Discussing a few aspects of the CLIC collimation system

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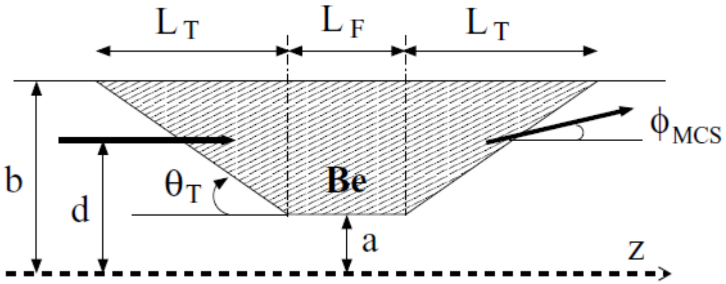
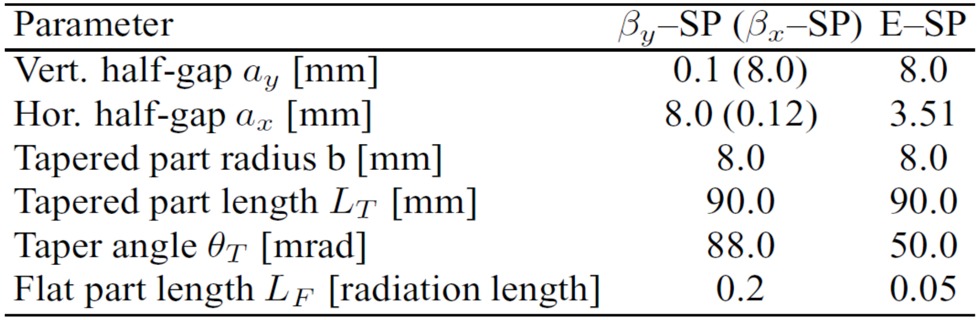
Spoiler and absorber scheme

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

Geometrical parameters of the CLIC spoilers [IPAC10] :





Parameter	β_y–SP (β_x–SP)	E–SP
Vert. half-gap a_y [mm]	0.1 (8.0)	8.0
Hor. half-gap a_x [mm]	8.0 (0.12)	3.51
Tapered part radius b [mm]	8.0	8.0
Tapered part length L_T [mm]	90.0	90.0
Taper angle θ_T [mrad]	88.0	50.0
Flat part length L_F [radiation length]	0.2	0.05

Spoiler protection

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

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

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

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

For Be spoiler:

ρ_{sp} (material density)=1.84 x 10^6 g/m^3
C (specific heat)=1.825 J/(g K)
$\Delta T_{fracture}$=370 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-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 Bethe-Bloch formula [PDG]:

$X_0\,(dE/dz)_{min}$=103.98 MeV is the minimum energy deposition per radiation length

Using these values we can compute the survival limit:

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

$$\sigma_x\sigma_y > 7016.61\ \mu\text{m}^2$$

$$\hat{\rho}(x,y) < 84.38\times 10^9\ \text{e/mm}^2\ \text{per bunch}$$

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

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

$$\sigma_\text{y} = 21.9\ \mu\text{m}$$

$$\sigma_\text{x}\sigma_y = 17073.24\ \mu\text{m}$$

More than 2 times higher than the limit

E-Spoiler protection

- However, the previous calculation underestimates the survival limit

- In order to determine the survivability of the spoiler simulations needed. For example, using the codes FLUKA and ANSYS (presentation by Luis)

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:

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

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:

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

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

$L_F >\sim 0.1\,\text{X}_0$

Spoiler thickness and absorber protection

Energy spoiler-absorber:

In this case 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

$$L_F >\sim 0.02\,\mathrm{X}_0$$

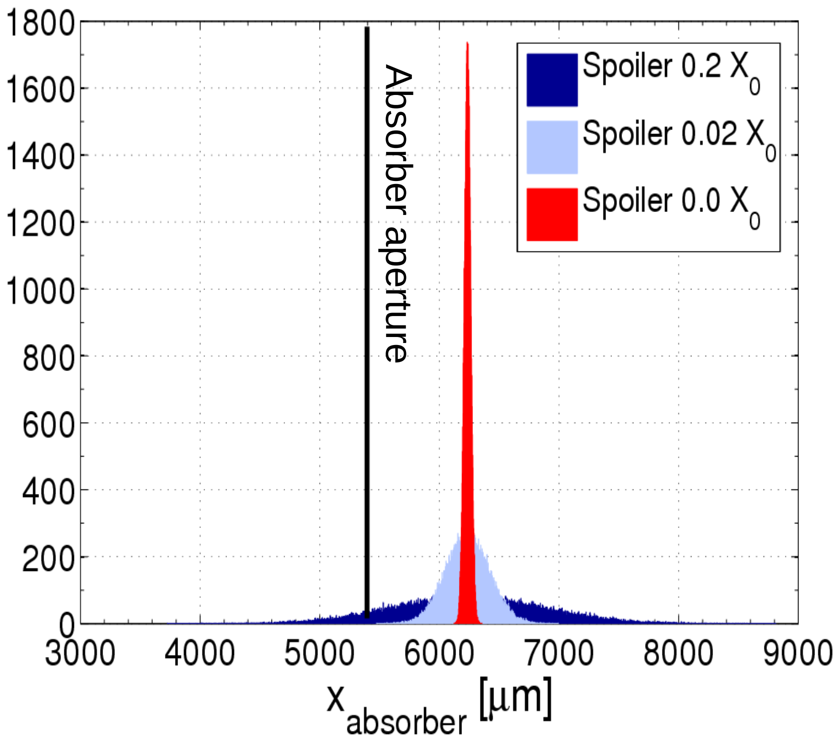
Perhaps these figures too optimistic or to pessimistic! In order to confirm these results we have performed montecarlo simulations including MCS at the spoiler position to study study the beam density at the downstream absorber for different values of spoiler thickness.

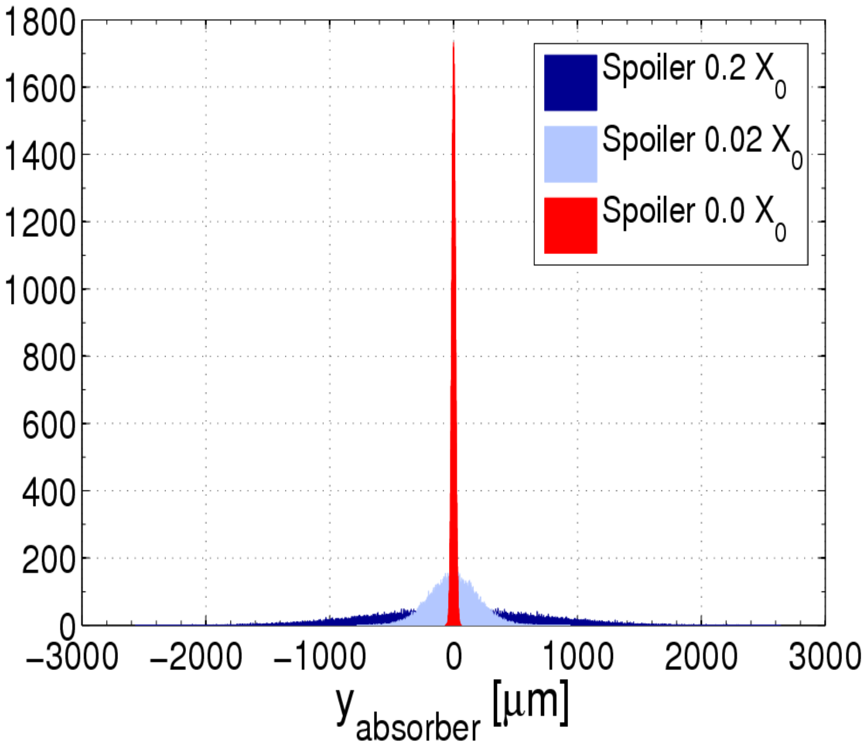
Transverse beam distribution at E-absorber

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)

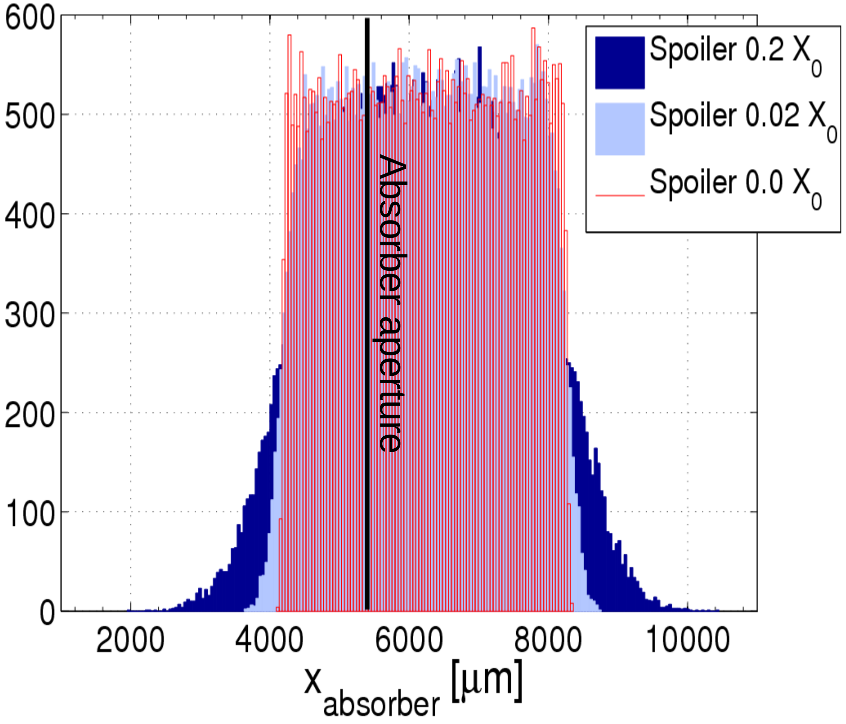
Assuming full beam transmission through the E-spoiler and applying MCS (function MCS.m created using octave)

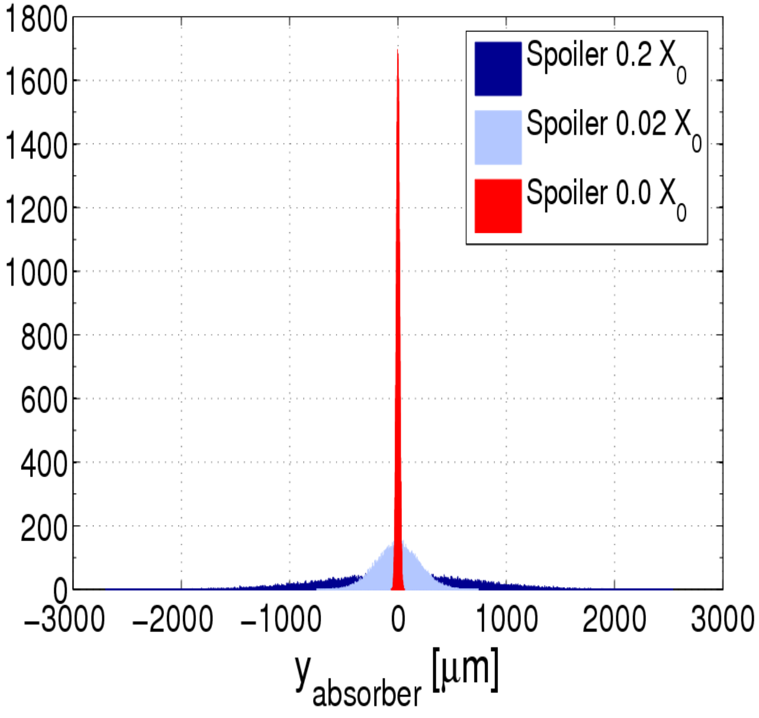




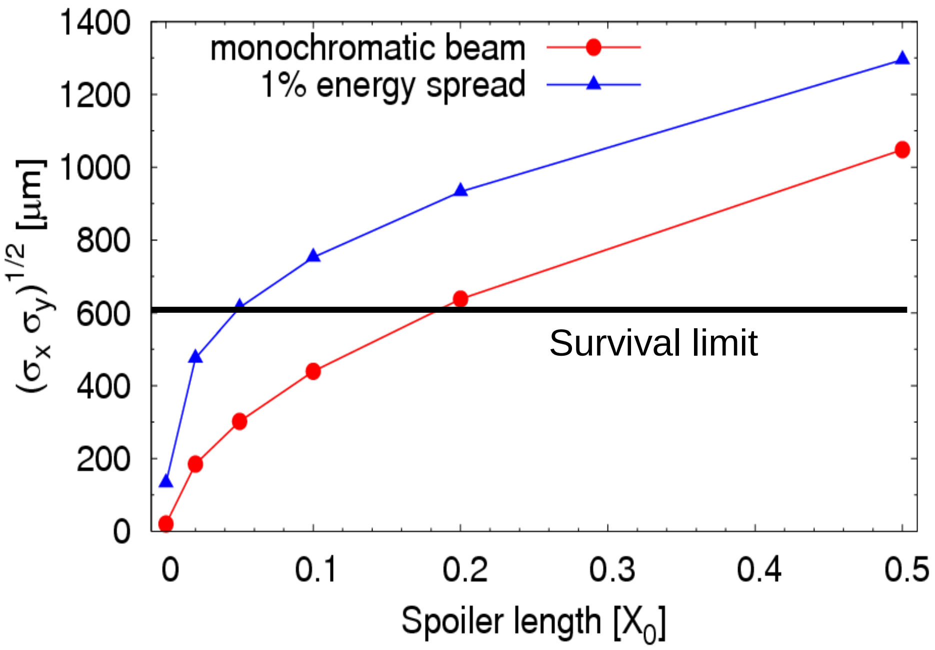
Transverse beam distribution at E-absorber

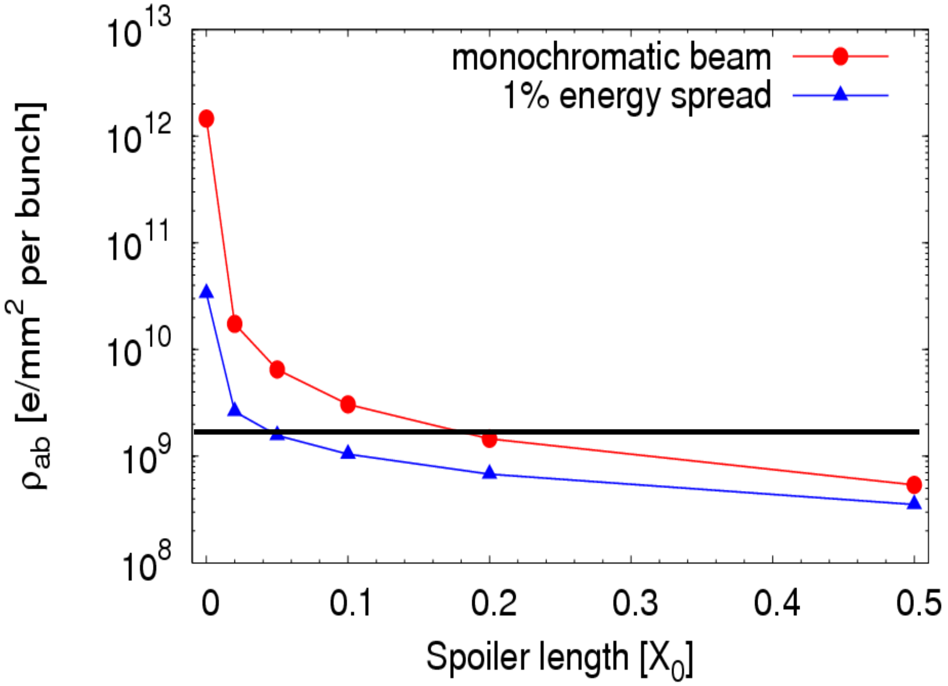
Considering a beam with 1.5% centroid energy offset and an uniform energy distribution with 1% full width energy spread





Transverse beam density at E-absorber





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

Transverse beam density at E-absorber

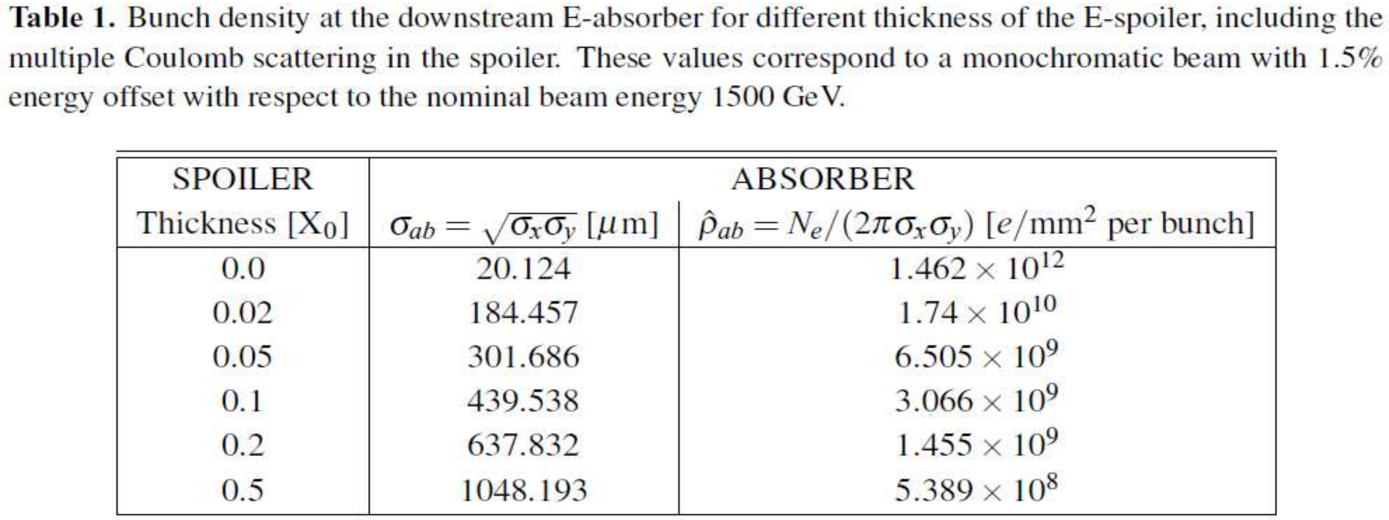


Table 1. Bunch density at the downstream E-absorber for different thickness of the E-spoiler, including the multiple Coulomb scattering in the spoiler. These values correspond to a monochromatic beam with 1.5% energy offset with respect to the nominal beam energy 1500 GeV.

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}

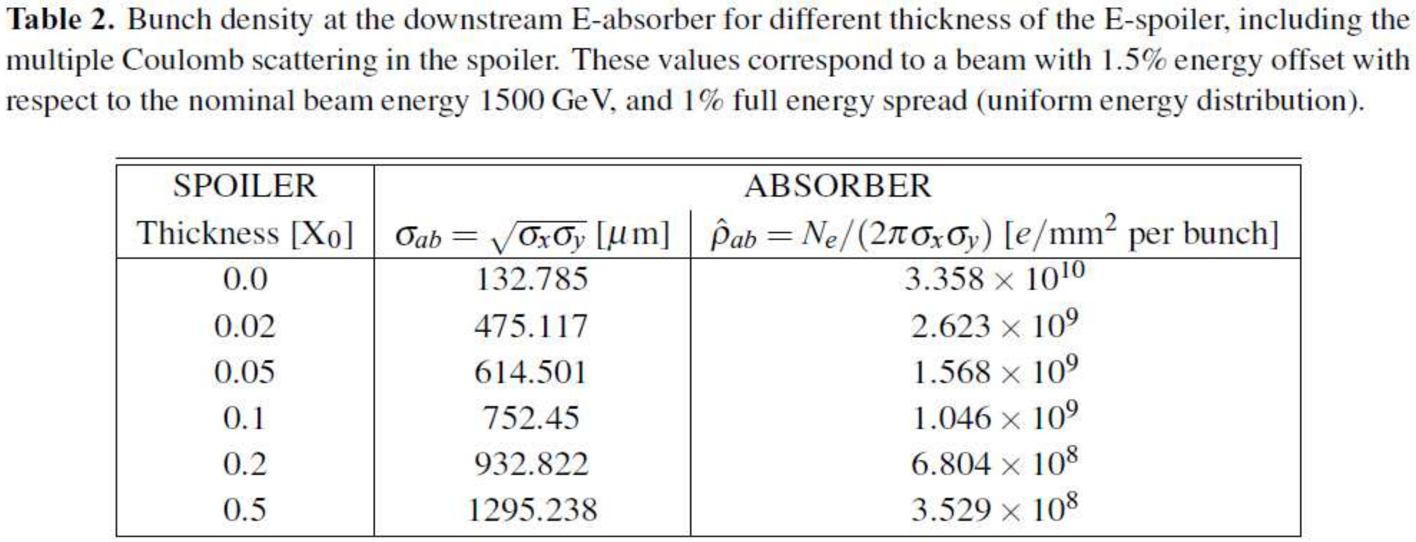


Table 2. Bunch density at the downstream E-absorber for different thickness of the E-spoiler, including the multiple Coulomb scattering in the spoiler. These values correspond to a beam with 1.5% energy offset with respect to the nominal beam energy 1500 GeV, and 1% full energy spread (uniform energy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

Some comments

- For the case with uniform energy spread with have also estimated the transverse density peak roughly using $\hat{\rho}_{ab} = N_e/(2\pi\sigma_x\sigma_y)\ [e/\mathrm{mm}^2 \text{ per bunch}]$

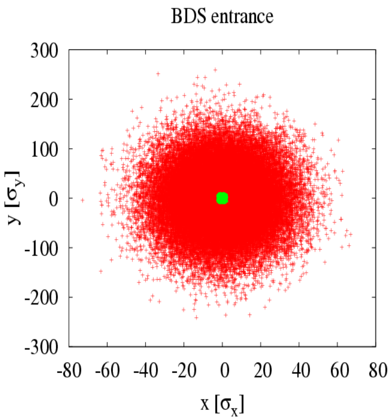
Taking $\sigma_{x,y}$ as the standard deviation of the particle distribution

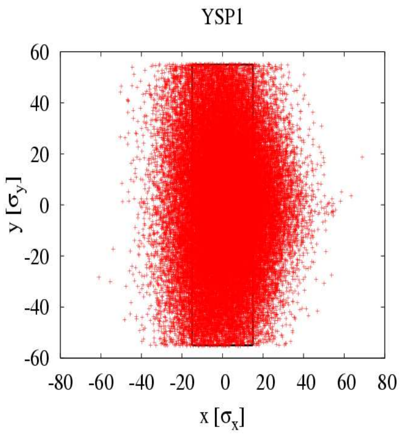
However, for x the distribution is no-Gaussian, it would be more precise to calculate

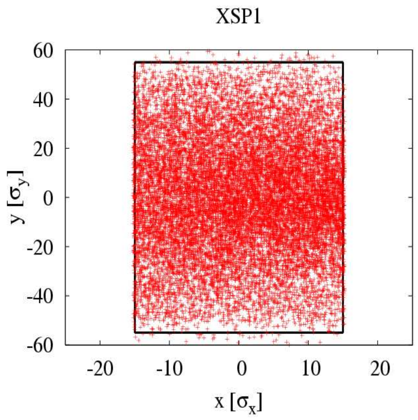
$$\hat{\rho}_{ab} = Max\,[\rho(x,y)]$$

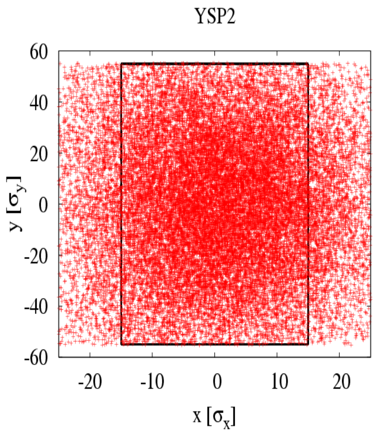
for an arbitrary transverse beam density $\rho(x,y)$

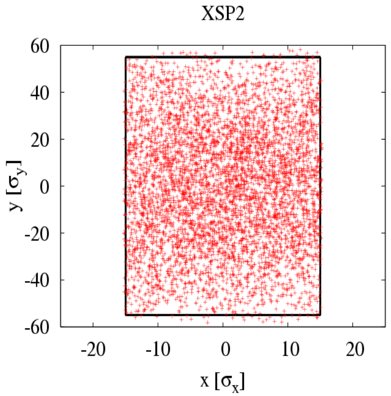
Betatronic collimation

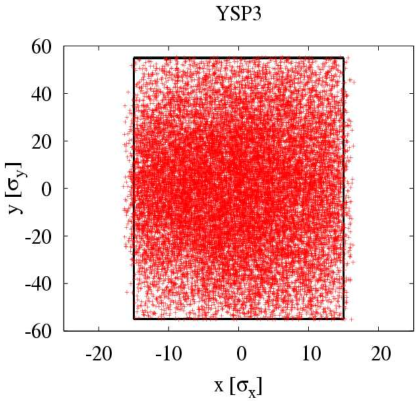


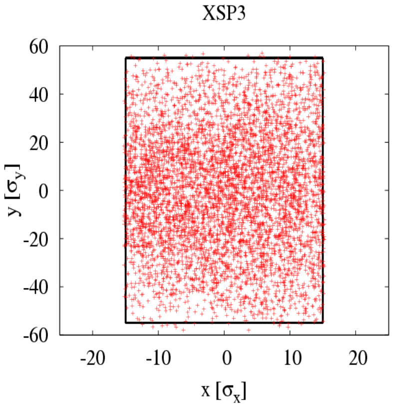


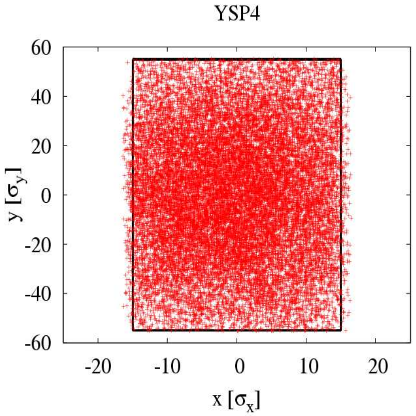


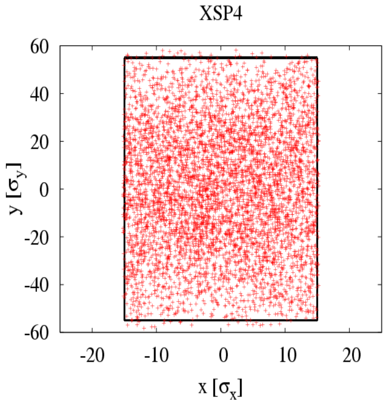


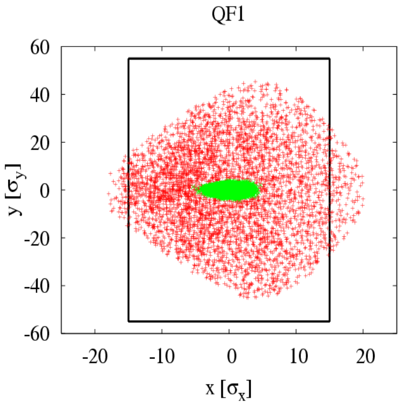












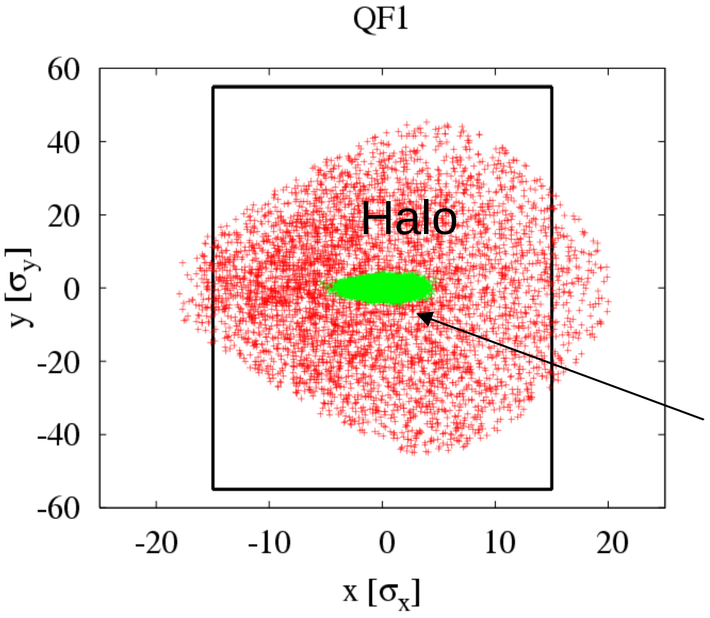
Using an initial Gaussian beam distribution of 50000 macroparticles with rms $10^{3/2}\ \sigma_{x,y}$

Betatronic collimation

Phase advance optimisation

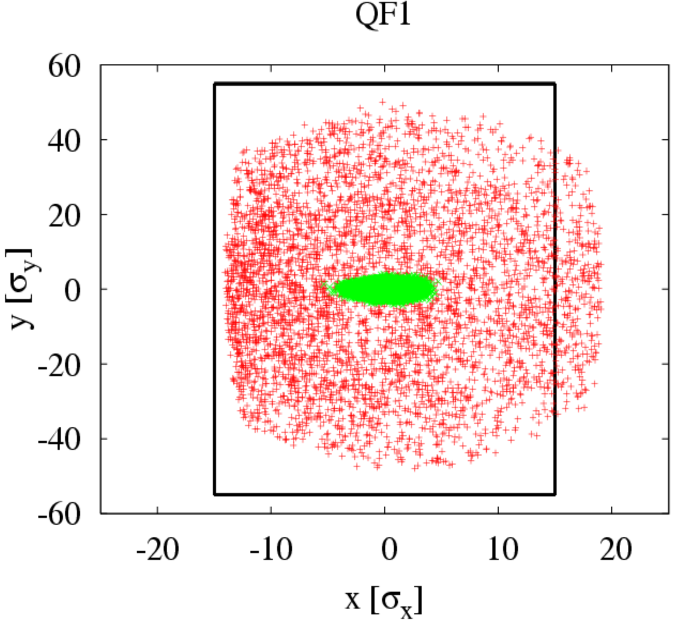
Halo transverse profile at the entrance of QF1:

Before optimisation



Nominal beam

After optimisation
(using Frank Jackson’s lattice)



9.65 % of the initial halo

4.8% of the this remaining halo outside the collimation window

8.89 % of the initial halo

6.25 % of this remaining halo outside the collimation window

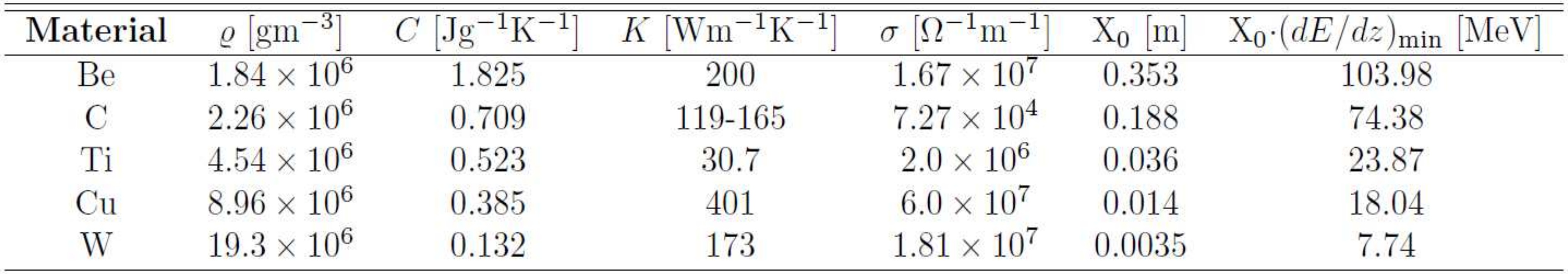
Summary and outlook

- Spoiler dimensions review: a flat part of length for 0.2 X_0 for the betatronic spoilers and about 0.05 X_0 for the energy spoiler may be enough in terms of downstream absorber protection.

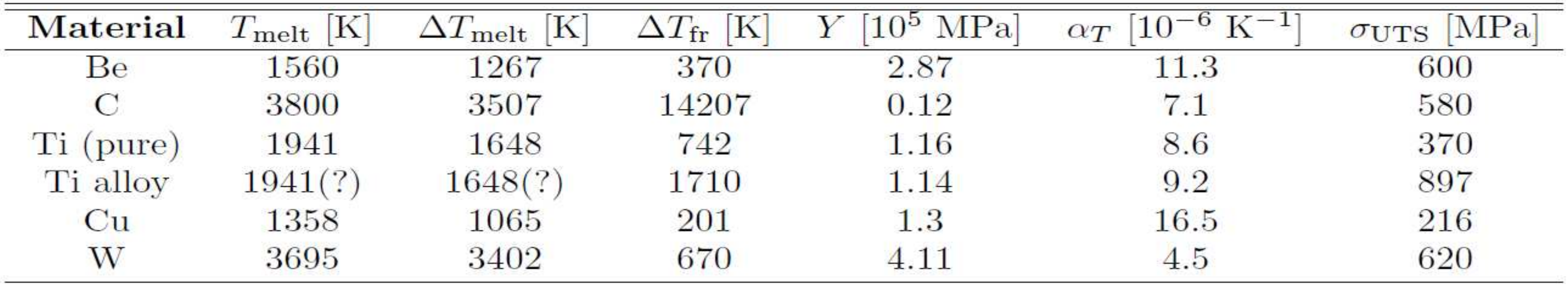
- Next:
  - Betatron efficiency studies:
    - With realistic halo
    - With MCS in the spoilers
    - Particles stopped only by the absorbers
    - For much more complete and realistic simulations necessary to use codes as BDSIM
    - Compare results with the simple case of “perfect collimators”

- We have also to discuss another material better than Be (Be is not a pleasant material to work with due to its toxicity) for the betatronic spoilers, since these are foreseen to be sacrificial and the survival condition is not a strong constraint in this case

Appendix: material properties



Material	ϱ [gm^{-3}]	C [Jg^{-1}K^{-1}]	K [Wm^{-1}K^{-1}]	σ [Ω^{-1}m^{-1}]	X$_0$ [m]	X$_0 \cdot (dE/dz)_{\text{min}}$ [MeV]
Be	1.84×10^6	1.825	200	1.67×10^7	0.353	103.98
C	2.26×10^6	0.709	119-165	7.27×10^4	0.188	74.38
Ti	4.54×10^6	0.523	30.7	2.0×10^6	0.036	23.87
Cu	8.96×10^6	0.385	401	6.0×10^7	0.014	18.04
W	19.3×10^6	0.132	173	1.81×10^7	0.0035	7.74



Material	T_{melt} [K]	ΔT_{melt} [K]	ΔT_{fr} [K]	Y [10^5 MPa]	α_T [10^{-6} K^{-1}]	σ_{UTS} [MPa]
Be	1560	1267	370	2.87	11.3	600
C	3800	3507	14207	0.12	7.1	580
Ti (pure)	1941	1648	742	1.16	8.6	370
Ti alloy	1941(?)	1648(?)	1710	1.14	9.2	897
Cu	1358	1065	201	1.3	16.5	216
W	3695	3402	670	4.11	4.5	620

Appendix: Multiple Coulomb Scattering

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

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

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