FCC BEAM BACKGROUND STUDIES WITH GUINEA-PIG

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Including information from:

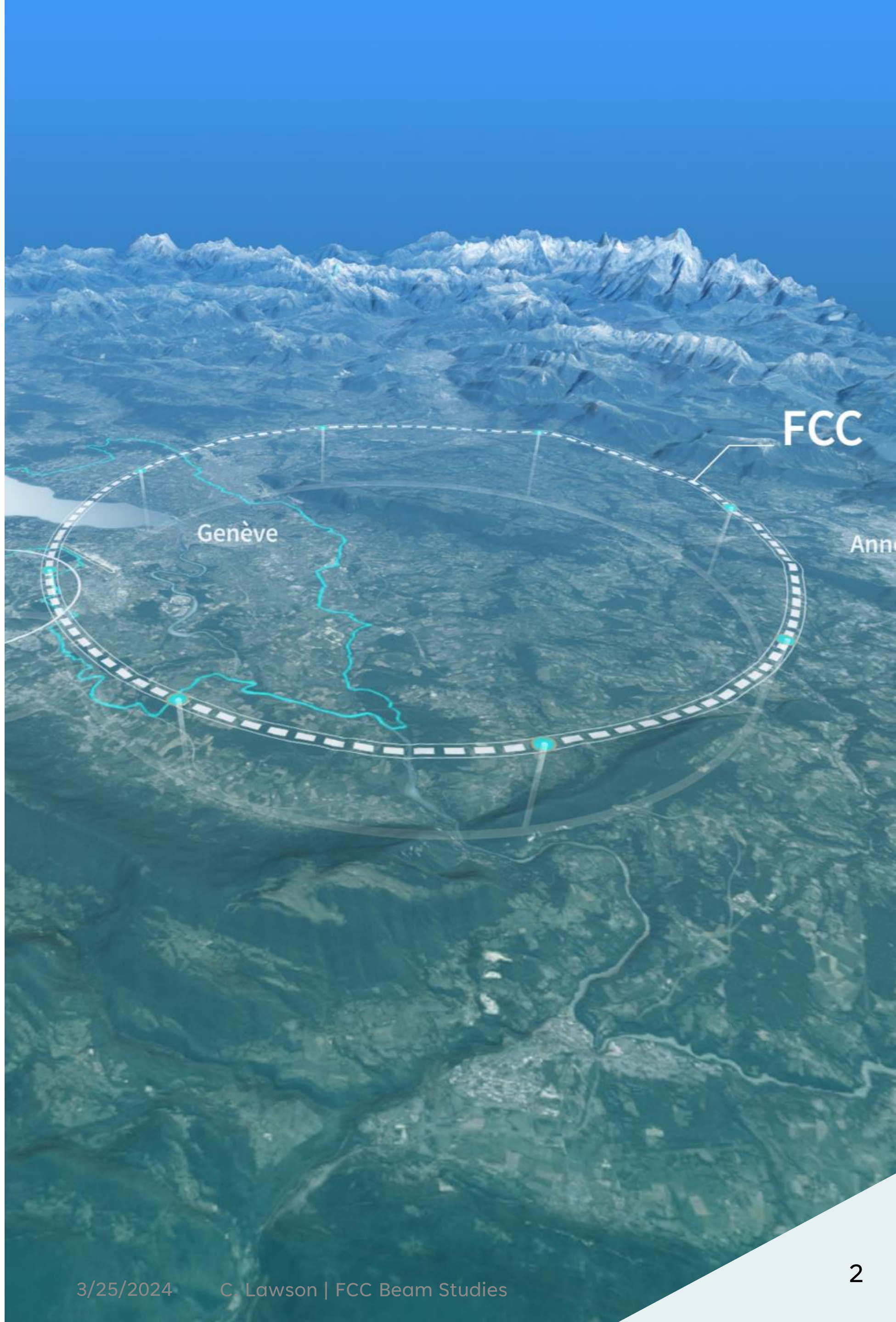
OVERVIEW

Design of the Machine Detector Interface area for the Future Circular Collider (FCC) is particularly challenging

- New beam-pipe central chamber design of the e+e- collider featuring a smaller radius and shorter length is being considered
- Critical to assess the background-induced occupancy and the impact of beam and machine-induced background

The importance of background varies with beam energies, emittance, bunch particle type etc.

- Can be simulated and understood using Guinea-Pig++



[CERN, FCC Schematic map]

GUINEA-PIG++

Generator of Unwanted Interactions for Numerical Experiment Analysis – Programme Interfaced to GEANT

- Simulates the interaction of two colliding ultra-relativistic beams containing electrons, positrons and photons (others can be approximated using tricks)
- Made for single collisions, can be used for repeated collisions at some level
- Capable of providing output in the common event data model in the key4hep framework

Includes:

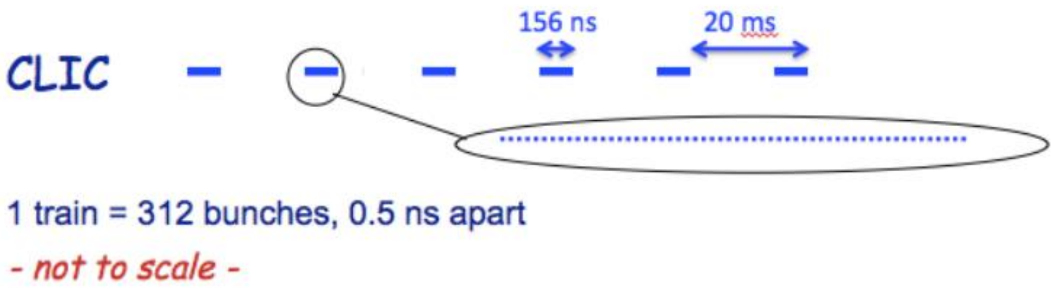
Pinching of the beams • Emission of beamstrahlung • Initial state radiation • Production of incoherent pair background • Bremsstrahlung • Beam size effect • Production of hadronic background (also minijets)

https://gitlab.cern.ch/clic-software/guinea-pig

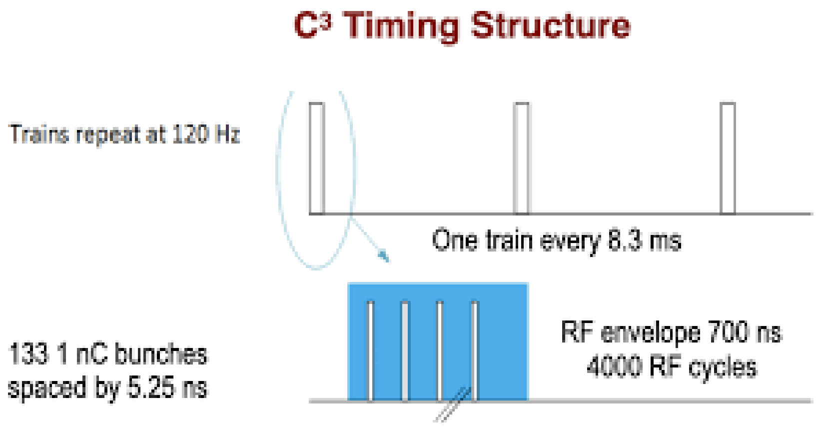
VERIFYING GUINEA-PIG OUTPUT WITH CLIC AND C3

C3 vs CLIC: Both proposed compact linear colliders designed for high-energy collisions

Compact Linear Collider (CLIC) is designed for energies in the multi-TeV range. To achieve such high luminosities at a linear collider, very small beams and a high beam repetition rate are needed



The Cool Copper Collider (C3) relies on normal copper conducting accelerating technology with a novel cavity design which can achieve cryogenic temperatures, likely in the sub-TeV range



[Levy, A. (2015). CLICdp Overview , Ntounis, Gray (2023) Beam Studies for the Cool Copper Collider]

GUINEA-PIG PARAMETERS: C3 AND CLIC

Definitions: https://gitlab.cern.ch/clic-software/guinea-pig/-/blob/master/doc/GuineaPigManual.pdf

Variable	**Definition**	CLIC	C3 (250 Com)
energy	The energy of the particles in GeV.	1500	125
particles	The number of particles per bunch in units of [10^10]	0.4	0.625
beta_x	The horizontal beta function in mm	8.0	12.0
beta_y	The vertical beta function in mm	0.15	0.12
emitt_x	Normalized horiz emittance in 10^-6 mrad	0.68	0.9
emitt_y	Normalized vertical emittance in 10^-6 mrad	0.02	0.02
sigma_z	The longitudinal beamsize in µm, the RMS value	44.0	100
espread	The RMS value of the relative energy spread of the beam particles.	0.001	0.003
dist_z	charge distribution (0 = normal)	0	0
offset_x	Horizontal offset in nm	-1.9055	5.0
offset_y	Vertical offset in nm	-0.242605	0.2
n_b	number of bunches per train (not used)	312	133
f_rep	repeition frequency (not used)	100	120

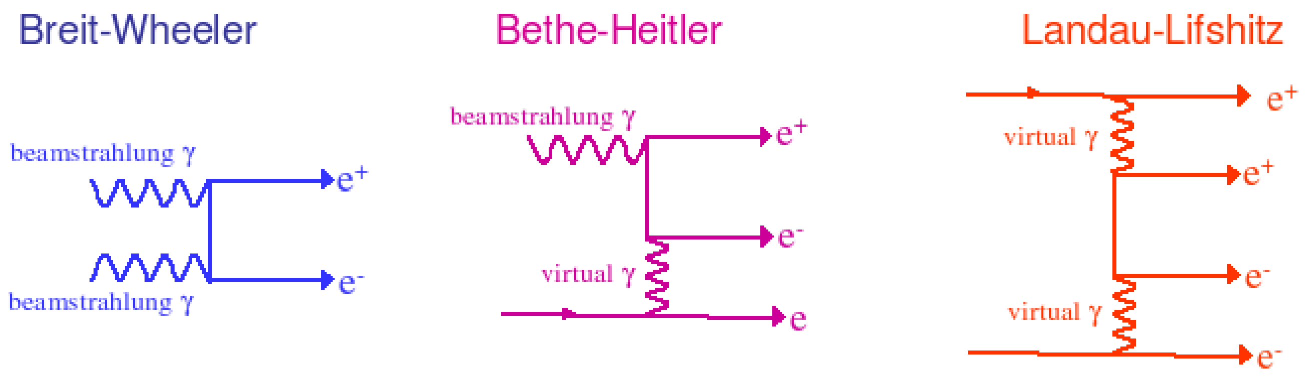
GUINEA PIG OUTPUT

Incoherent Pairs after beam-beam interaction:

Particle Energy [GeV] | Beta_x | Beta_y | Beta_z | x [nm] | y [nm] | z [nm] | process (*)

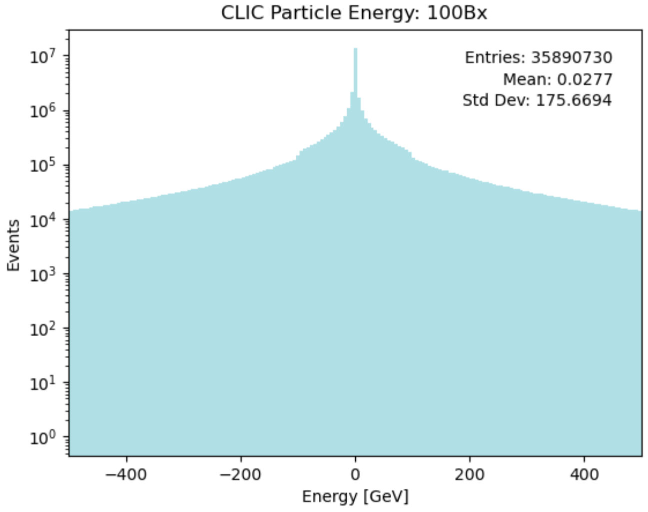
Pair Production Process

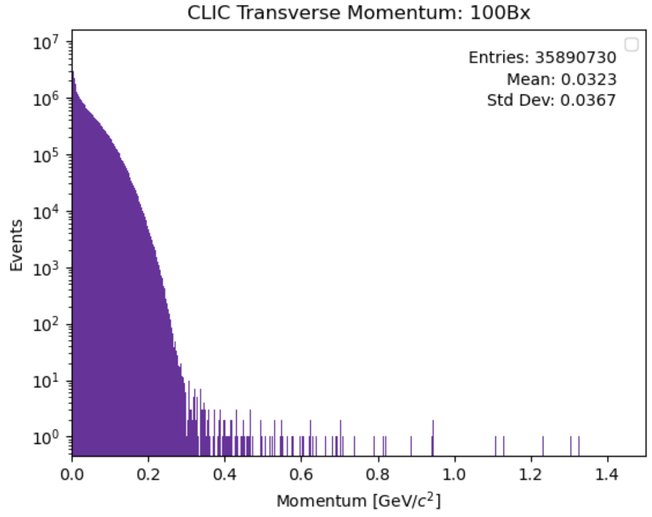
When beam electrons radiate photons (beamstrahlung), the produced photons may convert into pairs of an electron and a positron through one of the processes:

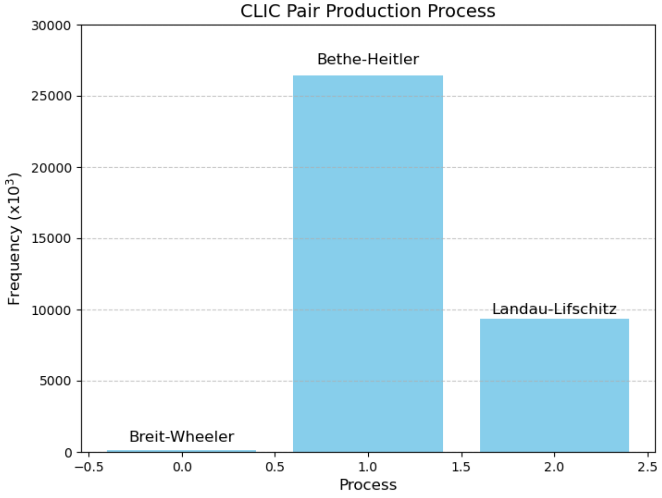


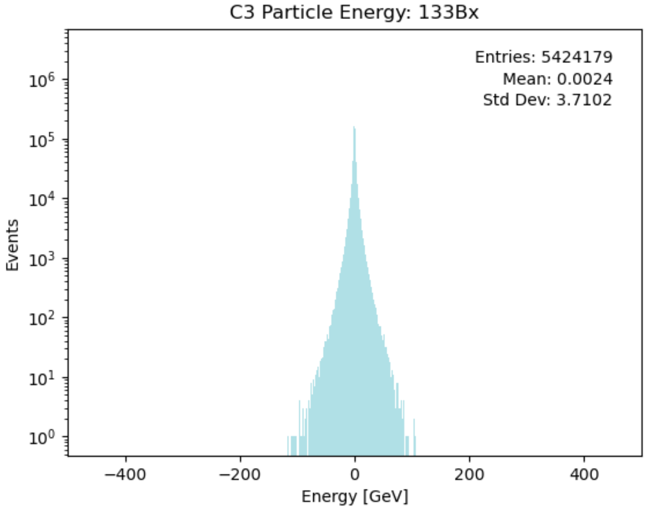
[IFIC. (n.d.). Machine Backgrounds https://ific.uv.es/~vos/ilc/ilcFastForward/MachineBackground.html]

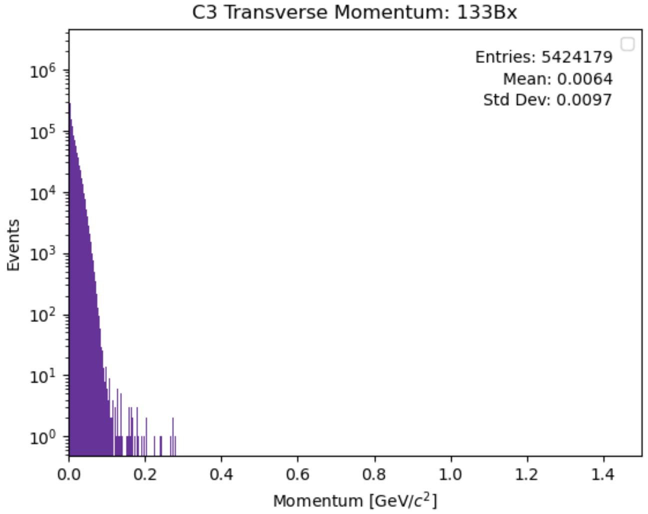
GUINEA PIG OUTPUT: C3 VS CLIC

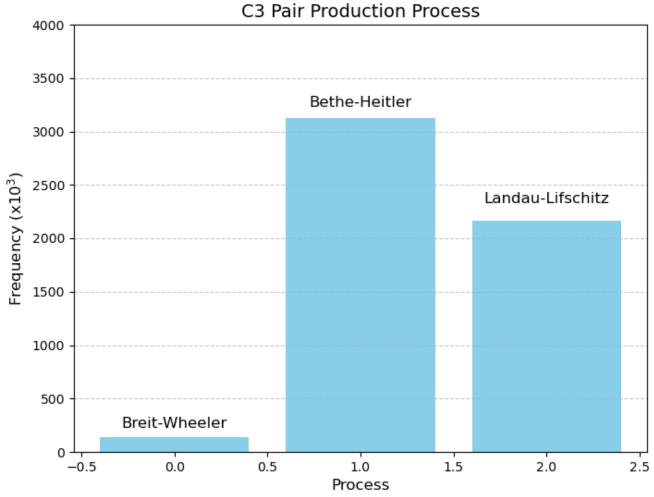




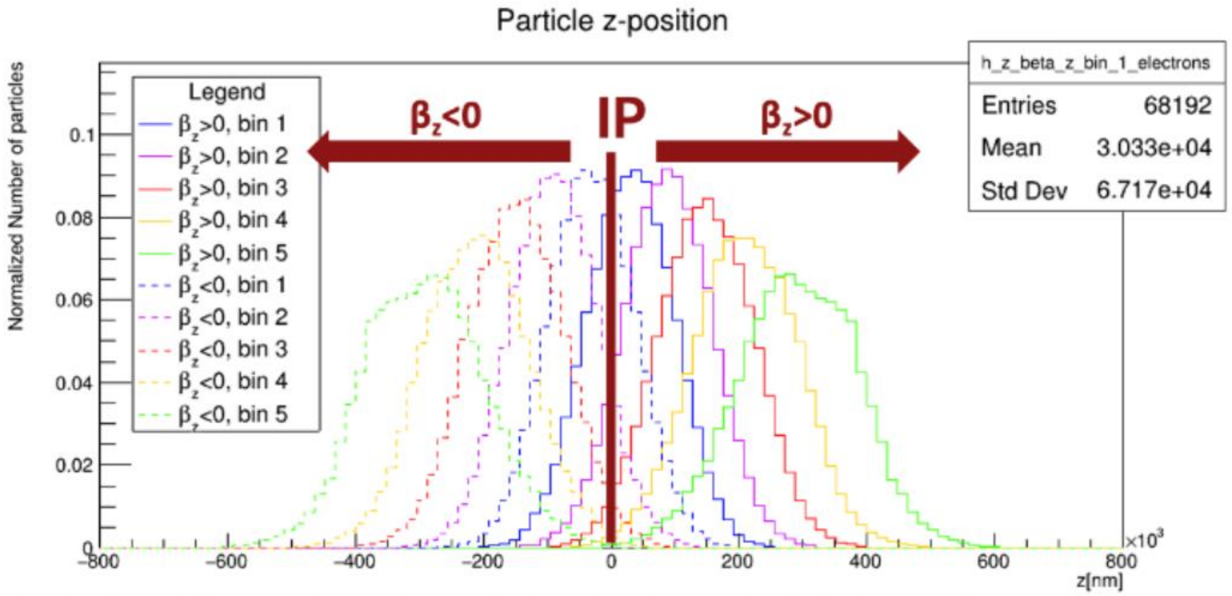








GUINEA PIG OUTPUT: BETA_Z



Distribution of the z-position of beam-induced e^+/e^- for the 133 simulated BXs for different bins of β_z:

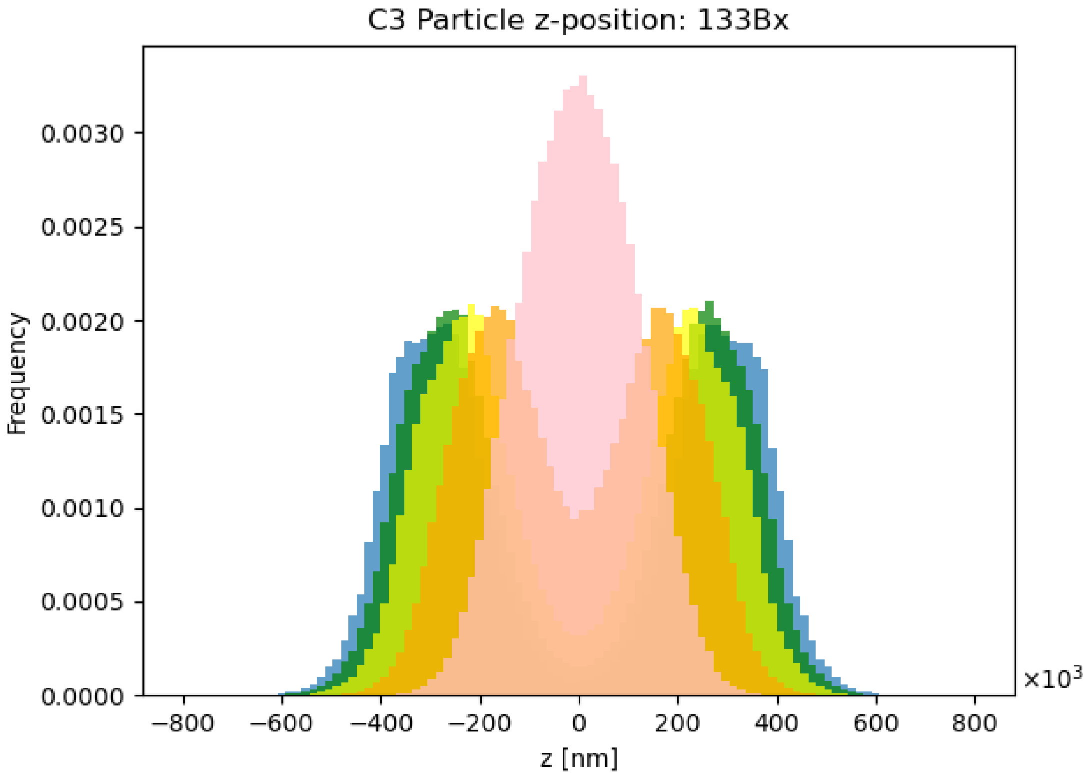
bin 1: 0.0< $|\beta_z|$< 0.2

bin 2: 0.2< $|\beta_z|$< 0.4

bin 3: 0.4< $|\beta_z|$< 0.6

bin 4: 0.6< $|\beta_z|$< 0.8

bin 5: 0.8< $|\beta_z|$< 1.0

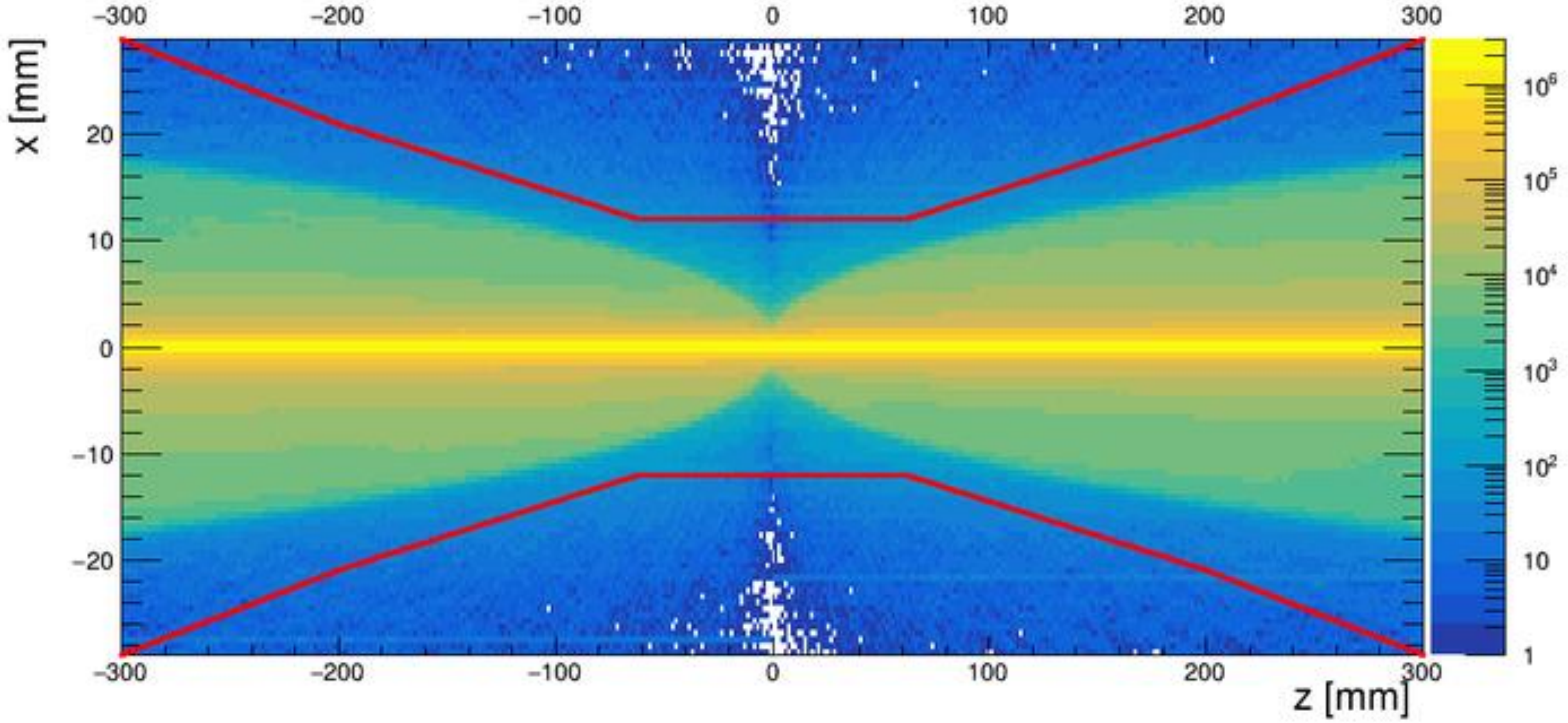


133 bunches configured with C³ parameters

[Lindsey Gray, Collider Background Studies, 2024]

ENVELOPE PLOT: C3

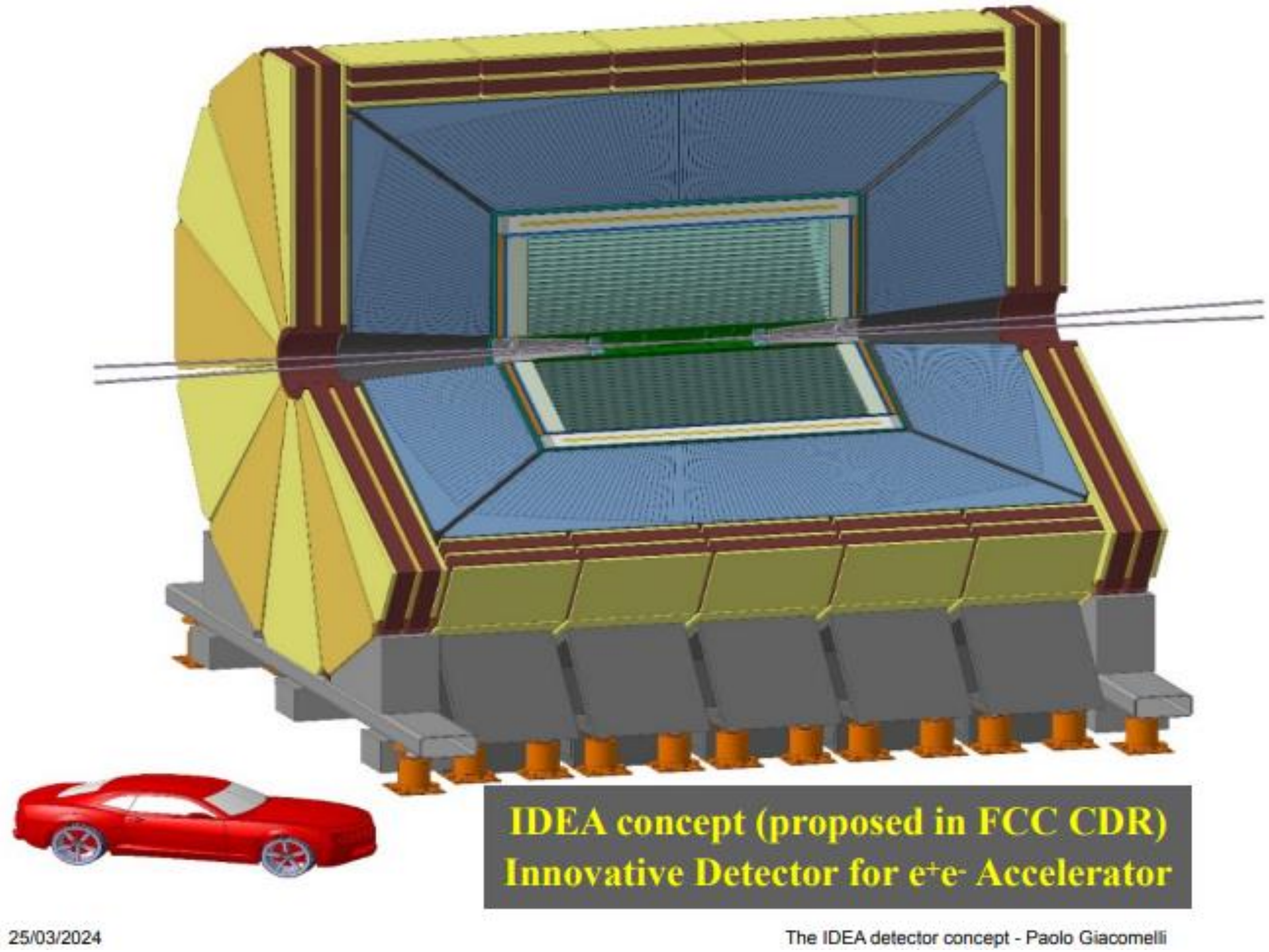
Qualitative depiction of beam interaction region



Red line is latest placement of beam pipe at C3

- most recent SiD geometry has first layer at 14mm away from IR

FCC-EE VERTEX DETECTOR



Detector concepts:

CLD Detector

ALLEGRO Concept

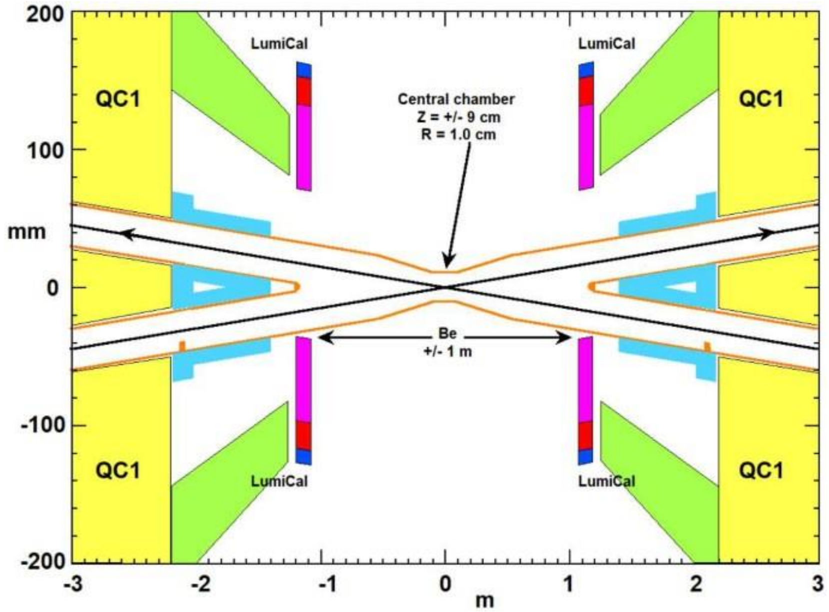
IDEA detector

- Silicon vertex detector
- Beam pipe R~1.0 cm
- 2T B field

[Giacomelli, Paolo. "The IDEA Detector Concept." INFN Bologna, FCC US Workshop, Mar. 2024]

FCC-EE BEAM PARAMETERS

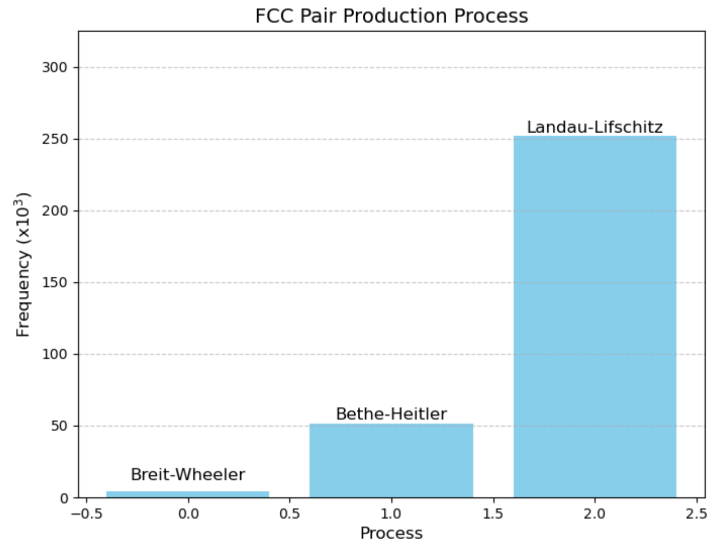
Variable	Definition	Input FCC [Z]
energy	The energy of the particles in GeV.	45.6
particles	The number of particles per bunch in units of [10^10]	24.3
beta_x	The horizontal beta function in mm	100
beta_y	The vertical beta function in mm	0.8
espread	The RMS value of the relative energy spread of the beam particles.	0.00038
sigma_x	The horizontal beamsize in nm	8426.1
sigma_y	The vertical beamsize in nm.	33.7
sigma_z	The longitudinal beamsize in µm, the RMS value	15400.0
angle_x	The horizontal angle in rad	0.015

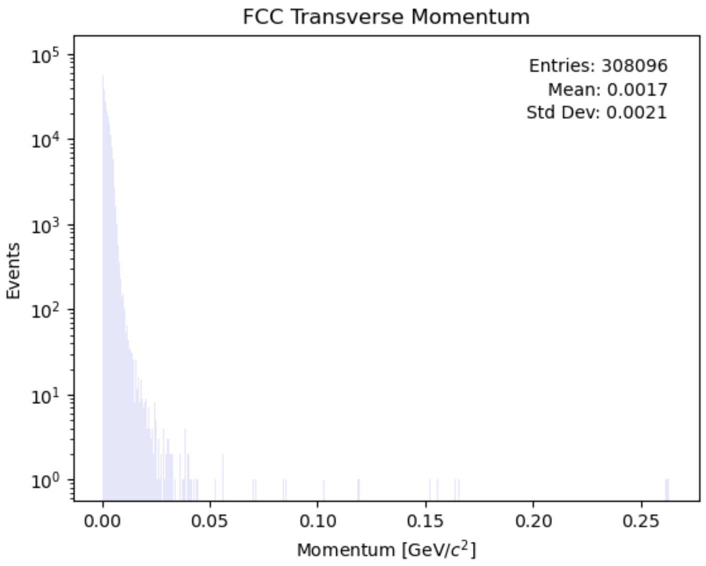


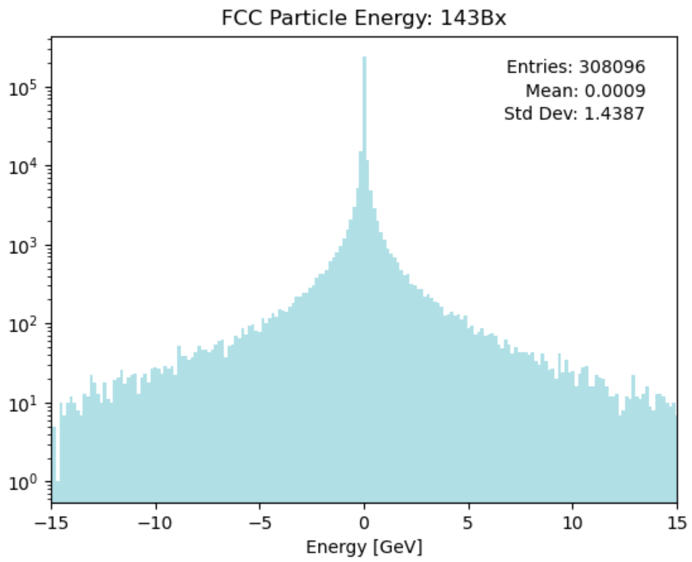
Key distinguishing feature:
30 mrad crossing angle

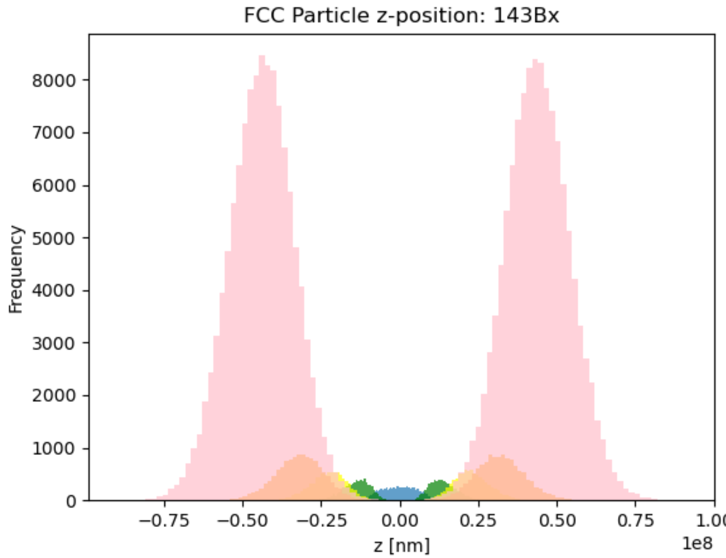
FCC-EE GP OUTPUT

- 1300 pairs per Bx
- Results agree with Ciarma et al 2022 FCC-ee background study
- Landau-Linfshitz dominates due to lower energy photons producing incoherent pairs





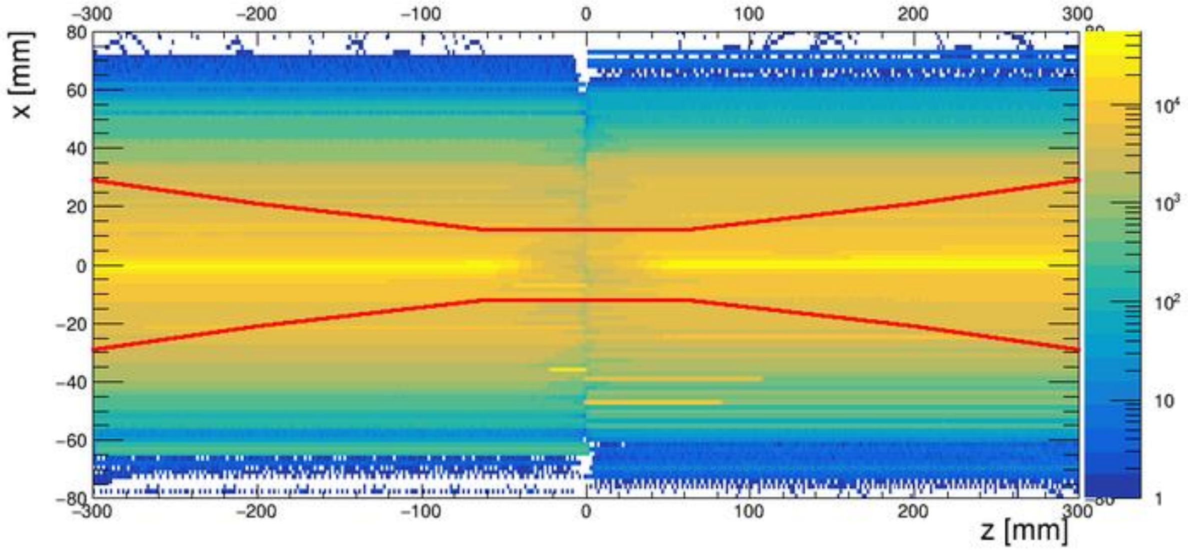


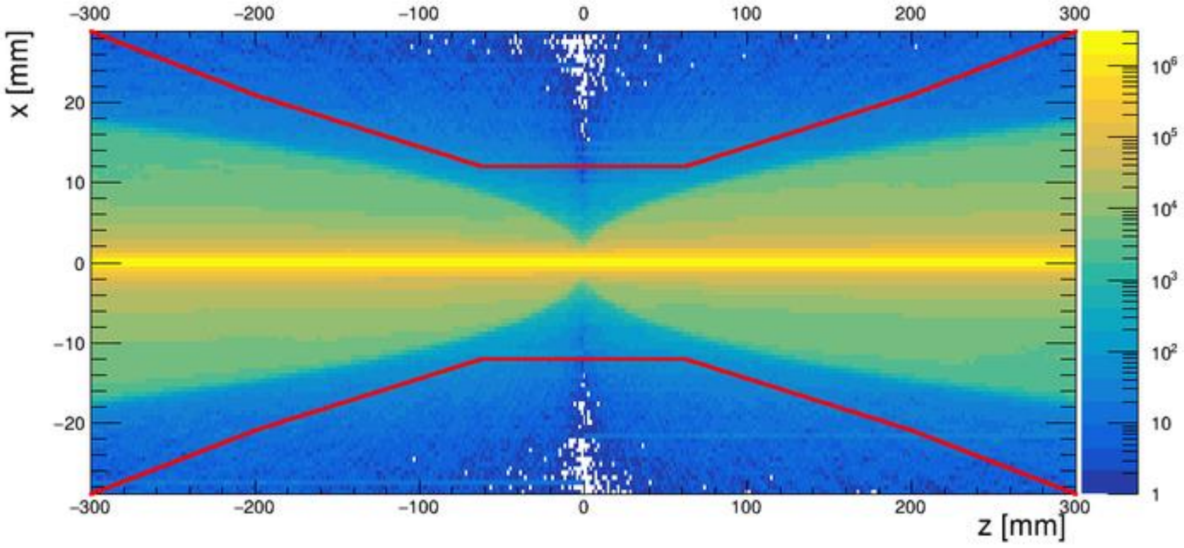


[Ciarma et al. doi : 10.18429/JACoW-eeFACT2022-TUZAT0203]

FCC-EE ENVELOPE

C3 envelope:





- Smearing of envelope pattern
- Beam intensity is an order of magnitude lower than C3, meaning we can push much closer to the beam interaction region

FCC pairs / Occupancy

		Z	WW	ZH	$t\bar{t}$
1	Pairs/BX	1300	1800	2700	3300
10^{-6}	O_{max}(VXDB)	70	280	410	1150
10^{-6}	O_{max}(VXDE)	23	95	140	220
10^{-6}	O_{max}(TRKB)	9	20	38	40
10^{-6}	O_{max}(TRKE)	110	150	230	290

[Ciarma et al. doi : 10.18429/JACoW-eeFACT2022-TUZAT0203]

CONCLUSION

Preformed incoherent pair background simulation for CLIC, C3, and FCC and compared results

- Guinea-Pig applicable to a wide variety of beam configurations

Compared FCC backgrounds to linear Higgs Factory

- Possible to get closer to beam line at FCC but at the cost of a more uniform increase in detector background hits due to diffuse background distribution
- Further investigation into occupancy is required to understand the impact on tracking from tracking combinations including background hits

Acknowledgments: Lindsey Gray, Dimitris Ntounis , Jan Eysermans, Luca Lavezzo, Christoph Paus

THANK YOU

SOURCES

- Levy, A. (2015). CLICdp Overview: Overview of physics potential at CLIC. https://www.researchgate.net/publication/270824816_CLICdp_Overview_Overview_of_physics_potential_at_CLIC

- Ntounis, D., Gray, L., & Vernieri, C. (2023, October 11). Beam-induced Background Simulation Studies for the Cool Copper Collider (C3). https://agenda.infn.it/event/34841/contributions/207749/attachments/111336/158925/C3_background_2nd_ECFA_workshop_Higgs_11Oct2023_DN.pdf

- Giacomelli, Paolo. "The IDEA Detector Concept." INFN Bologna, 25 Mar. 2024. Presentation https://indico.mit.edu/event/876/contributions/2670/attachments/1034/1695/IDEA_detector-concept-FCC-US-2024.pdf

- Ciarma, A., et al. "Machine Induced Backgrounds in the FCC-ee MDI Region and Beamstrahlung Radiation." *65th ICFA Adv. Beam Dyn. Workshop High Luminosity Circular* e^+e^- *Colliders eeFACT2022*, JACoW Publishing, 2022, pp. TUZAT0203.

FCC-EE BEAM PARAMETERS

Sources:

1. Ciarma et al., CERN, Geneve, Switzerland; Boscolo et al., INFN-LNF, Frascati, Italy: https://inspirehep.net/files/33fdd12f387b497d32d7fb35f3f09d55
2. Jeans, D. (KEK/IPNS). "Beam Background Studies with ILD.“: https://indico.slac.stanford.edu/event/7467/contributions/6057/attachments/2921/8092/lcws23-backgrounds.pdf
3. Bordry, F. et al. CERN, "Machine Parameters and Projected Luminosity Performance of Proposed Future Colliders at CERN.“: https://cds.cern.ch/record/2645151/files/CERN-ACC-2018-0037.pdf

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	90.836848			
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	$[10^{11}]$	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	$[10^{-6}]$	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.94 / 2.74
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.1 / 9.2
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	400.793257			
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.0
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y[a]		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.093 / 0.140
Luminosity / IP	$[10^{34}/cm^2s]$	182	19.4	7.26	1.25
Lifetime (q + BS + lattice)	[sec]	840	–	< 1065	< 4062
Lifetime (lum)	[sec]	1129	1070	596	741

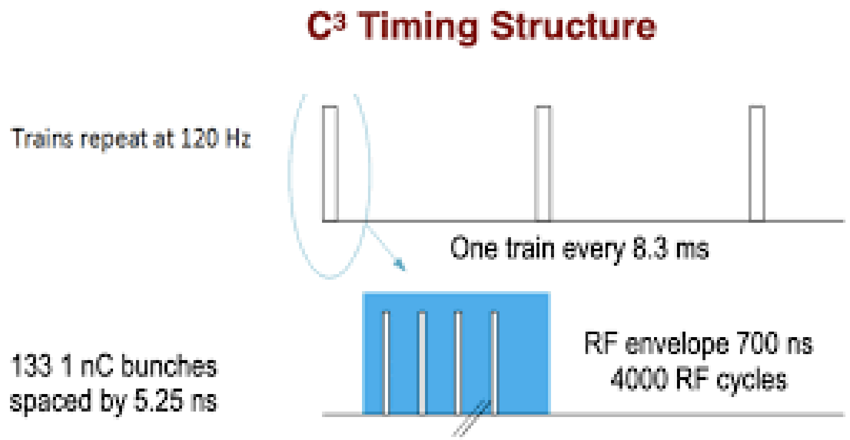
[a]incl. hourglass.

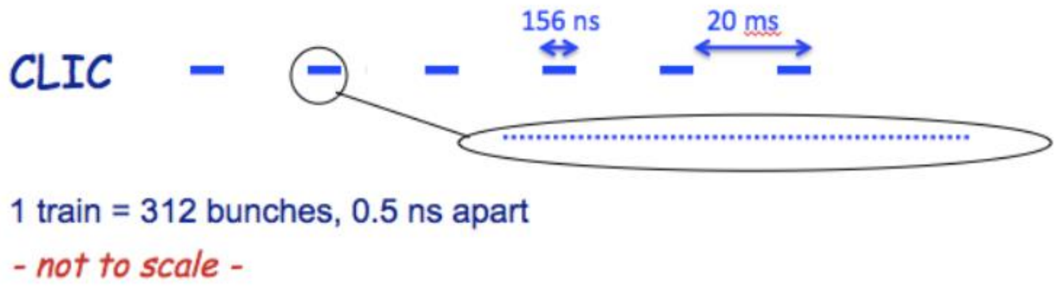
K. Oide, Nov. 2022

BACKUP

VERIFYING GUINEA-PIG OUTPUT

C3 vs CLIC: Both proposed compact linear colliders designed for high-energy collisions





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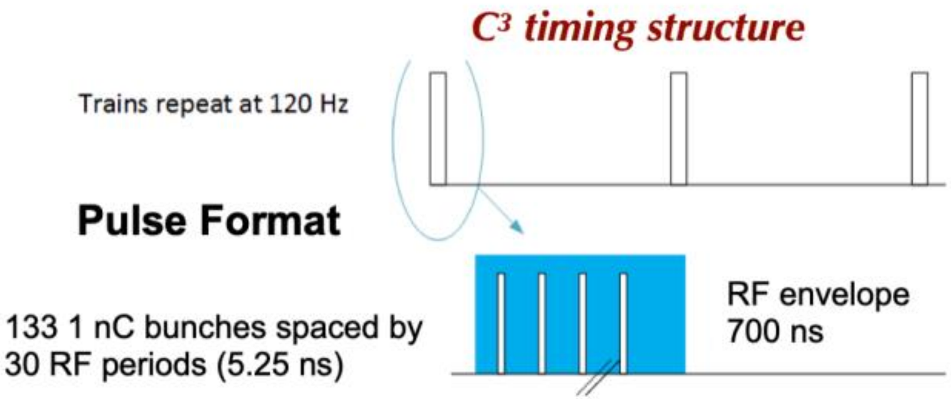
C3 PARAMETERS [250 GEV COM]



Parameter	Units	Value
β_x^*	mm	12
β_y^*	mm	0.12
$\epsilon_{N,x}^*$	nm	900
$\epsilon_{N,y}^*$	nm	20
σ_x^*	nm	210.12
σ_y^*	nm	3.13
σ_z^*	µm	100
n_b		133
f_{rep}	Hz	120
N		$6.25 \cdot 10^9$
θ_c	rad	0.014

	Initial Tests	Emilio's Values
Energy spread	0.1%	0.3%
Energy spread distribution	Gaussian	Flat
Offset in x direction (nm)	0	5
Offset in y direction (nm)	0	0.2
Waist shift in x direction (µm)	0	0
Waist shift in y direction (µm)	0	0
Crossing angles (not compensated by crab scheme)	0	0

[Lindsey Gray, Collider Background Studies, 2024]

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Lifetime (lum)	[sec]	1129	1070	596	741

[a]incl. hourglass.

K. Oide, Nov. 2022

Parameter [4 IPs, 91.2 km]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69

parameter (4 IPs, $t_{rev} = 304\ \mu s$)	value
circumference [km]	91.18
max. beam energy [GeV]	182.5
max. beam current [mA]	1280
max. # of bunches/beam	10000
min. bunch spacing [ns]	25
max. bunch intensity [10^{11}]	2.43
min. H geometric emittance [nm]	0.71
min. V geometric emittance [pm]	1.42
min. H rms IP spot size [μm]	8
min. V rms IP spot size [nm]	34
min. rms bunch length SR / BS [mm]	1.95 / 2.75

FCC-EE BEAM PARAMETERS

- We've been using multiple sources to cross check
- We can also verify the consistency of each dataset using the relationship of emittance ε , sigma σ and beta β

$$\sigma_n = \sqrt{\varepsilon\beta^*}$$

Table 1: FCC-ee beam parameters for the 4 IPs lattice

		Z	WW	ZH	$t\bar{t}$
GeV	E	45.6	80.0	120.0	182.5
nm rad	ϵ_x	71	2.16	64	1.49
pm rad	ϵ_y	1.42	4.32	1.29	2.98
mm	β_x/β_y	100/0.8	200/1	300/1	1000/1.6
μm	σ_x	8.426	20.78	13.86	38.60
nm	σ_y	33.70	65.73	35.92	69.05
mm	σ_z	15.4	8.01	6.0	2.8
10^{11}	N_e	2.43	2.91	2.04	2.37
1	N_{bunch}	10000	880	248	40

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