The constraints and limitations for the FCC detectors

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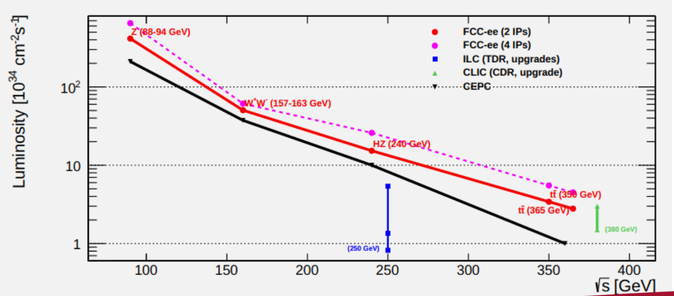
Introduction

- A trend for future HEP experiments is an increase in the data bandwidth produced from the detectors.
- This will pose new challenges in various aspects of the data-taking system and not only in detector development.
- The expected trigger rates and bandwidth will be much higher and that would require a faster and more robust electronics readout system as well as a fast data processing scheme.
- The readout electronics for future high-energy experiments must withstand high radiation rates and not significantly add to the material budget of the detectors.
- On the detector side, experiments require fast detectors with high precision.
- This would require to use of leading edge detector systems that are capable to meet these conditions.

DAQ - rates

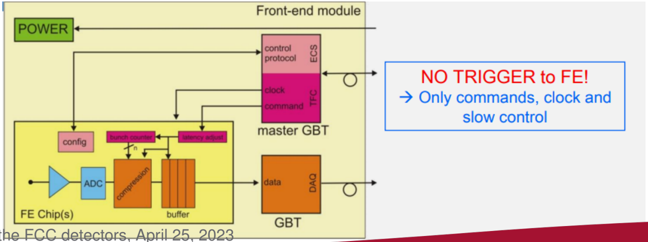
- The online, offline, and software requirements for the FCC-ee are dominated by those of the Z pole running with a physics event rate of ~ 200 kHz and the instantaneous luminosity of 2.3×10^{36} cm^{-2}s^{-1}
- The basic assumption for the FCC-ee is that “triggerless” DAQ system will be implemented that will store $\sim$ 100% of events interesting for physics for offline analysis
- Bunch spacing down to $\leq$ 20 ns at Z-pole run

Physics process	Rate (kHz)
Z decays	100
$\gamma\gamma \to$ hadrons	30
Bhabha	50
Beam background	20
Total	$\sim$ 200



DAQ - Triggers

- “triggerless” design mean software-based online selection system providing a flexibility that cannot be matched by traditional first-level hardware-based filtering systems
- Typically, as luminosity increases, a calorimeter- and muonbased filtering system cannot sustain the trigger rates without an increase of threshold values
- A purely software trigger allows increased complexity in the online selection by combining information from different systems
- R&D studies assume that zero-suppression will be routinely applied at read-out time
- The detector choice is important for the trigger design (Time Projection Chamber usually has slow readout, while fine-granularity calorimeters might produce significant noise)
- The triggerless system is already being implemented by the LHCb experiment for the LHC Run 3



DAQ - Data size

- In each hadronic Z decay, we expect about 20 tracks in average (this is used to calculate average size of the event)
- We expect 100 kHz of physics data at Z-pole run
- The data that have to be read out from CLD Vertex Detector amount to a bandwidth of 6 GB/s (simmilar to CLD tracker bandwidth of 10 GB/s)
- The data volume corresponding to the CLD calorimeter is under investigation
- For the IDEA detector with Drift chamber, Calorimeter and so on, altogether, the various contributions sum up to a data rate of about 1-2 TB/s.

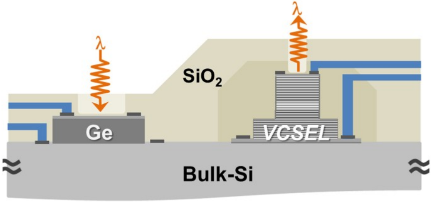
Subdetector	Physics	Background/noise
CLD Vertex Detector	150 MB/s	6 GB/s
CLD Tracker	160 MB/s	10 GB/s
IDEA Drift Chamber	60 GB/s	2 GB/s
IDEA Si Wrapper	32 MB/s	0.5 GB/s
IDEA DR Calorimeter	10 GB/s	1.6 TB/s *
IDEA pre-shower	320 MB/s	820 MB/s
IDEA Muon Detector	4 MB/s	67 MB/s

* Assuming no suppression for isolated counts

- Core to improvements in DAQ are a combination of reducing the data rate close to the detector, and increasing the data bandwidth

DAQ- bandwidth increase

- There is couple of technologies in advanced stage that could be used for the detector readout
- One promising technology is silicon photonics: that can allow integration of fiber-optic connections directly to sensor modules or readout chips (commercial devices already show high radiation tolerance)



- Other promising developments exist in Wavelength Division Multiplexing (WDM): where individual serial links can be transmitted on its own wavelength, reducing the need for data aggregation to maintain high data bandwidth per link

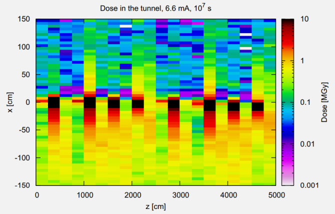
DAQ - Data size reduction

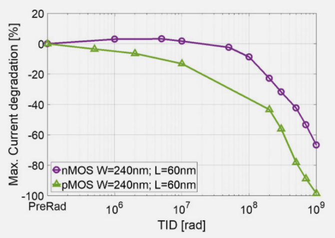
- The data reduction techniques need to be used in order to reduce the bandwidth
- More sophisticated data reduction techniques in detector electronics may be possible with advances in AI, particularly with improvements in translating low-latency machine-learning-developed compression and triggering algorithms to ASICs
- One example is real time fast readout algorithm implemented in an FPGA that digitize the information analyze the signal, stores the amplitude and the time of the peak, filters out spurious and isolated hits and sends these reduced data to the acquisition system
- In total, the data to be sent to the IDEA acquisition system for each trigger is of the order of 100 GB/s, i.e. more than one order of magnitude lower than the amount of data that will be readout by ATLAS and CMS at the HL-LHC
- On the other hand, the throughput to disk should be reduced by a factor of 5 to 10 in order to be comparable with the anticipated storage and processing capacities of ATLAS and CMS.

- **It is probably too early to choose the final DAQ scheme, but limitations and challenges need to be kept in mind during detector design.**

Radiation limits

- A FLUKA model of half an arc cell has been created for 175 GeV
- The pattern shows hot spots along the beam pipe corresponding to the interconnects where the synchrotron radiation absorbers are placed
- The results show that equipment installed in certain locations in the tunnel will be affected by the TID effects in range of 100 kGy–1 MGy
- The detector radiation exposure for all lepton-collider proposals: (NIEL: $< 10^{11}$ neq/cm2/y, TID: $<$ 1 kGy / year)
- Most of the on-detector ASICs make use of CMOS technologies in the 130 and 65 nm nodes
- With the reduction of the pattern size the TID tolerance is decreasing so it is not possible simply miniaturize current technology
- This will be more critical at FCC-hh where the Tracker must withstand up to 300 MGy

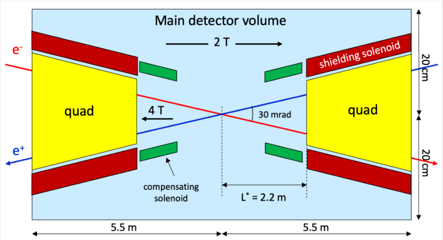




Detector requirements/limitation

- Constraints imposed by the machine-detector interface:
  - Due to 30 mrad crossing angle, the experiment magnetic field is constraint to 2T for the Z-pole run
  - Angular coverage can not extend below 100 mrad from the beam axis
  - The fast focusing quadrupole will be two meters from the IP
- Exp. environment at FCC-ee
  - E.g. no power pulsing of electronics, more cooling for VXD or less power
- The main physics requirements for the detector is:
  - Acceptances precision
  - Momentum resolution
  - Angular coverage resolutions

Central part of detector volume – top view

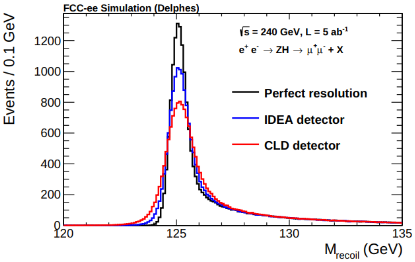


Acceptances precision

- One of the strongest requirements imposed by the physics program at the Z-pole is related to number of events
- In order to benefit from the high statistics the relative uncertainty need to be order of 10^{-5} to 10^{-4}
- This mean to keep luminosity measurement precision down to 10^{-5} (from low-angle Bhabha events)
- The LumiCal at $\sim$ 1m and the inner radius of the luminometer must be known to $\mathcal{O}(1\,\mu\text{m})$
- Angular acceptance boundaries must be defined with great accuracy, of the order of 5–10 μrad, for the high precision cross-sectional measurements
- Uncertainty of the Lepton acceptance for the FCC is requiter t be $\sigma(R)/R = 3 \times 10^{-6}$
- For a measurement at $\Phi > 15\,\mathrm{deg}$, bias in Φ should be less than $\mathcal{O}(8\mu\mathrm{rad})$
- This requirement for precision sets constraints for the design of LumiCal and endcap calorimeter

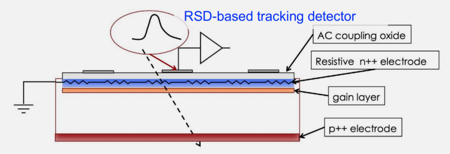
- The beam energy spread (BES), which amounts to 0.13% (0.16%) of its energy at $\sqrt{s} = 91.2$ GeV (240 GeV), sets a target for the track momentum resolution
- The reconstruction of the recoil mass should be limited by the BES and not by the detector resolution
- The very light tracker of IDEA, with a resolution of $\mathcal{O}(0.15\%)$ for central, 50 GeV muons, is close to this goal

- With the momentum resolution $\sim$ BES, the Z-pole program will largely benefit
- Flavor physics, rare decays and SM measurements could reach extreme precision
- This would allow to measure for example LFV decays $Z \to \tau\mu$ up to $BR = 2 \times 10^{-9}$



Inner tracker and vertex detectors

- The innermost detectors with highest granularity are expecting to be semiconducting pixel detectors
- There is various technologies developed in past decades (Hybrid detectors, monolithic sensors as well as silicon on insulator detectors)
- One technology is the Monolithic Active Pixel Sensors (MAPS) that were used for the ALICE detector (low material budget)
- Other technology with high potential is Low Gain Avalanche Detectors (LGADs) that have been proposed for the HL-LHC upgrades (fast timing)
- There is however many other technologies that are rapidly developing (PIXEL 2022)



Summary

- The detector design is formed by the physics requirements and technical constraints
- I have tried to highlight some of them but there is many more
- Several optimized detector concepts with different technology choices are proposed
- Fulfilling all Lepton-Collider requirements simultaneously remains challenging
- The DAQ scheme will be optimized to keep maximum of physics events and need to be kept in mind during detector choice
- Potential new physics hints could motivate dedicated detector designs that would increase the efficiency for reconstructing the unusual signatures of such processes

Thank You for Your Attention.

Bibliography

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