Nonlinear energy collimation system for CLIC

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LCWS 2011
26-30 September 2011, Granada

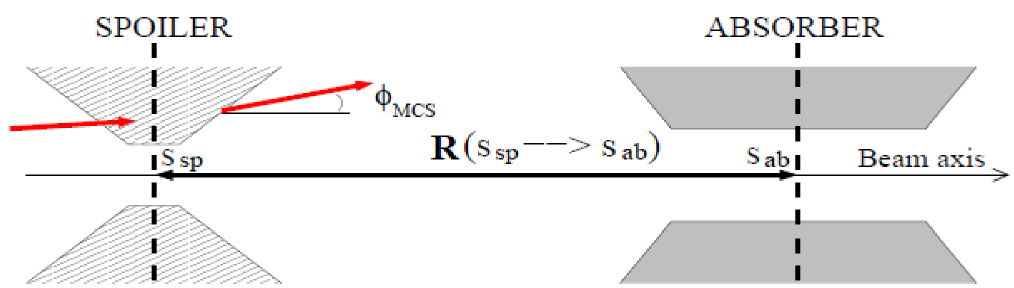
Introduction

- In the CLIC BDS there are two collimation sections:
  - E collimation
  - betatron collimation

- The E collimation system is conceived to fulfil a function of passive protection in the BDS against miss-steered beams

- Energy collimation depth determined by failure modes in the linac

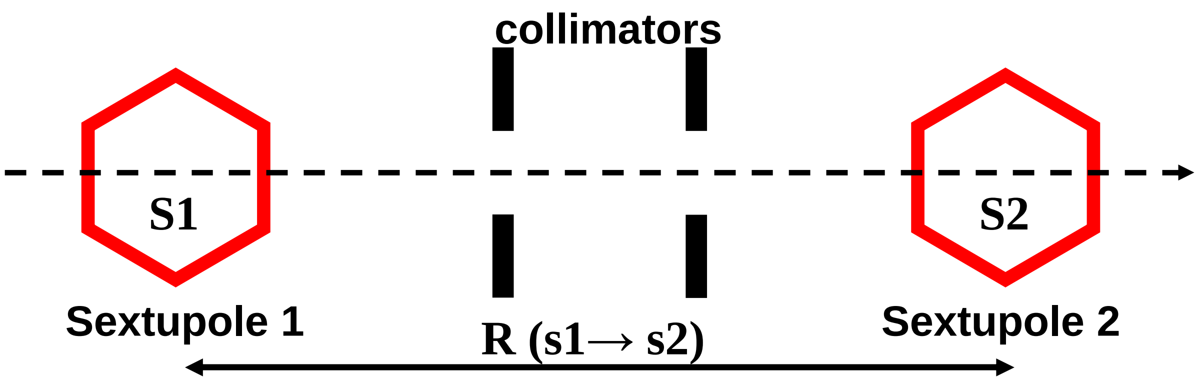
- The conventional E-collimation system is based in a spoiler-absorber scheme located in a region with non-zero horizontal dispersion



Introduction

- The CLIC E-collimators (spoiler and absorber) are required to withstand the impact of a full bunch train in case of abnormal operation.
- Survivability of the E-collimators hit by a bunch train is a very challenging task, considering the CLIC beam power of about 14 MW in the BDS with nominal parameters at 3 TeV CM energy.
- Preliminary thermo-mechanical simulations of the CLIC energy collimators (baseline design) have shown that spoiler and absorber may reach fracture levels when an entire bunch train hit them. For these simulations (using the codes FLUKA and ANSYS) a monochromatic bunch train with nominal emittances and nominal energy was considered, which is a very pessimistic case.
- Looking for solutions to guarantee the survival of the CLIC E-spoiler and E-absorber:
  - Study of novel materials
  - **Design of alternative optics**
- Here we study an optics design including nonlinear magnets to increase the beam spot size at collimator position

Nonlinear passive protection
Basic concept



- Use a nonlinear magnet, which somehow plays the role of a spoiler, to increase the beam spot size at the downstream collimators for a beam with mean energy offset > 1.3 % of the nominal energy
- Cancellation of optics aberrations using a second nonlinear element
- For CLIC we have studied an E collimation system based on a pair of skew sextupoles of moderate strength

Nonlinear energy collimation system

Optics design

Optics constraints to cancel nonlinear terms between the two nonlinear elements:

- $R_{12}=0$, $R_{34}=0$, $|R_{11}|=|R_{33}|$, $|R_{22}|=|R_{44}|$
- Phase advance:

$$\mu_x(s1\rightarrow s2)=n_x\pi,\ \ \mu_y(s1\rightarrow s2)=n_y\pi,\ \text{ where } n_x, n_y \text{ are integers}$$

- Relation between the strength of the two skew sextupoles:

$$K_{s1}\beta_{x1}^{3/2} = -(-1)^{n_y} K_{s2}\beta_{x2}^{3/2}$$

where K_{s1} and K_{s2} are the normalised strength of the 1st and 2nd sextupole respectively, and β_{x1} and β_{x2} are the horizontal betatron function at the 1st and 2nd sextupole position respectively

- We use ***–I*** transformer in both *x* and *y* planes between the sextupoles, which is a special case of the previous conditions: $n_x=1$, $n_y=1$

Nonlinear energy collimation system

Optics design

Additional optics constraints :

- Non-zero dispersion at the collimator position. However the strength and length of the dipoles (to generate the necessary dispersion) should be selected to avoid intolerable emittance growth due to incoherent SR effects.

- To cancel chromatic and chromo-geometric aberrations between the sextupole pair:

  $D_{x1}=-D_{x2}$ and $R_{16}(s1 \rightarrow s2)=0$ (D_{x1} and D_{x2} are the first order horizontal dispersion at the 1^{st} and 2^{nd} skew sextupole respectively).

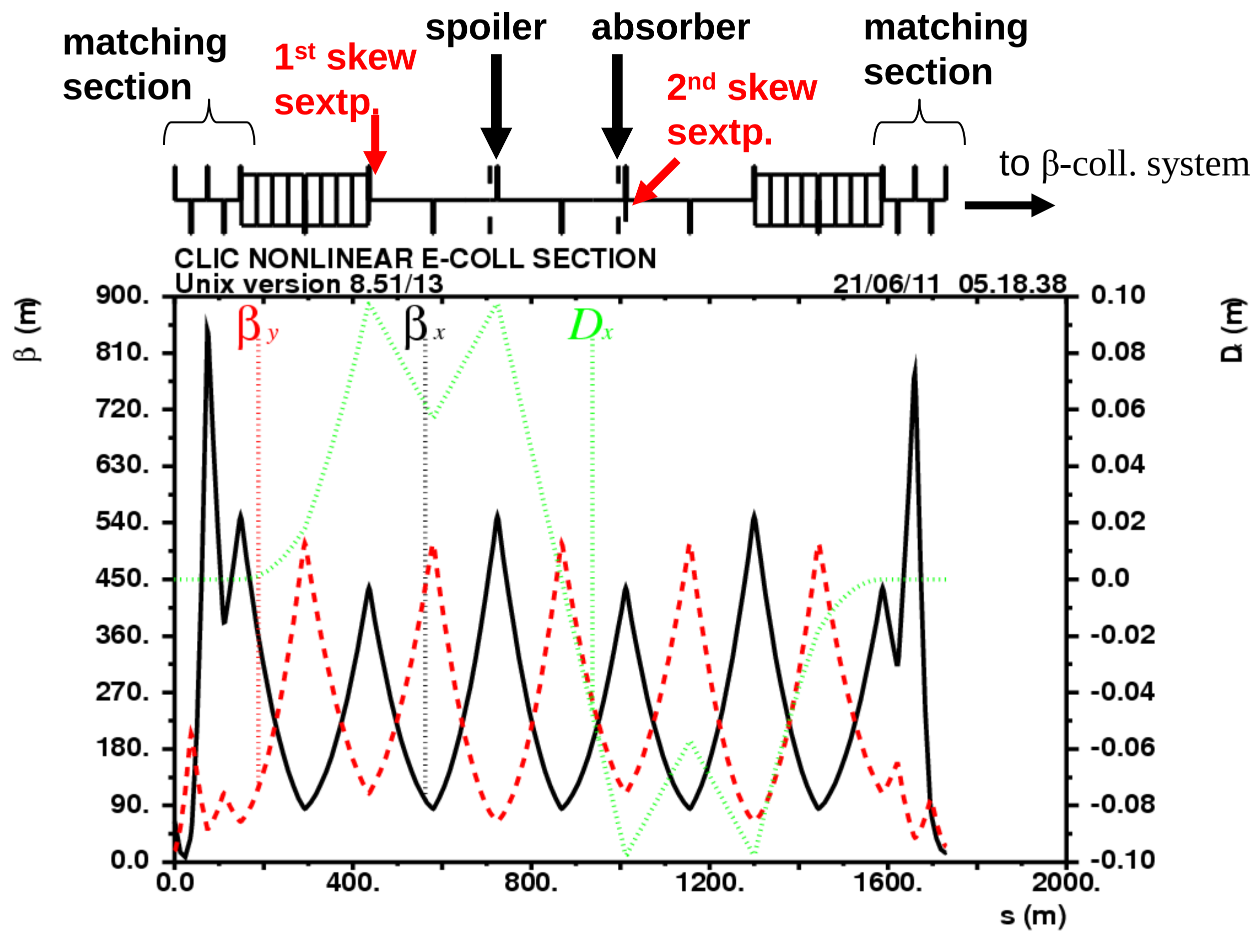
- At the end of the energy collimation section $D_x=0$ and $D_x'=0$ and matching with betatron collimation section

Nonlinear energy collimation system

Optics solution

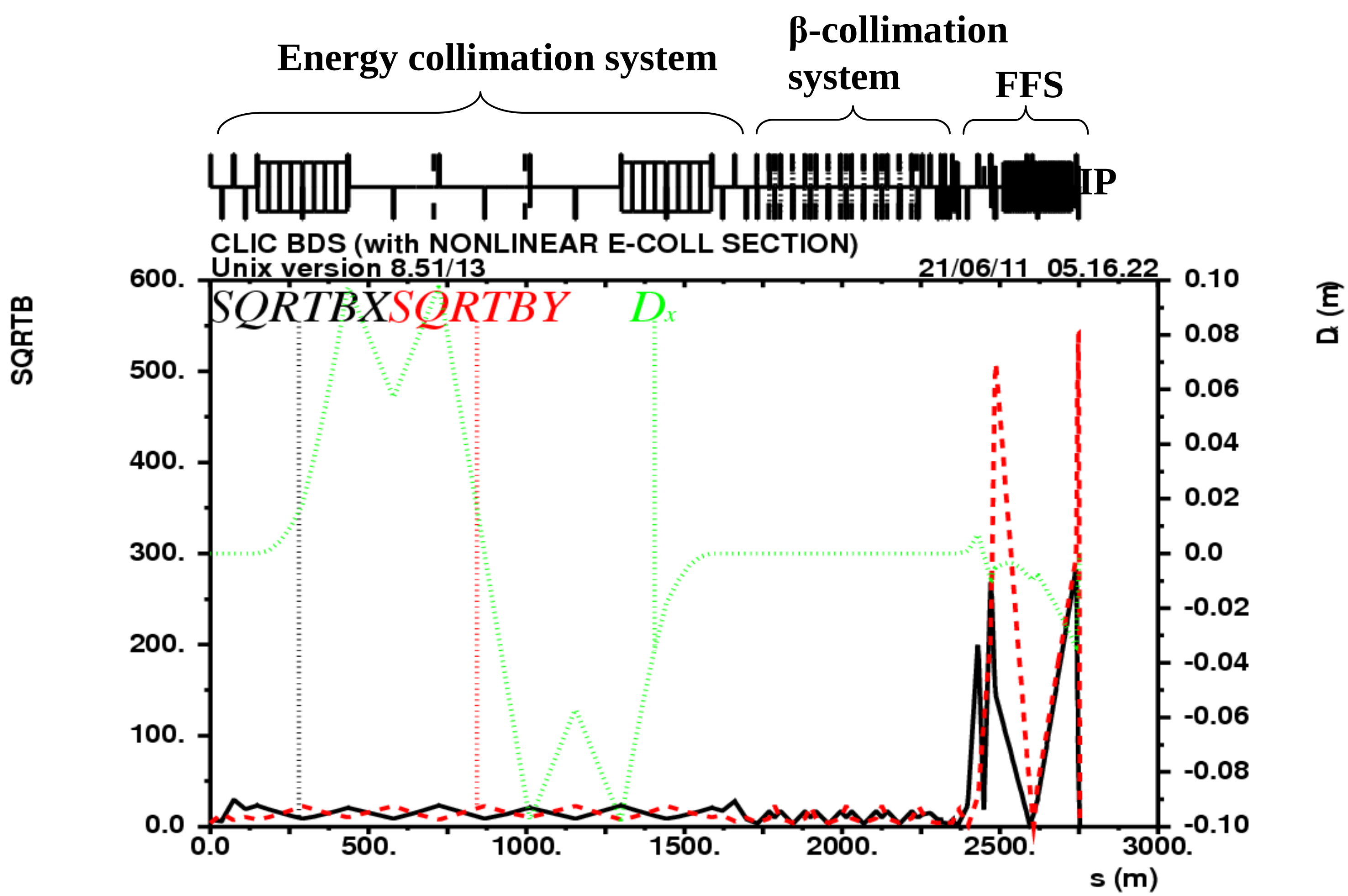
-I transfer matrix in x and y plane between the two skew sextupoles:

$$\beta_{x1} = \beta_{x2}$$
$$\beta_{y1} = \beta_{y2}$$
$$\alpha_{x1} = \alpha_{x2}$$
$$\alpha_{y1} = \alpha_{y2}$$
$$\mu_{x,y}(s1 \to s2) = \pi$$
$$K_{s1} = K_{s2}$$



Lattice about 400 m longer than the baseline E-collimation system

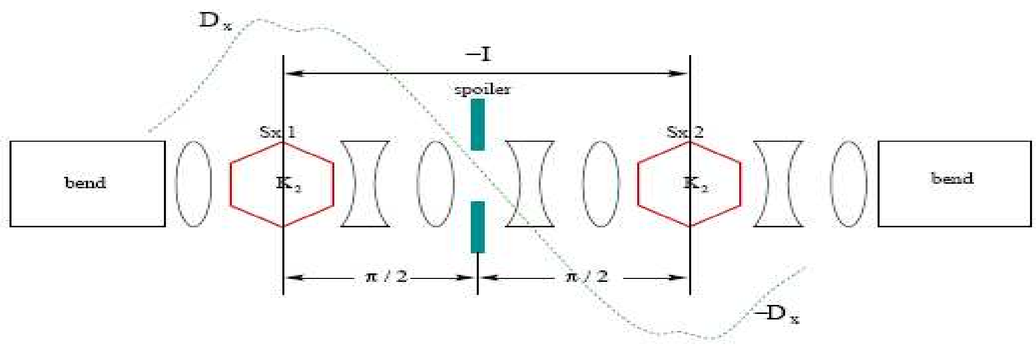
CLIC BDS



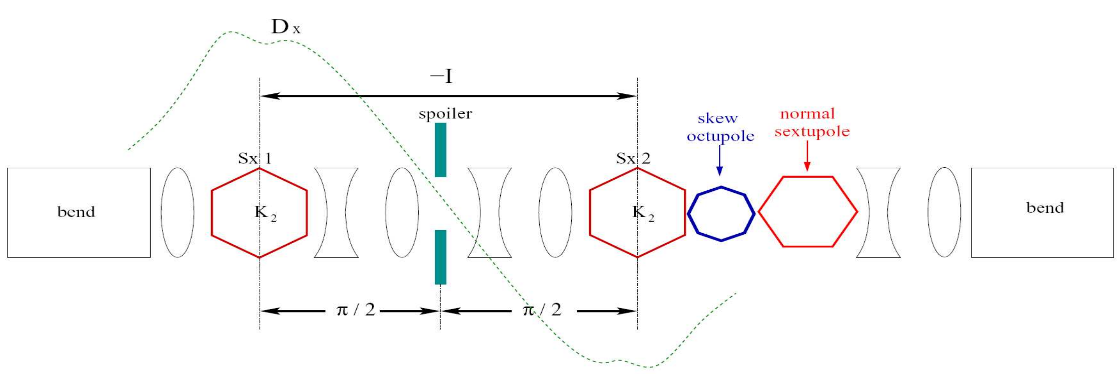
Energy collimation system
β-collimation system
FFS
IP
CLIC BDS (with NONLINEAR E-COLL SECTION)
Unix version 8.51/13
21/06/11 05.16.22
SQRTBX
SQRTBY
D x
SQRTB
D x (m)
s (m)
0.0
100.
200.
300.
400.
500.
600.
500.
1000.
1500.
2000.
2500.
3000.
0.10
0.08
0.06
0.04
0.02
0.0
-0.02
-0.04
-0.06
-0.08
-0.10

Optical optimisation

- No optimisation

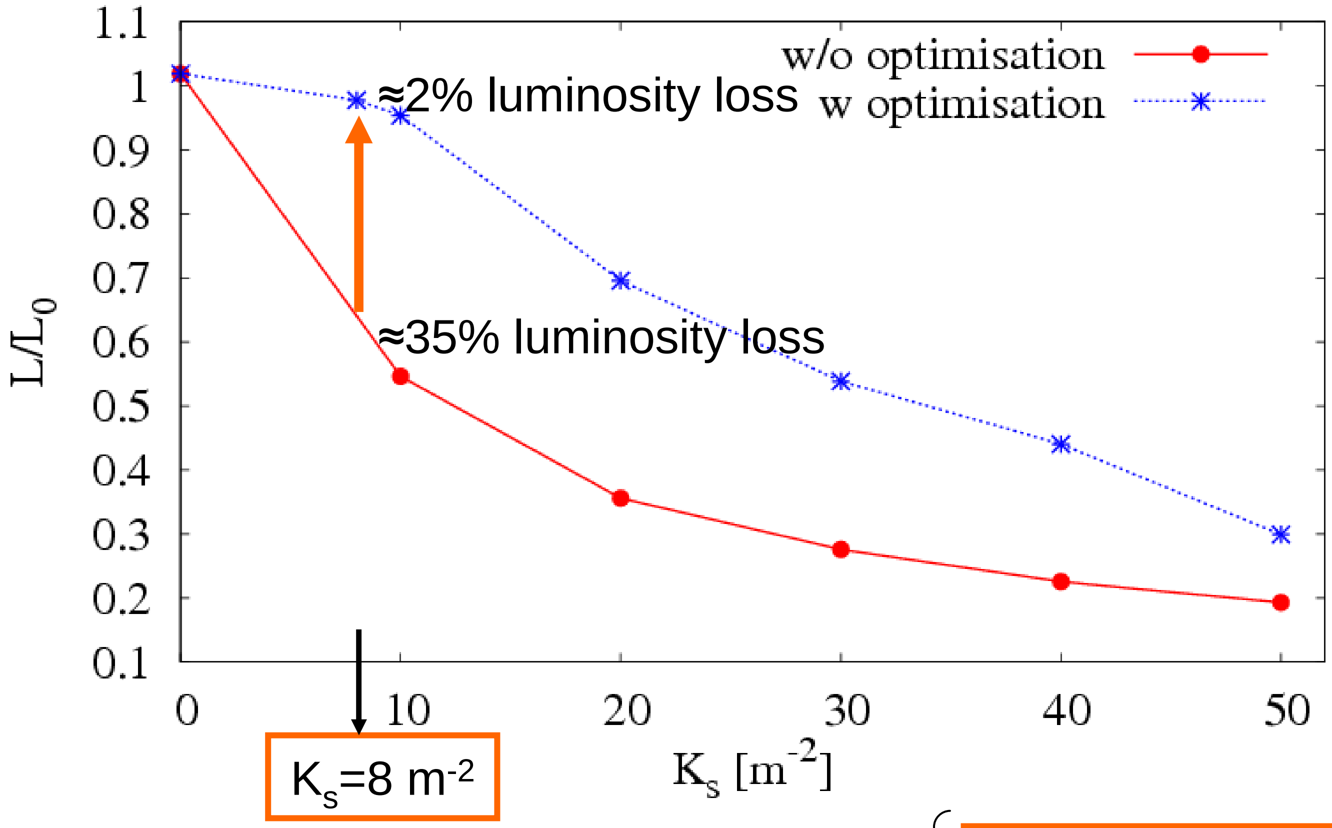


- With optimisation: Cancellation of higher order aberrations adding a skew octupole and a normal sextupole and using the code MAPCLASS



Luminosity performance

Peak Luminosity vs sk sextupole strength:

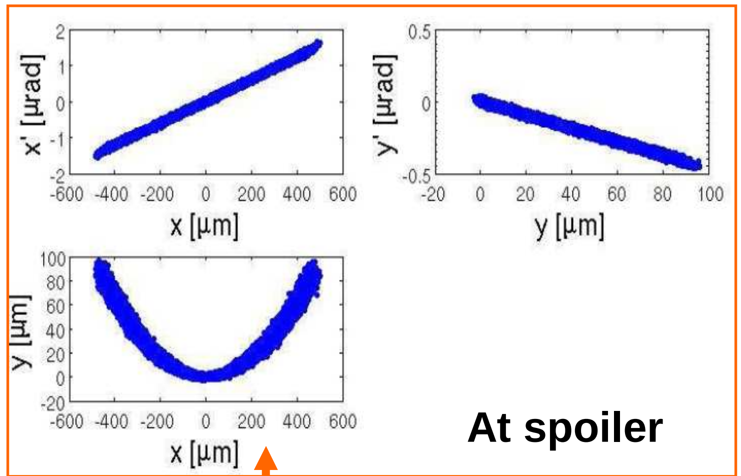


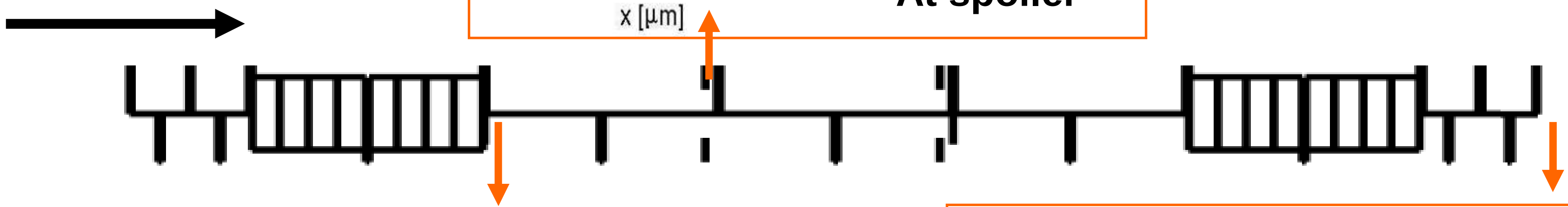
With optimisation (additional nonlinear elements)

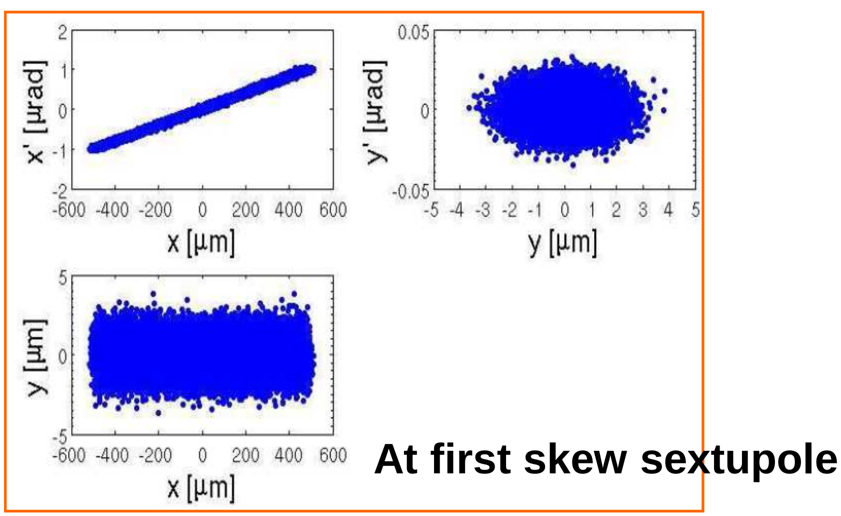
K(skew octupole) = -2400 m^{-3}
K(normal sextup.) = -0.4 m^{-2}

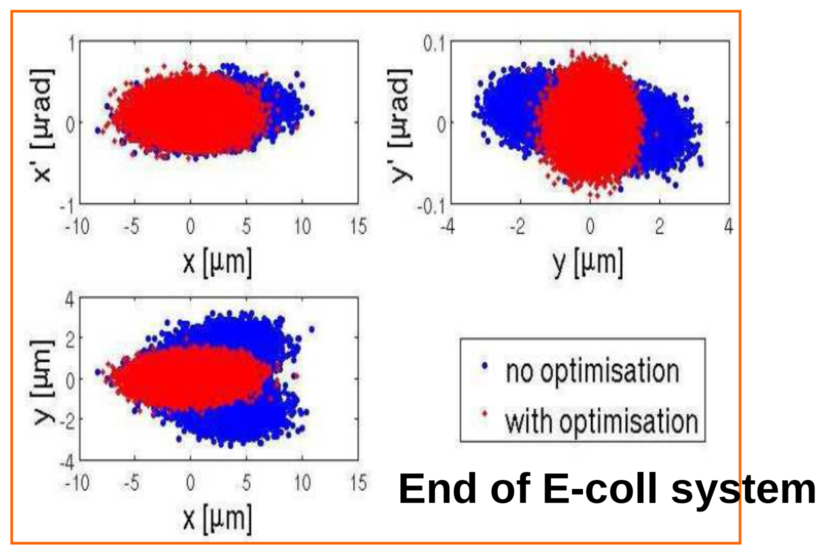
Beamline performance

Tracking of 50000 macroparticles for a beam with zero mean energy offset and with 1% full energy spread

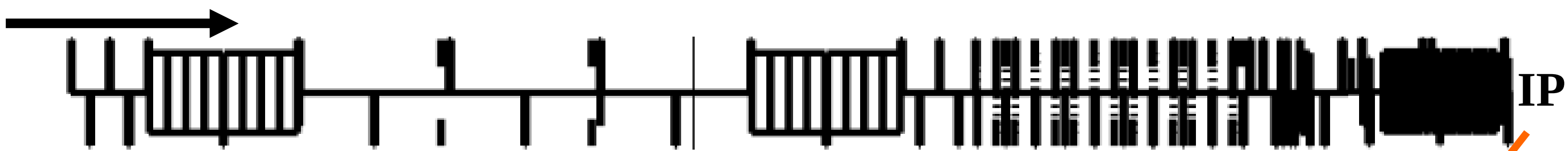




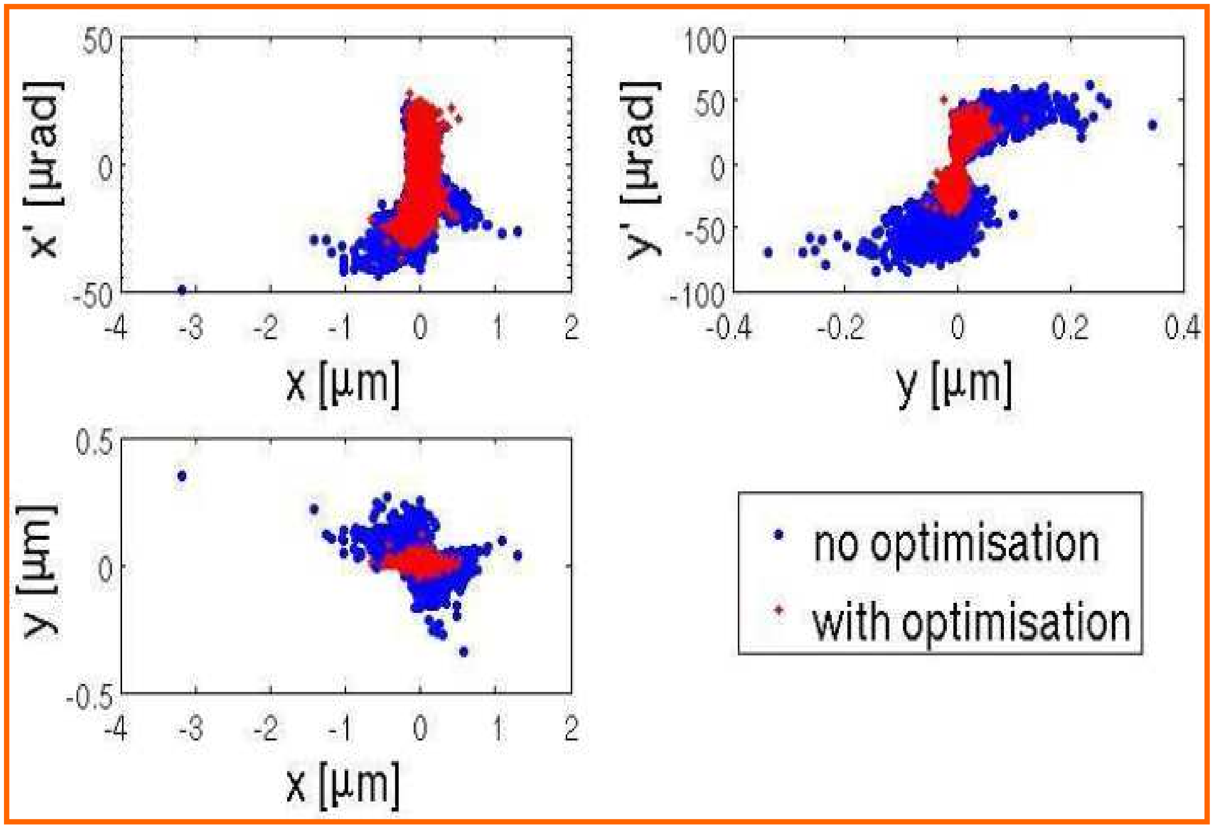




Beamline performance



At IP:

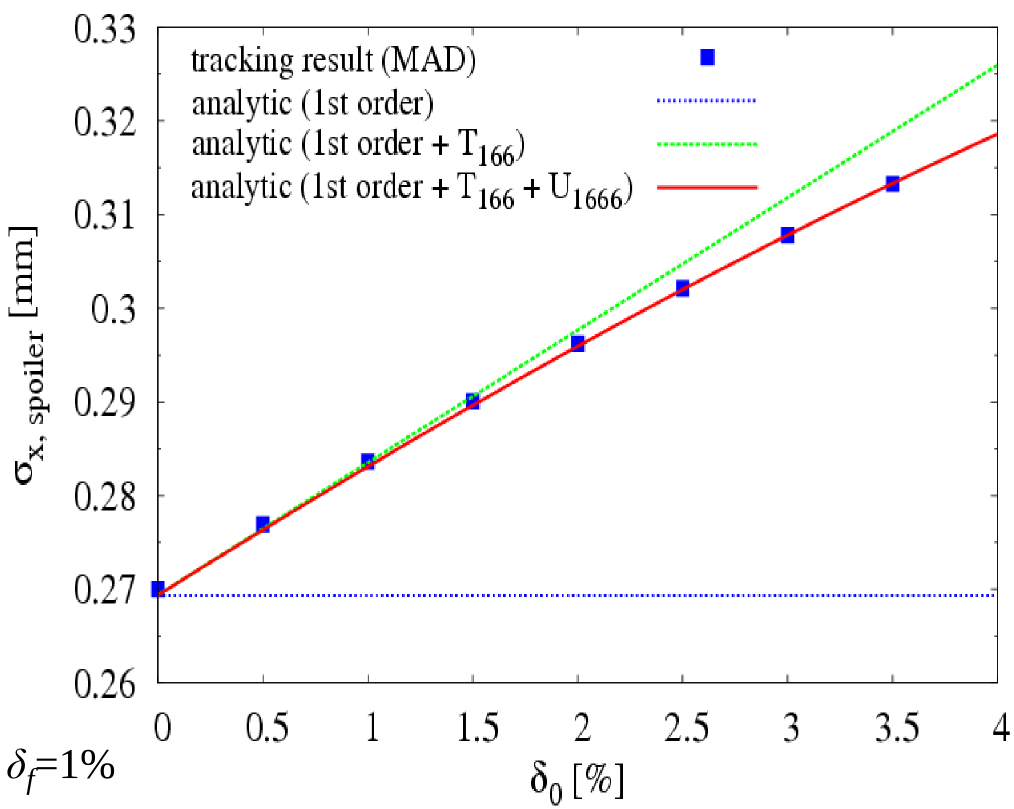


Luminosity=5.86 x 10^{34} cm^{-2} s^{-1}

Horizontal beam size at spoiler position
vs beam energy offset

$$\sigma_{x,sp} \simeq \left[D_{x,sp}^2 \frac{\delta_f^2}{12} + R_{12}^2 K_s^2 D_{x,s}^2 \left(\frac{\delta_f^2}{12} + \delta_0^2 \right) \beta_y \varepsilon_y \right.$$
$$+ 2T_{166} D_{x,sp} \frac{\delta_f^2 \delta_0}{6} + T_{166}^2 \left(\frac{\delta_f^4}{180} + \frac{\delta_f^2 \delta_0^2}{3} \right)$$
$$+ U_{1666}^2 \left(\frac{\delta_f^6}{448} + \frac{\delta_f^4 \delta_0^2}{8} + \frac{3}{4} \delta_f^2 \delta_0^4 \right)$$
$$+ 2D_{x,sp} U_{1666} \left(\frac{\delta_f^4}{80} + \frac{\delta_f^2 \delta_0^2}{4} \right)$$
$$\left. + 2T_{166} U_{1666} \left(\frac{\delta_f^4 \delta_0}{24} + \frac{\delta_f^2 \delta_0^3}{2} \right) \right]^{1/2}$$

For K_s=8 m^{-2}



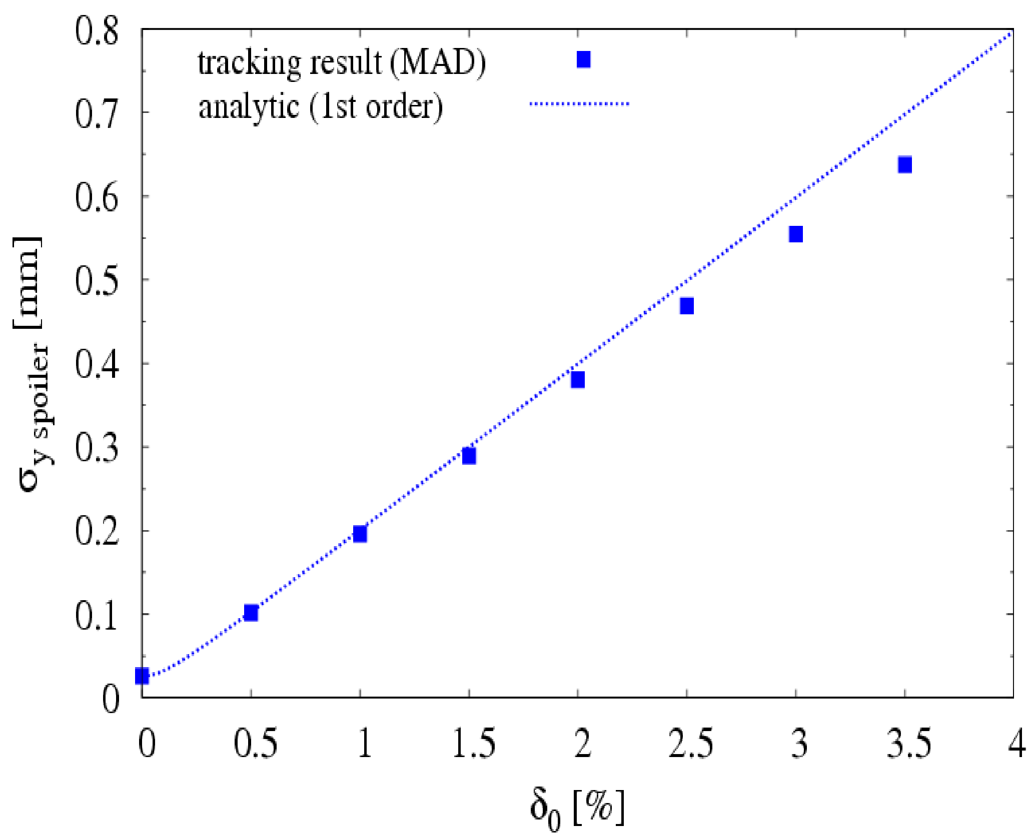
Full energy spread (uniform distribution) δ_f=1%
Mean energy offset δ_0
Second order dispersion T_{166} = 0.245 m
Third order dispersion U_{1666} = -0.45 m

Vertical beam size at spoiler position
vs beam energy offset

$$\sigma_{y,sp} \simeq \left[\frac{1}{4} R_{34}^2 K_s^2 D_{x,s}^4 \left(\frac{\delta_f^4}{180} + \frac{1}{3} \delta_f^2 \delta_0^2 \right) \right]^{1/2}$$

The rms vertical beam size from tracking as a function of the average energy offset (***δ_0***) is in good agreement with the analytical expression considering only 1st order horizontal dispersion

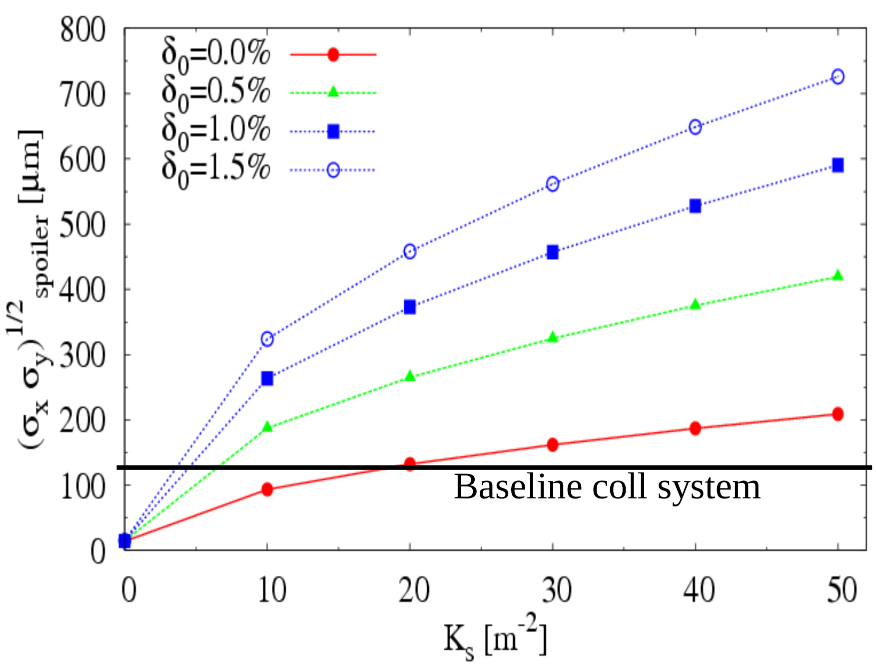
For K_s=8 m^{-2}



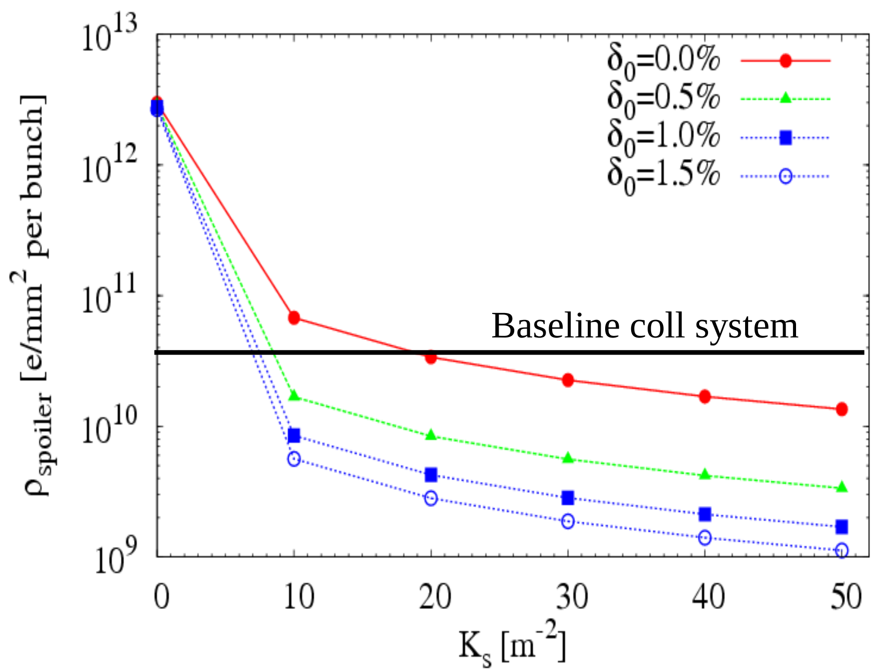
Transverse beam density at spoiler position

vs skew sextupole strength and vs mean energy offset

Spot size at spoiler position:



Transverse beam density at spoiler position:



In the case of 1.5% mean energy offset, the nonlinear collimation system increases 2 times the beam spot size (reduce 4 times the transverse beam peak density) at the energy spoiler with respect to the baseline linear collimation system

Emittance growth due to SR

The emittance growth due to SR emission must be constrained within tolerable levels

For a given lattice the horizontal emittance growth due to incoherent SR can be evaluated using the following expression:

$$\Delta(\gamma\epsilon_x) \simeq (4.13 \times 10^{-8}\ \mathrm{m}^2\mathrm{GeV}^{-6}) E^6 I_5$$

as a function of the beam energy E and the radiation integral I_{5}:

$$I_5 = \int_0^L \frac{\mathcal{H}}{|\rho_x^3|}\, ds = \sum_i L_i \frac{\langle\mathcal{H}\rangle_i}{|\rho_{x,i}^3|} \qquad \mathcal{H} = \frac{D_x^2 + (D'_x\beta_x + D_x\alpha_x)^2}{\beta_x}$$

	CLIC BASELINE COLLIMATION		CLIC NONLINEAR COLLIMATION	
Variable	Coll. system	Total BDS	Coll. system	Total BDS
I_5 [m^{-1}]	1.9×10^{-19}	3.8×10^{-19}	4.7×10^{-20}	2.4×10^{-19}
$\Delta\epsilon_x/\epsilon_x$ [%]	13.5	27.3	3.3	17.1
$\Delta\mathcal{L}/\mathcal{L}$ [%]	6.1	11.4	1.6	7.6

For nonlinear collimation system $\Delta\varepsilon_x/\varepsilon_x$ is ≈4 times lower than for baseline collimation system

Conclusions

- Increase of the transverse beam size at the collimators using nonlinear elements is a potential solution to guarantee the survival of the CLIC E-collimators in case of impact by a full bunch train
- For CLIC an alternative nonlinear E-collimation system based on a pair of skew sextupoles has been designed
- Simulation studies have shown that the beam transverse spot size increases 2 times at the E-spoiler with respect to the baseline linear collimation design for beam mean energy offsets > 1.3%
- Effective cancellation of higher order optical aberrations, improving the luminosity performance of the system
- Luminosity 5.86×10^{34} cm^{-2} s^{-1} (nominal =5.9 – 6 x 10^{34} cm^{-2} s^{-1})
- The simulation performance studies show that the system works and is competitive
- Next step: investigation of a more compact Nonlinear E-collimation lattice

Skew sextupole parameters

Parameter	Value
Sext. Strength K **[m^{-2}]**	8
Product of pole-tip field and length $B_T l_s$ **[T m]**	2
Pole-tip radius a_s **[mm]**	10
Effective length l_s **[cm]**	100
Optical Parameter	
Hor. beta function β_{xs} **[m]**	436.6
Vert. beta function β_{ys} **[m]**	110.2
Hor. Dispersion $\|D_{xs}\|$ **[m]**	0.097

Collimator parameters

Spoiler Parameter	Value
Geometry	Rectangular
Hor. half gap a_x [mm]	1.2
Vert. half gap a_y [mm]	10
Tapered half radius b [mm]	10
Tapered part length L_T [mm]	90
Taper angle θ_T [mrad]	97.5
Flat part length L_F [X_0]	0.05
Material	Be
Optical parameter	
Hor. beta function β_{xsp} [m]	471.8
Ver. beta function β_{ysp} [m]	79.02
1st order hor. dispersion D_{xsp} [m]	0.093
2nd oder hor. dispersion T_{166} [m]	0.245
3rd order hor. dispersion U_{1666} [m]	-0.45
R_{11}(sk1→sp)	0.032
R_{12}(sk1→sp) [m]	453.66
R_{33}(sk1→sp)	0.19
R_{34}(sk1→sp) [m]	90.93

Absorber Parameter	Value
Geometry	Rectangular
Hor. half gap a_x [mm]	1.1
Vert. half gap a_y [mm]	10
Tapered half radius b [mm]	10
Tapered part length L_T [mm]	90
Taper angle θ_T [mrad]	97.5
Flat part length L_F [X_0]	0.05
Material	Ti alloy
Optical parameter	
Hor. beta function β_{xsp} [m]	374.8
Ver. beta function β_{ysp} [m]	129.5
1st order hor. dispersion D_{xsp} [m]	-0.087
2nd oder hor. dispersion T_{166} [m]	0.
3rd order hor. dispersion U_{1666} [m]	--
R_{11}(sk1→sp)	-0.93
R_{12}(sk1→sp) [m]	15.93
R_{33}(sk1→sp)	-1.07
R_{34}(sk1→sp) [m]	16.07