Beam Gas studies for the FCC ee collider

(mostly study of Inelastic Beam Gas
for FCCee Z 45.6GeV/beam
in this presentation)

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Introducing myself, overview of my activity

LNF 2018/April/10

What is FCC ?

FCC is the project of a Future Circular Collider

to be built after the LHC run (at least until 2025)

It should exceed the Energy and Precision of the LHC to show hints of new physics
FCC is one of the many many possibilities : CLIC, ILC, HL-LHC, HE-LHC, SppC, … ???

How we answer the next fundamental questions will boil down to the uncertainty principle:

Energy Frontier

To probe nature at the smallest distance scales, we must push to the highest momentum scales:

$$\Delta x \geq \frac{\hbar}{2\Delta p}$$

If new particles exist with a tiny Compton wavelength, high energy is the only way to observe them directly.

Intensity Frontier

Alternatively, we may gain indirect access to physics at the highest energies with high precision measurements:

$$\Delta E \geq \frac{\hbar}{2\Delta t}$$

If new interactions exist, beyond the Standard Model, the first cracks could show up in high precision.

FCC week 2017
https://indico.cern.ch/event/556692/contributions/2483388/attachments/1466429/2267366/FCCWeekBerlin.pdf

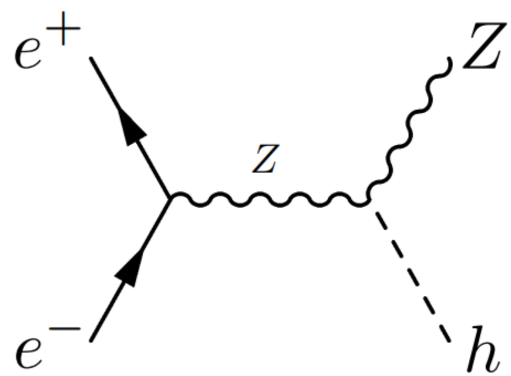
and, what is the ee in FCC-ee ?

e+e- collisions are considered for precise measurement of Higgs bosson properties

The measurements…

An e^+e^- collider is the surgeon's scalpel of particle physics.

- Dominant Higgs production at lower energies is associated production:



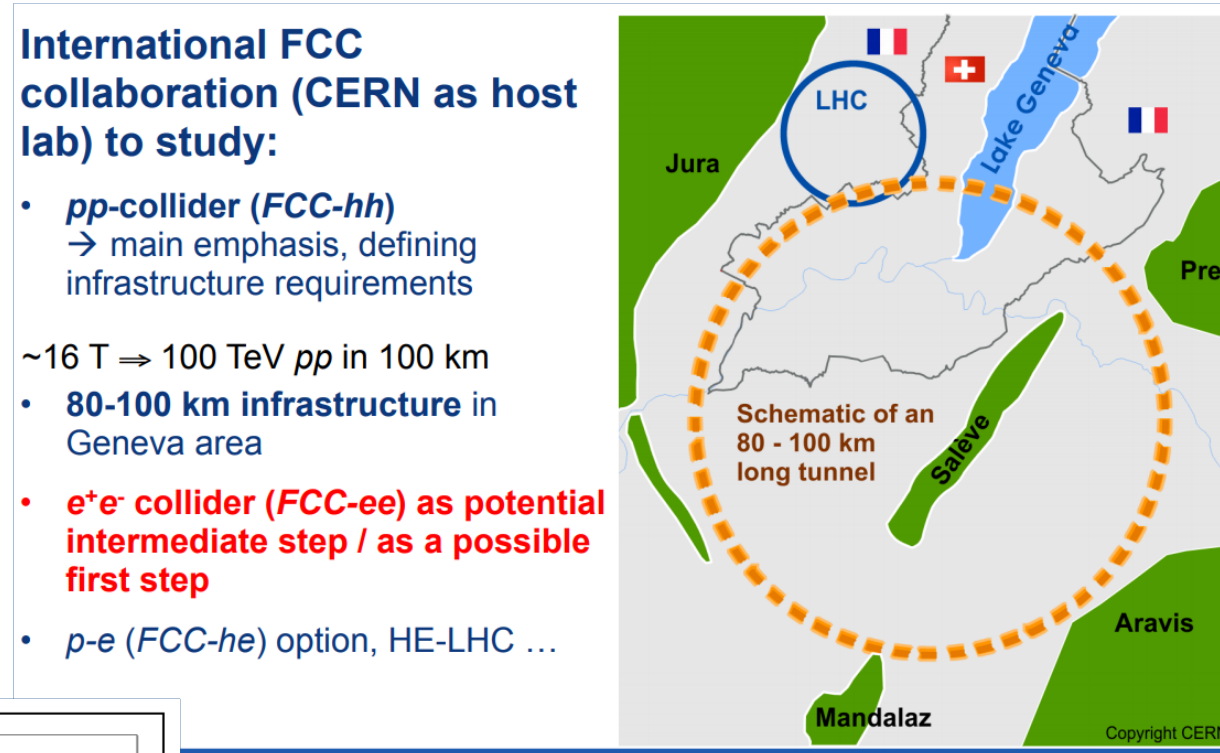
Can measure Z-recoils alone

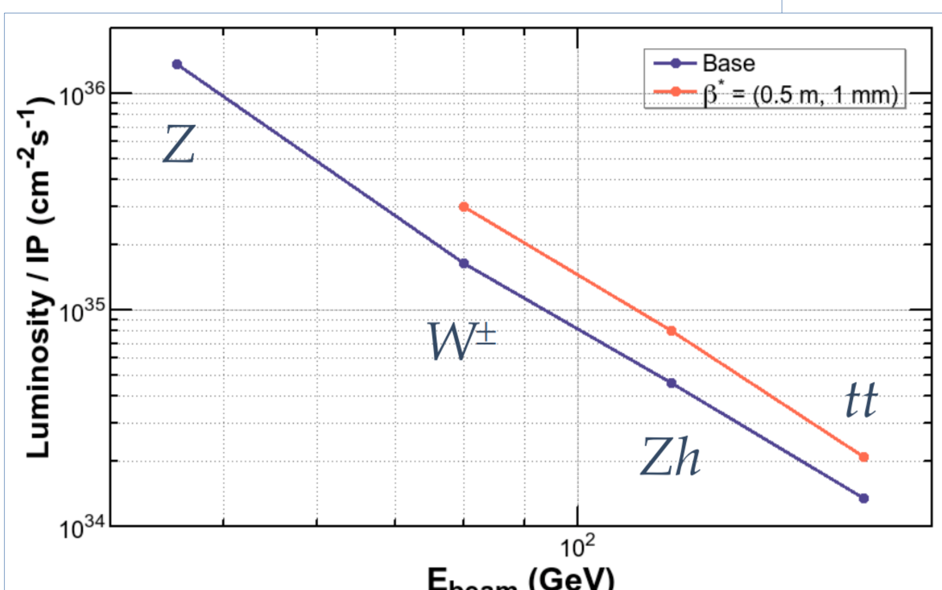
- Total cross section independent of Higgs decays, unique to e^+e^-! Clear determination of width!

FCC-ee, the machine

- A 100km tunnel in the CERN area,
- thought to be used for pp collision,

  and as a first stage e+e- collisions,
- At 4 different center of mass energies

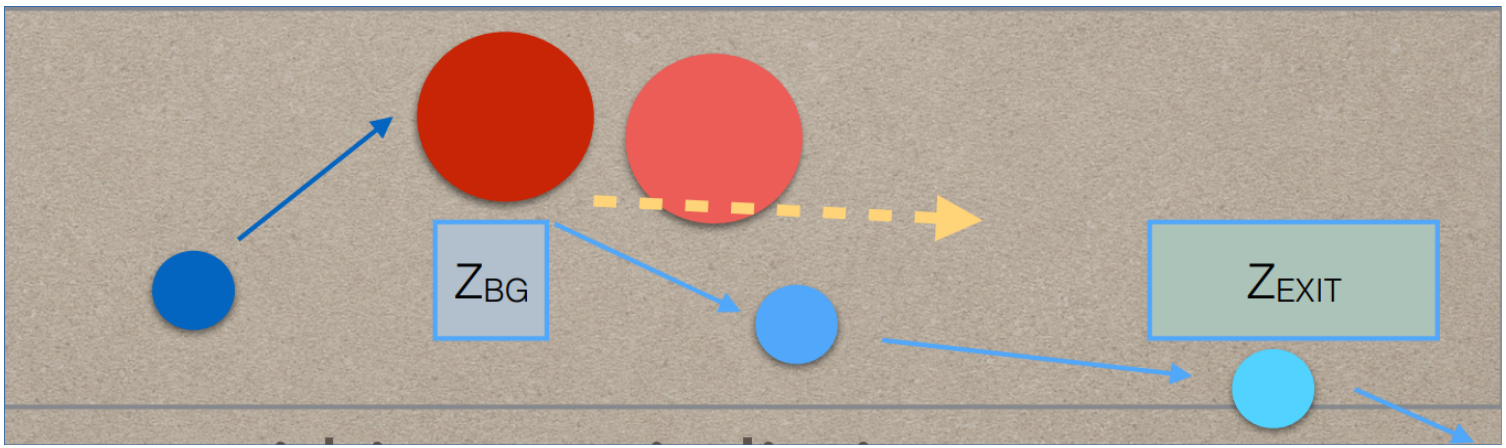




FCC week 2017
https://indico.cern.ch/event/556692/contributions/2483406/attachments/1466449/2271404/FCCee_Oide_170529.pdf

the BEAM GAS study

Gas in the beam pipe from the initial atmosphera (N2, O2, CO2, ...),
or from desorption of the material in the beam pipe surface (H2, CO, CH4, ...)
Interact with the beam



It seems that there are two main criteria to evaluate this process :

a) Beam life time

b) Background in the experiment

DAFNE Tech Note V-3. Vaccarezza, 1991/JUL/08
"Preliminary Study for the Choice of the DAFNE Vacuum Chamber Material".

I will mostly address beam life time ...

There is another issue about the gas pressure from desorption due to radiation but this presentation DOES NOT address that.

the BEAM GAS study
As in the books

Inelastic
e- losses energy in the interaction and is lost because of energy acceptance

$$\sigma(Z,\epsilon)$$

Cross section depends on :
Z, the atomic number
ε, the energy acceptance of the machine

Elastic
e- is kicked out of its trajectory and is lost because of large oscillation

$$\sigma(Z,\gamma,\langle\beta\rangle,a)$$

Cross section depends on :
Z, the atomic number
γ, the relativistic factor
‹β›, the average beta
a, the beam pipe aperture

The entire equation and references are in the back-up slides

Beam Gas Cross Section
for part of the ring

Equations give an estimate of the importance (order of magnitud) of the phenomena, mostly valid in the arcs.

However a detailed analisis requires a simulation, usually Monte Carlo.

Lattice Section	Gas	Elastic [barn]	Inelastic [barn]	
		(Z, γ, <β>, aperture)	(Z, ε)	
Arc	H2	0.0002 From Le Duff	0.3 Burkhardt	
Arc	N2	0.04 From Le Duff	**9.4** Burkhardt	
MDI	H2	0.2 New formula	-	
MDI	N2	**20** New formula	-	

WHAT WE DO WITH MDISim

First results of **Inelastic Beam-gas scattering** for the Z run with latest optics
Monte Carlo particle tracking simulation is performed using the MDISIM tool
→ Loss map and loss rates are obtained.

Results for:
1) arc only at the Z

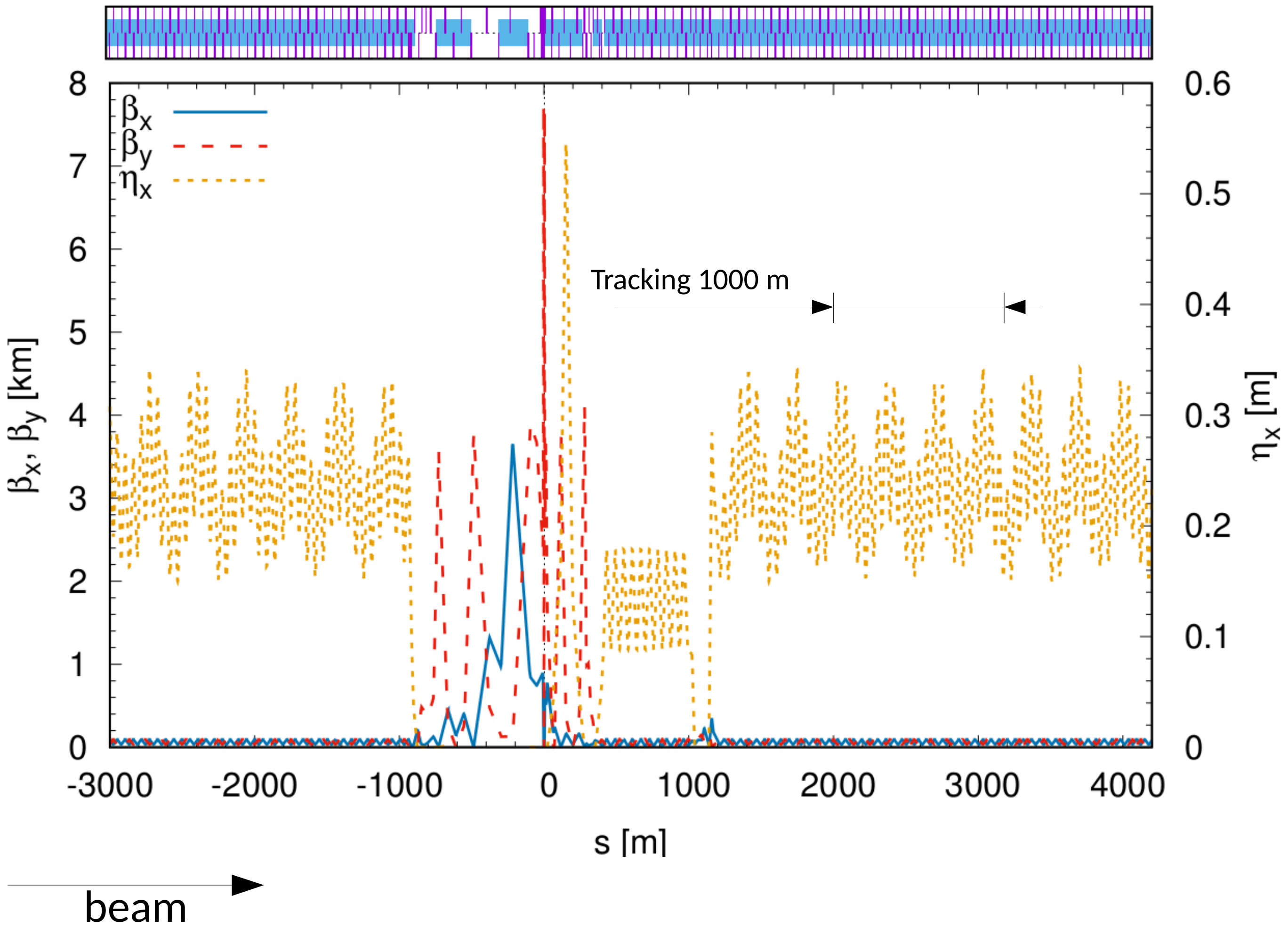
2) IR at Z, H, W.
I am showing plots for the Z

- Note that SR is not considered in the simulation.

Z 45.6GeV/beam
arc

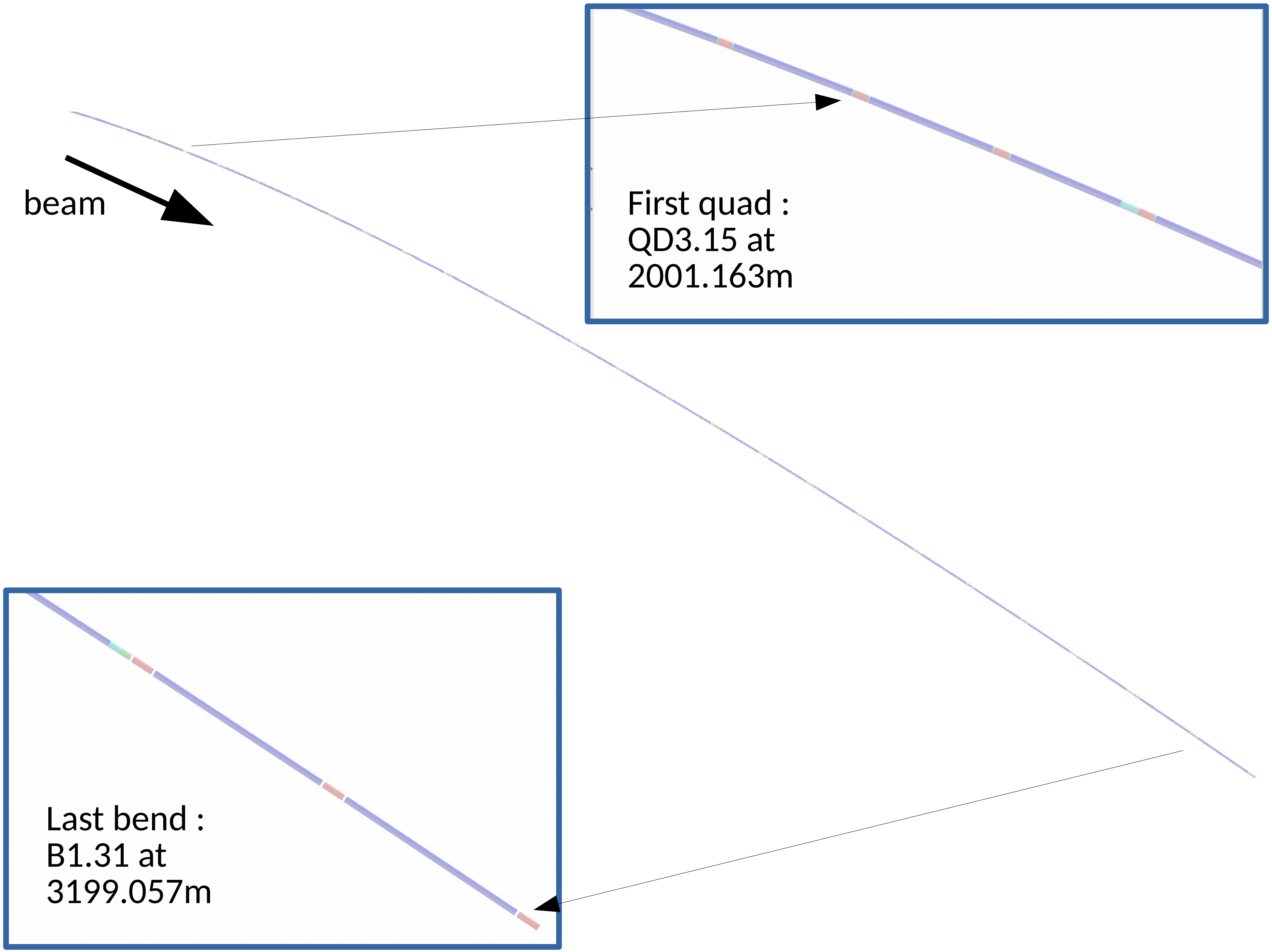
FCCee arc Z 45.6GeV/beam

Lattice : FCCee_z_213_nosol_4.seq (ZOOM)



Constant aperture : 35mm

FCCee Z geometry scalexy 50 :
(scalexy 1 is not displayed correctly, but IS used for the tracking studies)
Tracking starts at 2000m and ends at 3200m = 1200 m in total



WHAT IS THE PARTICLE LOSS RATE IN THE ARC ?

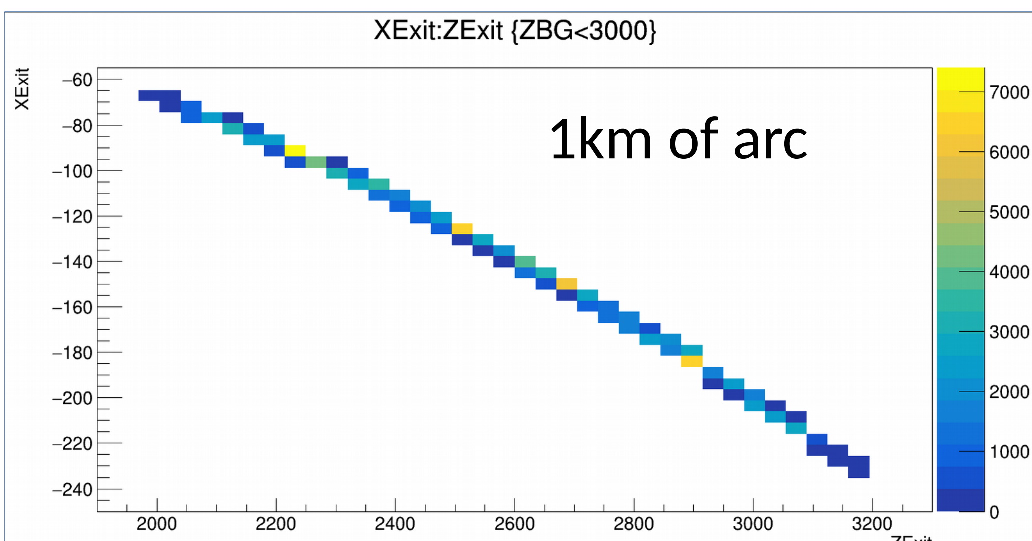
At 45.6GeV/beam : Npart = 1.7e11
Nbunches = 16640

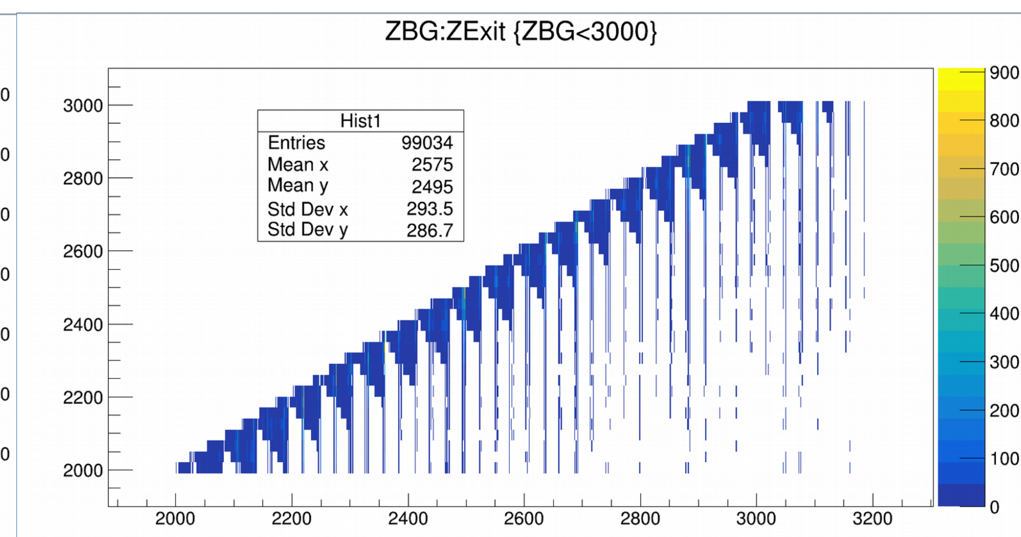
With an energy acc. of 2% and pressure of 10^{-9} mbar

	Scattering Rate/m/beam Expected	Scattering Rate/m/beam Simulation
H2 : 0.328 barn	6.7 KHz	6.2 KHz
N2 : 9.386 barn	192.3 KHz	189.1 KHz

As reference τ=100h → Scattering Rate = 78.6 Khz/m/beam

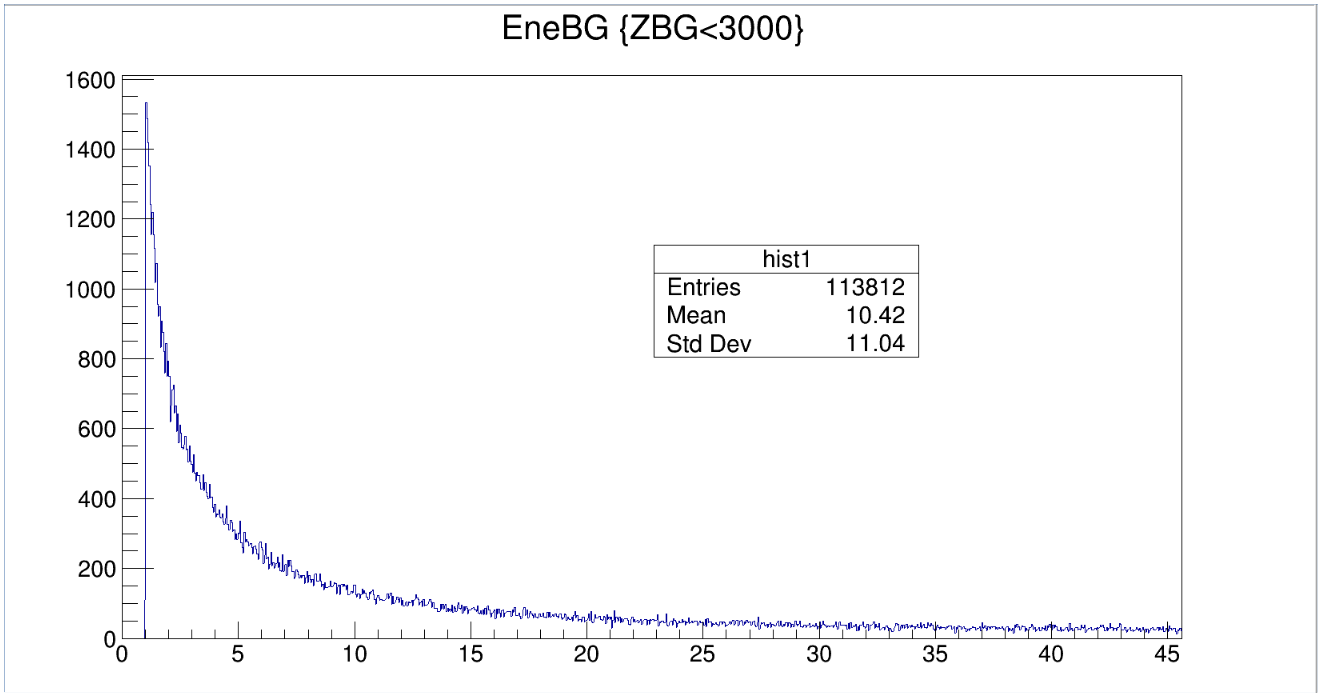
Beam gas particles generated in the arc are lost very soon, in the arc dipoles 100m~200m after interaction





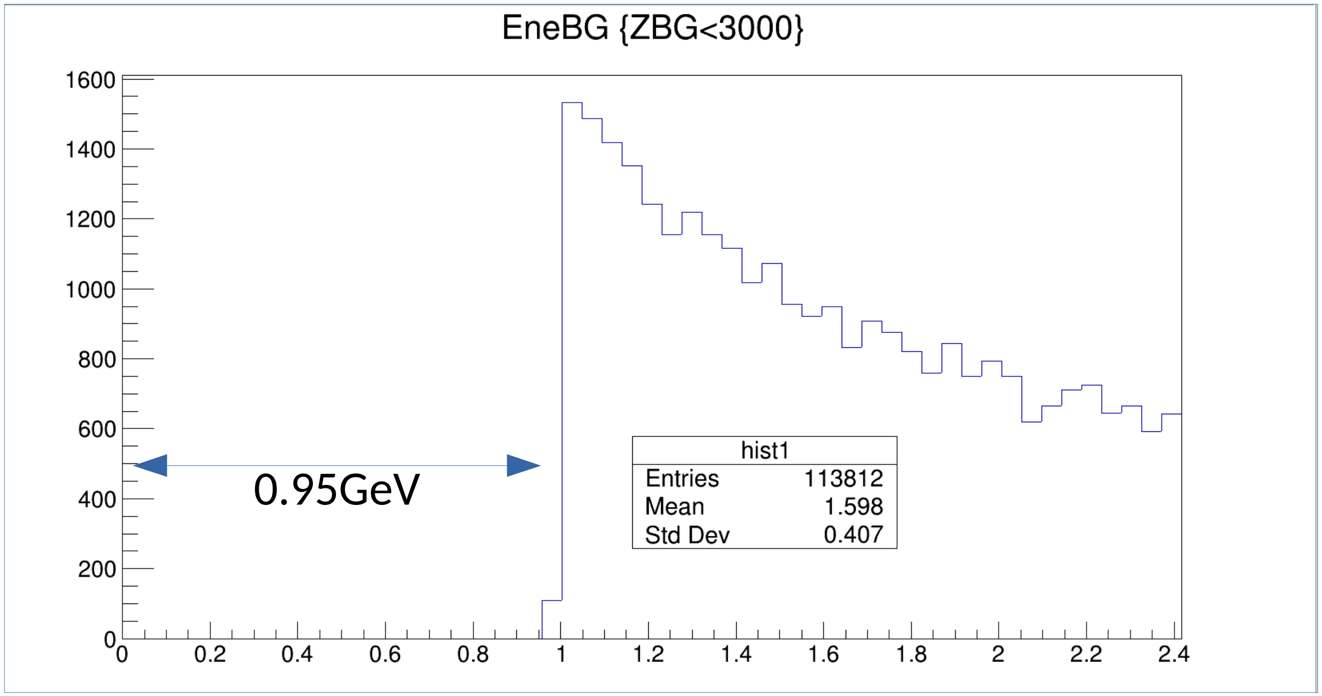
ENERGY EXCHANGE BETWEEN e- and gas ?

Energy loss
In the Beam Gas
event :



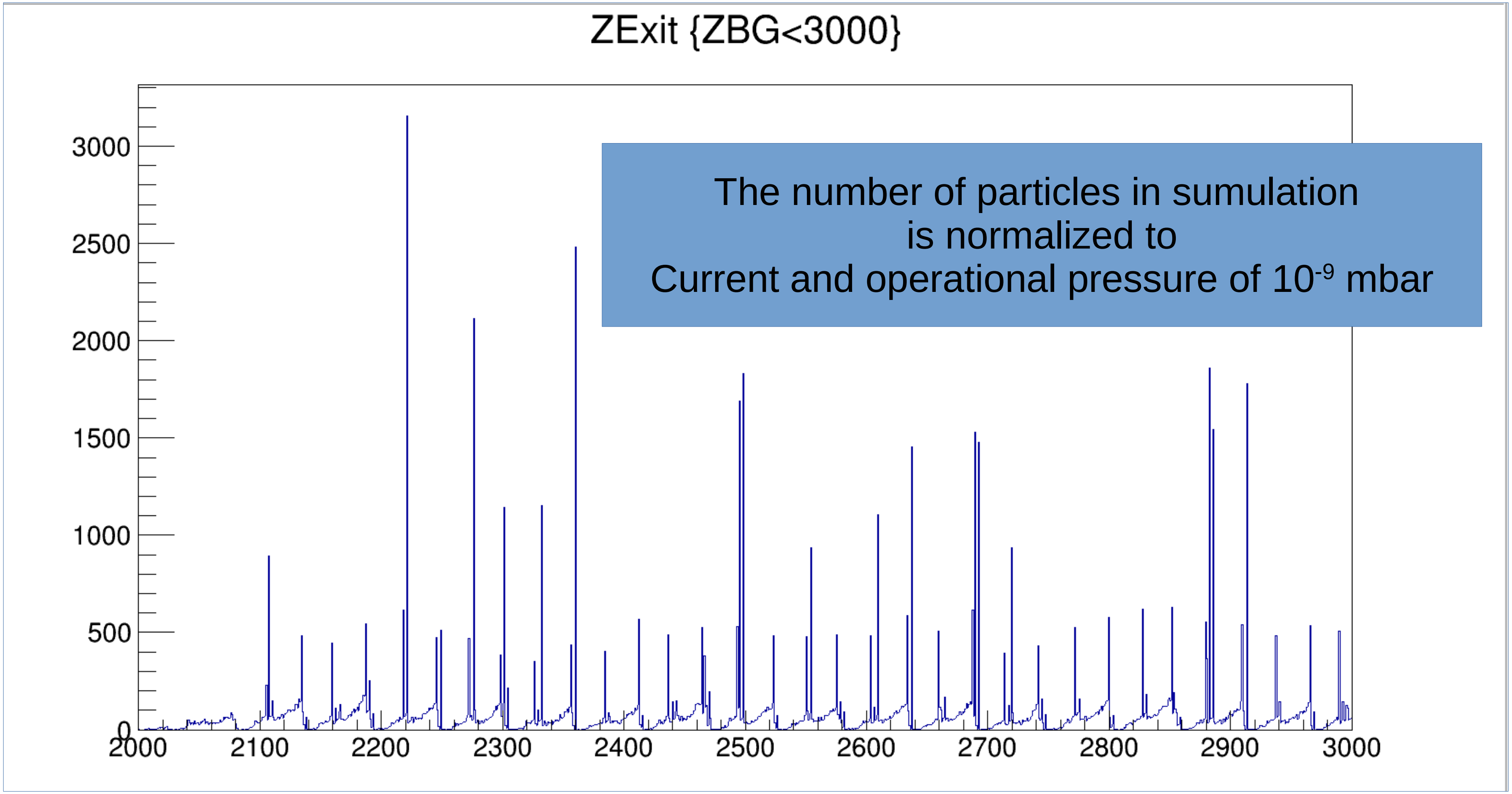
Particles loosing less
Than 0.95GeV continue
In the beam

Energy acceptance
0.95GeV , i.e.
0.95/45.6 = 2.1%



LOCATION OF PARTICLE LOSS ?

Particle distribution
Along Z :
Somehow uniform distribution of the particle loss

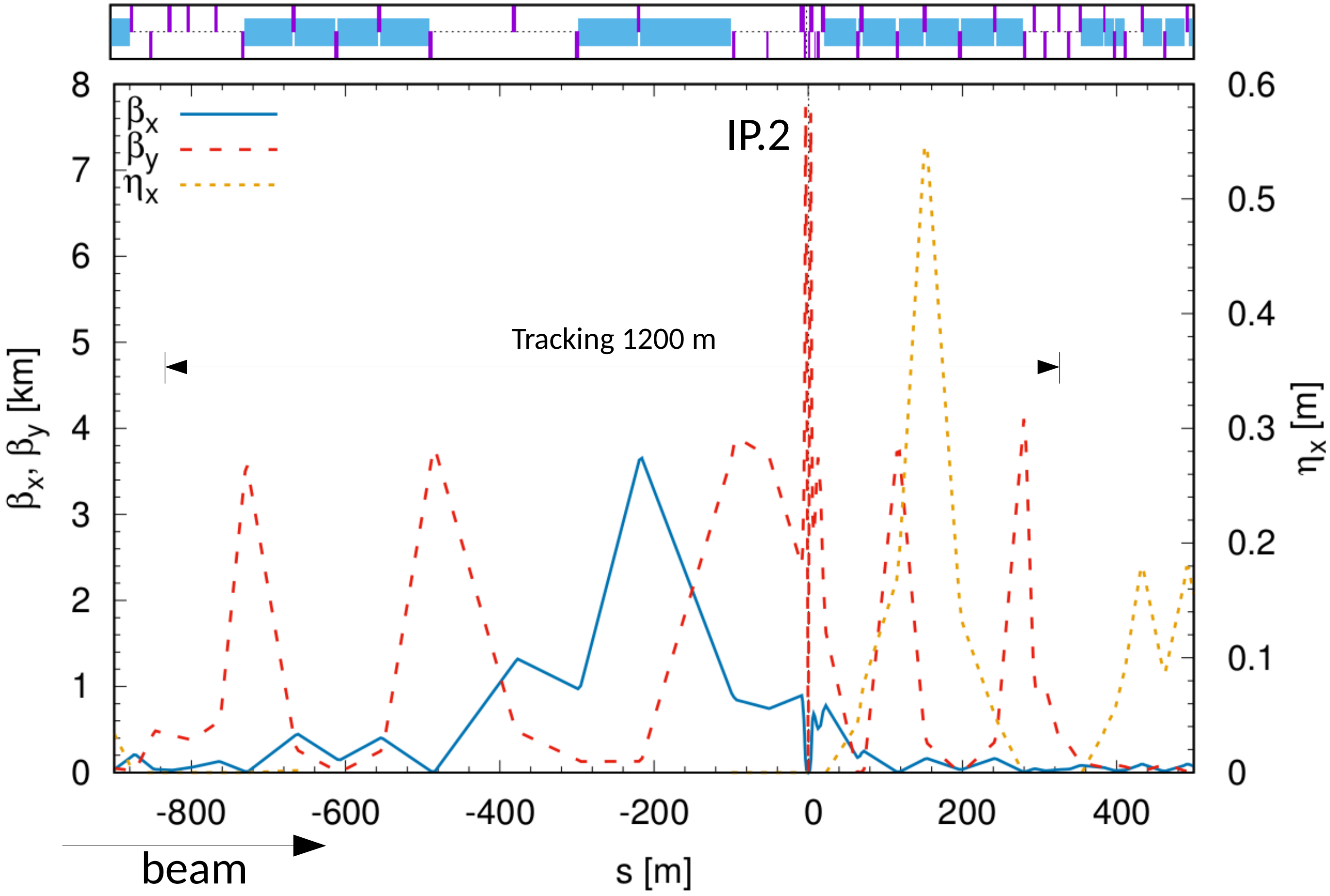


Z 45.6GeV/beam
MDI Region

at all energies the scattering distribution is similar, BUT, rate differs

FCCee Z 45.6GeV/beam

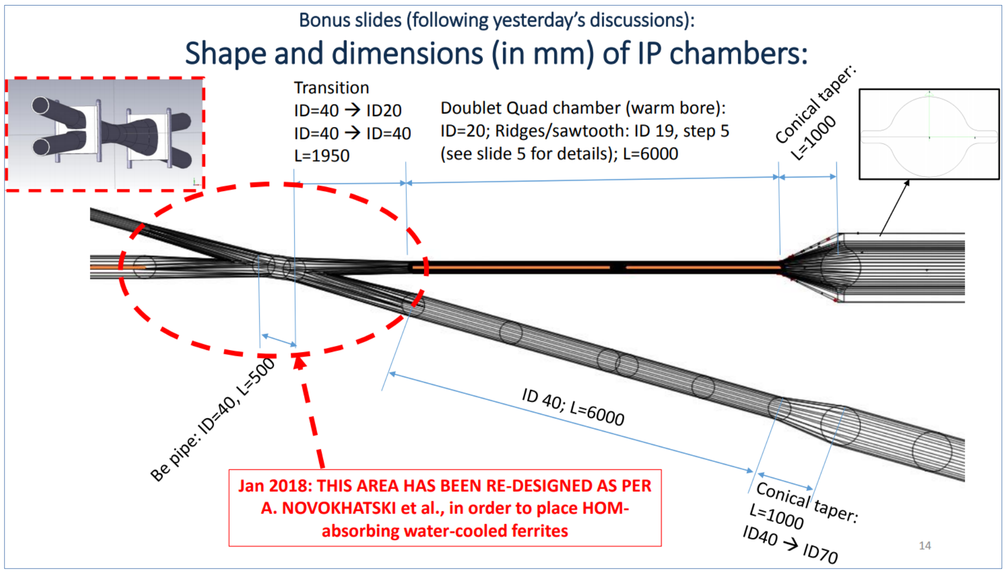
Lattice : FCCee_z_213_nosol_18.seq (ZOOM)

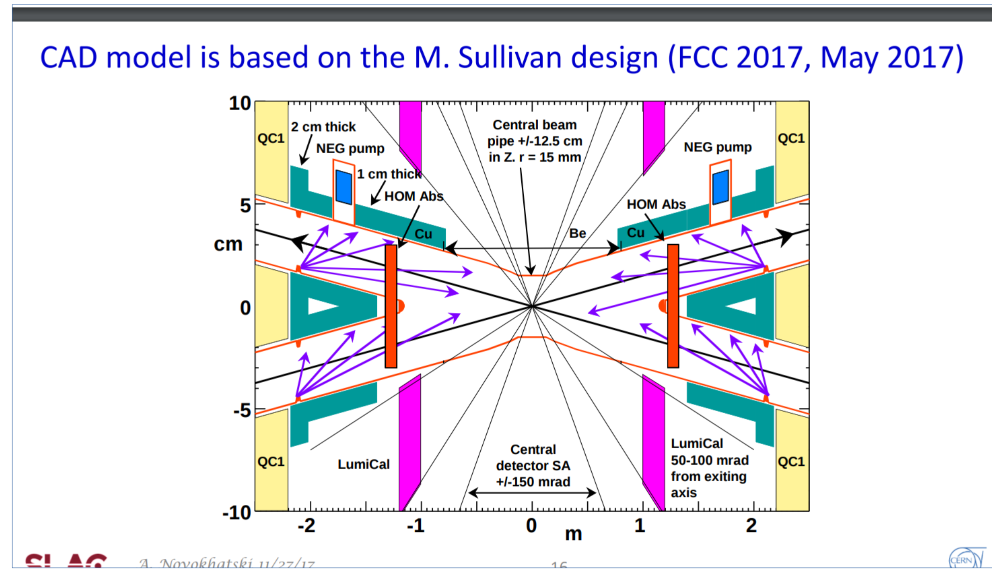


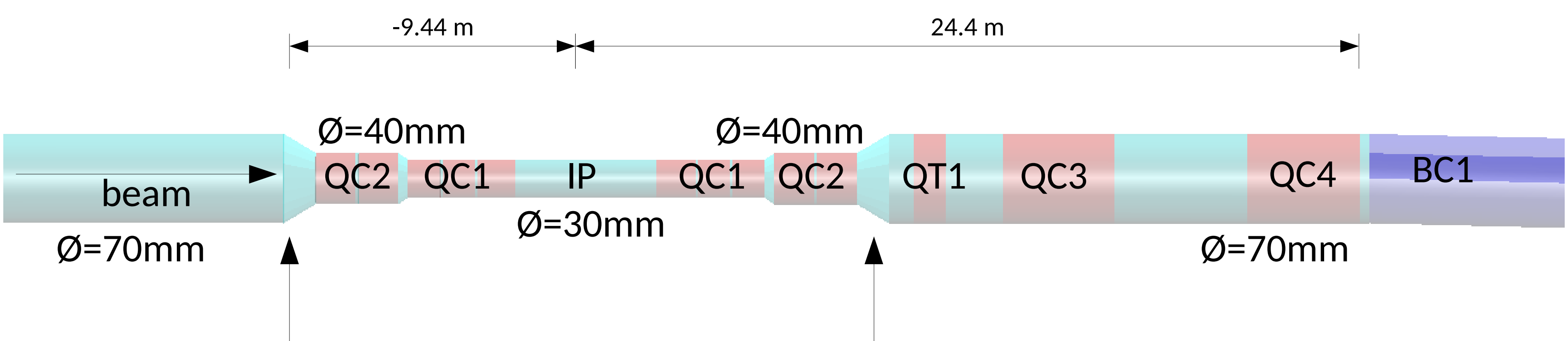
We consider to study from s=-830m to s=370m

Conical Tapers from Kersevan. IR Vacuum Concept.
Workshop on the Mechanical optimisation of the FCC-ee MDI
https://indico.cern.ch/event/694811/timetable/

The details between QC1's have been ignored for the moment

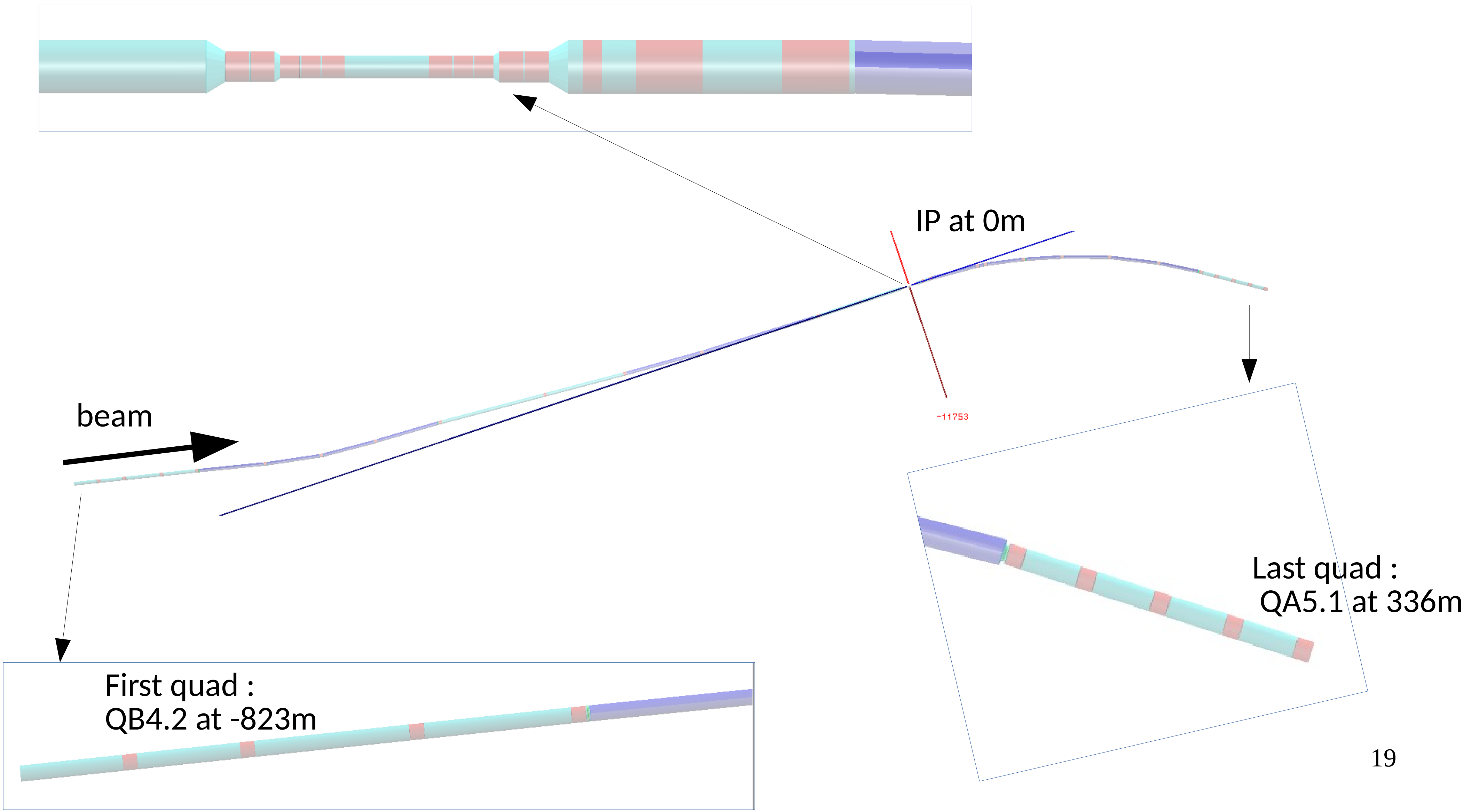






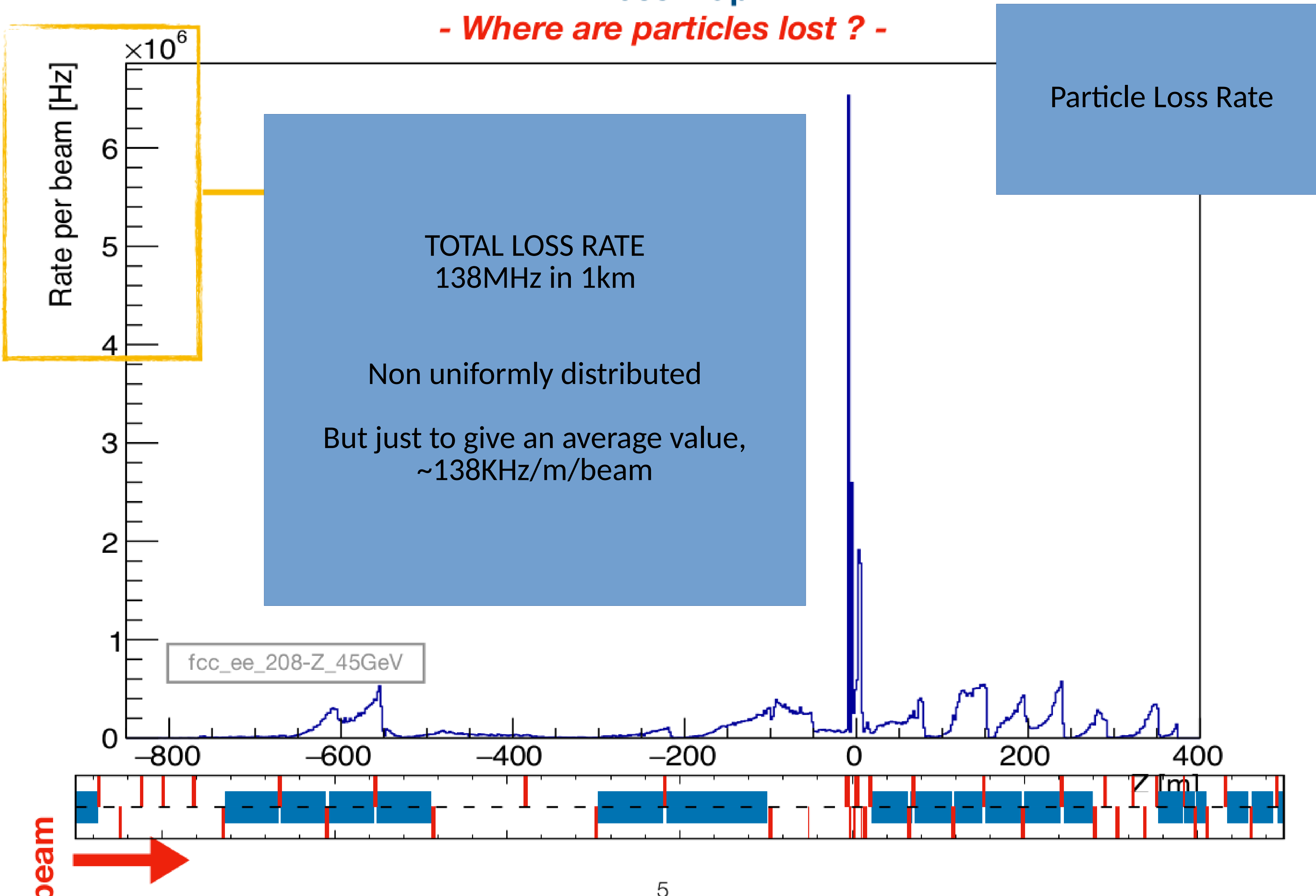
1m of conical taper between pipe diameters of 70mm and 40mm

FCCee Z geometry scalexy 50 :
(scalexy 1 is not displayed correctly, but IS used for the tracking studies)
Tracking starts at -830m and ends at 370m = 1200 m in total



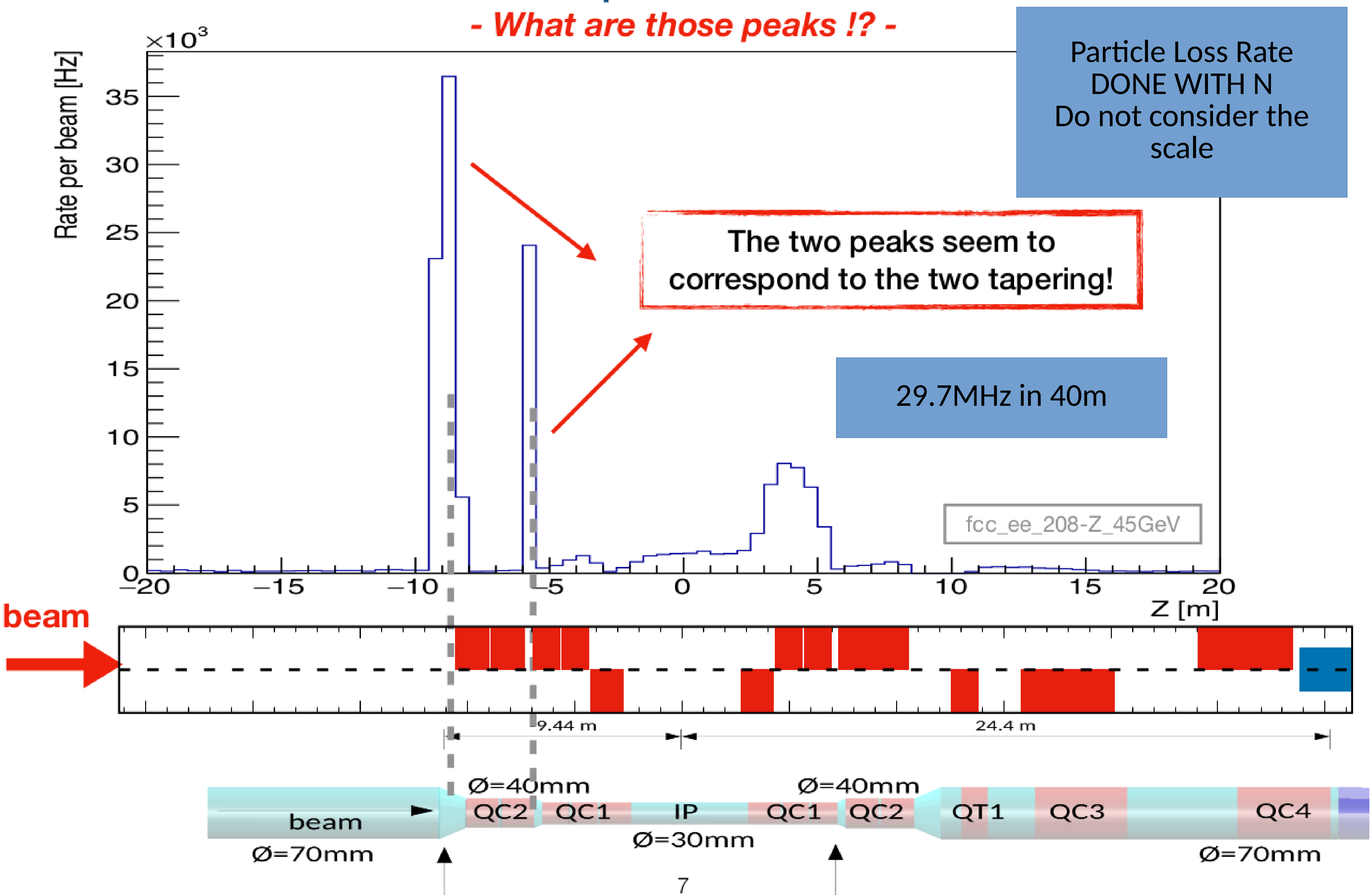
Z “loss map”

- Where are particles lost ? -



Z “loss map” - ZOOM around IP

- What are those peaks !? -



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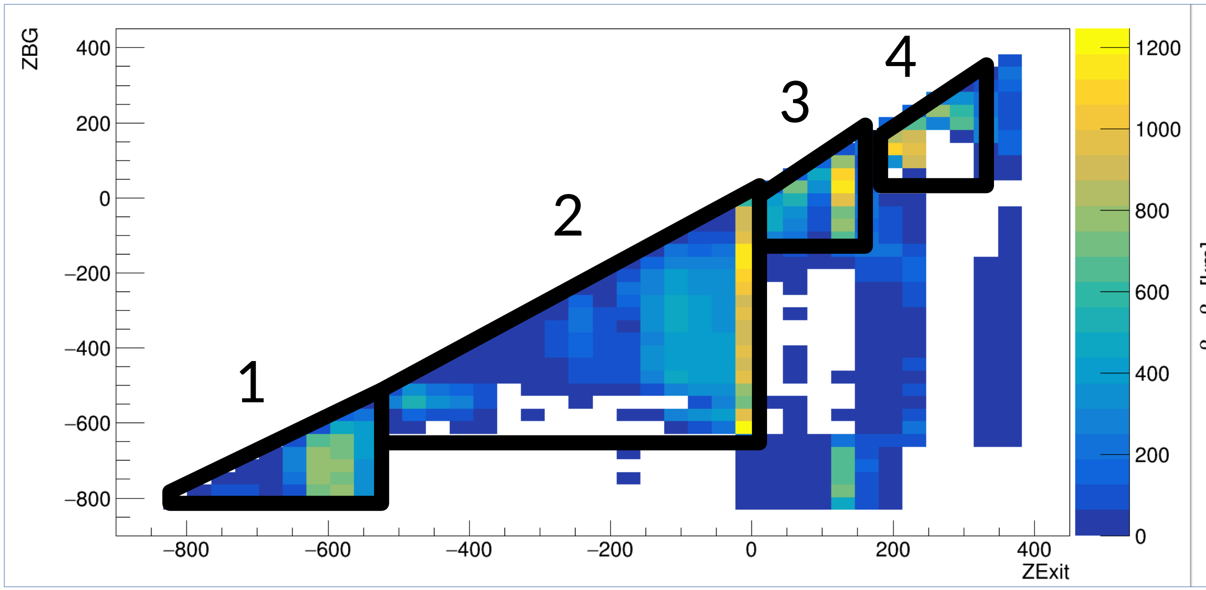
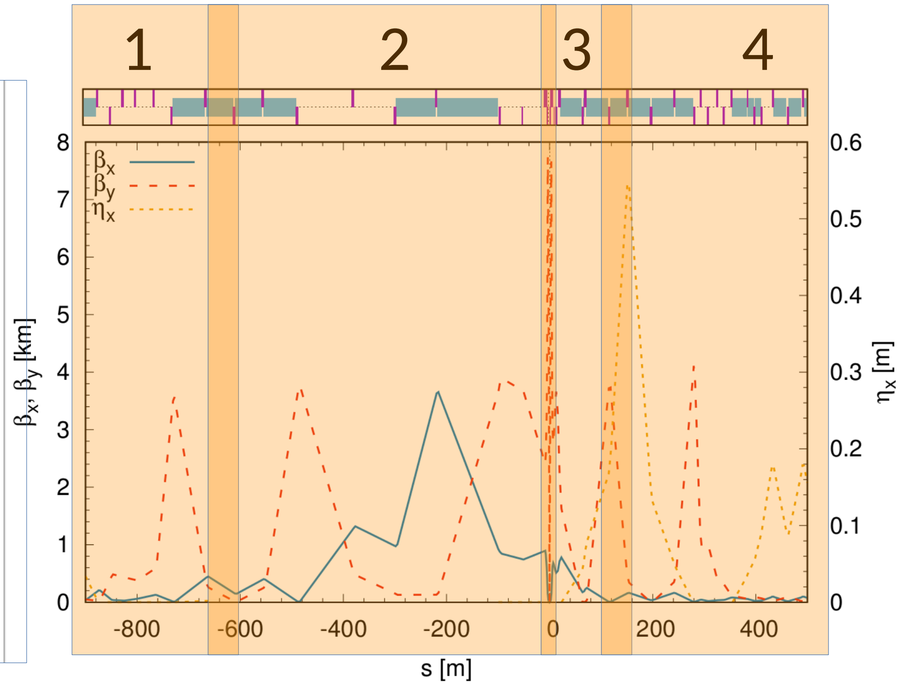
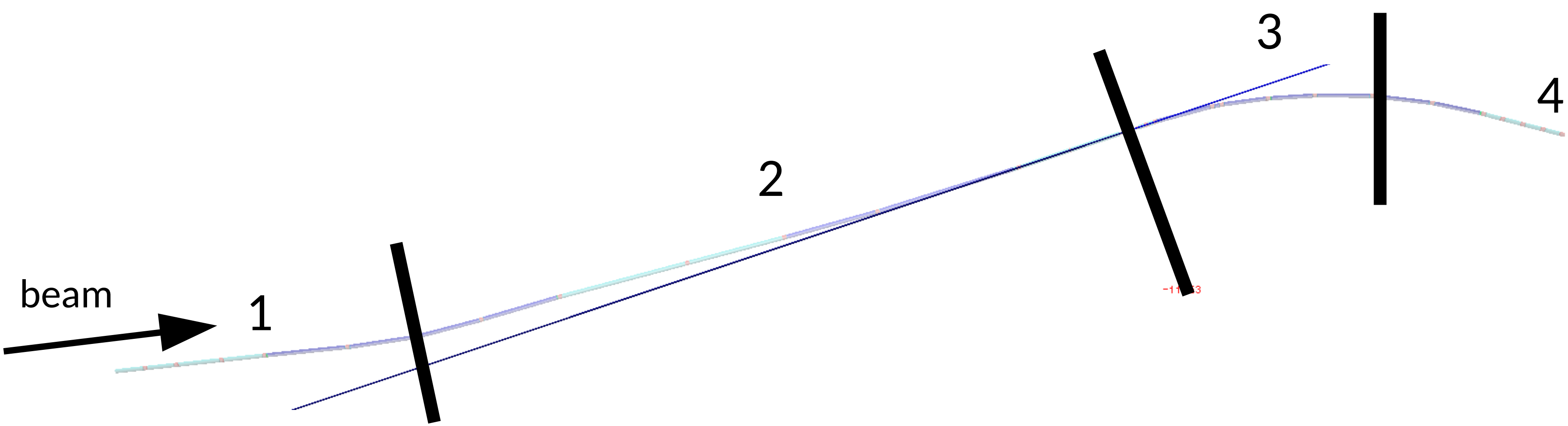
Particles hitting near the IP region, AREA 2, come from -600 m upstream.
The other regions show beam gas events that produce an immediate particle loss.



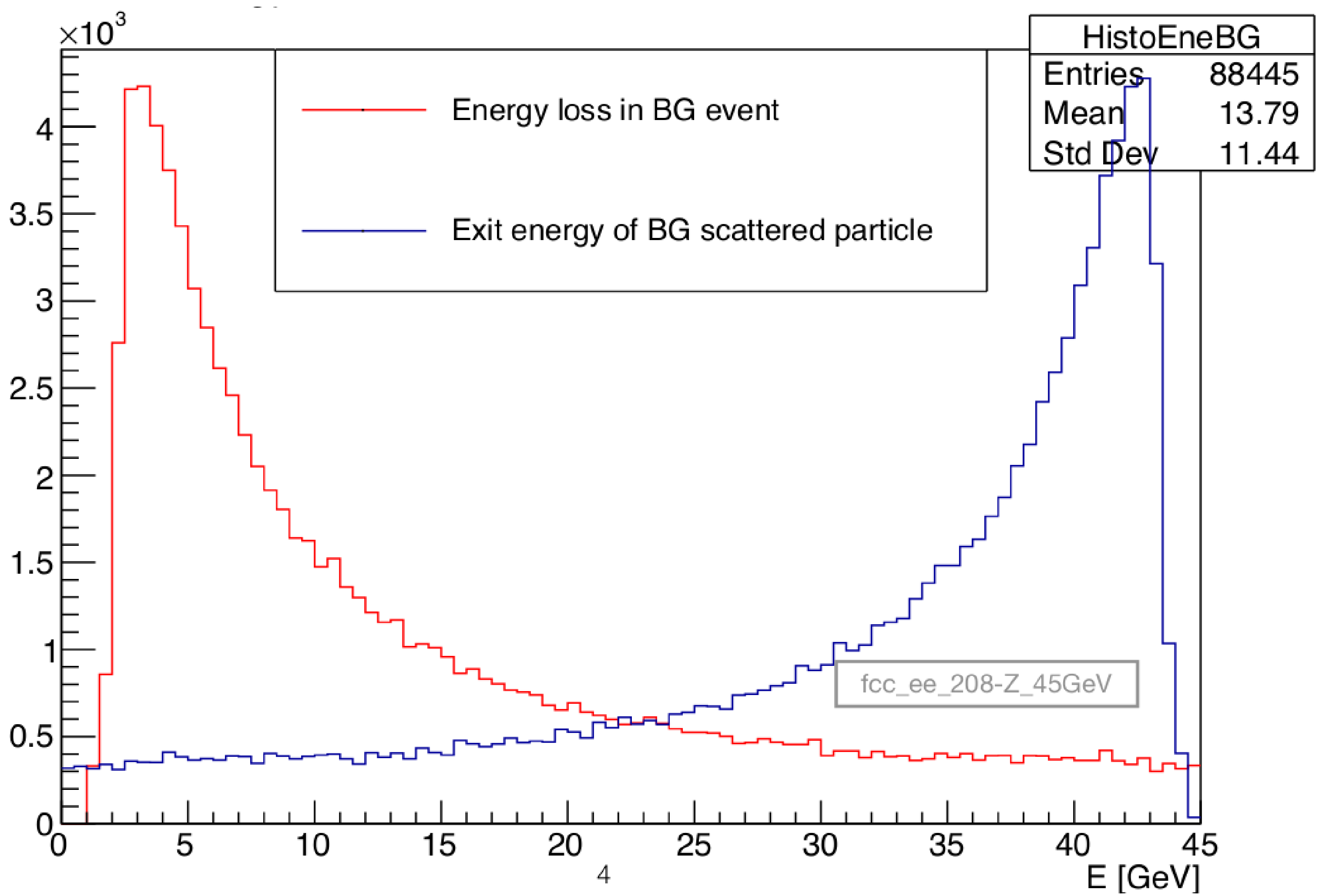




ENERGY OF THE LOST PARTICLES

Energy lost by the primary particle in the interaction with the gas molecule that led to particle loss

Energy of the particles that get lost due to BG when hitting the pipe



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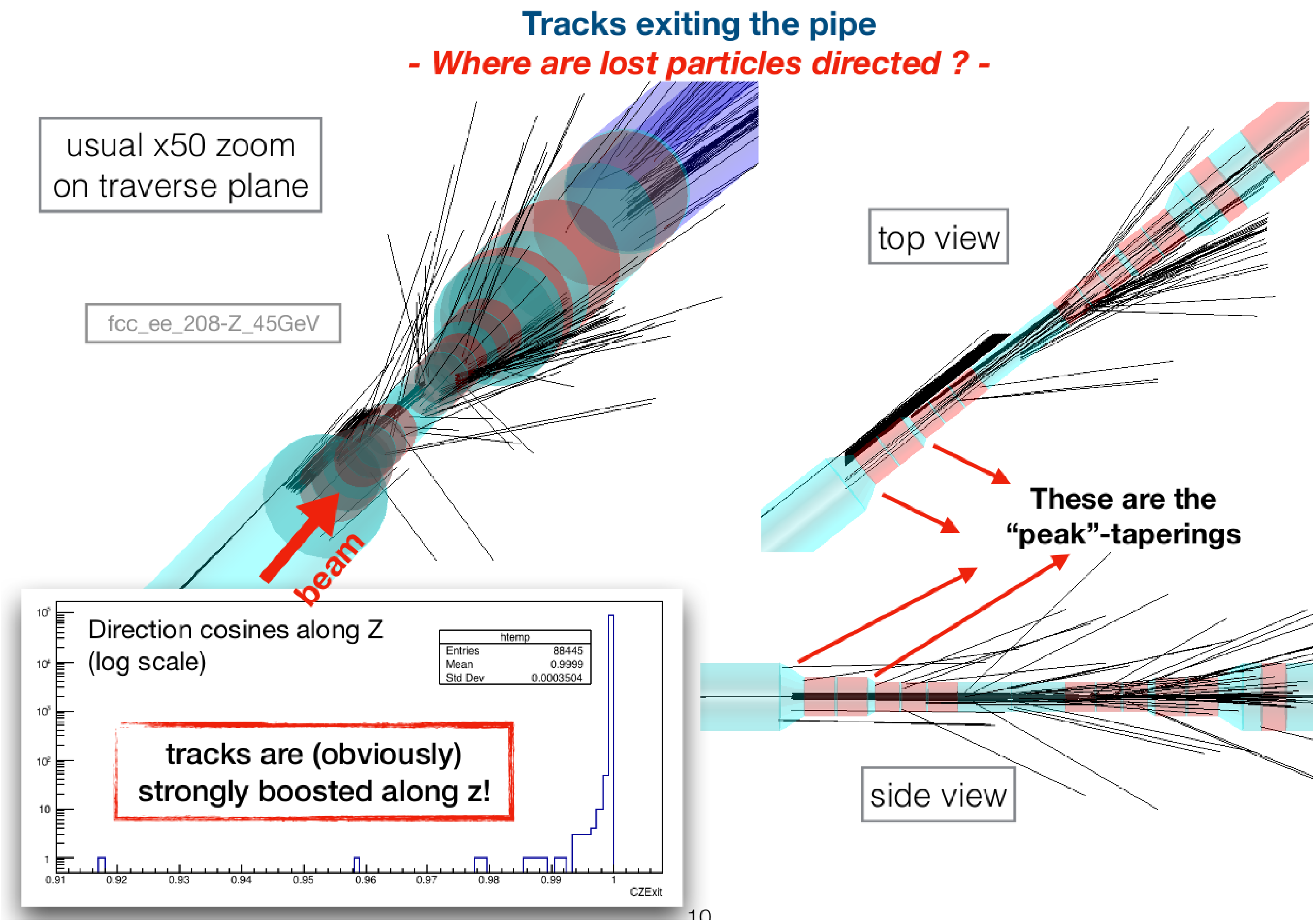
DIRECTION OF THE LOST PARTICLES



RATES FOR OTHER ENERGIES

Although, the rate is largely non-uniformly distributed along the MDI region,
We show the equivalent scattering rates per energy with N2

	Scat. Rates [Khz/m/beam]	Beam Current [mA]	Rate/Current [Mhz/A]
Z	147	1390	105
W	15.8	147	107
H	3.0	29	102
T	0.5	5.4	97

The constant rate/current ratio is a good indication because inelastic scattering is not dependent on energy.

This seems to be an small effect for the moment, however,
Background and variable pressure profiles studies are on – going.

CONCLUSIONS

MDISIM allows to get a detailed Loss Map and Loss Rate in the MDI region. For the arc the obtained loss rates are consistent with expectation from analytical formulas.

The geometry in the IR has been approximated with cilinders, and seems good enough for the moment.

A loss rate of 138 Khz/m/beam is found at The Z-pole with N2 at 10^{-9} mbar, Losses are concentrated in the conical tapers.

The study of other energies is on-going,
and points out to the similar loss map with lower rates,
IR losses originate ~600m upstream.

Loss map particles can be tracked in all the sub-detectors, and eventually, if dangerous, remedies could be considered.

BACK UP

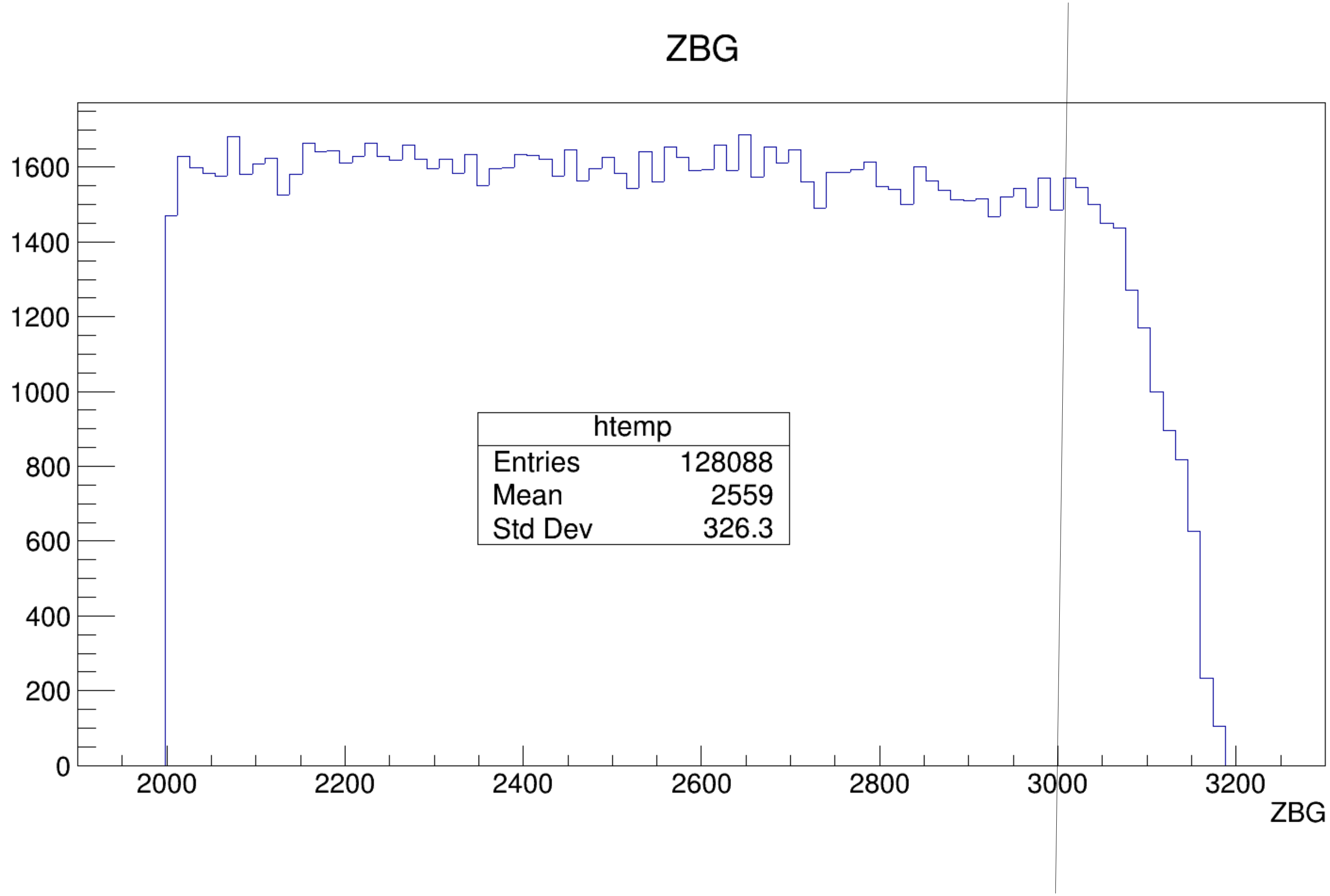
Lattices available in afs is X
Initial studies have been done with the ones marked with X
Latest lattice 213 for the t is now available

All these plots and numbers are available for all these optics/energies

	fcc_ee_208	fcc_ee_213
Z	X	X
W	X	X
H	X	X
T	X	–

Z (Euclidean) is NOT equal to S (C-S coordinates)
ZBG is the location along Z where a Beam Gas Interaction occurs.

It looks pretty flat up to 3000m, I cut at 3000m
For N :113812/1e7 = 1.13% are lost in 1km



WHAT IS THE LOSS RATE FROM BEAM GAS IN THE ARC ?

As calculated by Francesco :

Neloss = NelossMC/NeprimMC . Nebunch . Nbunches . Preal/Pmc

<u>For H the rate is 2.35 MHz per km of arc at 10^{-9} mbar</u>

Neloss = 68724/1e7 . 1.7e11 . 16640 . 1e-9/24.8
= 0.783e3
Rate_eloss = Neloss/Trev = 18.1e3/0.333ms = 2.35 Mhz

<u>For H2 the rate is 6.22 MHz per km of arc at 10^{-9} mbar</u>

Neloss = 90764/1e7 . 1.7e11 . 16640 . 1e-9/12.4
= 2.070e3
Rate_eloss = Neloss/Trev = 18.1e3/0.333ms = 6.22 Mhz

<u>For N the rate is 54.3 MHz per km of arc at 10^{-9} mbar</u>

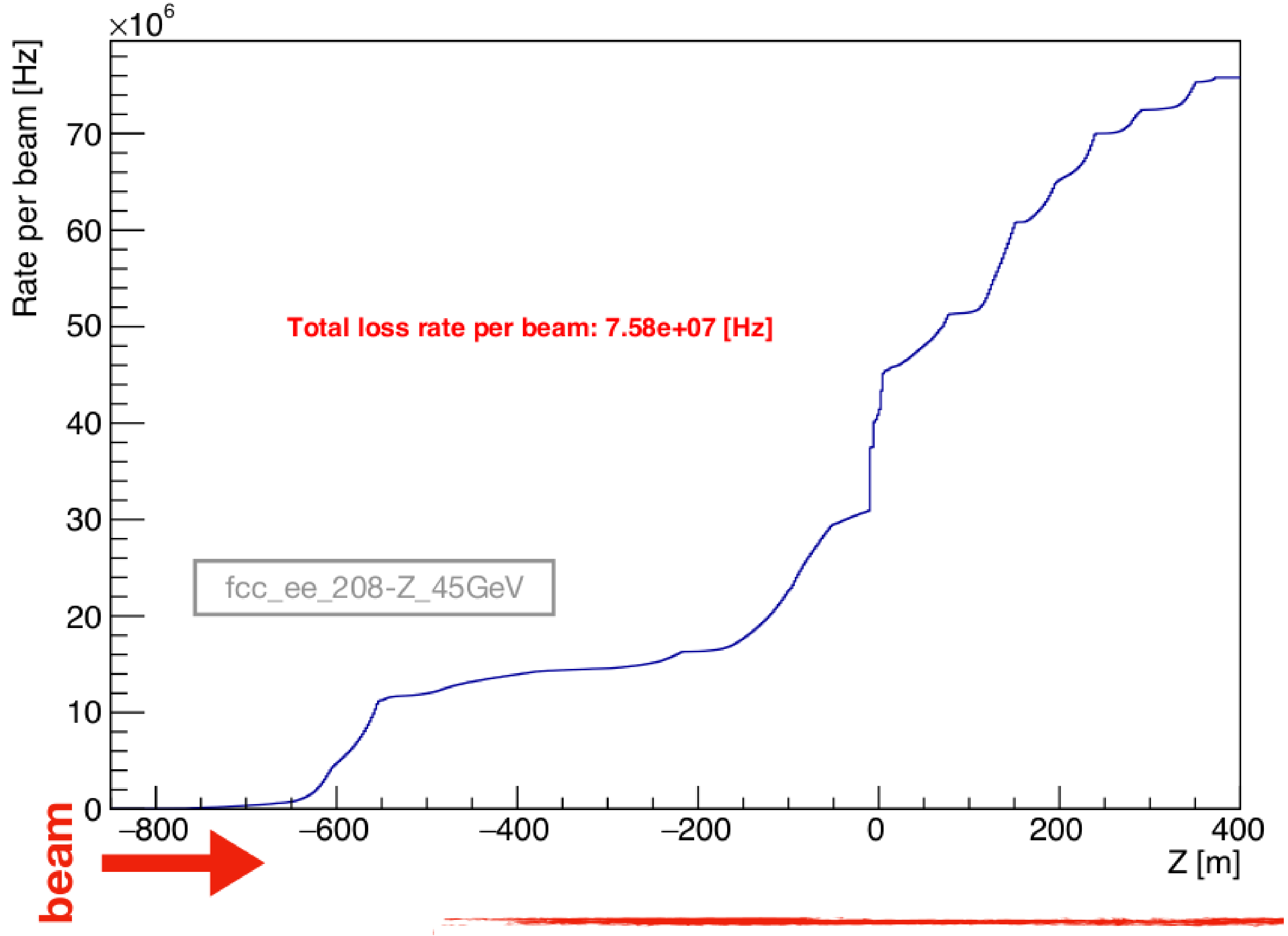
Neloss = 113812/1e7 . 1.7e11 . 16640 . 1e-9/1.78
= 18.1e3
Rate_eloss = Neloss/Trev = 18.1e3/0.333ms = 54.3 MHz

<u>For N2 the rate is 189.1 MHz per km of arc at 10^{-9} mbar</u>

Neloss = 99034/1e7 . 1.7e11 . 16640 . 1e-9/0.445
= 62.95e3
Rate_eloss = Neloss/Trev = 63.0e3/0.333ms = 189.1 MHz

THE PARTICLE LOSS IS NOT UNIFORMLY DISTRIBUTED

Cumulative distribution of losses



ELASTIC SCATTERING

Average cross section from average beta.
J Le Duff. Current and current density limitations in existing electron storage rings
Laboratoire de l'accélérateur Linéaire, LAL, NIM in Physics Research A239 (1985) 83-101.

Average beta is invalid in the MDI region.

2.1.1. The elastic scattering on nuclei

Elastic scattering on nuclei leads to an angular kick for the betatron motion. If the induced amplitude exceeds the vacuum chamber aperture the particle gets lost. The total cross section for this process is [1]:

$$\sigma_{t1} = \frac{4r_e^2Z^2}{\gamma^2}\frac{\pi}{2}\left(\frac{\langle\beta\rangle}{a}\right)_z^2,$$

where

r_e = the classical electron radius,
γ = the normalized energy (E/m_0c^2),
Z = the atomic number for residual gas components,
$\langle\beta\rangle$ = the average betatron envelope function,
a = the half chamber aperture,

and it is assumed that the loss will occur in the vertical plane (z direction).

In the case of a non-smooth optic and assuming the aperture limit a_0 is located at some azimuth where the envelope function is β_0 one should replace $(\langle\beta\rangle/a)^2$ by $\langle\beta\rangle\ \beta_0/a_0^2$ [2]. The elastic scattering effect goes up when the energy goes down.

References

[1] J. Haïssinski, Thèse, Laboratoire de l'Accélérateur Linéaire, Orsay (1965).
[2] H. Wiedemann, private communication.
[3] A. Berthelot, Rayonnement de particules atomiques, électrons et photons (Masson, Paris, 1956).
[4] F.F. Rieke and W. Prepejchal, Phys. Rev. A6 (4) (1972).
[5] H. Bruck, Accélérateurs circulaires de particules (Presses Universitaires de France, 1966).

ELASTIC SCATTERING

MODIFIED EQUATION

Based on Section 4.1 Elastic Scattering. CAS CERN Accelerator School. Fifth General Accelerator Physics Course, Vol 1. Jan/21/1994. Geneva, Switzerland.

$$\bar{\sigma} = \frac{1}{\sum L_k} \frac{1}{\sum L_i} \frac{\tau_2 Z^2 r_e^2}{\gamma^2} \sum_k \sum_i L_k L_i \frac{\beta_k \beta_i}{H_i^2} \; ; for\ k \neq i$$

Sigma = average cross section
k = index of element inside the considered region
i = index of element along the entire ring
Gamma = relativistic gamma factor
Tau_2 = 6.2832
L = total accelerator length
L_k = length of kth-element in the chosen region
L_i = length of the ith-element in the entire accelerator
Z = atomic number
r_e = the classical electron radius
Beta_i, Beta_k = the vertical beta at the kth/ith-sm element
H_i = the aperture of the ith-element

INELASTIC SCATTERING
Theoretical cross section from H. Burkhardt.
M Brugger, H Burkhardt, and B Goddard. Interactions of Beams With Surroundings. Landolt-Boernstein, 21C:5–1 – 5–17, 2013.

eN scattering relevant for electron rings

The elastic cross section for eN scattering scales strongly with energy (with $1/\gamma^2$) and scattering angle $1/\theta^4$. Elastic scattering is mostly relevant as halo production process for lower energy rings and becomes negligible for lifetime estimates for high energy electron rings.

At high energy, the dominating beam-gas process for electron rings is the inelastic scattering or bremsstrahlung in which the incident electron interacts with the field of the residual gas nucleus and radiates a photon.

The high energy cross section for eN scattering can be written in good approximation independently of the electron energy as [13]

$$\sigma_{\mathrm{eN}} = 4\alpha\, r_e^2\, Z(Z+1)\, \log(287/\sqrt{Z}) \left(-\frac{4}{3}\log k_{\mathrm{min}} - \frac{5}{6} + \frac{4}{3}k_{\mathrm{min}} - \frac{k_{\mathrm{min}}^2}{2} \right), \tag{5.4}$$

where k_{min} is the fractional energy loss or minimum photon energy in units of the electron energy, α the fine-structure constant (1/137) and Z the atomic number (or number of protons). We can see that the cross section scales with $Z(Z+1)$. Numerical values obtained from Eq. 5.4 for $k_{\mathrm{min}} = 0.01$ are shown in Tab. 5.4

Table 5.2. Numerical values for σ_{eN} for an energy loss of at least 1% and for σ_{pN}, the pN cross section at high energy ($p_{\mathrm{lab}} = 0.01$ to 10 TeV).

Gas	σ_{eN} b	σ_{pN} b
H_2	0.28	0.08
He	0.39	0.19
CH_4	3.02	0.43
H_2O	4.38	0.40
N_2	6.47	0.56
CO	6.56	0.56
CO_2	10.7	0.87
Ar	17.8	0.60

z*(z+1)*log(287/sqrt(z))