Design and Simulation of Intra-train Feedback Systems at ATF2: Current Status and Future Plans

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for the FONT project group

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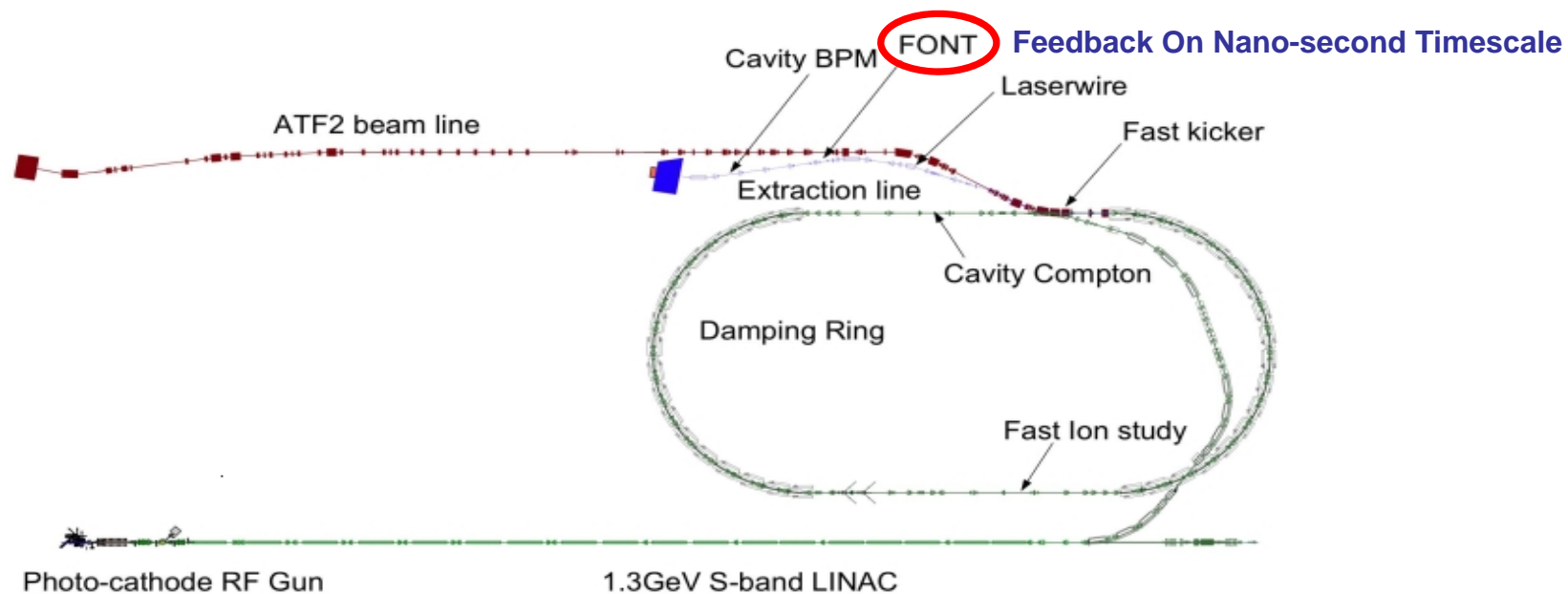 - Integration of FB systems
- Summary and ongoing studies

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).

The two major goals for the ATF2 facility:

1) achievement of 30-40 nm beam sizes

2) control of beam position down to 5% of the rms beam size at the IP, which will require a stability control better than $1 \mu m$ at the ATF2 final focus entrance.

Cavity BPM   FONT   **Feedback On Nano-second Timescale**

ATF2 beam line   Laserwire

Fast kicker

Extraction line

Cavity Compton

Damping Ring

Fast Ion study

Photo-cathode RF Gun   1.3GeV S-band LINAC

Bunch-Bunch FB Systems

Aim:

- Position and angle jitter corrections to achieve "ATF2 goal 2": control of the beam position at level $\approx 5\% \ \sigma^*_y$

Studies on progress:

- Design of a fast beam based intra-train FB to be located in the ATF2 EXT line (FONT project): to combat the ring extraction transverse jitters (for multibunch mode operation)

- Design of a fast beam based intra-train IP-FB: to combat jitter due to vibration of magnets in the FFS and reduce residual beam position jitter at the IP (for multibunch mode operation)

- 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

- Study the joint operation of the different FB systems: bunch-bunch, pulse-pulse (FB integration)

Layout of FONT at ATF2
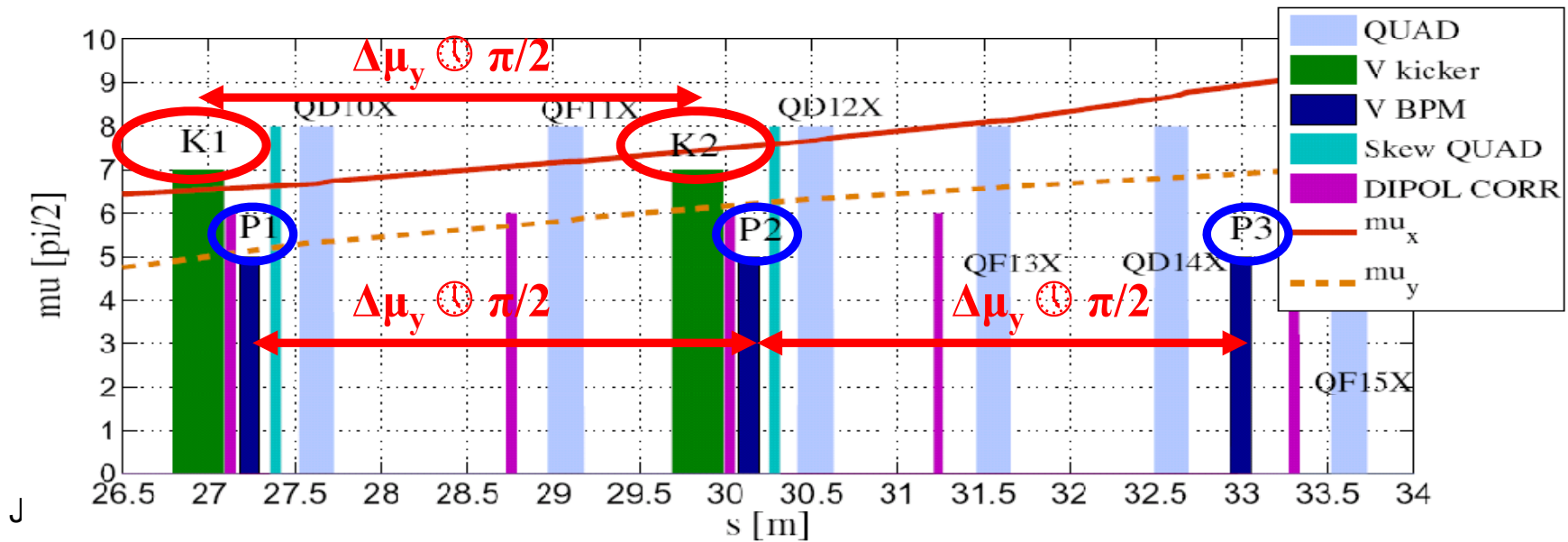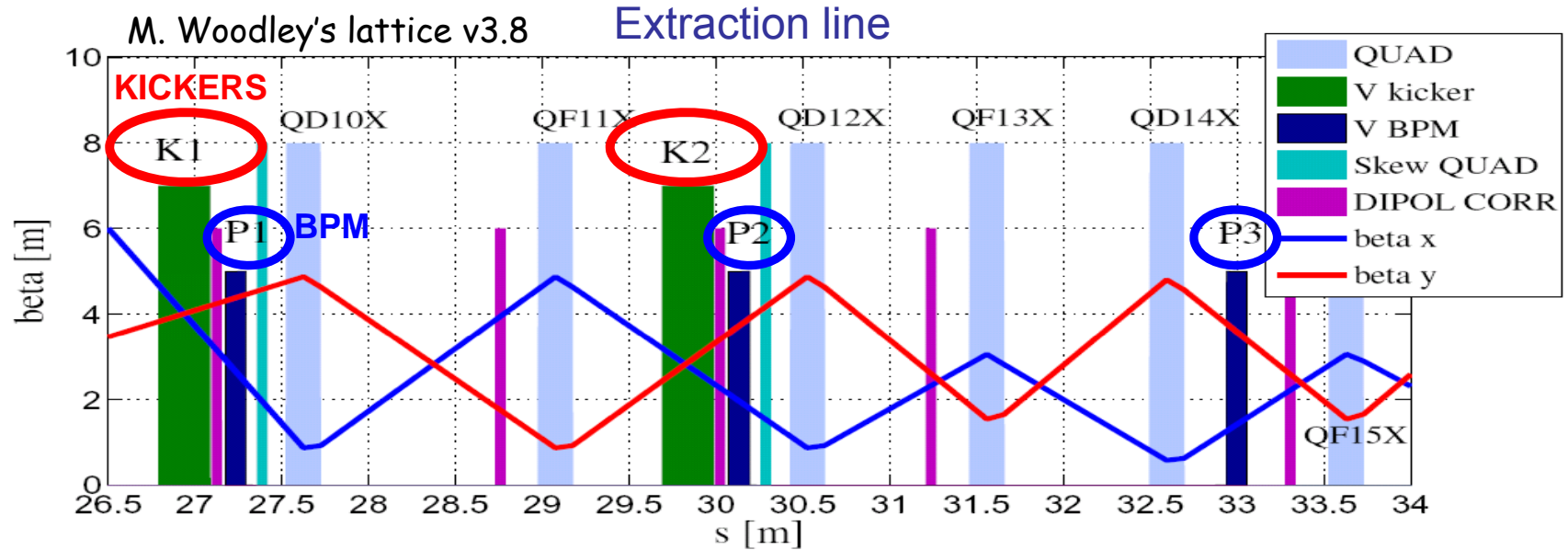
Layout of FONT at ATF2
Characteristics

- Hardware [*see talk by Phil Burrows*]:
  - A pair of stripline kickers (K1 & K2) for (y,y') correction
    Fast drive amplifiers

  - Three stripline BPMs
    Fast analogue front-end electronics

  - Digital FB processor(s)

- The EXT FB system can be carried over to feed-forward (FF):
  - Pre-extraction jitter correction

  - Based on correlation between vertical jitter measured in BPMs in the ATF damping ring and BPMs in the extraction line (FONT BPMs)

  - It could operate on a bunch-to-bunch basis as an intra-train "beam flattener", or on a pulse-to-pulse basis

Latency budget

- **Time of flight kicker – BPM:**   **9ns**
- **Signal return time BPM – kicker:**   **15ns**
-        **Irreducible latency:**   **24ns**

- **BPM processor:**   **7ns**
- **ADC/DAC (3.5 89 MHz cycles)**   **40ns**
- **Signal processing (9 357 MHz cycles)**   **28ns**
- **FPGA i/o**   **3ns**
- **Amplifier**   **35ns**
- **Kicker fill time**   **3ns**
-        **Electronics latency:**   **116ns**

- **Total latency budget:**   **140ns**

[see talk by Philip Burrows]

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 of jitter correction and residual jitter propagation

- **EXT-bunch-bunch FB system:**

  – Two kickers (K1 & K2) for vertical position (Y) and angle (Θ) correction

  – Three pickups (P1, P2, P3)

  – 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 displacement offsets for the extracted pulses with a width of +/- 40% σ_y (at the entrance of the extraction line)

- Apply static misalignment using "standard errors" + alignment procedure (connection with other tasks: BBA methods and orbit-steering/inter-train FB)

- Introducing ground motion (GM) misalignment (model K)

- **IP-bunch-bunch FB system:**

  – IP-BPM (resolution ~ nm)

  – Kicker near IP

  – Study in progress

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 we 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

• 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

BEAM → | Extr kicker KEX2 | --- π/2 ---> | K1 | | P1 | --- π/2 ---> | K2 | | P2 | --- π/2 ---> | P3 | --->

DP3

DP2
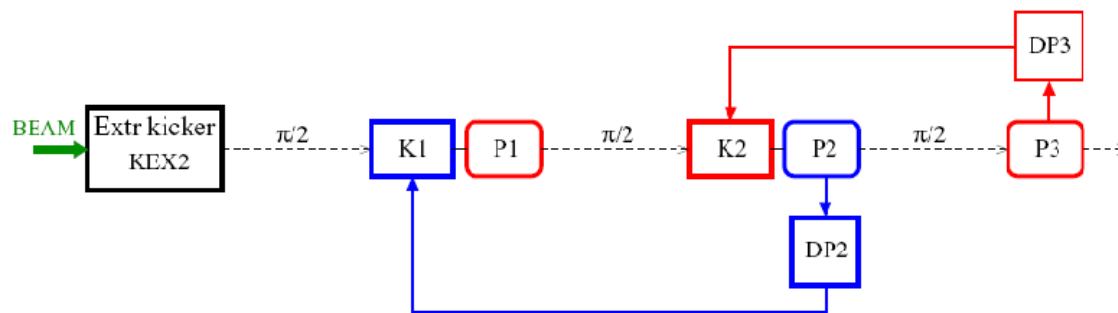
Time of flight P2-K1 = 10.65 ns
Time of flight P3-K2=10.53 ns

Sensitivity to BPM resolution

Considering an initial random vertical offset distribution with a rms 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
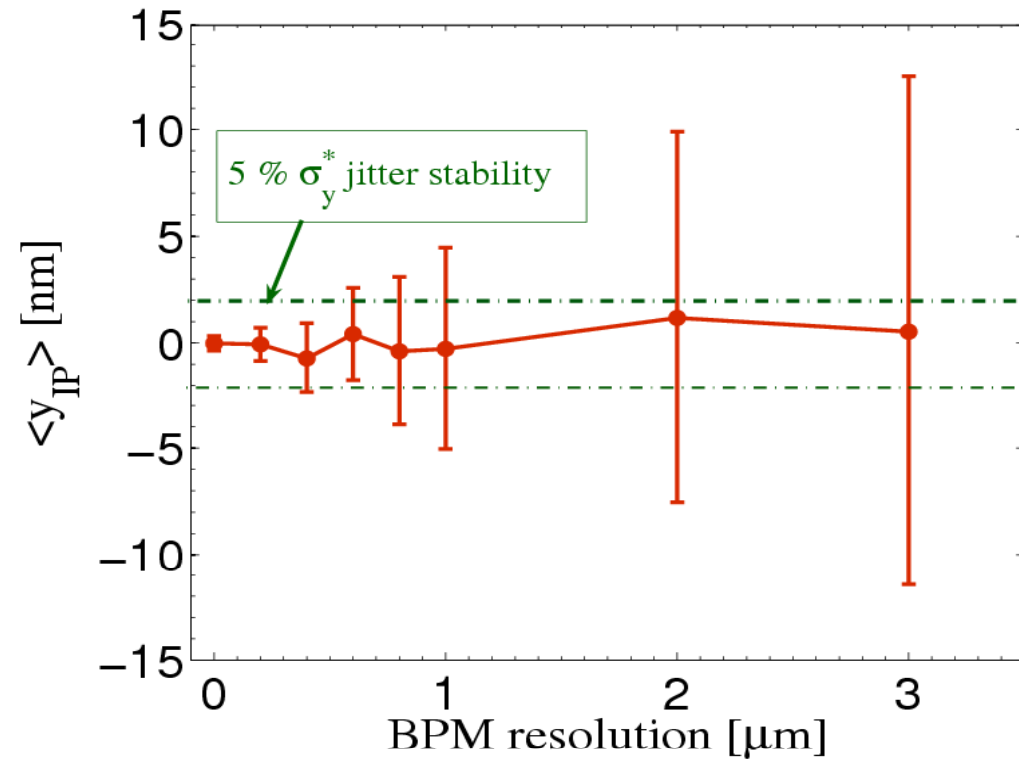
Sensitivity to kicker strength error

Considering an initial random vertical offset distribution with a rms of 40% of the initial beam size

Each point is the average over 50 seeds

The error bars correspond to the standard deviation

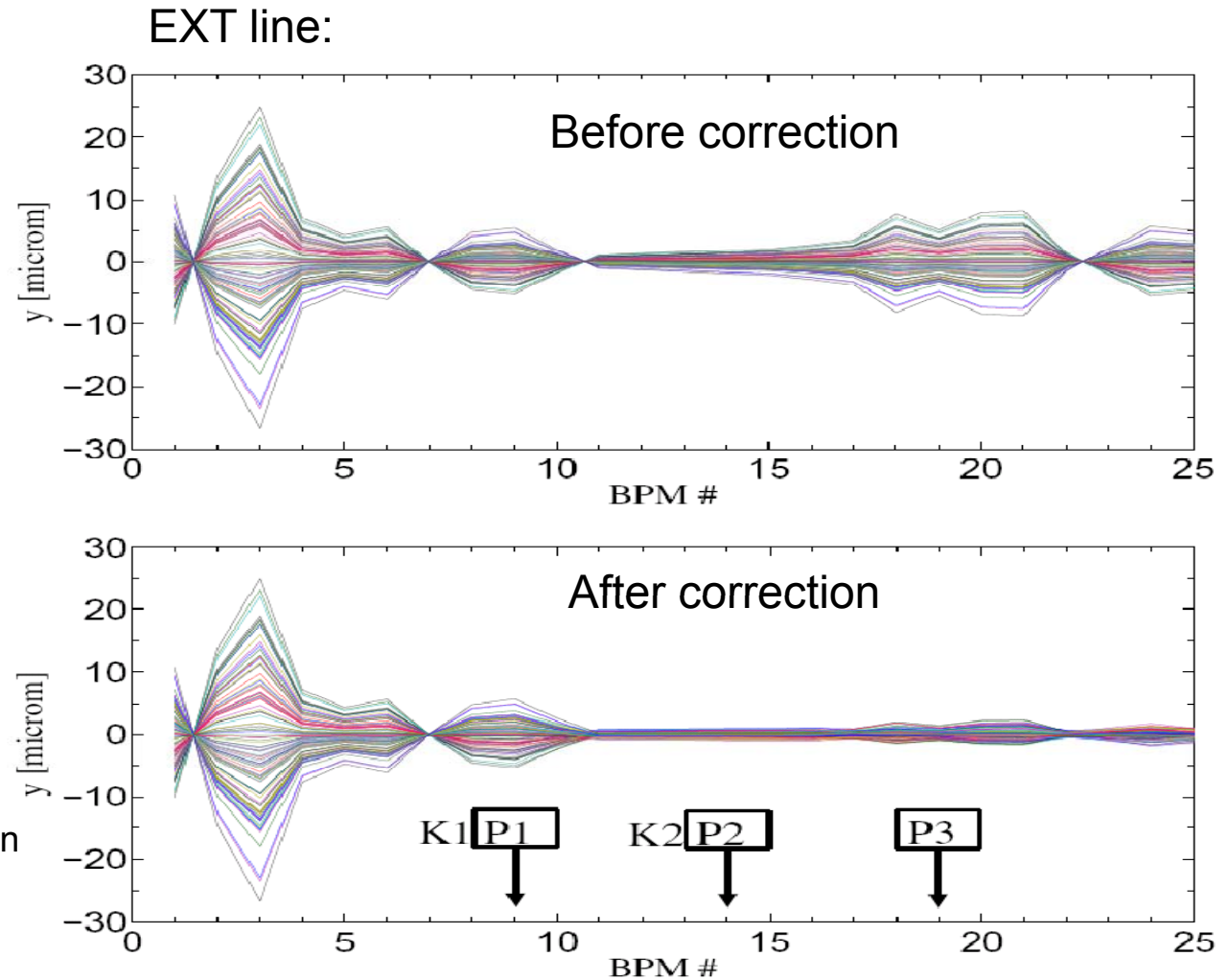Residual jitter at IP
vs kicker strength error
(FB gain error):

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 peak
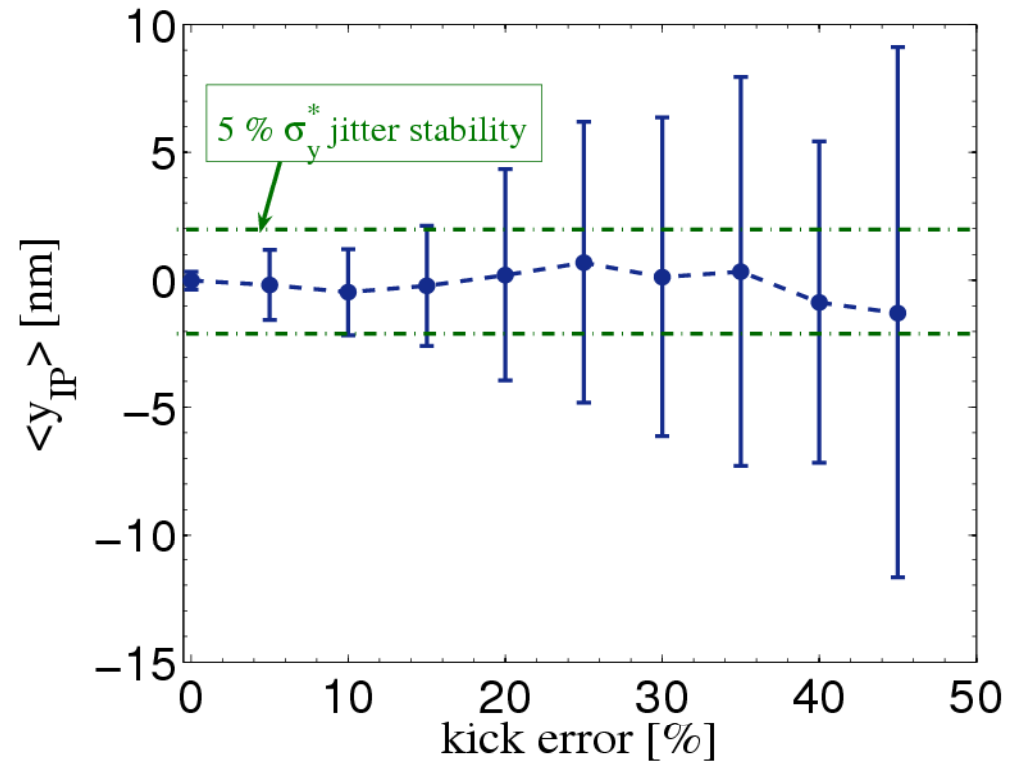
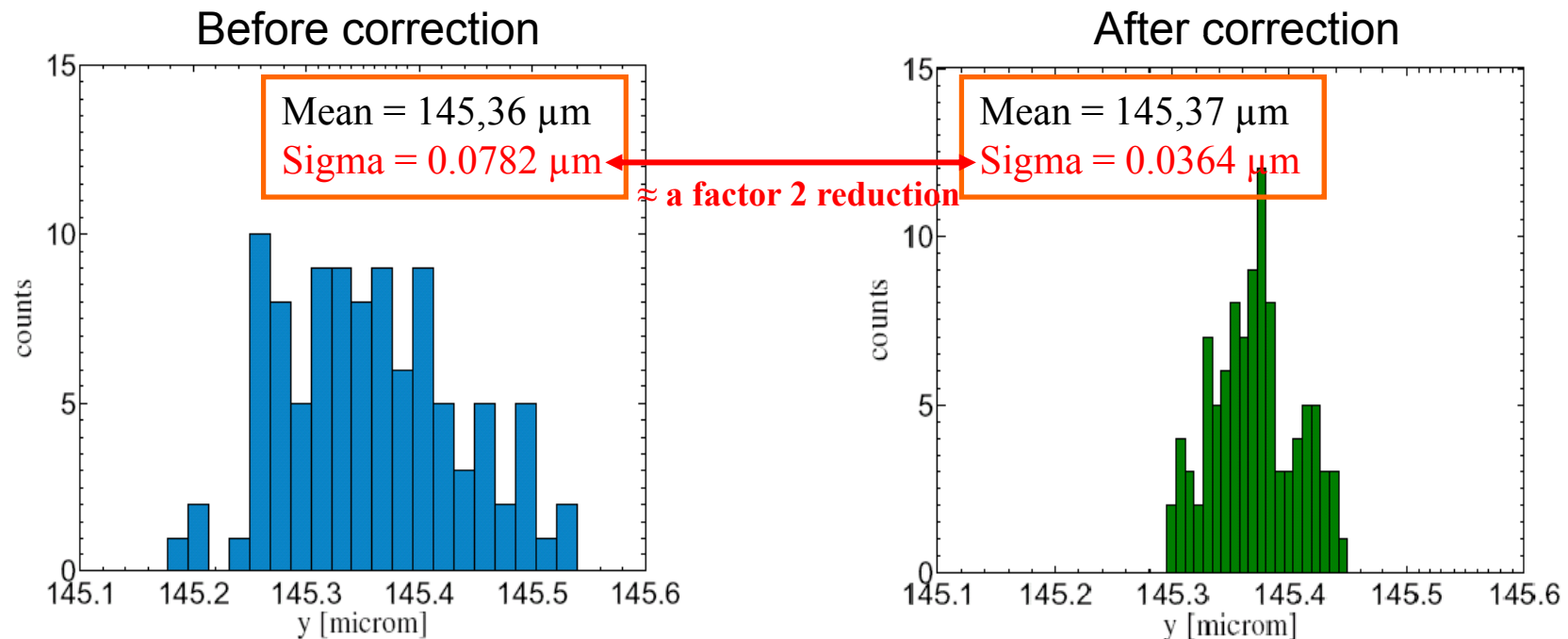# Correction of position jitter of extracted beam
Residual jitter propagation

EXT line:

- Example for 100 shots with $40\% \; \sigma^*_y$ 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-FB correction

Correction of position jitter of extracted beam
Residual vertical position jitter at the IP

The EXT fast intra-train FB help to reduce the shot-to-shot deviation in the EXT line

Before correction

After correction

Mean = 145,36 μm
Sigma = 0.0782 μm

≈ a factor 2 reduction

Mean = 145,37 μm
Sigma = 0.0364 μm

However …

Correction of position jitter of extracted beam
Remarks

… additional error sources in the FFS:

- Correlated GM ($\sim<$ 10 Hz) $\rightarrow$ inter-train jitter

- Fast magnet vibration $\rightarrow$ intra-train jitter

- Big impact coming from the final doublet alignment errors (tight jitter tolerance $\sim$ nm)

- If we want to achieve 5 % σ^*_y level stability, a combination of BBA methods, orbit steering techniques (inter-train feedbacks at EXT and FFS), fast intra-train feedback systems (at EXT and IP) will be necessary! Important to characterise the joint operation of the different feedback systems at different timescale

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 (we are planning an adaptive system)
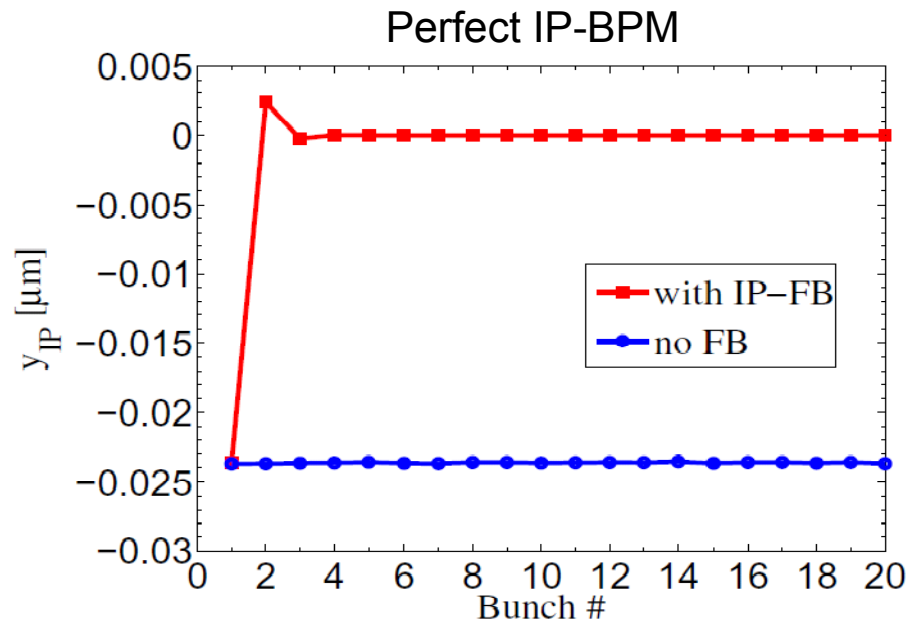Performance simulation and study of the limitations

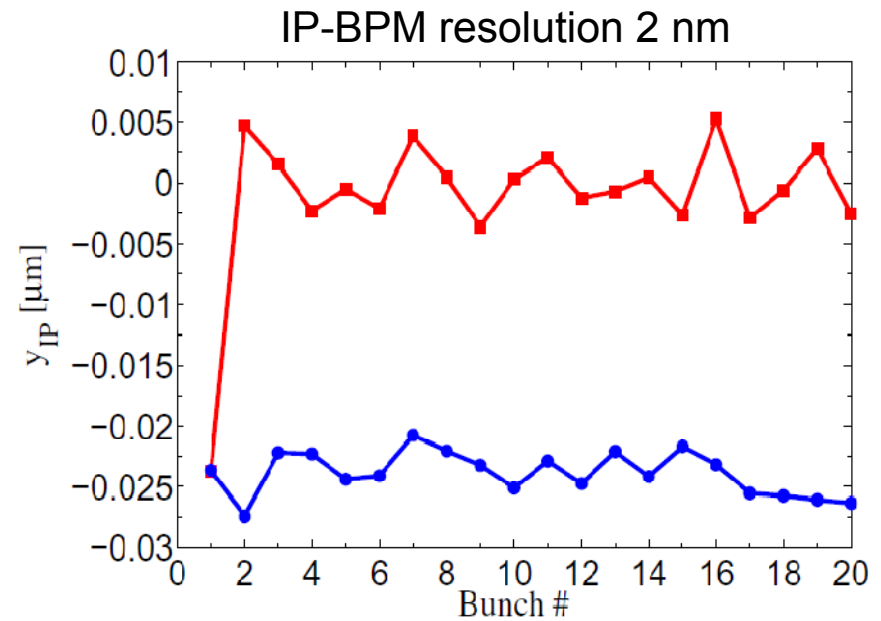Element positions:
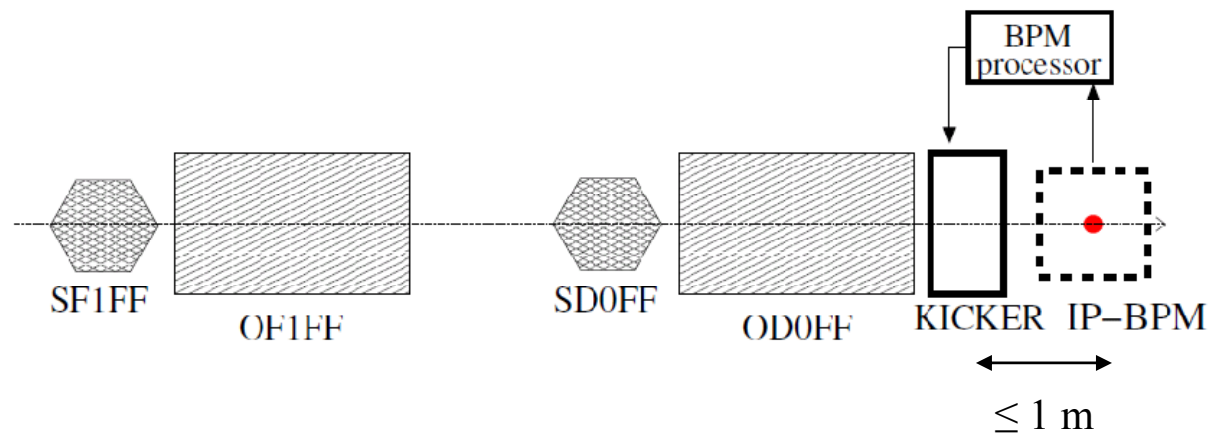
Simulations of the IP Bunch-Bunch FB

Example of GM effect and position jitter correction at the IP:

10 seconds of GM model K (1 seed), no other vibrations ✵ mean beam IP offset ☼ -0.024 μm (0.6 σ^*_y). Bunch-to-bunch correlated jitter
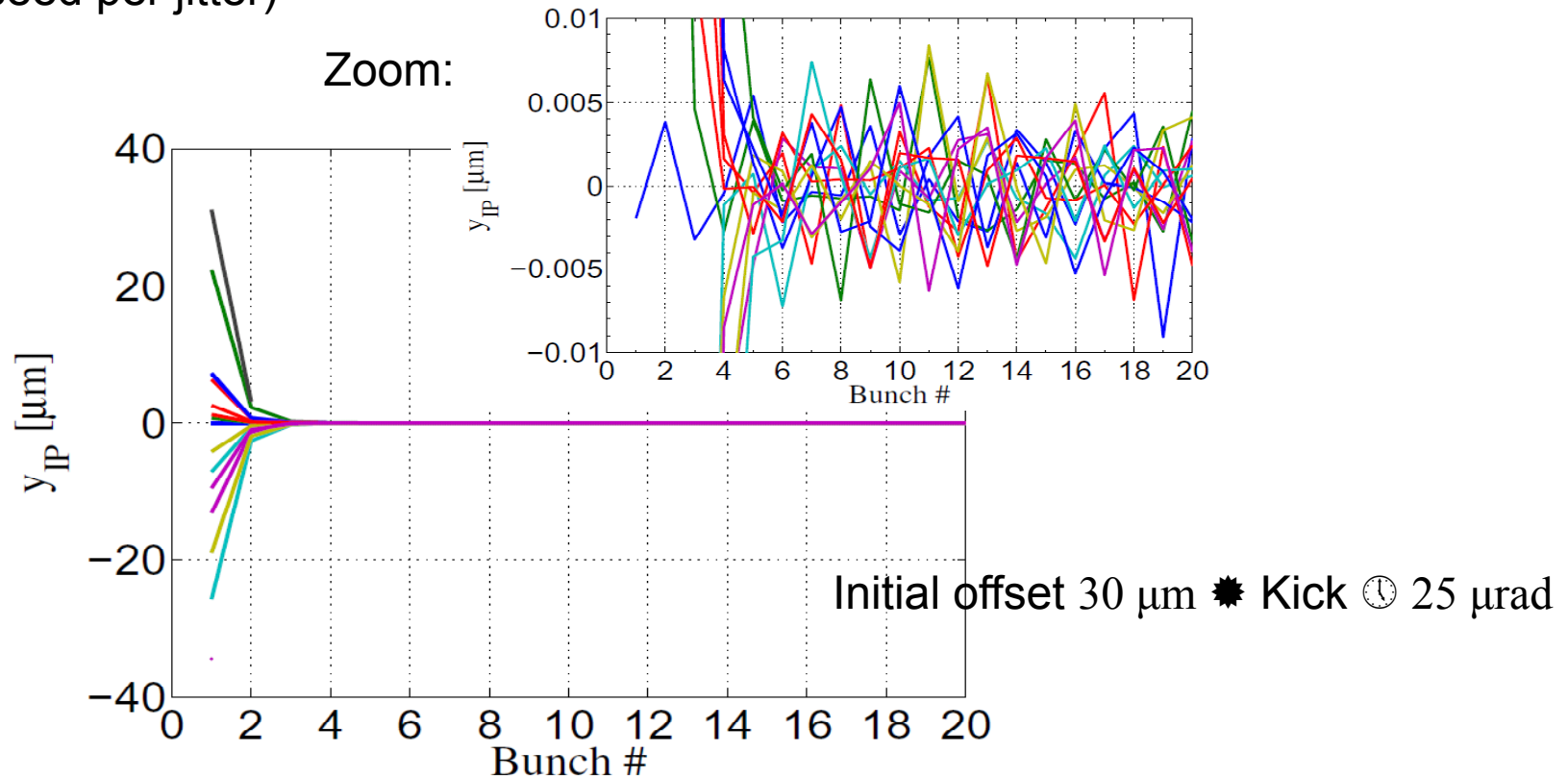
PI control loop. Gain tuning: K_p=0.8, K_i=0.85

Kick ☼ 0.023 μrad

Simulations of the IP Bunch-Bunch FB

Example of FD misalignment and position jitter correction at the IP:

- 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 position jitter error

Each point represent the average over 100 machines. The error bars correspond to the standard error $\mathrm{std}/\sqrt{100}$
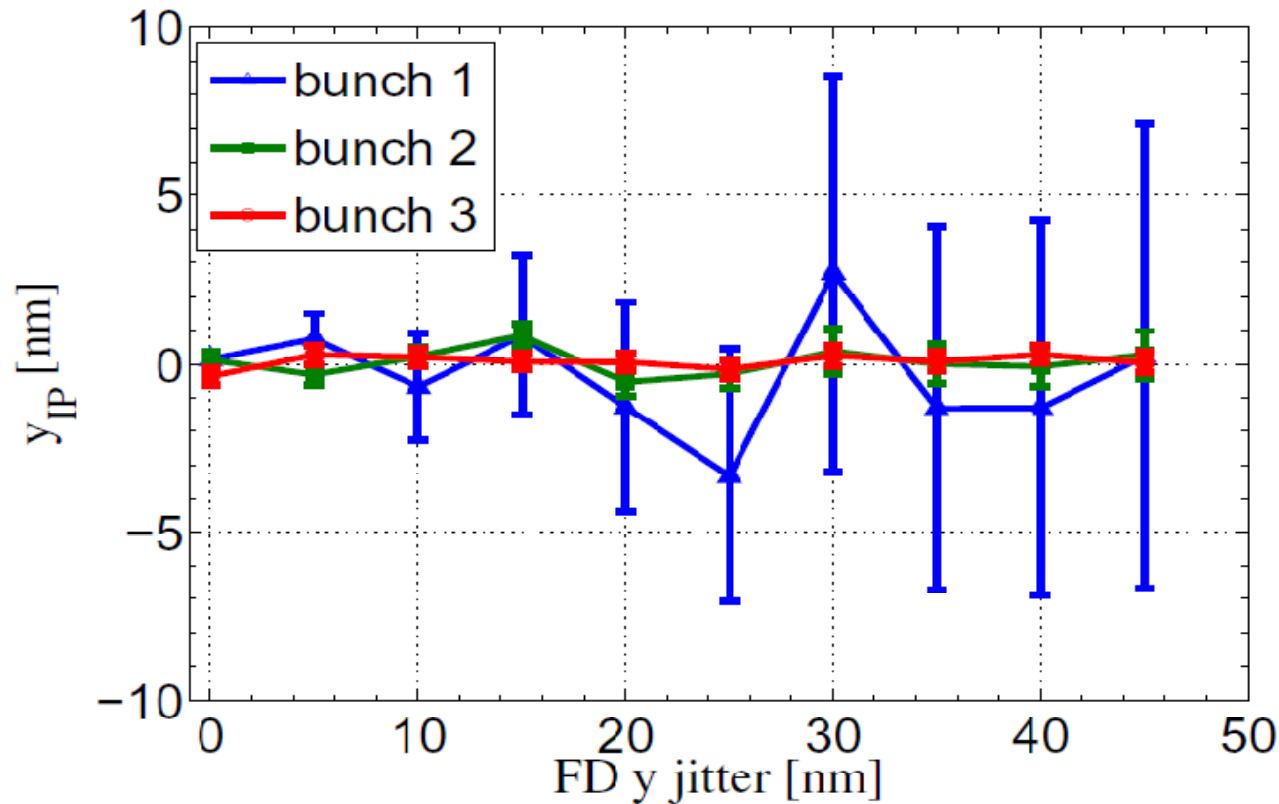
FB Integration
Simulation procedure

- Misalignment with "standard" errors (G. White's specifications): (https://confluence.slac.stanford.edu/display/ATF/Software+Projects)

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

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- Some jitter errors (to be completed with additional sources):
  - 40% σ_y shot-to-shot extraction jitter
  - Inter-train jitter from GM (f ~< 10 Hz): to be corrected by pulse-to-pulse FB systems in the EXT line [see talk by Y. Renier] and in the FFS [see talk by A Scarfe]

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- Joint operation EXT-FB + IP-FB (for multibunch mode):
  - 1st bunch → pilot bunch
  - EXT-FB corrects position of 2nd bunch according to the signal measured from 1st bunch
  - IP-FB uses the 2nd bunch signal as reference (which includes previous correction given by EXT-FB) and corrects the residual jitter of the 3rd bunch
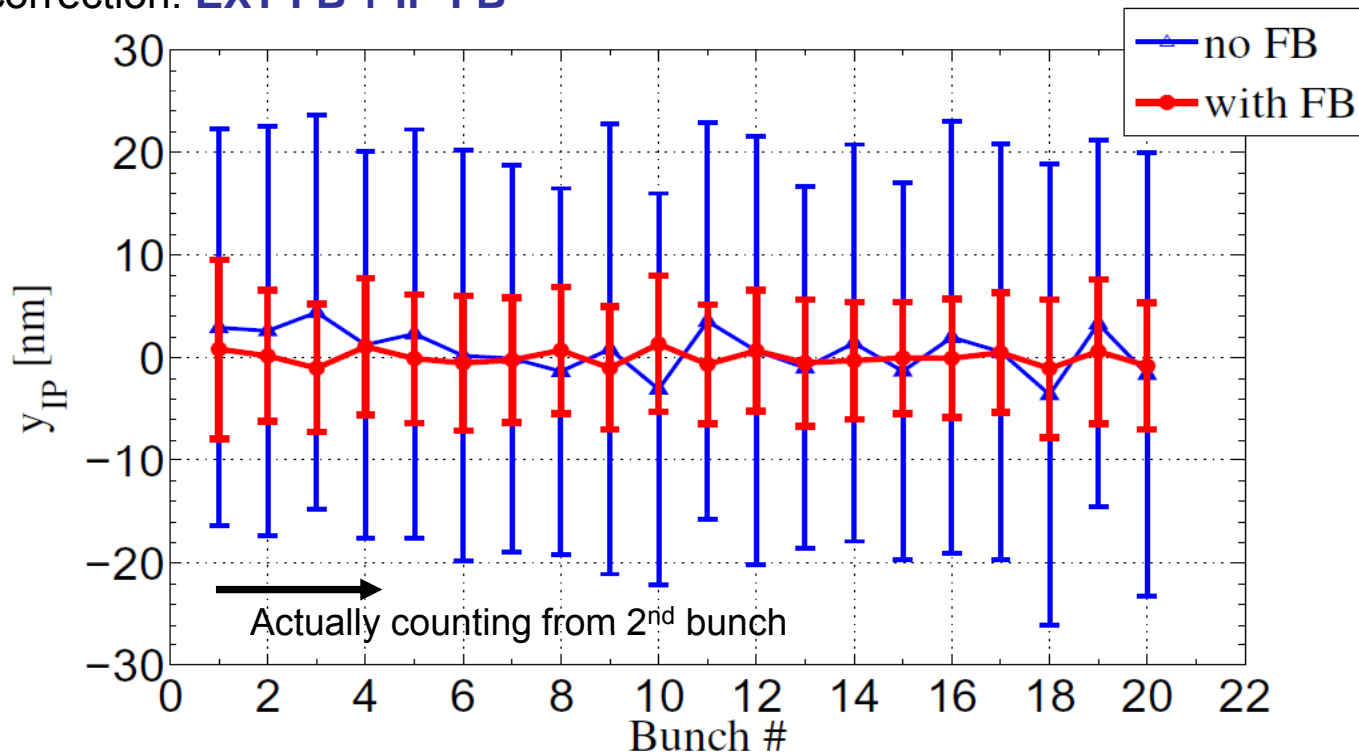
FB Integration
Example result

Simulation of 100 seeds for multibunch mode
(In this example we do not have applied static lattice misalignment and subsequent BBA)
Including: 40% σ_y , GM model K (applied during 10 s), FD misalignment (5 nm jitter)
FB correction: **EXT-FB + IP-FB**

Error bars: standard deviation. Jitter correction by a factor 2

Summary and ongoing studies

- We have presented the layout of an intra-train 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 jitter correction (FB system latency budget ~140 ns)

- A Placet-octave based model of 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

- Design and simulation of a IP-FB to correct intra-train residual jitter at the IP. Important for achievement of nm level bunch-bunch stability at IP (ATF2 goal 2)

- Simulation for multibunch mode (3 (20) – bunch train)

- We plan to improve the simulation model, adding the missing error sources, e.g. "standard" magnet strength errors

- Work in progress: study of the joint operation of different timescale feedback systems (inter-task software collaboration)

Reservoir

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:

$$g = \tanh\left(\frac{\pi\omega}{2d}\right) \le 1$$
(determined by the shape of the electrode)
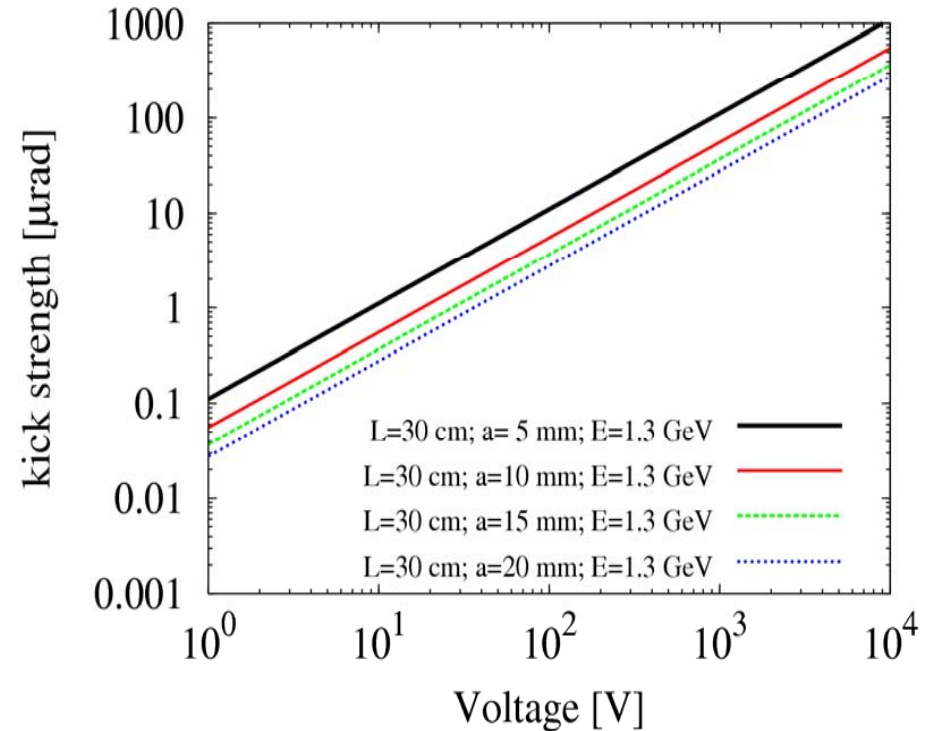
V: peak voltage
E: beam energy (1.3 GeV)
R: impedance (50 Ω)
L: kicker length (30 cm without flanges)
$a=2r$: kicker gap width (~15 mm)
r: half gap

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
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:
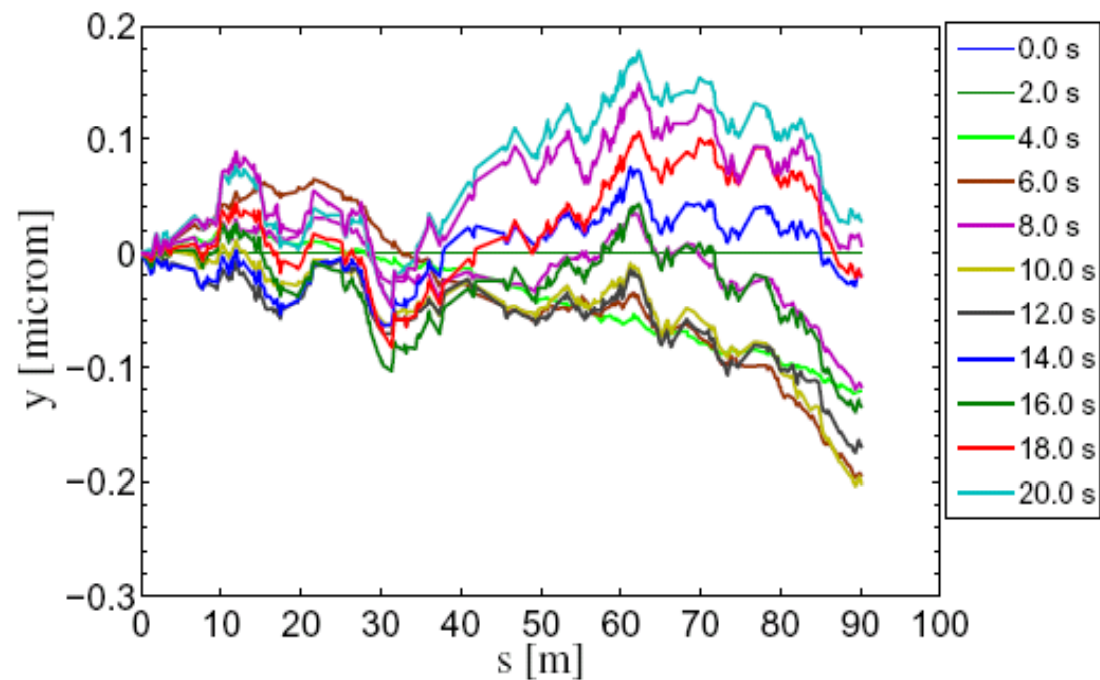
Appendix
Simulations of the IP Bunch-Bunch FB

- 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 response curve IP offset vs kicker strength (previous scan)