Beam Condition and Radiation Monitoring

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DESY.

Overview

- Radiation environment and typical beam monitors
- Beam Loss Monitoring
  - Active protection
- Beam Condition Monitoring
  - Luminosity with BCMs
- Polarization measurements at e+e-
- Beam parameter monitoring through beamstrahlung at e+e-
- Radiation Monitoring
  - Experimental cavern
  - Irradiation exposure monitoring
- Radiation Simulation

Radiation environment at collider experiments

Collision induced background, CIB

- Secondaries from collisions and from beam-beam interaction in collision.
- Instantaneous effects:
  - Background hits in detectors.
  - Exposure of electronics (SEU).
- Integrated fluence:
  - Radiation damage to detector components.
- Activation
  - Short half life: Out of time background
  - Long half life: Radiation exposure to personnel during interventions and decommissioning.
  - A mix of integrated and instantaneous luminosity relevant.

Beam induced background, BIB

- Sources:
  - beam gas (residual vacuum & e-cloud)
  - beam halo
  - Synchrotron, Touschek effect.
  - Accidents/failures in the accelerator
- Effects:
  - Fake hits in detectors:
    - Small R -> Hits in tracker from em–shower
    - high R -> Halo muons in calorimeters and muon detectors.
  - Permanent damage from catastrophic events.
    - Direct failure
    - Delivered dose

Experiment and accelerator

- Beam Condition/Loss monitoring similar at experiment and accelerator
  - Often same electronics or detectors used.
- Exchange of information:
  - Fast signals: bunch/turn clock, interlocks.
  - Feedback to accelerator: optimization (e.g. beam cogging), lumi leveling.
  - Beam data used by experiments:
    - vacuum conditions, beam separation, beam intensities.
- Simulation of BIB:
  - First Simulation of accelerator (tracking and radiation simulation)
    - Input to experiment simulation.
  - Feedback to accelerator design (collimators/absorbers to protect experiment).
- Good knowledge of the accelerator necessary on experiment side.

➢ **Strong collaboration of experiments with accelerator is vital.**

Beam condition monitoring

Many aspects of beam monitoring
Here: Beam induced background monitoring

Current monitors:
Dose like measurement.

- Integrating a certain time (e.g. LHC: 40 µs, Belle 2: 2.5 µs [1])
- Designed to identify high BIB rates.
    - Often used for active protection / beam abort.
- Can monitor nominal BIB levels, if not obscured by collision products.

Particle counters:
Flux like measurement.

- Count individual hits.
- Typically: Monitoring of normal background rates.
- Used for luminosity measurement (can be design driver for high precision)
- Can be used for beam abort.

[1] arXiv:2102.04800

Can be covered by the same system with high and low gain

Beam loss monitors and active protection

- **Intense, potentially damaging beam loss scenarios:**
  - Events at accelerator usually covered by machine protection.
  - Blind spot of accelerator instrumentation at experiment.
  - Need to avoid detector damage from high currents, high delivered dose,..
- **Integration into accelerator instrumentation and interlock systems.**
  - Damage mechanisms are fast -> Interlock needs to be fast.
  - Accelerator has different (slower) damage mechanism (quench) -> Different requirements.
  - Strong benefits, if design of beam loss systems include needs of experiments.
- **Beam loss monitor requirements:**
  - High radiation tolerance (hadron collider)
  - Small size (close to exposed detectors)
  - Efficient at catastrophic levels (no saturation)
  - 100 % availability and reliability (no fake aborts)
  - Fast (to allow fast interlocks)

Beam loss monitors - R&D

- **Effects on experiment systems, definition of damage thresholds.**
  - Test of final pixel and strip systems in intense beams, e.g. [1,2].
- **Calibration of loss monitor response at abort level intensities.**
  - Saturation can be electronics or sensor. Both need to be qualified.
  - Needs high rate facilities and high rate reference detectors.
- **Simulation of beam loss scenarios & particle showers in experiments.**
  - Understand particle environment in any conceivable scenario.
- **Optimization of instrumentation.**
  - detector choice, location, high reliability, redundancy, abort logic,...
- **Radiation hard miniature signal current detectors (solid state IC)**
  - Improve on existing technologies: Diamond, Sapphire,...

[1] NIM A 518 (2004) 328–330
[2] NIM A 924 (2019) 236-240

Beam condition monitoring

- **Purpose:**
  - Beam background monitoring: Safe condition verification.
  - Beam background triggering:
    - Study background events (comparison with simulation, detector optimizations)
    - Veto trigger against background contaminated events
  - Online luminosity monitoring.
- **System requirements:**
  - Fast particle counter, bunch-by-bunch
  - Features fast timing and/or directionality to separate BIB from collisions.
  - High availability:
    - Robust & minimal services/infrastructure
    - If used in active protection 100% availability
  - Positioned for exposure to BIB & good for timing based measurement.

Beam condition monitoring - R&D

- **Timing based:**
  - Follow technology developments of 4D tracking
  - Radiation hardness may comparable to inner most tracking layers
    - Follow technology development of tracker.
  - *Radiation hardness and fast timing both needed!*

- **Directionality based discrimination (e.g. Cherenkov)**
  - Muon monitoring at high radius (in cavern). [1]
  - Needs R&D to make it possible close to beam pipe.

[1] 2015 JINST 10 P11011

Luminosity (hadron collidier)

- **Beam condition monitors are capable to measure luminosity.**
  - Dedicated luminometer design can be highly optimized and well understood.
- **Calibration:**
  - Typically: van der Meer scans (vdM)
  - Comparison with high level events, e.g. Z-counting.
- **Precision 1% is target for HL-LHC.**
  - 0.7% calibration and 0.7% linearity & stability.
    - ➢ Understand systematic errors on permil level.
  - Calibration related: Need to understand beam-beam effects
    - ➢ R&D in collaboration with accelerator
  - Main detector challenge: linearity
    - vdM calibration at pileup .5 and operation at 200 (HL-LHC) / 1000 (FCC)

Luminometer requirements & R&D

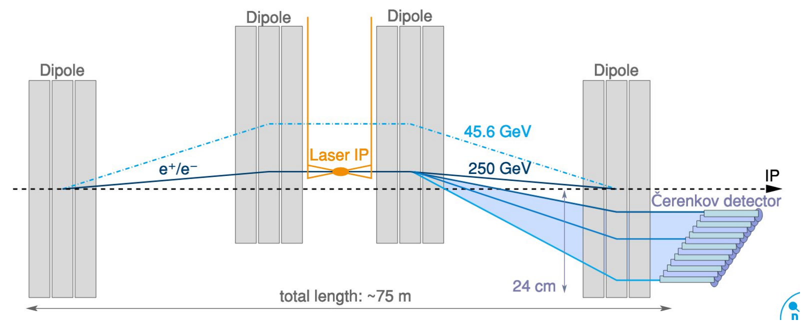
- **Luminometer key features:**
  - Highly linear response.
  - Long term stability (maintain calibration)
    - Radiation hard and high signal to noise
  - Bunch-by-bunch, with no dead time -> No influence on next bunch crossing
    - Fast analog FE or very low occupancy (high granularity).

- **R&D** (on top of beam condition monitoring)**:**
  - Highly efficient detector systems. (sensor design, electronics)
  - (Further) develop methods for monitoring of efficiency
    - Emittance scans (short vdM like scans in nominal operation)
    - Use experiment tracking.

Polarization measurement at ILC

J.List, Polarimetry at the ILC, LCWS2021

- **Measurement via inverse compton polarimetry**
  - Magnetic chicane with laser for photon scattering.
  - Scattered e+- (O(10^3) / BX) energy spectrum depends on polarization.
  - Position distribution measurement after dipole
- **Instrumentation requirements:**
  - Precisely controlled laser
    - <= 0.1% uncertainty on circular polarization
    - long distance distribution
  - Sufficiently rad hard detectors
    - O(100Mrad) from Compton e+-
  - Precise beam-detector alignment (~100 µm, ~1 mrad)
  - Detector: linearity < 0.5% & low noise
- **Comparison upstream and downstream measurements**
  - Need to have well understood spin tracking of the beam (magnet alignment, ground motion, ...)
  - Beam alignment at polarimeters and e+e- IP to $\Delta\theta_{bunch}$ = 50 µrad, $\Delta\theta_{pol}$ = 25 µrad
    - Requires extremely good BPMs with absolute position measurement

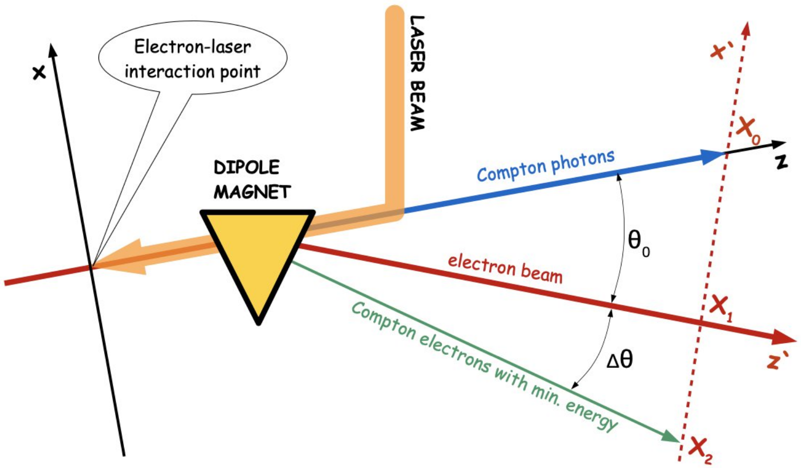


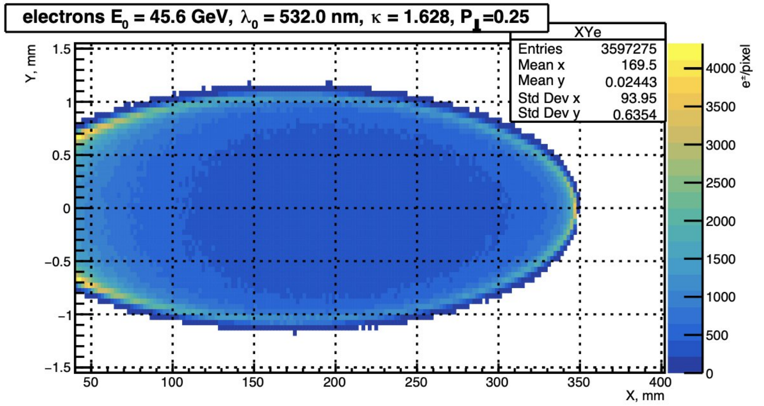
Polarization measurement FCC-ee

A. Blondel, P. Janot, J. Wenninger et al.
arXiv:1909.12245v1

- 2D imaging of compton electrons for transversal polarization measurement.
- Distance to compton photons as energy measurement.
- Challenges:
  - Well understood magnet
  - Precise beam detector alignment
  - Well designed laser system.
  - Detector system to be developed

➢ Combined R&D effort between experiment and accelerator.

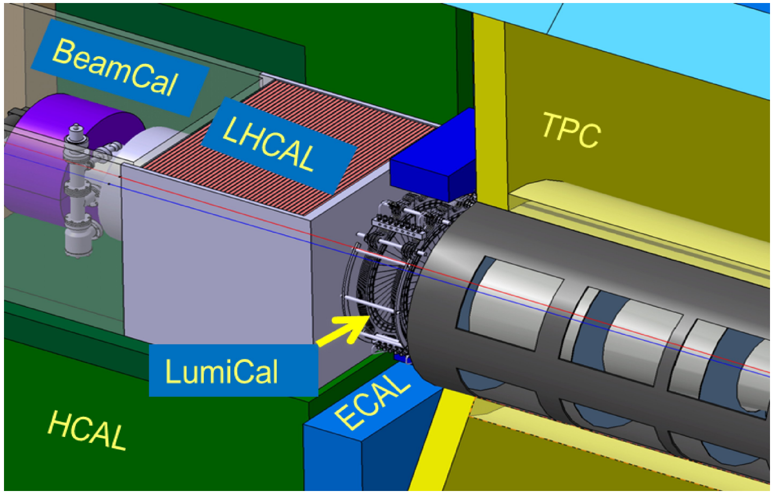


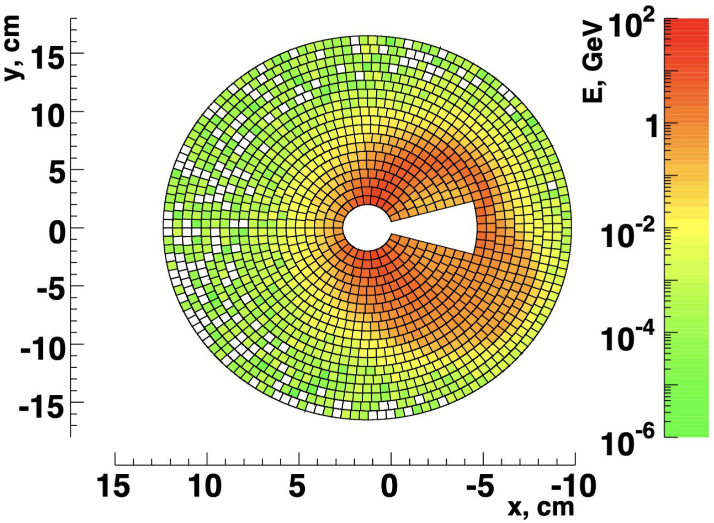


Beamstrahlung measurement

- Linear Collider detector concept: BeamCal to measure beamstrahlung bunch-by-bunch.
- Patterns in BeamCal depend on beam parameters.
- Extraction of beam parameters. [1]
  - Goal: very fast feedback (on ns level) for accelerator optimization.
- R&D:
  - Fast front end pattern processing.

- Beamstrahlung based beam parameter measurement at FCC-ee also highly relevant.
  - Significant R&D effort needed





[1] 2008 JINST 3 P10004

Radiation monitoring at experiment

- Motivation:
  - Shielding design, R2E, activation
- Constant monitoring not so critical (rate scales with luminosity)
  - ➢ Strategic particle type and spectral measurement campaigns beneficial
- Better understanding of radiation environment inside detector needed.
- Interplay with radiation simulations.
  - Benchmarking measurements needed to increase trust in simulation.
  - Interesting to design measurements strategically to improve on simulation imperfections.

R&D

- Further develop spectroscopic particle detectors:
  - e.g. Medipix based detectors with specialized conversion targets.
- Inside detector monitoring:
  - Small, rad-hard devices with low power consumption.
- On chip dosimetry & fluence measurement:
  - Development of radiation measurements fully integrated in FE electronics highly interesting.

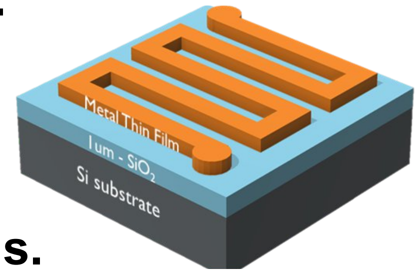
Radiation monitoring - R&D

- **Displacement damage in Silicon detectors scaling relies heavily on NIEL (1 MeV-n-eq)**
  - But: NIEL violating responses have been seen for certain devices.
  - R&D on better damage models very important. Needed for normalization of various irradiation types and to extrapolated to mixed field at colliders.
    - Research aspect tackled in AIDAinnova. [1]
- **New detector technologies and devices should be cross-checked against existing scaling rules.**
  - E.g. Diamond, sapphire, radiation monitoring devices,...
- **To compare irradiation studies at different particle types and energies, consolidated irradiation monitoring techniques crucial.**

[1] https://indico.cern.ch/event/1003419/

Radiation monitoring - R&D

- **Very high radiation levels expected at future experiments.**
  - FCC-hh: 10^{18} cm^{-2} 1Mev-n-eq, 300 MGy [1]
  - Current dosimeter and fluence monitors limited.
    - p-i-n diodes 10^{15} 1MeV-n-eq, RadFET ~100 kGy
- **R&D needed to develop devices to higher irradiation levels.**
  - e.g. Radiation dependent resistors as a possible NIEL monitor [2], Fiber based dosimeters (RaDFOS) [3]
  - PCB, bonding, cables, materials etc. need to be sufficiently rad hard.



[1] FCC CDR
[2] G. Gorine, CERN-THESIS-2020-040
[3] https://attract-eu.com/showroom/project/radiation-dosimetry-with-fiber-optic-sensors-radfos/

Irradiation facilities

- **Facilities include well understood infrastructure dedicated for irradiation tests with experienced manpower.**
  - Maintaining of facilities and know how is vital, even with future experiments far away.
  - Future needs being reviewed by the CERN Radiation Test Facility Steering Group [1]
- **Needed in the future: Facilities that can provide high radiation levels.**
  - Intense instantaneous beams: test BCMs, damage limits (e.g. HiRadMat)
  - Slow extracted beams / large gamma fields (e.g. IRRAD, GIF++)
  - High dose (many MGy) irradiation take a long time. Strong Co60 sources needed.
- **Improvement of quality of irradiation through standardization of exposure monitoring.**
  - Definition of monitoring technologies and evaluation techniques.
  - Cross calibration of irradiation facilities. [2]
  - Exchange of information (e.g. data management, common databases, etc.) [3]

[1] https://rtf-sg-info.web.cern.ch/
[2] https://indico.cern.ch/event/1003419/
[3] https://irradiation-facilities.web.cern.ch/

Radiation Simulation

- **Various radiation simulation tools available (FLUKA, MARS)**
  - Code maintenance and improvements important.
- **Radiation simulation is:**
  - Needed from early design phase
  - Gives a comprehensive picture, answers to things that can't or haven't been measured.
  - An essential tool to complement measurements.
- **Accelerator simulation and BIB radiation simulation:**
  - Input in experiment design (e.g. beam pipe, collimator/absorbers)
  - Definition of BIB monitoring goals (e.g. abort threshold)
- **R&D:**
  - Improving on cross sections
  - Event generators (at higher energies)
  - Consolidate radiation simulation with event simulation tools

Summary

- Collaboration of experiment and accelerator is vital in all aspects of beam condition monitoring.
- Radiation simulation is a vital tool to complement measurements
- Several different types of necessary beam monitoring systems
  - Requirements largely depend on accelerator type.
- Beam monitoring devices will need to profit from sensor R&D to cope with evermore challenging requirements.
- Irradiation facilities are vital for the development and qualification of new detectors with demanding requirements.

- **R&D needed on many aspects for all different kinds of beam condition and radiation monitoring.**