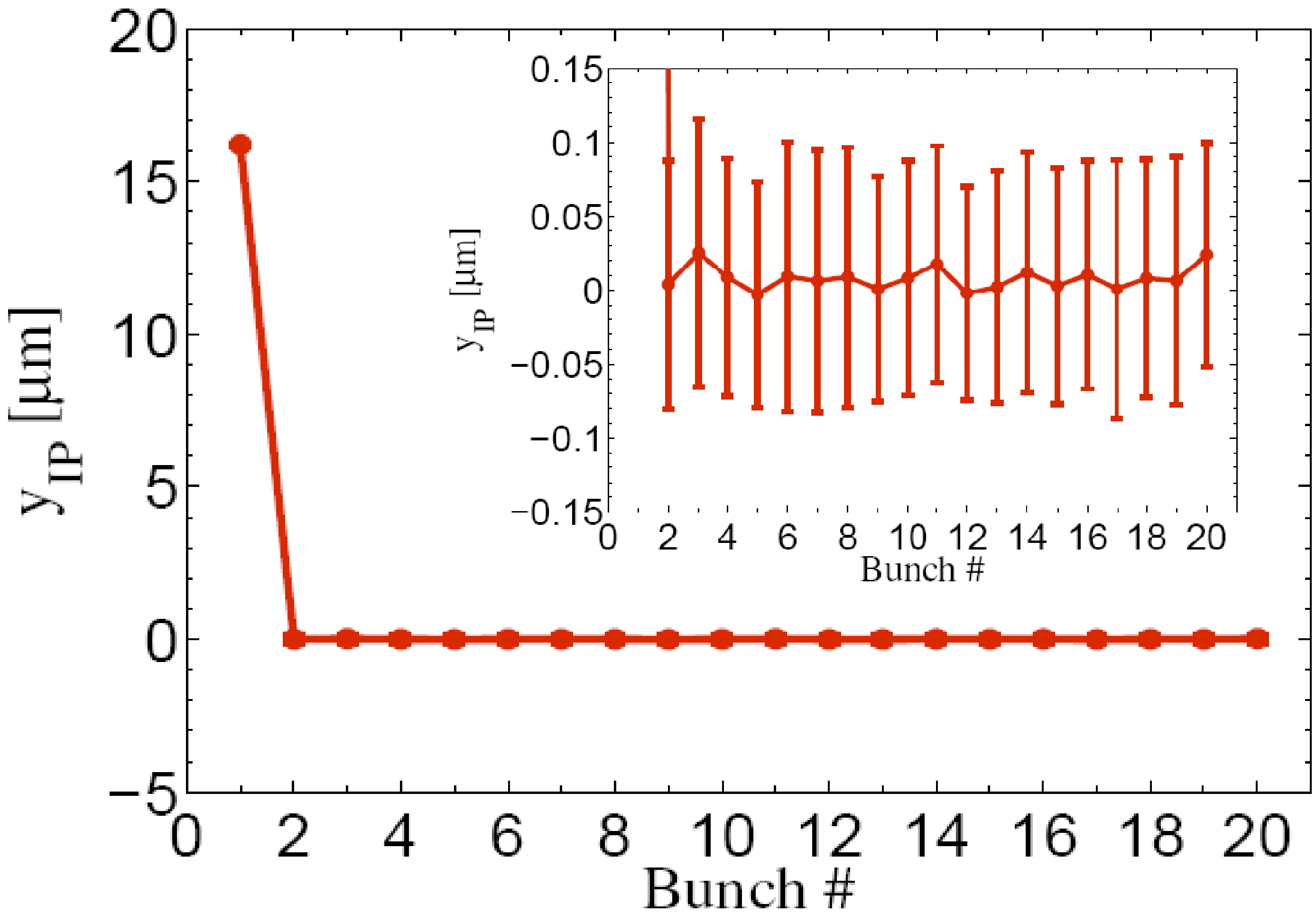
- EXT-FB & IP-FB (possibility to join both using a common response matrix and SVD method? In reality may be challenging!)

- Simulated 100 events (pulses), with 3 (20) bunches per event

- 40 % σ_y (rms beam size at the beginning of the EXT line) offset

- 10 % σ_y position jitter between events

FB Integration (preliminary)



WORK ON PROGRESS!

Summary and ongoing studies

- We have presented the layout of an intra-train feed-forward/feedback system to be placed in the extraction line of ATF2 (in the context of the FONT study)
  - Optimum BPM and kicker positions
  - Study of the necessary BPM and kicker parameters to show the feasibility and accuracy of bunch-to-bunch fast jitter correction (FB system latency budget ~150 ns)
- The necessary hardware is currently being developed and tested. The FONT FB hardware can be carried over to FF (see the talk by P. Burrows)
- A Placet-octave based model of the FONT system in the ATF2 beam line has been set up. This model allows us to perform beam dynamics tracking simulations with bunch-to-bunch jitter correction, including element misalignments and GM
- We plan to improve the model, adding the missing error sources
- Optimisation of the FB parameters (gain factors). Check the model robustness and benchmarking with other codes (?)
- Design of a IP intra-train FB system based on IP-BPM of 2 nm resolution
- Performance studies. Simulation multibunch mode (3/20- bunch train)
- Joint operation of the different FB system (EXT + IP). Integrated simulations with slow and fast FB systems. At this point, very important collaboration with other tasks:
  - Extraction line orbit correction/Feedback
  - FFS Orbit-Steering/FB
  - BBA alignment

Appendix
Simulations of the IP Bunch-Bunch FB

- Using a PI control loop (discrete implementation):

$$u_k = u_{k-1} + K_p(e_k - e_{k-1}) + K_i e_{k-1}$$
$$k = 1, 2, \ldots, N_b$$

N_b: number of bunches
$e_k = r_k - y_k$: error to be corrected
r_k:set-point (in our case $r_k=0$)
y_k: process value
u_k: output value
K_p: proportional gain
K_i: integral gain

Gain coefficient Tuning, different methods:
- Manual tuning (trial and error!)
- Ziegler-Nichols (some trial and error, very aggressive!), …

Plan: try some automatic tuning algorithm (?).

To obtain the necessary kicker strength: interpolation in a curve IP offset vs kicker strength (previous scan)