CLIC IP beam-based feedback

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Beam Control Stability Issues

- Degradation of the luminosity due to IP beam jitter
- Sources of IP beam jitter: ground motion, additional local noise (e.g. cooling water)
- IP jitter control:

“Cold-RF” based LC (e.g. ILC)

- A fast intra-train FB systems at the IP can in principle recover > 90% of the nominal luminosity
- The linac+BDS elements jitter tolerance and tolerable ground motion are not determined from IP jitter, but from diagnostic performance and emittance preservation

“Warm-RF” based LC (e.g. CLIC)

- IP beam stability mainly provided from:
  - Selection of a site with sufficiently small ground motion
  - Pulse-to-pulse FB systems for orbit correction in linac and BDS
  - Active stabilisation of the FD quadrupoles
- In this case a fast intra-train FB system is thought as an additional line of defence to recover at least ~ 80% of nominal luminosity in case of failure of the above stabilisation subsystems.
- A fast FB system can also help to relax the FD subnanometer position jitter tolerance

IP-FB Systems

ILC (500 GeV)

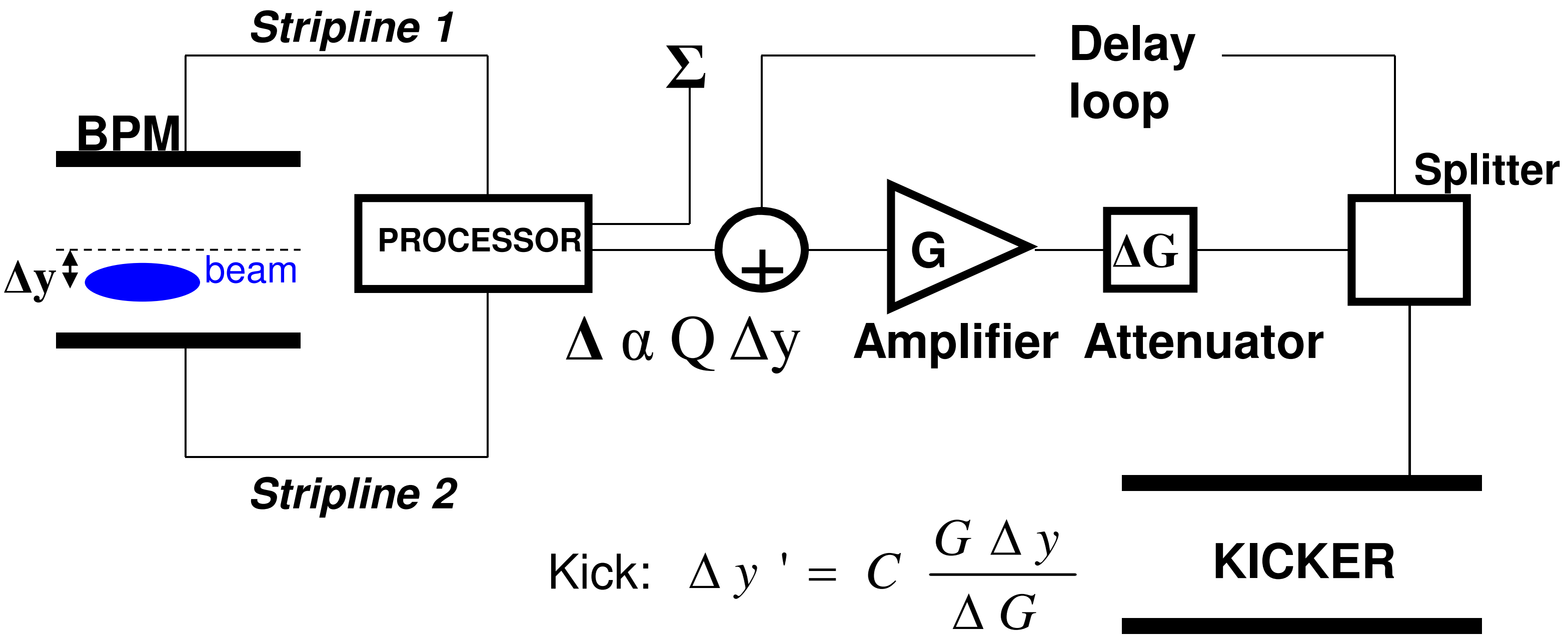
- Beam time structure:
  - Train repetition rate: 5 Hz
  - Bunch separation: 369.2 ns
  - Train length: 969.15 μs
- Intra-train (allows bunch-to-bunch correction)
- Digital FB processor (allows FPGA programming)
- Large capture range (10s of σ)
- IP position intra-train FB system + Angle intra-train FB system (in the FFS)

CLIC (3 TeV)

- Beam time structure:
  - Train repetition rate: 50 Hz
  - Bunch separation: 0.5 ns
  - Train length: 0.156 μs
- Intra-train (but not bunch-to-bunch)
- Analogue FB processor
- No angle intra-train FB system due to latency constraints

Analogue FB system

Basic scheme



Kick: $\Delta y' = C \dfrac{G \, \Delta y}{\Delta G}$

Equipment:

- BPM: to register the orbit of the out-coming beam
- BPM processor: to translate the raw BPM signals into a normalised position output
- Kicker driver amplifier: to provide the required output drive signals
- Fast kicker: to give the required correction to the opposite beam

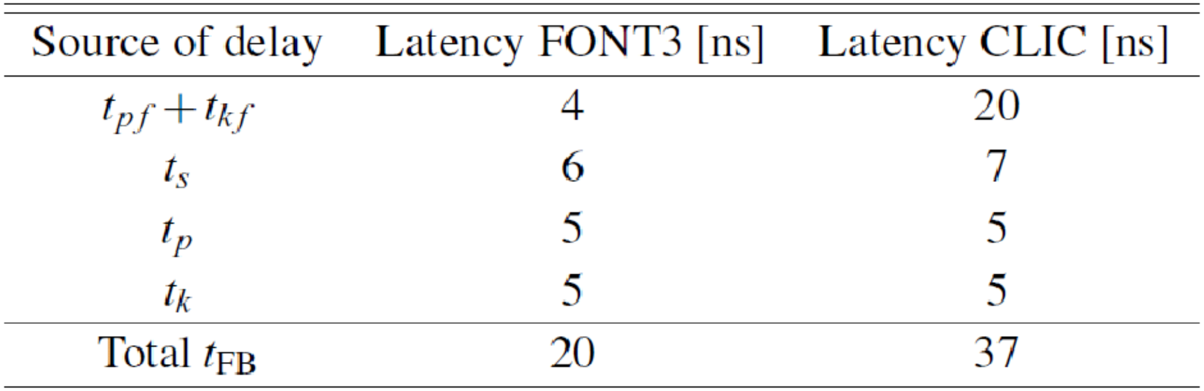
CLIC IP-FB system latency issues

- Irreducible latency:
  - Time-of-flight from IP to BPM: t_{pf}
  - Time-of-flight from kicker to IP: t_{kf}
- Reducible latency:
  - BPM signal processing: t_p
  - Response time of the kicker: t_k
  - Transport time of the signal BPM-kicker: t_s

Study and test of an analogue FB system for ‘warm’ linear colliders: FONT3:

P. Burrows et al. “PERFORMANCE OF THE FONT3 FAST ANALOGUE INTRA-TRAIN BEAM-BASED FEEDBACK SYSTEM AT ATF”, Proc. of PAC05.

Comparison of tentative latency times for a possible CLIC IP-FB system with the latency times of FONT3

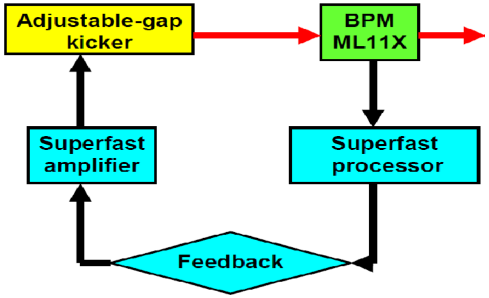


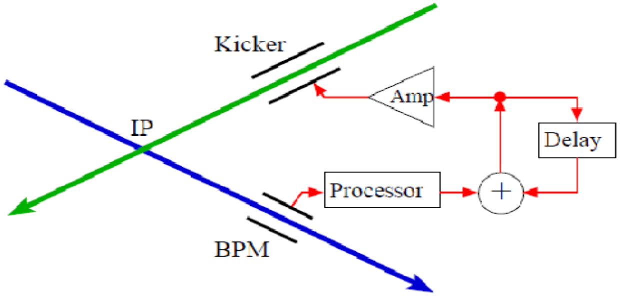
Source of delay	Latency FONT3 [ns]	Latency CLIC [ns]
$t_{pf}+t_{kf}$	4	20
t_s	6	7
t_p	5	5
t_k	5	5
Total t_{FB}	20	37

FONT (Feedback On Nano-second Timescales)

Obvious differences on time-of-flight:

- FONT3: BPM-kicker distance ≈ 1.2 m
- CLIC: Colliding beams; distance IP to BPM, distance kicker to IP ≈ 3 m





The FONT3 project succeeded in demonstrating feasible technology and operation of an intra-train FB for future “warm-RF” based LC. This technology can be applied to CLIC.

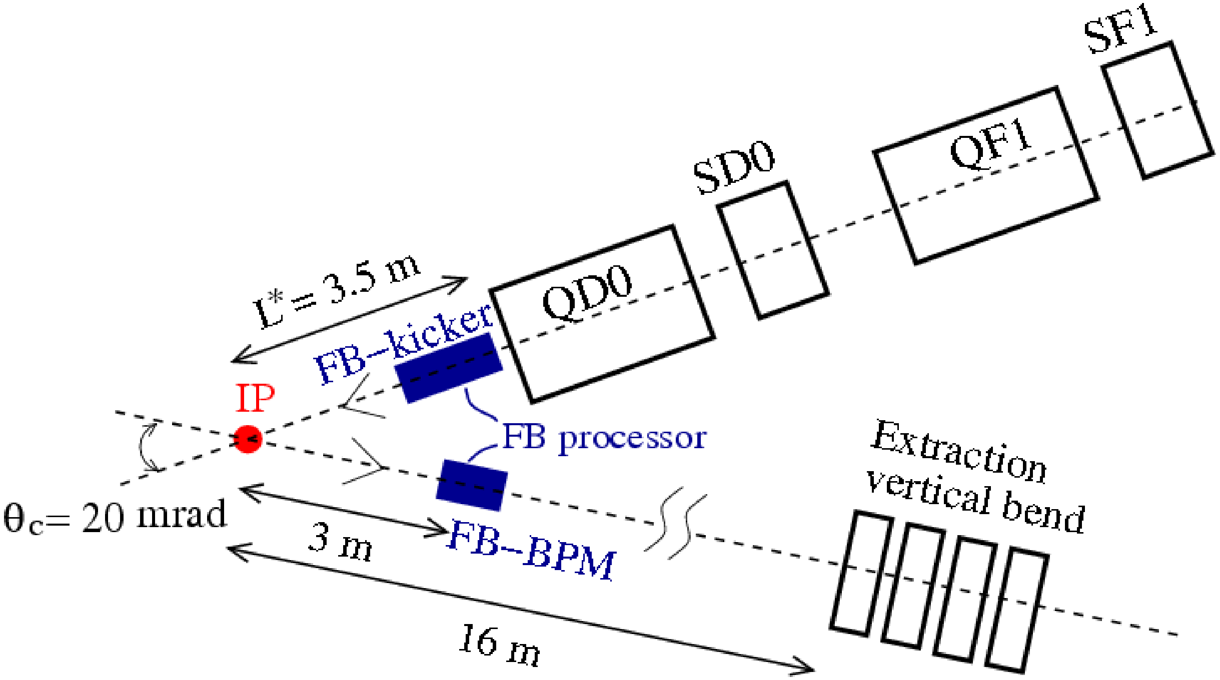
We could probably revisit the FONT3 technology to reduce the electronics latency < 10 ns (if we tried really hard!)

CLIC IR

IP-FB BPM and kicker positions

The choice of the position of the IP-FB elements is a compromise between:

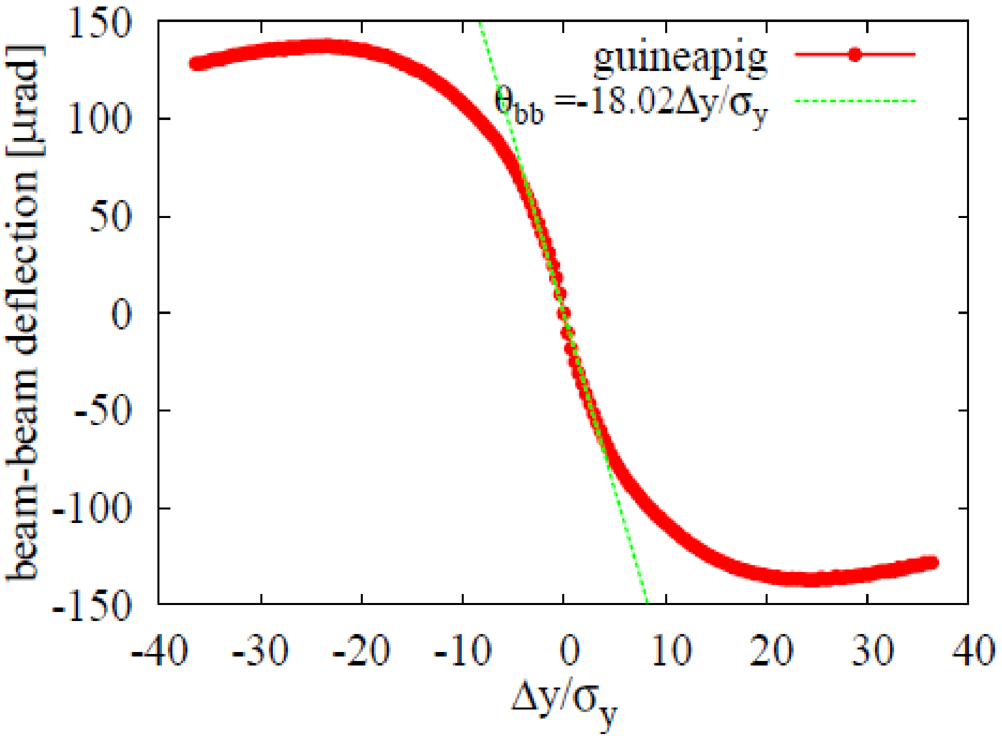
- Reduction of latency
- Avoiding possible degradation of the BPM response due to particle background/backsplash and possible damage of electronics components



If FONT elements 3 m apart from IP, then beam time-of-flight = 10 ns

Beam-beam deflection curve

The analysis of the beam deflection angle caused by one beam on the other is a method to infer the relative beam-beam position offset at the IP



Linear approximation in the range [-10, 10] σ^*_y:

$$\theta_{b-b}(\Delta y^*) = -18.02\frac{\Delta y^*}{\sigma^*_y}\ [\mu\text{rad}]$$

The convergence range is limited by the non-linear response of beam-beam deflection

FB system simulation

Gain factor

- Simple algorithm with a gain factor g:

$$\frac{\delta y}{\sigma_y^*} = g \cdot \frac{\theta}{\sigma_{y'}^*}$$

- where $\theta \approx y_{BPM}/d$ is the b-b deflection angle of the beam measured by the downstream BPM at a distance $d=3$ m from the IP.

- We consider a BPM resolution of about 1 μm.

- From the linear fit of the b-b deflection curve we can estimate a preliminary value (before optimisation) for this gain factor: $|g|/\sigma^*_{y'} = 1/18.02 = 0.055$

- The gain g from the simulations is related with the actual gain from the amplifier by:

$$g = C \frac{G}{\Delta G} \frac{\sigma^*_{y'}}{\sigma^*_y} d_{\mathrm{BPM}} d_{\mathrm{kicker}}$$

where *C* calibration constant
d_{BPM} distance IP – BPM
d_{kicker} distance kicker - IP

Beam tracking simulations

- Ground motion:
  - In the following simulations we apply 0.2 s of GM (A. Seryi's models) to the CLIC BDS
  - What is the RMS vertical beam-beam offset at the IP we have to deal with?
    - Simulation of 100 random seeds:

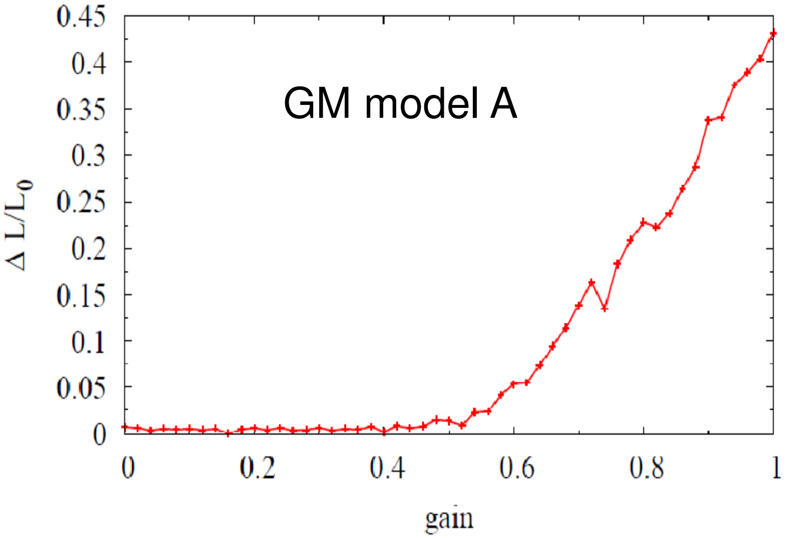
GM model	RMS Δy^* [nm]
A (CERN)	0.1
B (SLAC)	0.6
C (DESY)	22.7
K (KEK)	17.6

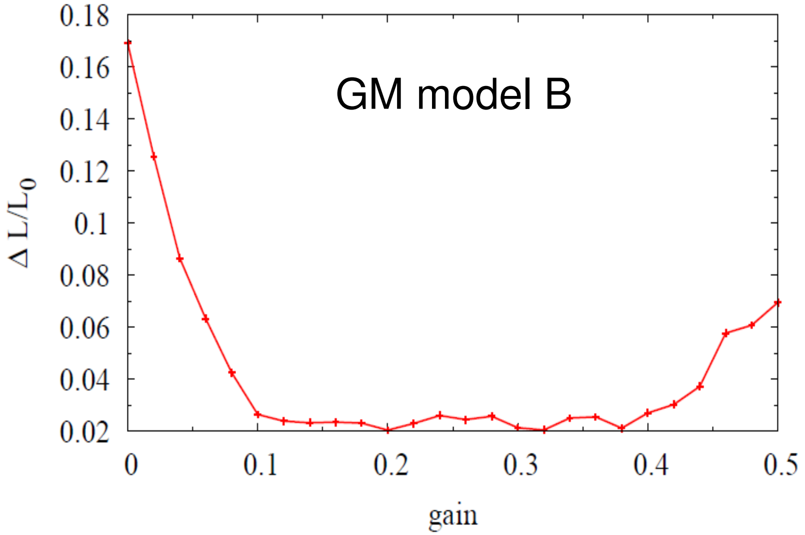
- Macroparticle tracking through the BDS using the code PLACET
- Luminosity calculation using the code Guinea-Pig

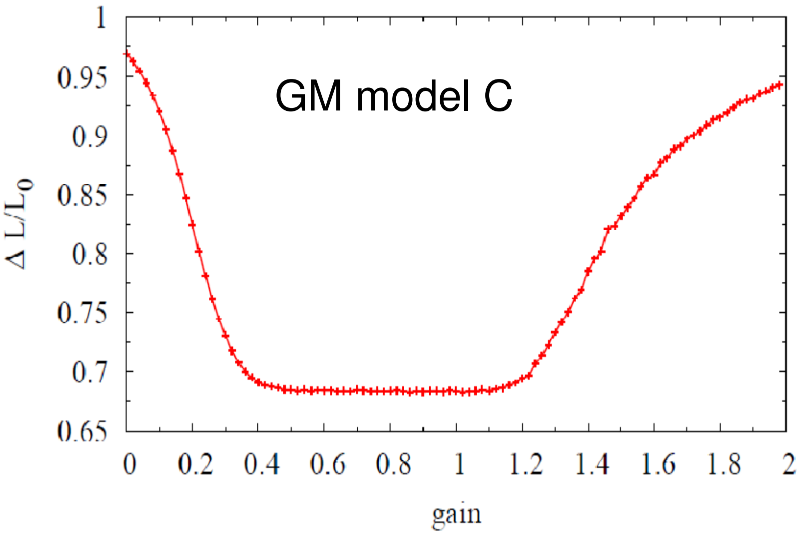
Gain factor optimisation

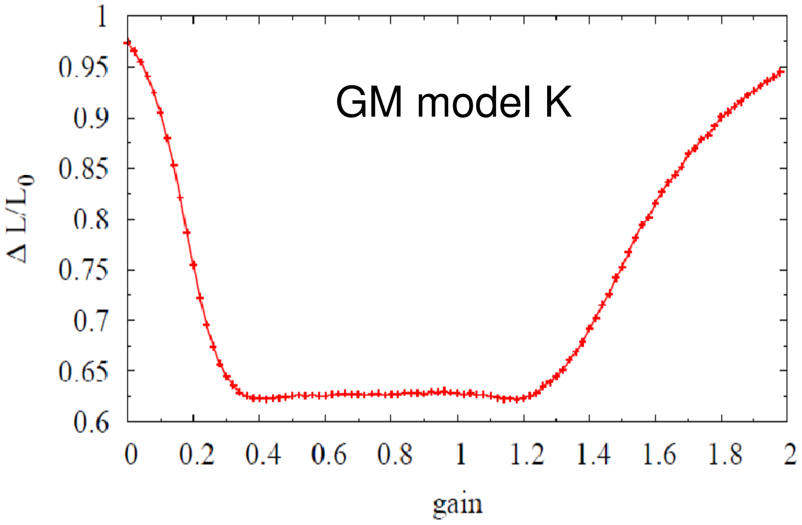
Luminosity loss vs FB system gain factor in presence of GM

Notation: here we use a gain factor normalized to $\sigma^{*}_{y'}$ $(g \rightarrow g/\sigma^{*}_{y'})$





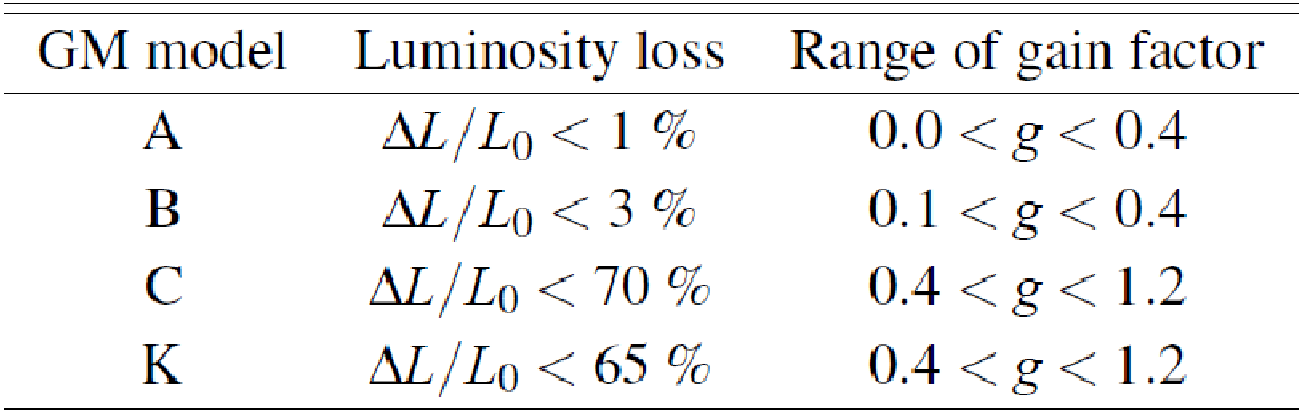




Gain factor optimisation

Summary

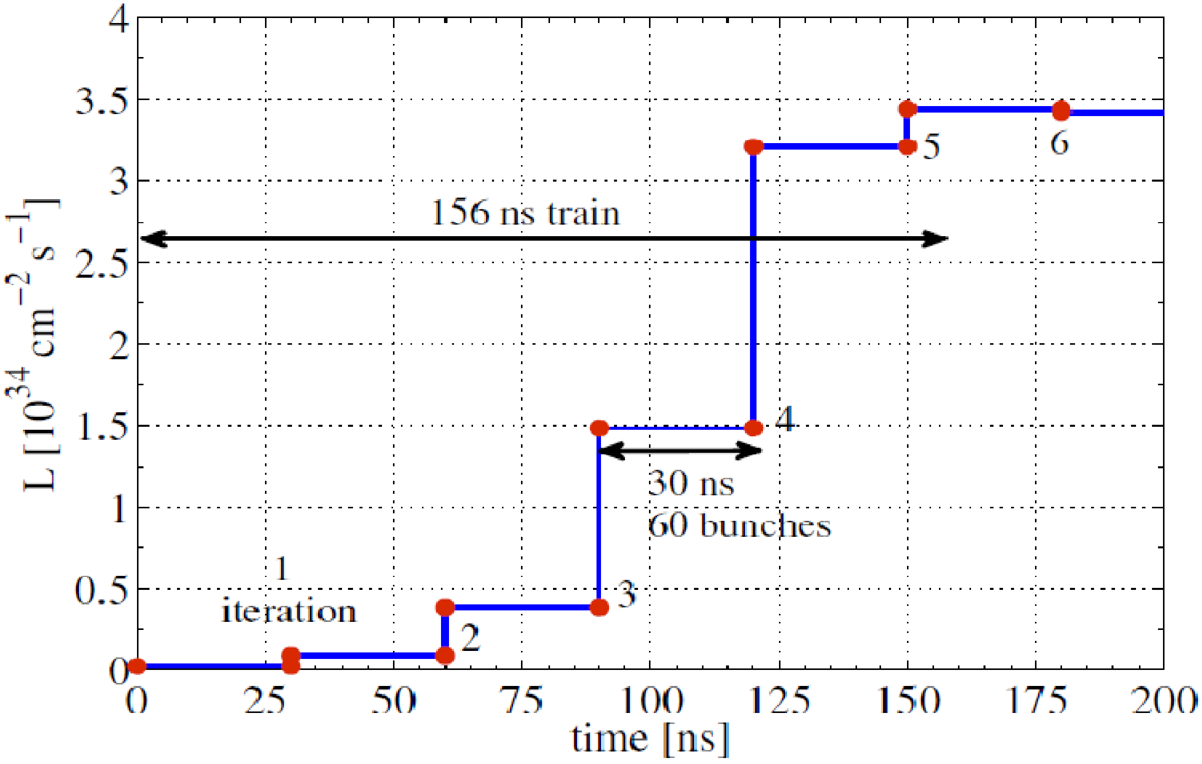
Gain factors limits in presence of different scenarios of GM



GM model	Luminosity loss	Range of gain factor
A	$\Delta L/L_0 < 1$ %	$0.0 < g < 0.4$
B	$\Delta L/L_0 < 3$ %	$0.1 < g < 0.4$
C	$\Delta L/L_0 < 70$ %	$0.4 < g < 1.2$
K	$\Delta L/L_0 < 65$ %	$0.4 < g < 1.2$

Luminosity performance

Simulation time structure:
Simulation applying a single random seed of GM C

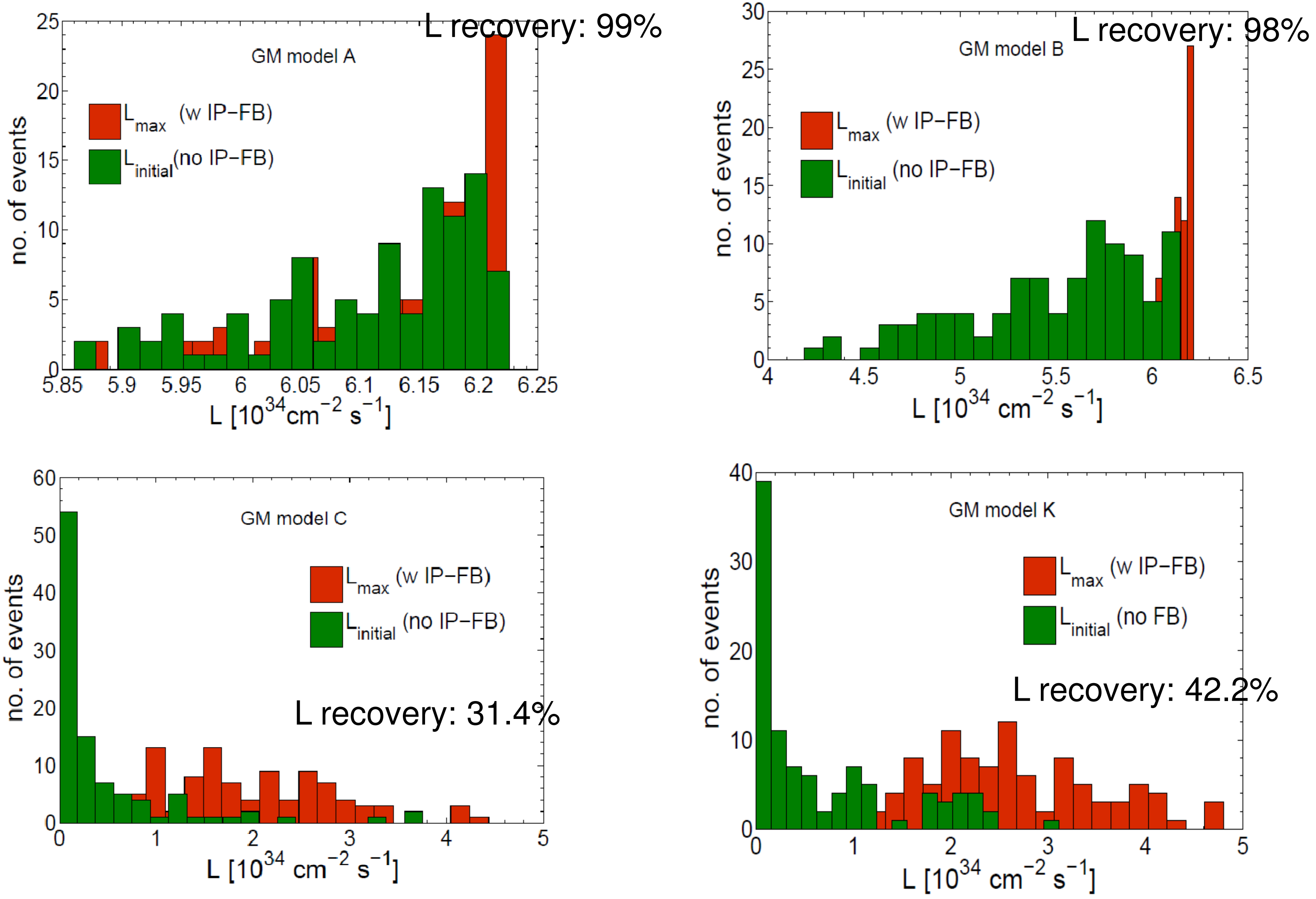


- For the simulations we have considered a correction iteration every 30 ns. The systems performs approximately a correction every 60 bunches (5 iterations per train)

CLIC luminosity result with IP-FB

Different scenarios of ground motion

Luminosity distribution for simulation of 100 random seeds of the GM



Luminosity result with IP-FB

Different scenarios of ground motion

- Remarks:

  Considering the most severe scenarios of GM (models C & K), intra-train FB systems at the IP are not enough to achieve the nominal luminosity. Obviously it is due to remaining uncorrected pulse-to-pulse jitter, which in principle can be corrected using a downstream inter-train FB systems.

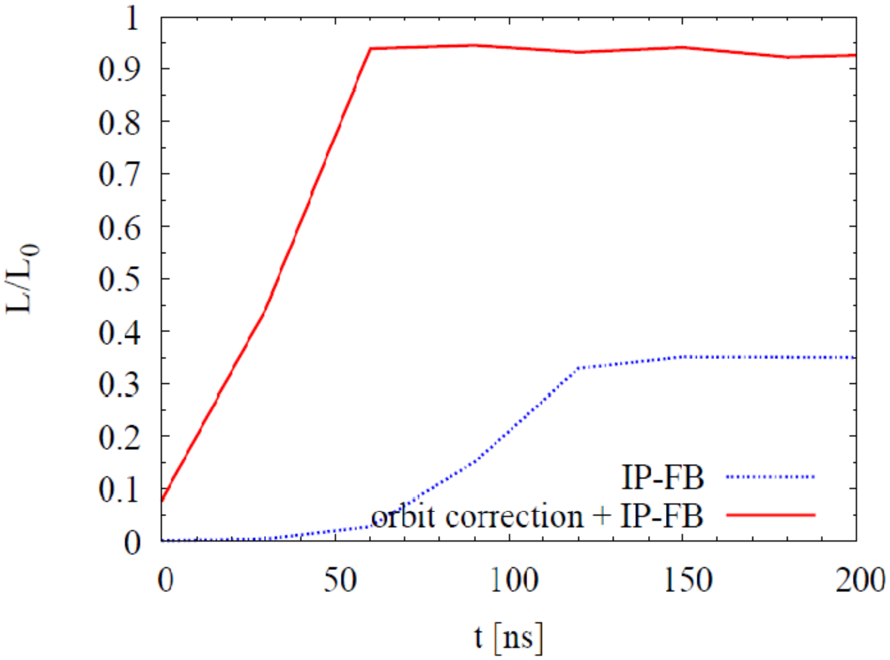
  For a more complete simulation we should consider the action of inter-train FB systems + intra-train FB systems + additional luminosity tuning.

Luminosity result with IP-FB

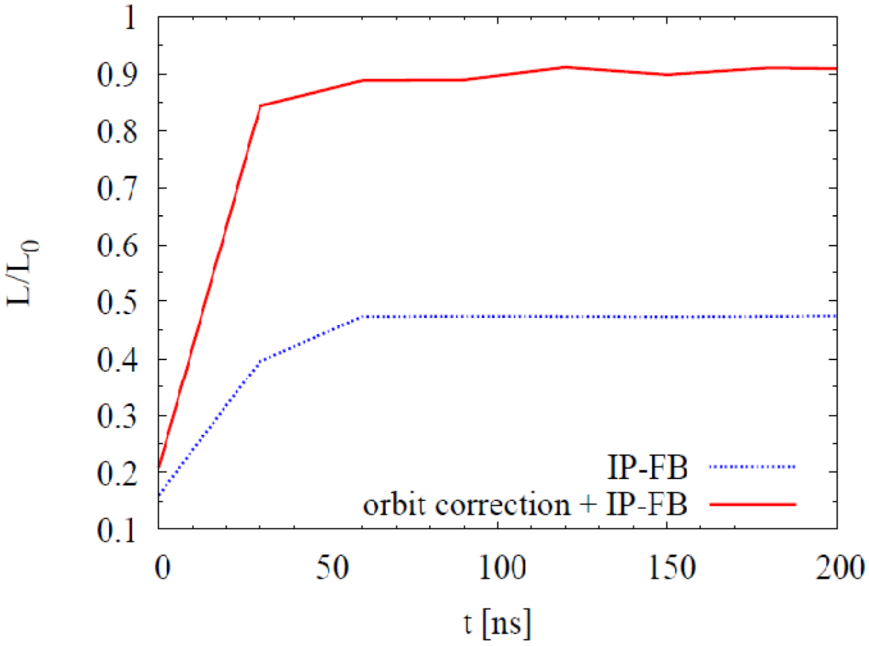
Different scenarios of ground motion

- If we consider:
  - GM (1 random seed)
  - orbit correction in the BDS (SVD) : using the available BPMs (resolution 100 nm) and dipole correctors in the BDS +
  - IP-FB

With GM model C



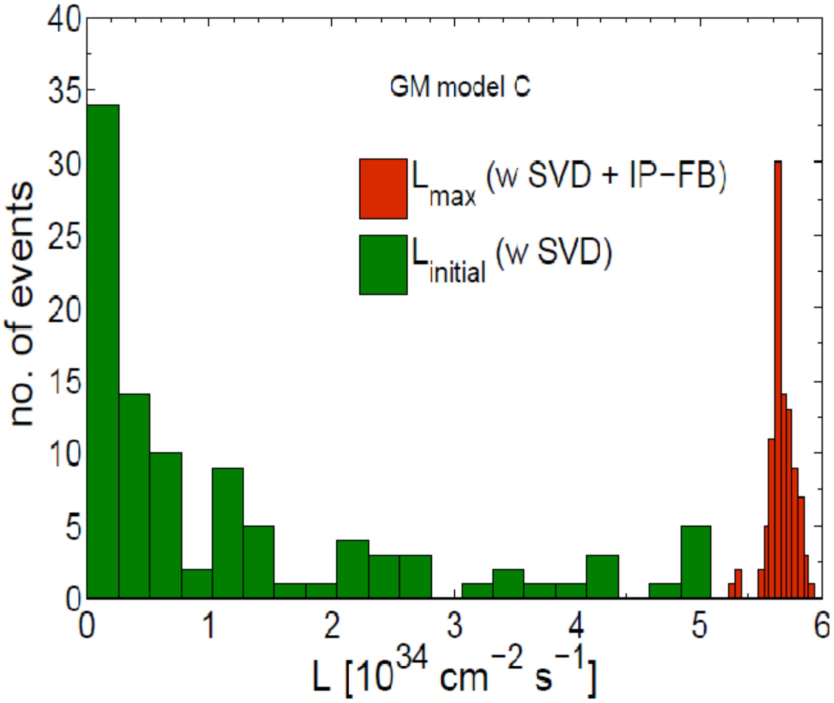
With GM model K



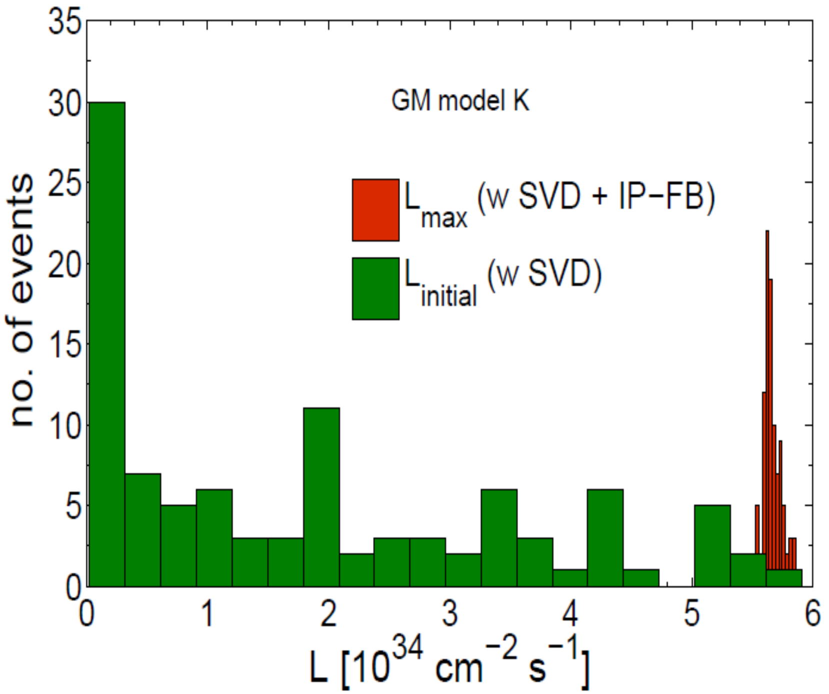
Luminosity result with IP-FB

Different scenarios of ground motion

- If we consider:
  - GM (100 random seed simulation) + orbit correction in the BDS (SVD) + IP-FB



Mean L recovery: 91.2%



Mean L recovery: 91.4%

Luminosity loss due to FD jitter

- Analytic approximation:

The expected value of the square of the vertical offset of the beam at the IP due to the final quadrupole QD0 position jitter σ_{FD}:

$$\langle \Delta y^{*2} \rangle = \sigma_{\mathrm{FD}}^2 K_{\mathrm{FD}}^2 \beta_y^* \beta_{y\mathrm{FD}}$$

The luminosity loss for small offsets can be approximate by:

$$\frac{\Delta L}{L_0} \approx \frac{1}{4} \frac{\Delta y^{*2}}{\sigma_y^{*2}} + \mathscr{O}(\Delta y^{*4})$$

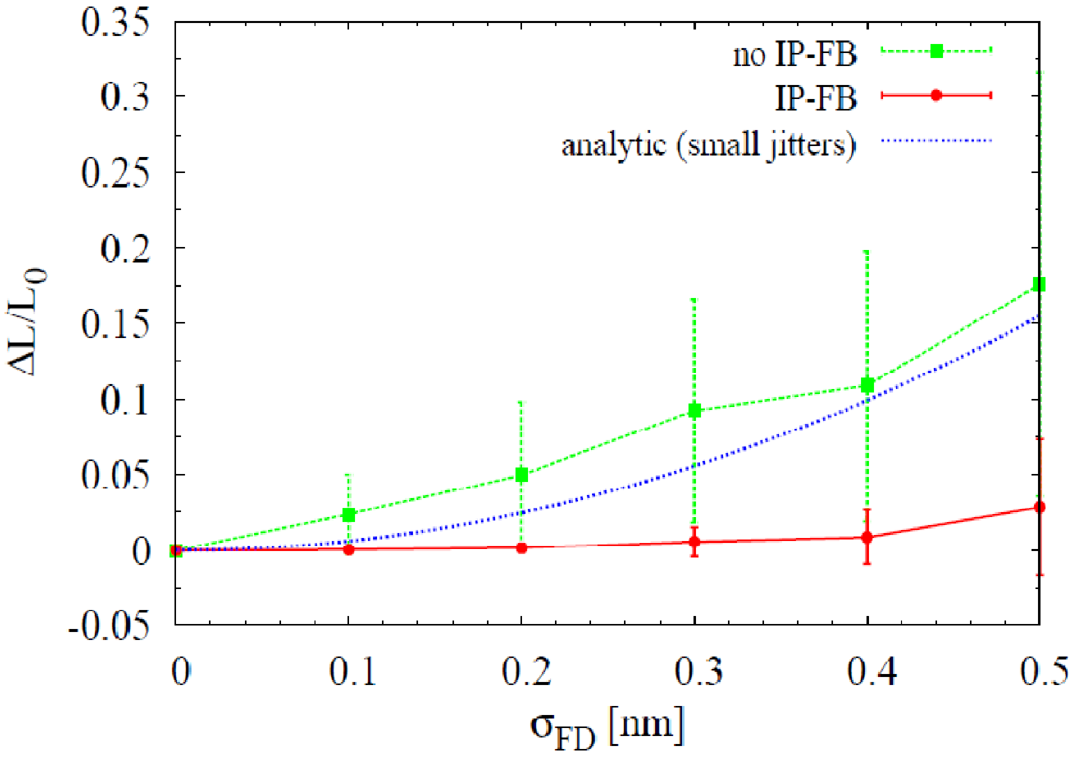
Therefore, the average luminosity loss is given by:

$$\left\langle \frac{\Delta L}{L_0} \right\rangle \approx \frac{1}{4} \frac{\sigma_{\mathrm{FD}}^2}{\sigma_y^{*2}} K_{\mathrm{FD}}^2 \beta_y^* \beta_{y\mathrm{FD}}$$

where σ^*_y (=0.9 nm) is the vertical IP core beam size, K_{FD} (=0.3176 m^{-1}) the integrated strength of QD0, β^*_{y} (=0.068 mm) the IP vertical betatron function, and β_{yFD} (=292274.6 m) the betatron function at QD0 position

FD position jitter tolerance

Luminosity loss vs FD vertical position jitter



Points: average over 100 tracking simulations using PLACET + Guinea-Pig

Error bars: standard deviation

Without IP-FB correction: $\left\langle \frac{\Delta L}{L_0} \right\rangle > 2\% \quad \text{for} \quad \sigma_{\text{FD}} > 0.1 \text{ nm}$

With IP-FB: $\left\langle \frac{\Delta L}{L_0} \right\rangle > 2\% \quad \text{for} \quad \sigma_{\text{FD}} > 0.5 \text{ nm}$

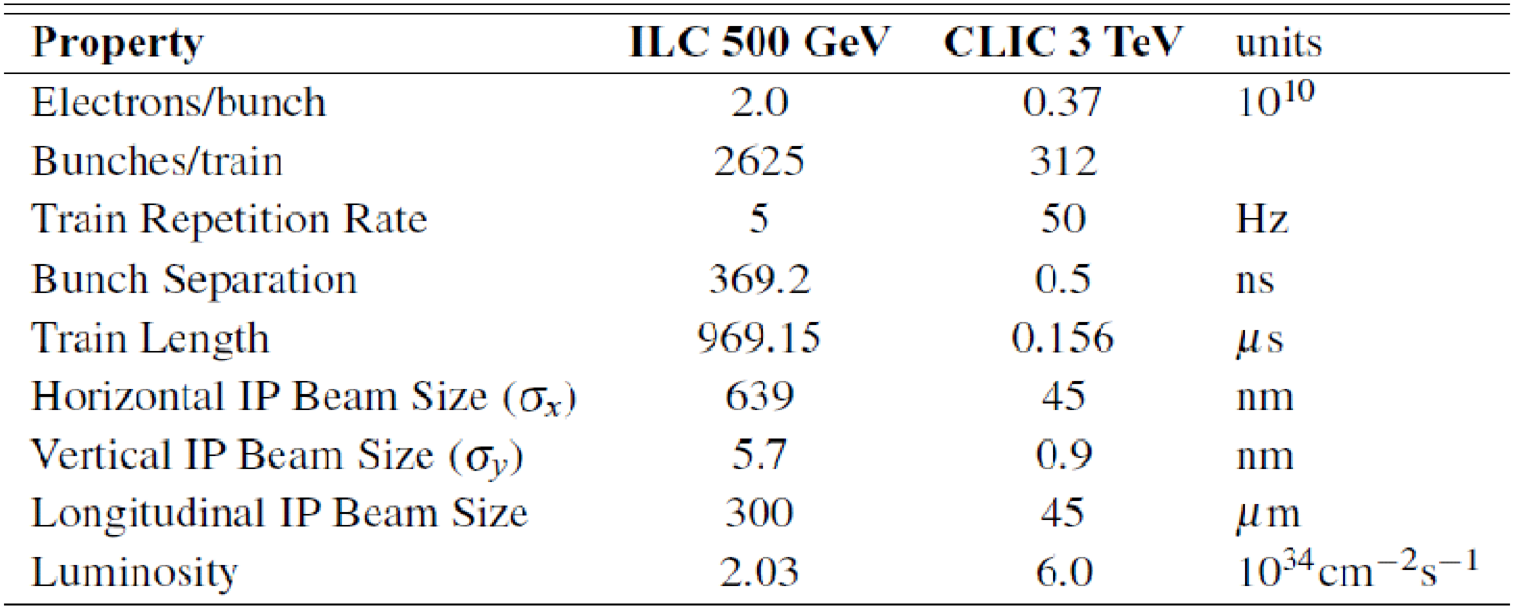
Summary and conclusions

- The design of a beam-based intra-train IP-FB system for CLIC is in progress
- Reducible latency times (contribution from the electronics) of about 10 ns have been demonstrated by the FONT3 system at ATF using a FB analogue processor. In principle we can apply this technology to the CLIC IP-FB
- We have started the optimisation of the system: gain factor optimisation. Necessary further optimisation of the position in order to harmonize the design according to the mechanical details of the interaction region
- Preliminary results of luminosity performance with IP-FB in presence of ground motion:
  - (assuming nominal emittances at the exit of the linac) with pulse-to-pulse feedback correction in the BDS and intra-pulse IP-FB, total luminosity recovery > 90% of the nominal one even for the nosiest sites (models C & K)
- The IP-FB system can help to relax the FD jitter tolerance requirements:
  - FD vertical position jitter tolerance (with IP-FB): $\sigma_{FD} \approx 0.5$ nm ($<\Delta L/L_0> \approx 2\%$)
- We plan to contribute in detail to the engineering design of the CLIC IP-FB system

Appendix

Train structure

Cold LC Warm LC



Property	**ILC 500 GeV**	**CLIC 3 TeV**	units
Electrons/bunch	2.0	0.37	10^{10}
Bunches/train	2625	312	
Train Repetition Rate	5	50	Hz
Bunch Separation	369.2	0.5	ns
Train Length	969.15	0.156	μs
Horizontal IP Beam Size (σ_x)	639	45	nm
Vertical IP Beam Size (σ_y)	5.7	0.9	nm
Longitudinal IP Beam Size	300	45	μm
Luminosity	2.03	6.0	$10^{34}\text{cm}^{-2}\text{s}^{-1}$

For CLIC 738 times smaller bunch separation and 6212 times smaller bunch train length than for ILC !
IP intra-pulse FB is more challenging.

Appendix
Kicker (IP-FB system for CLIC)

- In some cases the BPM IP-FB system has to deal with b-b deflection angles ~ 100 microrad.

- If we look at the b-b deflection curve, 100 microrad corresponds to Δy (at IP)$\approx 10\ \sigma^*_y = 9$ nm (considering $\sigma^*_y = 0.9$ nm nominal vertical beam size at the IP).

- If kicker located 3 m upstream of the IP, the necessary kick angle for correction: $\Delta\theta = \Delta y$ [m]/3

- The kick angle of a stripline kicker can be defined as:

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

Appendix
Kicker (IP-FB system for CLIC)

where “*g*” is the stripline coverage factor or geometry factor:

$g_\perp = \tanh\left(\frac{\pi\omega}{2a}\right) \leq 1$ (determined by the shape of the electrode). Generally $g_\perp \approx 1$

V: peak voltage
E: beam energy (1500 GeV)
R: impedance (~50 Ω)
L: kicker length (without flanges or electrical effective length)
a kicker aperture (distance between electrodes)

Considering L=10 cm and from $\frac{\Delta y[m]}{3} = 2 g_\perp \frac{eV}{E}\frac{L}{a}$ we obtain:

$$\frac{V}{a} = 22.5 \text{ kV/m}$$

Appendix
Kicker (IP-FB system for CLIC)

- For the sake of simplicity, if we consider that the kick applied to the beam is exclusively a result of the magnetic field generated by the current flowing in the striplines, then we can write it in terms of the magnetic field B as follows:

$$\Delta \theta = \frac{2ecBL}{E}$$

- And therefore, the transverse deviation at a distance l from the kicker to IP is given by

$$\Delta y = \frac{2ecBL}{E} l$$

- The delivered power is equal to the power dissipated on the two stripline terminations and is given by

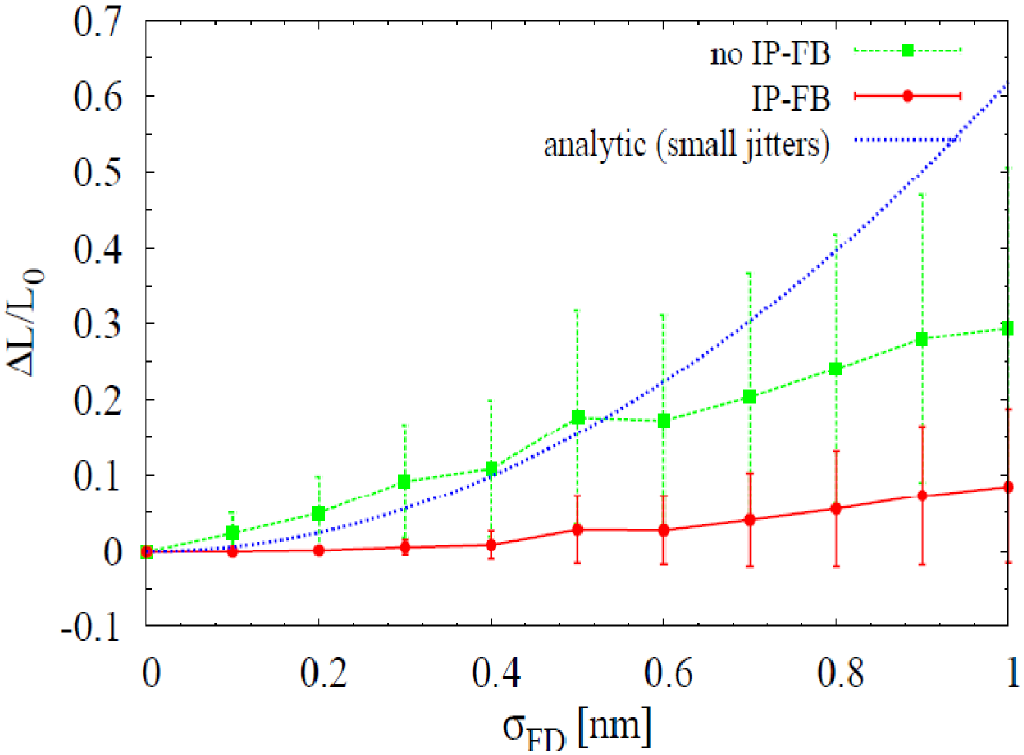
$$P = 2 \frac{V^2}{2Z}$$

Appendix
Kicker
Tentative parameters

Parameter	Value
Length L	10 cm ($\approx$ 15 cm with flanges)
Gap width d	15 mm
Kicker impedance	50 Ω
Maximum votage	337 V
Maximum magnetic field	7.5×10^{-5} T
Delivered power	2.278 kW

FD position jitter tolerance

Luminosity loss vs FD vertical position jitter



Points: average over 100 tracking simulations using PLACET + Guinea-Pig

Error bars: standard deviation

Without IP-FB correction: $\left\langle \frac{\Delta L}{L_0} \right\rangle > 10\%$ for $\sigma_{\mathrm{FD}} > 0.4$ nm

With IP-FB: $\left\langle \frac{\Delta L}{L_0} \right\rangle > 10\%$ for $\sigma_{\mathrm{FD}} > 1$ nm