Study of the CLIC Beam Delivery System: Linear versus Nonlinear Collimation

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Introduction

Required collimation depths for CLIC

- Collimation system has to collimate in the two transverse planes (betatron collimation) and clean in momentum (energy collimation)

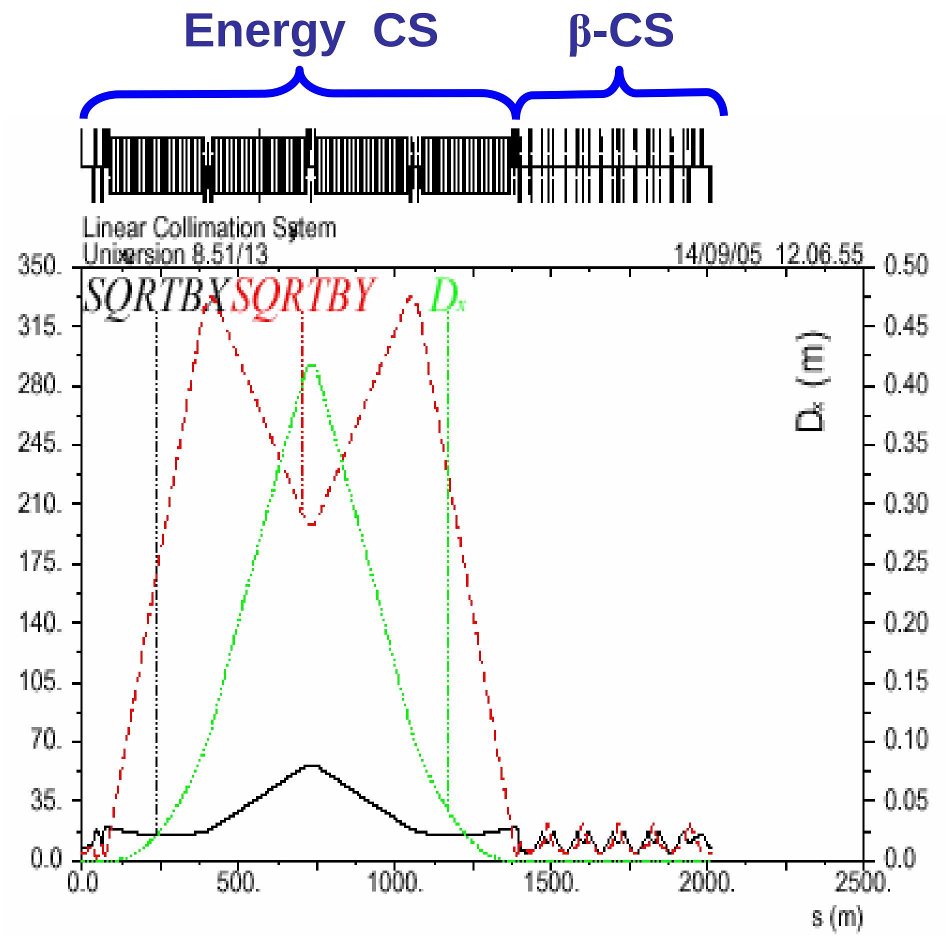
- The collimation depths for betatron collimation determined from the condition that beam particle and SR photons emitted in the final quadrupoles should not hit any magnet apertures on the incoming side of the IP. For CLIC: collimation depths should be less than $\mathbf{14\sigma_x}$ and $\mathbf{83\sigma_y}$

- The energy collimation depth determined by the failure modes in the linac. For CLIC: protection against misteered or errant beam with energy errors $\geq$ 1.5%

Overview of the CLIC baseline linear collimation system

Linear collimation parameters

CM energy	3 TeV	500 GeV
E spoiler gap	± 3.51 mm	± 4.8 mm
β_x spoiler gap	± 80 μm ($10\ \sigma_x$)	± 300 μm ($9\ \sigma_x$)
β_y spoiler gap	± 104 μm ($80\ \sigma_y$)	± 215 μm ($69\ \sigma_y$)
Spoiler material	Be	
Spoiler length	177 mm (0.5 r.l.)	
Absober material	Ti (Cu coated)	
No. E spoilers	1	
No. of $\beta_{x,\,y}$ spoilers	4	



CLIC BDS optics

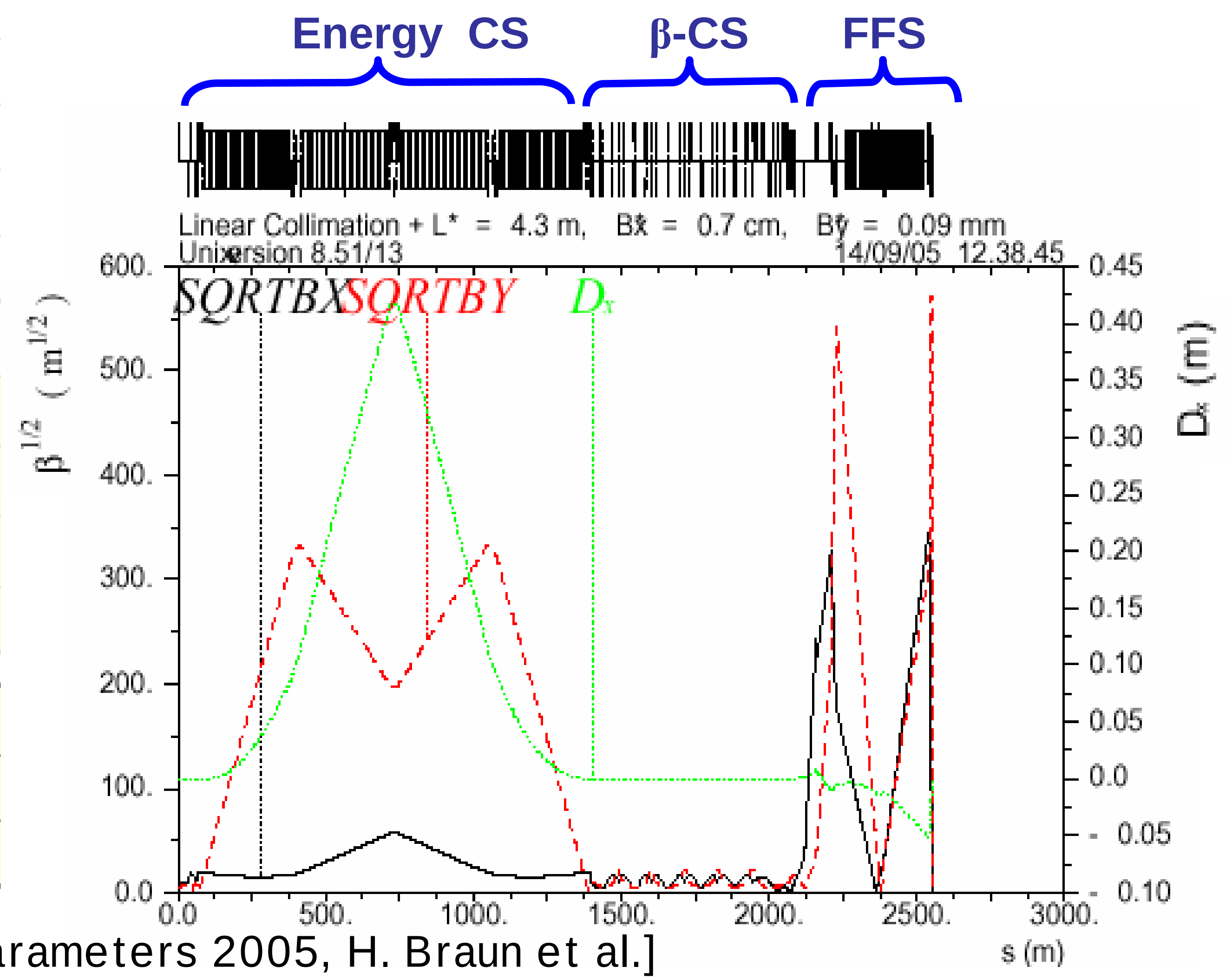
entrance

β_x	64.171 m
α_x	-1.95133
β_y	18.2438 m
α_y	0.605865

IP

β^*_x	7 mm
α^*_x	0.
β^*_y	90 µm
α^*_y	0.

E	1.5 TeV
$\gamma\varepsilon_x$	680 nm
$\gamma\varepsilon_y$	10 nm



[Updated CLIC Parameters 2005, H. Braun et al.]

Limits for collimator protection

For spoiler survival in case of full impact by missteered or errant beams:

Minimum transverse beam size at the spoiler

$$\sigma_{x,\mathrm{sp}}\sigma_{y,\mathrm{sp}} \gtrsim \sigma^2_{r,\min}$$

$$\rho_{E,\max} = \frac{N_\mathrm{e}}{2\pi\sigma^2_{r,\min}}\frac{E_0}{(\mathrm{GeV})}1.6\times 10^{-10}\,\mathrm{J}$$

$$\rho_E(x,y) \lesssim \rho_{E,\max}$$

Maximum transverse energy

From S. Fartoukh et al., CLIC Note 477

Material	$\sigma_{r,\min}$ [μm]	$\rho_{e,\max}$ [$\times 10^9$ p./(mm^2 bunch)]	$\rho_{E,\max}$ [kJ/(mm^2 bunch)]
C (conducting)	58	198.707	47.755
C (no conducting)	32	652.784	156.884
Be	120	46.42	11.156
Ti	100	66.845	16.065
Cu	200	16.711	4.016
W	270	9.169	2.204

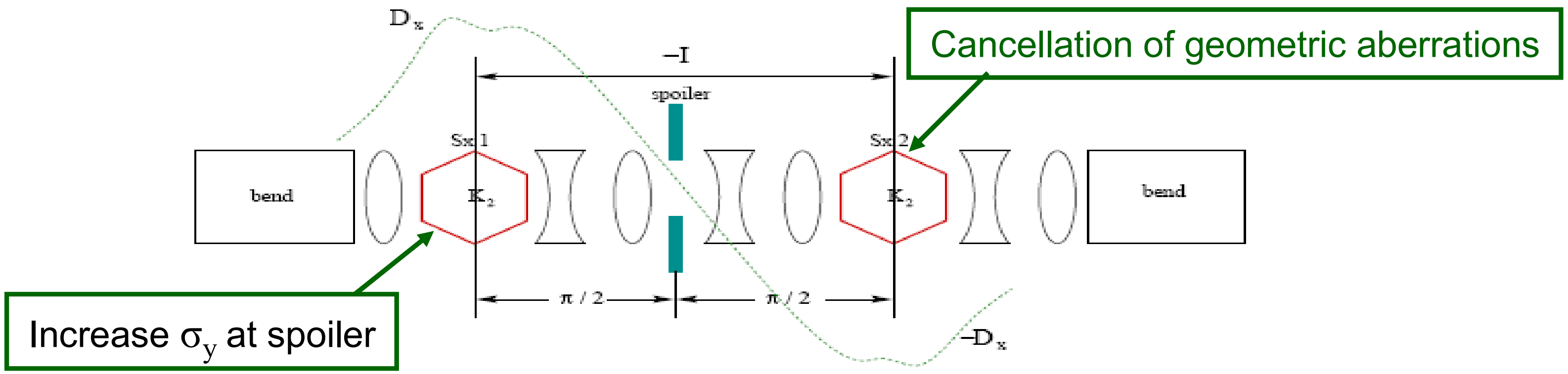
Overview of the nonlinear energy collimation system for CLIC at 1.5 TeV

Basic schematic

- Design of a nonlinear energy collimation system for **CLIC** → protection in case of mis-steered or errant beams with average energy offset ≥ 1.5 % (energy collimation depth)

- Spoiler survival in case of a full beam impact is required. Decrease the transverse beam energy density at the spoiler.

- Schematic based on a pair of skew sextupoles:



- Possibility of higher collimator aperture

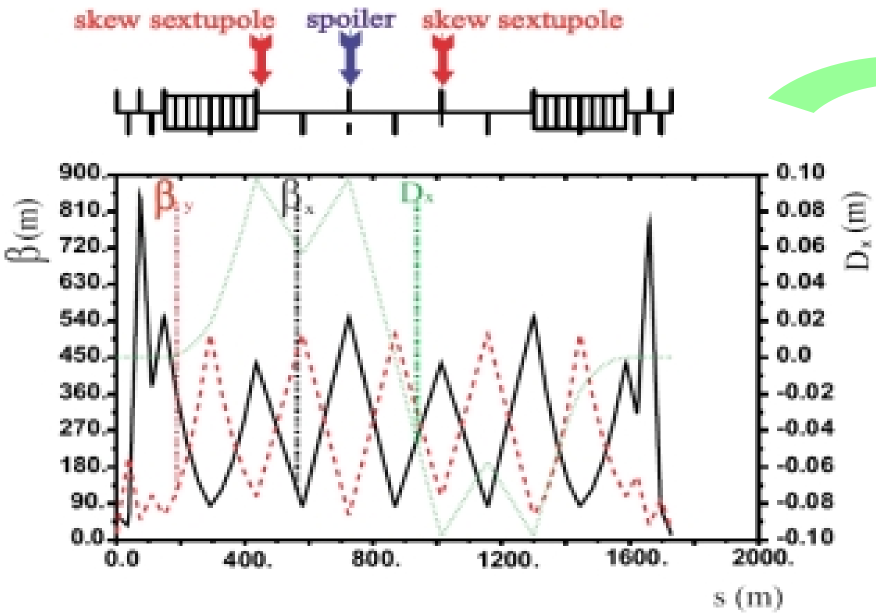
- Decrease the length of the system respect to the baseline linear system without degrading the luminosity ?

Optics layout

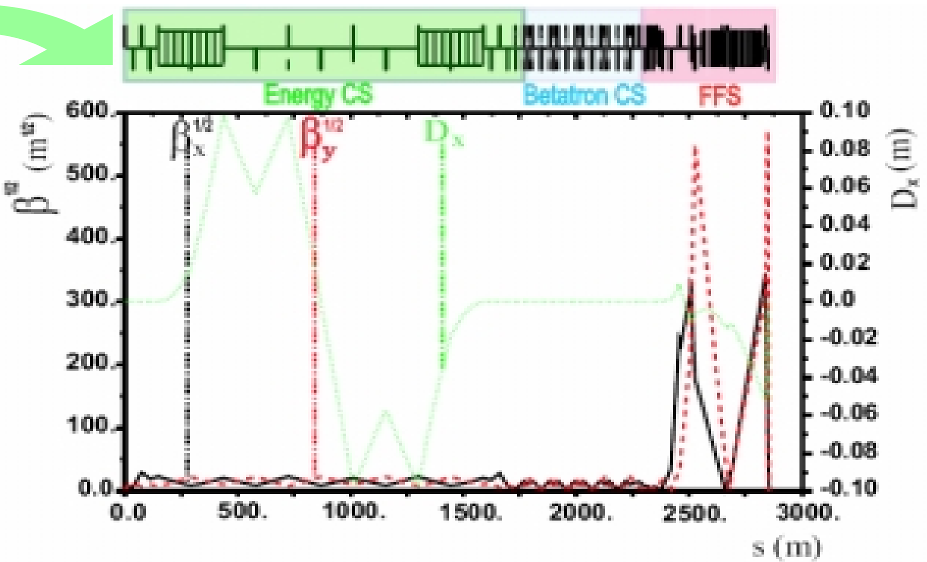
Optics matching by using the code **MAD**

Constraints:

- Transformation matrix –***I*** between the skew sextupoles to cancel geometric aberrations
- Dispersion $D_{x,}$ at the sextupoles with opposite sign and same absolute value in order to cancel first order chromatic aberrations
- The achievable value of the dispersion D_x at the sextupoles is limited by the emittance growth because of synchrotron radiation: $\Delta(\gamma\varepsilon_x) \leq 0.047\ \mu m$ (7% emittance growth)

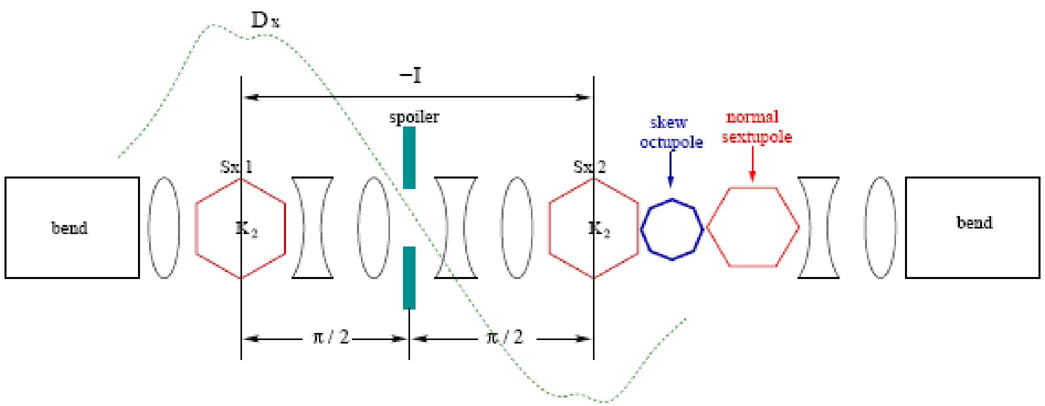


CLIC Beam Delivery System

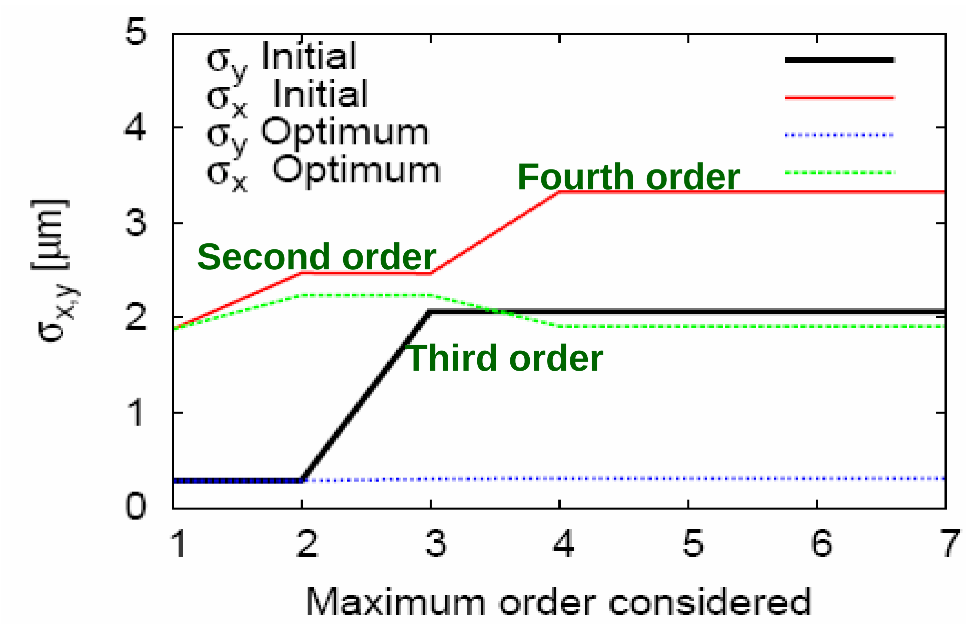


Performance and optics optimisation

Two additional multipoles for local cancellation of the higher order aberrations (dominant chromatic and geometric aberrations of **second**, **third** and **fourth order**)



The minimisation of aberrations computed by using the code **MAPCLASS** (R. Tomás, CERN-AB-Note-2006-017)



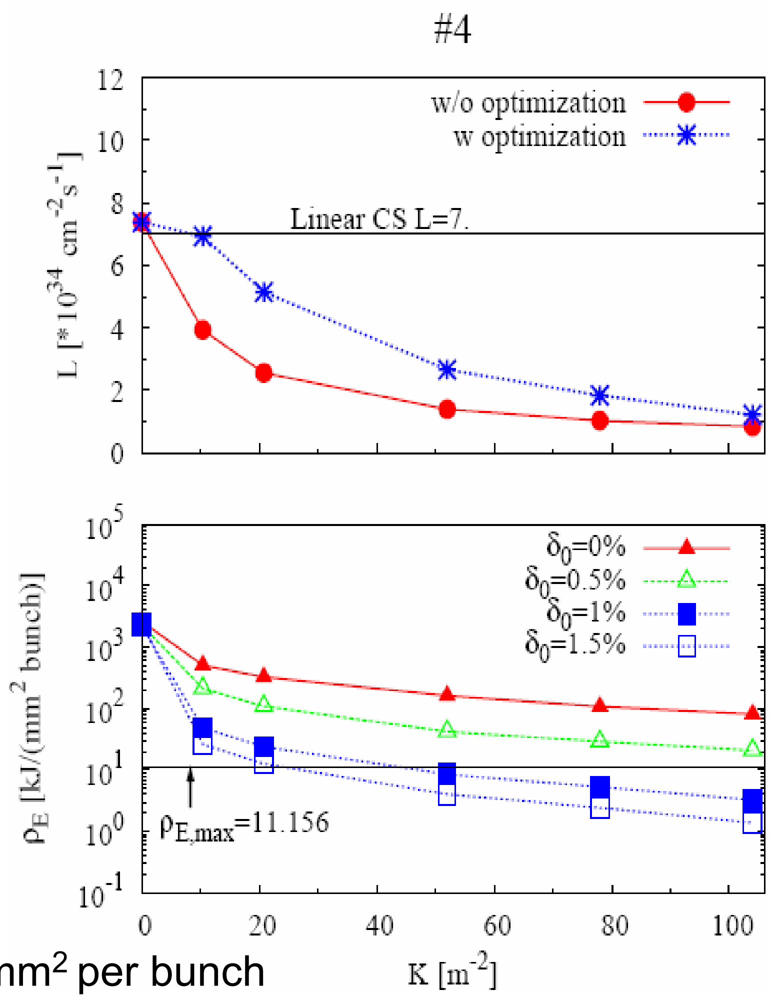
Performance and spoiler protection

- Luminosity and 2-D transverse energy density at the spoiler from multiparticle tracking results using the code **`Placet`**

- The goal is to find the most favourable scenario: trade-off between maximum luminosity and minimum transverse beam energy density at the spoiler

- The luminosity was improved (after optimisation) by more than a factor 2 for an integrated sextupole strength $K_2 = 20\ m^{-2}$

- The spoiler survival is guaranteed for off-momentum beams (> 1.5 %) using an integrated skew sextupole strength $K_2 \approx 20\ m^{-2}$

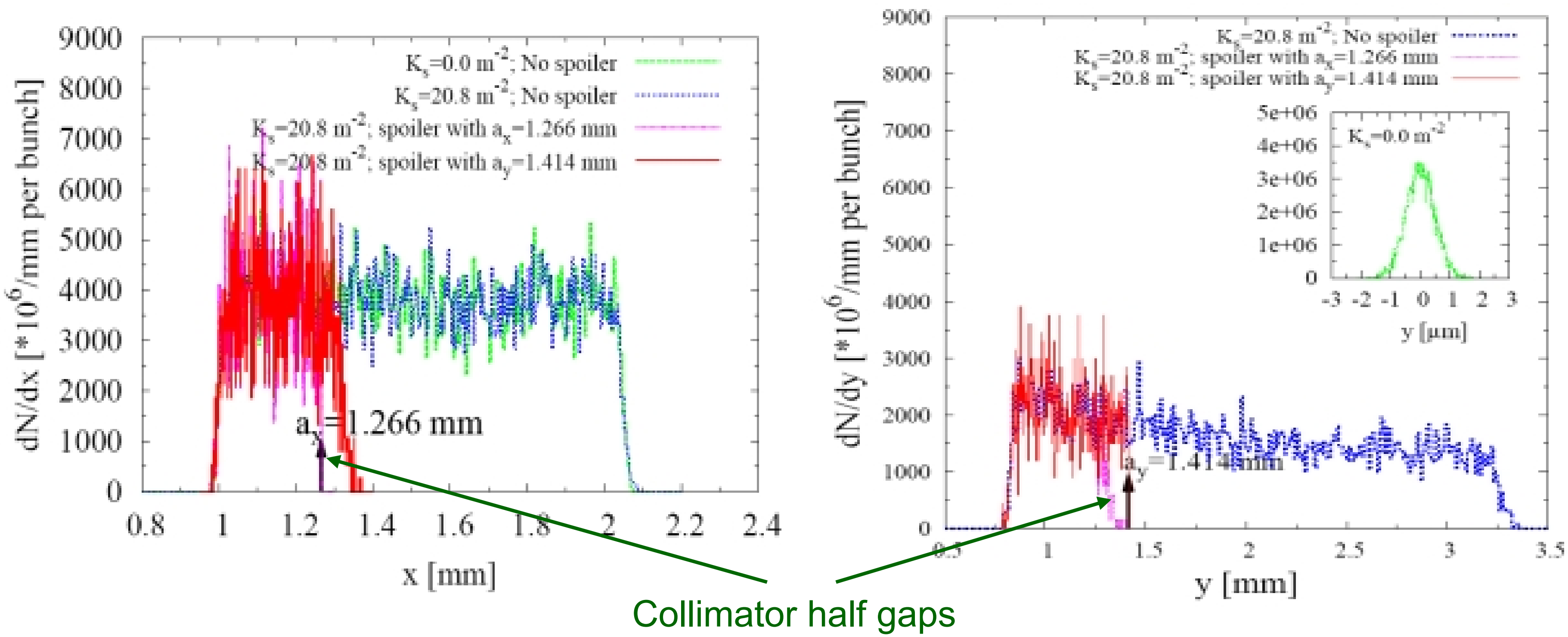


Criteria for spoiler protection: $\rho_E(x,y) \leq \rho_{E,\max}$

considering a **beryllium spoiler**: $\rho_{E,\max}$ = 11.156 kJ/mm^2 per bunch

Transverse beam density at the spoiler

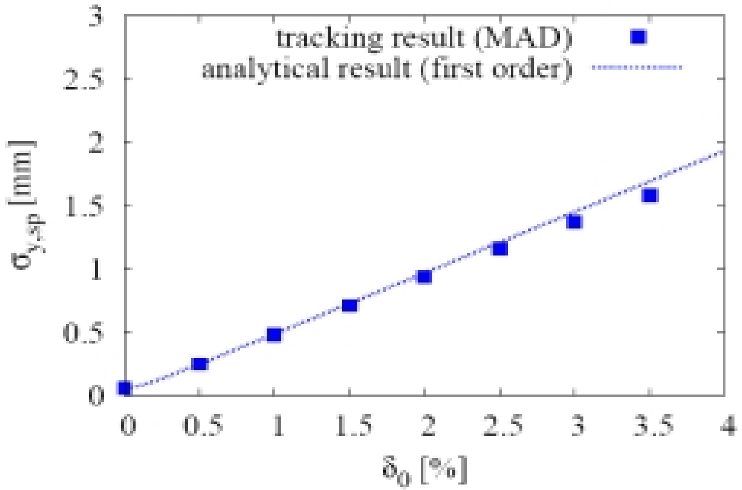
- From initial particle distribution with a full width energy spread of 1% and an average energy offset of 1%
- The particle distribution suffers a strong kick from the sextupole in the vertical plane
- The vertical beam density at the spoiler is approximately reduced by a factor 10^3
- In the horizontal plane the effect of the skew sextupole is very weak (as expected)



Transverse beam size at the spoiler (chromatic properties)

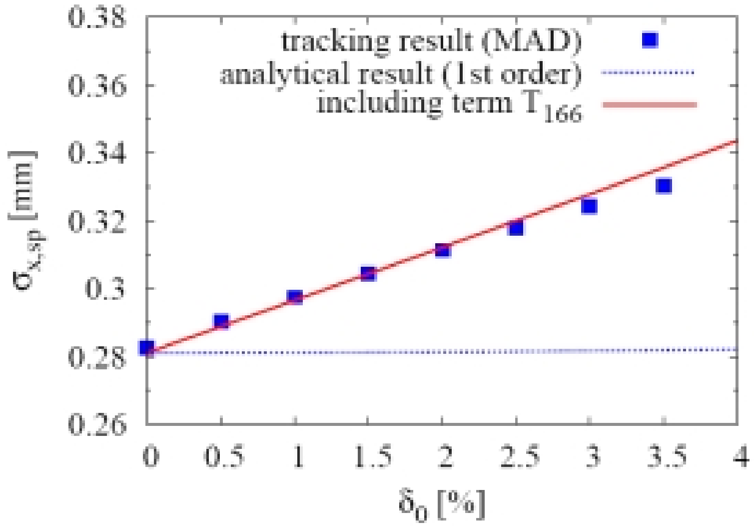
Multiparticle tracking results (code **MAD**) using initial particle distributions with $\delta_{\mathbf{flat}}=1\ \%$ (full width energy spread of an uniform flat momentum distribution) compared with analytical calculations (up to first and second order dispersion)

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



The rms horizontal beam sizes from tracking as a function of the average energy offset (δ_0) is in good agreement with the analytical expression if second order dispersion (T_{166}) is considered

$$\sigma_{x,\mathrm{sp}} \simeq \left(D_{x,\mathrm{sp}}^2\frac{\delta_{\mathrm{flat}}^2}{12} + R_{12}^2K_s^2D_{xs}^2\left(\frac{\delta_{\mathrm{flat}}^2}{12}+\delta_0^2\right)\beta_{y,s}\epsilon_y + T_{166}^2\left(\frac{\delta_{\mathrm{flat}}^4}{180}+\frac{1}{3}\delta_{\mathrm{flat}}^2\delta_0^2\right)+\frac{1}{3}T_{166}D_{x,\mathrm{sp}}\delta_{\mathrm{flat}}^2\delta_0\right)^{1/2}$$

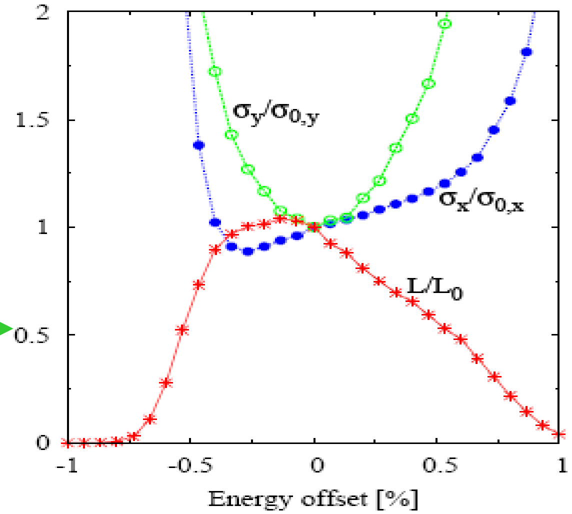


Linear vs. Nonlinear collimation

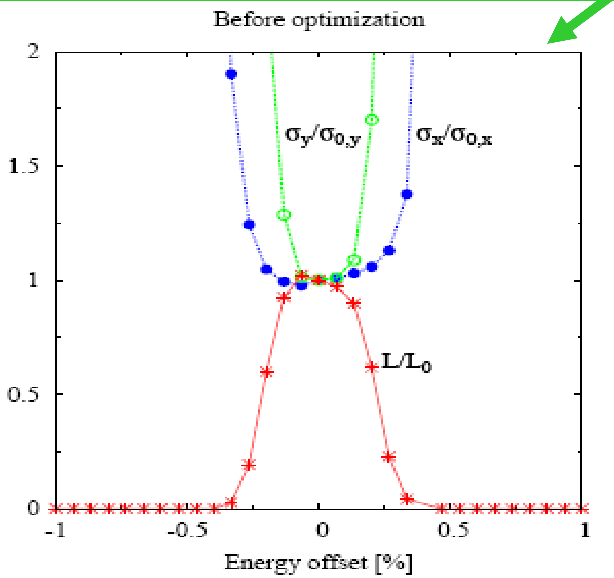
Bandwidth studies

Normalised luminosity and normalised transverse spot sizes at IP from multiparticle tracking using the code **Placet**

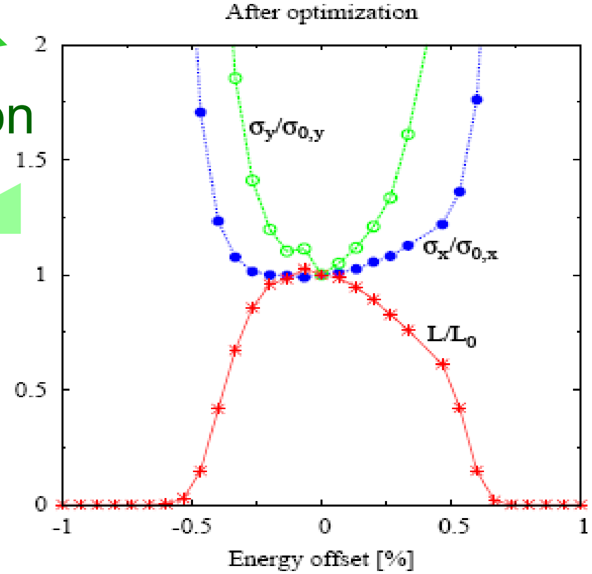
BDS with baseline linear collimation system



BDS with non linear collimation system



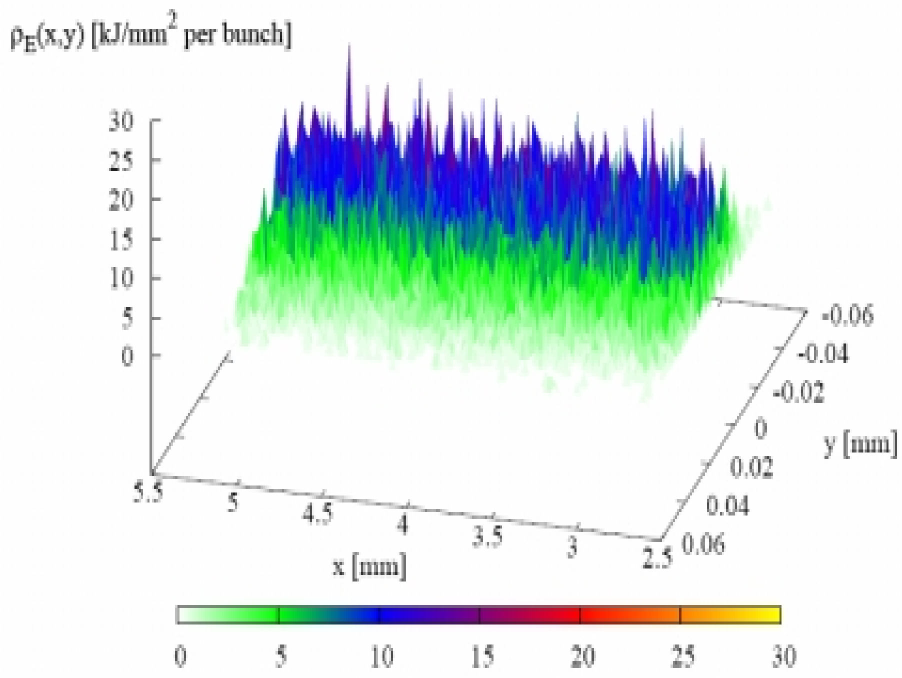
Optimisation



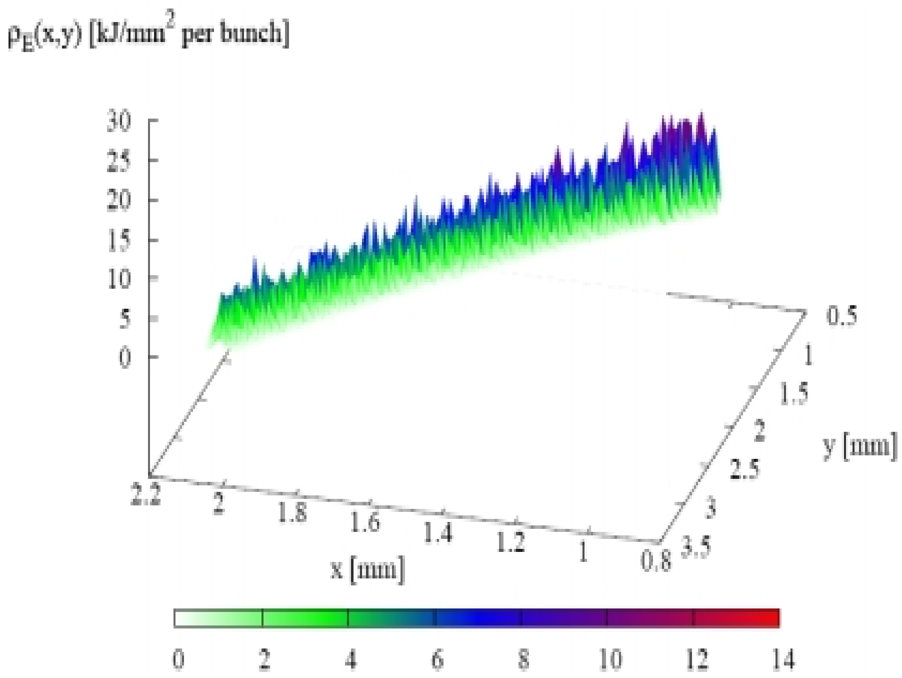
Spoiler protection

Transverse energy density of the beam at the spoiler position for a beam with a full width energy spread of 1% and an average energy offset of 1.5%

Linear collimation



Nonlinear collimation

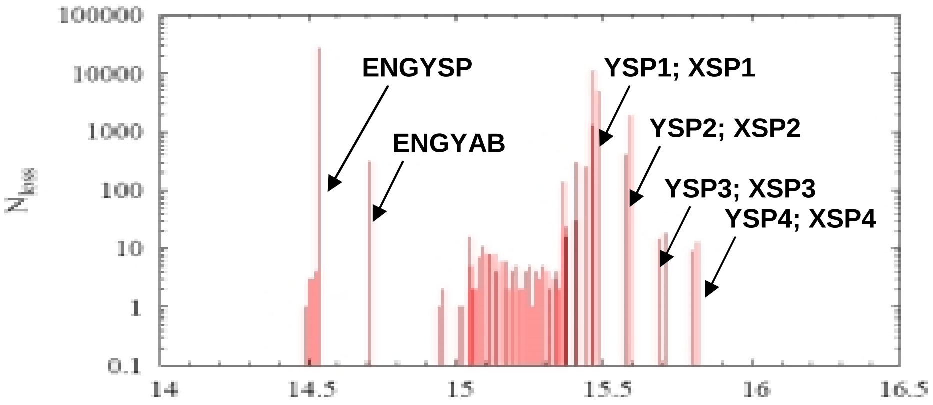


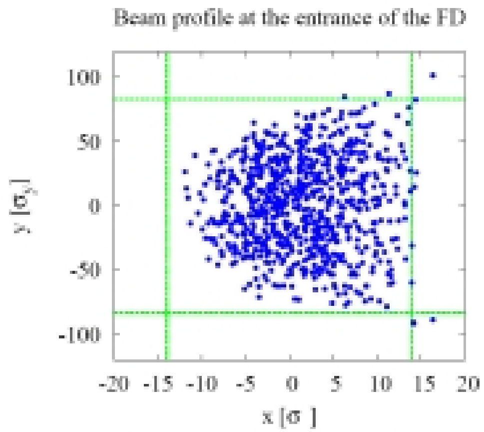
Collimation efficiency

Loss map

Tracking sample by using the code **`Placet`** with an input gaussian halo of 5×10^4 macroparticles: $12.5\sigma_x$, $100\sigma_y$ (a 25% increase over collimation depth: $10\sigma_x$ and $80\sigma_y$) and 4% full width energy spread (energy collimation depth: $\pm$ 1.5%)

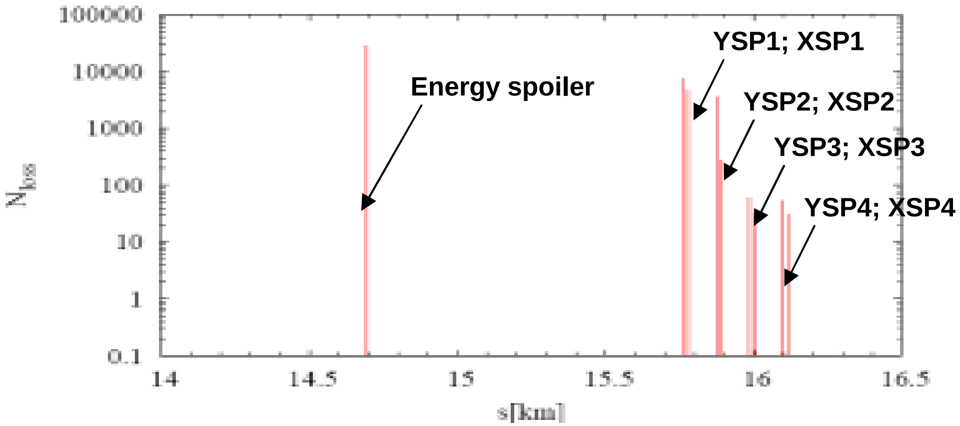
Linear collimation

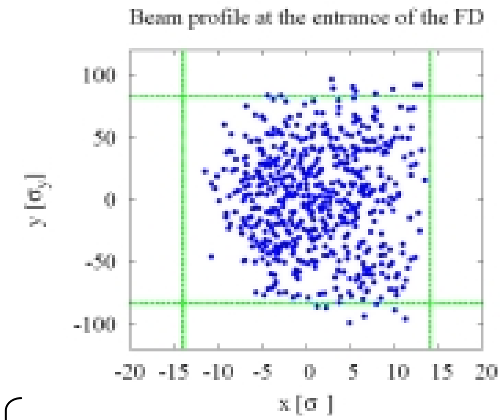




Aperture final doublet: $14\sigma_x$ and $83\sigma_y$

Non-linear collimation





Cleaning efficiency: $\dfrac{\text{\# outside collimation depth at FD}}{\text{\# total initial halo}}$

- Linear collimation system ≈ $5.\times10^{-4}$
- Nonlinear collimation system ≈ 5.5×10^{-4}

First experimental test on nonlinear collimation (08/11/2006)

- In the SPS a prototype of a LHC secondary collimator has been installed in order to perform experimental tests.
- The extraction sextupoles of the SPS, which in normal operation are used for the slow or resonant extraction of the beam, have been used to create nonlinear bumps.
- BLMs were installed around the vacuum chamber in order to measure and record the beam losses of the circulating beam.
- In the region where the nonlinear bumps are created by the sextupoles there are limited apertures, where an increase of beam losses is expected.

Sextupolar bumps

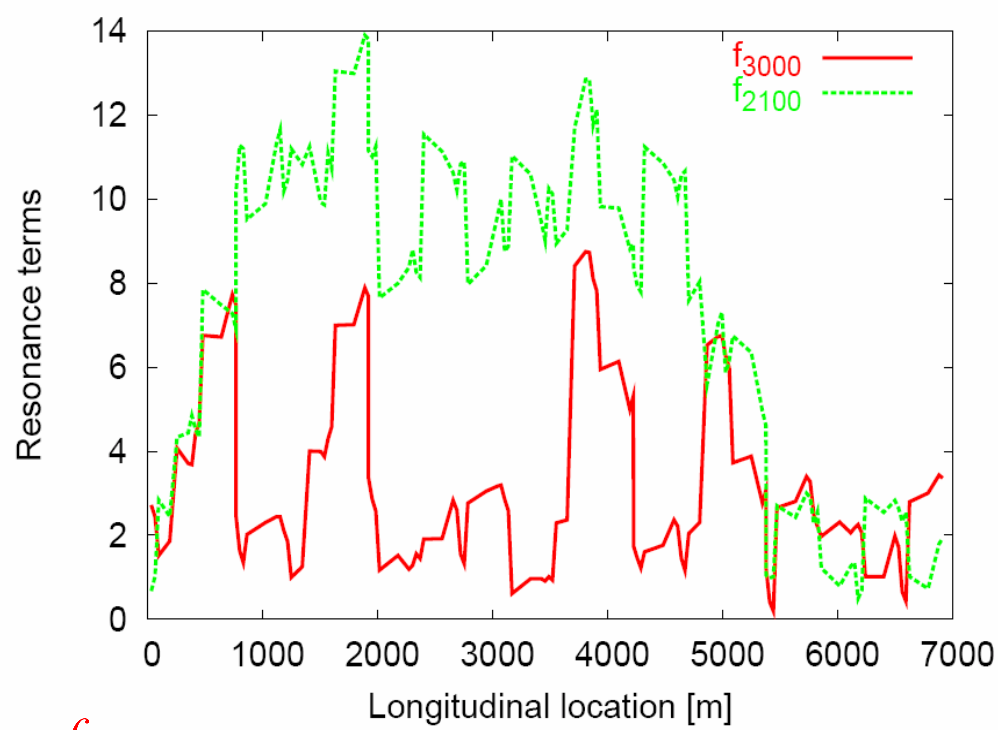
A number of 8 sextupoles connected in order to generate nonlinear bumps

Generating function terms f_{jklm}

Hamiltonian coefficients, contributions from the multipoles of order $n=j+k+l+m$

$$f_{jklm} = \frac{h_{jklm}}{1 - e^{-i2\pi[(j-k)Q_x + (l-m)Q_y]}}$$

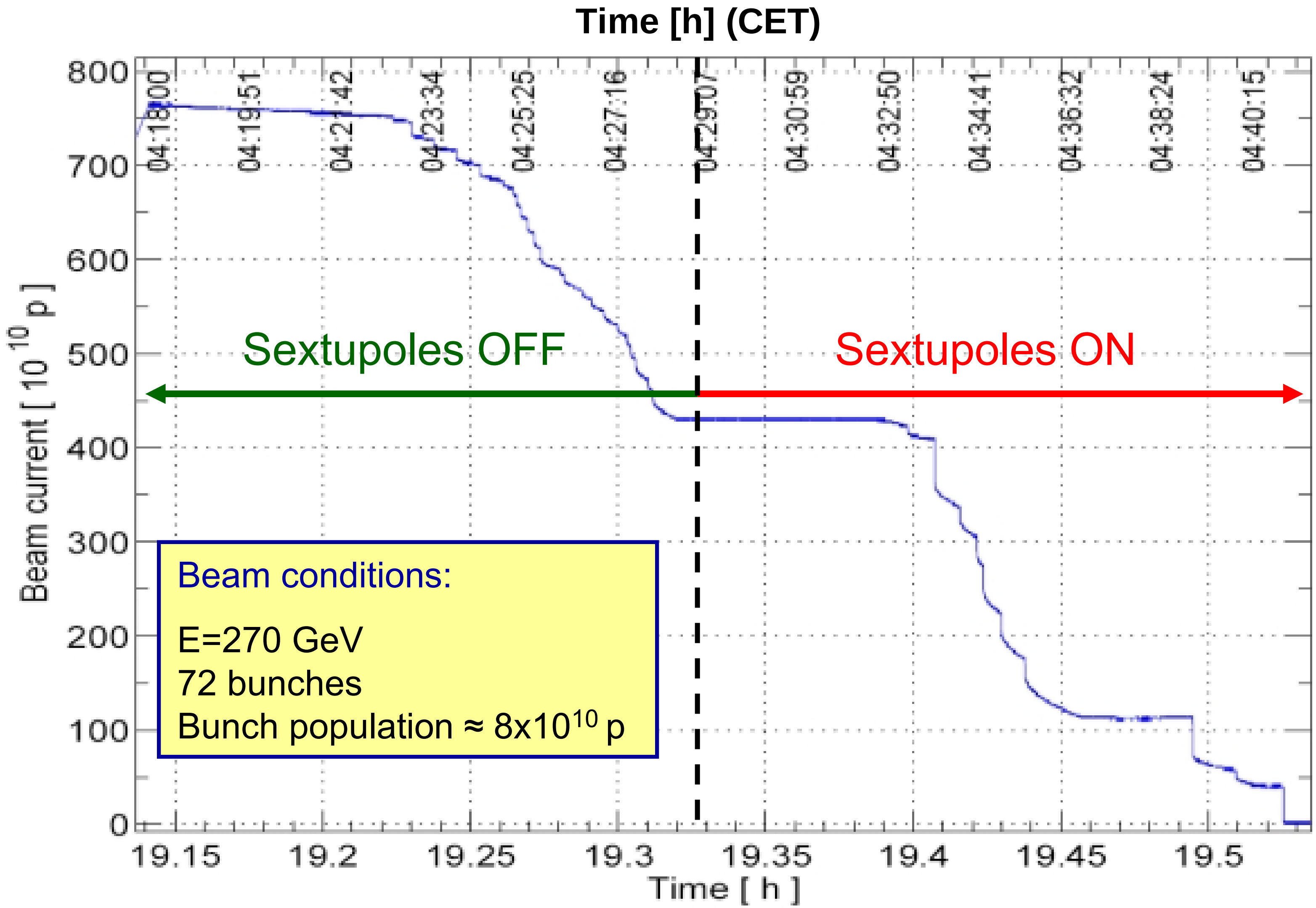
Tune



Normal sextupole contributions: f_{2100}, f_{3000}

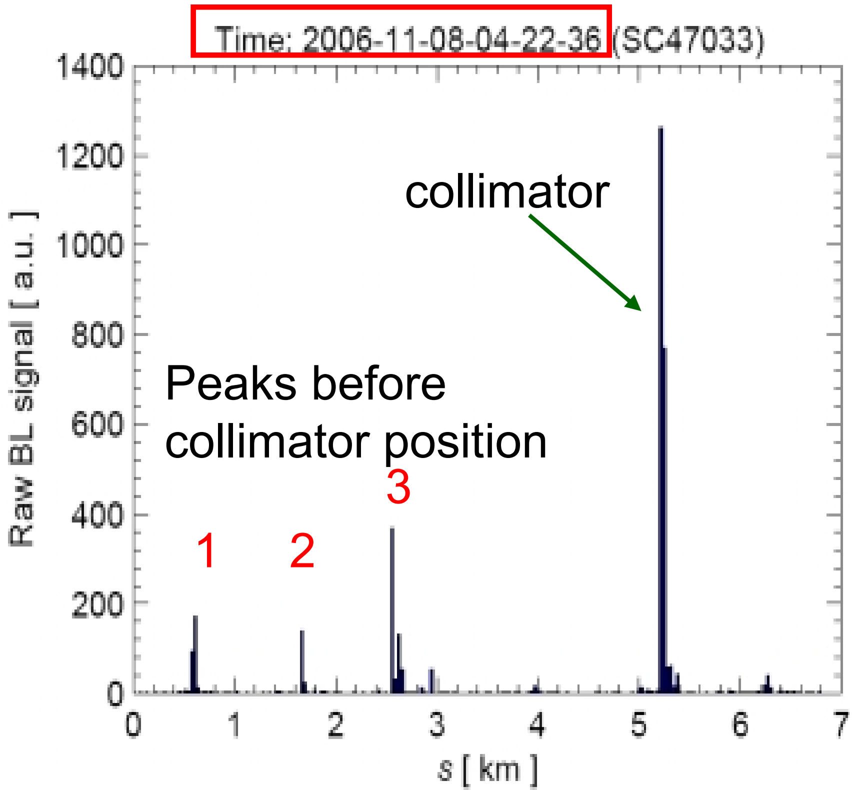
[R. Tomás]

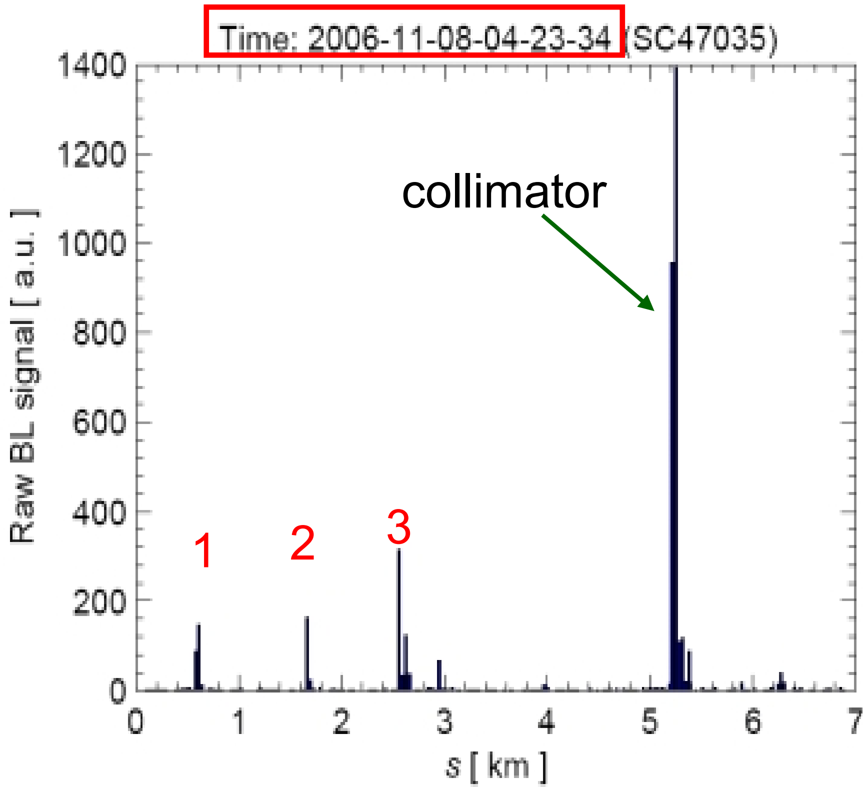
Beam intensity during the test



Preliminary results !

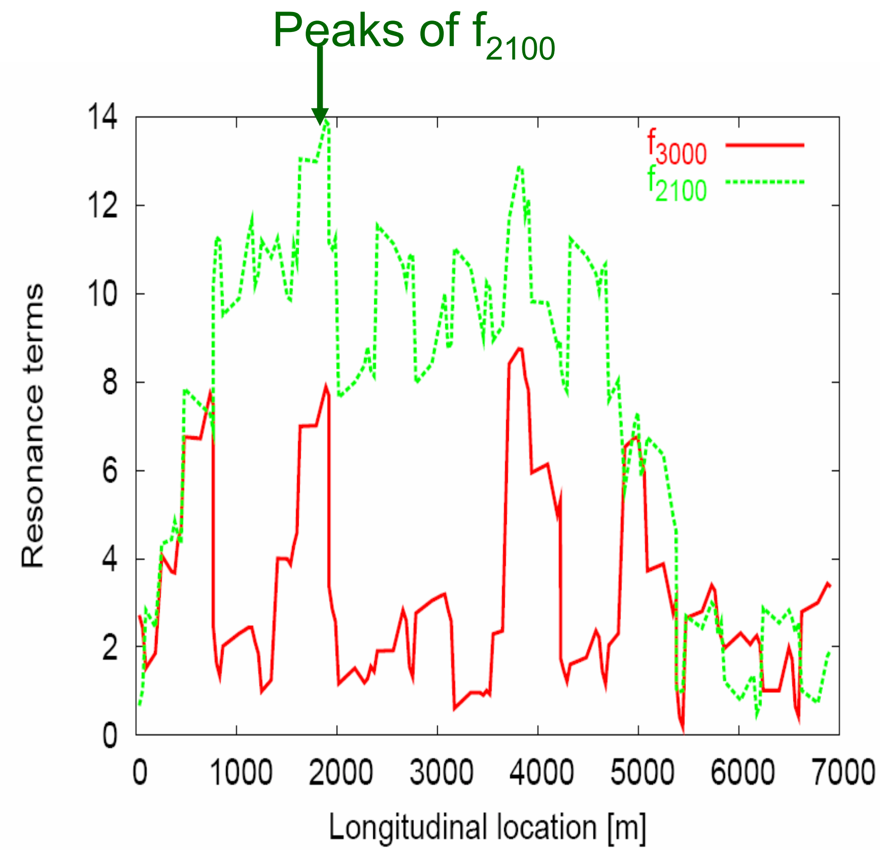
Pattern of integrated beam loss maps with sextupoles OFF

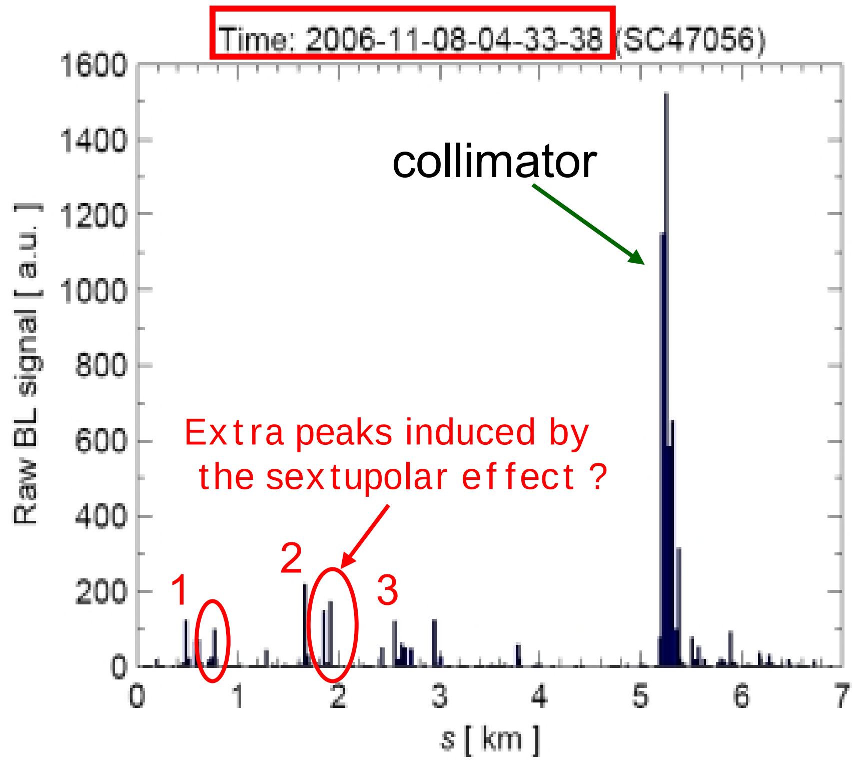




Preliminary results!

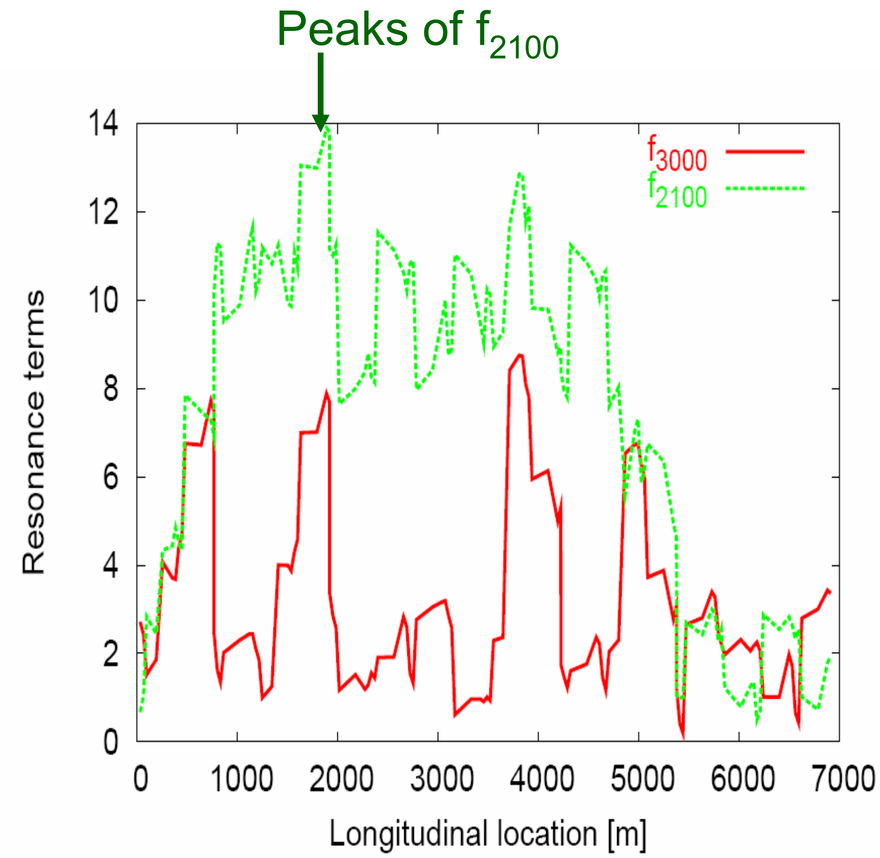
Sample of integrated beam loss map with sextupoles ON

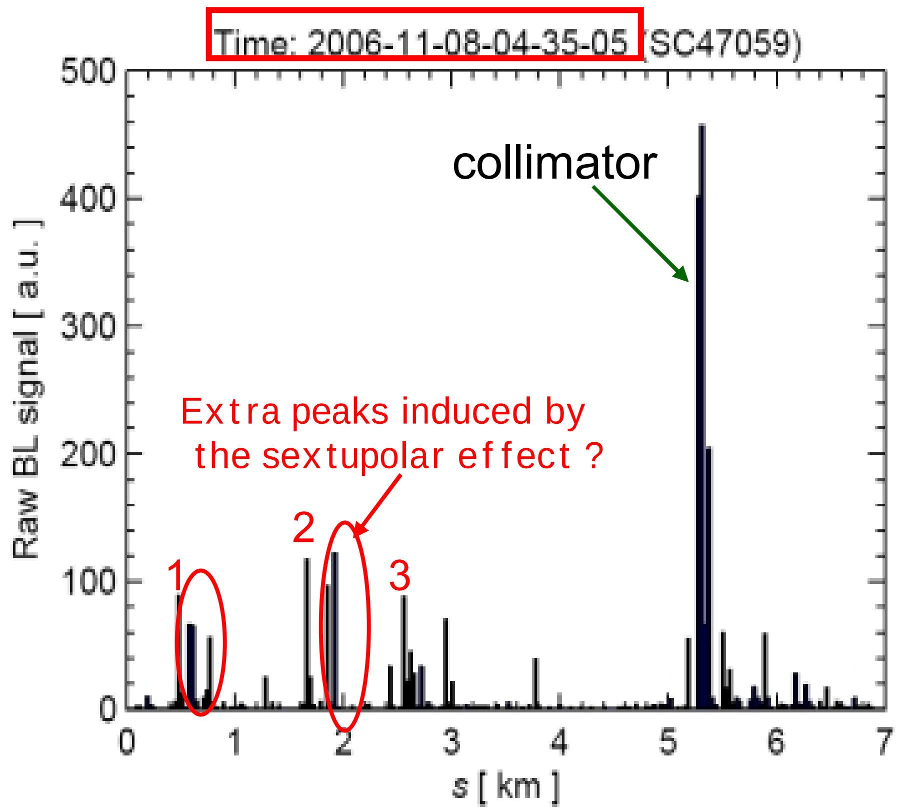




Preliminary results!

Another sample of integrated beam loss map with sextupoles ON





Outlook and Conclusions (I)

- A nonlinear collimation system for CLIC based on skew sextupoles has been explored. This system fulfils the following functions:
  - Cleaning of halo particles with energy offset ≥ 1.5 %
  - Postlinac protection system: interception of mis-steered or errant beams
- The transverse energy density is reduced at the spoiler, increasing thereby the spoiler survival probability in case of full beam impact
- The luminosity is degraded due to the sextupole excitation. However with a fine local high order aberration correction (2nd, 3rd and 4th order) the luminosity increased by a factor 2
- Similar halo cleaning efficiency (~ 10^{-4}) as the baseline conventional linear collimation system
- Similar length as the baseline conventional collimation system

Outlook and Conclusions (II)

- What can we learn from the first nonlinear collimation experiment in the SPS?
  - Different patterns of beam losses with sextupoles ON and with sextupoles OFF
  - Sextupoles ON: increase of the beam losses at the nonlinear bumps positions
  - Ideas for performing more sophisticate tests in the future
- Still a big amount of data should be analysed and compared with simulations !

Appendix A
(CLIC baseline linear collimation system)
CLIC Collimation database

s[m]	Name	β_x[m]	β_y[m]	D_x[m]	a_x[mm]	a_y[mm]	Geometry	Material
566.502	ENGYSP	1406.33	70681.9	0.27	3.51	25.4	rect	Be
731.502	ENGYAB	3213.03	39271.5	0.417	5.4	25.4	rect	Ti(Cu coated)
1490.28	YSP1	114.054	483.253	0.	10.	0.102	rect	Be
1506.1	XSP1	270.003	101.347	0.	0.08	10.	rect	Be
1583.3	XAB1	270.102	80.9043	0.	1.	1.	ellip	Ti(Cu coated)
1601.12	YAB1	114.054	483.184	0.	1.	1.	ellip	Ti(Cu coated)
1603.12	YSP2	114.054	483.188	0.	10.	0.102	rect	Be
1618.94	XSP2	270.002	101.361	0.	0.08	10.	rect	Be
1696.14	XAB2	270.105	80.9448	0.	1.	1.	ellip	Ti(Cu coated)
1713.96	YAB2	114.055	483.257	0.	1.	1.	ellip	Ti(Cu coated)
1715.96	YSP3	114.054	483.253	0.	10.	0.102	rect	Be
1731.78	XSP3	270.003	101.347	0.	0.08	10.	rect	Be
1808.98	XAB3	270.102	80.9043	0.	1.	1.	ellip	Ti(Cu coated)
1826.8	YAB3	114.054	483.184	0.	1.	1.	ellip	Ti(Cu coated)
1828.8	YSP4	114.054	483.188	0.	10.	0.102	rect	Be
1844.63	XSP4	270.002	101.361	0.	0.08	10.	rect	Be
1921.83	XAB4	270.105	80.9448	0.	1.	1.	ellip	Ti(Cu coated)
1939.65	YAB4	114.055	483.257	0.	1.	1.	ellip	Ti(Cu coated)

Appendix B

(Nonlinear energy collimation system for CLIC at 1.5 TeV)

Beam, optics and collimation parameters

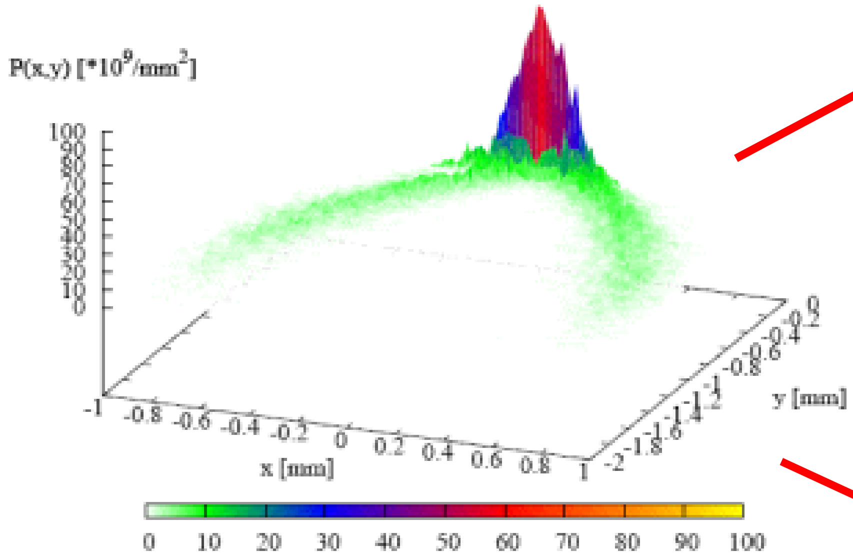
variable	symbol	value	
Beam energy	E	1500	GeV
Energy spread full width (*uniform distribution*)	δ_{flat}	0.01	
rms momentum spread	$\sigma_{\Delta E}$	2.8×10^{-3}	
Hor. normalized emittance	$\gamma\epsilon_x$	680	nm
Ver. normalized emittance	$\gamma\epsilon_y$	10	nm
Total length	l_t	1730.763	m
Dipole angle	θ_b	2.5×10^{-4}	rad
Skew sextupole strength	K_s	20.8	m^{-2}
Hor. beta function at entrance	β_x^0	65.0	m
Ver. beta function at entrance	β_y^0	18.0	m
Hor. phase advance from sext. to spo.	μ_x	0.25	2π
Ver. phase advance from sext. to spo.	μ_y	0.25	2π
Transport matrix from sext. to spo.	R_{12}	490.032	m
Transport matrix from sext. to spo.	R_{34}	84.628	m
Hor. dispersion function at sext.	$D_{x,s}$	0.097	m
Ver. dispersion function at spo.	$D_{x,sp}$	0.097	m
SR integral	I_5	4.71×10^{-20}	m^{-1}
Energy collimation depth	Δ	0.013	
Hor. spoiler half gap	a_x	1.266 (112.552)	mm ($\sigma_{\beta,x}$)
Ver. spoiler half gap	a_y	1.414 (3008.681)	mm ($\sigma_{\beta,y}$)
Transverse energy beam density limit (*spoiler survival*)	$\rho_{E,max}$	11.156	kJ mm^{-2} per bunch

Appendix C

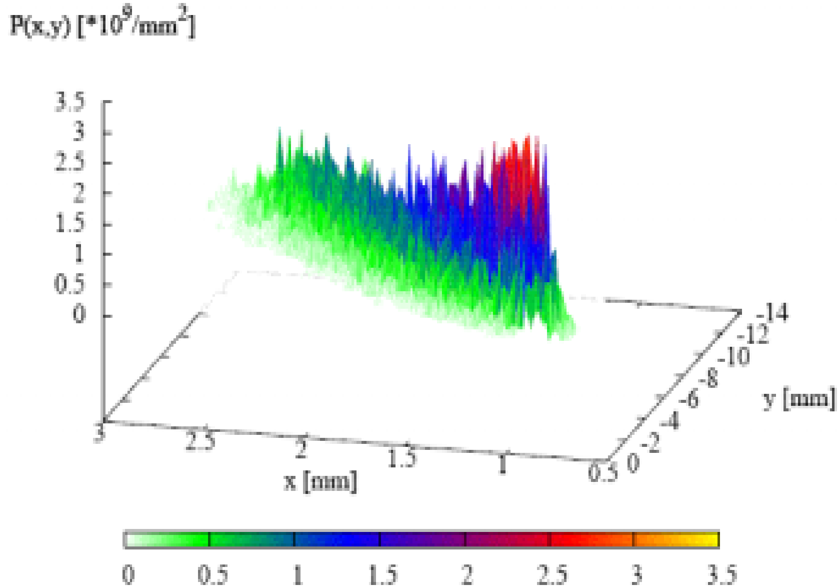
(Nonlinear energy collimation system for CLIC at 1.5 TeV)

Spoiler survival:

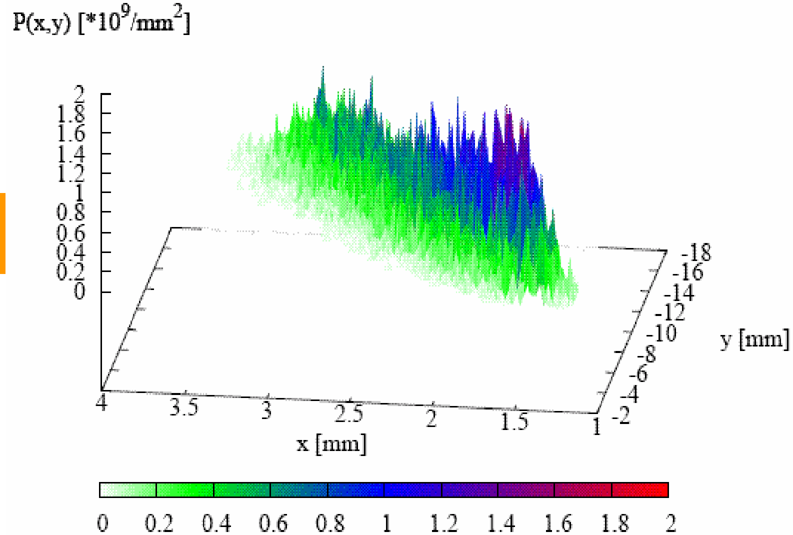
Average energy offset $\delta_0 = 0.0$



$\delta_0 = 0.01$



$\delta_0 = 0.013$



Machine protection: the sextupole blows the beam size up and reduces the beam charge density at the spoiler, increasing the probability for spoiler survival in case of beam impact