# Beam-based Intra-train Feedback Systems for Linear Colliders

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# Introduction
## 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. effects of cooling water in the quadrupoles)
- IP jitter control:
  - Selection of a site with sufficiently small ground motion
  - Pulse-to-pulse FB systems for orbit correction
  - Active stabilisation of the FD
  - Well-engineered detector environment for low vibration
  - Very fast intra-train FB system to keep the beams in collisions
- The fast beam-based intra-train FB system at the IP is foreseen to correct the relative displacement of the colliding beams at the IP.

# Beam parameters of linear colliders

| Property | ILC 0.5 TeV | CLIC 0.5 TeV | CLIC 3 TeV | units |
|---|---|---|---|---|
| Particles/bunch ($N_e$) | 2.0 | 0.68 | 0.37 | $10^{10}$ |
| Bunches/train ($N_{\text{train}}$) | 2625 | 354 | 312 | |
| Train Repetition Rate ($f_{rep}$) | 5 | 50 | 50 | Hz |
| Bunch Separation | 369.2 | 0.5 | 0.5 | ns |
| Train Length | 969.15 | 0.177 | 0.156 | $\mu$s |
| Horizontal IP emittance ($\varepsilon_x^*$) | 1000 | 2400 | 660 | nm·rad |
| Vertical IP emittance ($\varepsilon_y^*$) | 40 | 25 | 20 | nm·rad |
| Horizontal IP Beam Size ($\sigma_x^*$) | 639 | 202 | 45 | nm |
| Vertical IP Beam Size ($\sigma_y^*$) | 5.7 | 2.3 | 0.9 | nm |
| Bunch length ($\sigma_z^*$) | 300 | 44 | 44 | $\mu$m |
| Total luminosity ($L$) | 2.03 | 2.24 | 6.0 | $10^{34}\text{cm}^{-2}\text{s}^{-1}$ |

For CLIC, intra-train FB corrections at the IP are especially challenging due to its particular beam time structure with nominal bunch separation about 740 times smaller than for the ILC and bunch train length about 6200 times shorter than for the ILC

# 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)

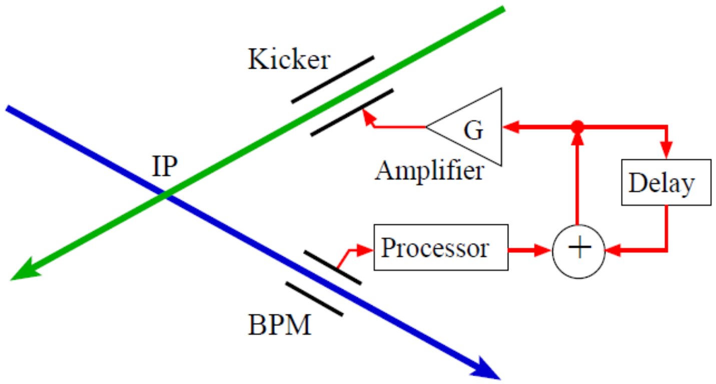
## CLIC (3 TeV)

- 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)
- All-analogue FB processor
- No angle intra-train FB system due to latency constraints

# Beam-based IP-FB system

## Basic scheme:

A fast IP-FB system for linear colliders is based on the measurement of the incoming trajectories of the early bunches in the electron or positron trains. This information is then used as the input to the feedback system for steering the later bunches into collisions at the IP




### Key elements:

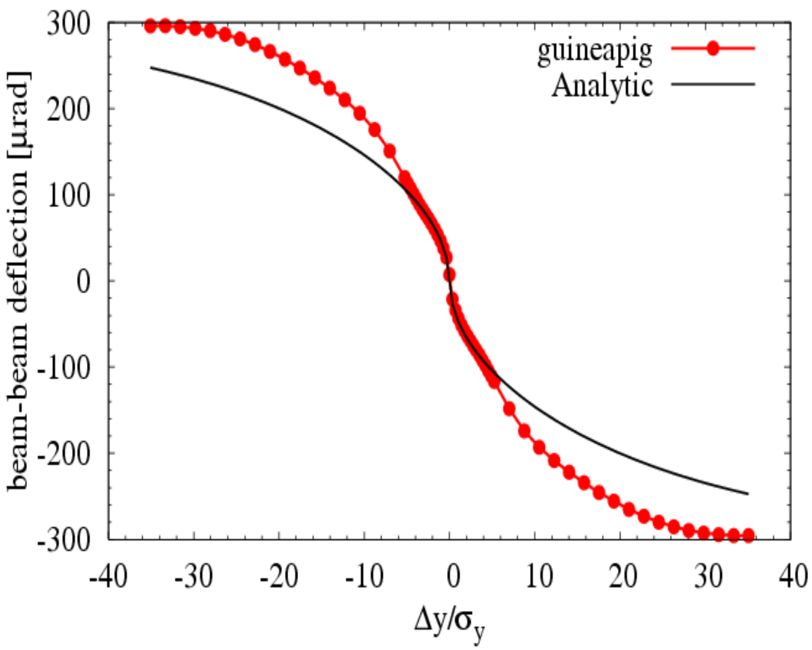
- BPMs: (based on stripline pickups) for registering the position (and hence kick angle) of the outgoing beam
- Fast signal processor: to translate the raw BPM pick off signals into a normalised position output
- FB circuits: delay loops, applying gain, …
- Amplifiers: to provide the required output drive signals
- Kicker: to apply the necessary angular correction to the opposite incoming beam

The total round-trip time, including beam time-of-flight, for the system to respond to a change in its input is referred to as one latency period

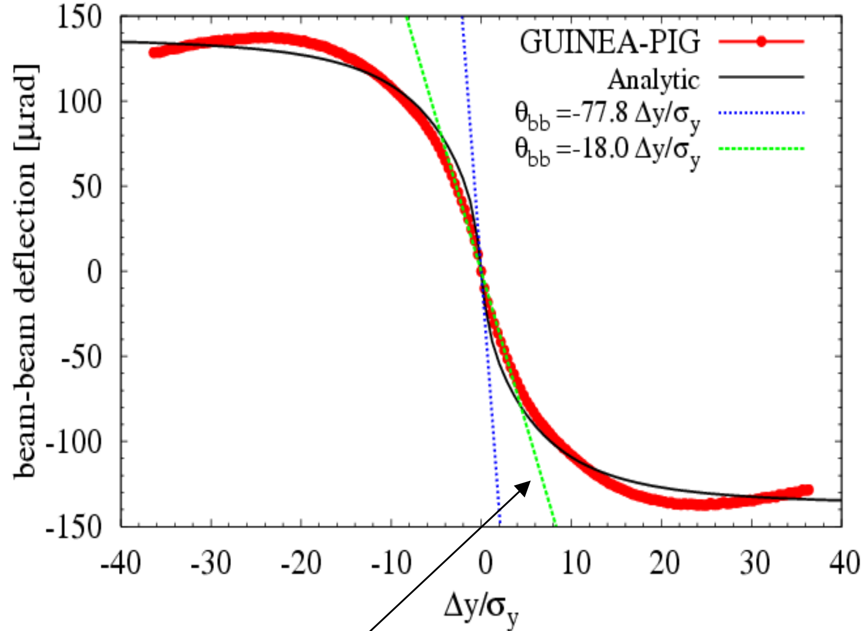
# Beam-beam deflection curve

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

**ILC**




**CLIC**




Linear approximation: $\theta_{b-b}(\Delta y^*) = -18.02\frac{\Delta y^*}{\sigma_y^*}\ [\mu\text{rad}]$

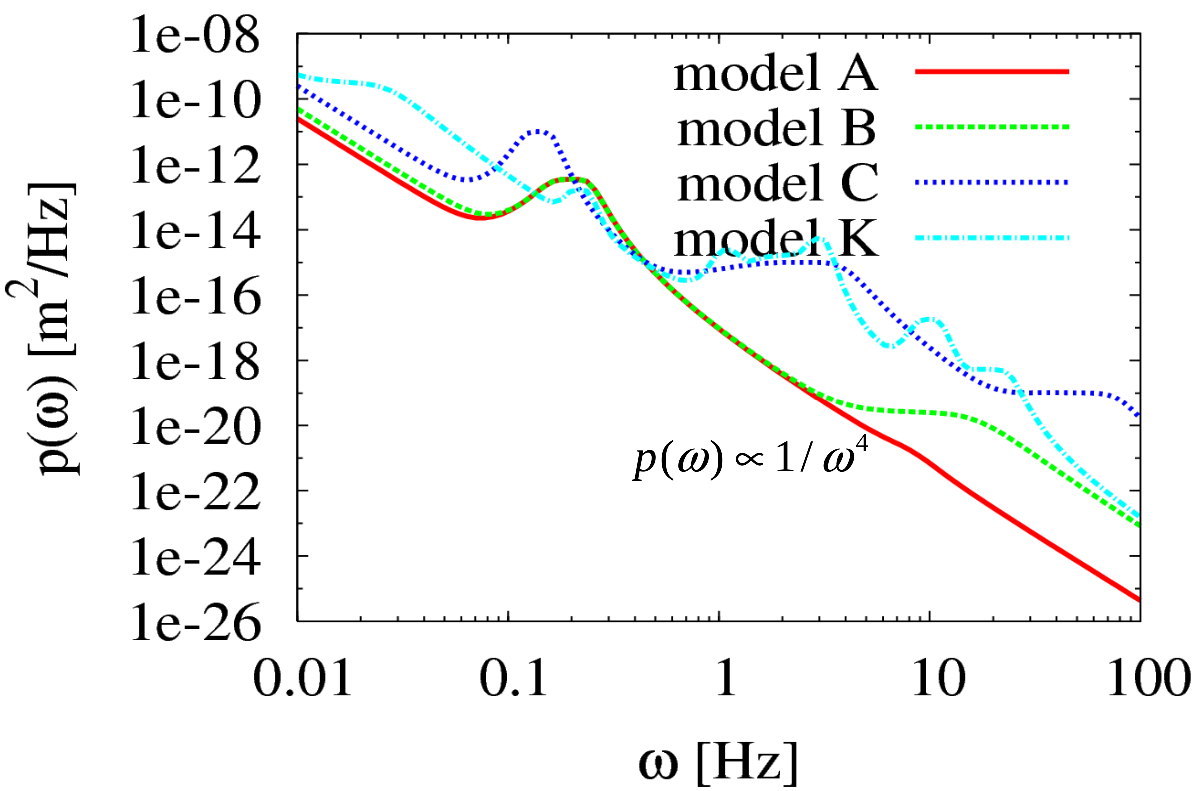
For instance, for $\Delta y \approx 10\sigma_y$ (ILC) $\rightarrow \Delta\theta_{b\text{-}b} \approx 200\ \mu\text{rad}$

$\Delta y \approx 10\sigma_y$ (CLIC) $\rightarrow \Delta\theta_{b\text{-}b} \approx 100\ \mu\text{rad}$

# Ground motion

Andrei Seryi's models:

Power spectrum: $$p(\omega) = \frac{B}{2\omega^4} + \sum_{i=resonances} \frac{a_i}{1 + \left[ d_i \left( \omega - \omega_i \right) / \omega_i \right]^4}$$




Model A=CERN
Model B=Fermilab
Model C=DESY
Model K=KEK

Slow motion: emittance growths
Beam size effects

Fast motion: beam jitters
Beam-beam offsets

# IP beam-based intra-train FB for ILC

- The ILC train timescale structure allows bunch-to-bunch feedback corrections using digital FB processors (demonstrated by the FONT4 and FONT5 project at ATF)

- For beam-beam relative position correction at the IP:

  - Stripline kicker near the IP in the incoming beamline between the sextupole SD0 and the final quadrupole QF1 (about 7 meters from the IP)

  - BPM (1$\mu$m resolution) at $\pi/2$ phase advance downstream of the IP

- Design to provide +/- 50 $\sigma_y$ level correction at IP

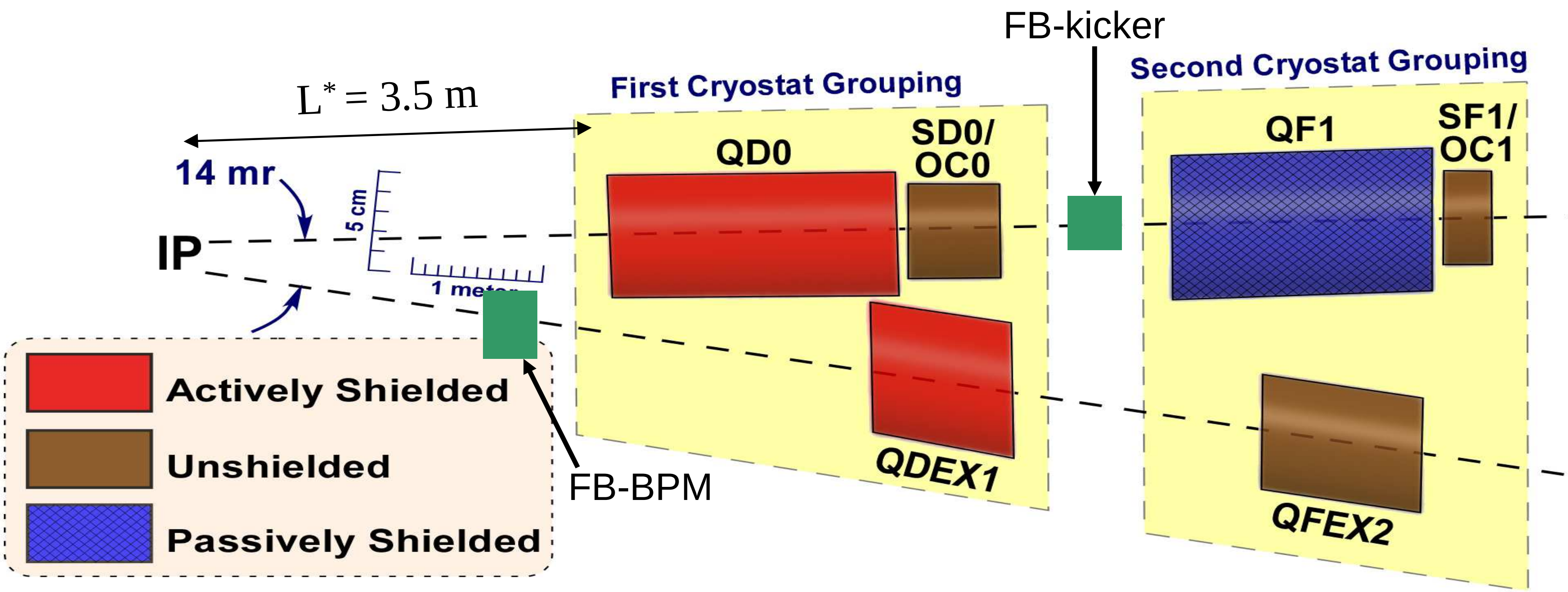
- For angle correction a stripline kicker at the entrance of the FFS with a downstream BPM at $\pi/2$

- For the simulations we use a FB loop based in a classical proportional and integral (PI) control algorithm implemented in Simulink/Matlab

# ILC interaction region

## Position of IP-FB system elements

**[ ILC RDR, August 2007]**

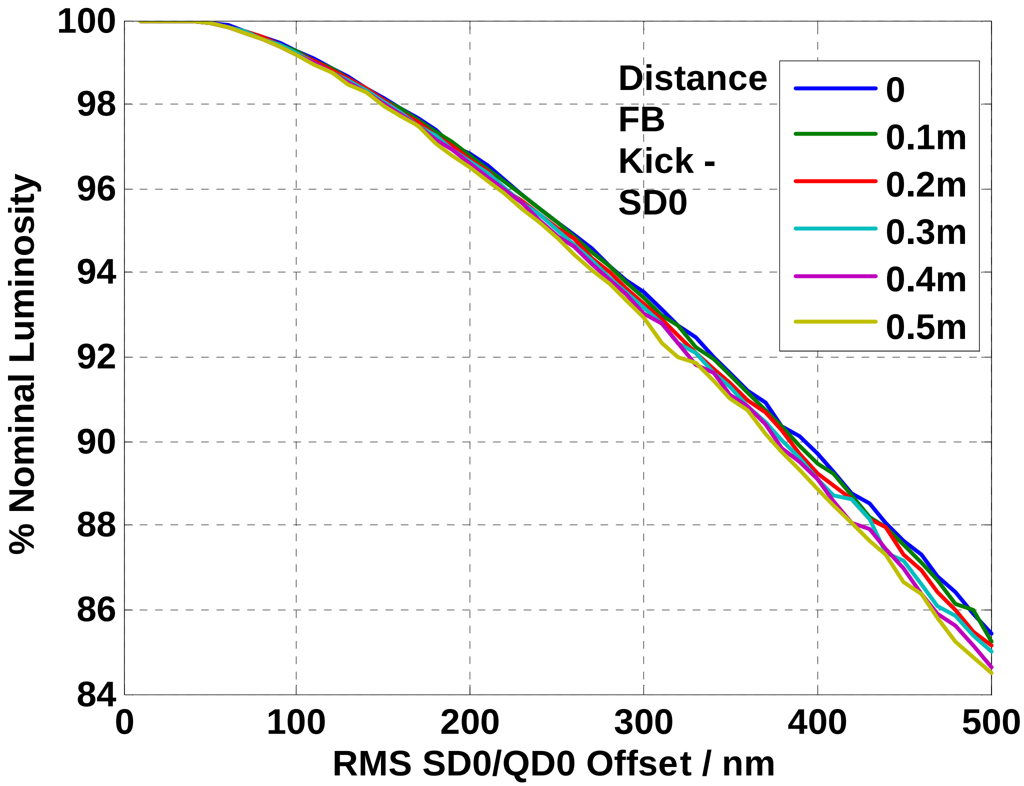



Kicker about 7 m upstream of the IP
BPM about 3 m downstream of the IP (in the post-collision extraction line)

# ILC interaction region

## Position of IP-FB system elements

- How does the distance of the kicker from SD0 face affect luminosity as beam is kicked off-centre through SD0 ?



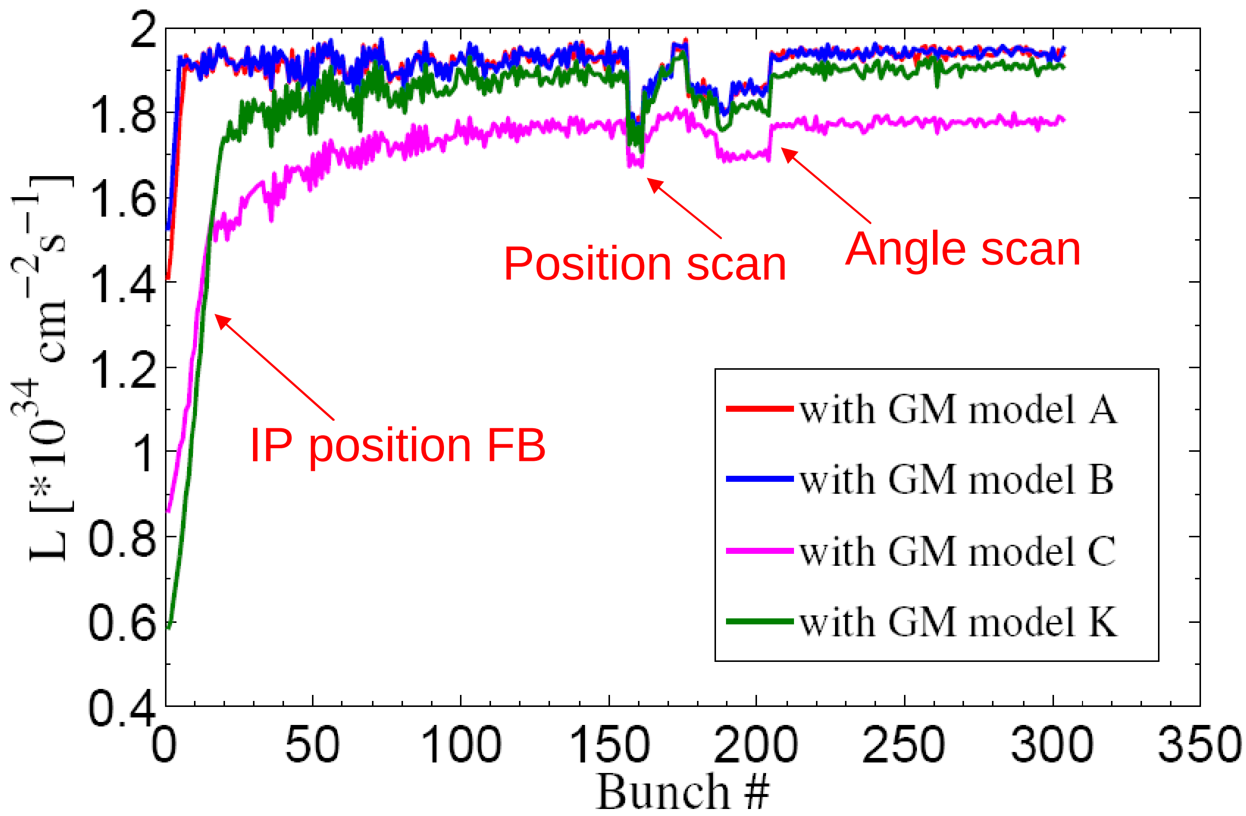

[Glen White]

Small effect due to kicker distance from SD0, probably not important

# Simulations: ILC luminosity result with IP-FB

## Different scenarios of ground motion

- Example for 1 single random seed of GM (0.2 s of GM applied to both main linac and BDS)
- Considering 40 % emittance growth in the main linac

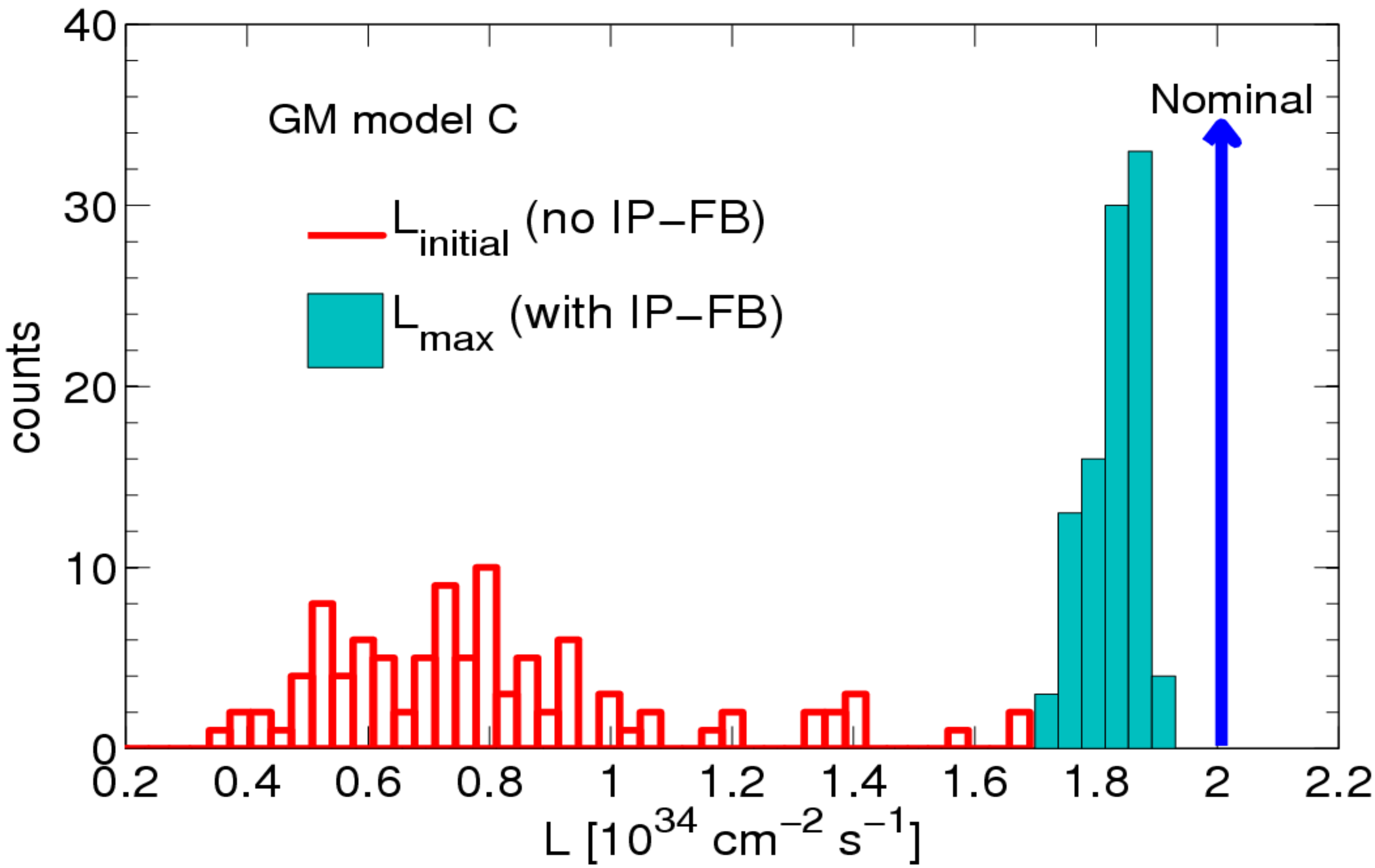



For the noisiest site (model C), applying fast position and angle FB stabilization, a recovery of 85 % of the nominal value is obtained

For quiet sites (model A and B) practically the 100 % of the nominal luminosity would be achievable.

# Simulations: ILC luminosity result with IP-FB

## Simulation of 100 random seeds of GM

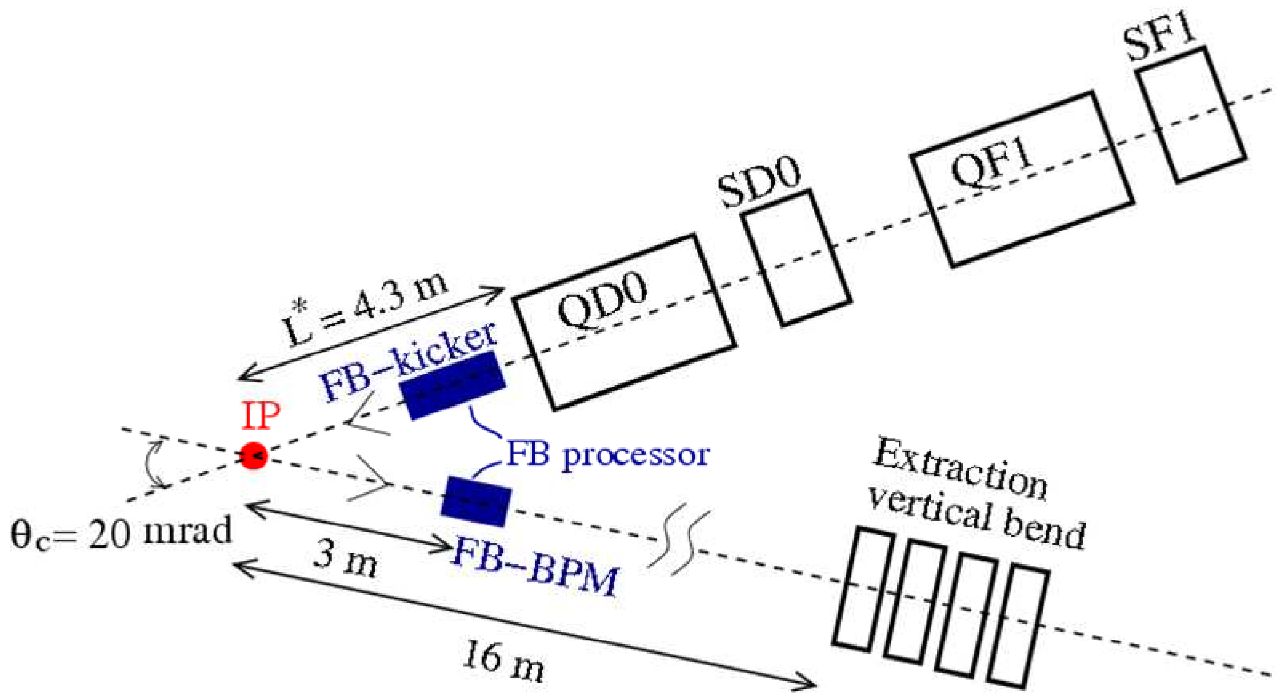


# IP beam-based intra-train FB for CLIC

- For CLIC with nominal bunch separation of 0.5 ns and a nominal train length of 156 ns the design of an IP intra-train FB is very challenging
- For beam-beam relative position correction at the IP:
  - Stripline kicker located the incoming beamline downstream of the final quadrupole QD0 (about 3 meters from the IP)
  - BPM (1$\mu$m resolution) at $\pi/2$ phase advance downstream of the IP
- Due to latency constraints no angle intra-train FB system designed for CLIC
- Latency times of about 20 ns have experimentally been demonstrated by the FONT3 system at ATF using a all-analogue FB processor.
- For the simulations we have considered a correction iteration every 37 ns. The systems performs approximately a correction every 74 bunches (4 correction iterations per train)
- In this case we have employed a FB control loop based in a simple proportional control algorithm

# CLIC interaction region

## Position of IP-FB system elements




In order to reduce the beam time-of-flight contribution to the latency, IP-FB system located as close as possible to the IP

The IP-FB system should be able to operate within the background environment, avoiding the degradation of the BPM response and the possible damage of the electronic components.

We adopt a similar scheme for L*=3.5 m (no change in the conclusions)

# 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 all-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.**

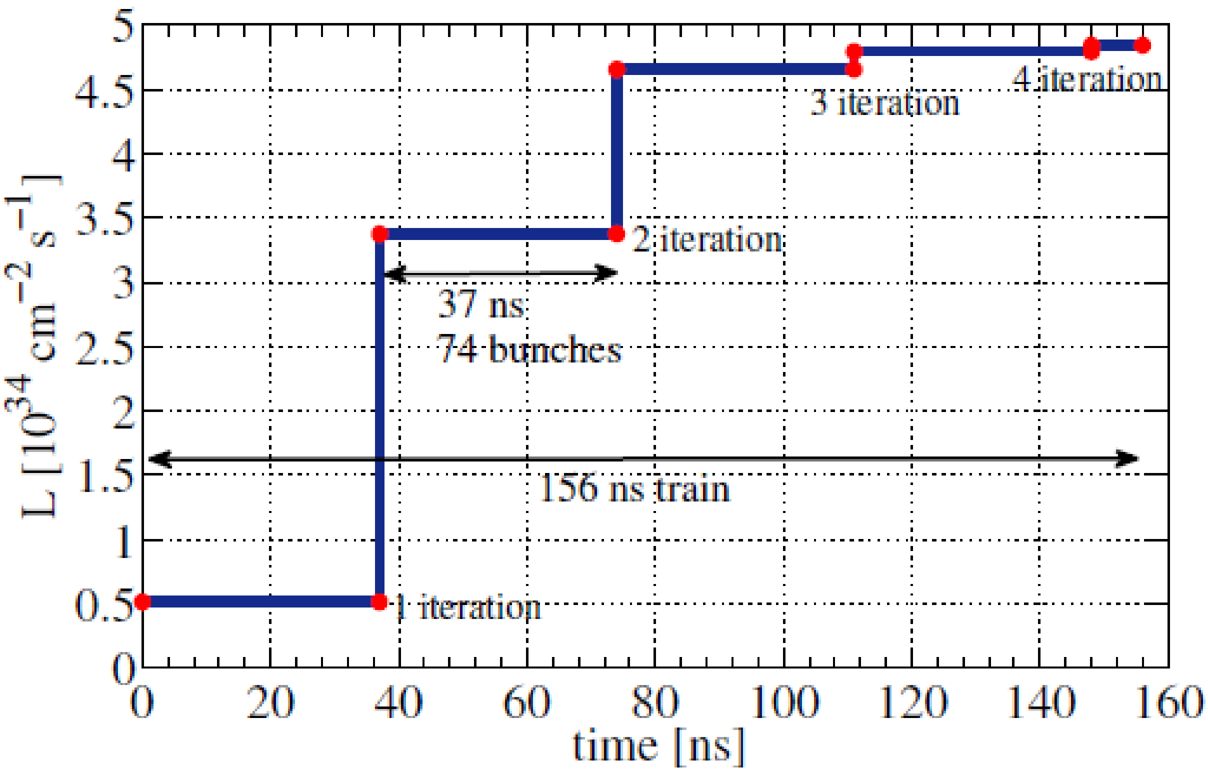
Comparison of tentative latency times for a possible CLIC IP-FB system with the latency times of FONT3

| 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 $t_{\mathrm{FB}}$ | 20 | 37 |

# Simulations: CLIC Luminosity result with IP-FB

Simulation time structure:

Example applying a single random seed of GM C (during 0.02 seconds) to the BDS and then IP-FB correction in a train.



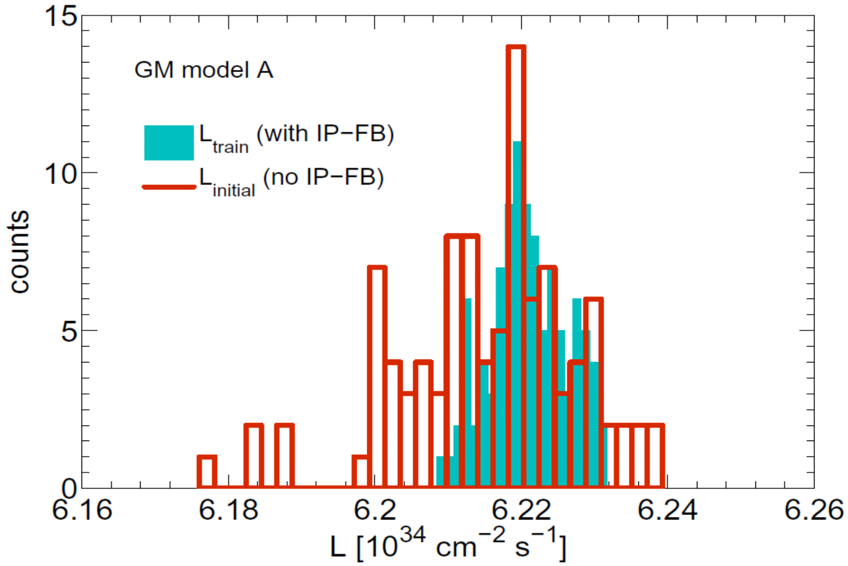

- For the simulations we have considered a total feedback latency of 37 ns. The systems performs approximately a correction every 74 bunches (4 iterations per train)

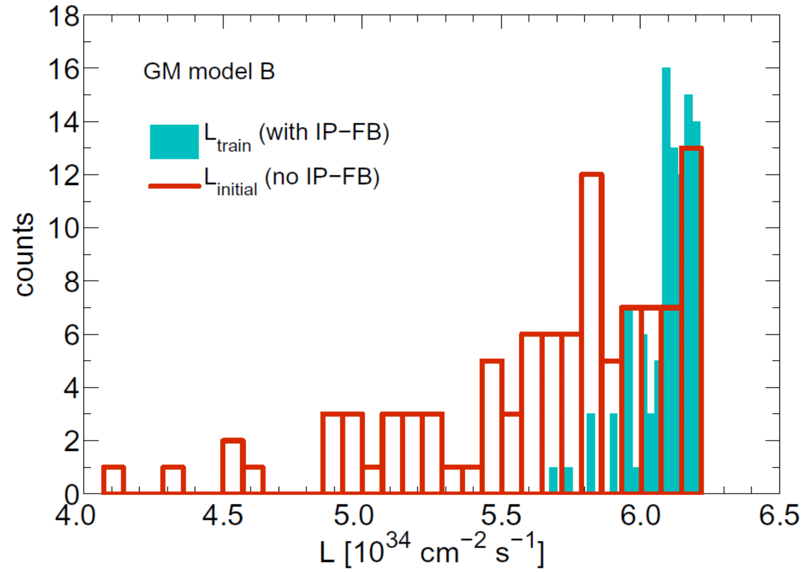
# Simulations: CLIC luminosity result with IP-FB

## Different scenarios of ground motion

Luminosity distribution for simulation of 100 random seeds of the GM

For quiet sites:




The generated IP-jitter is relatively small after 0.02 s of GM

Model A:

- Without any correction: mean $\langle L/L_0\rangle_{train}$=99.88%
- With IP-FB: mean $\langle L/L_0\rangle_{train}$=99.97%
  std reduced by a factor 2

Model B:

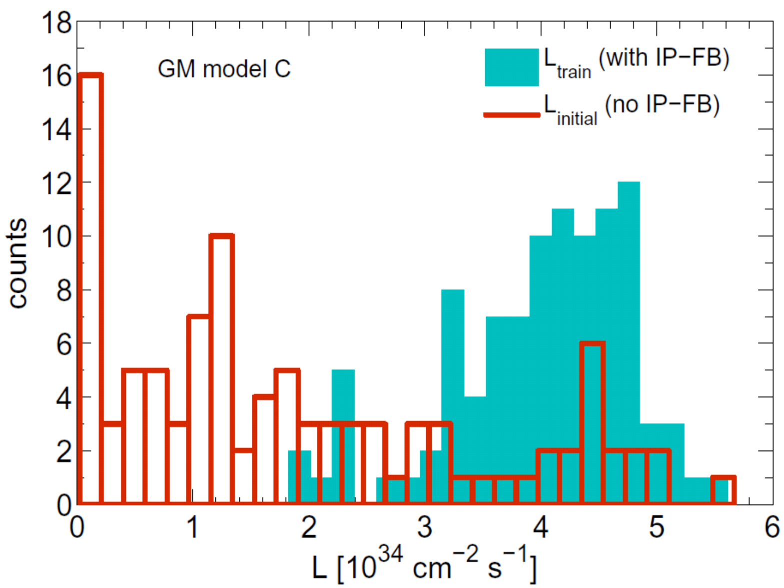
- Without any correction: mean $\langle L/L_0\rangle_{train}$=91.1%
- With IP-FB: mean $\langle L/L_0\rangle_{train}$=97.86%
  std reduced by a factor 4

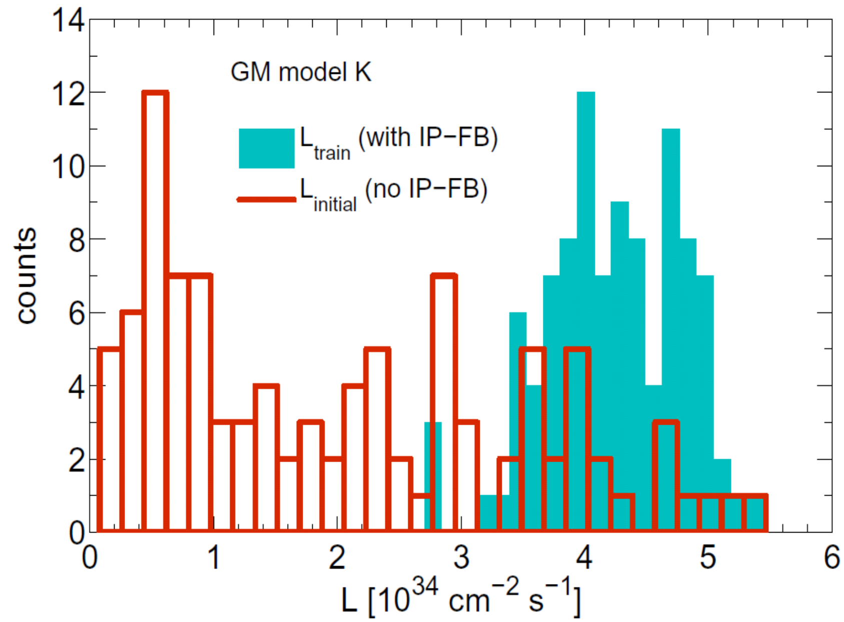
# Simulations: CLIC luminosity result with IP-FB

## Different scenarios of ground motion

Luminosity distribution for simulation of 100 random seeds of the GM

For noisy sites:




In these cases significant luminosity degradation

Model C:

- Without any correction: mean $\langle L/L_0 \rangle_{train}$=30.52%
  & High standard deviation!
- With IP-FB: mean $\langle L/L_0 \rangle_{train}$=64.15%
  std reduced by a factor 2

Model K:

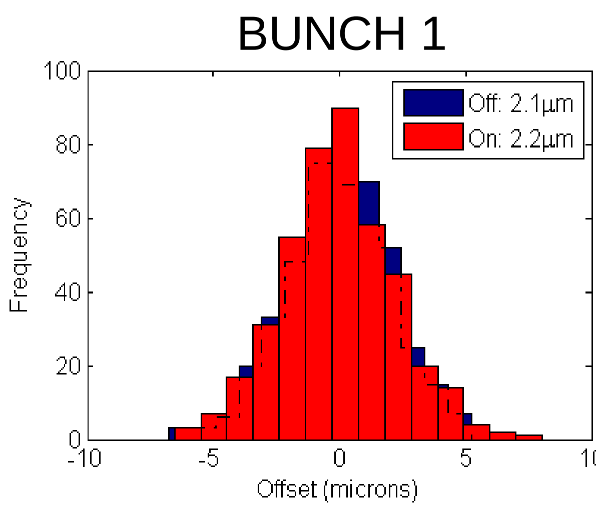
- Without any correction: mean $\langle L/L_0 \rangle_{train}$=32.53%
  & High standard deviation!
- With IP-FB: mean $\langle L/L_0 \rangle_{train}$=67.82%
  std reduced by a factor 3

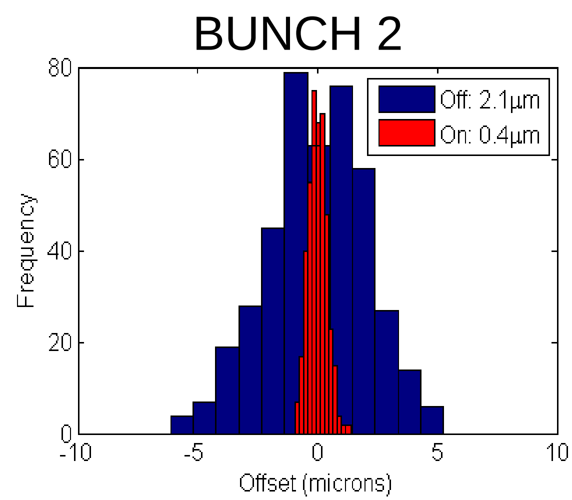
# R&D activities

## [See P. Burrows presentation]

- Successful tests of the intra-train FB principle have already been performed by the FONT (Feedback on Nano-second Timescale) group with both digital and analogue FB boards at available test beam facilities across the world, e.g. at ATF2

- A prototype beam-based digital feedback system for the ILC based on FPGA digital signal processing is currently being tested in the KEK ATF2:
  - Preliminary results have shown a reduction of the beam position jitter (generated during extraction from the DR) by a factor 5



# Summary

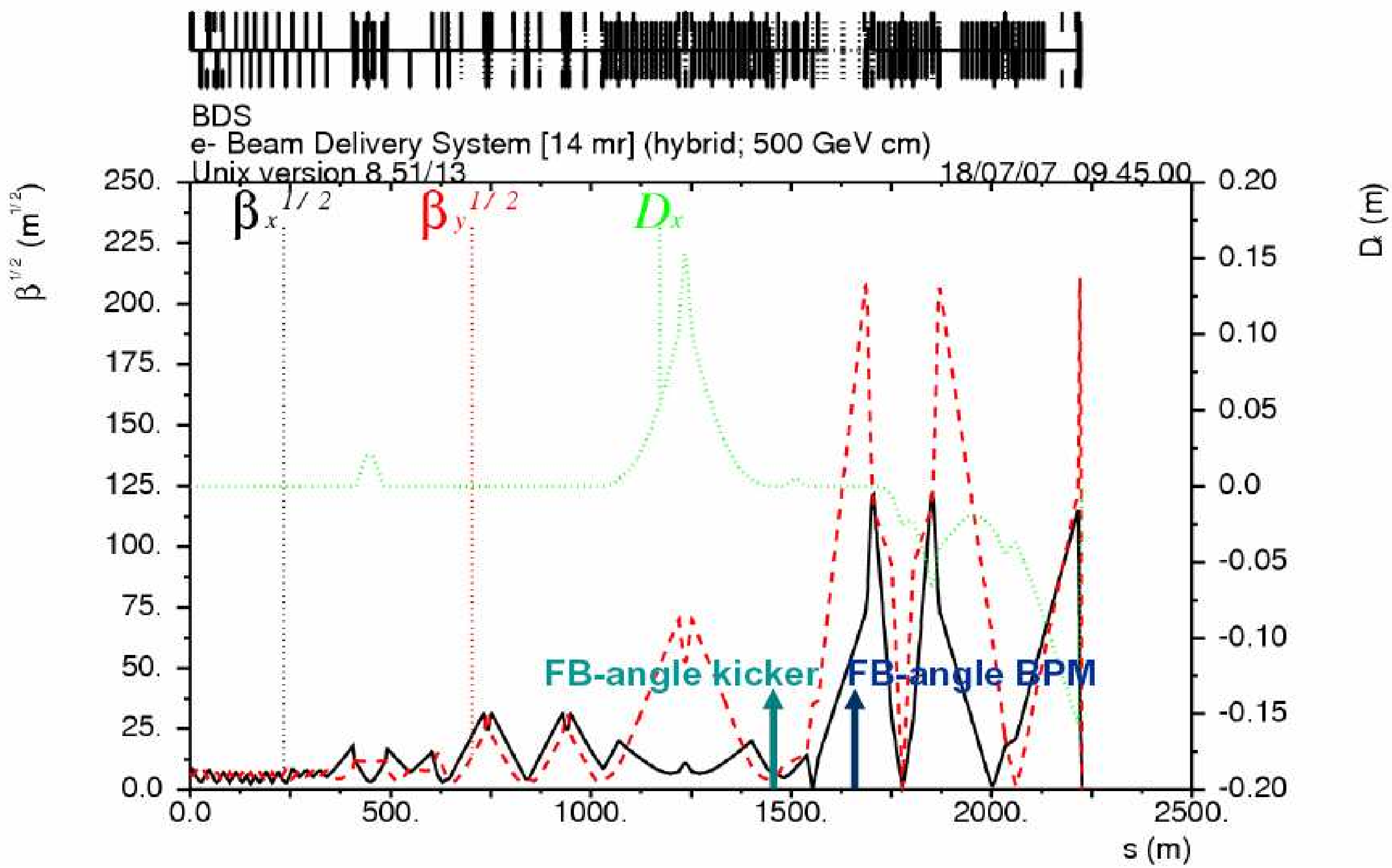
- To achieve the required luminosity of the future LC necessary FB systems operating on different time scales.

- We have briefly presented the conceptual design of beam based intra-train FB systems at the IP of both ILC and CLIC:
  - Bunch-to-bunch corrections are possible in the case of the ILC
  - The CLIC nominal bunch train structure makes the design of an intra-train FB system especially challenging.

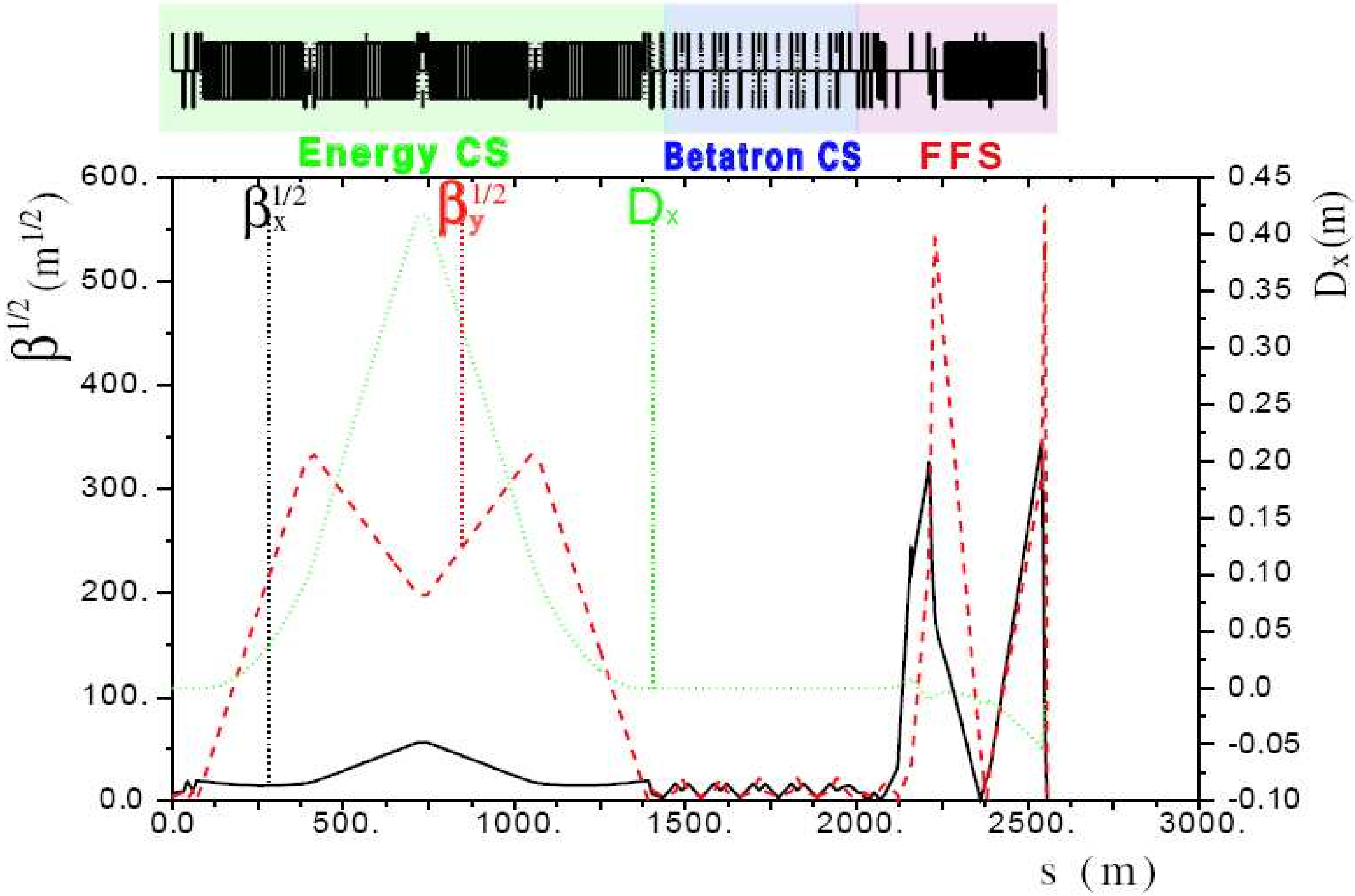
- Simulation results of luminosity performance with intra-train FB system (considering realistic assumptions based on the conceptual design) for different scenarios of GM:
  - For ILC, the combination of both position and angular fast intra-train FB systems can in principle recover >~ 90% of the nominal luminosity even for very noisy cases of GM
  - For CLIC, in the most severe scenarios of GM, the IP-FB system is able to recover ~60% of the design luminosity

- R&D efforts: FONT project

# ILC BDS (500 GeV cms)



# CLIC BDS (3 TeV cms)



# Kicker specifications

## (summary)

| Parameter | ILC | CLIC |
|---|---|---|
| Effective length [cm] | 30 | 25 |
| Aperture [mm] | 20 | 10 |
| Peak current [A] | +/-15 | +/-5 |
| Peak power [kW] | 11 | 3 |
| Inductance per unit length [µH/m] | 0.17 | 0.4 |
| Maximum voltage [V] | 750 | 600 |
| Magnetic field [T] | $1.3\text{x}10^{-4}$ | $2\text{x}10^{-4}$ |
| Impedance [Ω] | 50 | 120 |
| Rise time [ns] | 35 | 5 |
| Max kick [nrad] | ~50 | 10 |