CLIC RTML collimation systems and beam stabilisation

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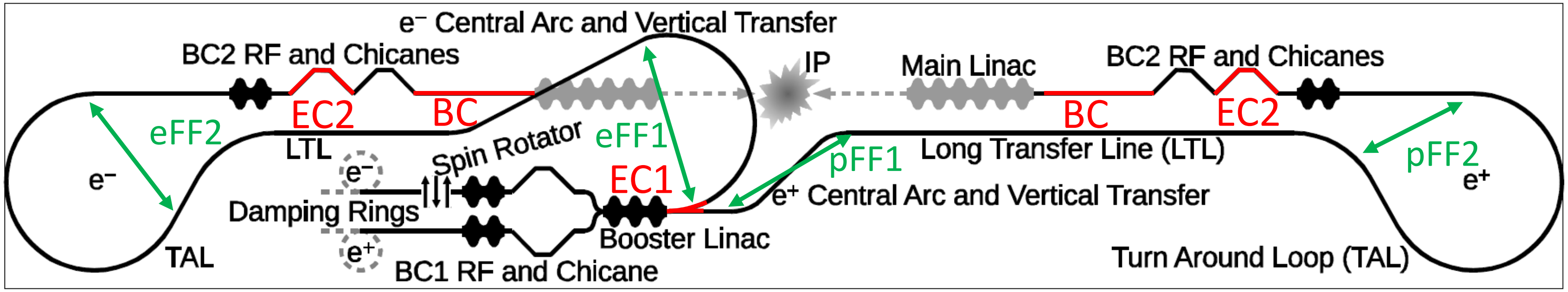
RTML layout



EC1 + EC2: Energy collimators
BC: Betatron collimators

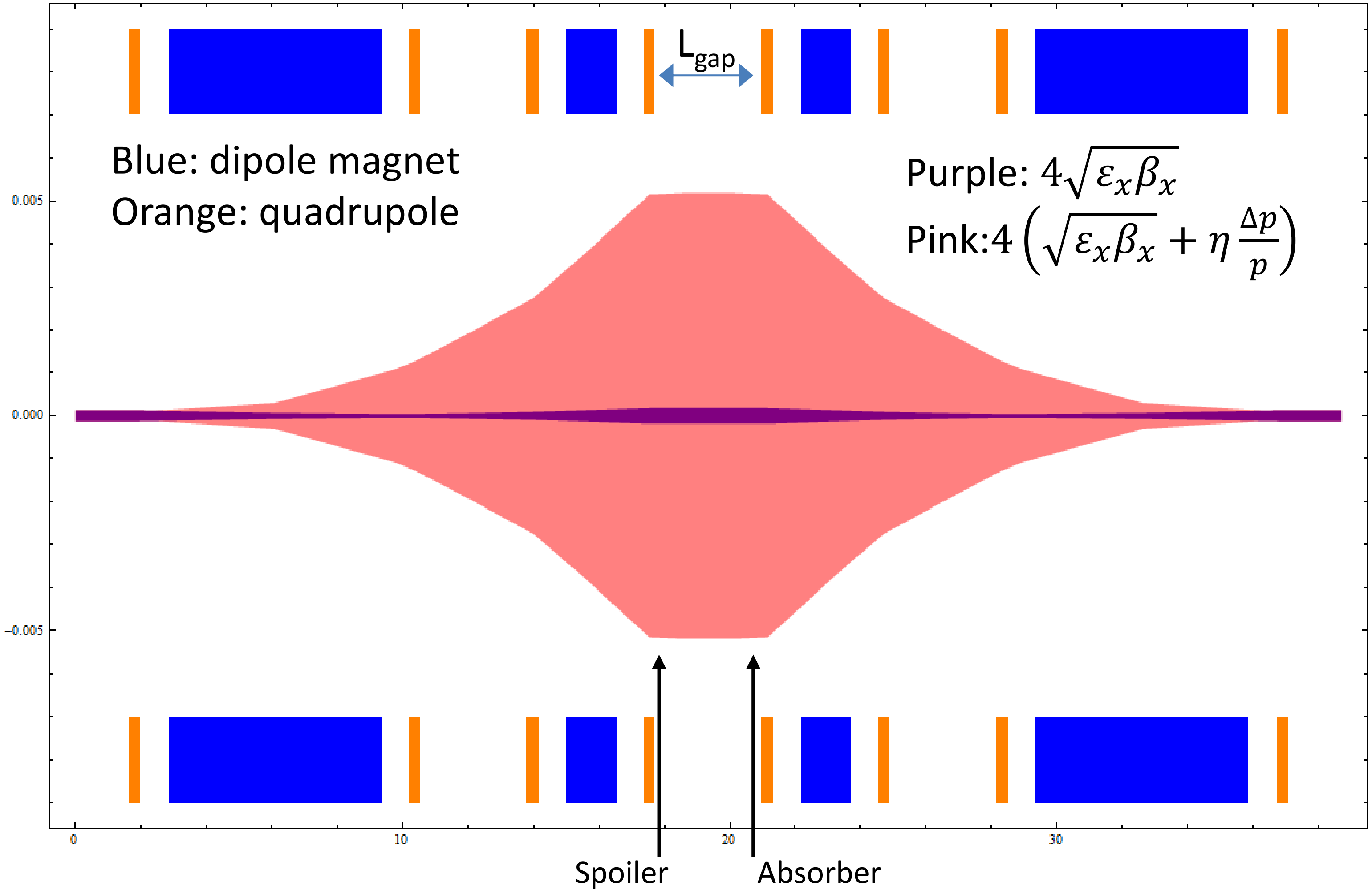
FF1 + FF2: Feed-forward jitter correction

Energy collimator assumptions

- Minimise beam impedance:
  - Spoiler aperture $a_x = N_\sigma D_x \sigma_E \geq \pm 5$ mm
- Energy spread
  - EC1: ±0.33%
  - EC2: ±1.7%
  - Cut at $4\sigma_E$
    - Assumed main linac acceptance
- Required dispersion:
  - EC1: $D_x \geq 0.375$ m
  - EC2: $D_x \geq 0.073$ m

EC1 design

Design matched to existing optics



Blue: dipole magnet
Orange: quadrupole

Purple: $4\sqrt{\varepsilon_x \beta_x}$
Pink: $4\left(\sqrt{\varepsilon_x \beta_x} + \eta \frac{\Delta p}{p}\right)$

EC2 design

- Propose placing absorber in BC2 chicane
  - $D_x = 0.29$m (chicane 1) and 0.19m (chicane 2)
    - $D_x > 0.073$m, both chicanes suitable for aperture
  - No space for spoiler: absorber survivability?
    - $\sigma_r = \sqrt{\sigma_x \sigma_y} \geq 600\mu m$
    - Chicane 1: $\sigma_r = 260\mu m < 600\mu m$
    - Chicane 2: $\sigma_r = 210\mu m < 600\mu m$
    - Need spoiler to ensure absorber survival
    - In comparison, for EC1: $\sigma_r \approx 6mm$
  - Modifications to chicane to be considered

Betatron collimation design

- Apply cuts at $8\sigma_x$ and $50\sigma_y$
- Emittance growth due to spoiler wakefields
  - Optimise parameters to minimise $\Delta\varepsilon$
    - Spoiler aperture
    - Spoiler geometry
  - Dependence on beam position jitter
- Collimation efficiency
  - Balance efficiency with emittance growth

Emittance growth (1)

- Emittance growth budget for RTML:

	Design	Static	Dynamic
$\Delta\varepsilon_{x,norm}$	60nm	20nm	20nm
$\Delta\varepsilon_{y,norm}$	1nm	2nm	2nm

- Target for emittance growth due to jitter in RTML:
  - Some part of this will be due to the betatron collimator
    - $\Delta\varepsilon_x \leq 15nm$
    - $\Delta\varepsilon_y \leq 0.5nm$

Induced wakefields in spoilers are the main source of emittance growth:
They consists of a geometric and a resistive component.
Geometric wakefields depend on the design of the spoiler
Resistive wakefields depend on the electrical properties of the spoiler.

Mathematical description

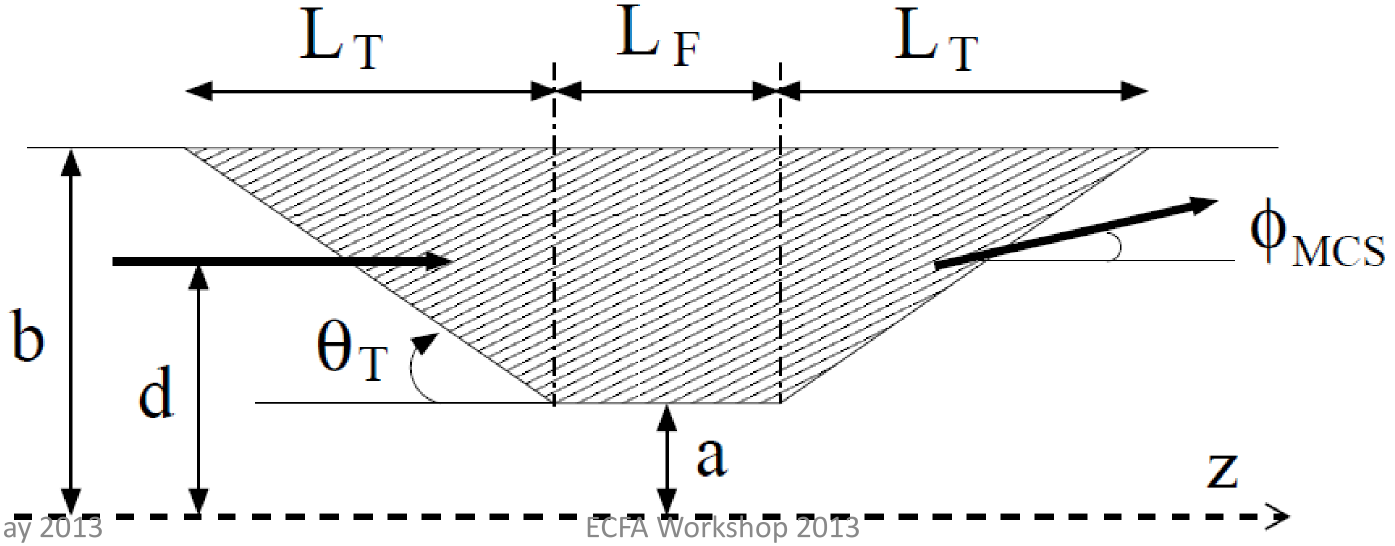
$$\langle y'_{RMS} \rangle = \frac{r_e N_b}{\sqrt{3}\gamma} \kappa y_0$$

$$\kappa = \kappa_g + \kappa_r$$

$$\frac{\delta\varepsilon_y}{\varepsilon_y} = \sqrt{1 + \frac{\beta_y}{\varepsilon_y} \langle y'_{RMS} \rangle^2} - 1$$

$$\kappa_g = \begin{cases} \dfrac{\pi\theta_T h}{2\sigma_z}\left(\dfrac{1}{a^2} - \dfrac{1}{b^2}\right) & \theta_T < 3.1^2 \dfrac{a\sigma_z}{h^2} \\ \dfrac{8}{3}\sqrt{\dfrac{\theta_T}{\sigma_z a^3}} & 3.1^2 \dfrac{a\sigma_z}{h^2} < \theta_T < 0.37^2 \dfrac{\sigma_z}{a} \\ \dfrac{1}{a^2} & \theta_T > 0.37^2 \dfrac{\sigma_z}{a} \end{cases}$$

$$\kappa_r = \frac{\pi}{8a^2}\Gamma(1/4)\sqrt{\frac{2}{\sigma_z \sigma Z_0}}\left[\frac{L_F}{a} + \frac{1}{\theta_T}\right]$$



Emittance growth (2)

Minimum for $\Delta\varepsilon$:

$a \to \infty$

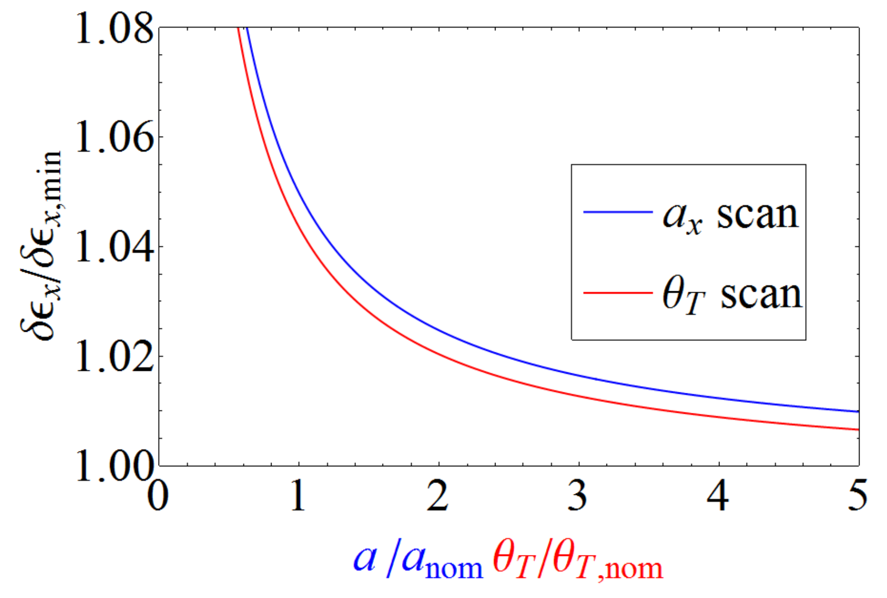
$\theta_T \to \frac{\pi}{2}$

Clearly we cannot have an infinite aperture.

$\theta_T \gg 0$ will excite long range wakefields, destabilising the bunch train.

To optimise the emittance growth, limits are set on the aperture and taper angle so that:

$\Delta\varepsilon_{coll} \leq 1.05\Delta\varepsilon_{min}$



Parameter	**Limit**
θ_T	$\geq 80\ mrad$
Spoiler aperture	$\geq 0.5\ mm$

Larger aperture
⇒ larger beam size
⇒ longer collimation system
Compromise between Δε and length of collimator system

Beam jitter

Optimisation of the collimator design is not enough to limit emittance growth in the betatron collimator.

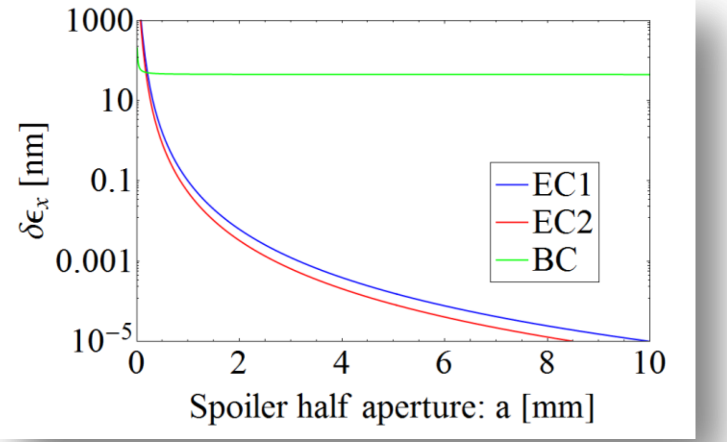
The emittance growth is strongly dependent on the beam jitter in the spoilers.

	#σ cut	**$\Delta\varepsilon_x$ 1σ offset**	**$\Delta\varepsilon_x$ 0.25σ offset**
x	8	62.6 nm	4.0 nm
y	50	2.5 nm	0.16 nm

The results in this table assumes 4 collimator cells

It is vital that the beam jitter is controlled in the betatron collimator.

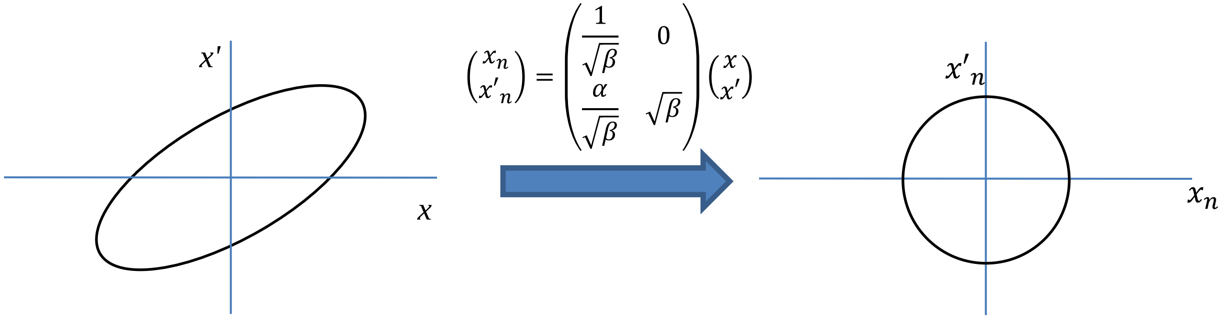
N.B. beam jitter is dependent on the betatronic beam size; therefore emittance growth in the energy collimators is negligible.



This plot shows emittance growth for a $1\sigma_\beta$ offset.

Collimation efficiency (1)

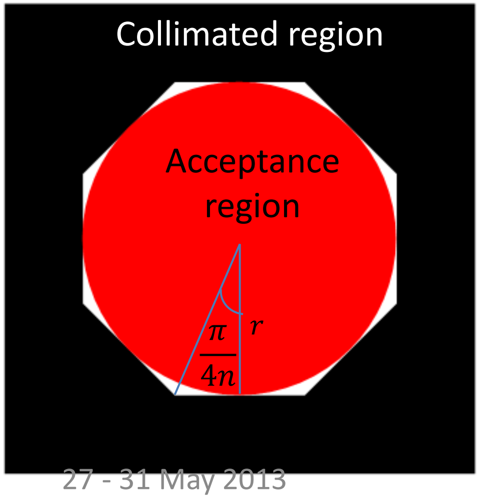
In normalised phase space, the acceptance of the beam forms a circle:



$$\begin{pmatrix} x_n \\ x'_n \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{\beta}} & 0 \\ \frac{\alpha}{\sqrt{\beta}} & \sqrt{\beta} \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}$$

Assume the betatron collimation system consists of n spoiler-absorber pairs, each separated by a phase advance $\frac{m\pi}{n}$ where m and n are mutually prime.

The collimated region will form a regular 2n-sided polygon in normalised phase space.



The volume of phase space occupied by the acceptance region is:

$$A_{beam} = \pi r^2$$

The volume of phase space occupied by the un-collimated region is:

$$A_{coll} = 4nr^2 \tan\frac{\pi}{4n}$$

The geometric collimator efficiency is defined as the ratio of these areas:

$$\eta_{geo} = \frac{\pi}{4n} \cot\frac{\pi}{4n}$$

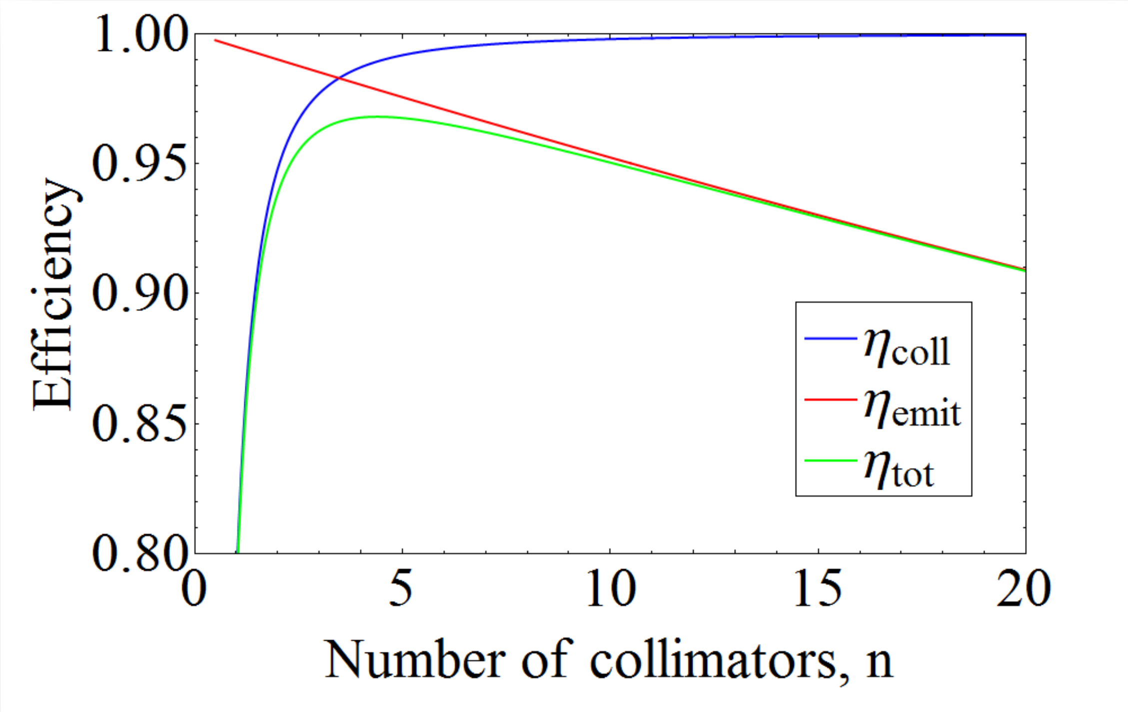
Collimation efficiency (2)

The emittance growth scales approximately linearly with the number of spoiler-absorber pairs. The efficiency in terms of emittance growth is defined as:

$$\eta_{emit} = \frac{\delta\varepsilon_{nom}}{\delta\varepsilon_{nom} + n\delta\varepsilon_{coll}}$$

The total collimation efficiency is the product of these two terms:

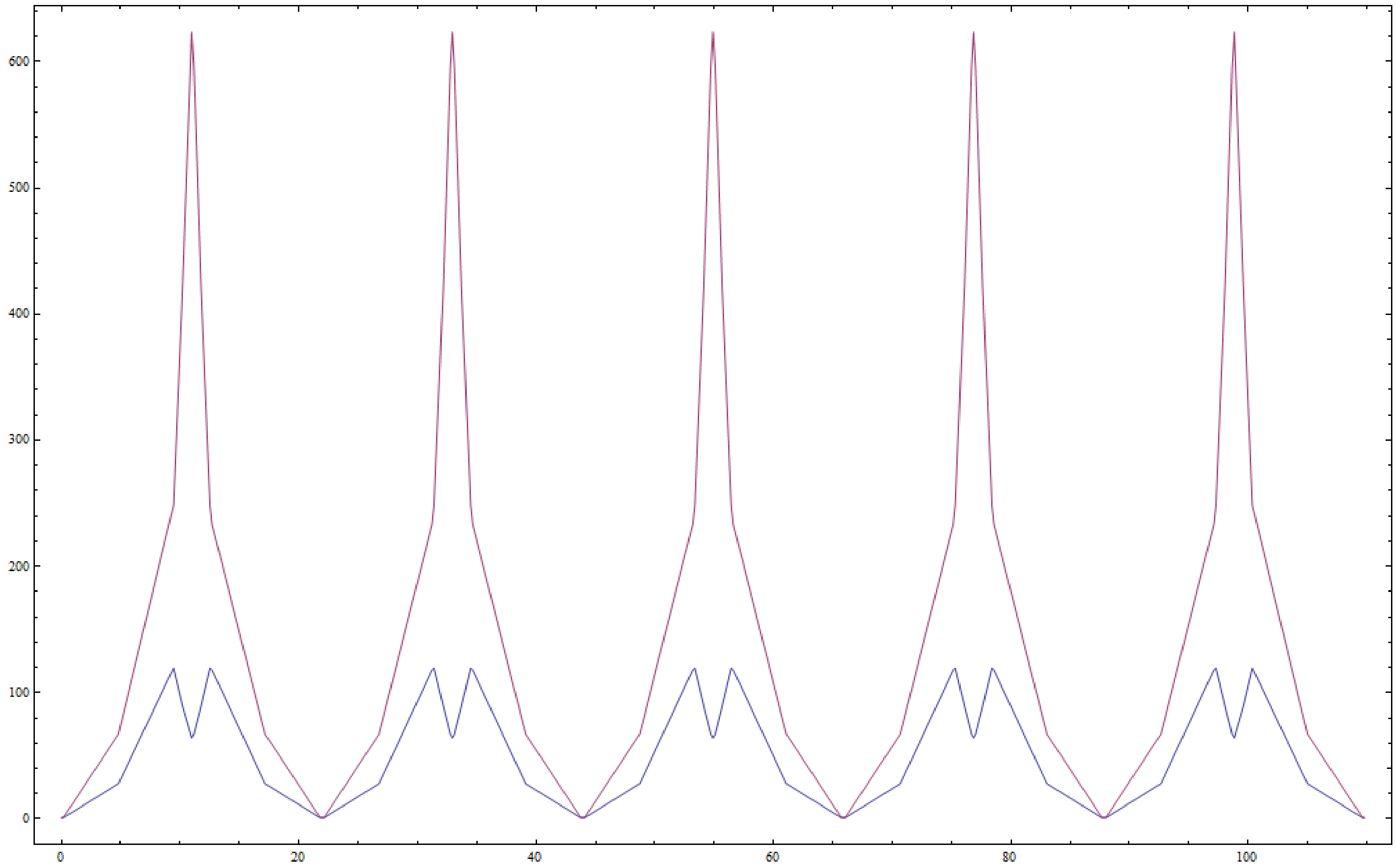
$$\eta_{tot} = \eta_{geo}\eta_{emit}$$



For the RTML betatron collimator parameters, η_{tot} is maximal when n = 4.4

Therefore n = 4 is chosen as the optimum number of collimator cells.

Betatron collimation optics



Jitter amplification in the RTML

Tracking simulations in PLACET have been used to determine the maximum jitter at the start of the RTML in order to meet the jitter requirements for the betatron collimation.

	Jitter at BC system	**Jitter at start of RTML**
Horizontal	$0.21\sigma_x$	$0.1\sigma_x$
vertical	$0.13\sigma_y$	$0.27\sigma_y$

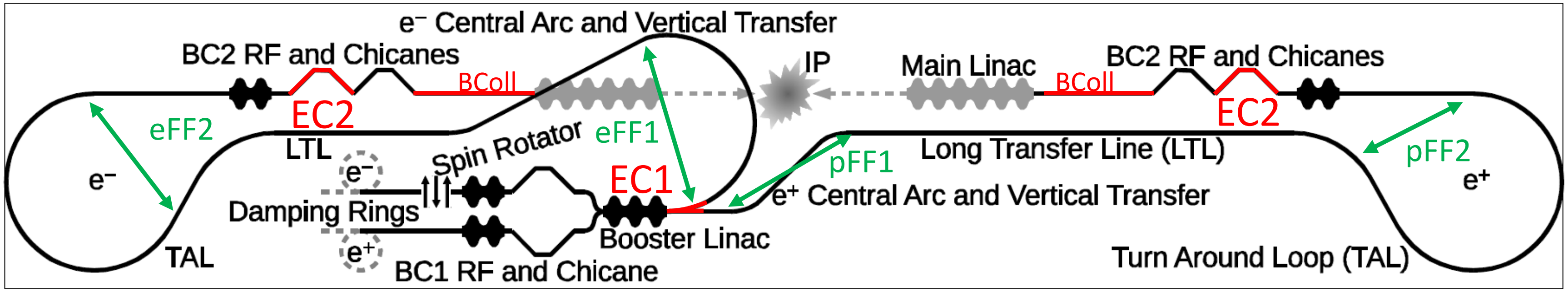
The jitter tolerances at the start of the RTML put very tight requirements on the stability of the extraction kicker and septum magnets[#].

Indications are that the kicker and septa cannot be designed and built with the required stability.

Feed forward systems in the RTML have been considered as a solution to relax the stability requirements of the damping ring extraction system and to meet the jitter requirements of the betatron collimation system.

[#] "Optics and protection of the injection and extraction regions of the CLIC damping rings", R. Apsimon et al. IPAC13 proceedings

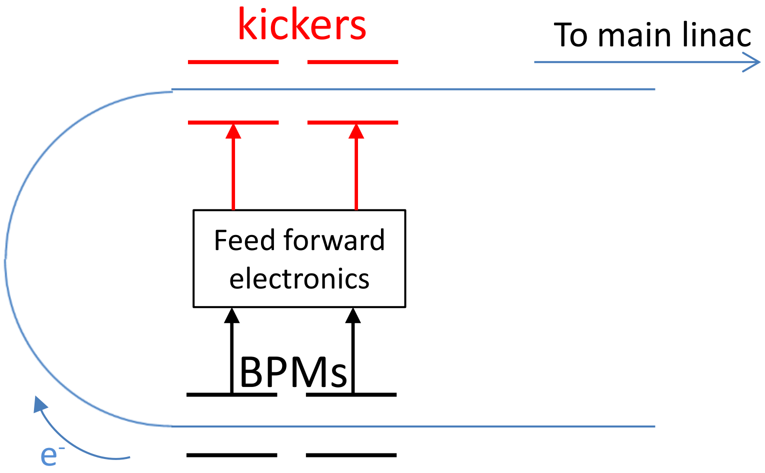
Proposed locations



The e$^+$ RTML has a chicane rather than a loop for the central arc; pFF1 will be different to the other FF systems.

BColl: betatron collimation system

EC1 + EC2: energy collimator systems



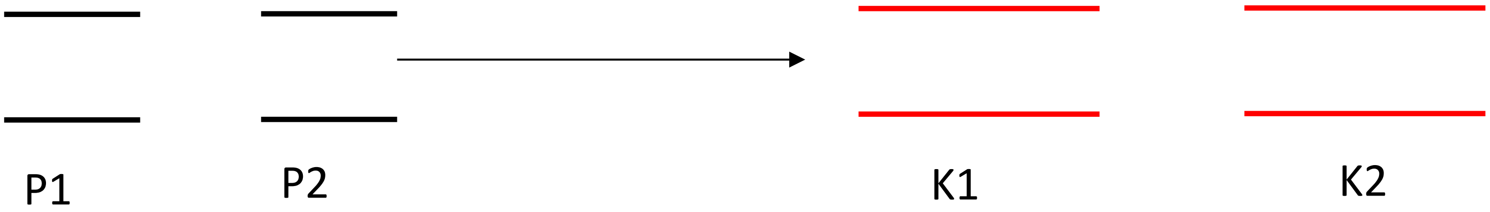
FF1:

- Correct DR extraction jitter
- Limits emittance growth along RTML

FF2:

- Correct jitter at entrance of betatron collimator system (BC)
- Prevents significant emittance growth in BC system

Feed forward corrections



P1 P2 K1 K2

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

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

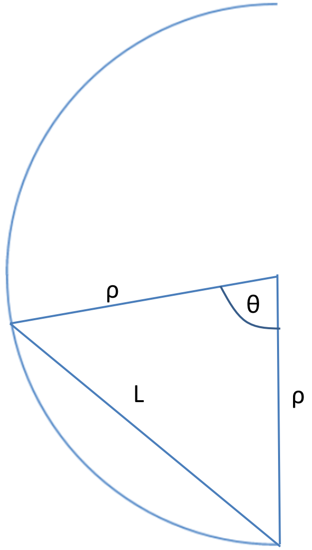
$$\theta_{K2} = -\frac{b_{12}}{a_{12}c_{12}} x_1 + \frac{[BA]_{12}}{a_{12}c_{12}} x_2$$

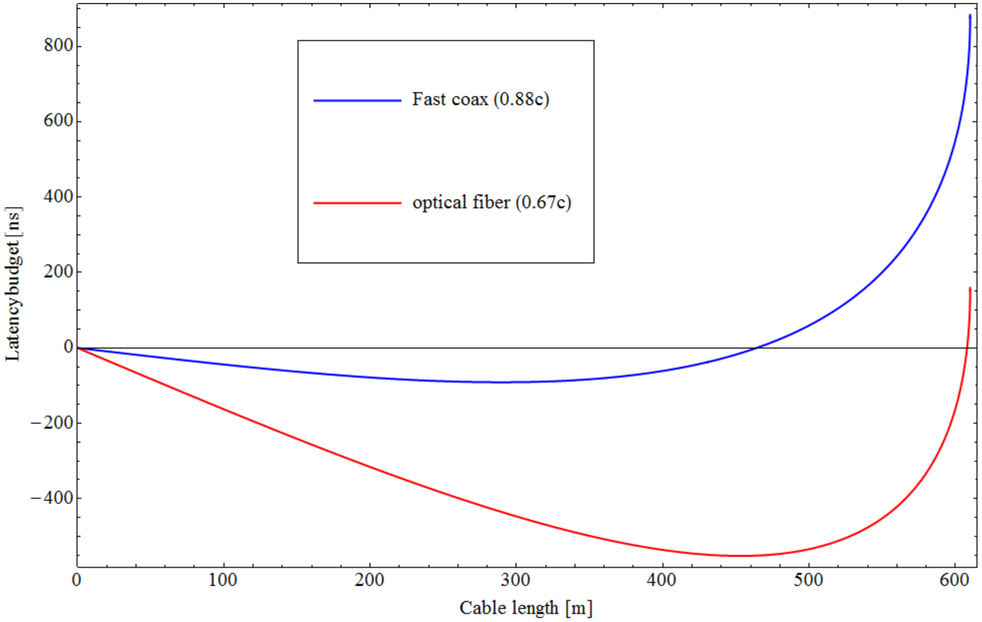
System latency

Latency budget = $t_{lat} = t_{signal} - t_{beam} = \frac{\rho\theta}{\beta c} - \frac{2\rho \sin\frac{\theta}{2}}{v_{cable}}$

ρ is the radius of curvature of the arc

v_{cable} is the transmission velocity of the FF signal cables





Coaxial cables are fast, but for low attenuation, very thick cables (~20 mm diameter) would be needed; this would be difficult to install and repair.

Optical cables are low loss, compact, but very slow; the latency budget might not be enough.

System latency

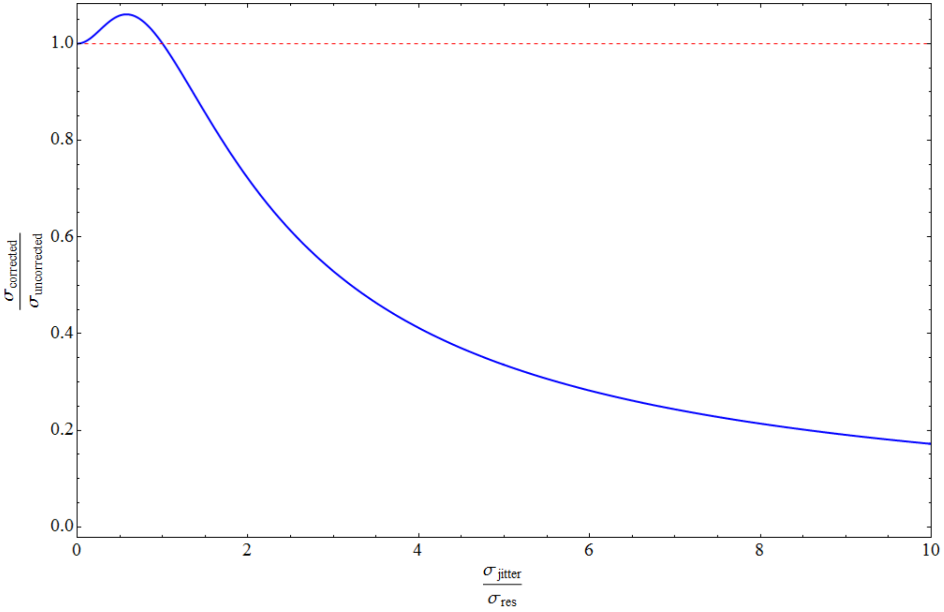
Experience from the FONT feedback system at ATF2 suggests that the minimum latency requirement would be ~150 ns [2].

Additional latency allows for improvements:

- Digitise BPM signals: less susceptible to noise
- Use of high resolution ADCs and DACs
- Use of high-bit processing for the digital feed-forward electronics
- Systematic correction of the bunch-to-bunch profile within the train
  - Analogue electronics to add “compensation ripple” to kicker pulse

In summary, the large latency budget provided by coaxial cables would allow for a very high resolution digital feed forward system. The limiting factor would be the resolution of the BPMs.

BPM resolution



To achieve good jitter correction, the BPM resolution must be much smaller than the expected beam jitter.

The expected beam jitter in the FF regions is ~10µm horizontally, but the required BPM resolution is ~140nm; probably not possible with 12 cm aperture…

Currently looking at dependence of required BPM resolution on value of β in BPMs.

$$\rho = \frac{\sigma_{jitt}^2}{\sigma_{jitt}^2 + \sigma_{res}^2}$$

$$\Rightarrow \frac{\sigma_{jitt}}{\sigma_{res}} = \alpha = \sqrt{\frac{\rho}{1-\rho}}$$

$$\frac{\sigma_{corrected}}{\sigma_{uncorrected}} = \sqrt{1+\rho-2\rho^2} = \frac{\sqrt{3\alpha^2+1}}{\alpha^2+1}$$

FF kicker specifications

Parameter	Value
Length	1 m
Kicker type	Electrostatic
Reproducibility	> 1 %
Field homogeneity	> 1 %
Rise / fall time	> 10 ns
Flat top duration	~160 ns
Deflection angle	~ 0.8 µrad

For a kicker stability of 2%, the resulting jitter at the entrance of the BC system will be ~20nm; smaller than the resolution of any existing BPM system.

Therefore we can assume the kickers are perfect for simulation purposes.

Tracking simulations

- Tracking in PLACET
    - No FF correction
    - Only FF1
    - Only FF2
    - FF1 + FF2
  - Jitter amplification + emittance growth
    - Vs. initial jitter
    - Vs. BPM resolution

Following slides only show horizontal beam as this is the more critical.

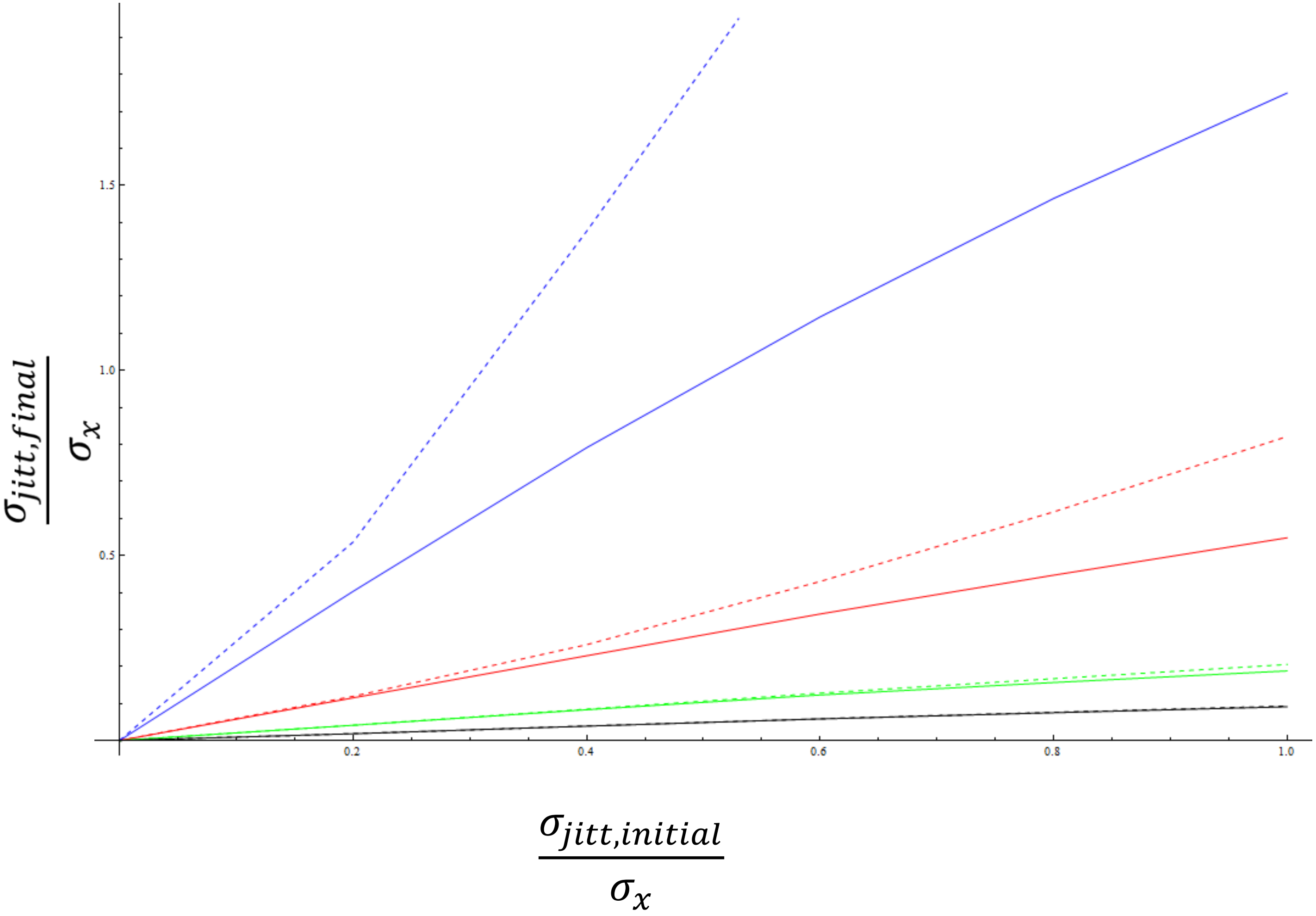
RTML emittance growth budget

	Design	Static	Dynamic
$\Delta\varepsilon_x$	60 nm	20 nm	20 nm
$\Delta\varepsilon_y$	1 nm	2 nm	2 nm

The aim is to allocate 25% of the dynamic budget to emittance growth due to beam jitter.

Tracking simulations show that only 50 nm of the horizontal budget is used, therefore the remaining 10 nm will be allocated to the beam jitter budget.

Final jitter vs. initial jitter

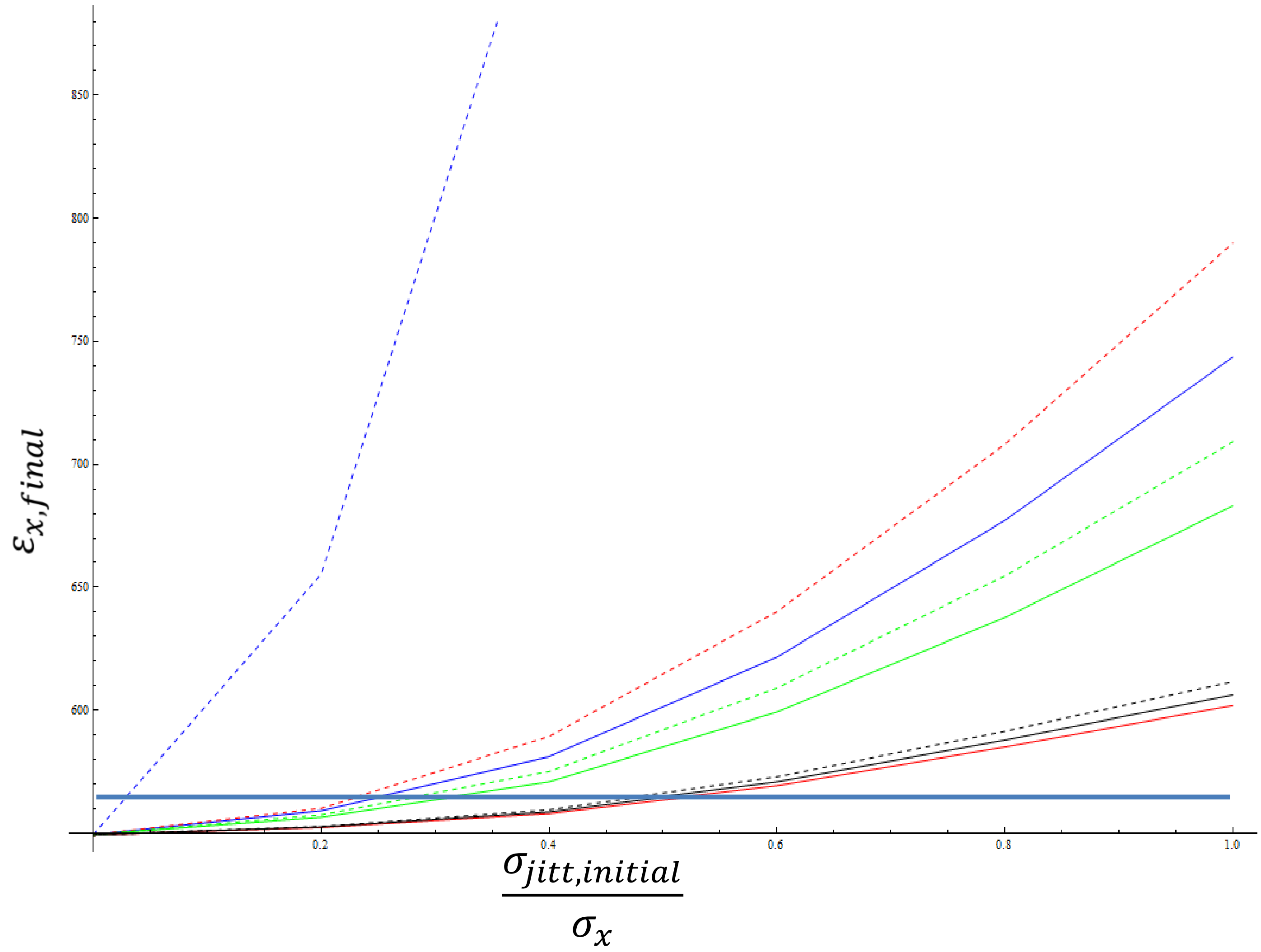


No FF
Only FF1
Only FF2
Both FF1 + FF2

Solid line:
no collimation

Dashed line:
with collimation

$\Delta\varepsilon_x$ vs. initial jitter



No FF

Only FF1

Only FF2

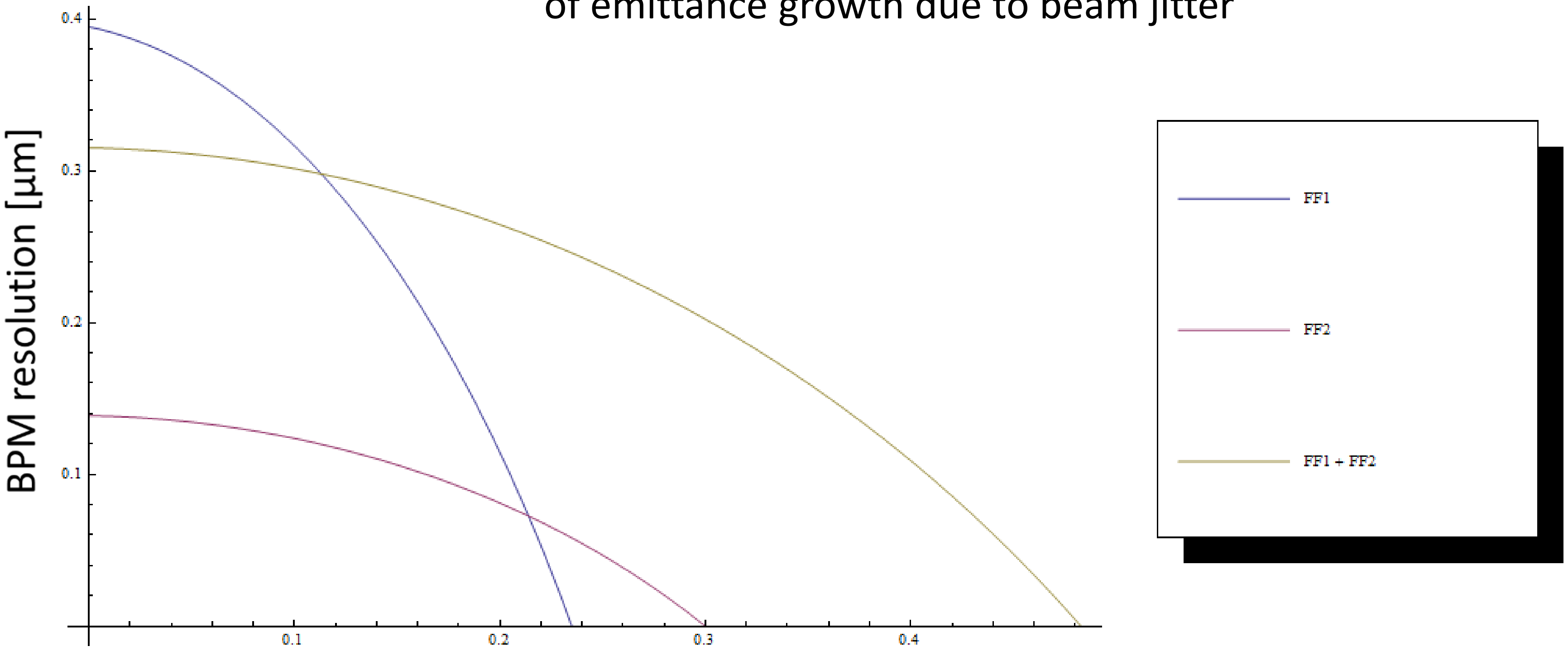
Both FF1 + FF2

Solid line:
no collimation

Dashed line:
with collimation

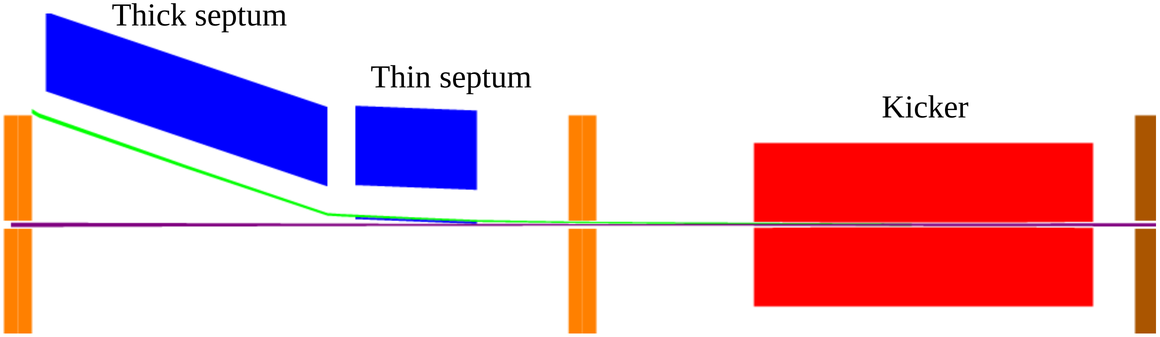
Required BPM resolution vs. initial jitter

This plot shows how the BPM resolution varies with initial jitter to produce 15 nm of emittance growth due to beam jitter



N.B. this plot assumed $\beta_x \approx 40\ m$ as is the case for the baseline RTML design. The optics are likely to change to relax the required BPM resolution.

Extraction system layout



Tolerances for damping ring extraction

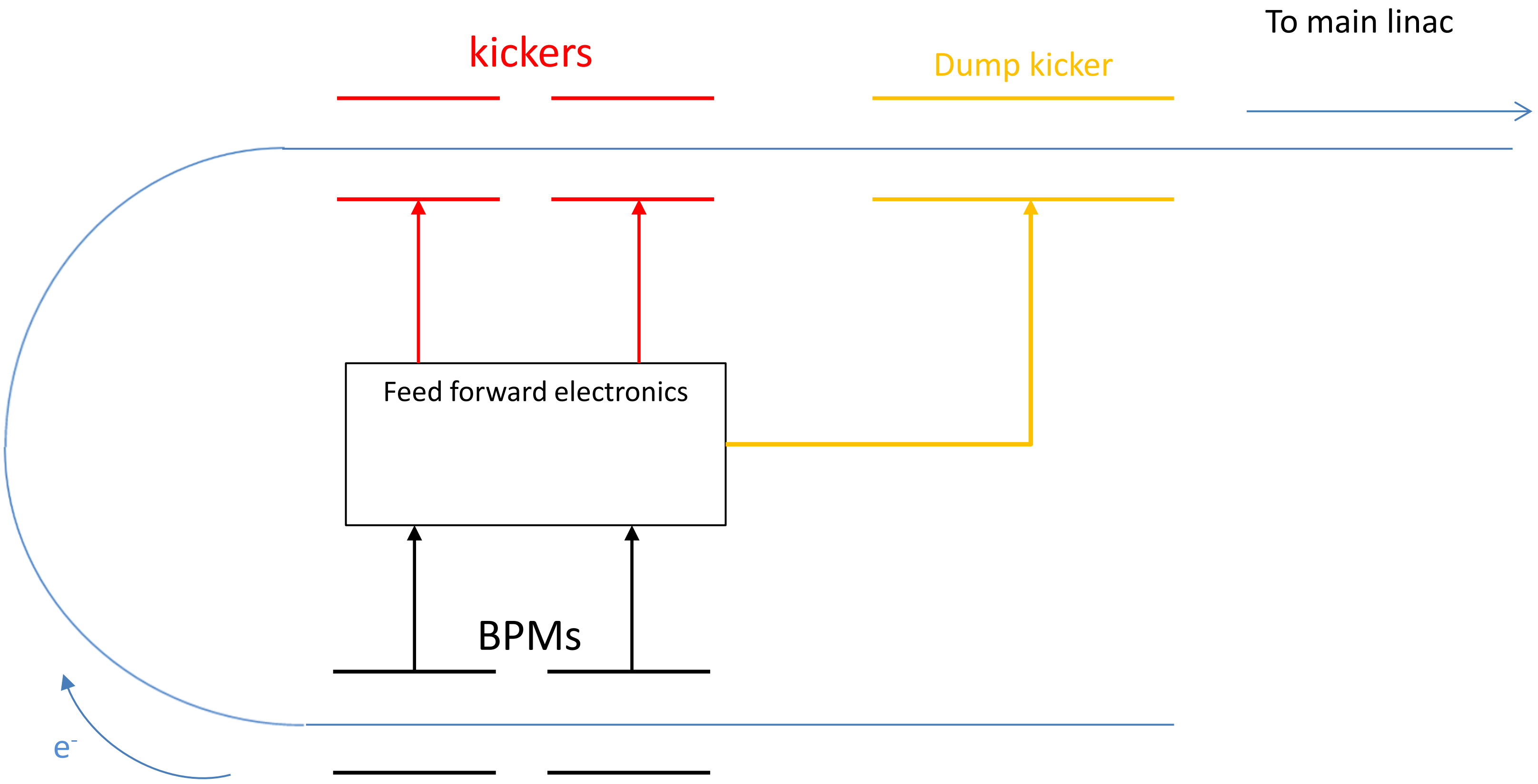
	W/o RTML FF systems	W/ RTML FF systems
Beam jitter	$0.1\sigma_x$ / $0.3\sigma_y$	~ $0.4\sigma_x$ / $0.7\sigma_y$
Kicker stability	3×10^{-4}	5×10^{-3}
Thin septum stability	$^*6 \times 10^{-6}$	1×10^{-4}
Thick septum stability	$^*1.2 \times 10^{-7}$	2×10^{-5}

The kicker good field region has been reduced from a radius of 1mm to 0.5mm.

This combined with the proposed FF systems relaxes the stability requirements for the extraction system by a factor of ~16.

The stability requirements for the extraction elements have been optimised to maximise the combined extraction stability.

* These values differ from the CLIC CDR because the CDR values were optimised for a previous design of the DR extraction system



kickers

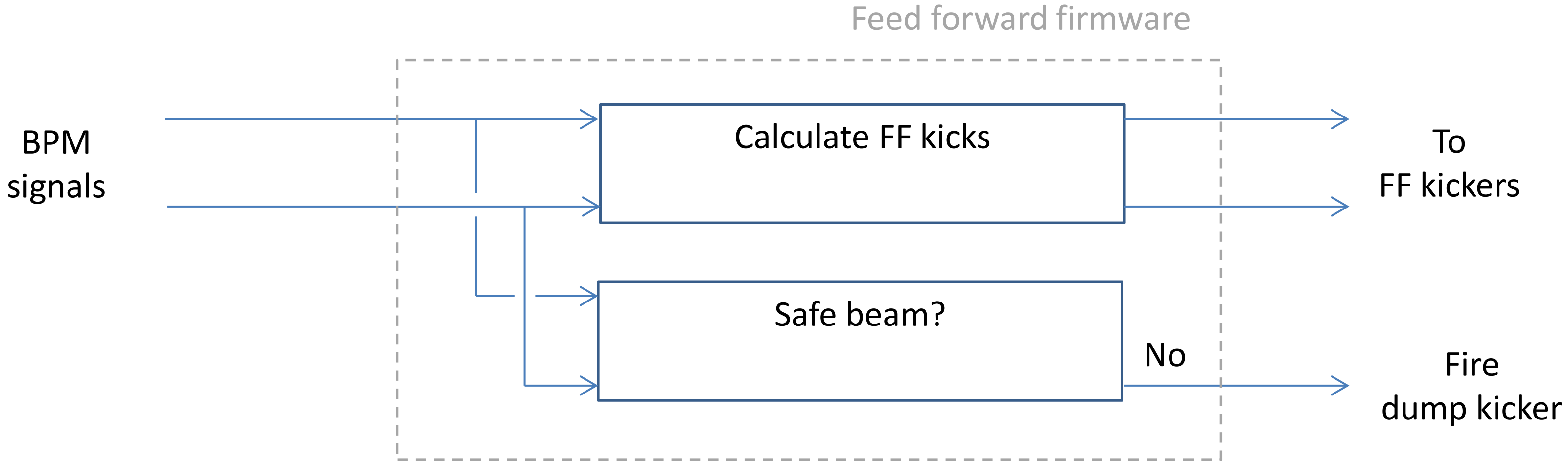
Dump kicker

To main linac

Feed forward electronics

BPMs

e⁻



Feed forward firmware

BPM signals

Calculate FF kicks

Safe beam?

No

To FF kickers

Fire dump kicker

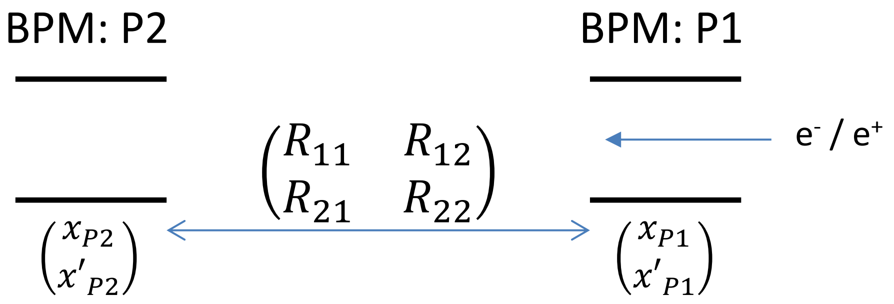
Possible machine protection

Due to the large available latency, the feed forward electronics could double as a fast emergency dump system. This would reduce the risk of damage to the collimation systems in the event of total beam loss; especially for EC2, which would not survive a total beam loss in the current design.

Off-trajectory
The FF kickers will only be able to correct orbit deviations of ~0.5σ. If the beam is dangerously off-trajectory, the digital feed forward electronics can be used to trigger a dump kicker downstream of the FF kickers.

Off-energy
BPMs situated in a dispersion region at the start of the turn-around loop can be used to trigger the dump kicker for large beam energy deviations. These measurements would also allow the FF kicks to be normalised for energy deviations.

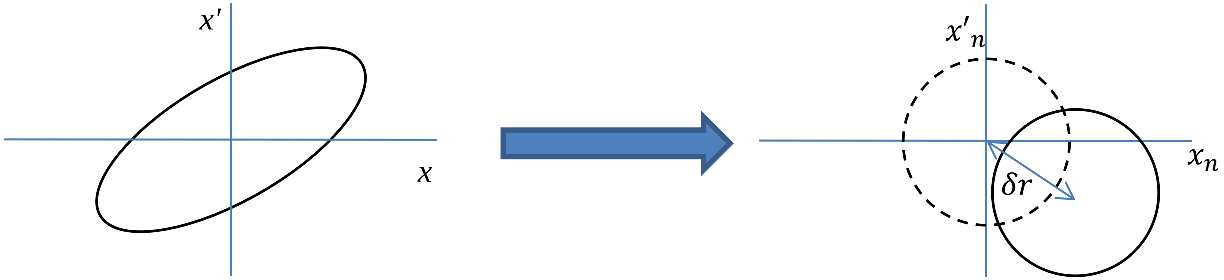
Determination of an “unsafe beam”



$$\begin{pmatrix} x_{P1} \\ x'_{P1} \end{pmatrix} = \begin{pmatrix} x_{P1} \\ \frac{x_{P2}-R_{11}x_{P1}}{R_{12}} \end{pmatrix}$$

Transform into normalised phase space:

$$\begin{pmatrix} x_n \\ x'_n \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{\beta_{P1}}} & 0 \\ \frac{\alpha_{P1}}{\sqrt{\beta_{P1}}} & \sqrt{\beta_{P1}} \end{pmatrix} \begin{pmatrix} x_{P1} \\ \frac{x_{P2}-R_{11}x_{P1}}{R_{12}} \end{pmatrix}$$



$$\delta r^2 = \frac{x_n^2 + x'^2_n}{\varepsilon}$$

$$= \frac{1}{\varepsilon\beta_{P1}\sin^2\mu}x_{P1}^2 - \frac{2\cos\mu}{\varepsilon\sqrt{\beta_{P1}\beta_{P2}}\sin^2\mu}x_{P1}x_{P2} + \frac{1}{\varepsilon\beta_{P2}\sin^2\mu}x_{P2}^2 \geq n_{thresh}$$

To maximise the sensitivity of the feed forward system:

$\mu = \frac{\pi}{2}$ and $\beta_{P1} = \beta_{P2} = \beta$

So the “unsafe beam” condition becomes: $\frac{x_{P1}^2 + x_{P2}^2}{\sigma^2} \geq n_{thresh}$

This can be calculated digitally in 3-4 clock cycles (5-10 ns for a clock frequency of ~500MHz)

e^+ FF1 Considerations

Without FF1, extremely low BPM resolution is required for the e^+ RTML to relax requirement for the DR extraction system: **probably not achievable.**

150 ns latency can be achieved if the signal velocity > 0.945c:

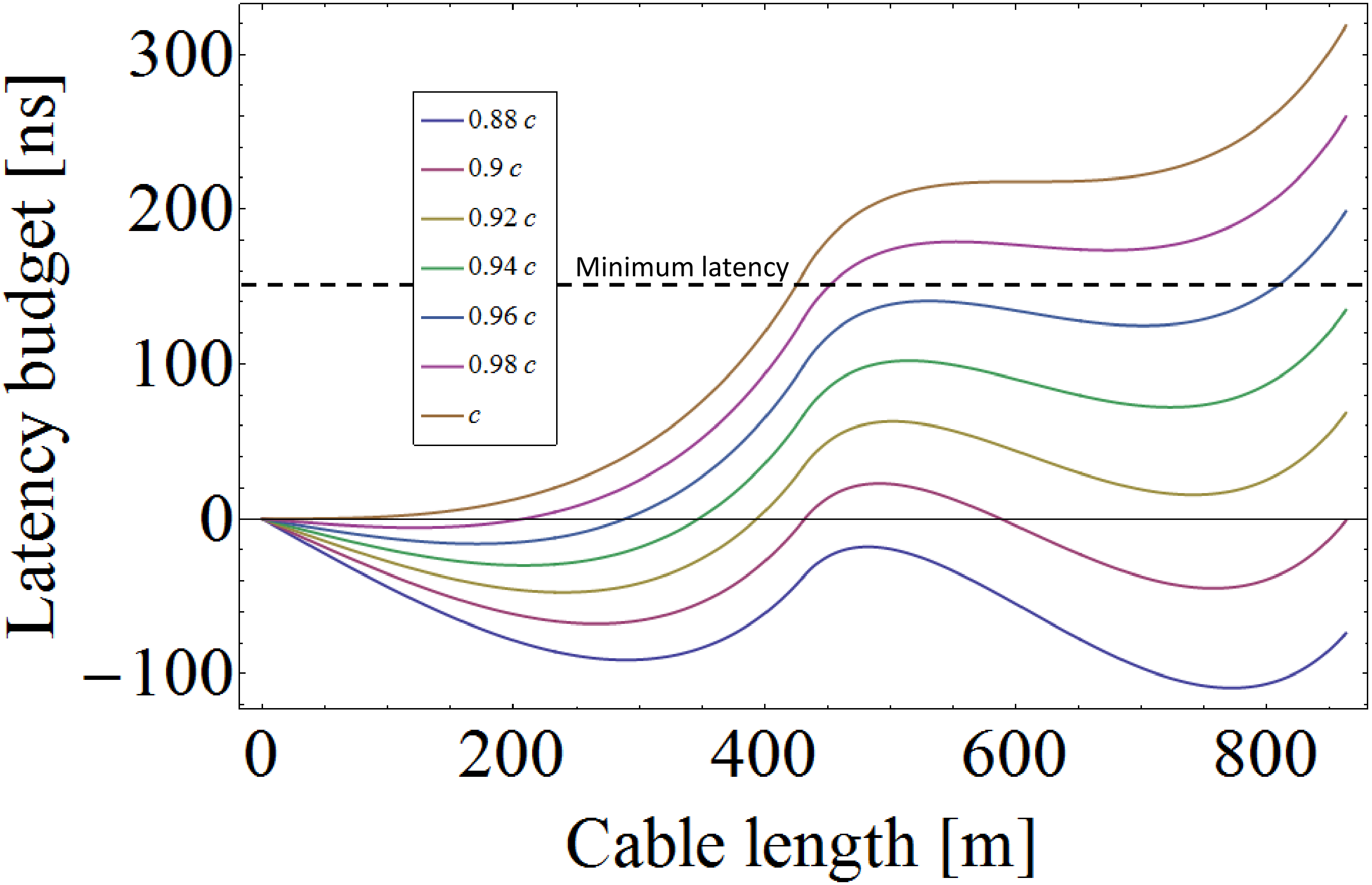
- Use free-space optical links (> 0.999c)
  - The signals are transmitted by a laser through a narrow tunnel
  - ~300 ns of latency

Due to the smaller latency budget for the e^+ FF1 system, some high-latency features may need to be disabled, but hopefully not. Some changes to feature may be:

- Lower resolution digitisation and processing
- No energy normalisation for the kick corrections

- The emergency dump feature should remain without any problem.

e⁺ FF1 latency curves



Summary

RTML collimation systems have been designed:
- Need to modify optics for EC2 to allow space for a spoiler

RTML FF systems are essential to:
- Minimise beam jitter at the entrance of the main linacs
- Respect the emittance growth budget of the RTML
    - Jitter through betatron collimator is critical
- Relax stability requirements of damping ring extraction system

The main requirements of the FF system have been outlined
- Latency requirement
- Cable type
- BPM resolution
- Kicker requirements
- e^+ FF1 system is possible, but will have a smaller latency budget
- Vertical beam is less critical since the vertical motion damps along the RTML

Tracking simulations investigated:
- Emittance growth and jitter amplification
- BPM resolution
- Limits on initial jitter

FF system requirements seem achievable given FONT and cavity BPM studies at ATF2

References

[1] “Optics and protection of the injection and extraction regions of the CLIC damping rings”, R. Apsimon et. al., IPAC 2013, Shanghai, MOPWO025

[2] “Latest performance results from the FONT 5 intra train beam position feedback system at ATF”, M. Davis et al., IPAC 2013, Shanghai, WEPME053