The Post-linac Collimation System of CLIC: Machine Protection Aspects

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Introduction

- The main functions of collimation systems for high energy colliders:

    – Reducing detector background at the interaction point
    – Protecting the machine by minimising the activation and damage of sensitive components

- In the BDS of the future linear colliders (ILC and CLIC) there are two collimation sections:

    – Betatron collimation: transverse halo cleaning
    – E collimation: collimation of particles with high energy deviation

- In this presentation we focus on the machine protection function of the CLIC collimation system

Introduction

- Machine protection in BDS usually relies on:

  – Emergency extraction kickers and dumps (fast abort systems)
  – BPMs and BLMs for abnormal operation detection, and interlock systems
  – **Passive protection: collimation system**, masks

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

- Energy collimation depth determined by **failure modes in the linac**

- The conventional collimation systems are based on mechanical collimation using spoilers (scrapers) and absorbers. It could include several stages
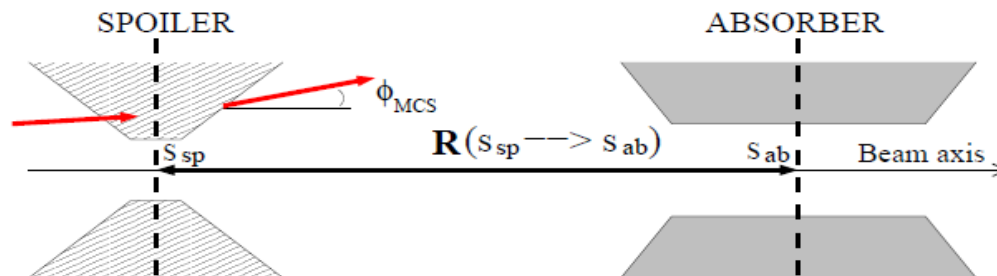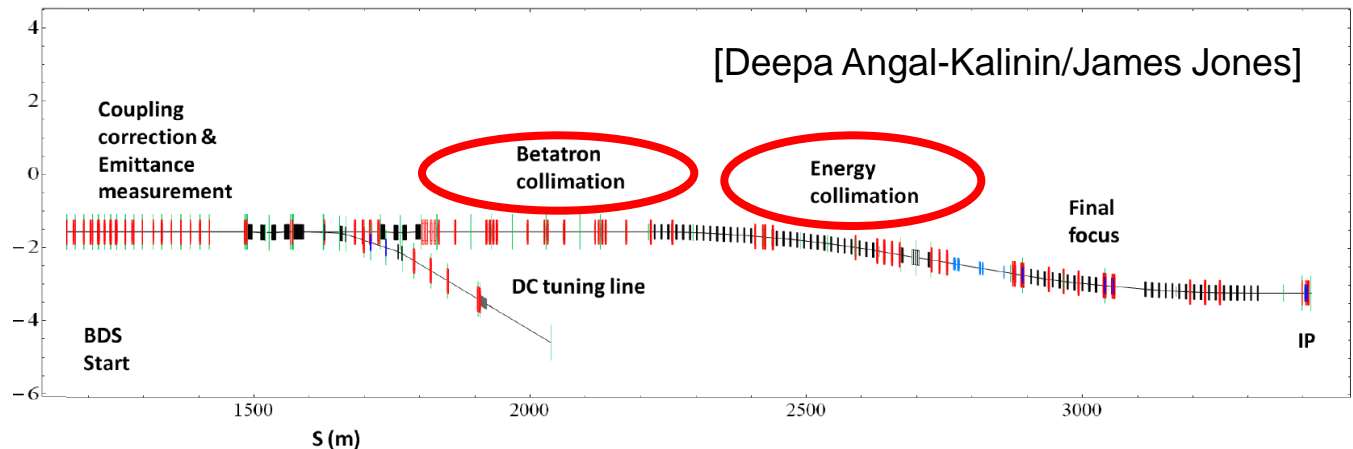
Beam delivery system
## CLIC BDS vs ILC BDS

**CLIC BDS
3 TeV CM**

**ILC BDS
0.5 TeV CM**

[Deepa Angal-Kalinin/James Jones]
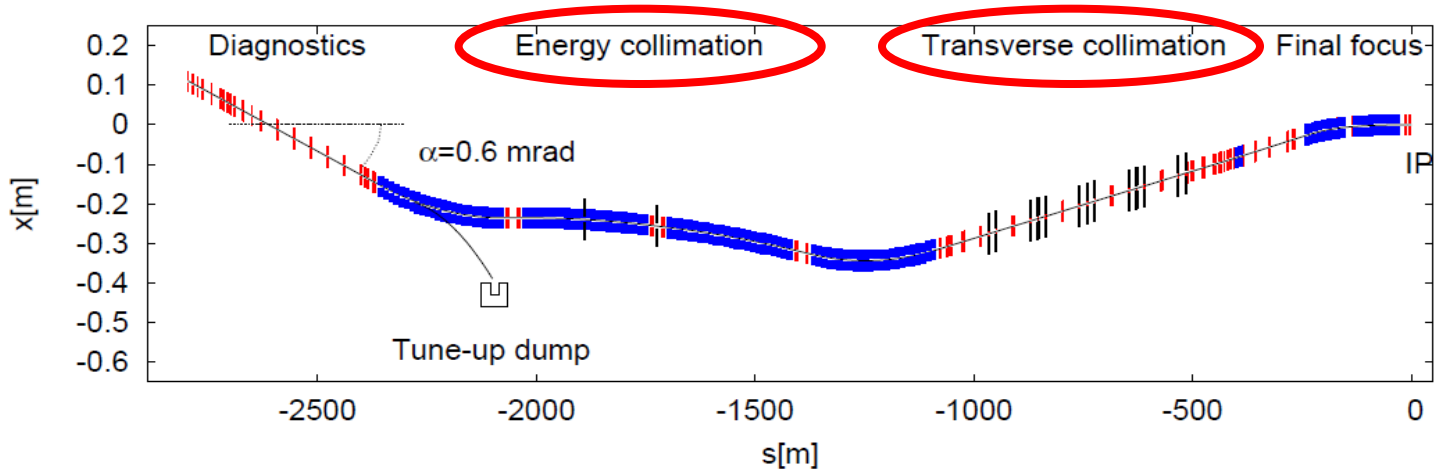
In CLIC BDS the E collimation system is upstream of the betatron one. The main reason for choosing this is because energy errors generated by failure modes in the CLIC main linac are expected to be much more frequent than large betatron oscillations with small emittance beams
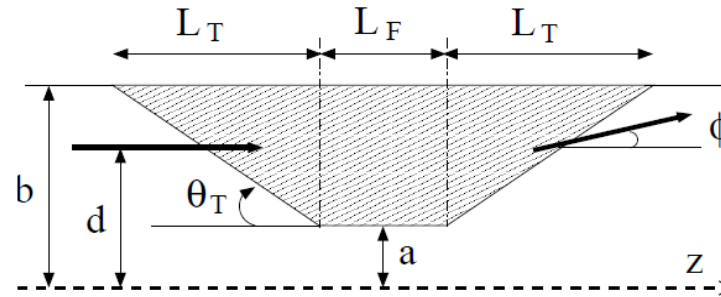
CLIC baseline BDS
Optics
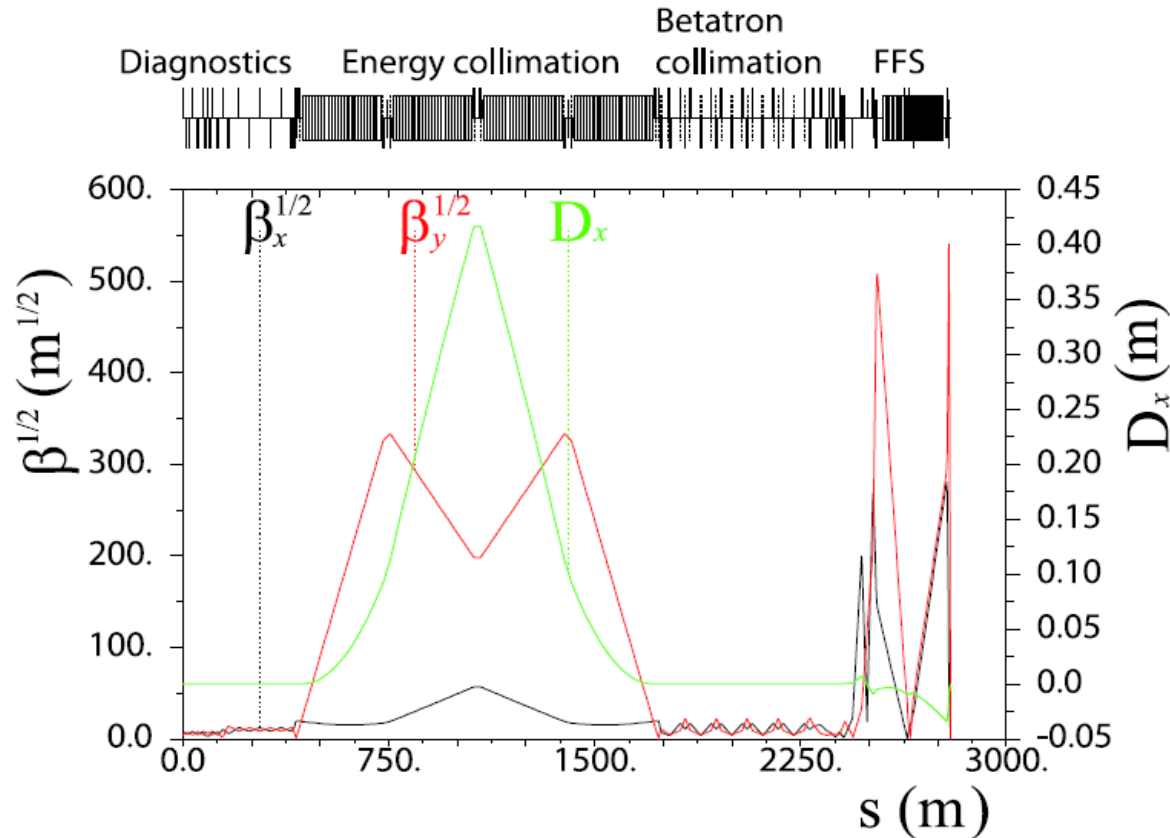
Energy collimation: Protection against miss-steered or errant beams with energy errors ~> 1.3%. E-spoiler half-gap: $a_x = D_x\delta = 3.51$mm

4 pairs of spoilers and absorbers in x,y plane to collimate at IP/FD phases

Collimator parameters

Name	a_x [mm]	a_y [mm]	θ_T [mrad]	L_F [X_0]	L_T [mm]	Mat.
ESP	3.51	8	50	0.05	90	Be
EAB	5.41	8	100	18	27	Ti
the following ×4						
YSP	8	0.1	88	0.2	90	Ti-Cu
XSP	0.12	8	88	0.2	90	Ti-Cu
XAB	1	1	250	18	27	Ti
YAB	1	1	250	18	27	Ti

Energy colllimators: ESP, EAB

Betatron collimators: YSP, XSP, XAB, YAB

Beryllium has been considered as a good material candidate for the E-spoiler. Its high electrical and thermal conductivity with a large radiation length compared with other metals makes Be an optimal candidate.
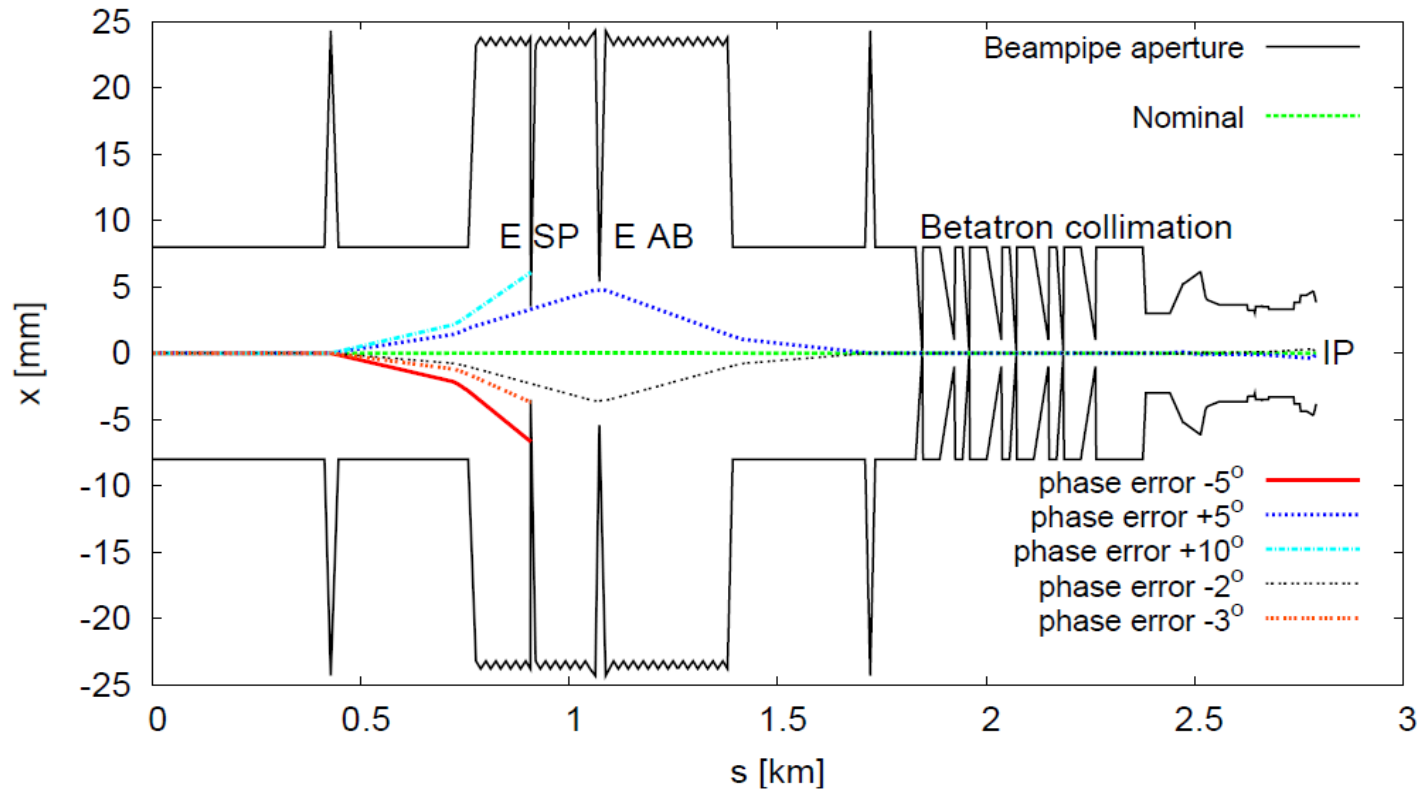
Failure modes

- Investigation of failure modes in the CLIC main linac which could generate significant energy deviation, in such a way that the beam hits the energy spoiler

- For example: Injection phase error, RF breakdown, missing drive beam, beam charge error

- Tracking simulations LINAC + BDS assuming failures between two pulses. Assuming nominal beam parameters and a perfect linac lattice (no additional lattice imperfections)

- Thermo-mechanical characterisation of the energy collimators using the output beam distribution from tracking simulations, and the codes FLUKA (energy deposition and temperature rise) and ANSYS (mechanical stress)

Failure modes

- ### Injection phase error:

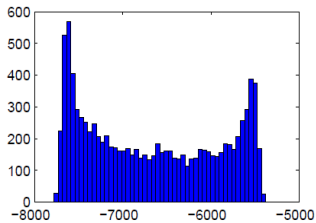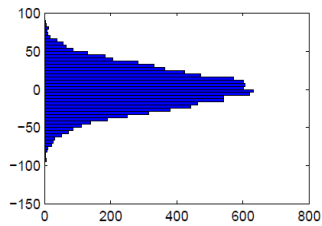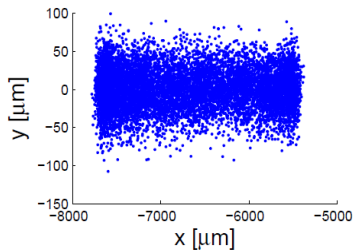Beam centroid trajectory in the BDS for different injection phase errors

For phase error ~> +5° and <~ -3° the beam hits the energy spoiler (ESP)

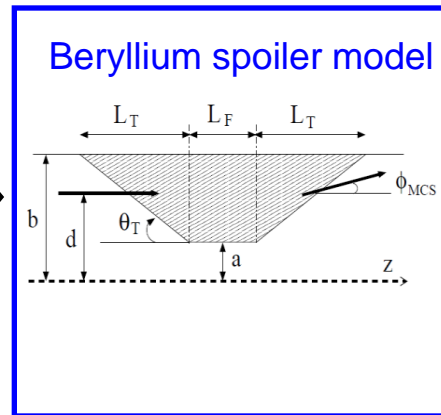# Failure modes

- Injection phase error (example 1):

For -5° phase error, transverse beam distribution at ESP

σ_x=757.72 µm
σ_y=26.45 µm
E_{mean}=1463.8 GeV
≈1% full energy spread

Beryllium spoiler model

FLUKA

Temperature increase along the spoiler
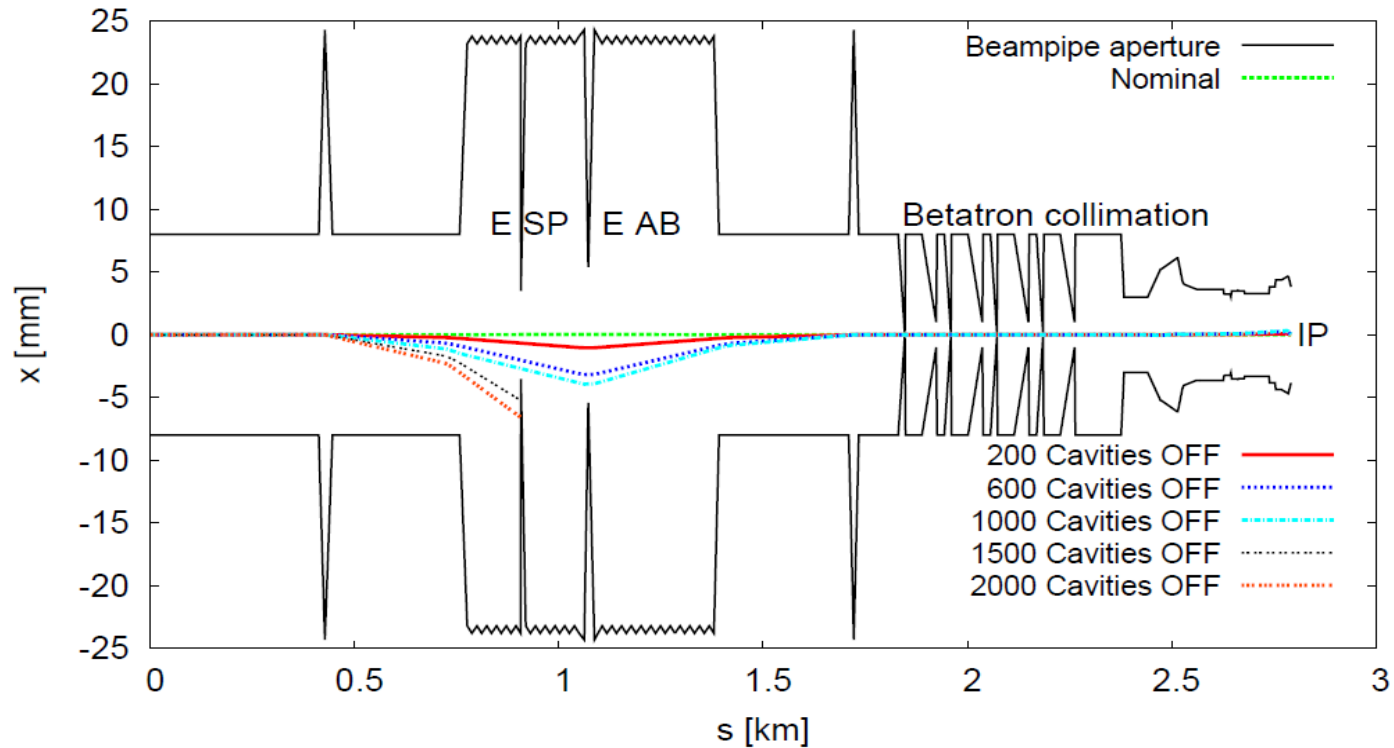

ΔT_{peak}=210 K
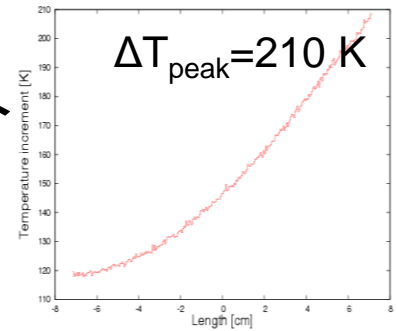
ANSYS
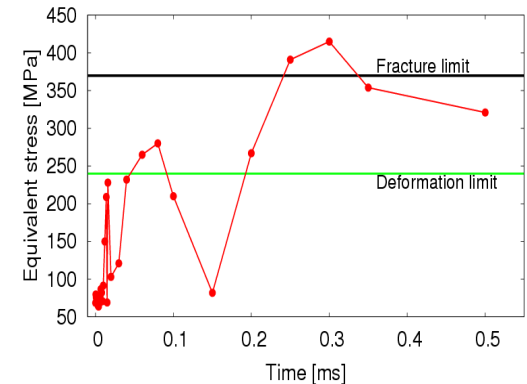
Equivalent stress

The equivalent stress reaches a peak (300 µs after the beam impact) which surpasses the **fracture** limit (> 370 MPa)

Failure modes

- ## RF cavity fail:

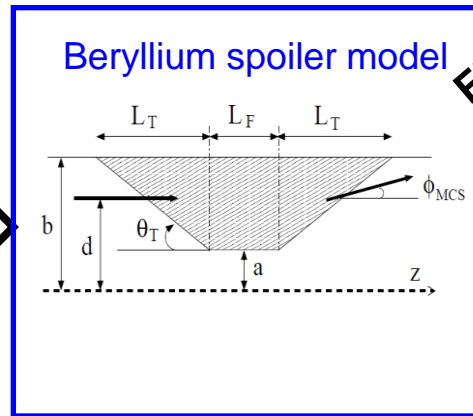Beam centroid trajectory for different number of RF structures switched off in the last section of the main linac
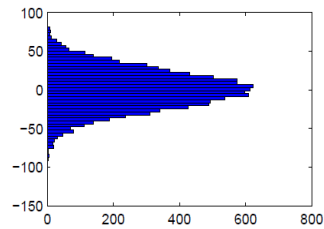
Failure modes

- RF cavity fail (example 2):

1500 cavities switched off in the last section of the main linac. Transverse beam distribution at ESP
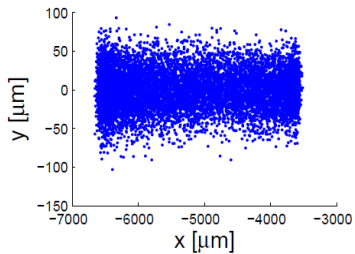
Temperature increase along the spoiler

Beryllium spoiler model

ΔT_{peak}=35 K

FLUKA
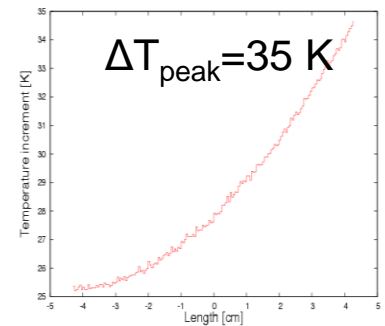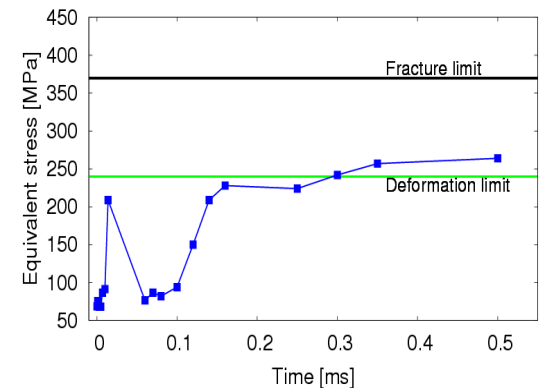
σ_x=1 mm
σ_y=25.4 μm
E_{mean}=1471 GeV
≈1% full energy spread

ANSYS

Equivalent stress

In this case, the equivalent stress is below the fracture limit, but it stabilises near the tensile yield strength (**deformation** limit, 240 MPa)

Failure modes

- Results show that, considering the previous failure scenarios and the nominal beam parameters, it may be difficult to avoid the spoiler fracture or a permanent deformation of the spoiler surface

- In order to reduce the risk of damage to the spoiler, we are considering the following alternatives:

  – Alternative materials

  – Alternative geometric structure

  – Alternative optics: nonlinear passive protection

Alternative spoiler design

- "Hollow" spoilers

Beampipe wall or spoiler support

Vacuum

L   L

Ti-alloy or Be

Beam axis
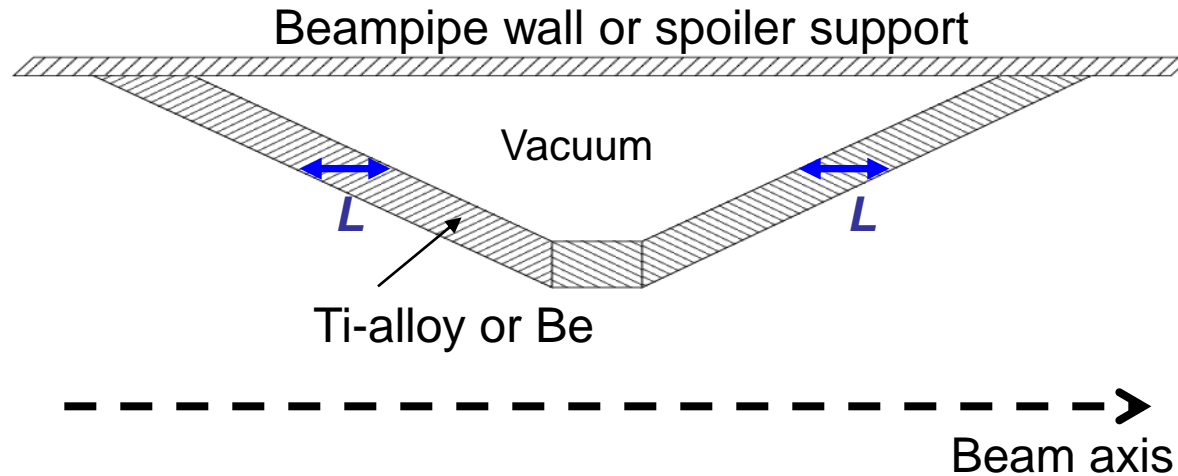
- **2L** is the minimum length of material that the beam has to see in order to obtain the necessary angular divergence Θ by MCS. In this way the beam spot size is increased at the downstream absorber position in order to avoid its damage or fracture.

- The empty inner part of the spoiler could accommodate a water cooling circuit or some other kind of cooling system

Alternative spoiler design

- "Semi-hollow" spoilers
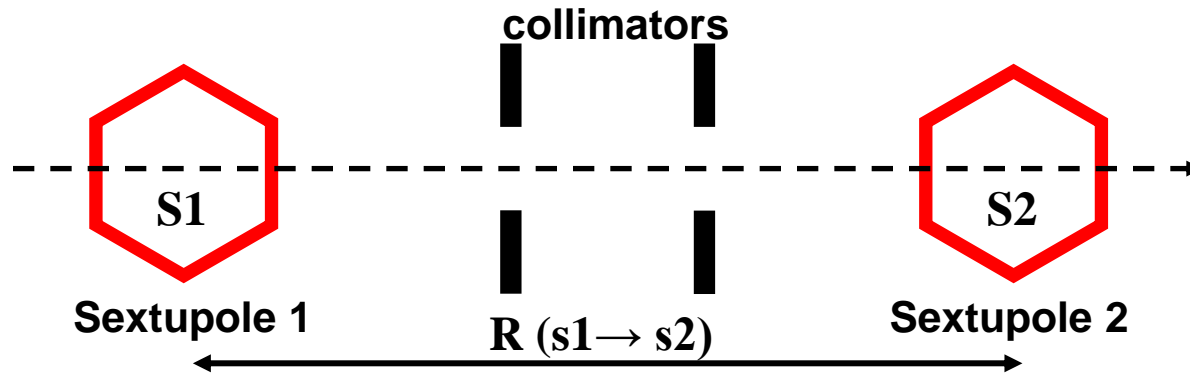
Beampipe wall or spoiler support

Cu

Ti-alloy or Be

SiC foam

Beam axis
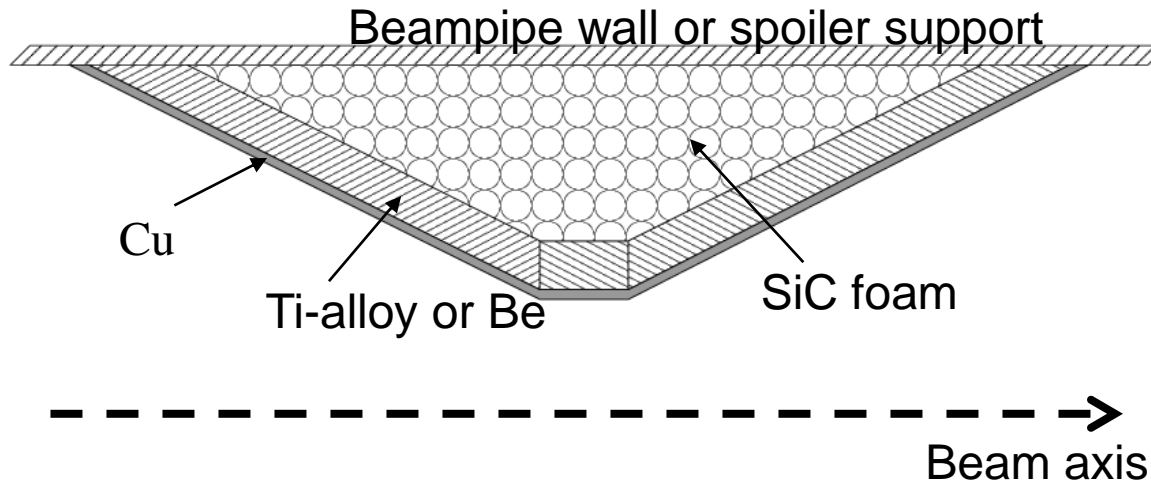
We plan to study the thermo-mechanical characteristics of these spoiler designs
using the codes FLUKA and ANSYS (following the same procedure as
for examples 1 and 2).

Nonlinear passive protection
Basic concept

collimators

$S1$

Sextupole 1

$S2$

Sextupole 2

$R\ (s1 \rightarrow s2)$

- Use a nonlinear magnet (e.g. sextupole, octupole), which somehow plays the role of a spoiler (or primary collimator), to increase the beam spot size at the downstream collimators for a beam with mean energy offset ~> energy collimation depth

- Cancellation of optical aberrations using a second nonlinear element

- For CLIC we have studied an E collimation system based on a pair of skew sextupoles of relatively moderate strength

Nonlinear passive protection

In the past …

Concept of Magnetic Energy Spoiler (MES) for TESLA

[R. Brinkmann et al., TESLA-01-12 (2001)]
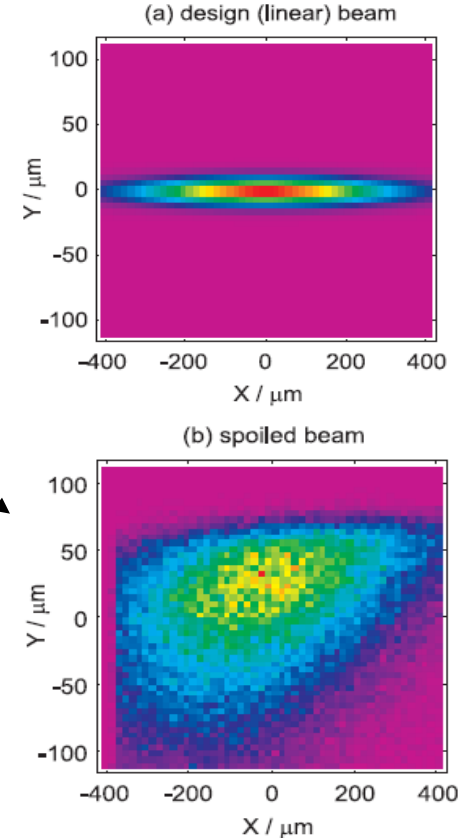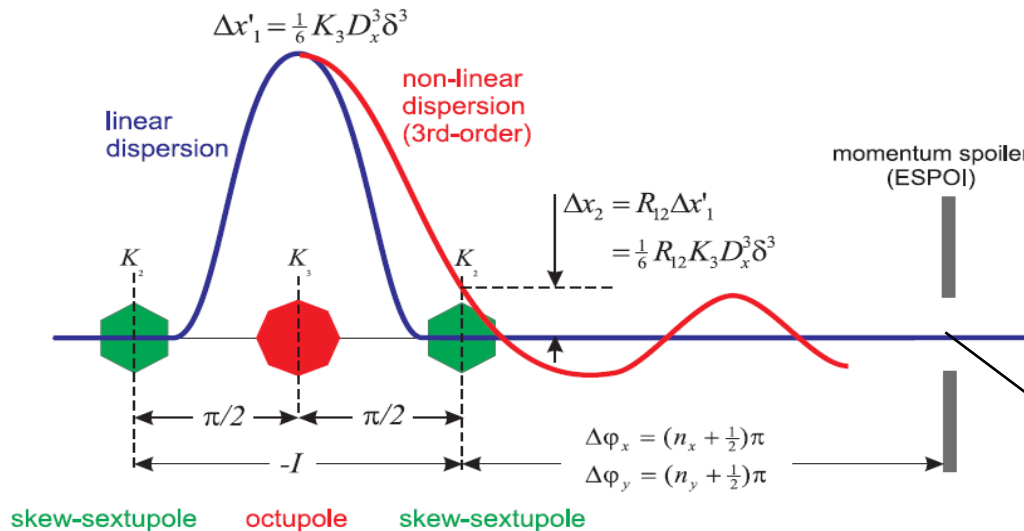
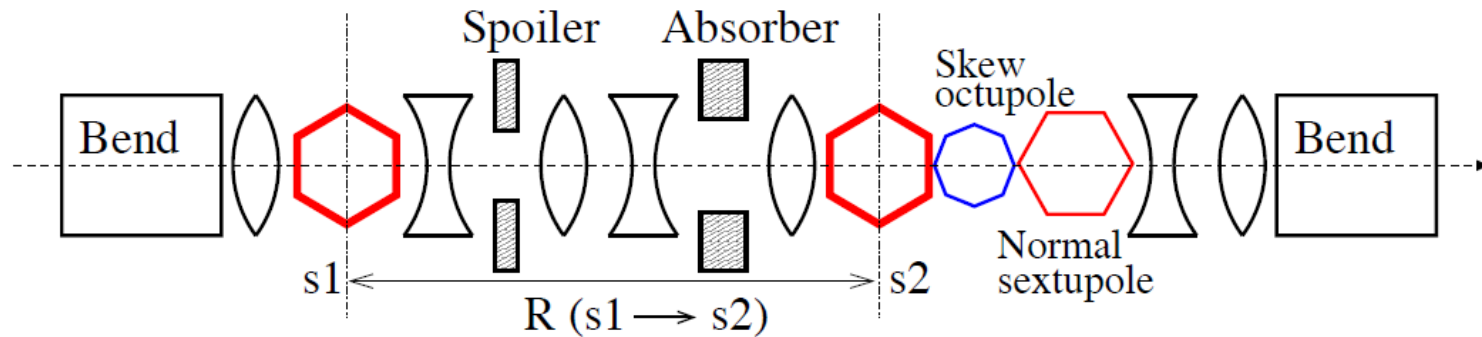According tracking simulations:

- The beam area is increased by a factor of 6 wrt the linear beam at the momentum spoiler position !

- However, significant luminosity degradation !

CLIC nonlinear energy collimation system

- Conceptual layout

Optical optimisation:

To cancel higher order aberrations a skew octupole and a normal sextupole have been added downstream of the second skew sextupole.

CLIC nonlinear energy collimation system

Optical constraints to cancel geometric nonlinear terms between two skew sextupoles:

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

- Phase advance:

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

- Relation between the strength of the two skew sextupoles:

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

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

- We use **–I** transform in both *x* and *y* planes between the sextupoles, which is a special case of the previous conditions: $n_x=1$, $n_y=1$, $\beta_{x1}=\beta_{x2}$, $\beta_{y1}=\beta_{y2}$, $\alpha_{x1}=\alpha_{x2}$, $\alpha_{y1}=\alpha_{y2}$. Therefore, $K_{s1}=K_{s2}$

- In addition, to cancel chromatic and chromo-geometric aberrations between the skew sextupole pair: $D_{x1}=-D_{x2}$

CLIC nonlinear energy collimation system

- Optical layout

BDS
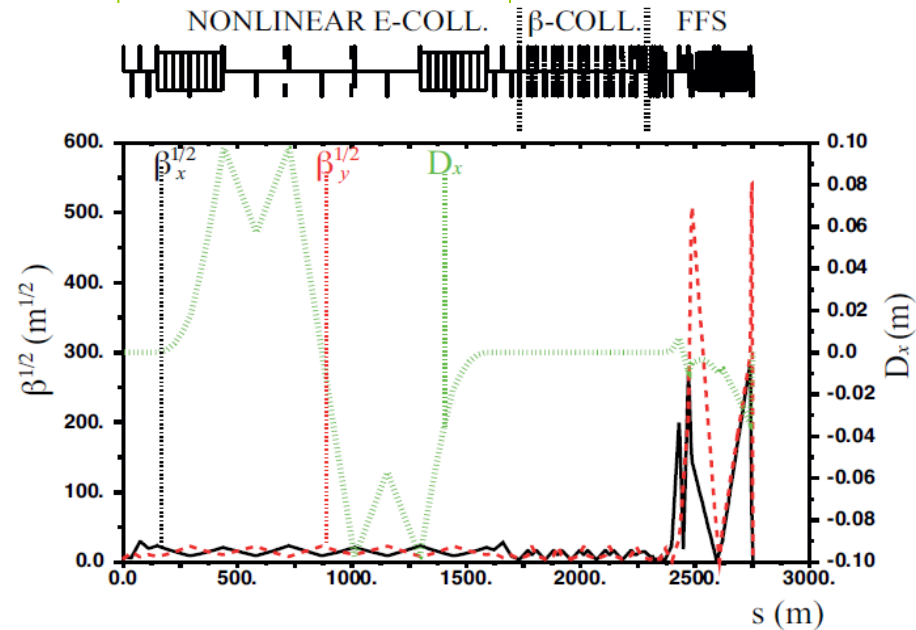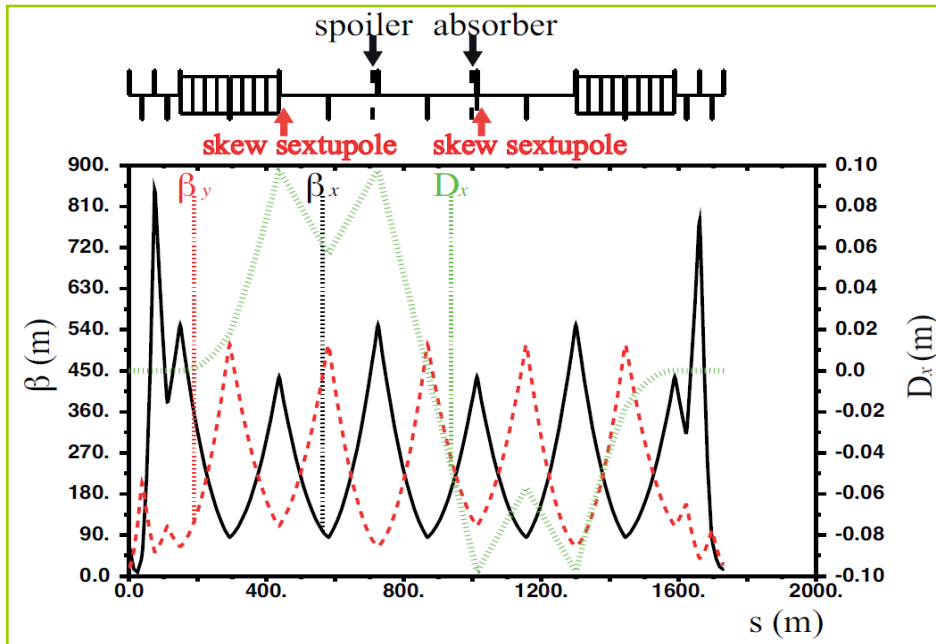
CLIC nonlinear energy collimation system
Beamline performance

- ## Multi-particle tracking simulations:

    - Using the code MAD
    - 50000 macroparticles tracked through the CLIC BDS
    - Gaussian beam distributions for the transverse phase space
    - 1% full energy spread (uniform distribution)

NONLINEAR E-COLL.   β-COLL.   FFS

BEAM

s1   s2
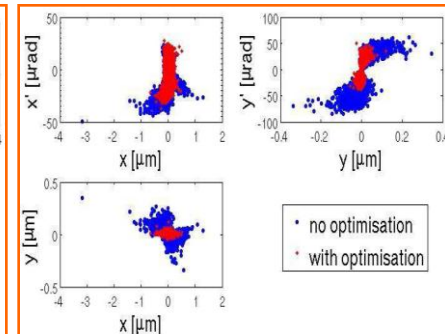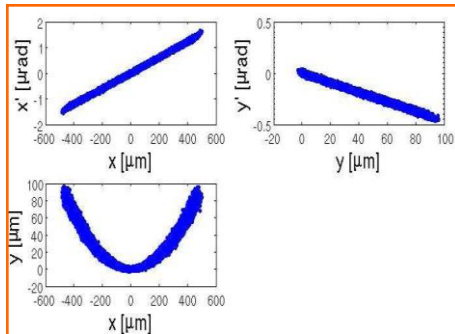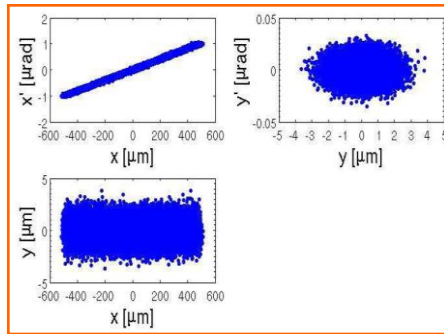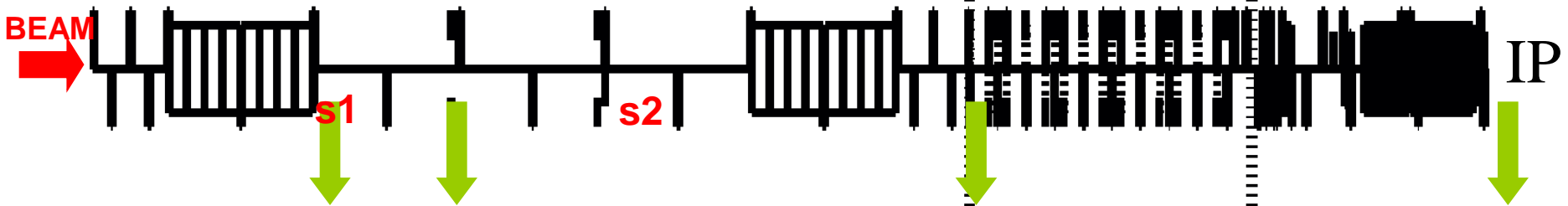
At 1st skew sextupole   At spoiler   At energy collimation system exit   At IP

CLIC nonlinear energy collimation system
Beamline performance

- Luminosity

Relative Luminosity vs skew sextupole strength

≈2% luminosity loss

≈35% luminosity loss

$K_s = 8$ m^{-2}
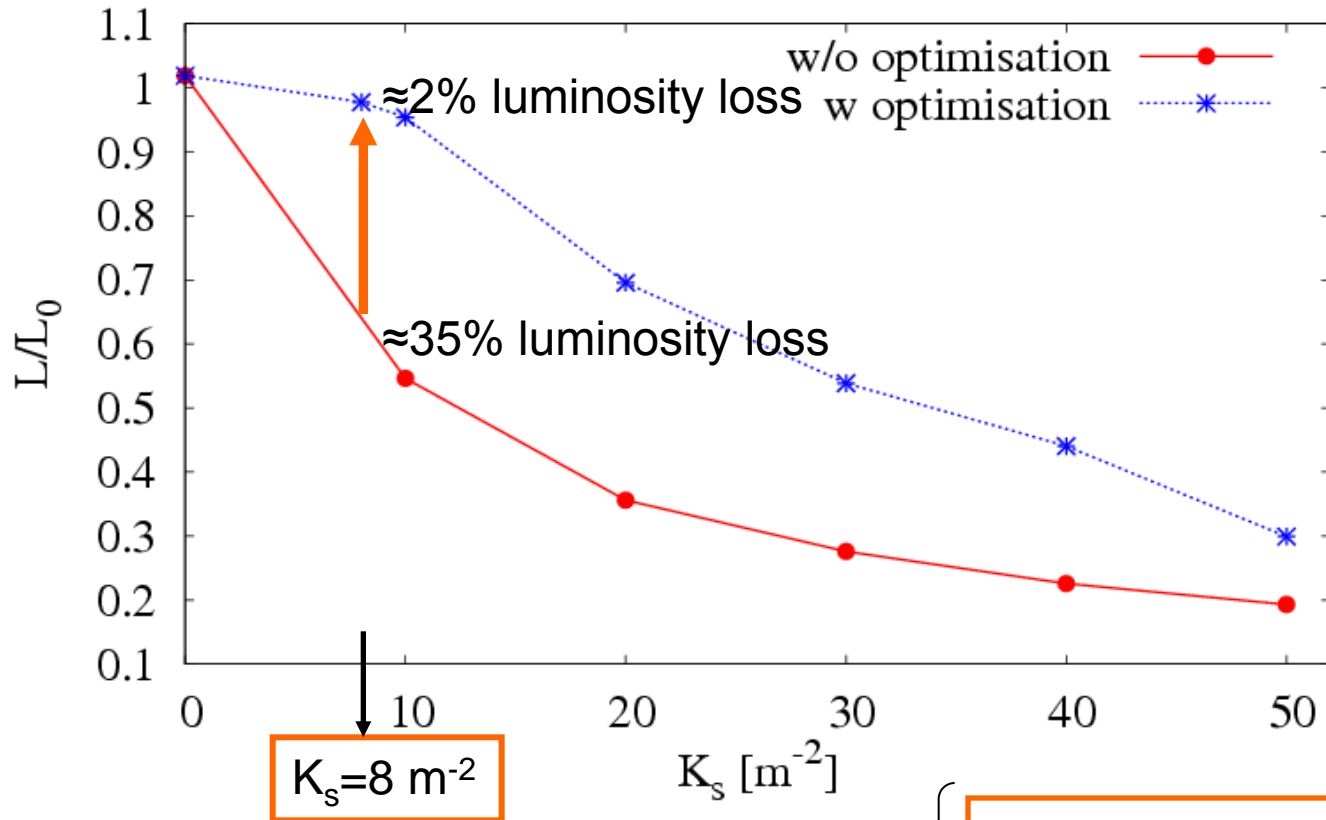
With optimisation (additional nonlinear elements)

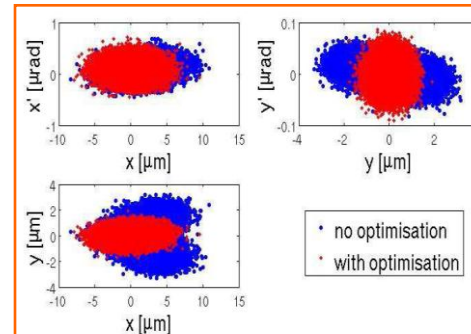K(skew octupole) = -2400 m^{-3}
K(normal sextup.) = -0.4 m^{-2}

CLIC nonlinear energy collimation system
Beamline performance

- ## Luminosity

Energy bandwidth: Relative peak luminosity (within 1% of Ecm) vs. beam energy offset $\delta_0 = \Delta E / E_0$
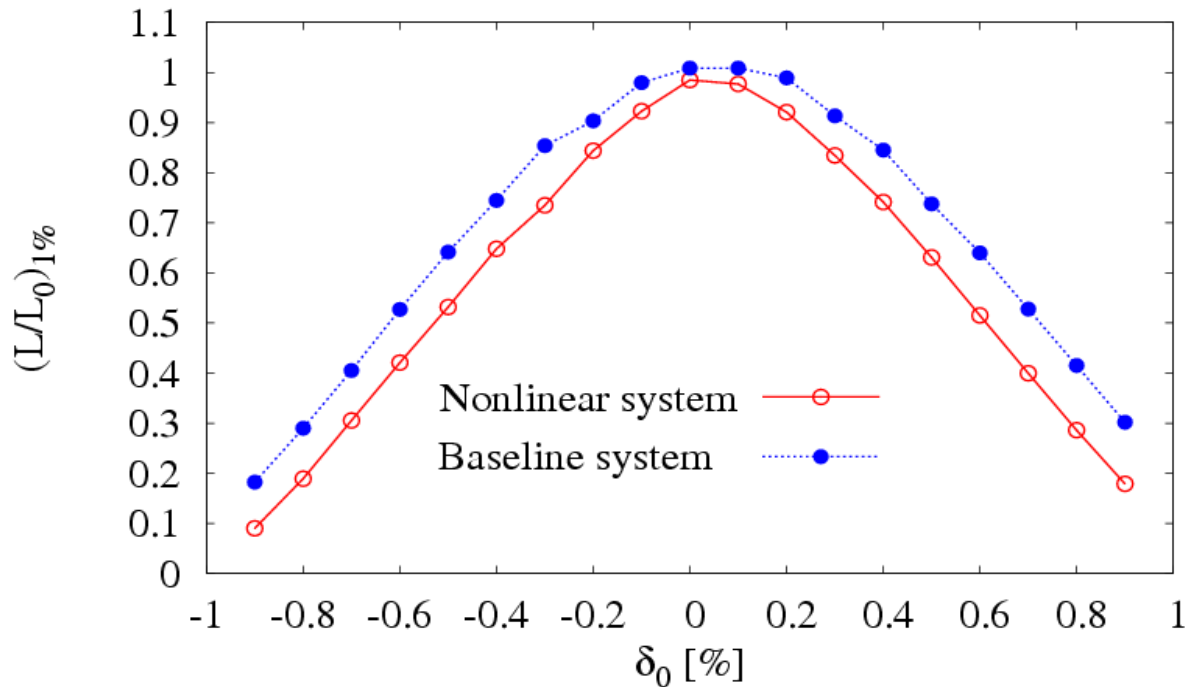
Both linear and nonlinear systems present a comparable bandwidth !

CLIC nonlinear energy collimation system
Beamline performance

- Beam size at spoiler position

Transverse beam spot size vs. skew sextupole strength for different beam energy offsets
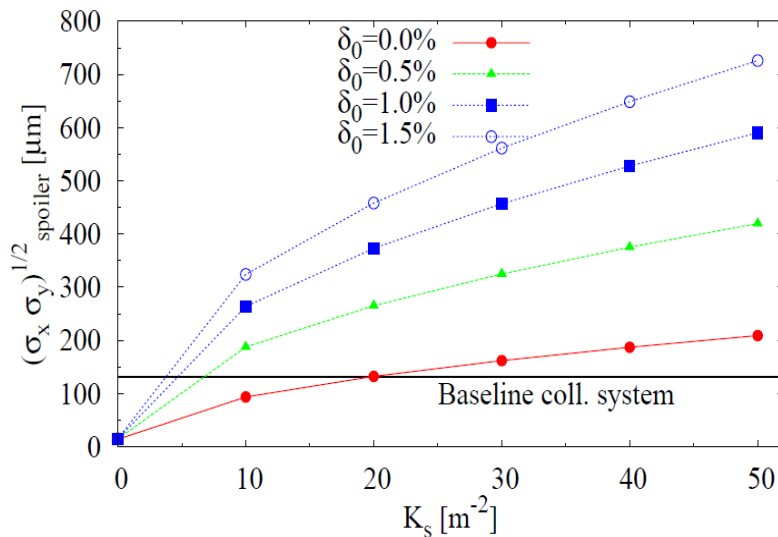
Transverse beam peak density vs. skew sextupole strength for different beam energy offsets
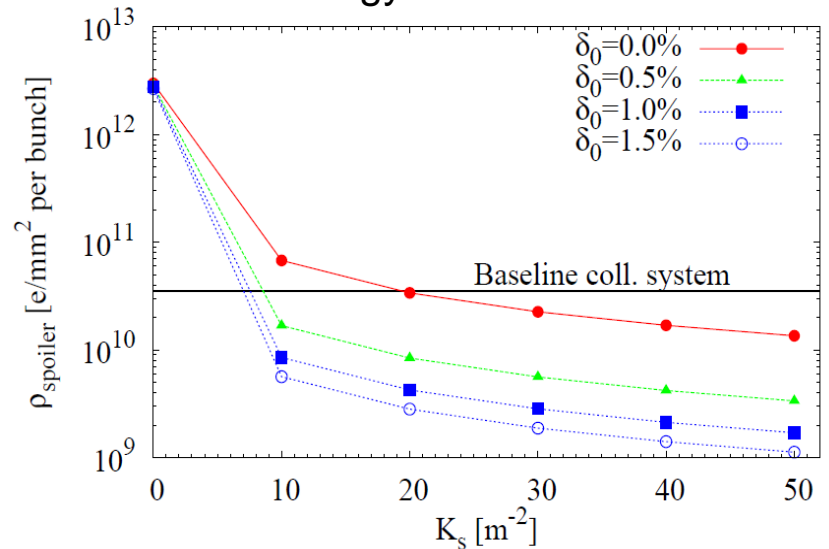
For 1.5% mean energy offset, the nonlinear energy collimation system (using Ks=8 m^{-2}) increases 2 times the beam spot size (reduces 4 times the transverse peak density) at the energy spoiler wrt the baseline linear collimation system

Conclusions

- The CLIC post-linac E-collimation system will play an essential role in protecting BDS against miss-steered beams

- The E-collimation depth is determined by failure modes in the main linac

- In order to improve the current baseline collimation system design, it is necessary to investigate and identify failure scenarios which could be critical in terms of collimator damage

- Concretely we have studied failures which could generate a significant beam energy deviation, in such a way that the beam directly impacts on the energy spoiler

- Tracking simulations LINAC + failure modes + BDS + thermo-mechanical analysis of the spoiler (FLUKA + ANSYS) for CLIC are in progress

- Preliminary results show that it may be difficult to avoid fracture or permanent deformation of the spoiler with the current baseline design

- Further studies have to be performed to evaluate the real magnitude of the fracture and the deformation. For example, a permanent deformation could translate into an increase of the roughness of the spoiler surface, hence increasing wakefield effects

- We are currently investigating alternative spoiler designs and alternative optical layouts, such as a nonlinear collimation system, to reduce the risk of damage to the energy collimators

Reservoir

MPS strategy for BDS

- The MPS strategy is determined by the bunch train time structure

Parameter	ILC	CLIC
Number of bunches	2625	312
Bunch spacing [ns]	369	0.5
Pulse length [µs]	969	0.156
Pulse repetition rate [Hz]	5	50
Charge per bunch [nC]	3.2	0.6

ILC:

- The relative long pulse and large bunch spacing allow that a fault can be detected and the pulse aborted within the train itself.

- An errant or miss-steered beam could be aborted at the beginning of the BDS by using a fast kicker system (rise-times ~100 ns) to send the beam to an emergency dump

- This fast abort system is intended to protect the BDS providing that the collimation system can survive one bunch

MPS strategy for BDS

CLIC:

- In case of fast failures in the main linac (at microsecond time scales), the extremely short bunch spacing (0.5 ns) and small pulse length (156 ns) make the fault detection and abortion within the same train very difficult (not attainable with current kicker technology)

- Then a first miss-steered train is detected and not extracted by the emergency kicker at the exit of the main linac, and the subsequent pulses could be extracted by the emergency abort system . After the detection of abnormal operation (in the pulse-to-pulse interval) an interlock system could stop operation

- In this case, the protection of the BDS relies mainly on the collimation system (passive protection). The E-collimation system is designed to withstands the impact of, at least, a bunch train.
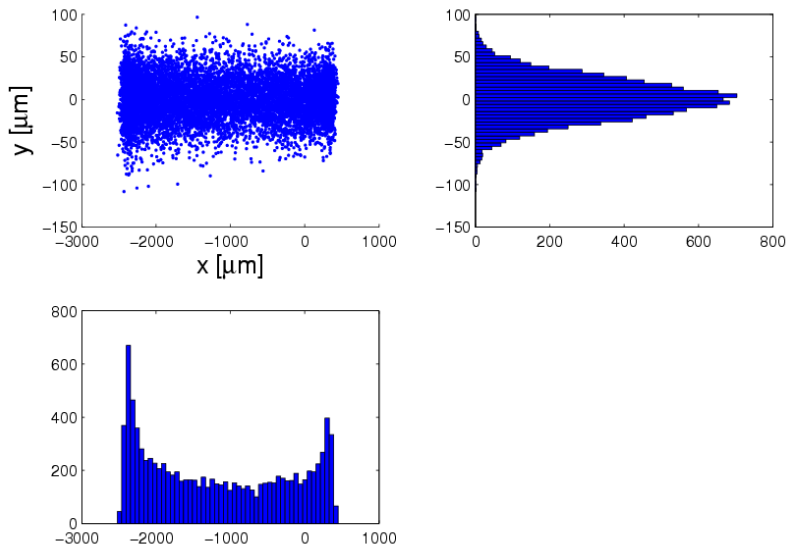
Failure modes

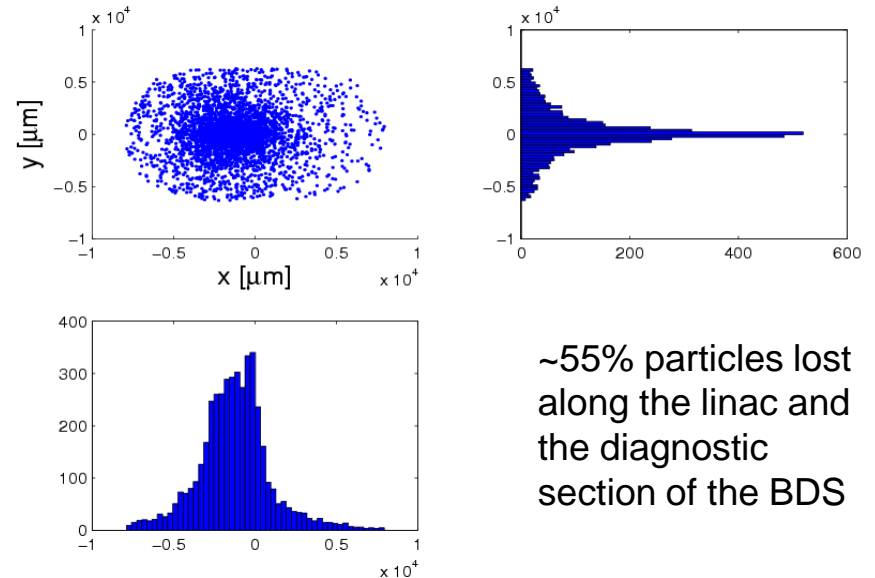- ## RF cavity fail:

In terms of spoiler damage, the case of the total failure of a series of RF cavities at the start of the linac is less critical, since the energy spread increases and the beam suffers a rapid filamentation

Transverse beam distribution at ESP

300 RF structures OFF   400 RF structures OFF
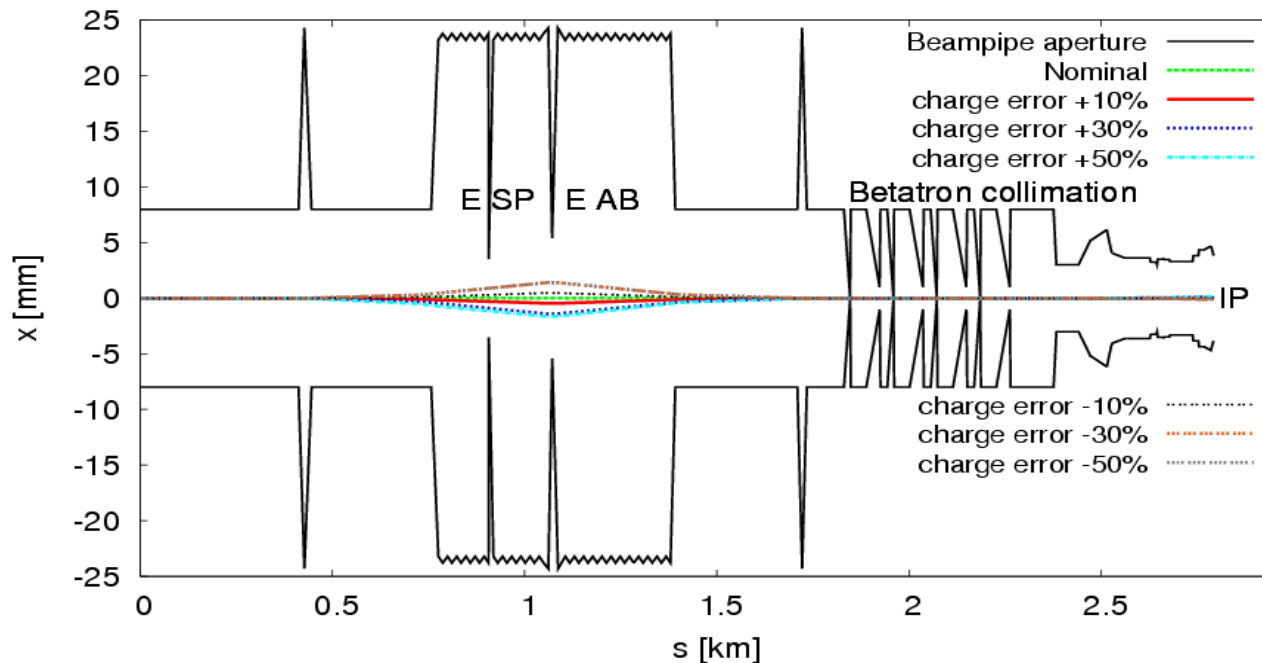

~55% particles lost along the linac and the diagnostic section of the BDS

Failure modes

- Beam charge error:

    Beam centroid trajectory in the BDS for different beam charge errors
    in the range [-50%, +50%]

    In this case, the resulting energy deviation is relatively small for the beam
    to be caught in the energy spoiler

Parameters for the CLIC nonlinear energy collimation

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

Spoiler 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