PyHEADTAIL simulations of resistive-wall wakes in the CLIC BDS

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Overview

Motivation

- Understand the limitations of beam pipe apertures in the Beam Delivery System
- Find or delevelop a tool to estimate the effect of resistive wall wakefields
- Propose an aperture model for CLIC BDS for further use, e.g. in synchrotron radiation reflections study

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 can interact with the following charged particles on the short- and long range

Classical treatment of resisitive wall wake:

$$W(z) = -L\frac{c}{\pi b^3}\sqrt{\frac{Z_0}{\pi \sigma_r z}}, \tag{1}$$

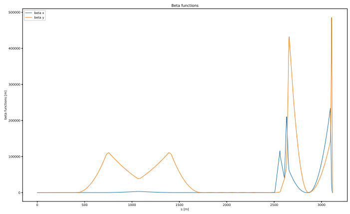
where: Z_0 - impedance of the vacuum, z - longitudinal distance between the source and the impacted particle, σ_r - conductivity of the wall, b - aperture radius, L - length of the considered wake element[1]

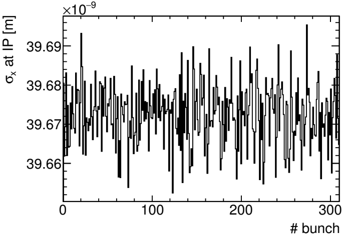
- Assumed are thick walls, ultra-relativistic particles
- Only fundamental transverse mode is considered

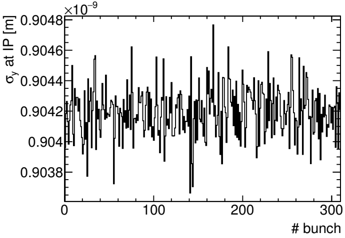
[1] From CLIC-Note-818

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







Analysis workflow

- The most recent designs of BDS at 380 GeV and 3 TeV with L* $=$ 6 m have been used
- Bunch trains have been created at the end of Main Linac with two kinds of offsets:
  - Coherent $+1\sigma_{x,y}$ for all bunches
  - gaussian distribution with $\sigma = 0.1\sigma_{x,y}$
- PyHEADTAIL's linear tracking with multibunch effects but no energy spread at the moment
- PLACET simulations used to establish beam envelopes along the lattice, with synchrotron radiation and non-linearities included
- The Initial aperture models have been checked by changing the beam pipe radii by -10%, +10%, 20% and 30 %. The results have been compared with calculations without wake fields effects

Assumptions

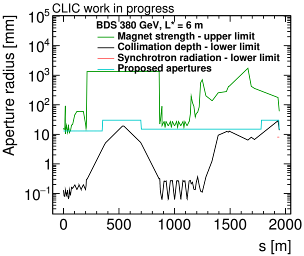
- Resistive wall wake fields have been calculated assuming round beam pipes made of copper with conductivity of $5.96 \cdot 10^7$ S/m or steel with $\sigma = 1.45 \cdot 10^6$ S/m
- Assumed maximal magnetic field at a pole of warm magnets: ~ 1.5 T
- Collimation depth for 380 GeV machine assumed to be the same as for 500 GeV and 3 TeV designs: 15 σ_x and 55 σ_y from proceedings on Optimization of CLIC Baseline Collimation System
- Figures of merit used to minimise the resistve wall effect consisted of:
  - Differences in ratio of average horizontal[1] offset and beam size between first and last bunch
  - Differences in normalised phase-space radii

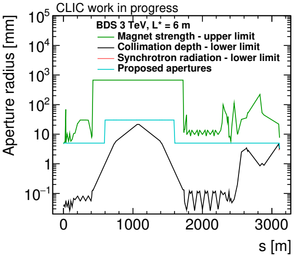
[1] Vertical variables available in additional material

Beam pipe aperture estimation - requirements

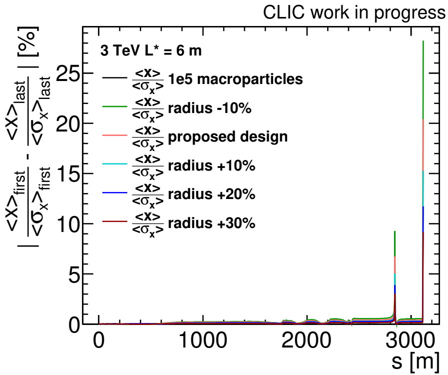
- Aperture is limited by the use of warm magnets, collimation depth, beam stability and machine safety

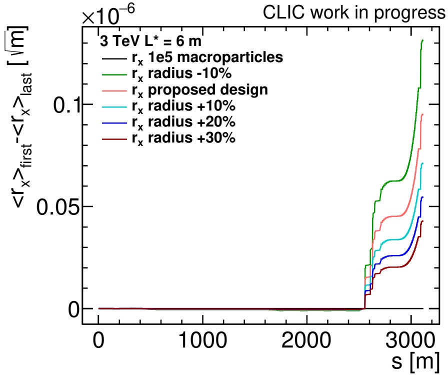
- Machine safety requires that no SR photon emitted from QF1 hits QD0 magnet of the final doublet; all direct SR photons should safely leave the detector without interacting with its material
- Beam pipe apertures should incur minimal impact on the bunch trains from resistive wall wake fields
- In the initial model the number of different beam pipe radii has been minimised





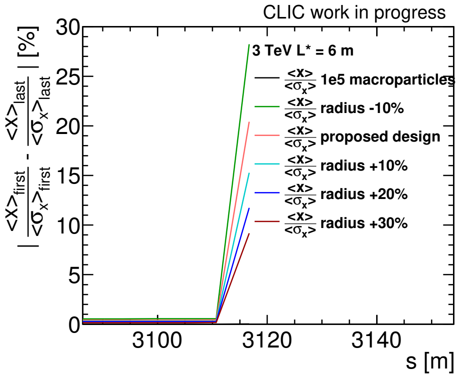
3 TeV - initial model

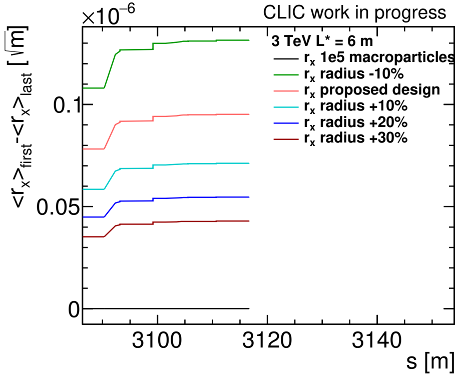




- The resistive wall impact on the beams is significant for $s > 2300$ m
- The starting point model has not been chosen optimally, even slight decrease in radius leads to a much stronger effect
- Increasing the radii offers decrease in the effect but with diminishing impact

3 TeV - initial model at IP

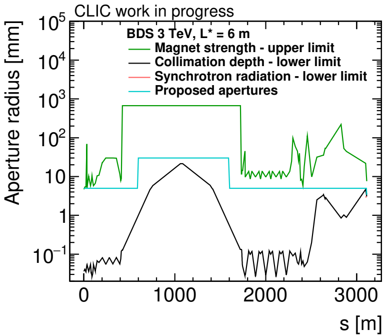




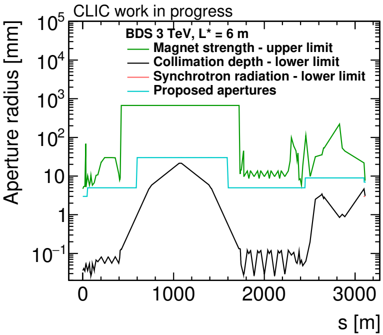
- The beam parameters with wake field effects turned on are significantly more distorted than the reference beam (black lines)
- The distortions in the IP region are of order of nominal beam parameters; horizontal offset is comparable with a bunch size

3 TeV - optimised design

initial model

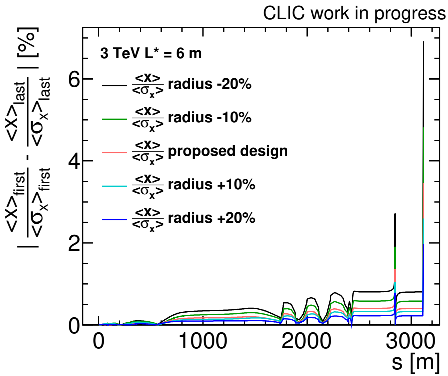


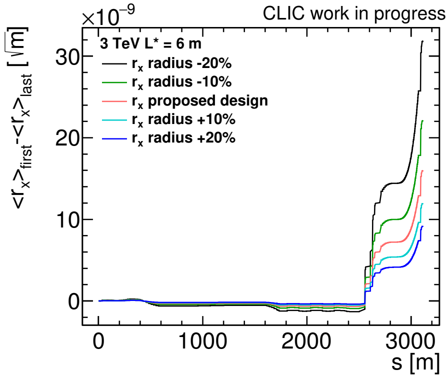
updated model



- An updated model had to be derived to address the wake field impact on the beams
- It uses the maximal available apertures in the last part of the Final Focus System while maintaining them as low as possible elsewhere

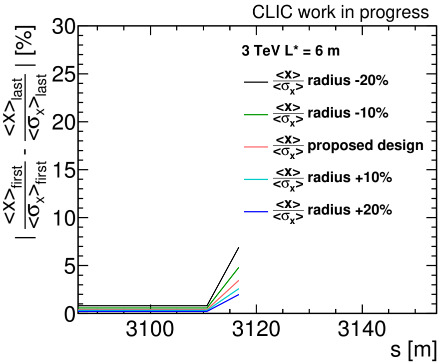
3 TeV - optimised design

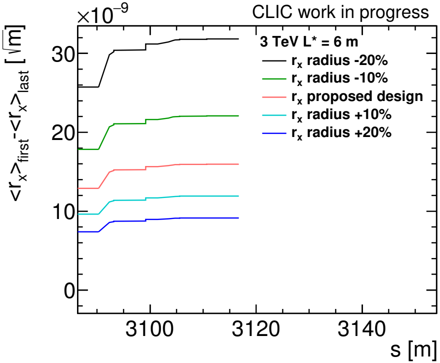




- Close to optimum - the penalty to go under the updated model seems to be larger than diminishing results from increasing radii
- Only small gain available when increasing the radii from +10% to +20%

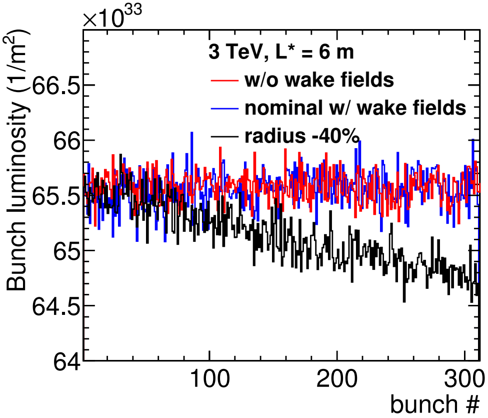
3 TeV - optimised design at IP





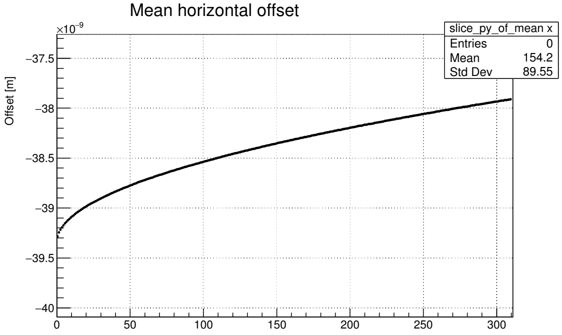
- The normalized phase-space radii difference has been found **6 times smaller** than in the initial model
- Reduced IP offset difference from 20% of the beam size to $< 3\%$
- Only small gain available when increasing the radii from $+10\%$ to $+20\%$

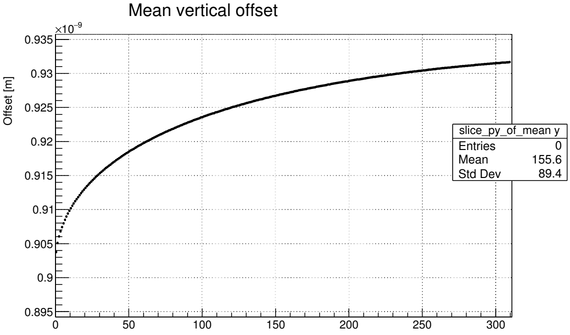
3 TeV - optimised design luminosity impact



- Luminosity obtained from Guinea-Pig using one-beam approach
- Averaged over 10 bunch trains
- The optimized case comparable with the no wakefield hypothesis

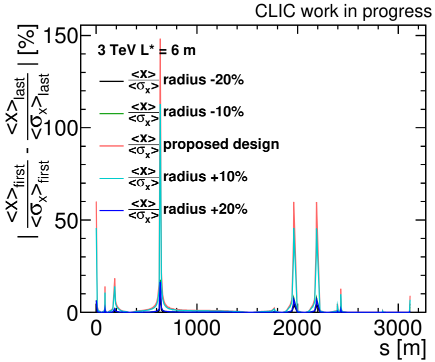
3 TeV - optimised design offsets distribution at IP

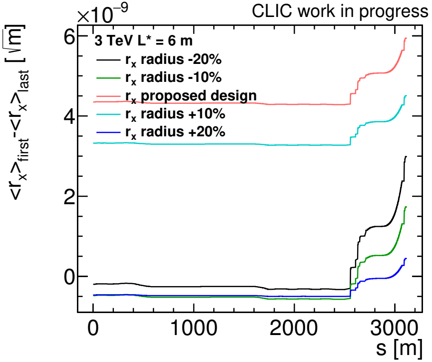




- Monotonic distribution of offsets growing by about 2-3% of beam size from the first to last bunch
- Correctable with current IP-feedback

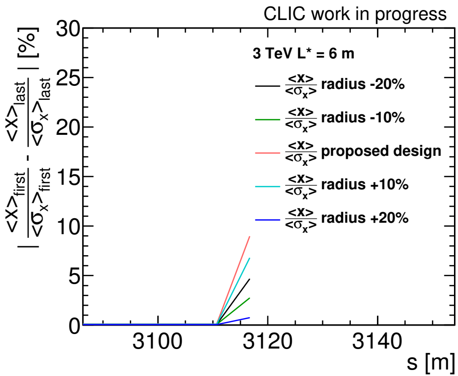
3 TeV - gaussian jitter

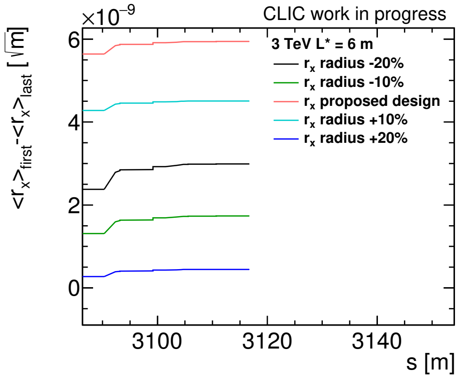




- Gaussian distribution of initial offsets should lead to smaller overall wake field impact on the beams
- Unobserved with uniform offset: spikes of large offsets in regard to beam sizes due to rapid shrinking of the denominator in those points - not expected to be a significant issue
- Possible to be addressed with increasing beam pipe aperture in the impacted area

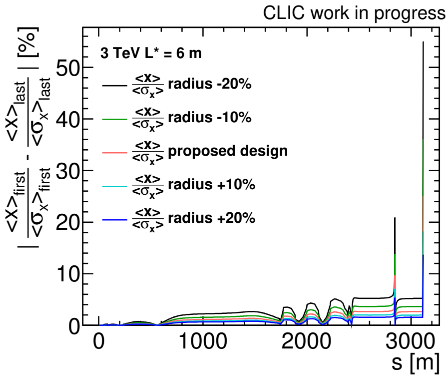
3 TeV - gaussian jitter at IP

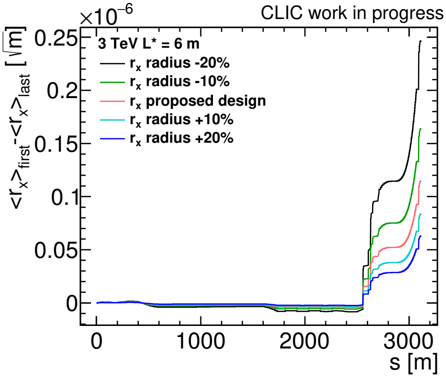




- Larger ratio of offset to beam size than with uniform offset
- Generally smaller radii than with coherent offset
- Surprisingly the nominal aperture model behaves the worst

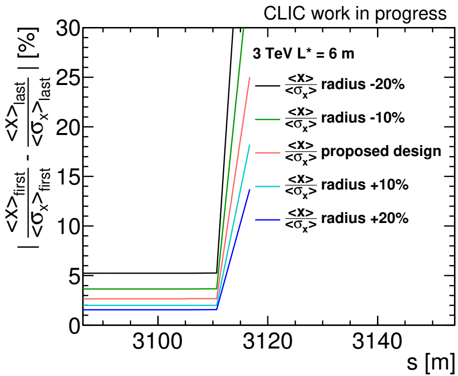
3 TeV - optimised design w/ steel beam pipe

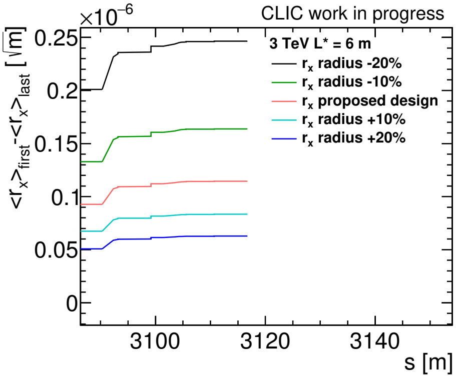




- The use of steel beam pipe instead of copper lead to much higher distortions of the beams
- Average offset ratio and normalized phase space radii were **at least 7 times larger**
- Use of steel beam pipe not advised for s $>$ 2400 m (collimators not taken into account)

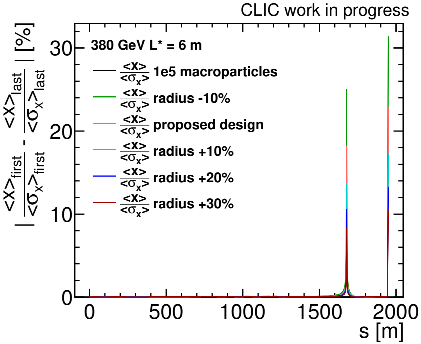
3 TeV - optimised design w/ steel beam pipe at IP

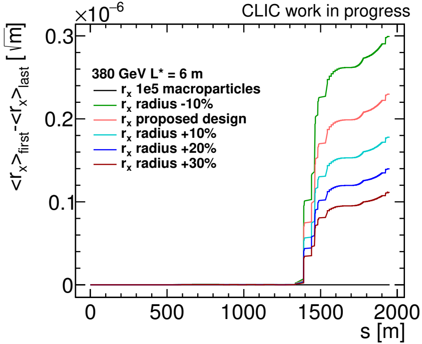




- The use of steel beam pipe lead to much higher distortions of the beams
- Average offset ratio to the beam size and normalized phase space radii were **7-10 times larger**

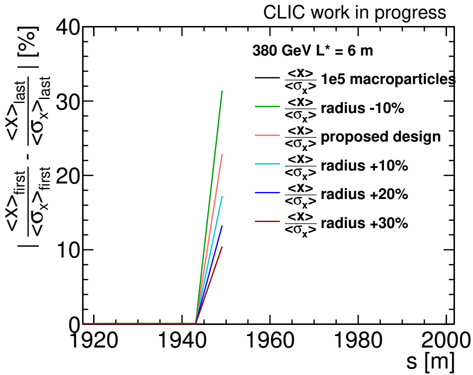
380 GeV - initial model

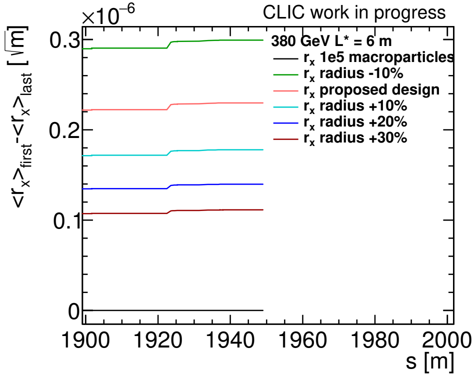




- 380 GeV beams are expected to be more sensitive to resistive wall effects due to lower energy, larger charge and longer bunch trains
- Strong impact of resistive wall effect on the beams present for $s > 1300$ m covering larger percentage of the lattice than at 3 TeV
- The initial model seemed to be far from optimum: significant changes in average offset distributions with changing radii

380 GeV - initial model at IP

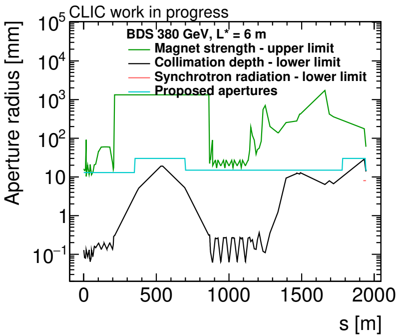




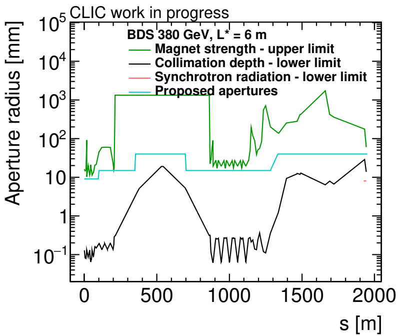
- Reference beam was well below the beams influenced by the wake fields
- Average offset difference was larger than beam size at IP unless the beam pipe radius would be significantly increased
- Meaningful gains available in normalized phase space radii differences

380 GeV - optimised design

initial model

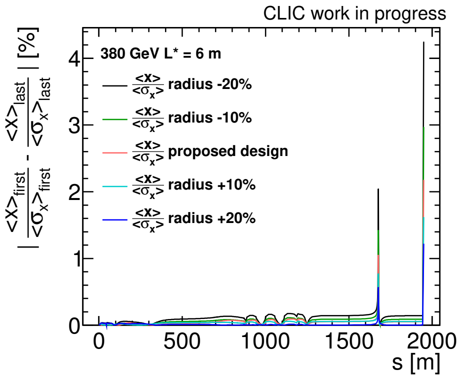


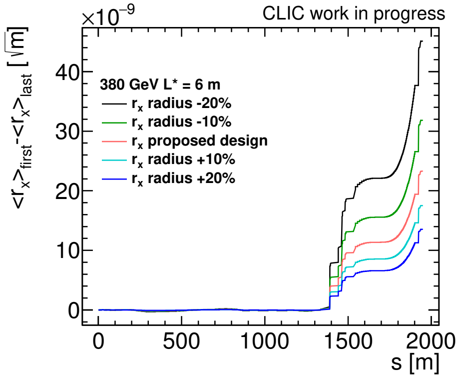
updated model



- Taking into account the previous experience the beam pipe radii have been extended in the most crucial areas for s $>$ 1300 m, with an additional step close to the IP
- Further extensions possible if needed

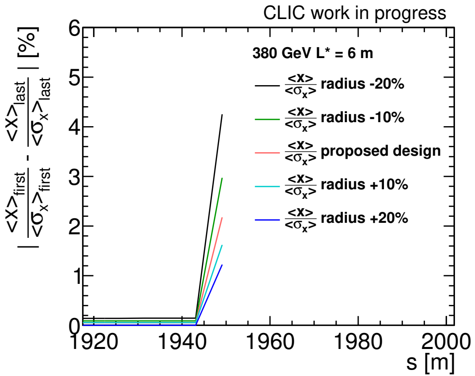
380 GeV - updated design

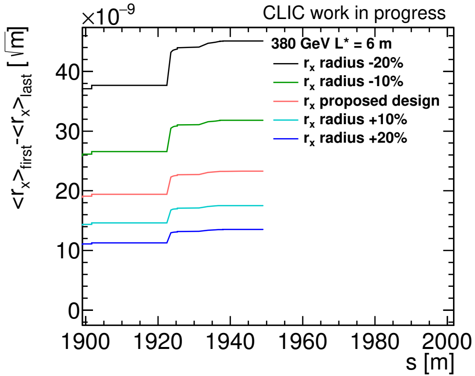




- Much better performance than in the initial model, factor 10 reduction in offset ratio and radii difference
- Resistive wall effect comparable with the optimised design at 3 TeV

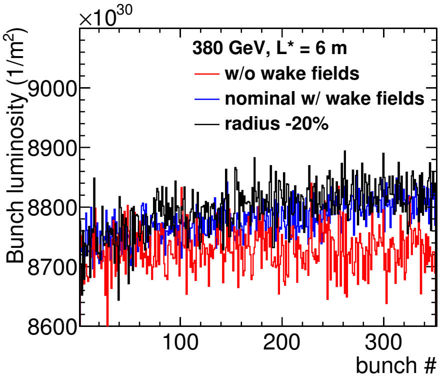
380 GeV- updated design at IP





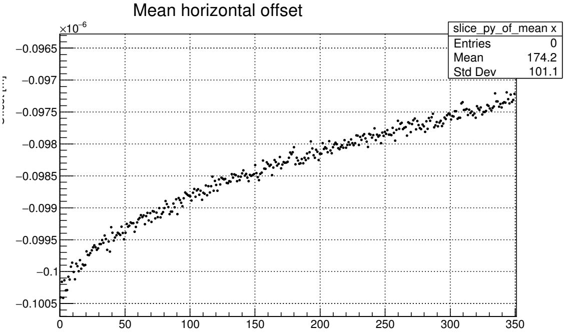
- Achieved **10 times lower** average offset ratio and radii difference at IP
- Resistive wall effect at IP comparable with the optimised design at 3 TeV

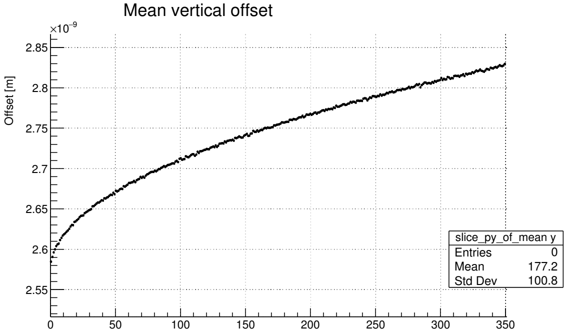
380 GeV - optimised design luminosity impact



- Not final results
- Unexpected behaviour - luminosity growth along the beam train - demands further study
- Proposed design still has sloped luminosity - requires further optimization

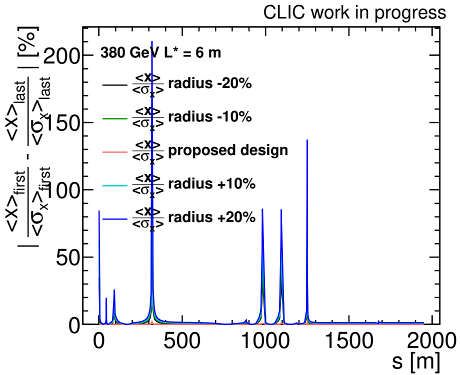
3 TeV - optimised design offsets distribution at IP

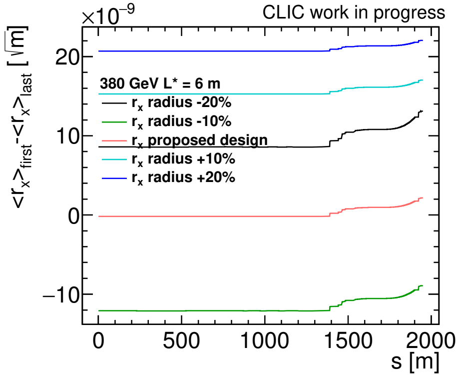




- Monotonic distribution of offsets growing by about 2% of beam size in horizontal plane but by 10% in the vertical one
- Correctable with current IP-feedback (?)

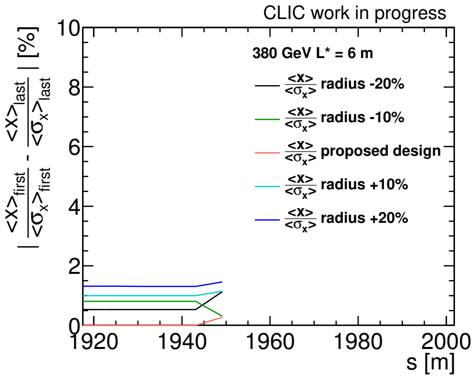
380 GeV - gaussian offset

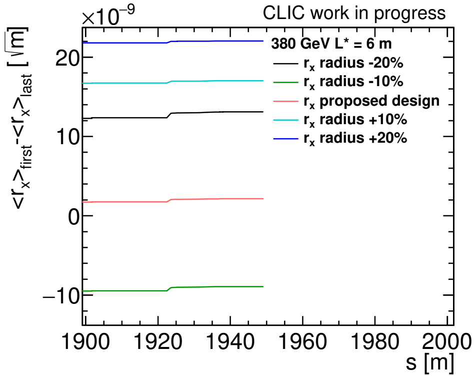




- Similar structures observed as at 3 TeV, unclear how to properly address them
- The proposed model minimises distortions, the figures of merit lower than at uniform offset (outside the peculiarities)

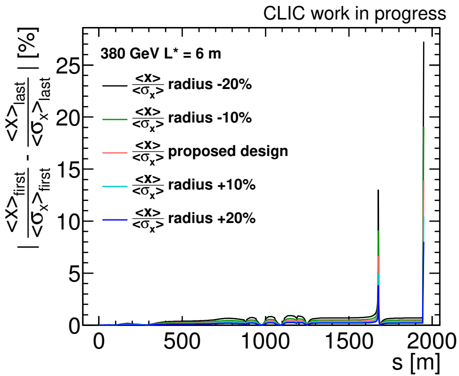
380 GeV - gaussian offset at IP

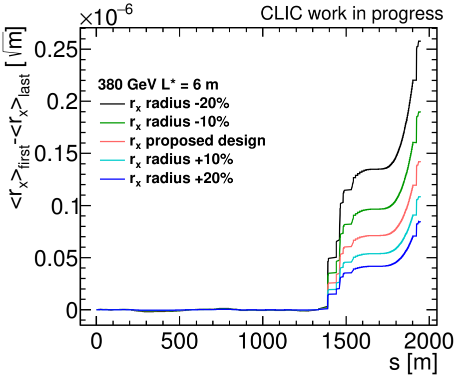




- As expected the gaussian offset has diluted the impact of wake field
- Beam properties much less distorted than with uniform offset

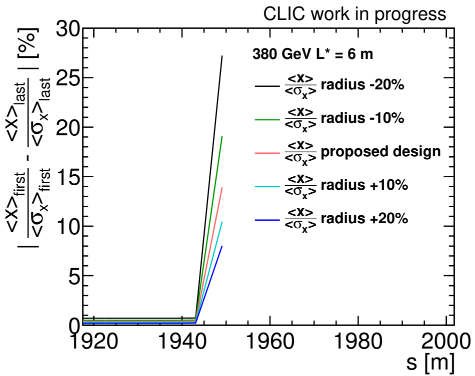
380 GeV - updated design steel beam pipe

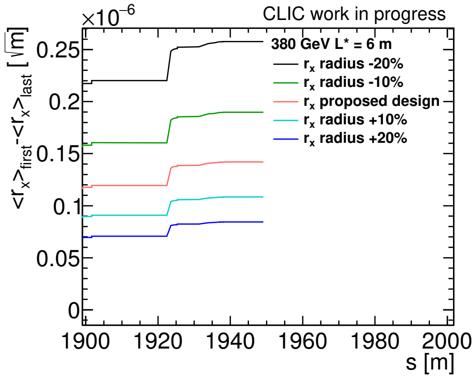




- The impact of resistive wall effect increased by a **factor 5-7** when the material has been changed to steel
- Steel offers fair performance where the wake fields effects were not strong, for $s < 1300$ m

380 GeV - updated design steel beam pipe at IP





- Larger effect along the beamline translated to a strong impact on beam quality at the IP, figures of merit **6 times worse** than for the copper beam pipe

Summary and outlook

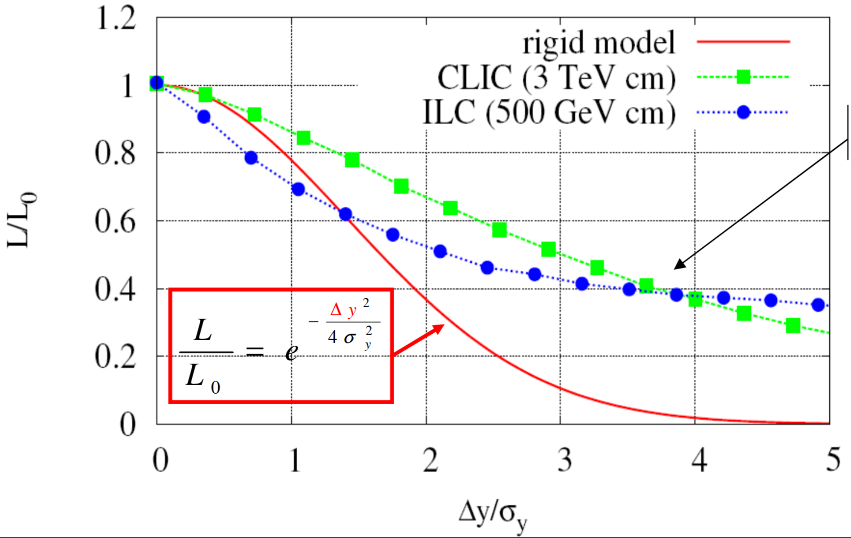
- More refined models of apertures at 380 GeV and 3 TeV with minimised impact of resistive wall wake fields have been proposed
- The wakefield's impact on luminosity at 3 TeV stage is under control, 380 GeV requires more work
- The use of steel beam pipe leads to much higher distortions in the beams, with average offset amounting to large percentage of bunch sizes
- The use of copper beam pipe advised for the FFS
- Interesting features of the wake field with an impact on the design found with gaussian offsets distribution - possibly addressable with changes in the affected regions

Future works:

- Further optimize the 380 GeV stage
- Use the devised aperture model in synchrotron radiation reflections study
- Take into account collimators and assess their impact on the beam quality if necessary

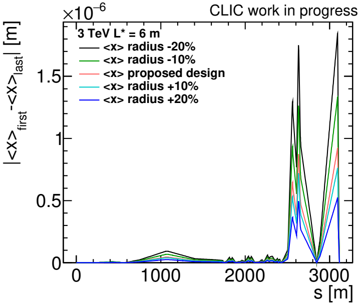
Additional material

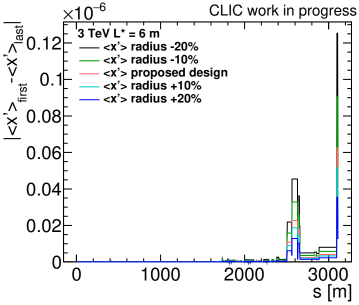
Luminosity dependence

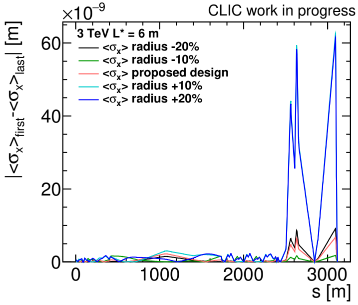


$$\frac{L}{L_0} = e^{-\frac{\Delta y^2}{4\sigma_y^2}}$$

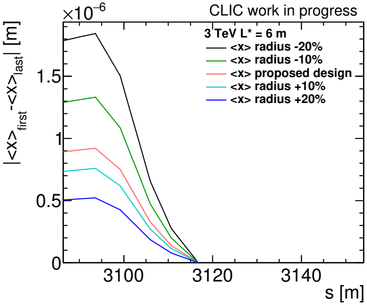
3 TeV - optimised design

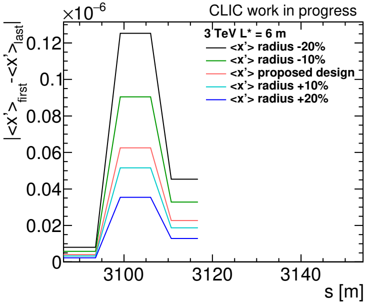


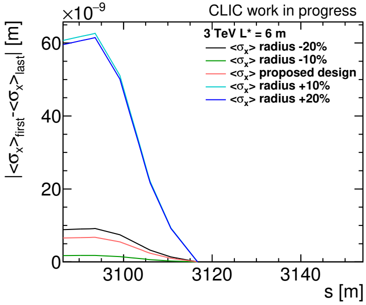




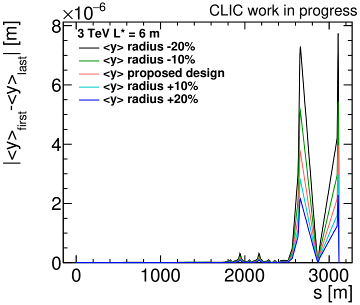
3 TeV - optimised design at IP

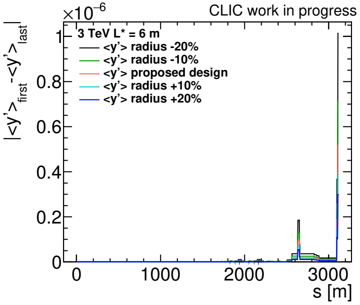


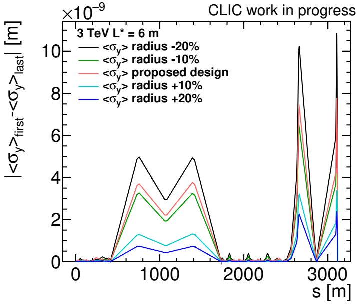




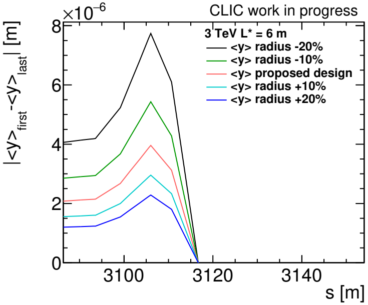
3 TeV - optimised design vertical variables

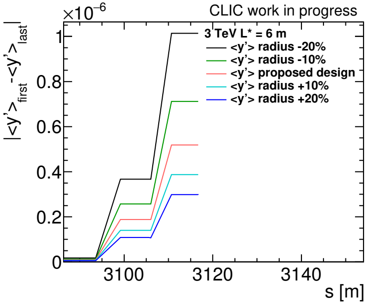


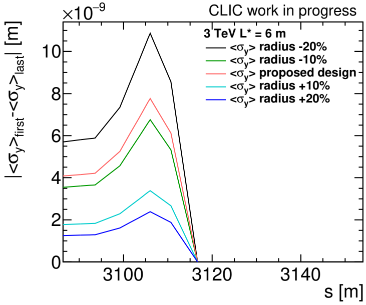




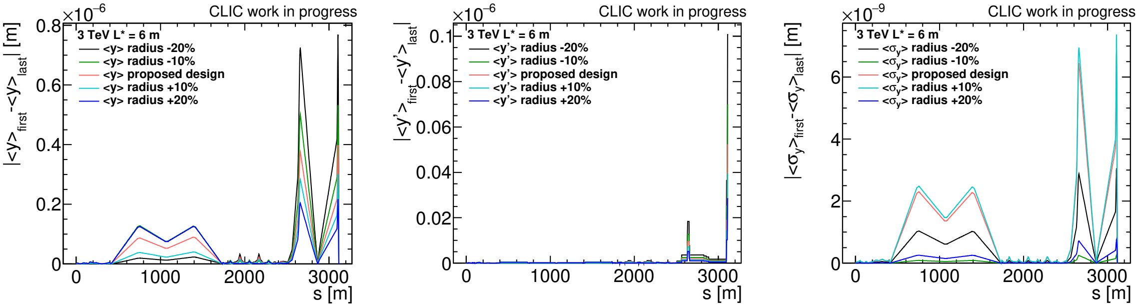
3 TeV - optimised design vertical variables at IP



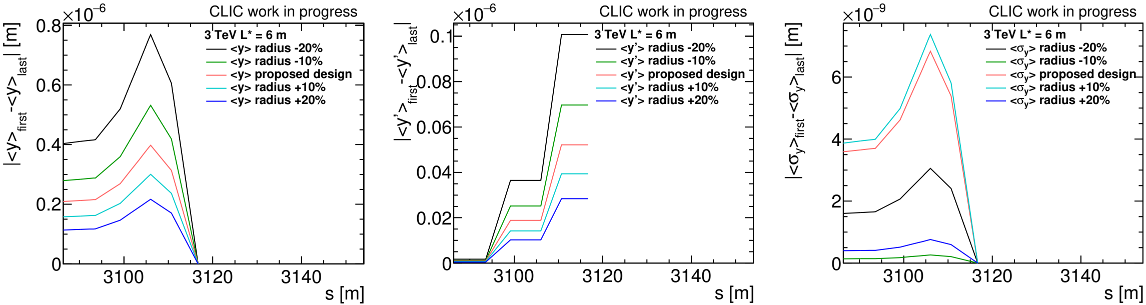




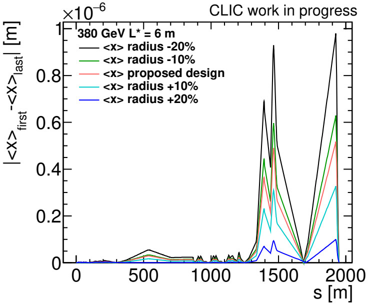
3 TeV - optimised design gaussian offset vertical variables

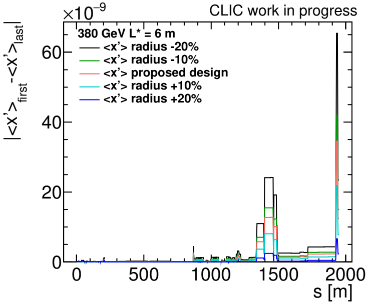


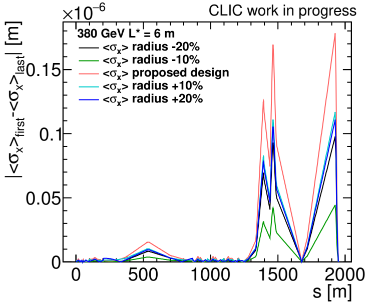
3 TeV - optimised design gaussian offset vertical variables at IP



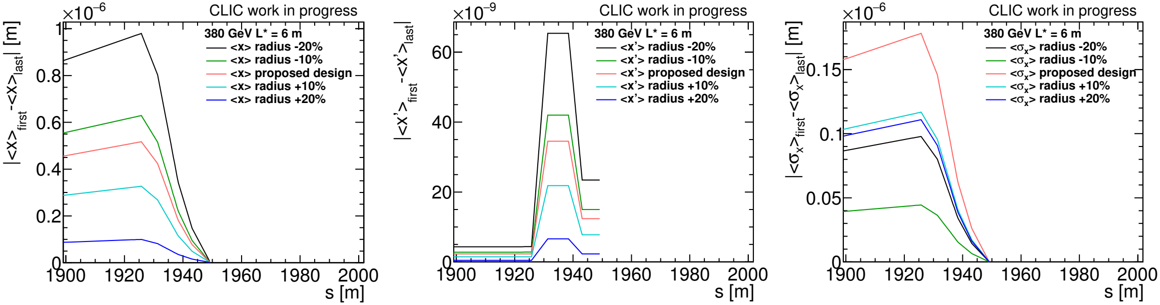
380 GeV - optimised design



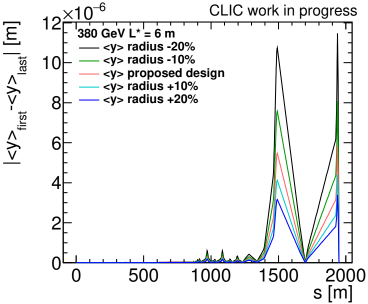


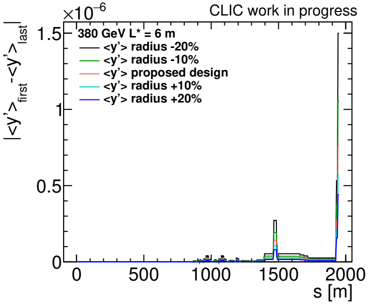


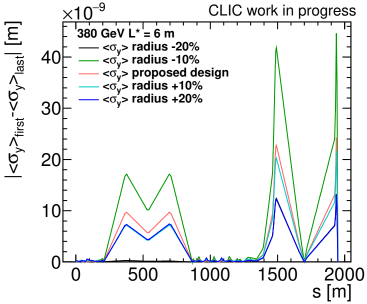
380 GeV - optimised design at IP



380 GeV - optimised design vertical variables







380 GeV - optimised design vertical variables at IP