CLIC Collimation System Review

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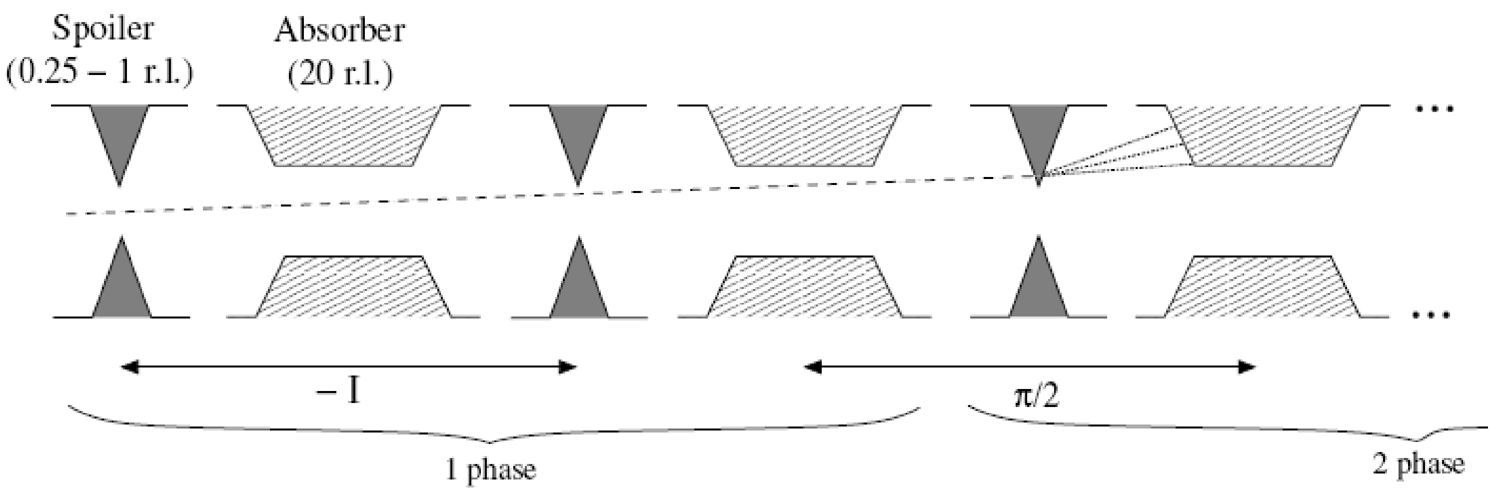
Collimation system

Simple spoiler/absorber scheme

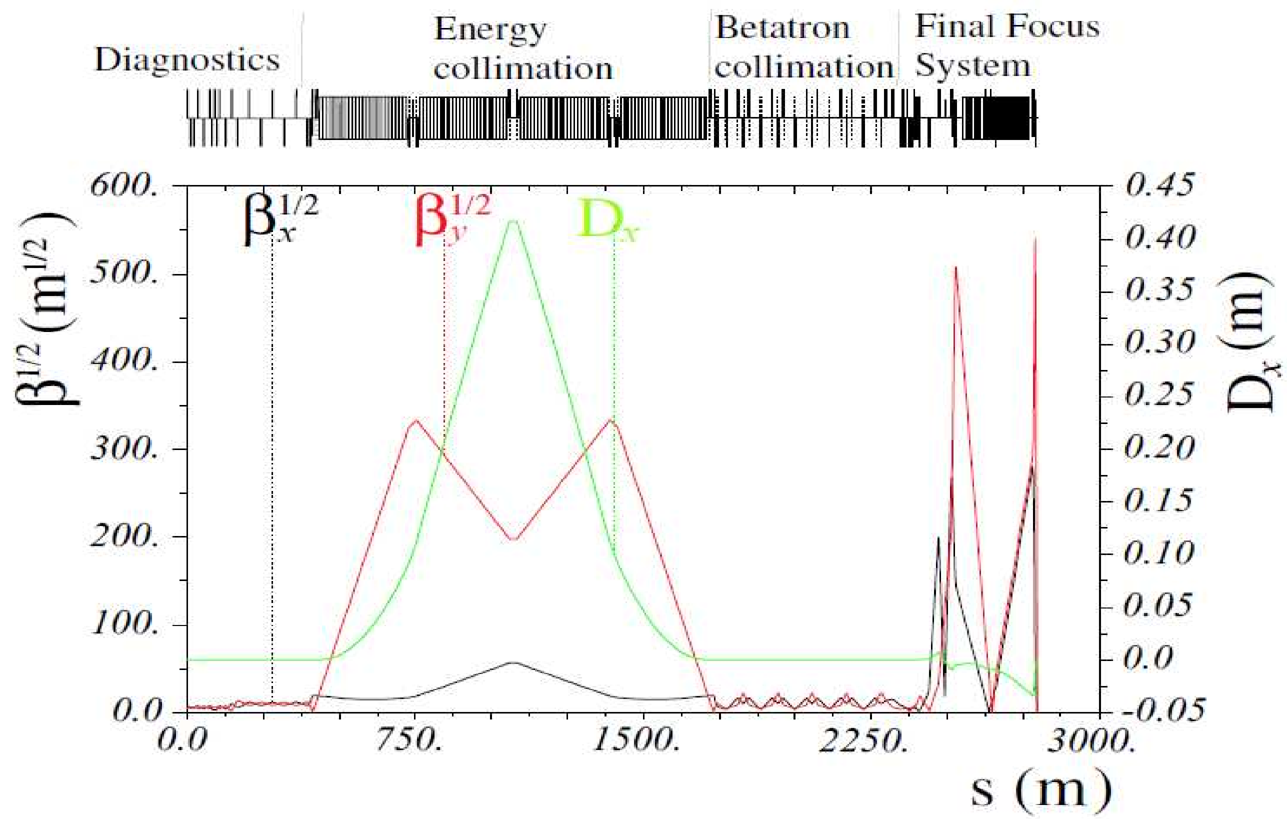
- Thin spoilers (thickness < 1 X_0) scrape the beam halo and, if accidentally struck by the full power beam, will enlarge the spot size via multiple coulomb scattering (MCS).

  This increases the beam size at the absorbers and reduces the risk of material damage

- The scattered halo and enlarged beam are then stopped on thick (~ 20 X_0) absorbers



CLIC collimation system



Energy collimation: Protection against mis-steered or errant beams with energy errors **>** 1.3**%.** E-spoiler half-gap: $a_x = D_x \delta = 3.51\text{mm}$

4 pairs of collimators in x,y plane to collimate at IP/FD phases

E-collimation system

- Beam power of the CLIC beam in the BDS: $\boldsymbol{P=f_{rep}N_eN_bE\approx 14}$ **MW,** which means high damage potential in case of failure !!!

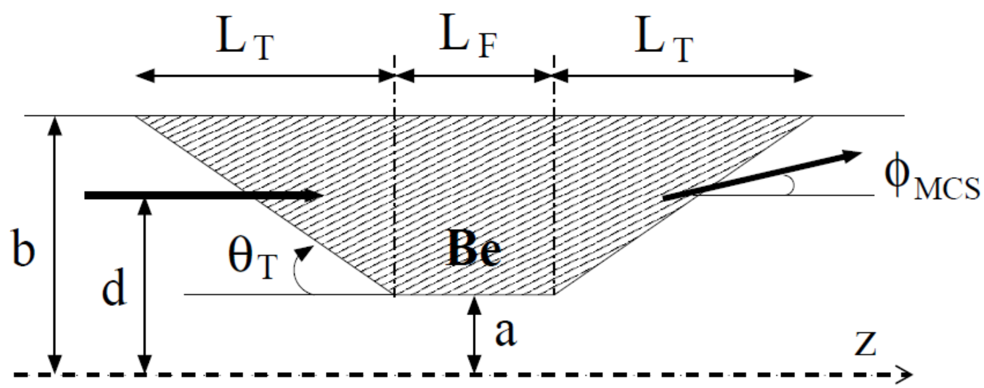
- Passive protection against miss-steered beams due to failure modes in the main linac

- The spoiler/absorber design must be robust enough to provide protection against the impact of an entire pulse

- Beryllium is being considered as an option material for the E-spoiler. Its high electrical and thermal conductivity with a large radiation length compared with other metals makes Be an optimal candidate.

E-collimation system

Spoiler design



Parameter	ENGYSP (spoiler)	ENGYAB (absorber)
Geometry	Rectangular	Rectangular
Vert. half-gap a_x [mm]	3.51	5.41
Hor. half-gap a_y [mm]	8.0	8.0
Tapered part radius b [mm]	8.0	8.0
Tapered part length L_T [mm]	90.0	27.0
Taper angle θ_T [mrad]	50.0	100.0
Flat part length L_F [radiation length]	0.05	18.0
Material	Be	Ti alloy (Cu coated)

E-collimation system
Spoiler protection

The instantaneous temperature rise due to beam impact on the spoiler:

$$\Delta T_{inst} = \frac{1}{\rho_{sp} C}\left(\frac{dE}{dz}\right)\rho(x,y) < \Delta T_{fracture}, \Delta T_{melt}$$

For Gaussian beam with horizontal and vertical rms sizes σ_x and σ_y:

$$\Delta \hat{T}_{inst} = \frac{1}{\rho_{sp} C}\left(\frac{dE}{dz}\right)\frac{N_e N_b e}{2\pi\sigma_x\sigma_y} < \Delta T_{fracture}, \Delta T_{melt}$$

For Be spoiler:

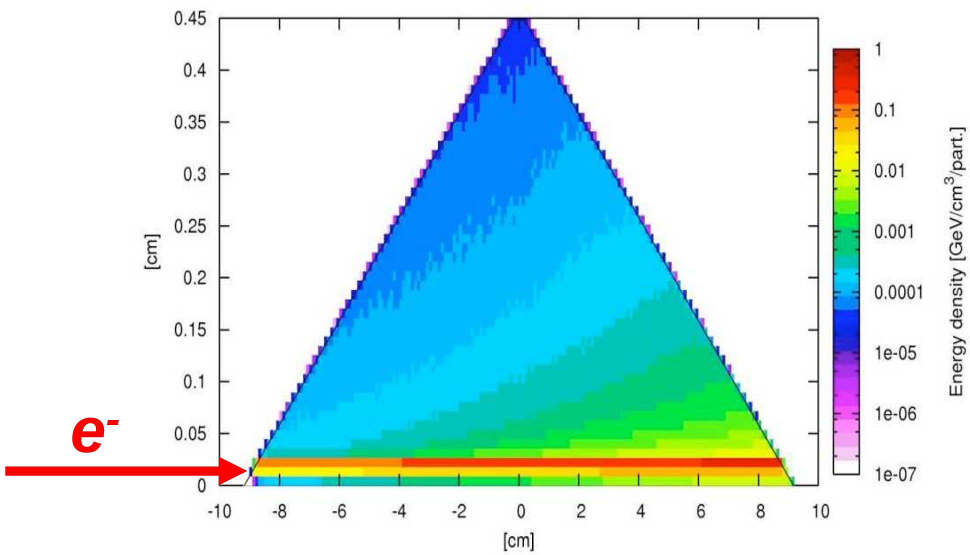
ρ_{sp} (material density)=1.84 x 10^6 g/m^3
C (specific heat)=1.825 J/(g K)
$\Delta T_{fracture}$=228 K (this limit of fracture determined by the so-called ultimate tensile strength of the material. Discrepancies of up to 30% in this parameter can be found between different bibliographic sources)

E-collimation system
Spoiler protection
Thermal and mechanical effects

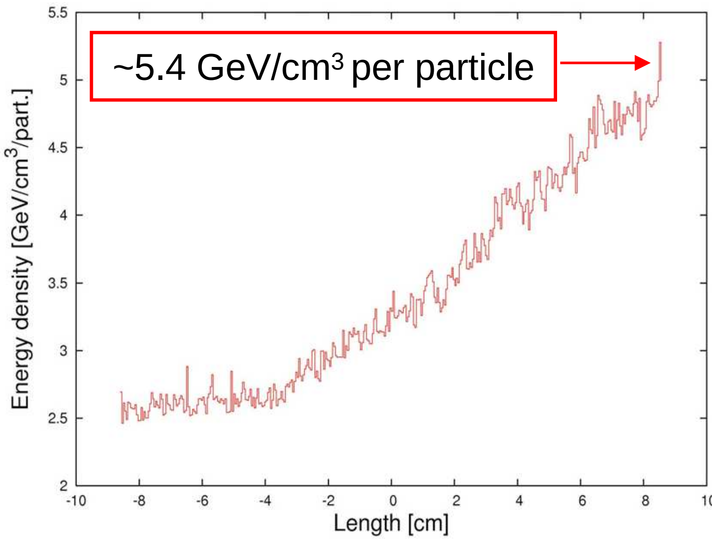
From simulations using the code FLUKA:

[L. Fernandez-Hernando]

Energy density deposition normalised per incident particle



Peaks of energy density deposition



$$\Delta \hat{T}_{inst} \approx 570\ \mathrm{K}\ !$$

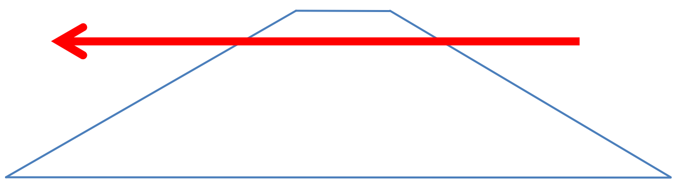
This temperature peak is below the melting limit ($\Delta T_{melt} \approx 1267$ K), but above the fracture limit for beryllium

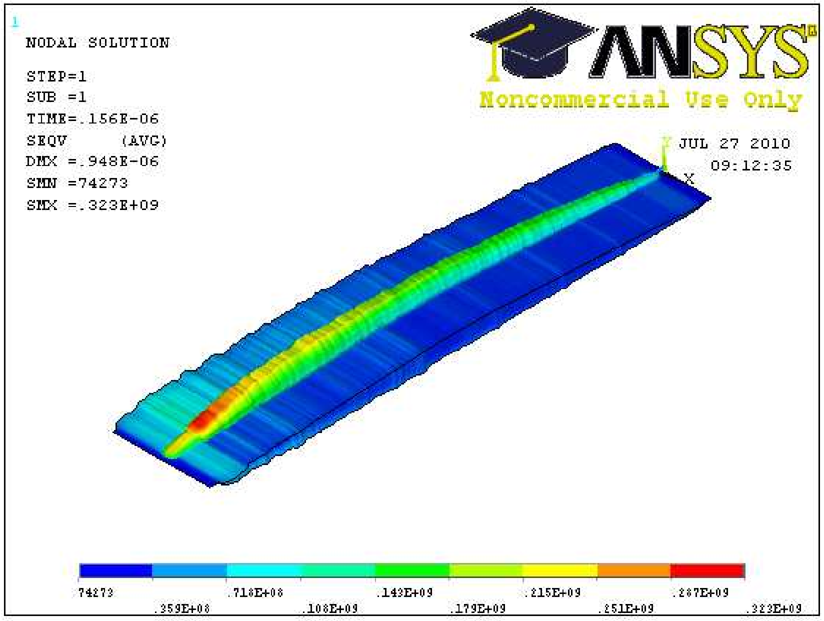
E-collimation system
Spoiler protection
Thermal and mechanical effects

[L. Fernandez-Hernando]

Material stress studies using FLUKA + ANSYS:

Bunch train hitting at 0.2 mm from the top (assuming a beam deviation of ≈ 169 σ_y)

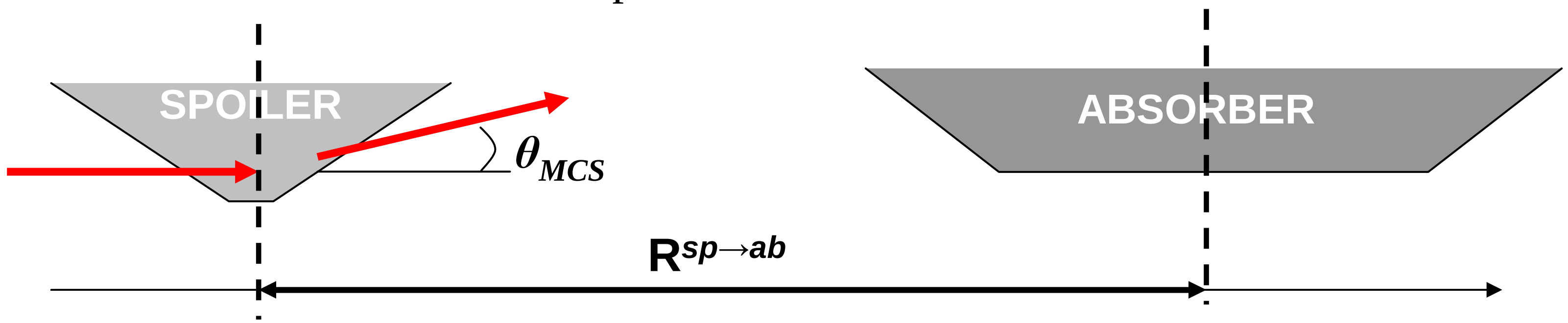




The top value of stress is ~320MPa and compressive. Meaning that **there will not be fracture** but **there will be a permanent deformation**, and in this case it is a vertical deformation of 5 µm, which represents **a 0.1% of the half gap**. Can we live with that?

E-collimation system
Spoiler thickness and absorber protection

- The spoilers must provide enough beam angular divergence by multiple coulomb scattering in order to reduce the damage probability of the downstream absorber and/or another downstream component



For the protection of absorbers made of Ti-Cu coated:

$$\sqrt{\sigma_x \sigma_y} > 600 \ \mu\text{m}$$

Value from studies for the NLC (see e.g. P. Tenenbaum, Proc. of LINAC 2000, MOA08). Necessary simulations to update this limit.

E-collimation system

Spoiler thickness and absorber protection

Energy spoiler-absorber:

We have to take into account the dispersive component of the beam size ($D_x\sigma_E$, with D_x the horizontal dispersion and σ_E the rms beam energy spread). In this case, the absorber survival condition can be approximated by

$$\sqrt{\sigma_x \sigma_y} \approx \left(\left| R_{34}^{sp\to ab} \right| D_x \sigma_E \theta_{MCS} \right)^{1/2} > 600\,\mu\mathrm{m}$$

Considering $R_{34}^{sp\to ab} = 160\,\mathrm{m}$ and $\sigma_E = 0.5\%$, then

$L_F >\sim 0.02\,X_0$

In order to validate these results we have performed montecarlo simulations including MCS at the spoiler position to study the beam density at the downstream absorber for different values of spoiler thickness.

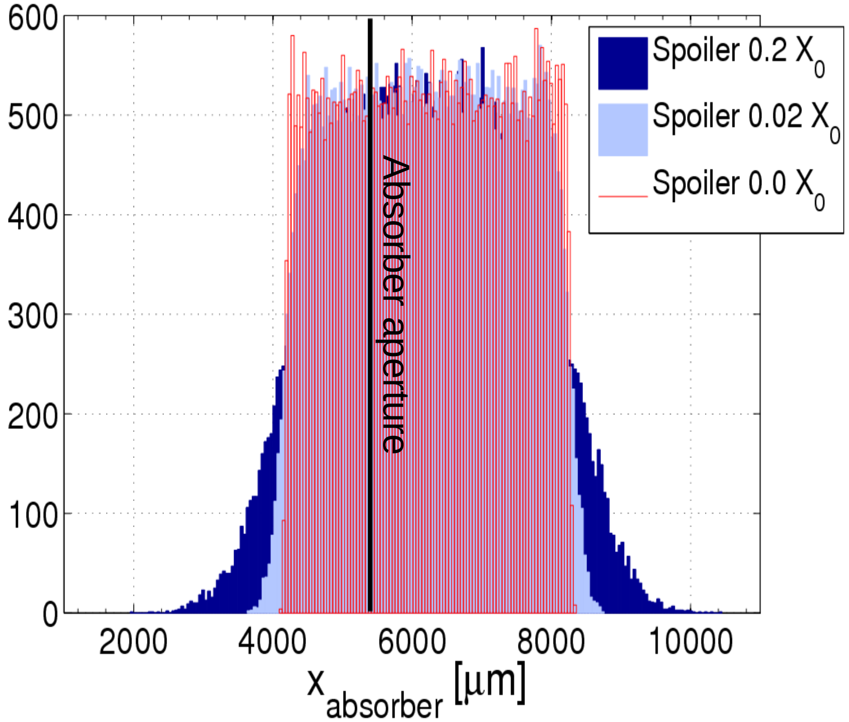
E-collimation system

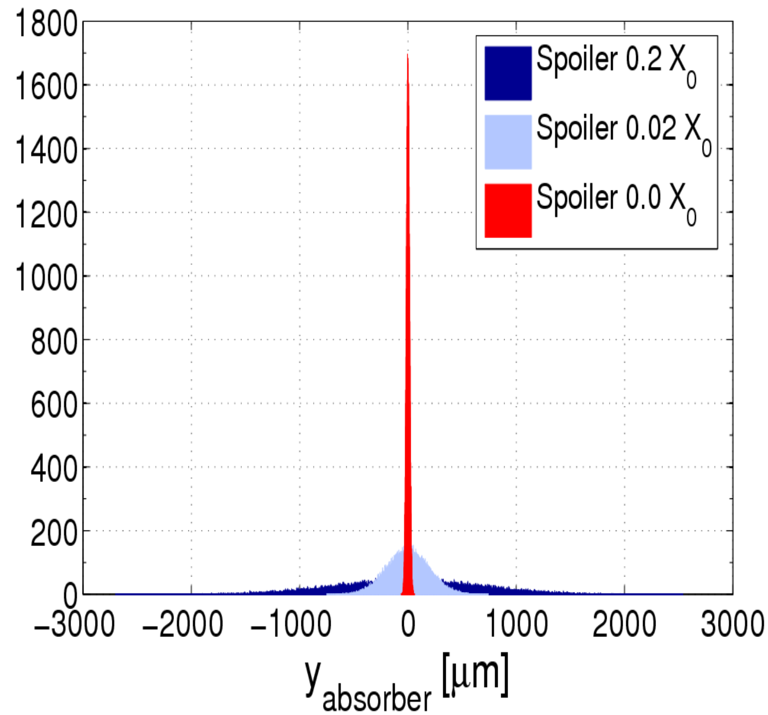
Transverse beam distribution at E-absorber

Considering a beam with 1.5% centroid energy offset and a uniform energy distribution with 1% full width energy spread

Tracking studies using the code placet-octave (50000 macroparticles)

Assuming all particles of the beam hit the E-spoiler and full beam transmission through the E-spoiler and applying MCS (function MCS.m created using octave)

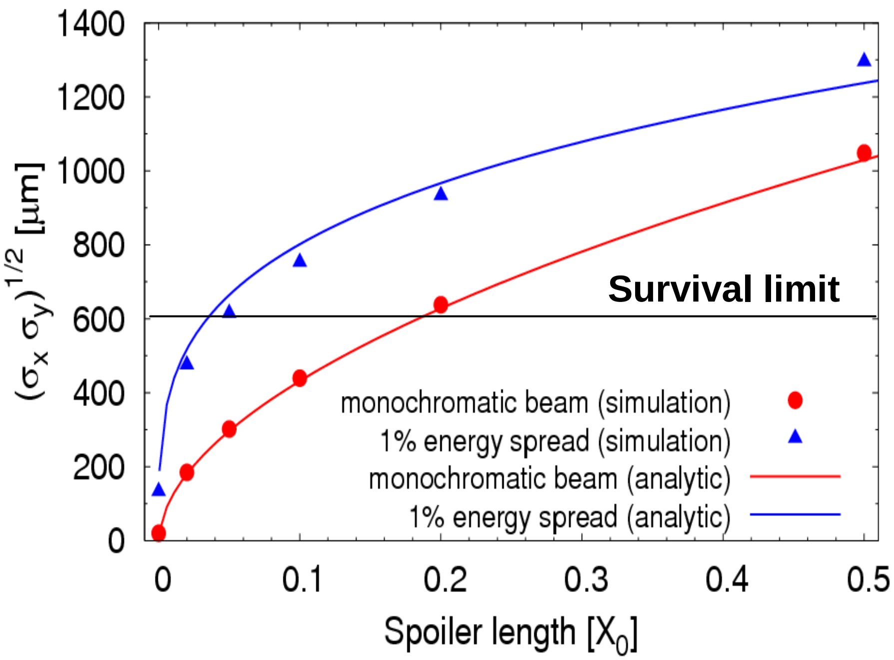


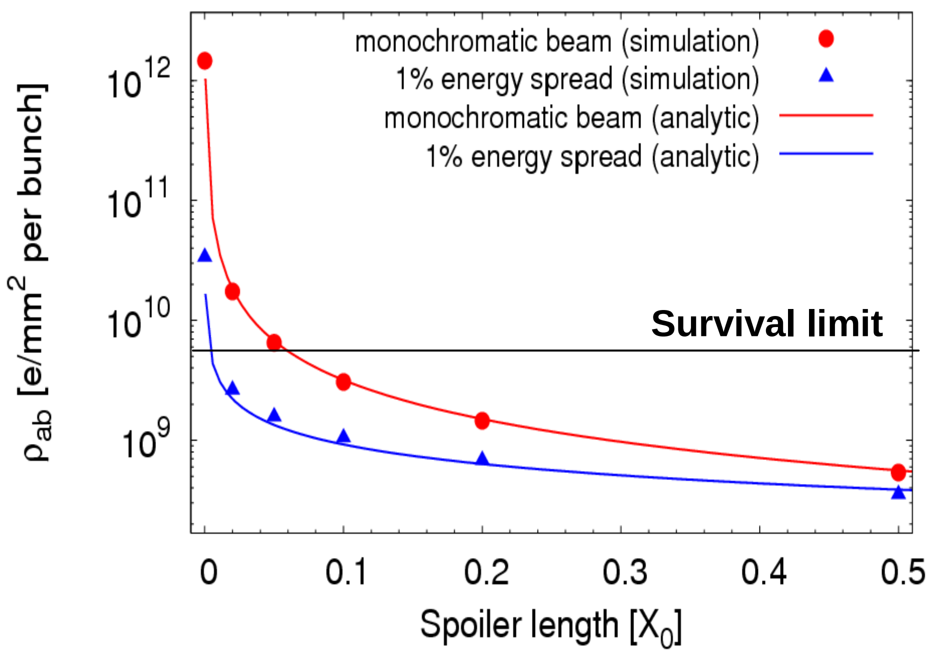


E-collimation system

Transverse beam density at E-absorber

$$\hat{\rho}_{ab} = N_e/(2\pi\sigma_x\sigma_y)$$





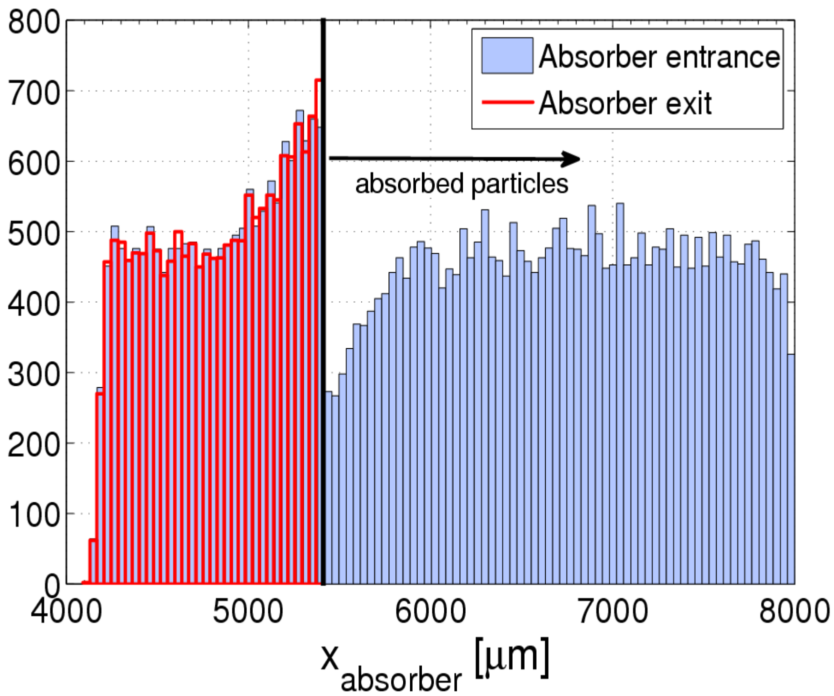
0.02 X_0 spoiler decreases the transverse beam density at the downstream absorber by almost two orders of magnitude

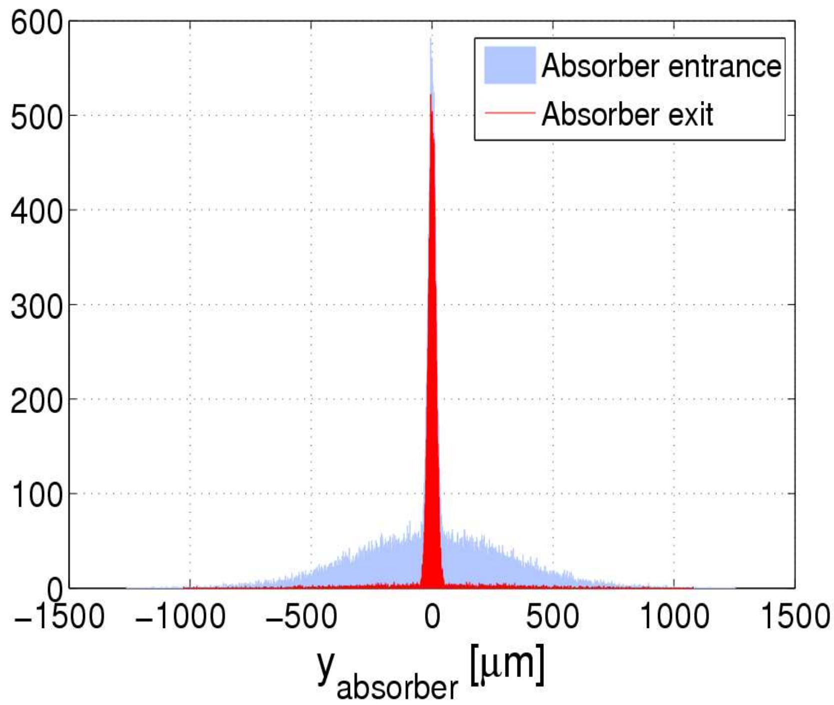
E-collimation system

Transverse beam distribution at E-absorber

Considering a beam with 1.5% centroid energy offset and an uniform energy distribution with 1% full width energy spread

Actually, assuming 1% full energy spread, part of the beam is not hitting the spoiler/absorber

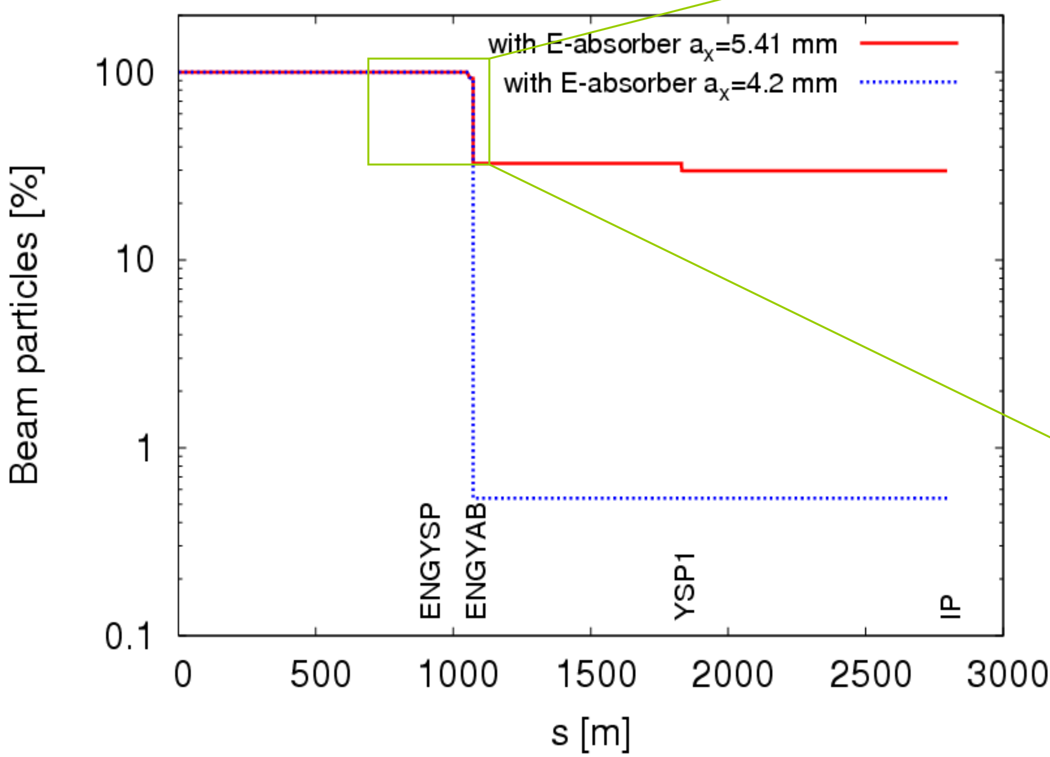


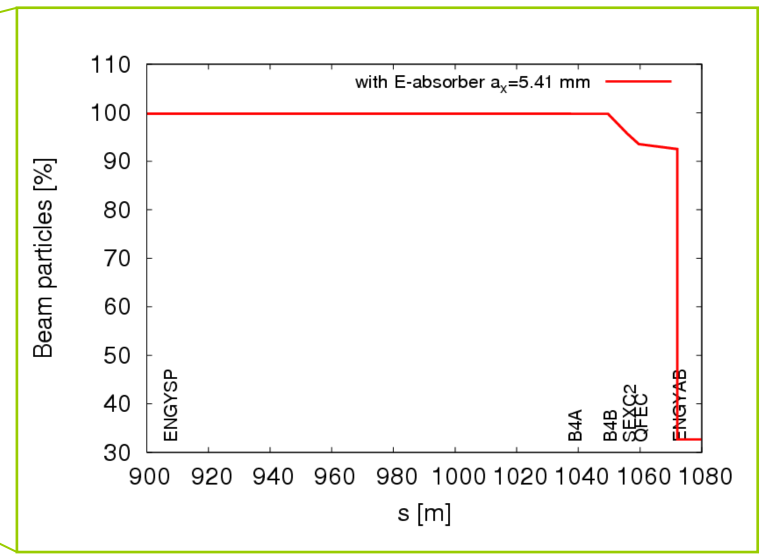


E-collimation system

Collimation of the off-energy scattered beam

Where are the particles deposited of the beam scattered by the E-spoiler?





If we reduce the E-absorber half gap to a_x=4.0 mm, practically all particles collimated in the E-absorber (ENGYAB)

Betatronic collimation

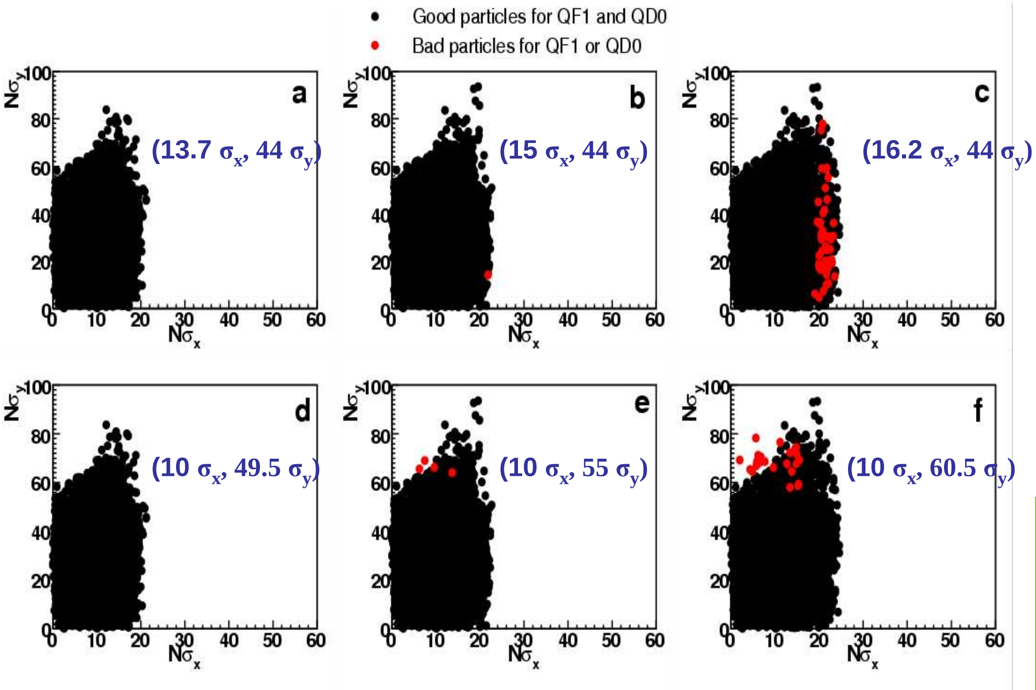
Optics and beam parameters

Name	s [m]	β_x [m]	β_y [m]	D_x [m]	σ_x [μm]	σ_y [μm]
YSP1	1830.872	114.054	483.252	0.	5.064	1.814
XSP1	1846.694	270.003	101.347	0.	7.792	0.831
XAB1	1923.893	270.102	80.905	0.	7.793	0.742
YAB1	1941.715	114.054	483.185	0.	5.064	1.814
YSP2	1943.715	114.054	483.189	0.	5.064	1.814
XSP2	1959.536	270.002	101.361	0.	7.791	0.831
XAB2	2036.736	270.105	80.944	0.	7.793	0.743
YAB2	2054.558	114.054	483.255	0.	5.064	1.814
YSP3	2056.558	114.054	483.253	0.	5.064	1.814
XSP3	2072.379	270.003	101.347	0.	7.791	0.831
XAB3	2149.579	270.102	80.905	0.	7.793	0.742
YAB3	2167.401	114.054	483.185	0.	5.064	1.814
YSP4	2169.401	114.054	483.189	0.	5.064	1.814
XSP4	2185.222	270.002	101.361	0.	7.791	0.831
XAB4	2262.422	270.105	80.944	0.	7.793	0.743
YAB4	2280.243	114.055	483.255	0.	5.064	1.814

Betatronic collimation

Optimisation of coll. apertures

[Barbara Dalena]



"Good particles":

- No emitted photons hitting QD0
- No particles hitting QF1 & QD0

"Bad particles":

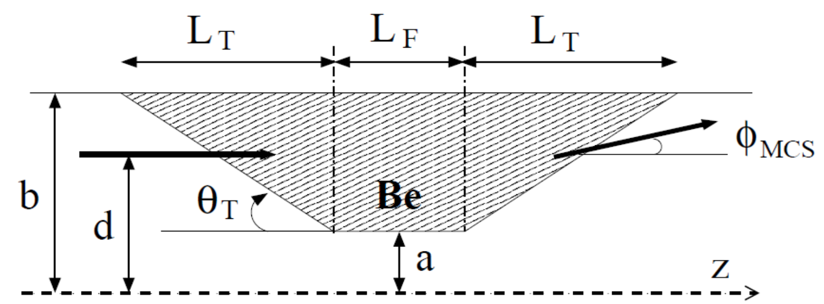
- Emitted photons hitting QD0
- Particles hitting QF1 or QD0

Old apertures (10 σ_x & 44 σ_y) clean the dangerous particle efficiently

Larger apertures (15 σ_x & 55 σ_y) give acceptable collimation efficiency, and would help to reduce wakefields

Betatronic collimation

Betatronic spoilers and absorbers



Parameter	XSP#	YSP#	XAB#	YAB#
Geometry	Rectangular	Rectangular	Elliptical	Elliptical
Vert. half-gap a_x [mm]	0.12	8.0	1.0	1.0
Hor. half-gap a_y [mm]	8.0	0.1	1.0	1.0
Tapered part radius b [mm]	8.0	8.0	8.0	8.0
Tapered part length L_T [mm]	90.0	90.0	27.0	27.0
Taper angle θ_T [mrad]	88.0	88.0	250.0	250.0
Flat part length L_F [radiation length]	0.2	0.2	18.0	18.0
Material	Be	Be	Ti alloy (Cu coated)	Ti alloy (Cu coated)

$$\sqrt{\sigma_x \sigma_y} \approx \left(\left|R_{12}^{sp\to ab}\right|\left|R_{34}^{sp\to ab}\right|\right)^{1/2} \theta_{MCS} > 600\ \mu\text{m}$$

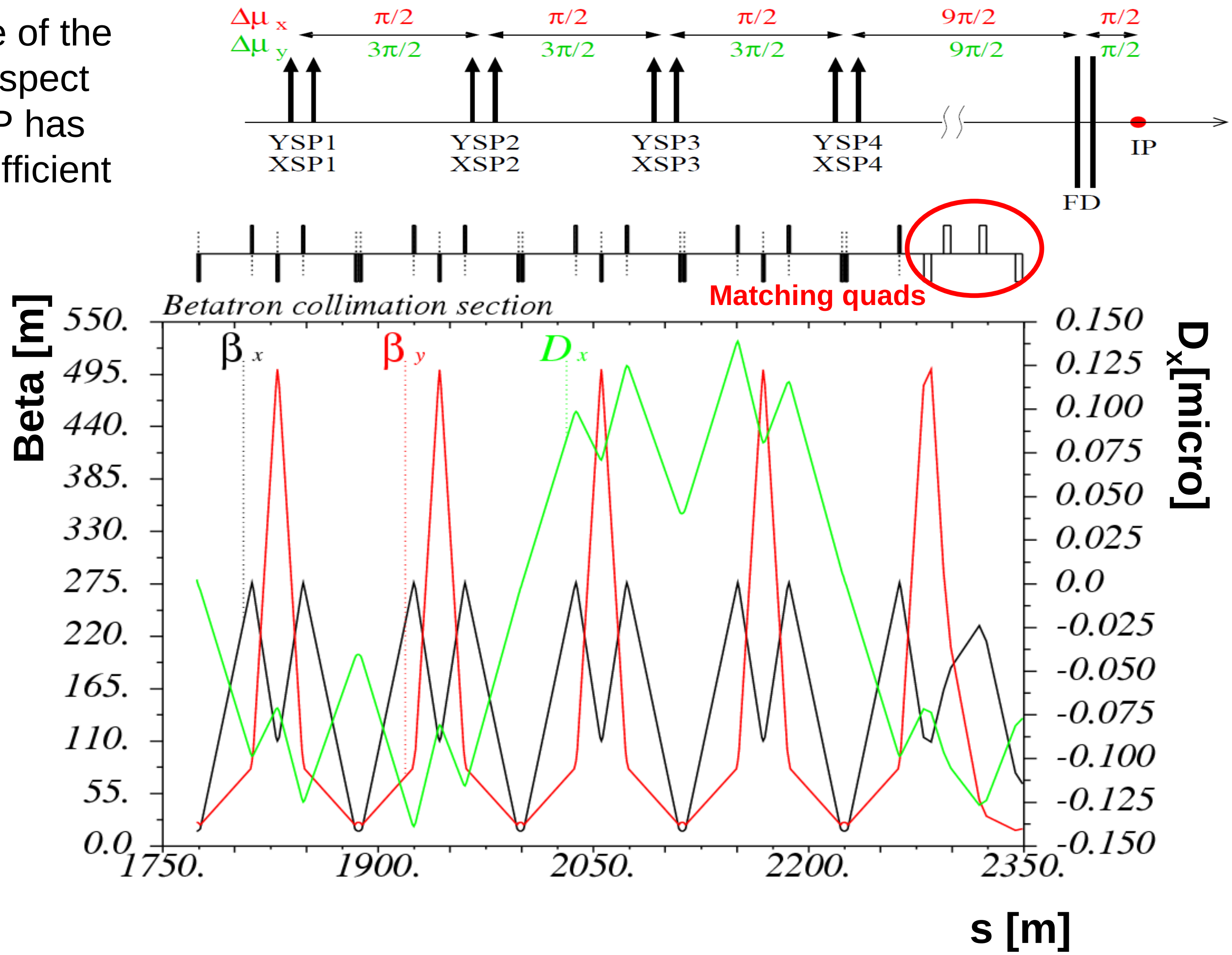
Knowing that $R_{12}^{sp\to ab} = 114.04$ m and $R_{34}^{sp\to ab} = -483.22$ m between the vertical betatron spoilers and absorbers then

the survival condition for the absorber is fulfilled if the Be spoiler is designed with a centre flat section of length L_F >~ 0.1 X_0

Betatronic collimation

Optics optimisation

The phase advance of the betatron spoilers respect to the FD and the IP has to be matched for efficient collimation



Betatronic collimation

Optics optimisation

[Frank Jackson]

In the lattice version 2008:

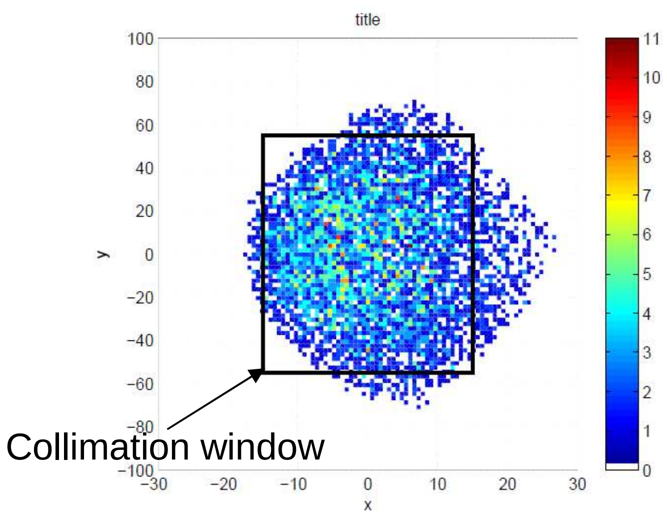
The phase advances between the fourth spoilers (YSP4 and XSP4) and the FD not an exact multiple of $\pi/2$: $\Delta\mu_{x,y}$ (SP4→FD)=9.7 $\pi/2$, 10.6 $\pi/2$

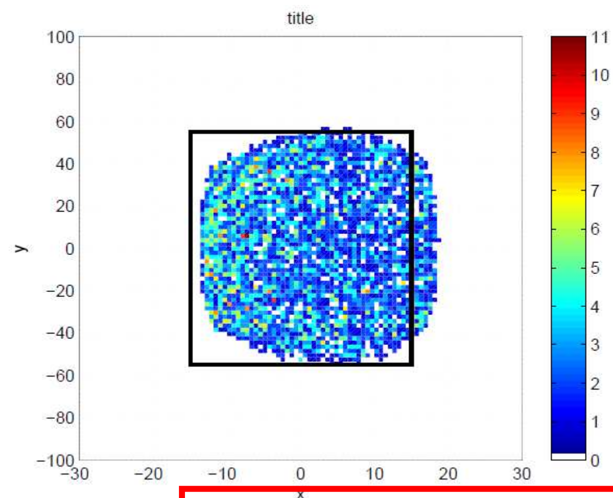
Phase-matched solution:

Beam halo x-y profile at the FD entrance:

For $\Delta\mu_{x,y}$ (SP4→FD)=9.7 $\pi/2$, 10.6 $\pi/2$ → For $\Delta\mu_{x,y}$ (SP4→FD)=10 $\pi/2$, 11 $\pi/2$

Optimisation

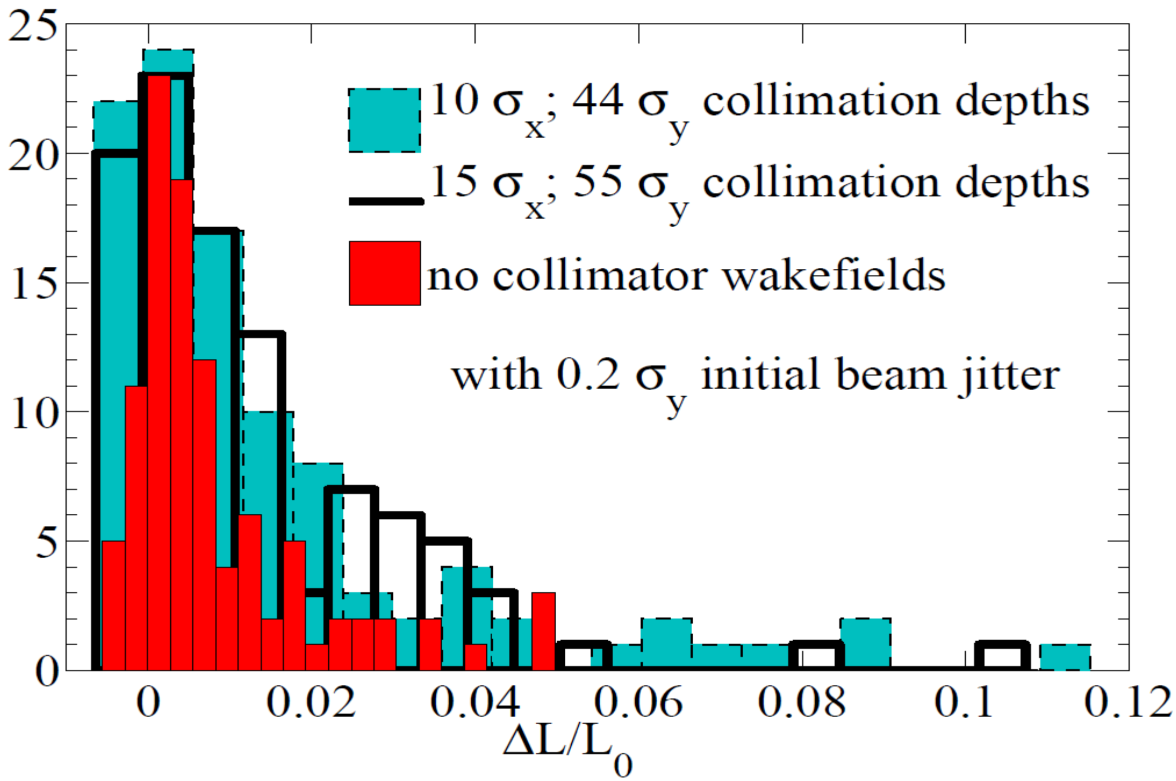




20% collimation efficiency improvement !

Collimator wakefield effects

Luminosity loss distribution from tracking studies of the CLIC BDS for 100 simulated machines considering an initial position jitter of 0.2 σ_y



- For (10 σ_x, 44 σ_y) collimation depths: 2.3% RMS luminosity loss
- For (15 σ_x, 55 σ_y) collimation depths: 1.8% RMS luminosity loss

Collimator wakefield effects
Spoiler taper angle optimisation

- Different geometrical wakefield regimes depending on the taper angle
- According to G. V. Stupakov:

$$\kappa_g = \begin{cases} \sqrt{\pi}\theta_T h/(2\sigma_z)\cdot\left(1/a^2 - 1/b^2\right) & \text{for } \theta_T < 3.1^2 a\,\sigma_z/h^2 \\ 8/3\sqrt{\theta_T/(\sigma_z a^3)} & \text{for } 0.37^2\sigma_z/a > \theta_T > 3.1^2 a\,\sigma_z/h^2 \\ 1/a^2 & \text{for } \theta_T > 0.37^2\sigma_z/a \end{cases}$$

INDUCTIVE

INTERMEDIATE

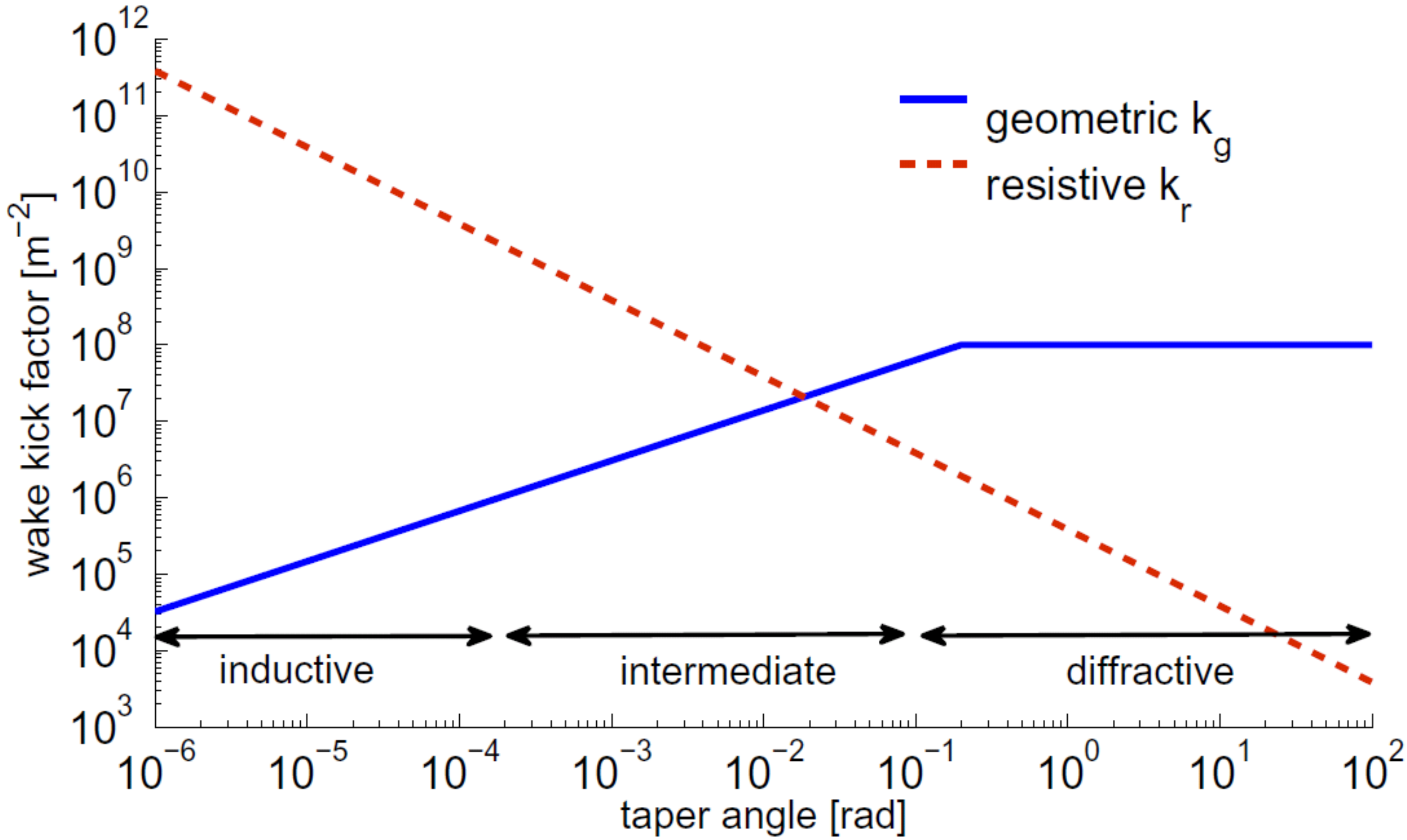
DIFRACTIVE

- For CLIC betatronic spoilers:

$$\kappa_g = \begin{cases} \sqrt{\pi}\theta_T h/(2\sigma_z)\cdot\left(1/a^2 - 1/b^2\right) & \text{for } \theta_T < 1.65\times10^{-4}\ \text{rad} \\ 8/3\sqrt{\theta_T/(\sigma_z a^3)} & \text{for } 0.06\ \text{rad} > \theta_T > 1.65\times10^{-4}\ \text{rad} \\ 1/a^2 & \text{for } \theta_T > 0.06\ \text{rad} \end{cases}$$

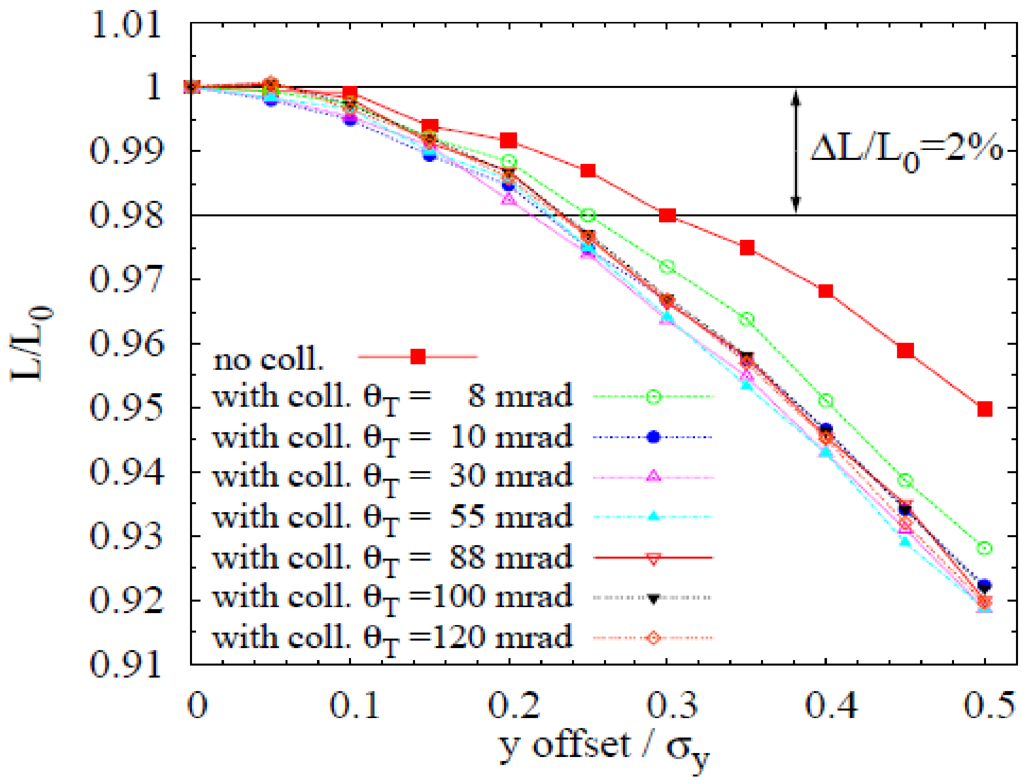
Collimator wakefield effects

Spoiler taper angle optimisation



Collimator wakefield effects
Spoiler taper angle optimisation

Relative luminosity versus y beam offset with collimator wakefield effects for different angle cases



Increasing the taper angle, practically no sensitivity.

Reducing the taper angle from 88 mrad (25 cm long betatron spoiler) to a new taper angle 8 mrad (2 m long spoiler) about 9% beam offset tolerance increase is observed

Real effect?

More investigation required

Betatronic collimation
Spoiler design review?

Due to the highly toxicity of beryllium dust special care must be taken when machining the material

Since the betatronic spoiler is not required to survive the impact of the entire train (it is planned to be sacrificial), we could use another different material for the betatronic spoiler design, e.g. Ti alloy, Ti-Cu coated.

Perhaps Ti-Cu coated is a good option to reduce the impact of wakefields

Resistive wakefield kick: $\kappa_r \propto 1 / \sqrt{\sigma_{material}}$ ($\sigma_{material}$: electrical conductivity)

$$\frac{\kappa_{Ti}}{\kappa_{Be}} = \frac{\sqrt{\sigma_{Be}}}{\sqrt{\sigma_{Ti}}} \simeq 3$$

$$\frac{\kappa_{Be}}{\kappa_{Cu}} = \frac{\sqrt{\sigma_{Cu}}}{\sqrt{\sigma_{Be}}} \simeq 2$$

Summary and outlook

- Optimisation of several aspects:
  - E-collimation:
    - Spoiler length $L_F \approx 0.05\ X_0$ seems to be enough in terms of protection of the downstream absorber
    - Considering an 1.5% energy-off beam (centroid) with 1% full energy spread , 10% losses in locations upstream of the energy absorber. Increasing the beam pipe aperture to 10 mm could help to avoid such losses in inconvenient places
    - Perhaps to reduce the present aperture of the E-absorber (5.4 mm) to 4.0 mm to improve the collimation efficiency and the protection of downstream elements

Summary and outlook

- β-collimation:
  - Optimisation of collimation apertures: (10 σ_x, 44 σ_y) → (15 σ_x, 55 σ_y)
  - Optimisation phase advance beta spoilers – FD: 20% improvement of cleaning efficiency

- Other remarks:
  - A complete tracking study using a realistic model of the halo and taking into account secondary particle emission + wakefield effects would be convenient
  - To explore other collimation alternatives, e.g. non-linear collimation, crystal collimation, other materials with special properties, for a possible CLIC phase II collimation (long term plan)

Spoiler protection

Quick calculation of the limit beam transverse density for material fracture

For thin spoilers deposition of energy per longitudinal unit, *dE/dz,* mainly due to ionization. We can calculate it using the stopping power formula of [S. M. Seltzer and M. J. Berger, Radiat. Isot. Vol. 35, No. 7 (1984) 665-675]:

dE/dz= 4.4 MeV/cm by an electron beam in a beryllium spoiler

Using these values we can compute the survival limit:

$$\sigma_x \sigma_y > \frac{1}{\rho_{sp} C} \left(\frac{dE}{dz} \right) \frac{N_e N_b e}{2\pi \Delta T_{fracture}}$$

$$\sigma_x \sigma_y > 10481 \ \mu\text{m}^2$$

$$\hat{\rho}(x, y) < 56.5 \times 10^9 \ \text{e/mm}^2 \ \text{per bunch}$$

For the CLIC E-spoiler:
Assuming a beam with an uniform energy distribution with 1% full energy spread:

$$\sigma_x = \sqrt{D_x^2 \sigma_E^2 / 12 + \beta_x \varepsilon_x} = 779.6 \ \mu\text{m}$$

$$\sigma_y = 21.9 \ \mu\text{m}$$

$$\sigma_x \sigma_y = 17073.24 \ \mu\text{m}$$

1.6 times higher than the limit !

Multiple Coulomb Scattering

- RMS scattering angle by MCS (Gaussian approximation of the Moliere formula) [PDG]:

$$\theta_{MCS} = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{l_r}\left[1 + 0.038 \ln\left(l_r\right)\right]$$

Where l_r is the thickness of the scattering medium (spoiler) in units of radiation length (X_0)

θ_{MCS} is accurate to 11% or better for $10^{-3} < l_r < 100$

For Montecarlo simulations, using the random variables (r_1, r_2) we can calculate transverse position and angle at the exit of the spoiler as follows:

$$y_{sp} = y_{sp0} + r_1 l_r X_0 \theta_{MCS} / \sqrt{12} + r_2 l_r X_0 \theta_{MCS} / 2 ;$$
$$y'_{sp} = y'_{sp0} + r_2 \theta_{MCS}$$

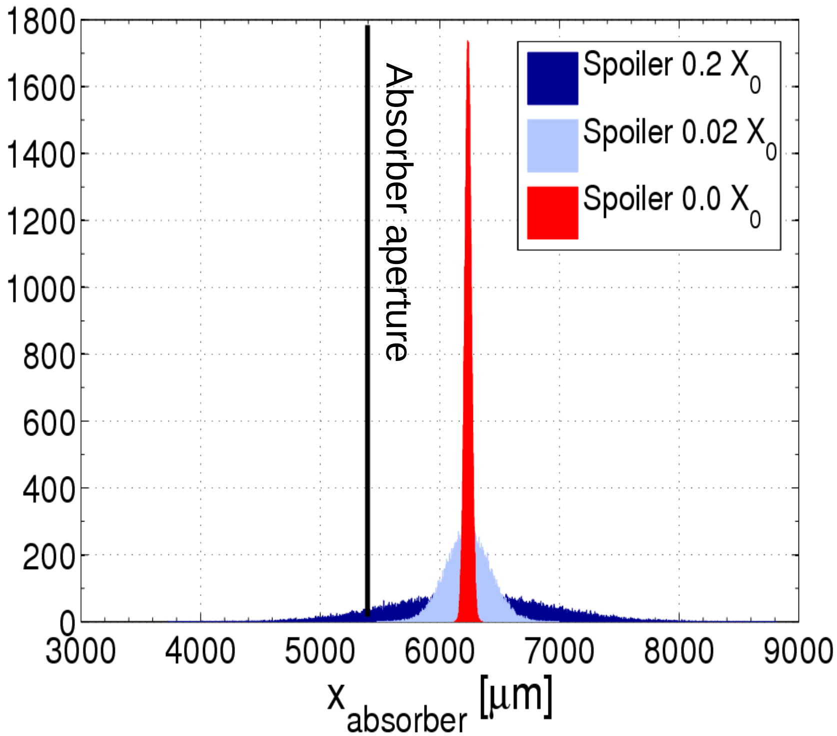
Where y_{sp0} , y'_{sp0} are the particle position and angle, respectively, at the entrance of the spoiler

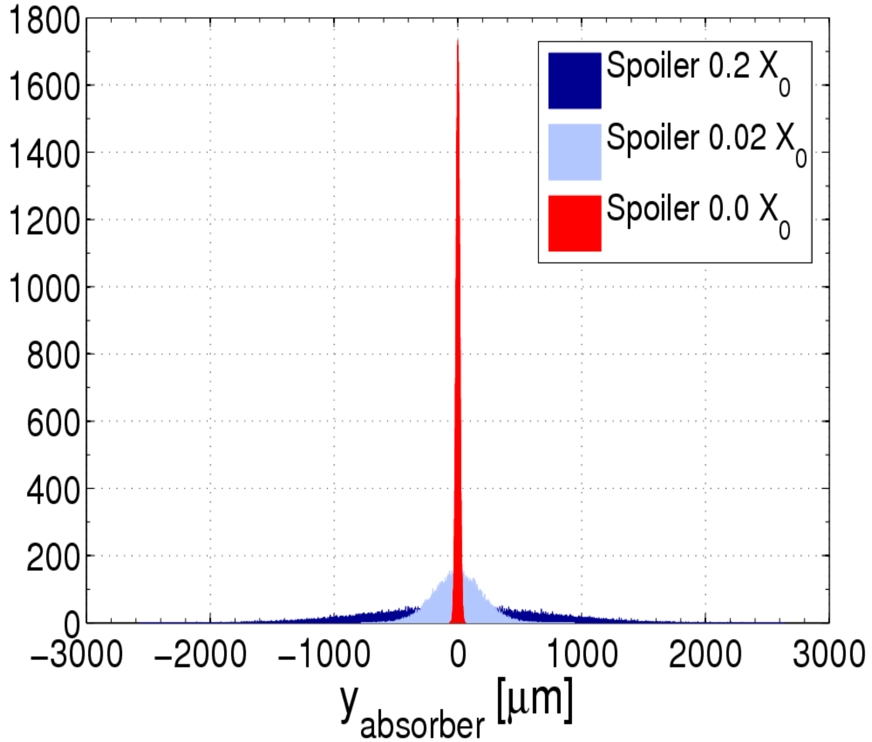
Transverse beam distribution at E-absorber

Considering a monochromatic beam with 1.5% energy offset respect to the nominal energy impinging on the spoiler for different cases of spoiler thickness

Tracking studies using the code placet-octave (50000 macroparticles)

Assuming full beam transmission through the E-spoiler and applying MCS (function MCS.m created using octave)





Transverse beam density at E-absorber

Table 1. Bunch density at the downstream E-absorber for different thickness of the E-spoiler, including the multiple Coulomb scattering in the spoiler. These values correspond to a monochromatic beam with 1.5% energy offset with respect to the nominal beam energy 1500 GeV.

SPOILER	ABSORBER	
Thickness [X_0]	$\sigma_{ab} = \sqrt{\sigma_x \sigma_y}$ [μm]	$\hat{\rho}_{ab} = N_e/(2\pi\sigma_x\sigma_y)$ [e/mm^2 per bunch]
0.0	20.124	1.462×10^{12}
0.02	184.457	1.74×10^{10}
0.05	301.686	6.505×10^{9}
0.1	439.538	3.066×10^{9}
0.2	637.832	1.455×10^{9}
0.5	1048.193	5.389×10^{8}

Table 2. Bunch density at the downstream E-absorber for different thickness of the E-spoiler, including the multiple Coulomb scattering in the spoiler. These values correspond to a beam with 1.5% energy offset with respect to the nominal beam energy 1500 GeV, and 1% full energy spread (uniform energy distribution).

SPOILER	ABSORBER	
Thickness [X_0]	$\sigma_{ab} = \sqrt{\sigma_x \sigma_y}$ [μm]	$\hat{\rho}_{ab} = N_e/(2\pi\sigma_x\sigma_y)$ [e/mm^2 per bunch]
0.0	132.785	3.358×10^{10}
0.02	475.117	2.623×10^{9}
0.05	614.501	1.568×10^{9}
0.1	752.45	1.046×10^{9}
0.2	932.822	6.804×10^{8}
0.5	1295.238	3.529×10^{8}

E-collimation system
Spoiler thickness and absorber protection

- The spoilers must provide enough beam angular divergence by multiple coulomb scattering in order to reduce the damage probability of the downstream absorber and/or another downstream component

For the protection of absorbers made of Ti-Cu coatted:

$$\sqrt{\sigma_x \sigma_y} > 600 \ \mu\text{m}$$

Value from studies for the NLC (see e.g. P. Tenenbaum, Proc. of LINAC 2000, MOA08). Necessary simulations to update this limit.

Betatronic spoiler-absorber:

$$\sqrt{\sigma_x \sigma_y} \approx \left(\left| R_{12}^{sp \to ab} \right| \left| R_{34}^{sp \to ab} \right| \right)^{1/2} \theta_{MCS} > 600 \ \mu\text{m}$$

Knowing that $R_{12}^{sp \to ab} = 114.04$ m and $R_{34}^{sp \to ab} = -483.22$ m between the vertical betatron spoilers and absorbers then

the survival condition is fulfilled if the Be spoiler is designed with a centre flat section of length

$L_F >\sim 0.1 \, X_0$