Muon Backgrounds from Beam Interactions with the Accelerator Structure at C^3

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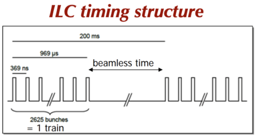
Outline

- 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.

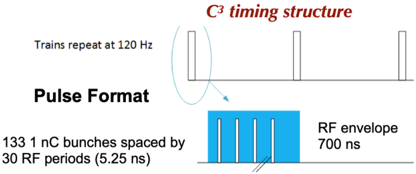
Beam Parameters

	C^3		ILC	
Parameter [Unit]	Value	Value	Value	Value
CM Energy [GeV]	250	550	250	500
Luminosity $[\cdot 10^{34}/\text{cm}^2 s]$	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.



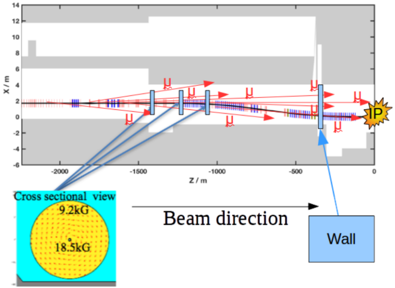
1 ms long bunch trains at 5 Hz
2820 bunches per train
308 ns spacing



- 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 account for various backgrounds that originate in the BDS or the IR and which can deteriorate detector performance:
  - Beam-induced Backgrounds: secondary e^+e^- pair background and $\gamma\gamma \rightarrow$ hadrons from beam-beam interactions in the IR, synchrotron radiation.
  - Machine-induced Backgrounds: halo muon production from beam-collimator interactions in the FF, neutron production in the beam dumps.
- These backgrounds have been studied extensively for other future colliders and are currently under study for C^3 as well, with the purpose of informing detector and BDS design & optimization.

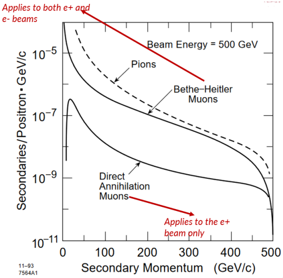
Halo Muon Background

- An important machine-induced background at linear e^+e^- machines is the halo muon background, consisting of energetic muons produced in the FF system due to interactions of beam halo particles with the material of collimators.
- The produced muons are boosted in the forward direction and, without proper deflection, can reach the detector and contribute to an overall increase in the occupancy.

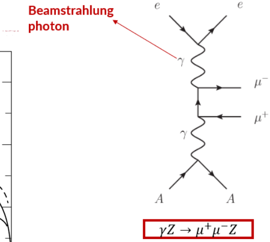


Halo Muon Background - Production Mechanisms

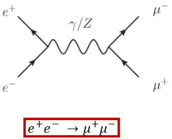
- Muons are mainly produced from interactions of beamstrahlung photons with nuclei in the accelerator material (Bethe-Heitler process) and secondarily from direct annihilation of e^+ with atomic e^-. There is also a small contribution from decays of charged pions produced through photopion production in nuclei.



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

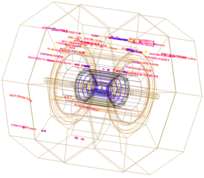


(b) Bethe-Heitler production of muon pairs. Main production mechanism (cross-section enhanced by Z^2.)

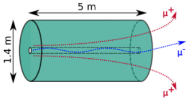


(c) Direct annihilation of e^+ with atomic e^-. This process takes place in the e^+ beam and leads to a larger number of muons being produced in the e^+ vs e^- beam.

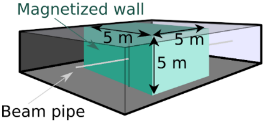
- The muon flux can be reduced significantly by placing magnetized spoilers along the beam direction in the FF or by directly shielding the detector with walls in the IR.
- For the positioning and size of the spoilers/wall, a detailed simulation of the muon flux is essential!



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



(a) *Cylindrical spoiler*

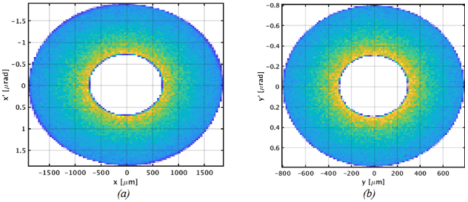


(b) *Magnetized wall*

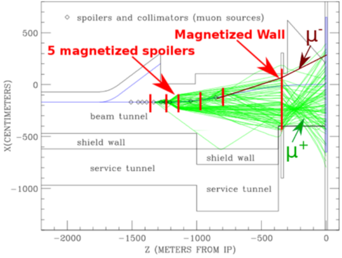
Figure 4: *Left*: detector hits from MUCARLO simulated muons at the ILC. *Middle, right*: schematics of a cylindrical spoiler and a magnetized wall that could be used for muon background reduction. Source: [3].

Halo Muon Background - Simulation

- 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 semianalytically simulates muon creation in the FF & tracks the muons throughout the FF and up to the IR.
- The muon 4-vectors then serve as input to a full detector simulation to determine the arising occupancy.



(a) Phase-space ellipses for the beam halo from ILC simulations. Source: [2].



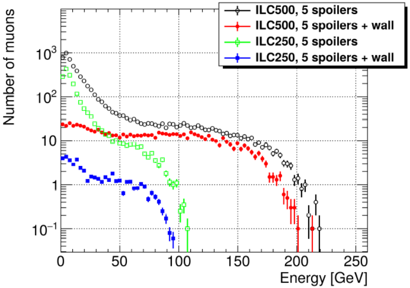
(b) Simulated halo muon 4-vectors for ILC obtained using MUCARLO. Source: [3].

- MUCARLO was last used for halo muon simulations for ILC in ∼ 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 → a coordinated effort is essential to regain knowledge of and modernize MUCARLO.

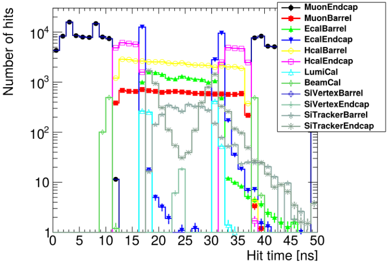
Scenario	**Muons per bunch crossing in a detector with 6.5 m radius**					
	ILC500			ILC250		
	positron line	electron line	total	positron line	electron line	total
No Spoilers	71.6	58.5	130.1	21,1	17,2	38.3
5 spoilers	2.3	2	4.3	0.73	0.57	1.3
5 spoilers + wall	0.34	0.26	0.6	0.016	0.014	0.03

Figure 6: Table of number of halo muons per bunch crossing that reach the IR for ILC for different shielding scenarios. Source: [3].

Results shown are from Anne Schütz's PhD thesis: [3]



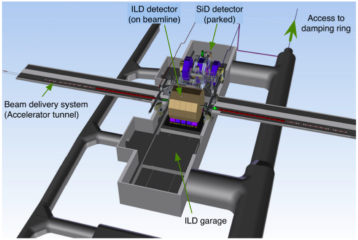
(a) Energy spectrum of the muons from an entire bunch train for different shielding scenarios and center of mass energies. Source: [3].



(b) Hit-time distribution of the muons from an entire bunch train in various SiD subdetectors for ILC-500 in the 5-spoilers scenario only. Source: [3].

[With inputs from Glen White]

- Previous Mucarlo studies were done using the ILC TDR design & have to be repeated for the C^3 BDS, which will have several differences:
  - Magnets scaled for $\sqrt{s} = 250$ GeV & excess bends removed.
  - Optics of the FFS adjusted.
  - Specs for the collimators reconsidered, e.g. survivable vs consumable collimators $\rightarrow$ consumable ones allow for much smaller β functions $\rightarrow$ more compact BDS design.
- All these adjustments have to be made in parallel to recalculating the muon flux, both in terms of detector occupancy and muon-radiation protection policy, e.g. if the wall is removed to reduce costs/build complexity, will on-beam servicing of the “out” detector be possible?



- A full, modern & modular BDS simulation in `Geant4`, including quads and collimation structures, will give the most accurate estimation about the muon flux → computationally intensive.
- Modernizing `Mucarlo` could be undertaken in parallel, in order to have an additional, semianalytical simulation tool and to ensure preservation of knowledge → requires considerable effort, given the lack of documentation and the need to convert Fortran code.
- Looking at the capabilities of other tools, such as `MARS` and `FLUKA`, would also be useful.
- Comparing and benchmarking multiple simulation tools against each other will build confidence in the accuracy of the halo muon flux simulation.

- The beam halo muon background is an important machine-induced background for future linear e^+e^- machines.
- It informs not only the detector design, but also the optimization of the BDS.
- Knowledge on `Mucarlo`, which was last used for the muon background simulation for ILC, has been lost.
- Effort to restore that knowledge, as well as put together a modern, modular simulation is under way.
- This will benefit the entire future collider community → all help is welcome!

Thank you for your attention!

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References

[1] Lewis Keller. "Muon background in a 1.0-TeV linear collider". In: 1993. URL: `https://www.slac.stanford.edu/pubs/slacpubs/6250/slac-pub-6385.pdf`.

[2] Lewis Keller and Glen White. *Simulation of Muon Background at the ILC*. 2019. arXiv: `1901.06449 [physics.acc-ph]`.

[3] Anne Schütz. "Optimizing the design of the Final-Focus region for the International Linear Collider". PhD thesis. Karlsruher Institut für Technologie (KIT), 2018. 160 pp. DOI: `10.5445/IR/1000083323`.

Acknowledgements

We thank Anne Schütz and Marcel Stanitzki for previous studies on the muon machine background for ILC [3] and useful feedback.

Backup

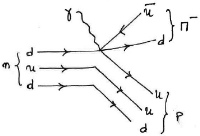
C^3 beam parameters at the IP

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

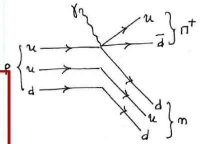
- The emittances on the table are normalized. The transverse beam size is calculated as:

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

- Production of muons from the decay of charged pions produced by the interaction of beamstrahlung photons with nucleons in the material of acc. components.
- Charged pions can decay to muons: $\pi^+ \to \mu^+ + \nu_\mu$, $\pi^- \to \mu^- + \bar{\nu}_\mu$, but with the decay length being several Km, only a small fraction of pions decays before they interact with material downstream in the BDS.
- As a result, the muons produced from photopions are considerably fewer than those from Bethe-Heitler.



$\gamma n \ \to p\pi^-$



$\gamma p \ \to p\pi^+$

Charged Pion Decay: $\tau_{1/2} = 2.6 \cdot 10^{-8}\ \mathrm{s}\,, L_0 \simeq c\tau_{\frac{1}{2}} = 3 \cdot 10^8\ \mathrm{m/s} \cdot 2.6 \cdot 10^{-8}\ \mathrm{s} = 7.8\ \mathrm{m}$

For a 250 GeV pion: $\gamma = \frac{E}{mc^2} = \frac{250\ \text{GeV}}{139.6\ \text{MeV}} = 1.79 \cdot 10^3$

$L_{\mathrm{lab}} = \gamma L_0 = 13.9\ Km$

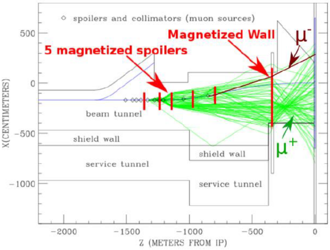
$N_\mu / N_{0,\pi} \simeq 1 - e^{-x/L_{lab}} = 7.2 \cdot 10^{-3}$ for x $\simeq 100$ m (typical collimator distance for ILC)

Mucarlo

- MUCARLO (developed @SLAC by G. Feldman for Mark II [6],[8]): semi-analytic simulation tool in Fortran to study muons produced by beam-machine interactions at linear colliders. Requires the BDS geometry as input.

- In MUCARLO, muons are generated at different regions across the BDS, where there is significant interaction of the beam halo w/ the material of acc. components. The muons are then trackec through the BDS as they are deflected by the magnetic fields of various acc. components and scatter during their interaction w/ the material, losing kinetic energy. Those muons that reach the IP are stored.

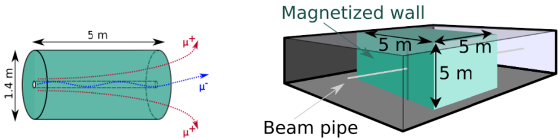
- Over the years MUCARLO has been expanded and has been used @SLAC in muon shielding designs for SLD, radiation protection, fixed target experiments, and in muon background estimates for the NLC and ILC [8].



- Shielding against muons aims to
  1. deflect muons away from the beam path using magnetic fields
  2. Absorb muons in the shielding material

with the purpose of reducing the detector occupancy due to muons reaching the detector.

- For ILC, two shielding systems were proposed
  1. Five cylindrical spoilers made of magnetized iron at different points along the BDS (~0.8 to 1.5 Km from the IP)
  2. Thick magnetized wall placed close to the IP (~0.4 Km) filling up the entire tunnel.



(a) *Cylindrical spoiler* (b) *Magnetized wall*

Beam Halo

- Muon bkg comes primarily from interactions of the beam halo with the collimators in the BDS.
- The beam core is defined as an ellipse in terms of σ_x, σ_y (RMS beam size values right before the 1st collimator) and the beam halo as an elliptical ring outside of the core.
- For ILC [1]: $\sigma_x = 146\ \mu m, \sigma_y = 9\ \mu m$, core: $\pm 5\sigma_x, \pm 36\sigma_y$, halo: $5 - 13\sigma_x, 36 - 93\sigma_y$
- The beam particle intensity in the core scales as $\frac{1}{r}$ and for ILC studies the beam power in the halo was normalized to 0.1% of the nominal beam power (pessimistic estimate: goal is for $\mathcal{O}(10^{-5})$ [2])
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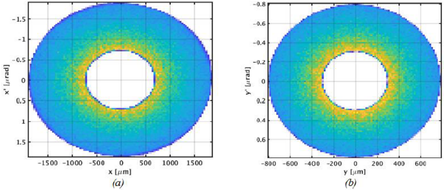

Phase-space ellipses for the beam halo from ILC simulations. Source: [8]

Mucarlo vs Geant4

- The Geant4 simulation is more general, as it simulates multiple physics processes and the muon production has a small rate, leading to limited statistics. Thus, in contrast to MUCARLO, where ~millions muons can be simulated, the Geant4 results are subject to considerable stat. errors.

GEANT4 vs. MUCARLO

- Comparative studies performed on simple beamline layout (no magnets, just collimation systems and tunnel)
  - Good (<10-20%) agreement
- MUCARLO
  - Semi-analytical, distributions and momenta parameterized at beam loss locations.
  - High-statistics possible (several 10,000's muons after full muon collimation @ IP)
  - "Generic" magnet models
- GEANT4
  - Full tracking simulation including all physics processes
  - Limited statistics (~1E2 muons at IP after muon spoilers implemented)
  - More representative magnet model using design ILC bends & quads & fields
- MUCARLO calculates more muons at detector. This may be due to higher statistics (especially from SPEX) or differences in magnet models.