Halo formation and losses in CLIC

by Helmut Burkhardt

General definition and concepts

Core : particles < n_σ

Halo = Tail : particles > n_σ

in x,y, z transverse and longitudinal

Luminosity is from the core

for Gaussian beams, 99.2 % of the luminosity from $n_\sigma < 3$

see H.B., R.S. Intensity and Luminosity after Beam Scraping, CERN–AB–2004–054

Important in 3 TeV CLIC to keep the halo at a very low ~ 10^{-6} level

halo collimation very difficult for small beams at very high energy

and source of radiation and muon background into the detector

Estimates for design conditions. Not dealing here with failure scenarios

Halo sources

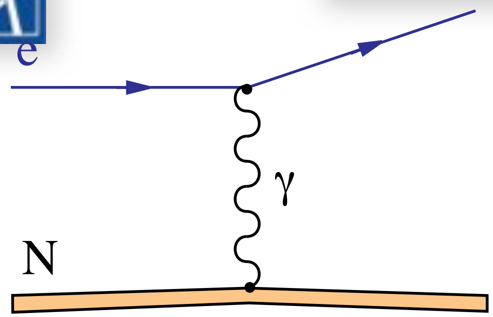
Known sources, 3 categories

- Particle processes : beam gas, (quasi) elastic and inelastic (Bremsstrahlung), thermal photon
- Optics related : mismatch, coupling, dispersion, non-linearities -- requires tracking for the "real" machine, tracking so far with ideal machine
- Various : noise and vibrations, dark currents, wakefields -- currently not simulated for halo

Caution, by experience :
the actual amount of beam halo is very hard to predict and may vary considerably in a given machine.

HTGEN : halo/tail generation, developed as EuroTeV FP6 activity ; fully integrated in PLACET applied to LINAC, BDS and drive beam; info and references on web page HTGEN.html

Beam gas elastic* scattering



Coulomb (Mott)

* small recoil correction - quasi elastic

total cross section $\sigma_{\rm el} = \dfrac{4\pi\, Z^2\, r_e^2}{\gamma^2\, \theta^2_{\rm min}}$

at constant normalized emittance $\epsilon_N = \gamma\, \epsilon$

scaling as 1/γ, 1/energy, ×β
beginning of LINAC and
high-β collimation section important

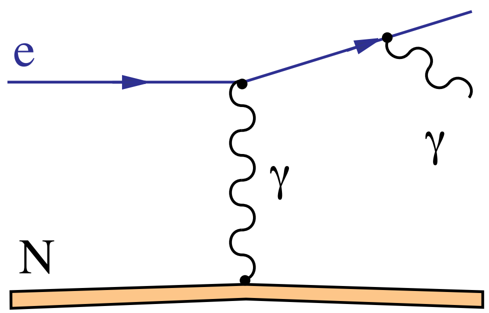
$$\sigma_{\rm el} = \frac{4\pi\, Z^2 r_e^2\, \beta_y}{\epsilon_N\, \gamma}$$

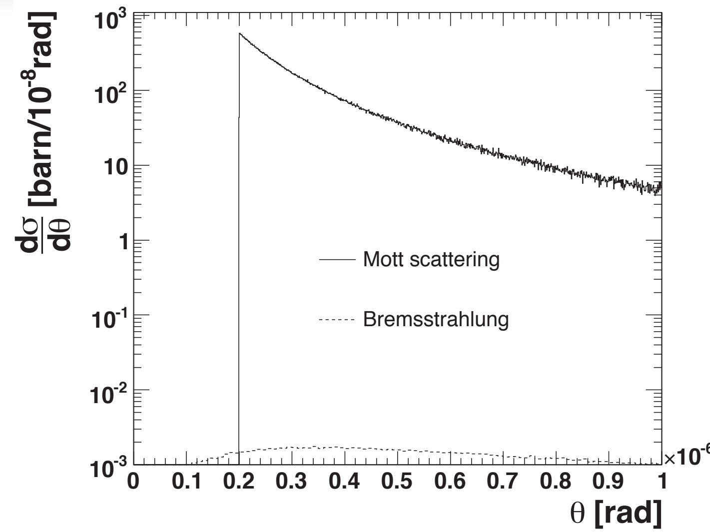
CLIC 2007 estimate. P = probability / m for scattering > 1 σ divergence

Location	E GeV	Gas	ρ m^{-3}	$\sigma_{\rm el}$ Barn	P m^{-1}
LINAC	9	CO	3.2×10^{14}	2.7×10^{7}	8.9×10^{-7}
BDS	1500	CO	3.2×10^{14}	1.7×10^{5}	1.1×10^{-8}

Probability 80x higher beginning of LINAC at 9 GeV compared to end at 1.5 TeV and BDS. Integrated over length using averaged β :
total LINAC Prob. $P = 1.16\times10^{-3}$, BDS $P = 6.0\times10^{-5}$ together 1.2×10^{-3} at 1σ
total LINAC Prob. $P = 1.29\times10^{-6}$, BDS $P = 6.7\times10^{-8}$ together 1.4×10^{-6} at 30 σ (loss)
placet-htgen simulation LINAC+CLIC fraction of 2×10^{-4} lost at spoilers (2007 estimate, 10nTorr)

Inelastic scattering





generated with htgen example TestProcess

scattering angle (of γ with respect to incident e)

$$f(\theta)d\theta \propto \frac{\theta\, d\theta}{(\theta^2+\gamma^{-2})^2}\,.$$

energy fraction k going to photon

$$\frac{d\sigma}{dk} = \frac{A}{N_A X_0}\,\frac{1}{k}\left(\frac{4}{3}-\frac{4}{3}k+k^2\right)$$

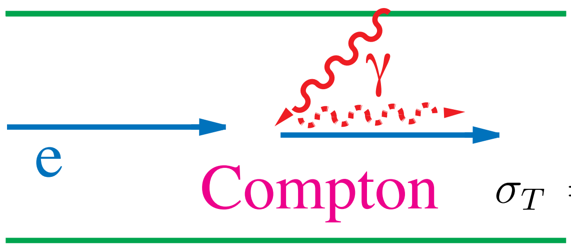
integrated for k > 1%, no E dependence
σ = 6.609 Barn for N_2

$$\sigma_{\rm in} = \frac{A}{N_A X_0}\left(-\frac{4}{3}\log\, k_{\rm min} - \frac{5}{6} + \frac{4}{3}k_{\rm min} - \frac{k_{\rm min}^2}{2}\right)$$

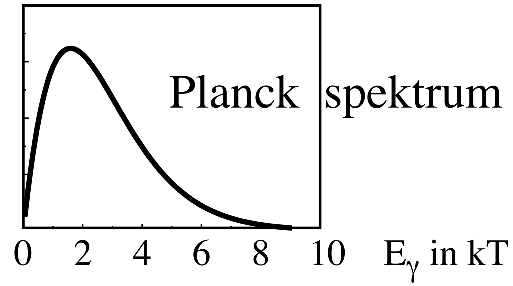
Probability: 2.1×10^{-13}/m
summing up over both LINAC and BDS : P = 5.0×10^{-9}

fully included in current HTGEN, minor contribution for CLIC

Scattering off thermal photons



$\sigma_T = \frac{8\pi}{3} r_e^2 = 0.6652 \text{ barn}$



mean energies:

initial : $E_\gamma^i = 2.7\ kT = 0.07\ eV$

e-rest: $E_\gamma = \gamma E_\gamma^i = 6.2\ keV \ll m_e$

$$\rho_\gamma = 8\pi \left(\frac{kT}{hc}\right)^3 \cdot \underbrace{\int_0^\infty \frac{x^2}{e^x - 1} dx}_{2.404114}$$

$5.32\times10^{14}/m^3$ at room temp.

Lab: $E_\gamma' = \gamma E_\gamma^* \cong \gamma^2 E_\gamma^i$

2.4% at 100 GeV, 5.3% at 250 GeV, 86% at 1.5 TeV

Was important for beam halo in LEP and the dominant single beam lifetime

CLIC 1.5 TeV $P = 1.9\times10^{-14}$/m for 2% energy loss.
integrated over LINAC + BDS   still below 10^{-9}
not an issue

MC generator, see SL/Note 93-73 (OP)

Halo estimate, CLIC drive beam

HTGEN beam-gas simulations for the drive beam

only meaningful for full intensity - even on todays computer not possible to simulate efficiently the full intensity with single particle codes as required for beam-gas scattering

Combined simulation of :

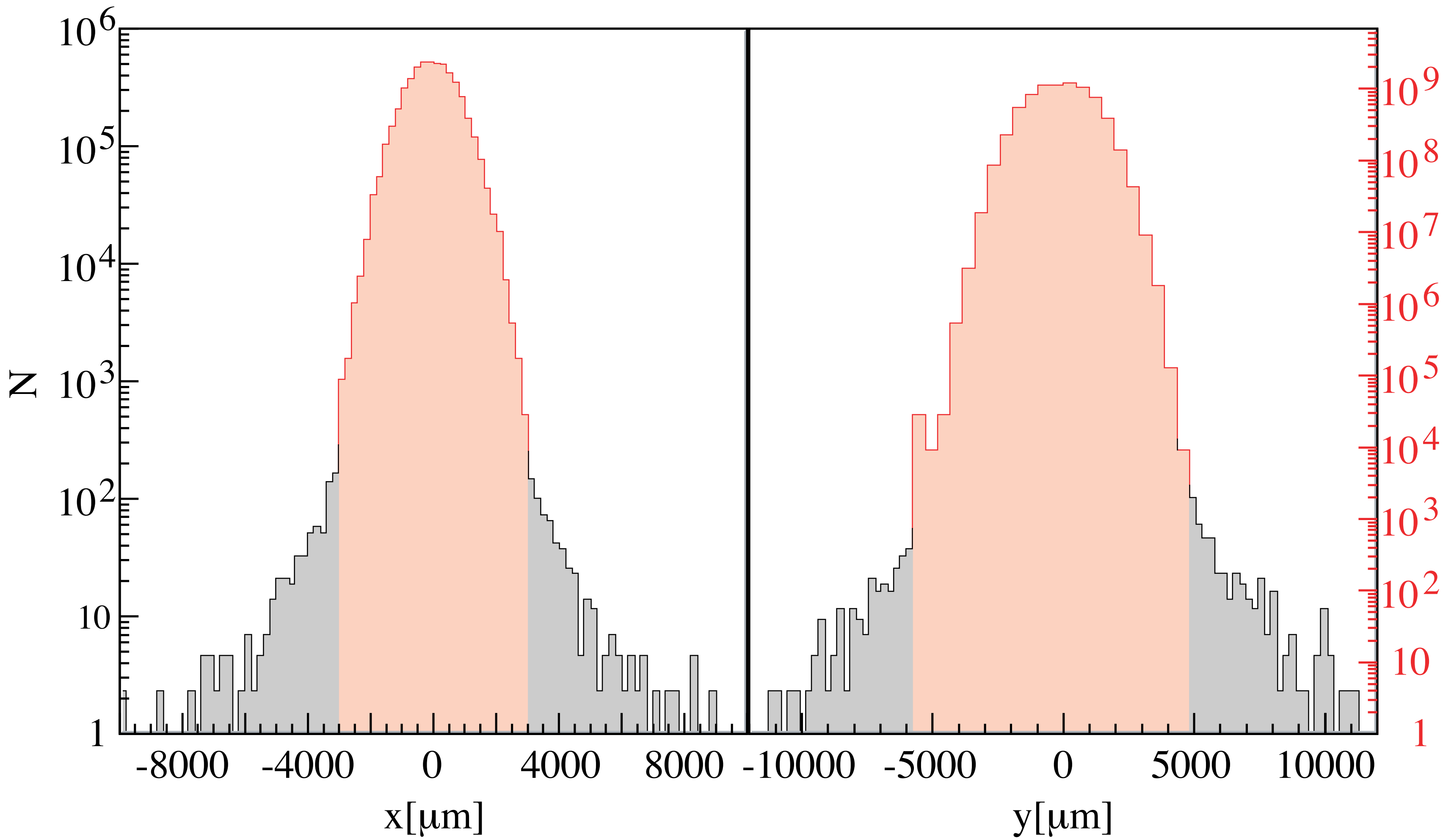
- **drive beam using macroparticles and slices**
- **halo simulation, scattering processes always done on single particle level**

possible by considering only collective effects from the core, acting on both core and tail neglecting collective effects of the halo

Subject of a diploma thesis by M. Fitterer

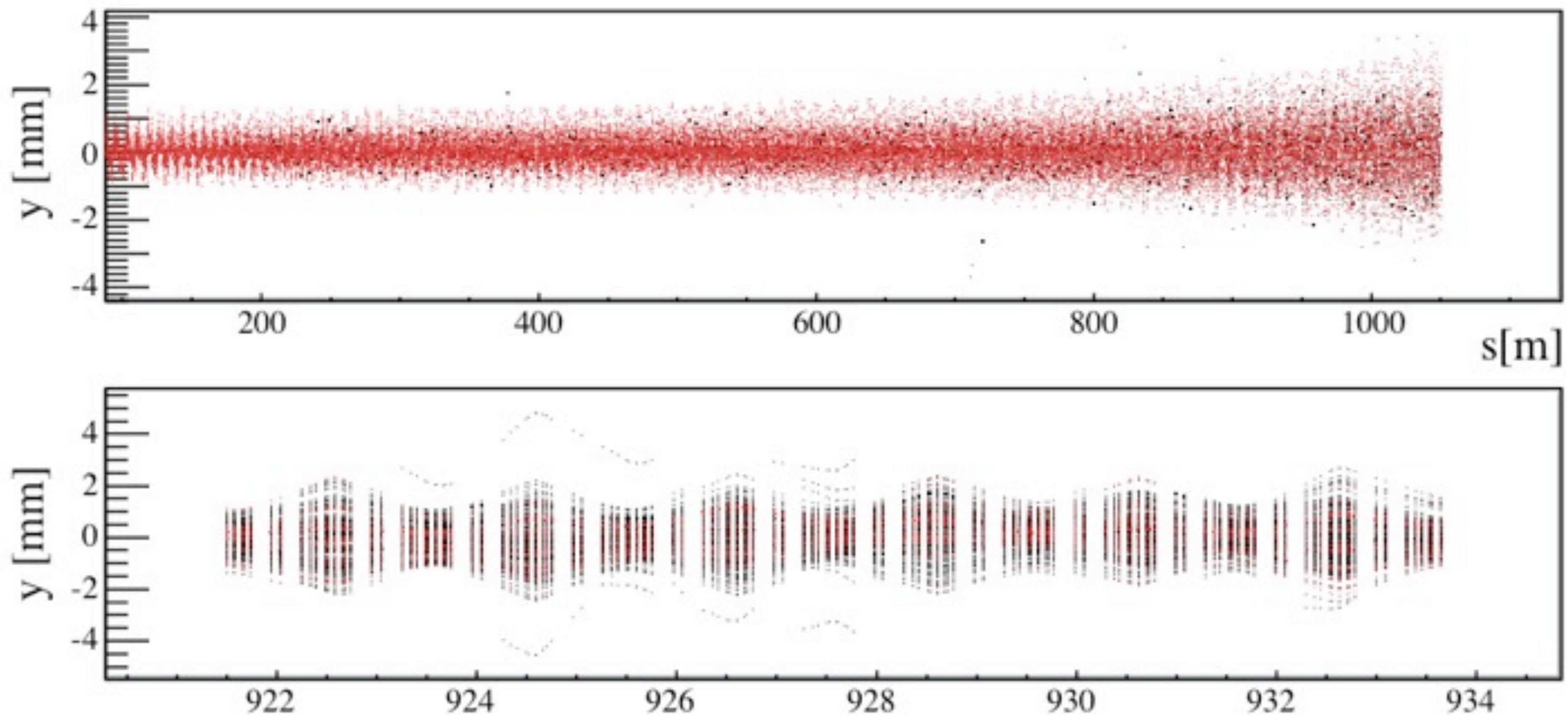
Short summary published as PAC 2009 paper WE6PFP085

Tracking results, CLIC drive beam



Transverse Beam profiles at the exit of the CLIC decelerator
PLACET + HTGEN simulation

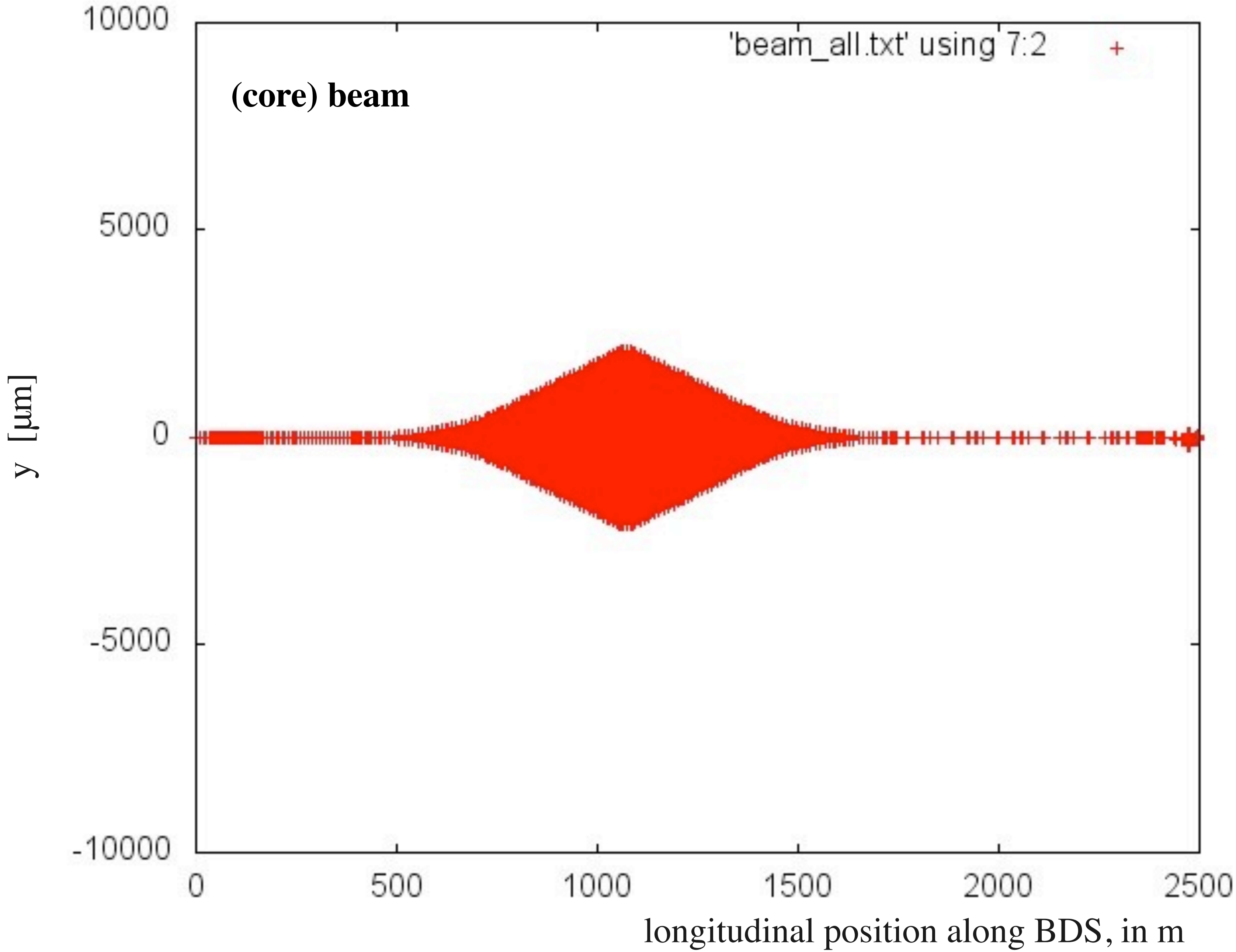
Tracking with halo, CLIC drive beam



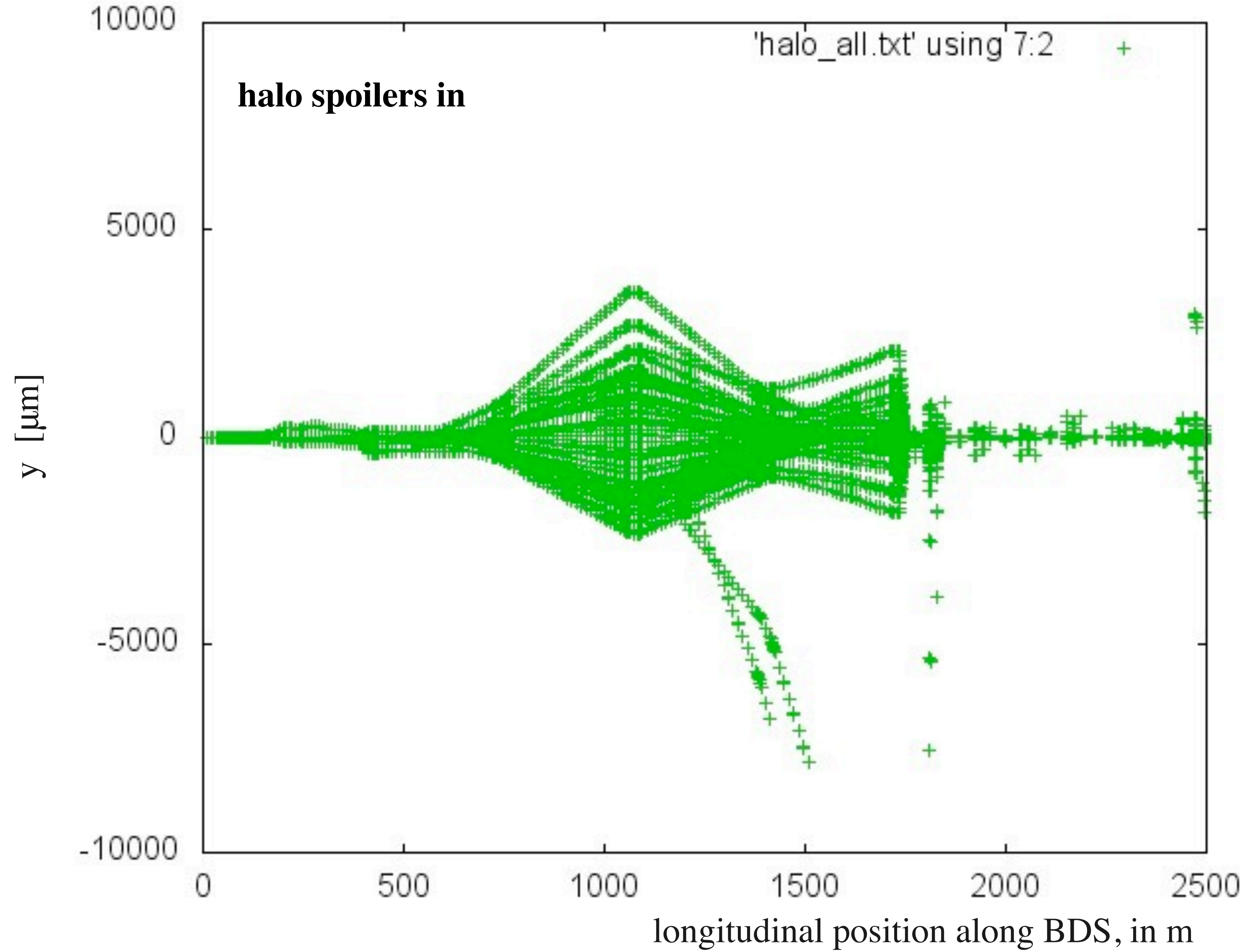
Vertical beam position along a complete CLIC decelerator + zoom towards end
Halo particles are shown in **black**, **beam (core) particles in red**

Main conclusion : fraction of halo particles lost at (the very large) aperture is small, of order 10^{-7} ; residual gas pressure 10 nTorr

PLACET-HTGEN tracking, CLIC BDS



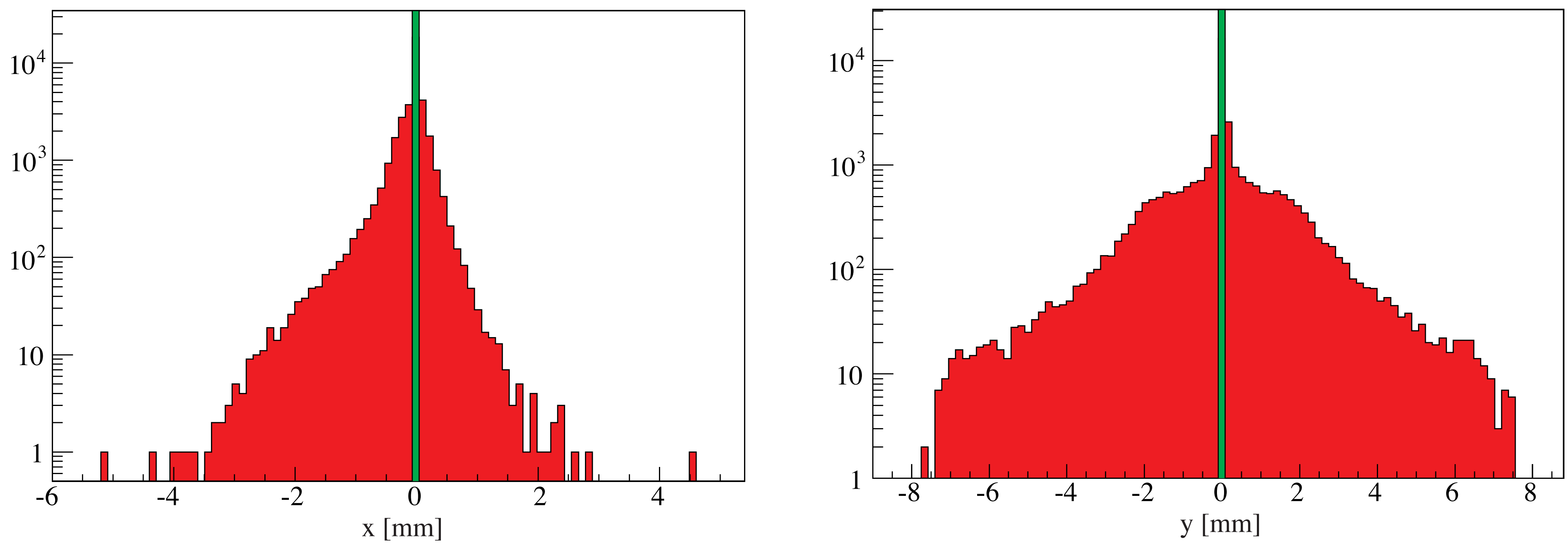
PLACET-HTGEN tracking, CLIC BDS



using apertures from v_09_04_01/bds.name.aperture.FixedSR.collaper

Projection at the 1st spoiler

HTGEN + PLACET, at XSP1, YSP1



Comments on the main CLIC beam core+halo PLACET-HTGEN simulations :

Can be done with any beam shape -- by default starting with Gaussian beam at LINAC entrance

Several years since last combined LINAC + BDS simulation -- should be redone for CLIC as described in the CDR, ideal and more realistic machine with errors

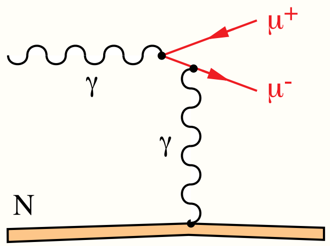
and with special attention on the collimation section which contributes significantly to beam-gas due to its very high-β ($\beta_y \sim 250$ km)

Halo collimation produces Muons

Came as bad surprise in the SLC, #muons produced in e.m. showers increases with energy

Electromagnetic muon production processes

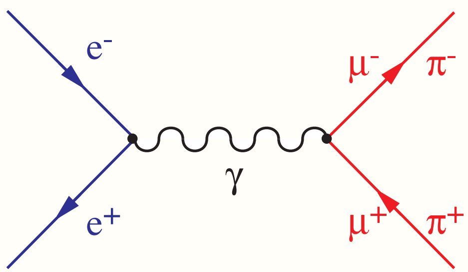
1. Monte Carlo Generator for Muon Pair Production, by Burkhardt, Kelner, Kokoulin, [CLIC-Note-511], 2002



Bethe-Heitler

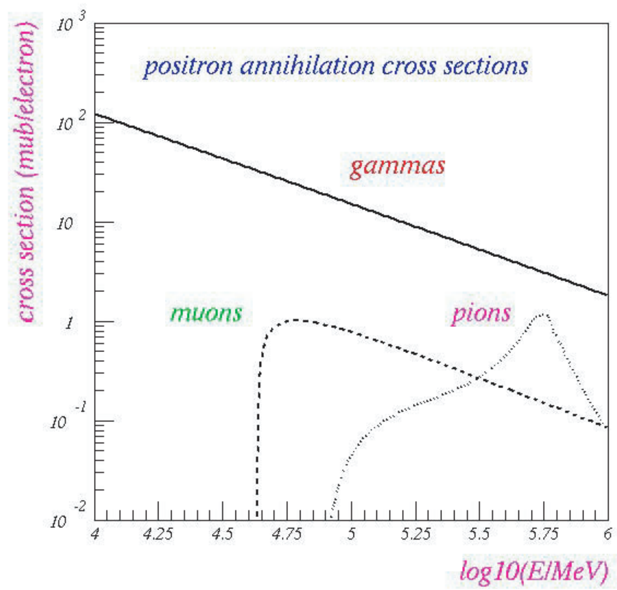
simulated by Geant4 process GammaToMuPair

2. Production of muon pairs in annihilation of high-energy **positrons** with **resting electrons** by Burkhardt, Kelner, Kokoulin, [CLIC-Note-554]



Ee+ > 43.7 GeV, μ+μ- pair production

Broad peak of π production at ϱ for Ee+ ≈ 570 GeV



simulated by Geant4 process AnnihiToMuPair, eeToHadrons.cc

Geant4, included in BDSIM, studied for CDR with Lawrence Deacon and Grahame Blair with Detector group

Roughly : CLIC aims for a halo < 10^{-6}, to minimize the degradation of the detector performance by muon background

Tail Population - analytic estimate

Daniel Schulte, review of the CLIC detector / physics CDR, 18 October 2011, on indico

Loss probability $$p \approx \sum \rho_i Z_i^2 \frac{4\pi r_e^2 mc^2}{n^2 \epsilon} \int_0^L \frac{\beta}{E} ds$$

Unbaked vacuum (1nTorr)
40% H_2, 40% H_2O, 10% CO, 10%CO_2
average Z^2=53.6
density=3.2 10^{22}molecules/Torr

Hence:

$$p \approx 8.64 \times 10^{-17}\,\mathrm{m}^{-1} \frac{1}{n^2 \epsilon} \int_0^L \frac{\beta}{E} ds$$

Tightest constraint is 55 σ_y:

Main linac $$\int_0^L \frac{\beta}{E} ds \approx 1000\,\frac{\mathrm{m}^2}{\mathrm{GeV}}$$ $p = 1.43\times10^{-9}$

BDS horizontal $$\int_0^L \frac{\beta_x}{E} ds \approx 832\,\frac{\mathrm{m}^2}{\mathrm{GeV}}$$ $p = 1.19\times10^{-9}$

For both sides together:
~530 particle/bunch

BDS vertical $$\int_0^L \frac{\beta_y}{E} ds \approx 48667\,\frac{\mathrm{m}^2}{\mathrm{GeV}}$$ $p = 6.95\times10^{-8}$

High-β collimation section designed to remove halo dominates beam-gas halo production !

Discussion

- **We will always have continuous losses from halo particles**
- **The expected losses for the ideal machine from known processes**
  (mostly quasi-elastic beam-gas scattering)
  are low, typically on the $\sim 10^{-6}$ level
  and mostly localized to the collimation section
- **Collimation of the tiny high-energy beams is hard,**
  and the collimation section itself a beam-gas halo generator
- **A much higher halo level ($> 10^{-4}$) would result in significant muon backgrounds in the detectors and degrade their performance**
- **Beam losses from halo will have to be low !**

Reserve

Halo estimate, main beam, CLIC 1.5 TeV

2007 estimate, 10 nTorr

total LINAC Prob. $P = 1.16\times10^{-3}$, BDS $P = 6.0\times10^{-5}$ together **1.2×10^{-3} at 1σ**

HTGEN simulation : losses **$\sim 2\times10^{-4}$** , mostly hitting the first spoiler

2011

several very significant changes compared to 2007

- significantly modified BDS optics / layout
- very good vacuum specified for the CDR (required for fast ion instability)

unbaked vacuum ~1nTorr, 40% H_2, 40% H_2O, 10% CO, 10%CO_2

PLACET+HTGEN updated and kept working, used as input to BDSIM for muon background estimates ;

Caution : done for ideal lattice and no recent complete tracking campaign

Estimates relying on extrapolations and analytical estimates

requirement from muon background **halo losses on the level of 10^{-6}**

purely analytic, spoiler at 55 σ_y **halo losses on the level of 10^{-7}**

with a **significant contribution from the very high beta collimation** region in the BDS