Wakefield effects in the CLIC BDS

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LCWS 2019
2019-10-29

Motivation

- Understand the limitations of beam pipe apertures in the CLIC Beam Delivery System
- Ensure the beam stability and luminosity performance
- Propose an aperture model for CLIC BDS for further use, e.g. in synchrotron radiation reflections study

Beam pipe aperture limits

- Resistive wall wake fields have been calculated assuming round beam pipes made of copper with conductivity of $5.96 \cdot 10^7$ S/m, or steel with $1.45 \cdot 10^6$ S/m
- Assumed maximal magnetic field at a pole of normal-conducting quadrupoles: ~ 1.5 T
- Collimation depth for 380 GeV machine assumed to be the same as for 500 GeV and 3 TeV designs: $15\sigma_x$ and $55\sigma_y$[1]
- Inner aperture calculation follows the formula:

$$R_{\text{inner}} = \max\{r_{\text{wake}}, 0.1 + max\{15\sigma_x, 55\sigma_y\}\}, \tag{1}$$

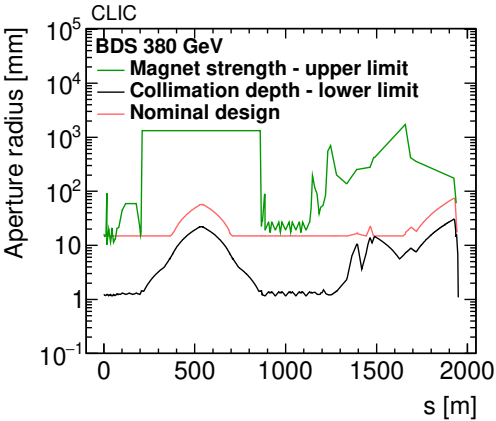
where: r_{wake} based on the previous resistive wall wakefield study[2]: 15 mm at 380 GeV (scaled from 500 GeV), and 6 mm at 3 TeV, and beam sizes with β functions coming from MAD-X:

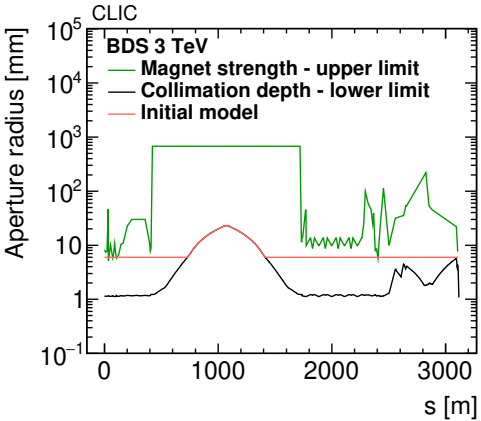
$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y} + (D_{x,y}\delta_E)^2}, \tag{2}$$

[1] From Optimization of CLIC Baseline Collimation System

[2] From Multi-bunch effect of resistive wall in the BDS of the CLIC

Initial aperture models





- Apertures significantly larger at 380 GeV
- A few problematic points, can be addressed by extending the magnet lengths

Resistive wall wake field

- Resistive wall effect is a result of finite vacuum chamber conductivity
- The surface current is delayed with respect to the source and the electric field can interact with the charged particles on the short- and long range

Classical formula of the resisitive wall wake:

$$W(z) = -L\frac{c}{\pi b^3}\sqrt{\frac{Z_0}{\pi z \sigma}}, \tag{3}$$

where: Z_0 - impedance of the vacuum, z - longitudinal distance between the source and the impacted particle, b - aperture radius, σ - conductivity of the wall, L - length of the accelerator element

- Assumed are thick walls, ultra-relativistic particles
- Only fundamental transverse mode (m = 1) is considered
- In simulations the wakefield effects are imposed by modyfing the momenta distributions by:

$$\Delta x'_k(s) = \frac{e^2}{E_0}\sum_{j=1}^{k-1} N_j < x >_j W(\Delta z), \tag{4}$$

where: e - electron charge,, E_0 - beam energy, N_j - number of charges, $< x >_j$ - centre of gravity in slice j, Δz - distance between slices

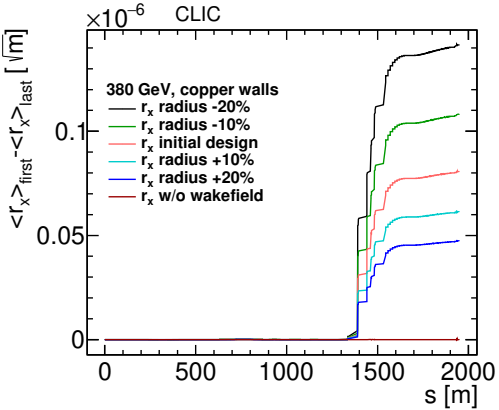
Analysis workflow

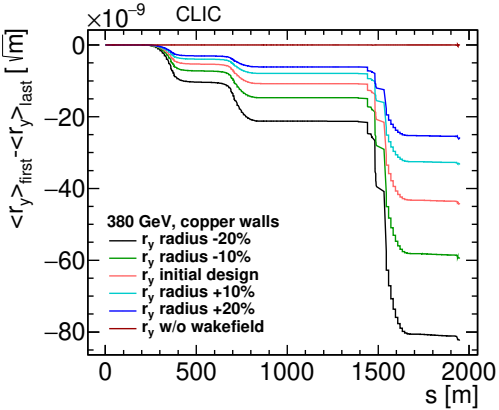
- Bunch trains are created at the beginning of the BDS with a uniform offset of $+0.5\ \sigma_{x,y}$ for all bunches (=worst-case scenario)
- PyHEADTAIL does linear tracking with multibunch wakefield effects up to the IP
- Impact on the beam quality checked by comparing radii of the normalised phase space between the first and last bunch, defined as:

$$r_{x,y}(s)[\sqrt{\mathrm{m}}] = \sqrt{\left(\frac{x(s)}{\sqrt{\beta_s}}\right)^2 + \left(\frac{x(s)\alpha_s + x'(s)\beta_s}{\sqrt{\beta_s}}\right)^2}, \tag{5}$$

  where: α_s, β_s - betatron functions, x - bunch centre position, x' - average bunch angle
- Impact on the luminosity checked by calculating the two-beam luminosity in Guinea-Pig, where a beam transported through the BDS is duplicated and one of the duplicates is centered at (0,0) while the other is fully impacted by the resistive wall wake
- Luminosity along the bunch train is compared with a benchmark that was not impacted by wakefields; 1% loss is acceptable

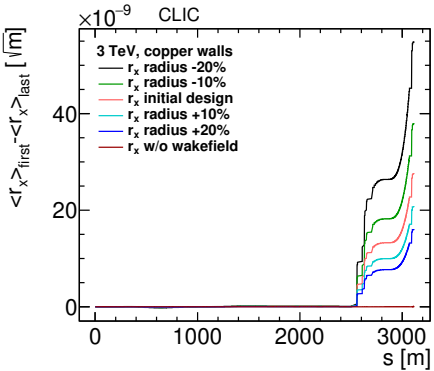
CLIC 380 GeV BDS impact

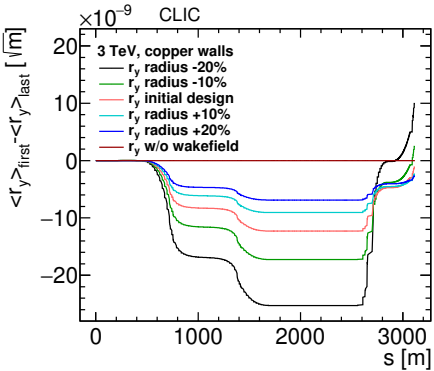




- The impact of the wakefields concentrates in the FFS ($s > 1200$ m) in both directions
- The ordering in response to the varying apertures is as expected

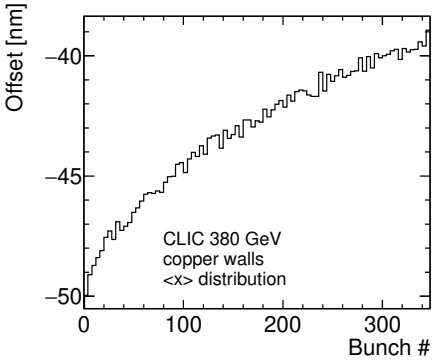
CLIC 3 TeV BDS impact

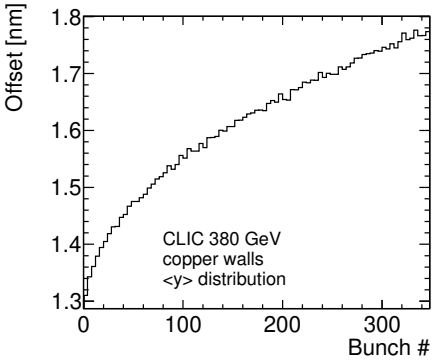




- Similar to 380 GeV, the impact concentrates in the FFS ($s > 2300$ m) in the horizontal direction
- Reverse of the trend in the vertical direction around $s = 2600$ m
- The ordering observed at 380 GeV not maintained in the vertical direction - non-monotonic behaviour

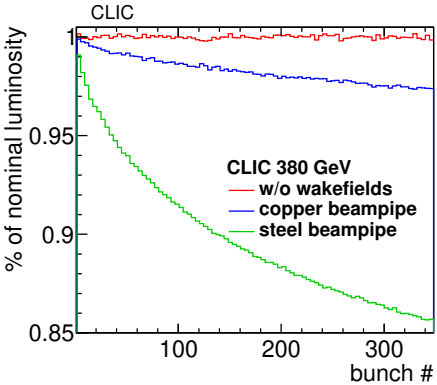
CLIC 380 GeV beams at the IP





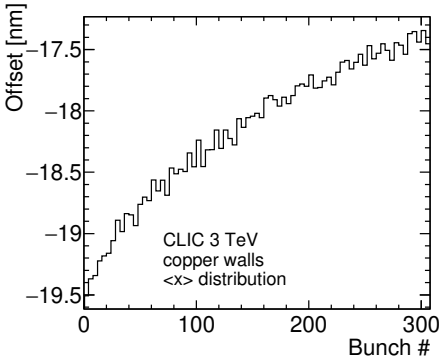
- Beams are focused in the horizontal direction and defocused in the vertical
- The vertical defocus effect dominates with 38% difference between the beginning and the end of a train (20% difference in the horizontal direction)

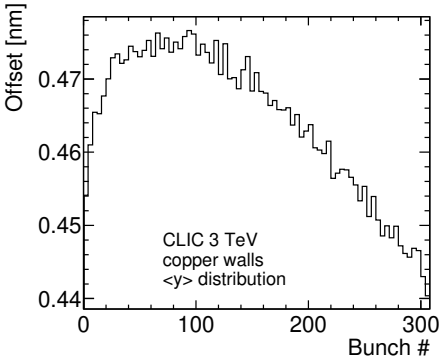
CLIC 380 GeV luminosity impact



- Copper beam pipe provides predictable beam behaviour
- Luminosity loss about 2-3% below benchmark at the end of the train, more than the 1% limit
- The use of steel leads to stronger impact of the wakefields
- Luminosity loss has a steeper slope, resulting in about 15% loss at the end of the train

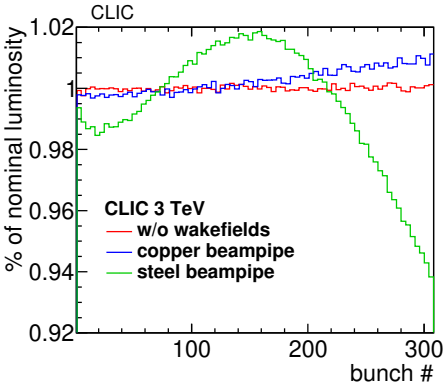
CLIC 3 TeV beams at the IP





- Similar behaviour as at 380 GeV, defocusing in horizontal direction and focusing (initially) in the vertical
- In the first half of the train, the wakefield impact changes the trend of the average vertical bunch position, decreasing the offset

CLIC 3 TeV luminosity impact



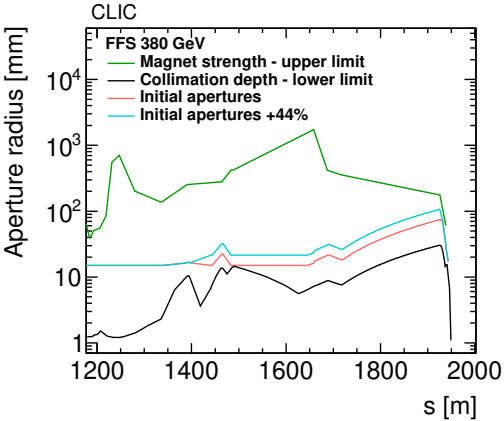
- Luminosity with copper beam pipe follows the offset distribution, strongly impacted by vertical offset
- Non-monotonic behaviour in all cases impacted by wakefields
- More challenging for the intra-train beam feedback to correct
- Steel not recommended - large total luminosity loss and unstable behaviour
- The inner radius of 6 mm does not provide the desired luminosity stability and behaviour

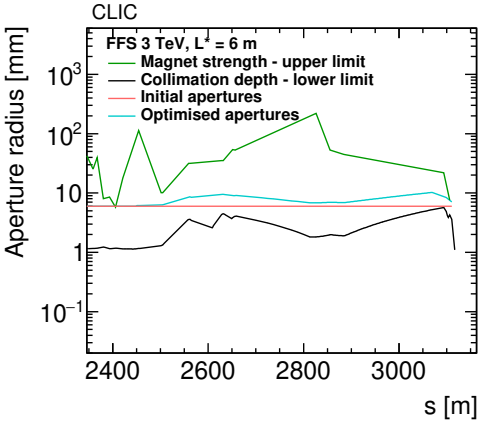
Mitigation approach

- Mitigation has different goals at each energy stage: limiting luminosity loss at 380 GeV, ensuring monotonic beam behaviour at 3 TeV
- The wakefields impact concentrates in the FFS at both energy stages
- At 380 GeV, the wakefields impact and luminosity loss have to be limited by $\frac{2}{3}$
- Achievable with a 44% extension of the apertures in the FFS
- At 3 TeV, the non-monotonic behaviour can be removed if the apertures are extended by a series of constant numbers:

$$a(s)[\mathrm{mm}] = \begin{cases} 3.0 & \text{if} \quad s < 2450\,\mathrm{m} \\ 5.0 & \text{if} \quad 2450\,\mathrm{m} < s < 3090\,\mathrm{m} \\ 3.5 & \text{if} \quad 3090\,\mathrm{m} < s \end{cases}$$

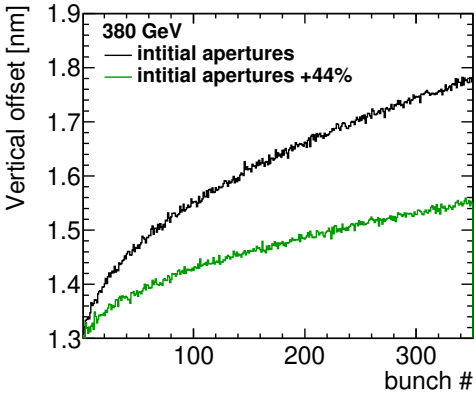
Optimised apertures

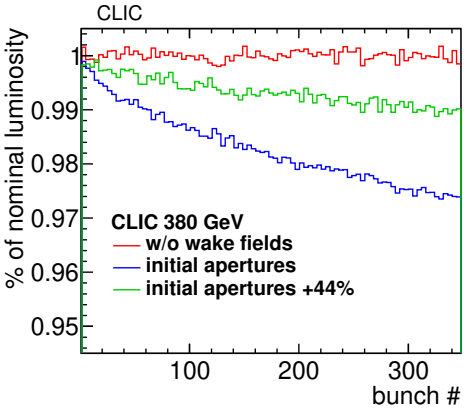




- At both energy stages the extended apertures can be easily accomodated
- The apertures of the last magnet of the final doublet remain unchanged due to cost optimisation; this does not impact the mitigation efficiency

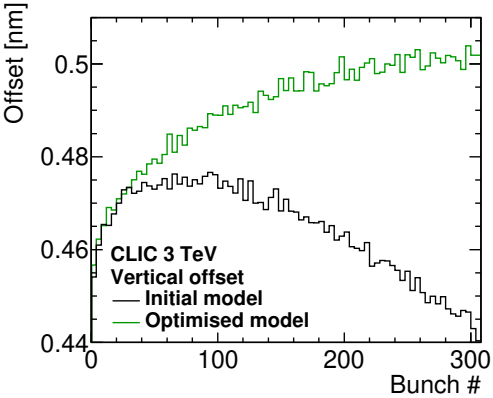
CLIC 380 GeV mitigation

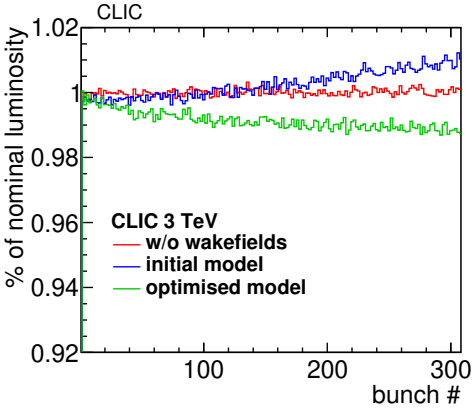




- Extending apertures by 44% reduces the vertical offset by 17% and luminosity loss by a factor of 3
- The final doublet magnets apertures remain unchanged

CLIC 3 TeV mitigation





- Vertical offset and luminosity monotonic in the optimised model
- The luminosity loss at the end of the trend 1% below benchmark

Summary and outlook

- Resistive wall wakefield impact concentrates in Final Focus System
- Steel is not a safe material to use for the beam pipe in the FFS, copper coating in the order of tens of microns necessary
- Non-monotonic beam and luminosity behaviour observed at 3 TeV
- Luminosity loss at 380 GeV larger than the 1% goal
- Most of the luminosity loss from the offset, which can be alternatively cured with intra-train feedback, but the wakefield impact is non-linear thus challenging
- Extending apertures in the FFS by 44% at 380 GeV and by about 50% at 3 TeV mitigates the wakefields impact

Outlook:

- Collimation region resistive wall and geometric wakefields simulations at 380 GeV

Additional material

PyHEADTAIL for CLIC

- Macroparticle simulation code library for modeling collective effects beam dynamics in **circular** accelerators
- Modular software allowing to prepare custom simulation scripts
- Special approach needed to simulate a linear machine:
  - Focus on element-by-element beam parameters instead of turn-by-turn
  - Lattice read from MAD-X Twiss table
  - Use of pre-calculated wakes
- Source code and examples available at: PyHEADTAIL repository and PyHEADTAIL wiki