Overview of beam- and machine-induced backgrounds for C^3

2nd general meeting of ILC-Japan Physics Working Group

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22 February 2023

Outline

1. Introduction
2. Beam & Machine Backgrounds
   - e^+e^- Pair Background
   - Halo Muon Background
   - Other backgrounds
3. Summary
4. Backup

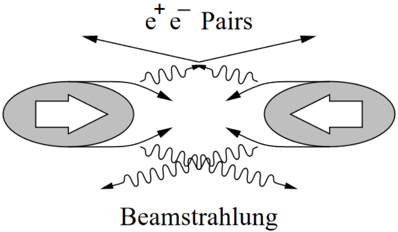
- The Cool Copper Collider (C^3) has been proposed as an e^+e^- Higgs Factory with a 250 GeV collision energy and based on a technology that offers the option for an upgrade to 550 GeV, with possible extensions to the TeV-scale.
- Some key differences in the proposed C^3 design with respect to the ILC are:
  - Accelerating Technology: Cu NC vs Nb SC RF cavities $\rightarrow$ achieve higher gradients & thus more compact design.
  - Train Structure: higher train repetition frequency with an order of magnitude fewer bunches per train
  - Bunch Structure: bunches spaced two orders of magnitude closer together with ~ 3 times smaller particle density.
- Despite these differences, the target $\sqrt{s}$ and instantaneous luminosity for C^3 and ILC are very similar.

	C^3		ILC	
Parameter [Unit]	Value	Value	Value	Value
CM Energy [GeV]	250	550	250	500
Luminosity [$\cdot 10^{34}/cm^2 s$]	1.3	2.4	1.35	1.8/3.6
Gradient [MeV/m]	70	120	31.5	31.5
Geometric Gradient [MeV/m]	63	108	20.5	31
Length [km]	8	8	20.5	31
Num. Bunches per Train	133	75	1312	2625
Train Rep. Rate [Hz]	120	120	5	5
Bunch Spacing [ns]	5.26	3.5	554	554/366
Bunch Charge [nC]	1	1	3.2	3.2
Crossing Angle[rad]	0.014	0.014	0.014	0.014
Site Power[MW]	~ 150	~ 175	111	173/215

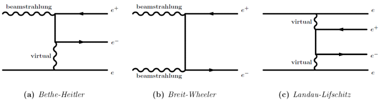
Table 1: Beam parameters for C^3 and ILC . For C^3 The final focus parameters are preliminary.

- The benefits of a clean collision environment that an e^+e^- collider offers can only be fully exploited with the use of highly granular & extremely precise detectors.
- The design of such detectors has to take into account various backgrounds that originate in the FF (Final Focus) or IR (Interaction Region) and which can deteriorate detector performance if not properly accounted for:
  - Beam-induced Backgrounds: secondary e^+e^- pair background originating from beam-beam interactions in the IR, $\gamma\gamma \rightarrow$ hadrons photoproduction.
  - Machine-induced Backgrounds: halo muon production from beam-collimator interactions in the FF, neutron production in the beam dump system.
- These backgrounds have been studied extensively in the context of ILC and are currently under study for C^3 as well, with the purpose of informing detector and FF design & optimization.

- As the e^- and e^+ beams approach each other in the IR, particles in one bunch are attracted by the electric space charge of the other and emit forward-boosted photons, called Beamstrahlung. These photons can in turn scatter to produce additional $e^+ - e^-$ pairs.

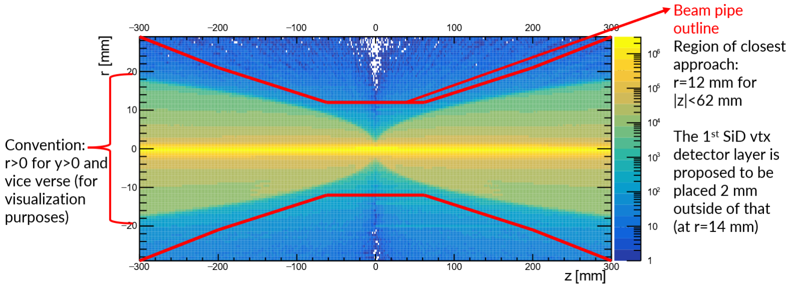


(a) Schematic representation of Beamstrahlung. From: [1].



(b) The 1st-order Feynman diagrams of the production processes of background pairs at an e^+e^- collider. From: [2]

- In the presence of the strong magnetic field of the detector solenoid, these additional, low p_T, e^+e^- pairs get deflected and form a characteristic bell-shaped hit pattern in the inner detector layers, called the pair envelope.
- The pair envelope is mostly contained within the beam-pipe. However, some of the highest p_T e^+e^- particles can reach inner detector layers and increase the detector occupancy.



- Simulations of the e^+e^- pair background were carried out using `GuineaPig` and assuming nominal beam C^3 FF beam parameters at $\sqrt{s} = 250$ GeV.
- The 4-vectors of the produced particles were then given as input to full detector simulation with `GEANT4`, assuming SiD detector geometry.
- Using the full simulation, the occupancy of the inner detector layers can be calculated as:

$$\text{occupancy} = \frac{\#\text{ of dead cells}}{\text{total }\#\text{ of cells}}$$

where a cell is declared as dead if it has received $N_{\text{hits}} >$ buffer depth.

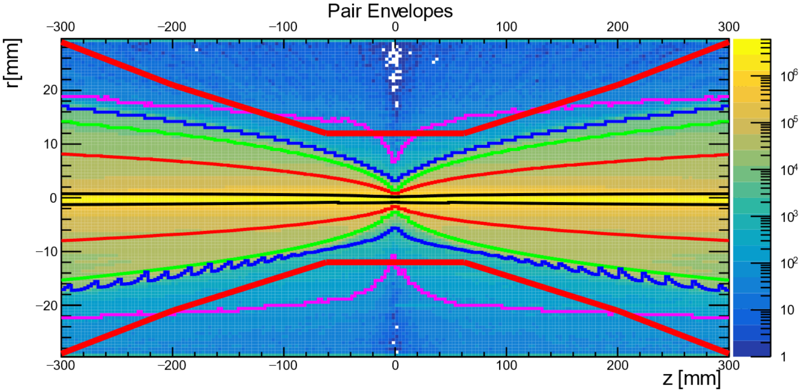


Figure 3: Example of pair background envelope for C^3 , where the histogram shows the hit density of the secondary e^+e^- pairs, and the solid lines enclose $68\%, 95\%, 99\%, 99.9\%$ and 99.99% of the hits.

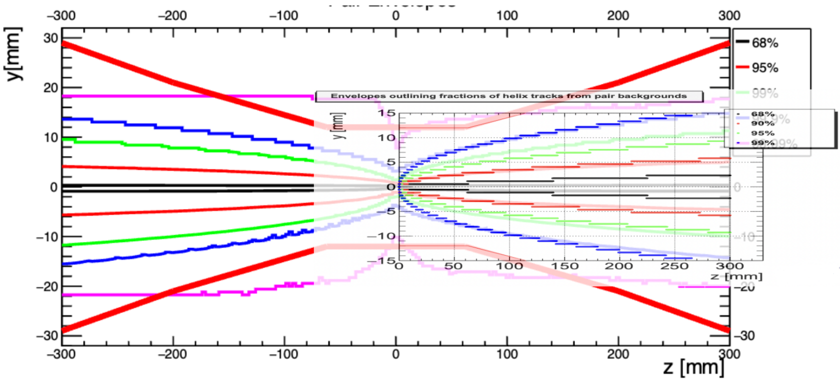


Figure 4: Example of pair background envelope for C^3 , with the corresponding envelope for ILC overlaid on the RHS of the plot. There is a marked similarity between the envelopes for the two colliders.

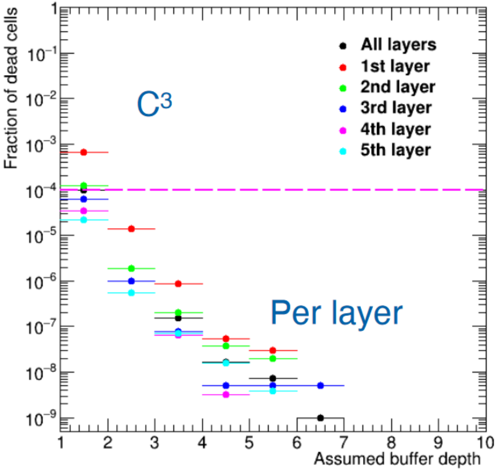
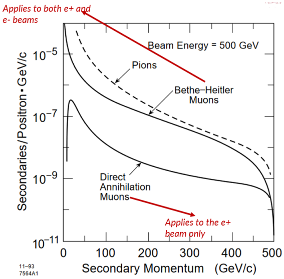


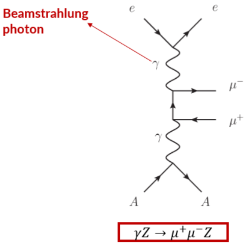
Figure 5: Occupancy of the vertex detector layers for the beam pair background at C^3.

Halo Muon Background

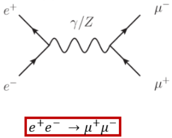
- An important machine-induced background at linear e^+e^- machines is the halo muon background, consisting of energetic muons that are produced in the FF system due to the interaction of beam halo particles with the material of collimators.
- Muons can be directly produced from interactions of beamstrahlung photons and direct annihilation of e^+, or through the decays of photoproduced pions.



(a) Muon production processes at a 1 TeV e^+e^- collider. From: [3]

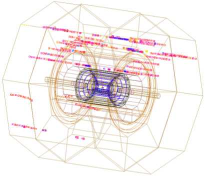


(b) Muon production through Bethe-Heitler process

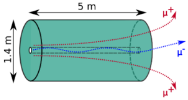


(c) Muon production through direct annihilation

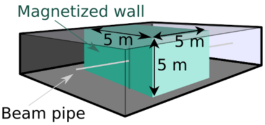
- The produced muons are boosted in the forward direction and are penetrating enough that, without proper deflection, can reach the detector almost perfectly horizontally and contribute to an overall increase in the occupancy.
- The muon flux can be reduced significantly by placing magnetized spoilers along beam direction in the FF or by directly shielding the detector with walls in the IR.



(a) *3D view, 5 spoilers + wall, ILC250*



(a) *Cylindrical spoiler*

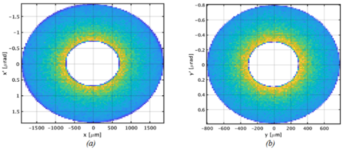


(b) *Magnetized wall*

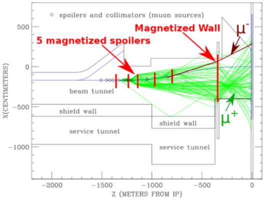
Figure 7: *Left*: detector hits from MUCARLO simulated muons at the ILC. *Middle, right*: schematics of a cylindrical spoiler and a magnetized wall that could be used for muon background reduction. From: [2]

Halo Muon Background

- For the design & optimization of the muon deflection and/or shielding mechanisms, a dedicated simulation tool is needed/
- MUCARLO was developed and used at SLAC to simulate the muon flux at SLC in the late 1980s. It simulates muon creation in the FF semianalytically and then tracks the muons throughout the FF and up to the IR. The muons 4-vectors can then serve as input to a full detector simulation to determine the detector occupancy from this background.



(a) Phase-space ellipses for the beam halo from ILC simulations. From: [4]



(b) Simulated halo muon 4-vectors for ILC obtained using MUCARLO. From: [2]

Halo Muon Background

- MUCARLO was last used for halo muon simulations for ILC in $\sim$ 2016 and informed the decision to place magnetized spoilers and/or wall in the FF and IR. With those additions, the muon flux was shown to be significantly reduced.
- However, expertise on MUCARLO has since declined drastically and, additionally, the source code in written in FORTRAN $\rightarrow$ a coordinated effort is essential to regain knowledge of and modernize MUCARLO.

Scenario	**Muons per bunch crossing in a detector with 6.5 m radius**					
	ILC500			ILC250		
	positron line	electron line	total	positron line	electron line	total
No Spoilers	71.6	58.5	130.1	21,1	17,2	38.3
5 spoilers	2.3	2	4.3	0.73	0.57	1.3
5 spoilers + wall	0.34	0.26	0.6	0.016	0.014	0.03

Figure 9: Table of number of halo muons per bunch crossing that reach the IR for ILC for different shielding scenarios. From: [2]

- Additional beam- and/or machine-induced backgrounds that need to be studied include:
  - Hadron photoproduction: production of hadrons from beamstrahlung photons: $\gamma\gamma \to$ hadrons. The `GuineaPig` simulation of this background has been found to be inaccurate, and a dedicated simulation using Pythia8 is currently being pursued.
  - Beam dump neutrons: neutrons can be produced from interactions of beam particles with the beam dumps. Such neutrons can travel back to the IR and increase the detector occupancy. Study of this background can be performed with FLUKA.

- A summary of the ongoing background simulation studies for C^3 has been presented, focusing on:
  - the e^+e^- pair background, which is the dominant background at a e^+e^- collider, and the
  - e^+e^- halo muon background, a subdominant background which, however, informs the design of the FF and IR.
- Studies of the pair background and hadron photoproduction are progressing well and we are in the process of exploring options with MUCARLO → important also for ILC in case muon background studies need to be repeated!
- Studies of additional backgrounds as well as overall detector simulation infrastructure are planned for the foreseeable future.

- Detailed understanding of these backgrounds is essential, as it directly affects the design and optimization of the Final Focus system and the detectors.
- Overall, there is a high degree of similarity & overlap between the background and detector simulation tools and needs for C^3 and ILC, and we believe that both parties could benefit from collaboration on those fronts.

Thank you for your attention!

If you have any comments or questions, you can reach as at:

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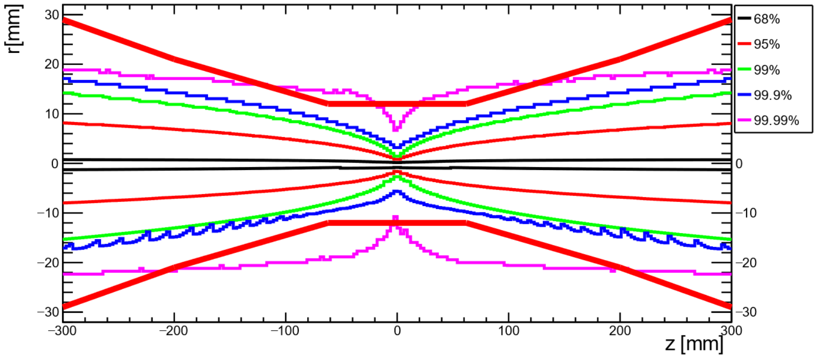
Backup

C^3 beam parameters at the IP

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

- The emittances on the table are normalized. The transverse beam size is calculated as:

$$\sigma_{x,y}^* = \sqrt{\epsilon_{x,y}^* \beta_{x,y}^*} = \sqrt{\frac{\epsilon_{L,x,y}^* \beta_{x,y}^*}{\gamma}}, \ \gamma = \frac{E}{m_e c^2} = \frac{\sqrt{s}}{2 m_e c^2}$$


r[mm]
z [mm]
68%
95%
99%
99.9%
99.99%
30
20
10
0
−10
−20
−30
−300
−200
−100
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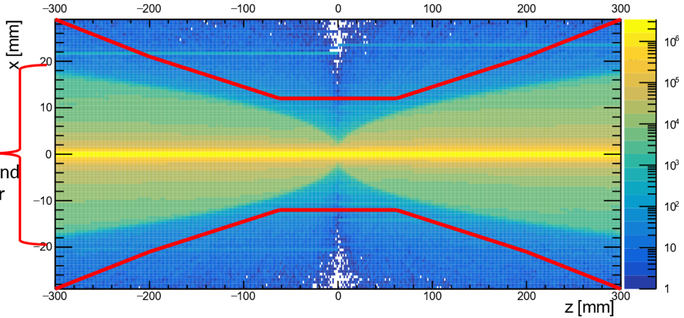
100
200
300

Convention: x>0 for y>0 and vice verse (for visualization purposes)



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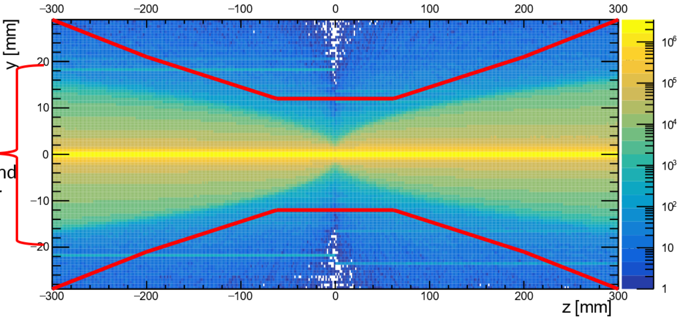

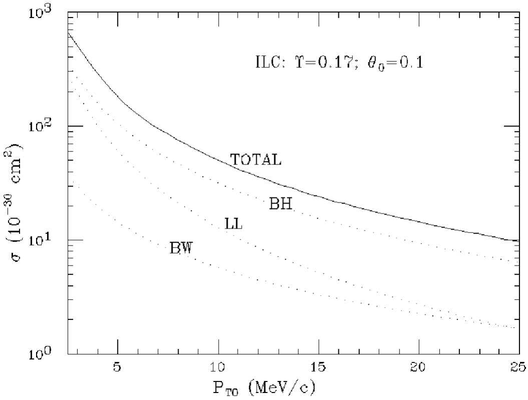

Figure 10: Cross Sections for the various e^+e^- pair production processes. From [5]

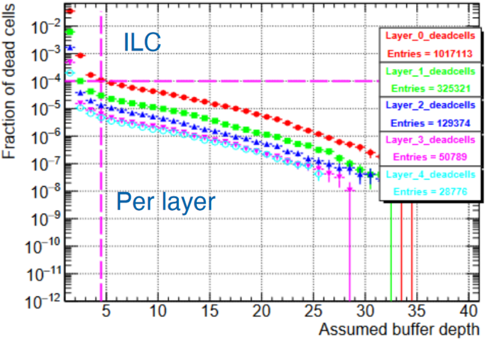

Figure 11: Occupancy of the vertex detector layers for the beam pair background at the ILC. From : [2]