Losses in IR Region

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for the FCC-ee MDI Team: H. Burkhardt (CERN) and N. Bacchetta

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Introduction

- Main Effects of IR Beam Losses
- Particle tracking tools
- First Results with FCC-ee Crab-waist Optics
- Perspectives and Conclusions

Goal (challenge) of the MDI group together with the IR design group: maximize performance (integrated luminosity) for experiments for good or at least tolerable experimental (background, stability) conditions.

Background Sources

Two Main Classes:

- **Beam particles e^+, e^-, e^+e^- effects**
  - Bhabha
  - Beamstrahlung
  - Beam-gas
  - Touschek
  - Thermal photons
- **Synchrotron Radiation**

  covered by H. Burkhardt's talk (Wed. 9.30)

- Both aspects deeply studied for present/past machines
- Beam particles effects (better) studied at Factories
- SR manageable extrapolation from LEP experience but very challenging machine, dedicated studies needed

Background Sources

- **Luminosity sources**
  - Beamstrahlung
  - Bhabha (Radiative)
  - 2-photon pair production
    $e^+e^- \to e^+e^- \, e^+e^-$
    $e^+e^- \to e^+e^- \, \mu^+\mu^-$
  - Beam-beam (Halo)
- **Linear with Currents**
  - Synchrotron radiation
  - Beam-gas Coulomb/ Bremsstrahlung (at constant Pressure)
- **Other sources**
  - thermal outgassing due to HOM losses
  - top-up injection background
  - High order modes
  - Compton thermal photons
  - ion or electron cloud
  - single / multiple Touschek scattering

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Some cause backgrounds due to direct beam losses: particle tracking needed.

The impact of these effects is of course dependent on machine parameters (like beam energy, energy acceptance)

- **Linear with Currents**
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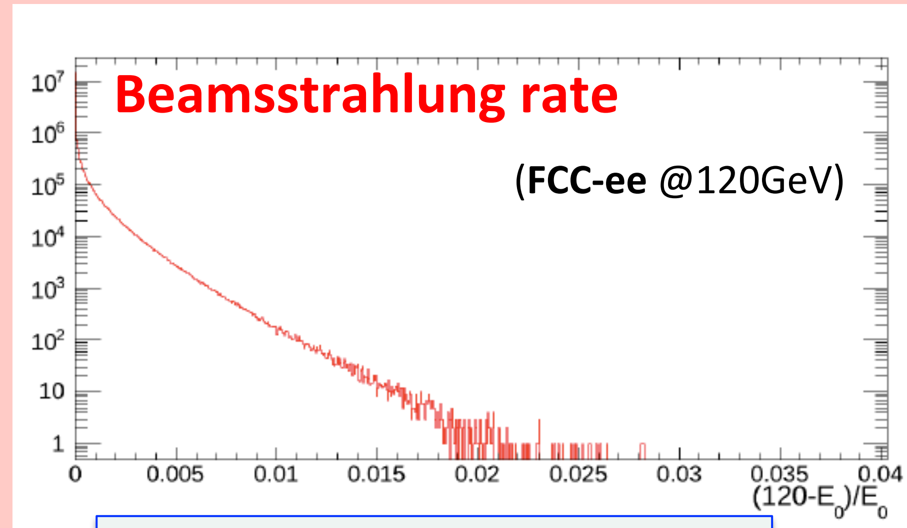
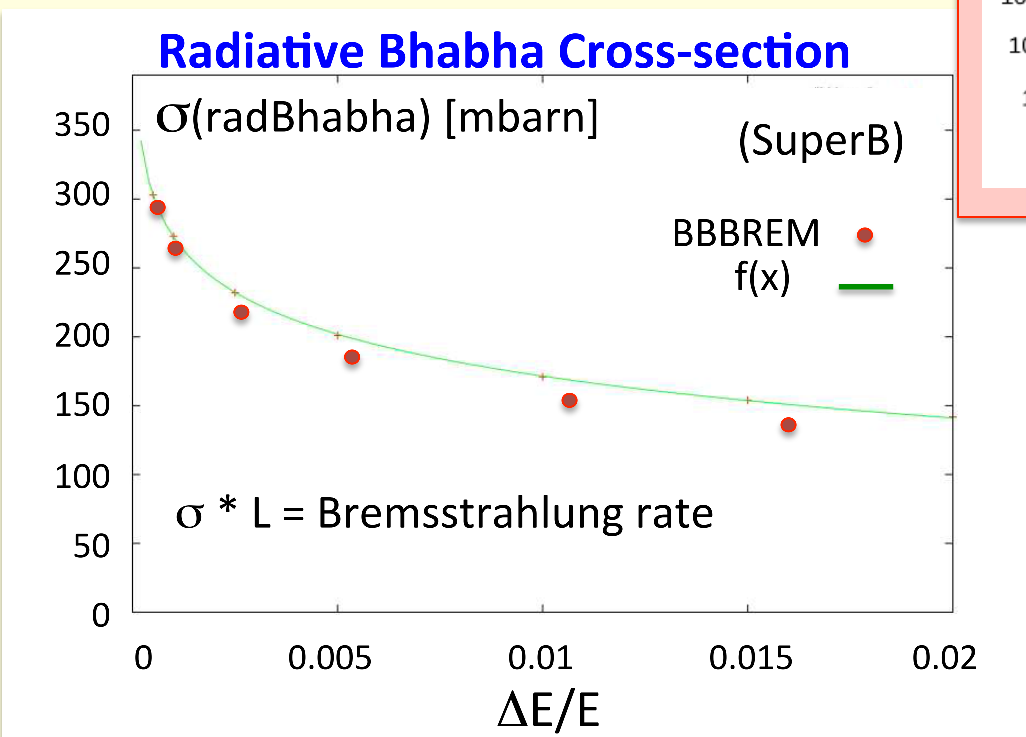
not expected to be determinant, but has to be checked.
I started from this one

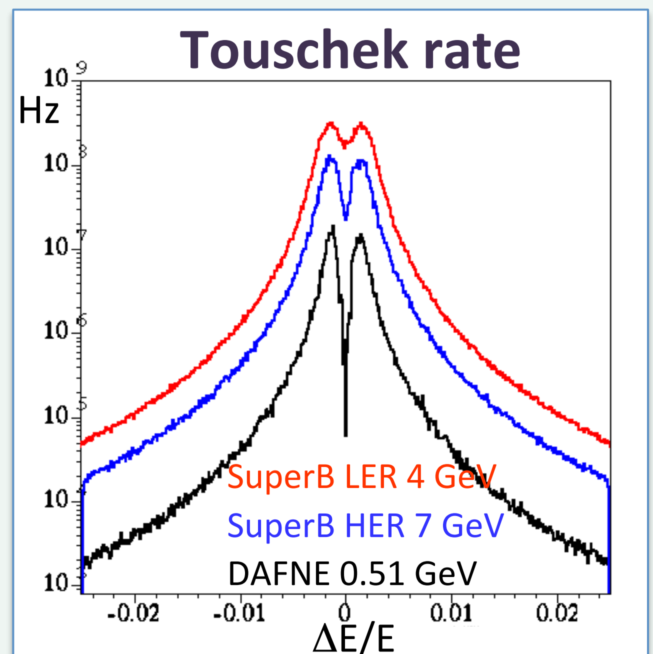
Dependence on Energy Acceptance

Analogies:
- dependence on energy acceptance
- direct losses





[H. Burkhardt's talk for FCC-ee case]



Energy dependent processes: scale law

$$P(\text{Beamstrahlung}) \propto \gamma \cdot \frac{N^2}{\sigma_x \sigma_y}$$

$$P(\text{Bremstrahlung}) \propto \ln\left(\sqrt{s}\right) \cdot L \propto \ln\left(\sqrt{s}\right) \cdot \frac{N^2}{\sigma_x \sigma_y}$$

$$P(\text{Touschek}) \propto \frac{1}{\gamma^3} \frac{N}{\sigma_x \sigma_y \sigma_z}$$

P = Probability function

√s = c.m. energy
L = Luminosity

Looking at the scaling with the beam energy that **Beamstrahlung** is the dominant effect at high energies

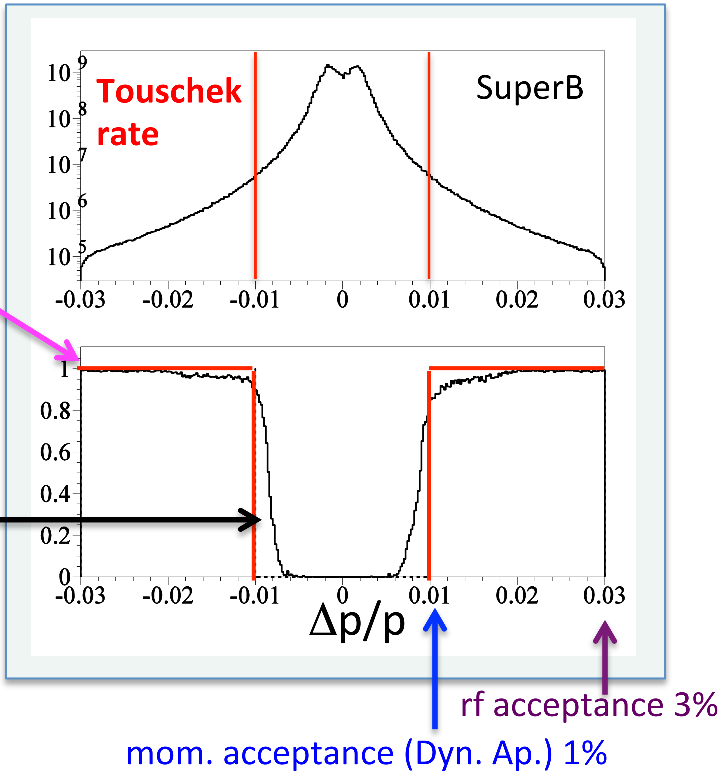
being strongly dependent on energy acceptance, energy acceptance needed as high as possible

Evaluation of Touschek Effect

1. **Touschek lifetime: usually evaluated by the formula, that is dependent on the momentum acceptance, so either**
   - Give the machine momentum acceptance as input, and calculate the formula of the Touschek lifetime averaging on the whole lattice *(rough evaluation)*
   - Calculate the local momentum acceptance through the lattice elements and calculate the formula for each small section of the lattice and then sum up *(more precise evaluation)*

Probability Loss is a step function when machine momentum acceptance is given as an input (resulting from Dynamic Aperture calculation)

Touschek Probability Loss function resulting from particle tracking (consistent, slightly worse, resulting about 0.6-0.8%)



The importance of this approach is more important if the distribution vs ΔE/E is very nonlinear (as for Touschek)

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2. **Touschek Beam Losses: particle tracking needed along the ring**
   - Macro-particles are tracked through each small slice of elements for many turns (slicing needed for a correct estimate of the Touschek scattering rate to take into account changes of beam density and for proper tracking)
   - Non-linear kicks included in the tracking.
   - **From the total particle losses it is possible to derive the lifetime**

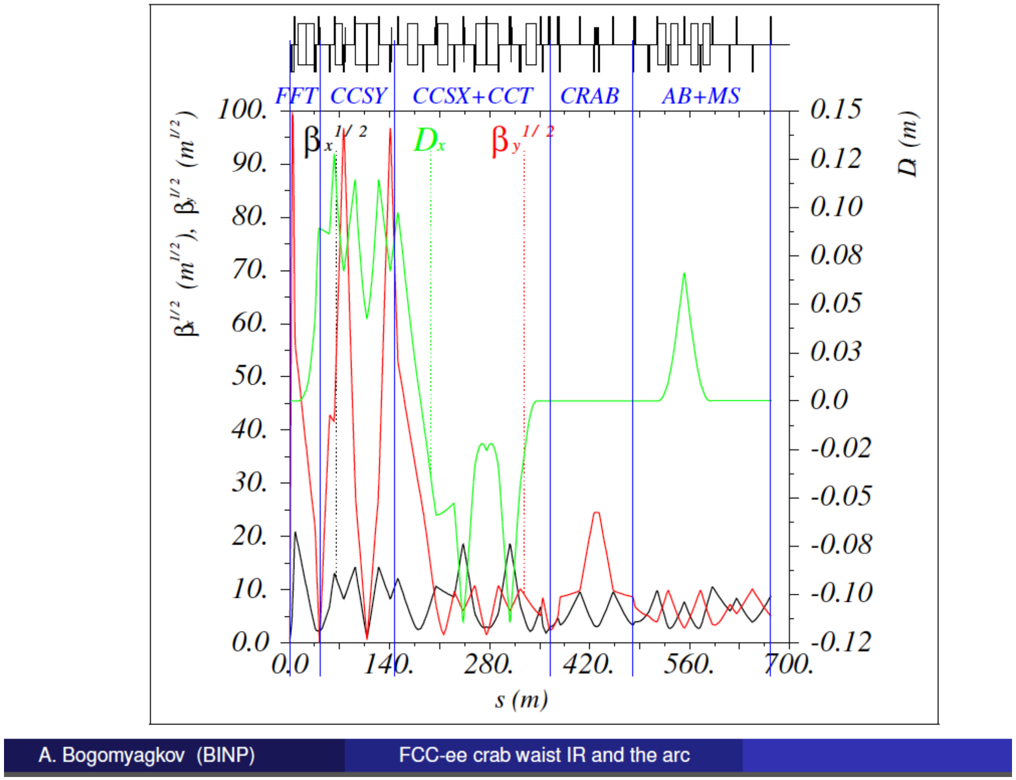
     lifetime (s) = N(beam) / Rate Beam Losses (s)

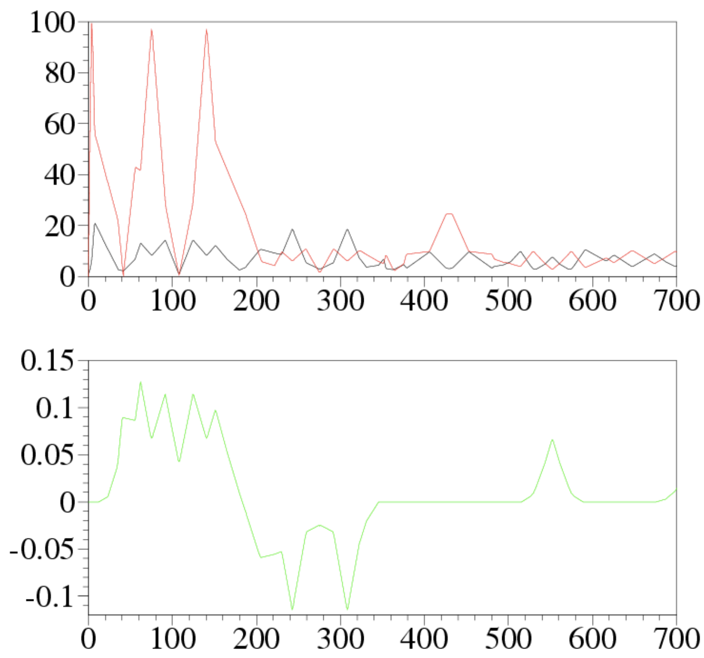
$\Rightarrow$ (approach used for DAΦNE, SuperB, Italian Tau/C) [Ref. PRST-AB 15 104201 (2012)]

Touschek Tracking code Monte Carlo: some details

- Lattice imported from MAD-X
- A randomly chosen set of macro-particles are launched out of a Gaussian bunch for each small segment of the ring -small enough not to have meaningful Twiss functions changes- and tracked trough the ring for few machine turns or until they are lost.
- These macro-particles are off-energy, as have undergone Touschek scattering, each one has weight proportional to the energy spectrum of the Touschek effect (very nonlinear and lattice dependent)
- once per turn the macroparticle's energy deviation is compared to rf acceptance.
  - Disadvantage: loss location due to rf acceptance exceed not determined
  - Advantage: 4-D tracking in the transverse dimensions for smaller machine turns
- Will interface output with ROOT (plotting and primaries handling)

Lattice: crab-waist option 4IPs
(TLEP_V14_IR_6-13-2)





perfect overlap of β_x, β_y and D_x as calculated by MADX and STAR

Lattice: crab-waist option 4IPs

TLEP_V14_IR_6-13-2 parameters:

Parameters for crab waist

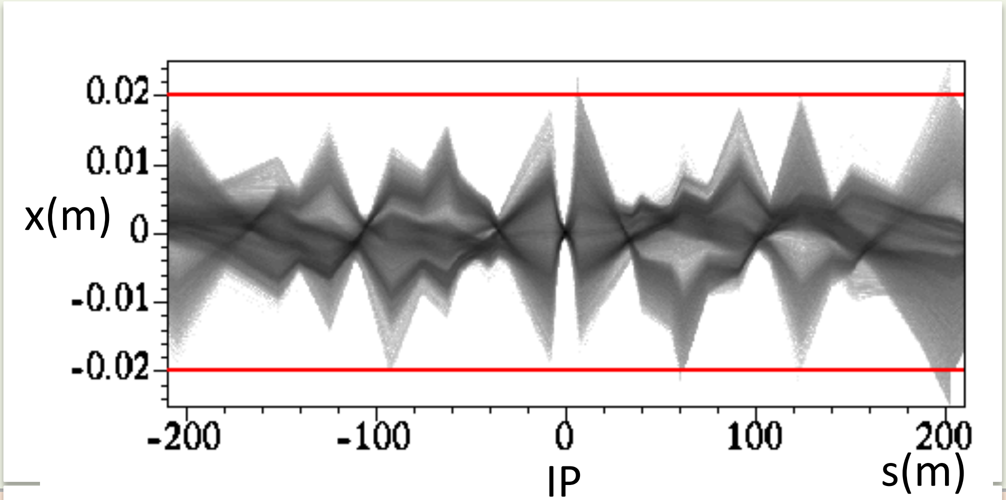
	Z	W	H	tt
Energy [GeV]	45	80	120	175
Perimeter [km]	100			
Crossing angle [mrad]	30			
Particles per bunch [10^{11}]	1	4	4.7	4
Number of bunches	29791	739	127	33
Energy spread [10^{-3}]	1.1	2.1	2.4	2.6
Emittance hor. [nm]	0.14	0.44	1	2.1
Emittance ver. [pm]	1	2	2	4.3
β_x^* / β_y^* [m]	0.5 / 0.001			
Luminosity / IP [$10^{34}\ cm^{-2} s^{-1}$]	212	36	9	1.3
Energy loss / turn [GeV]	0.03	0.3	1.7	7.7

Parameters of one quarter of the ring

	tt
Energy [GeV]	175
Perimeter [m]	24747.6
Momentum compaction	$5.7 \cdot 10^{-6}$
Emittance hor. [nm]	1.8
Energy spread [10^{-3}]	1.6
β_x^* / β_y^* [m]	0.5 / 0.001
Energy loss / turn [GeV]	2.15

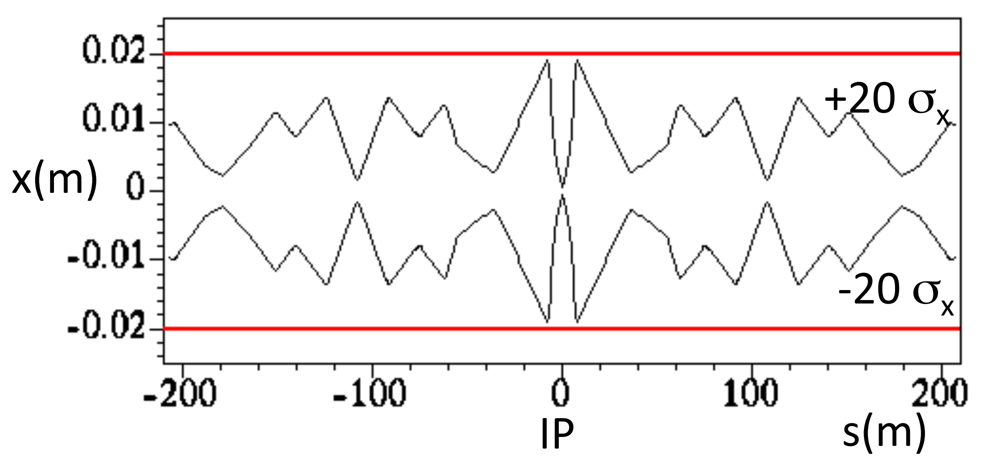
A. Bogomyagkov (BINP)

FCC-ee Touschek Off-energy trajectories



Horizontal Physical Aperture =2 cm constant

Trajectories of off-energy Touschek particles with an initial $\Delta E/E$ in the range between 0.3 - 4 %

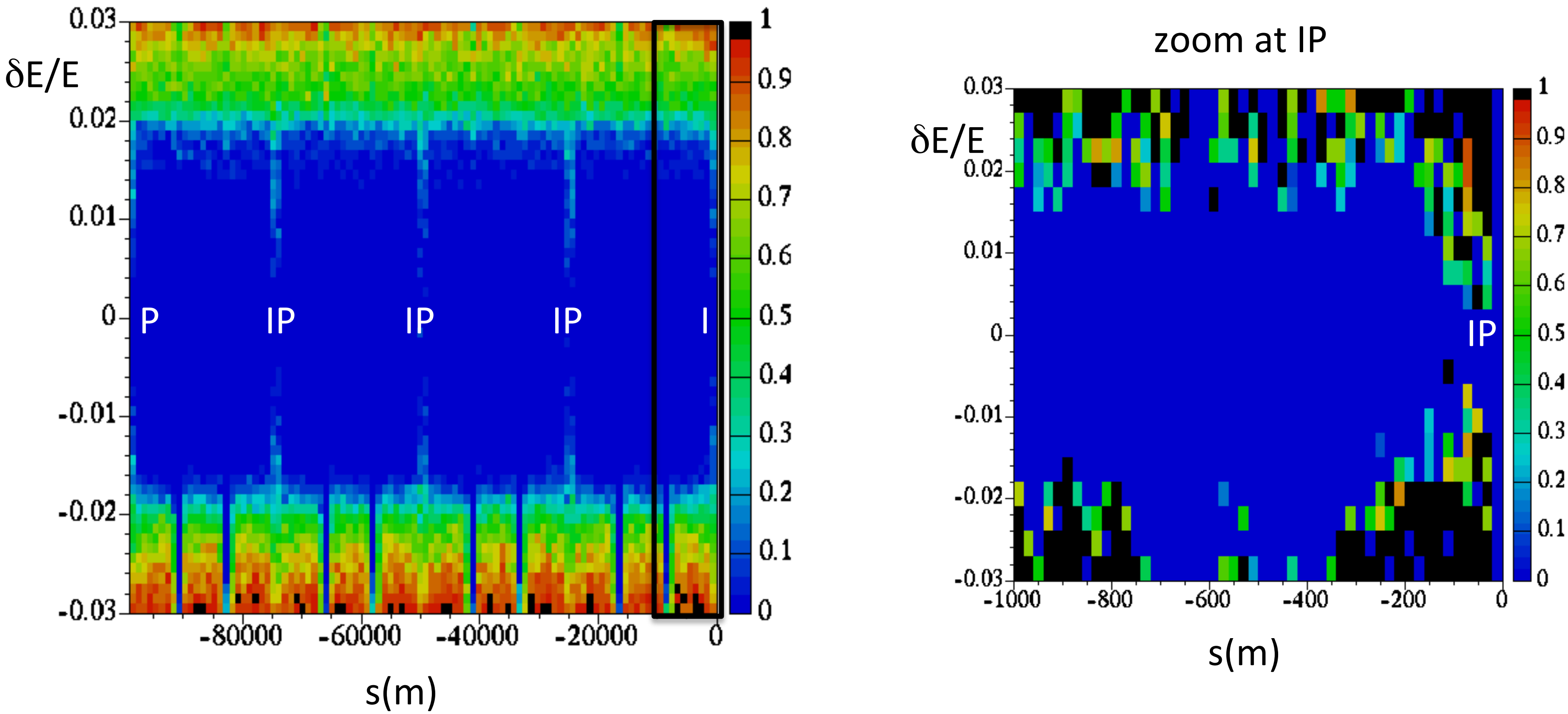


on-energy particles:
Beam envelope at 20 σ_x

Momentum Aperture of Touschek particles through the ring

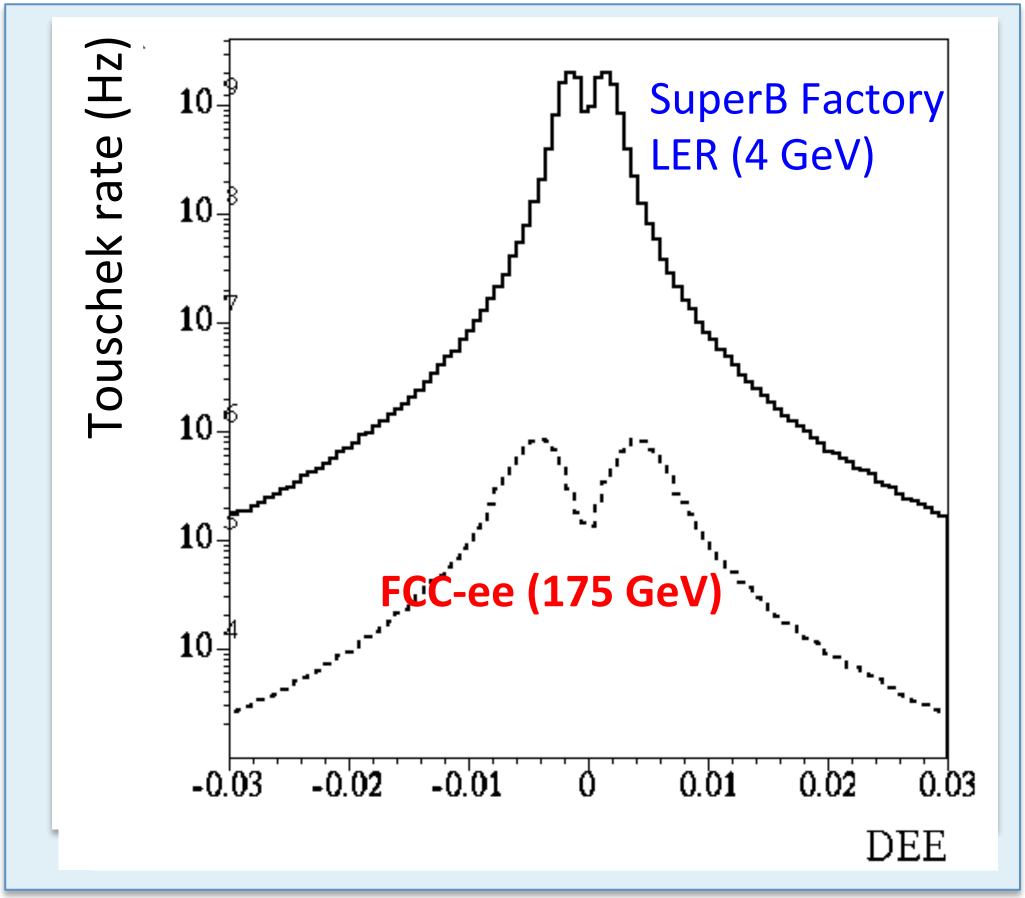
(from physical aperture)

Not simply an *s* dependent momentum aperture



- Crucial for all sources inducing a δE/E like Touschek, rad Bhabha, beamstrahlung (HE)
- Best determined with full tracking

FCC-ee Touschek Rate



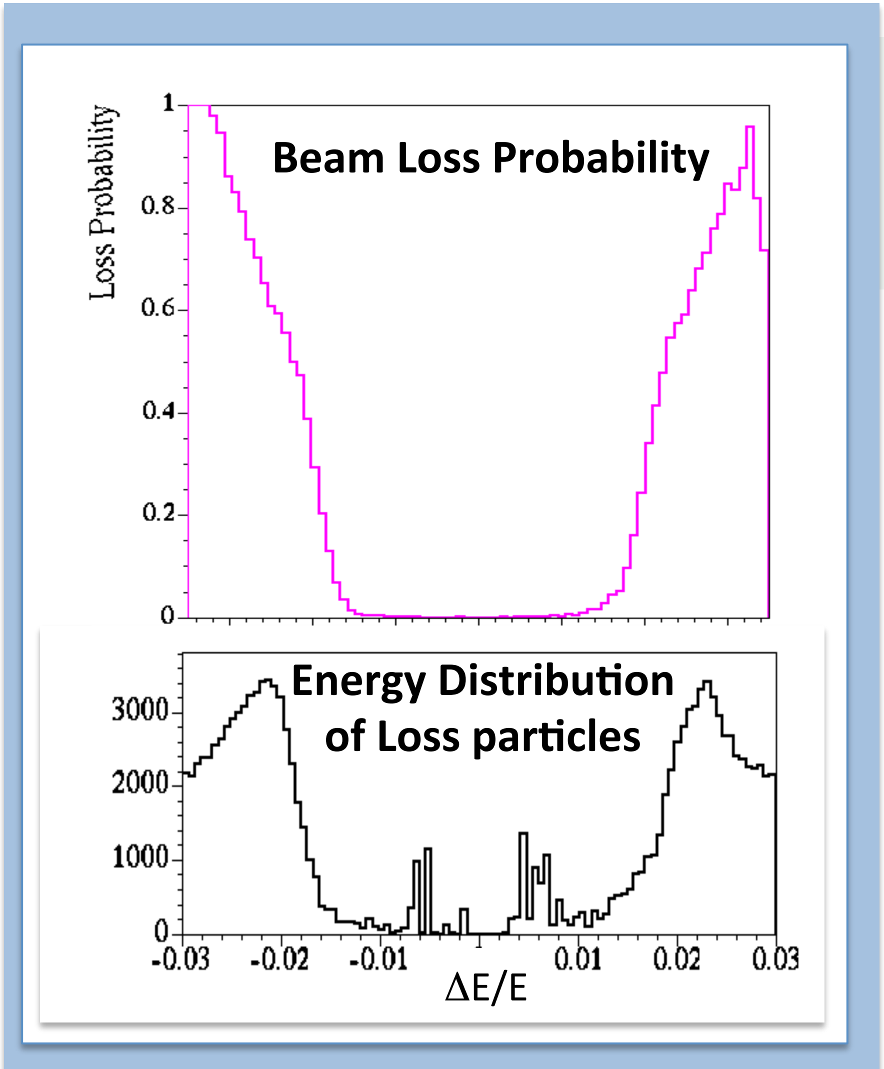
Touschek lifetime SuperB = 400 s with momentum acceptance ~1 % and realistic physical aperture

Touschek Rate scales like $1/E^{2.5}$ wrt $1/E^3$ naïve expectation -> Energy scaling largely dominates

First look confirms that Touschek not a dominant effect also for energy acceptance comparable to SuperB Factories

FCC-ee Off-energy Particles

1 full turn tracking only



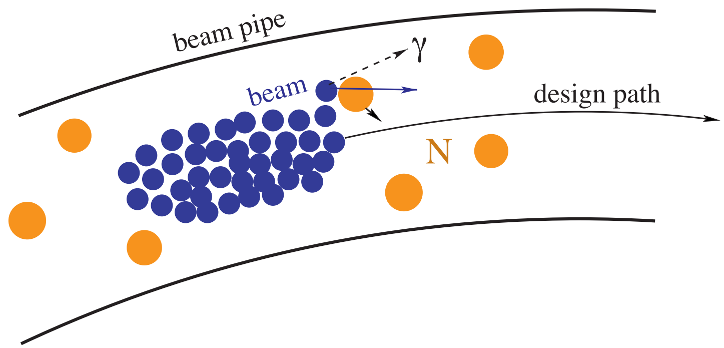
- Starting Touschek energy off-set range between 0.3% and 4%
- RF acceptance is cut-off at 3%
- constant physical aperture=2 cm

result consistent with A. Bogomyagkov's evaluation in the range (-1.8%; +1.4%)

Next Step: FCC-ee **multi-turn simulation**

- work in progress
- Long CPU time for such a long machine
- Many elements (sliced) and many macroparticles
- A small worsening (of the order of 0.5%) expected (from studies on other colliders)

Beam-gas scattering



- Mainly Coulomb and Bremsstrahlung interactions with residual gas molecules in the beam pipe
- As a start: the estimate based on LEP2 rates and rescale for beam currents

- For a more quantitative and accurate estimate the lattice description is needed

  TOOLS:
  - PLACET, HTGEN (Helmut)
  - MCGAS Monte Carlo developed for SuperB and Italian τ-charm (Manuela)

Beam-gas Coulomb scattering

		B-Factories					
LER parameters	**unit**	**KEKB**	**SuperKEKB**	**SuperB**	**LEP**	**CEPC**	**FCC-ee CW (175GeV)**
V beam pipe @QD0	mm	35	13.5	6			
β_y (max) @QD0	m	600	2900	1497	**150 m**	**12.1 km**	**9.9 km**
$<\beta_y>$ [m]	m	23	48	47			
Coulomb lifetime	hr/min	>10 hrs	35 min	24 min			

$$\frac{1}{\tau_{Coul}} \propto \frac{1}{\gamma^2}\left\langle \frac{1}{\theta_c^2} \right\rangle$$

- Coulomb rate decreases quadratically with energy → beneficial for FCC-ee
- Coulomb rate increases linearly with β_{ave} → worse for FCC-ee
- Losses happen vertically at β_y**(max)** (i.e. at QD0) larger by 1 order of magnitude with respect to SuperB Factories, at LEP there was no high beta close to the IP → worse for FCC-ee should be found a trade off for this value

Beam-gas Bremsstrahlung

- At **LEP** off-energy particle background was largely dominated by beam-gas Bremsstrahlung along the straight sections [τ_B= 430 hrs with P=10^{-10} Torr, NIM A 403 (1998) 205-246]
- From 45 GeV to 65 GeV dynamic pressure increased by a factor 5

- At FCC-ee Beam Losses needs to be studied with particle tracking
- General requirement: **P < 1.E-9 Torr**

Radiative Bhabha

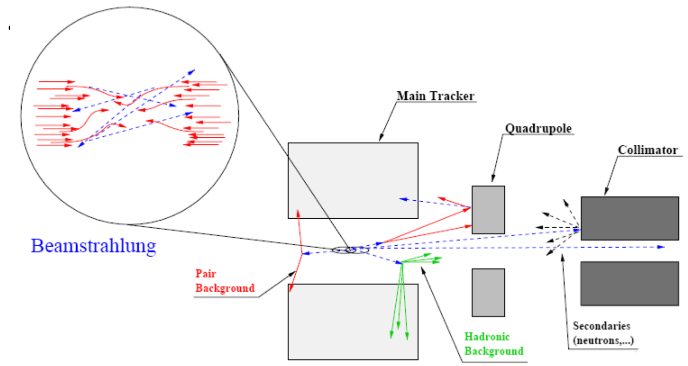
- ***Large* energy loss/angle** => lost almost immediately, closeby detectors
  - almost independent on machine lattice but the Final Focus
  - BBBREM generator [R. Kleiss, H.Burkhardt](collinear), BABAYAGA, BHWIDE(low angle)

- ***Small* energy loss/angle** => may be lost after few machine turns
  - multi-turn tracking with a dedicated Monte Carlo simulation* with BBBREM generator for the weights of the tracking particles
- Cross-section almost independent on sqrt(s)
- **Lifetime** depends essentially on energy acceptance at IP and on Luminosity
- **Multi-turn particle losses** best calculated by tracking

* M.Boscolo unpublished, used for SuperB and Italian τ-Charm

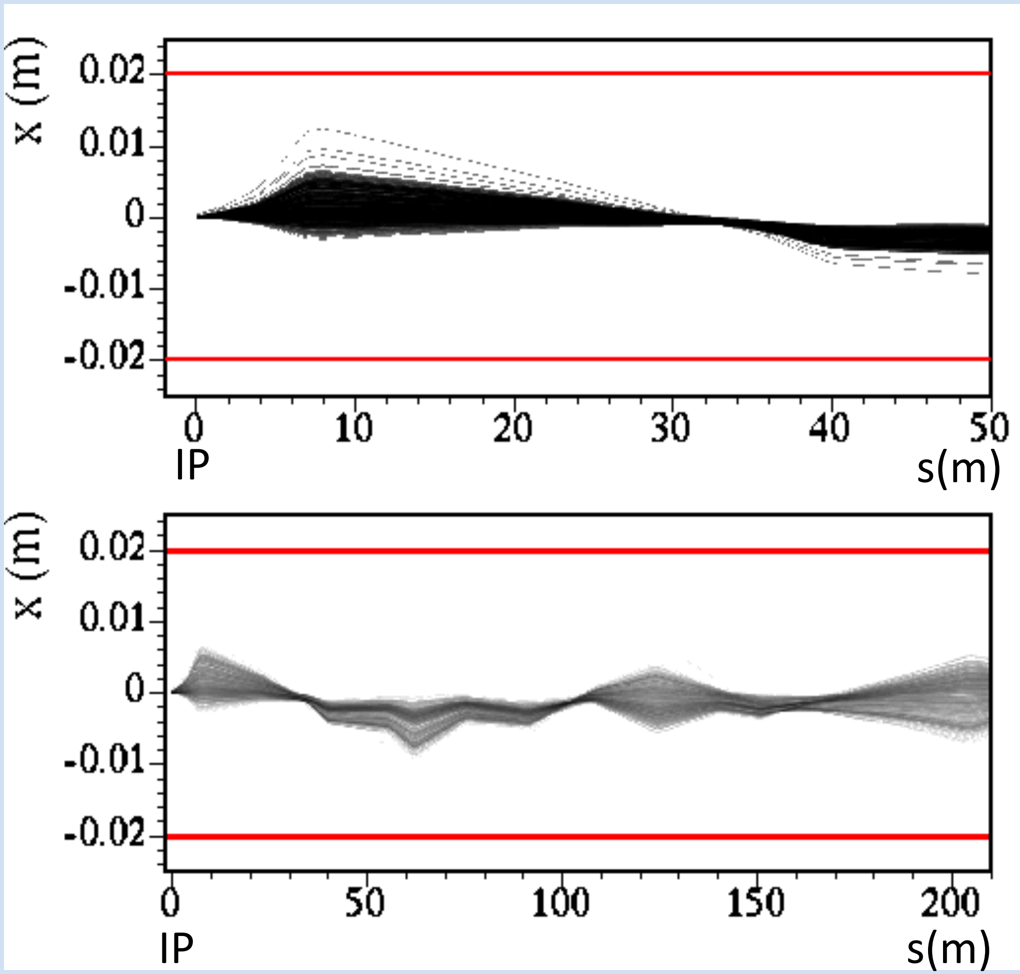
Beamstrahlung

- Beamstrahlung is synchrotron radiation in the field of the opposing beam
  - ➔ energetic photons are emitted -> produce background
  - ➔ –(ΔE/E) bunch particles get lost in '
    - -> Backgrounds from debris
    - -> Luminosity drops
    - -> beam energy spread affected



Many analogies (dependence on energy acceptance at IP, direct losses) with Radiative Bhabha but Beamstrahlung is the dominant effect at the high energies of FCC-ee

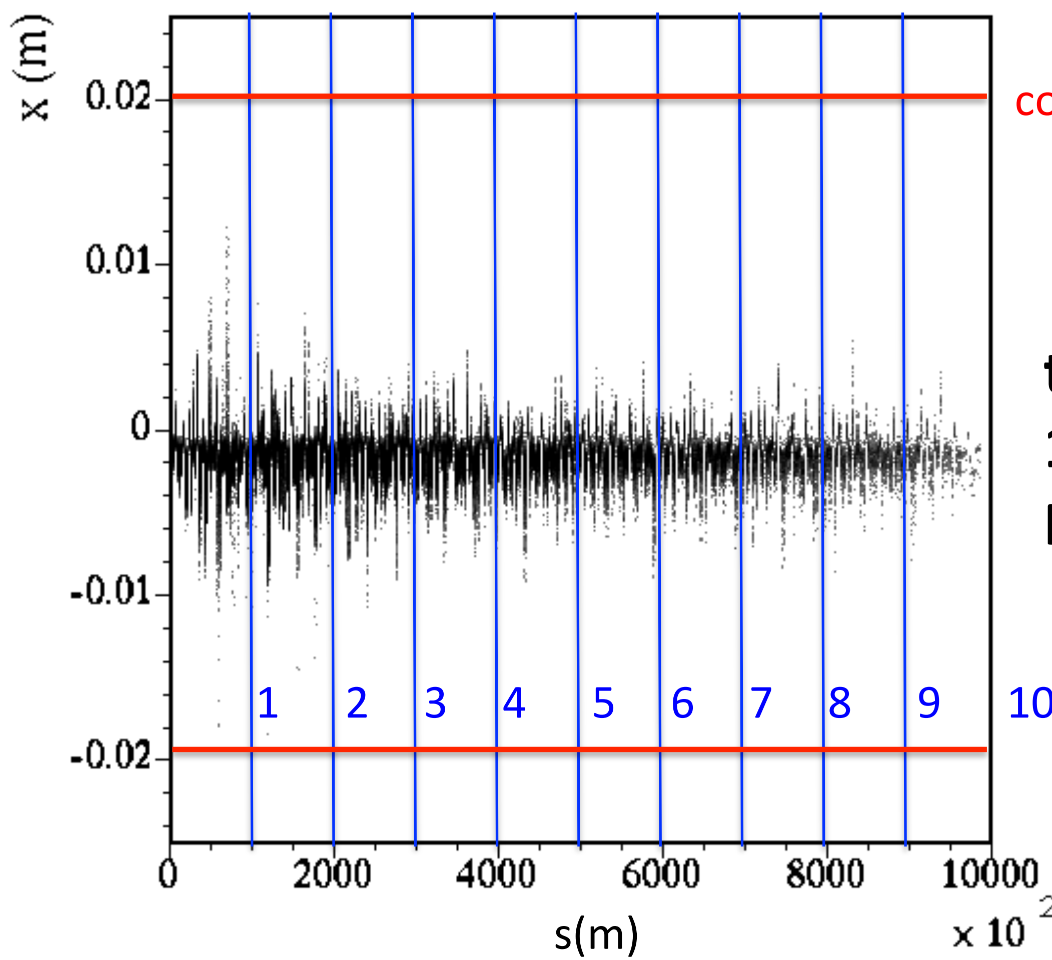
FCC-ee off-energy trajectories from IP
(Radiative Bhabha and Beamstrahlung)



to estimate off-energy particles loss rates from IP, due to Radiative Bhabha or Beamstrahlung,
weights are needed, *i.e.*
cross section as a function of $\Delta E/E$

it will be next step

FCC-ee off-energy trajectories from IP (Radiative Bhabha and Beamstrahlung)



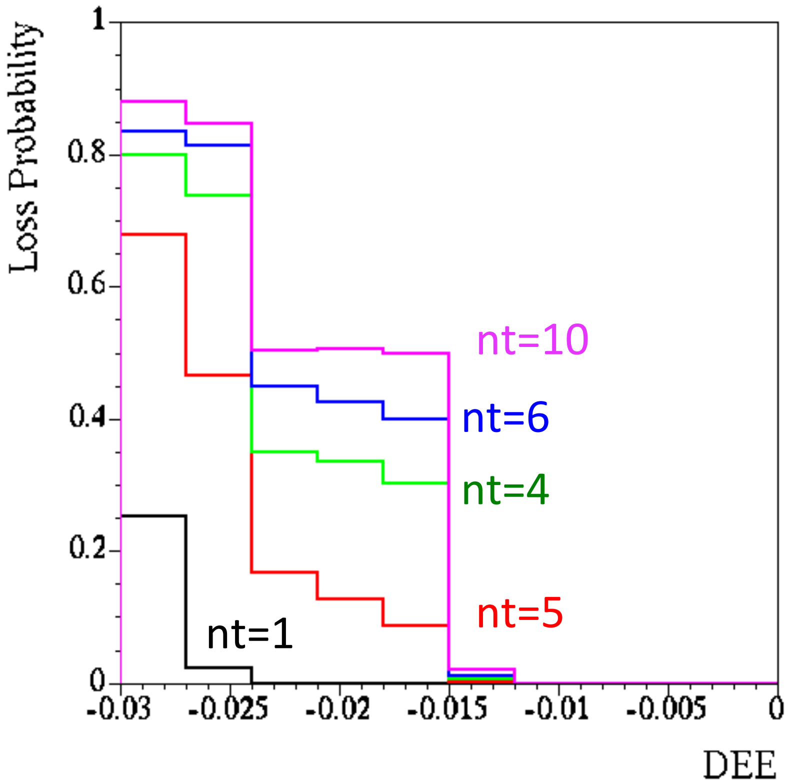
constant horizontal physical aperture

10 full machine turns

trajectories for 10 machine turns for FCC-ee 175GeV

much faster CPU time wrt Touschek: generation only once, at IP

IP off-energy particles: Multi-turn energy acceptance at IP



FCC-ee: 10 machine turns

TLEP_V14_IR_6-13-2 optics
175 GeV

Conclusions

- We need to check all beam loss effects, but priority is given to:
    - Bhabha (radiative)
    - Beamstrahlung
- First FCC-ee Touschek Losses simulation done, need progress with:
    - Multi-turn
    - Check at all energies (especially at the Z)
    - Keep-up with Lattice and parameters updates
- Beam-gas Losses similar studies to be done
- Benchmarking with e+e- machines (SuperKEKB, DAFNE)
- Top-up injection losses
- Muon backgrounds

Conclusions

- The design of the IR is a critical issue for the success of a collider
- Careful trade-off machine / detector constraints

detector constraints:

- Physics acceptance from the nominal beam axis
- Smallest possible beam pipe radius
- Thinnest possible beam pipe wall
- Solenoidal detector
- Separation scheme
- L* key parameter

- In this frame simulations of all the effects that induce machine backgrounds –as realistic as possible- are essential

Back-up

Perspectives for Software Development

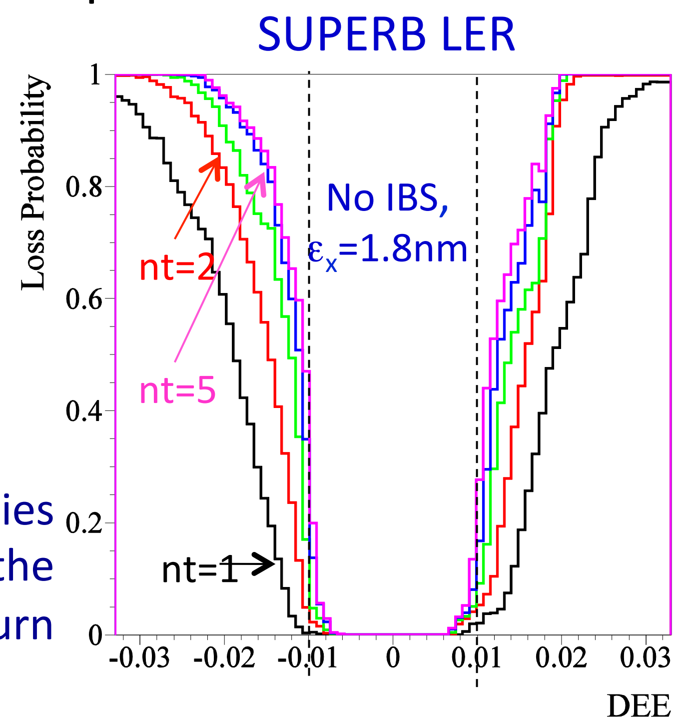
- Presently the Monte Carlo reads MAD-X output (tfs file), produce the input for the MC, that recalculates optics matrices needed both for tracking and twiss functions

We foresee:

- Tracking directly using MAD-X matrices->
- Touschek routine in ROOT or interfaced with ROOT –
- ROOT as a graphical interface similarly to MDISIM
- BBBrem + MC Tracking
- other effects (Beamstrahlung)

Machine Energy Acceptance: Multiturn

- Multiturn studies for **FCC-ee** are in progress
- Long CPU time for such a long machine
- Many elements (sliced) and many macroparticles



Experience from previous studies (DAFNE, SuperB, tau/charm) shows a worsening of the energy acceptance of about 0.5% in multi-turn