Feed forward orbit corrections for the CLIC RTML

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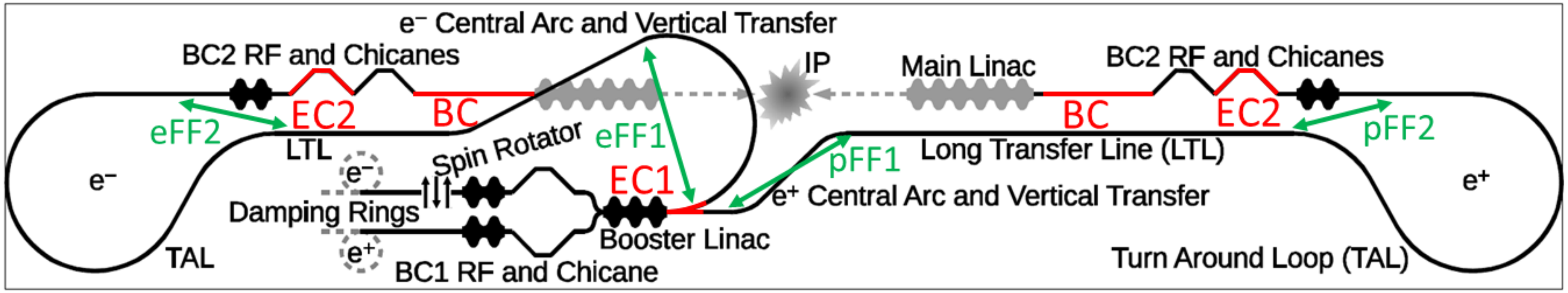
Motivation

- Emittance growth from betatron collimation
  - Strongly dependent on orbit jitter in collimators

- Damping ring extraction stability
  - Kicker and septa stability extremely stringent
  - FF systems relax requirements

RTML FF systems

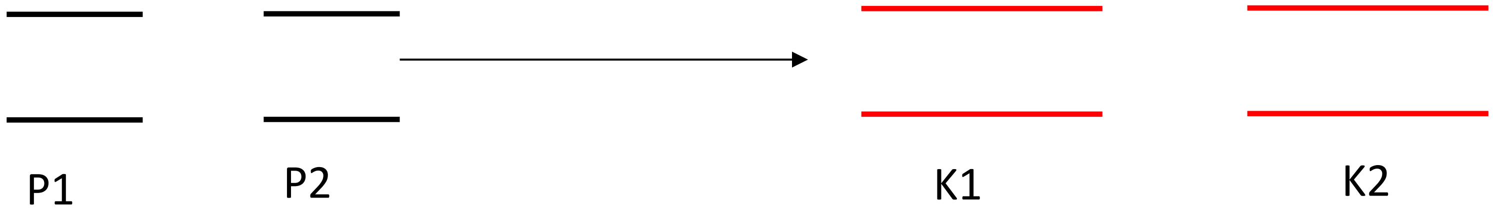


EC1: first energy collimator system
EC2: second energy collimator system
BC: betatron collimation system

eFF1: first feed forward system in electron RTML
eFF2: second feed forward system in electron RTML

pFF1: first feed forward system in positron RTML
pFF2: second feed forward system in positron RTML

Fundamentals of FF correction



Transfer matrices

$$R(P1 \to P2) = A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$$

$$R(P2 \to K1) = B = \begin{pmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{pmatrix}$$

$$R(K1 \to K2) = C = \begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix}$$

Kicker corrections

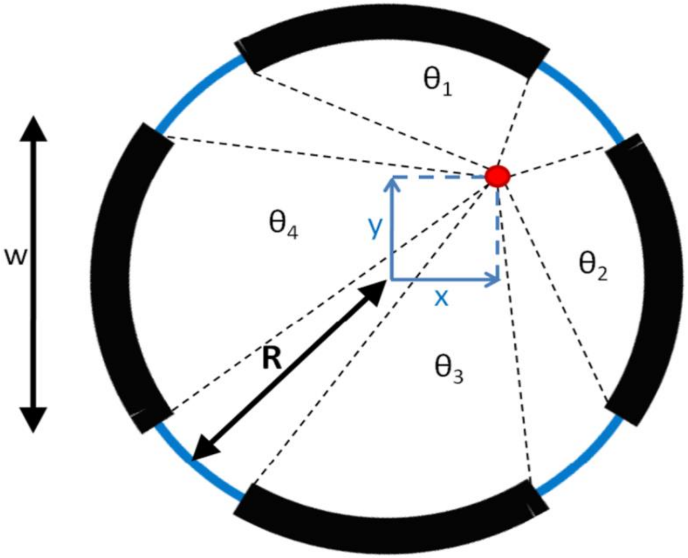
$$\theta_{K1} = \frac{[CB]_{12}}{a_{12}c_{12}} x_1 - \frac{[CBA]_{12}}{a_{12}c_{12}} x_2$$

$$\theta_{K2} = -\frac{b_{12}}{a_{12}c_{12}} x_1 + \frac{[BA]_{12}}{a_{12}c_{12}} x_2$$

Design considerations

- Hardware:
  - BPM design, resolution and signal processing
  - Transmission cable speed and latency budget
  - Kicker design and stability
  - Digital feed forward electronics
  - Machine protection
- Optics
  - Optics designs of BPM and kicker regions

BPM design



Use stripline BPMs for high bandwidth and reasonably low resolution.

Position $\sim \frac{V_\Delta}{V_\Sigma}$
where V_Δ and V_Σ are the difference and sum of opposing stripline signals.

Resolution $= \frac{R\sigma_V}{2V_\Sigma}\left(\frac{g_d}{g_s}\right)^{-1} \propto R$
Where $\left(\frac{g_d}{g_s}\right)$ is the gain ratio between difference and sum channels on the digital electronics, σ_V is the electrical noise on the BPM system and R is the BPM resolution.

FONT BPMs consistently achieve resolutions ~1.6 times thermal limit of noise. CLIC RTML BPMs aim for ~1.3 times thermal limit by digitising BPM signals immediately after analogue processing. RTML BPM radius is 6 cm, so expect resolutions ~ 1.4μm

Transmission speed

A minimum timing latency, $t_{min} = 150\ ns$ to allow for calculation of FF corrections

pFF2 and eFF2 layouts very similar, very small horizontal offset of beam after turnaround.
Beam travels ~1600 m, signals travel ~50 m.
Required cable speed: ~0.03c Extremely easy to achieve with any transmission cable

eFF1:
Horizontal offset after turnaround ~ 610 m
Minimum cable speed: $v_{min} \geq \frac{2\rho}{\pi\rho - ct_{min}} c = 0.67c$
Where ρ is the radius of curvature of the central arc
Use high speed (~0.88c), low attenuation (~6dB over 600 m) cables to maximise latency: e.g. LDF4.5-20

pFF1:S-shaped chicane
Minimum cable speed: $v_{min} \geq \frac{2\sqrt{2}\rho}{\pi\rho - ct_{min}} c = 0.95c$
Use free space optical communication: send IR signals between BPM and kicker regions

Kicker design

Feed forward systems should be capable of orbit corrections of $\leq 0.5\sigma_{x,y}$

Use electrostatic kickers:

- Fast rise and fall times (~5 ns)
- Relatively weak so good for small and precise corrections

Stripline voltage: $V_{strip} = \frac{dpc}{2qL}\sqrt{\frac{\varepsilon_{x,y}}{\beta_{x,y}\gamma_{rel}}}$

Where d is the stripline separation (12 cm), pc is the beam momentum (9 GeV) and L is the kicker length (~1 m)
Kicker voltage = ±220V horizontally and ±70V vertically.

A kicker stability of ~1% will result in ~0.01% increase in jitter compared to expected BPM resolution.

- Systematic effects (e.g. field homogeneity) can be calibrated out
- Very relaxed kicker stability requirements

Digital feed forward electronics

Latency of digital electronics expected to be similar to that of the FONT digital electronics, ~50 ns.

Total latency budget is ≥ 150 ns
Use remaining budget for additional features:

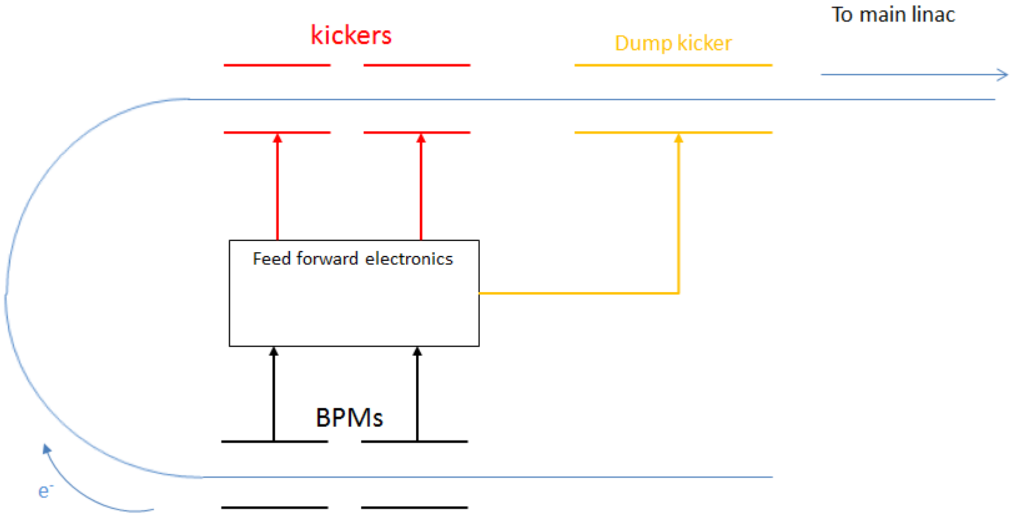
- FF systems can only correct orbit jitter ≤0.5 σ, so use BPM measurements to determine when beam is dangerously off-orbit and fire a downstream dump kicker.
- Systematic correction of oscillations on bunch train with tuneable analogue ripple on kicker pulses.

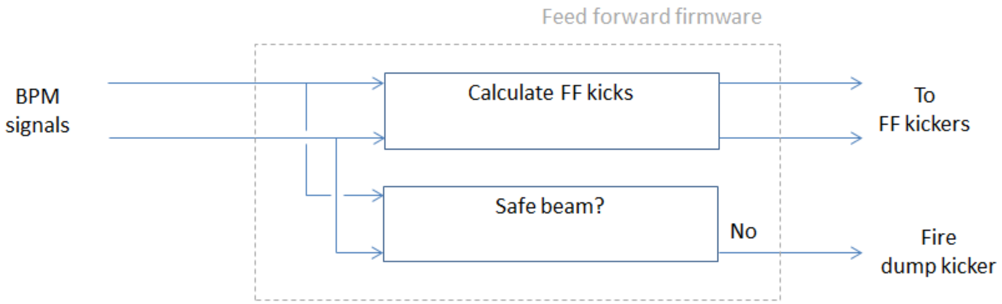
Machine protection

A safe beam determination algorithm can be run in parallel to the normal feed forward correction algorithm.

The safe beam determination can be performed in ~ 5 – 10 ns and a beam dump trigger sent to the dump kicker.

As the dump kicker will be more powerful than the feed forward kickers it will require a longer rise time, thus a dump signal should be sent a quickly as possible.





Given the beam optics described in the next slides, the beam positions in the two feed forward BPMs can be used to determine a safe beam condition by :

$$\frac{x_1^2 + x_2^2}{\sigma^2} \leq n_{thresh}$$

Optics considerations

In normalised coordinates, the sensitivity of a phase space measurement can be expressed in terms of the optics and BPM resolution:

$$\sigma_n^2 = \left(\frac{\beta_0 + (1+\cos^2\mu)\beta_1}{\beta_0\beta_1} - \frac{2\rho_{1,2}\cos\mu}{\sqrt{\beta_0\beta_1}}\right)\frac{\sigma_{BPM}^2}{\varepsilon_{geo}\sin^2\mu}$$

The second term vanishes when $\mu = \frac{\pi}{2}$ or an odd multiple. The first term is minimised when $\beta_0 = \beta_1$ according to the arithmetic to geometric mean inequality theorem.

Converting back into normal phase space it can be shown that $\alpha_0 = \alpha_1 = 0$

In conclusion: need a periodic lattice between BPMs

Use 90° FODO cells for the BPM and kicker regions.

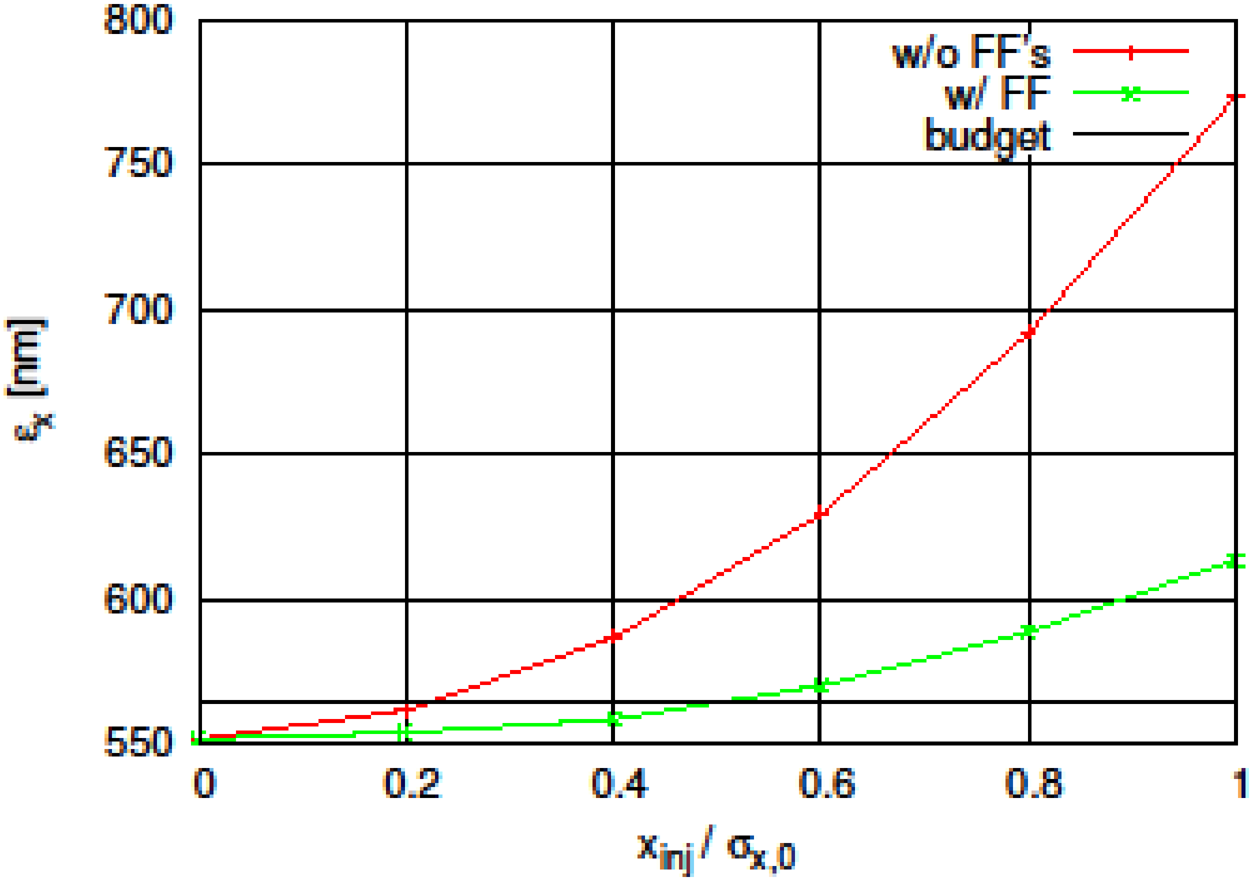
$$\beta_x = \frac{L}{\sin\frac{\mu}{2}}\sqrt{\frac{1+\sin\frac{\mu}{2}}{1-\sin\frac{\mu}{2}}} \approx 3.41L \quad \beta_y = \frac{L}{\sin\frac{\mu}{2}}\sqrt{\frac{1-\sin\frac{\mu}{2}}{1+\sin\frac{\mu}{2}}} \approx 0.58L \quad kl_q = \frac{4\sin\frac{\mu}{2}}{L} = \frac{2\sqrt{2}}{L}$$

Tracking simulations

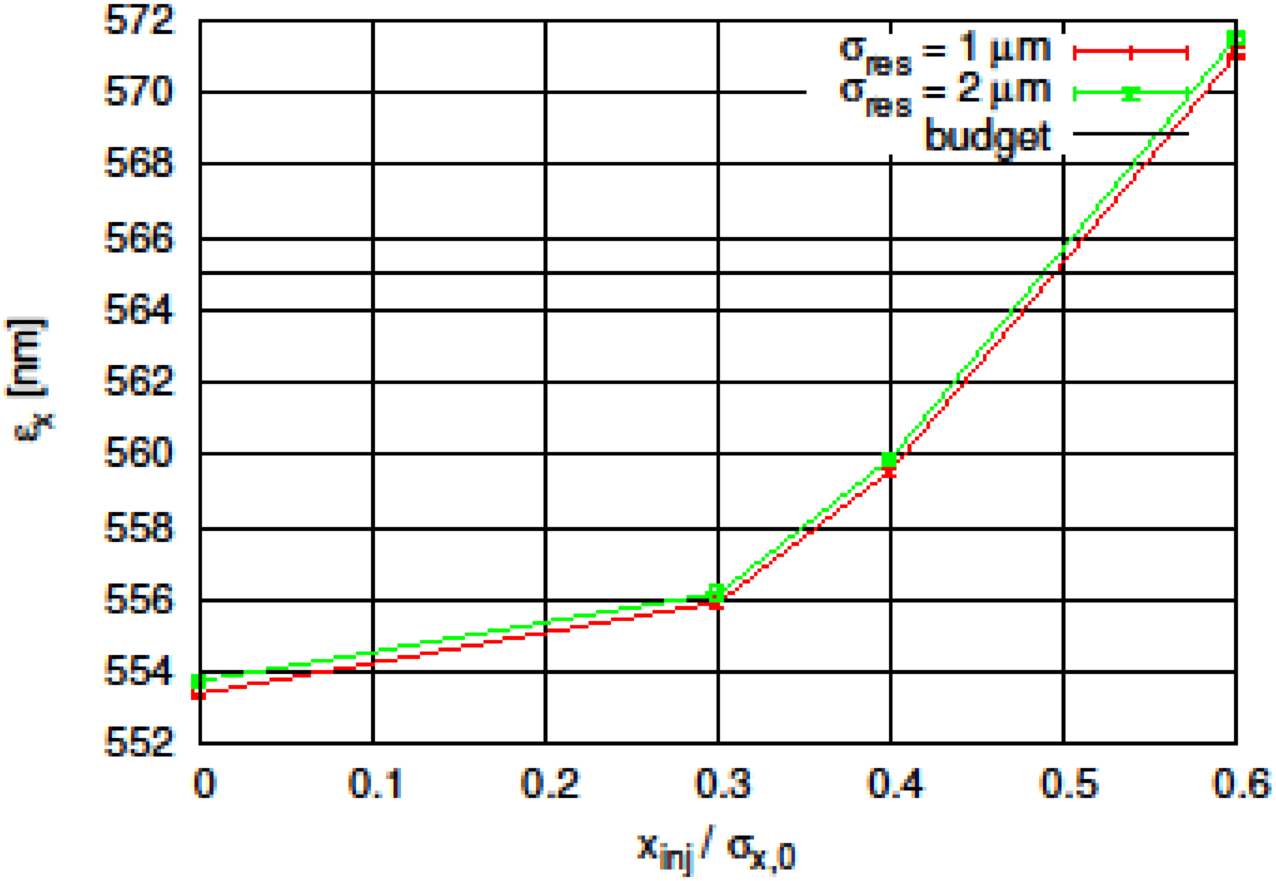
3 studies undertaken:

- Ideal system
  - Comparison of beam stability through RTML with and without feed forward corrections
    - Perfect BPM resolution and alignment
    - Initial beam offset at start of RTML varied to simulate DR extraction errors
- Precision study
  - Impact of BPM resolution of feed forward performance
    - Perfect BPM alignment
    - Initial beam offset at start of RTML varied to simulate DR extraction errors
- Accuracy study
  - Impact of BPM alignment errors on feed forward performance
    - Perfect BPM resolution
    - Perfectly extracted beam at start of RTML

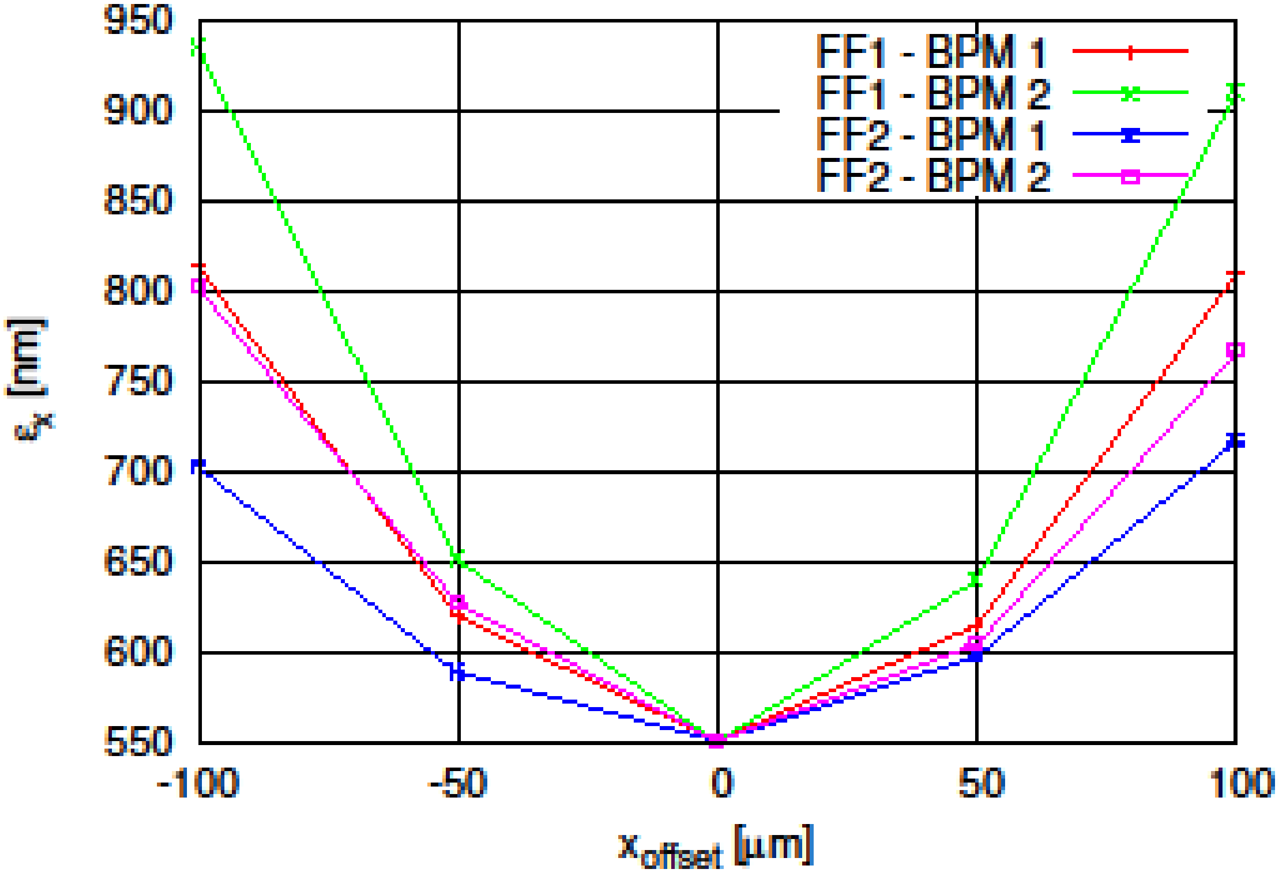
Tracking results: $\Delta\varepsilon_x$
Ideal system



Tracking results: $\Delta\varepsilon_x$
Precision study



Tracking results: $\Delta\varepsilon_x$ Accuracy study without BBA



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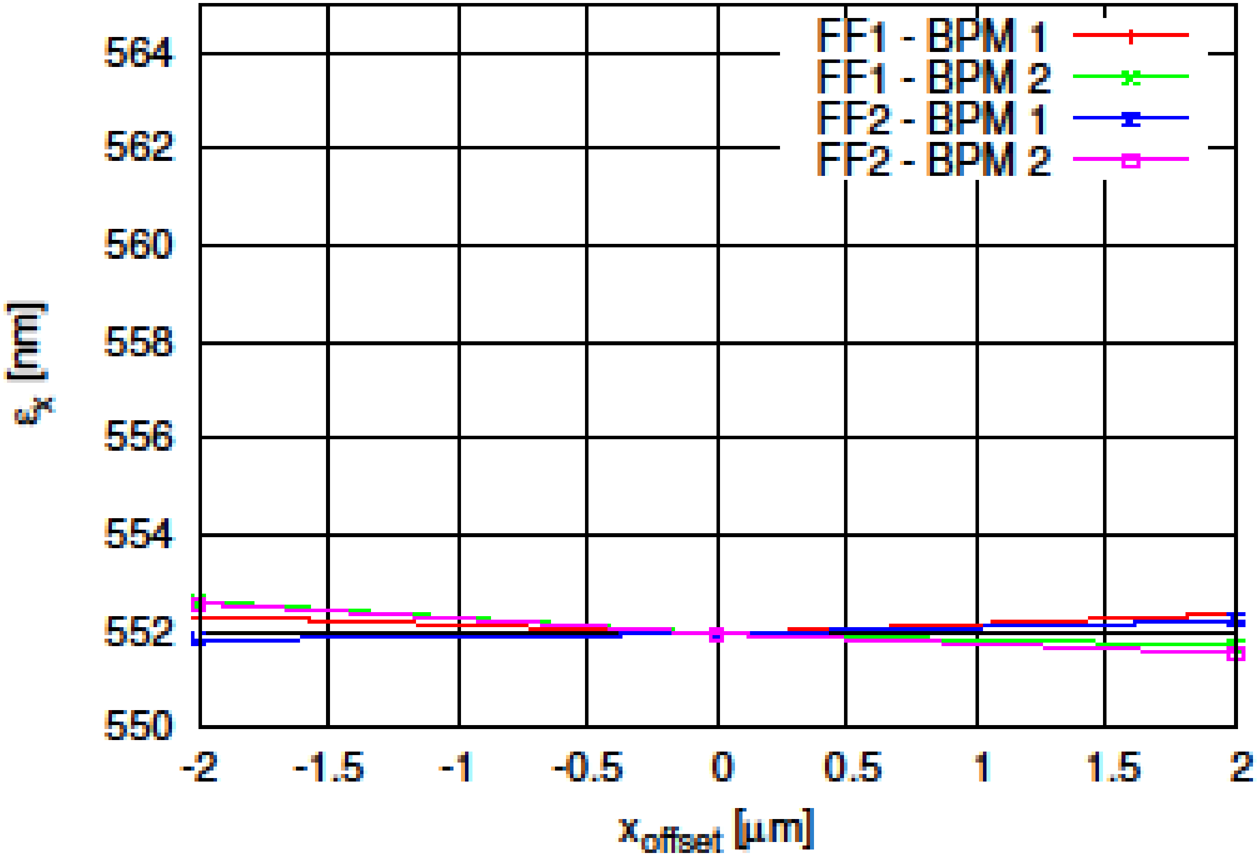
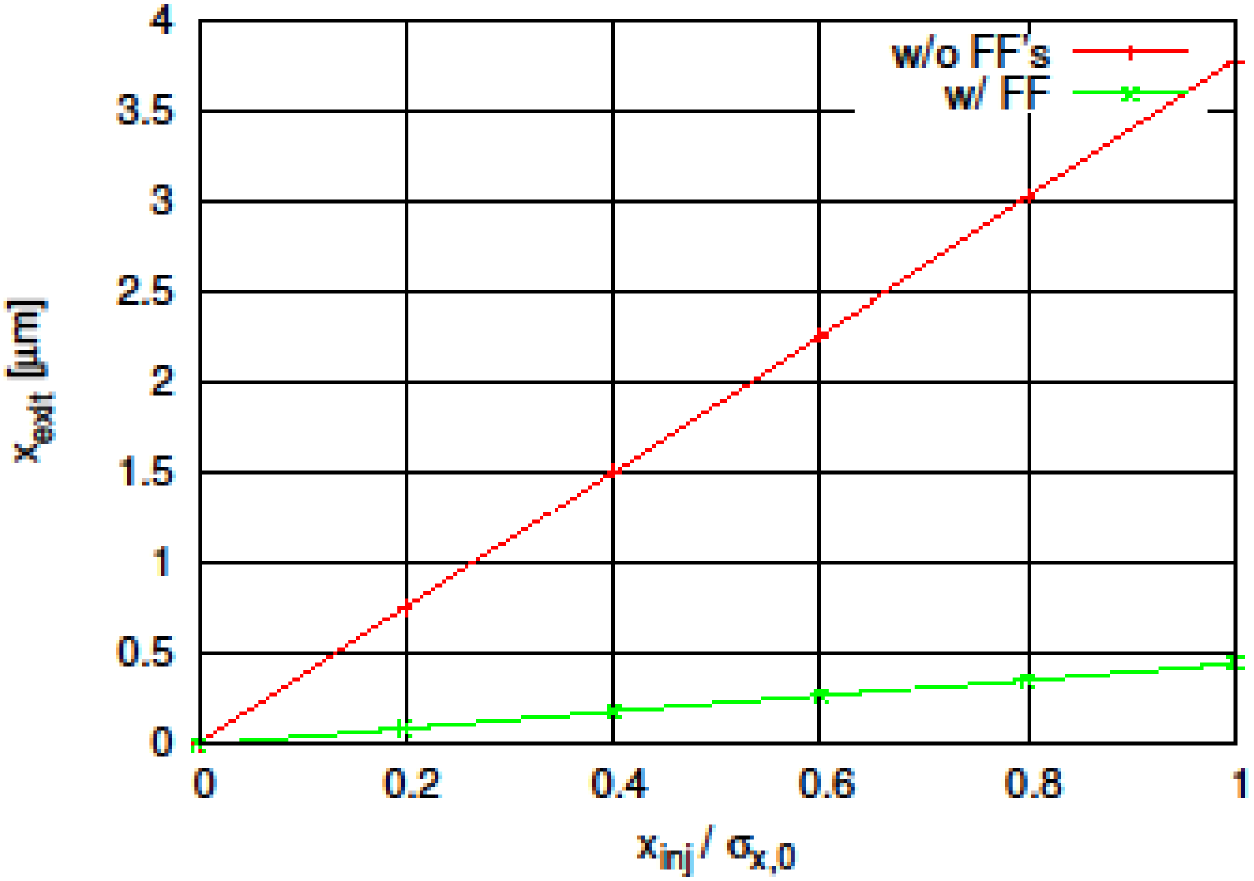
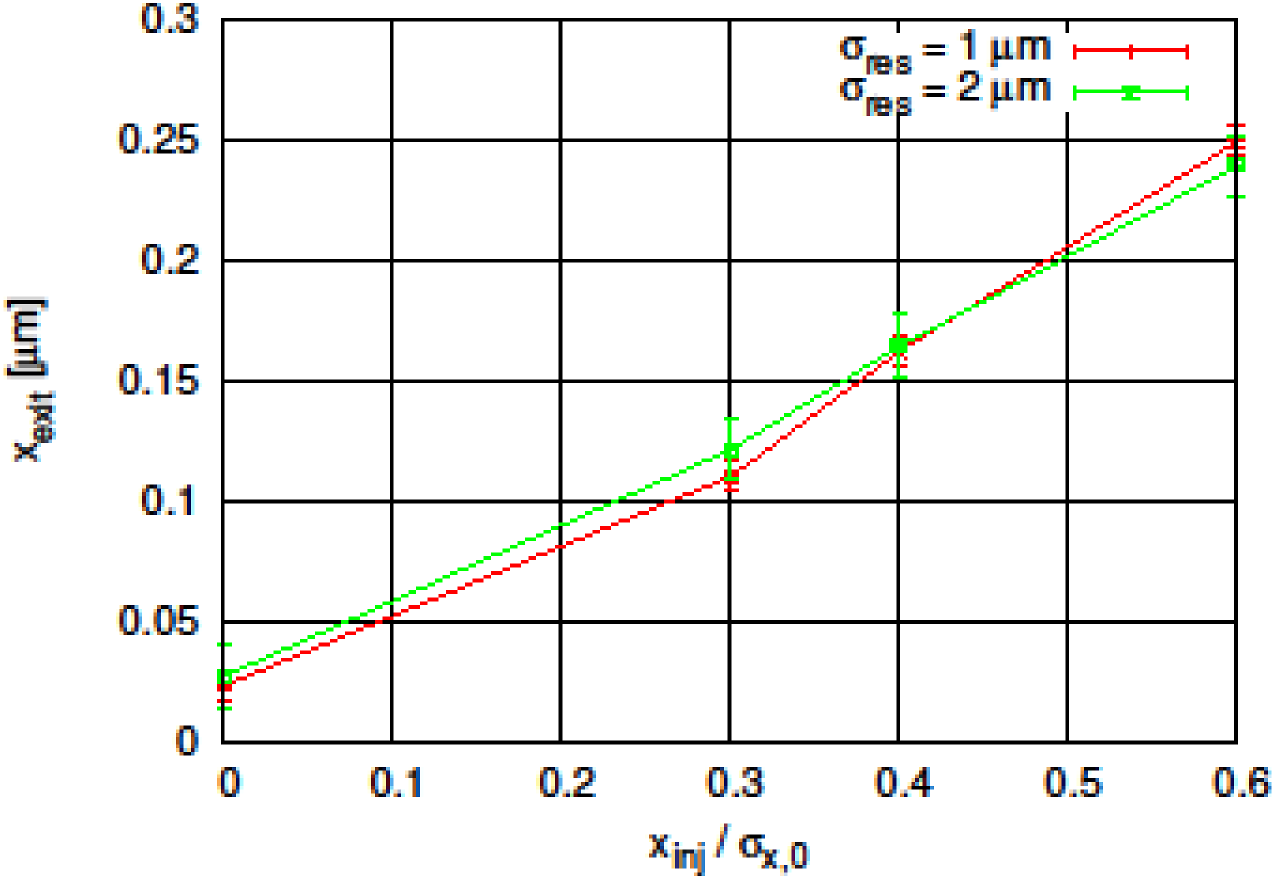


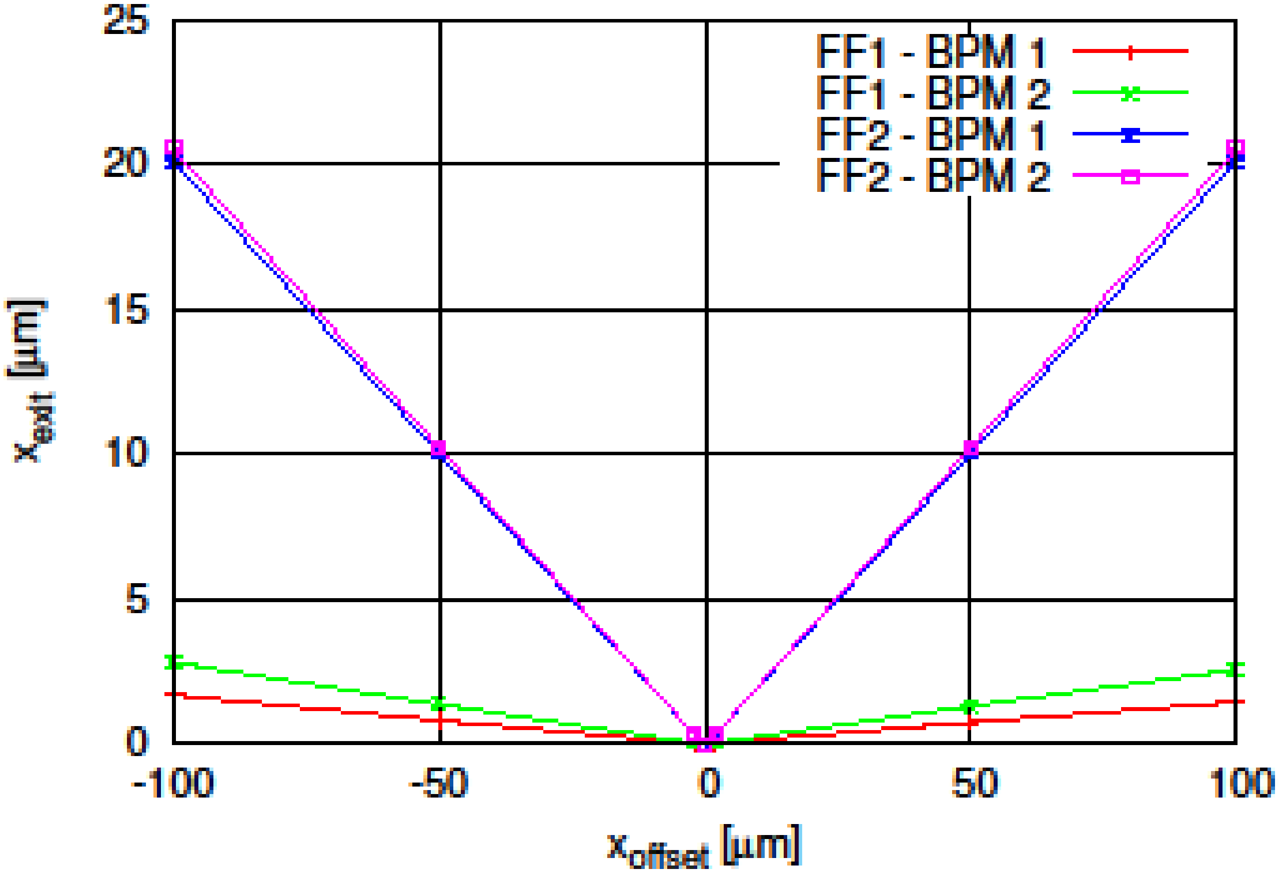
Tracking results: σ_x
Ideal system



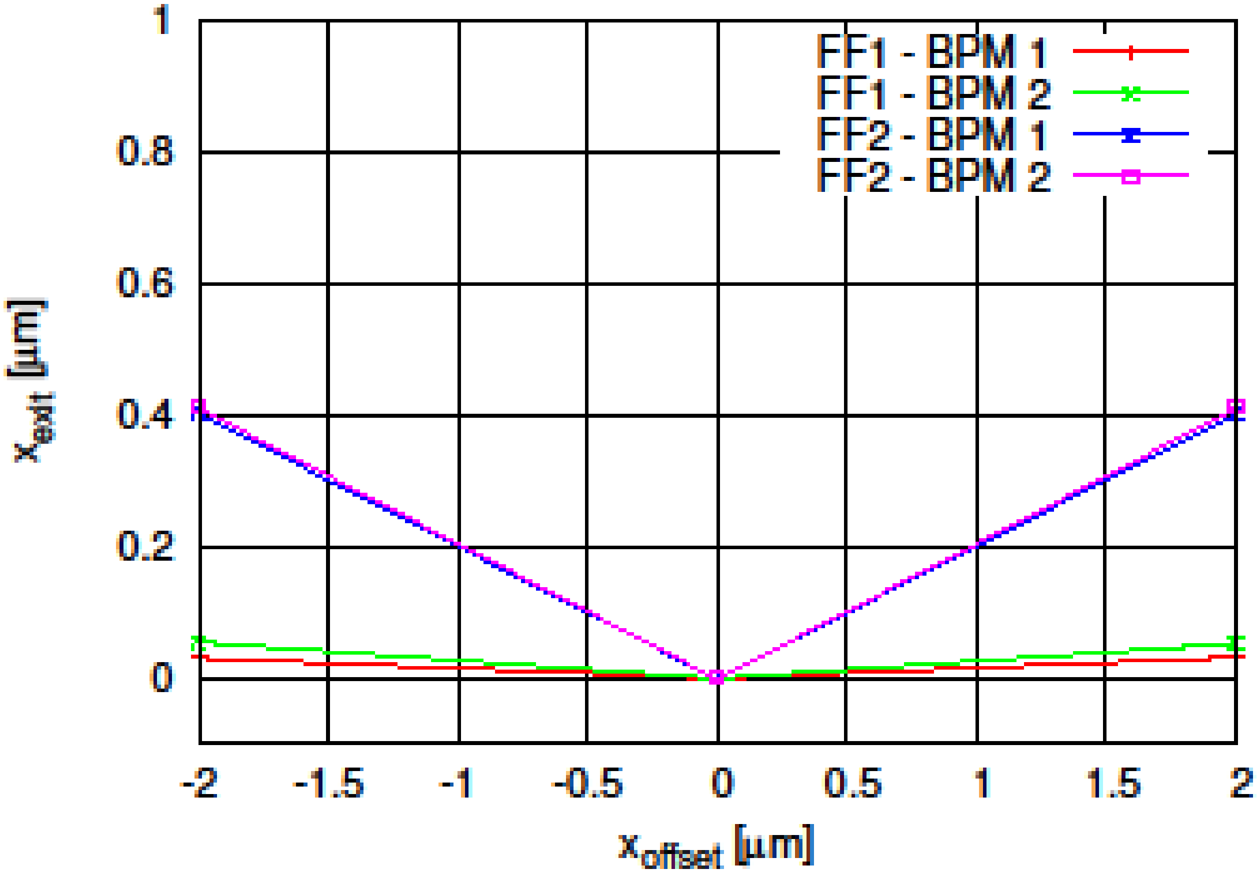
Tracking results: σ_x
Precision study



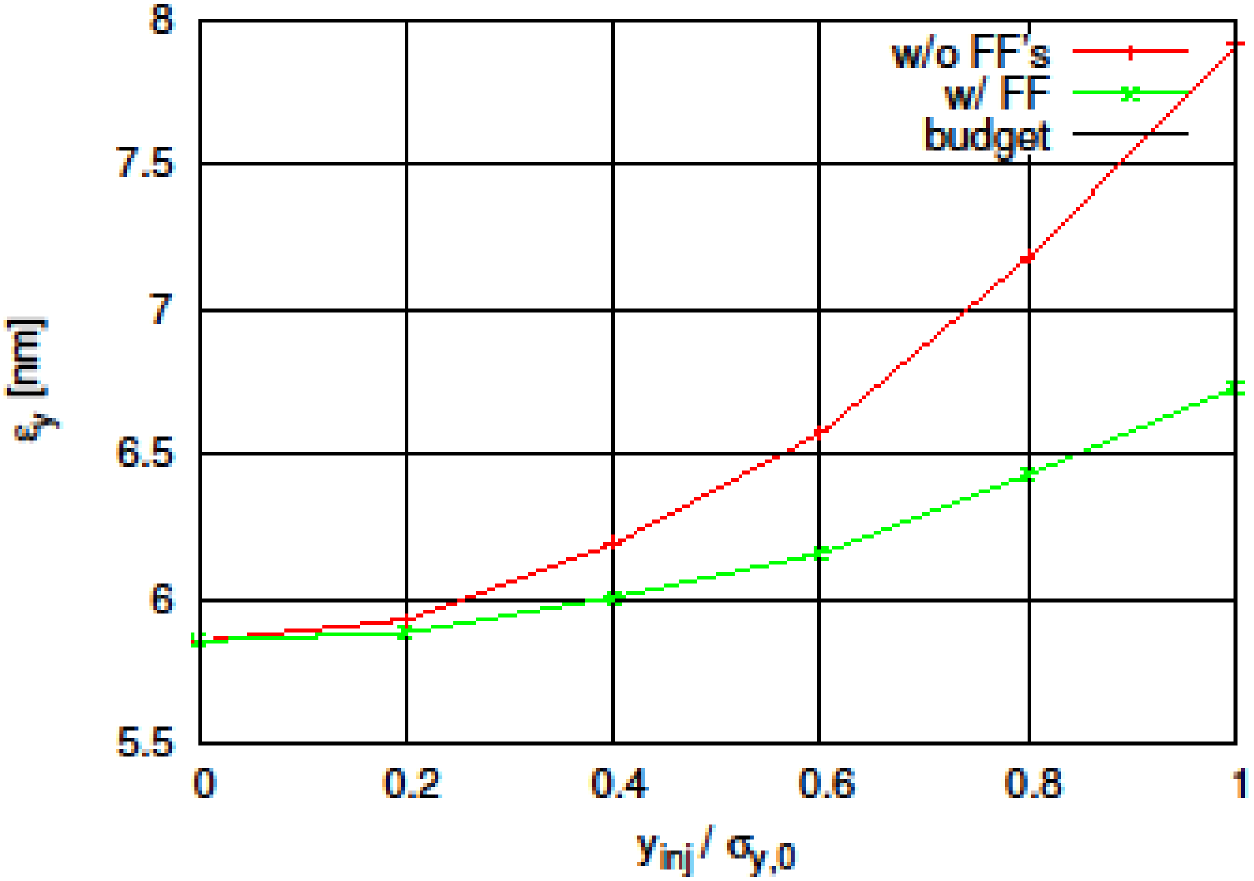
Tracking results: σ_x Accuracy study without BBA



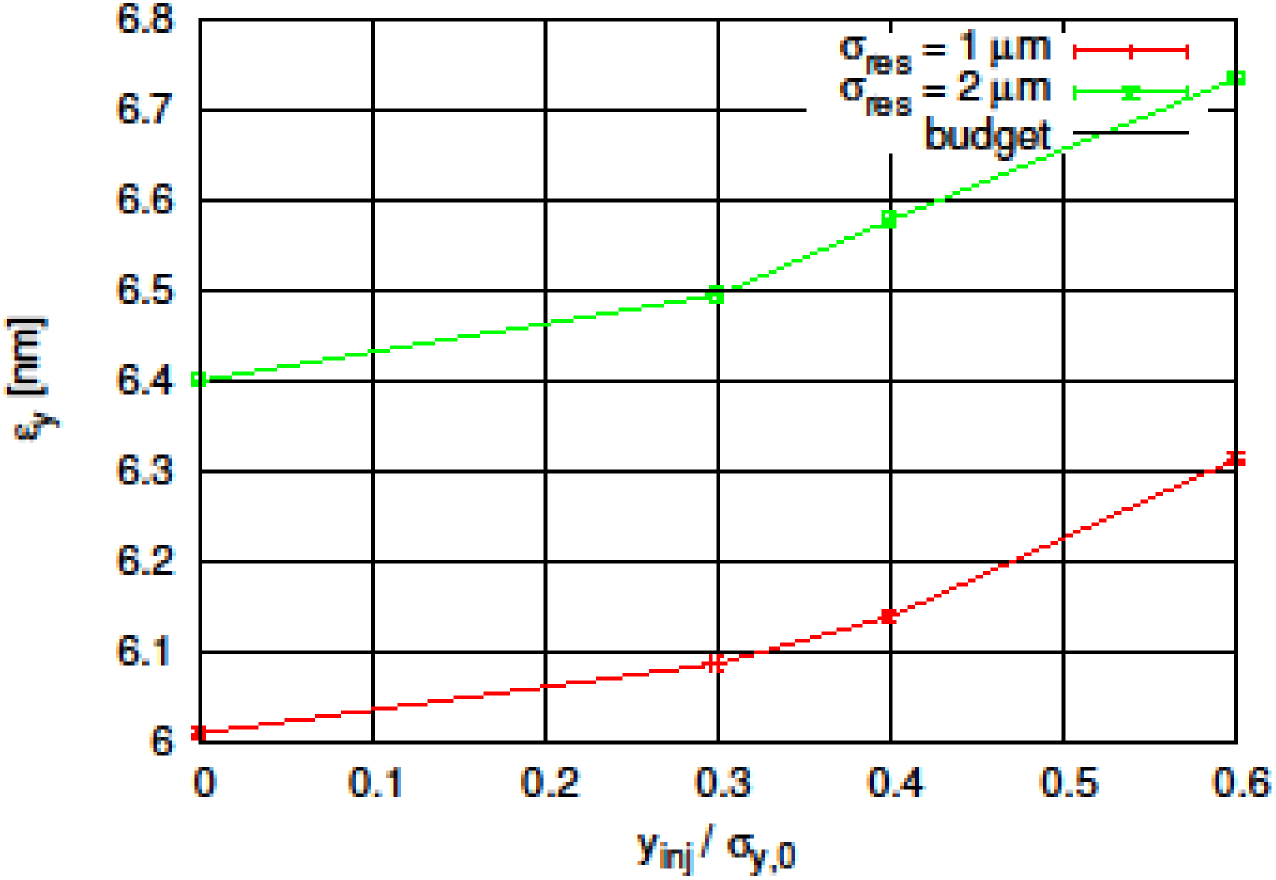
Tracking results: σ_x Accuracy study with BBA



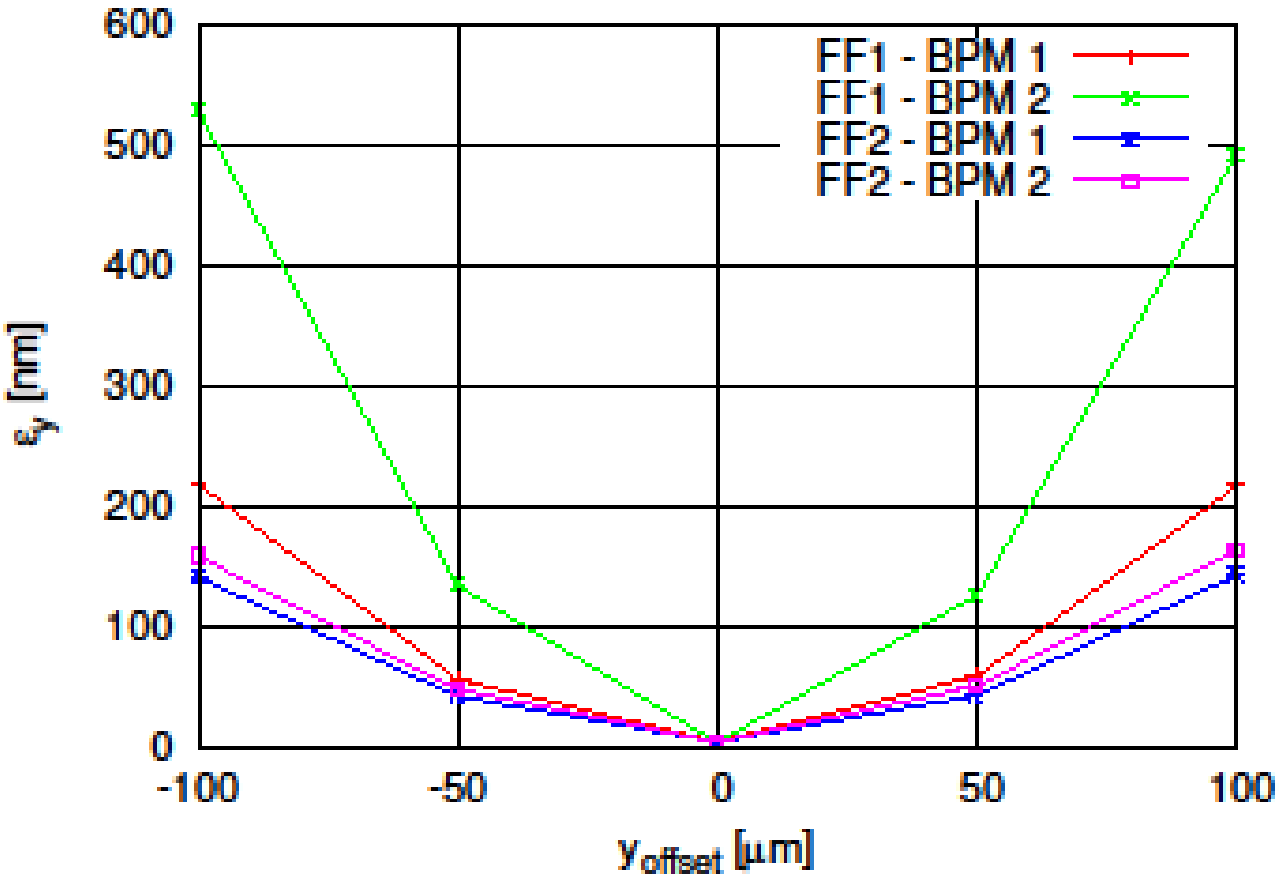
Tracking results: $\Delta\varepsilon_y$
Ideal system



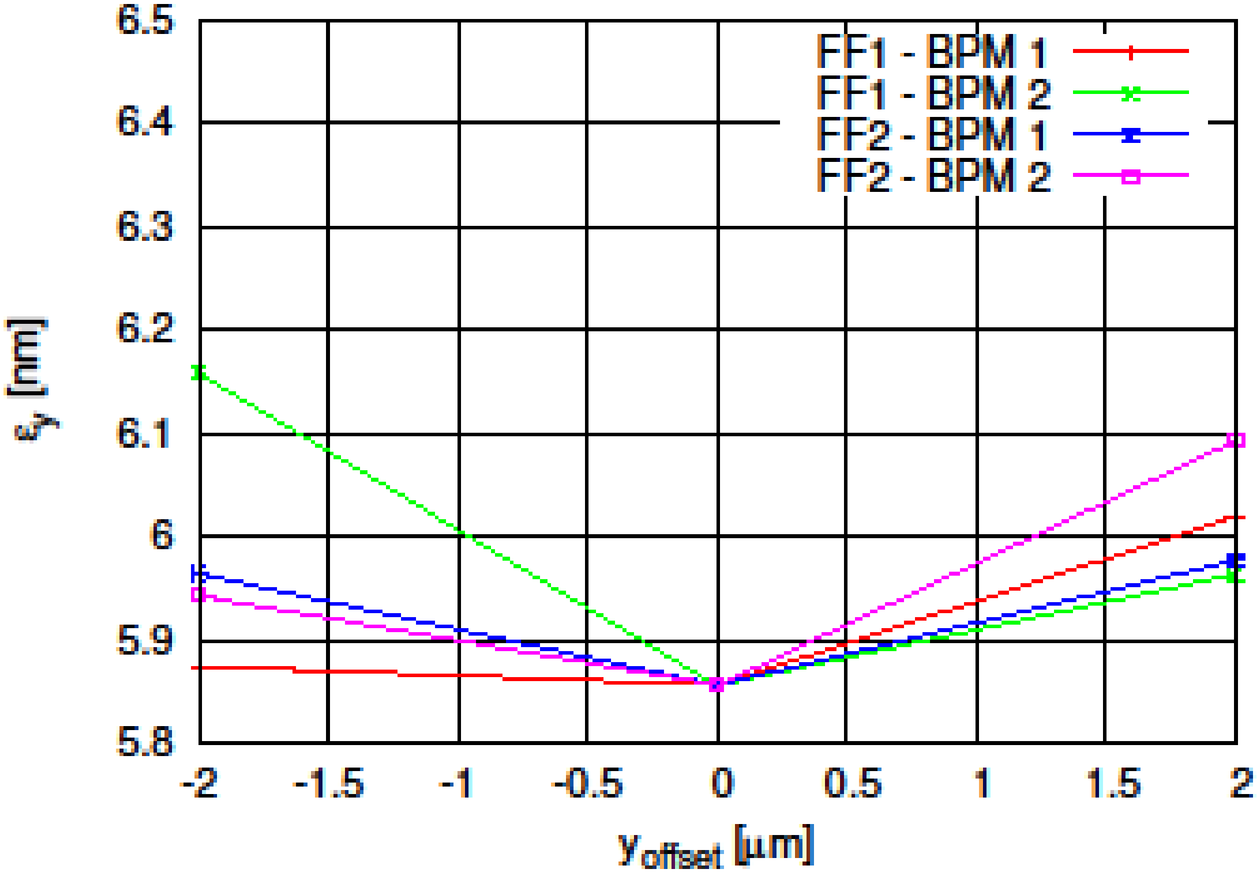
Tracking results: $\Delta\varepsilon_y$ Precision study



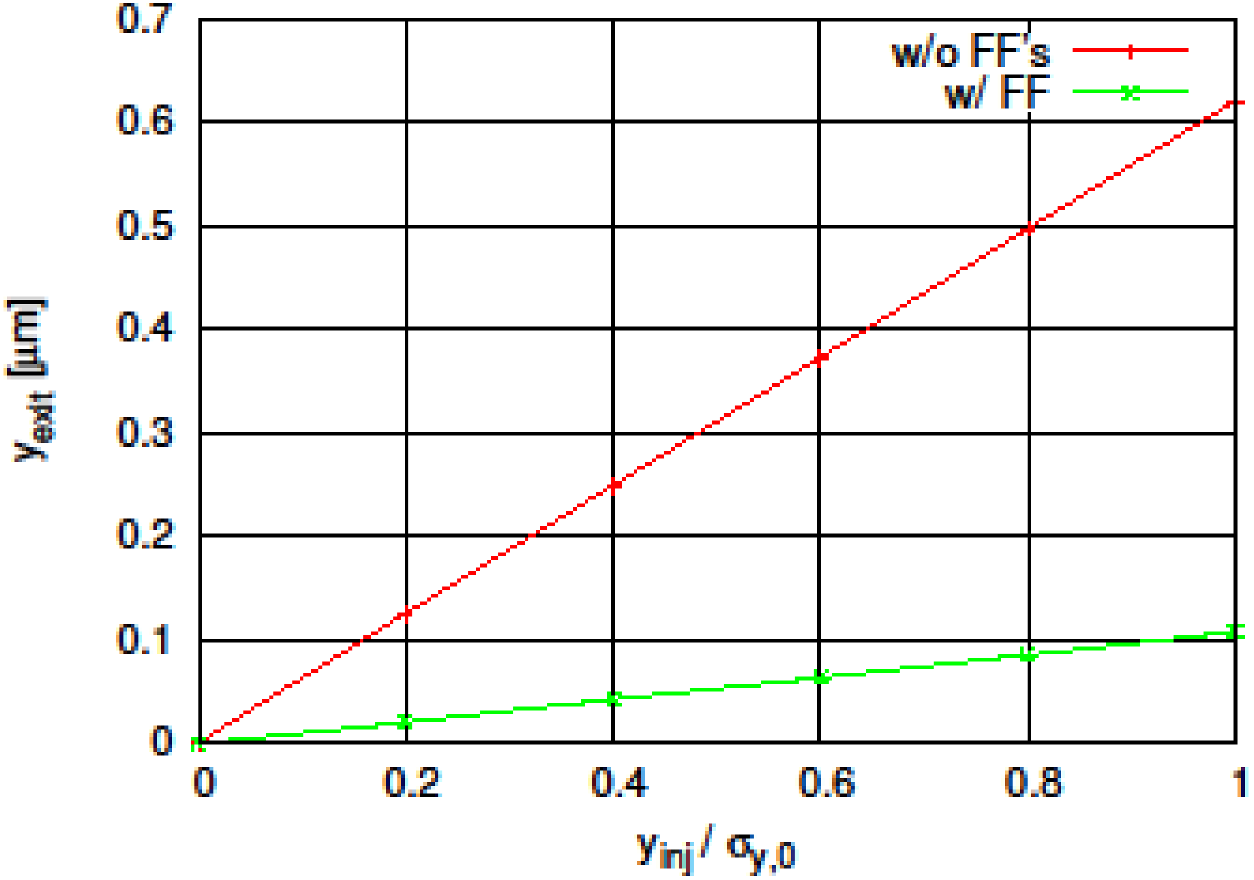
Tracking results: $\Delta\varepsilon_y$ Accuracy study without BBA



Tracking results: $\Delta\varepsilon_y$
Accuracy study with BBA



Tracking results: σ_y
Ideal system



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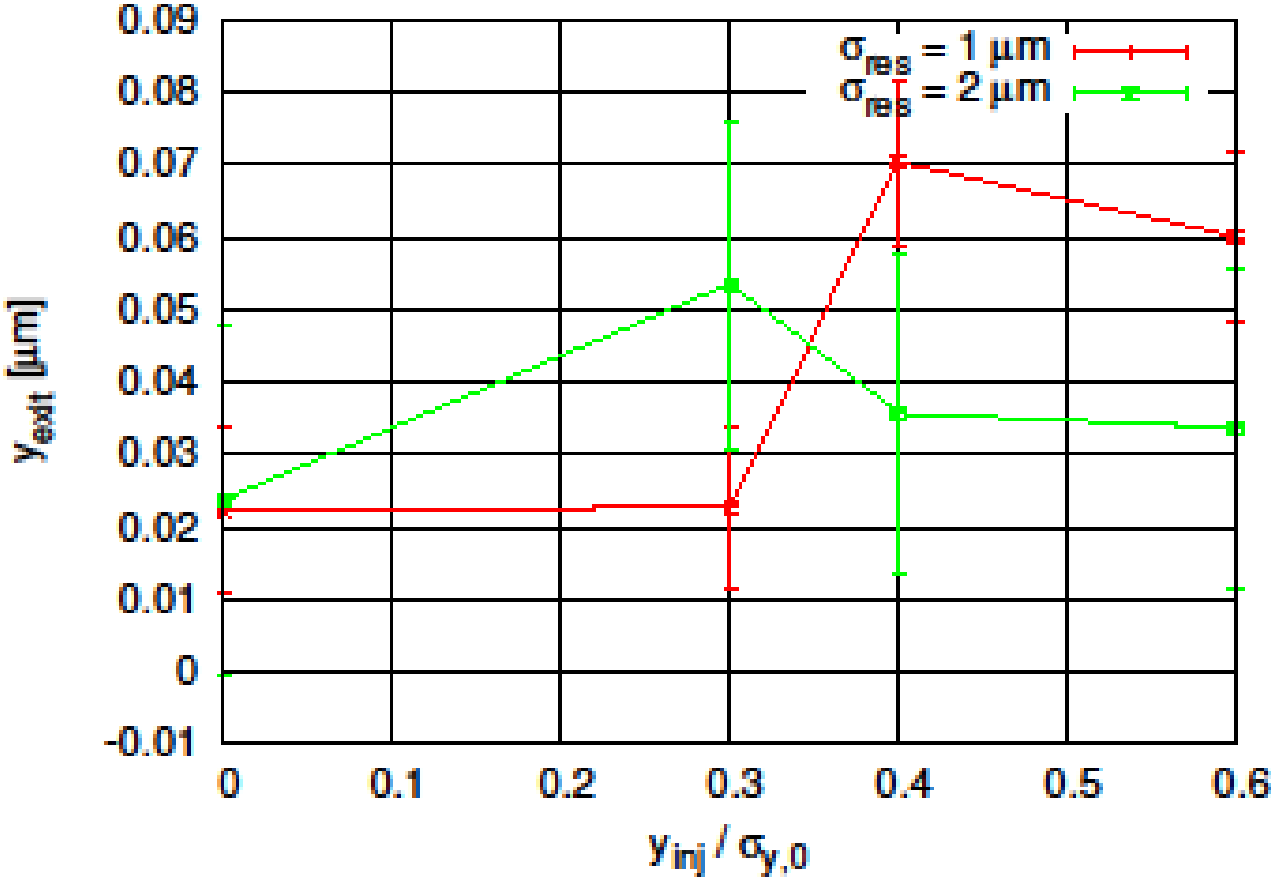
Precision study



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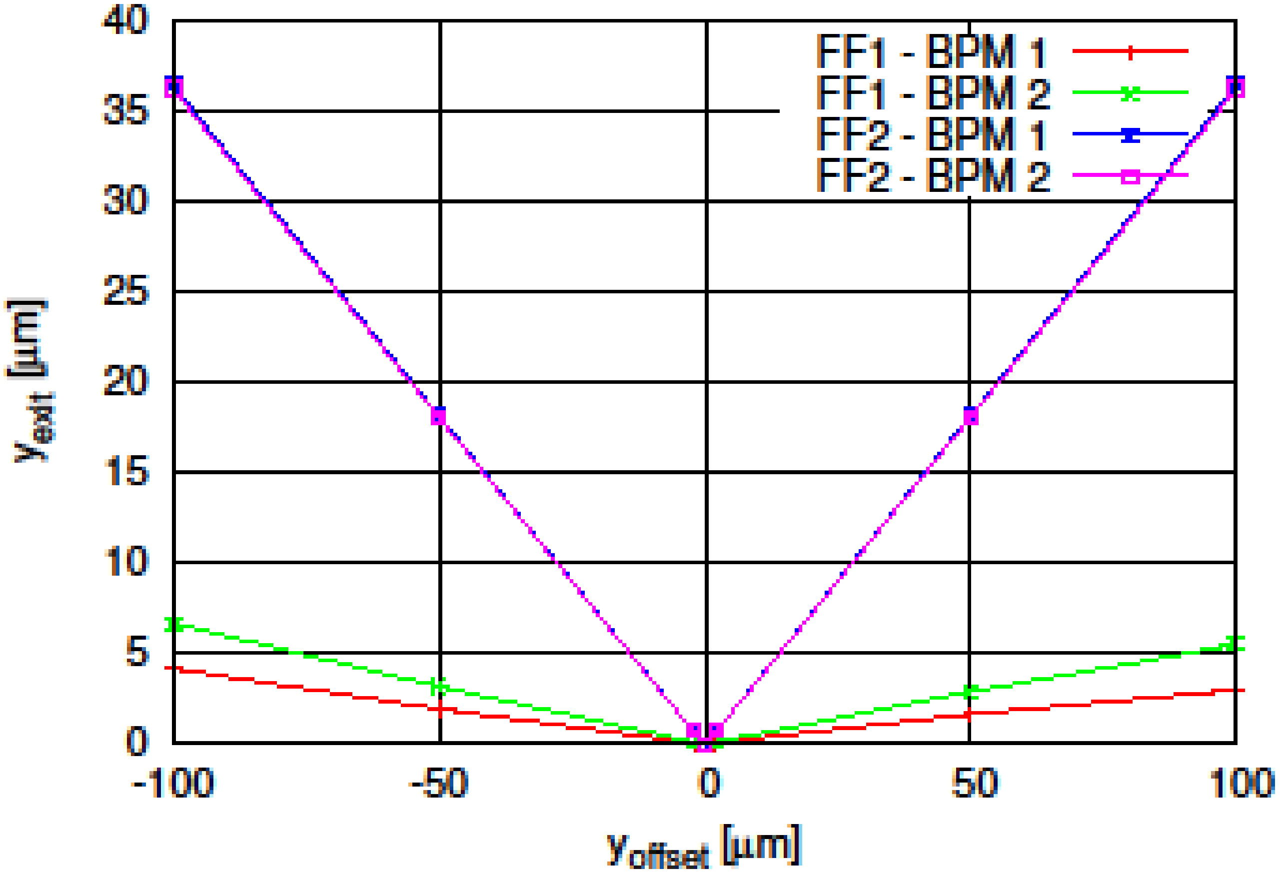
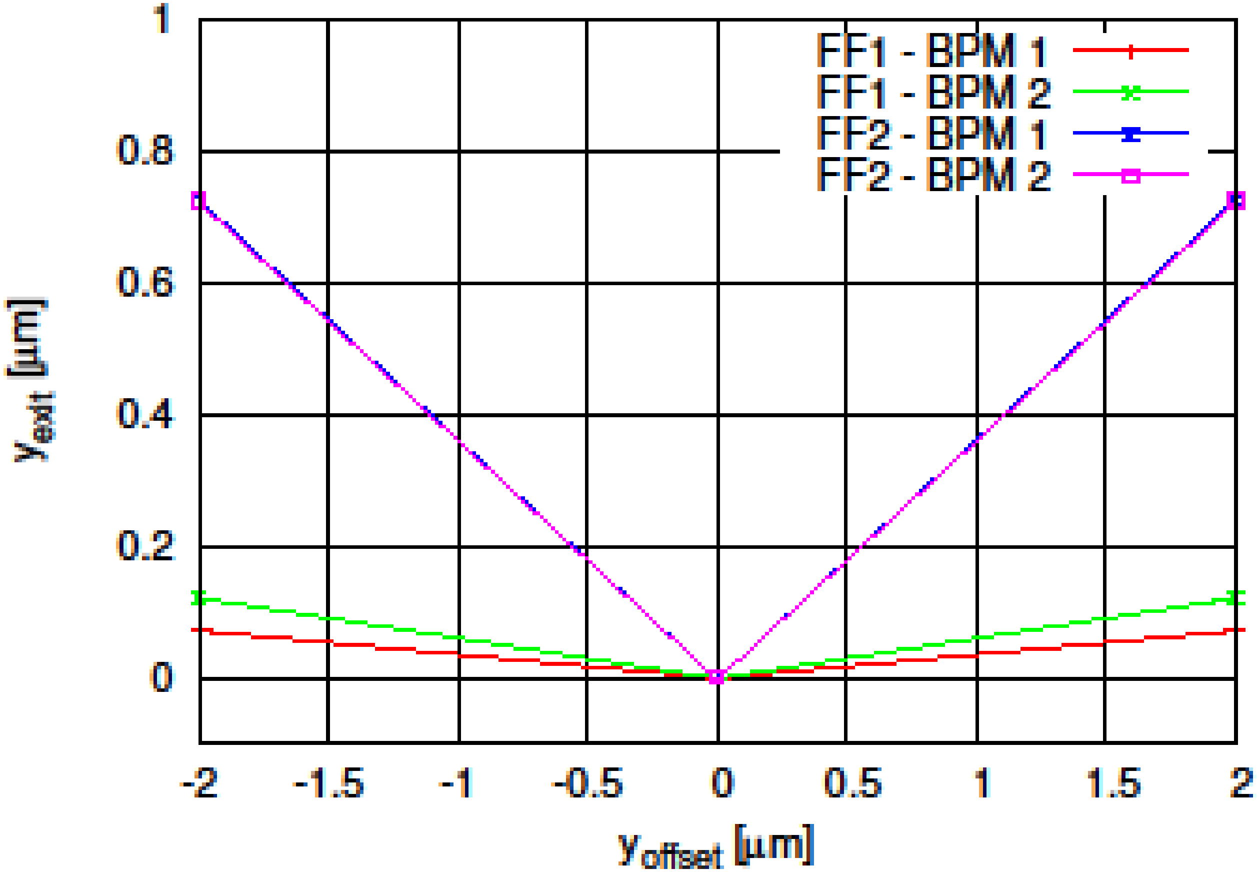


Tracking results: σ_y
Accuracy study with BBA



Summary of tracking results

Horizontal emittance growth:

- Factor 0f ~4 reduction in emittance growth
- 1-2 μm resolution has a negligible effect on FF performance compared to perfect BPMs
- With BBA, misalignment errors have negligible impact on emittance growth

Horizontal jitter amplification:

- Factor of ~7.5 reduction in jitter amplification
- 1-2 μm resolution has a negligible effect on FF performance compared to perfect BPMs
- With BBA, some jitter amplification, but tolerable

Vertical emittance growth:

- Factor 0f ~1.5 reduction in emittance growth
- 1-2 μm resolution has a tolerable effect on FF performance compared to perfect BPMs
- With BBA, misalignment errors have tolerable impact on emittance growth

Vertical jitter amplification:

- Factor of ~6 reduction in jitter amplification
- 1-2 μm resolution has a negligible effect on FF performance compared to perfect BPMs
- Large jitter amplification even with BBA
  - Check this as jitter is ~4 times larger than expected
  - Could be due to wakefields?

Conclusions

The design of the feed forward hardware has been based on existing technology and the required performance has been experimentally demonstrated (FONT feedback system at ATF2); thus confirming the feasibility of the system.

The optics of the BPM and kicker regions have been studied analytically to ensure a global optimisation.

Tracking simulations have shown a good performance of the feed forward systems, including resolution and misalignment errors (with one possible exception).

BBA will be essential for the success of the FF systems, particularly the FF2 systems.

- Use kHz quadrupole k modulations to align beam with magnetic centres of quadrupoles in BPM regions.
- Don’t need to align BPMs as the offset can be subtracted from FF calculations